eRHIC Conceptual Design

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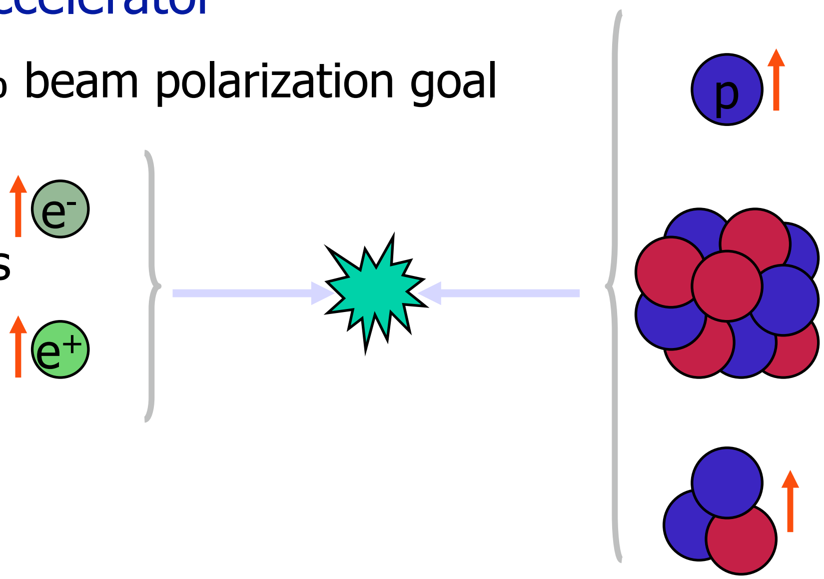
eRHIC Scope

Electron accelerator

70% beam polarization goal

Polarized leptons
3-10 Gev
(20GeV)



RHIC

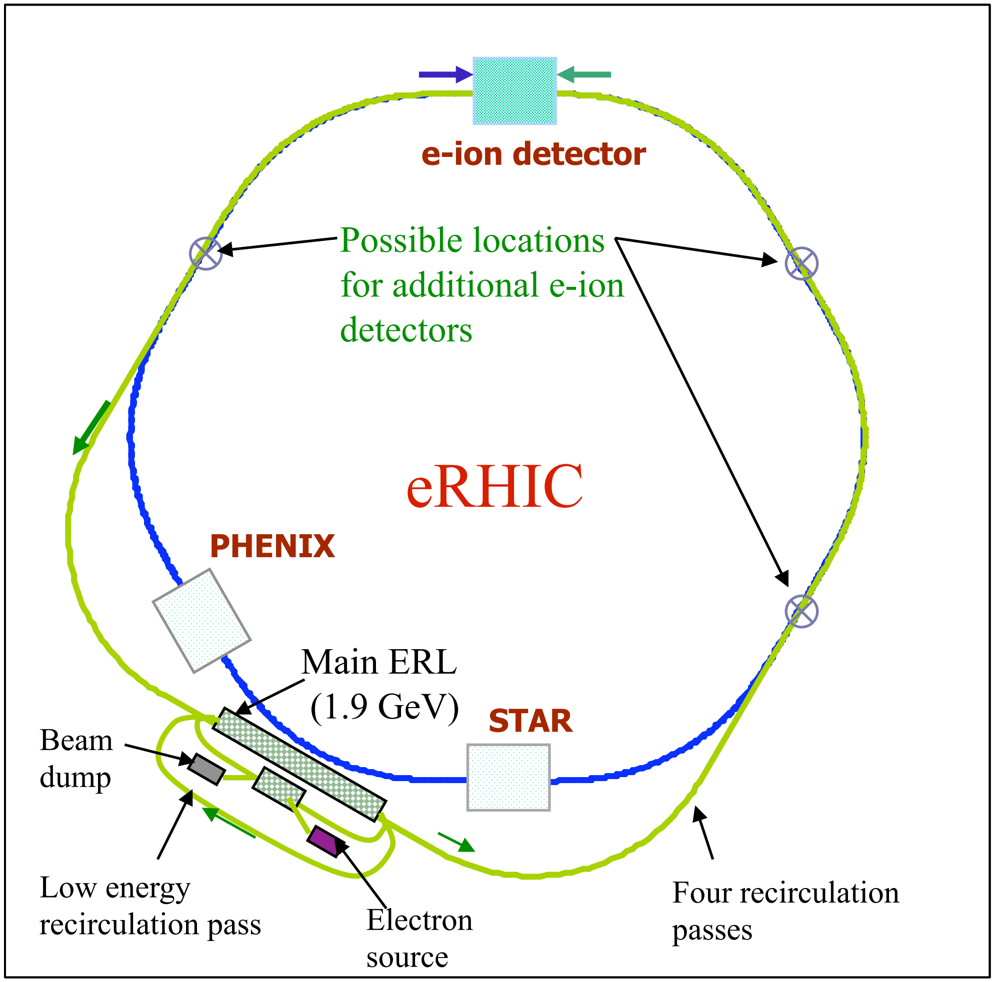
Polarized protons
50-250 Gev
(25 GeV)

Heavy ions
(Au)
50-100 Gev/u

Polarized light ions (^{3}He)
167 Gev/u

Exploration of QCD in great details:
Different Center-of-Mass Energy -> Different kinematic regions
Higher Luminosity-> Precision data
Polarized beams -> Spin structure of nucleons (still a puzzle!)
Ions up to large A -> Color Glass Condensate (state of extreme gluon densities)

ERL-based eRHIC Design



- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- Full polarization transparency at all energies for the electron beam;
- Ability to take full advantage of transverse cooling of the hadron beams;
- Possible options to include polarized positrons: compact storage ring; compton backscattered; undulator-based. Though at lower luminosity.

ERL-based eRHIC Parameters: e-p mode

	High energy setup		Low energy setup	
	p	e	p	e
Energy, GeV	250	10	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity,	$2 \cdot 10^{11}$	$1.2 \cdot 10^{11}$	2	1.2
Beam current (mA)	420	260	420	260
Normalized 95% emittance (π mm mrad)	6	460	6	570
Rms emittance, nm	3.8	4	19	16.5
β*, x/y, cm	26	25	26	30
Beam-beam parameters, x/y	0.015	0.59	0.015	0.47
Rms bunch length, cm	20	1	20	1
Polarization, %	70	80	70	80
Peak Luminosity,	$2.6 \cdot 10^{33}$ cm^{-2} s^{-1}		$0.53 \cdot 10^{33}$ cm^{-2} s^{-1}	
Aver. Luminosity x1.e33 $cm^{-2}s^{-1}$	0.87		0.18	
Luminosity integral /week pb^{-1}	530		105	

ERL-based eRHIC Parameters: e-Au mode

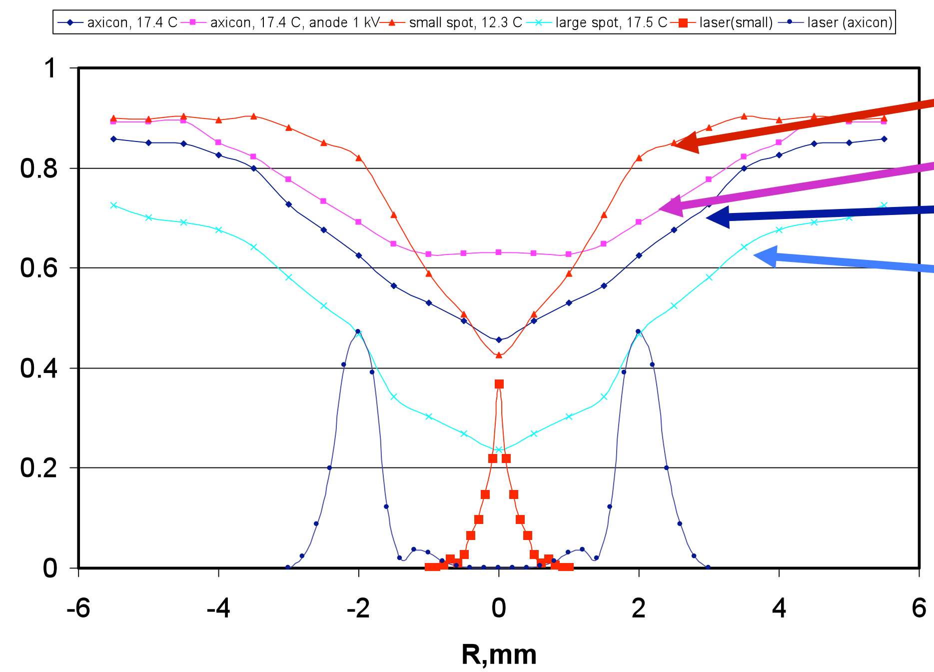
	High energy setup		Low energy setup	
	Au	e	Au	e
Energy, GeV	100	10	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity, 10^{11}	1.1	1.2	1.1	1.2
Beam current, mA	180	260	180	260
Normalized 95% emittance (π mm.mrad)	2.4	460	2.4	270
Rms emittance (nm)	3.7	3.8	7.5	7.8
β*, x/y (cm)	26	25	26	25
Beam-beam parameters x/y	0.015	0.26	0.015	0.43
Rms bunch length (cm)	20	1	20	1
Polarization (%)	0	0	0	0
Peak e-nucleon luminosity	$2.9 \cdot 10^{33}$ cm^{-2} s^{-1}		$1.5 \cdot 10^{33}$ cm^{-2} s^{-1}	
Average e-nucleon luminosity 1.e33 cm^{-2}s^{-1}	1.0		0.5	
Luminosity integral /week pb^{-1}	580		290	

Main R&D Items

- **Electron beam R&D for ERL-based design**:
  - **High intensity polarized electron source**
    - Development of large cathode guns with existing current densities ~ 50 mA/ cm^2 with good cathode lifetime.
  - **Energy recovery technology for high power beams**
    - Multi-cavity cry module development; high power beam ERL, BNL ERL test facility; loss protection; instabilities.
  - Development of compact recirculation loop magnets
    - Design, build and test a prototype of a small gap magnet and its vacuum chamber.
  - Beam-beam effects: e-beam disruption
- Main R&D items for ion beam:
  - Beam-beam effects: electron pinch effect; the kink instability …
  - Polarized ^3He acceleration
  - 166 bunches
- General EIC R&D item:
  - Proof of principle of the coherent electron cooling

Polarized source development

- eRHIC: ~ 250 mA average I, 20 nC/bunch
- MEeIC at RHIC: 50 mA average I, 5 nC/bunch



Laser beam forms:

- small central spot
- ring-like (+anode bias)
- ring-like
- large central spot

Cathode deterioration measured with various shape of laser spot on the cathode confirms possible advantages of ring-like cathode shape. (E. Tsentalovich)

R&D development for a source with large cathode area and, probably, ring like cathode shape is underway (MIT-Bates, E. Tsentalovich)

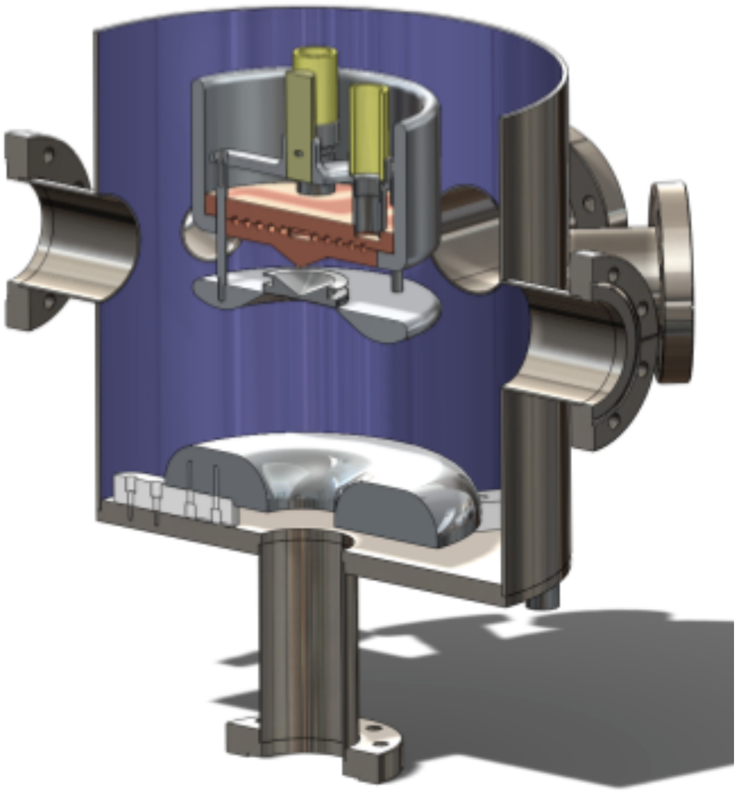
Major issues:

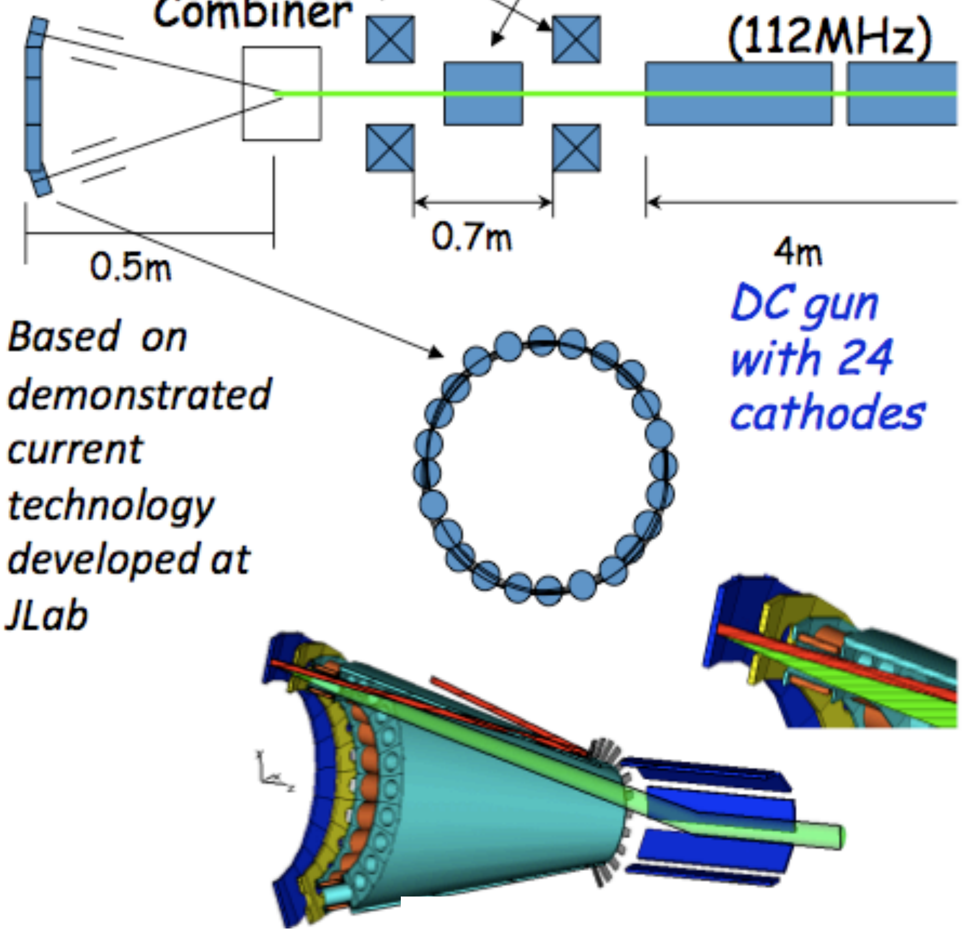
- Cathode deterioration by ion back bombardment
- Cathode heating -> requires cooling

