Machine R&D for eRHIC

Dmitry Kayran for eRHIC team

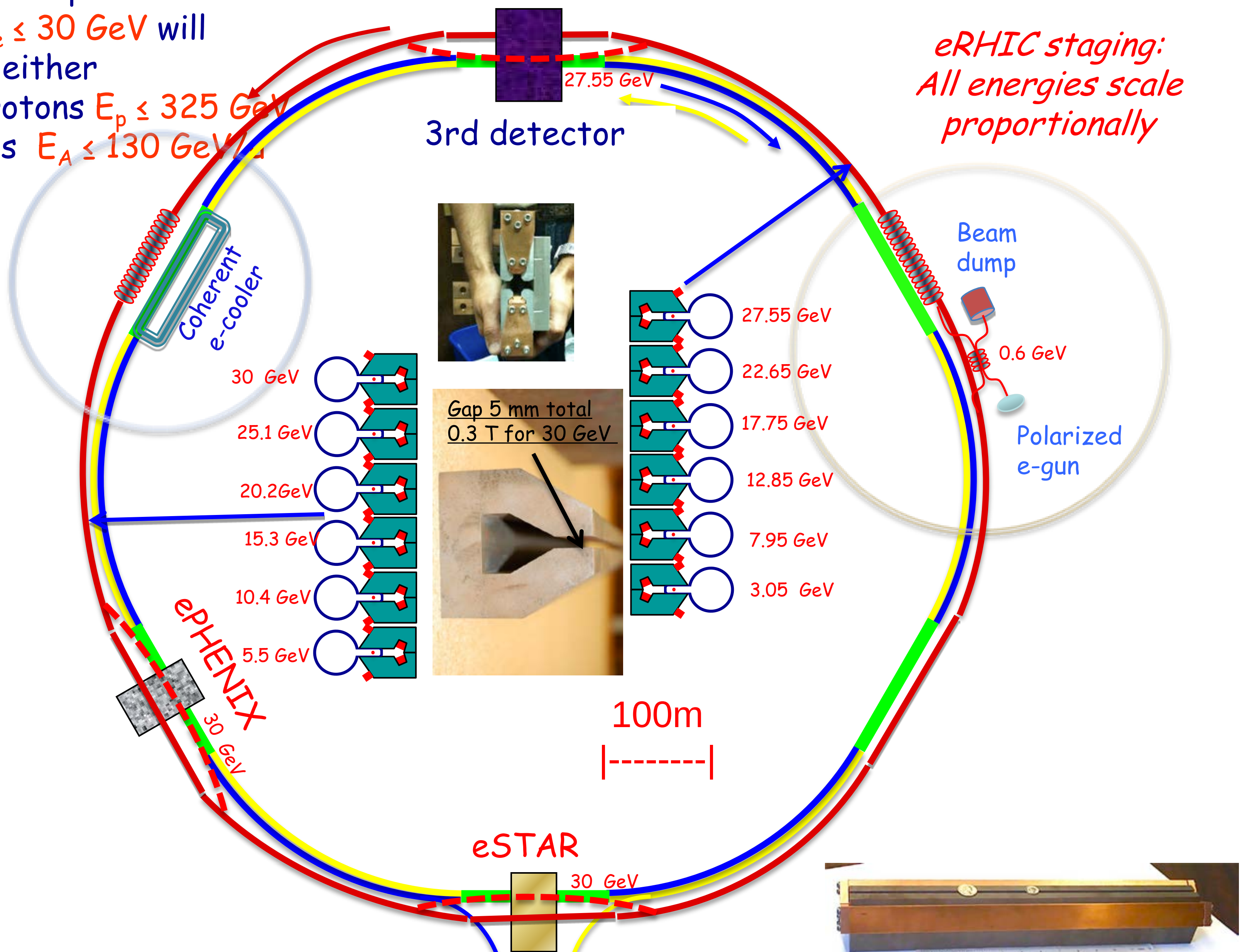
Collider-Accelerator Department,
Brookhaven National Laboratory

Outline

- Introduction
- eRHIC R&D progress:
  - (a) Single cathode and Gatling polarized electron guns
  - (b) Compact SRF linacs with HOM damping & SRF crab-cavities
  - (e) Small gap magnets and vacuum chambers
  - (f) Coherent electron cooling
  - (g) Beam-beam effects
- Summary

eRHIC: where polarized electrons $E_e \leq 30$ GeV will collide with either polarized protons $E_p \leq 325$ GeV or heavy ions $E_A \leq 130$ GeV/u

eRHIC staging: All energies scale proportionally



eRHIC luminosity

	e	p	$^{2}He^{3}$	$^{79}Au^{197}$	$^{92}U^{238}$
Energy, GeV	20	325	215	130	130
CM energy, GeV		161	131	102	102
Number of bunches/distance between bunches	74 nsec	166	166	166	166
Bunch intensity (nucleons) ,10^{11}	0.24	2	3	5	5
Bunch charge, nC	3.8	32	31	19	19
Beam current, mA	50	420	411	250	260
Normalized emittance of hadrons , 95% , mm mrad		1.2	1.2	1.2	1.2
Normalized emittance of electrons, rms, mm mrad		23	35	57	57
Polarization, %	80	70	70	none	none
rms bunch length, cm	0.2	4.9	8	8	8
β*, cm	5	5	5	5	5
Luminosity per nucleon, x 10^{34} $cm^{-2}s^{-1}$		1.46	1.39	0.86	0.92

Hourglass effect is included

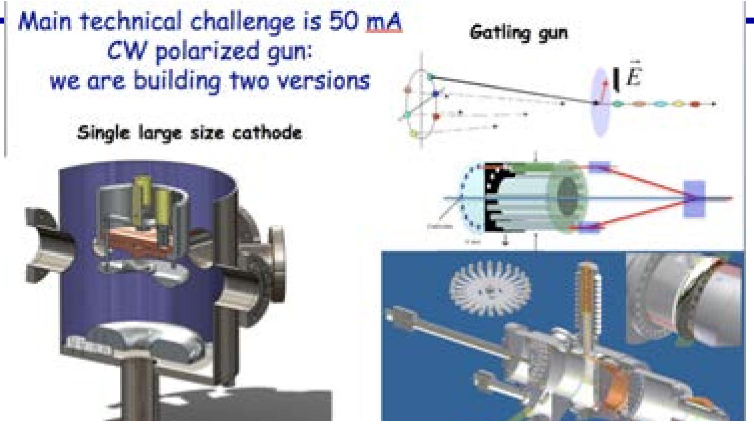
Main Accelerator Challenges

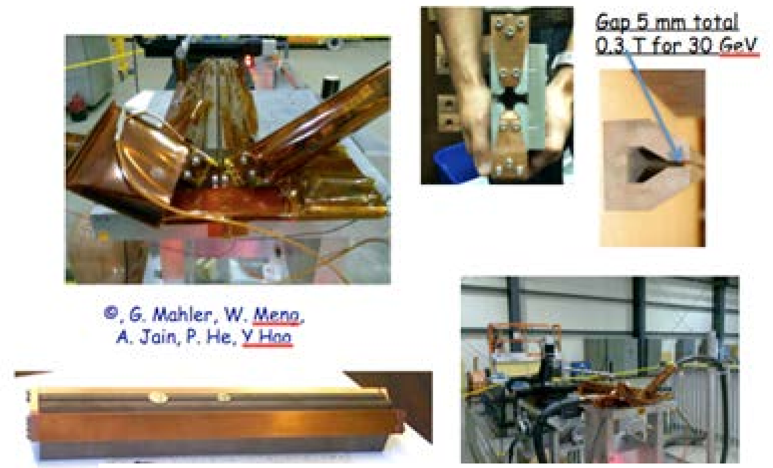
In red –increase/reduction beyond the state of the art

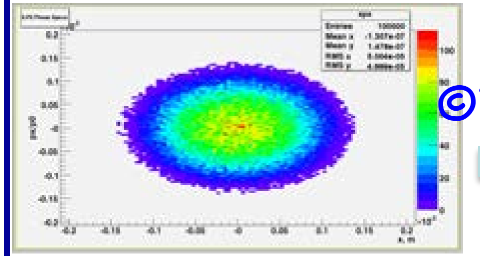
	eRHIC at BNL
	Polarized electron gun – 50x increase current
	Coherent Electron Cooling – New concept
	Multi-pass SRF ERL 5x increase in current 30x increase in energy
	Crab crossing New for hadrons
	Polarized ^{3}He production
	Understanding of beam-beam affects New type of collider
	β*=5 cm 5x reduction
	Multi-pass SRF ERL 3-4x in # of passes
	Feedback for kink instability suppression Novel concept

