BNL-90966-2010

Proceedings of Pulsed Magnet Design and Measurement Workshop

T. Shaftan, R. Heese and S. Ozaki

Workshop on Pulsed Design and Measurement

July 27-28, 2009
Brookhaven National Laboratory, Upton, NY 11973

NSLS II

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

BNL-90966-2010

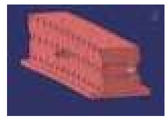
Proceedings of Pulsed Magnet Design and Measurement Workshop

T. Shaftan, R. Heese and S. Ozaki

BNL-2009

Pulsed Magnet Design and Measurement Workshop

(Brookhaven National Laboratory, July 27-28, 2009)



Attendees

- BNL NSLS-II: T. Shaftan, R. Heese, R. Fliller, G. Wang, S. Ozaki, G. Ganetis, I. Pinayev, A. Jain, D. Hseuh, S. Kowalski, M. Rehak, and S. Sharma.
- BNL NSLS: G. Rakowsky, and P. Zuhoski
- BNL CAD: A. Zhang
- BNL SMD: B. Parker
- SLAC: C. Burkhart, and A. DeLira
- KEK: A. Ueda, M. Shimada, and T. Miyajima
- TLS: J.-R. Chen, and C.-C. Kuo
- Duke University: S. Mikhailov
- Tokyo University: H. Takaki

Pulsed Magnet Design and Measurement (PMDM) Workshop Schedule

Monday	27-July	
8:30-8:50 am	F. Willeke	Welcome and workshop goal
8:50-9:15 am	T. Shaftan	NSLS-II injection system
9:15-9:35 am	R. Heese	NSLS-II pulsed magnets
9:35-9:50	S. Kowalski	Septum/Bumps Circuit Topology and Simulations
9:50-10:15 am	R.P. Fliller	Feasibility of NSLS-II injection scheme via pulsed sextupole magnet
10:15-11:00 am	J.-R. Chen	Pulsed magnets of the Taiwan Photon Source

11:00-11:20 am		*Break*
11:20-12:20 am	S. Mikhailov	Design and performance of fast injection- and extraction-kickers at Duke FEL/HIGS facility
12:20-1:35 pm		*Lunch*
1:35-2:20 pm	A. Ueda	Pulsed magnets for the photon factory (PF) at KEK
2:20-3:05 pm	H. Takaki	Design and field measurement of the PSM at the PF-ring
3:05-4:05 pm	H. Takaki	Results of the PSM operation at the PF-ring
4:05-5:35 pm	All attendees	Discussion on NSLS-II's pulsed magnet design
6:00 pm -		*Dinner*
Tuesday	28-July	
8:30-9:15 am	C. Burkhart/ A. DeLira	SLAC kicker systems applicable to NSLS2 requirements
9:15-10:00 am	A. Jain	Field measurements in pulsed magnets
10:00-10:45 am	A. Wu	Looking forward
10:45-11:00 am		*Break*
11:00-12:10 pm	R. Heese	Tour of PML
12:10-1:25 pm	All attendees	*Lunch*
1:25-2:25 pm	A. Jain	Tour of RHIC
2:25-3:55 pm	All attendees	Discussion on NSLS-II pulsed magnet measurement
3:55-4:15 pm	All attendees	*Closing comments*

Abstracts

Welcome and Workshop Goals,
F. Willeke, NSLS-II, BNL

The goals of the Workshop are to assess the design of pulsed system at the NSLS-II and establish mitigation strategies for critical issues during development. The focus of the Workshop is on resolving questions related to the set-up of the pulsed magnet laboratory, on measuring the pulsed magnet's current waveforms and fields, and on achieving tight tolerances on the magnet's alignment and field quality.

NSLS-II injection system,
T. Shaftan, NSLS-II, BNL

The presentation offers an overview of the NSLS-II injector and gives the specifications on the injector's parameters.

NSLS-II pulsed magnets,

R. Heese, NSLS-II, BNL

The talk details the NSLS-II's pulsed-magnet systems, their parameters, tolerances, and designs.

Sextupole magnet,

R.P. Fliller, NSLS-II, BNL

We investigated using pulsed multipoles to inject into the storage ring, an idea pioneered at the Photon Factory at KEK. A pulsed sextupole has the advantage that the field and gradient is zero at the center of the magnet and rises quickly off axis. We present a detailed analysis of a pulsed sextupole injection scheme for the NSLS-II storage ring. This analysis shows that the beam motion requirements on the stored beam can be met with precise alignment of the sextupole. This is weighed against difficulties in constructing the transport line. On particular, the strong position dependant gradient at the location of the injected beam makes the transport line difficult to construct and operate reliably.

Other pulsed injection schemes were also studied and are briefly discussed in this presentation.

The pulsed magnets of the Taiwan Photon Source,

J.-R. Chen, C.-K. Chan, C.-S. Chang, H.-P. Chang, P.-J. Chou, C.-S. Fan, J.-C. Huang, C.-C. Kuo, K.-K. Lin, Y.-H. Liu, G.-Y. Hsiung, and C.-S. Yang, National Synchrotron Radiation Research Center, Hsinchu 300, Taiwan

Studies were conducted to construct the Taiwan Photon Source (TPS), a 3 GeV synchrotron-light source with an emittance of 1.7 nm-rad. Among the many important parameters, a high-performance, top-up mode injection is essential to users. This report discusses the design of the pulse magnets of the TPS. The successful results are shown of reducing the stray fields, minimizing the noise, lowering the time jitter, and improving the components' reliability. The presentation also covers experiences at the Taiwan Light Source, a recently upgraded 1.5 GeV machine with top-up injection mode.

Design and performance of fast injection- and extraction-kickers at Duke FEL/HIGS facility,

S. Mikhailov, Duke University
PO Box 90319, Duke University, Durham, North Carolina 27708-0319

The Duke FEL/HIGS (Free Electron Laser/High Intensity Gamma-ray Source) facility has recently undergone through a series of major upgrades. As a part of this upgrade, a kicker system was designed to provide reliable injection from the booster into the storage ring at any chosen energy in the range between 240 MeV and 1.2 GeV. The kickers had to comply with a rather challenging specification, requiring a low jitter of about 1 nS, and a pulse as short as 15 nS for extraction, and 100 nS for injection. The extraction kickers also needed a large dynamic range of the high voltage magnitude covering 4-30 kV. The kicker system was designed and fabricated by Budker Institute of Nuclear Physics, Novosibirsk, Russia. We discuss our experience with the Duke kicker system design and operation in the prospective of their relevance for the NSLS II-kicker system.

Pulsed magnets for the photon factory (PF) at KEK,

A. Ueda, KEK, High Energy Accelerator Research Organization 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

I'll talk about the pulse magnets for the photon factory at KEK without the pulse sextupole magnet. (Dr. H. Takaki is going to talk about the pulsed sextuple magnet into detail.) Kicker magnets: low impedance out-vacuum traveling wave type kicker magnet Septum magnets: passive septum magnet with magnetic shield And I'll mention outline of the other pulse magnets Pulse bending magnet at the Linac Kicker and septum magnets at PF Advanced Ring.

Design and field measurement of the PSM at the PF-ring and Results of the PSM operation at the PF-ring,

H.Takaki, Synchrotron Radiation Laboratory (SRL), Institute for Solid State Physics(ISSP), University of Tokyo 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

This talk discusses three main topics:
The stored beam stability with the PSM injection at the PF-ring; issues with pulsed magnet injection; and a case study of the possibility of PSM injection at the NSLS-II.

SLAC kicker systems applicable to NSLS2 requirements, (lower case for words as above)

C. Burkhart and A. de Lira, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025

The parameters of several SLAC kicker systems are similar to those required for the NSLS2. The SPEAR3 injection kickers employ adder-type solid-state modulators, shorted strip-line kickers, and matched impedance loads. They generate 0.8 μs, 2- to 3-kA flattop pulses with a rise and fall of less than 0.4 μs. The damping-ring injection/extraction kickers of the SLAC linac are based on thyratron- switched PFLs that drive matched-impedance, ferrite-loaded kickers. At SLAC, these systems produce ~3 kA, 150 ns flattop pulses with ~60 ns rise/fall time. A modified version of this kicker system at KEK delivers 0.3 μs pulses. The LCLS's BXKIK and BYKIK systems for selective beam-bunch-dumping mate an IGBT-based solid-state modulator to an inductive kicker magnet. The systems produce a sinusoidal pulse with a period of 400 μs and up to 0.5 kA current. The design of these kicker systems, modulators and magnets, discussed.

Field measurements in pulsed magnets,

A. Jain, Superconducting Magnet Division, BNL

Field quality in accelerator magnets often is expressed in terms of harmonics that is measured very conveniently using rotating coils. However, this technique is unsuitable for fast changing fields, since the typical measurement time is several seconds. For pulsed magnets, a suitable technique must be based on the time scales of interest. For data-sampling rates in the KHz range, analog Hall probes can be employed. A non-rotating pick up coil of a suitable design will measure both the strength of the main field, and the homogeneity of the field (harmonics), over a very wide range of field strengths and time scales. Some examples are presented of recent measurements with sampling rates ranging from several tens of milliseconds to a few microseconds.

Looking forward,

W. Zhang and J. Sandberg, CAD, BNL

Repetitive-pulsed power technology is one of the fast growing areas in accelerator engineering. A trend analysis is described, and a brief review of history given. Recommendations are offered based on the NSLS II's requirements, the technology landscape, as well as our R&D, project management, and operational experiences.

Workshop Notes

Disclaimer: These notes were taken during two discussions at the PMDM Workshop. Their intent is to informally answer the questions that the workshop focused on; they are not flow coherently, but rather represent the most important questions, answers, and comments as the discussions evolved. The Workshop participants are responsible for correcting and revising the text if they feel any changes are necessary. We welcome comments and suggestions.

Glossary: Q=question, A=answer, C=comment

Q	**Did anybody use glass or quartz vacuum chamber for out-of-vacuum pulsed magnet?**	R. Heese
A	Ceramics is the usual solution.	all
C	Duke University adopted a different solution, viz., a 10-inch diameter, 40 cm long glass with a 10-µs pulsed magnet. This design always works well. In addition, quartz can be a solution, as it is easy to weld.	I. Pinayev
Q	What about the thermal properties of the glass material? Has anybody considered the heating the internal coating from the beam and pulsed power?	B. Sheehy
C	LCLS kicker's chambers, made from aluminum, are 1 m long with a 1 inch cross-section. However, the duration of the pulse is very slow (about 400 µs response time).	C. Burkhart
C	The vacuum-chamber's ceramic is very expensive (30-50 k$). What are the prices for the quartz materials?	R. Heese
A	We are waiting for pricing from the vendors.	J. Skaritka
Q	Where does NSLS-II plan to place the kicker modulators?	C. Burkhart
A	Below the kicker magnets, inside the storage-ring's injection girder.	R. Heese
Q	Are the parameters of the NSLS-II pulsed magnets fixed or are they still evolving?	Z. Wu
A	The main parameters of the magnets are defined by the injection/extraction straight-section geometry. However, optimization of the pulsed magnets and their kicker parameters is ongoing, and will continue until Final Design review in 2011.	T. Shaftan
Q	**What is the experience using SCRs on pulse-to-pulse timing jitter?**	G. Ganetis
A	The minimum achieved jitter is about 0.5ns for pulsed-magnet systems. This is possible with the Thyrotron systems, but difficult with the SCR-based systems.	S. Mikhailov

Q	What is the experience with short-pulse kickers at the Taiwan Photon Source? Why they chose to develop in-vacuum rather than out-of-vacuum extraction kickers for their booster?	T. Shaftan
A	We found that using a modulator-driving voltage higher than 25 kV results in poor reliability of the system. Thus, we designed kicker magnets with smallest possible aperture so to minimize the required voltage.	J.R. Chen
Q	**Have you considered other ceramics for the vacuum-chamber material?**	B. Sheehy
A	A Japanese company manufactured our ceramic chambers. We are investigating opportunities for producing and coating the ceramic chambers at other companies.	J.R. Chen
C	Comment: 25 kV is indeed the limiting voltage beyond which we might expect a dramatic reduction in the reliability of the pulsed system.	S. Mikhailov
C	Comment: To reduce stray fields from a pulsed magnet, a 0.35 mm silicon steel covers the KEK's 2mm septum copper coil. This has reduced the stray field, which was at the level of 350 Gs, to below 10 Gs. The high magnetic permeability of the silicon-steel helps in shielding the septum field.	A. Ueda
Q	Question to A. Ueda: Did you try high-pressure epoxy impregnation? Can this method help to prevent voids in the epoxy?	S. Mikhailov
A	That method would help. However, KEK did not use pressure impregnation for kicker high-voltage cells.	
Q	Question to H. Takaki: How was the location of PSM chosen in the lattice? In passing the PSM, does the injected beam see a different tune relative to the stored beam?	I. Pinayev
A	This consideration was taken into account during testing the PSM arrangement via one-turn tracking, which gave exact phase advance.	
C	Comment: The PSM experiment demonstrated that the injection rate with PSM is equal to approximately half of the rate with a conventional four-kicker bump.	H. Takaki
C	Comment: Also: The requirement of having a high rate of PSM injection severely restricts the choice of suitable betatron tunes for the PF ring.	
Q	Which bunch pattern was used for the PSM experiments, a single bunch or s train of bunches?	T. Shaftan
A	A single bunch was used.	H. Takaki
Q	What is the actual accuracy of measurement of PSM field?	T. Shaftan
Q	What is the accuracy of determining the PSM axis?	

A	The mechanical accuracy of the alignment fiducial on the PSM is better than 50 µm. The actual accuracy of measurements of the PSM field apparently is difficult to estimate.	H. Takaki
Q	**What are consequences of driving all four kickers in parallel using a single, high-current power supply?**	R. Heese
Q	In particular, how can you compensate for realistic differences between the kickers in terms of waveforms and timing?	B. Parker
A	One way to equalize the kicker fields is to shunt the others, rather than the weakest kicker. The shunting procedure should be transparent so the shunts can be retuned whenever this is required.	R. Heese
C	Comment: Duke University employs a composite kicker magnet with two coils. . Field oscillations between them make matching difficult.	I. Pinayev
C	The issue here is how to develop identical magnets, together with identical vacuum chambers. The complete four-kicker system can be characterized via beam-based measurement.	S. Mikhailov
Q	**Requirements for such a power supply driving all four kickers are 24 kA, 4 kA/µs, 3.6 kV half-sine. What are the potential issues with such supplies?**	T. Shaftan
A	A high current rate is needed. However, there exist IGCT devices that can generate 10kA/µs and these devices can operate at 6.5 kV. The high-voltage switch will see double voltage, but then an IGCT could be used (ABB will sell a stack of voltage).	C. Burkhart
A	Differences in kickers are adjustable by correcting the inductive loads on every magnet. However, this method has limited Not adjustable.	R. Heese
C	Comment: What was missing in the scheme presented in Steve Kowalski's talk are the parasitic losses; these losses make kicker systems different from device to device.	C. Burkhart
C	Comment: However, if the kickers + drivers can be made identical, using the same technology the losses can be made nearly identical for different devices.	S. Mikhailov
C	Comment: Driving all SCRs with a single pulser does not seem to be a good idea because of the potential mismatch.	B. Sheehy
A	Comment: Actually, this design is feasible if all kind of waveforms and field corrections are built into the pulsed-system’s design.	S. Mikhailov
A	Comment: You can minimize differences between different devices by fully optimizing the device’s parameters; a) using field- and current-measurements, and, b) characterizing the device’s performance using beam-based methods.	T. Shaftan

Q	**How accurately can storage-ring kickers be aligned?**	T. Shaftan
A	One way of correcting an undesirable horizontal field lies in using the skew dipole scheme of Bx correction.	R. Heese
C	Comment: The disadvantage of that scheme is the need of continuously monitoring the kickers' alignment.	I. Pinayev
C	Comment: There are limitations on the accuracy of alignment. There can be a 10 um discrepancy or worse in alignment between the survey on the measurement bench and then rechecking magnet survey in the tunnel.	S. Mikhailov
C	Comment: The measurement coils can be calibrated to increase accuracy of the alignment in the following way: Start with DC measurements, then make AC measurement with a sinusoidal current, and lastly measure the actual pulse to calibrate the coils.	S. Mikhailov
C	The last stage of the alignment is a final alignment with the electron beam.	S. Mikhailov
Q	What are the magnet errors achieved at the TPS?	T. Shaftan
A	TPS achieved about 1% of differences in the field amplitude; every kicker sits on its own positioning stage. The alignment accuracy then is limited to few µm across of 30 cm. Accelerator physicists set the specifications for acceptable kicker errors; nobody discussed these tolerances with the TPS users.	J.R. Chen
Q	How can you bleed the current off to feed the correction coils in a kicker?	C. Burkhart
A	We considered making slim correction coils (single turn) fed consecutively for the same power supply through a shunt so to adjust the amount of current flowing through the correction coil.	R. Heese
Q	How do you keep current in phase with the main pulse using correction coils?	C. Burkhart
A	If this appears to be a problem, we can consider using separate drivers for correction coils driven by a half-sine waveform.	R. Heese
Q	**Let us discuss the booster extraction kicker that requires 0.2% of the waveform flatness along the 300 ns-long portion of the kicker pulse (200 ns rise time, 300 ns flattop) so not to spoil the extracted beam's emittance.**	T. Shaftan
C	Adjusting the driver's impedance might compensate for the droop.	I. Pinayev
C	The CERN kicker assures 1% of the flattop's flatness.	Z. Wu
C	I believe that a 1% value is achievable.	P. Zuhosky
C	I concur that 1% is achievable; however, we did not specify this tolerance for the TPS machine.	J.R. Chen
C	Less than 1% is very difficult since it may take a lot of stages in the kicker's modulator.	S. Mikhailov

C	The NLC's kickers had 60 cells generating pulses 2-3 μs long.	C. Burkhart
C	The kicker-to-load distance is equivalent to the second pulse being ~100ns away. Therefore, a load mismatch will affect the pulse later.	C. Burkhart
C	The measured DCCT signal does not represent correctly the actual field waveform seen by the beam. Filtering out modulation through the kicker ferrite and the coating limits the bandwidth.	S. Mikhailov
Q	**If we assume that the modulator violates the specification, can we consider some kind of a correction circuit to correct the waveform modulation and slew?**	T. Shaftan
C	As we discussed, a separate correction magnet might be installed later in the beamline.	R. Heese
C	Rather than the magnet, which will require a ceramic break, a correction stripline might be developed with Z= 50 Ohm and high-power electronics for generating a programmable waveform.	T. Shaftan
C	This problem also can be solved by two extraction kickers with the same waveforms shifted by 1/2 period of modulation. Then, the second kicker's waveform will cancel the modulation of the bunch-to-bunch angle induced by the first kicker's nonuniform waveform.	J.R. Chen
C	A similar technique was used in the instrumentation of the NSLS's EPW (Elliptical Polarized Wiggler).	G. Rakowsky
C	In searching for a flat waveform, PFL might be used rather than PFN. It will take shaping a water line for 2 kA and 20 kV (10 Ohm impedance); for example, 150 ns is equivalent to 11 feet of water line. The challenge is using PFL is that it is not a constant impedance, but this can be improved by changing the geometry of the PFL's inner conductor to match the required value of the impedance. On other hand, aging of the PF can be a problem for the long-term operations.	C. Burkhart
C	A reduction in PS voltage is highly rewarding; to do so requires minimizing the magnet's aperture and, in turn, going to the in-vacuum magnet design. Advantageously, the in-vacuum fast kicker design is simple and perhaps less expensive than other designs. However, ferrite might be damaged by synchrotron radiation; hence, this needs to be checked.	J.R. Chen
	The voltage specifications are 12 kV for 100 ns rise time for the booster injection and extraction kickers. The charge voltage on the line is twice that of the required voltage on the magnet = 12 kV x 2= 24 kV. There are 70 kV/2 kA thyrotrons, which are discussed on the E2V's website. An issue is the required current rate, viz., dI/dt=20A/ns, which will be hard to meet. A two-gap thyrotron may be a good resolution for 10 kA/μs. We recommend calling E2V and asking if they have anything with 20 kA/ns.	C. Burkhart

C	Some other recommendations are exploring solid-state options. Adder is a good solution.	C. Burkhart
Q	**For the injection into the booster we are considering the four-kicker scheme that has not been used before in this context. What issues do you see with this scheme? We are planning on feeding two neighboring kickers with the same power supply because there are difficulties in controlling two pulses independently.**	T. Shaftan
C	The NSLS-II linac will generate high-charge beams with the longitudinal phase-space dominated by the energy droop along the bunch train. This may affect beam stacking using the four kickers.	I. Pinayev
C	A 50 kV thyrotron exists that can be used in the pulser simultaneously for both kickers. Its use requires prior analyses.	C. Burkhart
C	These will be relatively low-field devices, wherein magnet hysteresis may play a role in the mismatch between different kickers.	C. Burkhart
C	Hysteresis is very small at 500 Gs.	S. Mikhailov
C	The ferrite material CMD5005 is of the highest quality and has the smallest hysteresis.	R. Heese
C	Cable losses must be taken into account that may be quite significant for long lengths. For example, 100 feet of cable used in kicker system BYKIK (SLAC) result in large losses in the cable, equivalent to about 0.5 Ohm.	C. Burkhart
C	IGBTs may be of interest to use in such devices. Upeck (Mitsubishi) manufactures them.	C. Burkhart
C	Glazman, Lambda (ILE) produces IGBTs operating at 3.3 kV; even 6.5 kV versions of them exist.	A. DeLira
C	We use two-stage modulator with IGBT on first stage and Thyratron on the second stage, which may be useful. In the analysis of such a scheme, it may be important to explore the prepulse, relevant to energy transfer from the 1st to 2nd stage.	C. Burkhart
Q	**Two or four kickers in parallel may cause reflections between the different devices.**	A. De Lira
A	This can be carefully modeled in circuit analysis to see the importance of the effect.	G. Ganetis
A	AC measurements of the coupling between the magnets can help in minimizing the coupling.	S. Mikhailov
C	A back-up plan is needed for four separate modulators for the storage-ring kickers.	G. Ganetis

Q	**Let us discuss methods of the online measurement of kicker fields.**	T. Shaftan
C	The measurement circuit at Duke University uses 8 coils with BNC connectors on the ends. By subtracting the readings, this scheme allows us to deduce the aging of the pulsed-magnet ferrites.	S. Mikhailov
C	Today's Hall probes can measure magnetic fields in the MHz or even 10s MHz range. At these high frequencies, we must be careful with twisting the coils and creating other problems that might limit the bandwidth.	S. Mikhailov
C	Impedances in GOhm range define the time-constant of a measurement circuit. Therefore, the measurement circuitry must be analyzed carefully for any particular case.	A. Jain
C	There are several manufactures of fast transformers: Pierson from Palo-Alto Cal, Bergoz in GHz range. Stangenes also has them with a 2 ns bandwidth limit. To match the measurement device bandwidth we should buy 1 GHz and a10-bit digitizer.	G. Ganetis
C	To characterize the high-frequency modulation of the kicker waveform we could try offsetting the transformer pulse.	B. Sheehy
C	Another way to do this is to subtract the averaged (HF filterer) pulse from the measured pulse.	T. Shaftan
C	Aquarius sells a 3 GHz 10-bit digitizer.	B. Sheehy
Q	A problem with the Pulsed Sextupole Magnet lies in measuring the zero-field point at the maximum current.	H. Takaki
A	We considered building a differential coil with symmetric loop geometry to subtract fluxes from the two opposite halves of the magnet.	R. Heese
A	We at KEK are using a measurement system consisting of a coil and a filter.	H. Takaki
C	Commenting on storage-ring kickers that require very high precision on alignment and field quality, we note that the kicker field will change pulse-to-pulse as determined by hysteresis in ferrite. Hence, the actual BH curve must be taken into account while estimating the achievable tolerances for the kicker-magnet's design.	S. Mikhailov
C	Another comment is that defining the multipole magnetic center itself is quite unclear when the range of interest is only tens of microns. Thus, the center of the pulsed sextupole magnet may be determined only with limited accuracy (potentially limited to μm or so).	T. Shaftan, S. Mikhailov
Q	**How can we measure fields with accuracies of 0.1% of waveform in amplitude and time?**	G. Ganetis
C	We might employ a differential way by comparing the measurements between different kickers. Another differential method is to use two zero-flux transformers.	S. Mikhailov

C	DCCT's and Pierson's white band current transducers reach a measurement reproducibility of 1E-4 peak-to-peak.	G. Ganetis
C	A problem here might be shot-to-shot stability of the kicker waveforms at this level.	P. Zuhosky
C	A laminate construction might be used rather than ferrite. The permeability of this kind of material is much higher, thereby resulting in better magnetic properties. Hitachi produces a material called Finemet, including 3 different major classes of these materials with different anneals.	C. Burkhart
C	These magnetic materials were discussed by Hitachi at the PAC-2009 conference. We are considering to electrically discharge machine (EDM) the actual kicker's shape or cut it with a laser.	R. Heese
Q	**Temperature compensation of the pulsed magnets must be considered to achieve such high levels of the measurement accuracy. Also, aging of the magnets may necessitate online adjustment of power supplies.**	G. Ganetis
C	The kicker magnet's alignment can be lost within 5 min of operating at the 10 urad level.	I. Pinayev
C	The tunnel temperature is well maintained, within 0.1 degree. This will stabilize the performance of the magnet and driver.	G. Ganetis
C	The NSRRC achieves temperature stability within 0.1 deg.	J.R. Chen
Q	**What are your thoughts on measuring the parameters of thyrotrons?**	G. Ganetis
C	A bench procedure for assessing jitters in the switching devices should be developed before formulating the kicker drivers. For example, IGBTs exhibit a 2-ns jitter.	C. Burkhart
C	One way to resolve problems with the high dIdt in thyrotrons is to use a small magnetic switch in parallel with thyrotron ("saturable reactor") working whilst the thyrotron turns on.	C. Burkhart

NSLS-II pulsed magnet parameters as of July 2009

Pulsed Magnet/Parameter	Numbers required		Bend Angle (mR)		Length (m)		Max. Field (T)		Bend Radius (m)
Ring Injection Kicker (bump)	4		7.85		0.5		0.157		63.678
Ring Injection Septum	1		40		0.8		0.5		20
Ring Injection Septum DC	1		150		1.8		0.833		12
Pulsed Sextupole	1		2.83		0.5		0.055 @ 8.5mm		
Booster Extraction Slow Bump	4		7.5		0.2		0.375		26.667
Booster Extraction Kicker	1		5		1		0.05		200
Booster Extraction Septum	1		48		0.6		0.8		12.5
Booster Extraction Septum - DC	1		96		1		1.009		10.417
Booster Injection Septum	1		142.5		0.75		0.127		5.263
Booster Injection Kicker	1		7.5		0.2		0.025		26.67

Pulsed Magnet/Parameter	Horizontal Aperture (mm)		Vertical Aperture (mm)		Imax (A) or A-T		Pulse shape
Ring Injection Kicker (bump)	65		27		3710		1/2 sine
Ring Injection Septum	32		23		11810		Full sine
Ring Injection Septum DC	50		20		191.5 x 80 A-T		DC
Pulsed Sextupole	27		27		3200		1/2 sine
Booster Extraction Slow Bump	50		25		411 x 20 A-T		1/2 sine
Booster Extraction Kicker	50		25		1100		<200 ns risetime, 300 ns flat-top

Booster Extraction Septum	32		23		16100		1/2 sine
Booster Extraction Septum - DC	50		20		220.6 x 80 A-T		DC
Booster Injection Septum	20		15		1800		Full sine
Booster Injection Kicker	50		25		600		100 ns rise/fall time, 300 ns flat-top

Pulsed Magnet/Parameter	Pulse length (μs)		Inductance (μH)		Drive Voltage (kV)		Drive Capacitance (μF)
Ring Injection Kicker (bump)	5.2		1.513		3.525		1.675
Ring Injection Septum	100		1.191		0.885		212.6
Ring Injection Septum - DC							
Pulsed Sextupole	5.2		14		27		
Booster Extraction Slow Bump	1000		201		0.025 - 0.030		504
Booster Extraction Kicker			2.513		19.62 at magnet		n/a
Booster Extraction Septum	60		1.049		0.885		348
Booster Extraction Septum - DC							
Booster Injection Septum	150		1.257		0.175		114
Booster Injection Kicker			0.754		4.5 at magnet*		n/a

Names and contact information of the participants

Attendees	phone	Org.	E-mail
C. Burkhart	1 650 926-3212	SLAC	burkhart@slac.stanford.edu
J. R. Chen	(03)578-0281 (6323)	NSRRC	jrchen@nsrrc.org.tw
A. De Lira	1 650 926-3463	SLAC	aclira2000@gmail.com
R. Fliller	1 631 344 2356	BNL	rfliller@bnl.gov
G. Ganetis	1 631 344 4476	BNL	ganetis@bnl.gov
R. Heese	1 631 344 4902	BNL	rheese@bnl.gov
D. Hseuh	1 631 344 4890	BNL	hseuh@bnl.gov
A. Jain	1 631 344-7329	BNL	jain@bnl.gov
S. Kowalski	1 631 344 4834	BNL	skowalski@bnl.gov
C.C. Kuo	(03)578-0281 (6323)	NSRRC	cckuo@nsrrc.org.tw
S. Mikhailov	1 919 660-2647	Duke University	smikhail@fel.duke.edu
T. Miyajima	+81-29-864-5200	KEK	tsukasa.miyajima@kek.jp
S. Ozaki	1 631 344 5590	BNL	ozaki@bnl.gov
B. Parker	1 631 344-3231	BNL	parker@bnl.gov
I. Pinayev	1 631 344 5706	BNL	pinayev@bnl.gov
G. Rakowsky	1 631 344-5298	BNL	rakowsky1@bnl.gov
M. Rehak	1 631 344 4708	BNL	rossum@bnl.gov
T. Shaftan	1 631 344 5144	BNL	tshaftan@bnl.gov
S. Sharma	1 631 344 4423	BNL	sharma@bnl.gov
B. Sheehy	1 631 344 3720	BNL	sheehy@bnl.gov
M. Shimada	+81-29-864-3880	KEK	miho.shimada@kek.jp
H. Takaki	+81-4-7136-3563	Tokyo University	takaki@issp.u-tokyo.ac.jp
A. Ueda	+81-29-864-5651	KEK	akira.ueda@kek.jp
G. Wang	1 631 344-7329	BNL	gwang@bnl.gov
F. Willeke	1 631 344 2216	BNL	willeke@bnl.gov
A. Wu	1 631 344-5369	BNL	arling@bnl.gov
P. Zuhosky	1 631 344-4742	BNL	zuhoskip@bnl.gov


LIGHT SOURCES DIRECTORATE
NSLS-II
PROJECT OFFICE
817

Pulsed Magnet Design and Measurement Workshop

Brookhaven National Laboratory, July 27-28, 2009

Workshop Goals

F. Willeke, NSLS-II AS Division Head

Introduction

NSLS-II Main Design Features and Requirements:

- 3GeV Beam Energy
- Small emittance <1nm, 10% relative stability
- Large beam current,
- Touschek limited lifetime,
- Frequent (top-off) Injection

➔ **Requirement on Injection System**

Present Status and Time Line

- Building construction in Progress
- Procurement of major components (linac, booster, magnets, vacuum chambers in progress)
- Production of components in 2010-2011
- Installation 2011-2012
- Testing and commissioning 2013-2014

Requirement on Injection System

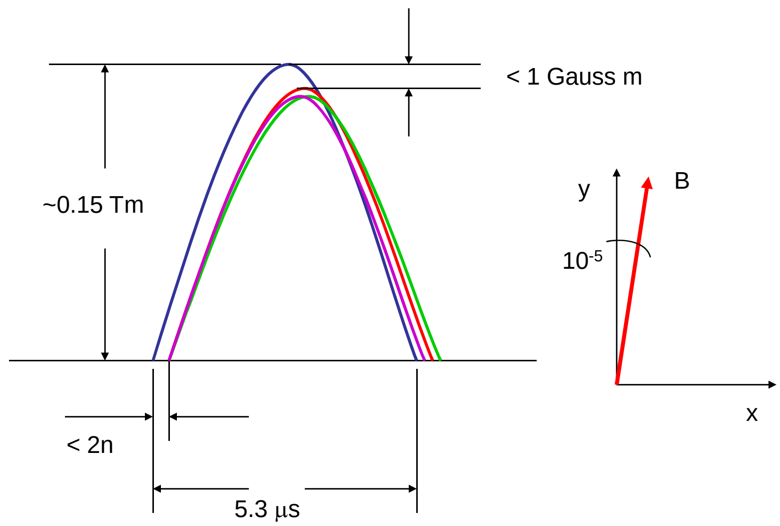
- Injected beam oscillates within a 10mm aperture (measured in centre of long straight)
- Stored beam should not oscillate more than 10% of its size
  σ_x~100μm, σ_y~5μm

→ Rel Kicker Amplitude Precision (kicker-to kicker over entire pulse referring to peak)
10^{-3} horizontal (over pulse referring to peak)

→ Field Angle
$5 \cdot 10^{-5}$ vertical (field angle)

→ Timing precision and stability <2ns
(kicker-to-kicker)

Schematics of Kicker Bump



Workshop Goals

- Discussion of alternative injection schemes, dipole kickers, nonlinear kickers, DC Bump ….
- Pulsers: Discussion of Switching Technology
- Pulse Shaping Methods: PFN, Cable Discharge, others
- Quest of Pulsed Correction Circuits
- How to achieve idential pulse shapes and amplitudes?
- How to measure and verify

Biggest Challenge: Field Direction (~1E-5)

Injector Overview

T. Shaftan
Injector group leader
Pulsed Magnets Design and Measurement Workshop
July 27-28, 2009

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

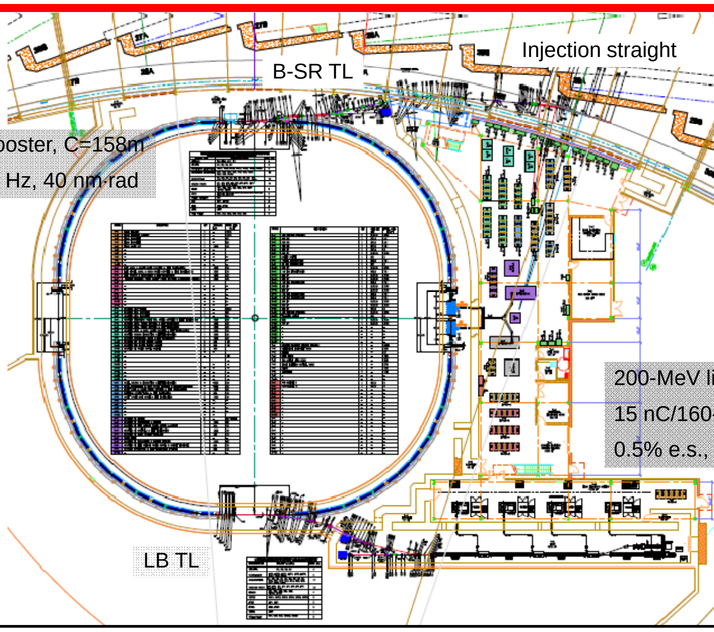
Scope Overview

- NSLS-II requires a reliable injector capable of filling and maintaining storage ring current. Top-off mode of injection is required
- Specifications for NSLS-II injector
  - Storage ring: 3 GeV, 0.5 A, 1080 bunches in 1320 RF buckets, 3 hr lifetime
  - Top-off: deliver 80…150 bunches with 7.3 nC total charge once a minute → total stability of ring current 0.55%, bunch-to-bunch charge deviation 20%
  - Repetition rate of 1 Hz (initial fill 0 → 0.5 A in 3 min)
- Supported Storage Ring Bunch patterns:
  - Baseline: uniform fill with 20% ion-clearing gap
  - Baseline: 4-5 bunch trains with short gaps
  - Future upgrade: camshaft bunch(es), uniform fill
  - Future upgrade: Bunch cleaning, Empty/Full RF bucket charge ratio 0.01%
- Injector scope:
  - 200-MeV linac with 100-keV thermionic gun
  - Linac-to-booster transport line
  - 3-GeV booster
  - Booster-to-Storage ring transport line
  - Storage ring injection straight section

U.S. DEPARTMENT OF ENERGY

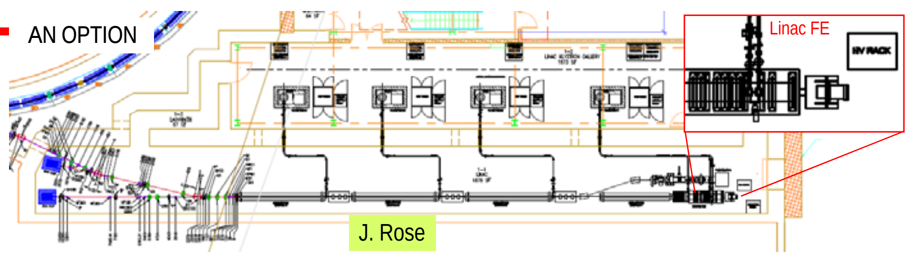
BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

NSLS-II injection system



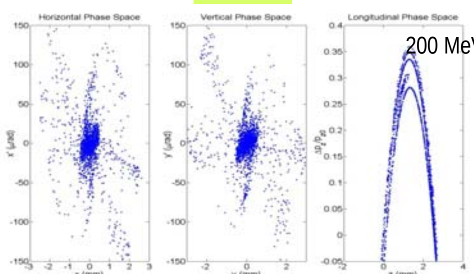
Linac

AN OPTION



- Procurement is under way
- Design and Modeling
  - Linac model is developed
  - Linac beam dynamics study completed
  - Linac Front-End diagnostics station design is assessed
  - Set-points and tolerances
  - Initial conditions for transport line
  - Diagnostics performance