Polarized source development

Single cathode DC gun

E.Tsentalovich, MIT





Based on demonstrated current technology developed at JLab

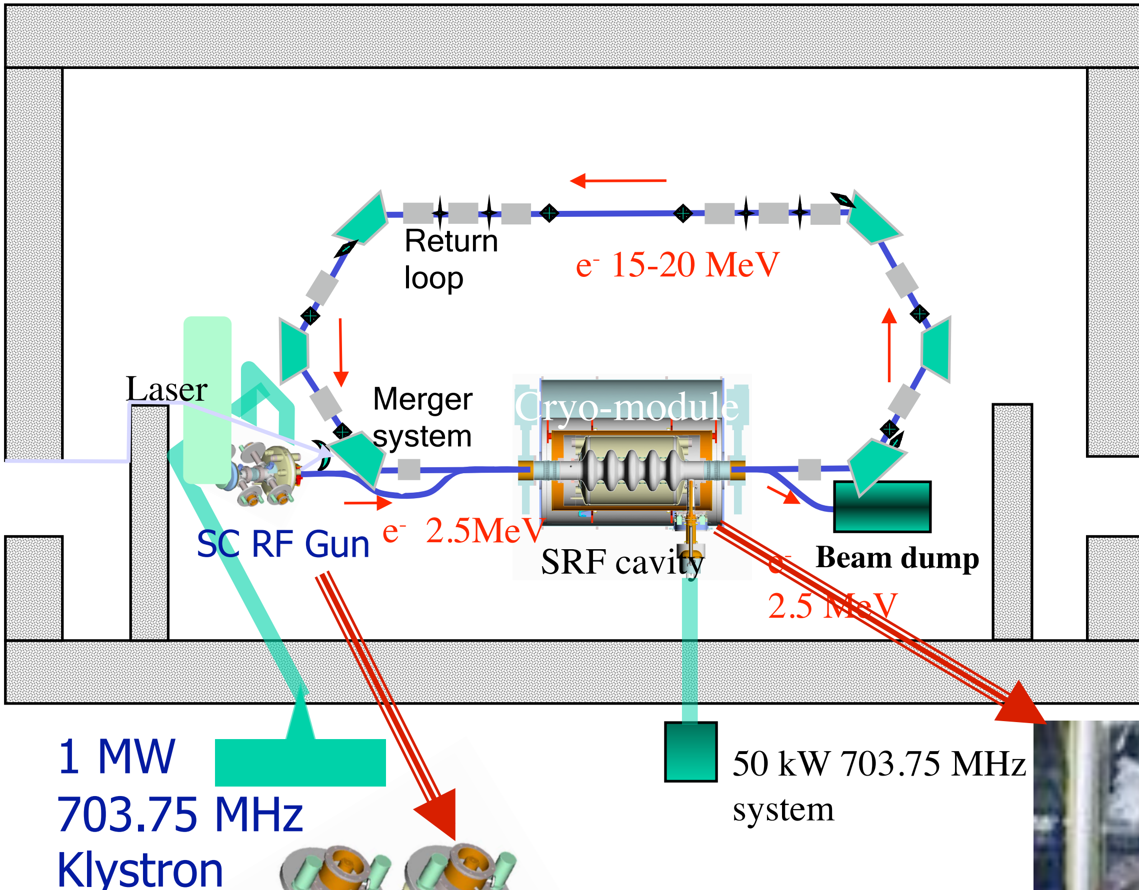
DC gun with 24 cathodes

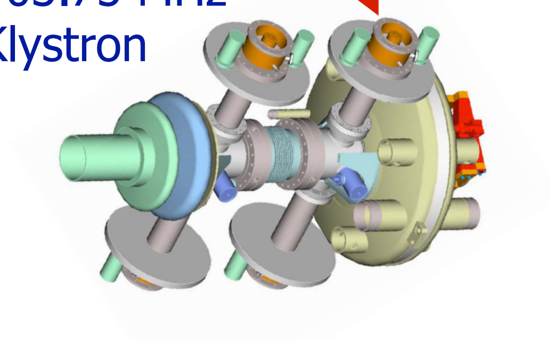
ERL Test Facility

from D. Kayran

- test of high current (several hundred mAmps) high brightness ERL operation
- test of high current beam stability issues
- 5-cell cavity SRF ERL
- highly flexible lattice
- 704 MHz SRF gun test

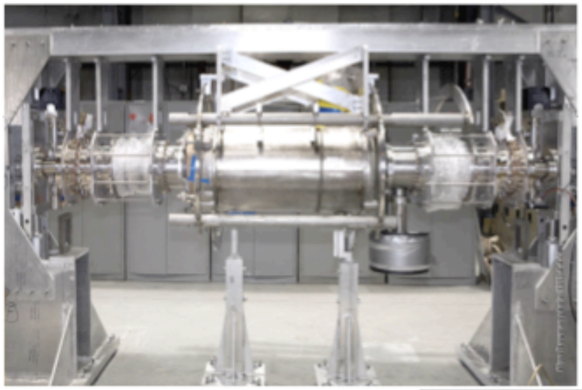
Start of the commissioning in 2009.

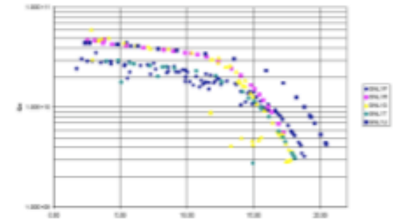


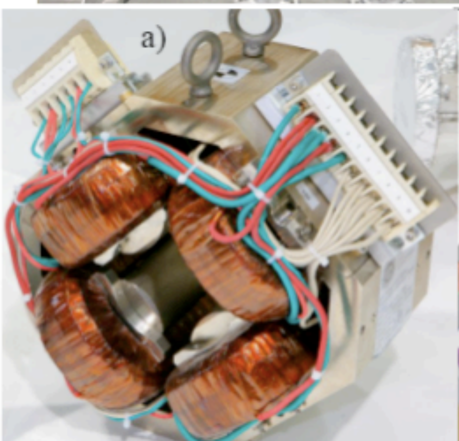


5 cell SRF cavity arrived in BNL in March 2008 .

R&D ERL Commissioning start 2009

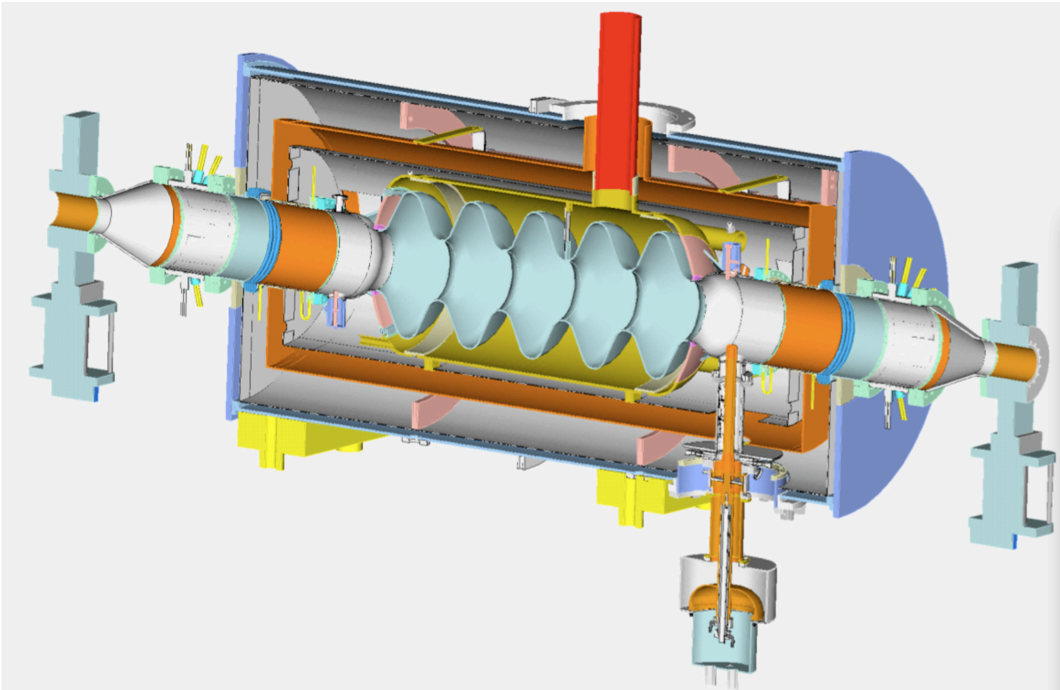


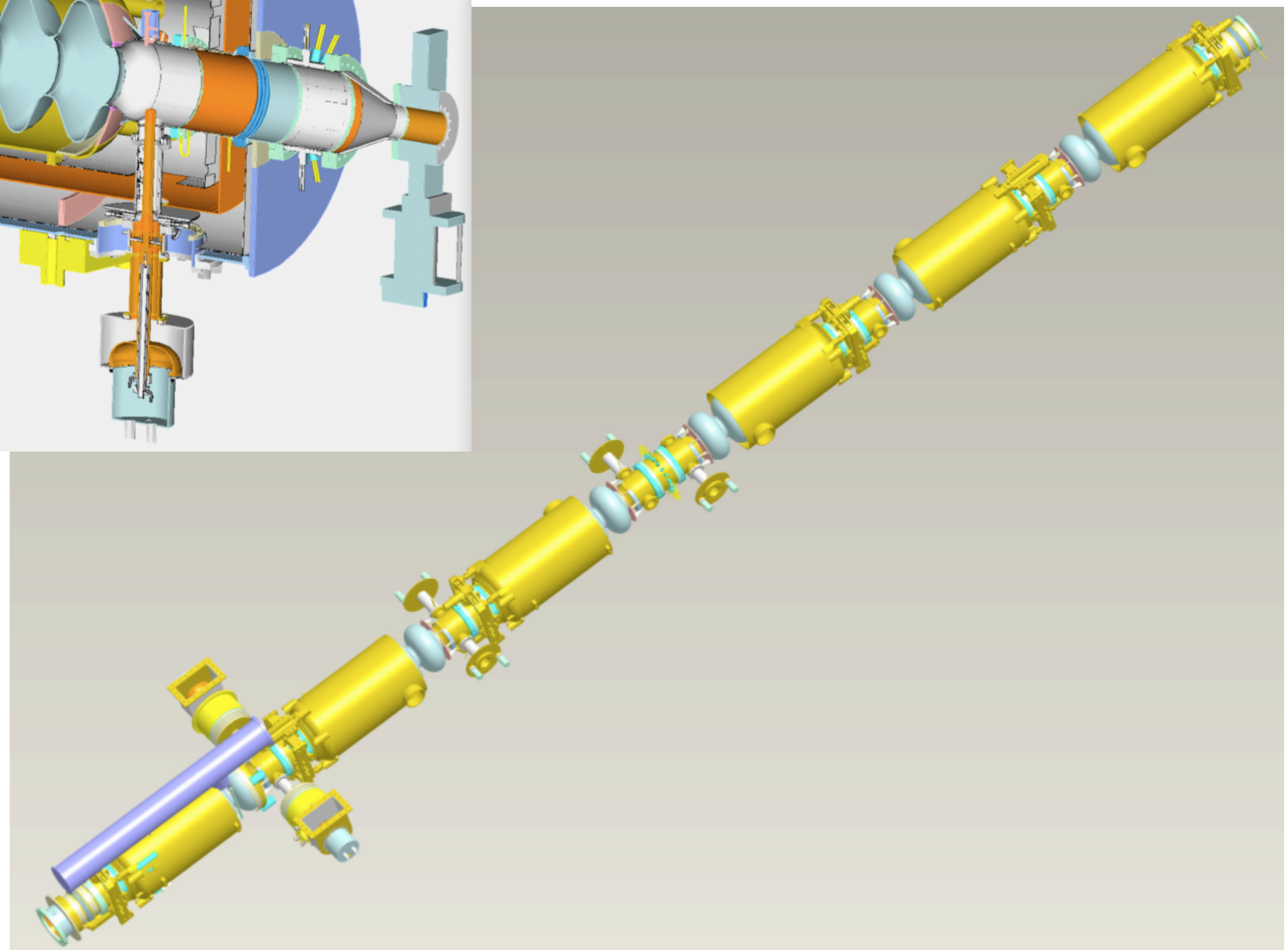




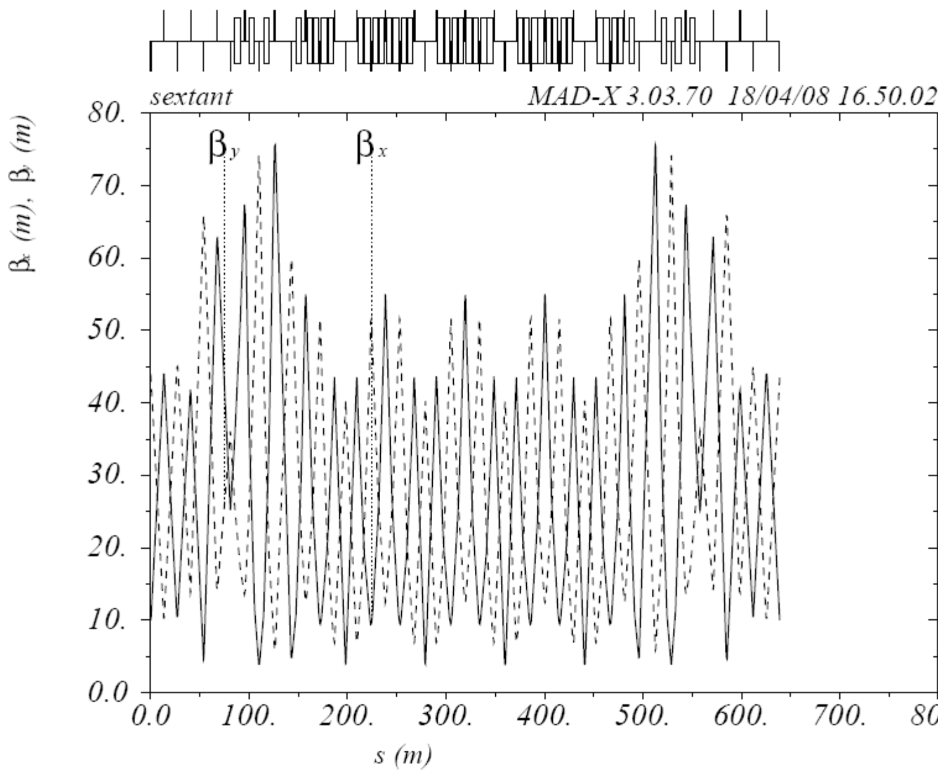
Electron beam R&D for ERL:

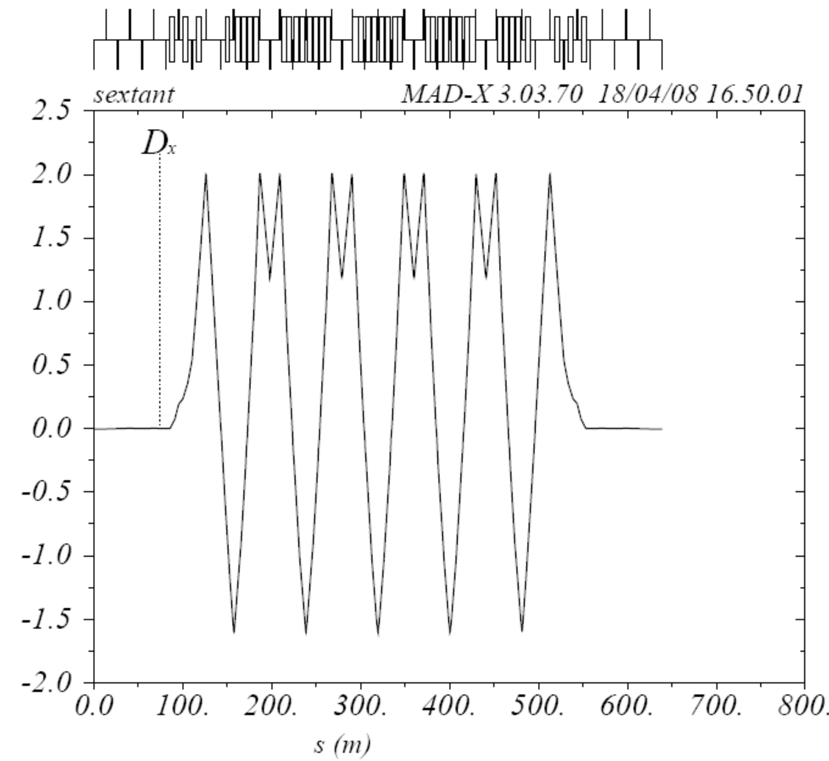
Linac design for eRHIC as well as for the MeRHIC





Recirculation Pass Optics Modification



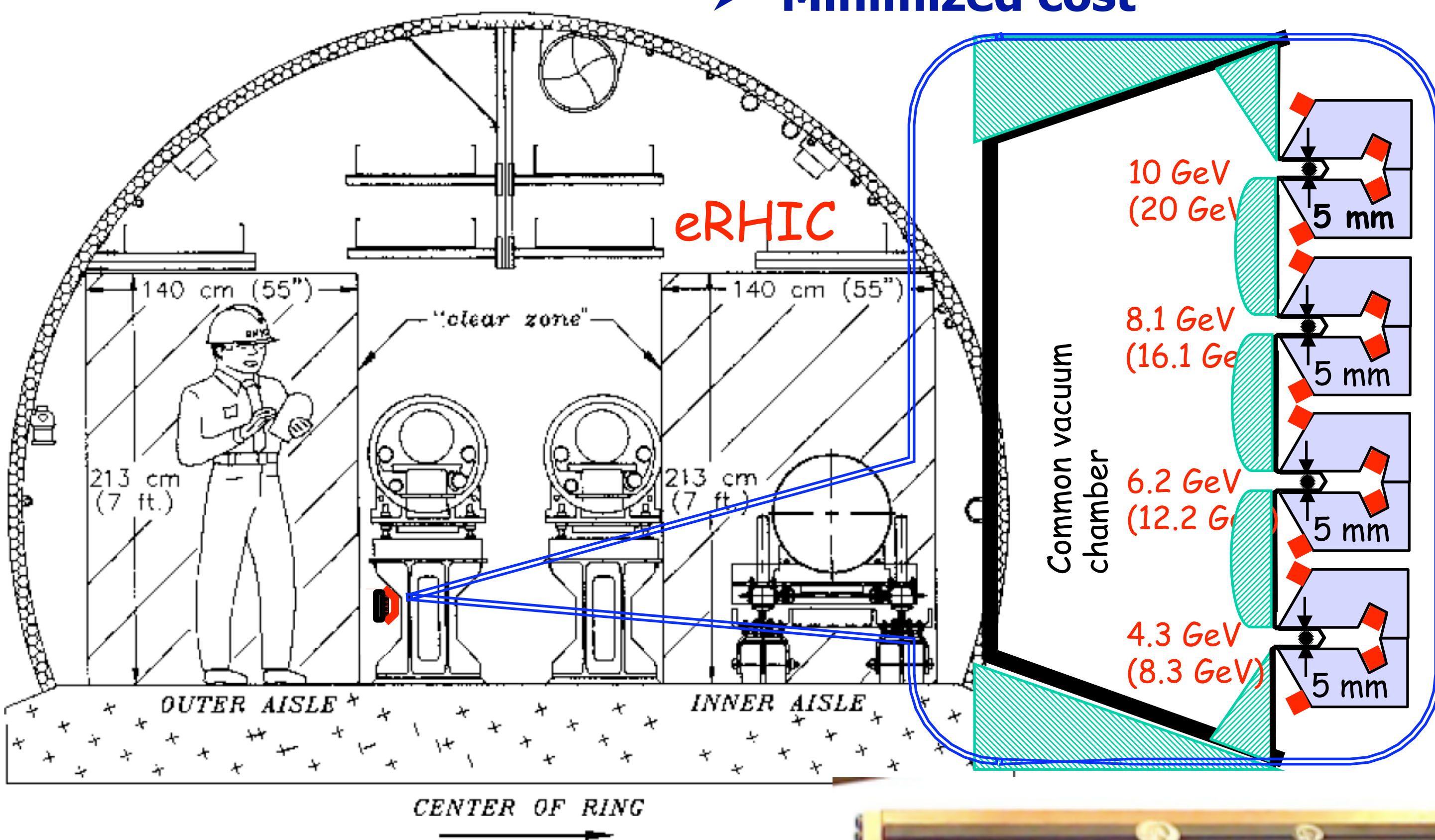


Other features:
-phase trombone (in the straight sections)
-path length control (at 12 o'clock region)
-initial design for separator/merger

The optics based on Flexible Momentum Compaction cell provides achromatic and isochronal transfer through each arc and allows for flexible adjustment of R_{56} parameter.

Four recirculation passes:

- **Separate recirculation loops**
- **Small aperture magnets**
- **Low current, low power consumption**
- **Minimized cost**



Prototype magnets are already built
(V. N. Litvinenko)

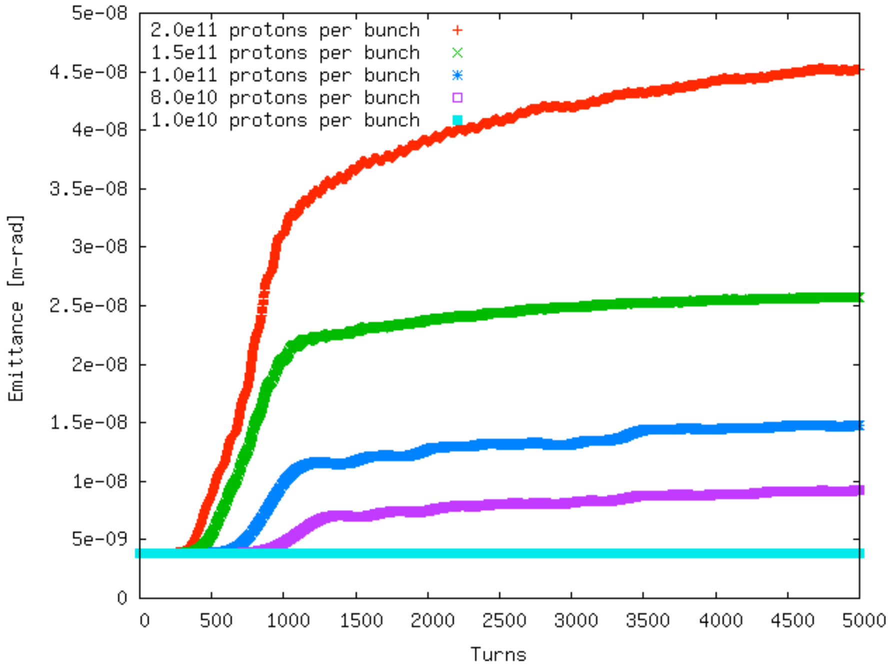
Beam-beam interaction studies

Several features of the beam-beam interactions are under consideration:

- The kink instability is stabilized for design beam intensities by proper choice of the chromaticity.
- Techniques for compensation of the mismatch caused by the beam-beam are under consideration.
- Both electron beam disruption and proton beam-beam parameter benefit from lower β^* of electrons.
- More investigations are underway for incoherent proton beam emittance growth in the presence of electron pinch, including the optimal choice of the working point.
- For details see a presentation in the Parallel session as well as a talk at previous meeting.

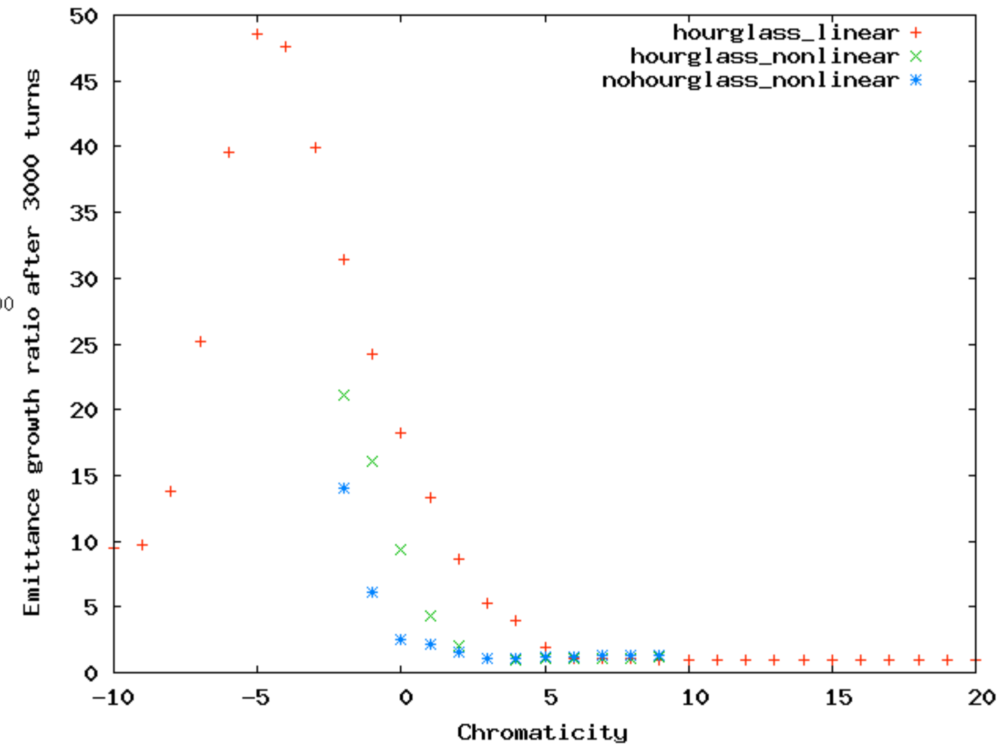
Kink instability

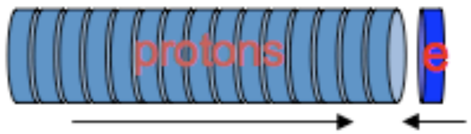
Simulations done by Y. Hao



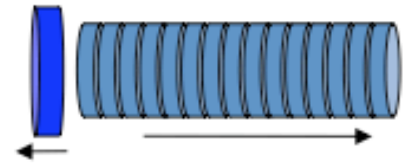
The tune spread stabilizes the instability. **Required chromaticity: >3 units.** Nonlinearity character of the beam-beam Interactions also helps.

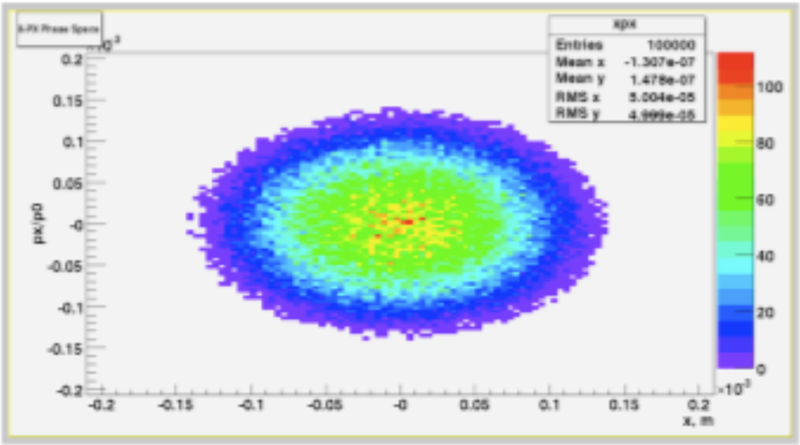
Proton emittance growth caused by transverse instability. The head of the proton bunch affects the tail through the interactions with the electron beam. Includes synchrotron oscillations. Without tune spread (zero chromaticity) the instability threshold is at 1.6e10 proton per bunch.