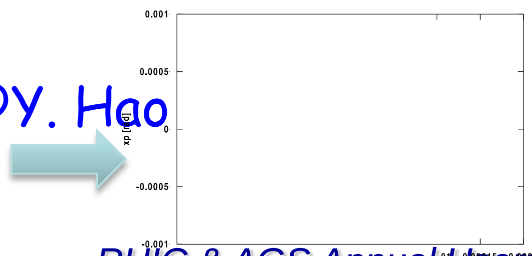
eRHIC R&D highlights

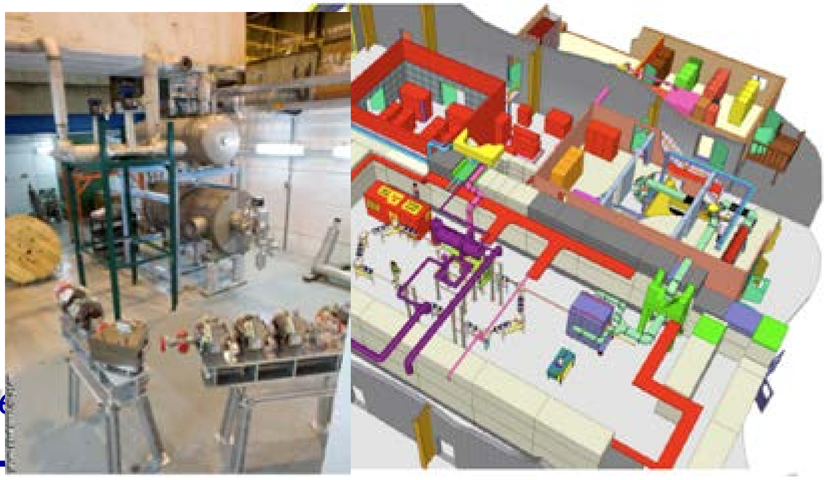
- Polarized gun for e-p program – **LDRD at BNL + MIT**
- Development of compact magnets - **LDRD at BNL, ongoing**
- SRF R&D ERL – **ongoing**
- Beam-beam effects, beam disruption, kink instability suppression, etc.
- Polarized He^3 source
- Coherent Electron Cooling including PoP – **plan to pursue**









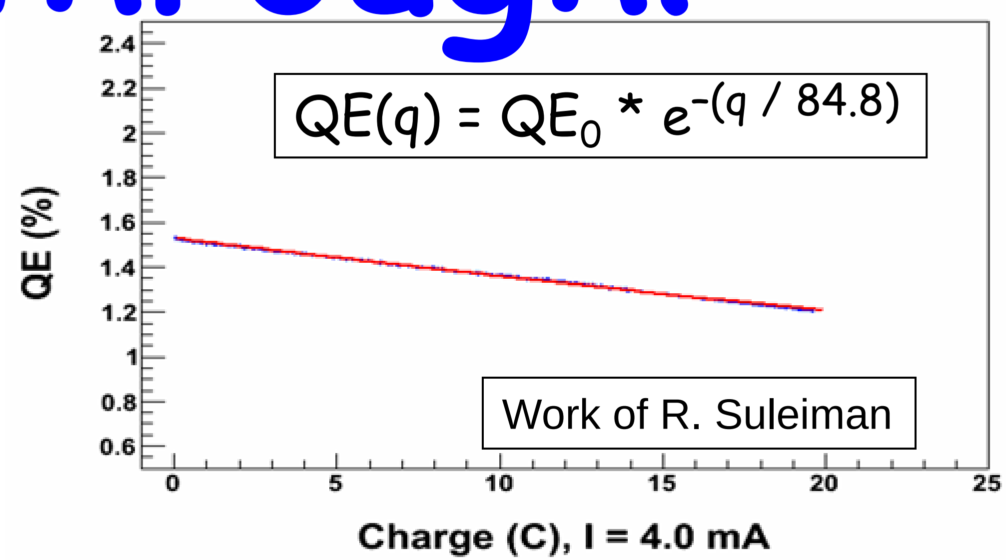


200kV Inverted Gun + SSL GaAs/GaAsP + RF-Fiber Laser → 4 mA

Breakthrough!

Test Parameter	Value
Laser Rep Rate	1500 MHz
Laser Pulselength	50 ps
Laser Wavelength	780 nm
Laser Spot Size	350 μm FWHM
High Polarization Photocathode	SSL GaAs/GaAsP
Gun Voltage	200kV DC
CW Beam Current	4 mA
[illegible]	1.4 hr
Extracted Charge	20 C

- High QE ~ 1.5% (~6 mA/W/%)
- Current-limited by available laser power
- Higher 200kV voltage => supersede 1mA demo
- Pushes technology in support of Electron Ion Colliders > 50 mA, High-P e^- Drivers



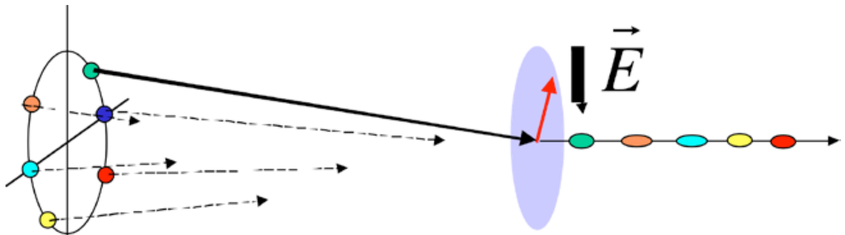
 http://www.c-ad.bnl.gov/pac2011/proceedings/papers/weods3.pdf

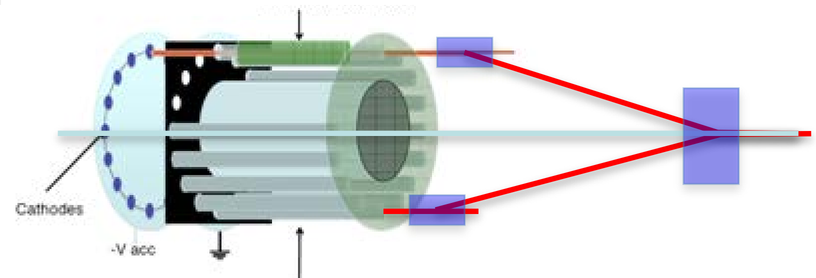
LDRD DC gun that can deliver ~ 50 mA

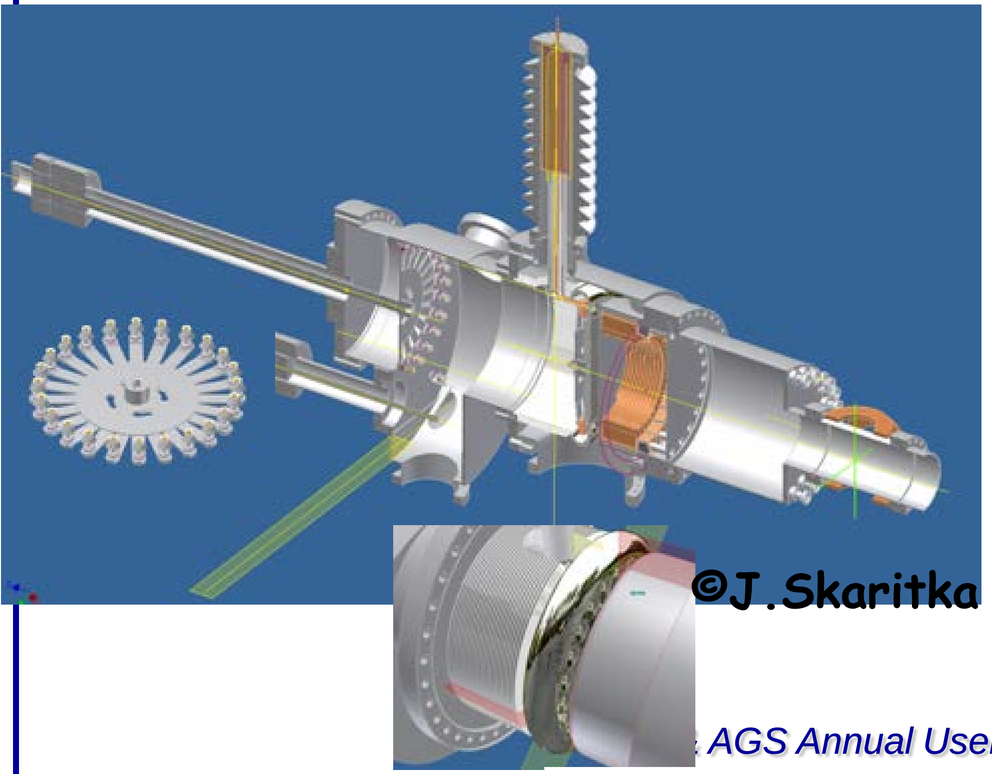
- The objective of this program :
- 1) Achievement of good vacuum in this complex, tight geometry.
- 2) Insertion and activation of the individual gallium arsenide cathode.
- 3) Questions of isolation of the near-by cathodes, to prevent cross-interference.
- 4) Question of jitter caused by the combination of multiple beams.
-

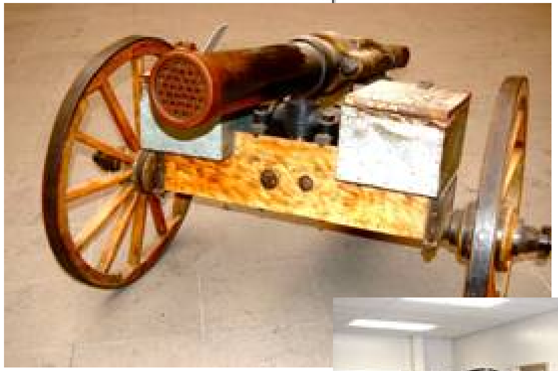
Main eRHIC's technical challenge is 50 mA CW polarized gun