R. Fliller



U.S. DEPARTMENT OF ENERGY

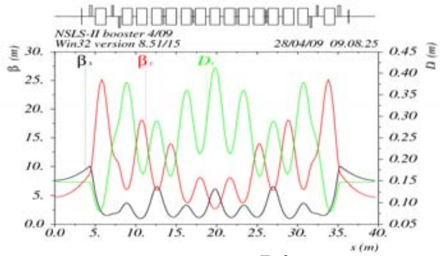
BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Booster

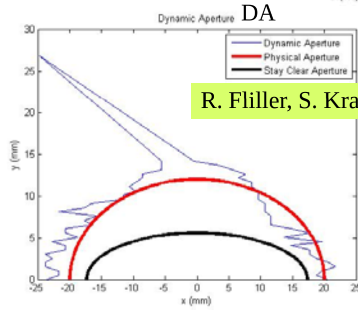
- Design is completed
- Final lattice has been developed
- Lattice is tested with realistic errors (150µm misalignments, 0.2 mrad rolls, 0.02% in B, 0.5% in Q)
- Orbit correction scheme is efficient
- Conclusion: booster lattice is robust and has sufficient DA for injection
- Turn-key procurement

- Injection
  - Septum
  - 4-kicker bump
  - Beam stacking
- Extraction
  - Septum
  - Slow 4-magnet bump
  - Kicker

Final lattice



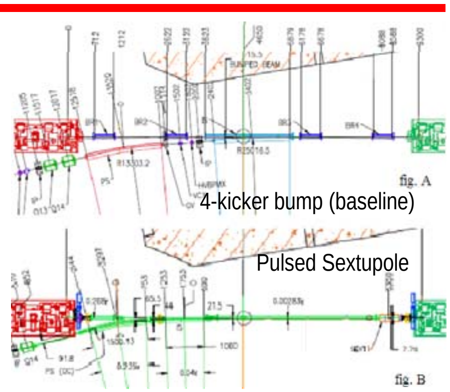
DA



R. Fliller, S. Kramer

Storage ring injection straight section

- Pulsed magnet tolerances were estimated
- To keep the disturbance of the electron beam below 0.1 of the beam size:
  - 1E-4 in relative kicker amplitude mismatch
  - 12 µrad in the tilt angle of the kicker magnet.
- Other LS run with much weaker tolerances
- Feasibility studies of "quiet" magnets to begin once PML is available
- Alternative idea of injection via Pulsed Sextupole (PSM, as in KEK) have been studied as an option
  - Injection straight section layout is altered to accommodate new scheme
  - Magnet parameters are calculated; magnetic design is completed
- Search for advanced PSM schemes
  - Reduce magnet inductance (and V_{PS})
  - Reduce focusing of injected beam

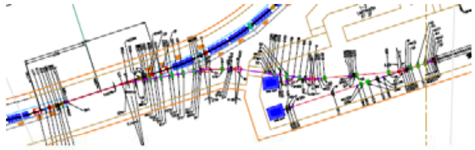


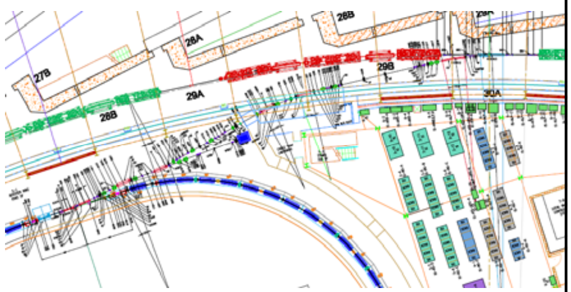
Pulsed Sextupole optimization

Transport lines

- List of TL components below
- Diagnostics TLs will be used for linac and booster commissioning

TL equipment	LTB	BSR
Dipole	4	4
Quad	17	16
Corrector	10	17
Dipole PS	1+1	4
Quad PS	12+6	12+4
Corrector PS	9x2	9x2
ICT	2	2
FCT	2	2
BPM	6	7
Flag	9	9
Energy slit	1	1
Pumps	10	11
Gauges	3	4
Valves	5	6
Dipole chambers	2	3
Chamber to dump - Y	2	1
Quadrupole pipes	8	7
BPM block machining	8	7
Drift pipes	18	27





U.S. DEPARTMENT OF ENERGY

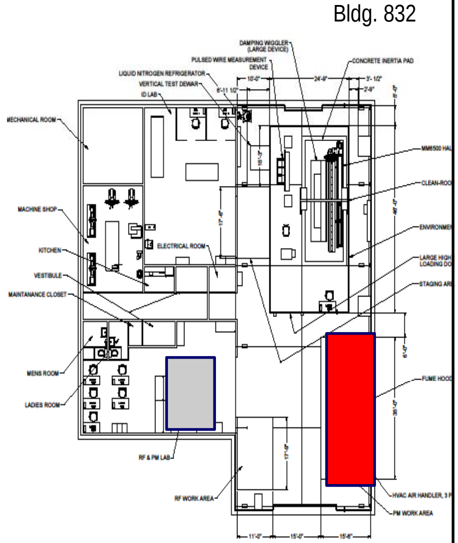
7

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Pulsed Magnet Lab Status

- Pulsed Magnet lab is being set up for
  - performance evaluation and calibration of final magnets
  - test innovations and concepts required to make top-off operation transparent to NSLS-II users
- Tolerances required to have non-invasive top-off injection will be difficult to meet and maintain, some innovation is required
- PML status
  - Lab space assigned, materials/tools on order
  - 35 ft. x 15 ft. caged, interlocked test area under construction
  - Sr. Scientist, Experienced Head Technician, post-doc, EE, consultants are on board full time
  - First order of business: Pulsed sextupole prototype construction and evaluation

Bldg. 832



Injector schedule

- Prior to CD-3 injector schedule was motivated by funding limitations
- Current situation is favorable for expediting the injector schedule to:
  - Meet advanced building schedule
  - Procure major injector subsystems earlier
- Injector building BOD – 18 May 2011
- Linac turn-key procurement award – Nov 2009
- Booster RFP solicitation begins – Oct 2009
- Schedule of utility distribution will match the linac and booster delivery schedule
- Development of Diagnostics TLs to be advanced for early linac/booster commissioning
- Injection straight section is tied to the SR schedule
- Complete Pulsed Magnet lab soon for building prototypes of challenging pulsed magnets

Working on injector

J. Rose, R. Fliller, R. Heese, B. Parker, M. Rehak,
S. Ozaki, F. Willeke, E. Weihreter, Y. Li, S. Kramer,
W. Guo, B. Nash, M. Fallier, M. Ferreira, R. Alforque,
G. Wang, S. Krinsky, E. Johnson, A. Blednykh, O. Dyling,
R. Meier, S. Sharma, D. Hseuh, G. Ganetis, H. Ma,
T. Shaftan, O. Singh, J. Skaritka, N. Tsoupas,
J. O'Connor, C. Lavelle, I. Pinayev, E. Trakhtenberg,
P.K. Job, B. Casey, T. Mennona, G. Woods,
S. Kowalsky, M. Boland (ASP), J. Safranek (SSRL)

Injection/Extraction System Status

Richard Heese
NSLS-II Pulsed Magnet Workshop
July 27 - 28, 2009

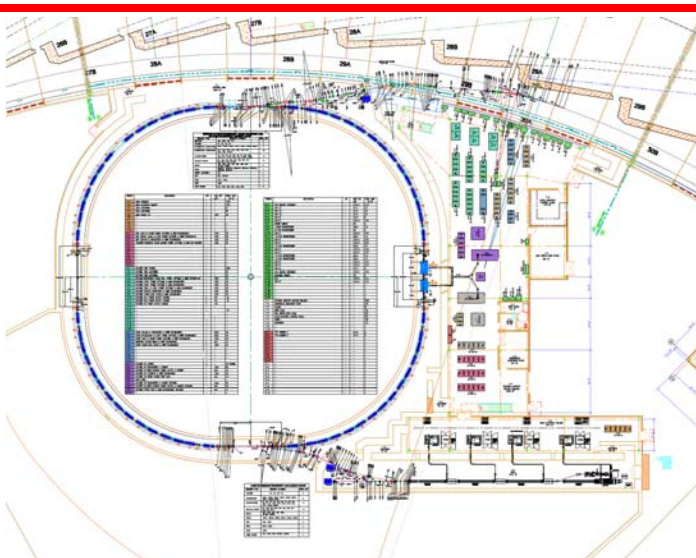
Acknowledgements

T. Shaftan, J. Rose, R. Fliller, B. Parker, M. Rehak, S. Ozaki, F. Willeke, E. Weihreter, Y. Li, S. Kramer, W. Guo, B. Nash, M. Fallier, M. Ferreira, R. Alforque, S. Krinsky, E. Johnson, A. Blednykh, O. Dyling, R. Meier, S. Sharma, D. Hseuh, G. Ganetis, H. Ma, G. Wang, O. Singh, J. Skaritka, N. Tsoupas, J. O'Connor, C. Lavelle, I. Pinayev, E. Trakhtenberg, P.K. Job, B. Casey, T. Mennona, G. Woods, J. Zipper

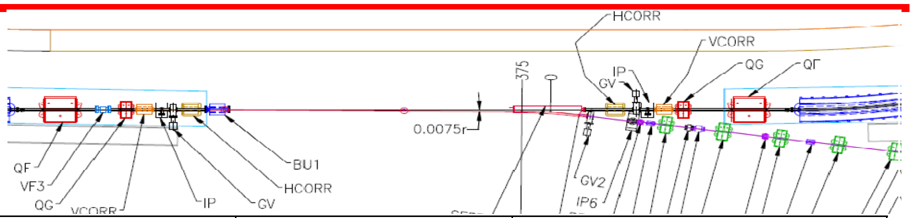
Outline

- Booster Injection, single pulse train or more
- Booster extraction, stability criteria for two types of ring injection
- Storage ring injection, top-off user requests, kicker stability and alignment requirements
- Pulsed sextupole or four kickers?
- Pulsed magnet lab

NSLS-II Injection Complex



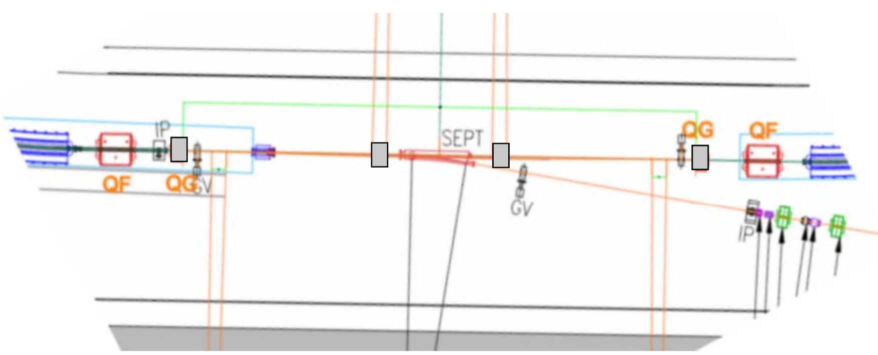
Baseline Booster Injection



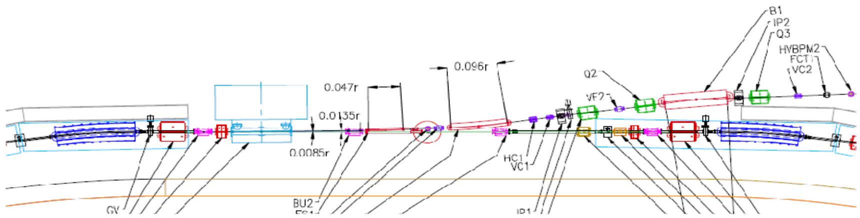
Parameter	Pulsed septum	Kicker
Length, m	0.75	0.2
Field, T	0.127	0.025
Angle, mrad	142.5	7.5
Aperture x/y, mm	20/15	67/27
Pulse shape, Î, Ê	Full sine 100μsec 1800A, 200V	300 nsec flat-top, <100 nsec rise/fall time, 800A, 7800V
Field Error tolerance, %	<1	~1
Align.tol., roll (mrad)	100/100/0.2	100/100 /0.2

Booster injection with 4 bumps

- **To reduce demand for linac charge – two pulse train transverse stacking injection, 0.1 to 0.2 seconds apart may be an alternative injection scheme**
- **Bump parameters: Same as injection kicker, but 0.05T, 100 nsec rise and fall time with 300 nsec flat-top**



Baseline Booster Extraction

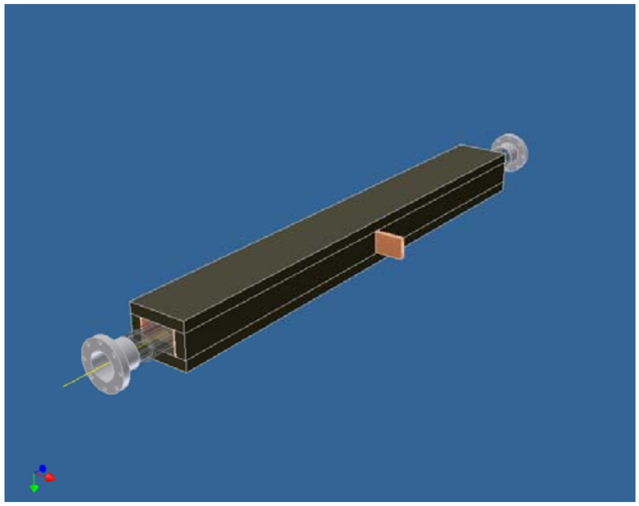


Parameter	Orbit Bump	Extraction Kicker	Pulsed Septum	DC Septum
Length, m	0.2	1	0.6	1
Field, T	0.375	0.05	0.8	0.96
Angle, mrad	7.5	5	48	96
Aperture x/y, mm	70/27	70/44	32/23	50/20
Pulse shape/width (Flat-top), Î, Ê	½sine 1000μs, 440A, 365V	200nsec risetime (300ns), 1926A, 31kV	½sine 50 μs, 16100A, 1062V	n/a
Flatness/ Field Error tolerance, %	n/a/0.5	**0.2 ripple & droop**	**0.02**	n/a/0.01

Extraction Kicker Parameters

Bending Angle:	**5.0 mR for 3 GeV**
Magnetic Field:	**0.05 T**
Magnet length:	**1 m**
Full magnet vertical gap:	**0.042 m**
Full magnet horizontal gap:	**0.07 m**
Type of magnet:	**Window frame**
Required current:	**1900 A in 1 turn**
Current pulse shape:	**100 nsec rise time, 300 nsec flat-top, fall time not critical**
Ripple and droop of current pulse:	**<0.2 %**
Repetition rate	**1 Hz**
Magnet Inductance:	**1.737 μH**
Magnet resistance:	**10 – 12 mΩ @ 2.5 MHz**
Magnet Impedance (calculated):	**1.6 mΩ**

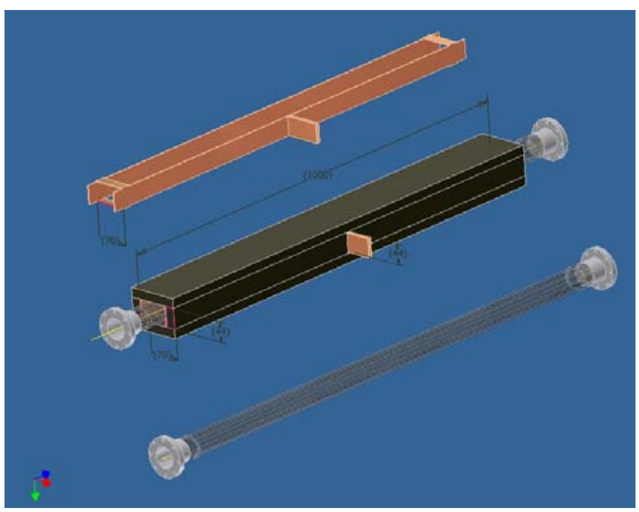
BEK Assembled



U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

BEK Exploded



U.S. DEPARTMENT OF ENERGY

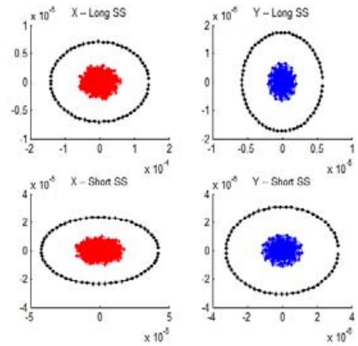
BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Tolerances for Storage Ring Top-off Injection

- Transparent top-off cycle is highly desirable
- Orbit motion of 10% of rms beam size of damped beam in synchrotron is a challenging requirement for top-off

For the two alternative injection schemes, four kickers or pulsed sextupole magnet, the following parameters are required due to the very small ring emittance:

- Relative field tolerance among the injection bumps of <0.008%
- Vertical alignment of injection bump roll to better than 12.5 µrad
- For alternative PSM injection, vertical placement of magnet to <10 µm
- **Many modern Light Sources run successfully with more moderate tolerances**

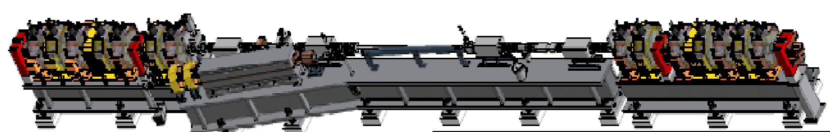


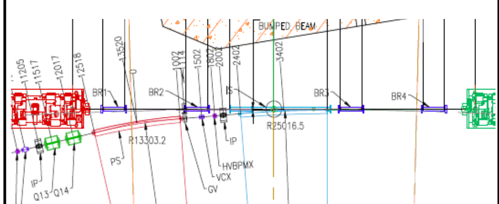
Phase space in ring straight sections

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Baseline Ring Injection Straight Section





- Four Kickers
- Pulsed Injection Septum Magnet
- Thick Injection Septum replaced by DC magnet

Parameter	DC septum	Pulsed septum	Kicker
Length, m	1.8	0.8	0.5
Field, T	1.056	0.5	0.157
Angle, mrad	190	40	7.85
Aperture x/y, mm	50/20	32/23	70/44
Pulse shape/ width,µs	n/a	Full sine,100	½ sine 5.2
Flatness/ Field Error tol. %	n/a/0.03	0.2/0.2	8x10E-3
Align. tol, µm/µm/mrad	100/100/0.2	100/100/0.2	100/100,0.012
Inductance, µH	n/a	1.399	1.009
Î, kA/Ê,kV		11.9/0.885	6.05/3.594

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Approaches to Precision Matched Orbit Bumps

- Careful construction of bump drivers and connections
- High resolution voltage regulation charging supplies
- Precise magnetic measurements and careful trimming of capacitances and inductances
- Installation of H_t windings in bump magnets to compensate for roll errors
- Precision measurement of pulse currents and possible feed-forward
- Beam-based alignment of individual bumps
- Sturdy construction to alleviate mechanical vibration effects
- Possible magnet placement on externally controlled micro-positioning supports

Pulsed Sextupole Injection Straight

4-Kicker – PSM Comparison

Magnets

Parameter	DC sept.	Pulsed sept.	Kicker
Length, m	1.8	0.8	0.5
Field, T	0.833	0.5	0.157
Poletip field, T	0.833	0.5	0.157
Bend angle, mrad	190	40	7.85
Half aperture mm x mm	50/20	32/23	70/44
Design	¼ SiS lam.	¼ SiS lam.	CMD5005
Inductance, μH	n/a	1.399	1.009

Parameter	DC sept.	Pulsed sept.	PSM
Length, m	1.5	0.8	0.5
Field, T or else	1.5	0.5	1550 $T{\cdot}m^{-3}$
Poletip field, T	1.5	0.5	0.484
Bend angle, mrad	225	40	2.8
Half aperture, mm x mm	50/20	32/23	25/25
Design	¼ SiS lam.	¼ SiS lam.	¼ SiS lam
Inductance, μH	n/a	1.399	14

Power Supplies

Pulse shape/width, μs	n/a	100 μs sine	½ sine/5.2
Capacitance of driver, μF	n/a	181.1	2.83
Current, kA	191.5x80AT	10.07	6.047
Voltage, kV	0.06	0.885	3.59
Flatness/ Field Error tol., %	n/a/0.03	0.2/0.2	8x10E-3
Align. tolerances, roll (rad)	100/100/0.2	100/100/0.2	1.2E-5 vert

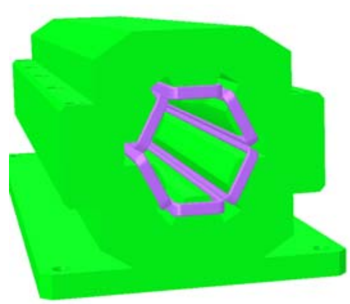
Pulse shape/width, μs	n/a	100 μs sine	½ sine/5.2
Capacitance, μF	n/a	181.1	200
Current, kA	0.33x80AT	10.07	3.2
Voltage, kV	0.083	0.885	27
Flatness/ Field Error tol., %	n/a	0.2/0.2	n/a/1
Align. tol, μm/μm/mrad	100/100/0.2	100/100/0.2	100/10/1

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Injection Magnets for Ring PSM Injection

Parameter	DC septum	Pulsed septum	PSM
Length, m	1.5	0.8	0.5
Field or gradient	1.5 T	0.5 T	1550 $T{\cdot}m^{-3}$
Bend angle, mrad	225	40	2.8
Aperture, mm	5/20	32/23	25/25
Pulse shape/width, μs	DC	Full sine/100	½ sine, 5.2
Flatness/ Field Error tol, %	n/a	n/a	<1
Align. tol, μm/μm/mrad	$10^2/10^2/0.2$	$10^2/10^2/0.2$	100/**10**/1
Inductance μH	n/a	1.399	14
I(ka)/V(kV)	n/a	10.07/0.885	3.2/27



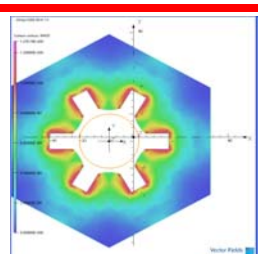
Aspects

- 2 pulsed magnets only
- Transport line so far not satisfactory due to large gradient of sextupole at end of transport line
- Magnet made of thin 0.2 mm laminations, final pole contour EDM cut after assembly
- Micro-positioning table for vertical adjustment designed

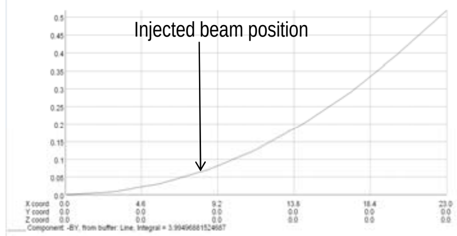
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

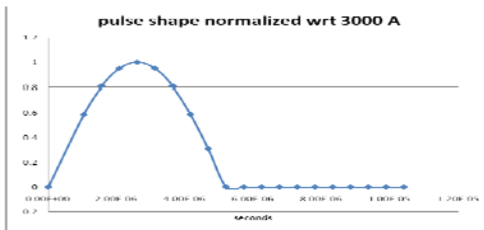
Pulsed Sextupole Characteristics



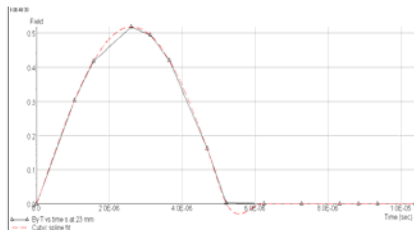
Magnetic field in magnet body



By of pulsed sextupole



Current pulse used for calculation



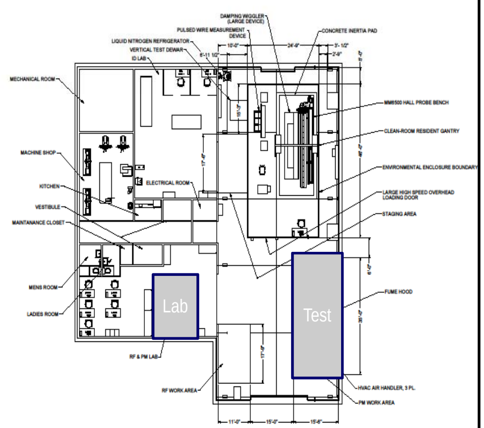
Resultant pole-tip field of pulsed sextupole

Pulsed Magnet Lab

- Pulsed magnet lab is being set up, not only for performance evaluation and calibration of final magnets, but to test innovations and concepts required to make top-off operation transparent to NSLS-II users.
- The tolerances required to have non-invasive top-off injection will be difficult to meet and maintain, innovation is required

Pulsed Magnet Lab Status

- Lab space assigned, materials/tools on order
- 35 ft. x 15 ft. caged, interlocked test area under construction
- Scientist on board full time
- Experienced Head Technician hired
- Post-Doc on board since April
- Engineer hired and beginning work
- First order of business: Booster extraction kicker and pulsed sextupole prototypes construction and evaluation



Plan view of Bldg. 832 – Lab area and test area highlighted

Pulsed Magnet Test Area (5/29/09)

Pulsed Magnet Test Area

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Injection System Value Engineering Activities

- Booster injection septum moved to upstream end of injection straight to adapt to more capable transport line and reduction of field requirement of injection kicker magnet*

Further investigations

- Ring injection with pulsed sextupole magnet
- Double Lambertson septum PSM for ring injection
- Can septum magnets be built similar to NSLS septum magnets
- Four bump injection into booster as back-up for reduced linac charge**

*The simple single bump booster injection scheme has been de-emphasized for now because…

**The four bump booster injection scheme is being pursued to guard against reduced charge output from linac by injecting 2 consecutive linac pulses spaced by no less than 100 milliseconds (transverse stacking) before accelerating.

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Looking Ahead

- Completion of pulsed magnet lab set-up
- Construction of prototype booster extraction kicker, pulsed sextupole, and their drivers
- Finalizing ring injection scheme
- Decision on in-house construction or procurement of pulsed magnets
- Pulsed magnet workshop 27, 28th July

U.S. DEPARTMENT OF ENERGY 23 BROOKHAVEN NATIONAL LABORATORY BROOKHAVEN SCIENCE ASSOCIATES

Summary and Conclusions

- Injection magnets and parameters are well understood and require engineering solutions
- Due to small emittance of storage ring (especially vertical), top-off injection without disturbing the users is a challenge for the ring injection system
- Pulsed sextupole injection shows promise but presents other complexities for the transport line
- Stability of extraction out of the booster is part of this challenge
- Back-up booster injection is viable
- Pulsed magnet lab is a necessity to resolve these issues and find solutions

U.S. DEPARTMENT OF ENERGY 24 BROOKHAVEN NATIONAL LABORATORY BROOKHAVEN SCIENCE ASSOCIATES

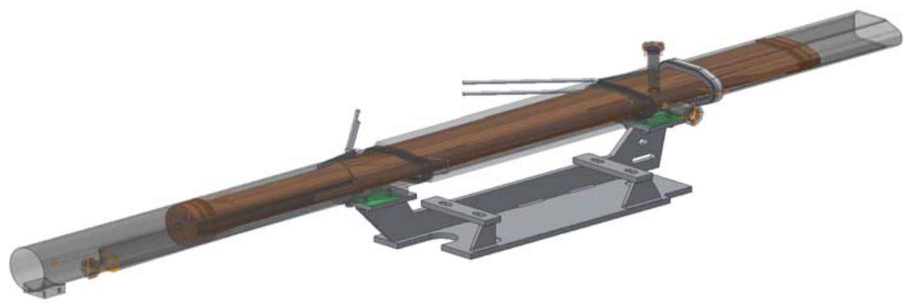
Extra Stuff

- NSLS Septum - 4 slides
- Half/full sine wave model - 2 slides
- NSLS laminated septum 1.1T @ 16,100 A
- Flat-top driver

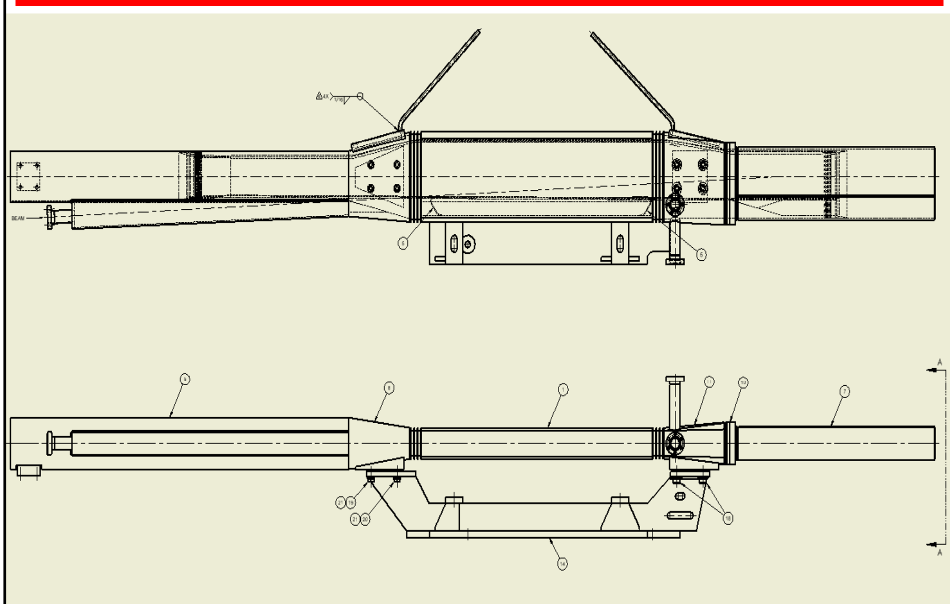
NSLS Type Septum Magnets

- Main advantage is that there are no feed-throughs for high current pulsed power into vacuum
- Sturdy, simple construction with very little perturbation in beam chamber as seen by circulating electrons
- Experience with these magnets very positive – they can, however, be improved as far as fringing fields

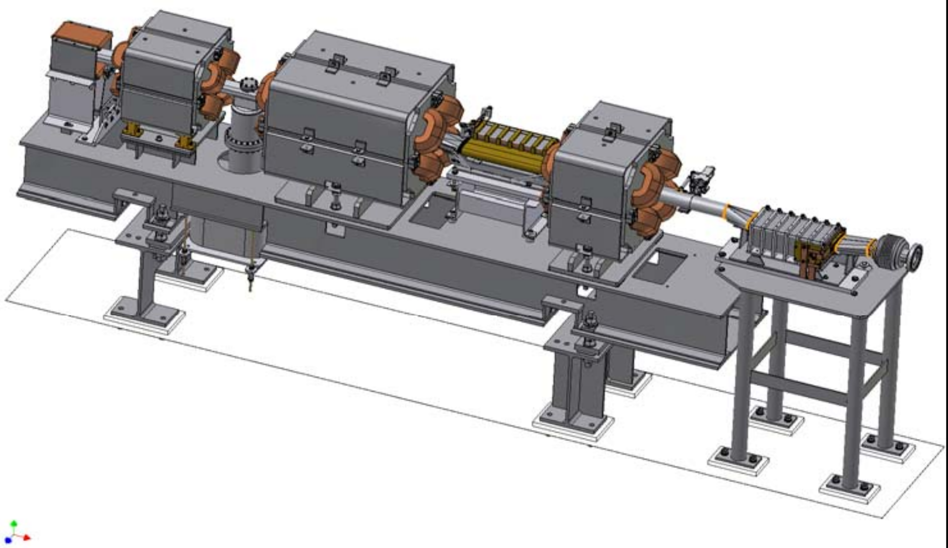
NSLS Injection Septum, Transparent Beam Pipe



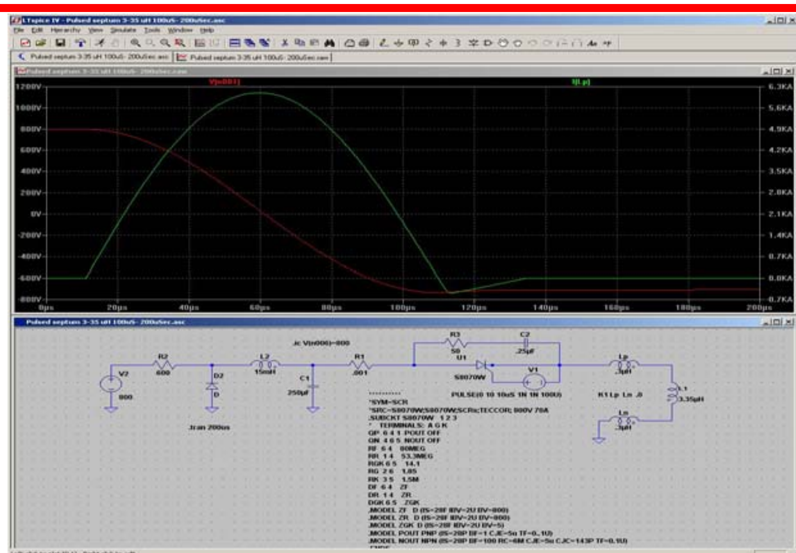
NSLS Injection Septum Chamber



NSLS Injection "Straight"

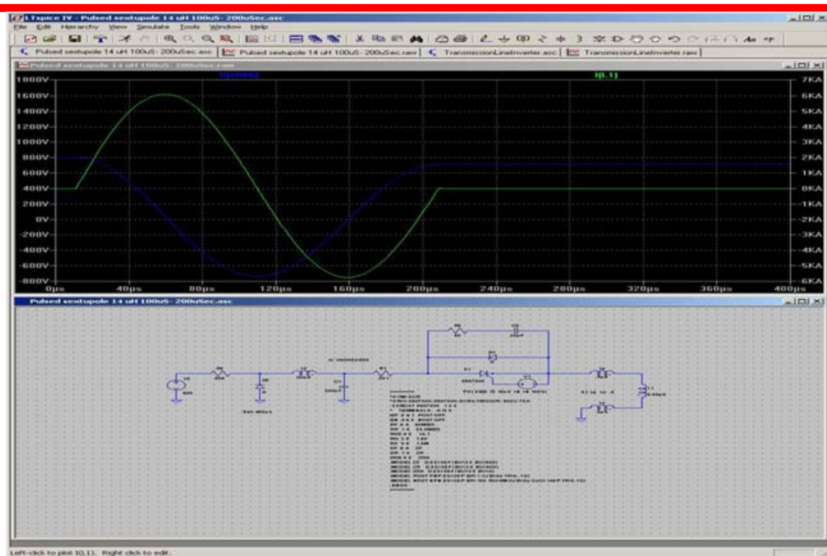


Modeled Injection Bump



BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

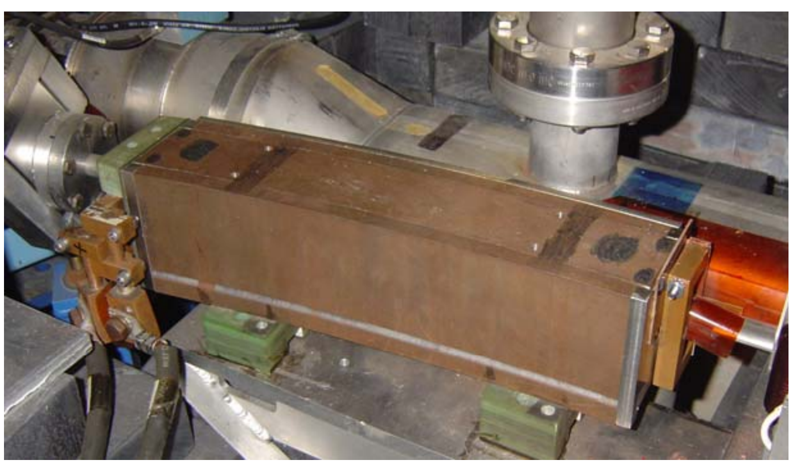
Modeled Full Sine Wave Septum Pulse



U.S. DEPARTMENT OF ENERGY

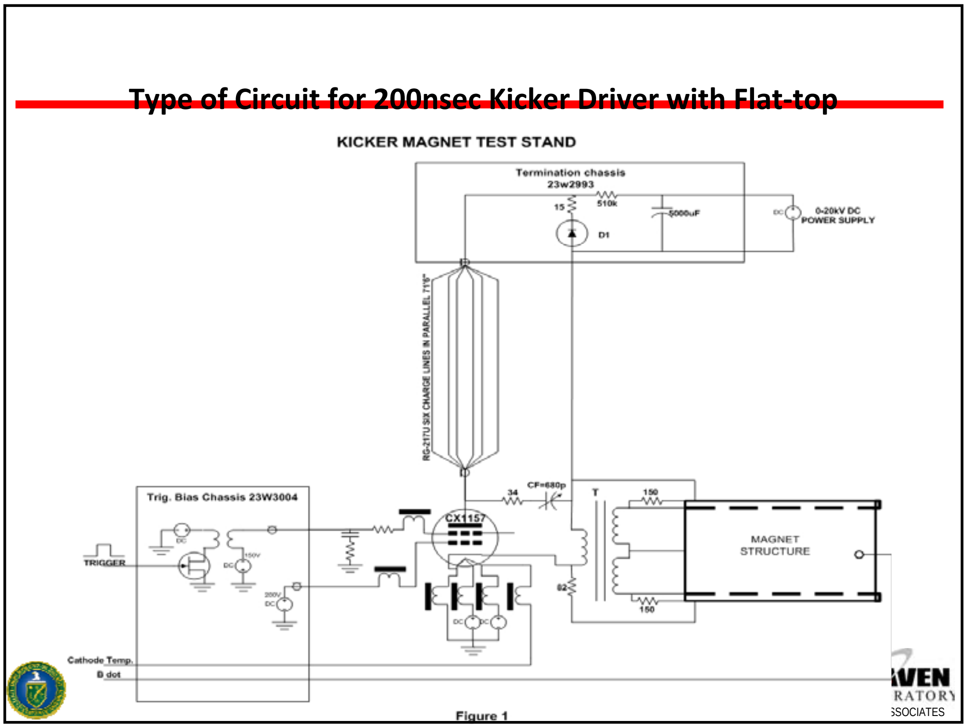
BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Extraction Septum