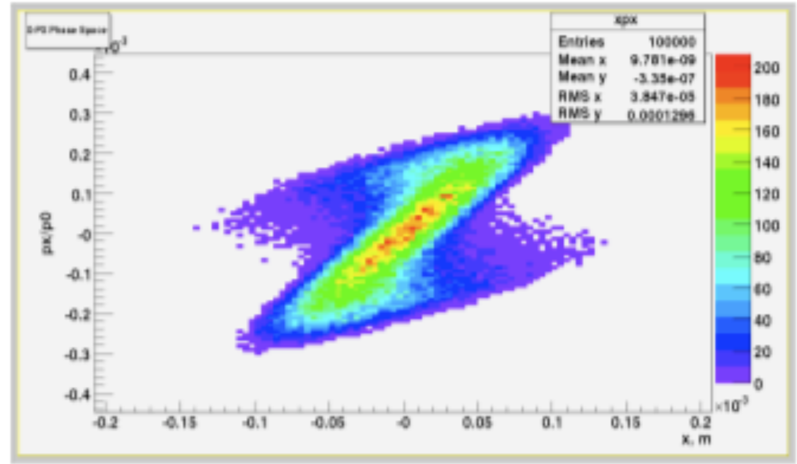


Beam disruption

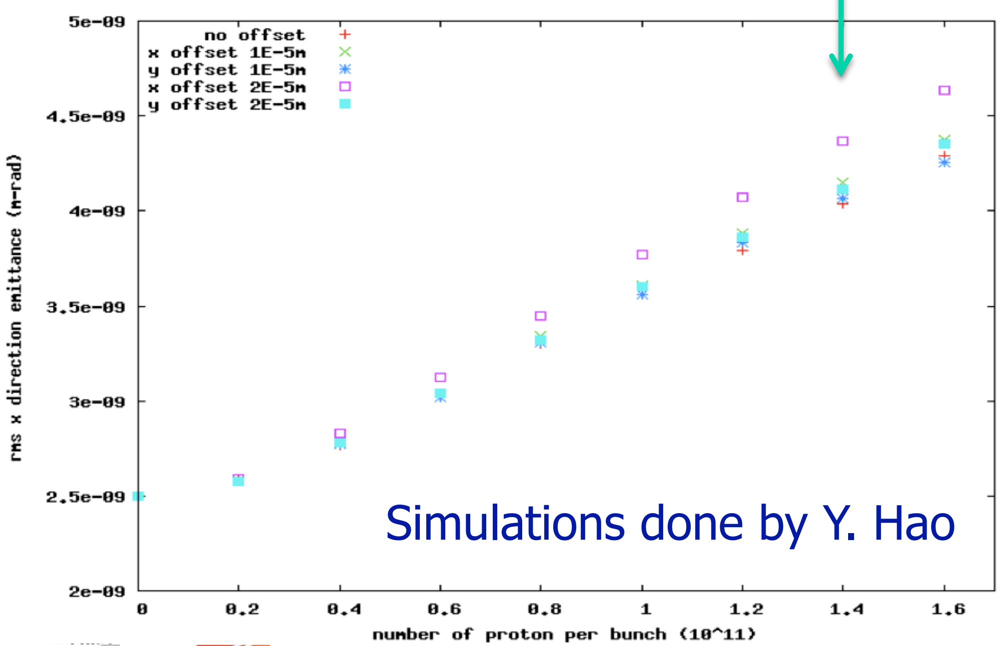


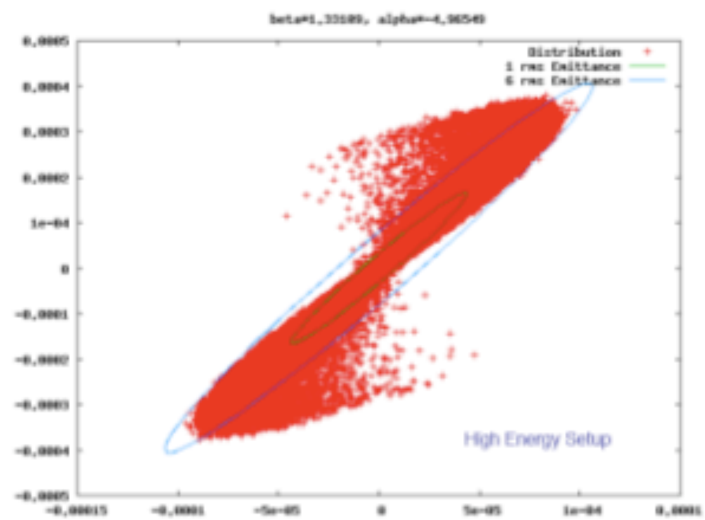


Interaction



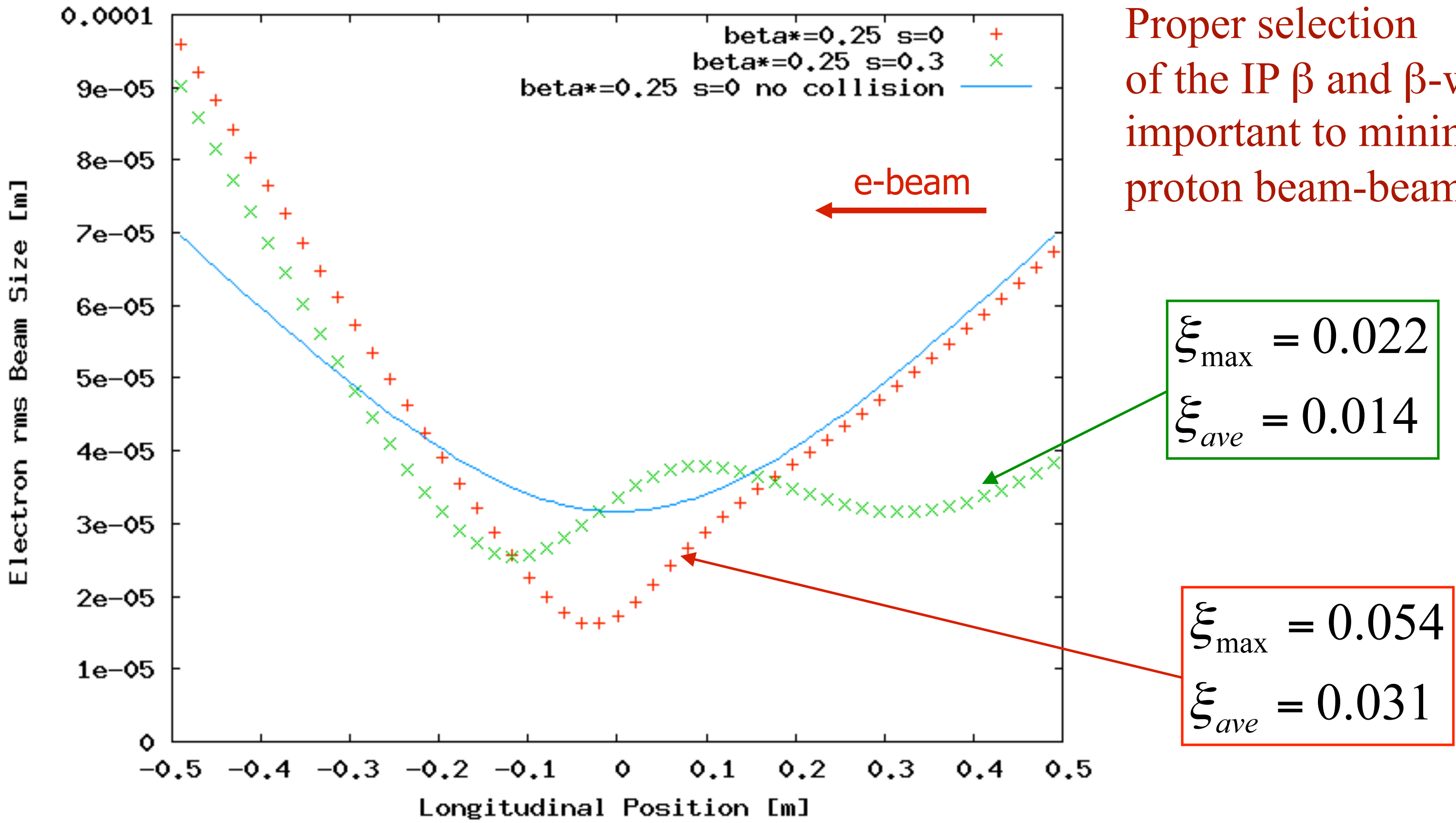
Optimized





Effect of electron pitching on the proton beam

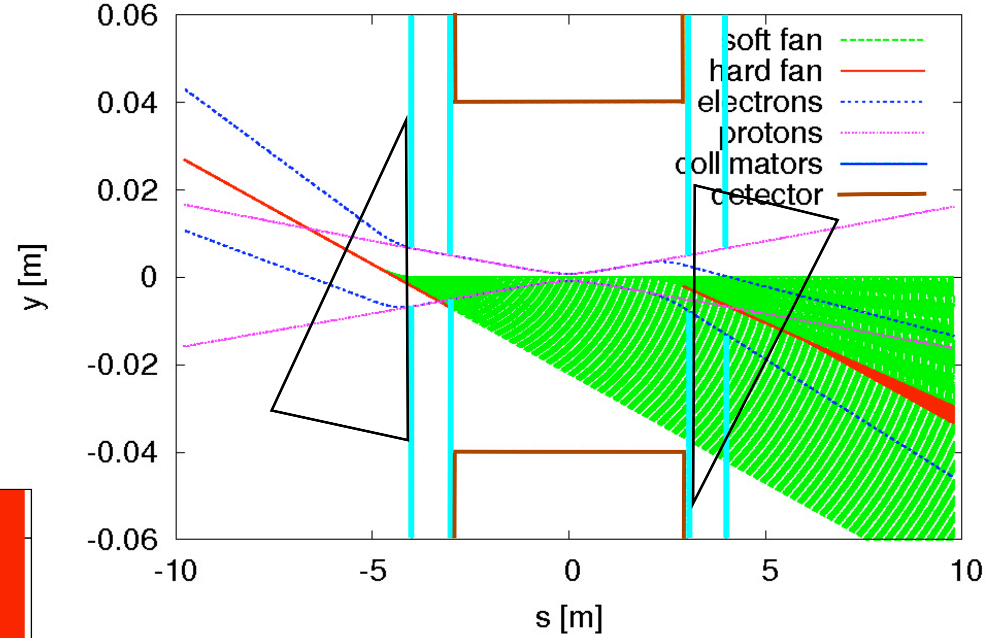
The electron beam is focused by strong beam-beam force.
That in turn leads to larger proton beam-beam parameter



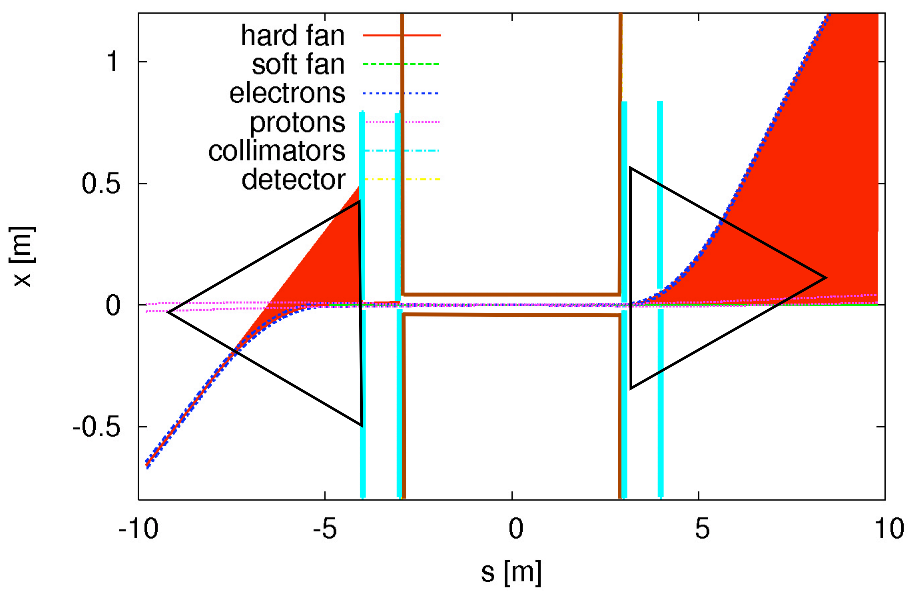
Proper selection of the IP β and β-waist is important to minimize the proton beam-beam parameter

Zero dispersion IP and detector protected Interaction Region
Christoph Montag, Brett Parker – synchrotron radiation protection

SIDE VIEW

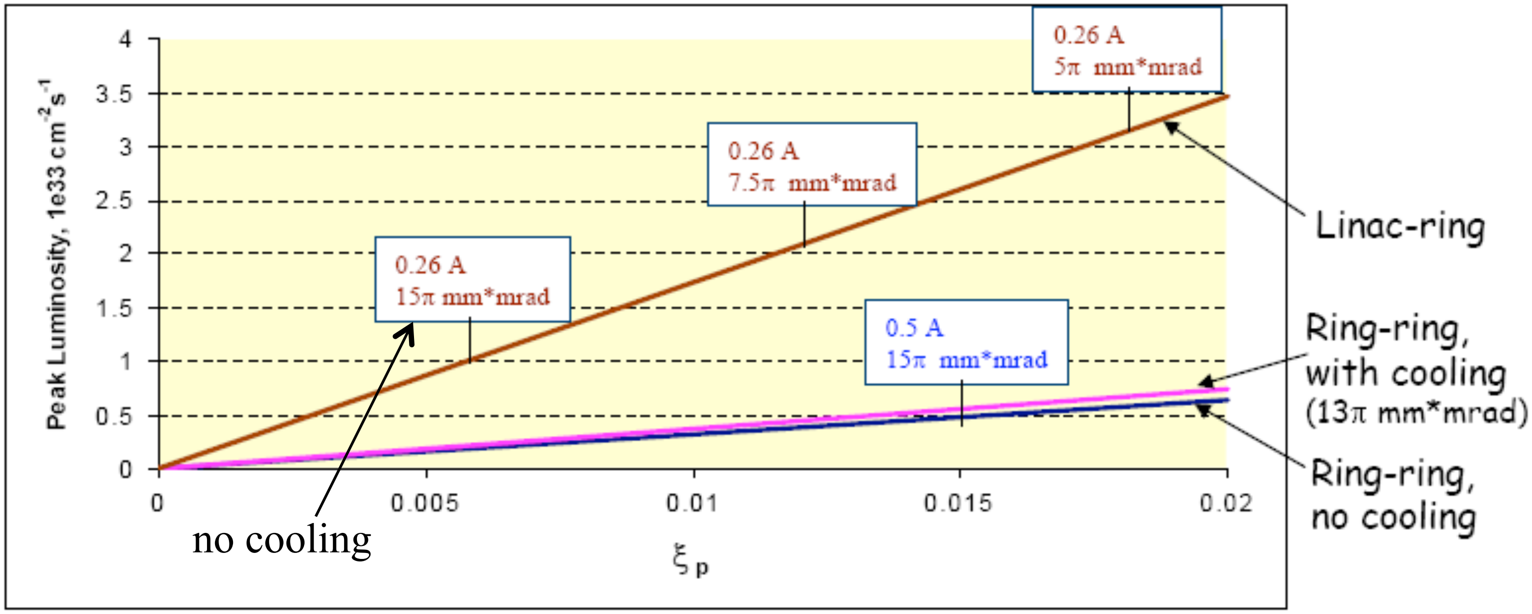


TOP VIEW



Luminosity and cooling

Calculations for 166 bunch mode and 250 Gev(p) x 10 Gev(e) setup;



