RHIC R&D - eCooling

Annual DOE/Nuclear Physics Review
of RHIC Science and Technology

July 18-20, 2007
Berkner Hall, BNL

Presented on behalf of the many people who contribute
to the electron cooling R&D effort by
Ilan Ben-Zvi,
Collider-Accelerator Department
Brookhaven National Laboratory

The RHIC II Upgrade

- Evolution of RHIC to a QCD laboratory calls for a luminosity increase.
- A significant part of the luminosity increase will be through electron cooling.
- Electron cooling is also important for the eRHIC – a high-energy, high-luminosity lepton-hadron collider based on RHIC.
- The energy range (54 MeV electrons) is an order of magnitude increase past the FNAL cooler (4.5 MeV), which is an order of magnitude above all previous coolers (under 0.4 MeV).

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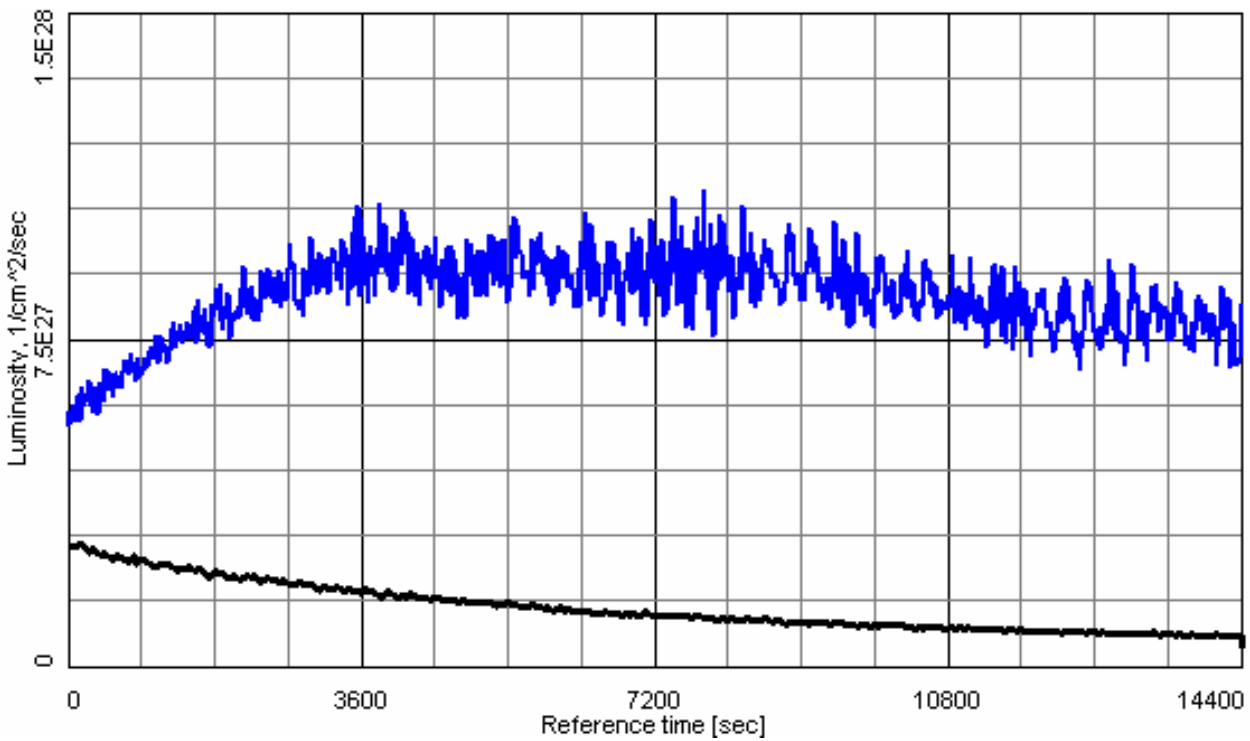
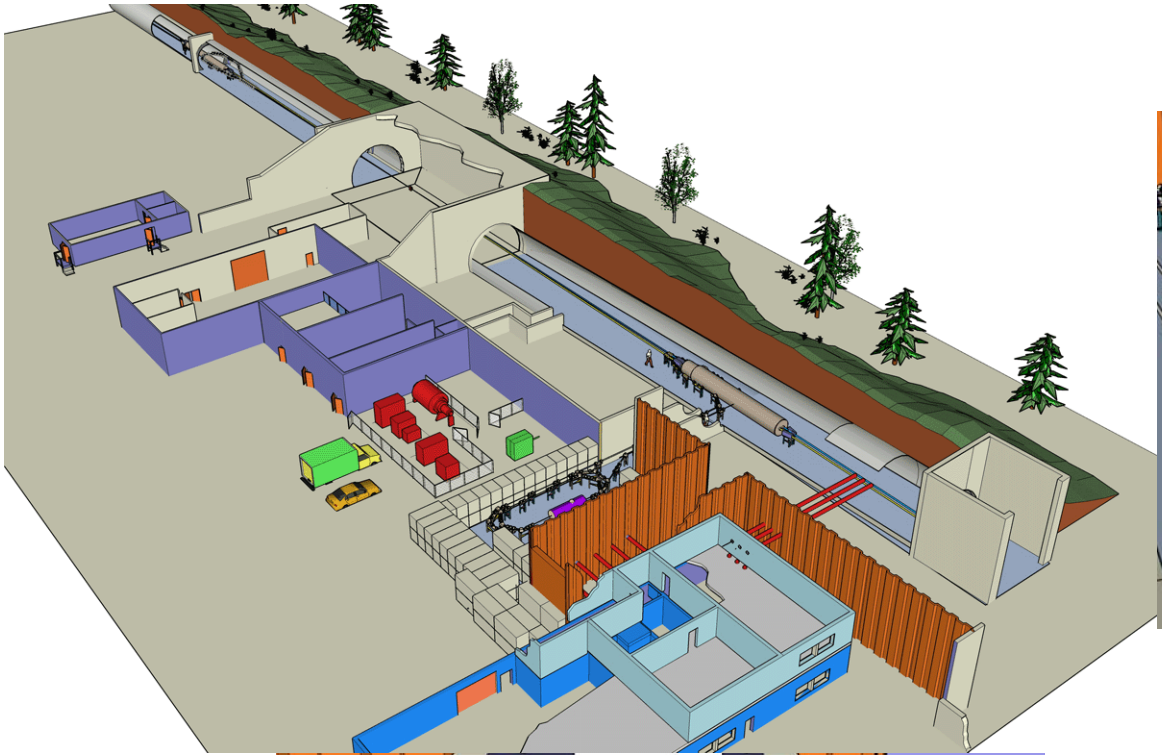
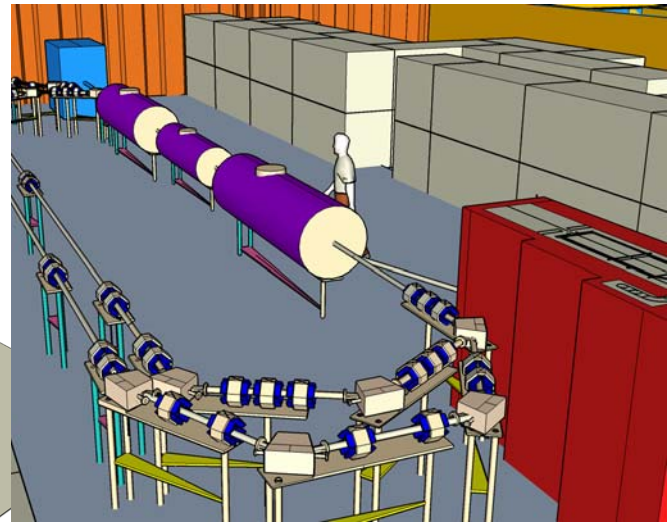
Luminosity of 100 GeV/A gold

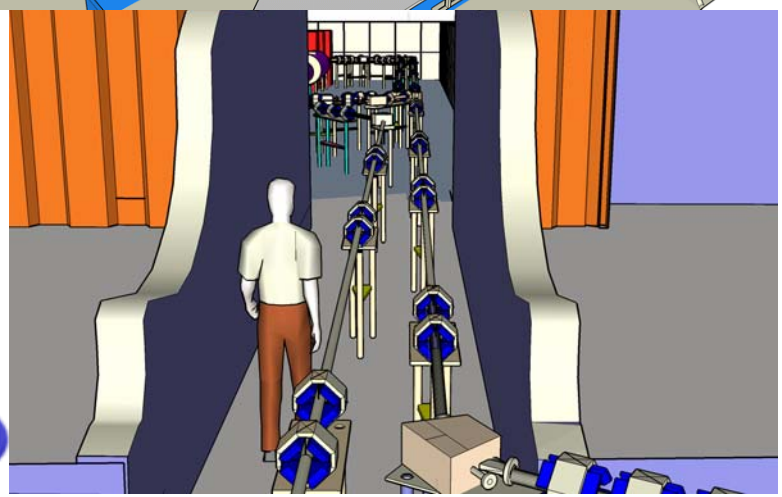


Beta function at IP 0.5m Bunch length 20 cm rms Ave. Lumin 8.5 *10^{27}
Beam disintegration at 2 IPs included, 2 gauss, 12 cm period undulator

Layout of RHIC electron cooler at IP2







Objective:
Cool RHIC stored ion beams at ~100 GeV/A.
Reduce background Maintain smaller vertex

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Proof-of-principle attained

- Proof-of-principle of feasibility of cooling RHIC achieved
  - Theory is within better than a factor of 2 in predicting cooling speed, supported by simulations and experiments
  - Start-to-end simulations of electron beam show that the beam parameters can be achieved.
- Additional theory R&D on refinements.
- Significant R&D on hardware risk reduction.

From previous review

- … (R&D) plan for increasing machine luminosity should be generated which defines milestones, performance goals and deliverables, required resources, critical path and schedule contingency, … 'checkpoints' … should be delivered to DOE by January 31, 2007.
- A comprehensive R&D plan was generated and submitted well before that date.
- … simulation … indicates that the beam parameters for electron cooling should be well within reach, these beam parameters are never-the-less considerably beyond anything yet demonstrated ...
- These beam parameters have been demonstrated and documented.

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Great progress also this year

25 presentations at PAC07:

A. Fedotov, RHIC Plans Towards Higher Luminosity, TUZAKI01
D. Bruhwiler et al, Scaling VORPAL Electron Cooling Simulations to Larger Domains on >1,000 Processors THPAS018
G.I. Bell et al, Numerical Algorithms for Modeling Electron Cooling in the Presence of External Fields THPAS017
A. Sobol et al, Quantifying Reduction of the Friction Force due to Magnet Imperfections THPAS024
A. Fedotov et al, High-Energy Electron Cooling Based on Realistic Six-Dimensional Distribution of Electrons THPAS093
A. Fedotov et al, Electron Cooling in the Presence of Undulator Fields THPAS092.
G. Wang et al, Coherent Instability of RHIC Ion Beam due to Electron Cooling THPAS104
D. Kayran et al, Optics of a Two-Pass ERL as an Electron Source for a Non-Magnetized RHIC-II Electron Cooler THPAS096
J. Kewisch et al, Low Emittance Electron Beams for the RHIC Electron Cooler THPMS087
J. Kewisch et al, Emittance Compensation for Magnetized Beams THPMS088,
V. Ranjbar et al, High-Order Modeling of an ERL for Electron Cooling in the RHIC Luminosity Upgrade FRPMS032
E. Pozdeyev et al, Collective Effects in the RHIC-II Electron Cooler THPAS100
E. Pozdeyev et al. Electron Beam Alignment in the RHIC II Cooling Section FRPMS117
E. Pozdeyev et al. Diagnostics of BNL ERL FRPMS116
X. Chang et al, High Average Current Low Emittance Beam Employing CW Normal Conducting Gun WEPMS090
V.L. Litvinenko et al, Status of R&D Energy Recovery Linac at Brookhaven National Laboratory TUPMS076
D. Kayran et al, Merger System Optimization in BNL's High Current R&D ERL THPAS097
V.L. Litvinenko et al, Unique features in magnet designs for R&D Energy Recovery Linac at BNL MOPAS097
A. M. Todd et al, High-Current Accelerator Development for FELs and ERLs
A. Burrill et al, Challenges Encountered during the Processing of the BNL ERL 5 Cell Accelerating Cavity WEPMS088
A. Burrill et al, Multipacting Analysis of a Quarter Wave Choke Joint Proc WEPMS089
X. Chang et al, Recent Progress on the Diamond Amplified Photo-cathode Experiment WEOCC04
D. Dimitrov et al, 3D Simulations of Secondary Electron Generation & Transport in a Diamond THPAS020
Q. Wu et al, Thermal Emittance Measurement Design for Diamond Secondary Emission TUPMS089
H. Hahn et al, Ferrite-lined HOM Absorber for the e-Cool ERL THPAS095

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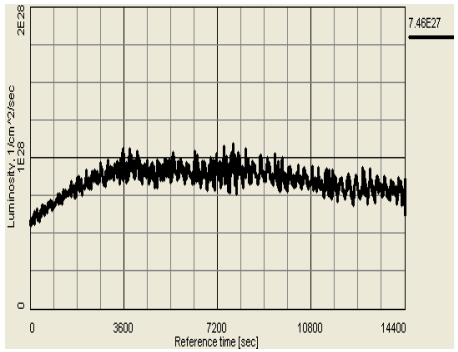
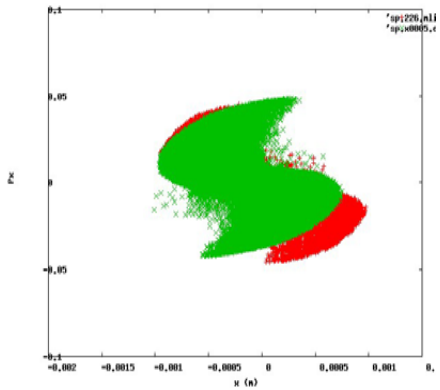
Selected items from **last year**

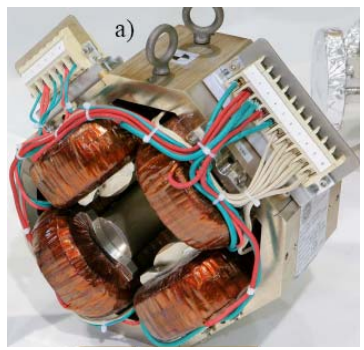
- Cooling modeling





- Beam dynamics

- Hardware development



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Cooling modeling
Fedotov, with Tech-X and JINR

Last year's new achievements:

1. **Studies of friction force in the presence of external fields.**
2. **More experiments at the FNAL Recycler cooler and further benchmarking of cooling dynamics simulations.**
3. **Development of friction force model based on realistic 6-D electron distribution in BETACOOL and cooling dynamics simulations.**
4. **Development of IBS model for arbitrary distribution in BETACOOL.**
5. **Estimates of various contributions to rms angular spread in the cooling section and cooling dynamics studies.**
6. **Estimates of ion beam stability as a result of electron cooling.**
7. **Studies of recombination suppression and new undulator parameters.**

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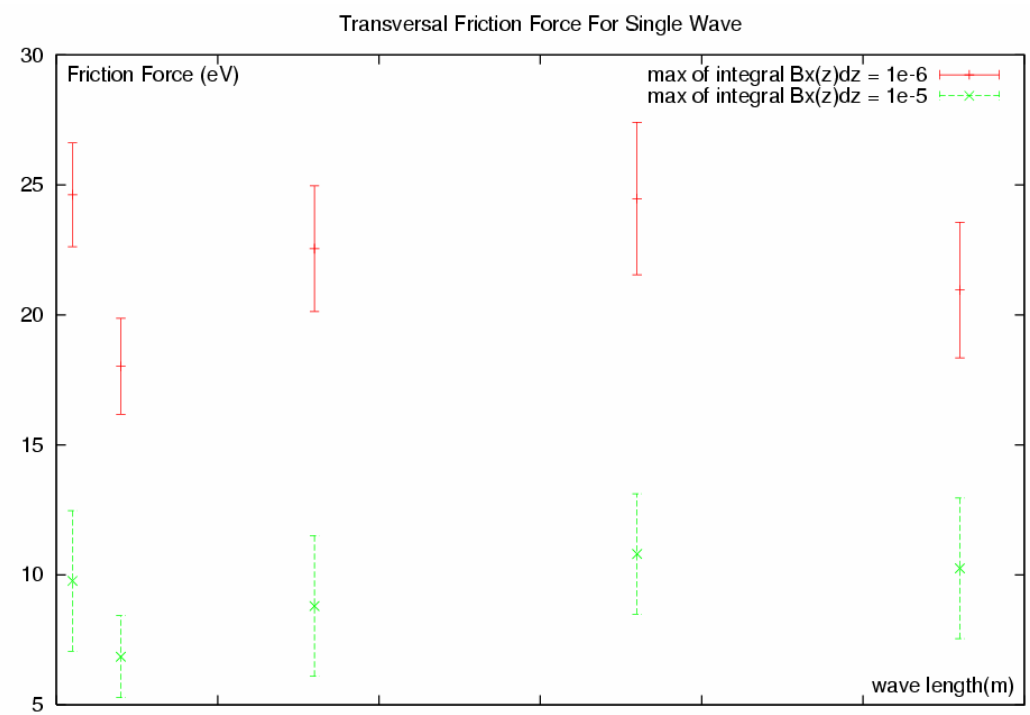
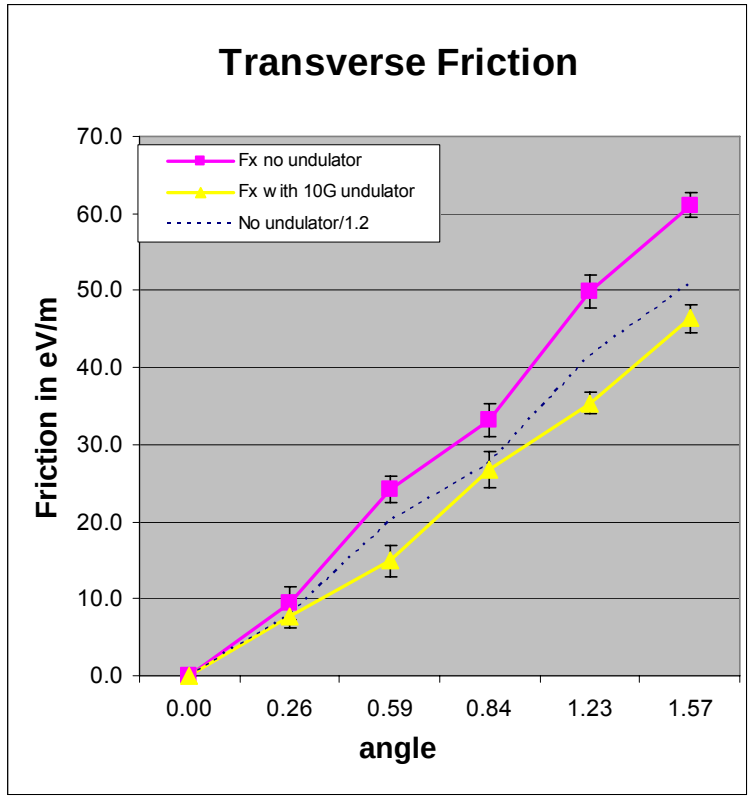
Undulator studies, including errors