U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES


Type of Circuit for 200nsec Kicker Driver with Flat-top
KICKER MAGNET TEST STAND
Termination chassis
23w2993
15
510k
5000uF
D1
0-20kV DC
POWER SUPPLY
Trig. Bias Chassis 23W3004
TRIGGER
34
CF=680p
CX1157
T
150
82
150
MAGNET
STRUCTURE
Cathode Temp.
B dot
Figure 1

Septum/Bumps Circuit Topology and Simulations

Stephen Kowalski
Special Thanks to Richard Heese, Peter Zuhoski and Arlene Zhang

NSLS-II Pulse Magnet Workshop
June 27-28, 2009

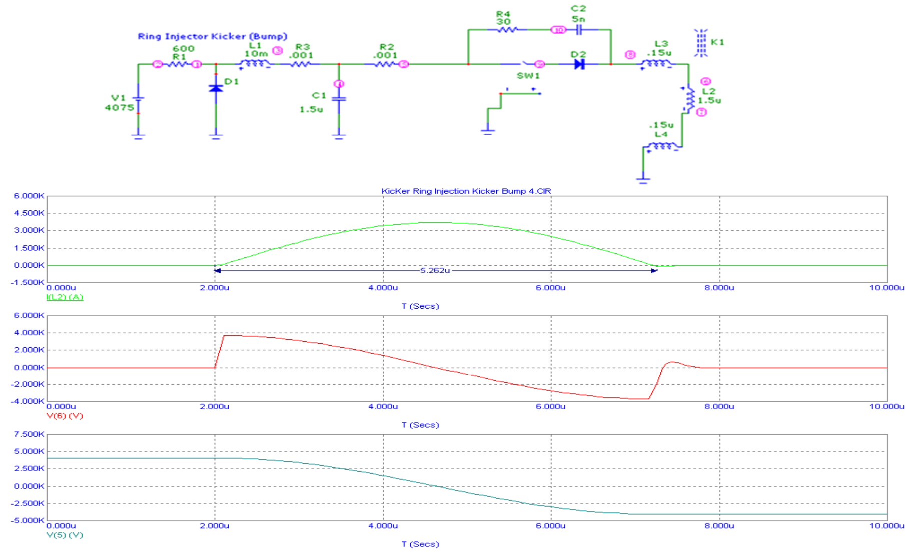
U.S. DEPARTMENT OF ENERGY
BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Outline

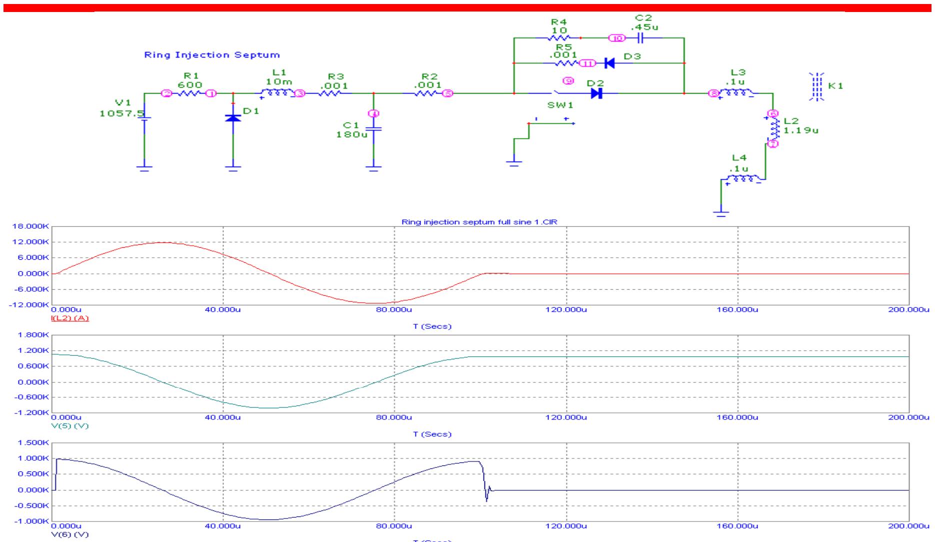
- Ring Injection Kicker Bump
- Ring Injection Septum
- Booster Extraction Slow Bump
- Booster Extraction Septum
- Booster Injection Septum
- Simulation Results

U.S. DEPARTMENT OF ENERGY
BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

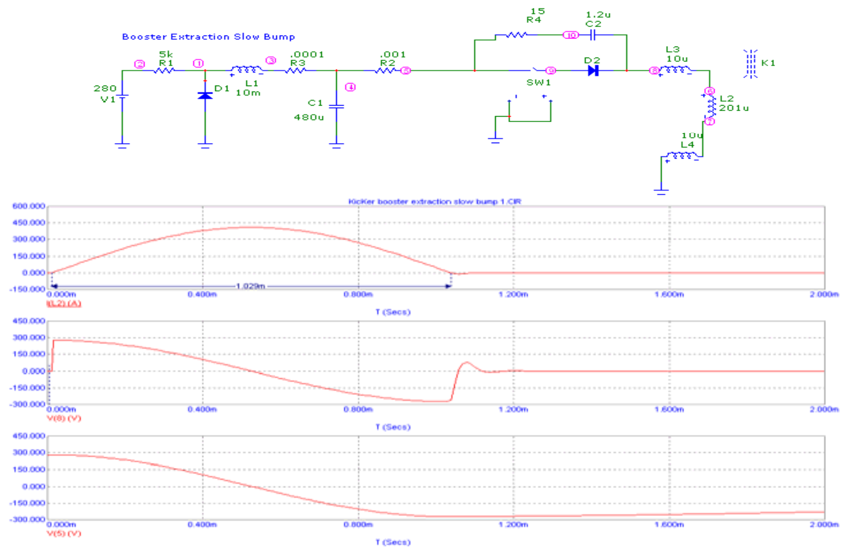
Ring Injection Kicker Bump



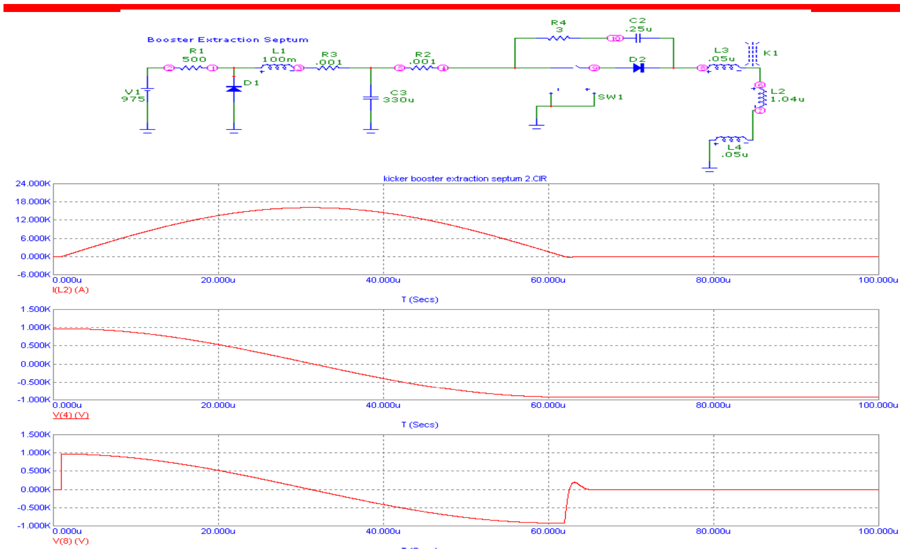
Ring Injection Septum



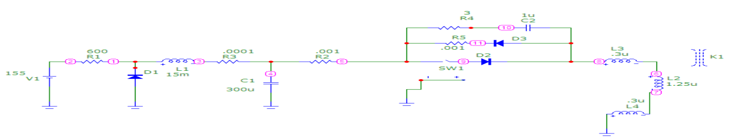
Booster Extraction Slow Bump

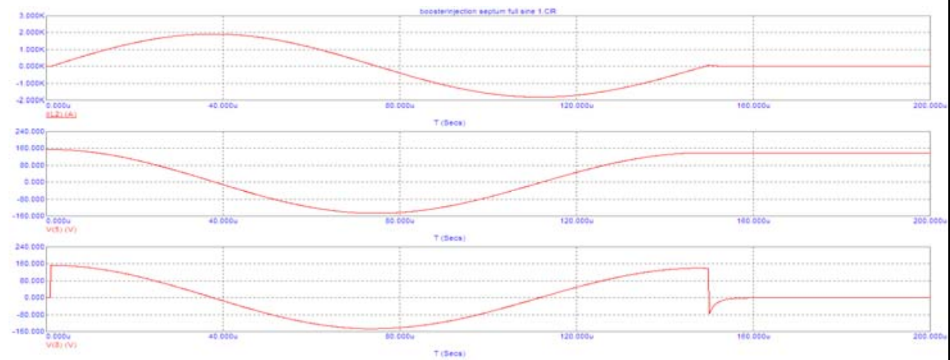


Booster Extraction Septum



Booster Injection Septum





Simulation Results

Pulsed Magnet/ Parameter	#	Pulse shape	Imax (A) or A-T	Pulse length (µs)	Inductance (µH)	Drive Voltage (kV)	Drive Capacitance (µF)	di/dt	dv/dt
Ring Injection Kicker (bump)	4	1/2 sine	3710A	5.2us	1.5uH	4075V	1.5uF	1426A/us	2037V/us
Ring Injection Septum	1	Full sine	11810A	100us	1.19uH	1057V	186uF	472A/us	53V/us
Booster Extraction Slow Bump	4	1/2 sine	411A	1000us	201uH	280V	480uF	2.06A/us	2V/us
Booster Extraction Septum	1	1/2 sine	16100A	60us	1.049uH	975V	330uF	536A/us	55V/us
Booster Injection Septum	1	Full sine	1800A	150us	1.25uH	155V	300uF	48A/us	6.9V/us

NSLS-II Pulsed Sextupole Injection Status

Ray Fliller
Pulsed Magnet Workshop
July 27-28, 2009

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

1

Worked on PSM Injection

- T. Shaftan, R. Heese, E. Weihreter, F. Willeke, M. Rehak, R. Fliller, G. Wang, R. Meier, B. Parker

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

2

Outline

- Baseline design
- Pulsed Sextupole Injection Scheme
- Design of the sextupole, injection straight and transfer line
- Effect of sextupole on the stored beam
- Storage ring acceptance
- Injected Beam tolerance limits at sextupole
- Transport line tolerances
- Dual pulsed “Distorted Sextupole” or “Triple Dipole” injection scheme
- Other possible injection schemes
- Conclusion

NSLS-II Baseline Injection System

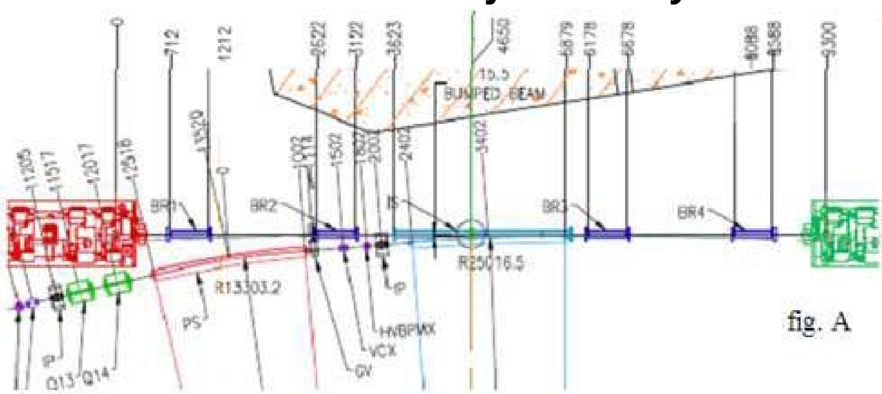


fig. A

- Bumps displaces stored beam by 15 mm
- Injected beam leaves the septum displaced 8.5mm from stored beam.
- Beams are parallel at the end of the injection straight, separated by 8.5 mm
- Orbit bumps must be closed enough not to disturb the orbit in the rest of the machine more than 1/10σ.

NSLS-II Pulsed Sextupole Injection System

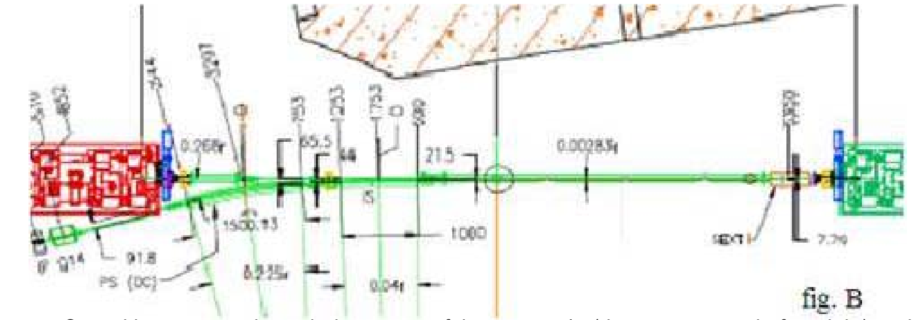
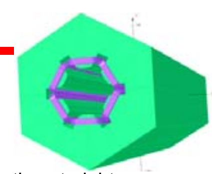


fig. B

- Stored beam goes through the center of the sextupole (downstream end of straight) and recieves no kick.
- Pulsed injection septum moved upstream as far as possible.
- Adjusted pre-Septum, additional dipole prior to Q13 (off slide – more later)
- Injected beam arrives at sextupole at 8.5mm from the stored beam (and center of sextupole)
- Sextupole produces a 2.83mrad kick so injected beam is parallel to stored beam.

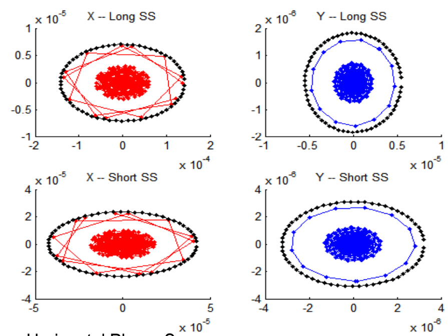
Magnet Parameters

Parameter	DC septum	Pulsed septum	PSM
Length, m	1.5	1	0.5
Field or gradient	1.5 T	0.4 T	1550 $T \cdot m^{-3}$
Angle, mrad	225	40	2.8
½ aperture, mm	5/20	20/15	25/25
Pulse shape/width, μs	DC	sine/100	½ sine 5.2
Flatness/ Field Error tol., %	n/a	0.2/0.2	<1
Align. tol., μm/μm/mrad	100/100/ 0.2	100/100/ 0.2	100/10/1
Inductance, μH	n/a	3.35	14
Current, kA/ Voltage, kV	26400at/ 0.083	5.25/ 0.56	3.2/ 27



- Injection straight optimized to reduce the strength of the sextupole as much as possible while maintaining requirement that injected beam is 8.5mm from stored beam.
- Magnet design optimized to lower inductance of sextupole as much as possible
- Alignment tolerances for sextupole determined by stored beam motion (next slide)

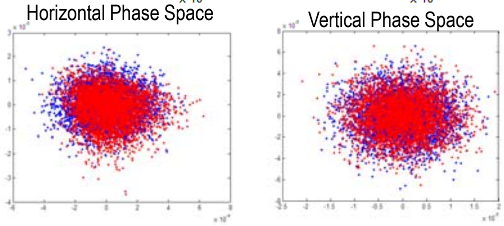
Sextupole effect on stored beam



•The black dots show the RMS beam phase space at the center of the long and short straight sections. The red and blue dots shows the beam centroid at each source location in the ring. The centroid position moving less than 1/10th of the beam size

Horizontal Phase Space

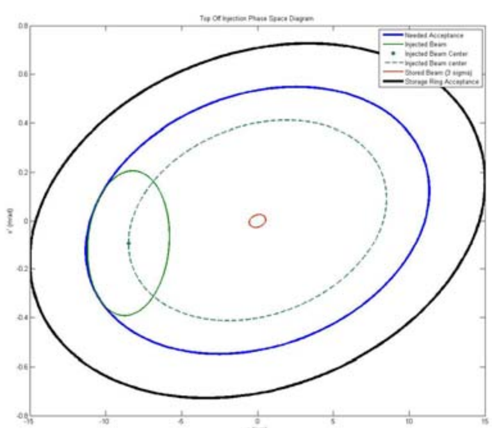
Vertical Phase Space



•The effect of the sextupole on the horizontal (left) and vertical (right) phase spaces. The blue dots show the unperturbed phase space. The red dots show the perturbed phase space. Very little distortion is seen.

Optimal Twiss Functions for TOI

- Twiss functions for injected beam should be chosen to minimized the acceptance needed by the injected beam.
  - In vertical plane this means that the injected beam twiss functions should match the stored beam functions
  - A. Streun worked out what the injected beam twiss functions should be for SLS. (Technical Note SLS-TME-TA-2002-0193)
  - We extended his theory to include nonzero α so that it can be applied to sextupole injection (NSLS II Technical Note 59)
  - If twiss functions are computed at the end of the injection straight, they are independent of the injection scheme.



•Most of the acceptance needed for the injected beam is taken up by the offset. (dotted green ellipse)

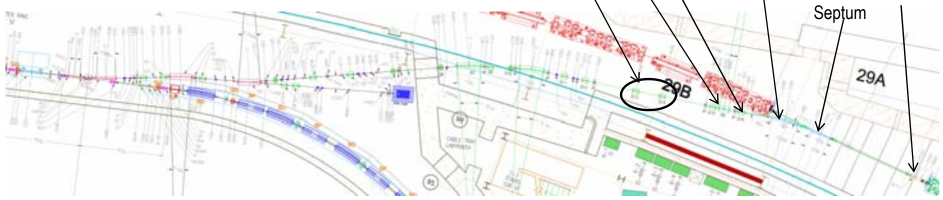
•Twiss functions of injected beam optimized to minimize the total acceptance (blue ellipse)

•The storage ring dynamic aperture is the maximum acceptance we can use (black ellipse)

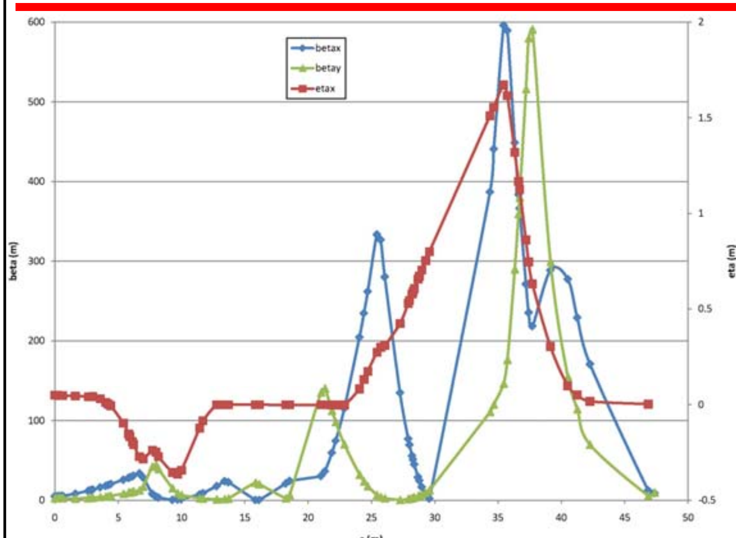
Stored Beam	Injected Beam
•β_x=21.4	•β_x=9.1
•α_x=-0.23	•α_x=-0.1
•β_y=9.8	•β_y=9.8
•α_y=-1.4	•α_y=-1.4

Transport Line Design

- The sextupole has a gradient of 1550 T/m^2 and is 0.5 m long
- At 8.5mm this gives an effective dipole field of 56mT, and a gradient of 13 T/m.
  - The gradient is on the same order as other quadrupoles in the transfer line.
- This has ramifications for transfer line and tolerances
  - Beta functions get large because of long drift (9m) between last quadrupole and the sextupole.
  - Moving quads closer is not an option
  - Gradients in preseptum and pulsed septum are impractical due to high fields
  - Moving the injected beam out and reducing the sextupole strength will run into dynamic aperture.
- Other modifications
  - Additional 2 quads needed to control beta function
  - Weak dipole needed to make small trajectory change

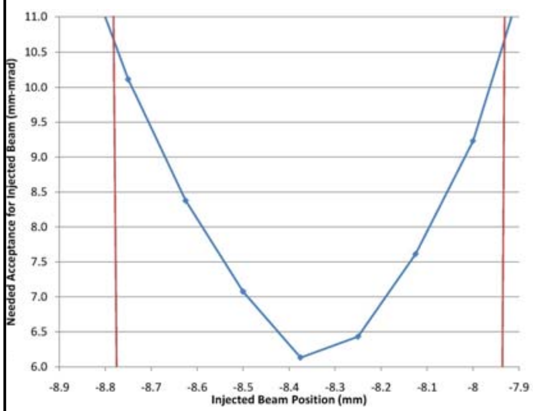


Twiss Functions



- Sextupole gradient forces β functions to be highest as final 2 quads.
- The maximum β functions for the four bump injection scheme is about 60m

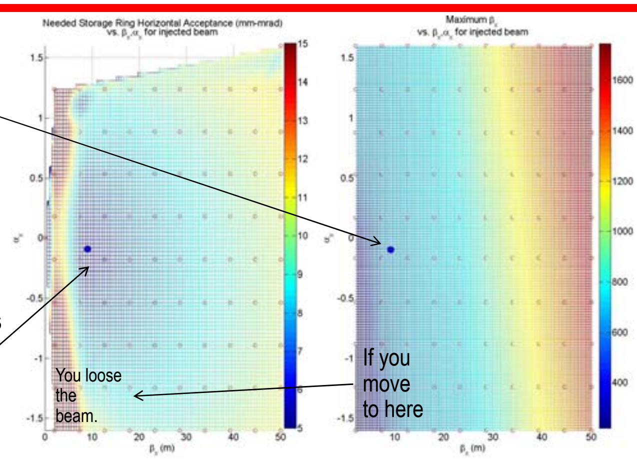
Tolerance limits on injected beam position



- Changes in the injected beam position at the enterance of the sextupole will lead to
  1. Change in dipole kick and gradient in sextupole.
  2. Change in output angle
  3. Change in output position
  4. Change in output twiss functions
  5. More required acceptance.
- The blue line is the acceptance vs. change in injected beam position.
- The red lines show the position when the injected beam hits the max acceptance of the storage ring (**black**
- **ellipse**)
- The beam can move -300 μm and +500 μm before the injected beam needs the entire storage ring acceptance.

Can the large β functions be reduced?

- No.
- Decreasing the max β function required decreasing β for the injected beam at the end of the injection straight, and making a large negative α.
- This quickly increases the required acceptance beyond the maximum.
- Yellow on these scales is the **black ellipse** in the acceptance phase space



Transport Line Tolerances

Static (Time Independent) error		Jitter (Time Dependent) error	
Dipole field error	0.1%	Booster extraction kicker	0.2%
Quads field error	0.1%	Booster extraction septum	0.02%
All magnet and BPM roll error	2 mrad	Storage ring pulsed septum	0.02%
Quads transverse misalignment	0.15mm	DC dipole power supply	0.002%
Dipole longitudinal misalignment	1 mm	DC quads power supply	0.01%
Quads longitudinal misalignment	1 mm	Booster beam position	15um
BPM transverse misalignment	0.1 mm	Booster beam angle	10urad
BPM transverse misalignment before PSM	0.025 mm		

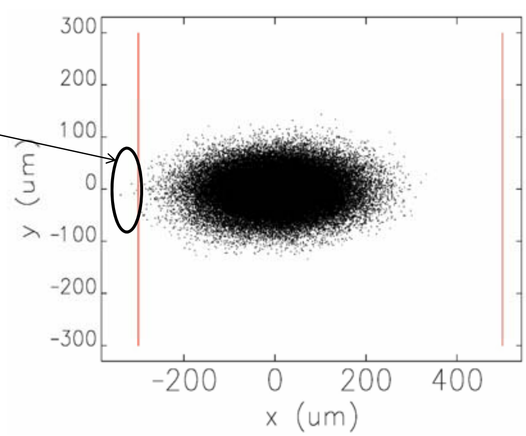
Tolerances in red are difficult or impossible to achieve. All have a large effect on the beam position at the pulsed sextupole magnet.

The storage ring pulsed septum needs to meet or exceed this tolerance. This is on the edge of not meeting specification.

Effect at Sextupole

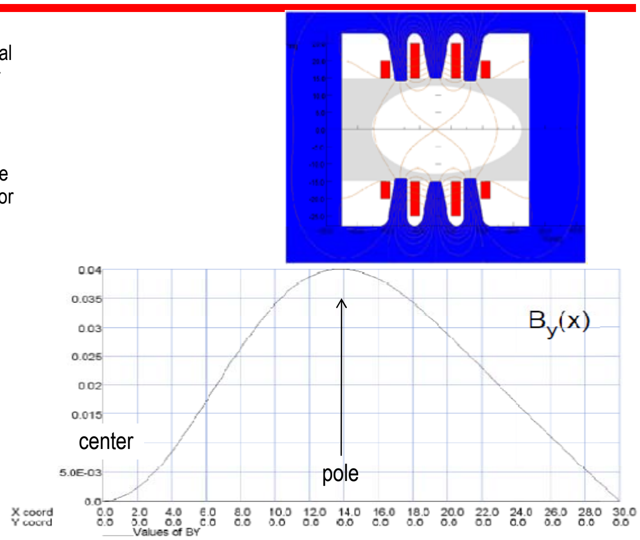
- The effect of these tolerance on the beam position at the sextupole.
- Some seeds start to fall out of tolerance.
- An increase in any tolerance will make it difficult to make this scheme work.

- These tight tolerances on the transfer line are causing us to consider abandoning the sextupole injection idea



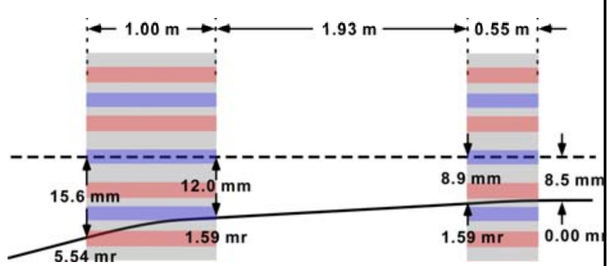
Brett's "Triple Dipole"

- Brett Parker designed this sextupole magnet with the goal of getting field maximum near the injected beam location to reduce the graident that the injected beam sees.
- The maximum field is not quite what is needed for the kick, nor is it practical to place the field maximum any closer to the center of the magnet.
- The field in some parts of the iron approach 1 T.
- The field in the center is sensitive to the gap in the middle poles. This will be difficult to shim.
- Two of these can be used for the injection system.



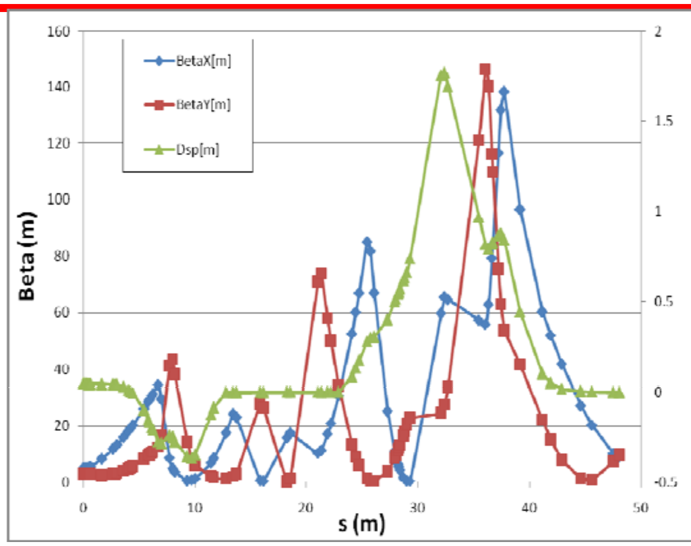
Injection straight with Brett's "Triple Dipole"

- The first magnet produces a kick with a little defocusing.
- The second magnet finishes removing the angle and provides focusing. The focusing is about ½ of the sextupole.
- Transport line unchanged from sextupole design.



Transport line Twiss functions

- The effect of the smaller gradient is clear, the maximum β function drop a factor of 4 from the single sextupole design.



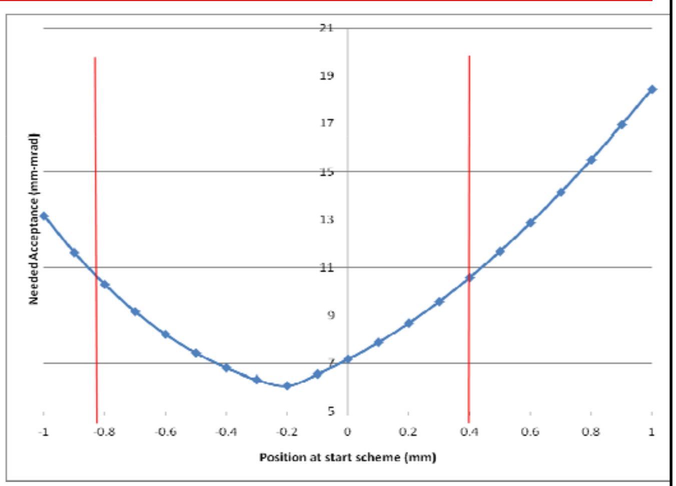
U.S. DEPARTMENT OF ENERGY

17

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Injected Beam Position tolerance

- The tolerance limits on the injected beam are looser than in the single sextupole scheme – but not much.
- +400 μm or -800 μm from the ideal trajectory
- Compared with -300 μm and +500 μm in the single sextupole case



U.S. DEPARTMENT OF ENERGY

18

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Transport line Tolerances

Static error		Jitter Error	
Dipole field error	0.1%	Booster extraction kicker	0.2%
Quads field error	0.2%	Booster extraction septum	0.03%
All magnet and BPM roll error	2 mrad	Storage ring pulsed septum	0.03%
Quads transverse misalignment	0.15mm	DC dipole power supply	0.003%
Dipole longitudinal misalignment	1 mm	DC quads power supply	0.1%
Quads longitudinal misalignment	2 mm	booster beam position	15 μm
BPM transverse misalignment	0.1 mm	booster beam angle	6 μrad
BPM transverse misalignment before the1st sextupole	50μm		

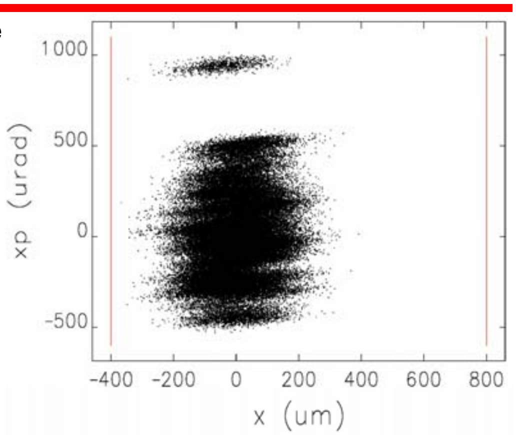
Tolerances in green are looser than in the single sextupole case.

Tolerances in black are identical to single sextupole case.

Tolerances in red are still difficult to achieve.

Horizontal Phase Space at enterance

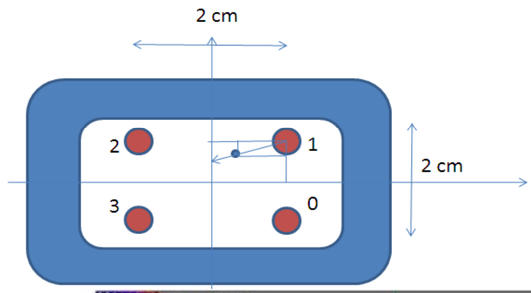
- This is the horizontal phase space at the enterance of the double sextupole
- There are a few shots outside of tolerance.
- The angle change was not included in the tolerance calculation, but is large enough to have a negative effect on the acceptance. This will tighten the tolerances
- This does not include the effect of misalignment or jitter in the sextupoles themselves. This will also tighten tolerances.
- The effect on the stored beam has not been evaluated.

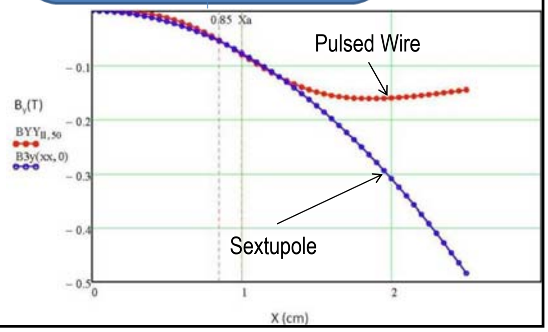


We are no longer considering this option because there are serious doubts about the ability to accurately build these magnets and it will be difficult to commission and operate reliably. Tolerance limits on the transfer line are only marginally improved.

Pulsed Wires

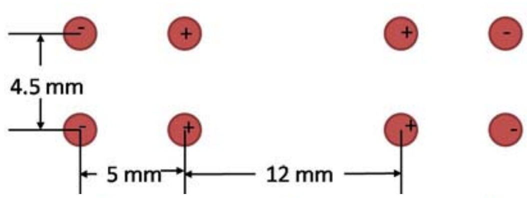
- P. Kuske to use pulsed wires to generate the necessary field at the injection point.
- To get the flat part of the field near where the injected beam is, the wires have to be closer together. This is a concern.

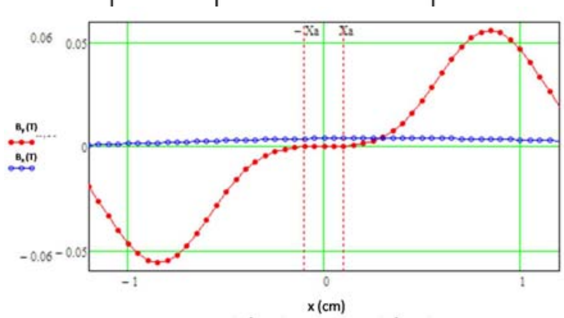




"Ferdinand's Wires"

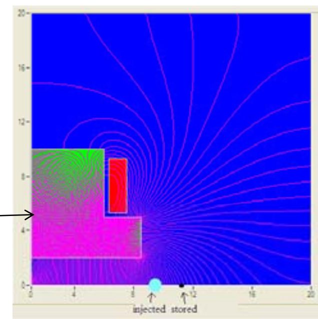
- Ferdinand Willike came up with an 8 wire configuration
- This places the field maximum near the injected beam
- The field is flat near the stored beam.
- But still, the wires are very close to the beams.





Other Miscellaneous Ideas

- Sextupole in Another Straight
  - Rejected because it takes up user space, and may cause losses in the intervening cells
- Doublet Sextupole
  - Rejected, only made the large β issue worse. Acts like a doublet quad.
- Mirror septum quad & sextupole
  - Use a mirror septum quad like in the HERA upgrade to steer and focus the injected beam. Desired kick gives the anti-desired gradient. Rejected.
- Sextupole-Octopole combination
  - Use a sextupole superimposed on an octopole to get a low gradient for the injected beam. Both magnets are very powerful for a very weak field. Rejected.
- Edge fields
  - Use the edge of a C magnet to have a strong field at the injected beam and taylor it to have zero field by stored beam. Gradient may be an issue.



Conclusion

- We have investigated using a pulsed sextupole for NSLS-II injection using two different schemes
- This type of injection seems difficult to do for a variety of reasons
  - Transfer Line
  - Difficult to build (Triple dipole)
- We also investigated a number of alternative ideas, some not impossible, other rejected outright.