Gatling gun



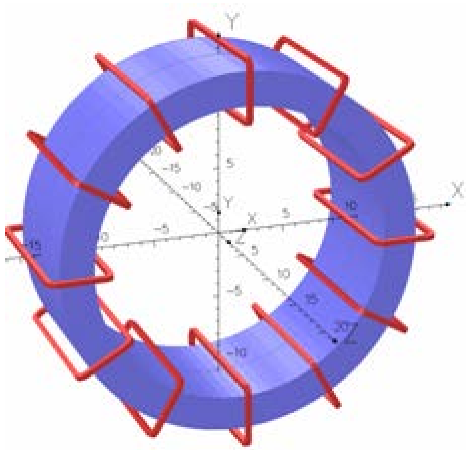




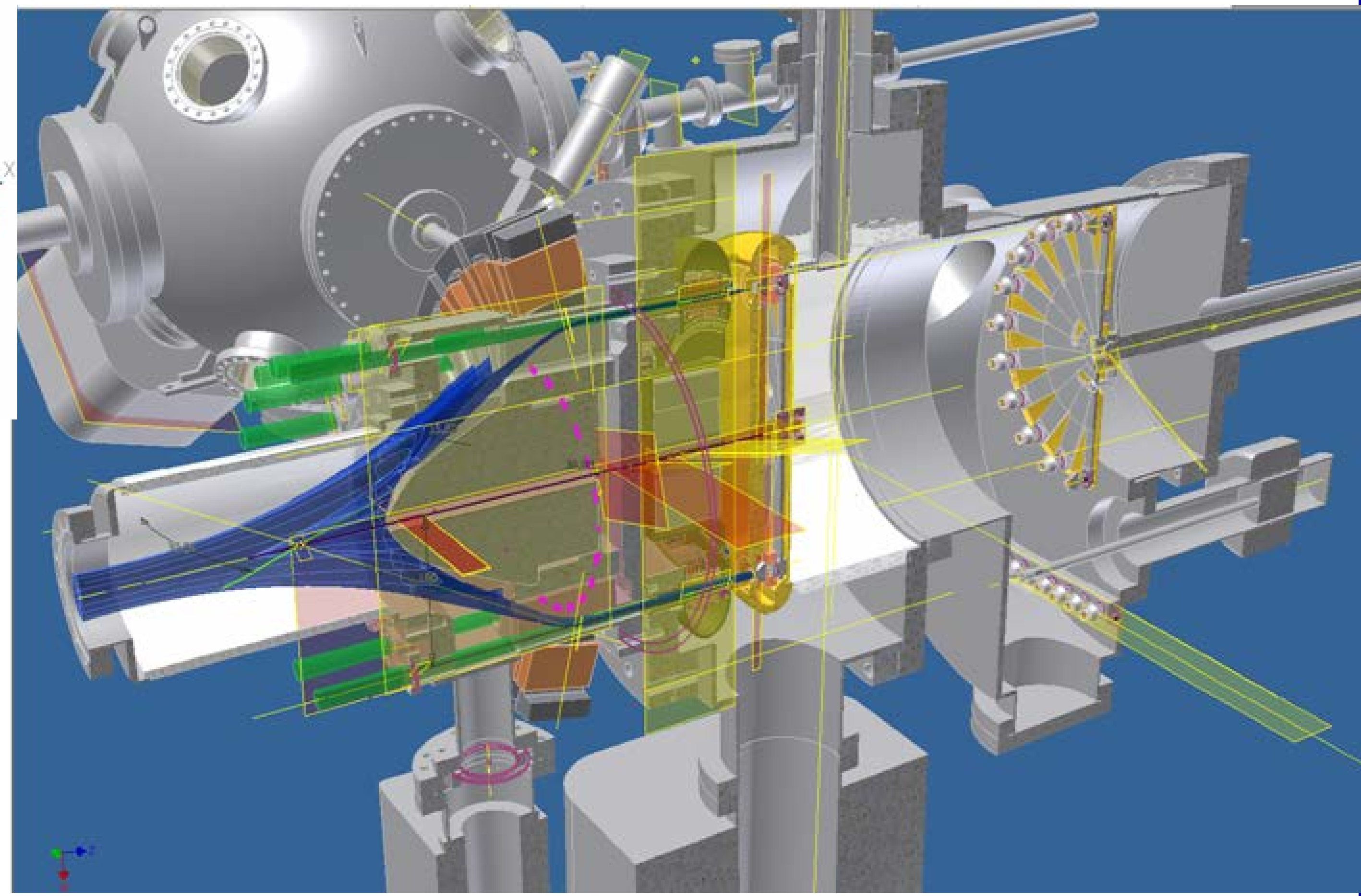


* the Gatling gun is the first **successful** machine gun, invented by Dr. Richard Jordan Gatling.

LDRD on EIC Polarized Electron Gun (PI: Ilan Ben-Zvi)



Sectioned view of the gun: Green –indicate Laser, Blue- indicate electron beam paths. Near center is the cathode shroud and anode, and to the right is the cathode magazine. The cathode preparation chamber can be seen on upper left.

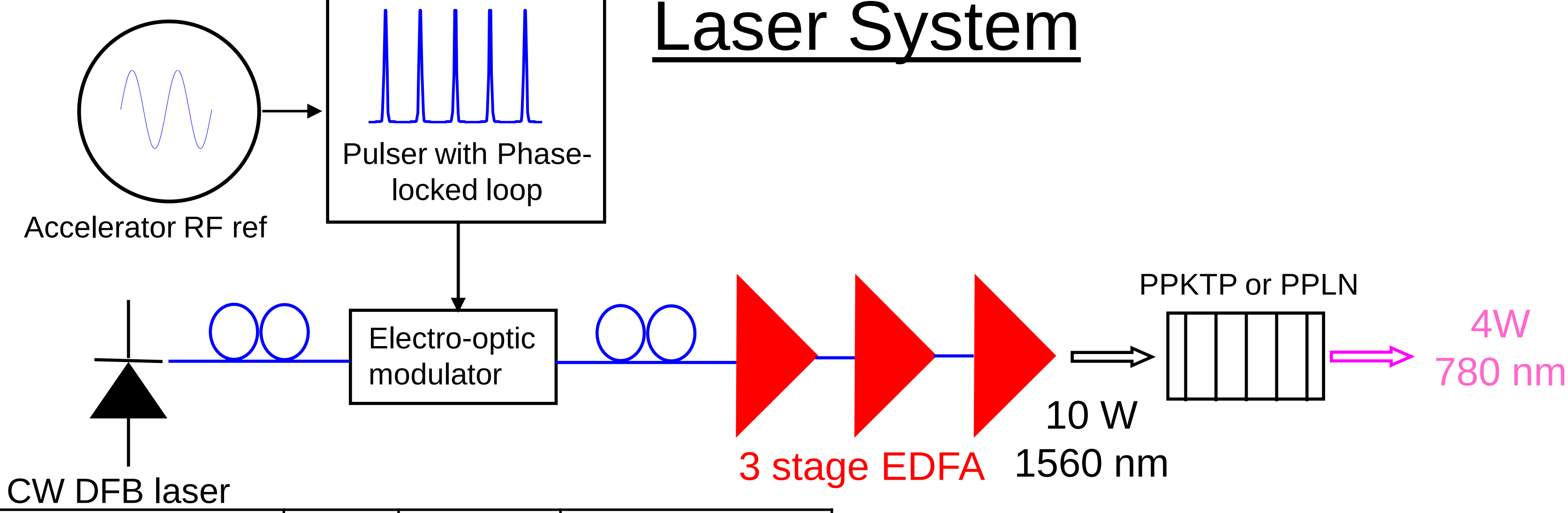


Current 2-D simulation results are very close to our goals. Detailed mechanical design has been done. Most components have been ordered. 3D tracking is in progress.

Laser Requirements

- 14 uJ energy per pulse in the 1560 nm fundamental
  - will frequency double to 780 nm in PPKTP or PPLN, expect 40% conversion (conservative) for 5.6 uJ at 780 nm
    - 5.6 uJ is based on 3.5 nC pulse, 0.2% QE in photocathode and ~100% overhead (ie 3.5 nC requires 2.8 uJ of 780 nm light)
    - more headroom welcome for losses in spatial pulse shaping, beam transport, QE drop, etc.
      - Developments in high power fiber laser will likely make higher power available in the near future
- 1.2 nsec FWHM Gaussian pulses
  - EO modulated CW DFB laser for front end
- 704 kHz (14.07 MHz/20)
  - i.e average power is 9.8 W @1560 nm, 3.9 W @ 780 nm
- Contrast -30 dB in the fundamental, -60 dB at 780 nm
- Synchronization jitter with respect to RF reference: 10 psec rms
  - beam dynamics requirement not determined, but probably between 10-100 psec
- Amplitude stability
  - will need 10^{-3} to 10^{-4} in the photocathode pulse for eRHIC. Expect maybe 10^{-2} from EDFA amplifier and polarization extinction ratio, and use noise-eater before the photocathode

Laser System



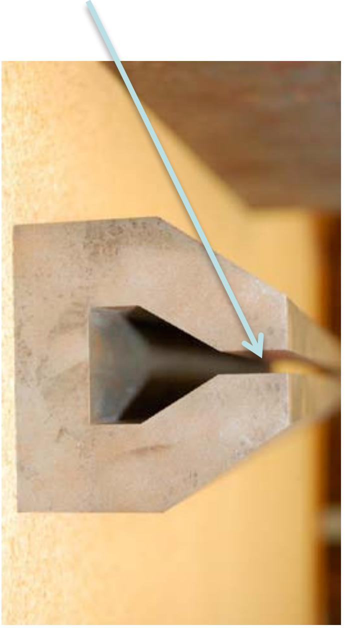
parameter	unit	spec	comment
wavelength	nm	780	
repetition rate	kHz	704	14.07 MHz / 20 cathodes
pulse energy at photocathode	uJ	2.8	assuming QE=0.2% & 3.5 nC bunch chg
average laser power at cathode	W	2	assuming QE=0.2%
average laser power	W	4	
pulse width	nsec	1.2	Gaussian FWHM
jitter	psec	10	rms
amplitude stability		1.00E-03	requires noise-eater
contrast		1.00E-06	