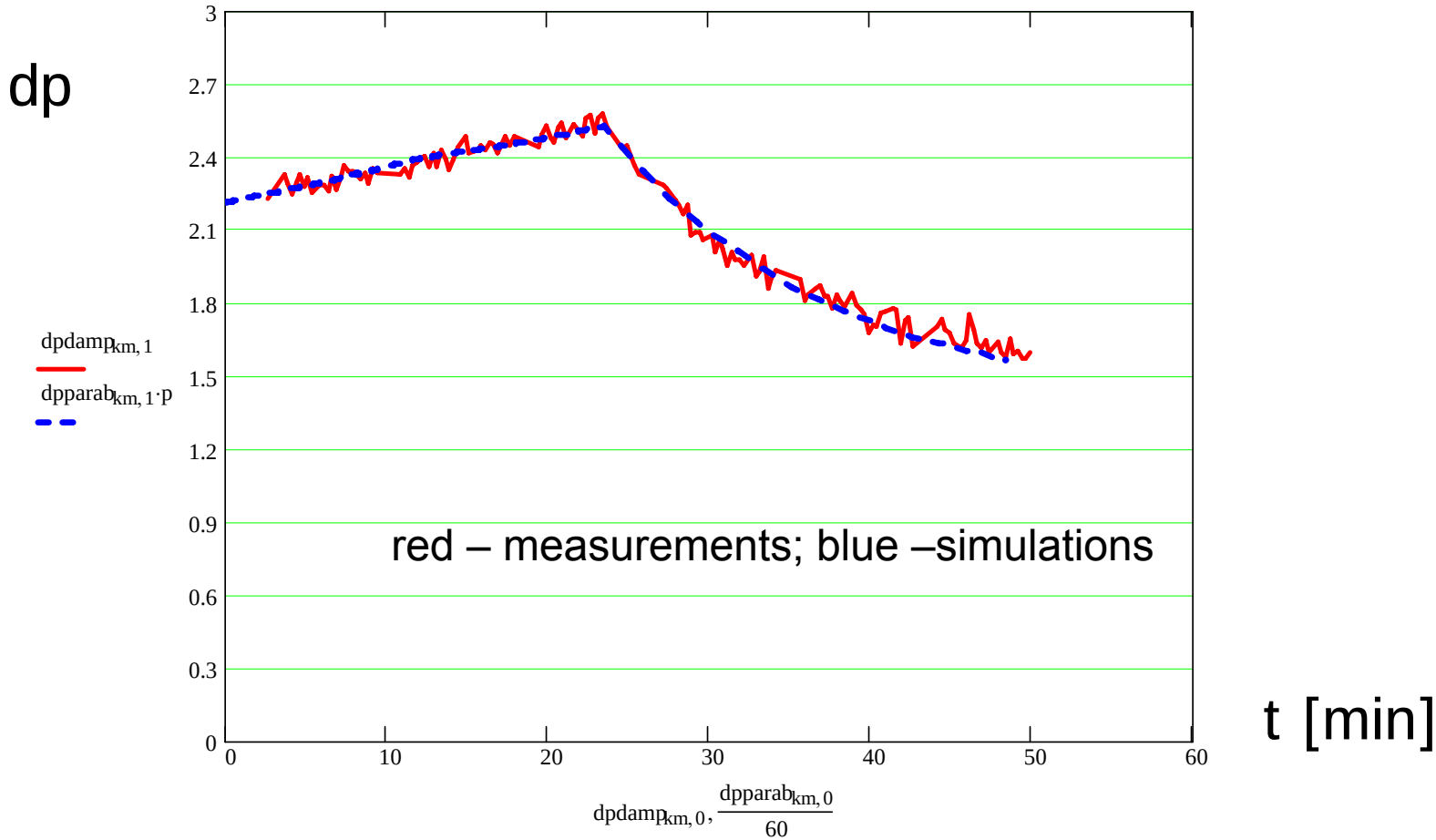


Effect of magnetic field errors in undulator on the friction. Integral of 1e-6 Tm corresponds to rms angular spread of 5 mrad (A. Sobol et al)

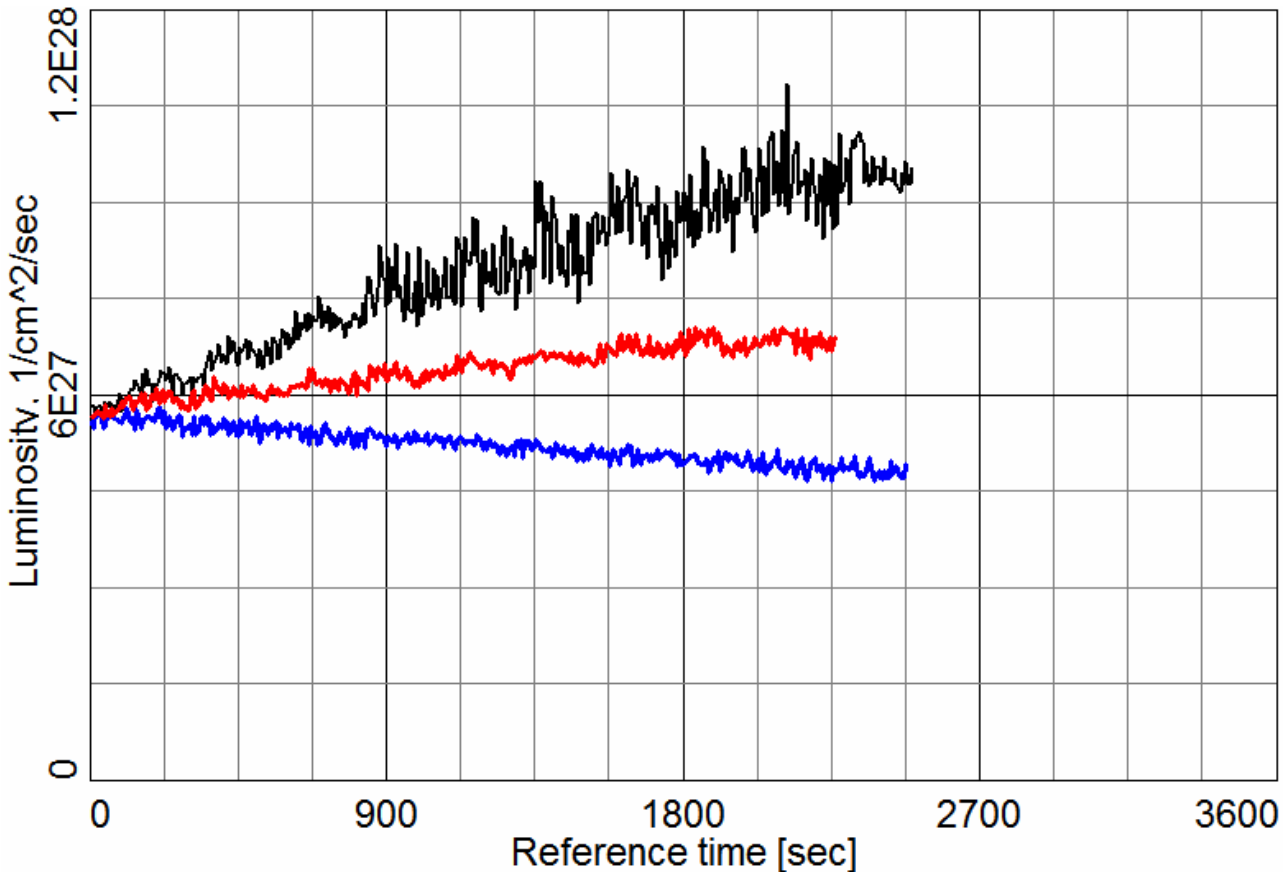


Cooling with and without undulator (G. Bell et al)

Using FNAL cooler for benchmarking: Simulations & measurement of longitudinal cooling



Using realistic electron beams: Simulations using actual electron beam distribution



Simulations of initial luminosities. Black – using electron distribution from PARMELA at the start of the cooling section. Red (based on local model) and blue (based on global rms parameters) using electron distribution at the end of the cooling section.

Cooling high intensity Au ions

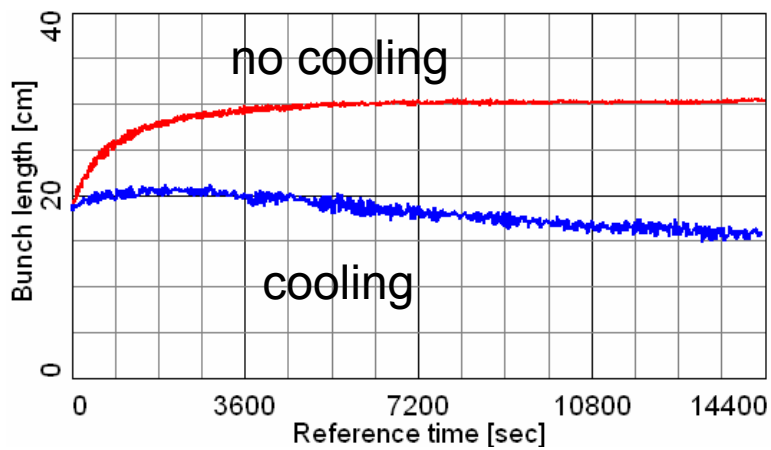
number of bunches: 111

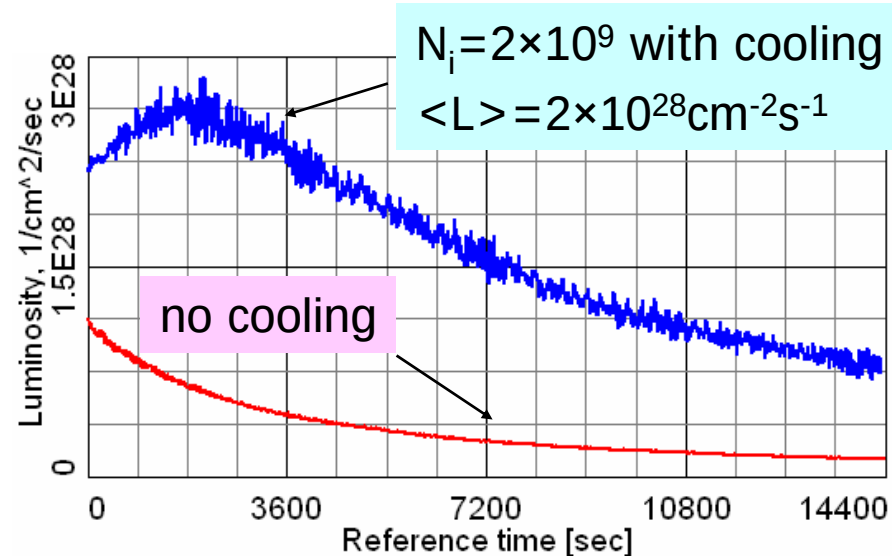
initial $\varepsilon_{95\%,n}$ =15 μm

rms momentum spread 5×10^{-4}

β^*=0.5m bunch length 19 cm rms

Using 2 electron bunches separated by 40 cm
BETACOOL (JINR, Russia) simulation.
included effects: intra-beam scattering,
particle loss in collisions, loss from bucket.

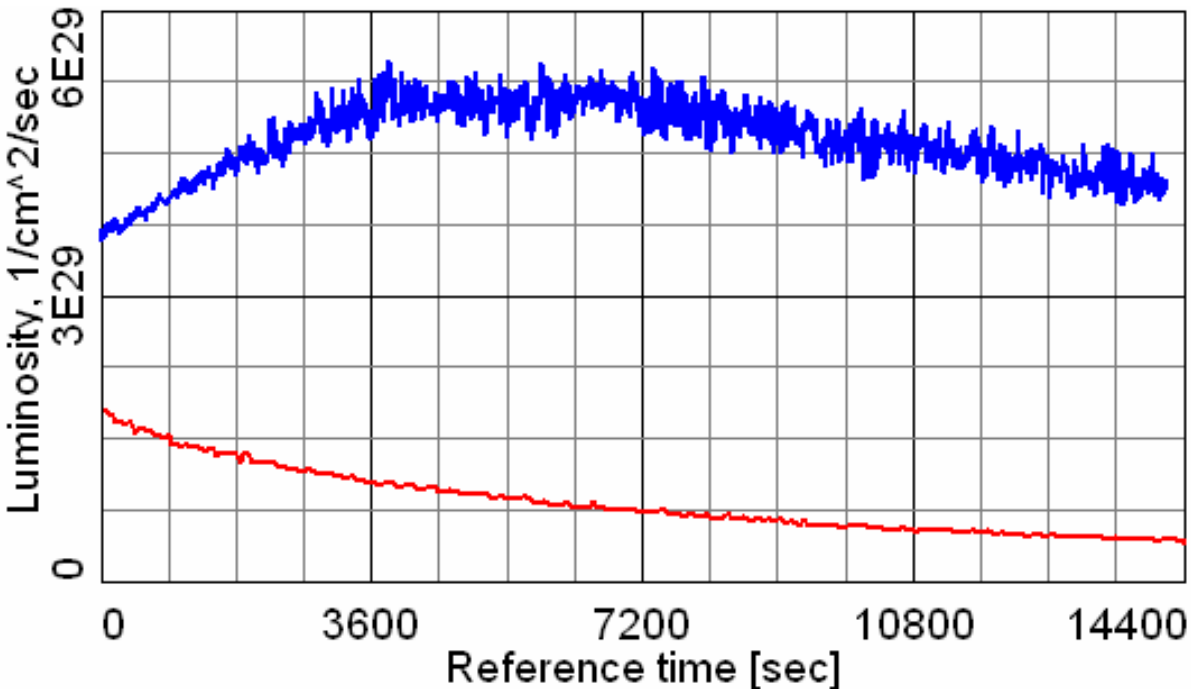




Maintaining short bunch length.
Shaping of the longitudinal
distribution is possible to eliminate tails.

With possible improvement of the
number of gold ions stored in RHIC
the luminosity can be further increased.
This option is closed to stochastic cooling.

Cooling Cu ions at 100 GeV/n



Ratio of average luminosity with cooling to the one without Cooling is 5.6

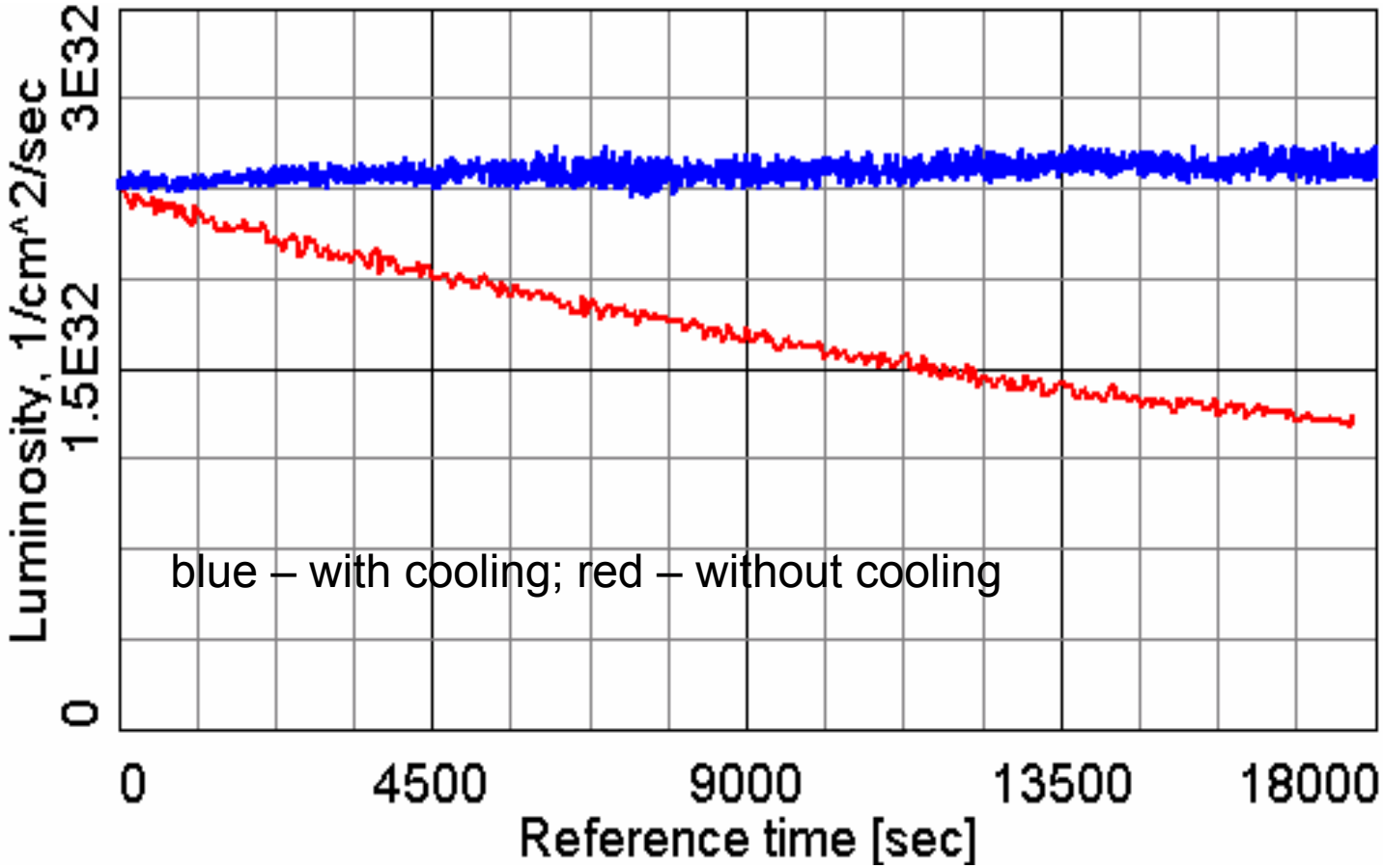
$8*10^9$ copper ions.

Rms bunch 19 cm

Beta* 0.5 m (cooling)

Beta* 1 m (no cooling)

Cooling protons at 100 GeV



$2*10^{11}$ ions
Beta* 0.5m
2 e bunches

Electron Beam Dynamics

Kayran, Kewisch, Chang, Pozdeyev

1. Electron cooler beam dynamics studies
2. Collective effects
3. Comparing Space-charge tracking codes
4. Tolerance to errors
5. Development of back-up option gun

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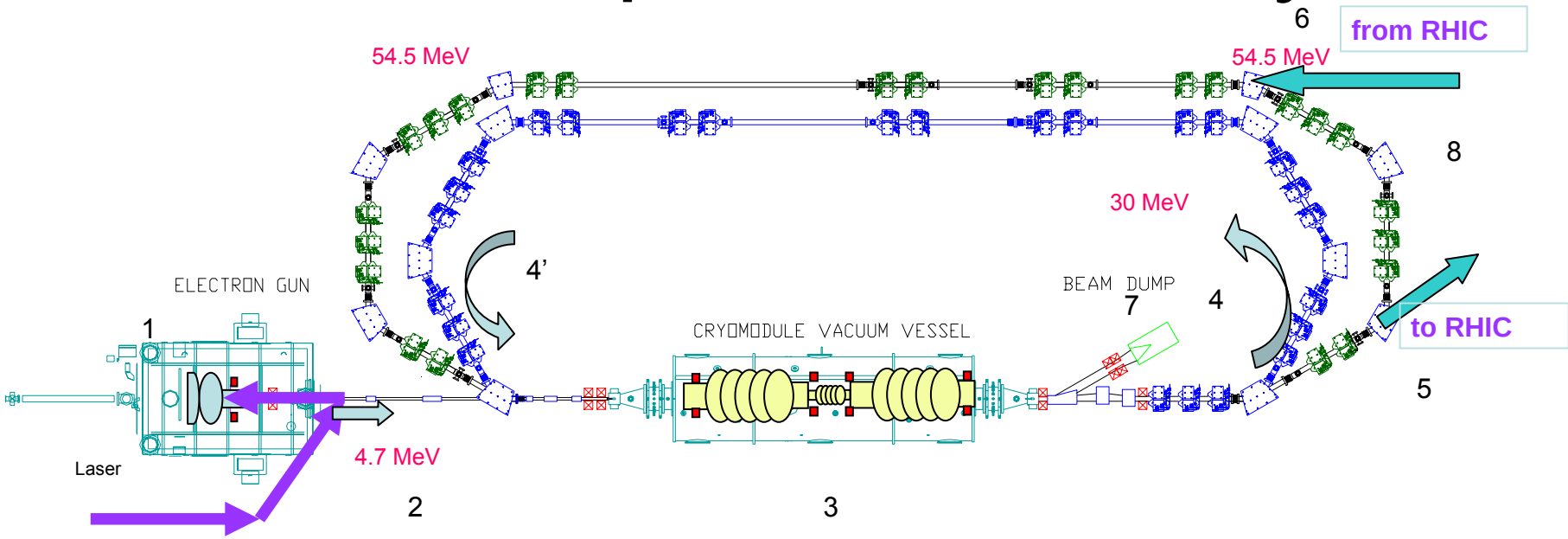
E-cooler: 2 passes ERL layout



1. SRF Gun,
2. Injection merger line
3. SRF Linac two 5-cell cavities and 3rd harmonic cavity

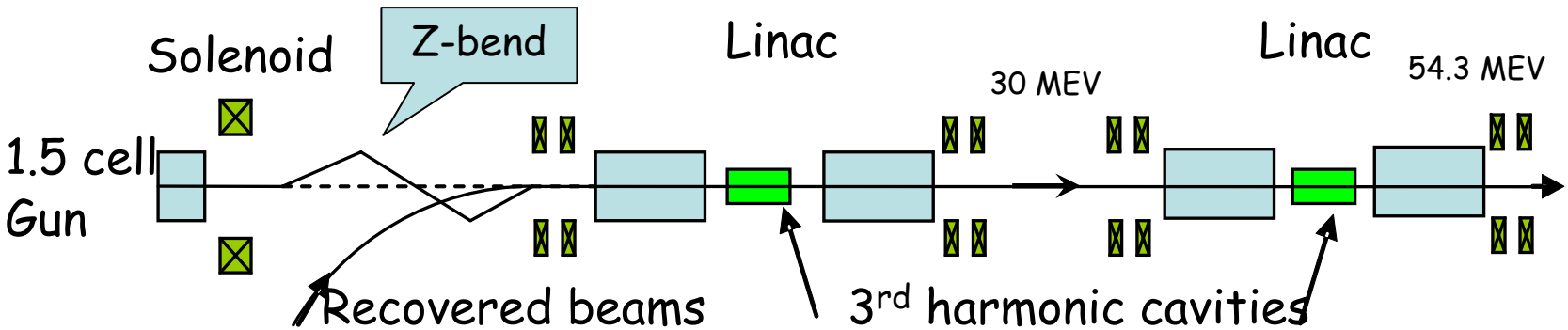
4, 4'. 180° achromatic turns

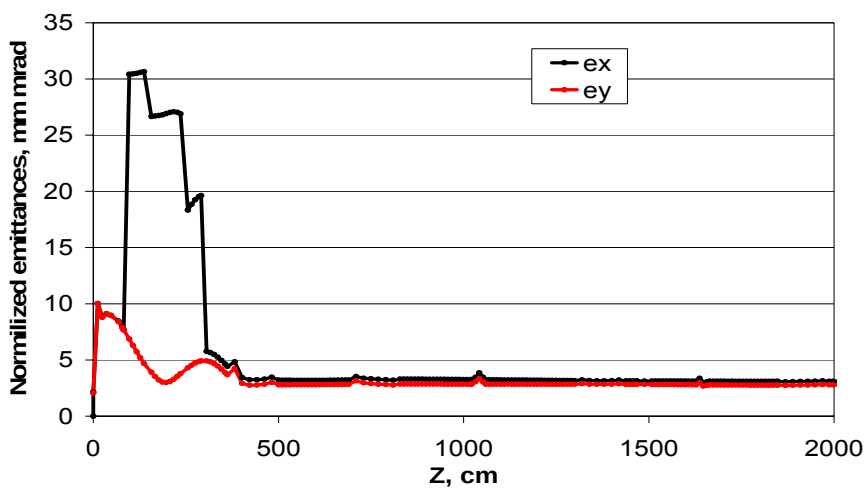
5, 6. Transport lines to and from RHIC,

7. Ejection line and beam dump
8. Short-cut for independent run of the ERL.

54 MeV, 5 nC at 9.4 MHz. RF 703.75 MHz. Gun 5 MeV

Evolution of emittance





Evolution of the projected normalized transverse emittances rms in the test-bed system for beer-can distribution 5nC per bunch (final horizontal emittance black 3.1 mm mrad, vertical emittance red 2.8 mm mrad) D. Kayran et al,

Collective effects in electron beam dynamics

- Various effects estimated:
  - Multi-bunch, multi-pass Beam Breakup
  - Space charge in cooling section
  - ERL impedances
  - CSR
  - ion trapping
  - e-cloud
  - wall charge images in cooling section

  (E. Pozdeyev et al. PAC07).