The pulsed magnets of the Taiwan Photon Source

National Synchrotron Radiation Research Center

Pulsed Magnet Design and Measurement Workshop, NSLS-II

July 27-28, 2009

1

Acknowledgement

Beam Dynamic Group

H.-P. Chang, P.-J. Chou, C.-C. Kuo

Injection Group

C.-S. Fan, K.-K. Lin

Magnet Group

C.-S. Chang, J.-C. Huang, C.-S. Yang

Utility Group

Y.-H. Liu

Vacuum Group

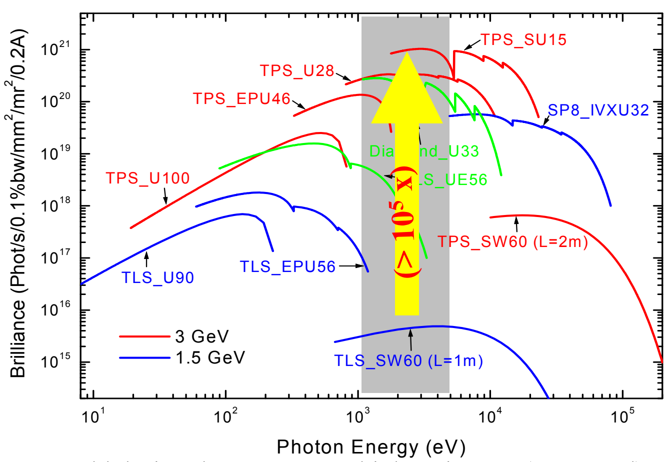
C.-K. Chan, G.-Y. Hsiung, L.-H. Wu

OUTLINE

I. The Taiwan Photon Source
II. TPS Injection System and Design Considerations
III. Booster Injection and Extraction
IV. Storage Ring Injection
V. Pulsed Magnet Prototypes and Field Mapping System
VI. Summary

NSRRC Brightness of TPS

"Dark band at TLS" (at ~20keV)



* TLS – Old design, low e-Energy, high emittance (25nm-rad)。
* Brightness of TPS > 10^5 of TLS at ~20keV。

NSRRC

Site of TPS

NSRRC

Site of TPS

TPS Tunnel

Parameters of TPS Storage Ring

• Beam energy :	3 GeV
• Beam current:	300 mA (Phase-1)
• Emittance:	1.7 nm-rad
• Lifetime:	> 10 hours
• Straight Sections:	7 m (x18); 12 m (x6)
• Lattice structure:	24 DBA
• Circumference:	518.4 m
• Critical photon energy:	7.13 keV
• RF frequency	500 MHz

Parameters of TPS Booster

• Injection Energy:	150 MeV
• Extraction Energy :	3 GeV
• Repetition Rate:	3 Hz
• Emittance:	10.32 nm-rad
• Straight section:	6 m
• Superperiod:	6
• Circumference:	496.8 m
• Harmonic Number:	828
• RF frequency	500 MHz

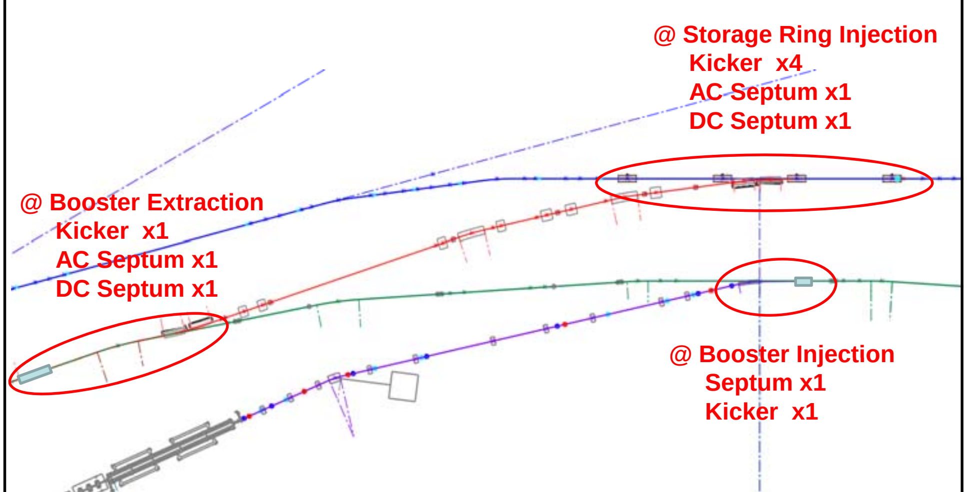
9

Milestones of TPS Construction

• Oct. 2007	Lattice approved by BOT Architect firm selected
• Dec. 2007	TPS final approval by Legislative Yuan
• June 2008	EPA approval; site plan completed
• June 2008	Accelerator design book issued
• Oct. 2009	1/24 ring (one cell) prototype construction
• Dec. 2009	Groundbreaking
• July 2012	Starting storage ring installation
• Oct. 2014	Open to users

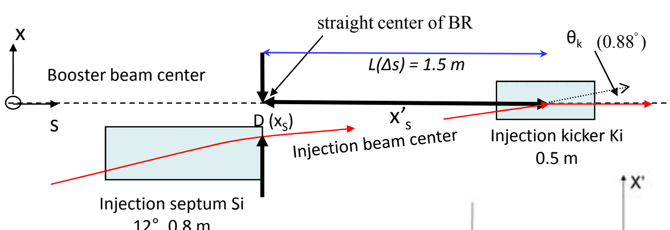
10

NSRRC TPS Injection System



NSRRC Booster Injection Scheme

On-axis injection configuration



$D = 14 + 3\ (\text{Si}) + 6\ (3\sigma_{inj})\ = 23\ (\text{mm})$

$L = 1.5\ (\text{m}),\ \text{Ki}\ =\ 0.5\ \text{m}$

$x_s = -D = -0.023\ (\text{m})$

$x'_s = 0.0154\ \text{rad}\ \text{ or } (0.88^\circ)$

$\theta_k = -x'_k = -0.0154\ \text{rad}\ \ (-0.88^\circ)$

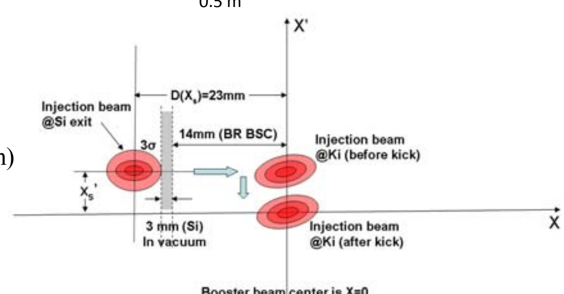
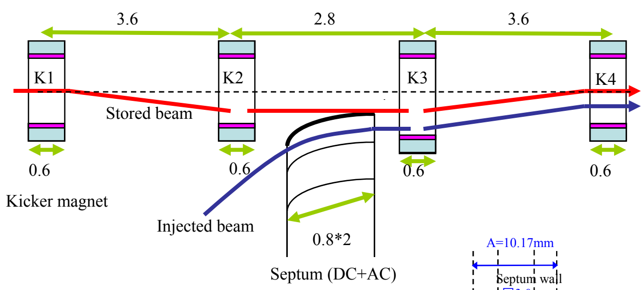


Diagram of the booster injection process in horizontal phase space.

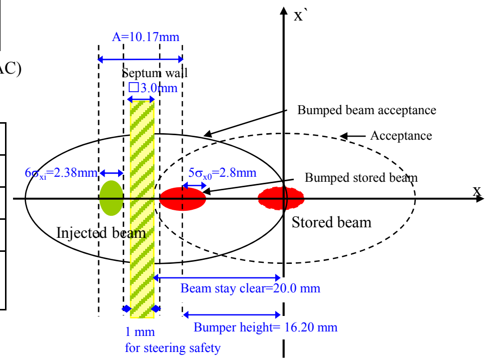
12

H. P. Chang

NSRRC Storage Ring Injection Scheme



	Septum	Kicker
Magnetic Length (m)	0.8	0.60
Maximum Field (T)	0.694	0.075
Deflection (mrad)	55.5	4.5
Magnet Current Waveform	300 μs (full-sine)	5.2μs (half-sine)



C. H. Chang

NSRRC Design Considerations for the TPS Injection System

1. High injection efficiency
2. Low disturbance to the stored beam
3. High reliability
4. Low noise (EMI and Ground noise)
5. Low outgas
6. TLS experiences
7. Large Booster

NSRRC Main Features of the TPS

- **Low emittance and high brightness**
  -- Brightness >10^{21} p/s/0.1%bw/mm^2/mrad^2 (@ 10 keV)
  -- Emittance ε< 2nm-rad
- **High stability**
  -- Photon intensity fluctuation <0.1%
  -- Beam orbit fluctuation < 0.2μm ($d\sigma/\sigma \approx 5\%$)
  -- Beam size fluctuation < 0.1μm
- **High reliability**
  -- High injection efficiency (> 90%)
  -- Machine Up-time > 98%
  -- Trip rate < 1/week
- **Superconducting Technologies**
- **Top-up injection**
- **Same-tunnel Booster**

NSRRC Design Considerations *(conti.)*

Small Field Error

-- Stable power supply (septum & kicker)
-- Small time jitter (matching of SR inj. kickers)
-- Short rise time and fall time (BR kickers)
-- Precise alignment (to reduce horizontal field)
-- Stable loads on circuit

Low Leakage Field and Field Distortion

-- Septum and shielding material (septum)
-- Thickness and uniformity of coating (ceramic chamber)
-- Full sine waveform (Injection septum)
-- To reduce thermal induced effects (septum & kicker)

NSRRC Design Considerations *(conti.)*

High Reliability

-- Low drive voltage (to reduce breakdown)

-- High quality manufacturing (coating, brazing, etc.)

-- Reduced heating load

(on magnets, chamber and circuit components)

*-- Out-of-vacuum device (septum, also **Low Outgas**)*

Low Electrical Noise

-- Independent power feeder and grounding line

-- EMI shielding

To Use the Advantage of a Large Booster

-- Precise condition of the injected beam

-- Long bunch train for injection

NSRRC Booster Injection and Extraction

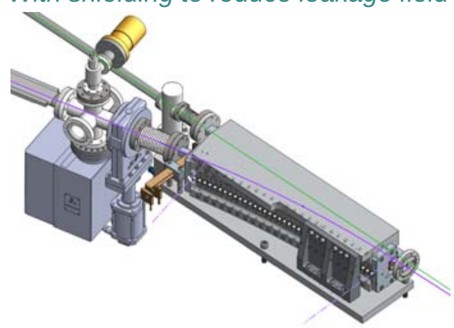
1. Booster Injection Septum
2. Booster Injection Kicker
3. Booster Extraction Septum
4. Booster Extraction Kicker

NSRRC Booster Injection Septum

Booster Injection Septum	3 Hz
Electron energy (GeV)	0.15
Bend angle (mrad)	209.44
Mag. aperture (mm)	28*22
Length (m)	0.8
Maximum field (T)	0.131
Bend radius (m)	3.8197
Beam aperture (mm)	26*20
Max. current (A)	2292
Pulse shape	full sine
Pulse duration (us)	300
Energy in magnet (J)	3.36
Impedance (Ohm)	0.027
Inductance (mH)	1.28
Inductance (simulated)	1.95
Capacitance (mF)	1782
Drive voltage (kV)	0.061
Leakage field (%)	< 0.1
Field error (%)	0.5

Features

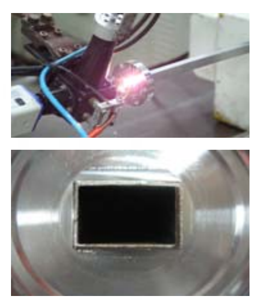
- *Less critical for power supply*
  -- Injection energy is low (150 MeV)
- *Septum (out-of-vacuum)*
  -- easy fabrication for septum
  -- easy fabrication for chamber
  -- 0.4 mm thickness (less heat and field distortion)
- *With shielding to reduce leakage field*

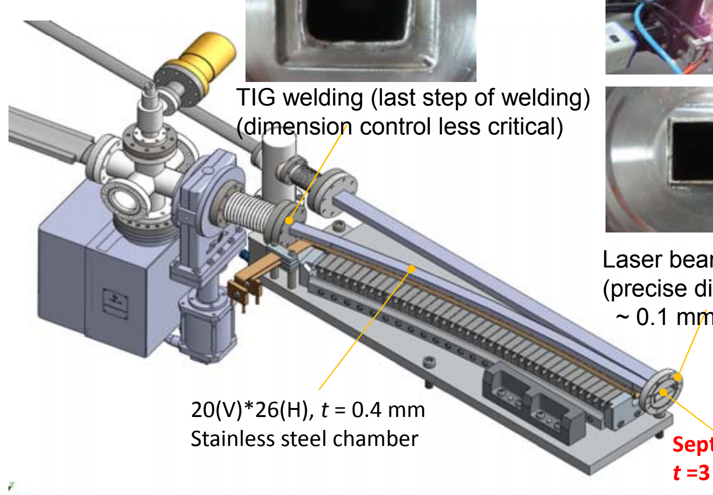


NSRRC Booster Injection Septum *(conti.)*

(Septum Chamber)

TIG welding (last step of welding)
(dimension control less critical)





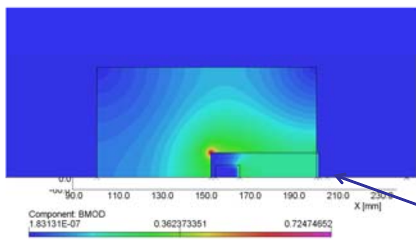
Laser beam welding
(precise dimension control ~ 0.1 mm)

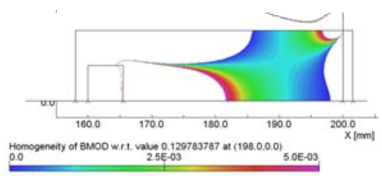
20(V)*26(H), *t* = 0.4 mm
Stainless steel chamber

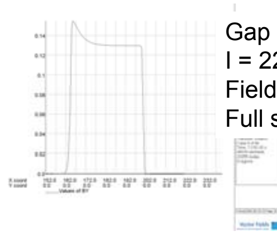
Septum thickness
***t* =3 mm**

NSRRC Booster Injection Septum *(conti.)*

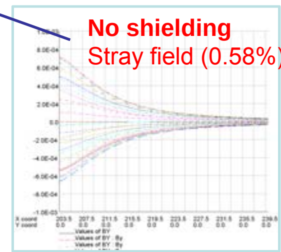
(Stray Field without Shielding)







Gap = 22mm
I = 2282 A
Field = 0.13T
Full sine , 300 μs

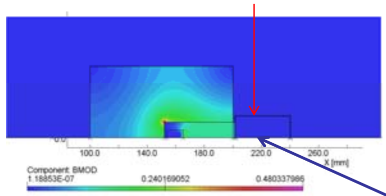


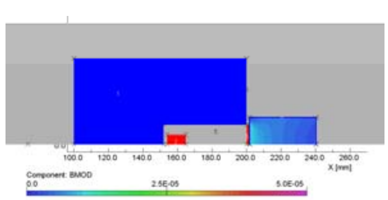
J.-C. Huang

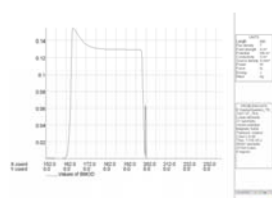
NSRRC Booster Injection Septum *(conti.)*

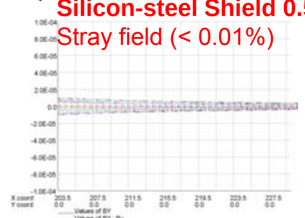
(Stray Field with Shielding)

Silicon-steel Shield 0.5 mm







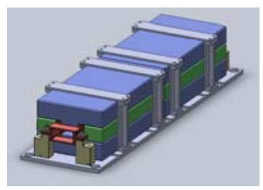


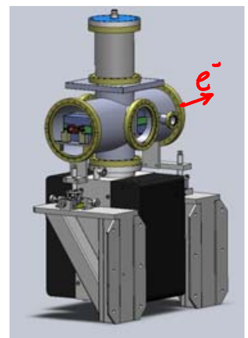
NSRRC Booster Injection Kicker

BR inj. Kicker	3Hz
Energy (GeV)	0.15
Bend angle (mrad)	16
Mag. aperture (mm)	50*21
Length (m)	0.5
Maximum field (T)	0.016
Bend radius (m)	31.25
Beam aperture (mm)	35*20
Max. current (A)	267
Pulse shape	Flat top
Fall time (ns)	100
Pulse duration (ns)	1000ns-FT
Energy in magnet (J)	0.053
Impedance (Ohm)	25
Inductance (mH)	1.50
Capacitance (mF)	--
Drive voltage (kV)	13.4

Features

- *Less critical for power supply*
  -- Injection energy is low (150 MeV)
- *Long pulse injection 1000ns*
- *In-vacuum kicker*
  -- Outgassing rate OK, after baking
- *PFN circuit*

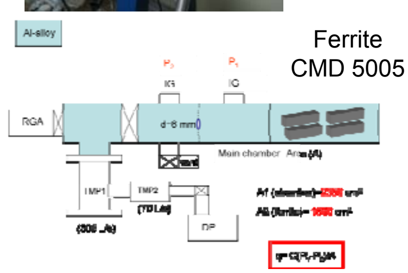




NSRRC Booster Injection Kicker (conti.)

(Outgassing Rate of Ferrite)

After baking at 150 °C for 24 hr
$P_1 = 2.26\times10^{-9}$ torr
$q = 1.38\times10^{-12}$ torr.L/s.cm²



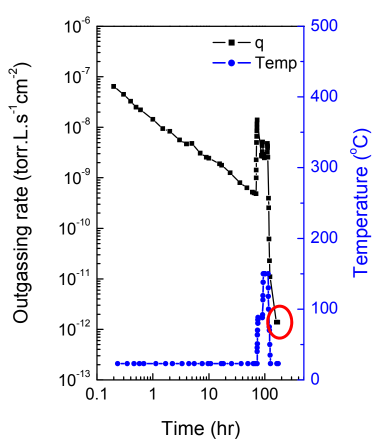


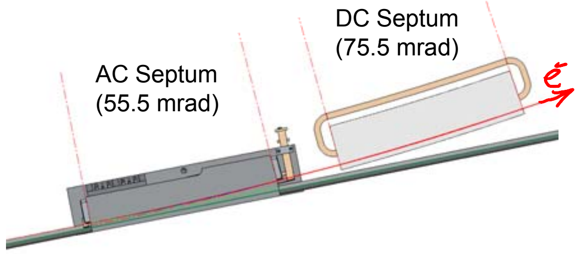
Figure . System for measuring the rate of thermal outgassing

NSRRC Booster Extraction Septum

BR Extraction AC septum	3Hz
Energy (GeV)	3.0
Bend angle (mrad)	55.5
Mag. aperture (mm)	22*15
Length (m)	0.8
Maximum field (T)	0.694
Bend radius (m)	14.4144
Beam aperture (mm)	20*13
Max. current (A)	8281
Pulse shape	half sine
Pulse duration (us)	150
Energy in magnet (J)	50.6
Impedance (Ohm)	0.031
Inductance (mH)	1.47
Inductance (simulated)	2.85
Capacitance (mF)	1546
Drive voltage (kV)	0.302
Leakage field (%) (DC)	<0.01%
Field error (%)	< 1

Features

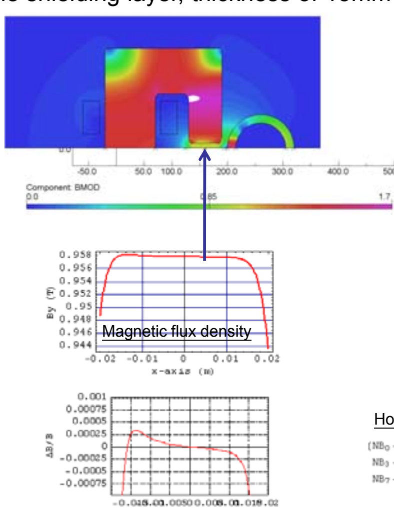
- *Septum AC+DC*
  -- to reduce the field of AC septum
- *DC septum*
  -- double layer shielding
- *AC Septum*
  -- out-of-vacuum
  -- easy fabrication for septum and chamber
  -- 0.4 mm thickness (less heat and field distortion)

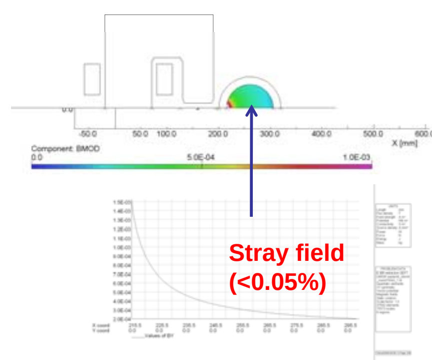


NSRRC Booster Extr. Septum *(conti.)*

DC leakage field (one shielding layer)

One shielding layer, thickness of 15mm





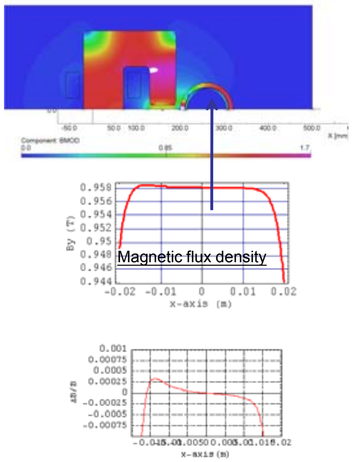
Homogeneity tests

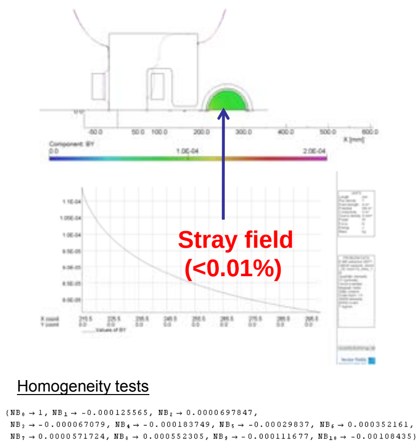
{$NB_0 \rightarrow 1$, $NB_1 \rightarrow -0.000127174$, $NB_2 \rightarrow 0.0000683878$, $NB_3 \rightarrow -0.0000684547$, $NB_4 \rightarrow -0.000185527$, $NB_5 \rightarrow -0.000301595$, $NB_6 \rightarrow 0.000349662$, $NB_7 \rightarrow 0.0000571401$, $NB_8 \rightarrow 0.000552019$, $NB_9 \rightarrow -0.000112983$, $NB_{10} \rightarrow -0.00108493$}

NSRRC Booster Extr. Septum *(conti.)*

DC leakage field (two shielding layer)

Two shielding layers, thickness of 10mm and 3.5mm



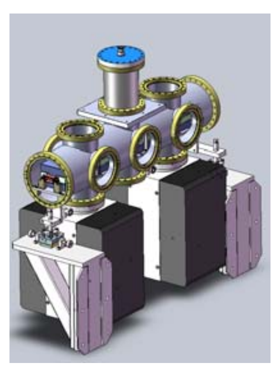


NSRRC Booster Extraction Kicker

BR ext. Kicker	3 Hz
Energy (GeV)	3.0
Bend angle (mrad)	2.6
Mag. aperture (mm)	50*18
Length (m)	1
Maximum field (T)	0.026
Bend radius (m)	384.6154
Beam aperture (mm)	35*18
Max. current (A)	372
Pulse shape	Flat top
Rise time (ns)	200
Pulse duration (ns)	1000ns-FT
Energy in magnet (J)	0.24
Impedance (Ohm)	25
Inductance (mH)	3.49
Capacitance (mF)	--
Drive voltage (kV)	18.6
Field error (%)	1

Features

- *Similar to the booster injection kicker*
- *Long pulse extraction 1000ns*
- *1m in-vacuum kicker*
  -- high outgassing rate (increase pumping)
  -- high inductance
- *PFN circuit*

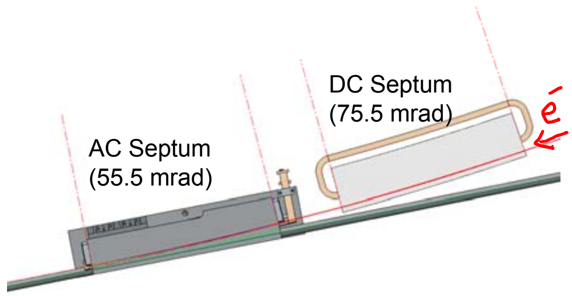


NSRRC SR Injection Septum

AC septum	3Hz
Energy (GeV)	3.0
Bend angle (mrad)	55.5
Mag. aperture (mm)	22*15
Length (m)	0.8
Maximum field (T)	0.694
Bend radius (m)	14.4144
Beam aperture (mm)	20*13
Max. current (A)	8281
Pulse shape	full sine
Pulse duration (us)	300
Energy in magnet (J)	50.6
Impedance (Ohm)	0.031
Inductance (mH)	1.47
Inductance (simulated)	2.85
Capacitance (mF)	1546
Drive voltage (kV)	0.302
Leakage field (%) (AC)	< 0.1%
Field error (%)	1

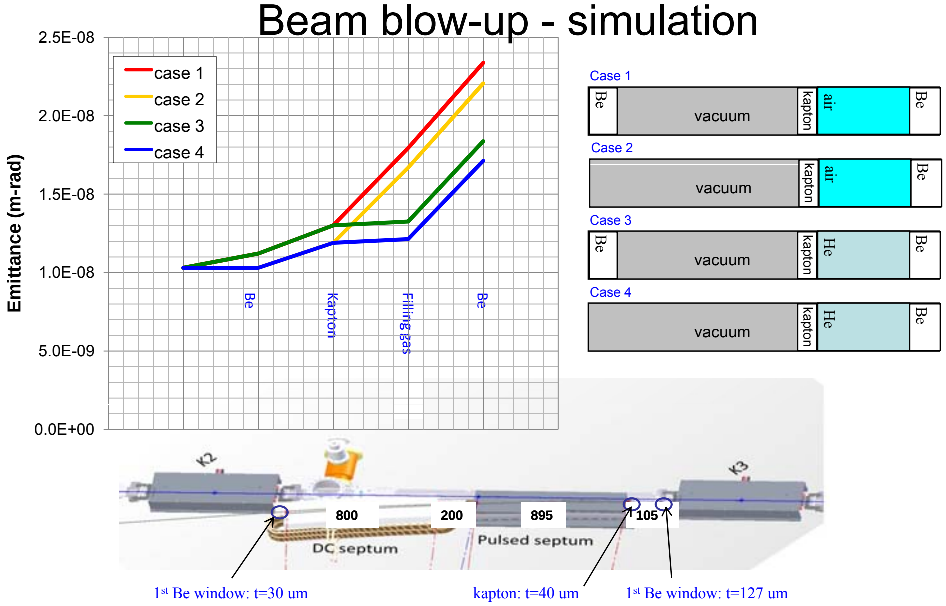
***Features** (similar to the booster ext. septum)*

- *Septum AC+DC*
  -- to reduce the field of AC septum
- *DC septum*
  -- double layer shielding
- *AC Septum (out-of-vacuum)*
  -- easy fabrication for septum and chamber
  -- 0.4 mm thickness (less heat and field distortion)



NSRRC SR Injection Septum (conti.)

Beam blow-up - simulation

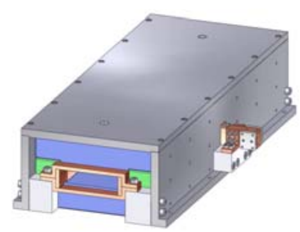


NSRRC SR Injection Kicker

SR inj. Kicker	3Hz
Energy (GeV)	3.0
Bend angle (mrad)	4.5
Mag. aperture (mm)	92*35
Length (m)	0.6
Maximum field (T)	0.075
Bend radius (m)	133.3333
Beam aperture (mm)	68*20
Max. current (A)	2089
Pulse shape	half sine
Pulse duration (us)	5.2
Energy in magnet (J)	4.32
Impedance (Ohm)	1.202
Inductance (mH)	1.98
Capacitance (mF)	1.372
Drive voltage (kV)	2.51
Field error (%)	1

Features

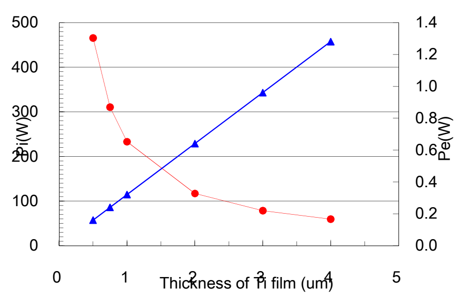
- *4-kicker bump*
- *Ceramic chamber with Ti coating*
  -- to reduce resistance heating
  -- field distorted (→ thin coating)
- *Thermal protection emphasized*
- *Small time jitter*
- *Shielding for EMI noise*

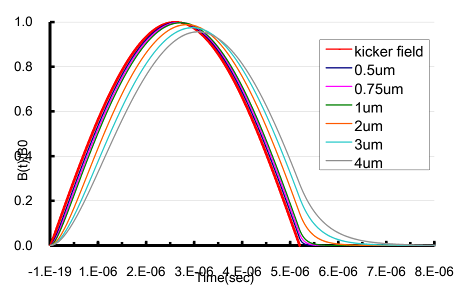


NSRRC SR Injection Kicker (conti.)

(Coating Considerations for Ceramic Chamber)

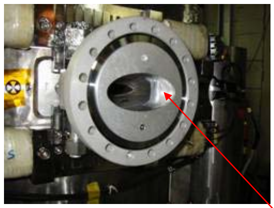
- Thickness ⬆ → Ohmic heating from beam image current, P_i ⬇
- Thickness ⬆ → Deposited power due to eddy current, P_e ⬆
- Thickness ⬆ → Field flux attenuation ⬆
- Coating uniformity (coating process, metallization grain, surface roughness of ceramic....) ~ ± 10 % based on TLS experience



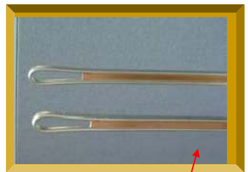


NSRRC SR Injection Kicker (conti.)

Thermal protections – TLS injection section

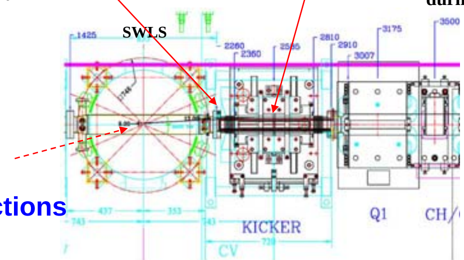


Pre-absorber in aluminum flange to protect the downstream bellows.

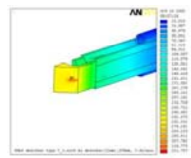


Absorber inside the 4th kicker chamber

Ceramic insulators on top of absorber to avoid the arcing during kicker firing.



Thermal protections
-- Bellows
-- Ceramic chamber



ANSYS Thermal Analysis
330°C hot spot near Cu cold head cover of absorber with upstream pre-absorber (5.3 T)

NSRRC SR Injection Kicker (conti.)

Fatal failure – TLS injection section

Ceramic chamber for 4th Kicker was leaked.
Ceramic insulator outboard the absorber was melt and broken.

NSRRC

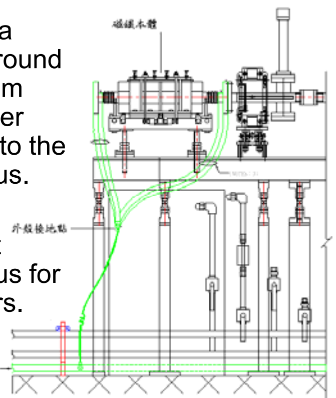
SR Injection Kicker (conti.)

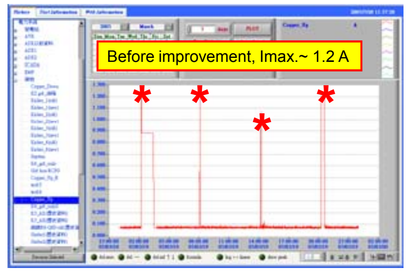
(Kicker EMI Reduction - TLS)

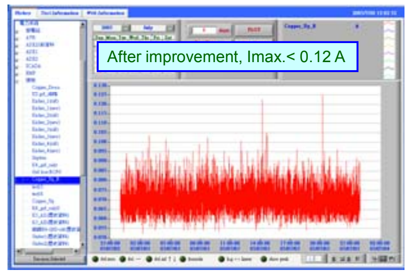
Sensors around injection section and the SRF system (50m far away from the injection section) tripped frequently due to short time noises.

Established a special ground routes from each kicker chamber to the ground bus.

Independent ground bus for the kickers.







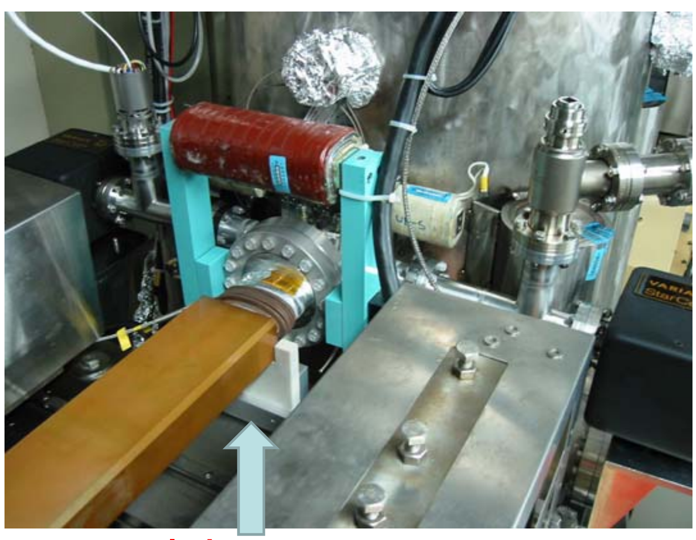
The currents flowed through girder.

35

NSRRC

SR Injection Kicker (conti.)

(Kicker EMI Reduction - TLS)

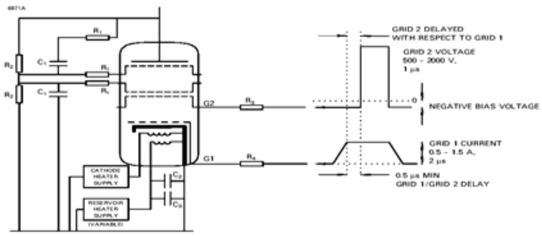


Insulation support

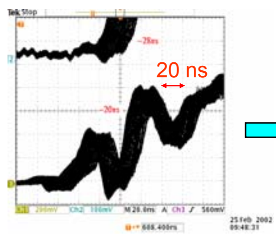
NSRRC SR Injection Kicker (conti.)

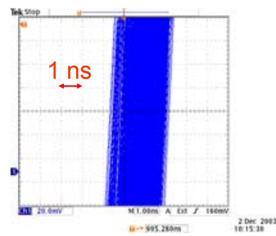
(Jitter Reduction of Kicker Pulser -TLS)

Double pulsing method



Time jitter improved
25 ns ➔ < 3 ns (10 min warm up) ⇒ **Injection efficiency significantly improved.**



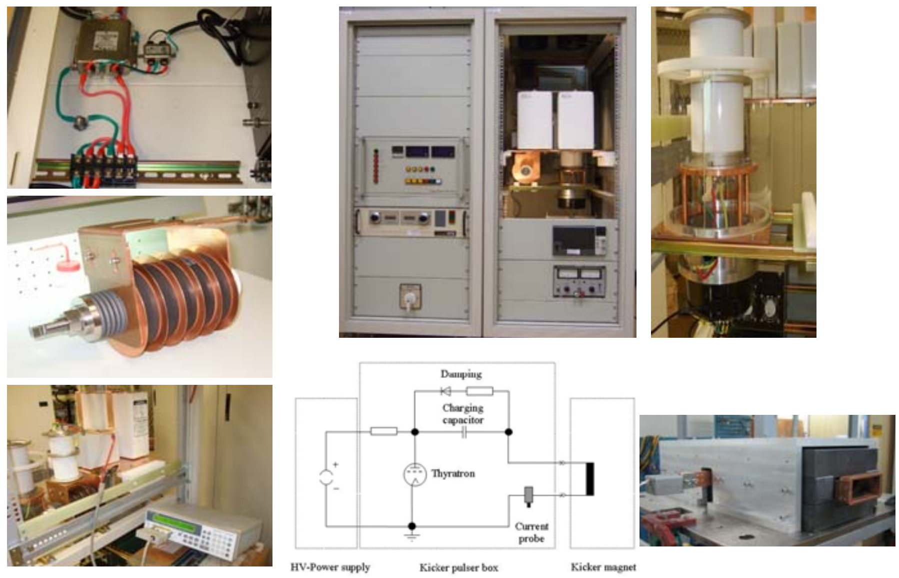


K.B. Liu et al.

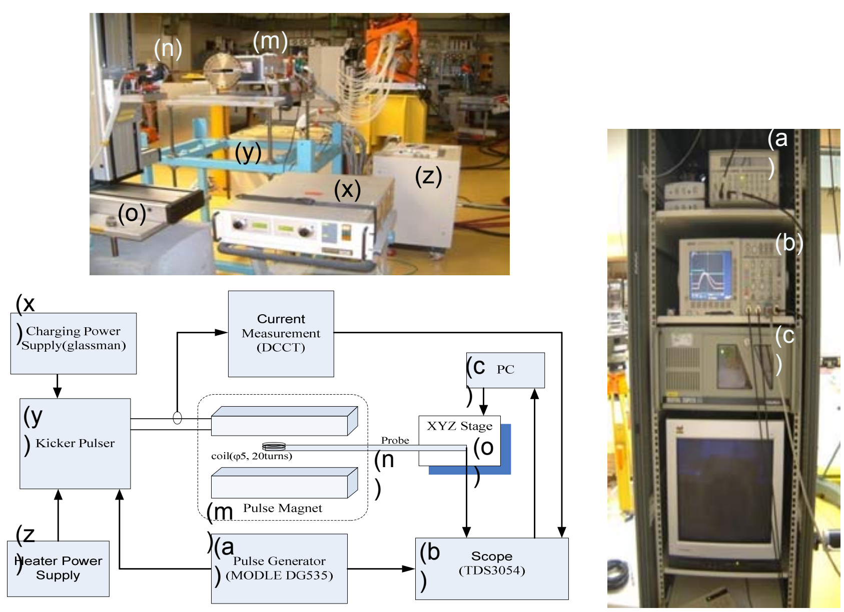
NSRRC Pulsed Magnet Prototypes and Field Mapping System

- Prototypes of Kicker and Pulser
- Field Mapping System
- Test for Shielding Material

Prototypes of Kicker and Pulser

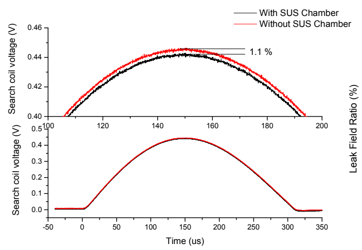


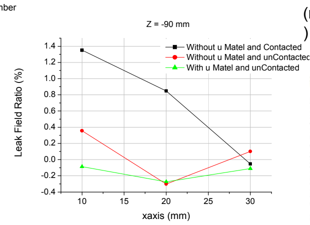
Field Mapping System

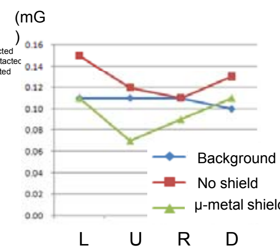


NSRRC *Field Mapping System* (conti.)