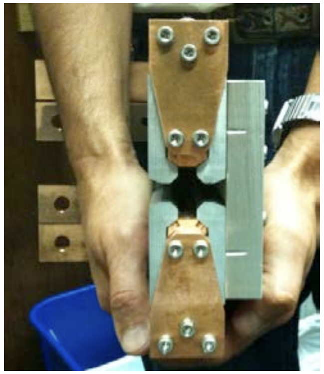
- 10 W Erbium doped fiber amplifier (EDFA) system at 1560 nm, frequency doubled in periodically-poled material (KTP or $LNBO_3$)
- CW distributed feedback laser + electro-optic modulation for pulse source
  - control of pulse shape, low jitter
- Frequency double to 780 nm in periodically poled material (40% efficiency)
- Will be built by Optilab & Covesion. Cost $120K, delivery July 2011

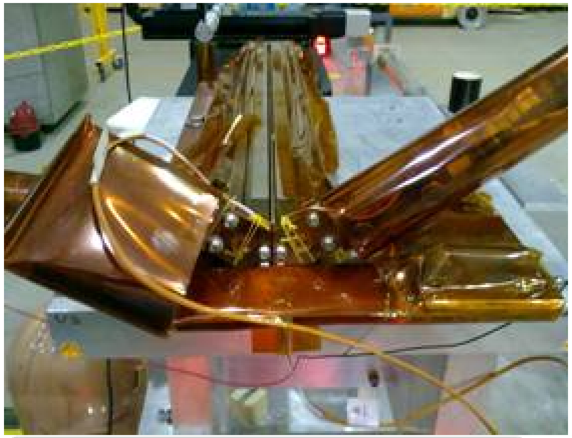
LDRD: Development of Small Gap Magnets

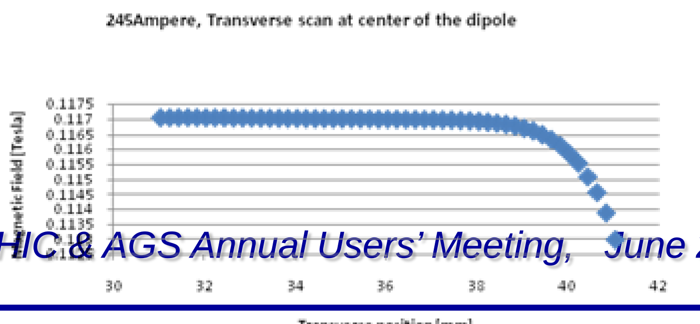
- Small gap provides for low current, low power consumption magnets
  - -> **low cost eRHIC**
  - Dipole prototype satisfy our reqs !!!
  - Fab. Technique used for quads did not satisfy our reqs
    - –but pawed the way to better fabrication technique

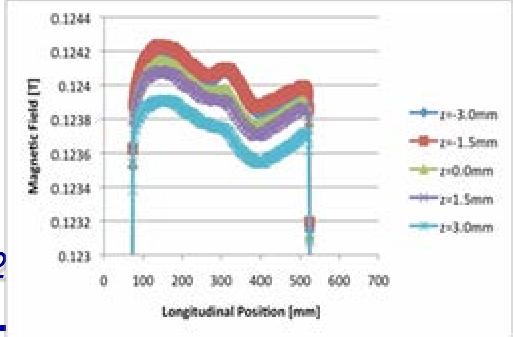
Gap 5 mm total
0.3 T for 30 GeV











Coherent Electron Cooling (CeC) is required to reach the luminosity

At a half of plasma oscillation

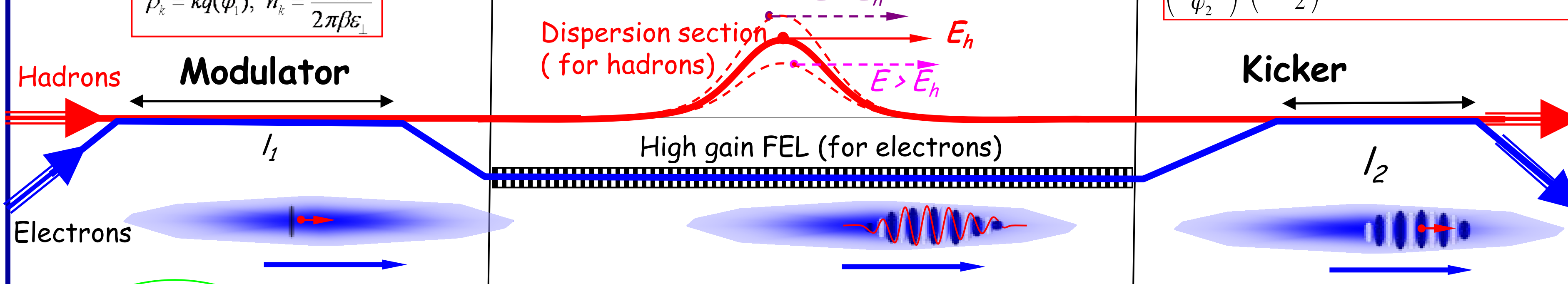
$$q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

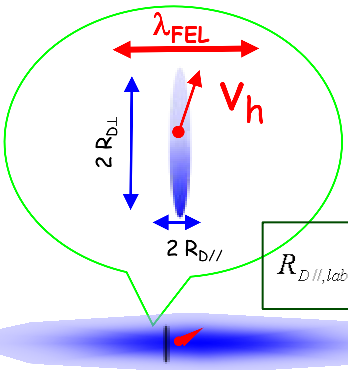
$$\rho_k = kq(\varphi_1);\ n_k = \frac{\rho_k}{2\pi\beta\varepsilon_\perp}$$

Dispersion

$$c\Delta t = -D\cdot\frac{\gamma-\gamma_o}{\gamma_o};\ D_{free} = \frac{L}{\gamma^2};\ D_{chicane} = l_{chicane}\cdot\theta^2 ....$$

$$\Delta E_h = -e\cdot \mathbf{E}_o\cdot l_2\cdot\sin\left(k_{FEL}D\frac{E-E_o}{E_o}\right)\cdot\left(\frac{\sin\varphi_2}{\varphi_2}\right)\cdot\left(\sin\frac{\varphi_1}{2}\right)^2\cdot Z\cdot X;\ \ \mathbf{E}_o = 2G_o e\gamma_o/\beta\varepsilon_{\perp n}$$





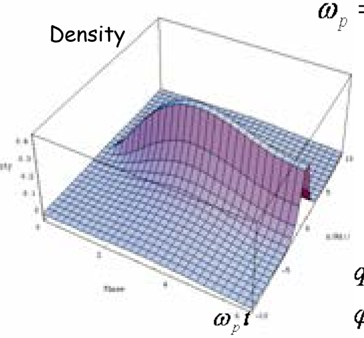
Debay radii

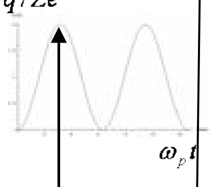
$$R_{D\perp} >> R_{D//}$$

$$R_{D\perp} = \frac{c\gamma\sigma_{\theta e}}{\omega_p}$$

$$R_{D//,lab} = \frac{c\sigma_\gamma}{\gamma^2\omega_p} << \lambda_{FEL}$$

$$\omega_p = \sqrt{4\pi n_e e^2/\gamma_o m_e}$$



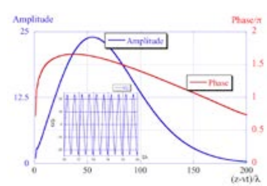


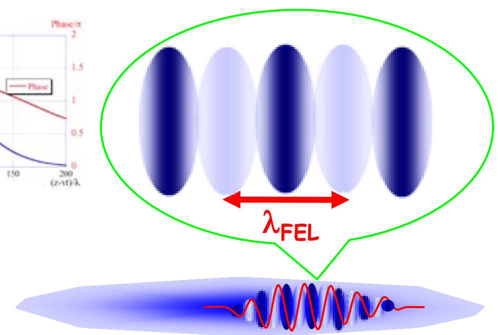
$$q = -Ze\cdot(1-\cos\varphi_1)$$

$$\varphi_1 = \omega_p l_1/c\gamma$$

$$q_{peak} = -2Ze$$

Amplifier of the e-beam modulation in an FEL with gain G_{FEL}~10^2-10^3





$$\lambda_{fel} = \lambda_w\left(1+\langle\vec{a}_w^2\rangle\right)/2\gamma_o^2$$

$$\vec{a}_w = e\vec{A}_w/mc^2$$

$$L_{Go} = \frac{\lambda_w}{4\pi\rho\sqrt{3}}$$

PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

Coherent Electron Cooling

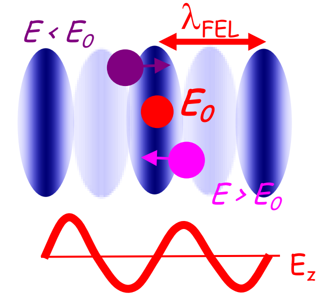
Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]

