Designs of Electron-Ion Colliders in the USA

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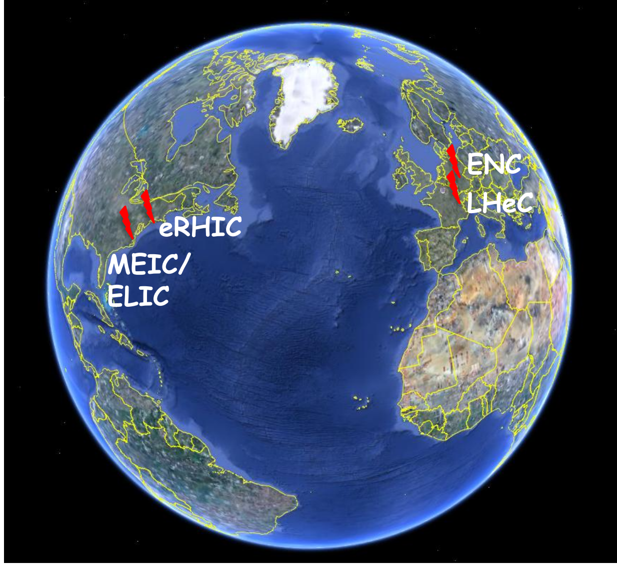
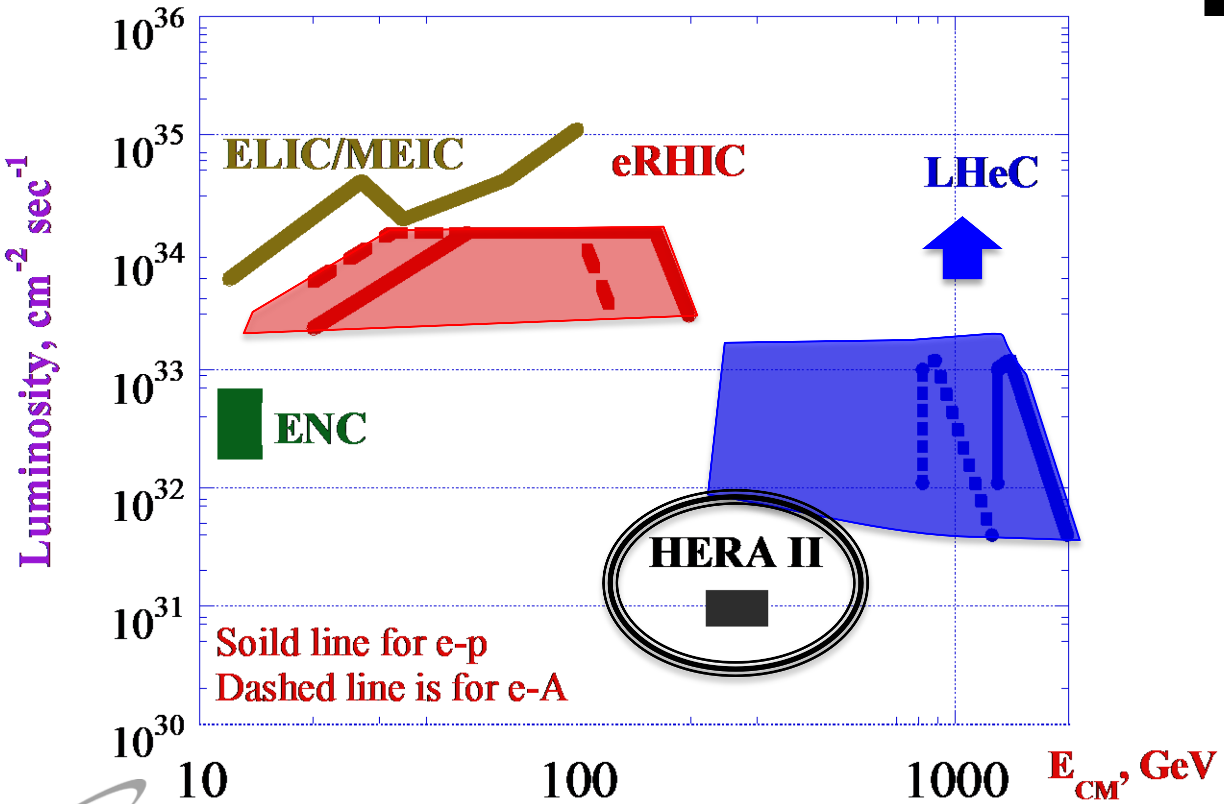
Energy Reach and Luminosities of future electron-hadron colliders



$$E_{CM} @\sqrt{4E_e E_h}$$



CM energy is shown for e-p collisions

In e-A collisions the CM energy of a pair e-nucleon is ~1.58-fold lower

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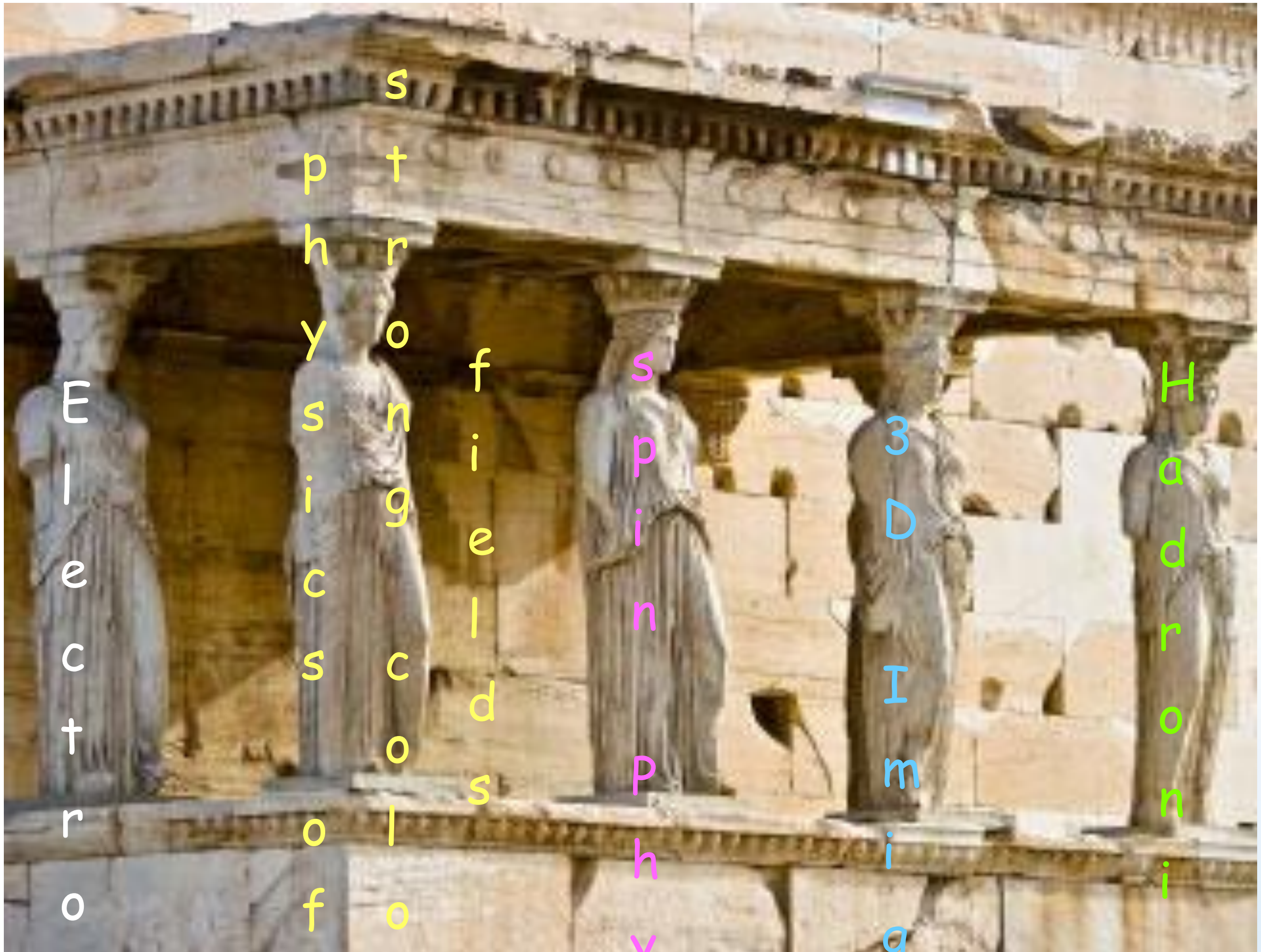
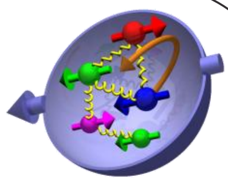
THE PILLARS OF THE EIC PHYSICS PROGRAM



Wide physics program with high requirements on detector and machine performance

MOST COMPELLING PHYSICS QUESTIONS

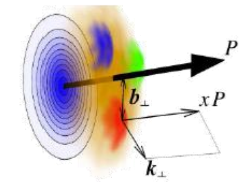
spin physics



- what is the polarization of gluons at small x where they are most abundant
- what is the flavor decomposition of the polarized sea depending on x

determine quark and gluon contributions to the proton spin at last

imaging

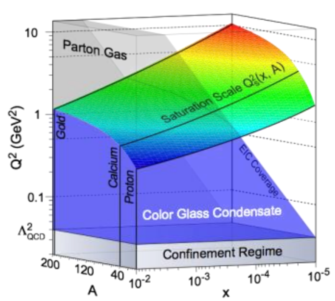


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- understand deep aspects of gauge theories revealed by k_T dep. distr'n

possible window to orbital angular momentum

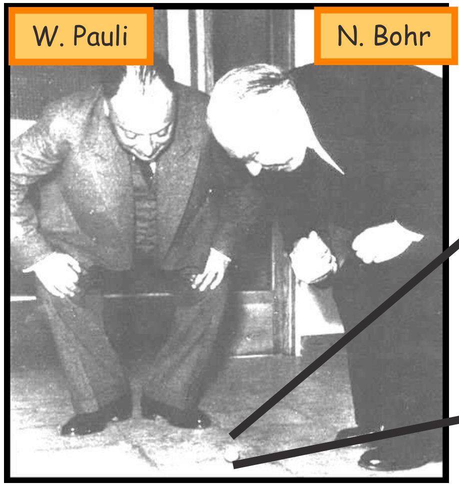
physics of strong color fields

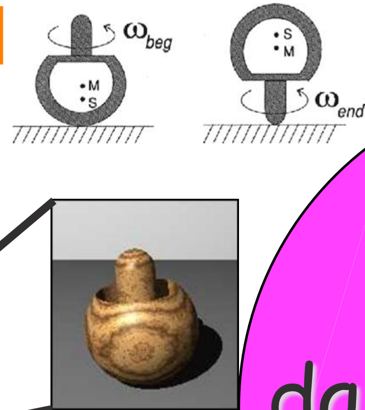
quantitatively probe the universality of strong color fields in AA, pA, and eA

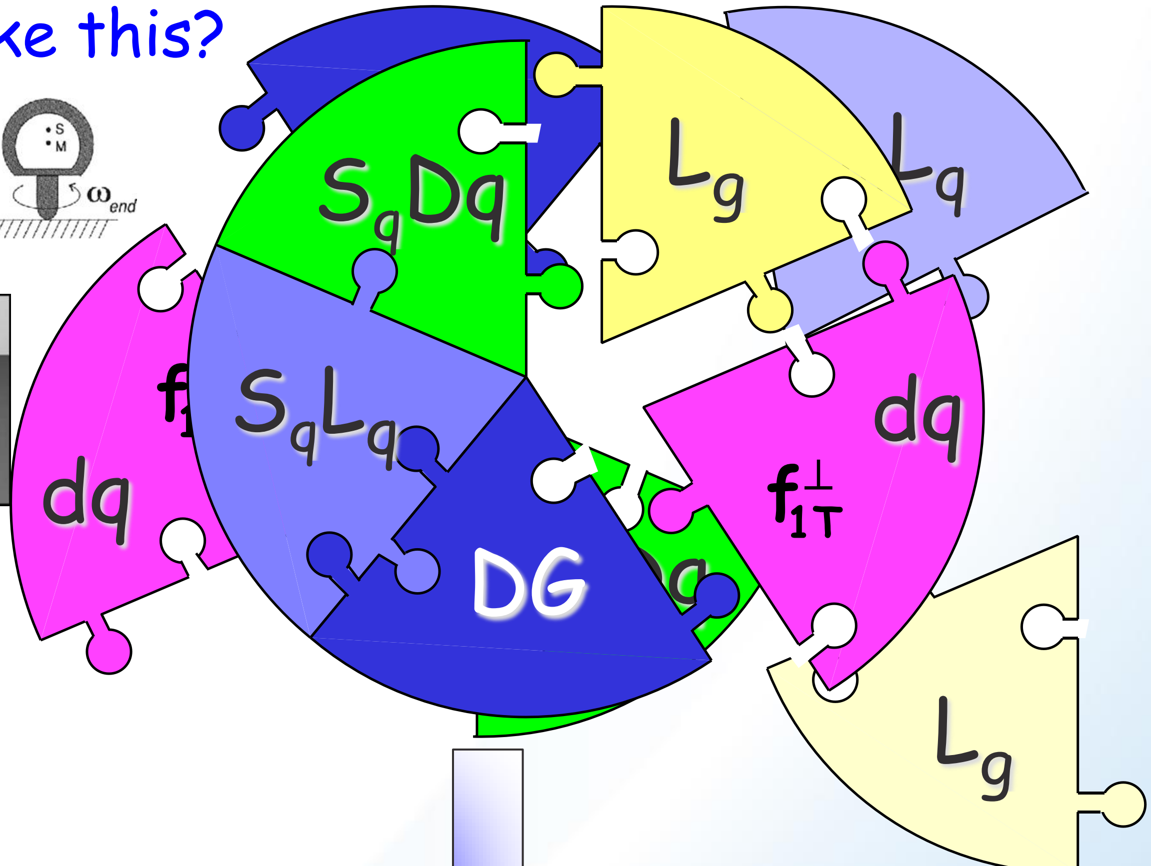


- understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- how do hard probes in eA interact with the medium

Is the proton spinning like this?







