ERLs in High Energy and Nuclear Physics

Ilan Ben-Zvi and Vladimir Litvinenko

Collider-Accelerator Department

Brookhaven National Laboratory

Acknowledgements:

The large BNL teams working on electron cooling and eRHIC

MIT collaborators

Lia Merminga and JLab ELIC team

The Role of ERLs in High-Energy and Nuclear Physics

- Electron cooling of hadron storage rings

The requirements:

1. Low-energy
2. High brightness
3. High-Charge
4. High-current

- Provide electron beams for high-luminosity colliders.

The requirements:

1. High-energy
2. Polarization
3. High-current

The Physics Requirements: Depend on existing machines

- Electron cooling of RHIC tailored to cool RHIC and eRHIC
- eRHIC uses RHIC as a basis (from protons to heavy ions, bunch structure slightly modified)
- ELIC uses CEBAF as a basis (emphasis on light ions)

Nuclear Physics Motivation

- Over the past two decades we have learned a great amount about the hadronic structure
- Some crucial questions remain open:
  - What is the structure of the proton and neutron in terms of their quark and gluon constituents?
  - How do quarks and gluons evolve into hadrons?
  - What is the quark-gluon origin of nuclear binding?
  - How do the quarks and gluons manifest themselves in the properties of atomic nuclei?

Nuclear Physics Requirements

- Center-of-mass energy between 20 GeV and 150 GeV with energy asymmetry of ~10
- CW Luminosity from 10^{33} to 10^{35} cm^{-2} sec^{-1}
- Ion species: protons, deuterons, ^{3}He, heavy ions
- Longitudinal polarization of both beams in the interaction region $\geq$ 50% –80% required for the study of generalized parton distributions and transversity
- Transverse polarization of light ions extremely desirable
- Spin-flip of both beams extremely desirable

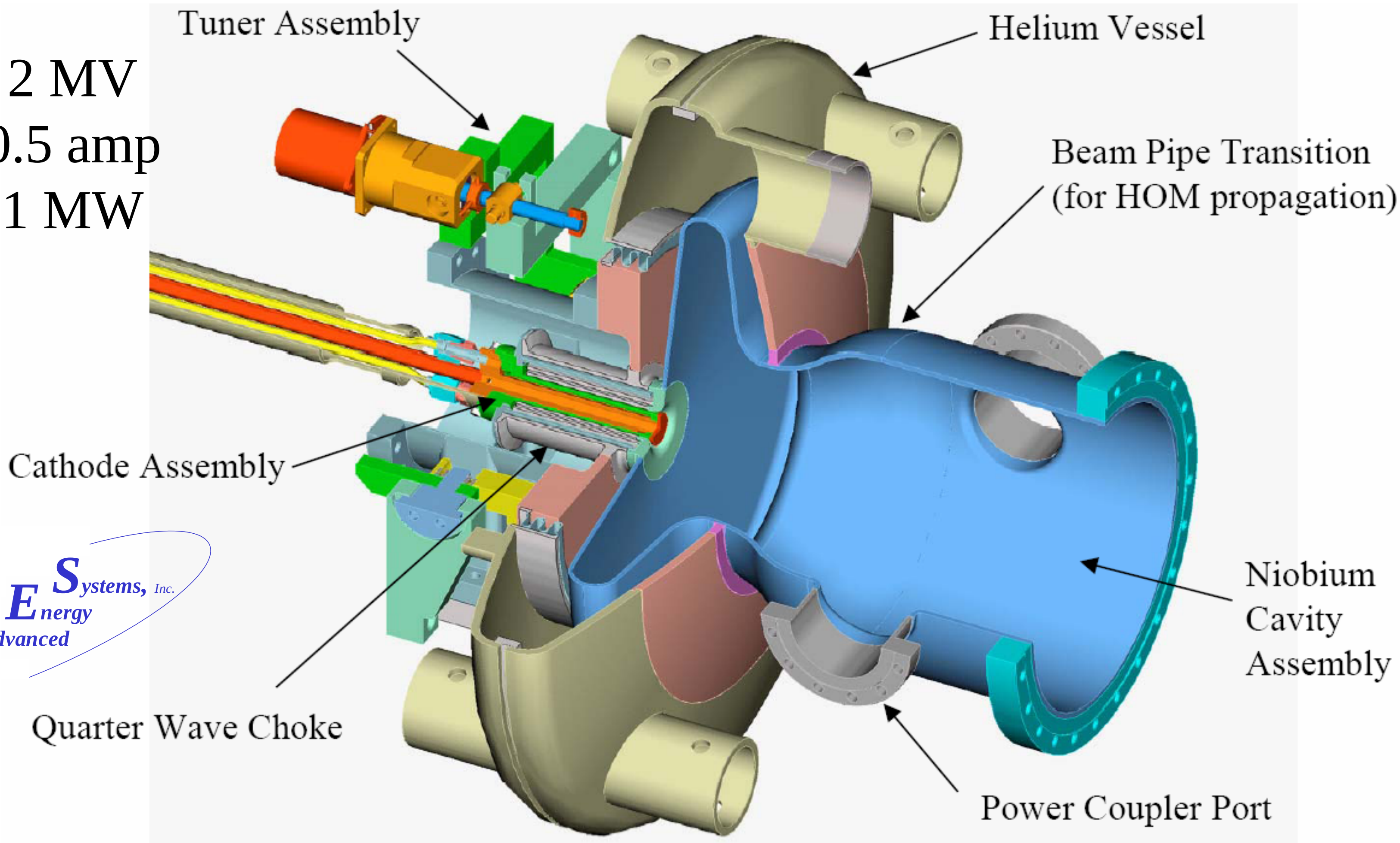
The Technology Challenges

- Beam Break-Up
- HOM power
  - Minimization
  - Safe removal from cavities
- The electron source