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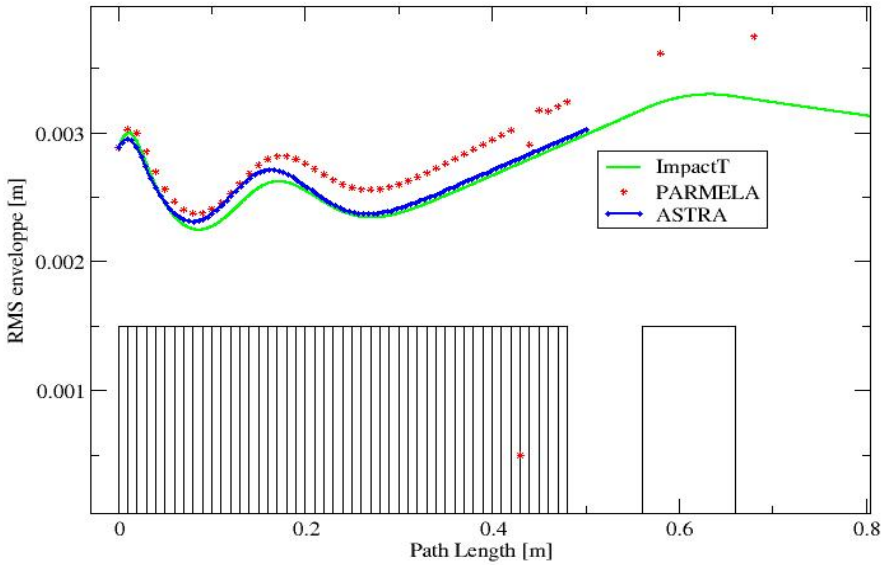
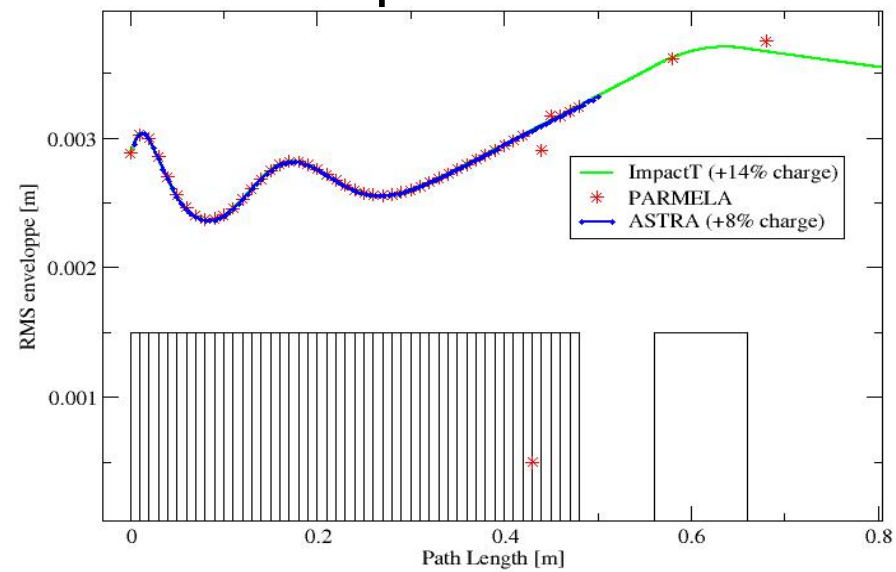
Comparing space-charge code performance PARMELA with ASTRA and ImpactT





Beam envelopes calculated with PARMELA and ImpactT and ASTRA with space charge forces included.

The envelopes agree when the bunch charge is increase by 14% in ImpactT and by 8% in ASTRA.

	Projected Emittance	Max Slice Emittance
PARMELA	2.21μ	0.94 μ
ImpactT	1.45 μ	1.29 μ
ImpactT +14%	1.72 μ	1.42 μ
ASTRA	2.17 μ	2.18 μ
ASTRA +8%	2.28 μ	2.28 μ

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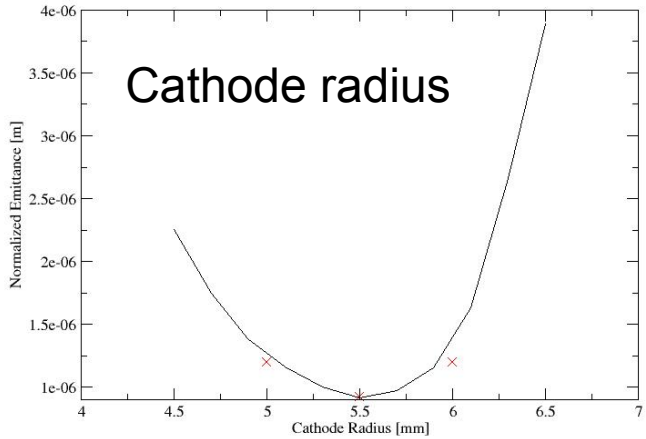
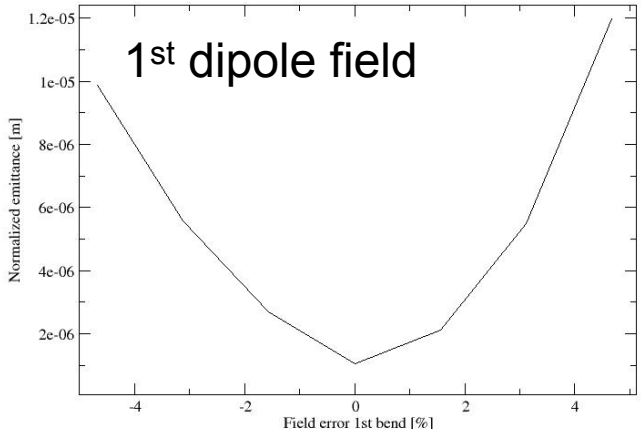
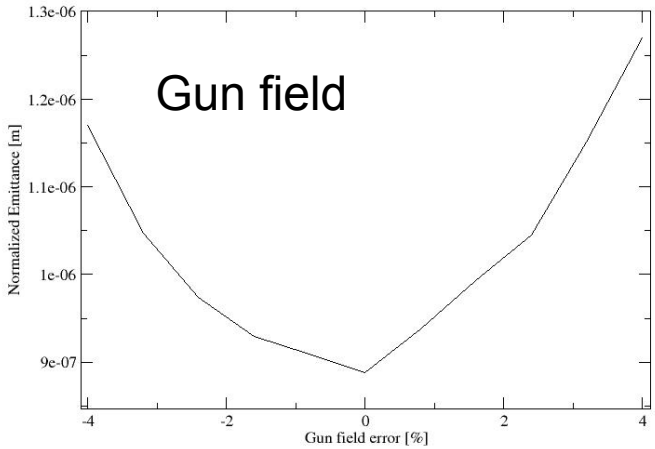
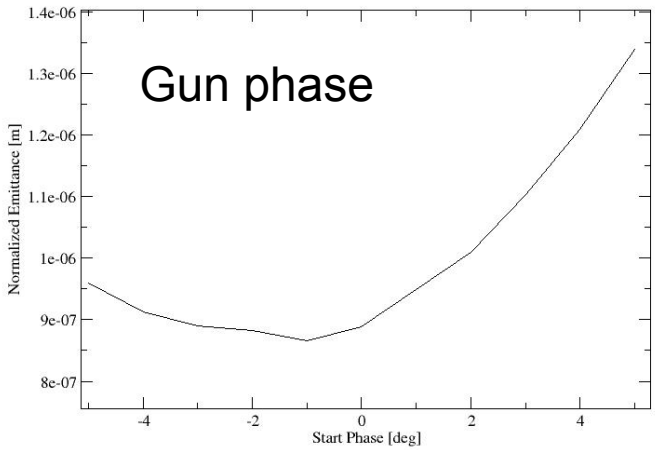
Emittance variation for the most sensitive parameters.



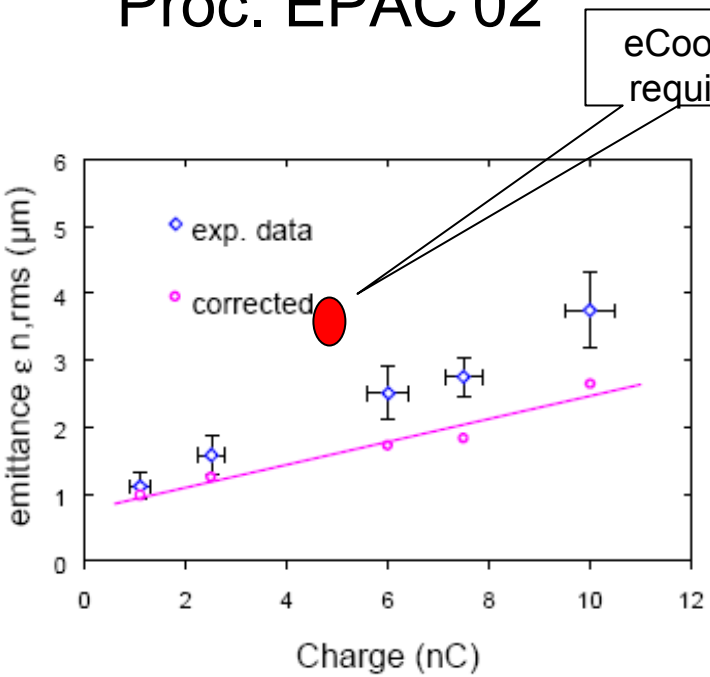


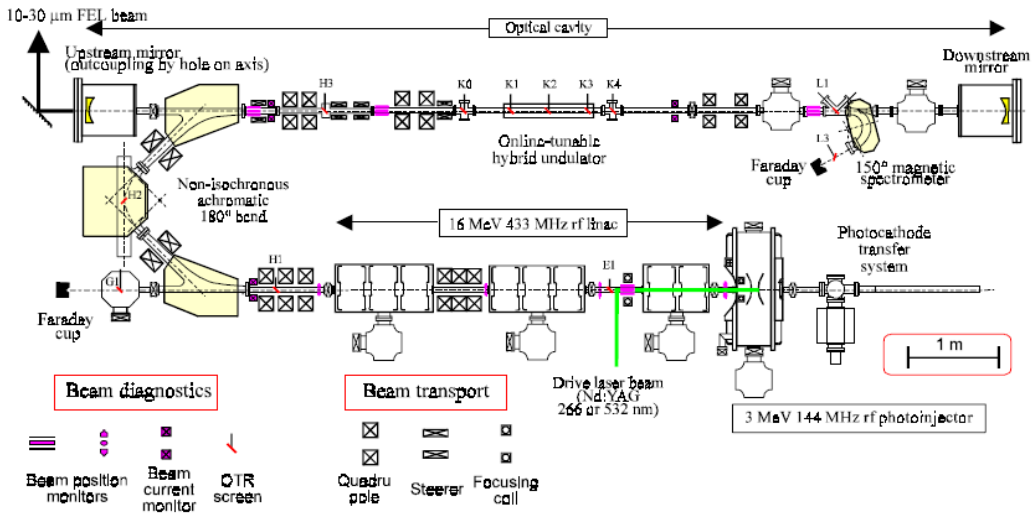




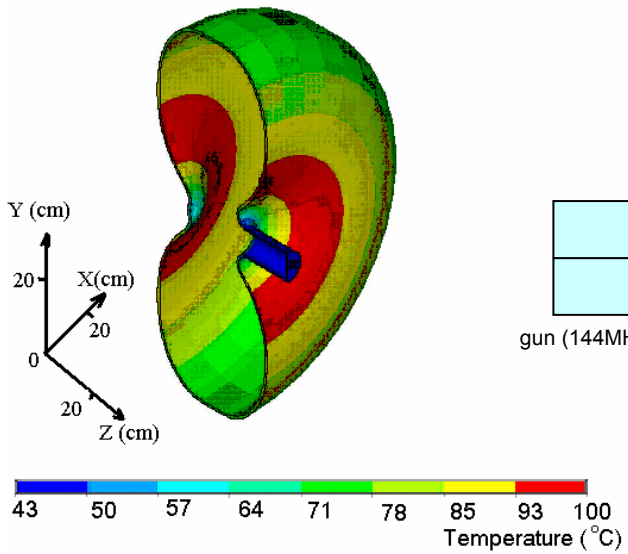
The RHIC II cooler electron beam brightness has been demonstrated

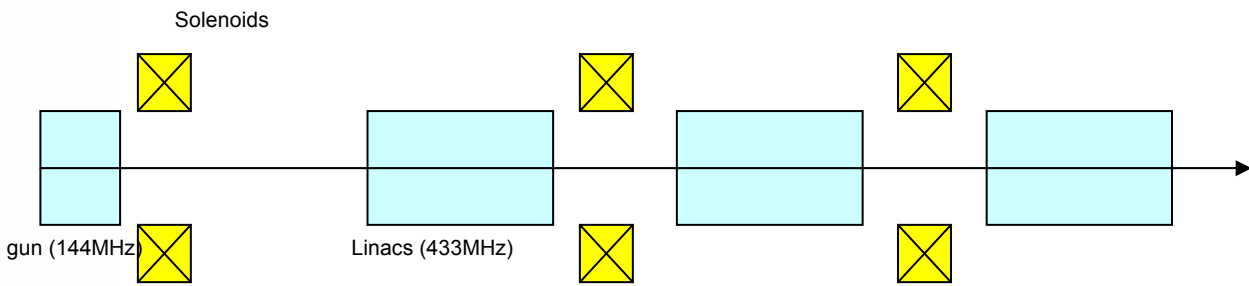
- J.-G. Marmouget, et. al, present performance of the low-emittance, high-bunch charge elsa photo-injected linac, Proc. EPAC'02



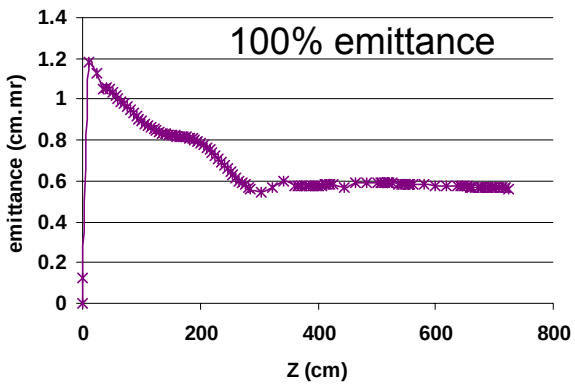


Back-up option 144 MHz gun based on the ELSA copper gun. Can be used in a very short time.





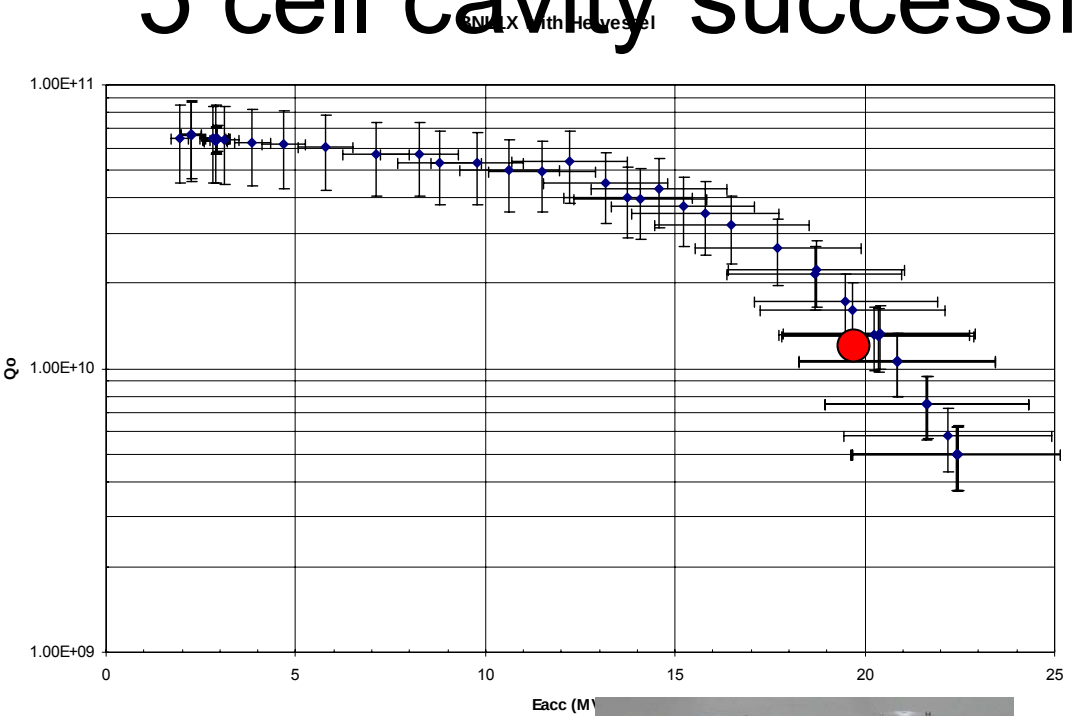
Energy at linac exit	19 MeV
Transverse emittance (100% particles)	5.6 mm.mr
Transverse emittance (90% particles)	3.3 mm.mr
Thermal emittance	1.3 mm.mr

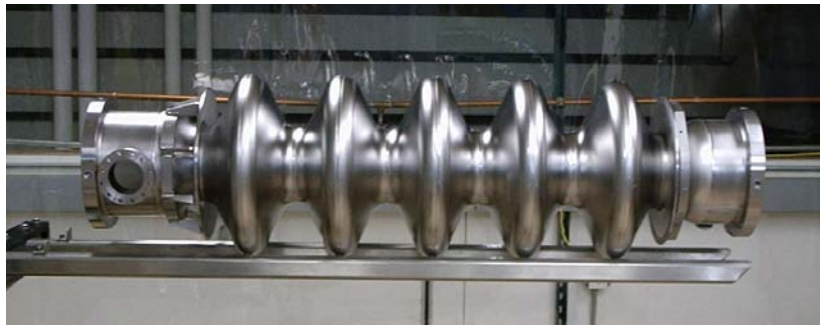


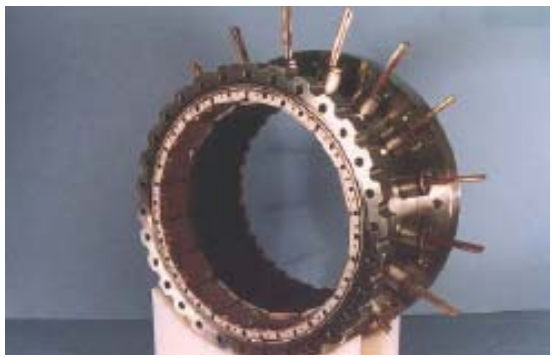
Hardware development

- 5-cell, high-current accelerating cavity
- ½ cell SRF gun
- Photocathode R&D
- ERL