"Helicity sum rule"

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\right| J^z_{QCD} \left| P,\frac{1}{2}\right\rangle = \sum_q \frac{1}{2} S^z_q + S^z_g + \sum_q L^z_q + L^z_g$$

gluon spin

total u+d+s quark spin

angular momentum

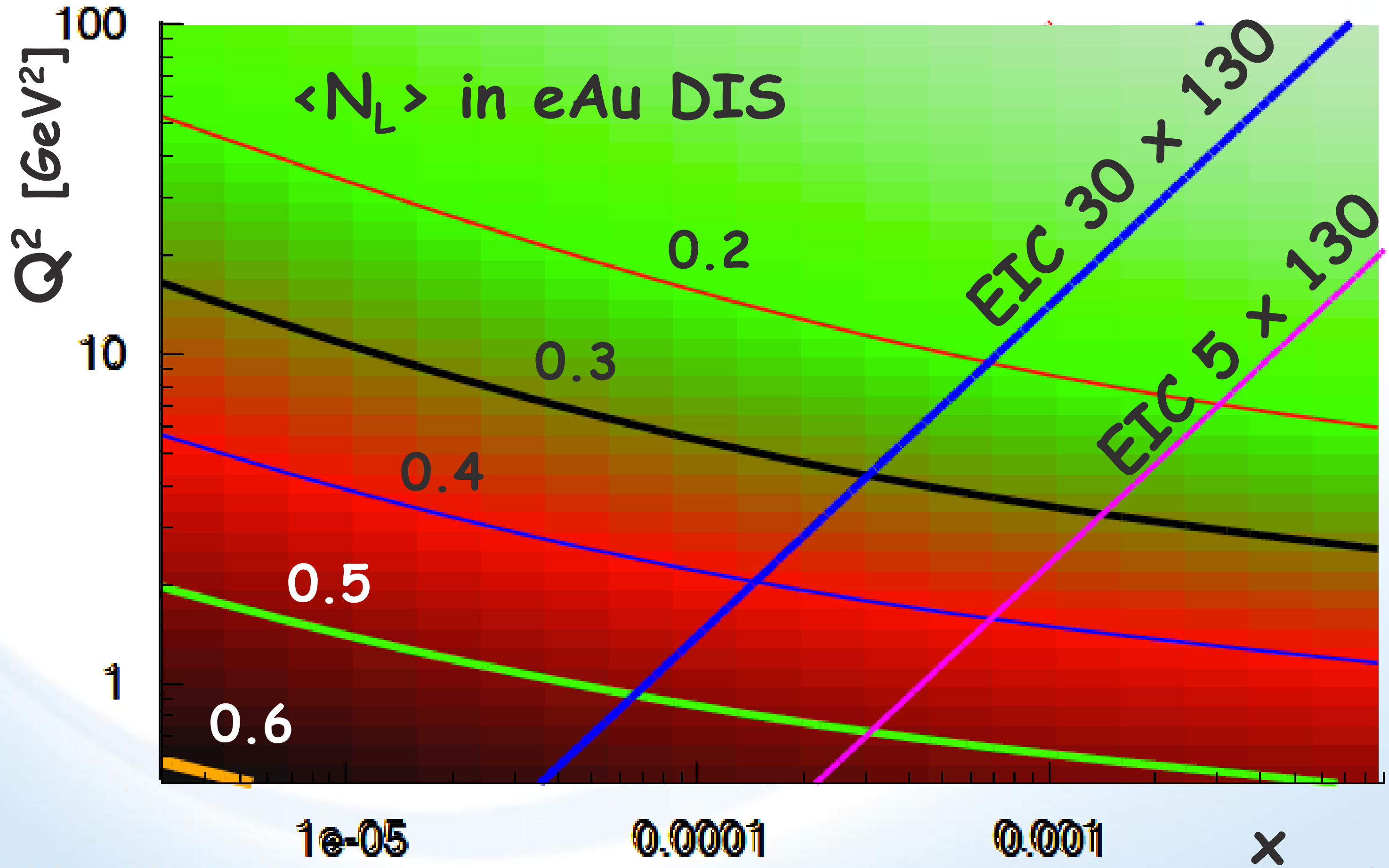
Where do we go with solving the "spin puzzle" ?

SATURATION IN eA DIS

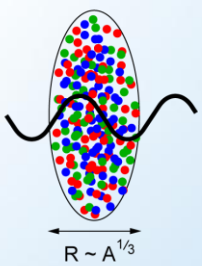
quantitative estimates

M. Diehl, T. Lappi

- find: $\sigma_L^{\gamma^*}(x, Q^2) \leftrightarrow F_L(x, Q^2)$ most sensitive to gluons
- as expected (HERA): no chance in ep
- eA much more favorable to study saturation than ep



saturation effects in eA benefit from nuclear oompf



$$Q_{s,p}^2 = A^{1/3} Q_{s,A}^2$$

Electron-Ion Collider At JLab (ELIC)

ELIC Design Goal

- **Energy** Wide CM energy range between 10 GeV and 100 GeV
  - Low: 3 to 10 GeV e on 3 to 12 GeV/c p (and ion)
  - Medium (**present focus**): up to 11 GeV e on 60 GeV p or 30 GeV/n ion
  - High (***future upgrade***): up to 10 GeV *e* on 250 GeV *p* or 100 GeV/n *ion*
- **Luminosity**
  - **10^{33} up to 10^{35} cm^{-2} s^{-1} *per* collision point, over multiple interaction points**
- **Ion Species**
  - Polarized H, D, ^{3}He, possibly Li
  - Up to heavy ion A = 208, all stripped
- **Polarization**
  - Longitudinal at the IP for both beams
  - All polarizations >70% desirable
- **Positron Beam** *desirable*

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Advantages (and a great opportunity) at JLab

- 12 GeV CEBAF as a full energy injector into the electron collider ring
  - High polarization high repetition CW electron beam
- New Ion Complex
  - High repetition high average current ion beams with short bunch length
- New Figure-8 shape collider rings for high polarization

ELIC Schematic Layout

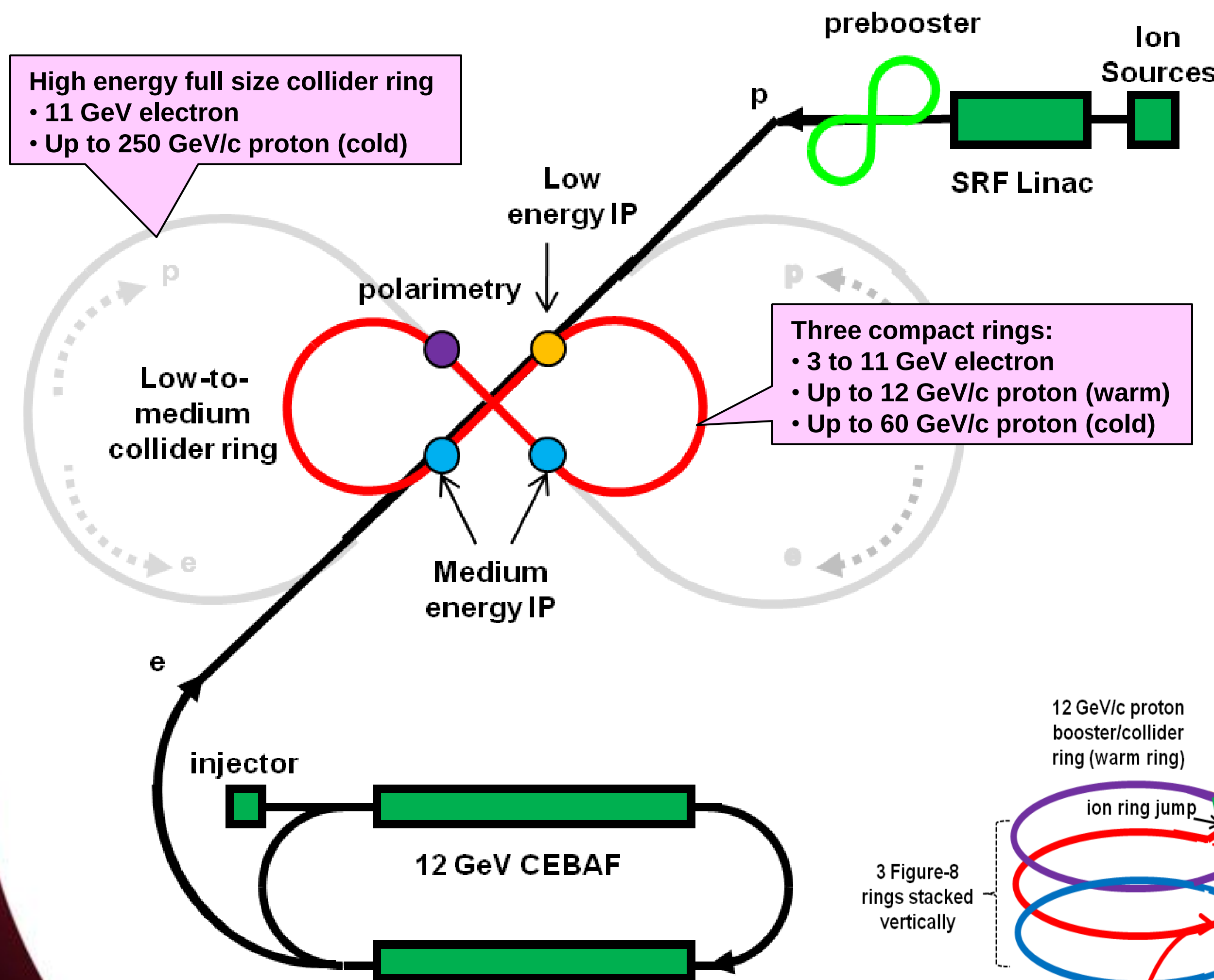
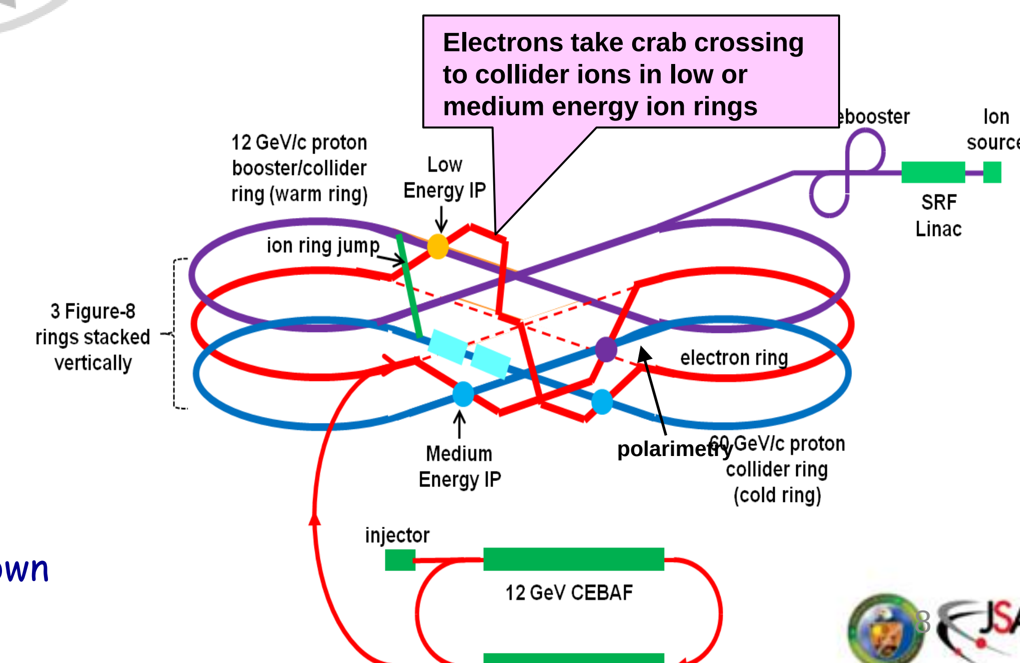


Figure-8 ring optimum for polarized ion beams
- Preserving polarization by avoiding spin resonances during acceleration
- Energy independence of spin tune
- Only practical way for including polarized deuterons (*g-2* very small)



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ELIC Main Parameters

Beam Energy	GeV	250/10	150/7	60/5	60/3	12/3
Collision freq.	MHz	499	499	499	499	499
Particles/bunch	10^{10}	1.1/3.1	0.5/3.25	0.74/2.9	1.1/6	0.47/2.3
Beam current	A	0.9/2.5	0.4/2.6	0.59/2.3	0.86/4.8	0.37/2.7
Energy spread	10^{-4}	7.3	5.1	8	4.8	4.8
RMS bunch length	mm	5	5	5	5	50
Horiz.. emit., norm.	µm	0.7/51	0.5/43	0.56/85	0.8/75	0.18/80
Vert. emit. Norm.	µm	0.03/2	0.03/2.87	0.11/17	0.8/75	0.18/80
Horizontal beta-star	mm	125	75	25	25	5
Vertical beta-star	mm	5	5	5	5	5
Vert. b-b tune shift/IP		0.01/0.1	0.015/.05	0.01/0.03	.015/.08	.015/.013
Laslett tune shift	p-beam	0.1	0.1	0.1	0.054	0.1
Peak Lumi/IP, 10^{34}	$cm^{-2}s^{-1}$	11	4.1	1.9	4.0	0.59