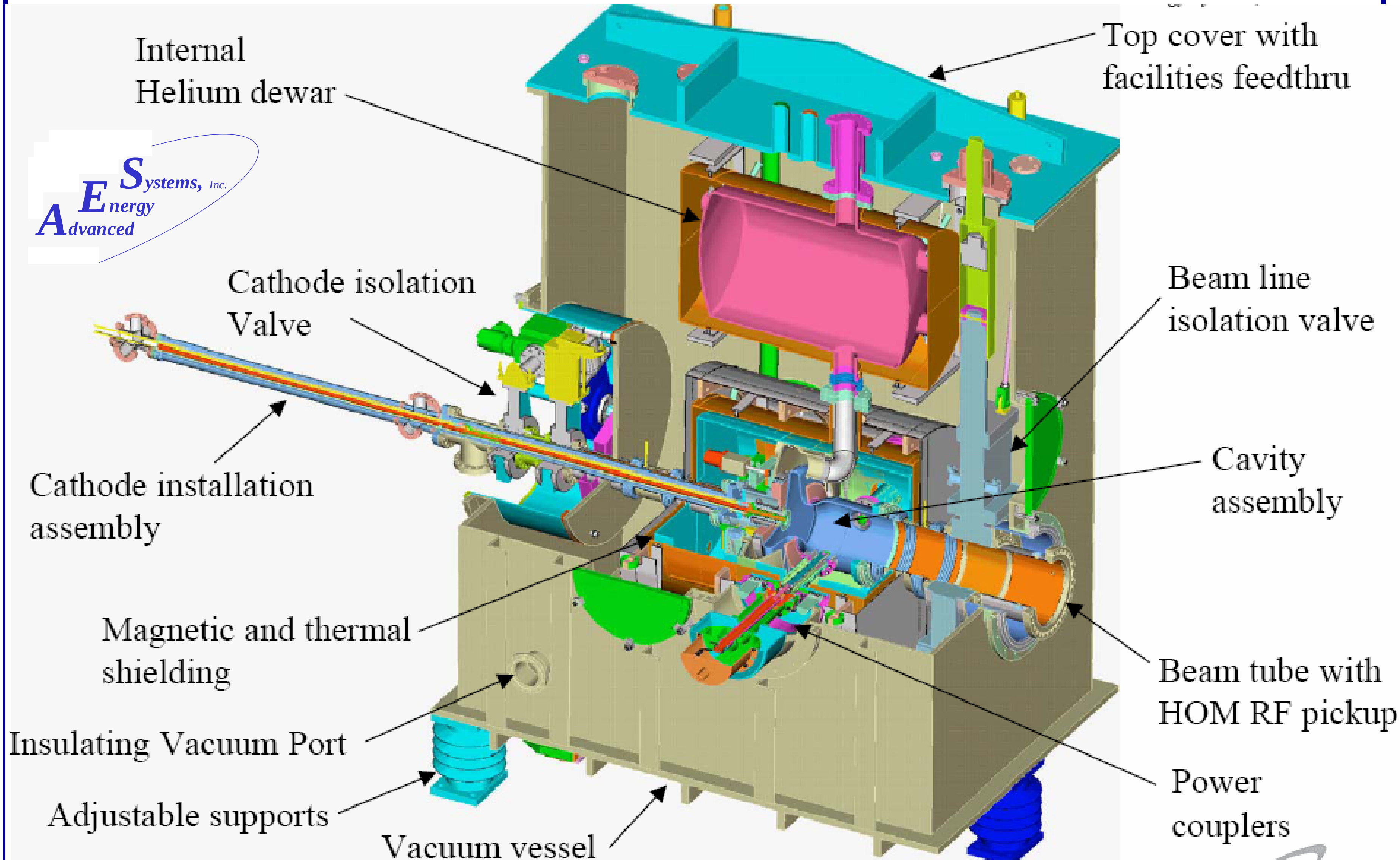
Ampere-class SRF gun

See next talk by A. Todd

2 MV
0.5 amp
1 MW

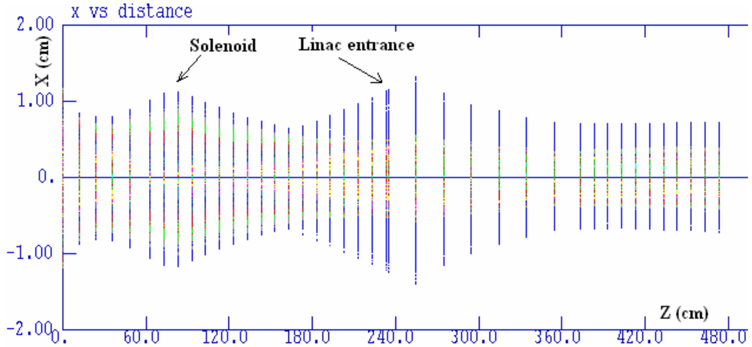


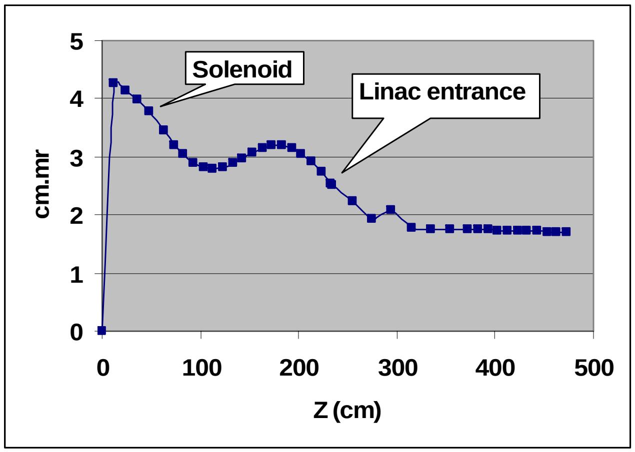
Advanced Energy Systems, Inc.


Internal
Helium dewar
Top cover with
facilities feedthru
Cathode isolation
Valve
Beam line
isolation valve
Cathode installation
assembly
Cavity
assembly
Magnetic and thermal
shielding
Beam tube with
HOM RF pickup
Insulating Vacuum Port
Adjustable supports
Vacuum vessel
Power
couplers
Advanced Energy Systems, Inc.

20nC/bunch, transverse uniform, longitudinal Gaussian, 30° (X. Chang)

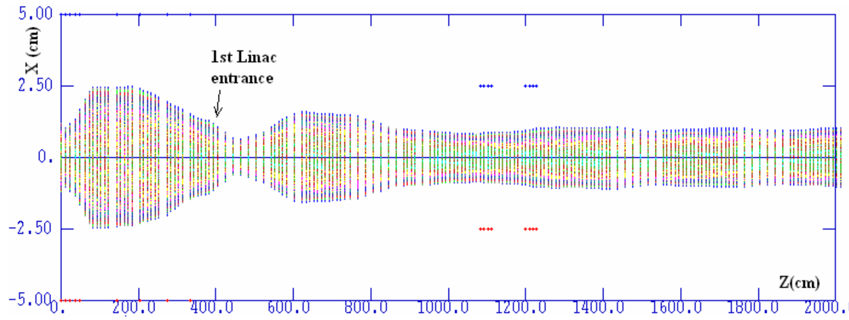
Non-magnetized beam in a straight line:

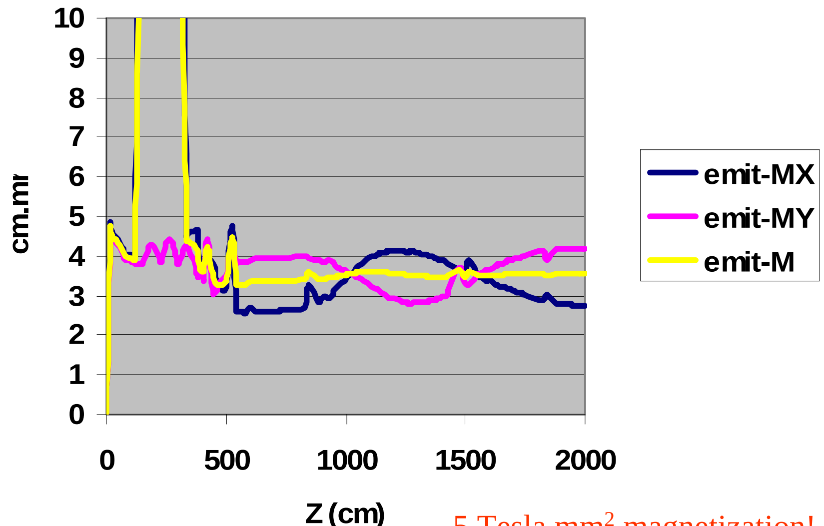




Final emittance=***17mm.mr.***

Magnetized beam with Z beam merging:

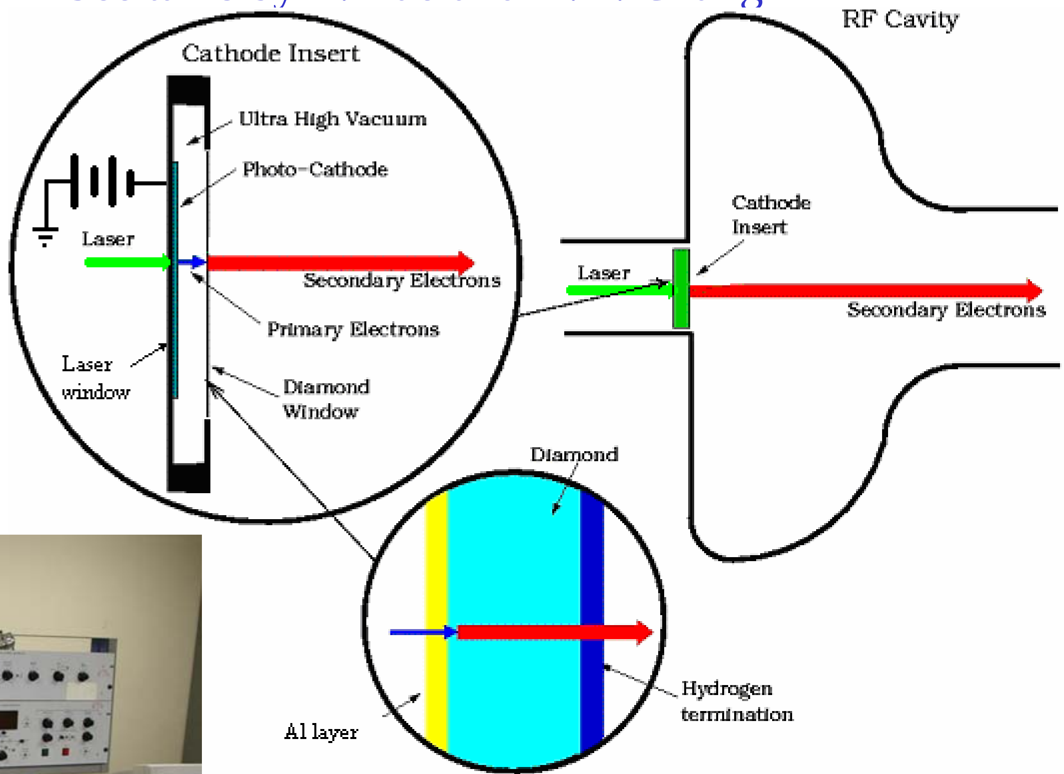




5 Tesla mm^2 magnetization!

The diamond amplified photocathode

See talks by T. Rao and X.Y. Chang

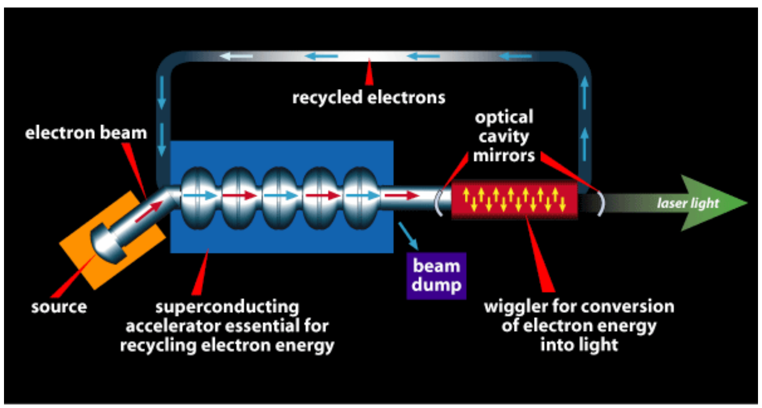


2 MeV

Mean ionization energy of diamond: 15 eV.
Thus 15 KeV primaries will generate 10^3 gain.

New ideas in polarized guns

FEL for polarized gun:



- Use an FEL for generating high laser power with optimal pulse structure and wavelength. Scale the area of the cathode to maintain the current density.
- NLC-TESLA (eRHIC) requirements:
  - Charge 2.6-3.2 (16) nC
  - Spacing 2.8-337 (36) nS
  - Train -0.95 (CW) mS
  - Polarization >80%
- Scaling from JLAB gun by increasing cathode area.