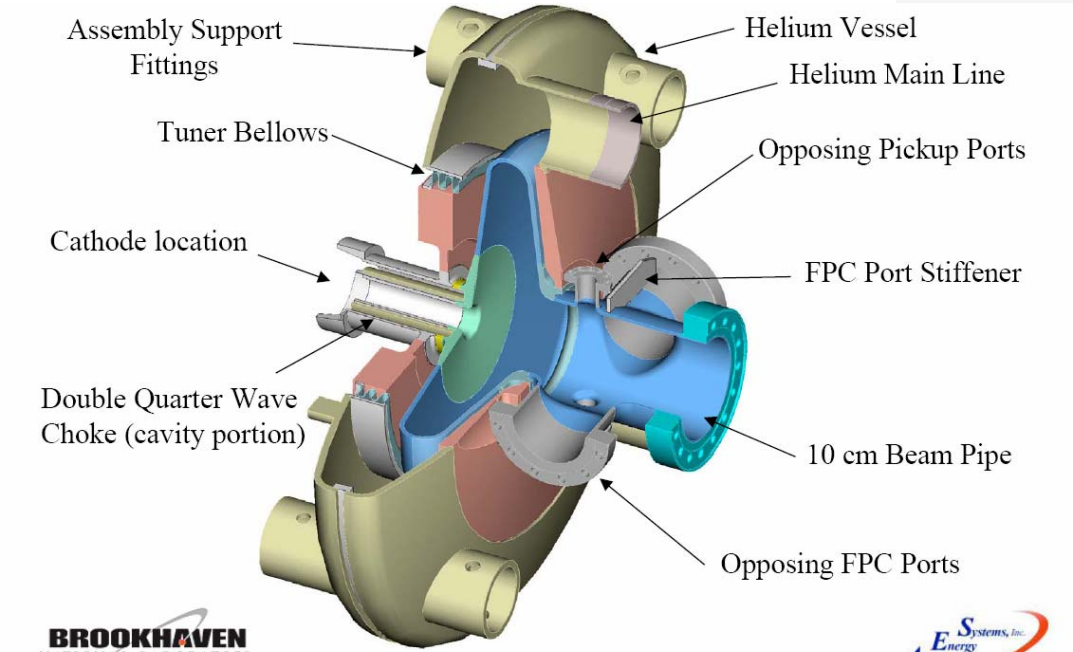
5 cell cavity successfully processed

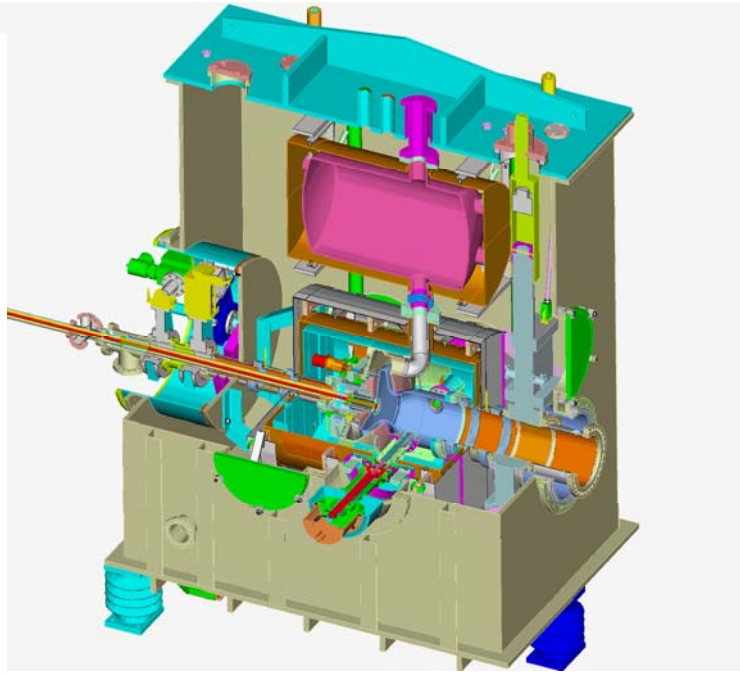


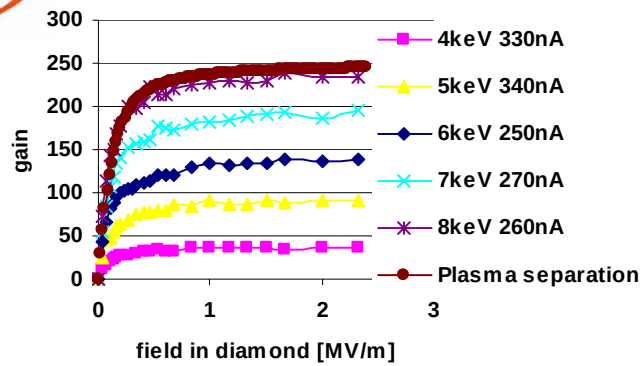




0.5 ampere SRF gun





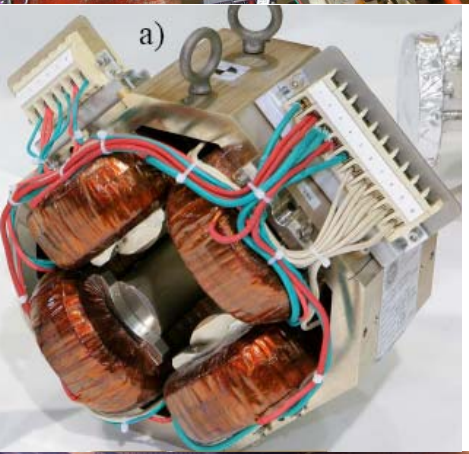


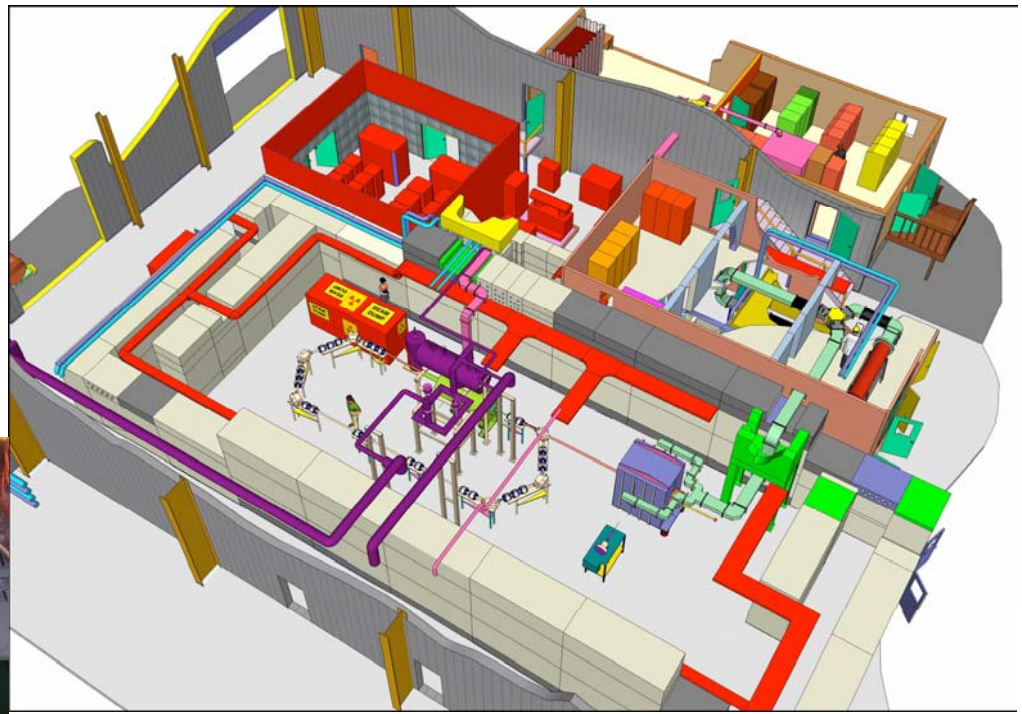
Diamond amplified photocathode R&D

ERL (led by Vladimir Litvinenko)

Test bed for ecooling and eRHIC

Commissioning start 2/09





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Summary: Status of the R&D

- A lot of information at http://www.bnl.gov/cad/ecooling/
- Research towards electron cooling of RHIC is now in its 6th year
- Feasibility was demonstrated through
  - numerical simulations of the electron cooling process,
  - Benchmarking experiments, and
  - numerical simulations of the electron beam dynamics of the electron cooler.
  - Past year's work refined many of the details.
- Risk reduction (technical, cost and schedule) R&D on:
  - Photocathode
  - SRF gun
  - ERL cryomodule
  - ERL beam merging system
  - Demo ERL

  } **Also for eRHIC!**

To be finished in 2009

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Summary (continued)

- Status of R&D – Upgrades, competencies needed
  - The status was presented in great detail. Competency in SRF technology and high-current, high-brightness ERL are needed for ecooling AND eRHIC, and are being developed.
- Update on plans to establish feasibility
  - Feasibility has been established a year ago. Refinements are going on, presented above in some detail.
- How is the plan integrated with BNL Strategic Plan? Impacts?
  - Cooling is an essential part of RHIC II and eRHIC, right down the center of the BNL Strategic Plan. Cooling high-intensity beams such as protons can only be done by electron cooling.
- Issues
  - Cost and schedule for the RHIC electron cooler are being developed. Various cost cutting ideas are being studied, large items were identified are are being studied.

Backup slides

R&D issues

- Understanding the cooling physics in a new regime to reduce uncertainty
  - cooling dynamics simulations with some precision
    - **IBS**, recombination, disintegration
    - benchmarking experiments
    - stability issues
- Developing a high current, energetic, low emittance electron beam
  - Photoinjector (inc. photocathode, laser, etc.) 5 nC, 4μm
  - Energy Recovery Linac, at x2.5 of state-of-the-art current
    - Preservation of high-charge, low emittance beam
    - Collective effects: Wakes, CSR, space-charge…

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Many collaborations and multiple support sources

- BNL divisions
  - Instrumentation, Magnet
- National Laboratories
  - Fermilab, JLab, SLAC
- Universities
  - Indiana, Stony Brook, UCLA
- International
  - BINP, JINR, Uppsala, GSI
- Industry
  - AES, Tech-X

- C-AD eCooling group
  - 10 FTE
  - Matrix support
  - 1 MS in last year
  - 1 current students

- Support from
  - BNL Director's Office
  - DOE ONP
  - DOD / ONR
  - DOD / JTO
  - SBIR (various offices)

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Friction force studies in the presence of external fields

These studies were done in collaboration with Tech-X. Corp. using their code VORPAL.

The following problems were studied:

A. Reduction of friction force values for various parameters of undulator (A. Fedotov et al., PAC07; G. Bell et al., to be submitted to Journal of Computational Physics).

B. Effect of magnetic field errors in undulator – different wavelength and different amplitudes (A. Sobol et al., PAC07)

C. Effect of space-charge compensated solenoids in cooling section (G. Bell et al., PAC07).

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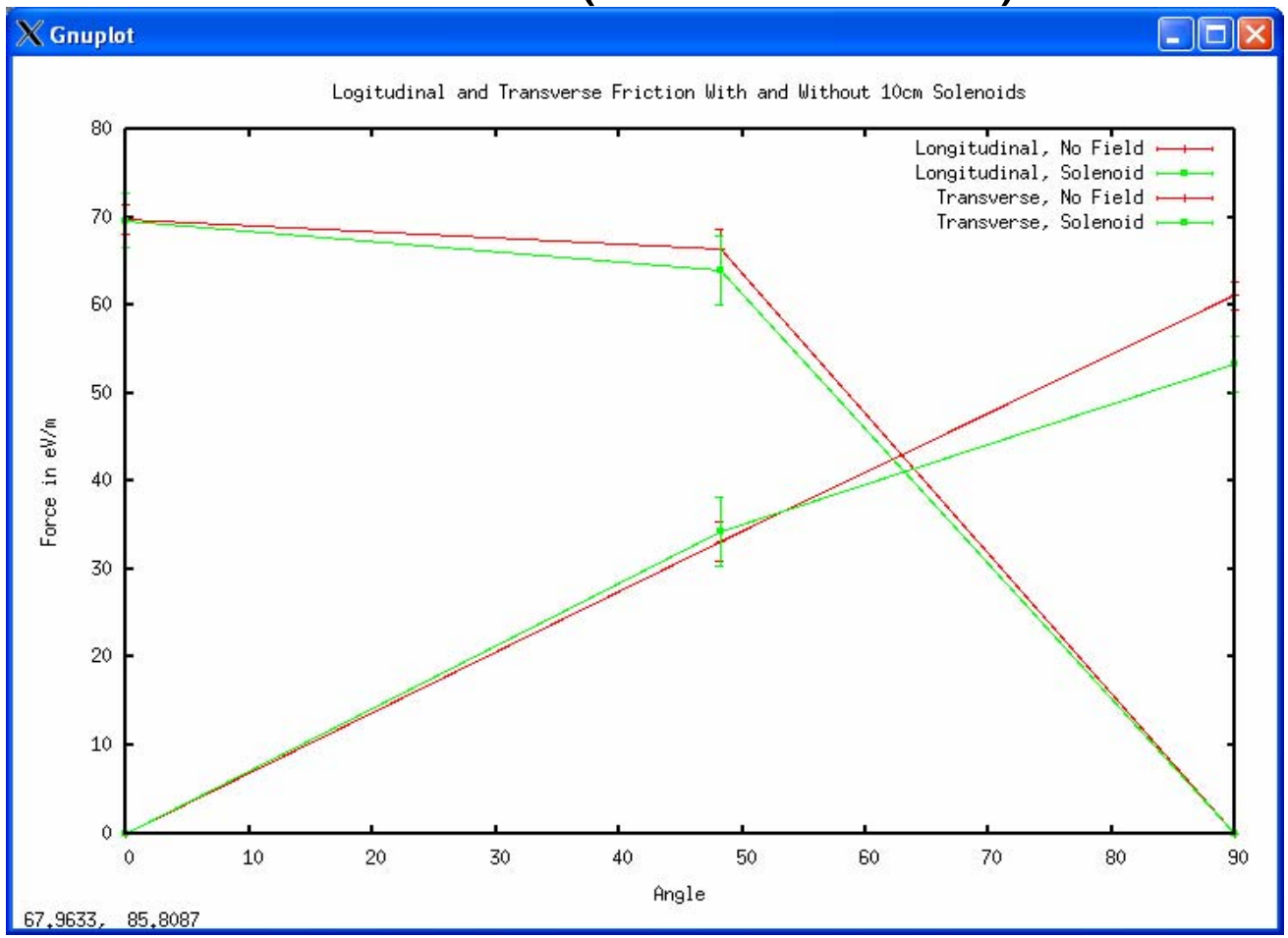
Longitudinal and transverse friction force vs angle of ion velocity vector with (green) and without (red) space-charge compensating solenoids in cooling section (G. Bell et al.)



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Experimental benchmarking: using Recycler (FNAL) E-cooling

A) Benchmarking of non-magnetized friction force.
B) Fitting electron beam parameters (e.g. transverse angular spread)
C) Saturation of friction force with the current of electron beam.
D) Magnitude of transverse cooling.

Two types of measurements:

- Longitudinal Friction force (drag rate).
- Study longitudinal and transverse cooling:
  - measure diffusion rates for different current densities of anti-proton beam: to find out what contribution comes from gas-scattering, dampers, IBS.
  - study cooling rates: both transverse and longitudinal for high intensities and low-intensities of anti-protons.

Results will be reported at COOL07 (A. Shemyakin, L. Prost, A. Fedotov, A. Sidorin)

- MoU on studies of electron cooling and benchmarking BNL's codes using Recycler data was signed between BNL and FNAL.

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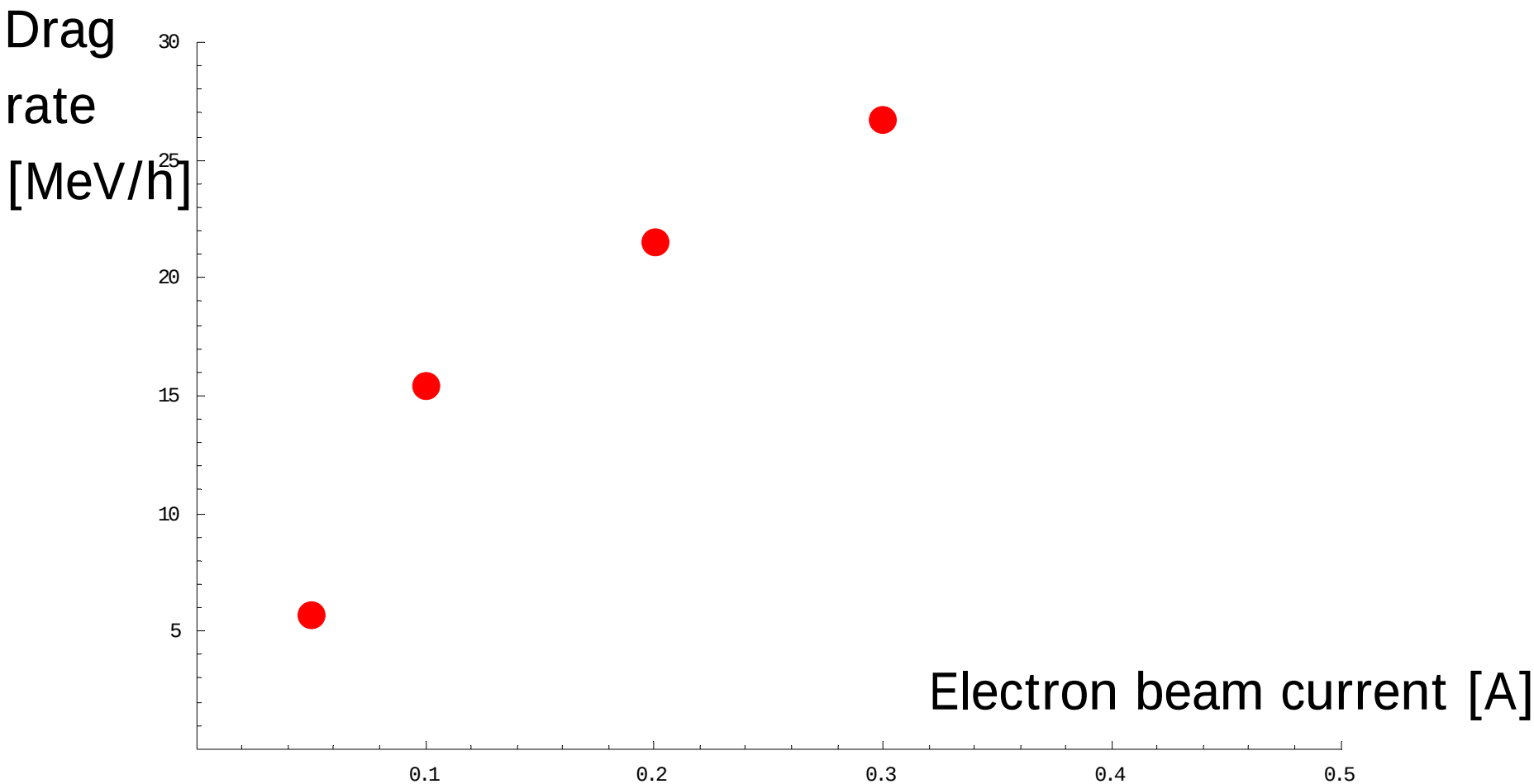
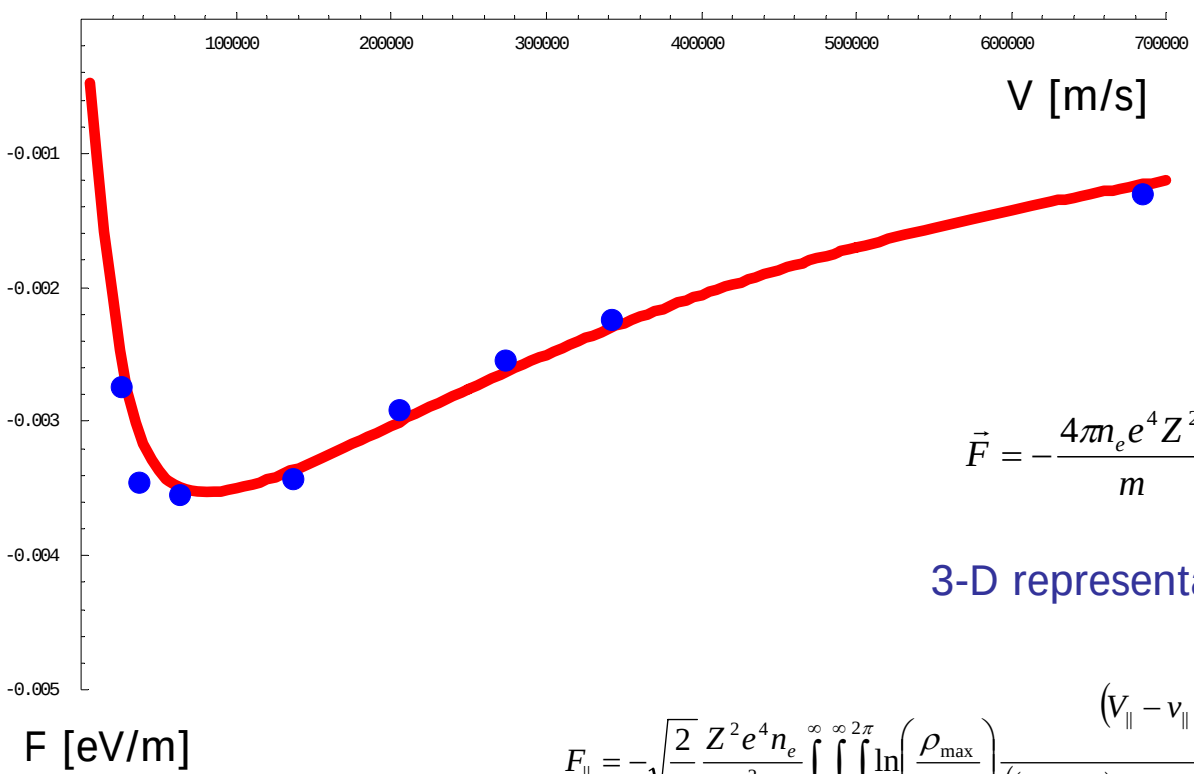
December 6, 2006 measurements – dependence of longitudinal friction force on the current of electron beam (data for 5 keV jump)



Red curve - longitudinal friction force
Blue dots – measurements.