High energy **Medium energy** **Low energy**

ELIC Luminosity Concepts & Design Features

Luminosity concepts (**L~ 4×10^{34} $cm^{-2}s^{-1}$** for 60 x 3 GeV)

- **High bunch collision frequency (0.5 GHz, can be up to 1.5 GHz)**
- Very small bunch charge (10^{10} or less protons per bunch)
- **Very small beam spot size at collision points (β^*_y ~ 5 mm)**
- Short ion bunches (σ_z ~ 5 mm)

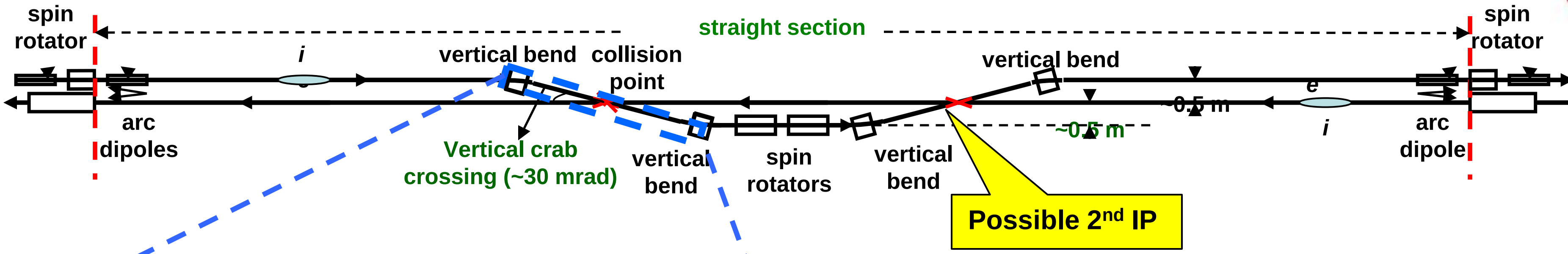
Keys to implementing these concepts

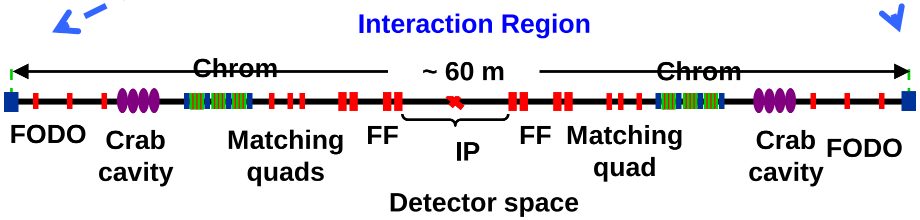
- Making very short ion bunches with small emittance
- SRF ion linac and (staged) electron cooling
- Need crab crossing for colliding beams

Other design features

- Ultra high luminosity
- Polarized electron and light ion beams
- Up to three IPs (detectors) for high science productivity
- "*Figure-8*" ion and lepton storage rings
  - Ensures spin preservation and ease of spin manipulation
  - Avoids energy-dependent spin sensitivity for all species
- Present CEBAF injector meets MEIC requirements
- Simultaneous operation of collider & CEBAF fixed target program if required
- Experiments with polarized positron beam would be possible

Some Design Details





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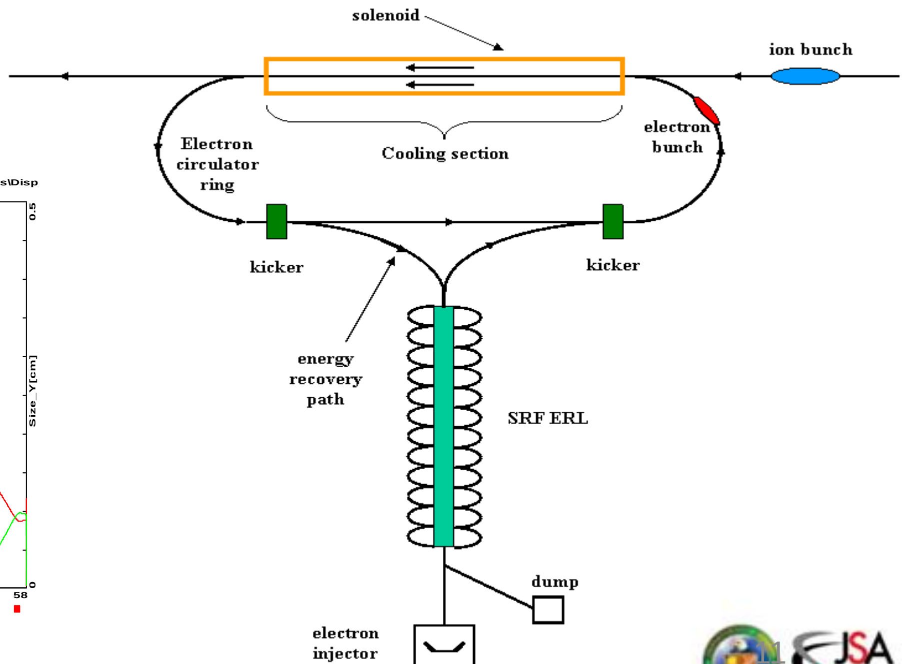
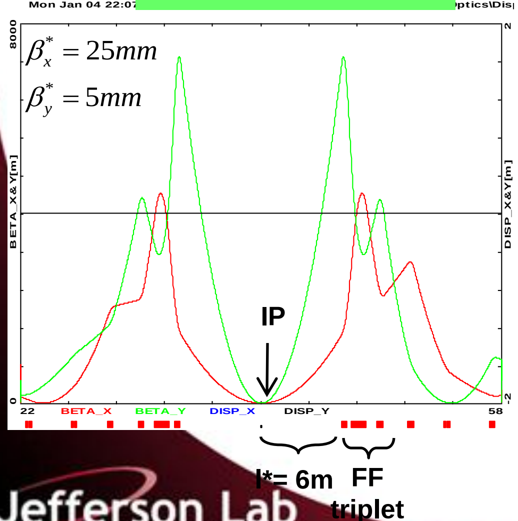
ERL Circulator e-Cooler

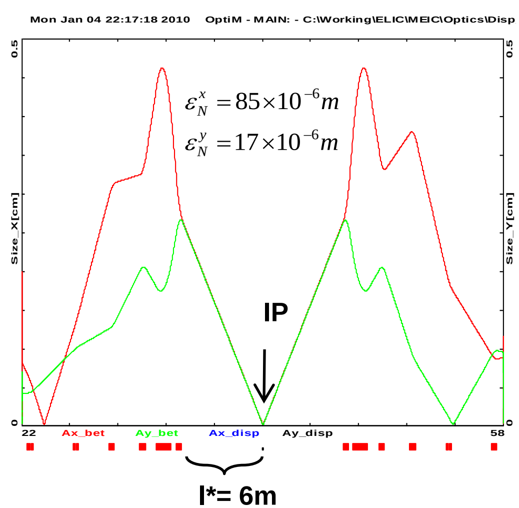
(for delivering a 3A CW electron beam)



Q1 G[kG/cm] = -3.4
Q2 G[kG/cm] = 2.1
Q3 G[kG/cm] = -4.1

Natural Chromaticity
ζ_x = -278 ζ_y = -473





ELIC R&D and Path Forward

Short Term Design Goals

- focusing on completion of a conceptual design with sufficient technical details for delivering to the next EIC AC meeting
- Scaling back several key parameters (particularly, increasing vertical beta-star to 2 cm) for reducing immediate R&D requirements.
- Concentrating available resources and manpower strategically to a minimum set of required R&D issues
- Optimizing ELIC design iteratively

ELIC Long Term R&D Issues

- IR design with chromatic compensation
- High energy electron cooling
- Crab crossing and crab cavity
- Forming high intensity low energy ion beam
- Beam-beam effect
- Beam polarization and tracking
- Traveling focusing for very low energy ion

Intermediate ELIC R&D Goals

Focal Point 1: Complete Electron & Ion Ring designs
sub tasks: Insert interaction region design
Chromaticity correction w/ tracking
Led by Ya. Derbenev & A. Bogacz (JLab)

Focal Point 2: IR design, feasibilities of advanced schemes
sub tasks: Develop a complete IR design
Beam dynamics with crab crossing
Traveling final focusing
Led by M. Sullivan (SLAC)

Focal Point 3: Conceptual design of ion injector/prebooster
sub tasks: bunch dynamics & space charge effect
Led by P. Ostroumov (ANL)

Focal Point 4: Beam-beam interaction
sub tasks: Single and multiple IPs
With crab crossing and/or space charge
Led by Y. Zhang & B.Terzic (JLab)

Established Collaborations

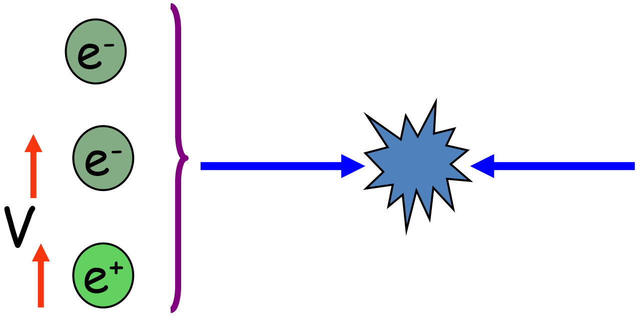
- Interaction region design M. Sullivan (SLAC)
- ELIC ion complex front end P. Ostroumov (ANL)
  Ion source V. Dudnikov, R. Johnson (Muons, Inc)
  V. Danilov (ORNL)
  SRF Linac P. Ostroumov (ANL), B. Erdelyi (NIU)
- Beam-beam simulation J. Qiang (LBNL)

eRHIC: QCD Facility at BNL

Add electron accelerator to the existing $2B RHIC

RHIC

Unpolarized and 80% polarized leptons, 5-30 GeV

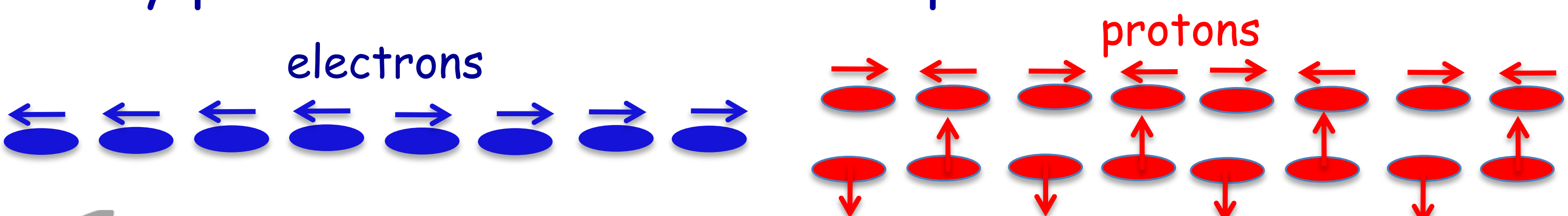


p 70% polarized protons 100-250 (325*) GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 (130*) GeV/u

Polarized light ions (He^3) 167 (215*) GeV/u

Center of mass energy range: 30-175 GeV
Any polarization direction in lepton-hadrons collisions



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* We are exploring a possibility of increasing RHIC ring energy by 10% - 30%

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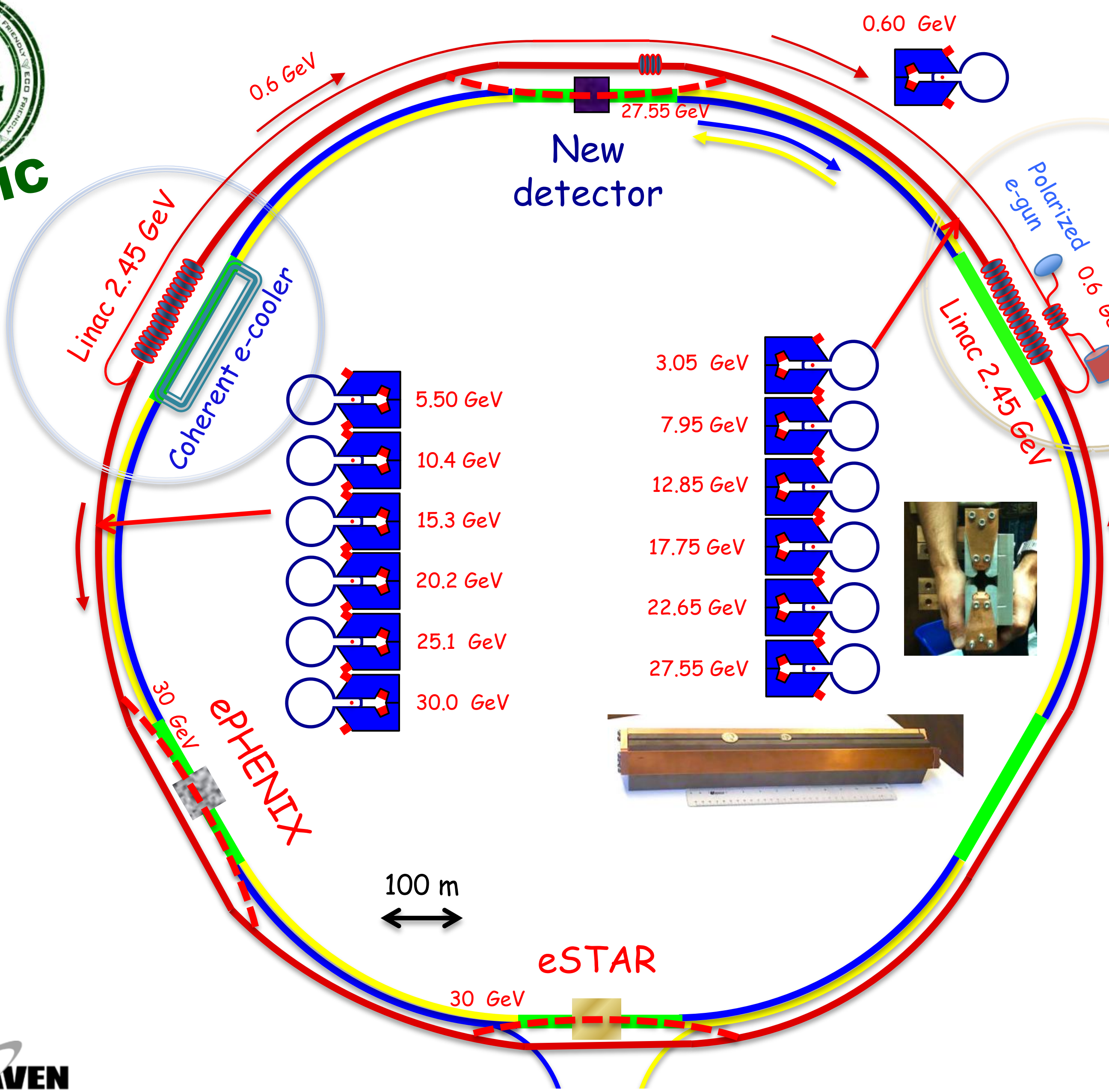
eRHIC: polarized electrons with $E_e \leq 30$ GeV will collide with either polarized protons with $E_e \leq 250^*$ GeV or heavy ions $E_A \leq 100^*$ GeV/u