[1]Brookhaven National Laboratory, Upton, Long Island, New York, USA

[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA

(Received 24 September 2008; published 16 March 2009)

$$A_\perp = 2\pi\beta_\perp\varepsilon_n/\gamma_o$$



$$k_{FEL} = 2\pi/\lambda_{FEL};\ k_{cm} = k_{FEL}/2\gamma_o$$

$$n_{amp} = G_o\cdot n_k\cos(k_{cm}z)$$

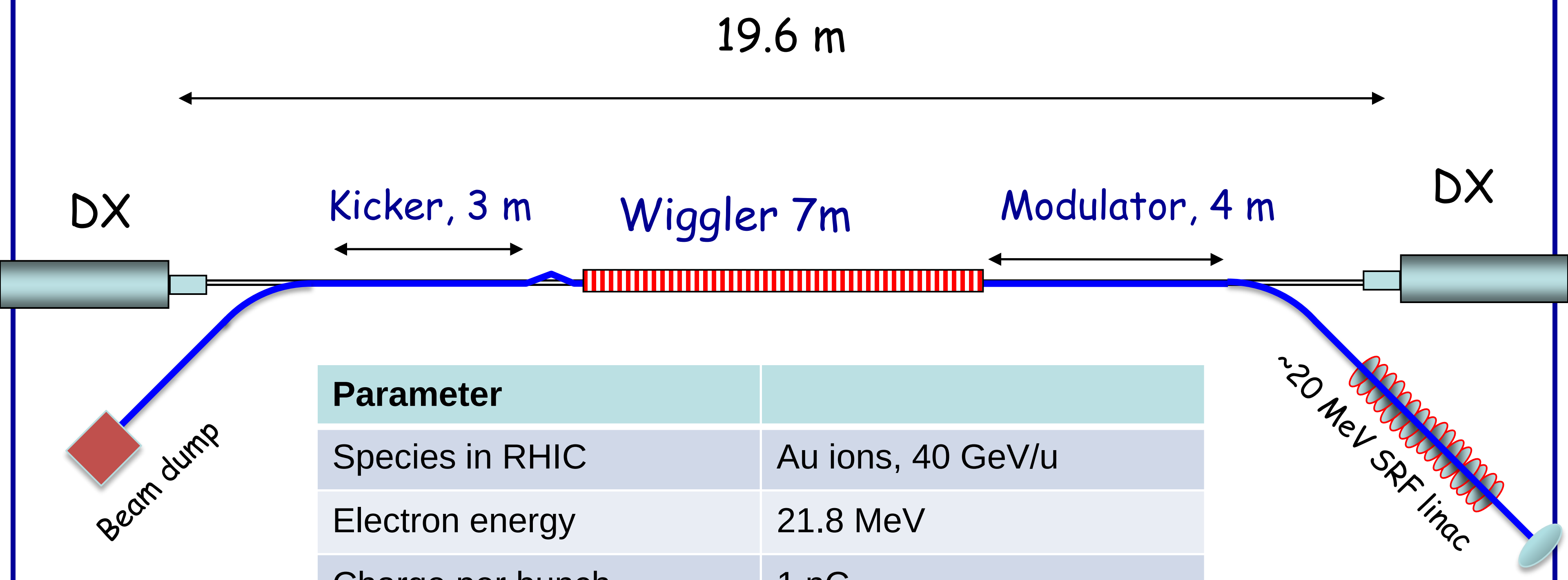
$$\Delta\varphi = 4\pi en \Rightarrow \varphi = -\varphi_0\cdot\cos(k_{cm}z)$$

$$\vec{\mathbf{E}} = -\vec{\nabla}\varphi = -\hat{z}\mathbf{E}_o\cdot X\sin(k_{cm}z)$$

$$\mathbf{E}_o = 2G_o\gamma_o\frac{e}{\beta\varepsilon}$$

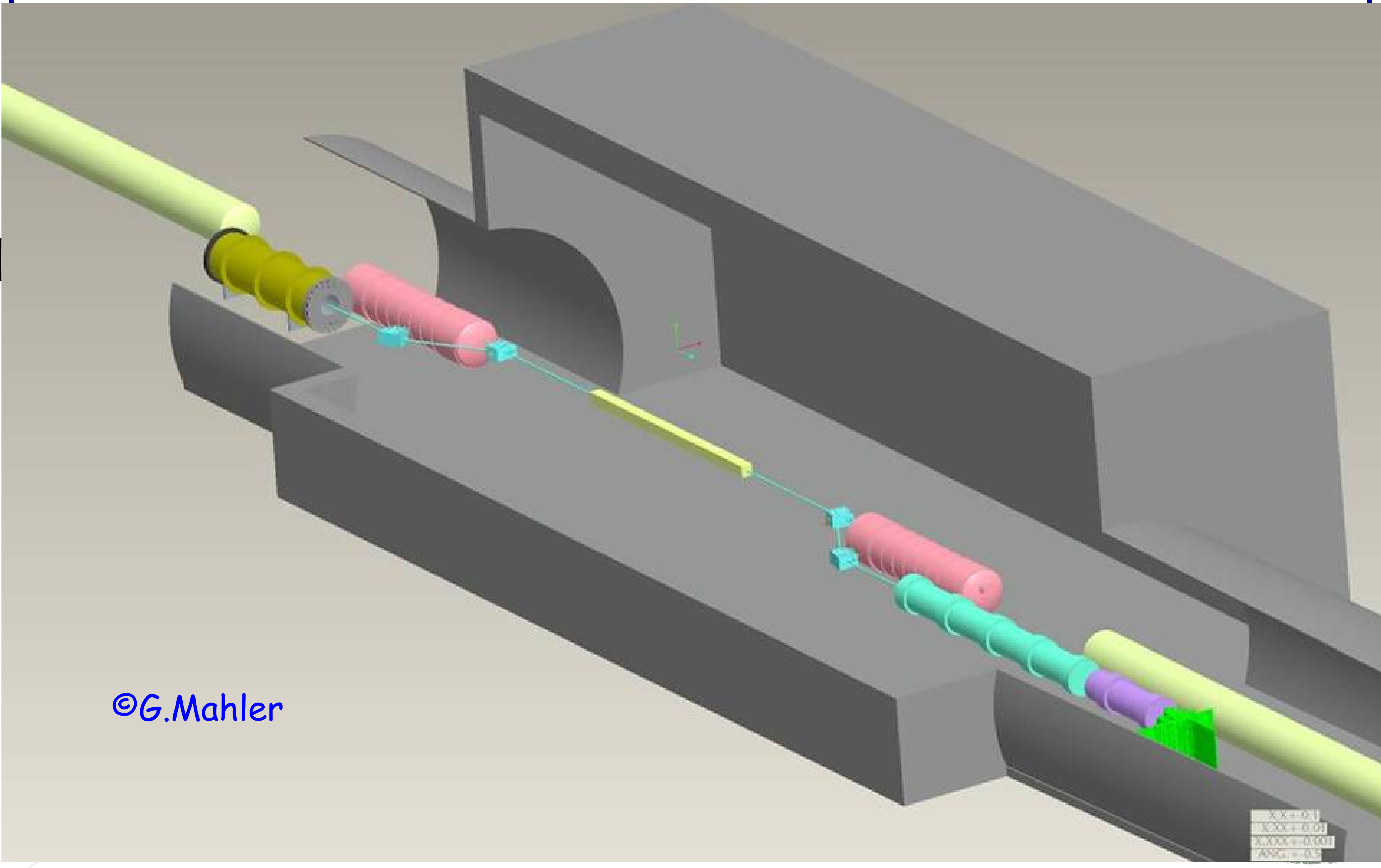
$$X = q/e \cong Z(1-\cos\varphi_1) \sim Z$$

The layout for Coherent Electron Cooling proof-of-principle experiment in RHIC IR

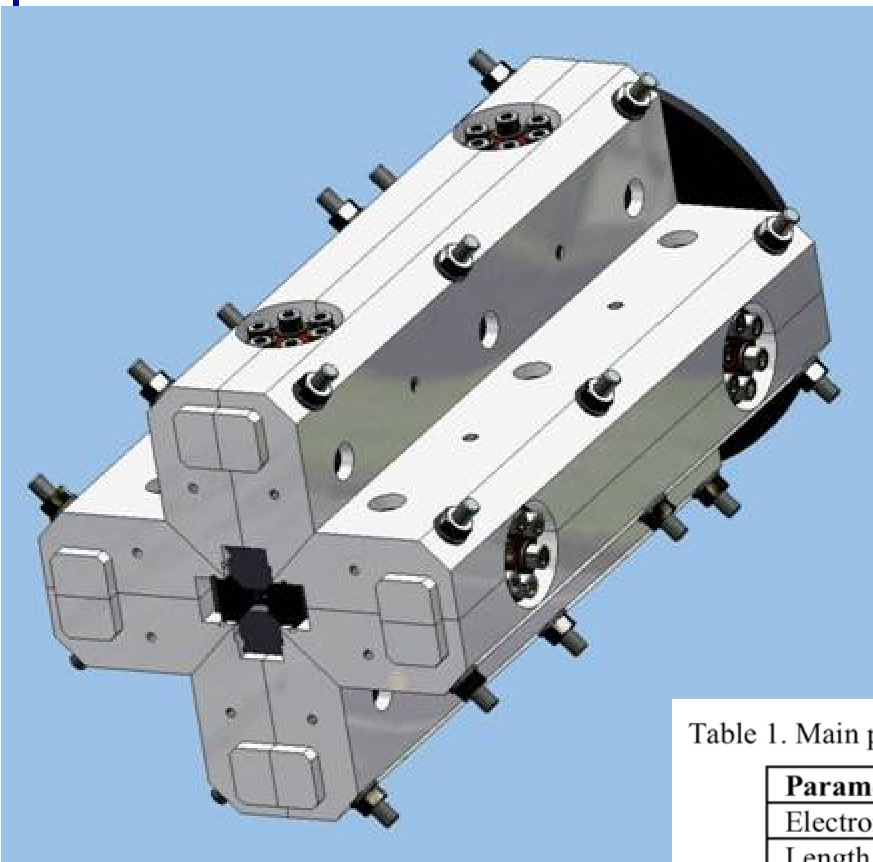


Parameter	
Species in RHIC	Au ions, 40 GeV/u
Electron energy	21.8 MeV
Charge per bunch	1 nC
Train	5 bunches
Rep-rate	78.3 kHz
e-beam current	0.39 mA
e-beam power	8.5 kW

Layout for Coherent Electron Cooling proof-of-principle experiment in RHIC IR 2 Collaboration between BNL & JLab



Helical undulator prototype
Ordered!