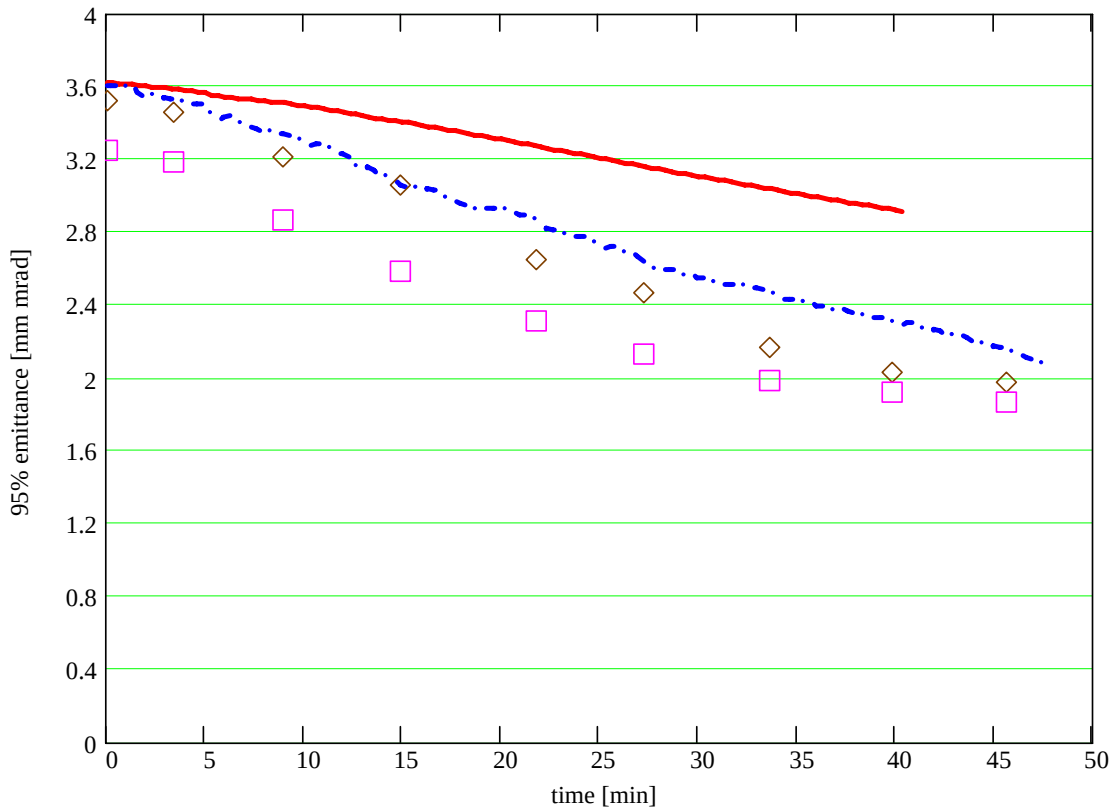


$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{\vec{V} - \vec{v}_e}{\left|\vec{V} - \vec{v}_e\right|^3} f(v_e) d^3 v_e$$

3-D representation:

$$F_{\parallel} = -\sqrt{\frac{2}{\pi}} \frac{Z^2 e^4 n_e}{m \Delta_{\perp}^2 \Delta_{\parallel}} \int_0^{\infty} \int_{-\infty}^{\infty} \int_0^{2\pi} \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{(V_{\parallel} - v_{\parallel}) \exp\left(-\frac{v_{\perp}^2}{2\Delta_{\perp}^2} - \frac{v_{\parallel}^2}{2\Delta_{\parallel}^2}\right)}{\left((V_{\parallel} - v_{\parallel})^2 + (V_{\perp} - v_{\perp}\cos\varphi)^2 + v_{\perp}^2 \sin^2\varphi\right)^{3/2}} v_{\perp} d\varphi dv_{\parallel} dv_{\perp}$$

Simulations and measurement of transverse cooling (using RuPAC'06 data)



Red – emittance based on rms of full distribution

Blue – emittance based on Gaussian fitted to the core

Dots – FW measurements

Friction force based on realistic 6D electron distribution

Models implemented in BETACOOL:

A. Using local density of electrons and assuming Gaussian distribution in velocity.

B. Using local density and arbitrary velocity distribution.

C. Studies with electron distribution which was propagated through the cooling section with space-charge spreading compensated by solenoids.

(A. Fedotov et al., PAC07), (A. Sidorin et al, COOL07)

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IBS model for arbitrary distribution

To estimate correctly luminosity gain for ion distribution under cooling, an accurate treatment of IBS for non-Gaussian distribution based on diffusion coefficients is needed.

A. Several “core-tail” models were developed within the BETACOOL. Each of them have different degrees of approximation for diffusion kicks.

B. A new model “local IBS” was recently developed which calculates numerically amplitude dependent diffusion coefficients in 6-D which will test “core-tail” models.

C. The “local IBS” model is presently being debugged for various numerical effects.

Effective angular spread in the cooling section

A. Various effects which may contribute to rms angular spread in the cooling section and thus effect cooling performance were estimated.
B. BETACOOL simulations were performed with various “effective” rms angular spreads.
C. Requirements on rms angular spread needed for effective cooling were identified.

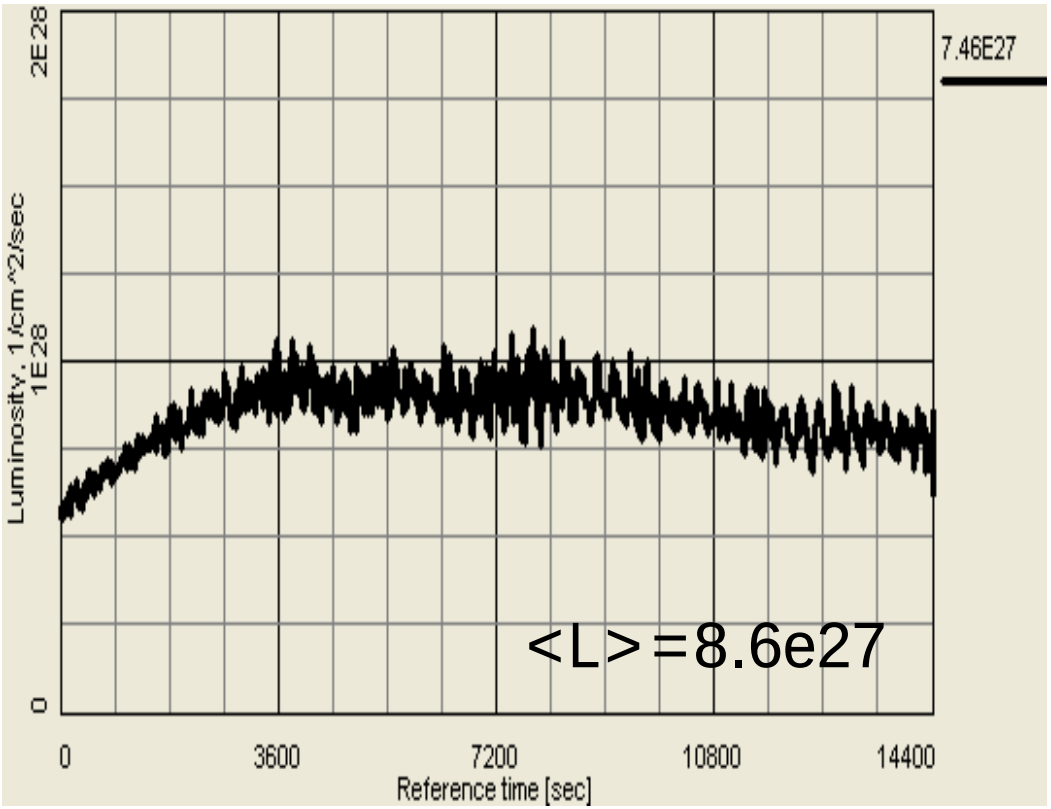
Table of some effects and their contribution to angular spread.

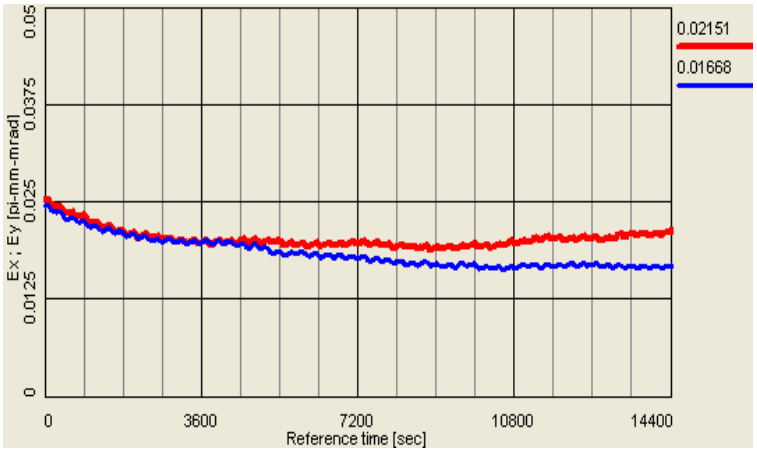
Effects	Contribution without correction [μ rad]	Measures/tasks	Remaining contribution [μ rad]
Emittance (thermal contribution)	7.5 (for 3 μm rms normalized emittance)		7.5
Space-charge	50	Compensating solenoids. Develop approach to minimize non-linear contribution	5 (presently achieved for ideal distribution; studies are under way to achieve good compensation for realistic distribution).
Effect of wall images		Requirement on beam centroid 1 mm offset from beam pipe center	<1
Undulator errors		integral of transverse mag. fields < 1e-6Tm	5
Residual magnetic field		Shielding to 3mGauss (complications when there is interplay with undulator fields)	5
Neutralization (ni/ne in transport channel)	Control of neutralization to better than 1e-5 level	Find which level of neutralization can be achieved	<1
e-cloud	200	NEG coating – reduction by about factor of 10. suppression of e-cloud with undulator	<1
Aberrations/non-linearities		Needs to be addressed	to be studied
Envelope mismatch		Needs to be addressed	<1
Collective effects (resistive wakes, bellows, cavities)			<1
e/e IBS, e/ion IBS, CSR, e/ion defocusing			<1

Table 3.5.2: Contributions to the rms angular spread of 5nC electron beam in the cooling section.

Based on Table 3.5.2, the total rms angular spread expected (assuming 5nC electron bunch with 3 [μm] rms normalized emittance) is $(7.5^2+3\cdot5^2)^{-1/2}=11.5$ [μrad]. Efforts are presently being made to minimize contributions to this effective angular spread by a proper design of the cooling section.

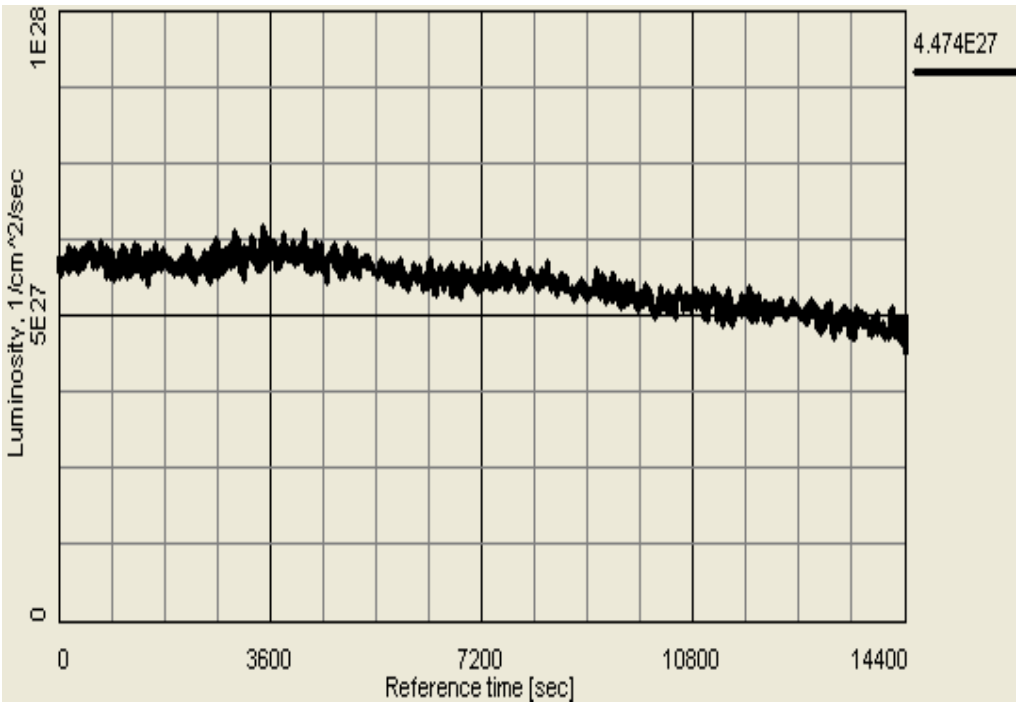
Baseline parameters: L=80m, 5nC electron bunch, no loss from the bucket

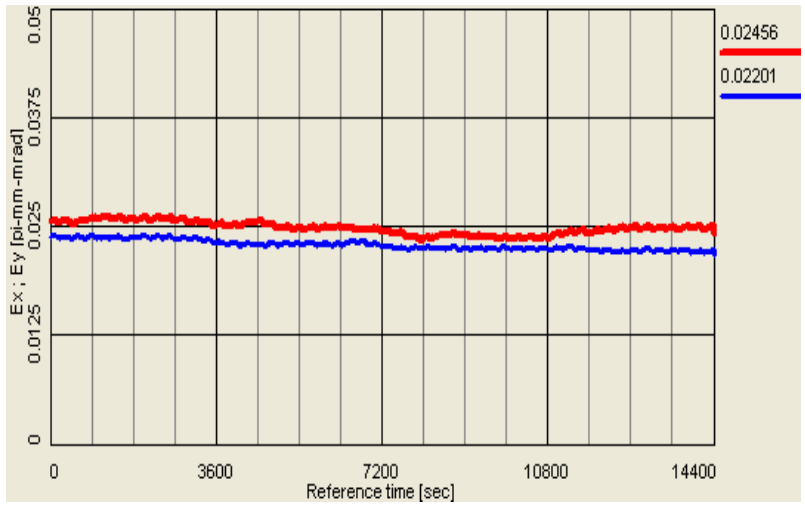




rms angular spread of electrons: 8.7e-6 rad.

Rms angular spread 13e-6 rad





<L>=5.6e27 – 50% drop compared to the baseline spread of 8.7e-6 rad

Ion beam stability as a result of cooling

A. Ion beam stability due to interaction with electron beam was studied. Thresholds for the instability were identified.

B. Thresholds of collective instabilities driven by RHIC impedances for cooled ion bunches were identified.

(G. Wang, M. Blaskiewicz, PAC07)

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Recombination effect.

Experimental measurement of recombination coefficient α_r for fully stripped ion (ESR, GSI, 2001) is in good agreement with theoretical models for relative energies > 20 meV.

$$\frac{1}{N}\frac{dN}{dt} = -\frac{\alpha_r n_e}{\gamma^2}\frac{l_{cool}}{C} \qquad \alpha_r = \langle v\sigma(v)\rangle$$

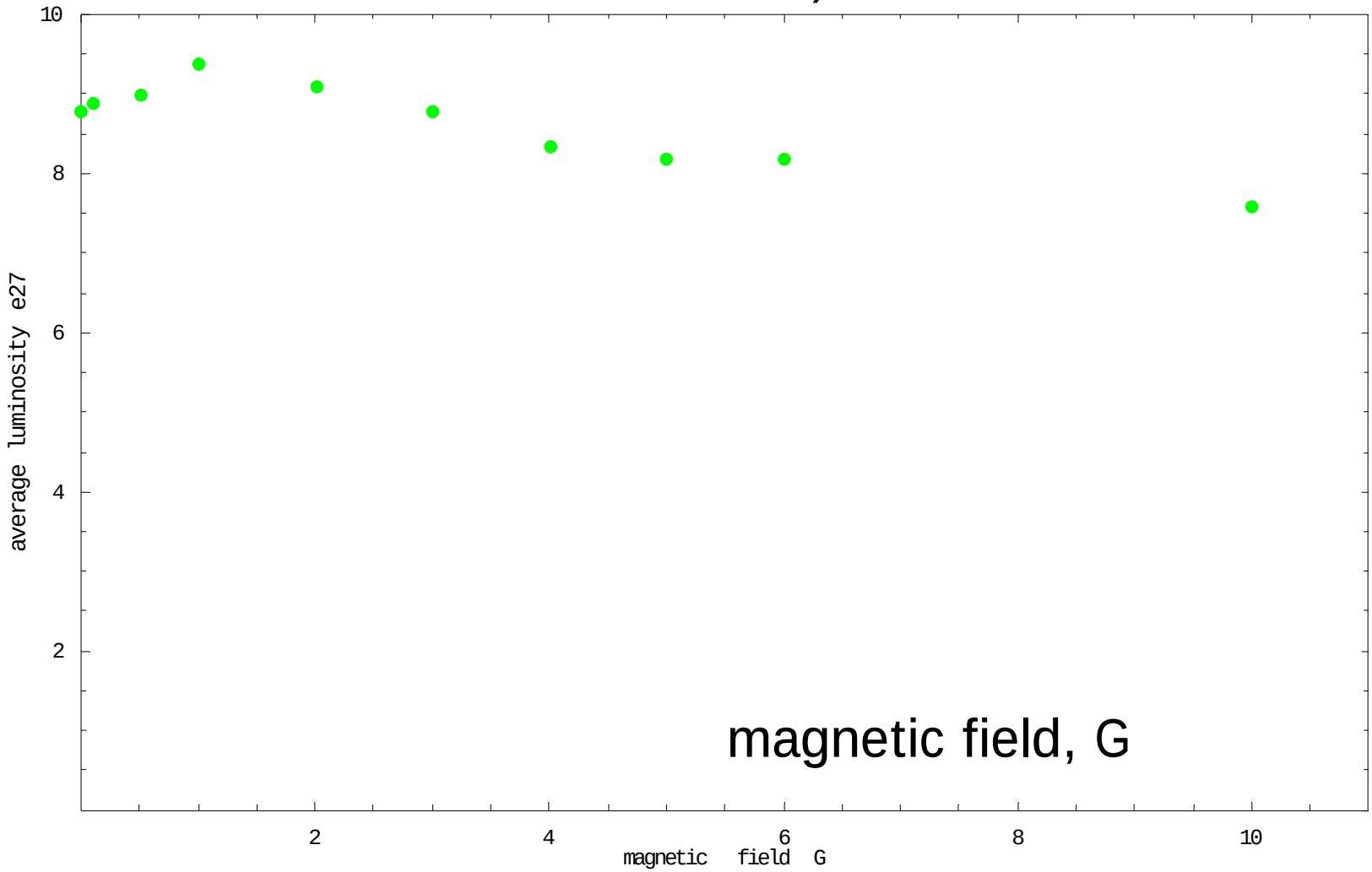
We use numerical integration:

$$\alpha_r = \frac{1}{Int}\int_0^{3\Delta_\perp}\int_{-3\Delta_\parallel}^{3\Delta_\parallel}\sigma(E)\sqrt{(v_\perp + v_{und})^2 + v_\parallel^2}\exp\left(-\frac{(v_\perp + v_{und})^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)v_\perp dv_\parallel dv_\perp$$

where the cross section is given by

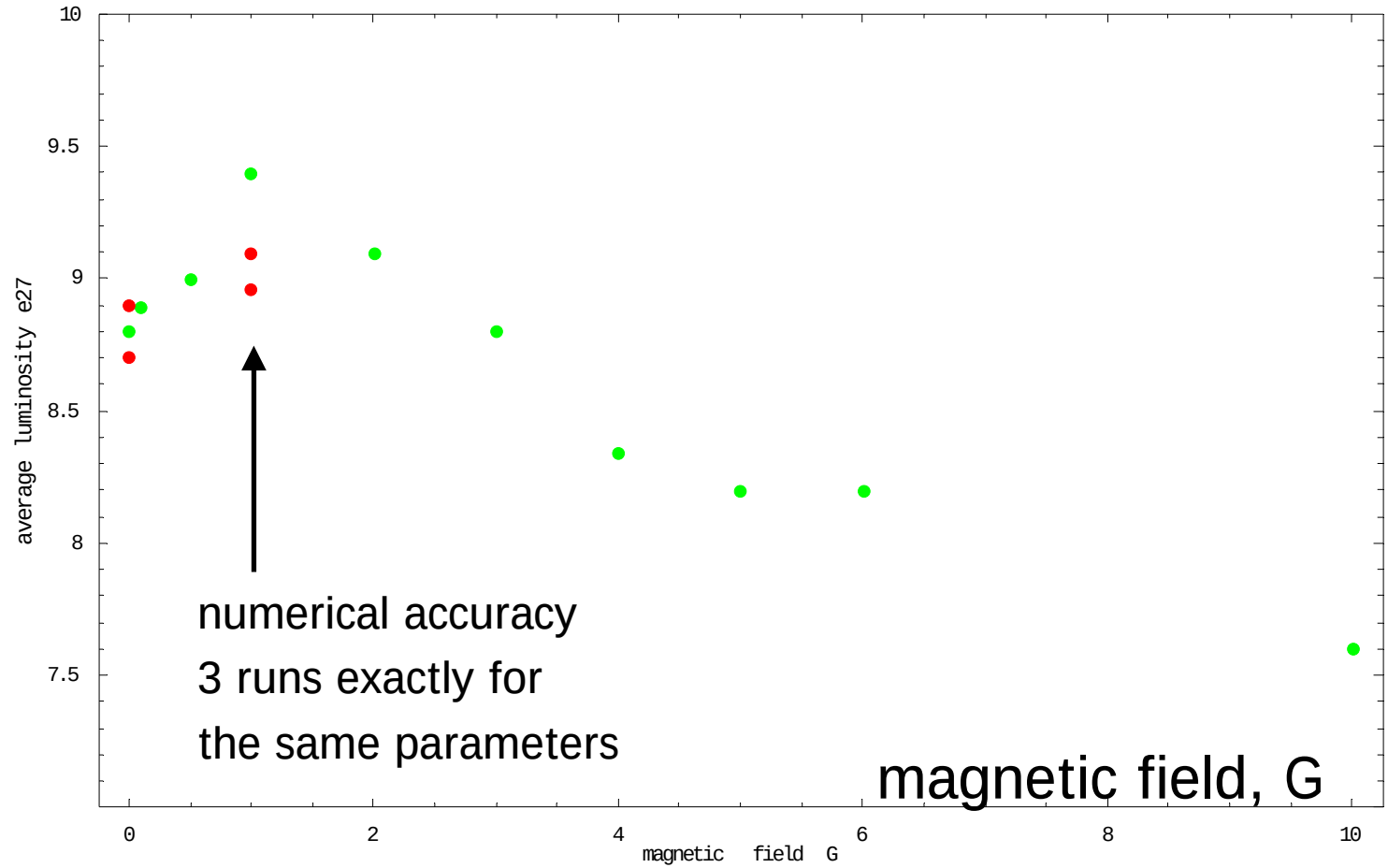
$$\sigma = A\left(\frac{h\nu_0}{E}\right)\left(\ln\sqrt{\frac{h\nu_0}{E}} + 0.1402 + 0.525\left(\frac{E}{h\nu_0}\right)^{1/3}\right)$$

For new value of undulator period λ=12cm (Results of full scale simulations, including all effects)



For pitch λ=12cm

Average luminosity,
x10^{27}



Undulator summary

For pitch λ=12 cm

One gets reduced average luminosity if B > 4G.