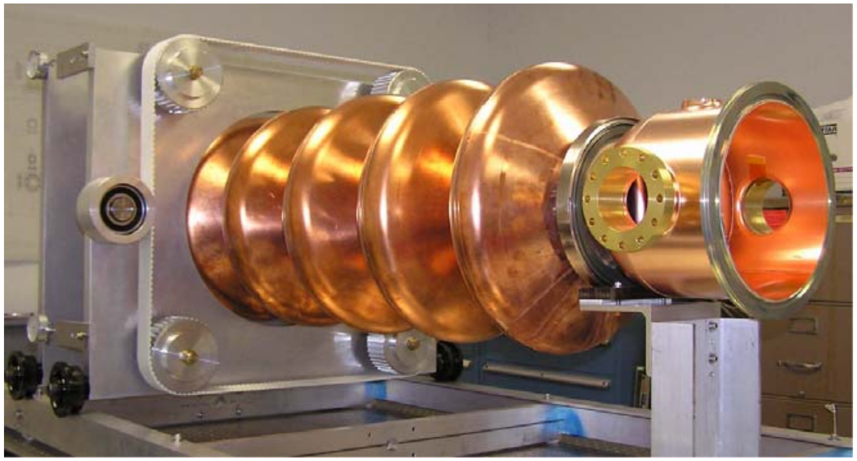
I. Ben-Zvi & V. Litvinenko, March 19, 2005

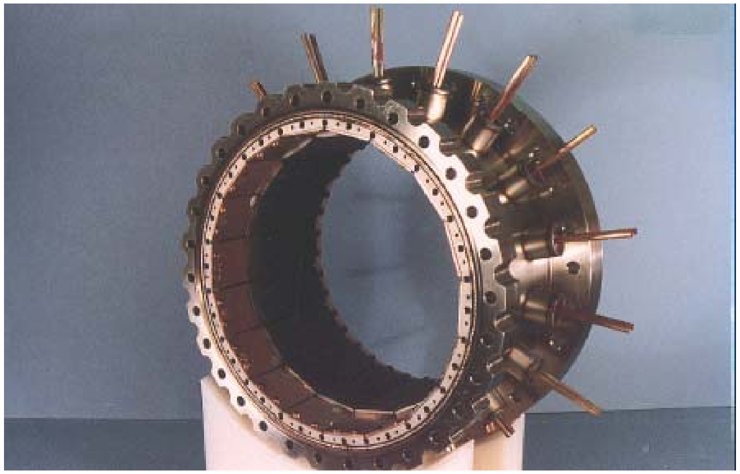
New Dedicated ERL Service Cavity

See talk by R. Calaga

- Superconducting linac cavity has new features:
  - 703.75 MHz
  - Very large apertures
  - Ferrite HOM damping in beam pipes
  - No trapped modes
- Will tolerate very high beam current
- Beam breakup > ampere

The Ampere-Class ERL Cavity



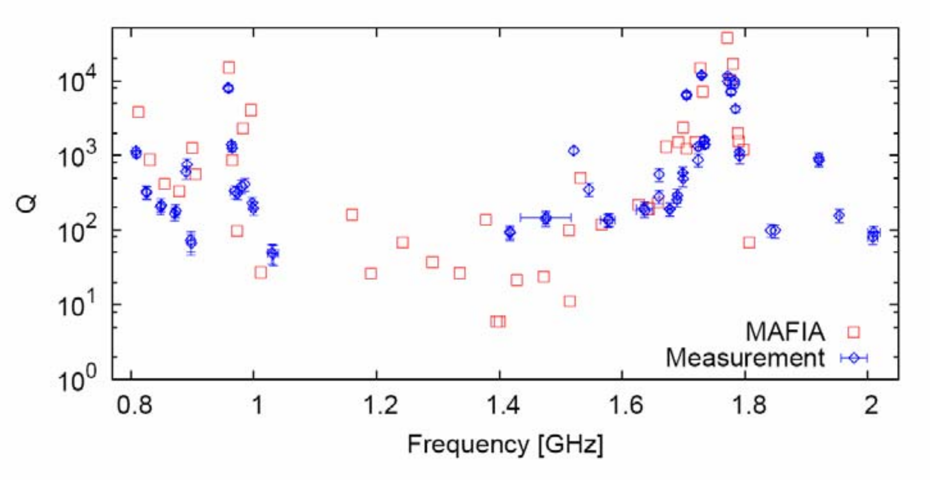


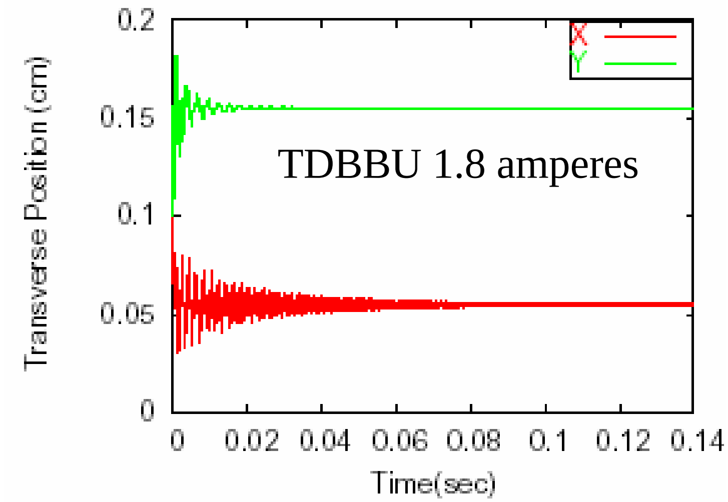
Copper model of the 703.75 MHz
high-current ERL cavity and the HOM absorber.
The niobium cavity is under construction

ERL cavity of over 1 ampere

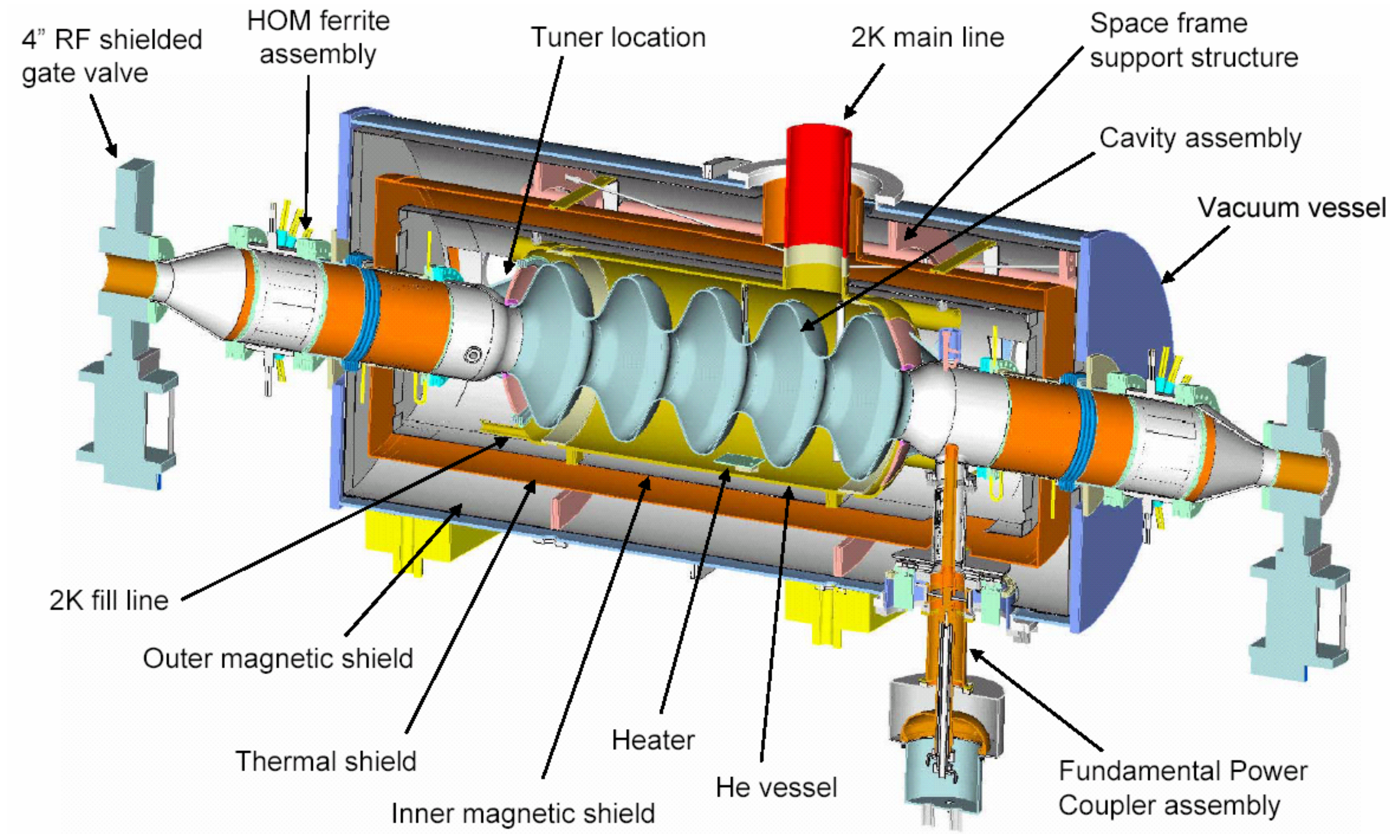
- Good cavity / HOM design, using very large beam ports to guide HOM to ferrite absorbers.
- Design has excellent SRF cavity properties, low loss factor and high BBU threshold