Small gap magnets
5 mm gap
0.43 T @ 30 GeV

* We are exploring a possibility of increasing RHIC ring energy by 10% - 30%

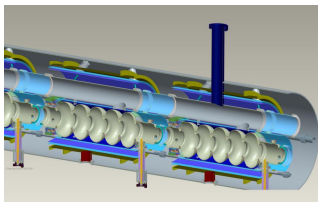
eRHIC luminosity

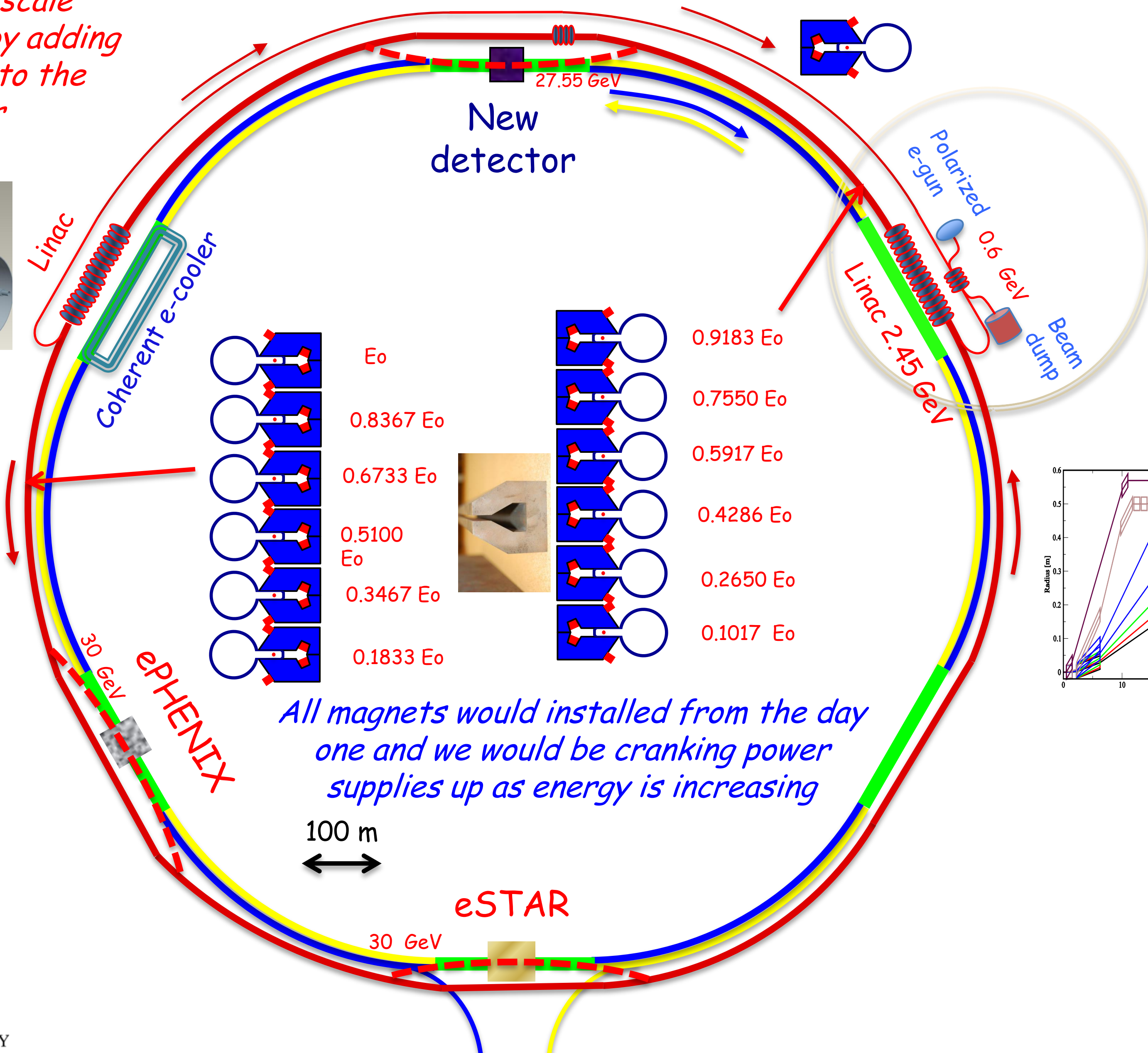
	e	p	$^2He^3$	$^{79}Au^{197}$	$^{92}U^{238}$
Energy, GeV	20	250	167	100	100
CM energy, GeV		141	115	89	89
Number of bunches/distance between bunches	74 nsec	166	166	166	166
Bunch intensity (nucleons) ,10^{11}	0.24	2	1.3	0.79	0.83
Bunch charge, nC	3.8	32	10	5.2	5.2
Beam current, mA	50	420	140	67	67
Normalized emittance of hadrons , 95% , mm mrad		1.2	1.2	1.2	1.2
Normalized emittance of electrons, rms, mm mrad		32	48	80	80
Polarization, %	80	70	70	none	none
rms bunch length, cm	0.2	8.3	8.3	8.3	8.3
β*, cm	5	5	5	5	5
Luminosity per nucleon, × 10^{34} $cm^{-2}s^{-1}$		0.97	0.65	0.39	0.41

Hourglass effect is included
Luminosity falls as the cube of hadron energy E_h^3 because of space charge limit
Luminosity is the same at energy of electrons from 5GeV to 20 GeV
e-beam current and luminosity fall as E_e^{-4} at electron energy >20 GeV

Staging of eRHIC: E_o : 5 -> 30 GeV

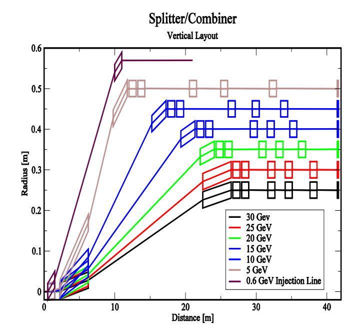
All energies scale proportionally by adding SRF cavities to the injector





All magnets would installed from the day one and we would be cranking power supplies up as energy is increasing

E/Eo
0.0200
0.1017
0.1833
0.2650
0.3467
0.4283
0.5100
0.5917
0.6733
0.7550
0.8367
0.9183
1.0000



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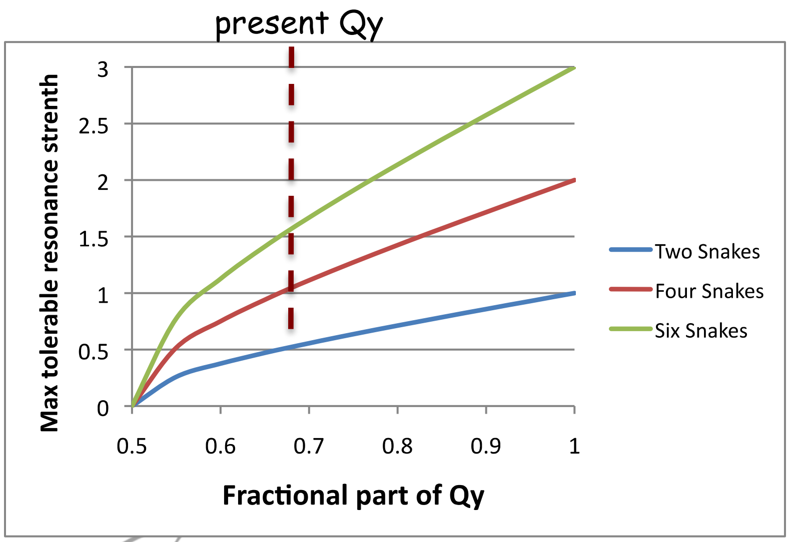
Polarized protons -> 70%

	Polarization
OPPIS source	~80%
AGS extraction	~65-70%
RHIC, 250 GeV	~45-50%

Polarization loss happens after 100 GeV

For isolated spin resonance (Courant-Lee). The Snake efficiency may depend also on their locations



Improvements in Run 11:

- AGS: jump quads improved considerably the slope of the polarization dependence on the bunch intensity
- RHIC: betatron tunes placed further away from the 0.7 higher-order spin resonance and the vertical realignment of all magnets led to better polarization transmission on the ramp

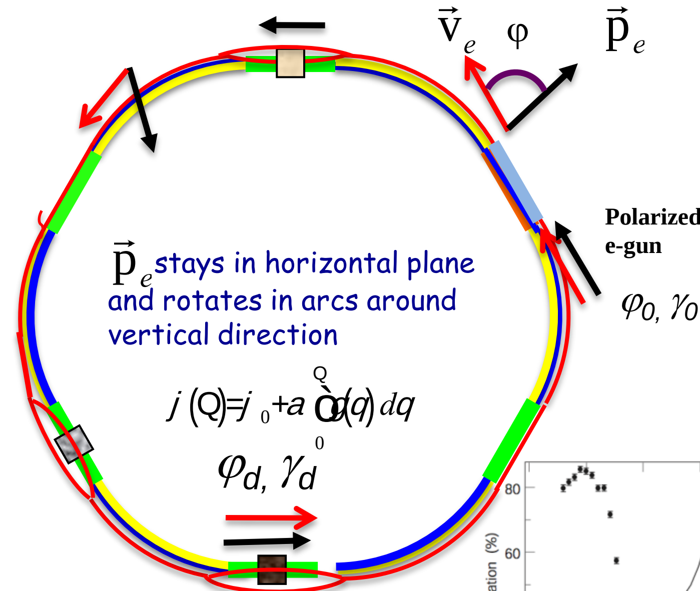
Possible future developments:

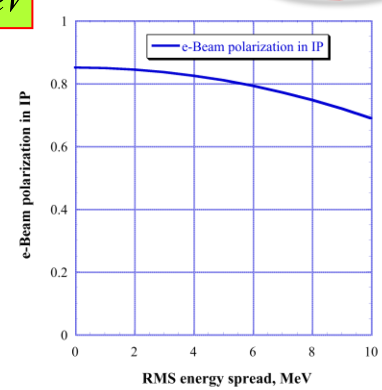
- Working point near integer (allowed by recent success of 10 Hz orbit feedback):
  - Fewer high-order spin resonances
  - Reduced strength of those resonances
- Increased number of the Snakes

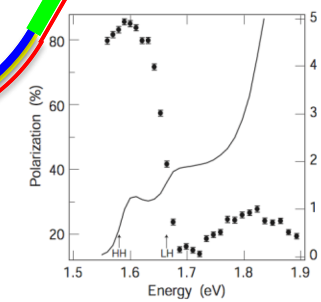
From T.Roser & V.Ptitsyn

Electron polarization in eRHIC

- Only longitudinal polarization is needed in the IPs
- High quality longitudinally polarized e-beam will be generated by DC guns with strained-layer super-lattice GaAs-photocathode
- Direction of polarization will be switch by changing helicity of laser photons in and arbitrary bunch-by-bunch pattern
- We continue relying on our original idea *(©VL 2003)* to rotate spin integer number of 180-degrees between the gun and the IP
- With six passes in ERL the required condition will be satisfied at electron energies: $E_e = N \times 0.07216\ GeV$
- It means that tuning energy in steps of 72 MeV (0.24% of the top energy of 30 GeV) will provide for such condition
- Energy spread of electrons should kept below 6 MeV to have e-beam polarization in IP above 80%