(To check the effect of shielding material)







Summary

1. Pulsed magnet system for the TPS have been designed.
2. High injection efficiency, low disturbance to the stored beam, high reliability of the components, low noise, low vacuum outgas and the experiences gained at TLS are considered in the design.
3. Techniques to reduce the stray field, field distortion, thermal effect, noise, and time jitter are studied and applied to the design of the TPS injection system.
4. Field mapping system and prototypes for the TPS pulsed magnets are under testing.

Thank you for your attention.

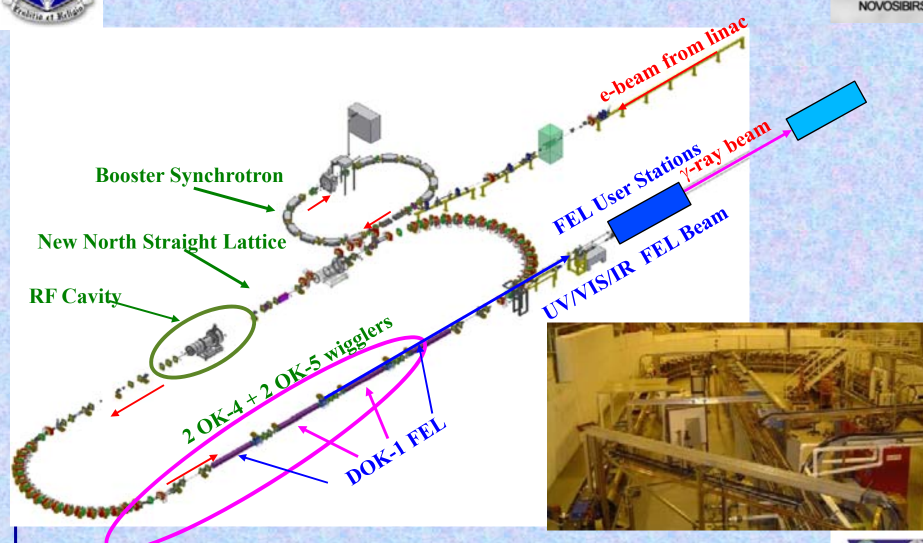
Design and performance of fast injection and extraction kickers at Duke FEL/HIγS facility

Speaker: **Stepan Mikhailov**

(DFELL, Duke University, Durham, USA)

Yu.Matveev, D.Shvedov, O.Anchugov, L.Shvedova , N.Gavrilov
(BINP, Novosibirsk, Russia)
S.Mikhailov , V.Popov, P.Wallace
(DFELL, Duke University, Durham, USA)

Duke FEL/HIγS facility



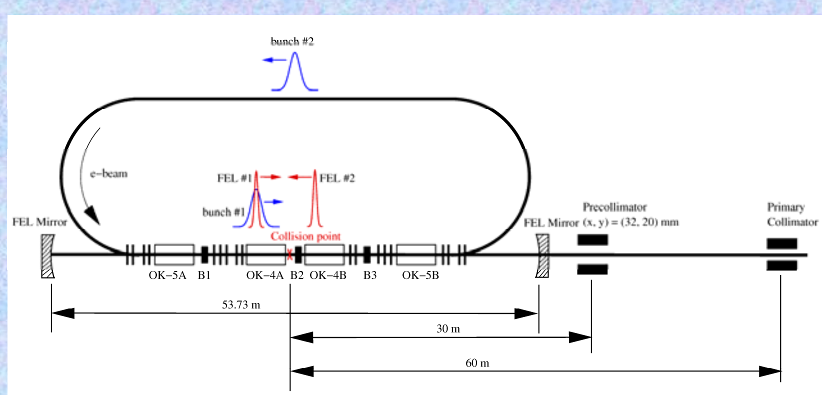
Parameters of the 1.2 GeV Duke FEL ring

Maximum beam energy E_{max} [GeV]	1.2
Injection energy E_{inj} [GeV]	0.24 - 1.2 GeV
Stored beam current [mA]	
- in single bunch/in multibunch	100/400
Circumference [m]	107.46
Bending radius [m]	2.1
RF frequency [MHz]	178.55
Harmonic number	64
@ E_{max} = 1.0 GeV:	
Beam emittance ε_x	18
Betatron tunes Q_x / Q_y	9.11 / 4.18
Momentum compaction factor	0.0086
Natural chromaticities C_x / C_y	-10.0 / -9.8
Damping times $\tau_{x,y} / \tau_s$ [ms]	18.3 / 17.0
Energy spread	$5.8 \cdot 10^{-4}$
Energy of Compton γ-rays by HIγS	1.0 – 60 MeV
Energy spread of γ-rays (collimated)	0.5 - 4.5%
γ-ray flux on target (collimated)	$10^4 - 10^9$ γ /sec

Stepan Mikhailov
July 27, 2009

Pulsed Magnet Design Workshop at
BNL, NSLS-II

γ production using Compton back-scattering at FEL storage ring



Stepan Mikhailov
July 27, 2009

Pulsed Magnet Design Workshop at
BNL, NSLS-II

Parameters of the booster

	Single bunch		Multi bunch
Maximum beam energy E_{max} [GeV]		1.2	
Injection energy E_{inj} [GeV]		0.18	
Stored beam current [mA]	1.5 – 3.0		10-12
Circumference [m]		31.902	
Bending radius [m]		2.273	
RF frequency [MHz]		178.55	
Harmonic number		19	
Operation cycle [sec]	1.8-2.0		3.3-5.5
Energy rise rate [sec]		0.70	
@ E_{max} = 1.2 GeV:			
Beam emittance ε_x, ε_y		440 / 6	
Betatron tunes Q_x/ Q_y		2.375 / 0.425	
Momentum compaction factor		0.158	
Maximum β_x/ β_y/ η_x [m]		9.9 / 27.2 / 1.65	
Natural chromaticities C_x/ C_y		-1.7 / -3.7	
Damping times $\tau_{x,y}$/ τ_s [ms]		3.16 / 1.60	
Energy loss per turn [KeV]		80.7	
Energy spread		$6.8 \cdot 10^{-4}$	

List and specs of Duke fast kickers

Kicker	Switch type	#	Voltage range	Pulse width	Jitter	Charge/ Pulse (max)
Booster Injection	TPI1-1k/20	1	4-10kV	106 ns/ 17 ns	1-2 ns	12 µC/ 2 µC
Booster Extraction	TPI1-1k/20	2	4-20kV	10 ns	1-2 ns	7 µC
Ring Injection	TPI3-10k/25	3	4-25kV	50 ns	~5 ns	100 µC

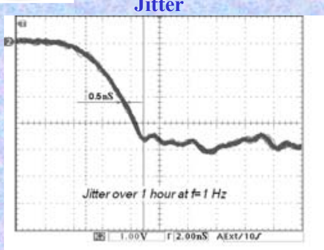
Injection and extraction kicker specification

Parameter	Injection	Extraction
Min e-Beam Energy, MeV	150	250
Max e-Beam Energy, MeV	300	1200
Min Angle Kick, mrad	0.6	0.6
Nominal Angle Kick, mrad	0.675	0.675
Max Angle Kick, mrad	0.75	0.75
Max Repetion Rate, pps	2	25
Geometrical Kicker Gap, mm	27	27
Effective Kicker Gap, mm	27	27
Effective Kicker Length, cm	30	30
Min Kicker Voltage, kV	2.0	3.4
Max Kicker Voltage, kV	5.1	20.3
PFN Type	Single Line	Double Line
Pulse shape	trapezoid	bell-shape
Rise/Fall Time 10%-90%, nsec	5	7
Flat Top Time, nsec	100/0	4
Impedance, Ohm	50	50
Min Kicker PS Voltage, kV	4.1	3.4
Max Kicker PS Voltage, kV	10.1	25.3
PFN Capacitance, nF	2.1	0.4
Charging Rate, J/sec	0.22	3.52
Jitter peak-to-peak, nsec (from trigger signal)	<2	<1.6
Overshoot (Undershoot)	< 10%	
Flatness	< 10% peak-to-	< 10% peak-to-
Pulse Form Reproducibility	within 5%	within 5%

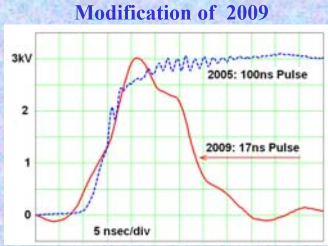
Booster injection and extraction

Injection kicker pulse

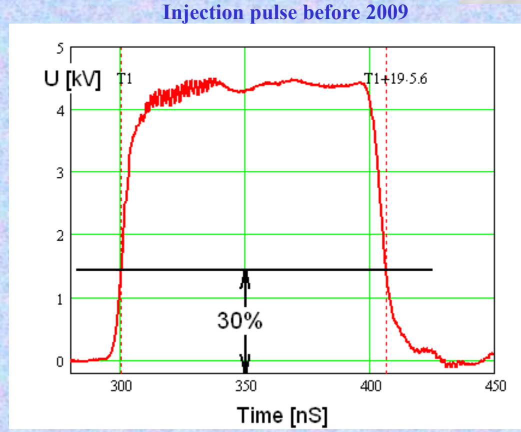
Jitter



Modification of 2009



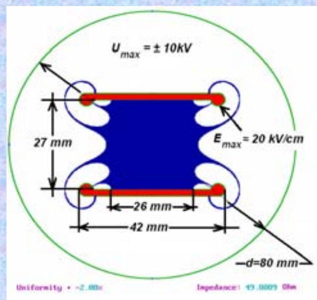
Injection pulse before 2009



PFN cable was shortened in 2009 to produce a short pulse

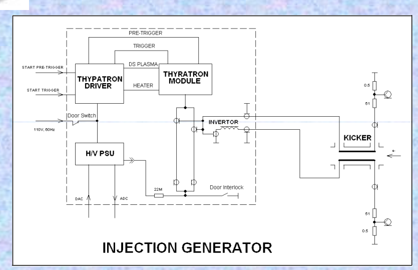
Injection and extraction kickers

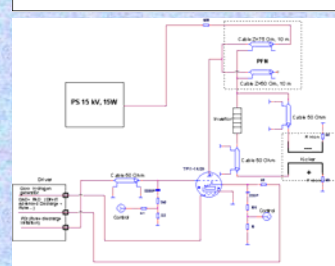
Outside | **2D geometry** | **Inside**



- Maximum electrical field — < 20 kV/cm
- Impedance — 50 Ω
- Gap — 27.0 mm
- Maximum kick angle @ 1.2 GeV — 0.8 mRad
- Effective electric length — 33 cm

Injection kicker driver



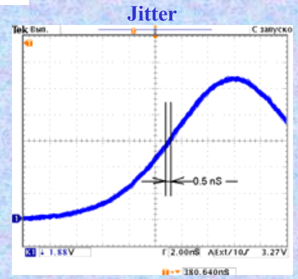


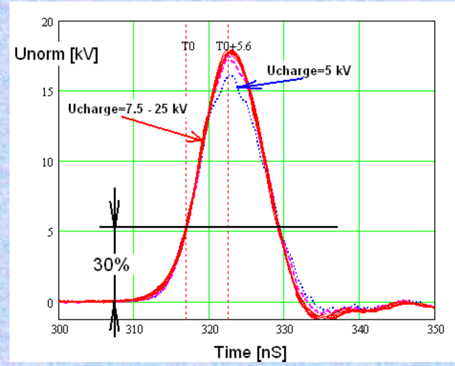
- Minimum voltage — 4 kV
- Maximum voltage — 10 kV
- Flat top duration — 100/0 ns
- Jitter — ~1-2 nS
- Maximum repetition rate — 10 Hz
- Impedance — 50 Ω

Stepan Mikhailov
July 27, 2009
Pulsed Magnet Design Workshop at
BNL, NSLS-II

Extraction kicker pulse

Jitter





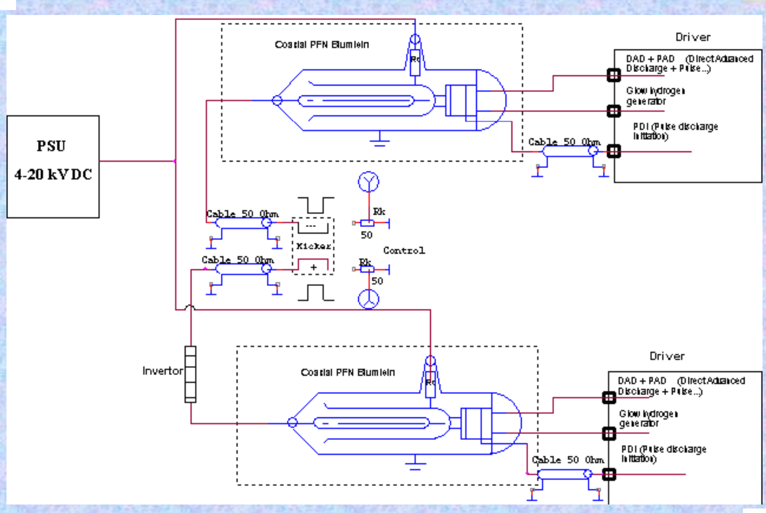
- Minimum voltage 4 kV
- Maximum voltage 25 kV
- Pulse width by 30% level ~12 ns
- Jitter ~1-2 nS
- Maximum repetition rate 25 Hz
- Impedance 50 Ω

Extraction pulse for
dynamic range of 0.18-1.2 GeV

Stepan Mikhailov
July 27, 2009

Pulsed Magnet Design Workshop at
BNL, NSLS-II

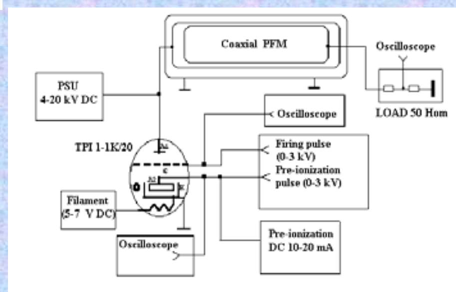
Extraction kicker driver

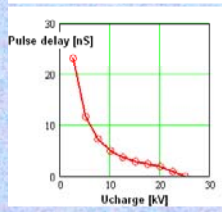


Stepan Mikhailov
July 27, 2009

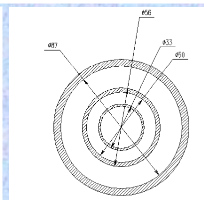
Pulsed Magnet Design Workshop at
BNL, NSLS-II

Extraction kicker driver





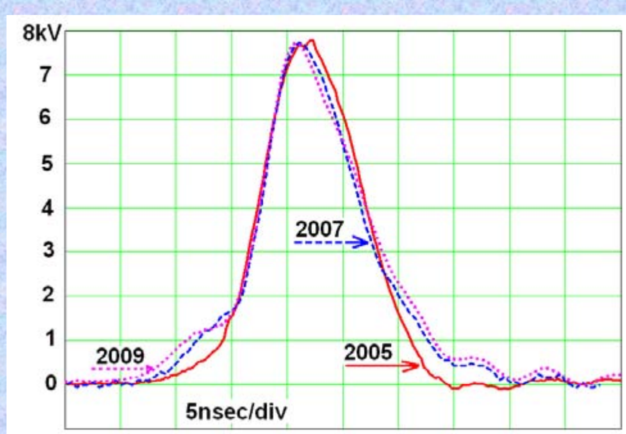
Peak time vs. voltage



Double coaxial PFN

1 – Thyratron Drivers; 2 – Thyratron Assemblies; 3 – Blumlein PFNs; 4 – Pulse Inverter

Evolution of the extraction kicker pulse



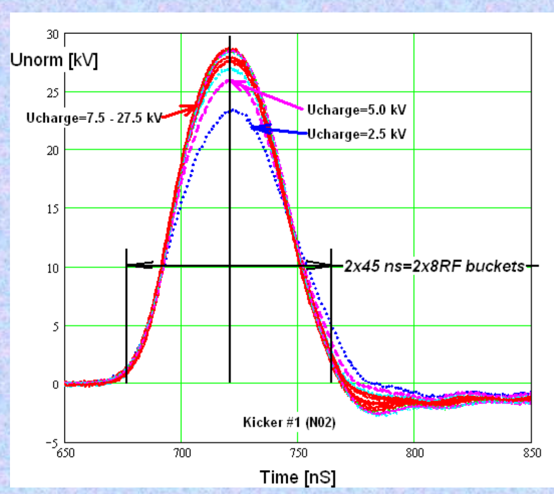
Widening of the booster extraction pulse (positive) caused by aging of cold cathode thyratron switch

Storage Ring kicker specification

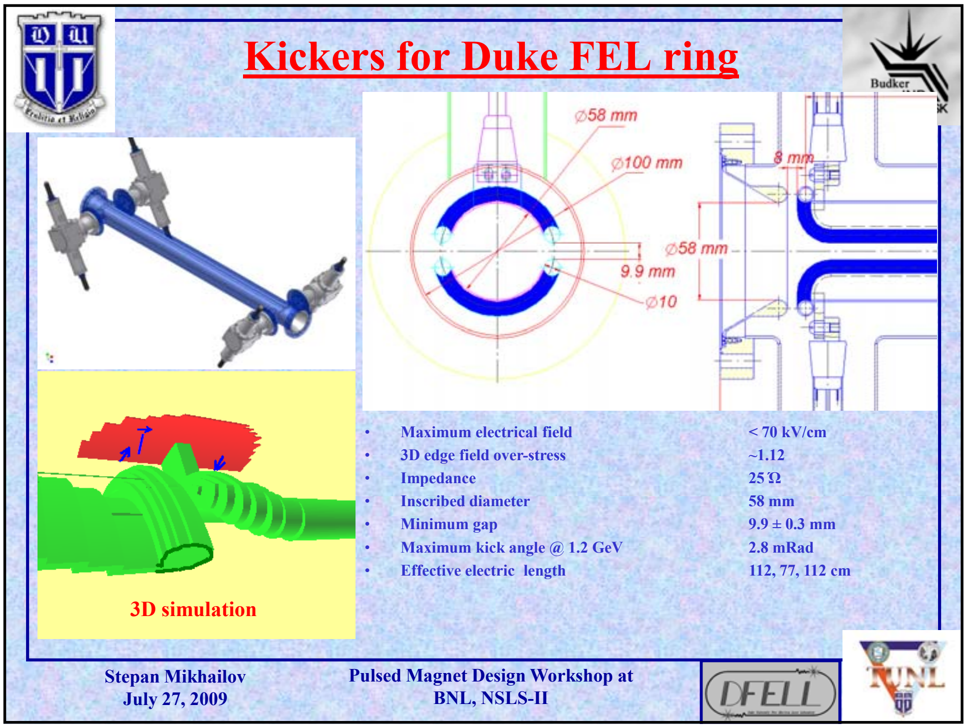
Parameter	Kicker #1	Kicker #2	Kicker #3
Min e-Beam Energy, MeV	250	250	250
Max e-Beam Energy, MeV	1200	1200	1200
Min Angle Kick, mrad	1.5	0.3	1.5
Nominal Angle Kick, mrad	1.8	0.4	1.8
Max Angle Kick, mrad	2	1.38	2
Max Repetion Rate, pps	25	25	25
Geometrical Kicker Gap, mm	58	58	58
Effective Kicker Gap, mm	46	46	46
Effective Kicker Length, cm	111.8	77	111.8
Min Kicker Voltage, kV	3.8	1.1	3.8
Max Kicker Voltage, kV	24.6	24.6	24.6
PFN Type	Double Line	Double Line	Double Line
Pulse shape	bell-shape	bell-shape	bell-shape
Rise/Fall Time 10%-90%, nsec	30	30	30
Flat Top Time, nsec	5	5	5
Impedance, Ohm	25	25	25
Min Kicker PS Voltage, kV	3.8	1.1	3.8
Max Kicker PS Voltage, kV	24.6	24.6	24.6
PFN Capacitance, nF	2.8	2.8	2.8
Charging Rate, J/sec	17.8	18.6	17.8
Jitter peak-to-peak, nsec (from trigger signal)	TBD	TBD	TBD
Flatness	< 10% peak-	< 10% peak-	< 10% peak-
Pulse Form Reproducibility	within 5%	within 5%	within 5%

North straight section

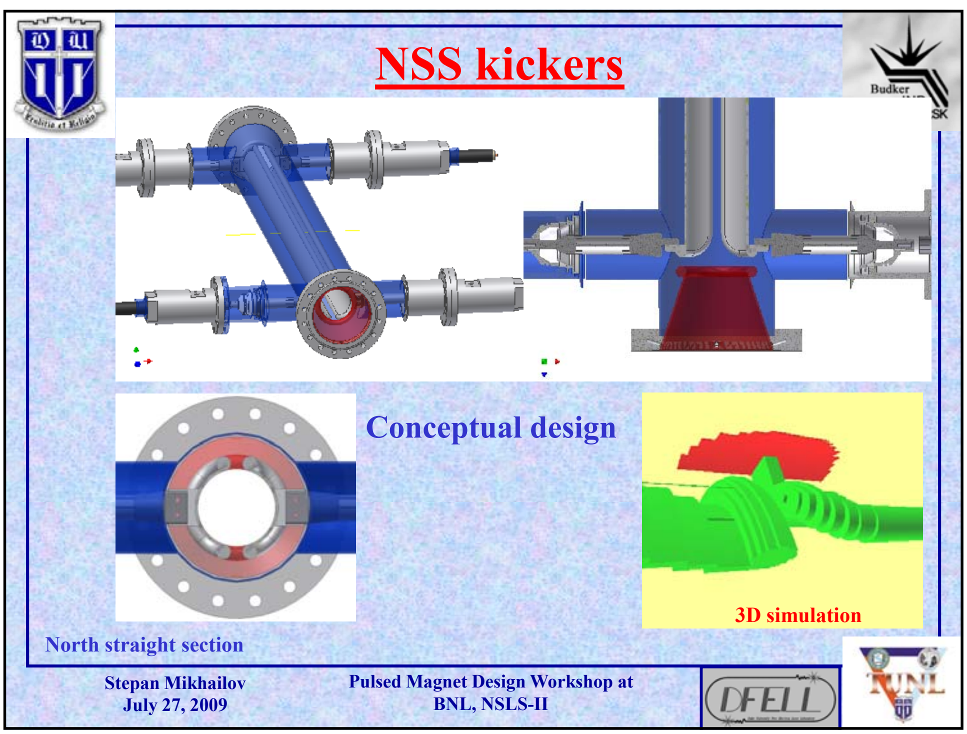
Storage ring kicker pulse



Injection pulse for dynamic range of 0.18-1.2 GeV

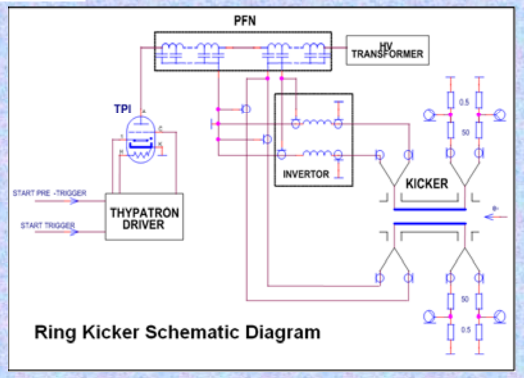


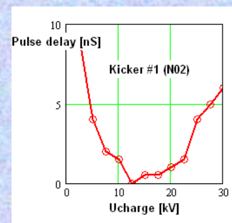
Kickers for Duke FEL ring
∅58 mm
∅100 mm
8 mm
∅58 mm
9.9 mm
∅10
3D simulation
Maximum electrical field < 70 kV/cm
3D edge field over-stress ~1.12
Impedance 25 Ω
Inscribed diameter 58 mm
Minimum gap 9.9 ± 0.3 mm
Maximum kick angle @ 1.2 GeV 2.8 mRad
Effective electric length 112, 77, 112 cm
Stepan Mikhailov
July 27, 2009
Pulsed Magnet Design Workshop at
BNL, NSLS-II
DFELL



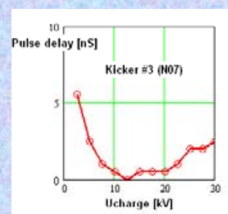
NSS kickers
Conceptual design
3D simulation
North straight section
Stepan Mikhailov
July 27, 2009
Pulsed Magnet Design Workshop at
BNL, NSLS-II
DFELL

Storage ring kicker driver





Peak time vs. voltage



- Minimum voltage 2 kV
- Maximum voltage 30 kV
- Pulse width by 30% level ~12 ns
- Jitter 2-4 nS
- Maximum repetition rate 25 Hz
- Impedance 25 Ω

Conclusion:

- Specs, design and development of the Duke FEL/HIγS kickers and drivers had a number of challenges;
- The design in principle proved to be adequate enough for the Duke FEL/HIγS operation purposes;
- Reliability of the drivers still leaves a lot to be desired;
- We are still working on it, the system is still under ongoing modification to make it adequate for SR facility capable of 24/7 operation

Pulsed magnets for the photon factory at KEK

Pulsed Magnet Design and Measurement Workshop
27 July 2009

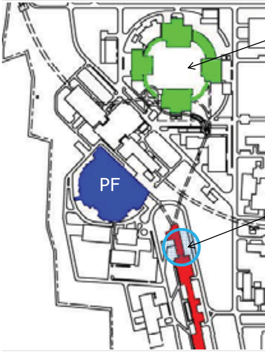
Akira Ueda
Photon factory ,KEK

Pulsed magnets for the photon factory

2 Septum magnets
4 Kicker magnets
(for injection)

1 pulsed sextuple magnet
↓
Takaki's talks

Other pulsed magnets

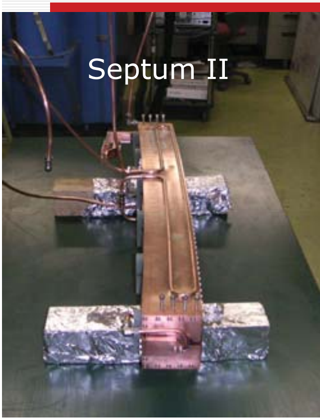


PF- AR
2 septum magnets
4 kicker magnets
(for injection)

Linac
1 pulsed Bending magnet
(for separation electron beam)

Septum magnets

Septum magnets



Passive type septum
(eddy current septum wall)

Septum I
7deg@2.5 Gev electron beam
1.5m
5mm copper

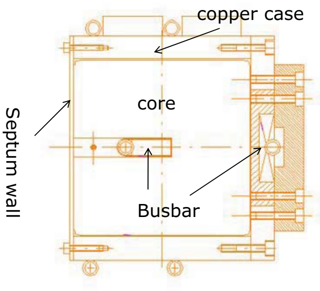
Septum II
5deg@2.5 Gev electron beam
1m
2mm copper &0.35mm silicon steel

1988 :first install this type magnets
2004: exchange the magnets
(almost same magnets)

Septum magnets parameters

	septum I	septum II
Bend angle	7deg	5deg
Length	1.5m	1m
Max. Field	0.7 4T	0.7 4T
Horizontal Aperture	23mm	23mm
Verical Aperture	9.5mm	9.5mm
Imax	6000A	6000A
Pulse shape	half sine	half sine
pulse length	120μsec	80μsec
Inductance	6.8μH	4.8μH
Septum wall	5mm copper	2mm copper with 0.35 mm silicon steel

Cross section



cross section of the septum II

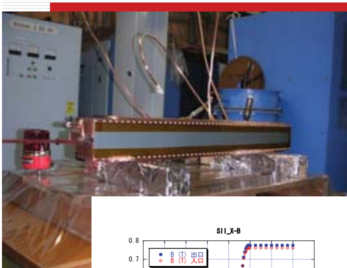
0.35mm silicon steel core

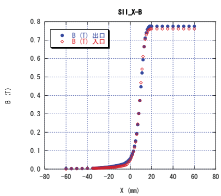
stacked in

Copper case

Molding with polyimide

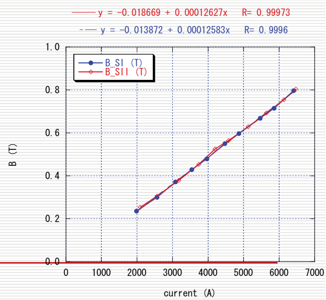
Field measurement



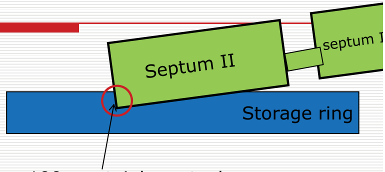


Sort coil

Integrate on the scope



Installation in the vacuum chamber



100μm stainless steel

(Separate ring vacuum from BT vacuum)

Leakage field

Septum I 5mm Cu leakage field is very low

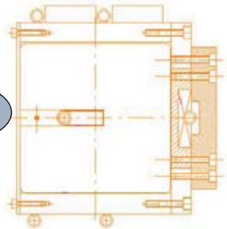
Septum II only 2mmCu over 350Gauss leakage field

Septum II 2mm Cu+0.35mm silicon steel

leakage field is very low

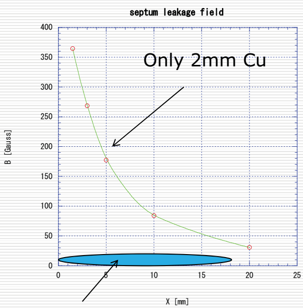
Leakage field(septum II)

Leakage field



2mm copper wall → Over 350Gauss leakage field by the septum wall

Leakage field(measurement)



2mmCu & 0.35mm silicon steel

2mm copper wall

↓

Over 300Gauss leakage field by the septum wall

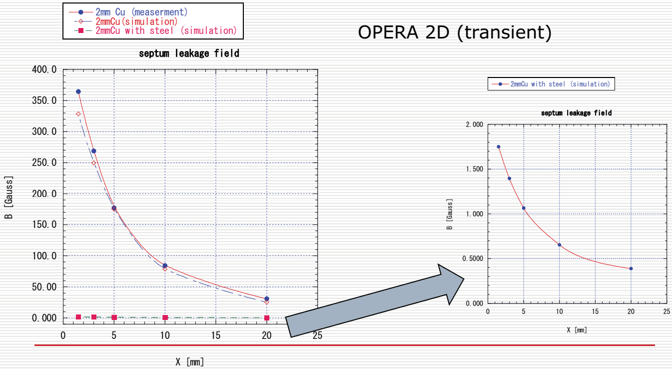
2mm copper & 0.35mm silicon steel

↓

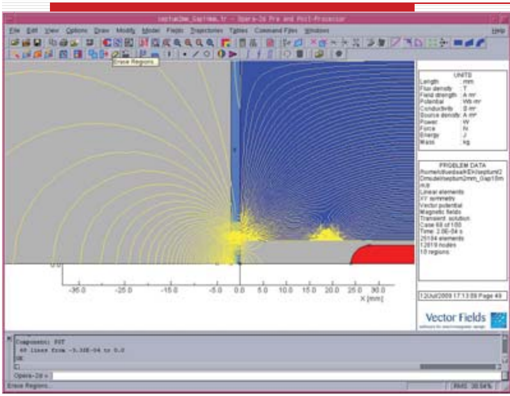
Less than 10 Gauss

Leakage field(simulation)

OPERA 2D (transient)



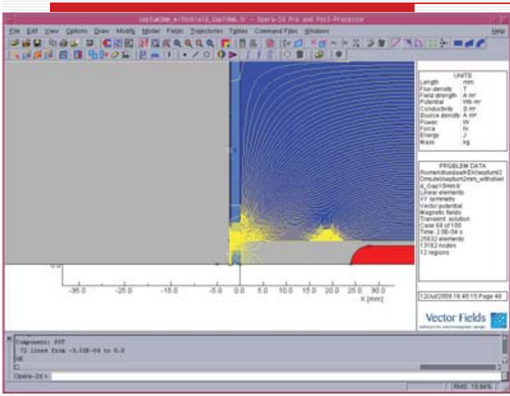
Leakage field(2mm Cu)



after 200μsec

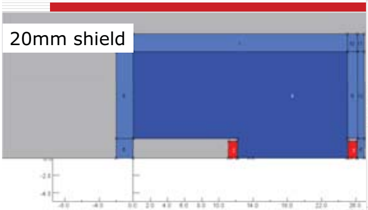
Field leaks out of septum wall

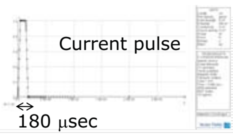
Leakage field(Cu & silicon steel)

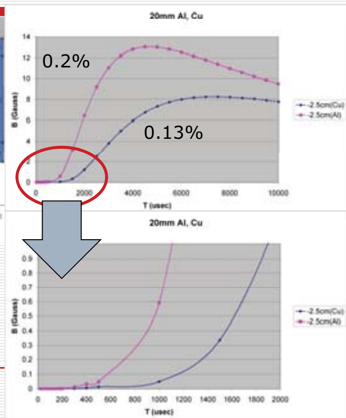


Leakage field is gathered in the Silicon steel

Why a leakage field delayed from current pulse ?

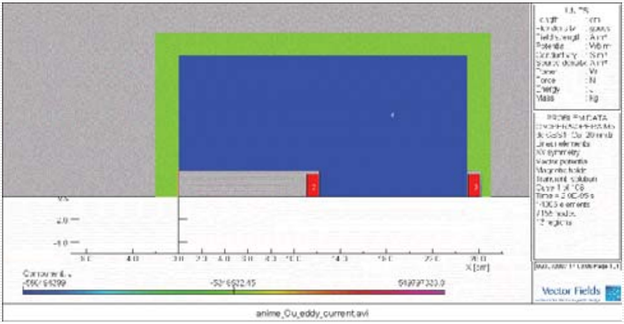






Field rise up after 500μsec

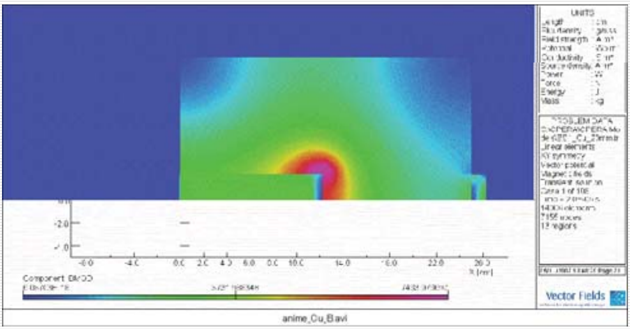
Animation
eddy current (Cu)



Amplitude is auto scale

time intervals are 20μsec within current pulse, 500μsec after current pulse.

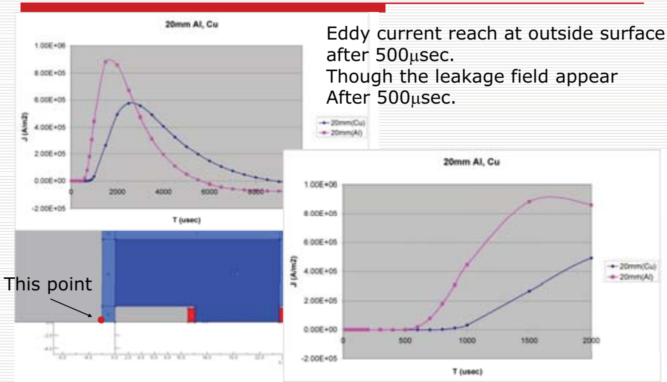
Animation
B field (Cu)



Amplitude is auto scale

time intervals are 20μsec within current pulse, 500μsec after current pulse.

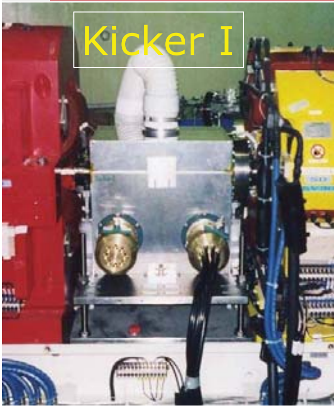
Eddy current at outside surface



Eddy current reach at outside surface after 500μsec.
Though the leakage field appear After 500μsec.