Measurements match MAFIA



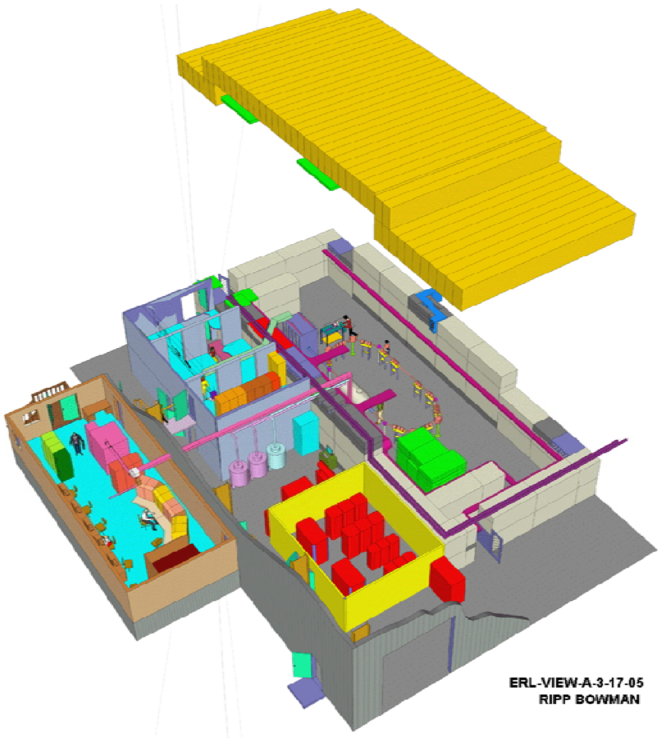


High-current ERL Cryomodule



0.5 amp ERL under construction

See talk by Vladimir Litvinenko



Luminosity is determined by the hadron beam!

$$L = f_c \frac{N_e N_h}{4\pi\beta_h^* \varepsilon_h}$$

$$L = \gamma_h \cdot \left(f_c \cdot N_h\right) \cdot \frac{\xi_h \cdot Z_h}{\beta_h^* \cdot r_h}$$

Round beams $\beta_e^* \varepsilon_e = \beta_h^* \varepsilon_h$

$$\xi_h = \frac{N_e}{\gamma_h} \frac{r_h}{4\pi Z \varepsilon_h}$$

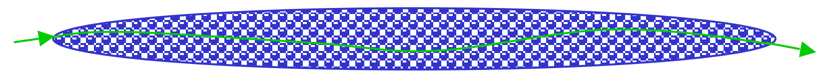
Strategy:

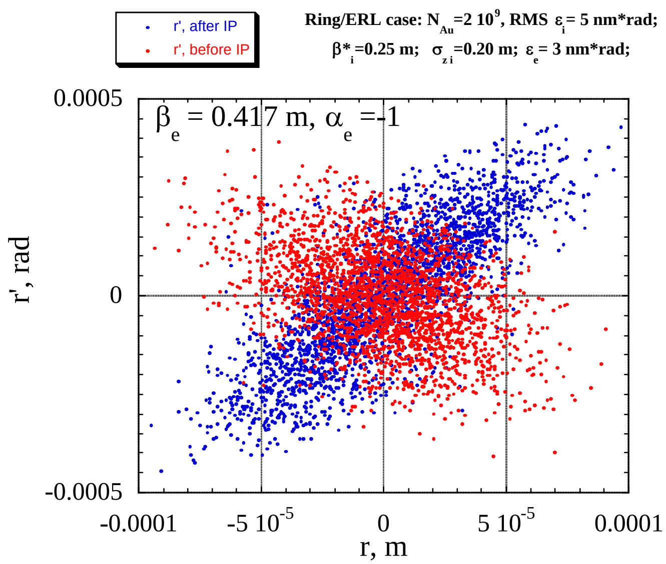
1: Maximize N_h for luminosity
2: Minimize ε_h AND N_e (if possible)
3: Small ε_e is good for IP

IP issues

$$D = \frac{Z_h N_h}{\gamma_e} \frac{r_e}{\sigma^2_{r(h)}} \sigma_{s(h)}$$

For the linac-ring collider, the beam-beam effect on the electron beam is better described not by a tune shift but by a disruption parameter, i.e. additional betatron phase advance

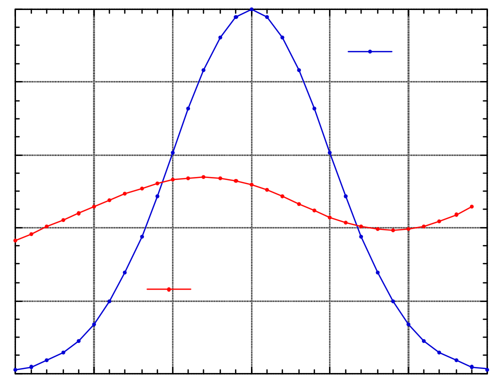




Round 10 GeV electron beam from ERL with initial transverse RMS emittance of 3 nm·rad passes through the IP with the disruption parameter 3.61 (**tune shift ξ_e = 0.6**). Poincare plots for e-beam distribution before (red) and after (blue) the IP.
After removing the *r*-*r*' correlations, the emittance growth is only 11%.

Does e-beam survives?

YES



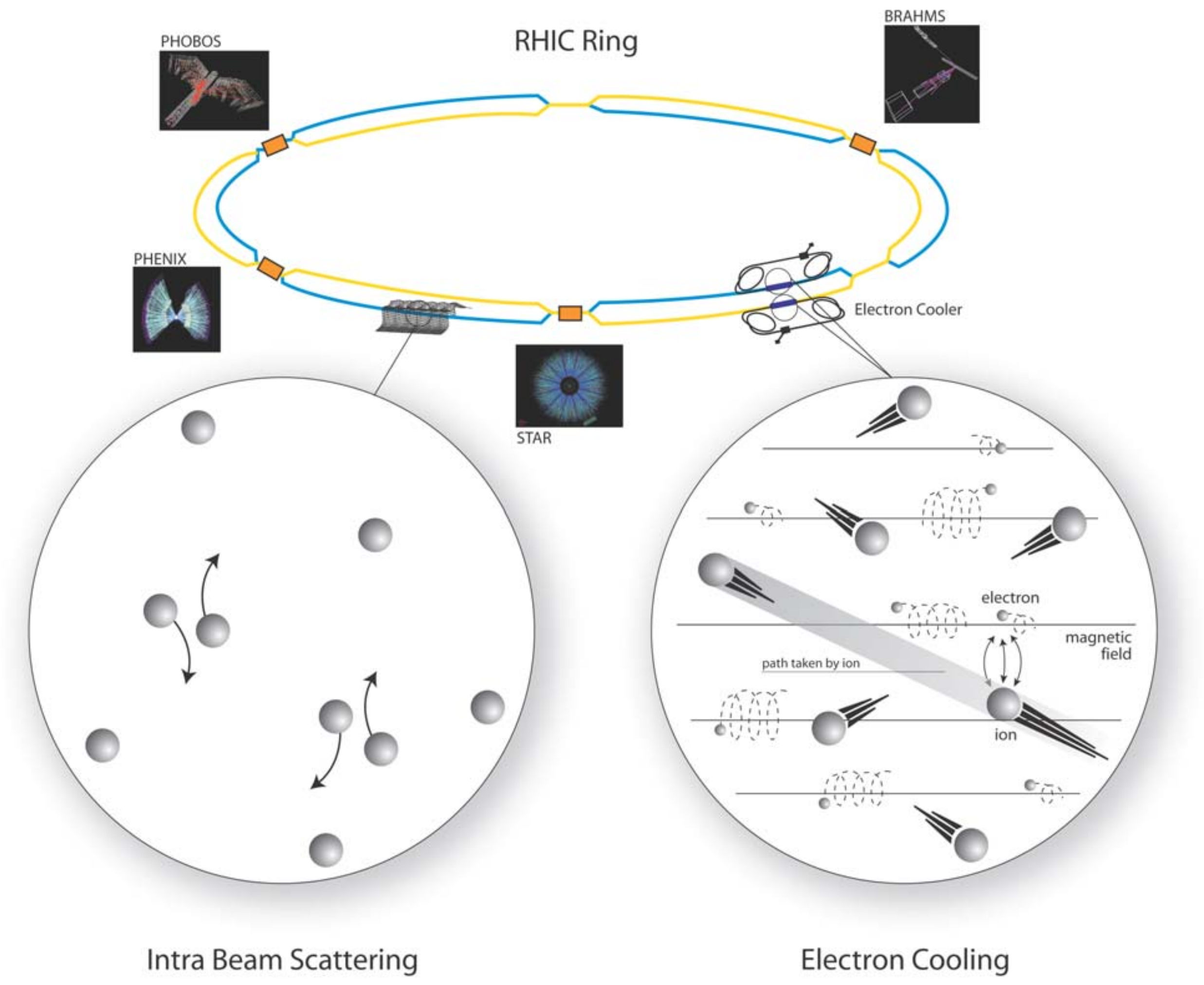
Matching the beam's size with the ion beam and a negative α=-1 at *z*=-0.3m. The e-beam's size does not shrink below the matched value and the hadron tune shift does not exceed **ξ_h = 0.005**