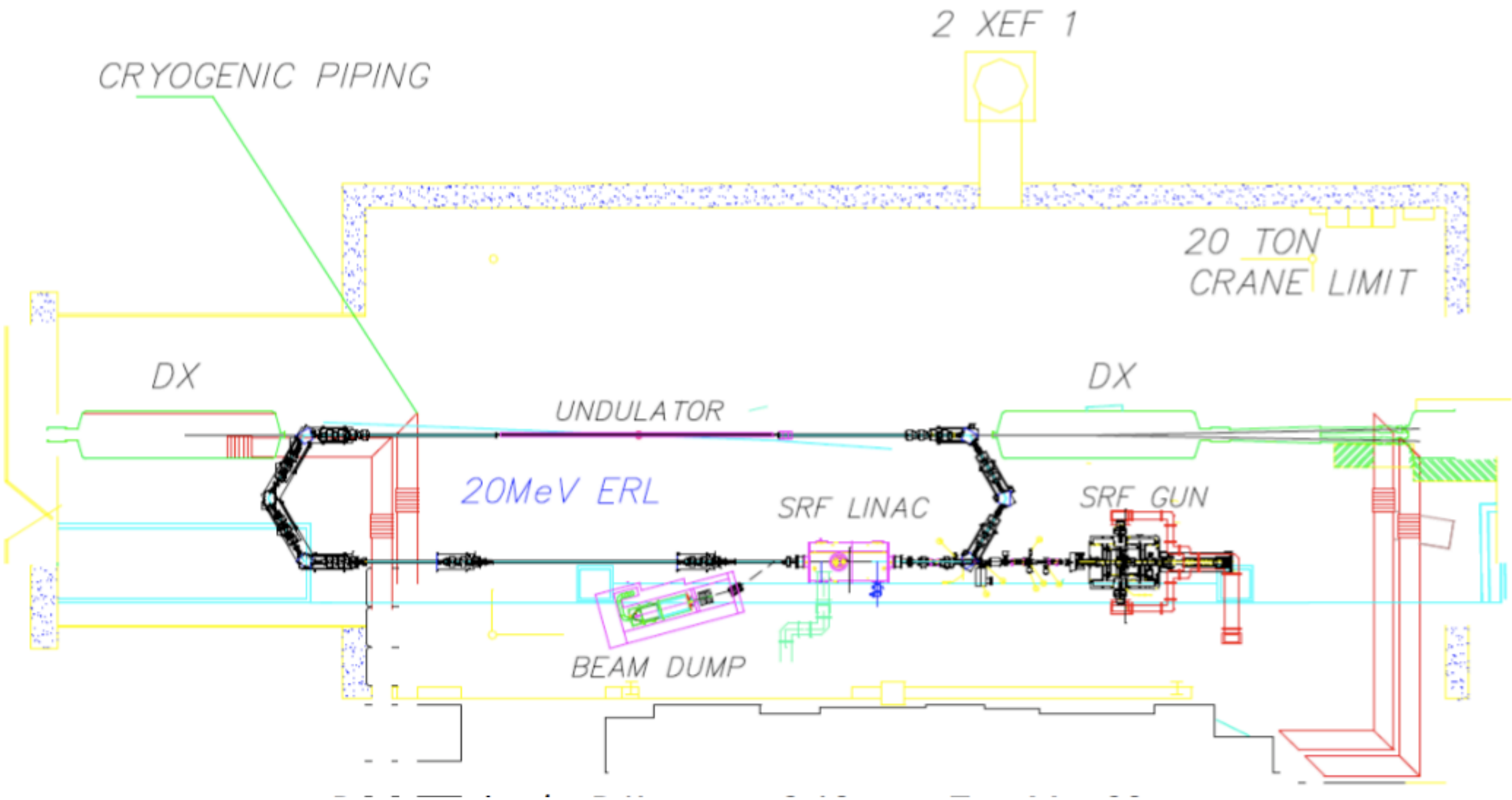
Pre-cooling of the protons at the injection energy (22 GeV) is required to achieve proton beam-beam limit (ξ_p=0.015) and maximize the luminosity. It can be done by the electron cooling (in ~1h).

To reduce the electron current requirements it would be great to have the effective transverse cooling at the storage energy (250 GeV) which can effectively counteract IBS and maintain the emittance well below 6π mm*mrad.

Recent revival of the Coherent Electron Cooling idea (V.N.Litvinenko, Ya.S.Derbenev) brings the possibility of the effective longitudinal and transverse cooling for high energy protons.

Proof of principle test of CEC has been suggested at RHIC.

Proof of Principle of for coherent electron cooling



Increase of number of bunches

Presently RHIC operates with maximum 111 bunches.

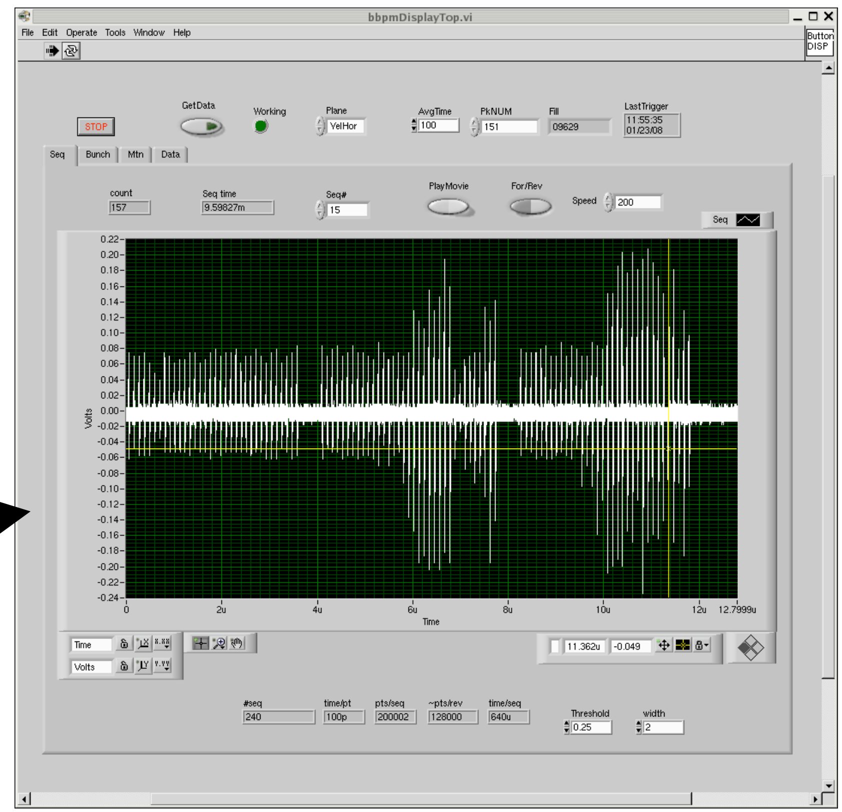
That should be increased to 166 bunches for eRHIC.

Corresponding reduction of the distance between bunches from 106 ns to 71 ns.

Issues to be resolved:

- Injection system upgrade for shorter kicker rise time.
- High intensity problems with larger number of bunches: instabilities, electron cloud, vacuum pressure rise.

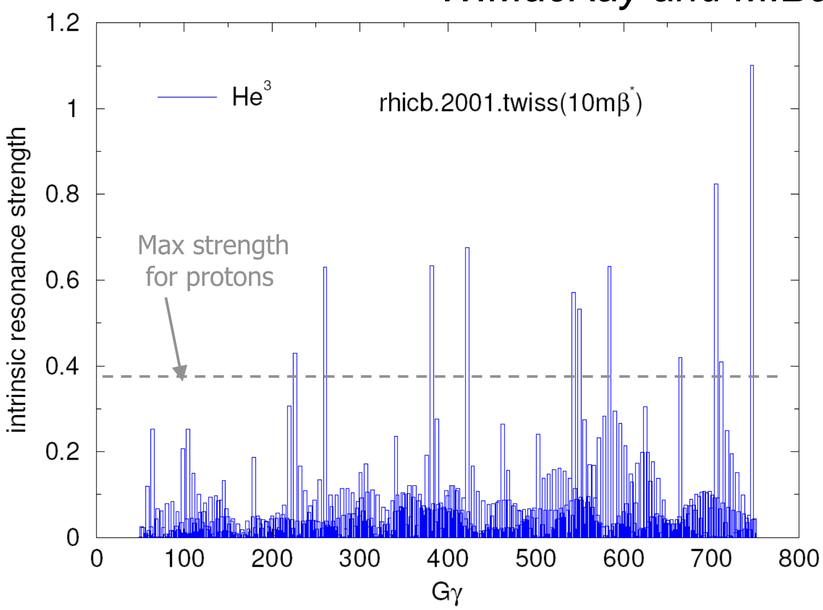
For instance, the transverse instability at the transition presently limits the beam intensity of ion beams.



Polarized $^3He^{+2}$ for eRHIC

- Larger G factor than for protons
- RHIC Siberian snakes and spin rotators can be used for the spin control, with less orbit excursions than with protons.
- More spin resonances. Larger resonance strength.
- Spin dynamics at the acceleration in the injector chain and in RHIC has to be studied.

W.MacKay and M.Bai



	$^3He^{+2}$	p
m, GeV	2.808	0.938
G	-4.18	1.79
E/n, GeV	16.2-166.7	24.3-250
γ	17.3-177	25.9-266
$\|G\gamma\|$	72.5-744.9	46.5-477.7

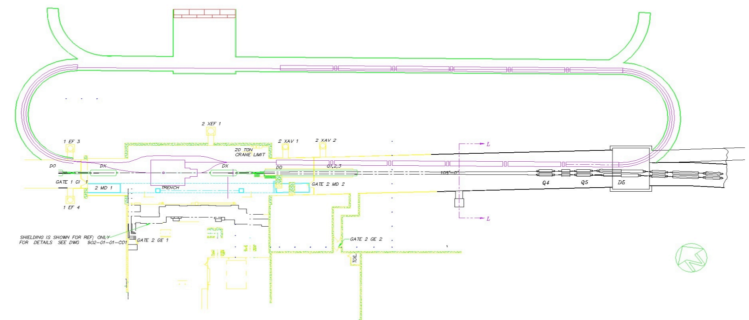
Design options:

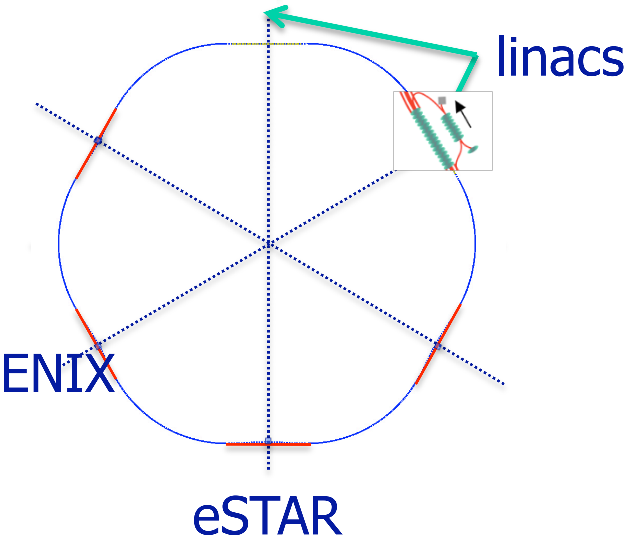
Under serious consideration : STAGING eRHIC with Medium Energy EIC at RHIC (ME-RHIC)

Electron energy up to 4 GeV. Acceleration done by an ERL linac partially placed in the RHIC tunnel. Its serves as first stage for following higher electron energy machine. Luminosity ~ 10^{32} cm^{-2}s^{-1}

➢ *High energy (up to 20-30 GeV) ERL-based design* ***with all accelerating linacs and recirculation passes placed in the RHIC tunnel.***
Considerable cost saving design solution.
Luminosity exceeds 10^{33} cm^{-2}s^{-1}