Kicker magnets

Kicker magnets



traveling wave type

Impedance 6.25Ω

Out of the vacuum

Total length: 400mm

4mrad @ 2.5GeV electron

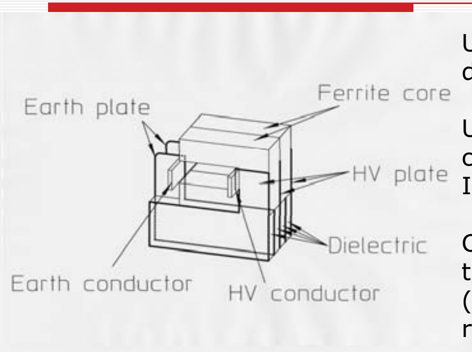
Pulse length 1.4μsec

2000 Jan: Install in the PF ring
2001 Jun: PFL break down
(change old kickers)
2002 Aug: reinstall

Kicker design parameters

Magnetic length	345mm
Gap height	60mm
Gap width	170mm
Peak field	942Gauss(at 4500A)
Characteristic impedance	6.25Ω
Field propagation time	187nsec
Number of cell	30cell
Inductance of 1cell	31.9nH (34.3nH measured)
Capacitance of 1cell	815pF (849pF measured)
Dielectric material	Alumina ceramics
Molding material	Silicone Rubber

Magnet design

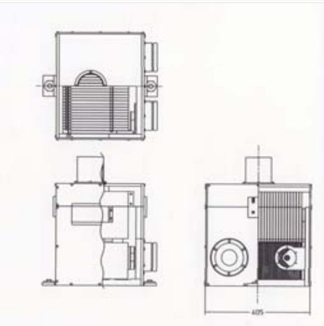


Using ceramics for dielectric

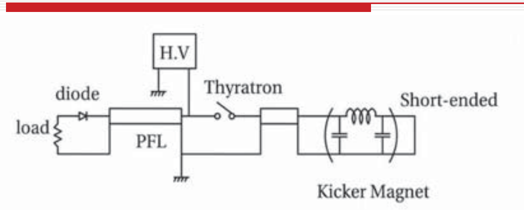
Upper ferrite core can be removed at Installation

Capacitor put under the magnet
(bean level: high radiation)

Assembly of the kicker magnet

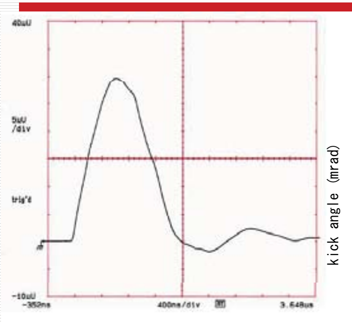


Power supply

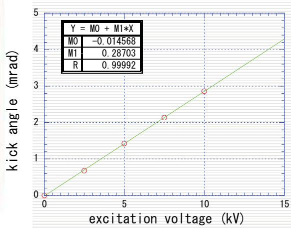


Impedance	6.25Ω
Output terminal	Shorted
Max. PFL (magnet) Voltage	30KV (15KV)
PFL impedance	25Ω
Number of PFL	4 (parallel)
Length of PFL	75m
Thyratron	e2v CX1175

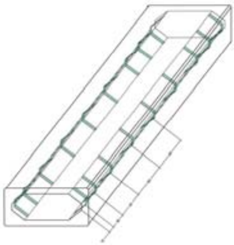
Magnetic field measurement



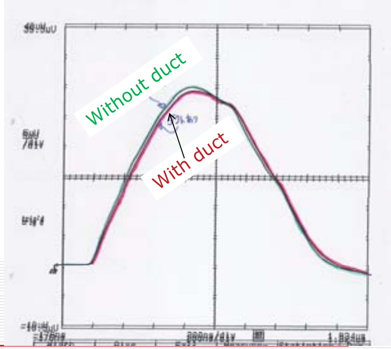
Using a Long coil



Ceramics duct



1mm Ti coating with slit



Installation of the kicker magnet

Remove upper ferrite cores

↓

Set the magnet under the ceramics duct

↓

Lift the magnet

↓

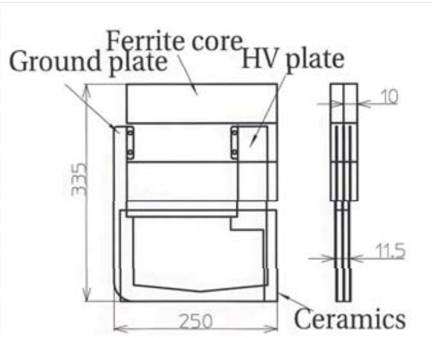
Assemble the upper ports

Ceramics breakdown

Ceramics is breakdown during pulse test

(Beginning of my work)

Schematic drawing of a cell

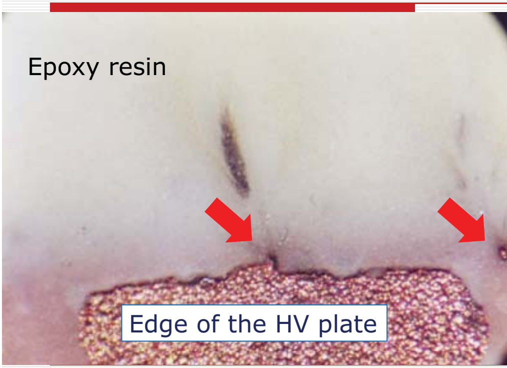


Ceramics thickness:4mm (HV plate to earth plate)

HV plate is buried in the molding material

Max Voltage :15kV

Voids in the molding material



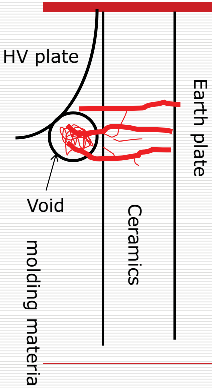
Void :0.1mm

Epoxy shrink few % at hardening

↓

Voids remain at edge of the HV plate

Void model of the Ceramics breakdown



Voids in the molding material

↓

Discharging in the Void

↓

Treeing in ceramics

↓

breakdown

Silicon Rubber molding cell

Making many type cell

molding material

plate shape

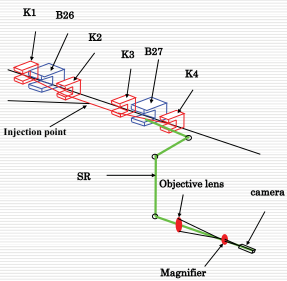
impregnant

Silicon Rubber cell

good performance

(Safe under 15 KV)

Optical Observation



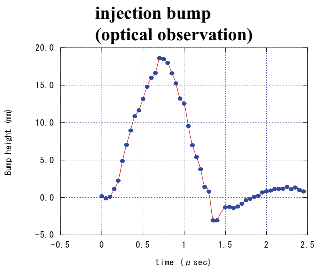
optical layout of the SR monitor.

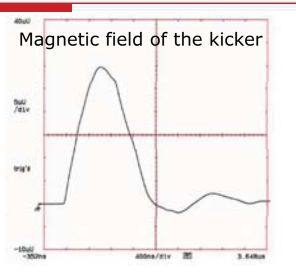
SR monitor
(source point in B27)

In the injection bump

Observed injection bump &turn by turn injected beam profile

injection bump Observation



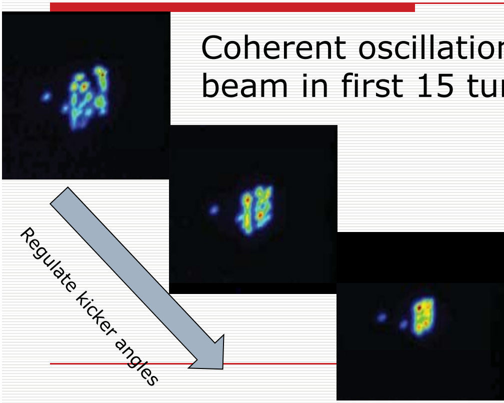


Almost same shape

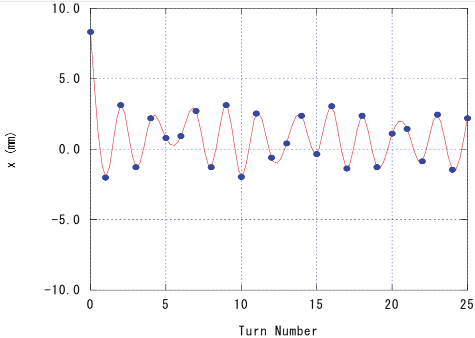
Timing error of the 4 kickers are small

turn by turn injected beam profile Observation

Coherent oscillation of injected beam in first 15 turns



Coherent oscillation of injected beam (horizontal)

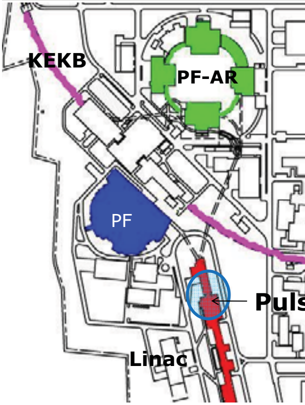


Coherent motion

- 3mm to + 3mm

Other pulsed magnets

Pulsed Bending magnet at Linac



Linac deliver → KEKB (continuous injection) → PF (Top-up) → PF-AR (twice a day)

Simultaneous injection

Pulsed Bending Magnet

2008:Install at the end of Linac

Pulsed Bending magnet

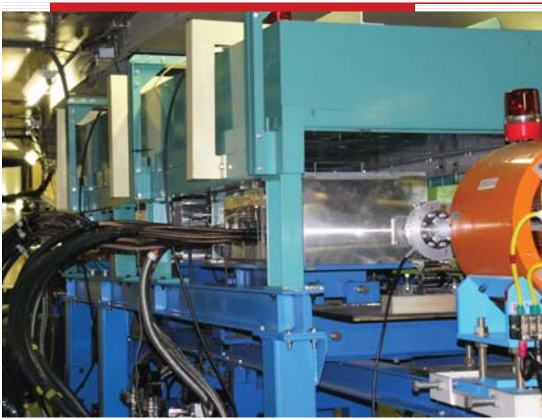
Max. peak current
32KA

200μsec half sine
Max 25Hz

Pulsed bending magnet parameters

Max. beam energy	3 GeV
Deflection angle	114.4mrad
Field strength@3GeV	1.15T
Magnet core length	990mm
Magnet core gap & width	30x155mm
Max.PS peak current	32kA
Pulse width & shape	200μsec & half sine
Max repetition	25Hz
Stability	1×10^{-3}(p-p)
Magnet inductance	6.6μH
Coil turn	1

Septum magnets PF-advance ring(PF-AR)



Active type

SI 1 turn
SII 2 turn

Half sine
(0.5msec
&1.3msec)

Septum magnets parameters

	septum I	septum II
Type	Active	Active
Bend angle	45mrad	80mrad
Length	1.2m	1.2m
Max. Field	3750Gauss	6670Gauss
Horizontal Aperture	70mm	70mm
Vertical Aperture	16mm	916mm
Imax	4800A	4250A X 2
Pulse shape	half sine	half sine
pulse length	0.5msec	1.3msec
Inductance	7.0μH	27.4μH
Number of turn	1	2

Kicker magnets
PF-advance ring(PF-AR)

Window frame

1turn

2.5μsec half sine

Kicker magnets parameters

Type	Window frame
Bend angle	1.85mrad (3GeV)
Length	250mm
Max. Field	740Gauss
Horizontal Aperture	116mm
Vertical Aperture	68mm
Imax	2000A
Pulse shape	half sine
pulse length	2.5μsec
Inductance	5μH
Number of turn	2

END

2009-07-26

Design and field measurement of the PSM at the PF-ring

Hiroyuki Takaki
Institute of Solid State Physics (ISSP),
University of Tokyo

Outline

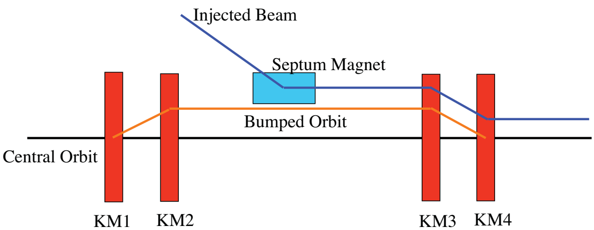
- Principle of the Pulsed Sextupole Magnet (PSM) injection
  - Differences from the conventional injection
  - How does the PSM work?
- Design of the PSM as an application for the PF-ring
- Field measurements

- Installation
- Multi-particle simulation
- Experimental results
- Case study of NSLS-II injection

→ Next talk

Photon Factory (PF) and Photon Factory Advanced Ring (PF-AR)

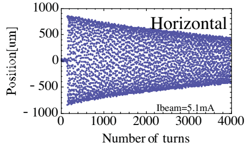
Conventional Injection Using Bumped Orbit



- To reduce coherent dipole oscillation of an injected beam
- Imperfection of the bumped orbit
  - field errors, timing jitters and mismatch of injection kickers
  - non-linear magnetic field like sextupole magnets inside the bump

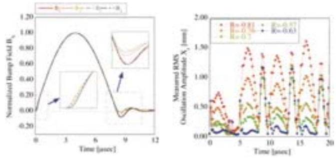
Examples of Stored Beam Oscillation in beam injection

PF-ring



Mismatch of the injection kicker magnets.

Spring-8 (2005)



"Suppression of injection bump leakage caused by sextupole magnets within a bump orbit", H. Tanaka et al., Nucl. Inst. Meth. A 539, 547 (2005).

BESSY

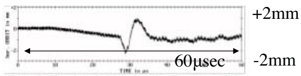
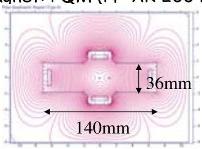


Figure 2: Transient horizontal orbit distortions of the stored beam measured bunch-by-bunch induced by the stray field of the septum and the mismatch of the 4 injection kicker magnets. The amplitude of the vertical orbit distortion reaches also 1 mm.

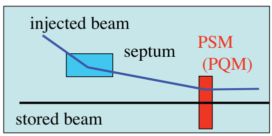
P. Kuske et al., Proc. of the EPAC 2008, Genoa, p2067.

Beam Injection with Pulsed Multi-pole Magnets

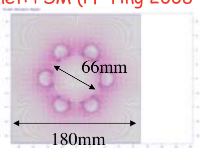
Pulsed Quadrupole Magnet: PQM (PF-AR 2004~)



"New injection scheme using a pulsed quadrupole magnet in electron storage rings", K. Harada, Y. Kobayashi, T. Miyajima and S. Nagahashi, Phys. Rev. ST Accel. Beams 10 123501 (2007).



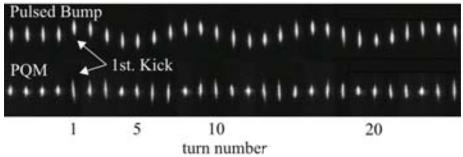
Pulsed Sextupole Magnet: PSM (PF-ring 2008~)



Stored Beam Profile (PQM Injection at the PF-AR)

fast gated camera

Horizontal direction

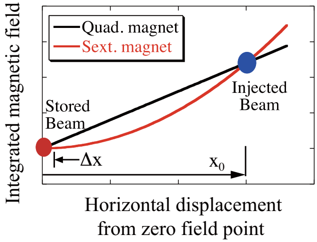


PQM Injection:
beam oscillation -> small

But, stored Beam is Blinking!
Quadrupole Mode Oscillation?

To reduce the effect to the stored beam, we selected the PSM at the PF-ring.

$$\frac{B_{y,S}}{B_{y,Q}} = \frac{\Delta x}{x}$$



PSM injection in normalized phase space

$$\theta = \frac{1}{2} K_2 x^2$$

$$W = X^2 + P^2$$

$$X_2 = X_1 = \frac{x_1}{\sqrt{\beta_1}}$$

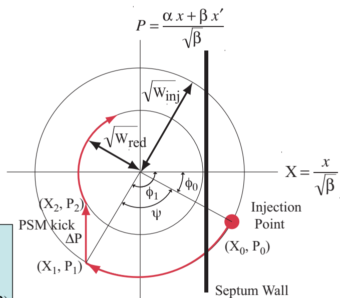
$$P_2 = \frac{1}{\sqrt{\beta_1}} \{\alpha_1 x_1 + \beta_1 (x_1' + \theta)\} = P_1 + \sqrt{\beta_1}\theta$$

$$\Delta P = P_2 - P_1 = \sqrt{\beta_1}\theta = \frac{1}{2}\beta_1^{3/2} K_2 X_1^2 \cdots (1)$$

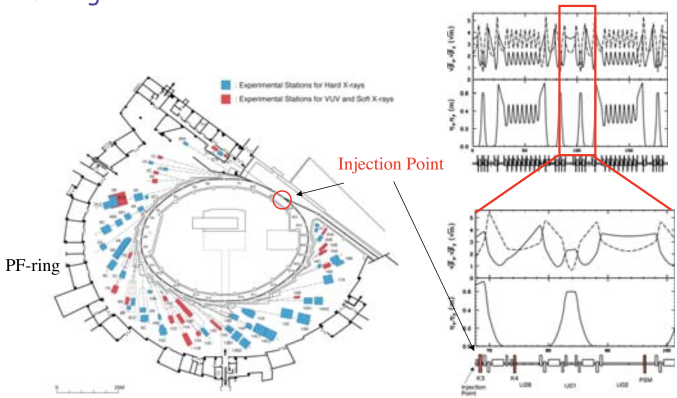
$$|\Delta P| = |P_1| - |P_2| = \sqrt{W_{inj}}|\sin\phi_1| - \sqrt{W_{red} - W_{inj}\cos^2\phi_1} \cdots (2)$$

$$|K_2| = \frac{2\left(\sqrt{W_{inj}}|\sin\phi_1| - \sqrt{W_{red} - W_{inj}\cos^2\phi_1}\right)}{\beta_1^{3/2} W_{inj}\cos^2\phi_1} \cdots (3)$$

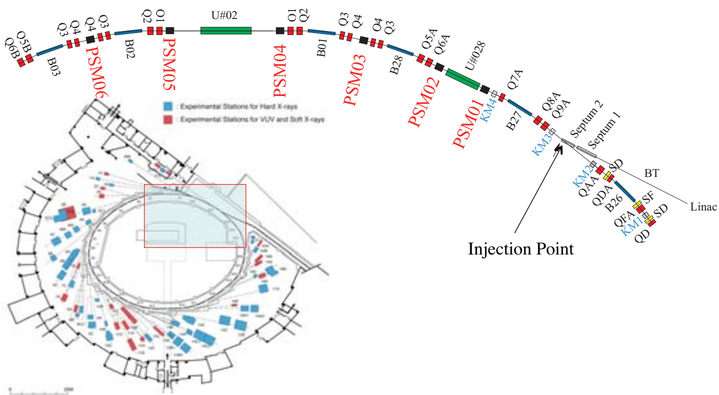
$$K_2(W_{inj}, W_{red}, \phi_1, \beta_1)$$



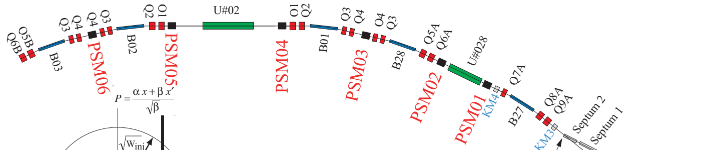
PF-ring

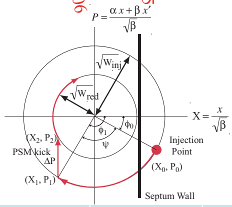


Installation candidates at the PF-ring



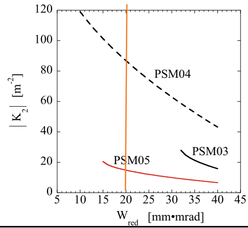
Installation candidates at the PF-ring





$$W_{red} = \gamma x^2 + 2\alpha x x' + \beta x'^2$$
$$= 20[mm \cdot mrad]$$

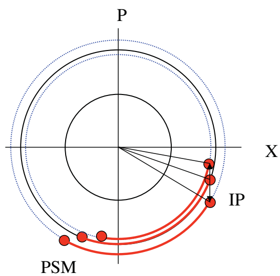
	βx [m]	ϕ1 [degree]
PSM01	~~4.23~~	145
PSM02	17.80	~~171~~
PSM03	~~5.44~~	313
PSM04	12.66	100+360
PSM05	12.66	118+360
PSM06	~~4.91~~	221+360



Tunability of PSM Position in Phase Space

(1) Changing phase advance ->betatron function
- may change the operating tune
- may break periodicity of the ring optics

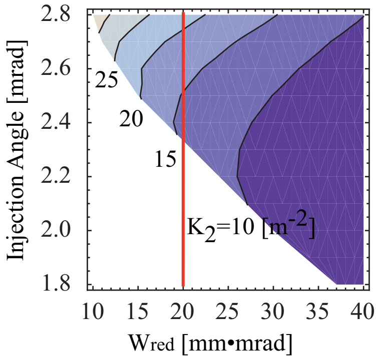
(2) Changing injection angle (x') -> septum kick angle

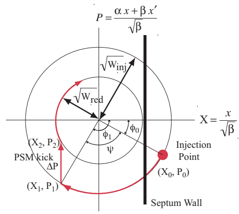


$$X = \frac{x}{\sqrt{\beta}}, \quad P = \frac{\alpha x + \beta x'}{\sqrt{\beta}}$$

$$tan\varphi = \frac{P}{X}$$

K_2 as a function of reduced injection amplitude and injection angle





$$|K_2| = \frac{2\left(\sqrt{W_{inj}}\,|\sin\phi_1| - \sqrt{W_{red} - W_{inj}\cos^2\phi_1}\right)}{\beta_1^{3/2} W_{inj}\cos^2\phi_1}$$

$$K_2 = \frac{B''l}{B\rho}$$

PSM parameters (PF-ring)

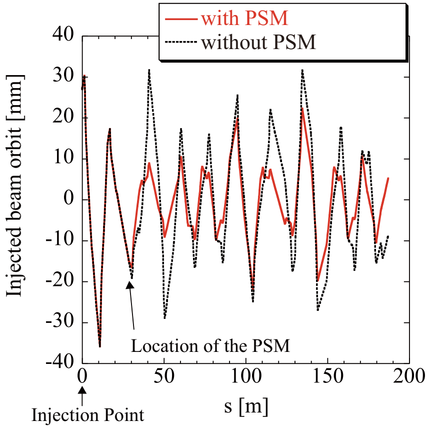
$$K_2 = \frac{B''l}{B\rho} = 13\,[m^{-2}]$$

$$E_{beam} = 2.5\,[GeV]$$

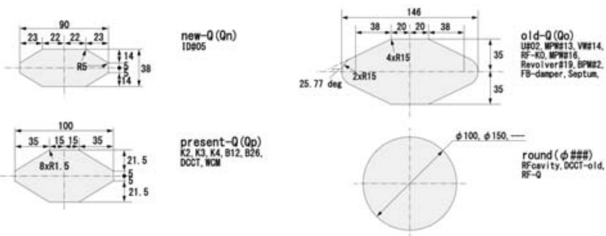
$$B'' = \frac{K_2 E_{beam}}{0.3l} = 416\,[T/m^2]@L = 0.3m$$

$$By\,L = \frac{1}{2}B''x^2 L \sim 120\,[G\cdot m]@x = 15mm$$

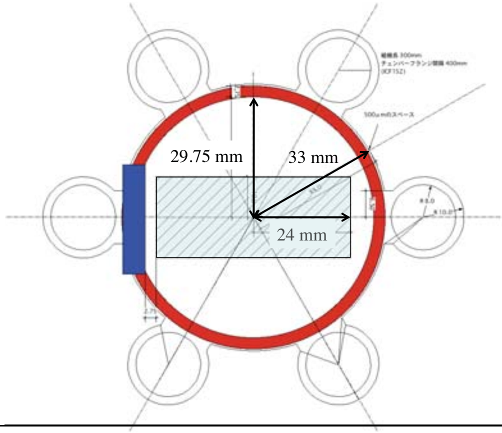
Horizontal orbit of the injected beam with and without PSM



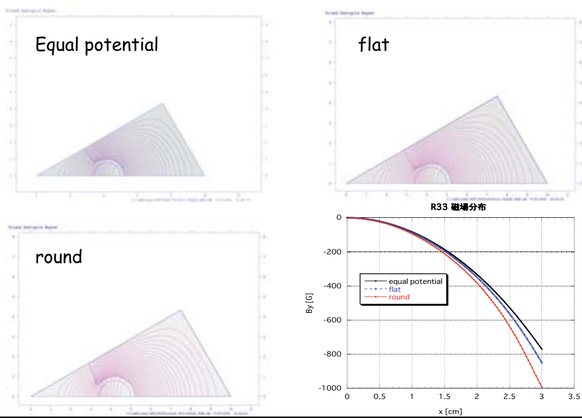
Beam ducts for quadrupole magnets



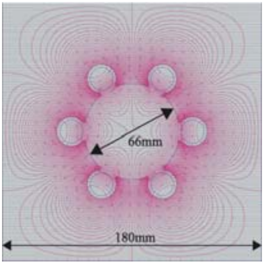
Beam stay clear at the PSM

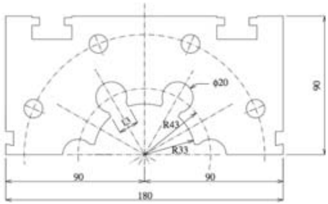


Field strength with different pole shape



Cross-sectional view



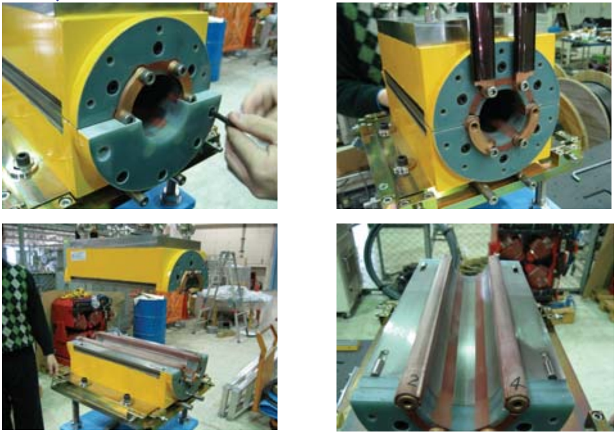


pole:0.15-mm-thick laminated silicon steel sheet
coil:one-turn Cu bar (15mmϕ)

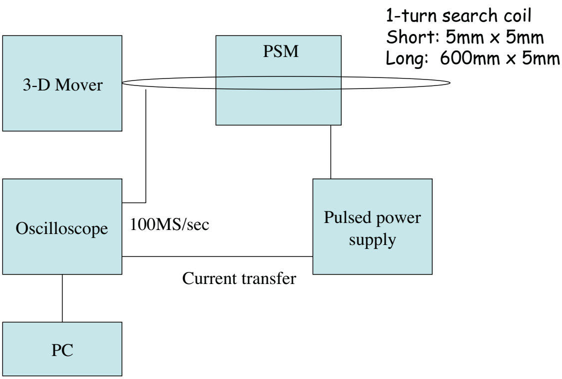
Cross-sectional view

PSM photo

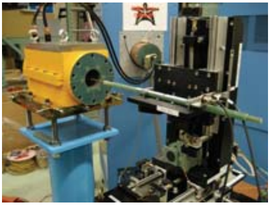
PSM photo



Field measurement set up



Search coil (single turn fine cupper wire)

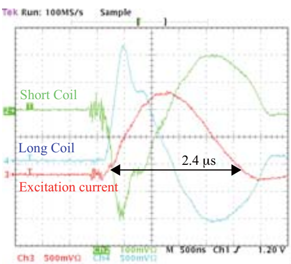


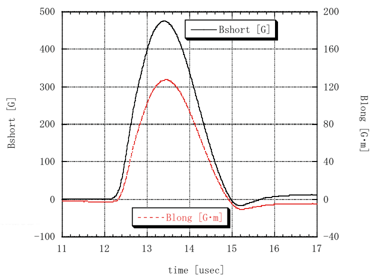
Glass epoxy

Typical waveform from search coils

$$V_{coil} = -\frac{d\Phi}{dt} = -S_{coil}\frac{dB}{dt}$$

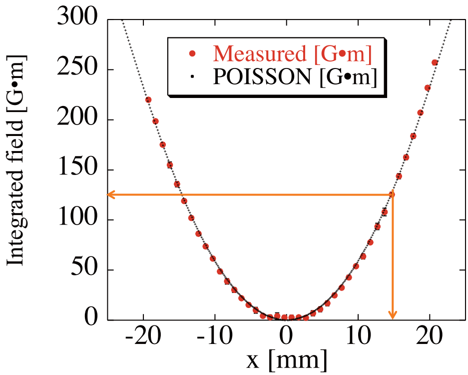
$$B_{peak} = -\frac{1}{S_{coil}}\int_0^{peak} V_{coil}\,dt$$



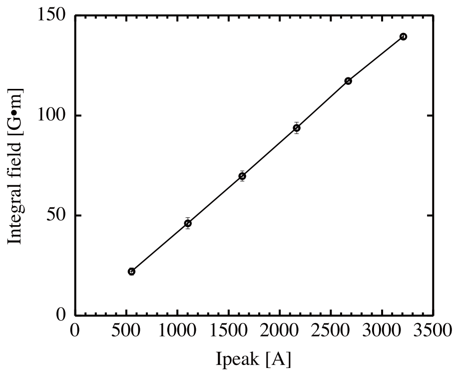


By

I=3000A
Y=0mm
Z=0mm
L=320mm

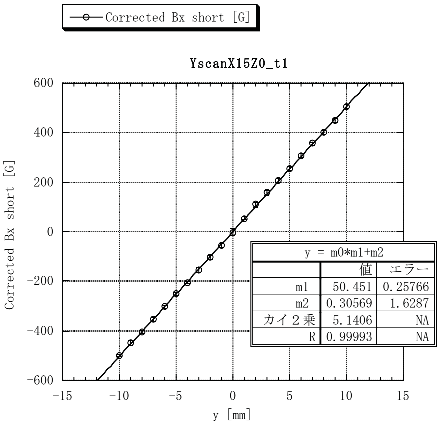


Excitation curve of the magnetic field



Bx

I=3000A
X=15mm
Z=0mm

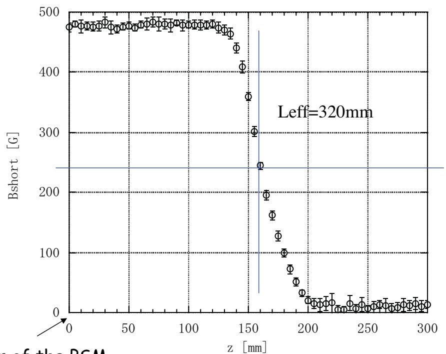


y = m0*m1+m2		
	値	エラー
m1	50.451	0.25766
m2	0.30569	1.6287
カイ２乗	5.1406	NA
R	0.99993	NA

07-09-18

Z distribution

I=3000A
x=15mm
Y=0mm



Center of the PSM

070720_3kA_Z

SUMMARY

- Design and Fabrication of the PSM was done.
- The magnetic field satisfied the requirement.
- Next step is whether the PSM injection system will work well.

2009-07-26

130

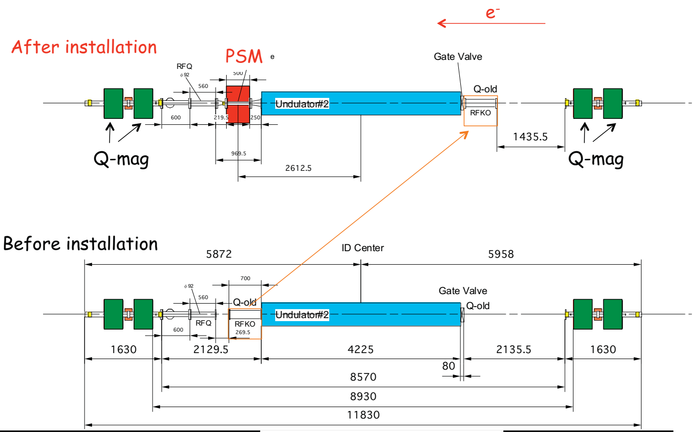
Results of the PSM operation at the PF-ring

Hiroyuki Takaki
Institute of Solid State Physics (ISSP),
University of Tokyo

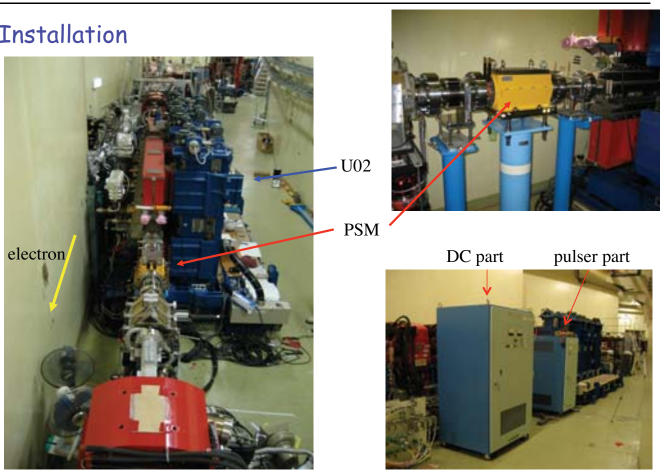
Outline

- Installation of the PSM
- Multi-particle tracking simulations
- Latest experimental results of the PSM injection
- NSLS-II case study (single particle simulation)

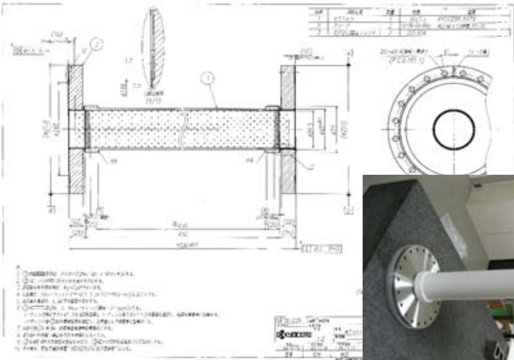
PSM installation



Installation

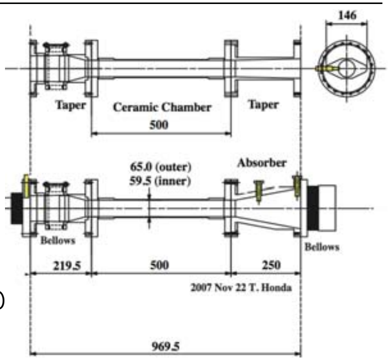


Ceramic chamber Al_2O_3

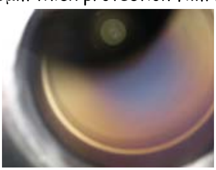


Ceramic chamber

Ceramic Chamber (white)
100μm thick protection film (brown)

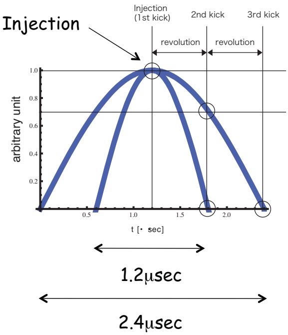


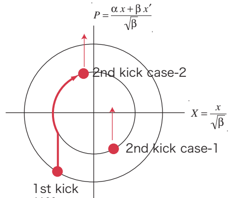
PSM core length 300mm

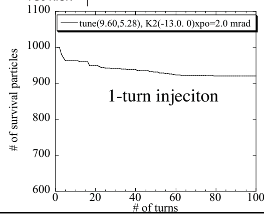


The inner side is coated with a titanium layer of 3 μm thick

2-turn injection (specific problem of the PF-ring)



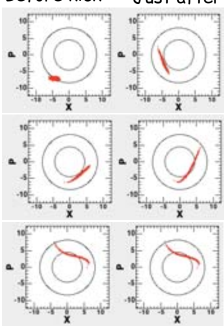




Example of 2-turn injection

$$X = \frac{x}{\sqrt{\beta}}, \quad P = \frac{\alpha x + \beta x'}{\sqrt{\beta}}$$

Before kick Just after kick



1st turn

2nd turn

3rd turn

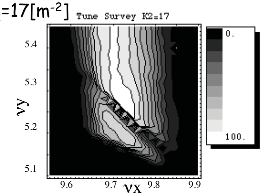
K_2=10 [m^{-2}]
# of particles: 1000
emittance
x: 150 nm·rad
y: 150 nm·rad
z: 12 mm·rad

Septum Kick Angle 1.7mrad
Timing Delay 467nsec

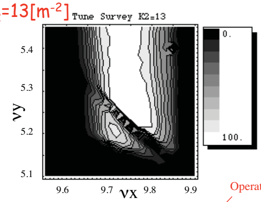
Optimum operating tune for the PSM injection

$$K_2 = \frac{B''L}{B\rho}[m^{-2}]$$

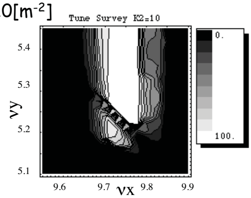
K_2=17[m^{-2}]

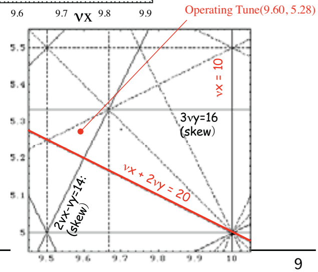


K_2=13[m^{-2}]



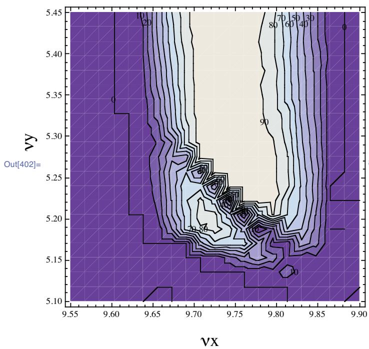
K_2=10[m^{-2}]