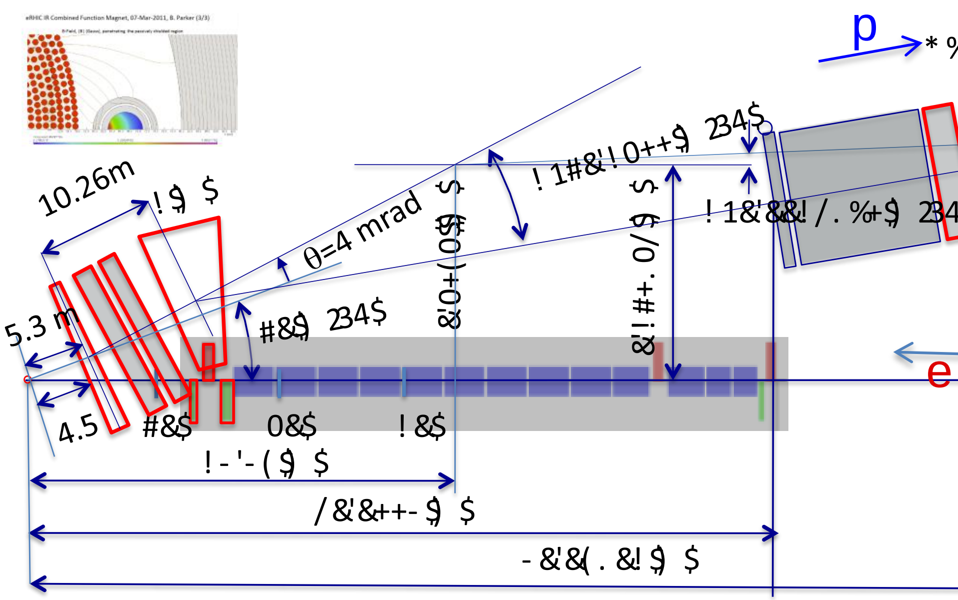


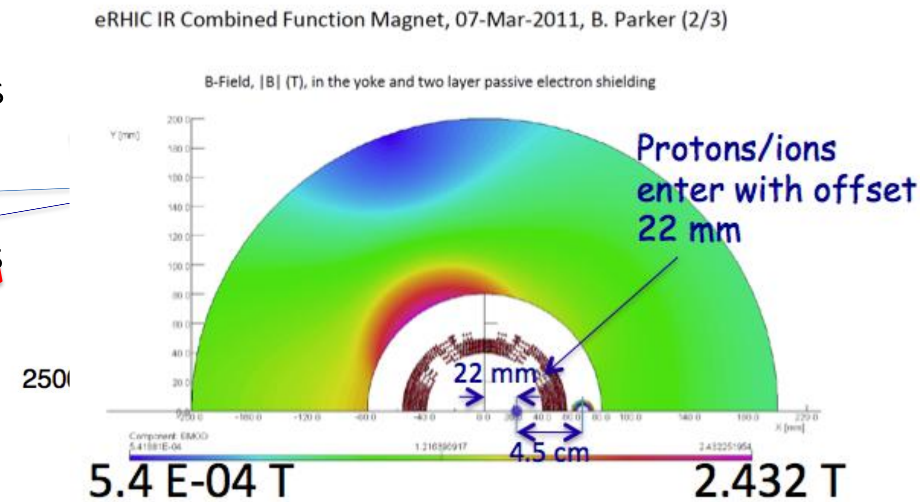


***The GaAs-GaAsP cathode achieved a maximum polarization of 92±6% with a quantum efficiency of 0.5%**

Highly polarized electrons from ..strained-layer super-lattice photocathodes, T. Nishitani et al., J. OF APPL. PHYSICS 97, 094907 (2005)

eRHIC high-luminosity IR with β*=5 cm





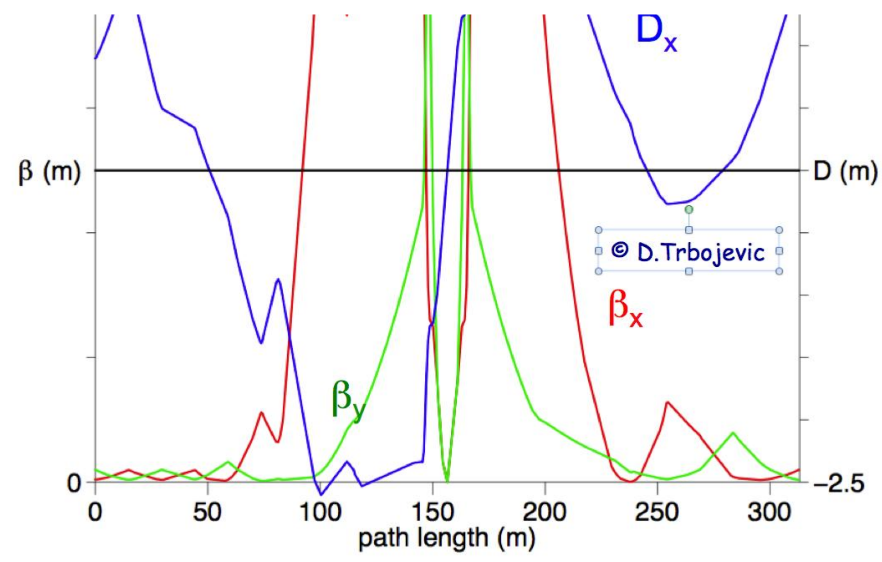
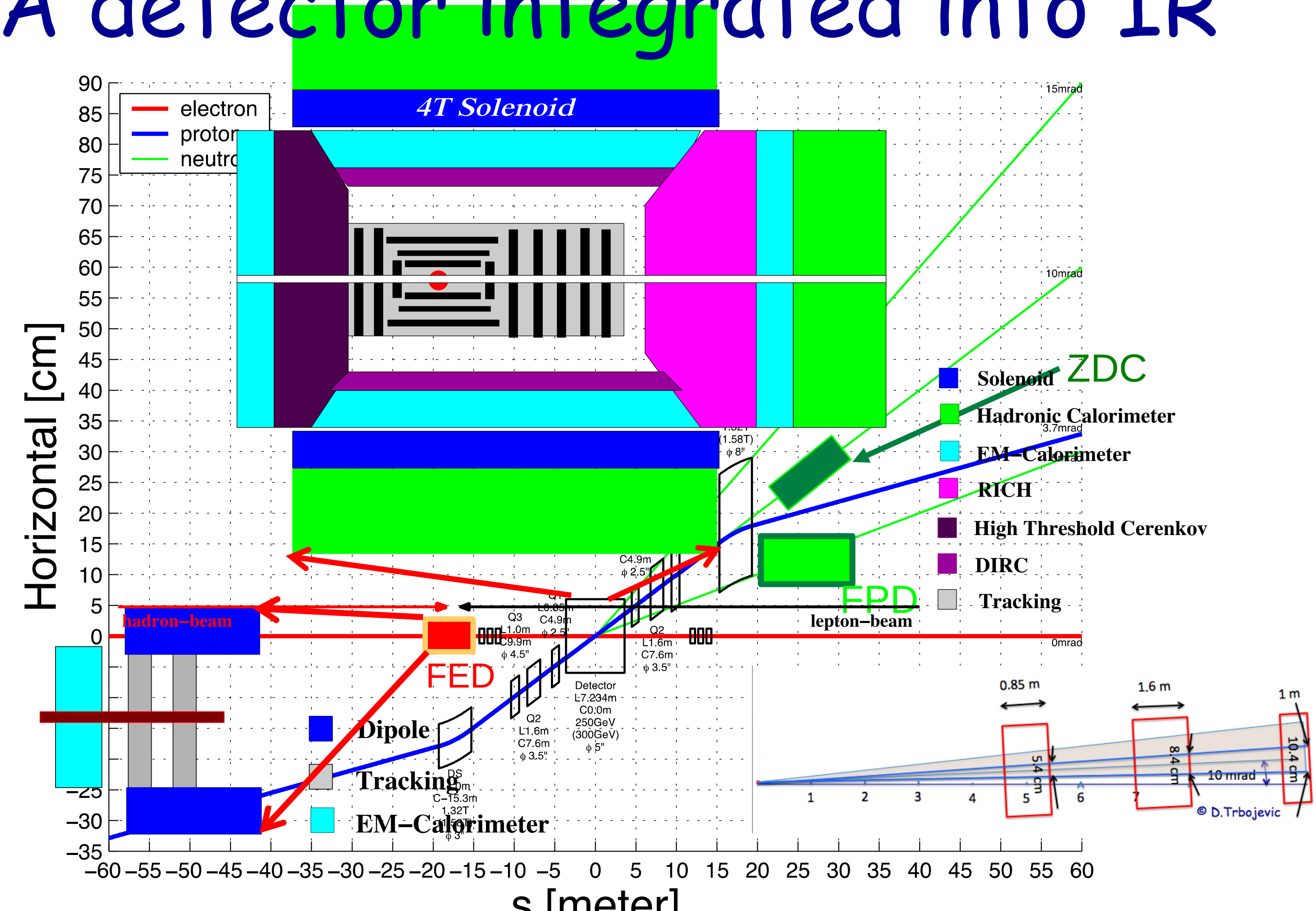


Fig. 1 Crab crossing scheme for KEKB

- 10 mrad crossing angle and crab-cros
- High gradient (200 T/m) large apertu
- Arranged free-field electron pass thi
- Integration with the detector: effici low angle collision products
- Gentle bending of the electrons to a

© D.Trbojevic, B.Parker, S. Tepikian, J. Beebe-Wang

A detector integrated into IR



❑ Dipoles needed to have good forward momentum resolution

➢ Solenoid no magnetic field @ r ~ 0

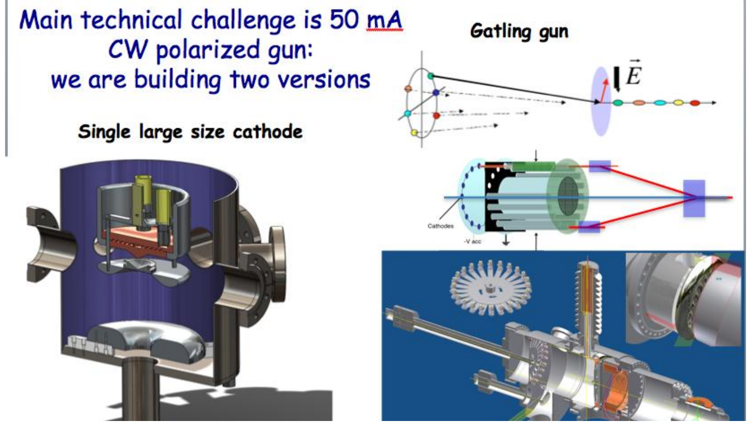
❑ DIRC, RICH hadron identification → π, K, p

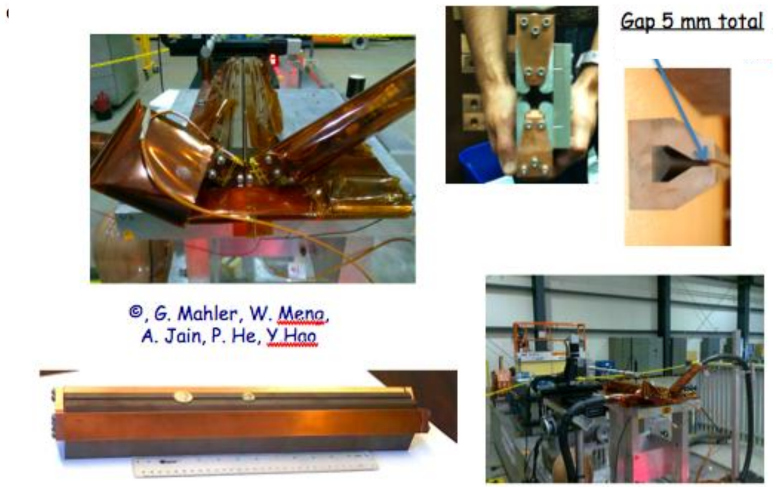
❑ high-threshold Cerenkov → fast trigger for scattered lepton

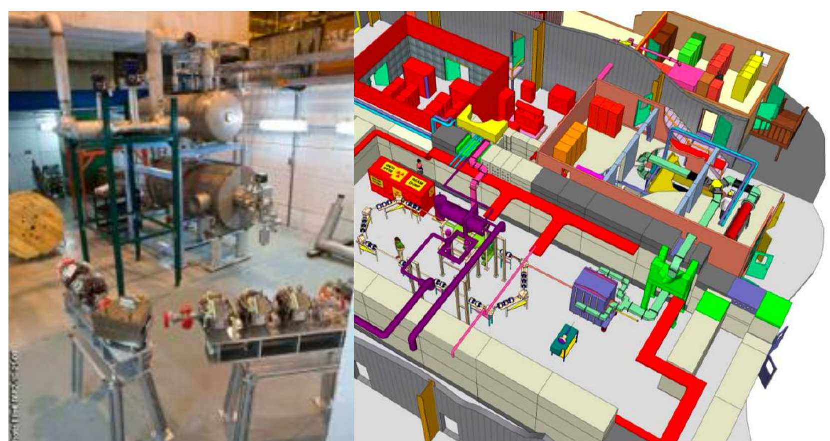
❑ radiation length very critical → low lepton energies

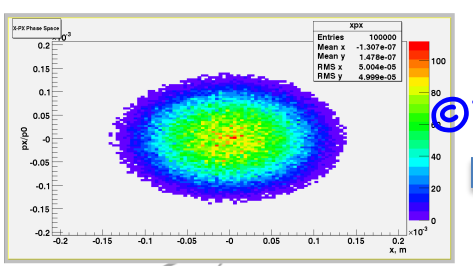
eRHIC R&D highlights

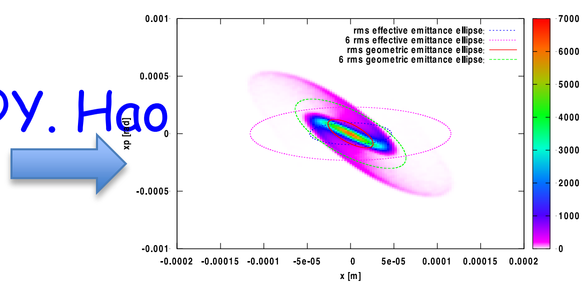
- Polarized gun for e-p program – **LDRD at BNL + MIT**
- Development of compact magnets - **LDRD at BNL, ongoing**
- SRF R&D ERL – **ongoing**
- Beam-beam effects, beam disruption, kink instability suppression, etc.
- Polarized He^3 source
- Coherent Electron Cooling including PoP – **plan to pursue**