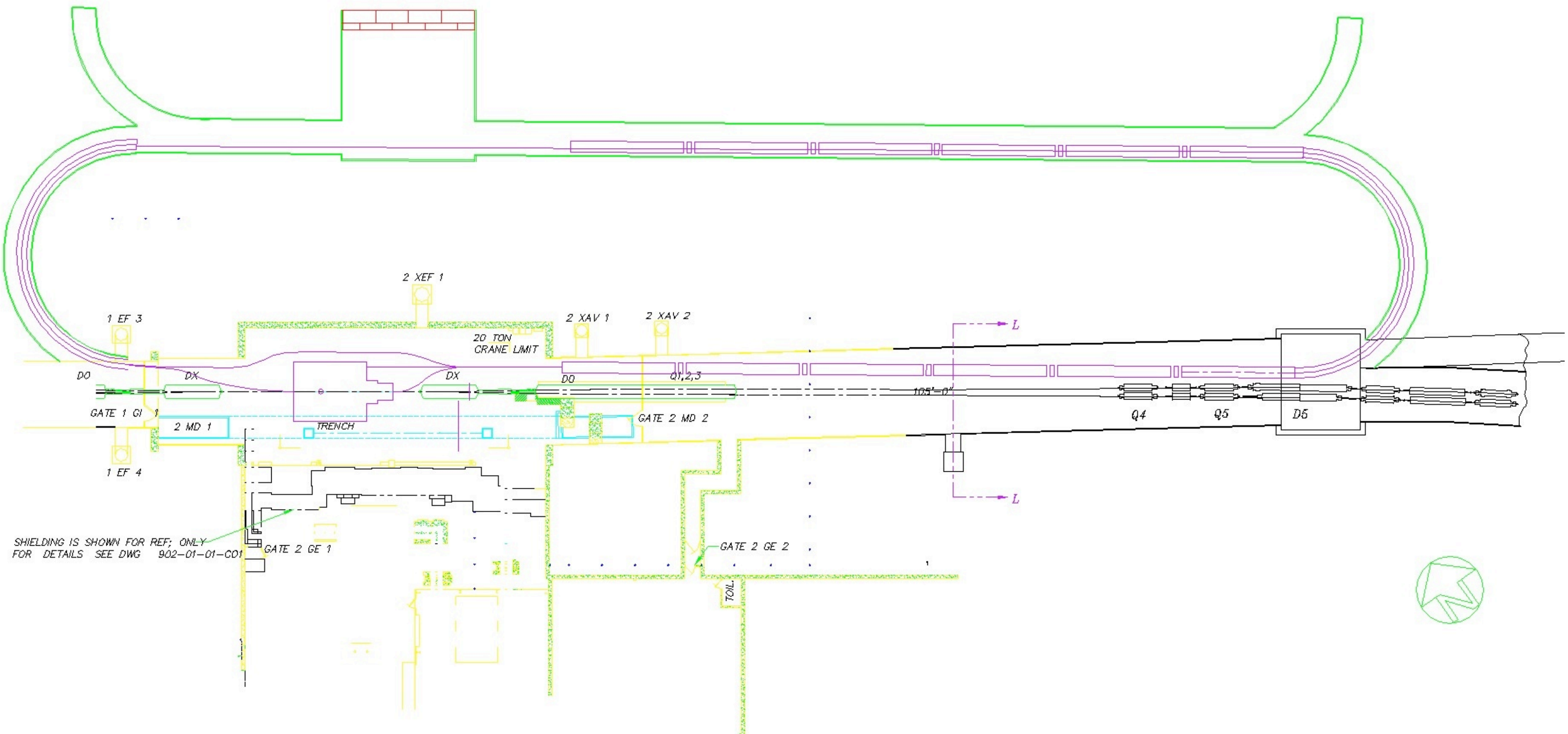
➢ *Ring-ring design option.*
Backup design solution which uses electron storage ring. See eRHIC ZDR for more details. The average luminosity is at 10^{32} cm^{-2}s^{-1} level limited by beam-beam effects.



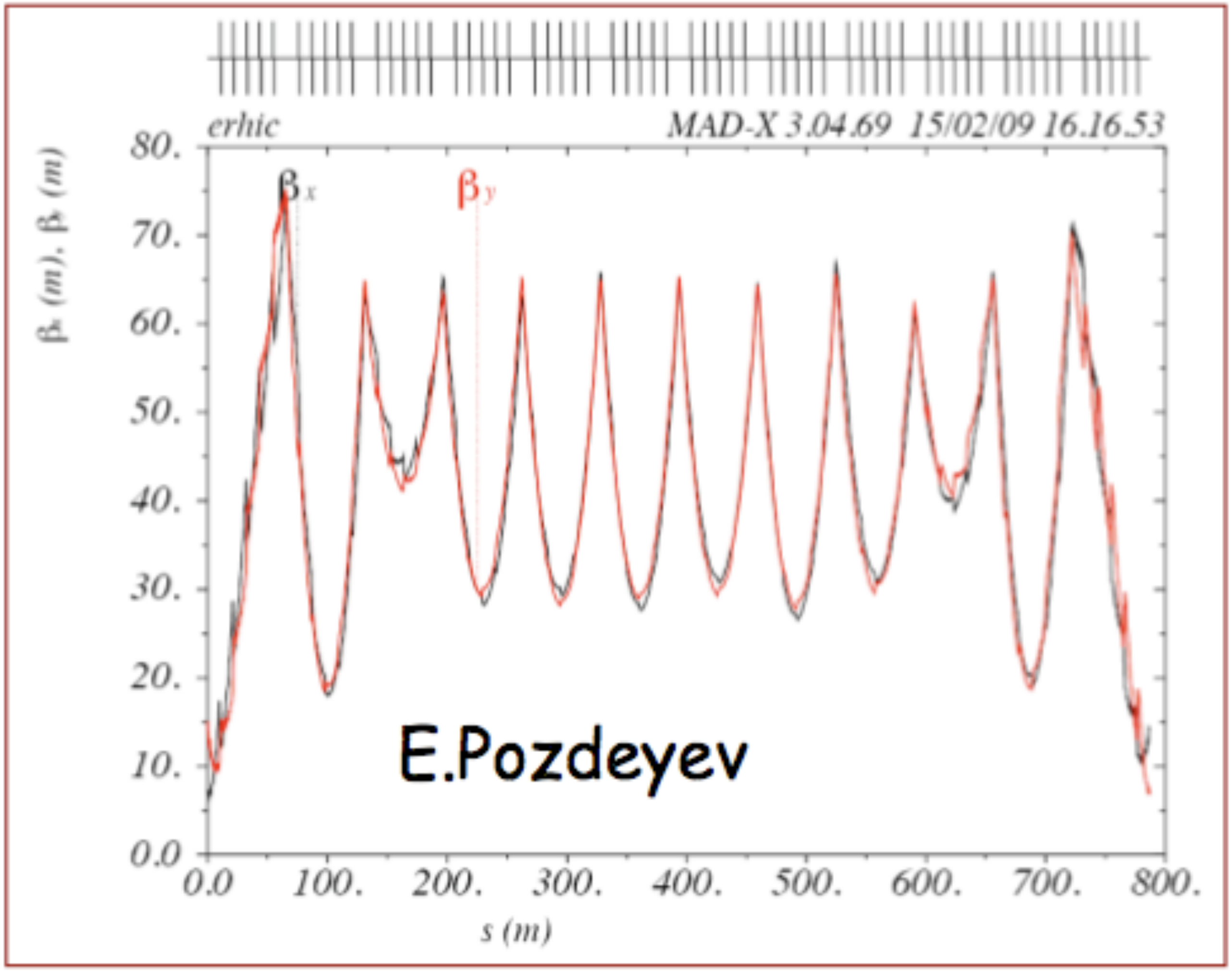


Medium Energy Electron Ion Collider in RHIC: race track concept

- Geometrical constraints: If it is possible use the existing interaction region at RHIC 2 o'clock and wider tunnel to place the superconducting linac inside it. Minimize civil construction cost and use for eRHIC already built and installed linac.

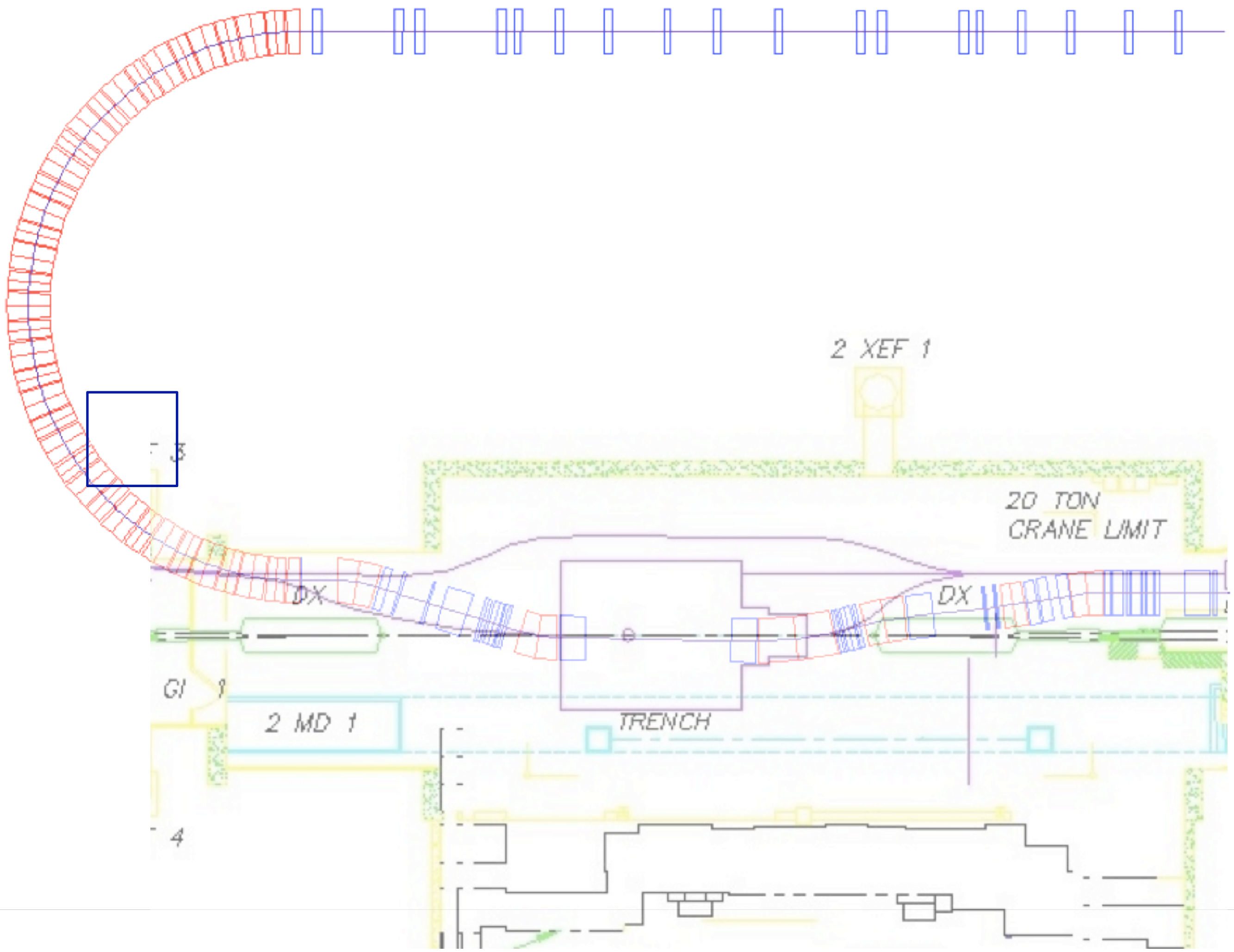


Lattice design for the ME-RHIC



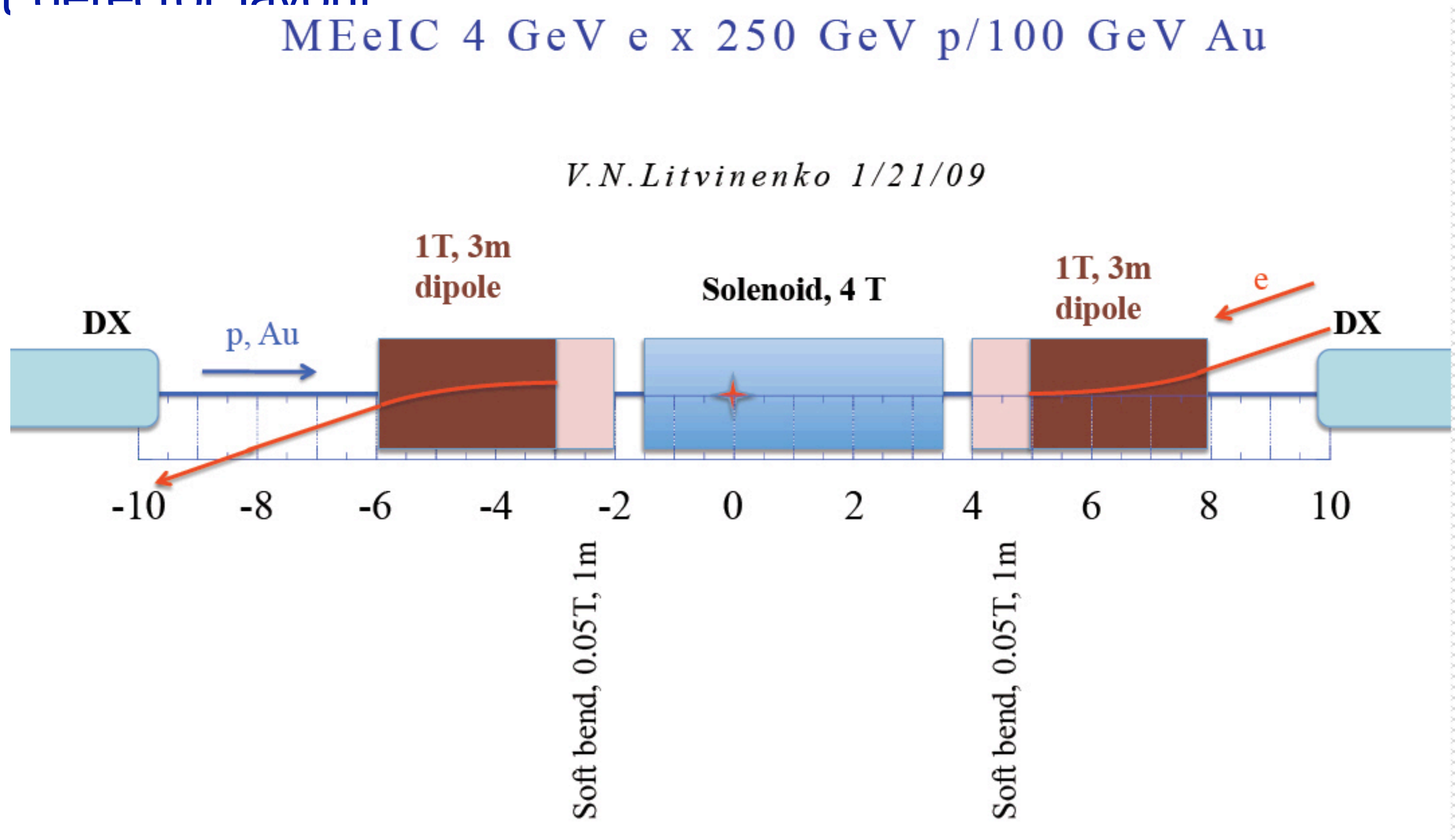
Arc with Interaction Region connected to the Energy Recovery Linac:

- Geometrical constraints: If it is possible use the existing interaction region at RHIC 2 o'clock and wider tunnel to place the superconducting linac inside it. Minimize civil construction cost:

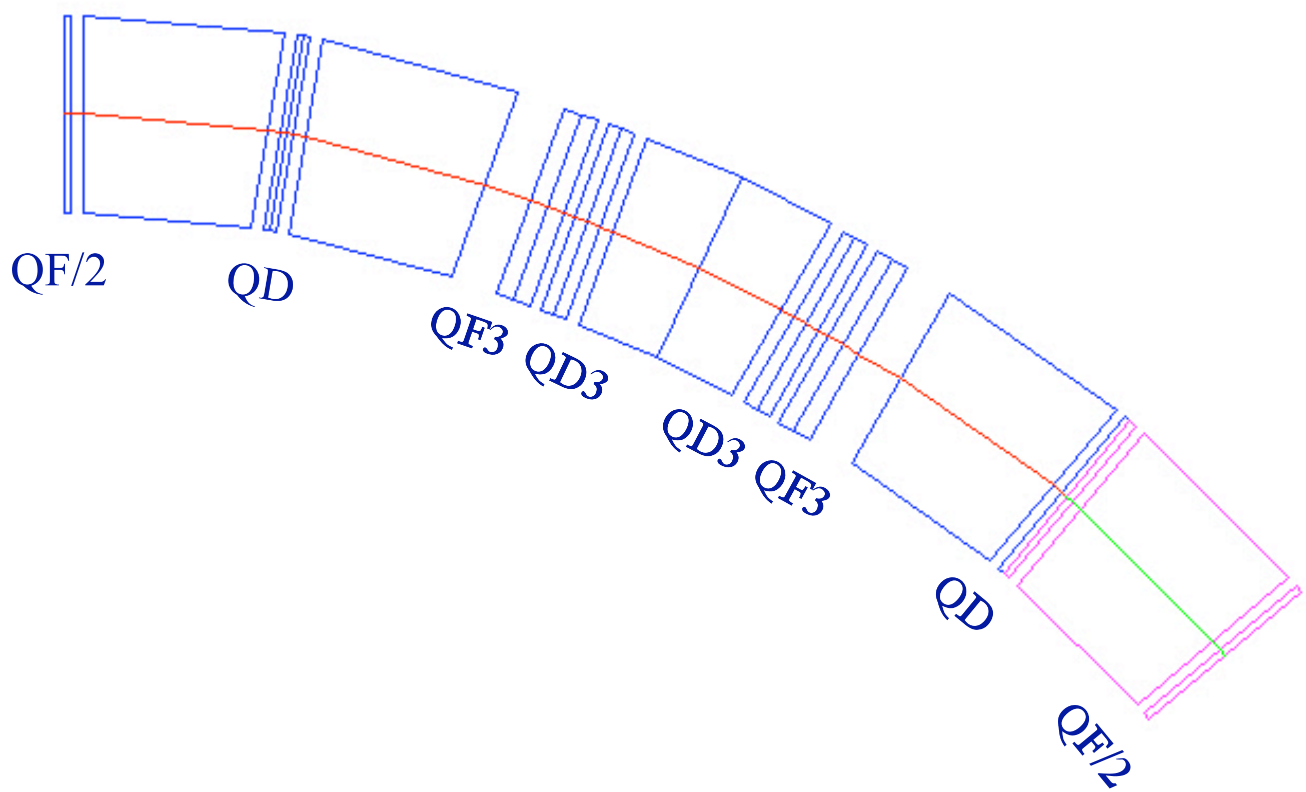


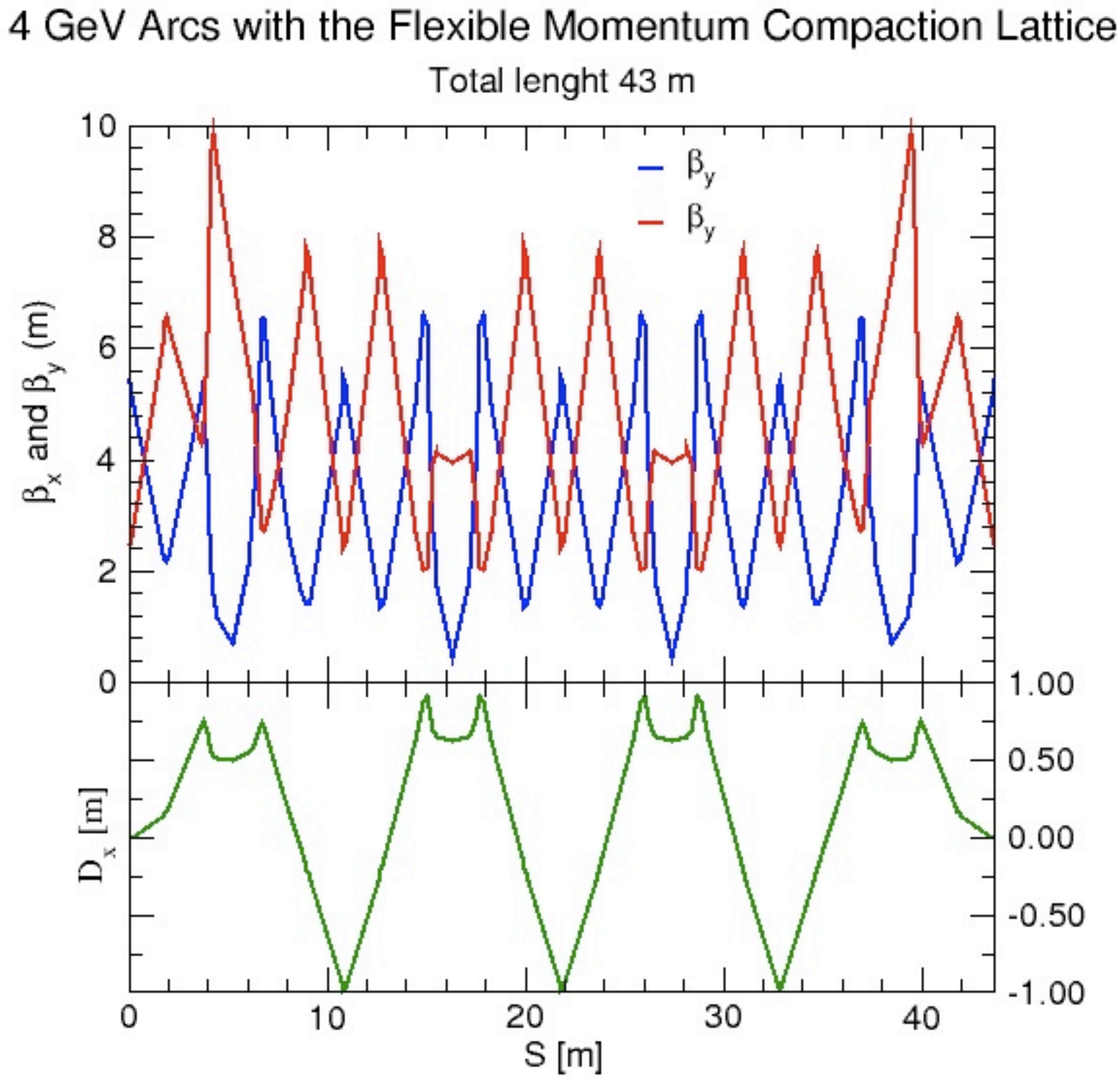
• Lattice constraints:

Passes during acceleration or energy recovery between the two linacs should be asynchronous ($M_{56}=0$), have small dispersion due to large $\delta p/p$ ($x_{\delta p}=D\ \delta p/p$), dipole and the quadrupole magnetic fields should be ~1.5-1.8 T, with zero dispersion through linacs and at the interaction point, reduce/remove the synchrotron radiation through detector, use vertical beam splitting, use the present detector layout



A Flexible Momentum Compaction Cell for ME-RHIC 4 GeV arc :





4 GeV Arcs with the Flexible Momentum Compaction Lattice
Total lenght 43 m
β_x and β_y (m)
β_y
β_y
D_x [m]
S [m]
0
2
4
6
8
10
1.00
0.50
0.00
-0.50
-1.00
0
10
20
30
40

MeRHIC parameters for e-p collisions

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	not cooled		With cooling	
	p	e	p	e
Energy, GeV	250	4	250	4
Number of bunches	111		111	
Bunch intensity, 10^{11}	2.0	0.31	2.0	0.31
Bunch charge, nC	32	5	32	5
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.5	7.3
rms emittance, nm	9.4	9.4	0.94	0.94
beta*, cm	50	50	50	50
rms bunch length, cm	20	0.2	5	0.2
beam-beam for p /disruption for e	1.5e-3	3.1	0.015	7.7
Peak Luminosity, 1e32, $cm^{-2}s^{-1}$	0.93		9.3	

Summary

- The accelerator design work continues on various aspects of the ERL-based design of eRHIC, which presently aims to provide e-p average luminosity at 10^{33} $cm^{-2}s^{-1}$ level.
- Recent advances are done in several design areas, including linac design, optics of re-circulating passes, studies of beam-beam effects.
- R&D subjects, such as polarized source development, ERL test facility and compact magnet design, are financially supported. So, one can expect advances on those directions in coming 2 years.
- Other design options under consideration: ERL-based designs with linac(s) inside of the RHIC tunnel and the ring-ring design.
- Effective cooling of high energy protons can reduce requirements on electron beam intensity and simplify the design of the electron accelerator.
- Modifications of existing RHIC machine include new interaction region(s) and higher number of proton bunches.

Staging of eRHIC: Re-use, Beams and Energetics

- **MeRHIC**: Medium Energy electron-Ion Collider
  - 90% of ERL hardware will be use for full energy eRHIC
  - Possible use of the detector in eRHIC operation
- **eRHIC – High energy and luminosity phase**
  - **Based on present RHIC beam intensities**
  - With coherent electron cooling requirements on the electron beam current is 50 mA
  - 20 GeV, 50 mA electron beam losses 4 MW total for synchrotron radiation.
  - 30 GeV, 10 mA electron beam loses 4 MW for synchrotron radiation
  - Power density is <2 kW/meter and is well within B-factory limits (8 kW/m)
- **eRHIC upgrade(s)**
  - **High luminosity, low energy requires crab cavities, new injections, Cu-coating of RHIC vacuum chambers, new level of intensities in RHIC**
    - Polarized electron source current of 400 mA at10 GeV, losses 2 MW total for synchrotron radiation, power density is 1 kW/meter
  - **High energy option requires replacing one of RHIC ring with 8 T magnets**

Gains from coherent e-cooling:

Coherent Electron Cooling vs. IBS

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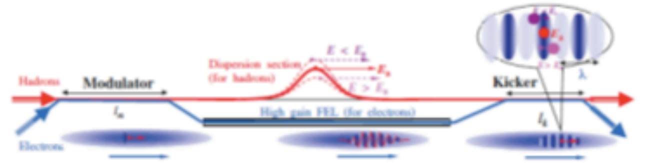


FIG. 1 (color). A general schematic of the Coherent Electron Cooler (CEC) comprising three sections: A modulator; a FEL plus a dispersion section; and, a kicker. The FEL wavelength, λ, in the figure is grossly exaggerated for visibility.

$$X = \frac{\varepsilon_x}{\varepsilon_{xo}};\ S = \left(\frac{\sigma_s}{\sigma_{so}}\right)^2 = \left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$

$$\frac{dX}{dt} = \frac{1}{\tau_{IBS\perp}}\frac{1}{X^{3/2}S^{1/2}} - \frac{\xi_\perp}{\tau_{CeC}}\frac{1}{S};$$

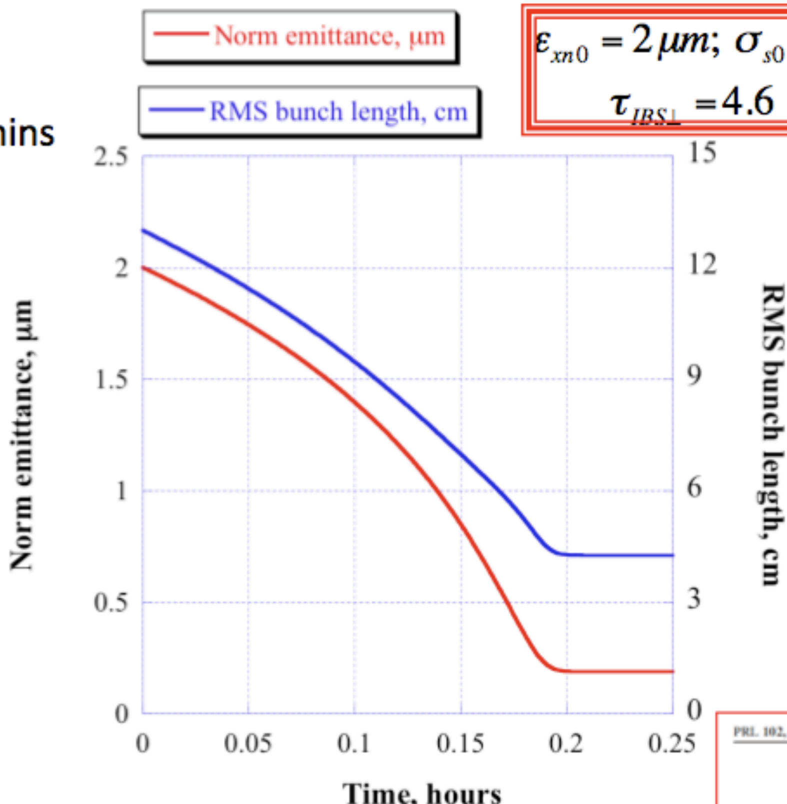
$$\frac{dS}{dt} = \frac{1}{\tau_{IBS//}}\frac{1}{X^{3/2}Y} - \frac{1-2\xi_\perp}{\tau_{CeC}}\frac{1}{X};$$

$$X = \frac{\tau_{CeC}}{\sqrt{\tau_{IBS//}\tau_{IBS\perp}}}\frac{1}{\sqrt{\xi_\perp(1-2\xi_\perp)}};\quad S = \frac{\tau_{CeC}}{\tau_{IBS//}}\cdot\sqrt{\frac{\tau_{IBS\perp}}{\tau_{IBS//}}}\cdot\sqrt{\frac{\xi_\perp}{(1-2\xi_\perp)^3}}$$

$$\varepsilon_{xn0} = 2\,\mu m;\ \sigma_{s0} = 13\ cm;\ \sigma_{\delta 0} = 4\cdot 10^{-4}$$
$$\tau_{IBS\perp} = 4.6\ \ hrs;\ \tau_{IBS//} = 1.6\ \ hrs;$$