Integration with IP

- Round-beam collision geometry to maximize luminosity
- Smaller e-beam emittance resulting in 10-fold smaller aperture requirements for the electron beam*
- Possibility of moving the focusing quadrupoles for the e-beam outside the detector and the IP region, while leaving the dipoles used for separating the beam
- Possibility of further reducing the background of synchrotron radiation

* C.Montag - IP lattice for linac-ring

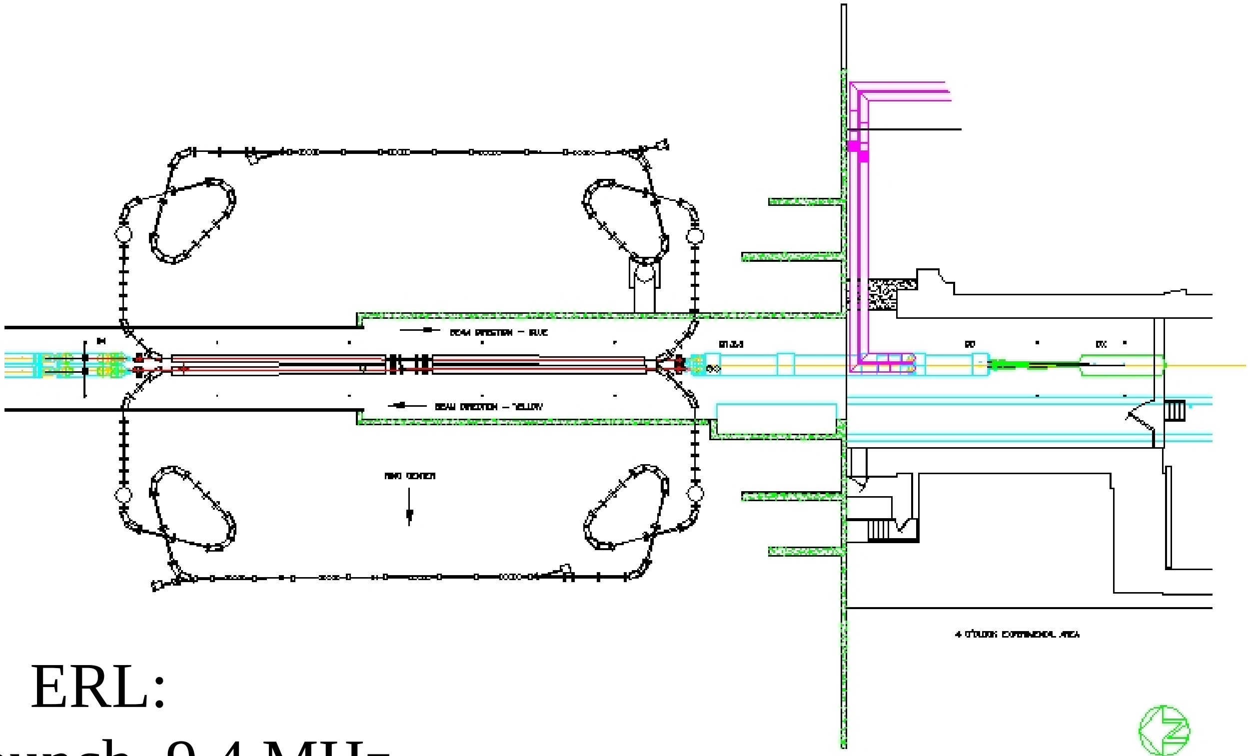
Electron Cooling



Electron Cooler

See talk by J. Kewisch

- Electron cooled RHIC (RHIC II)

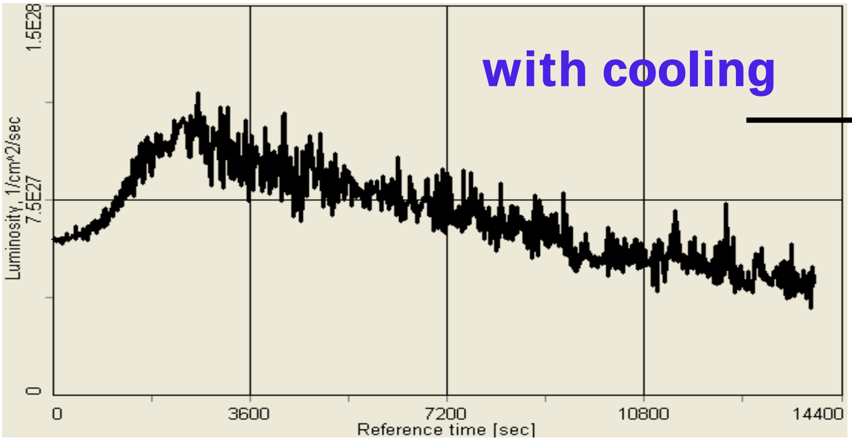


ERL:
20 nC/bunch, 9.4 MHz

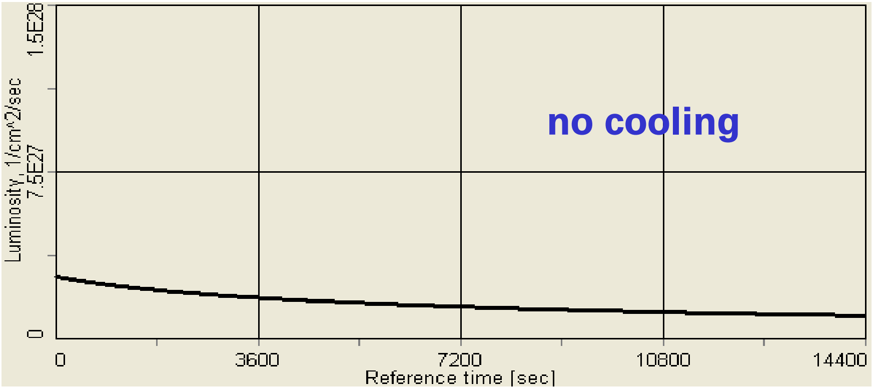
RHIC-II Luminosity (Au 100 GeV)

$N=10^9$ per bunch, 112 bunches

Alexei Fedotov



$\langle L \rangle = 7*10^{27}$



E-cooling: factor of 10 increase in average luminosity per store

Two Proposed Electron-Ion Colliders

ELIC

- Multi-turn circulation ring for electrons
  - Lower injector current
  - Need injection / ejection
  - Partial benefit for electron beam-beam
- Very high bunch frequency
- Novel ion ring complex of “figure 8” rings
- Light ions only

eRHIC

- Single pass ERL
  - High e source current required
  - Simplified structure
  - Maximum benefit from beam-beam in electron machine
- Bunch frequency of RHIC
- Well known ion ring
- All ions

What does the ERL give us?

- We can increase the ion charge and reduce number of bunches.
- The luminosity is determined just by the ion beam and can be enhanced by increasing ion bunch charge.
- Greater luminosity :
  - The linac is much more immune to the beam-beam tune spread (One pass in IP for e bunch).
  - The emittance is smaller, allowing a larger beta function.
  - The beam needs less ‘stay clear’ space.
  - See C. Montag’s presentation.
- Wider range in energy – luminosity does not depend on the electron’s energy.
- Optional energy upgrade – just extend the linac’s length.
- Polarization at any electron energy. No forbidden bands.

No issue with BBU for large ERLs

- The circumference of RHIC provides Tr~13 μs
- The BNL cavity HOM Q's is 10^2 to 10^4
- The typical frequencies are >1 GHz
- $\tau = Q/\omega \sim 10^{-8}$ to 10^{-6} seconds, or between e^{20} to e^{2000} attenuation from exponent:

$$I_{th} = \frac{-2 p_r c^2}{e\left(R/Q\right)_m Q_m \omega_m M_{12}^r \sin\left(\omega_m t_r\right) \exp\left(-\omega_m t_r / 2Q_m\right)}$$