Maximum appears to be somewhere around 1-2G.

But B=1G gives addition to relative energy of only 0.64 eV (contribution from electron's is about 0.5 eV and from ions 0.4 eV) – so that it is hard to justify undulator if it practically does not introduce additional spread.

B=2G gives additional 2.5 eV – this is factor of 5 bigger than the electron transverse temperature – so that such undulator could be justified.

New parameters:

λ=12cm, B=2G

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The parameters of the electron beams at cooling section region at required kinetic energy 54.3 MeV

	Units	Required	Simulation
Kinetic energy	MeV	54.34	54.34
Charge per bunch	nC	5.0	5.0
Average current	mA	10	10
R.m.s. emittance normalized	mm·mrad	<4	3.2
R.m.s. momentum spread		<5·10-4	3.6·10-4
R.m.s. bunch length	cm	~1	0.78

✓The results of the beam dynamics studies in 2 passes ERL according of start-to-end PARMELA simulation are very promising and provide the needed parameters for RHIC e-cooling project.

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Electron angular distribution in cooling section

At the beginning of cooling section

After 100 m cooling section with solenoid Bsol=40 G on

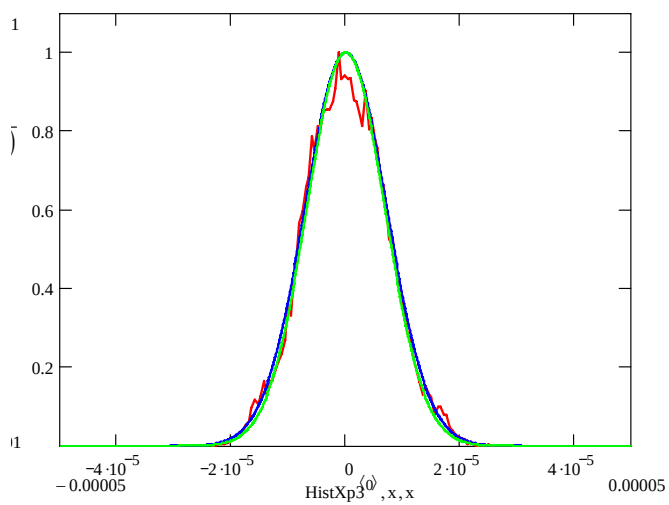
RED- simulation result, BLUE- Gauss fit using r.m.s. parameters, GREEN- Gauss fit using FWHM parameters

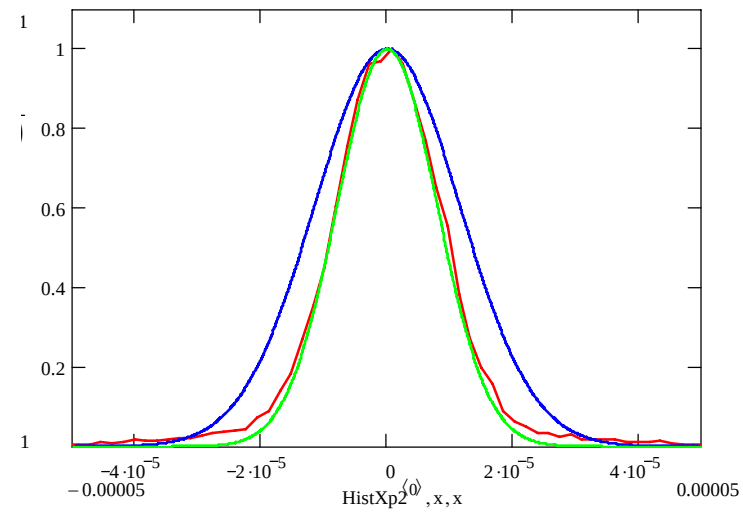
Effective focus straight of space charge force

$$\frac{I \cdot L}{2Ia \cdot (\gamma\beta)^3 \cdot \sigma x \cdot \sigma y}$$

Focus straight of solenoid

$$\left(\frac{eBsol}{2pc}\right)^2 Lsol$$





$\sigma xp_rms = 7.16 \cdot 10^{-6}$

$\sigma xp_FWHM = 6.82 \cdot 10^{-6}$

$\sigma xp_rms = 1.030 \cdot 10^{-5}$

$\sigma xp_FWHM = 7.36 \cdot 10^{-6}$

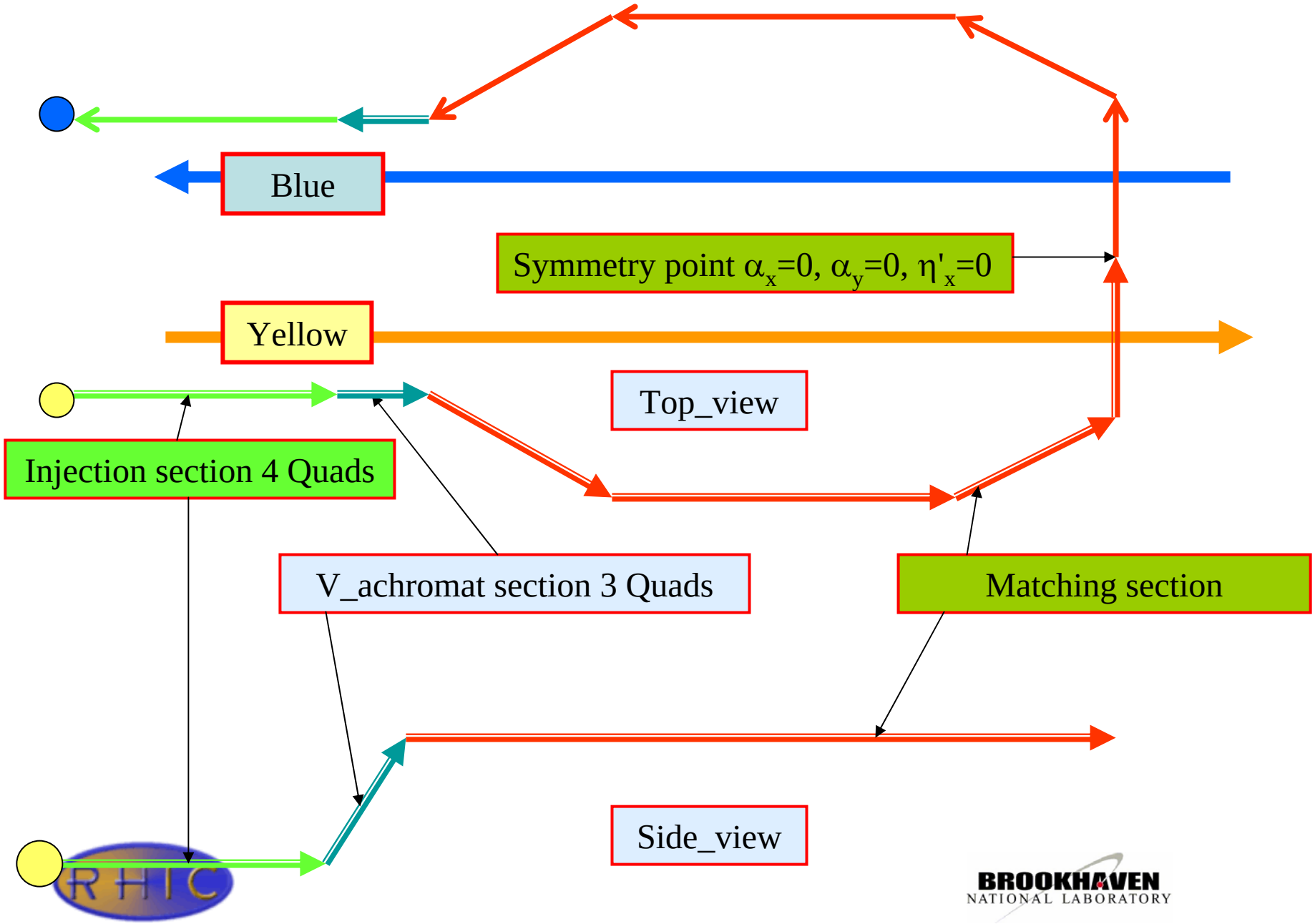
✓The linear part of space charge defocusing is compensated by solenoids. As a result the angular spread of electron beam core is satisfied of required parameters.

✓The electron angular distribution doesn't stay Gaussian in cooling section. The real distribution has to be used to calculate friction force for cooling rate simulation.

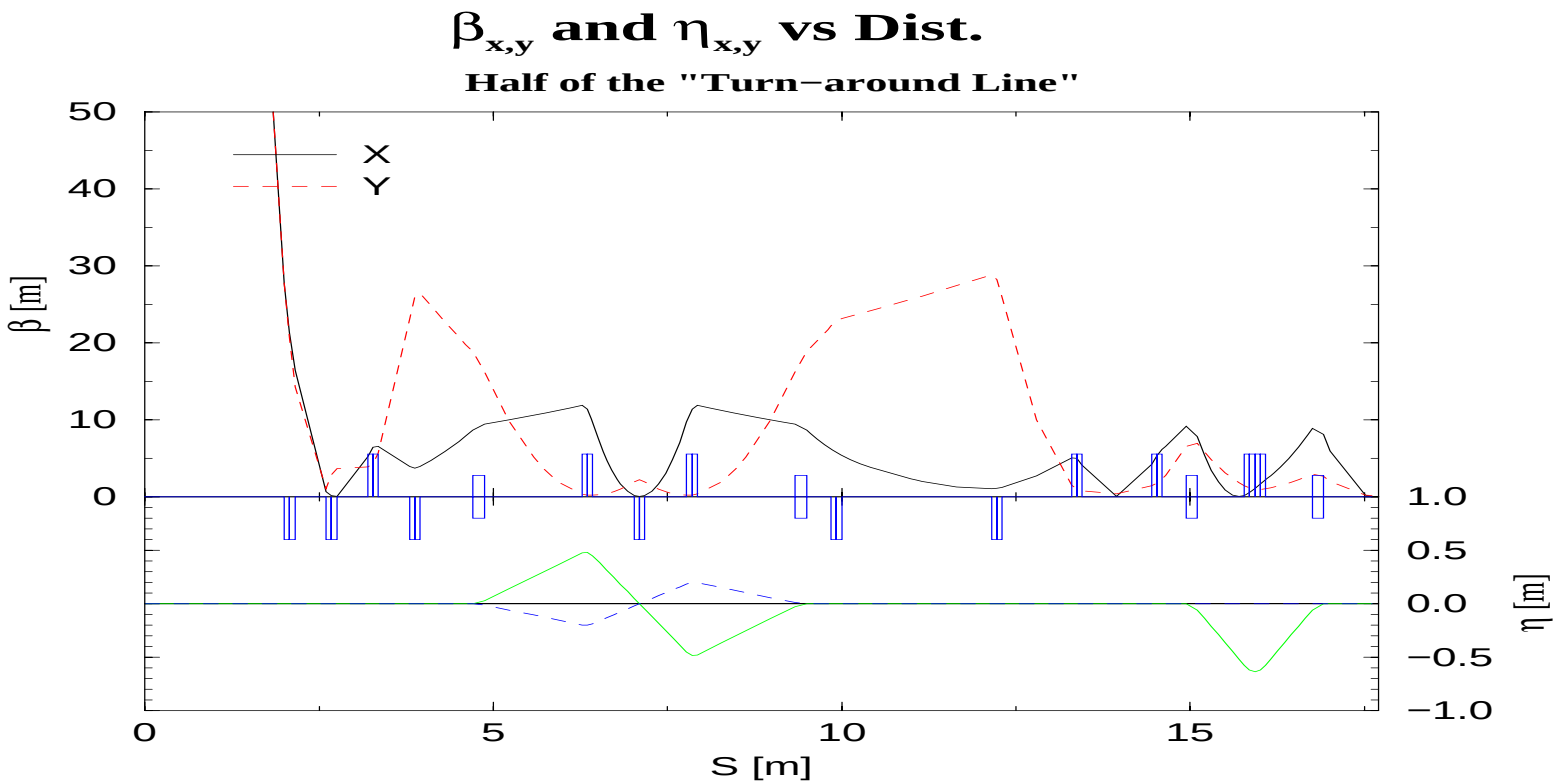
Design procedure for designing the optics of the "Turn-around line"
Design by Nick Tsoupas

- Define the beam parameters ($\alpha_{x,y}$ and $\beta_{x,y}$) at the entrance and exit of the "HV_achromat" section.
- Define the beam parameters ($\alpha_{x,y}$ and $\beta_{x,y}$) at the entrance and exit of the "H_achromat" section.
- Match the beam parameters at the exit of the "Injection section" to those at the entrance of the "HV_achromat" section.
- Match the beam parameters at both ends of the "Matching section" to those at the exit of "HV_achromat" line and those at the beginning of the "H_achromat" line respectively.

Schematic diagram of the proposed "Turn around" line;



Optics of half of the “Turn-around line”



✓The proposed turn around line transports electron beam with 500 m beta function and zero dispersion from the RHIC yellow ring to the RHIC blue ring.

✓Due to significant beta changes the stability of this system has to be studied more accurately.

Benchmarking of Space charge tracking codes for extremely low emittance beams

- Compare PARMELA with ASTRA and ImpactT.
- Optics for beams with elliptical charge distribution, optimized with PARMELA.
- Calculation of electron gun, where space charge forces are most important
- Good agreement between all codes when space charge forces are turned off.
- Poor agreement of envelopes with space charge
- Agreement can be improved by adjusting the bunch charge

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Conclusions-Benchmarking

- We find a disagreement in the space charge calculation between PARMELA, ASTRA and ImpactT, which is not mentioned in other benchmarking papers.
- The disagreement is also inconsistent: In some aspects ASTRA agrees with PARMELA, in other aspects ASTRA agrees with ImpactT, in other aspects ASTRA agrees with ImpactT. Due to the closed source of PARMELA and ASTRA it is not possible for us to investigate the cause of the difference.
- On the 30% level the codes agree reasonably well. This may be the best one can expect from the particle tracking method.
- PARMELA gives the most conservative results. It is also the most widely used and benchmarked program. It is therefore a reasonable approach to base the design of the RHIC electron cooler on PARMELA results.

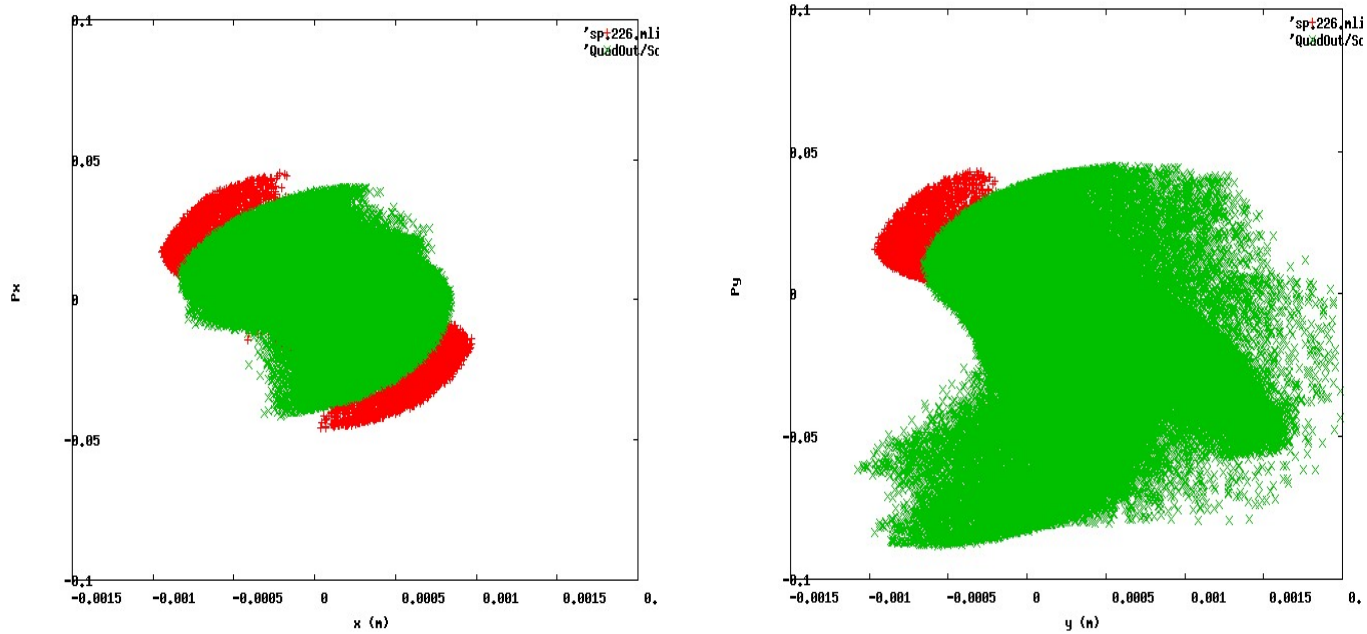
Tolerances

Investigation of errors that preserve radial symmetry with PARMELA:

- The cathode radius
- The RF start phase
- The gun gradient
- The bunch charge
- The strength of the two solenoids
- The longitudinal position of two of the four meging dipole magnets.
- The field of those two dipoles.

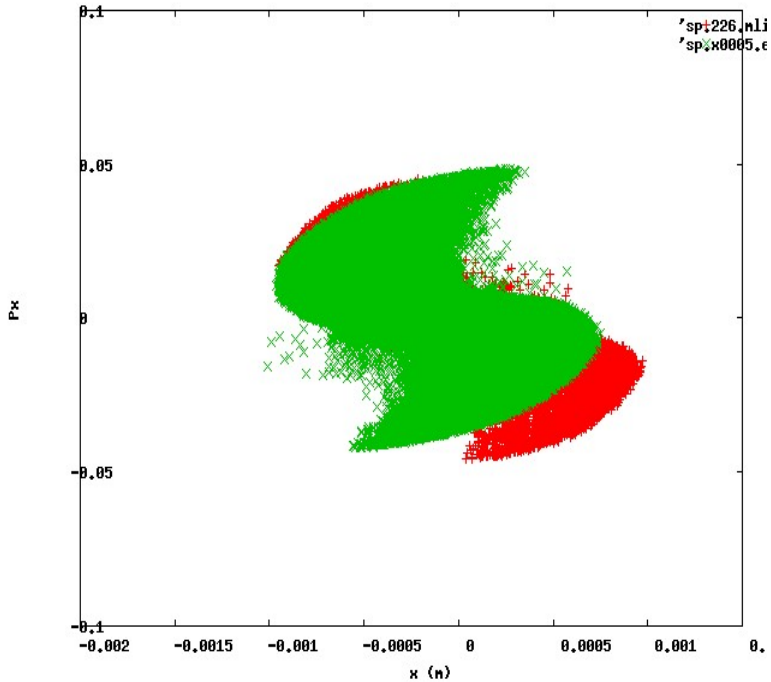
- Investigation of errors that break radial symmetry with Marylee/Impact (with Tech-X).
- If errors are systematic their effect can be corrected by adjusting the field of focusing solenoids and bending magnets. Such correction is on-going work.