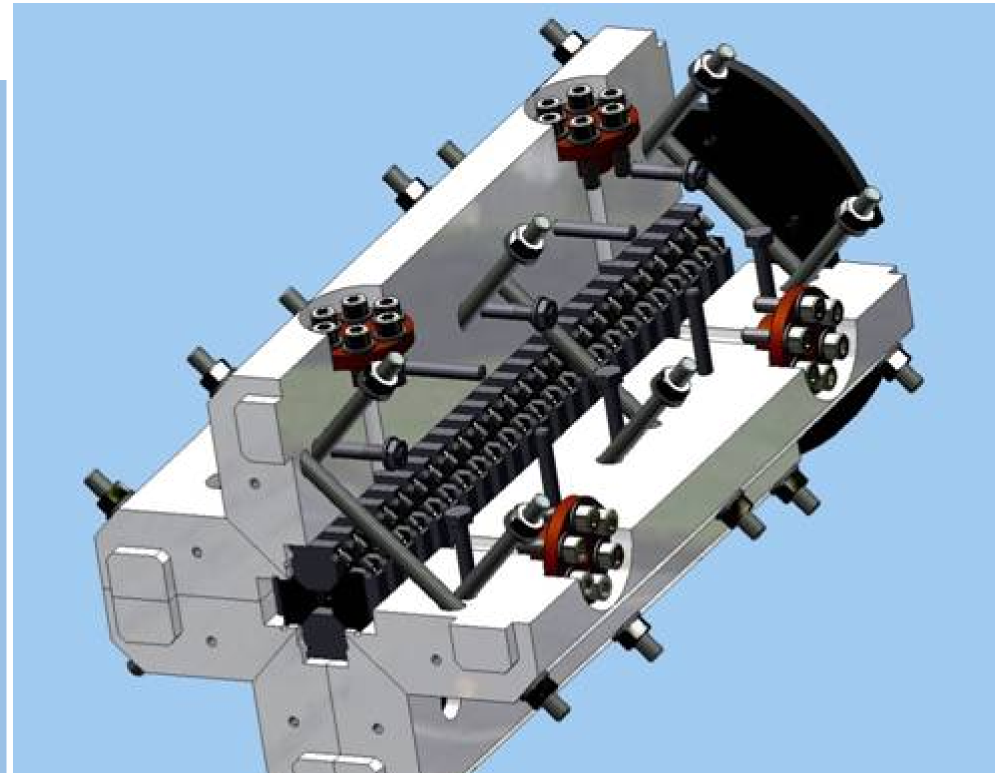


Table 1. Main parameters for the CeC demonstration experiment

Parameter	Units	
Electron beam energy	MeV	**21.8**
Length of the CeC straight section	m	**14**
Length of the modulator straight section	m	**3**
Length of the kicker straight section	m	**3**
Length of FEL wiggler	m	**7**
Type of wiggler		**Helical**
Wiggler period	cm	**4**
Wiggler parameter, a_w		**0.437**

Goals for R&D ERL at BNL

R&D ERL will serve as a test-bed for future RHIC projects:

- ERL-based electron cooling (conventional or coherent).
- 10-to-20 GeV ERL for lepton-ion collider eRHIC.

Test the key components of the High Current ERL based solely on SRF technology

•SRF Photoinjector (703.5 MHz SRF Gun, photocathode, laser, merger etc.) test with 500 mA.

-Preservation of high-charge, low emittance.

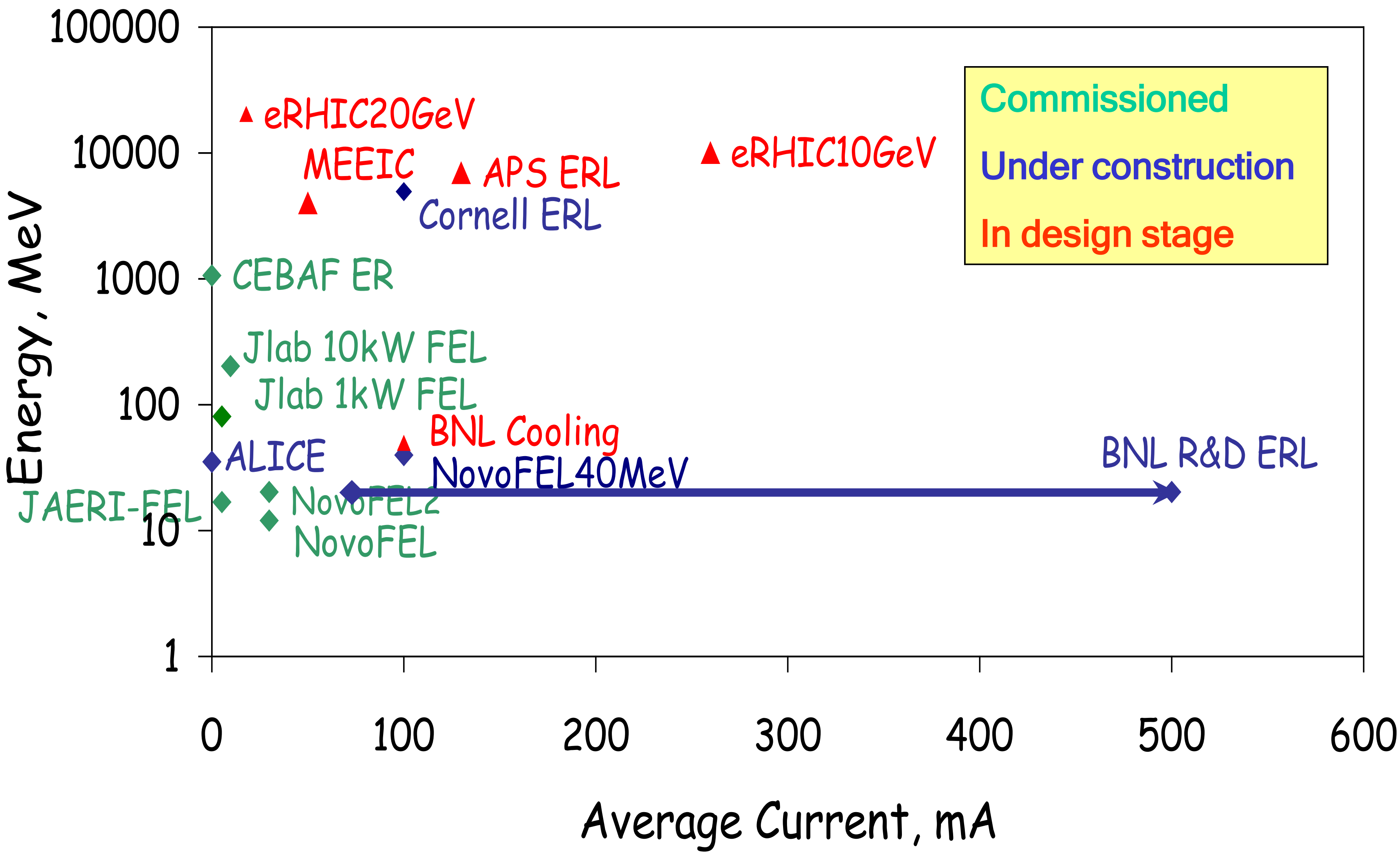
•High current 5-cell SRF linac test with HOM absorbers