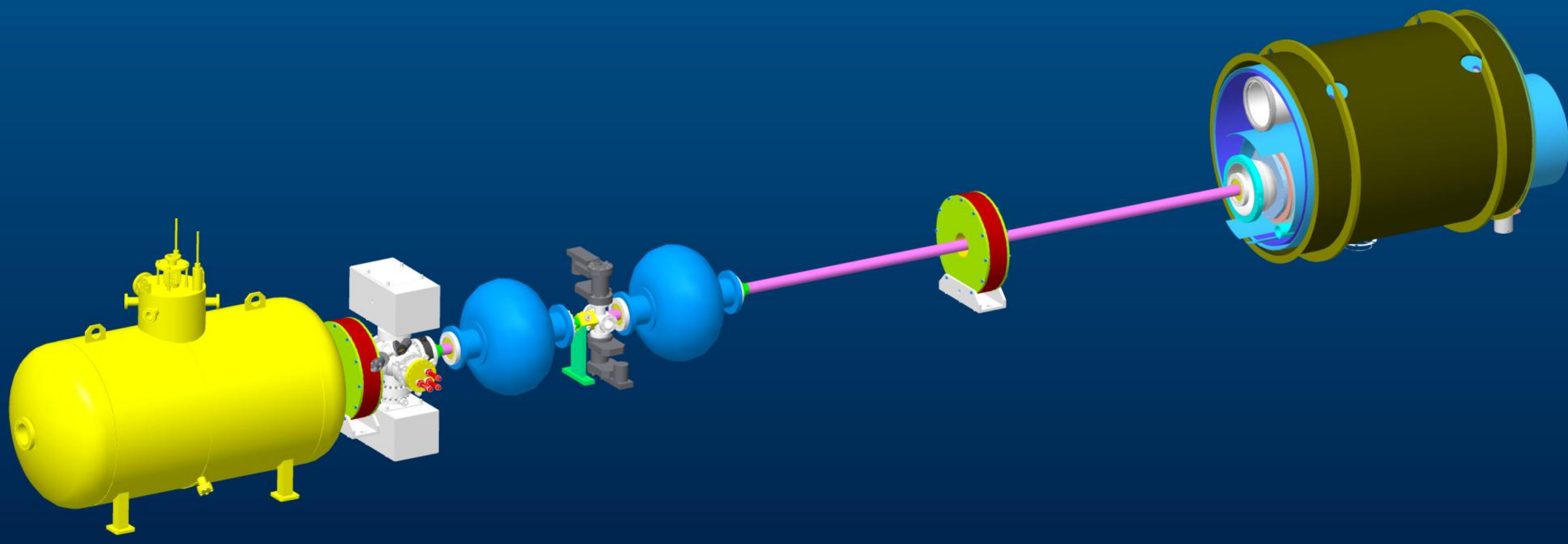








Coherent Electron Cooling demonstration experiment at RHIC IR2



Conclusions

- There are two competing designs for EIC in the US:
  - MEIC/ELIC at Jlab
  - eRHIC at BNL
- While luminosity numbers (on the paper) are similar, there are conceptual differences between these designs
  - MEIC/ELIC is based on ring-ring with very high collision rep-rate (0.5 to 1.5 GHz), very small $\beta^* \sim$ 0.5-2 cm and very large e-beam currents from 2.5A to 5 A
  - eRHIC is based ERL-ring collider with low collision reprate of 14 MHz, β^* of 5cm and e-beam current of 0.05 A at below 20 GeV and 0.01A at 30 GeV
- Both designs are progressing and both have significant challenges and need aggressive R&D
  - eRHIC conceptual design went through external review on August 1-3, 2011. The cost estimating for eRHIC is in progress and planned to be completed by January 2012.

Acknowledgements

- All people who provided slides for this talk
- ELIC team, especially Bob McKeown
- All members of eRHIC/RHIC teams for their numerous contributions

- Elke-Caroline Aschenauer ,Abhay Deshpande, Thomas Ulrich and Steven Vigdor for their input on question "Why electron-ion collider?"

- Supported by Brookhaven Science Associates under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy

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……BACK-UPS………

Coherent Electron Cooling vs. IBS: 250 GeV, $N_p = 2 \cdot 10^{11}$

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

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

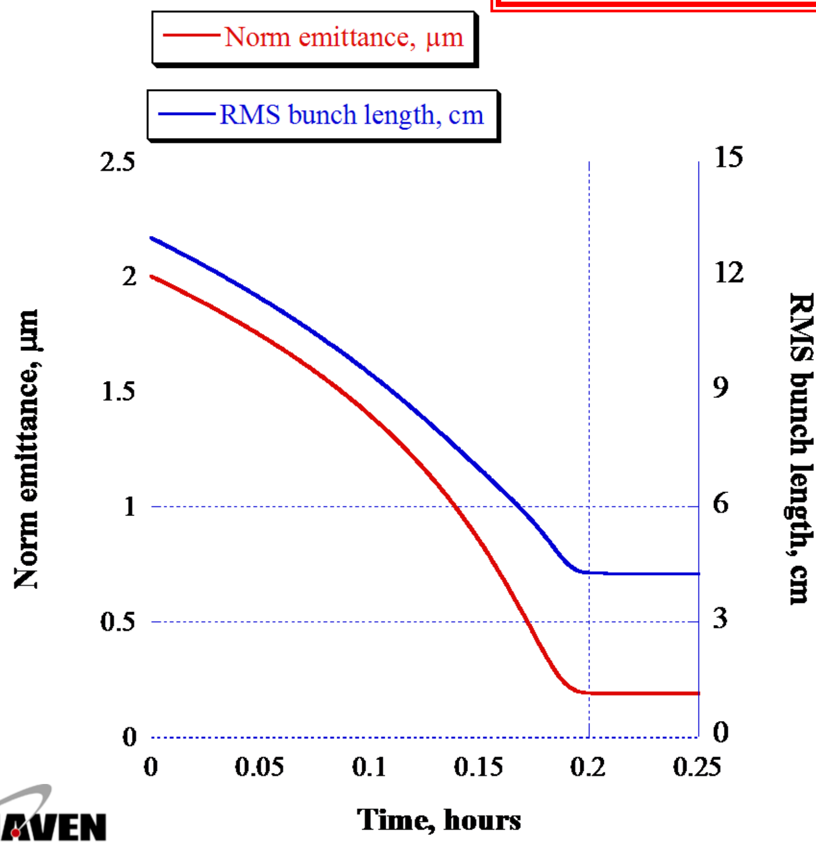
$$\frac{dS}{dt} = \frac{1}{\tau_{IBS//}}\frac{1}{X^{3/2}Y} - \frac{1-2\chi_\perp}{\tau_{CeC}}\frac{1}{X};$$

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

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

IBS growth time calculated by by A.Fedotov using Beta-cool

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



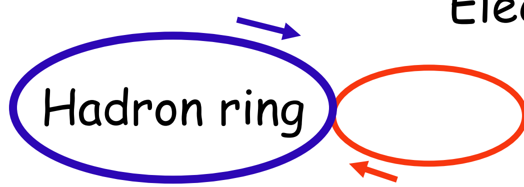
Important for:

a) keeping the luminosity constant
b) Reducing need for polarized beam current
c) Increase electron beam energy to 30 GeV
d) Increase luminosity by reducing β^* to 5 cm

ERL or ring for electrons?

- Two main design options for electron-hadron collider
  - Ring-ring: ENC, MEIC/ELIC

$$L = \left(\frac{4\pi\gamma_h\gamma_e}{r_h r_e}\right)(\xi_h\xi_e)(\sigma'_h\sigma'_e)f$$

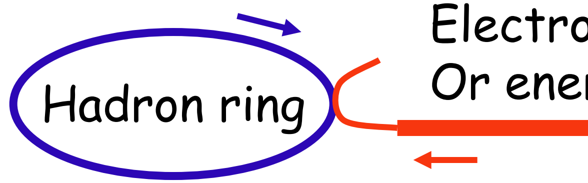


Electron storage ring

$$\xi_e \leq 0.1$$

  - Linac-ring: eRHIC

$$L = \gamma_h f N_h \frac{\xi_h Z_h}{\beta_h^* r_h}$$

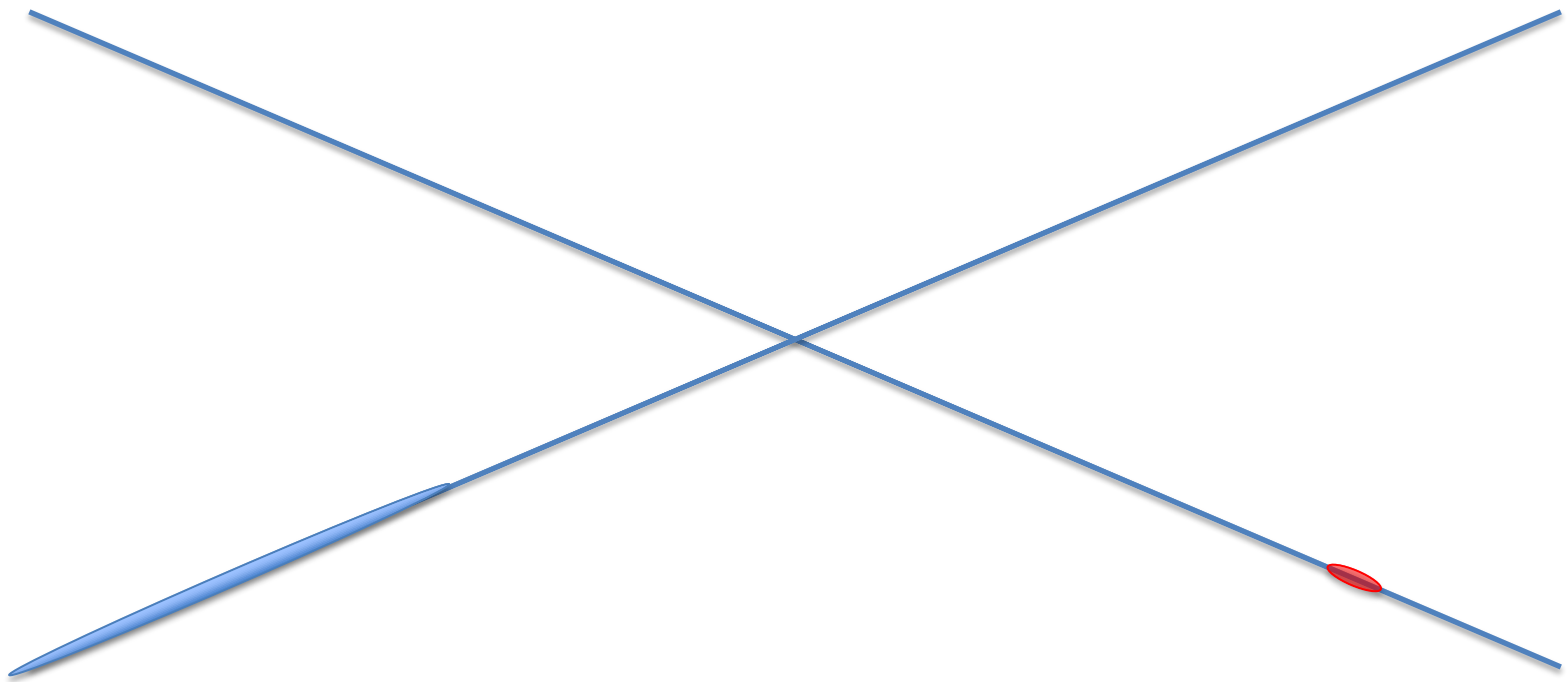


Electron linear accelerator
Or energy recovery linac

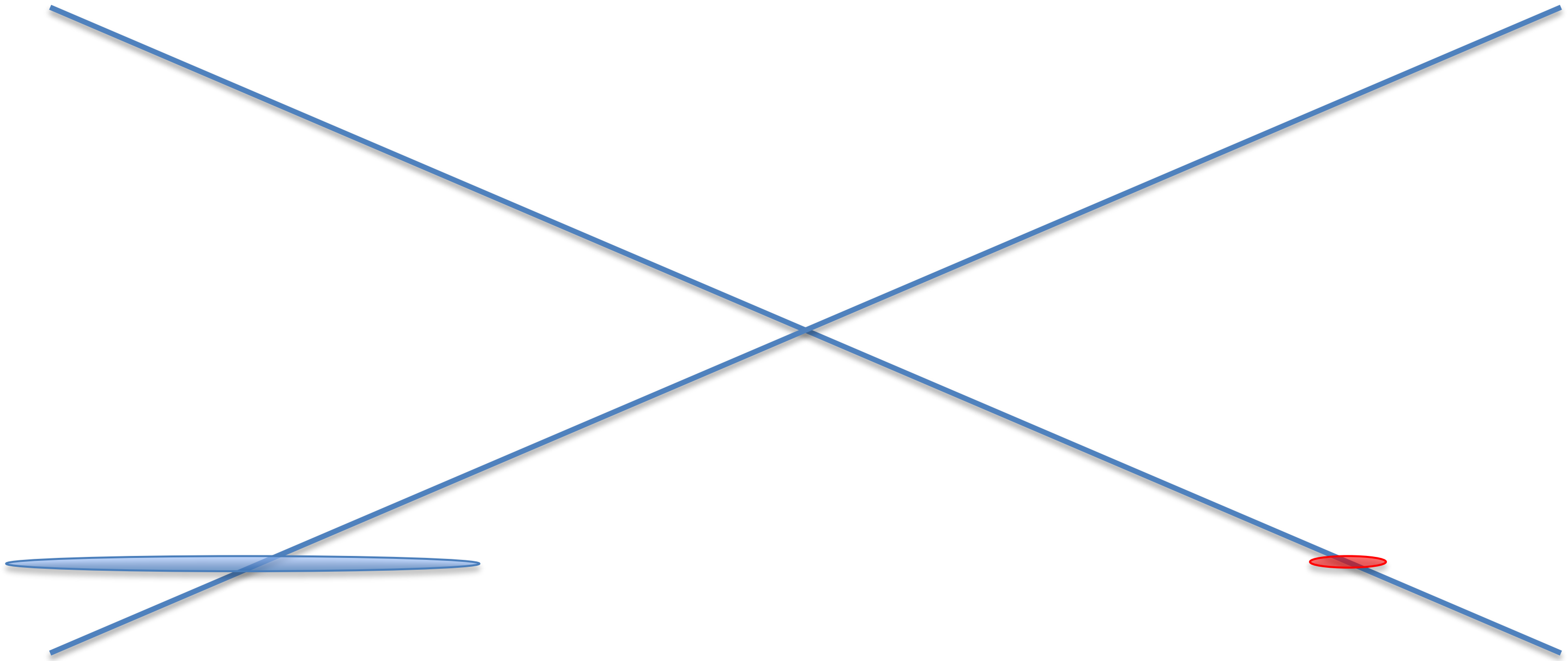
$$\xi_e > 1$$

LHeC still pursuing both ring-ring and linac-ring options

"No crabbing"