Rotations of Bending Magnets



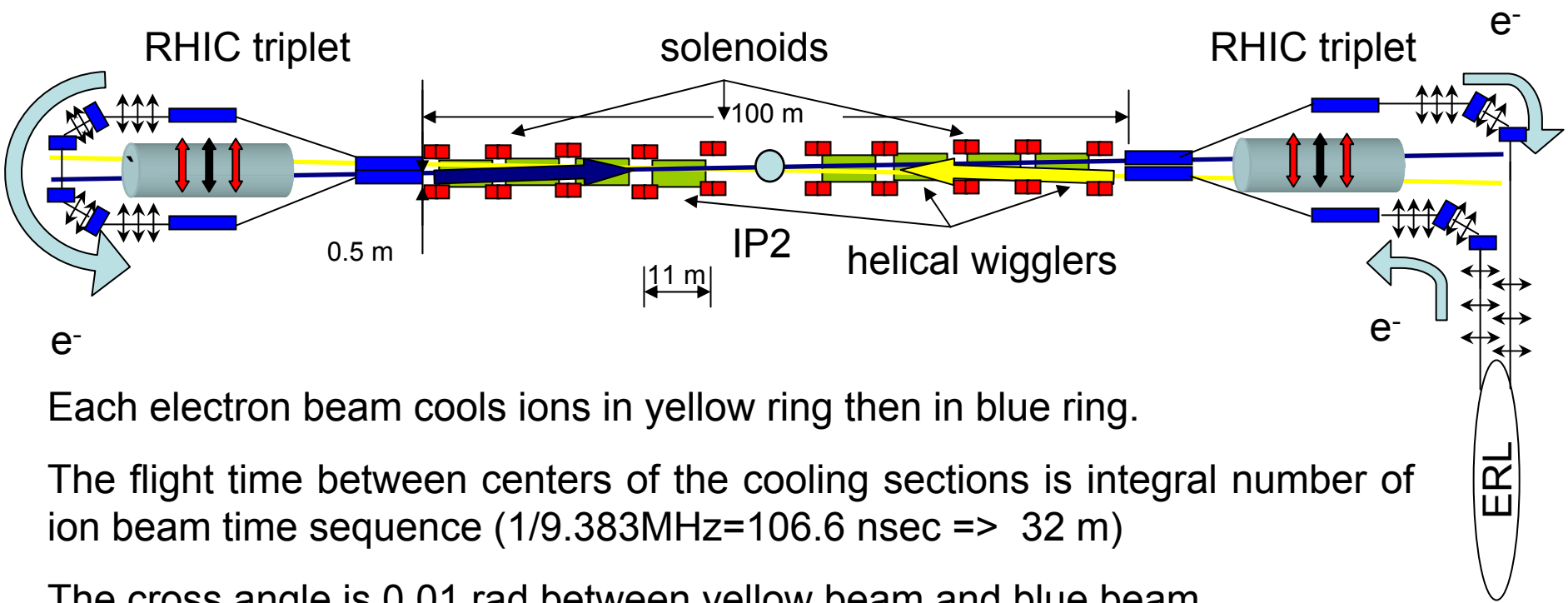
Phase space plots after tracking with space charge from exit of RF gun through last 5 cell RF cavity (MLI in green and Parmela in red). With xy-plane random rotations of 0.5 degrees applied to the bending magnets. The left plot shows the vertical phase space and the right plot shows the horizontal phase space. (From Tech-X status report)

Misplacement of bending magnets



MaryLie/Impact parallelized 3D code with 5th-order tracking.
X - Px phase space after tracking from exit of RF gun through last 5 cell RF cavity (MaryLie-Impact in green and Parmela in red). With Horizontal (X) random misalignments xrms errors of 0.5 mm applied to the bending magnets. (V. Ranjbar et al)

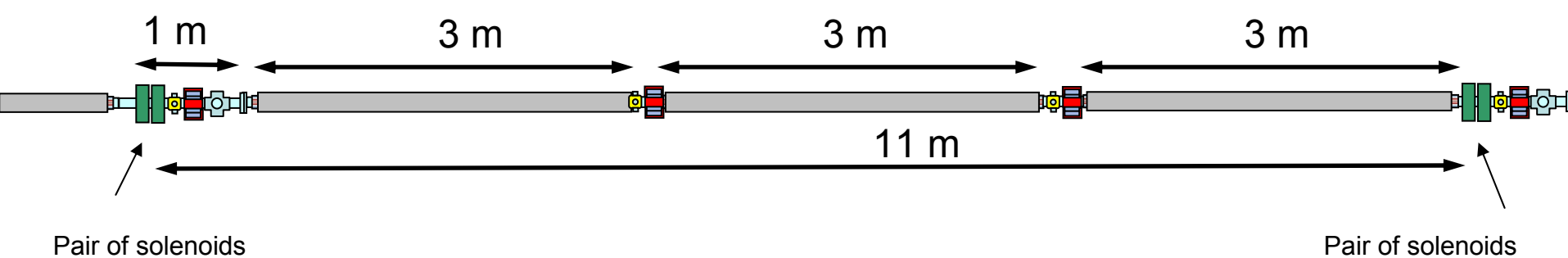
E-cooling ERL attached to the RHIC at 2 o'clock IP



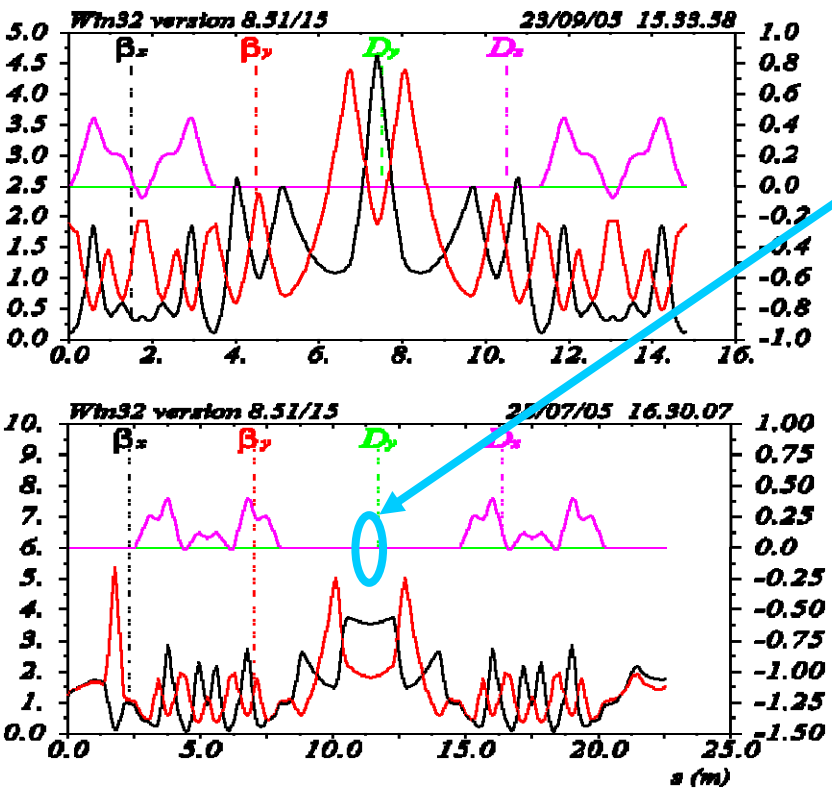
Each electron beam cools ions in yellow ring then in blue ring.

The flight time between centers of the cooling sections is integral number of ion beam time sequence (1/9.383MHz=106.6 nsec => 32 m)

The cross angle is 0.01 rad between yellow beam and blue beam.

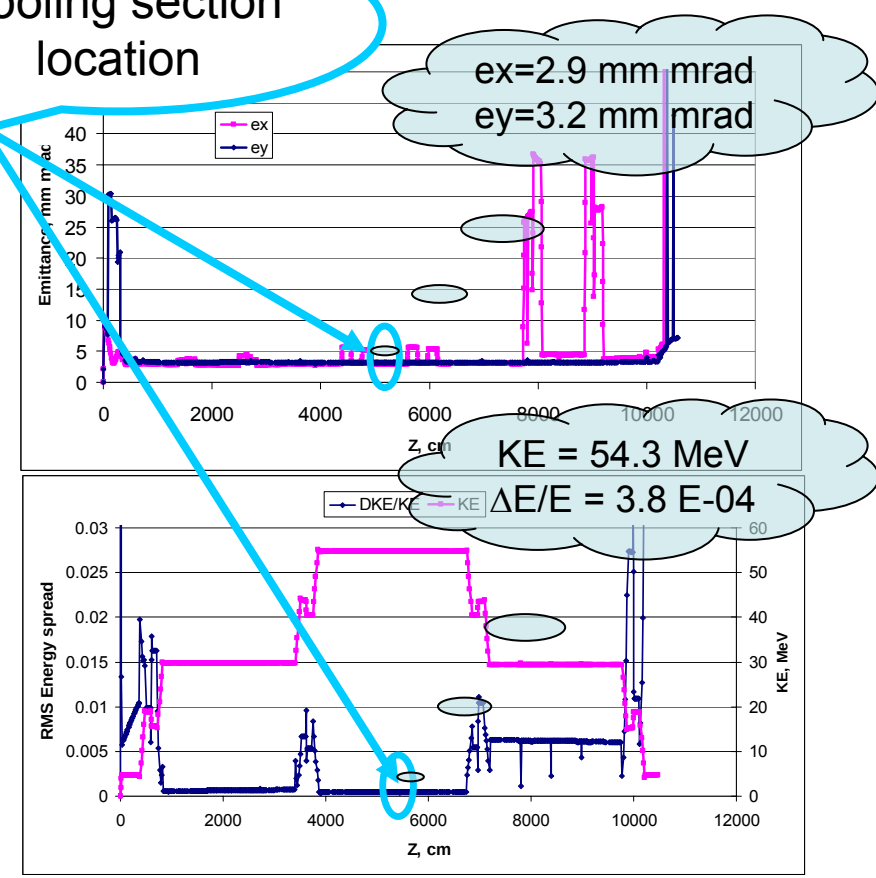


Electron beam dynamics from the cathode to the dump



The optic functions in the first (top) and in the second loop with short-cut (bottom)

Cooling section location



Result of PARMELA simulation RMS normalized emittances (top) RMS energy spread and kinetic energy (bottom)

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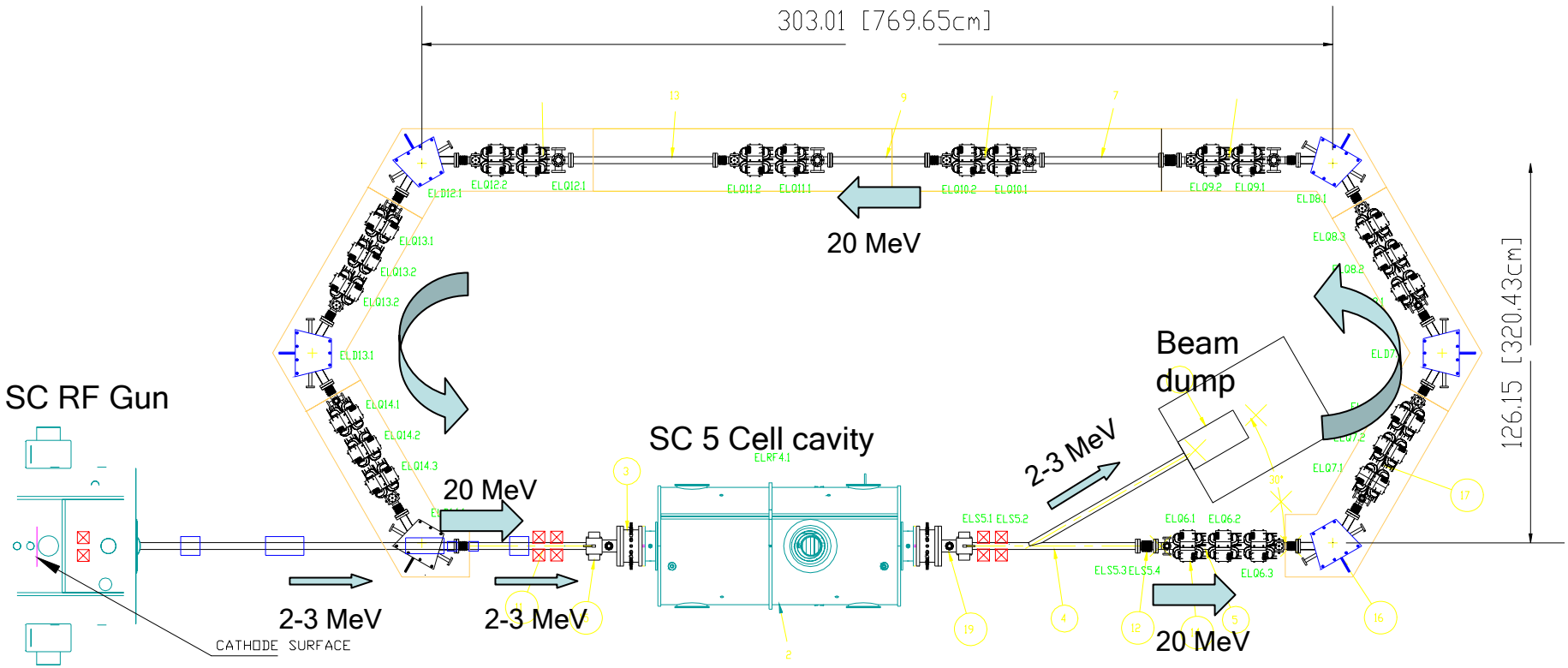
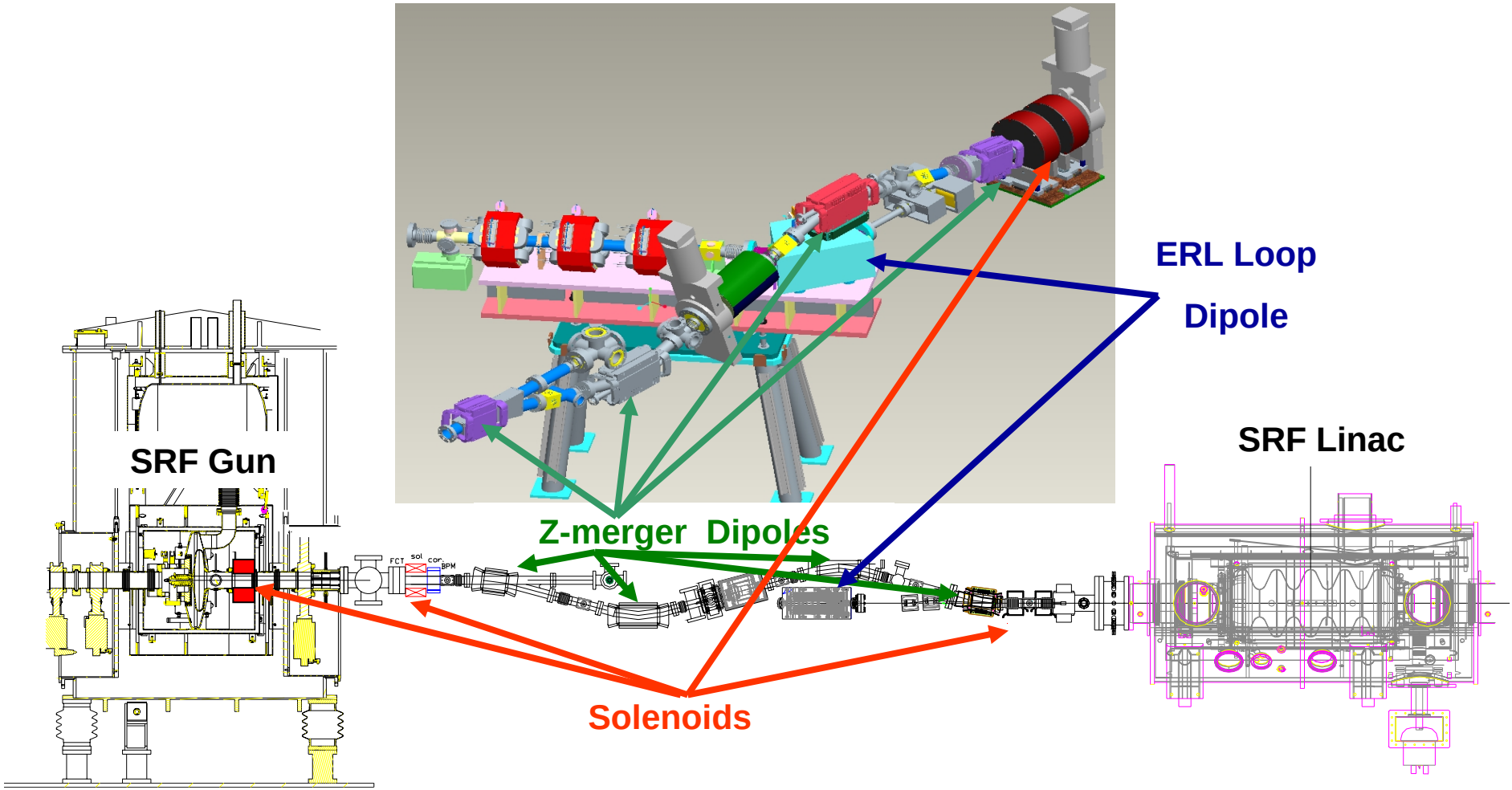
R&D ERL: loop layout
Design Dmitry Kayran



Layout of the BNL R&D ERL Injector



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Electron beam parameters of the R&D ERL
Result of PARMELA simulation.