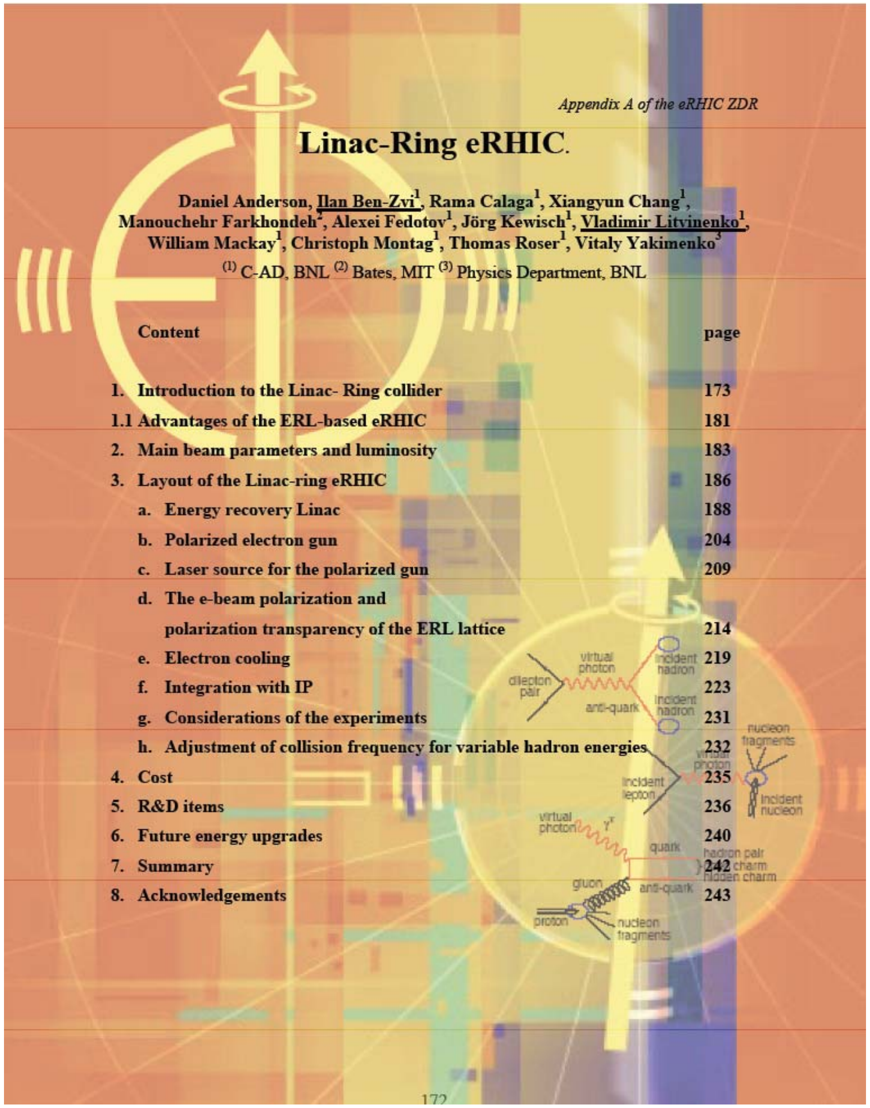
Beam-beam head-tail instability

The beam-beam force between the head of the ion bunch and the electrons will deflect the electrons. The deflected electrons subsequently interact with the tail of the proton bunch.

- The electrons appear as a transverse impedance to the ions
- Observed in numerical simulations [Li, Bisognano, (1993)]. Linear theory [Lebedev, Li & Yunn (2001) predicts threshold.
- Landau damping introduced by tunespread by electron beam and perhaps chromaticity expected to increase the threshold.
- Simulation methods have been developed at JLab to study the general nonlinear problem.

eRHIC Design

eRHIC has two options:
A ring-ring design and a linac-ring design.
Here we discuss the linac-ring design which is based on an ERL.



Appendix A of the eRHIC ZDR

Linac-Ring eRHIC.

Daniel Anderson, Ilan Ben-Zvi[1], Rama Calaga[1], Xiangyun Chang[1], Manouchehr Farkhondeh[2], Alexei Fedotov[1], Jörg Kewisch[1], Vladimir Litvinenko[1], William Mackay[1], Christoph Montag[1], Thomas Roser[1], Vitaly Yakimenko[3]
(1) C-AD, BNL (2) Bates, MIT (3) Physics Department, BNL

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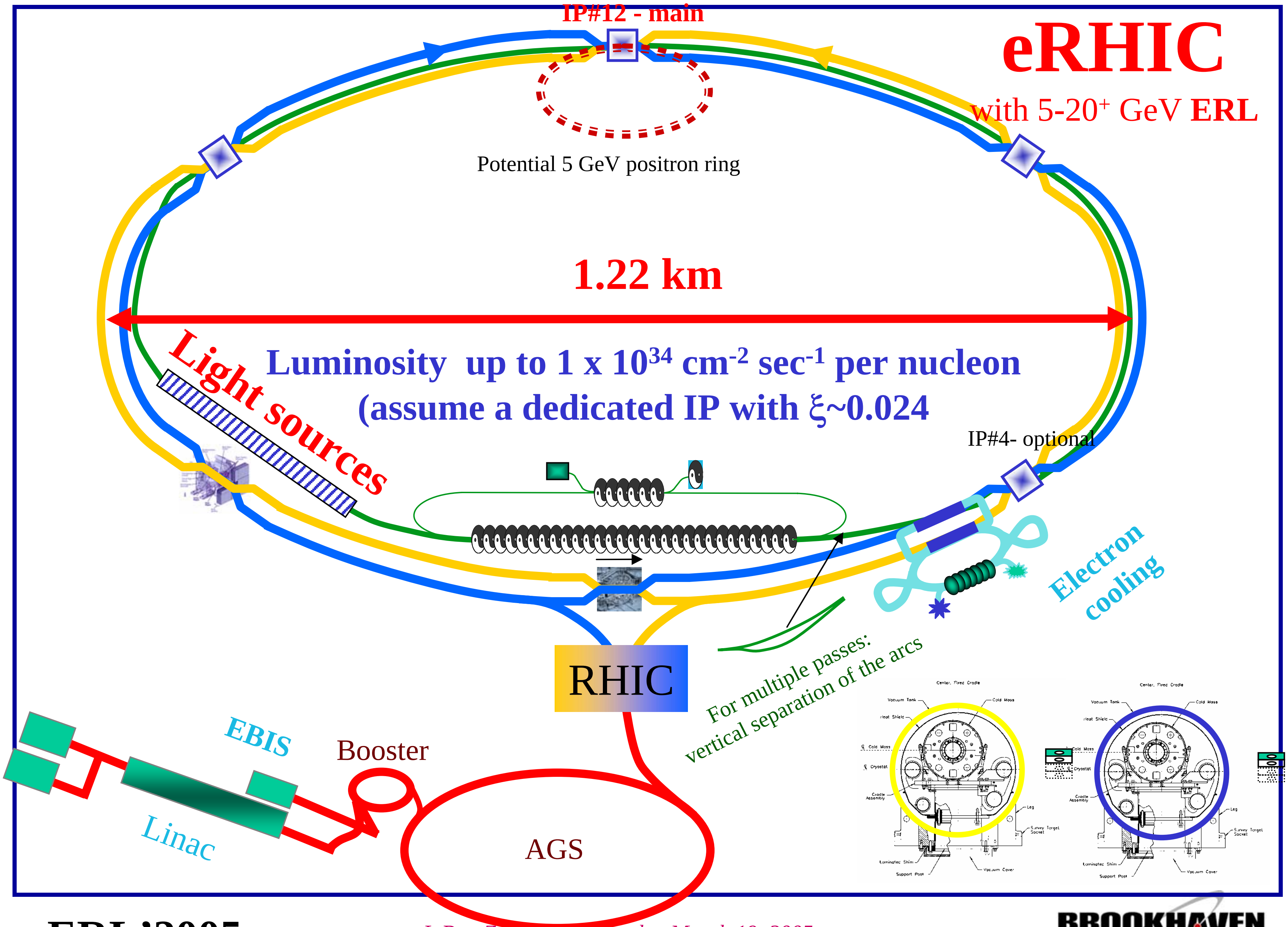

eRHIC
with 5-20+ GeV ERL
IP#12 - main
Potential 5 GeV positron ring
1.22 km
Light sources
Luminosity up to 1 x 10^34 cm^-2 sec^-1 per nucleon
(assume a dedicated IP with ξ~0.024
IP#4- optional
Electron cooling
RHIC
For multiple passes:
vertical separation of the arcs
EBIS
Booster
Linac
AGS

Electron cooled eRHIC

- The purpose of the luminosity upgrade for eRHIC is to decrease the emittance of the stored ion
- beams and maintain it at a required level. Present baseline parameters require the following:

1. Decrease of the transverse emittance of Au ions at 100 GeV energy from the 95% normalized emittance of 15 p mm to 6 p mm. Presently, emittance is increased during storage time from 15 p mm to 40 p mm due to the IBS.
2. Decrease of the transverse normalized emittance of protons to 5 p mm at lower energies 25-50 GeV.
3. Decrease of the longitudinal emittance which provides bunch shortening. The beta-star function at IP requires shortening of the rms bunch length below 25 cm for both protons and Au ions.

- An initial study indicates that all three major tasks described above can be achieved with the electron cooler under design for RHIC II.

Center-of-mass energies for linac-ring eRHIC

Energy, GeV **proton** / **electons** c.m.	**26**	**50**	**100**	**250**
1	10.20	14.14	20.00	31.62
2	**14.42**	20.00	28.28	44.72
5	22.80	31.62	44.72	70.71
10	32.25	44.72	63.25	**100.00**
20	45.61	63.25	89.44	141.42
30	55.86	77.46	109.54	173.21

Energy, GeV **Au/u** / **e** c.m.	**50**	**100**
1	14.14	**20.00**
2	**20.00**	28.28
5	31.62	44.72
10	44.72	**63.25**
20	63.25	89.44
30	77.46	109.54