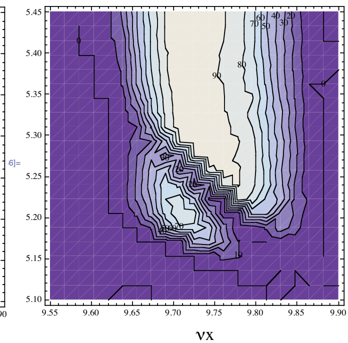


COD correction

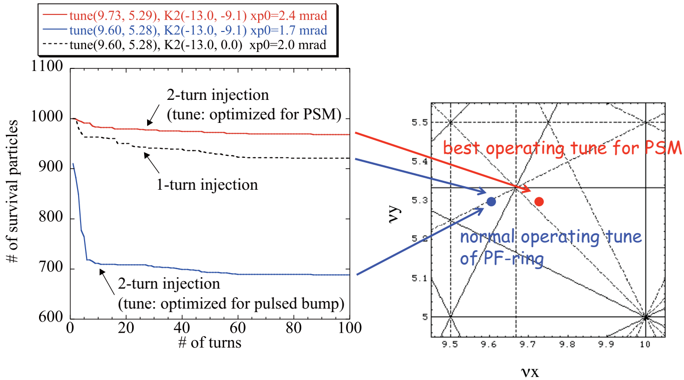
After correction



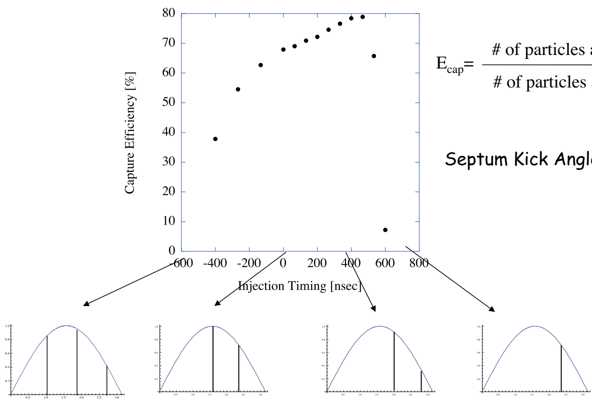
Before correction



Operating point for the PSM and pulsed bump



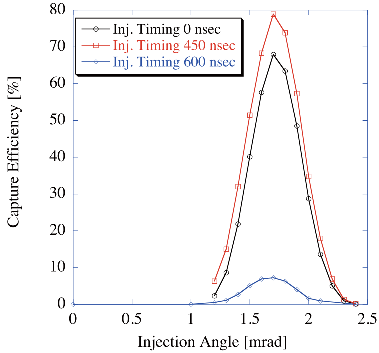
Capture efficiency vs injection timing



$$E_{cap} = \frac{\text{\# of particles at } 100^{th} \text{ turn}}{\text{\# of particles at } 1^{st} \text{ turn}}$$

Septum Kick Angle: 1.7mrad

Capture efficiency vs injection angle



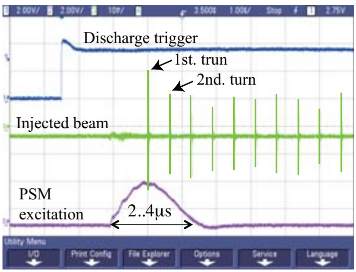
$$X = \frac{x}{\sqrt{\beta}}, \quad P = \frac{\alpha x + \beta x'}{\sqrt{\beta}}$$

$$\tan\varphi = \frac{P}{X}$$

$$E_{cap} = \frac{\text{\# of particles at } 100^{th} \text{ turn}}{\text{\# of particles at } 1^{st} \text{ turn}}$$

Timing tuning

RF power off



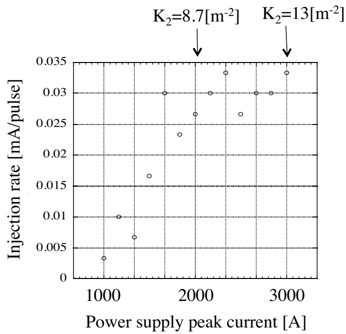
- Revolution period ~ 0.6 μsec
- Excitation pulse width of 1.2 μsec or less is preferable
- The existing pulsed power supply has the full width of 2.4 μsec

↓

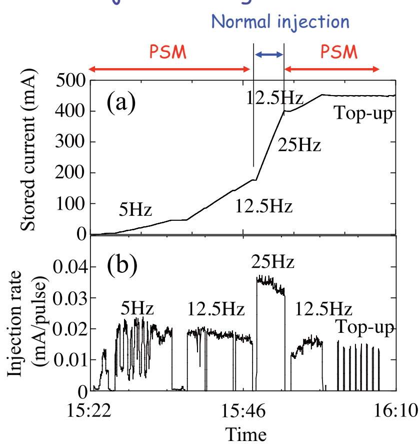
2nd. kick to injected beam

- Peak current is 3000A at 16.7kV
- WCM with 150MHz HPF

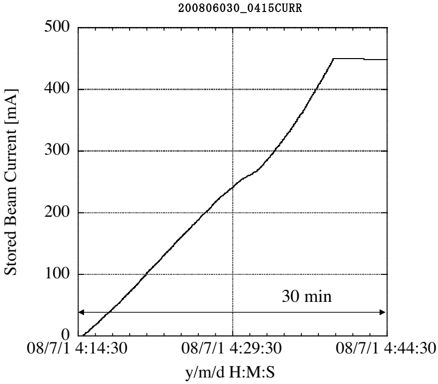
Injection rate (K$_2$ dependency)



Multi-bunch beam injection using the PSM



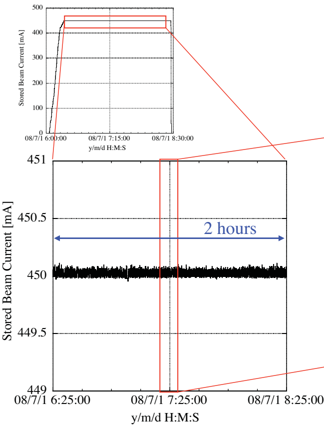
Multi-bunch injection with PSM

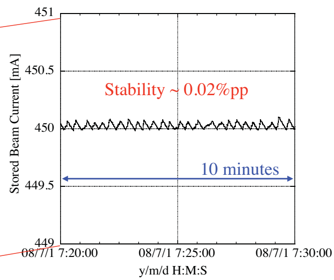


Repetition frequency of 12.5 Hz
We could store the beam up to the current of 450 mA

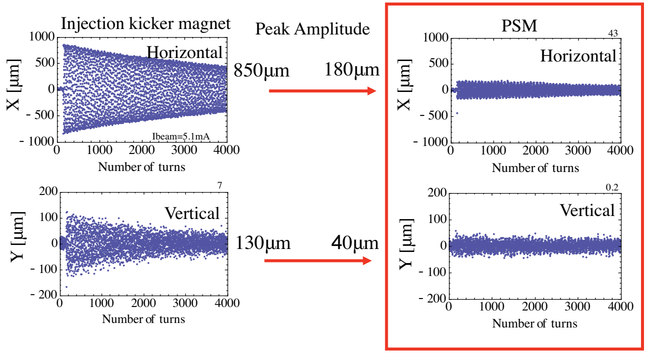
Continuous (Top-up) beam injection with PSM

Start 1Hz injection at 450.00 mA
Stop injection at 450.05 mA
Beam current monitor: 2 Hz



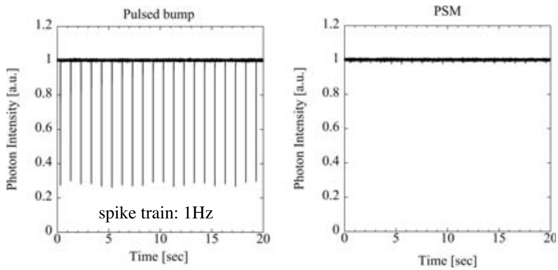


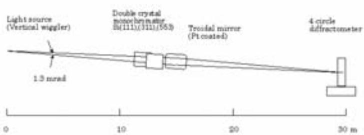
Stored beam oscillation during beam injection



The dipole oscillations of the stored beam in the PSM injection were sufficiently reduced.

BL-14A PIN photodiode output

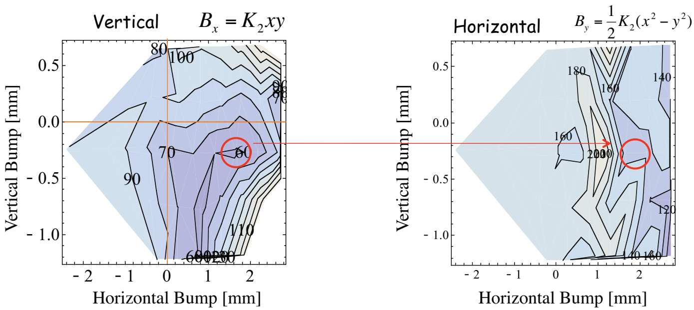




Beam based field center search (preliminary)

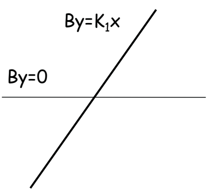
Maximum vertical oscillation amplitude of the stored beam

NOT decreasing horizontally



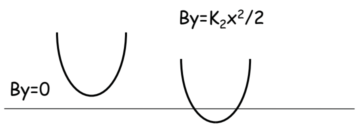
Zero field point problem of the sextupole magnet

Quadrupole magnet



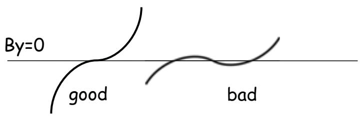
Q-mag has only one “zero point” somewhere

Sextupole magnet



NOT for a sextupole magnet or higher.

Octupole magnet



Solutions

(1) Pulsed dipole magnet for correction
- 180 μm needs 0.03 mrad kick (K_2=13 m^{-2} ~1.5 mrad @ 15 mm)
- may produce mismatch of 2 magnets (discarding PSM policy)

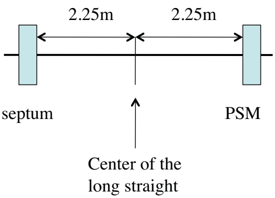
(2) Remote controllable end-shim to produce dipole field

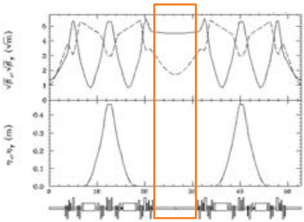
(3) Something else

NLSL-II injection parameters (single particle simulations)

- Injected beam is 25 mm off axis at the exit of injection septum
- Septum magnet is 4.5 m away from PSM in the same straight.
- The ring horizontal acceptance is +/- 15 mm in the center of the straight section, where betax=20m.

Injection point



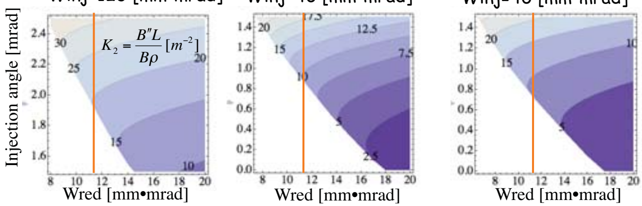


x0 = 25 mm at the exit of the septum magnet

K_2 (High-beta section)

$$W_{red} = \gamma x^2 + 2\alpha x x' + \beta x'^2 = 11.25 [mm \cdot mrad]$$ (x=15mm,x'=0,β=20m, α=0)

L = 2.25 [m]	L = 2.25 [m]	L = 2.5 [m]
x0= 25 [mm]	x0= 20 [mm]	x0= 20 [mm]
Winj=123 [mm·mrad]	Winj=40 [mm·mrad]	Winj=40 [mm·mrad]



Septum width + beam size, etc.

$$15[mm]\frac{\sqrt{20.5\ (septum)}}{\sqrt{20\ (center)}} + 5[mm] \sim 20[mm]$$

Physical aperture at the center of the straight section

SUMMARY

- Experimental results
  - We successfully injected an electron beam with PSM.
  - Stored beam oscillation was smaller than that of the conventional injection system.
  - The PSM injection is suitable for "top-up injection".

143

SLAC Kicker Systems Applicable to NSLS-II Requirements

Craig Burkhart & Antonio de Lira

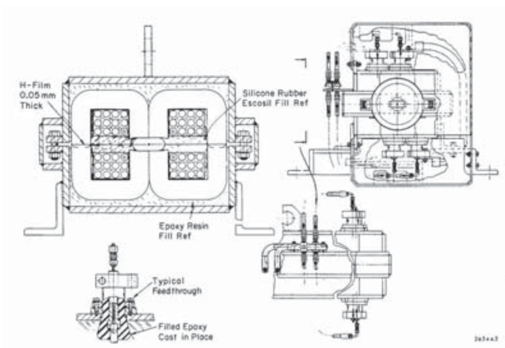
SLAC Kicker Technologies Applicable to NSLS-II Requirements

- Slow-sinusoidal kickers
  - Magnets
    - Air-core: LCLS BX/BYKIK
    - Steel-core: A-line
  - Modulators
    - Thyristor: A-line
    - IGBT : LCLS BX/BYKIK
- Fast-matched impedance kickers
  - Magnets
    - Air-core: SPEAR3
    - Ferrite-core: Linac DR-ATF
  - Modulators
    - PFL-thyratron: Linac DR-ATF
    - Inductive adder-IGBT: SPEAR3

Slow-Sinusoidal Kickers

- A-line
  - Direct bunches to ESA
    - Two to three, 1-m magnets
    - 4.0 kG-m
  - Tape wound magnet: commissioned ~'75
  - Solid state modulator: commissioned '95
- LCLS
  - BXKIK: direct bunches onto diagnostic screen
    - One, 1-m air-core magnet
    - 0.05 kG-m
  - BYKIK: direct unwanted bunches to dump
    - Two, 1-m air-core magnets
    - 0.85 kG-m
  - Solid state modulators
  - Commissioned '08

A-line Kicker Magnet Design



A-line Kicker Magnet Field

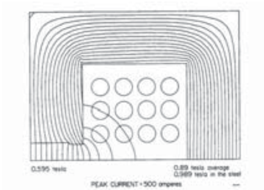


Fig. 3--Computer generated flux plot at I_{peak} = 500A

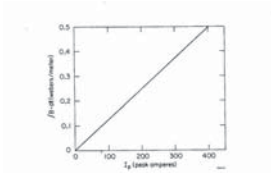
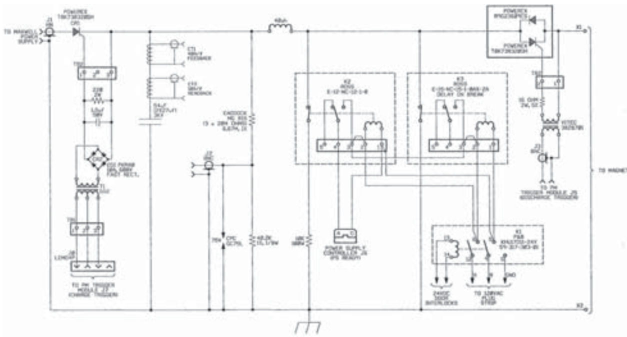


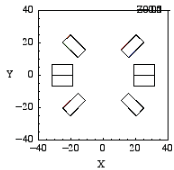
Fig. 4-- $\int$ Bdl vs I_{peak} as measured

A-line Kicker Modulator Design



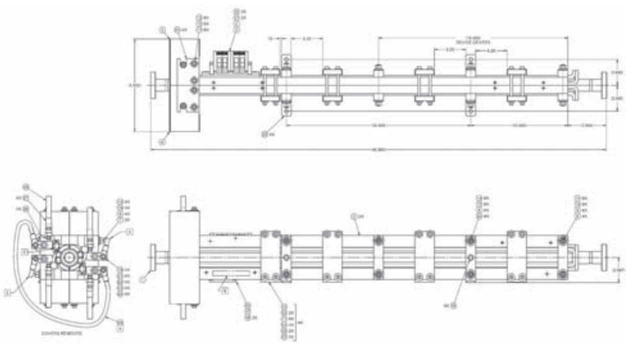
LCLS BX/BYKIK Magnet Design

- 8-turns (rectangle ≡ 2 turns), 1meter long sections, water cooled magnet.
- Ceramic beam pipe (BXKIK)
  S.S. beam pipe (BYKIK)
  Coil ID = 1.5”.
- 31μH (BYKIK, 2 in series 62μH)
- Nominal peak current = 0.4 kA
  Maximum peak current = 0.5 kA
- 400ft cable, 29 μH



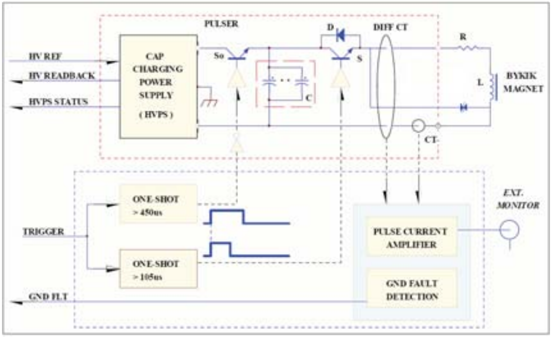
Pulsed Magnet Design & Measurement Workshop
July 27-28, 2009 Brookhaven National Laboratory
C. Burkhart
T. Beukers
7

LCLS - BX/BYKIK Magnet Assembly

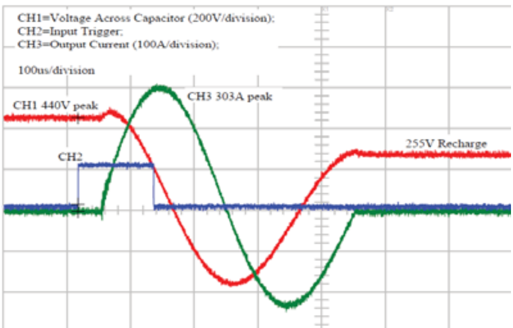


Pulsed Magnet Design & Measurement Workshop
July 27-28, 2009 Brookhaven National Laboratory
C. Burkhart
8

LCLS BX/BYKIK Modulator Design

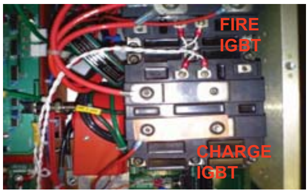


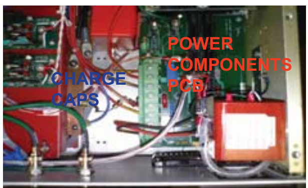
BYKIK Current/Voltage Waveforms



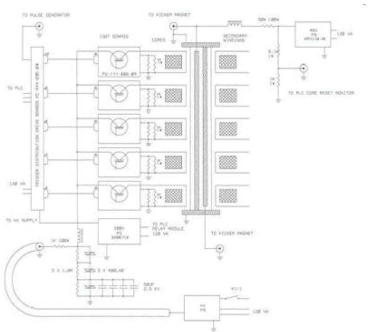
BYKIK Pulser System

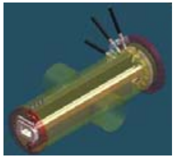
BYKIK Modulator





SPEAR3 Injection Kickers





SPEAR3 Injection Kickers

- SPEAR3 injection system
- Parameters and requirements for operation
- Magnet design
- Modulator design
  - Waveforms
  - Timing
- Operation
  - Programming output voltage
  - Optimizing for top-up injection

SPEAR3 Injection Kickers

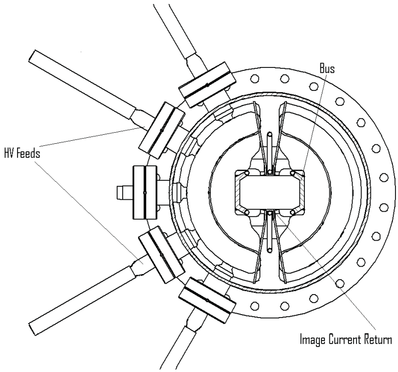
– Injection system:

- 3 kicker magnets and their associated pulsers
- magnet design based on the DELTA kicker magnets
  - Low RF impedance to the beam
  - Straightforward to construct
- Pulsers:
  - cascaded IGBT stages (adder topology)

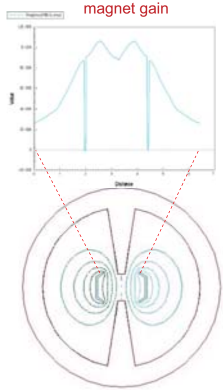
SPEAR3 Injection Kickers

Parameter	K1	K2	K3	Units
Beam Energy	3.3	3.3	3.3	GeV
Bend Angle	2.2	1.2	2.2	mrad
Magnet Length	1.2	0.6	1.2	m
Magnet Aperture	60 x 34	60 x 34	60 x 34	mm
Magnitude **B**	20	22	20	mT
Magnetic Gain	8.7	8.7	8.7	μT/A
Current	2381	2619	2381	A
Output Voltage	20	10	20	kV
Rise/Fall Time	<375	<375	<375	ns
Pulse Width	<750	<750	<750	ns
PRF	10	10	10	Hz

Magnet Design

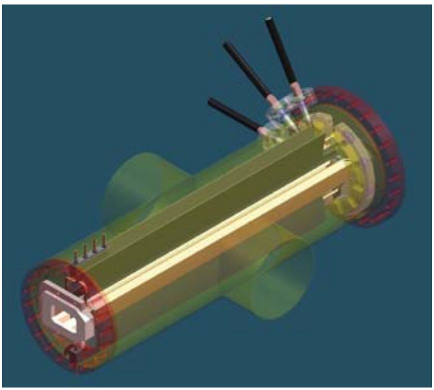


MAXWELL calculated magnet gain

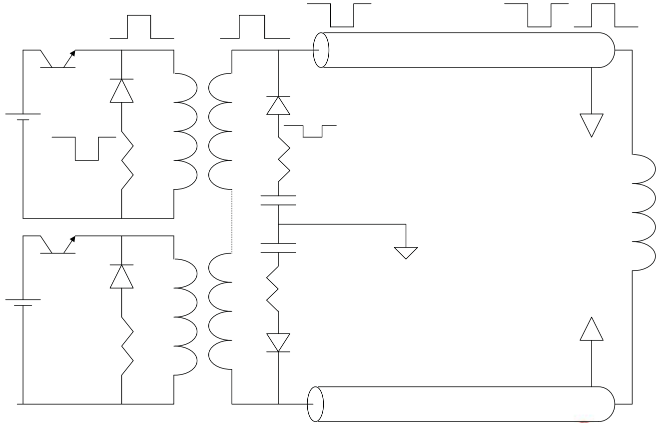


Flux lines in magnet

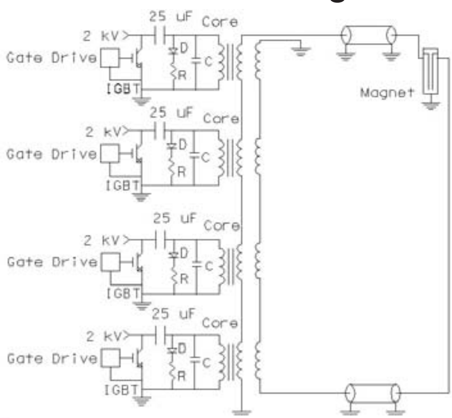
K2 Magnet - 3D Model



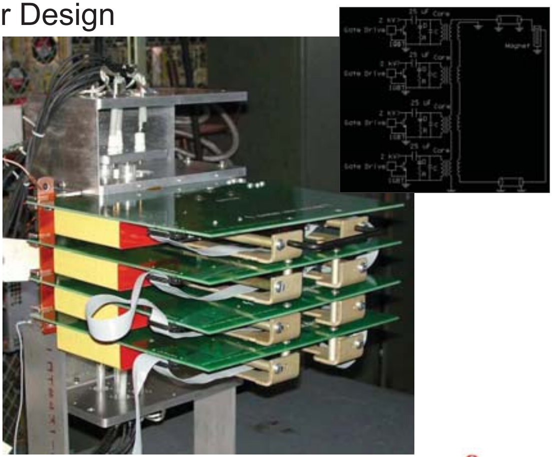
Modulator Design



Modulator Design

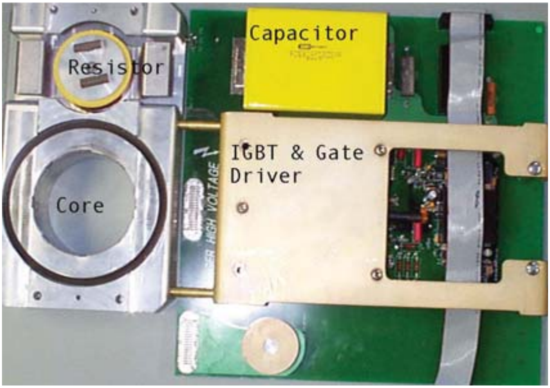


Modulator Design

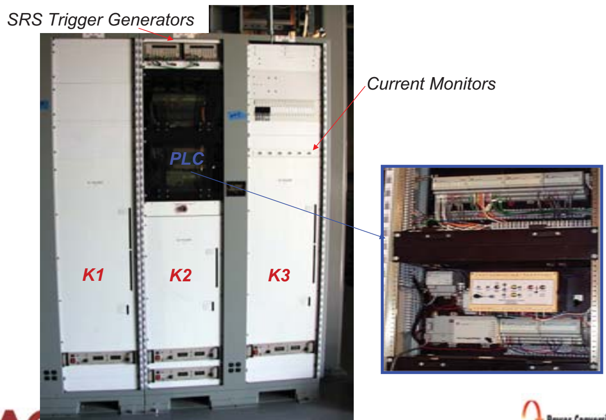


K2 and K3 Mechanical Assembly

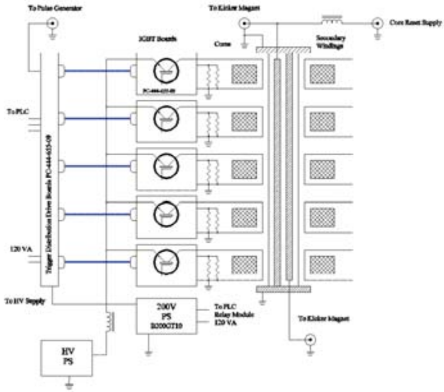
IGBT Driver & Transformer



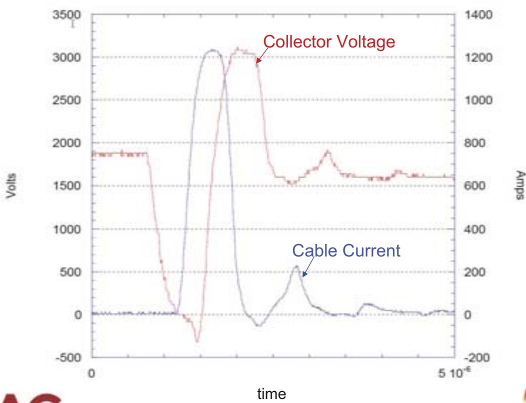
Pulser Rack Assembly



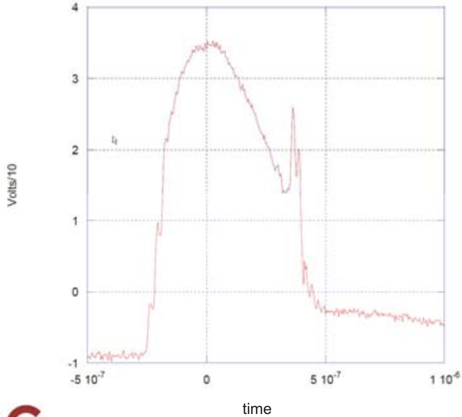
K2 Modulator



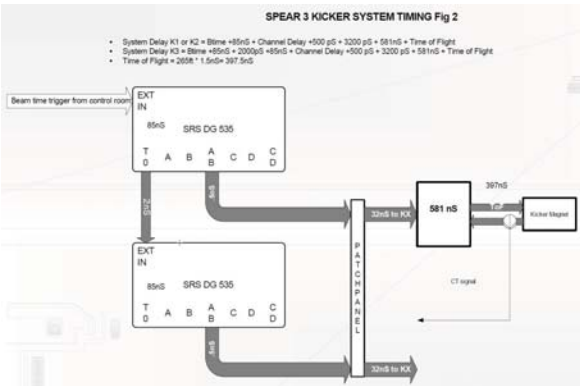
IGBT Current & Voltage



IGBT Gate Voltage



IGBT Timing Delays



SLAC NATIONAL ACCELERATOR LABORATORY
Pulsed Magnet Design & Measurement Workshop
July 27-28, 2009 Brookhaven National Laboratory
A. de Lira
C. Pappas

Power Conversion

Programming Output Voltage

Variable	Definition	Units
I	Magnet Current	*Amps*
N	Number of Cells	
Vo	HVPS Output Voltage	*Volts*
Z	Modulator Impedance	*Ohms*
Mg	Magnet Gain	*Tesla/Amp*
Vg	Voltage Gain	*Tesla-meter/Volt*
Gdw	Digital Word Gain	*Tesla-meter/bit*

Programming Output Voltage

- Modulator output current

$$I = 2N\frac{V_0}{Z}$$

- Beam Kick

$$K = M_g M_l I$$

- Voltage gain of modulator

$$V_g = 2N\frac{M_g M_l}{Z}$$

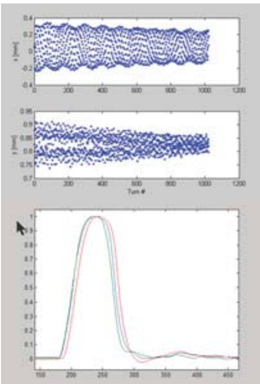
- The 3000 V supply is controlled by a 0-10 VDC reference which is programmed by a 16 bit word.
- Digital word gain (Tesla-meter/bit)

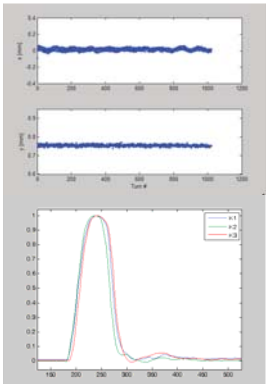
$$G_{dw} = 0.18N\frac{M_g M_l}{Z}$$

Programming Output Voltage

Kicker	Voltage Gain	Digital Word Gain
K1	1.55×10^{-5}	1.4×10^{-6}
K2	7.73×10^{-6}	0.71×10^{-6}
K3	1.55×10^{-5}	1.4×10^{-6}

Optimizing for Top-up Operation

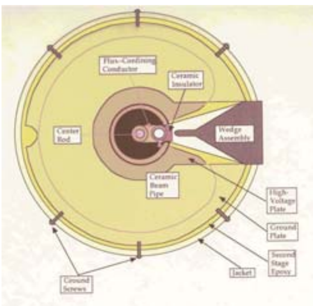


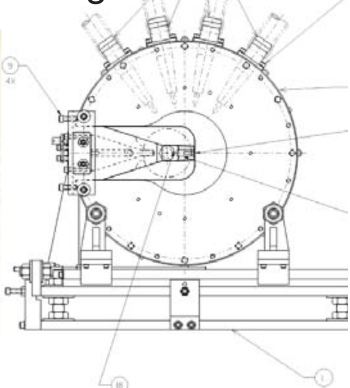


SLC Damping Ring-ATF Kickers

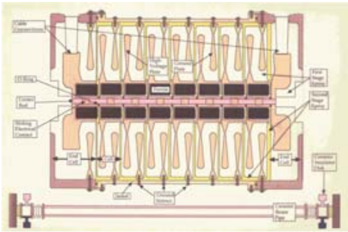
- Developed for SLAC Linac damping rings during SLC, mid-80's
- 3rd generation "Epoxy" magnet
  - Ferrite loaded, matched impedance, slow-wave structure
  - 0.5 m (35 ns)
  - 0.21 kG-m
- Modulator
  - Commercial co-ax cable (RG-220) PFL
  - Thyratron switched (pulse-charged, inductively-isolated)
  - 70 kV charge
  - SLAC: 12.5 Ω, 2.8 kA, 60 ns
  - ATF: 16.7/2 Ω, (2)(2.1) kA, 300 ns

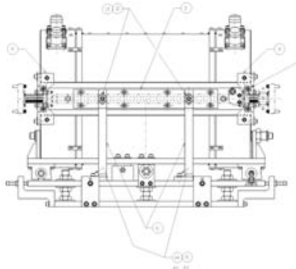
"Epoxy" Magnet



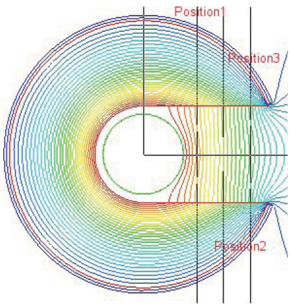


“Epoxy” Magnet

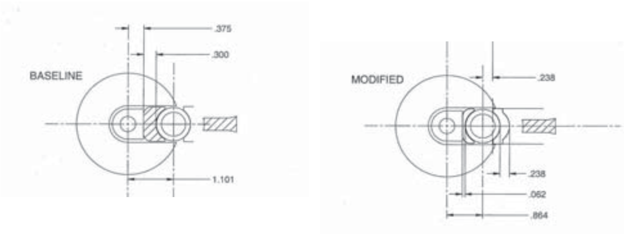




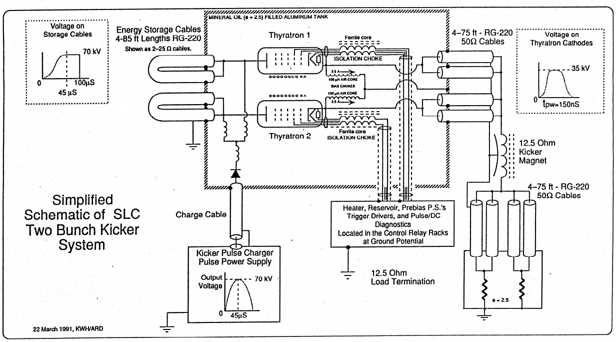
“Epoxy” Magnet Flux Lines



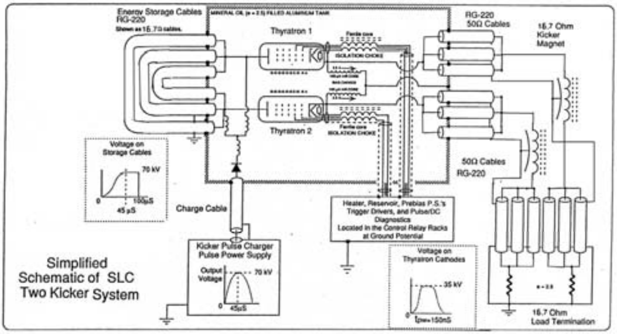
Vacuum Chamber Position



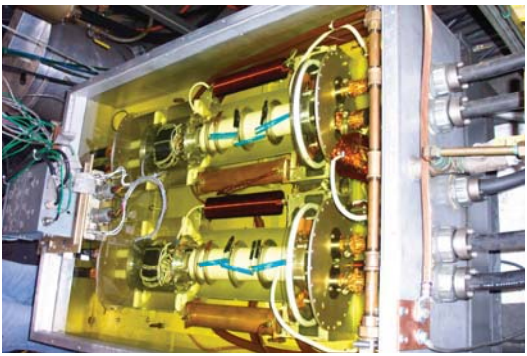
SLC Kicker Pulser



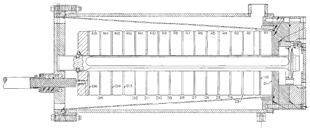
ATF Kicker Pulser



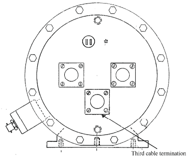
SLC Kicker Pulser



Kicker Pulse Loads

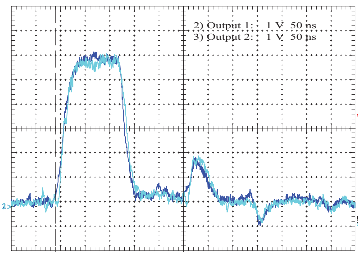


Change # of resistor 15 to 10 each

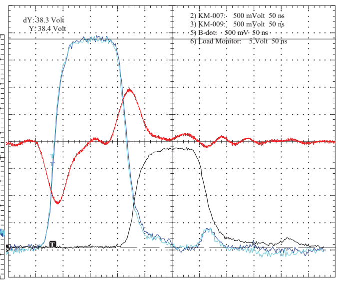


Use third cable termination

Kicker Pulser

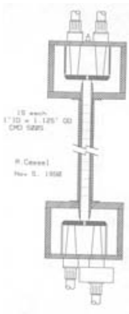


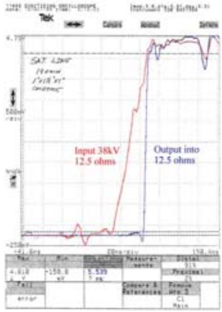
Pulser Current



Magnet current 2200A
Load Current & dB/dt

Shock Lines - Ferromagnetic

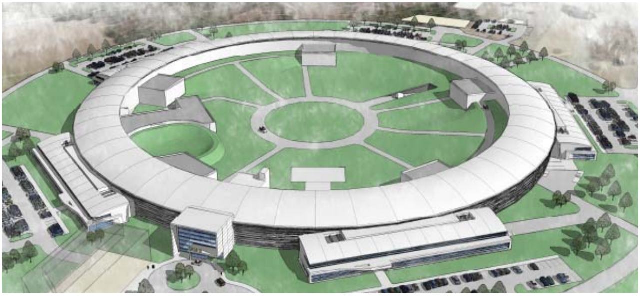




Summary: SLAC Kicker Technologies Applicable to NSLS-II Requirements

- Slow-sinusoidal kickers
  - A-line
    - 3.2 kG-m per 1-m magnet
    - 1.7 ms period
  - LCLS BX/BYKIK
    - 0.43 kG-m per 1-m magnet
    - 420 μs period (BYKIK: 2 magnets, 400’ cable)
- Fast-matched impedance kickers
  - SPEAR3
    - 3.1 kG-m per 1.2-m magnet
    - Solid state modulator
    - T_R/T_F < 375 ns (reduce with magnetic switching?), T < 750 ns
  - SLC Damping Ring/ATF
    - 0.21 kG-m per 0.5-m magnet
    - T_R/T_F ~ 30 ns, T = 60 ns (SLC), 300 ns (ATF)

Field Measurements in Pulsed Magnets



Pulsed Magnet Design and Measurement Workshop
July 27-28 2009

Animesh Jain, BNL

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

Introduction

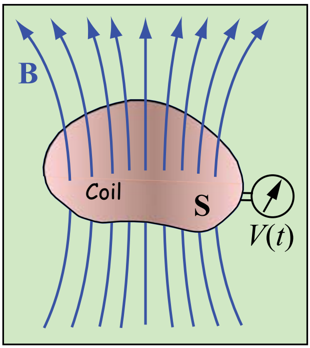
- Measurement techniques for field measurements in magnets operating at a DC field are well established.
  - *Rotating coils, Flip coils, Hall probes, NMR, ...*
- For time varying fields (AC or pulsed), several of the well established techniques can not be used.
- The most appropriate measurement method depends on the time scale of interest, and the field parameters that need to be measured.
- Some examples of AC and pulsed magnetic field measurements will be presented in this talk.