IBS in RHIC for eRHIC, 250 GeV, $N_p=2\cdot 10^{11}$
Beta-cool, ©A.Fedotov

Dynamics: Takes 12 mins to reach stationary point



$$\varepsilon_{xn} = 0.2\,\mu m;\ \sigma_s = 4.9\ \ \text{cm}$$

This allows

a) keep the luminosity as it is
b) reduce polarized beam current down to 25 mA (5 mA for e-I)
c) increase electron beam energy to 20 GeV (30 GeV for e-I)
d) increase luminosity by reducing β* from 25 cm down to 5 cm

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Coherent Electron Cooling

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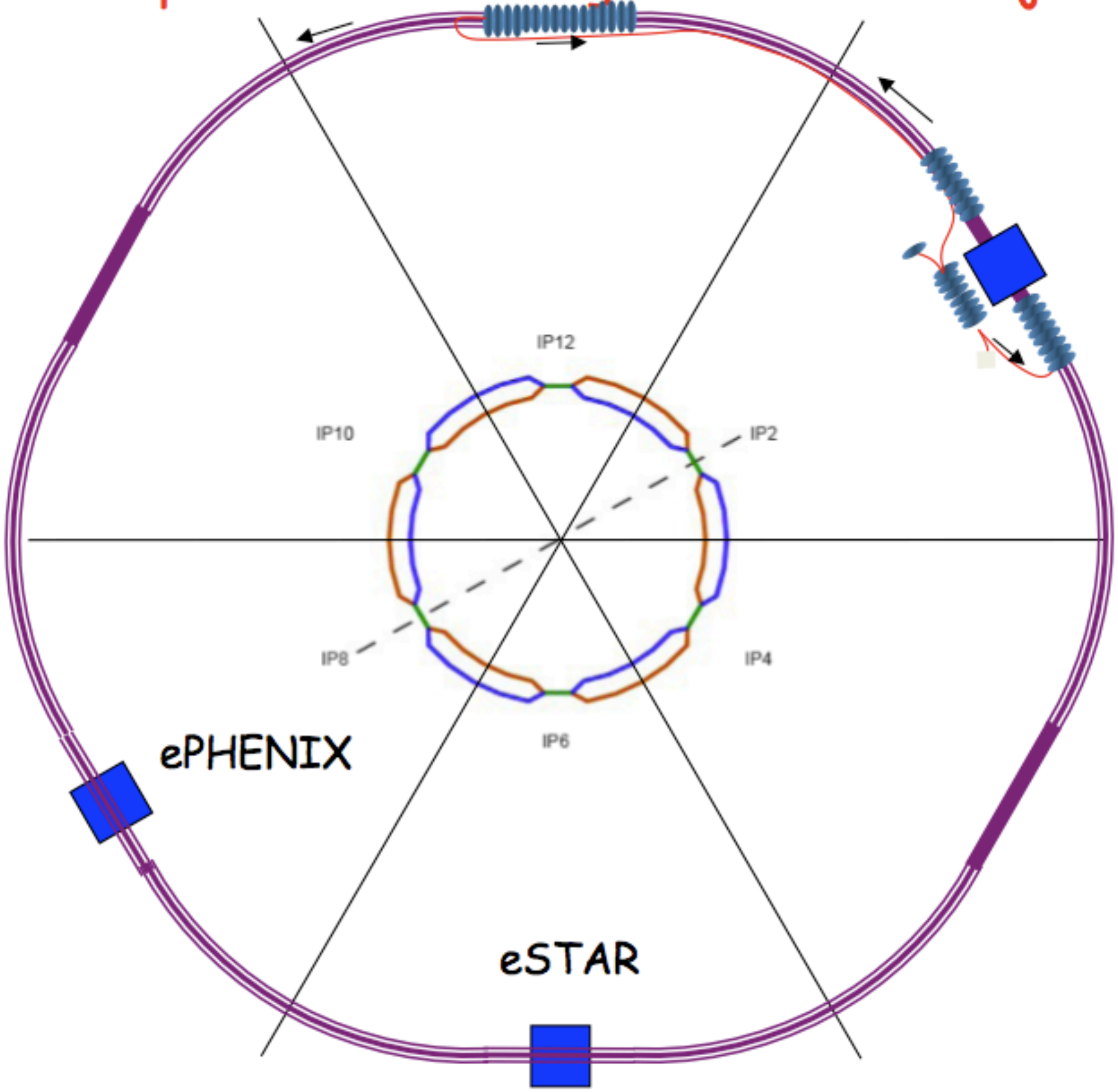
20 (10 & 30) GeV e x 800 GeV p eRHIC
with ERL inside RHIC tunnel
One of present RHIC rings serves as an injector

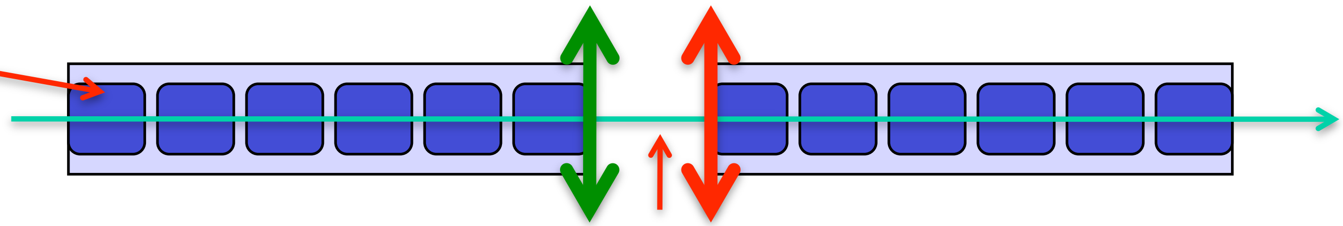


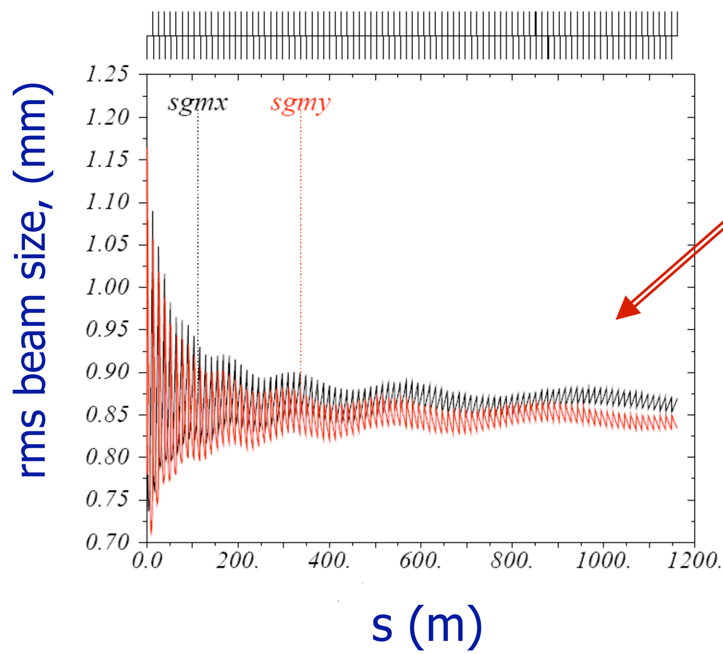
2 x 200 m SRF linac
10 (12.5) MeV/m
4 (5) GeV per pass

5 (6) vertically separated passes

Electron beam R&D for ERL-based design:

Increased number of 700MHz cavities inside one cryostat to 6 cavities.
3rd harmonic cavities (2 per cryostat) for the momentum spread minimization.
Cavity gradient: 19.5 Mev/m; Average acceleration rate: 8.2 MeV/m;
Total length of 1.9 GeV linac: 232m (instead of ~360m in the previous design).





E. Pozdeyev

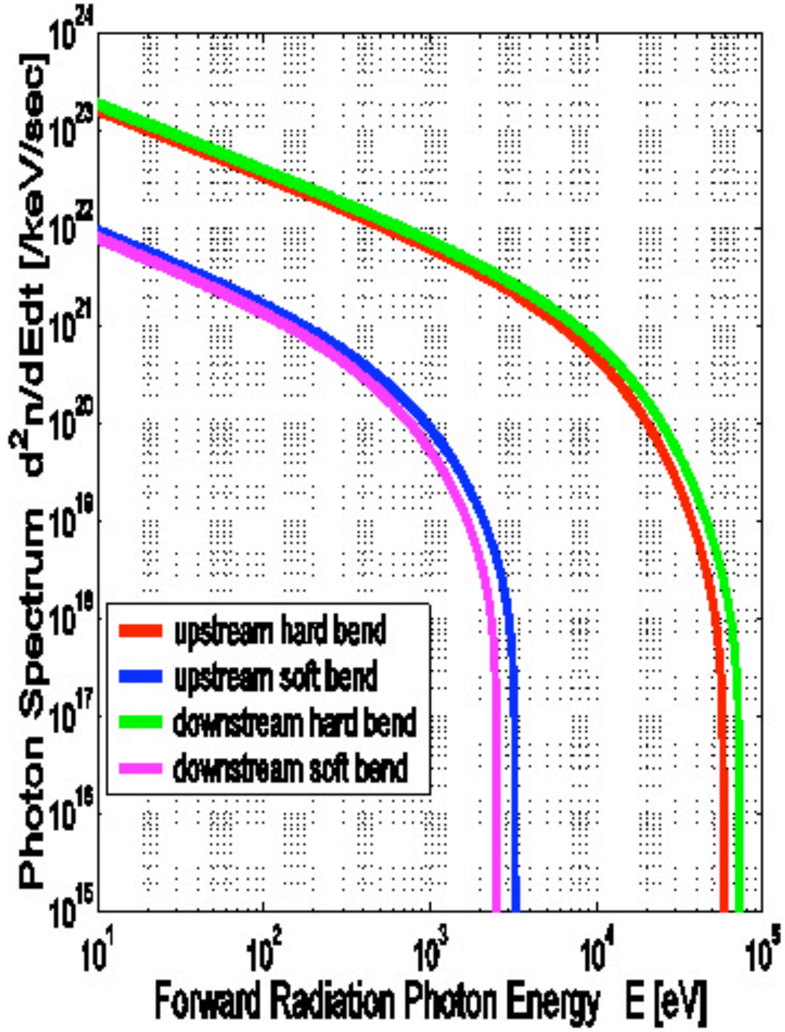
Evolution of rms beam sizes along the linac on all acceleration passes.
Doublet focusing (90º phase advance per cell)
Constant quadrupole gradient.

Compact linac design makes more realistic a design option with linac(s) placed inside the RHIC tunnel

Detector Synchrotron Radiation Background

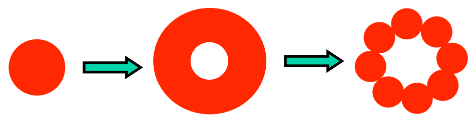
1. A horizontal hard bend and a vertical soft bend on both side of the detector;
2. The forward radiation from the up stream hard bend (red) is completely masked. No hard radiation passes through the detector;
3. The forward radiation from the up stream soft bend (blue) will passes through the detector without hitting detector wall.
4. The secondary backward radiation induced by the forward radiation generated in down stream bends will be largely masked from the detector;
5. The detector radiation background due to multiple scattering from the vacuum system, masks, collimators and absorbers will be investigated with computer simulations.

Forward Radiation Spectrum

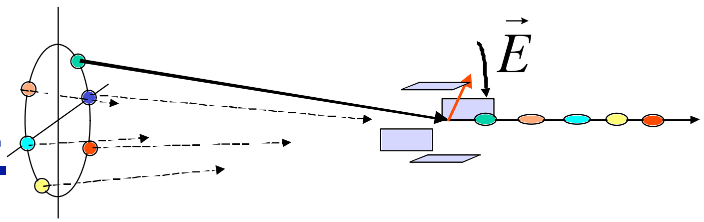


Polarized Electron Source Design Items

-Large area cathodes (diameter > 1cm)
-Ring-like cathode, to minimize ion bombardment damage.



-Multiple gun approach. RF-combiner.



-Active cooling, to accommodate ~100W of heating load from laser power

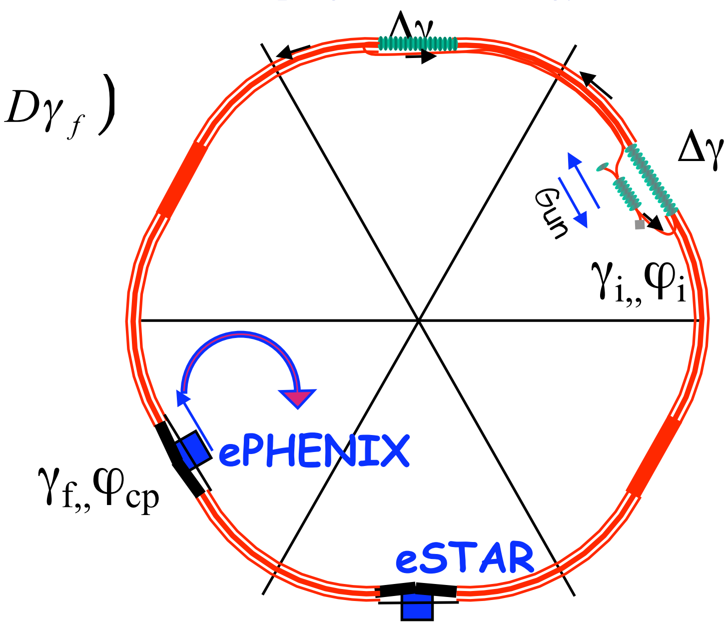
R&D efforts are led by MIT-Bates experts leading by Y. Tsentalovich's

Electron polarization in ERL eRHIC

- No problem with depolarizing resonances
- Spin orientation control at the collision point:
  - Spin rotators after the electron source (Wien filter, solenoid)
  - Slight adjustment of energy gain in main and pre-accelerator linacs (keeping the final energy constant) *(V.N.Litvinenko)*

$$\varphi_{cp} + k\pi = \varphi_i + 2\pi a \cdot \left(A\gamma_i + B\Delta\gamma\right) = \varphi_i + 2\pi a \cdot \left(C\gamma_i + D\gamma_f\right)$$

a is anomalous magnetic moment
A,B,C,D are constants depending on general configuration: location of linacs and collision point, number of recirculation passes (*n*).



Variation of pre-accelerator linac energy:

$$\delta E_{i\,max} = \pm 37 \ \ MeV \ \ \vee n = 5$$