Beam parameters

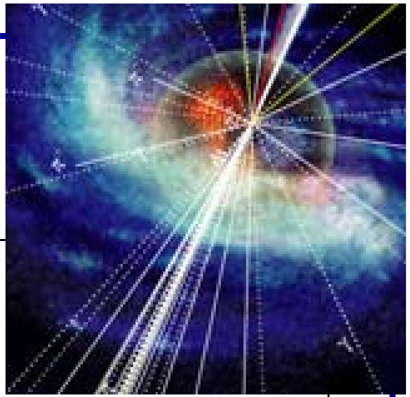
	main case	*option*
RHIC		
Ring circumference [m]	3834	
Number of bunches	360	
Beam rep-rate [MHz]	28.15	
Protons: number of bunches	360	*120*
Beam energy [GeV]	26 - 250	
Protons per bunch (max)	$2.0 \cdot 10^{11}$	*$6 \cdot 10^{11}$*
Normalized 96% emittance [μm]	14.5	
β* [m]	0.26	
RMS Bunch length [m]	0.2	
Beam-beam tune shift in eRHIC	0.005	
Synchrotron tune, Qs	0.0028 (see [2.4])	
Gold ions: number of bunches	360	*120*
Beam energy [GeV/u]	50 - 100	
Ions per bunch (max)	$2.0 \cdot 10^{9}$	*$6 \cdot 10^{9}$*
Normalized 96% emittance [μm]	6	
β* [m]	0.25	
RMS Bunch length [m]	0.2	
Beam-beam tune shift	0.005	
Synchrotron tune, Qs	0.0026	
Electrons:		
Beam rep-rate [MHz]	28.15	*9.38*
Beam energy [GeV]	2 - 10	
RMS normalized emittance [μm]	5- 50 *for $N_e = 10^{10} / 10^{11}$ e^- per bunch*	
β*	~ 1m, *to fit beam-size of hadron beam*	
RMS Bunch length [m]	0.01	
Electrons per bunch	$0.1 - 1.0 \cdot 10^{11}$	
Charge per bunch [nC]	1.6 – 16	
Average e-beam current [A]	0.045 – 0.45	*0.015 – 0.15*

Special features

- Wide range of collision energies (E_{cm}/nucleon from 15 GeV to 100+ GeV. e^- energy as low as 1 GeV as high as 30 GeV).
- High luminosity
  - 10^{34} cm^{-2} s^{-1} for high energy protons,
  - 10^{32} cm^{-2} s^{-1} for high energy Au ions.
- High degree of polarization (>80%) of the electrons at any energy, no forbidden energies.
- One, two, three … interaction regions with dedicated detectors
- Energy of electron is simply upgradeable up to 20 GeV.
- Reduction of synchrotron radiation in detector by cooling ions.
- Simplified IP: No quadrupoles in detector, low e emittance, easy separation of beams.
- Simple compensation for ion velocity.
- Possibility of γ-ion collider.

Limitations and challenges

- No positron-ion collisions (can be provided separately in a small self-polarizing ring).
- Need for intense R&D program on
  - High intensity, high current polarized electron source
  - High current ERL (on-going program)



ELIC Design

Ya. Derbenev, K. Beard, S. Chattopadhyay, J. Delayen, J. Grames, A. Hutton, G. Krafft, R. Li, L. Merminga, M. Poelker, E. Pozdeyev, B. Yunn, Y. Zhang

Center for Advanced Studies of Accelerators

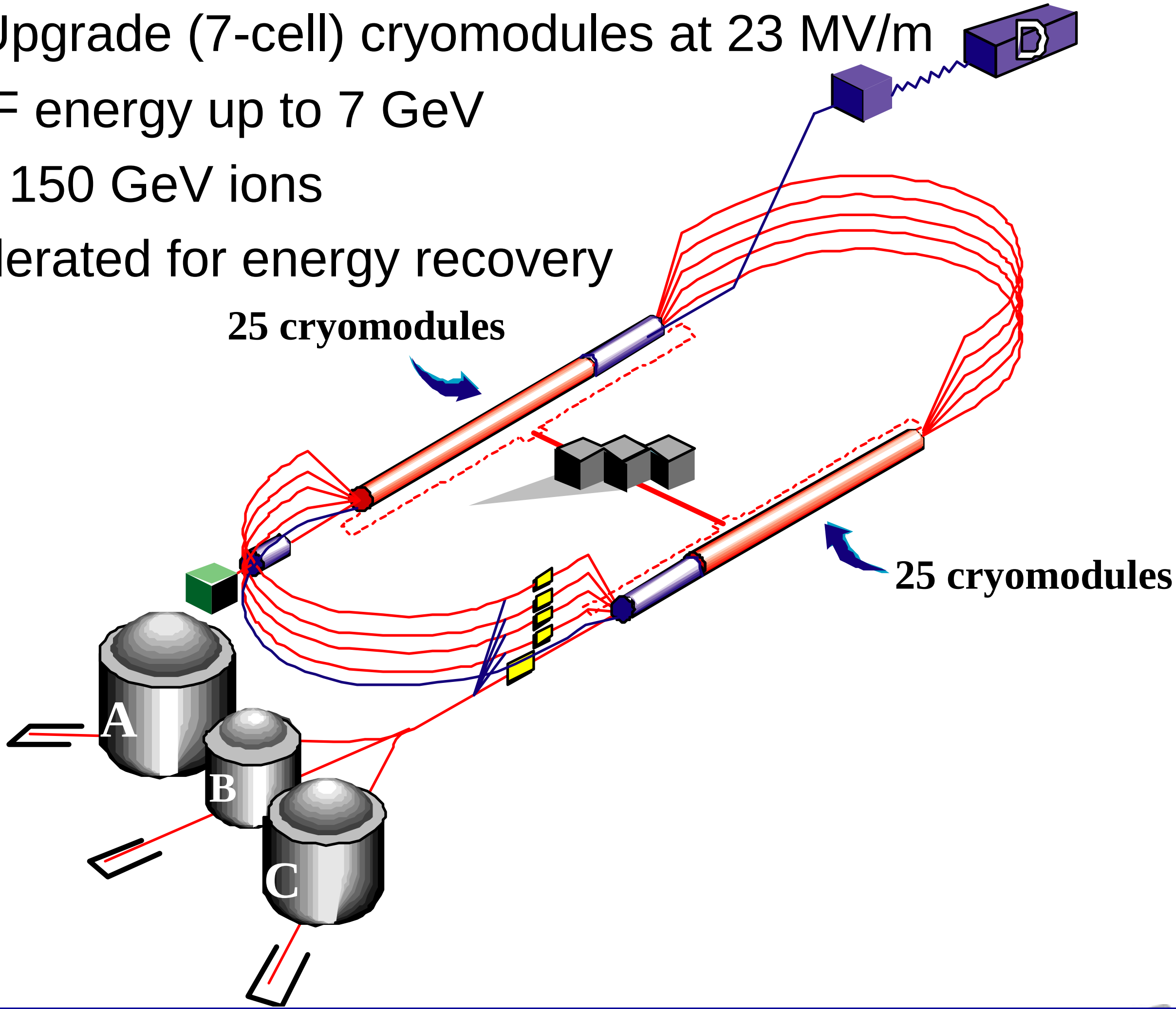
Jefferson Lab

Second Electron-Ion Collider Workshop
Jefferson Lab
March 15 - 17, 2004

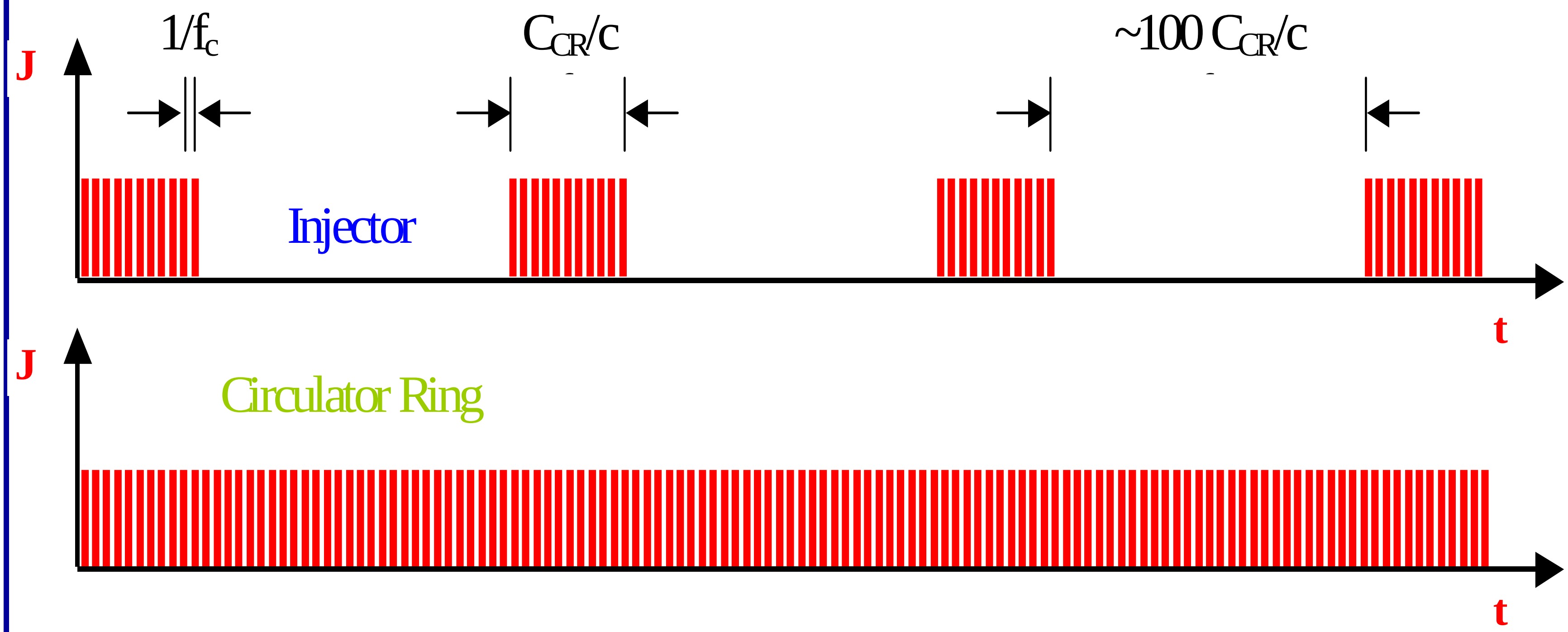
CEBAF with Energy Recovery

- Install 50 CEBAF Upgrade (7-cell) cryomodules at 23 MV/m
- Single-pass CEBAF energy up to 7 GeV
- Collisions with 30 - 150 GeV ions
- Electrons are decelerated for energy recovery