	R&D ERL			**Required for cooling**
Charge per bunch, nC	0.7	1.4	5	5.0
Injection energy, MeV	2.5	2.5	3	5.2
Max. beam energy, MeV	20	20	20	54.8
Average beam current, mA	500	500	50	50
Bunch rep-rate, MHz	700	350	9.4	9.383
Normalized emittance ex/ey, μm	1.4/1.4	2.2/2.3	4.8/5.3	<5
Rms energy spread, %	0.35	0.5	0.97	0.04
Rms bunch length ps	18.5	21	31	35

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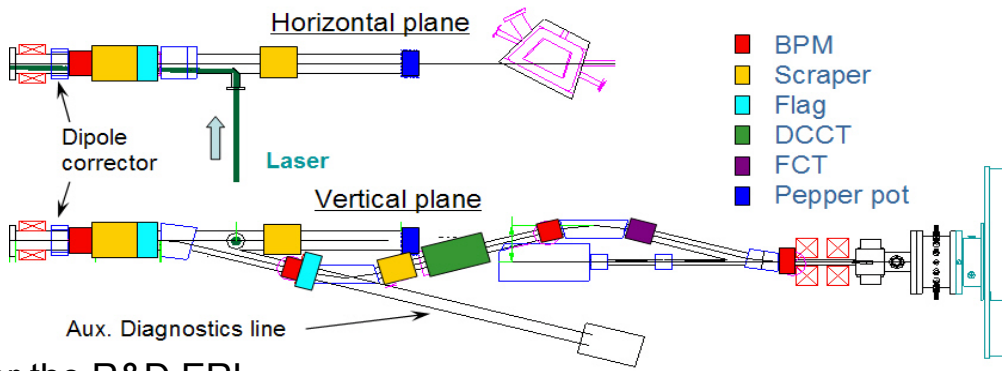
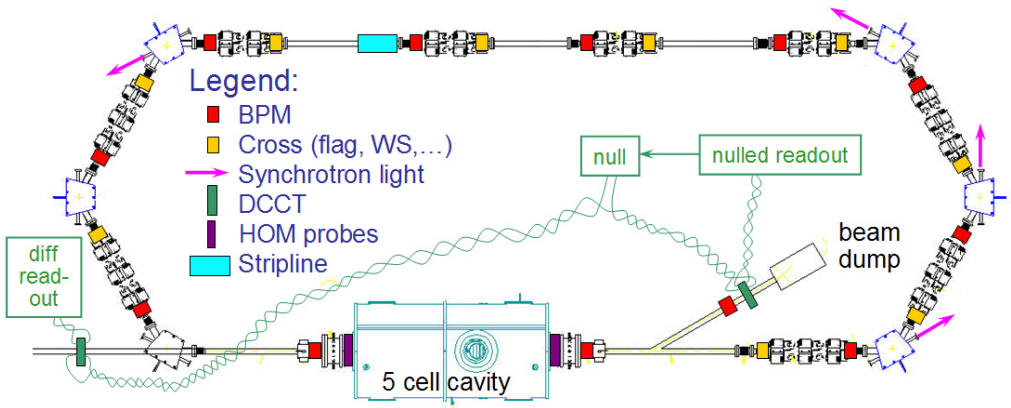
Diagnostics for ERL
Pozdeyev, Cameron, Russo, Gassner



Diagnostics for the R&D ERL.
Above: Gun-injection line. Below: ERL
E. Pozdeyev et al. Diagnostics of BNL ERL.
FRPMS116

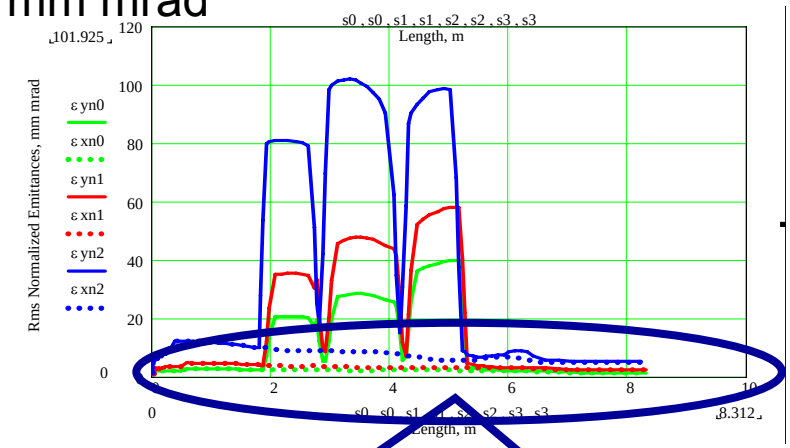


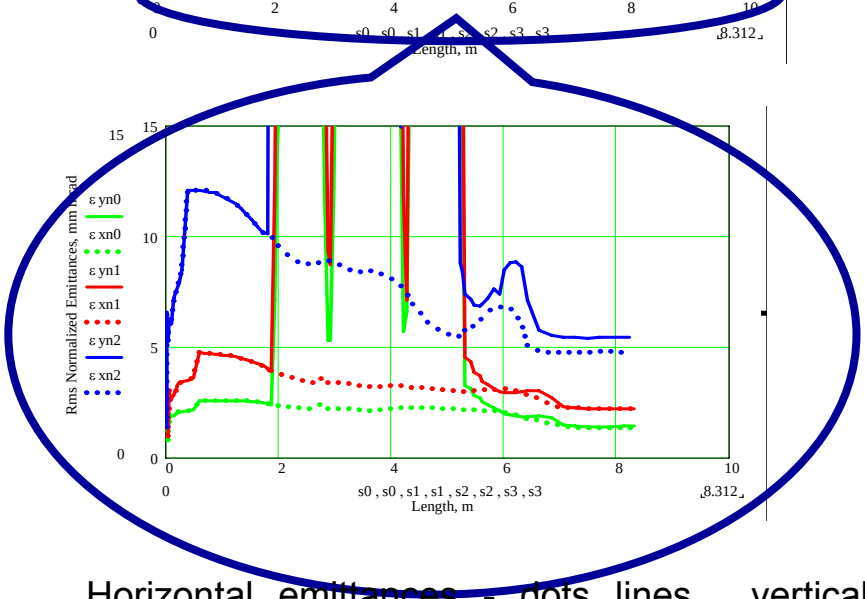
Physics requirements were established. Following that, a detailed diagnostics plan has been developed, both for the critical injection path and for the ERL loop.

Result of beam dynamic simulations in the ERL injector

Bunch charge: 0.7 nC-GREEN, 1.4 nC- RED, 5nC –BLUE.

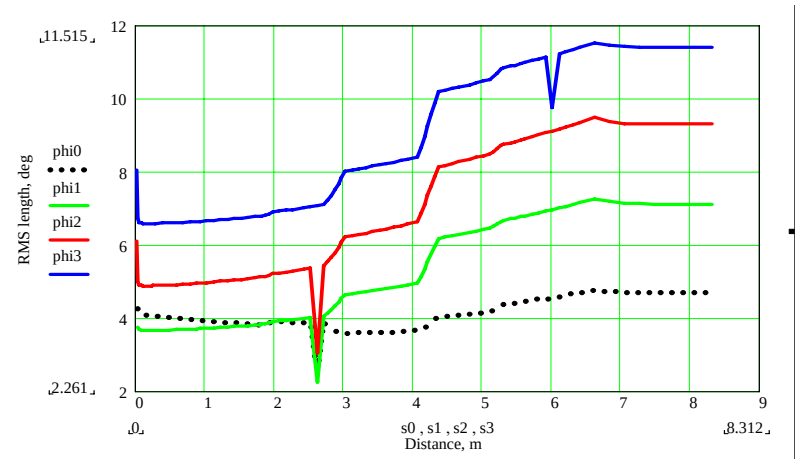
Rms normalized beam emittances, mm mrad



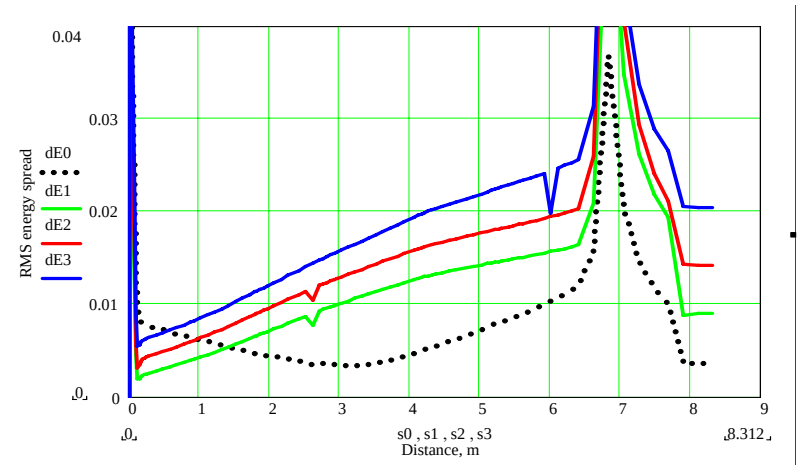


Horizontal emittances - dots lines, vertical emittances - solid lines

Rms bunch length, deg



Rms energy spread



For 35 degrees solid lines. For 25 degrees bunch charge 0.7 nC – BLACK DOTS

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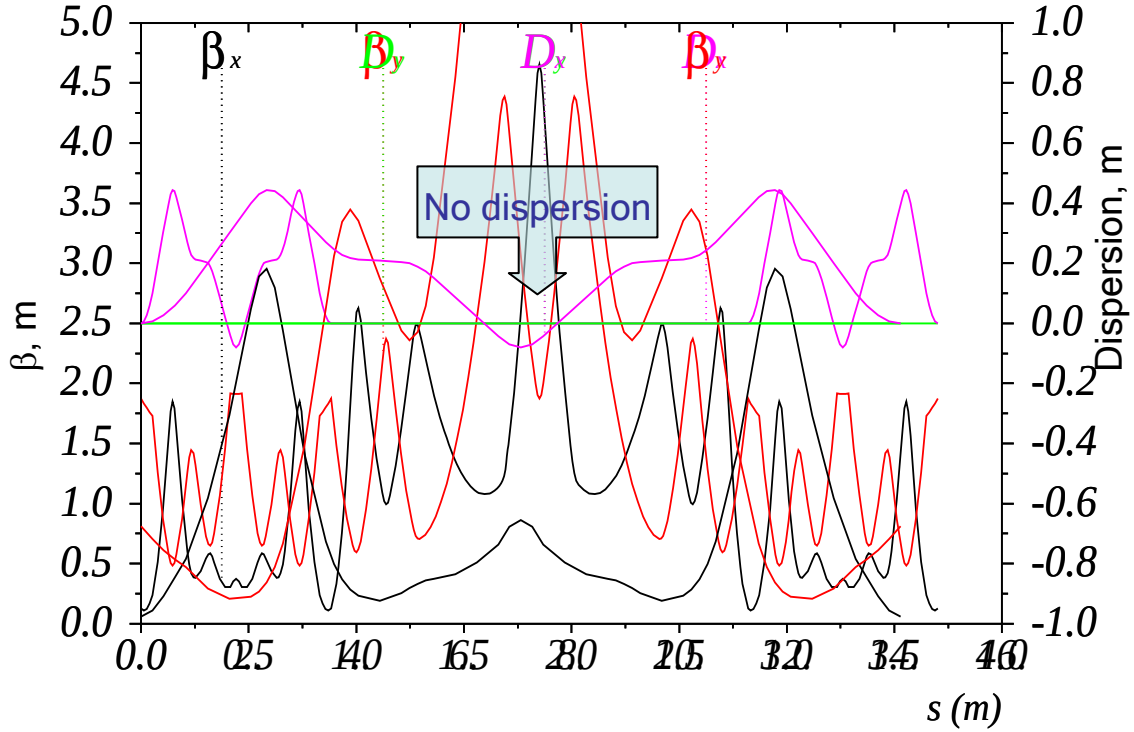
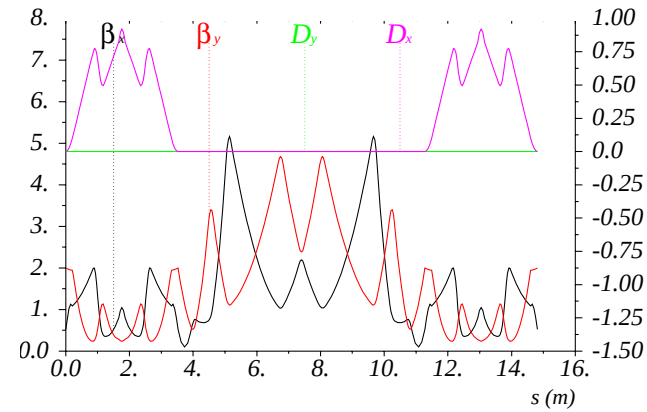
ERL loop lattice is very flexible

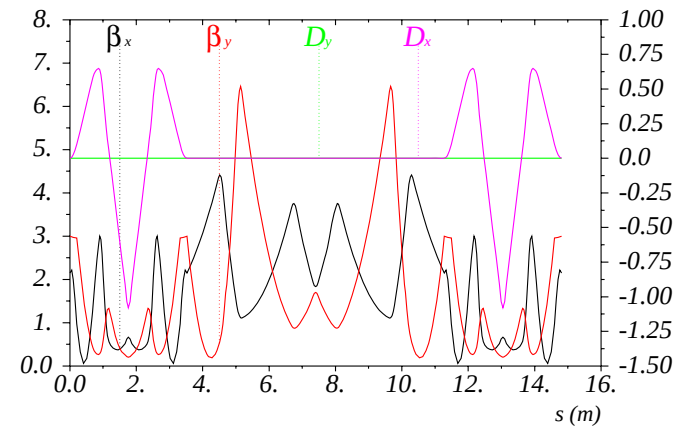
Lattice β and D functions of the ERL for the different cases longitudinal dispersions (Ds=M56):



Zero longitudinal dispersion



Positive longitudinal dispersion



Negative longitudinal dispersion

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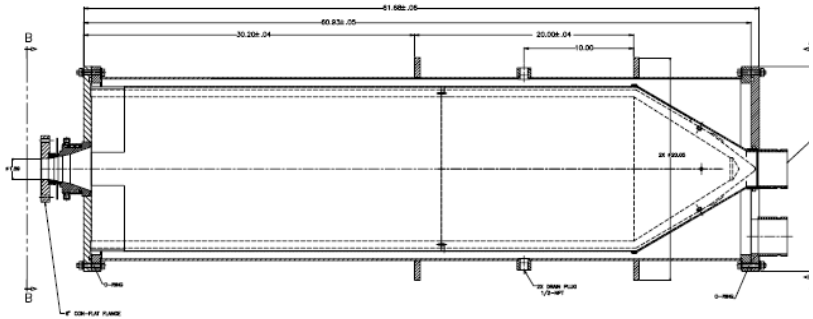
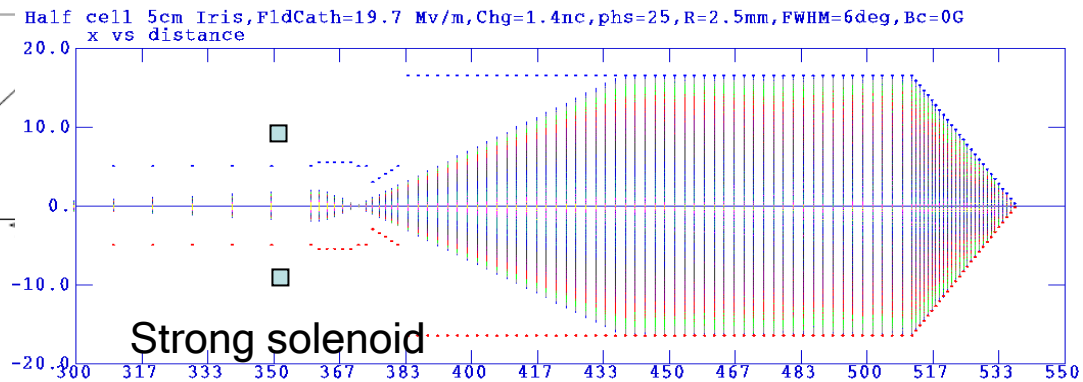
Beam collector study





Particles trajectories in collector

Setup:

Gun-to Dump test

Bending dipole:

30 degree, R=60 cm

Spreader:

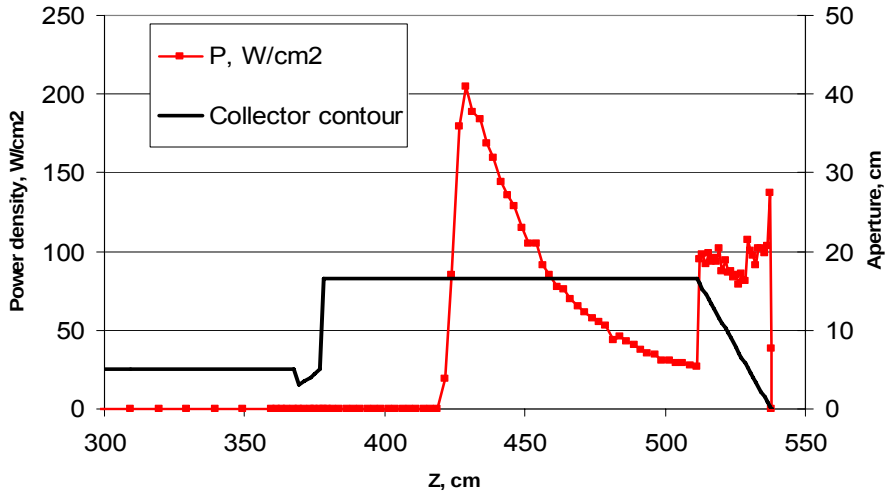
Focusing solenoid:

L= 10 cm, B= 2.7 kG

Electron Beam parameters:

Charge per bunch = 1.4 nC

KE= 2MeV, I=0.4 A, P=1 MW



Power density distribution

✓The design of ERL for BNL R&D ERL can produce ampere electron beam with low emittance.

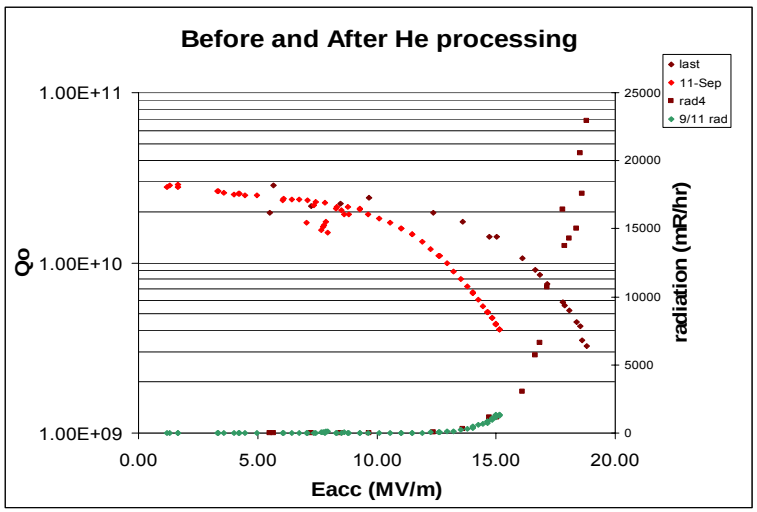
✓ High brightness injector will serve as a electron source for the prototype ERL. The results of the design studies of the R&D ERL and PARMELA simulation are very promising.

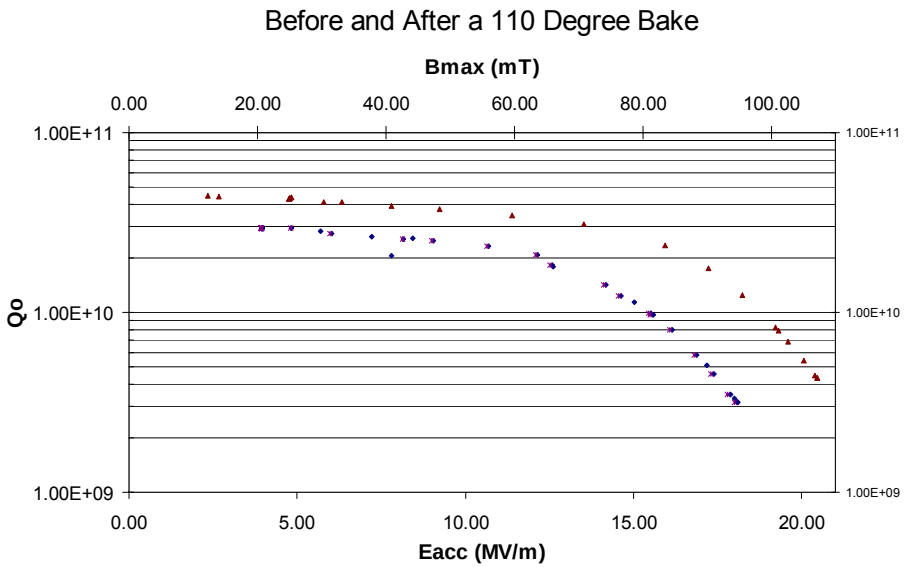
✓Optimization of the transverse beam emittance and the longitudinal beam emittance for BNL R&D ERL injector results in different launch phases. We plan to use both modes of operation.

Processing milestones and achievements

Significant gains in performance have been realized by implementing additional processing techniques.

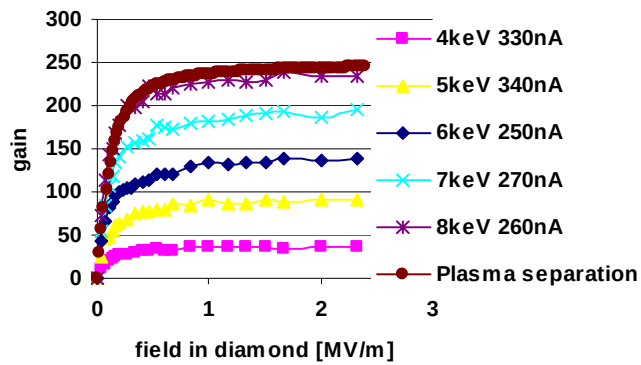
- Helium processing helped increase the maximum achieved gradient 33%
- A low temperature 110 degree bake for 48 hours improved both the low field Q as well as the overall performance an additional 18%

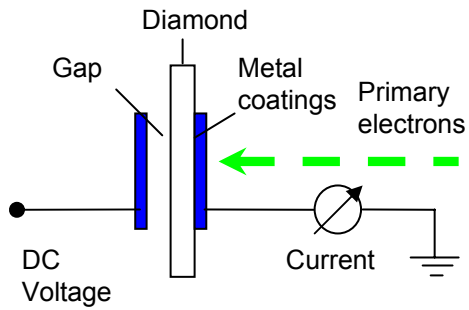




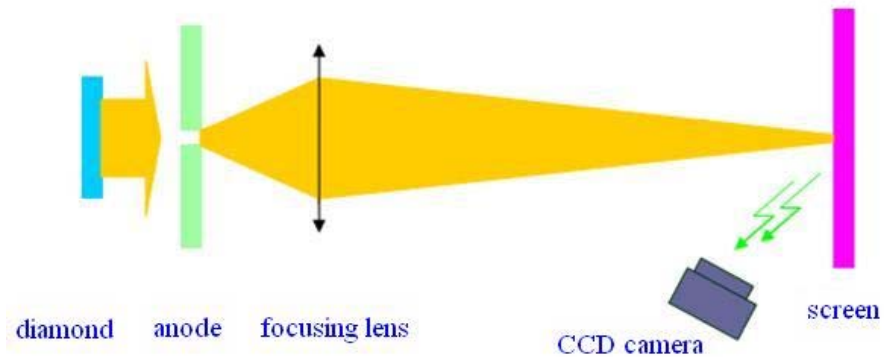
Photocathode R&D

Rao, Smedley, Chang, Wu, Grover





X. Chang et al, Recent Progress on the Diamond Amplified Photo-cathode Experiment, WEOCC04



Q. Wu et al, Thermal Emittance Measurement Design for Diamond Secondary Emission

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