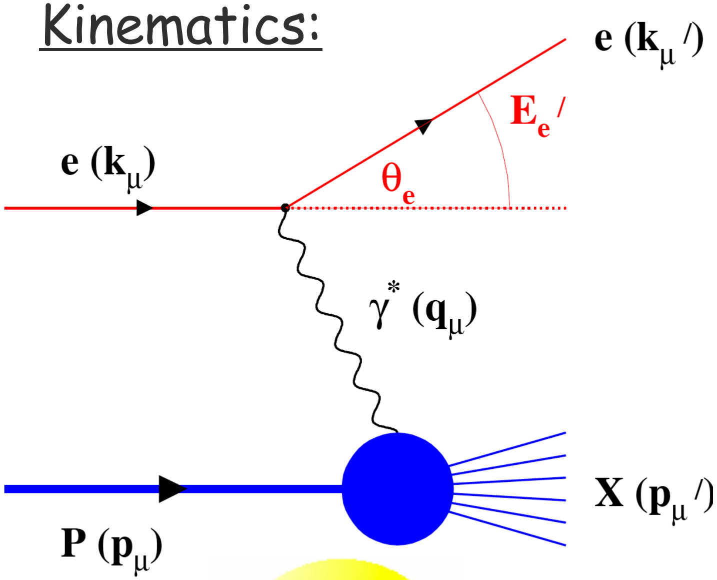


"Ideal crabbing"



THE PROBE: DEEP INELASTIC SCATTERING

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

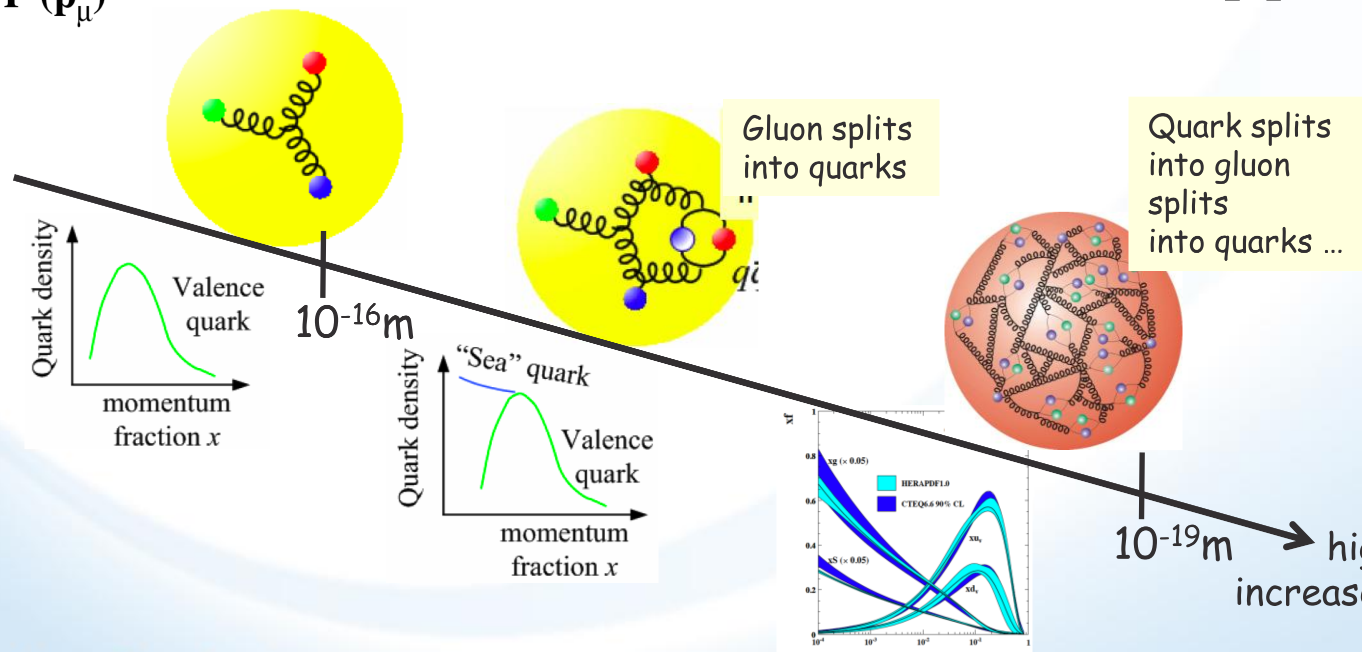
Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

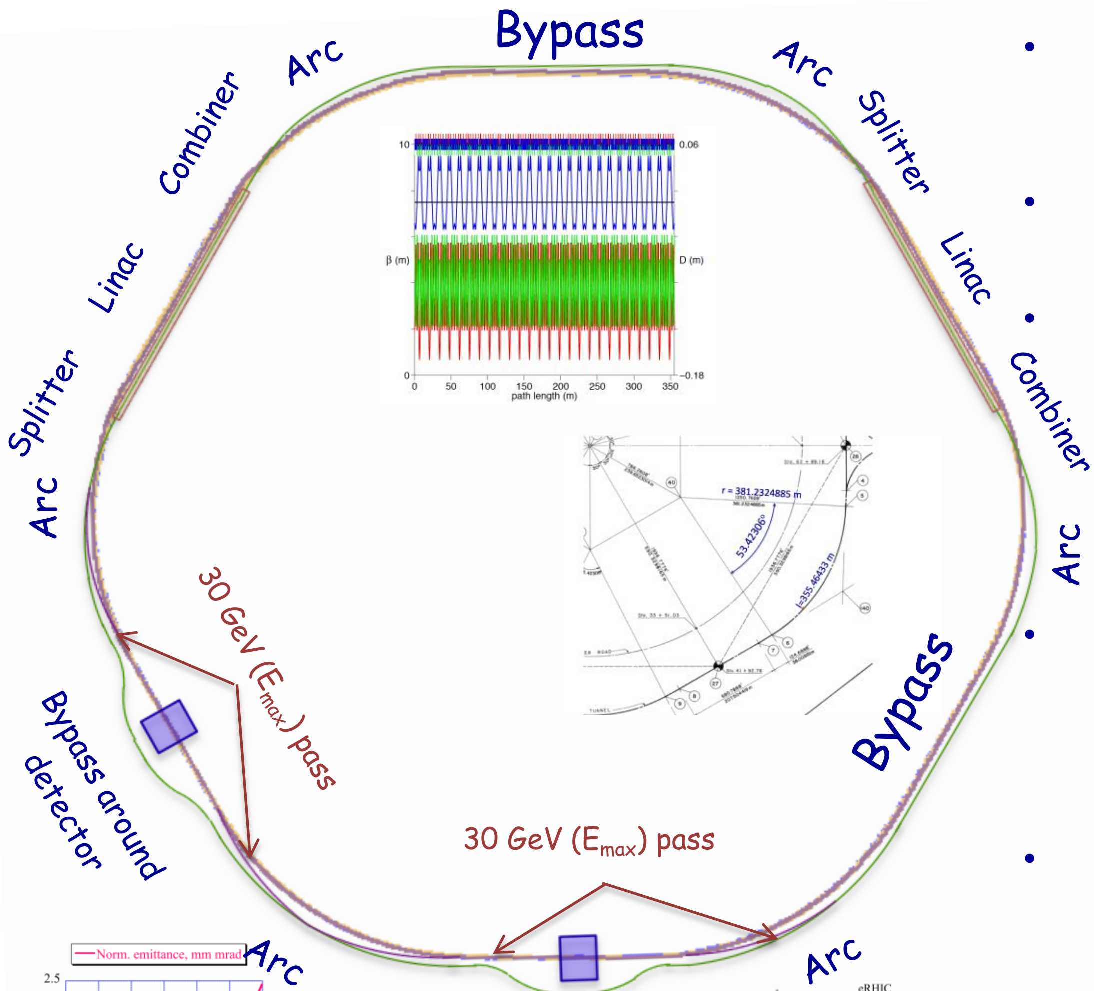
Measure of inelasticity

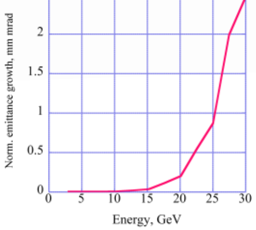
$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

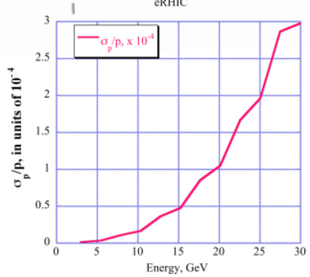
Measure of momentum fraction of struck quark



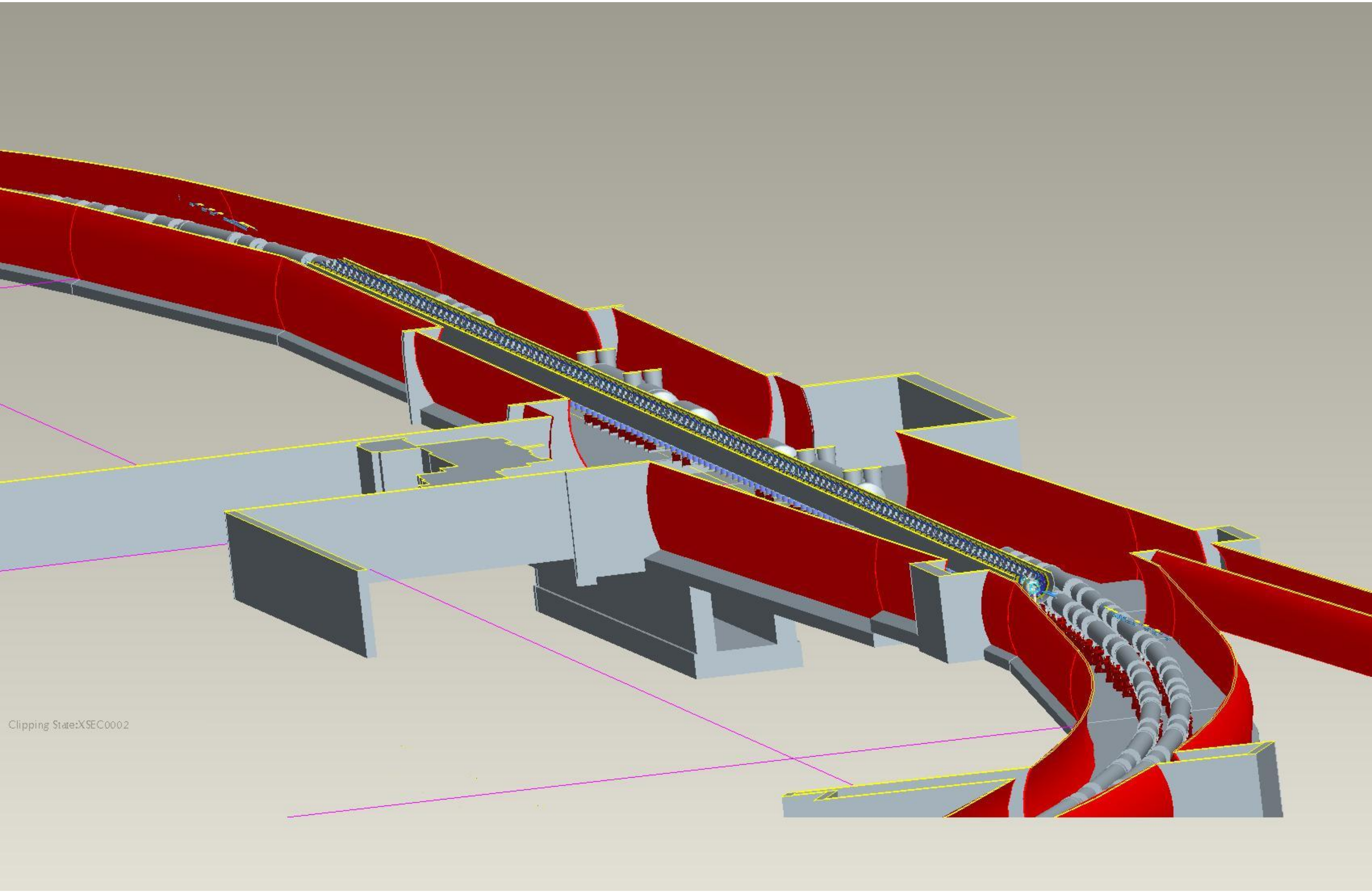
ERL Lattice with two detectors







- Based on asynchronous cell lattice developed by Dejan Trbojevic et al., AIP CONFERENCE PROCEEDINGS, V. 530, (2000) p. 333
- This cell is used for six arcs, two bypasses and bring the beam to the IR
- Figure on the left is exact survey of all magnets in eRHIC with
  - The circumference of of each paths tuned to match 250 GeV beam proton sequence and SRF period with accuracy of few microns
  - Location of all 14,781 magnets is determined
- Electron beam stays within the envelope of RHIC tunnel while providing maximum possible length (201 m) for SRF linacs, which are located inside the RHIC
- Splitters and combiners are vertical and are brining e-beam to the outside of the RHIC ring
- Two setting of dipole field are used to fit the ERL arcs into irregular RHIC tunnel
- Both emittance energy spread growth are under control