Disclosure: *Examples are drawn from personal experience only*.

Some Measurement Techniques & Time Scales

Time Scale	Measurement Technique	Quantity Measured
DC	Rotating Coils	Main field and harmonics
	Sliding Coils/Flip Coils	Main field and field homogeneity
	Hall probes (1D/3D)	Local field (Component/Vector)
	Stretched Wire	Main field; Magnetic Center
	NMR (in uniform field only)	Field Magnitude
~ 1 s	Rotating Coils with special analysis	Main field and harmonics
	Hall probes (1D/3D)	Local field (Component/Vector)
> 100 ms	Fast Rotating Coils (Special Geometry)	Specific harmonics
	Hall probe arrays	Specific harmonics
	Hall probes (1D/3D)	Local field (Component/Vector)
> 1 ms	Stationary Coils (Special Geometry)	Main field
	Stationary Coil Array	Main field and harmonics
	Hall probe arrays	Specific harmonics
	Analog Hall probes (1D/3D)	Local field (Component/Vector)
< 1 ms	Stationary Coils (Special Geometry)	Main field
	Stationary Coil Array	Main field and harmonics

Pick up Coils: General Principle



Time dependence of flux gives:

$$V(t) = -\frac{d\Phi}{dt} = -\frac{d}{dt}\left[\int_S \mathbf{B}\cdot d\mathbf{S}\right]$$

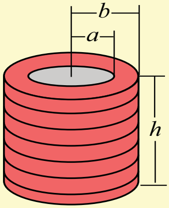
The change in flux is given by:

$$\Phi_{end} - \Phi_{start} = -\int_{t_{start}}^{t_{end}} V(t)\cdot dt$$

and can be measured by integrating the voltage signal.

To know the flux at a given instant, one needs to know Φ_{start}
$\Rightarrow$ (1) Use $\Phi_{start} = 0$; (2) Flip Coil/Rotating coil: $\Phi_{end} = -\Phi_{start}$

Some Coil Geometries



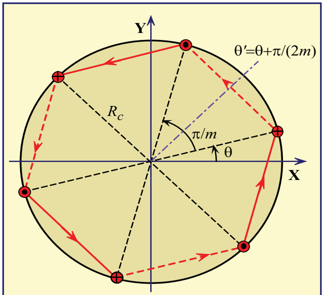
Point Coil

Insensitive up to 4th order spatial harmonics (octupole) with proper choice of height and radii.

$$h=\sqrt{\left(\frac{9}{5}\right)\left(\frac{b^5-a^5}{b^3-a^3}\right)}$$

Flat Coil (Line or Area Coil)

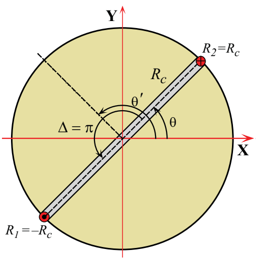
- Fixed coil, Varying field
- Flip Coil/Moving Coil, Static field
- Rotating Tangential/Radial Coils
- Can be made insensitive to higher order terms with special designs.

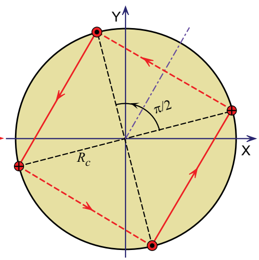


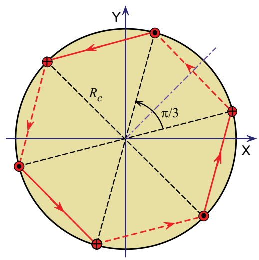
Multipole Coil

Sensitive to only odd multiples of a specified harmonic (Morgan Coils)

Examples of Multipole Coils







Dipole Coil

- Single 180 deg. Loop
- Sensitive to n = 1, 3, ...

Sensitive to *all* terms if loop ≠ 180/k (k = integer)

Quadrupole Coil

- Two 90 deg. Loops, 180 deg. apart, in series
- Sensitive to n = 2,6,10,...

Sensitive to *all* even terms if loop ≠ 90 deg.

Sextupole Coil

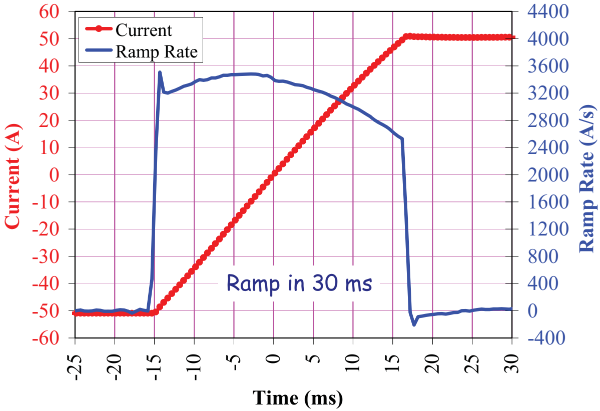
- Three 60 deg. Loops, 120 deg. apart, in series
- Sensitive to n = 3,9,15,...

Sensitive to *all* multiples of n =3 if loop ≠ 60 deg.

Pulsed Quad Using Fixed Quadrupole Coils

Gamma-T Jump in CRF132; Run 41; March 28, 2001

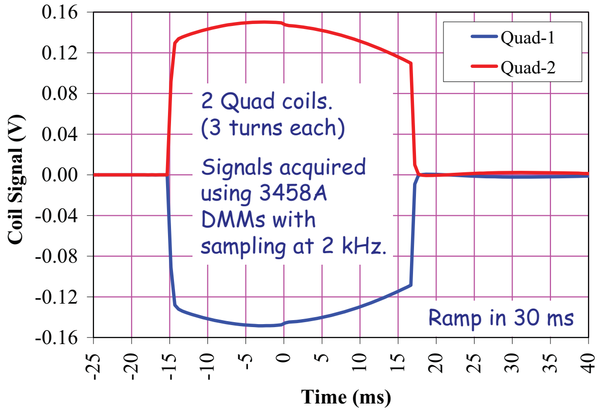
Gamma-T Jump from –50A to +50A; Other Supplies at 0 A.



Pulsed Quad Using Fixed Quadrupole Coils

Gamma-T Jump in CRF132; Run 41; March 28, 2001

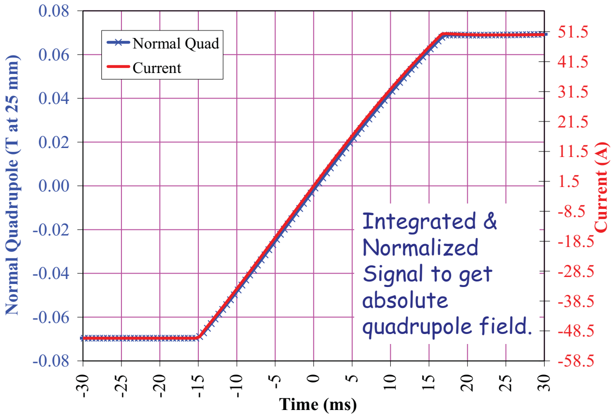
Gamma-T Jump from –50A to +50A; Other Supplies at 0 A.



Pulsed Quad Using Fixed Quadrupole Coils

Gamma-T Jump in CRF132; Run 41; March 28, 2001

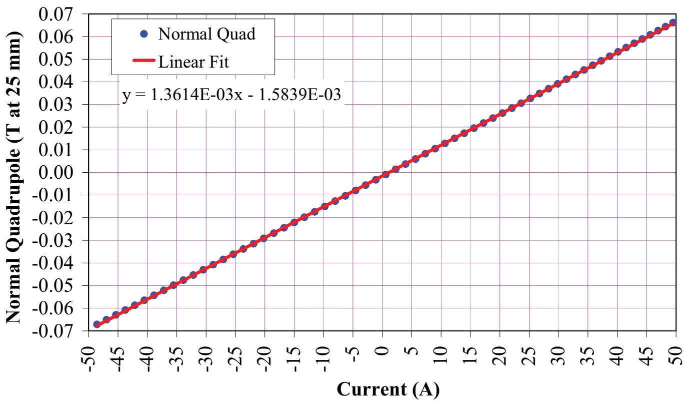
Gamma-T Jump from –50A to +50A; Other Supplies at 0 A.



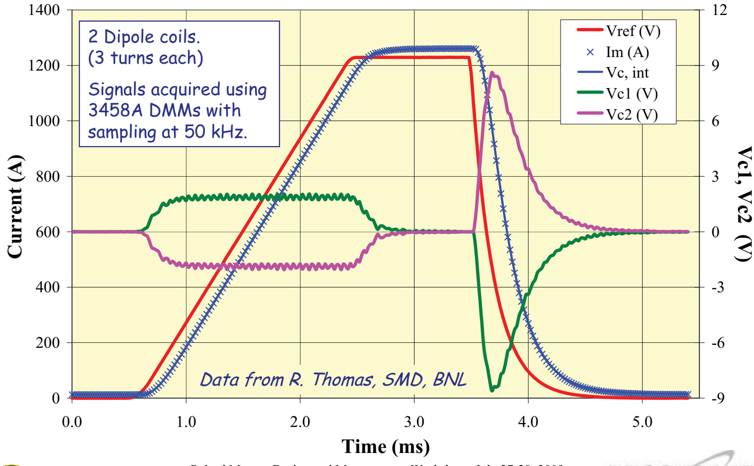
Pulsed Quad Using Fixed Quadrupole Coils

Gamma-T Jump in CRF132; Run 41; March 28, 2001

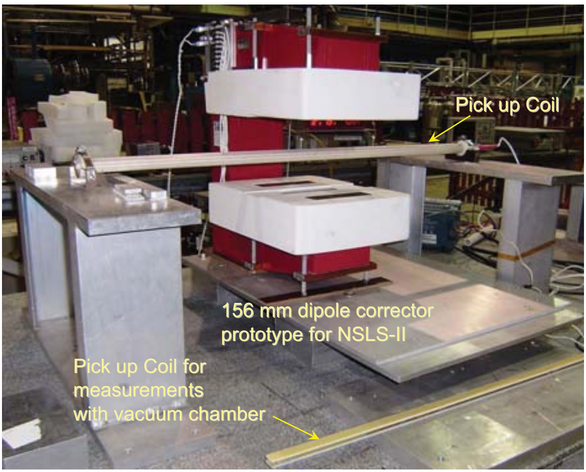
Gamma-T Jump from –50A to +50A; Other Supplies at 0 A.



SNS Injection Kicker Using Fixed Dipole Coils



Sinusoidal Excitation: NSLS-II Dipole Correctors



Data Analysis

Power Supply Control Voltage: $V(t) = V_0 \sin(2\pi f t)$

Current in Magnet: $I(t) = I_0 \sin(2\pi f t - \alpha)$

Field in Magnet: $B(t) = B_0 \sin(2\pi f t - \alpha - \varphi)$

Pickup Signal: $S(t) \propto \dfrac{dB}{dt} = S_0 \cos(2\pi f t - \alpha - \varphi)$

$$\langle I(t) * I(t) \rangle = \tfrac{1}{2} I_0^{\,2} \; ; \; \langle S(t) * S(t) \rangle = \tfrac{1}{2} S_0^{\,2} \; ; \; \langle I(t) * S(t) \rangle = \tfrac{1}{2} I_0 S_0 \cdot \sin\varphi$$

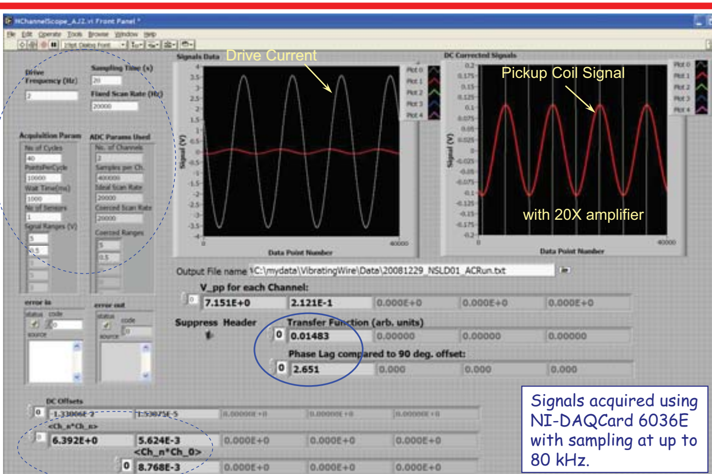
Phase Shift between Current and Field:

$$\sin\varphi = \frac{\langle I(t) * S(t) \rangle}{\sqrt{\langle I(t) * I(t) \rangle \cdot \langle S(t) * S(t) \rangle}}$$

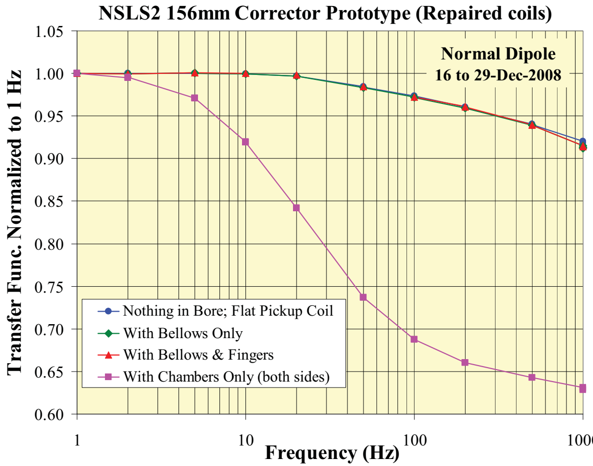
Transfer Function:

$$\frac{B_0}{I_0} \propto \left(\frac{1}{f}\right) \cdot \left[\frac{\langle S(t) * S(t) \rangle}{\langle I(t) * I(t) \rangle}\right]^{1/2}$$

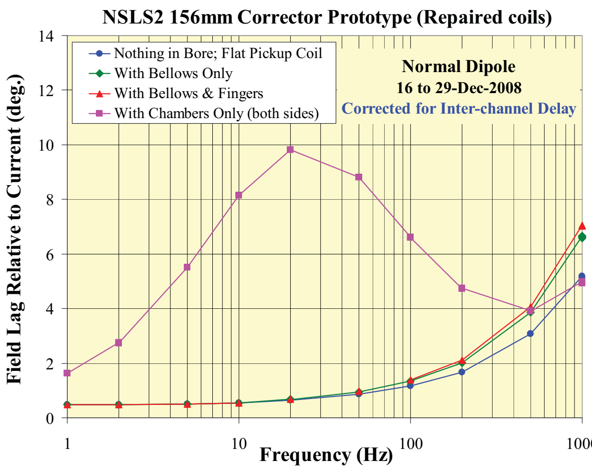
An Example of Data and Analysis



Effect of Vacuum Chambers: Integral Field



Effect of Vacuum Chambers: Phase Shift

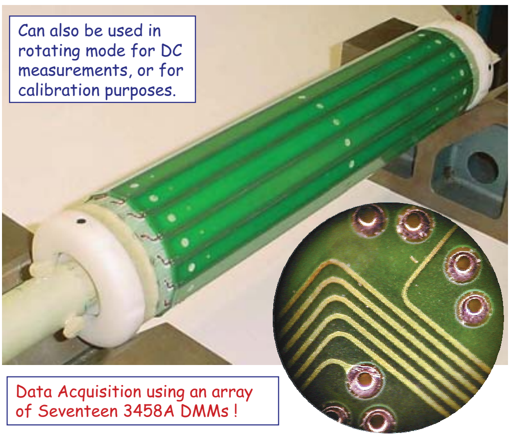


Measurements Using an Array of Coils

- Sometimes it may not be enough to measure just the main field.
- In order to measure field homogeneity (equivalently, the field harmonics), it is necessary to measure the field at many points in space.
- Ideally, one needs an array of similar coils to measure field harmonics. The number of coils depends on the number of harmonics of interest.
- For precise measurement of harmonics, all coils in the array must be built as close to each other as possible, and inter-calibrated precisely.
- It may be possible to use fewer coils and several angular positions to effectively increase the array size, provided ramps are reproducible.

BNL Harmonic Coil Array

Can also be used in rotating mode for DC measurements, or for calibration purposes.



Data Acquisition using an array of Seventeen 3458A DMMs !

16 Printed Circuit coils, 10 layers

6 turns/layer

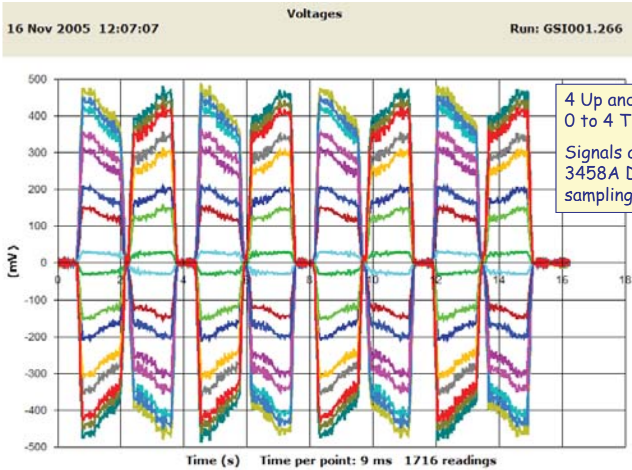
300 mm long

0.1 mm lines with 0.1 mm gaps

Matching coils selected from a production batch

Radius =
26.8 mm (GSI)
35.7 mm (BioMed)

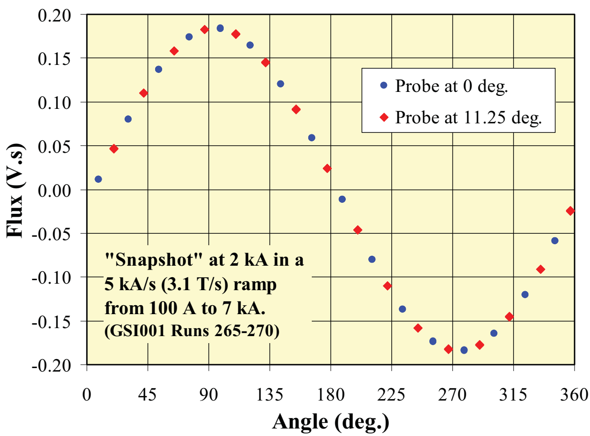
Linear Up & Dn Ramps: Superconducting Dipole



4 Up and Dn Ramps
0 to 4 T at 3 T/s

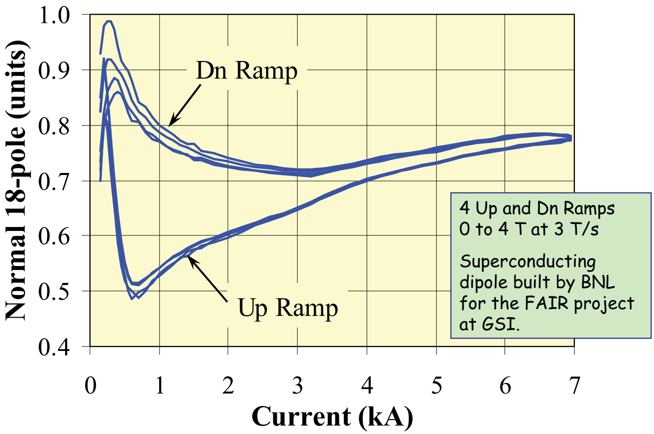
Signals acquired using 3458A DMMs with sampling at ~105 Hz.

32 Angular Positions Using 2 Steps of 16 Coils



Harmonics up to the 26-pole (n = 13) have been measured accurately (< 10^{-4} of the main field) at ramp rates up to 3 T/s using this technique.

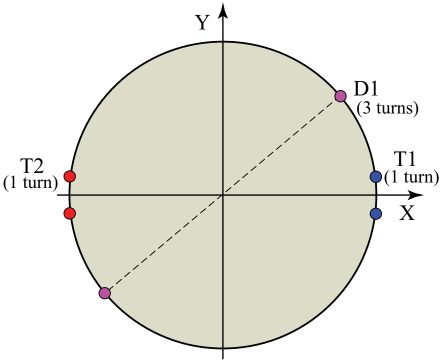
Harmonic Analysis: Cycle to Cycle Consistency



Fast Tune Jump Quads in AGS

- Fast tune jump quadrupoles will be installed in the Alternating Gradient Synchrotron at BNL to overcome horizontal depolarizing resonances.
- The pulse profile is given by:
  - 100 μs rise time (0 to 1 kA), 4 ms flat top, 100 μs fall time (0 to 1 kA)
- Quadrupole field and some harmonics were measured using a coil with 3 different windings (D1, T1 and T2) in 72 orientations.
- D1 is a dipole winding (180 deg.) with 3 turns, and is sensitive to all odd harmonics.
- T1 and T2 are two tangential windings, 180 deg. apart, with ~14 deg. opening angle and a single turn.
- (T1+T2) contains all even terms, (T1–T2) contains all odd terms.

Measuring Coil for Fast Tune Jump Quads



An existing RHIC coil was modified for these measurements.

Measurements were made at 72 different coil orientations to get harmonics.

D1 is sensitive to odd harmonics only.

T1 and T2 are sensitive to all harmonics.

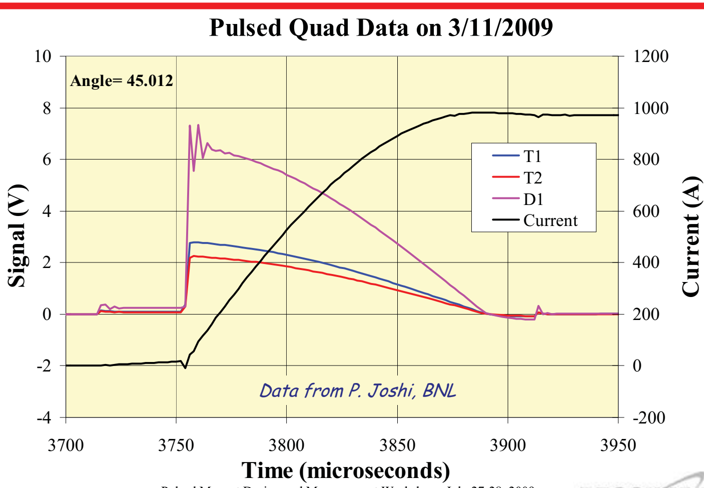
(T1+T2) is *predominantly* sensitive to even terms only.

(T1-T2) is *predominantly* sensitive to odd terms only.

Comparison of (T1-T2) and D1 gives an estimate of errors.

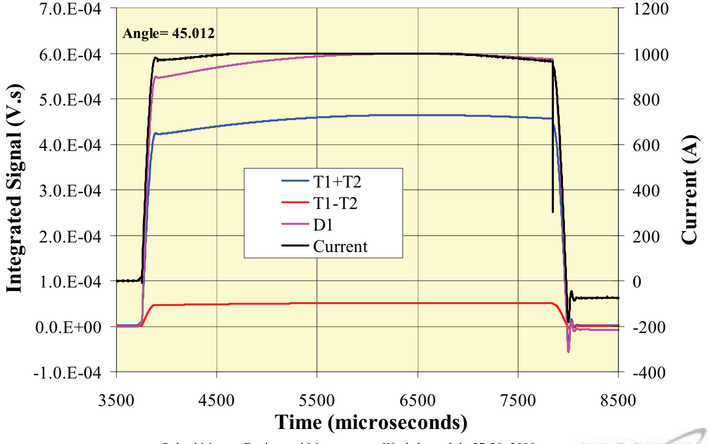
Data acquired using NI-6123 ADC at 500 kHz (2 μs time resolution).

Fast Tune Jump Quads: Raw Data



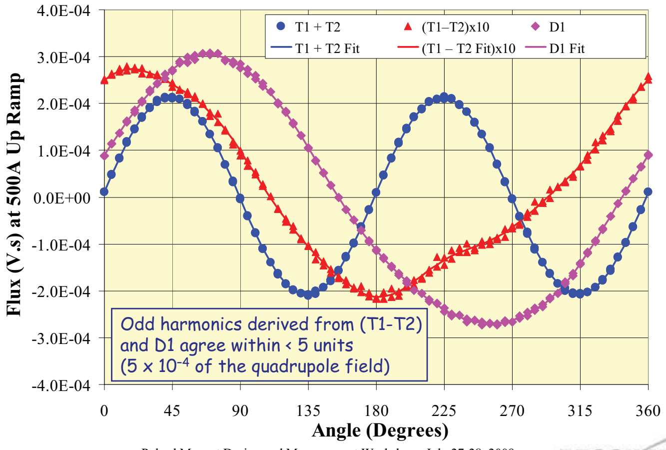
Fast Tune Jump Quads: Instantaneous Flux

Pulsed Quad Data on 3/11/2009



Fast Tune Jump Quads: Angular Profiles

Pulsed Quad Data on 3/11/2009 (72 Angles)



Summary

- Field quality measurement techniques for DC fields are well established.
- Measurements of field quality in changing fields become increasingly more difficult as the time scales become shorter.
- Pick up coils are perhaps the most convenient means of characterizing pulsed fields on a test bench.
- The main field component is relatively easy to obtain, but the measurement of harmonics requires extra care in probe calibration and control of other experimental parameters.
- Field quality measurements at microsecond time scales, and shorter, remain quite challenging at present.

Acknowledgements

M. Anerella J. Cintorino
S. Dimaiuta J. Escallier
G. Ganetis P. Joshi
W. Louie A. Marone
D. Oldham A. Sauerwald
D. Sullivan R. Thomas
P. Wanderer

Thank You !

181

Looking Forward

Arlene W. Zhang and Jon Sandberg
Collider-Accelerator Department
Brookhaven National Laboratory
July 28, 2009

Introduction

- Repetitive pulsed power technology
- Trend analysis
- Technology landscape
- NSLS II Requirements & Constraints
- Recommendations
- R&D, PM, and Operation experiences

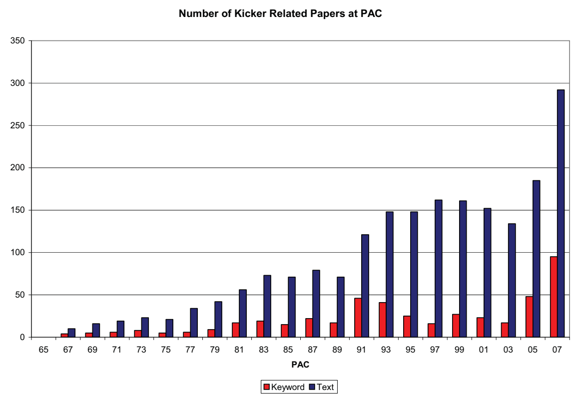
Growth Trend

Kicker is a typical repetitive fast pulsed power system. Numbers of kicker related papers at PAC and EPAC have grown rapidly over last four decades.

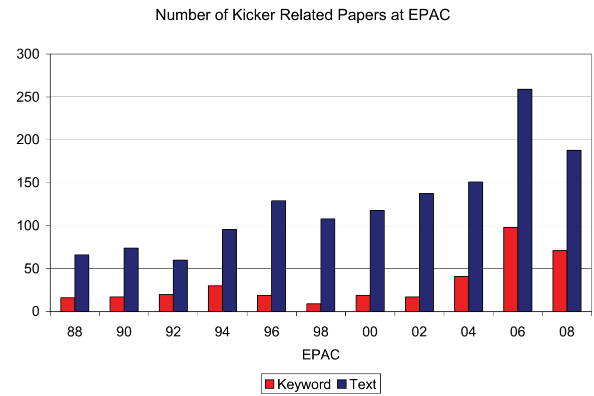
PAC	Kicker (key word)	Kicker (text)
65	0	0
67	4	10
69	5	16
71	6	19
73	8	23
75	5	21
77	6	34
79	9	42
81	17	56
83	19	73
85	15	71
87	22	79
89	17	71
91	46	121
93	41	148
95	25	148
97	16	162
99	27	161
01	23	152
03	17	134
05	48	185
07	95	292

EPAC	Kicker (key word)	Kicker (text)
88	16	66
90	17	74
92	20	60
94	30	96
96	19	129
98	9	108
00	19	118
02	17	138
04	41	151
06	98	259
08	71	188

Growth Trend Graph (PAC)



Growth Trend Graph (EPAC)



Technology Landscape

- Switch
- Topology
- Magnetic Material
- Measurement
- Magnet Design
- Advanced Approach

Switch

- Closing switch
  - Thyratron
  - SCR
- Opening switch
  - IGBT, IGCT, etc.
  - MOSFET
- Fixed on time switch

Topology and Advanced Concepts

Topologies

- PFN, PFL, Blumlein, …
- Capacitor discharge
- Inductive Adder
- Marx Generator
- …

Advanced Concepts

- FFT
- Wakefield
- …

Magnetic Material

- Laminated Steel
- Ferrite
- Metglass
- Finemet

Magnet Design

- Traveling Wave Magnet
  - High impedance magnet designs exist for both in vacuum or in air depending on voltage requirement.
  - Low impedance, high field magnet is challenging.
- Lumped Magnet
  - Ferrite magnets in vacuum are common in large colliders and accelerators. Beam protection design has matured and well tested for decades.

Measurement

- Spot or integrated magnetic field probe measurement
  - Probe conductor and magnet conductor interaction
  - Shielding, grounding, high voltage arcing, etc.
- Laser measurement

NSLS II Requirements

- Light Source pulsed power system requirements differ from large collider or high power accelerators
- Advantage
  - Lower peak power and lower average power
  - Smaller magnetic loads
- Challenge
  - Tighter stability and regulation level
  - Tighter space

NSLS II Constraints

- Resource
- Technology
- Schedule
- Cost
- Performance

Parameter Evaluations

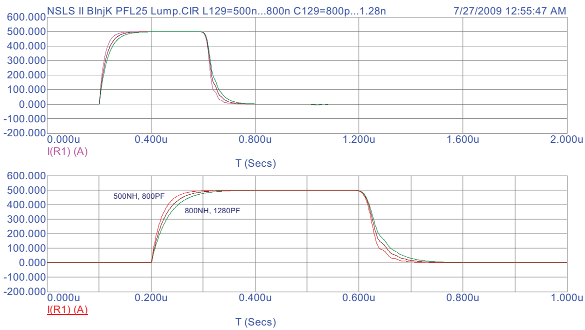
- Most specifications are well within performance range of existing accelerator pulsed power systems.
- If the required regulation and precision were in the range of a percent, then the parameters are achievable with today's technology.
- High precision and stability will need further development.

Booster Kickers

- Specification
  - Baseline stability: a few percent tolerance
- Pulser
  - Inductive Adder
  - PFL
  - …
- Kicker
  - Lumped magnet
  - Transmission line magnet
  - Parallel plates

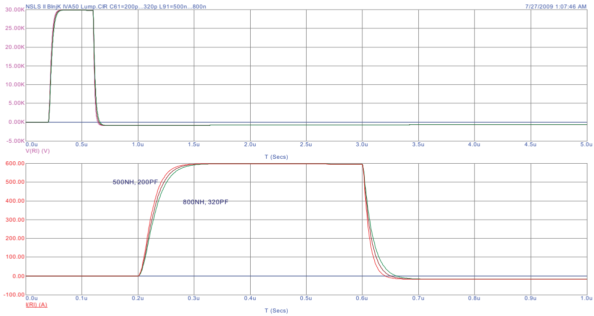
Booster Injection Kicker

- PFL Design Example
- 25 ohm PFL, lumped magnet, 25 ohm load with capacitor compensation.



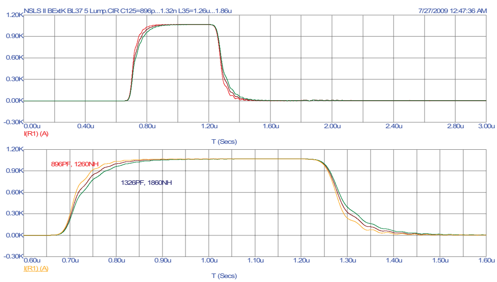
Booster Injection Kicker

- IVA Design Example
- 50 ohm stalk, 30 kV output
- Lumped Magnet, 50 ohm load with capacitor compensation



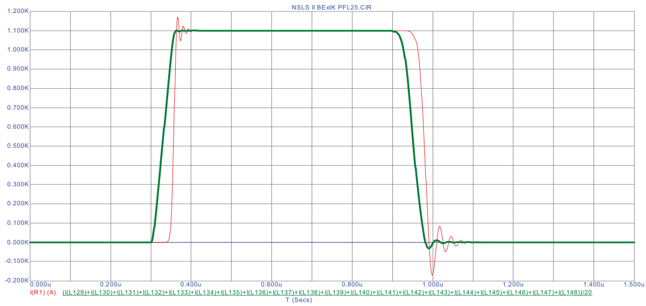
Booster Extraction Kicker

- Blumlein Design Example - Charging before injecting beam
- Push-Pull lumped magnet structure, magnetic field deflection
- 37.5 ohm Load with capacitor compensation
- +/- 40 kV charging voltage & nominal magnet voltage
- Simulation - Slow rise time



Booster Extraction Kicker

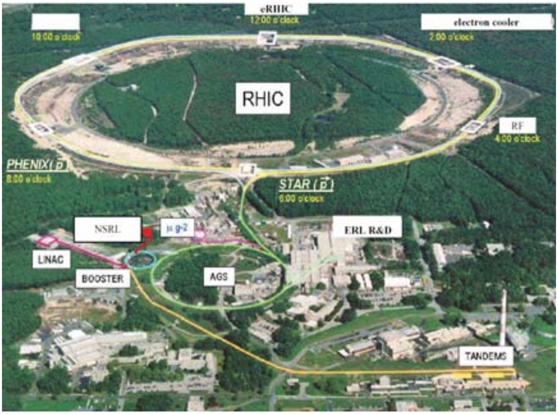
- PFL Design Example: Loss Less PFL and transmission cable, Push-Pull traveling wave magnet structure
- 25 ohm impedance, +/- 55 kV charging voltage, +/- 27.5 kV nominal magnet voltage for 1100A magnet current.
- Contribution of electrical field deflection should be included.



Design Concerns

- Low Loss PFL and transmission cable availability
- Cable length vs. pulse flat top ripple due to impedance mismatch
- Accessibility and maintainability
- Radiation and safety issues
- Lumped magnet → Magnetic field deflection
- Traveling wave magnet or parallel plate → Electrical field & Magnetic field deflection

Collider-Accelerator Complex



C-A Pulsed Power Systems

- Fast kickers
- Septa
- Pulsed and DC bumps
- Gamma Transition PS
- EBIS pulsed power systems
- Tune meters
- Polarized Proton fast quads power supply
- Experiments' pulsed power systems
- Other Systems for Accelerators

Achieved System Capability

- Pulsed Power: > 1 Giga-Watts
- Maximum Voltage: 100 KV
- Maximum Current: > 20 kA / module
- Pulse Duration: ns, us, or ms
- Rise / Fall Time: ns, us, or ms
- Burst Repetition Rate: 2000 PPS (test only)
- Continuous Operation Repetition Rate: 60Hz

Pulsed Power System Design

- Complete Pulsed Power System design, such as high voltage modulators, pulse transmission systems, trigger systems, auxiliary systems, diagnostic and instrumentation systems, PLC and PLD design and programming, grounding and shielding designs, etc.
- Analysis and simulations, system layout, modulator layout, mechanical packaging, customer components development, installation, commission, etc.
- Experienced with both thyratrons & solid state devices

Design and Operation Experience

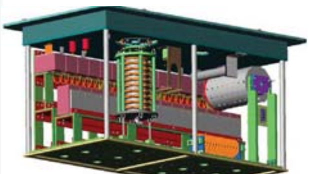
- High voltage modulators located inside accelerator tunnels or in service buildings, driving load magnets directly or through high voltage transmission cables
- Control and auxiliary system located remotely in service buildings
- Unattended operations since 1990

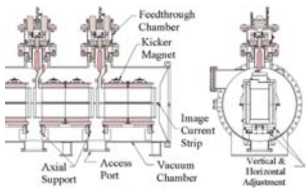
SNS Extraction Kicker System by BNL

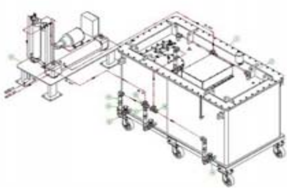
ORNL SNS Extraction Kicker System by BNL

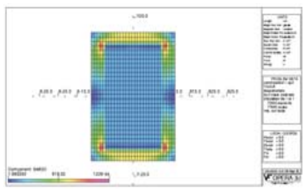
- A giga-watt class pulsed power system
- A state-of-art continuous operation high repetition rate pulsed power system
- Under budget, within schedule, excellent system performance, total customer satisfaction

SNS EXTRACTION FAST KICKER









SNS EXTRACTION FAST KICKER

Thank You!