CEBAF ER experiment:
1 GeV ERL
1 km, 39 modules
50:1 energy ratio
Phase space evolution

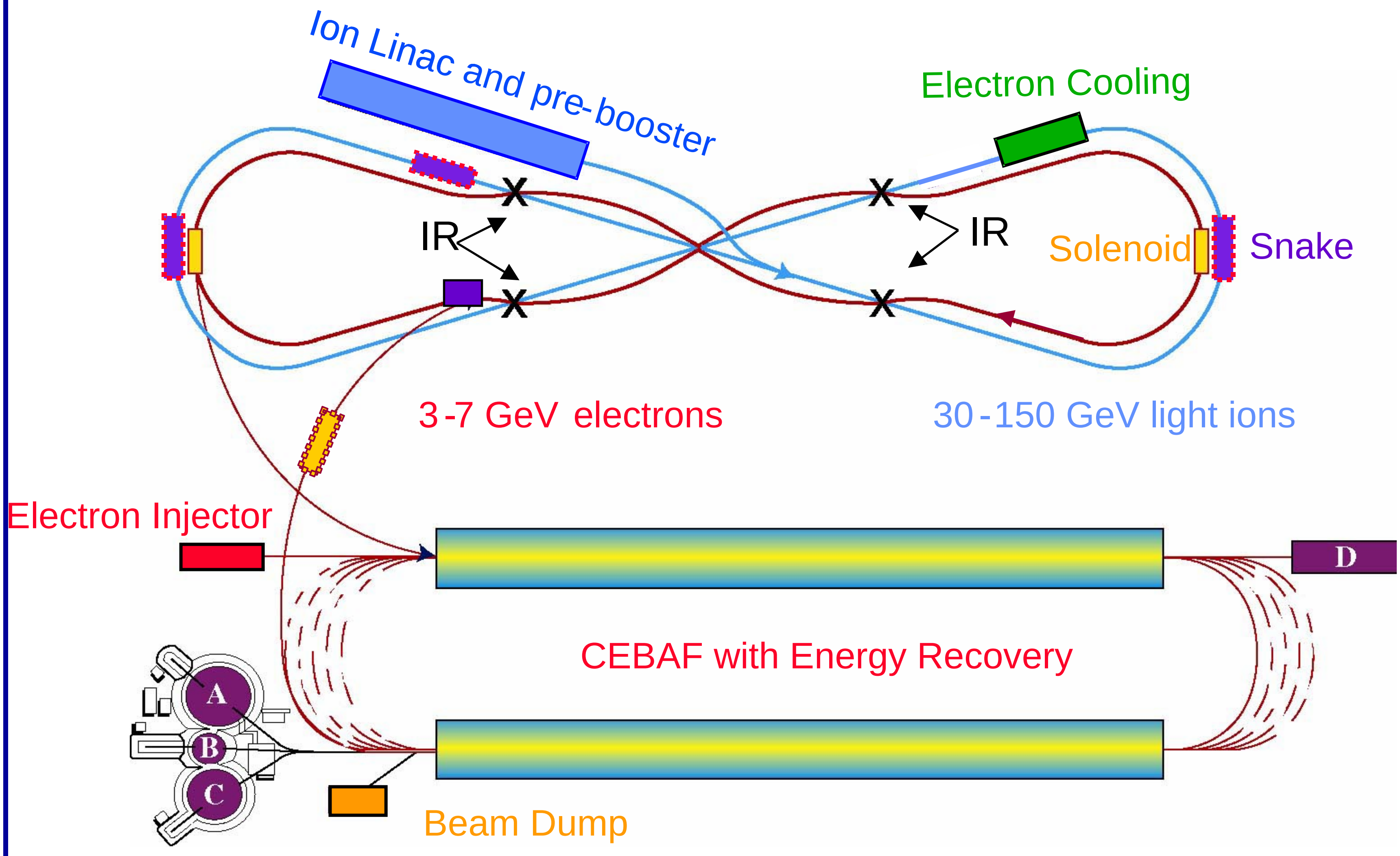


Circulator Ring



Different filling patterns are being explored (Derbenev, Hutton, Litvinenko)

ELIC Layout



Ion Linac and pre-booster
Electron Cooling
IR
IR
Solenoid
Snake
3-7 GeV electrons
30-150 GeV light ions
Electron Injector
D
CEBAF with Energy Recovery
A
B
C
Beam Dump

ELIC vs. CM energies

Parameter	Unit	Value	Value	Value
Beam energy	**GeV**	**150/7**	**100/5**	**30/3**
Cooling beam energy	**MeV**	**75**	**50**	**15**
Bunch collision rate	**GHz**	**1.5**		
Number of particles/bunch	10^{10}	**.4/1.0**	**.4/1.1**	**.12/1.7**
Beam current	**A**	**1/2.4**	**1/2.7**	**.3/4.1**
Cooling beam current	**A**	**2**	**2**	**.6**
Energy spread, rms	10^{-4}	**3**		
Bunch length, rms	**mm**	**5**		
Beta-star	**mm**	**5**		
Horizontal emittance, norm	μ**m**	**1/100**	**.7/70**	**.2/43**
Vertical emittance, norm	μ**m**	**.04/4**	**.06/6**	**.2/43**
Number of interaction points		**4**		
Beam-beam tune shift (vertical) per IP		**.01/.086**	**.01/.073**	**.01/.007**
Space charge tune shift in p-beam		**.015**	**.03**	**.06**
Luminosity per IP*, 10^{34}	$cm^{-2}\ s^{-1}$	**7.7**	**5.6**	**.8**
Core & luminosity IBS lifetime	**h**	**24**	**24**	**> 24**
Lifetime due to background scattering	**h**	**200**	**> 200**	**> 200**

ELIC Parameter choices

- An evolutionary upgrade path: start at ~ 10^{33} cm^{-2} sec^{-1} at bunch rep rate of 150 MHz, progresses to ~ 10^{34} cm^{-2} sec^{-1} at higher bunch rep rate while ~ 1 Ampere of electron beam current will require the use of circulator ring, and reaches the ultimate potential of nearly $8x10^{34}$ cm^{-2} sec^{-1} at maximum rep rate of 1.5 GHz. In addition to the circulator ring, this scenario assumes that strong SRF fields in the SR together with electron cooling allow very short ion bunches, which in turn allow very low beta-star and make crab crossing feasible.
- All parameter sets assume electron cooling and the resulting flat beams at equilibrium and parameters have been calculated at the beam-beam tuneshift limit for the ion beam of 0.01. Equal beam sizes for electrons and ions are assumed at the IP.

ELIC Luminosity evolution

Parameter	Unit	Value	Value	Value
Beam energy	**GeV**	**150/7**		
Cooling beam energy	**MeV**	**75**		
Bunch collision rate	**GHz**	**.15**	**.5**	**1.5**
Number of particles/bunch	**10^{10}**	**.4/1.0**		
Beam current	**A**	**.1/.24**	**.3/.8**	**1/2.4**
Cooling beam current	**A**	**.2**	**.6**	**2**
Energy spread, rms	**10^{-4}**	**3**		
Bunch length, rms	**mm**	**25/5**	**10/5**	**5/5**
Beta-star	**mm**	**25**	**10**	**5**
Horizontal emittance, norm	**μm**	**1/100**		
Vertical emittance, norm	**μm**	**.04/4**		
Number of interaction points		**4**		
Beam-beam tune shift (vertical) per IP		**.01/.086**	**.01/.086**	**.01/.086**
Space charge tune shift in p-beam		**.003**	**.007**	**.015**
Luminosity per IP*, 10^{34}	**$cm^{-2}\ s^{-1}$**	**.15**	**1.2**	**7.7**

The Electron Linac

- Electron Source
  - State of the art in high average current, polarized sources: ~1 mA at 80% polarization [M. Poelker, JLab]
  - State of the art in high average current, unpolarized sources: JLab FEL Upgrade achieved 7 mA, design 10 mA
  - Circulator ring concept greatly reduces source requirements
- Accelerator Transport in the ERL
  - Demonstrate energy recovery with large energy ratio
  - High current stability in the ERL, adequate damping of longitudinal and transverse HOMs
- SRF/RF/Cryogenics issues

R&D Topics

- High charge / average current polarized e gun
- High energy electron cooling of protons/ions
  - Electron cooling requires SRF-ERL technology
  - BNL, JLab and others collaborate on ERL-based electron cooling at RHIC
- Integration of interaction region design with detector geometry
- High current and high energy demonstrations of energy recovery

Conclusions

- Excellent scientific developing for a high luminosity, polarized electron-ion collider.
- JLab design: luminosities 10^{33} up to nearly 10^{35} (cm^{-2} sec^{-1}), for electron-light ion collisions at 20 to 65 GeV CM.
- BNL-MIT design: luminosities 10^{33} up to nearly 10^{34}, electrons with any ion up to 100 GeV CM.
- Planned R&D will address open readiness issues