-Single turn - 500 mA

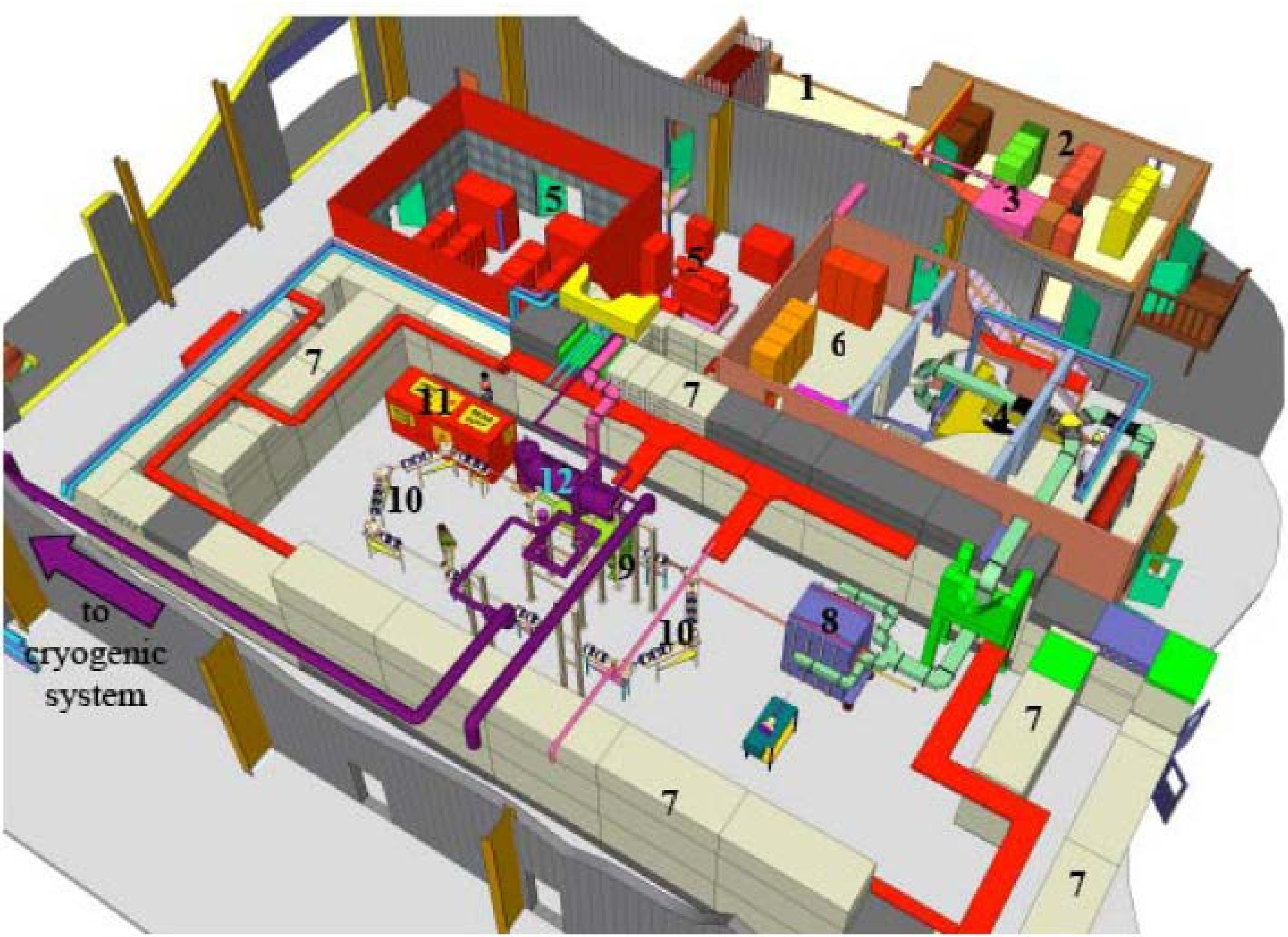
•Stability criteria for CW beam current.

•Attainable ranges of electron beam parameters in SRF ERL.

High Power ERL landscape



Layout of R&D ERL in Bldg. 912 at BNL



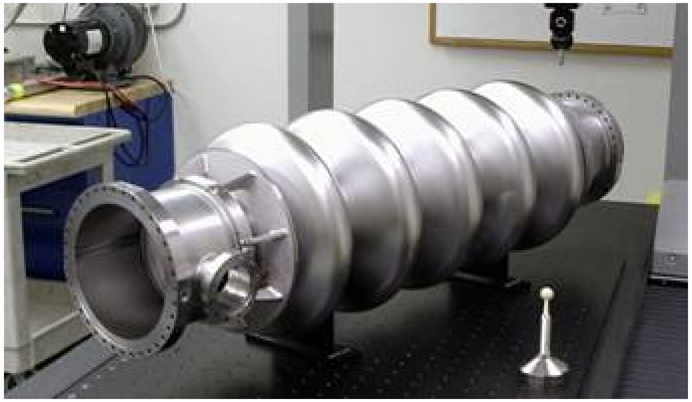
RHIC

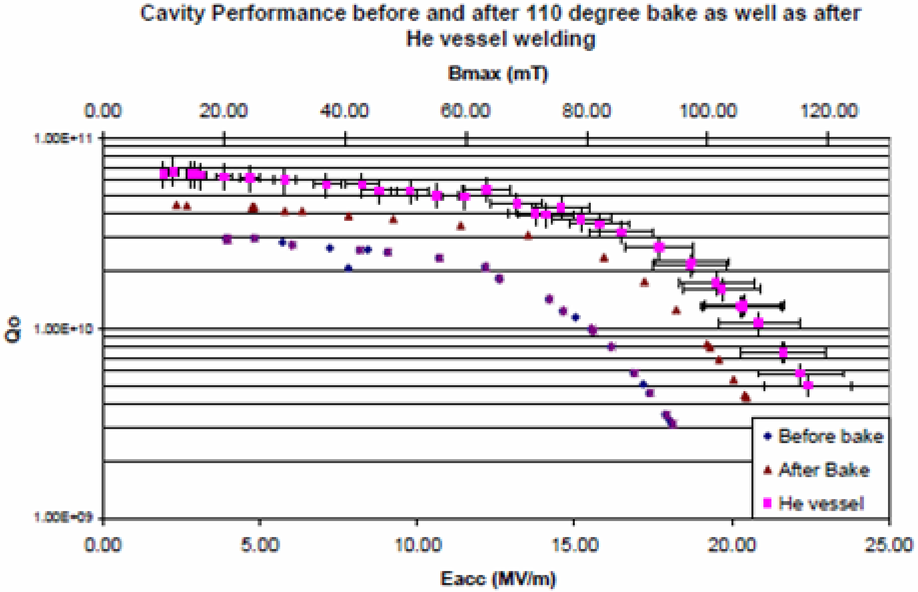
BNL R&D ERL beam parameters
(PARMELA simulation result two operational regimes)

Parameter / Operation regime	High Current	High charge
Charge per bunch, nC	0.7	5
Numbers of passes	1	1
Energy maximum/injection, MeV	20/2.5	20/3.0
Bunch rep-rate, MHz	700	9.383
Average current, mA	500	50
Injected/ejected beam power, MW	1.0	0.15
R.m.s. Normalized emittances ex/ey, mm*mrad	1.4/1.4	4.8/5.3
R.m.s. Energy spread, $\delta E/E$	3.5×10^{-3}	1×10^{-2}
R.m.s. Bunch length, ps	18	31

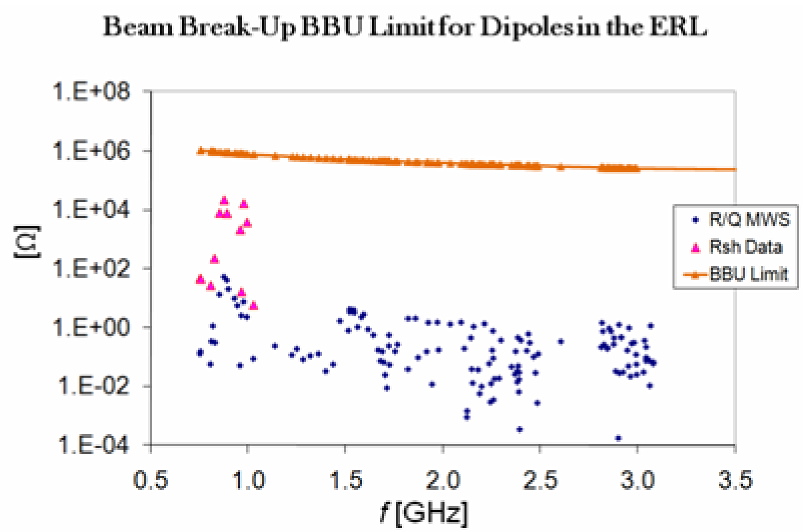
R&D ERL: 5cell SRF Cavity

- 5 cell SRF cavity, 17 cm iris, 24 cm beampipe
- 703.75 MHz, 20 MV/m @ Q_o=$1e^{10}$
- No trapped HOMs
- Cavity is inherently stiff, so no additional stiffeners are needed
- Coaxial FPC for power delivery
- Ferrite Dampers for HOMs
- 5 K heat intercept on beampipe
- Mechanical Tuner with 100 kHz tuning range, piezo provides 9 kHz fast tuning

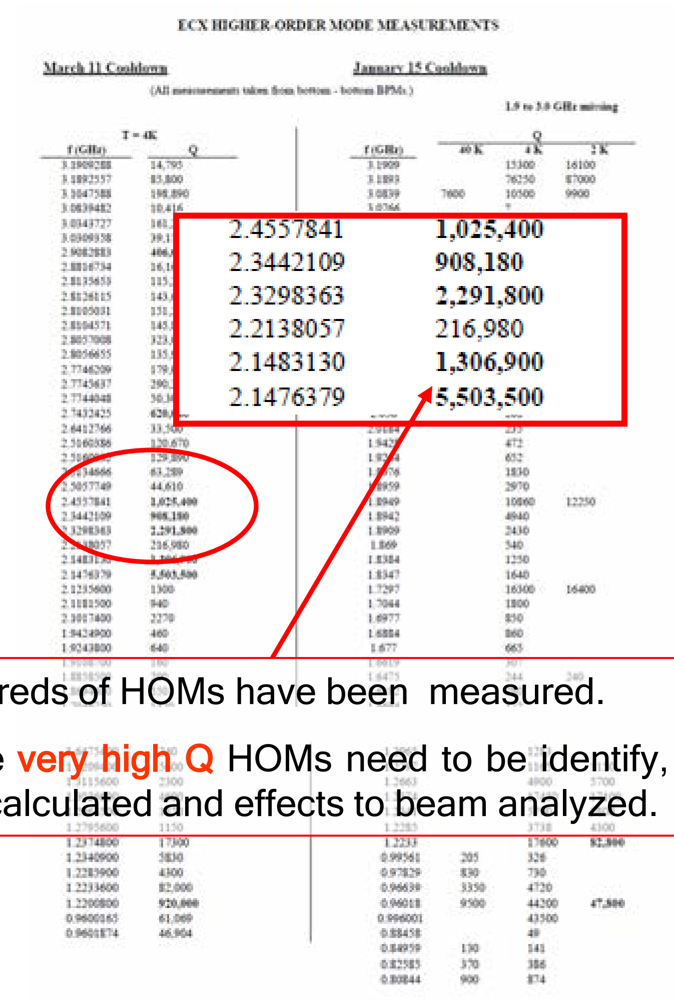




ERL 5cell cavities HOM's studies



Comprehensive HOMs table measurements



Data				Simulations					
f_{2-12} [MHz]	f_{6-6} [MHz]	Q_{NC}	Q_{SC}	f [MHz]	R/Q_{1cm} $\times 10^3$ [Ω]	R/Q [Ω]	Q_{ext} [Ω]	Q_{FRT} [Ω]	$R_\perp$ [Ω]
770				752	3.2	0.13	174	382	49
780				755	3.6	0.14	18	322	46
808	808.4	900	874	806	1.4	0.05	611	586	28
826	825.9	370	386	825	20.8	0.70	174	335	233
850	849.6	130	141	852	432.1	13.6	89	605	8,225
878				875	1777.8	52.9	18	433	22,921
894				890	1593.3	45.6	15	176	8,020
959	960.2	9,500	47,800	958	2.0	0.1	2,820	44,391	2,216
966	966.4	3,350	4,720	964	103.9	2.6	927	6,683	17
978	978.3	630	730	976	317.6	7.6	379	2,288	17,392
998	995.6	205	326	993	98.9	2.3	9	1,735	3,969
				1026	4.0	0.1	9	67	6

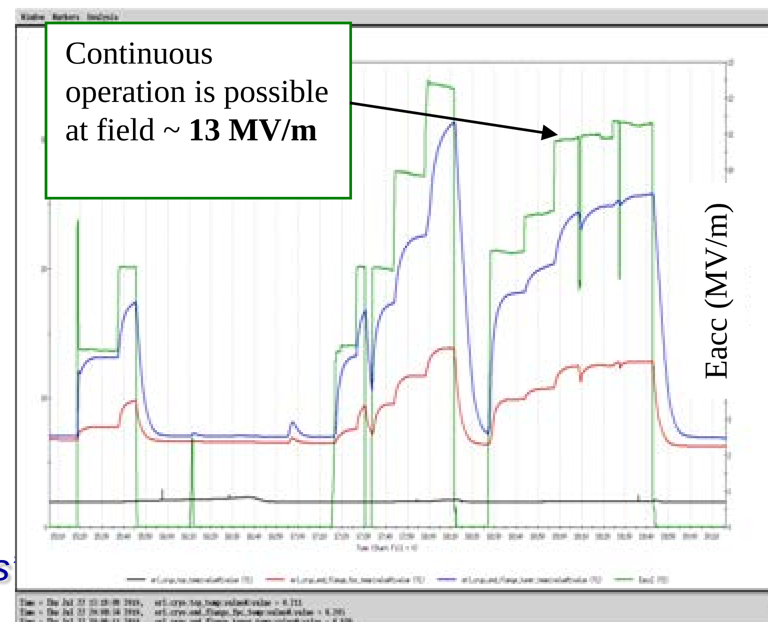
First two bands high order dipole modes

Hundreds of HOMs have been measured.

Some **very high Q** HOMs need to be identify, R/Q calculated and effects to beam analyzed.

5cell cavity horizontal tests summary

- The BNL 703 MHz superconducting cavity has been installed and operational tests are ongoing.
- HOMs studies were done during all cool downs.
- In CW mode 13 MV/m is well repeatable and stable. No radiation observed.
- The 22 MV/m gradient is demonstrated in quasi-CW mode operation (3-4 seconds.)
- CW higher gradient operation is limited by the temperature rising of thermo- transition near the FPC and the tuner.
- Preliminary studies of the microphonics spectrum reveal some discrete noise sources of moderate strength, and a large resonance which occurs infrequently and is still under investigation.
- Next test is scheduled at end of June, 2011 to commissioning digital LLRF

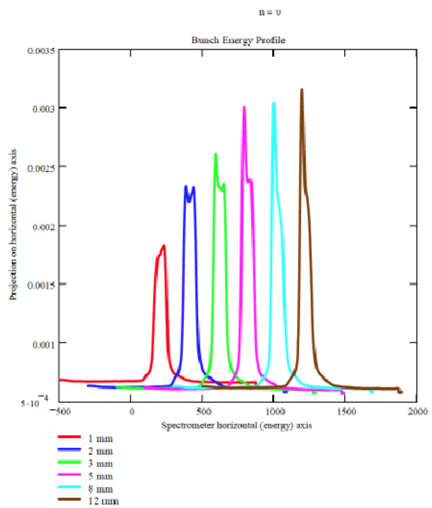


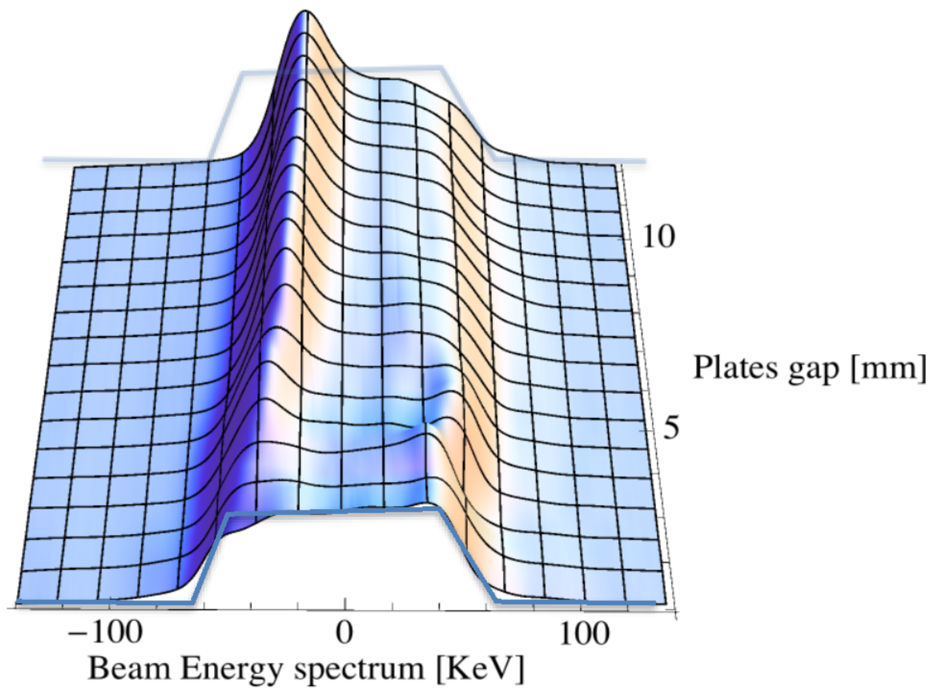
G5 test stands installed

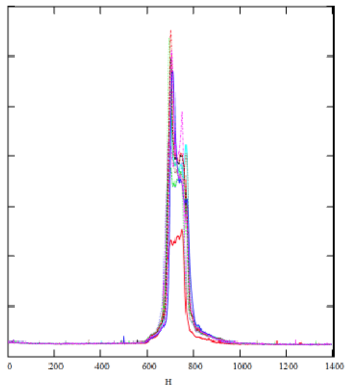
ERL fixed arc magnets: preinstalled

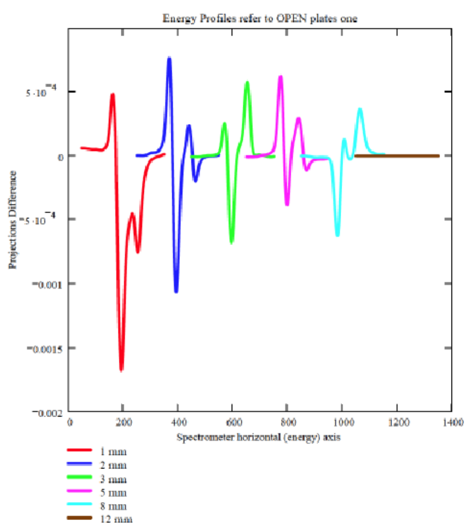
Movable arc magnets stands (horseshoe) ready to “roll” into the block house

Summary of experimental results









With closed gap the distribution is close to that from the HE slit – opening gap increases the distortions

Beam dynamics studies

Recent results on:
-electron beam energy losses and energy spread caused by the interaction with the beam environment (cavities, resistive walls, pipe roughness)
-incoherent and coherent synchrotron radiation related effects: energy losses, transverse and longitudinal emittance increase of the electron beam
-electron beam patterns; ion accumulation
-electron beam break-up, single beam and multi-pass
-electron beam-ion and intra-beam scattering effects
-electron beam disruption
-frequency matching

The issues presently under investigation:

- How small can be the electron beam pipe size?
- Compensation of the energy losses and the energy spread of the electron beam.
- How long should be the electron bunch? Do we need harmonic cavities?
- Crab cavities and their effect on beam dynamics

Summary:

- We are taking full advantages of extensive eRHIC LDRD program running
- LDRD grants are very critical for successful and steady progress of the accelerator R&D towards high-energy high-luminosity eRHIC
  - Small-gap magnets for eRHIC save energy and cost making QCD-factory into a reality
  - Gatling-gun test is novel approach toward beyond-state-of-the-art polarized electron sources
  - CeC LDRD proved possibility of economic CeC option and resulted in new revolutionary helical wiggler design
- LDRD are exploring high-risk high-payoff directions in the eRHIC R&D
- All completed LDRDs were very successful in identifying the pathways to eRHICs success

- More R&Ds are underway

Thank you