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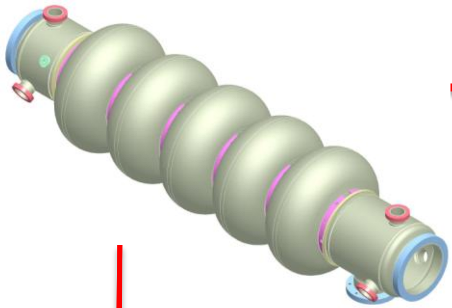
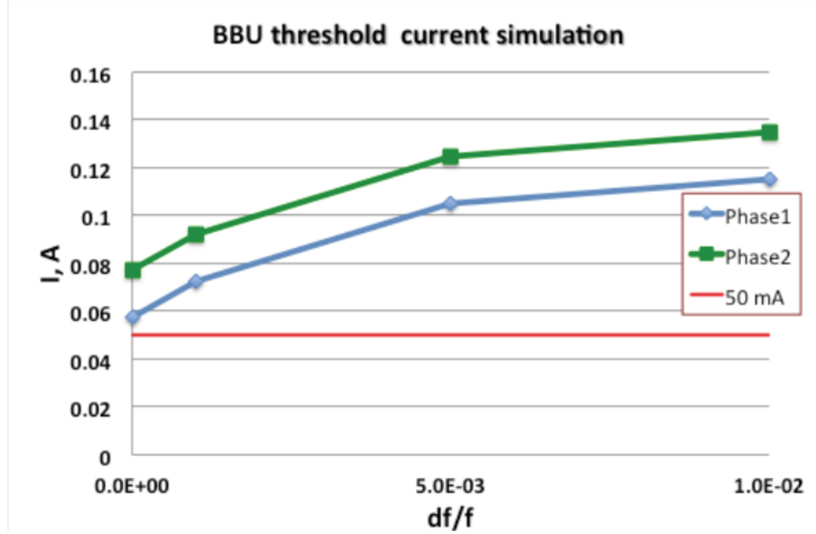
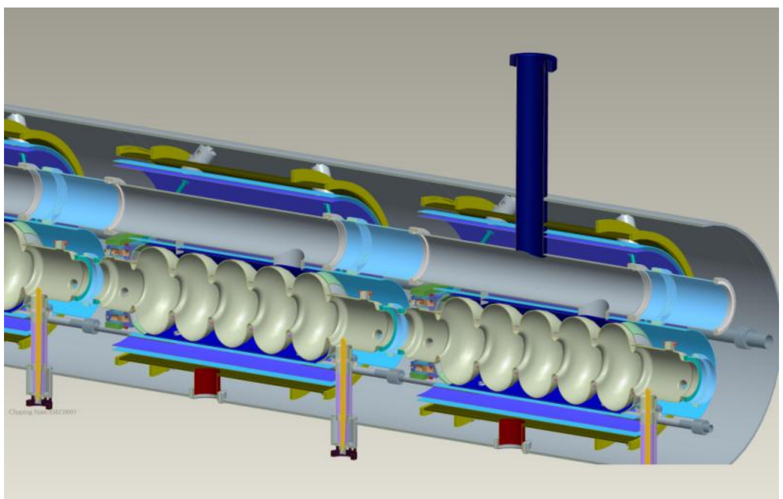
eRHIC Linac

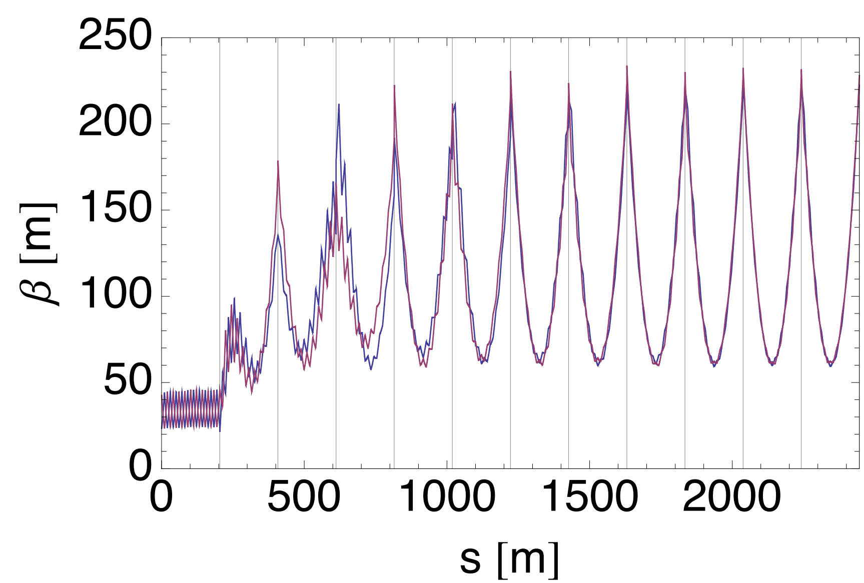




Total linac length -> 200 m plus
two warm-to-cold transition only at the ends
Maximum energy gain per pass -> 2.45 GeV
Accelerating gradient – 19.2 MV/m



Injection → E max



- ✓ **Based on BNL SRF cavity with fully suppressed HOMs**
- ✓ **This is critical for high current multi-pass ERL**
- ✓ **eRHIC cavity & cryostat designs are still evolving**

With Quadrupole strength from 0.72T/m to 2.93T/m that scales with the electron beam energy in the first linac. The quad length is assumed to be 0.2m The resulting length of one linac is 203.8m+cold warm transition.

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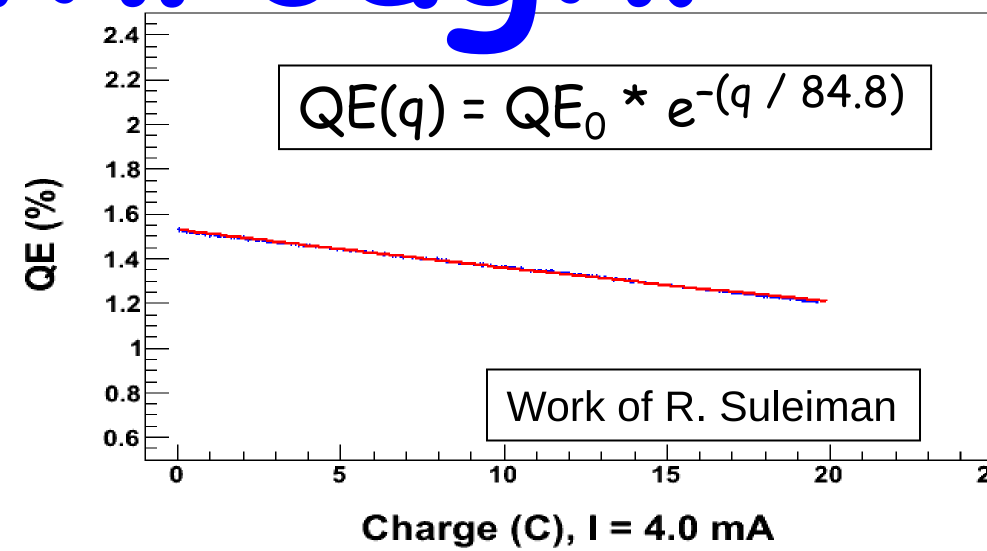
200kV Inverted Gun + SSL GaAs/GaAsP + RF-Fiber Laser → 4 mA

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**
Run Duration	**1.4 hr**
Extracted Charge	20 C
1/e Charge Lifetime	85 C

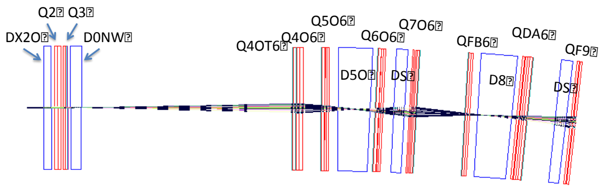
Breakthrough!

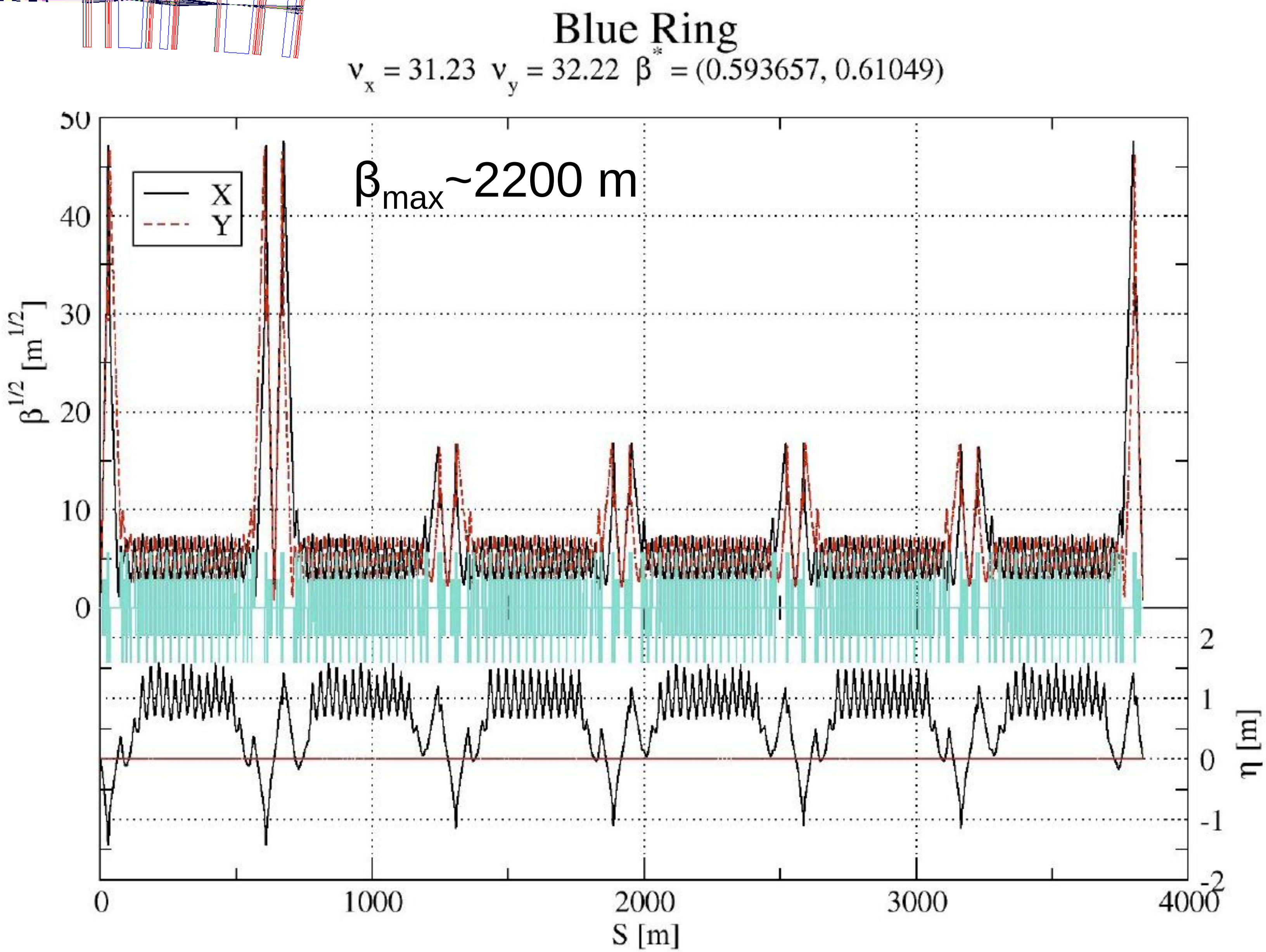
- High QE ~ 1.5% (~6 mA/W/%)
- Current-limited by available laser power
- Higher 200kV voltage => supersede 1mA demo
- Pushes technology in support of Electron Ion Colliders > 50 mA, High-P e^- Drivers



Main elements of the concept

- We chose ERL for electrons to reach high luminosity at high energy
- We assumed that we can cool hadron beam 10-fold in both longitudinal and transverse directions using coherent electron cooling
- We take advantage of small beam size in ERL and plan to use small magnets with gaps of 5 mm (and 10 mm at two lowest orbits)
- We had found a solution unique for Linac-ring colliders which would allow us to change energy of colliding hadrons from 50 GeV to 250 GeV
- We took advantage of recent advances in super-conducting quadrupole technology to design IR with β^* to 5 cm
- Following success of KEK-B with crab-crossing we accommodated this approach into new IR layout
- We assumed that we can generate up to 50 mA of polarized electrons
- These assumptions bring eRHIC top luminosity to 10^{34} cm^{-2} sec^{-1}
  - If polarized positrons are needed for the program, we suggest to build positron ring and use ERL for generating and accelerating positrons. Luminosity of this collisions will be much lower, i.e. at 10^{32} cm^{-2} sec^{-1} level and not all energies of hadrons could be used in the collisions


Q2 Q3
DX2O
D0NW
Q4OT6
Q4O6
Q5O6
Q6O6
Q7O6
QFB6
QDA6
QF9
D5O
DS
D8
DS


Blue Ring
$\nu_x = 31.23 \;\; \nu_y = 32.22 \;\; \beta^* = (0.593657, 0.61049)$
β_{max}~2200 m
X
Y
$\beta^{1/2}\ [m^{1/2}]$
η [m]
S [m]
0
1000
2000
3000
4000
50
40
30
20
10
0
2
1
0
-1
-2

Beam dynamics

Studied:

- 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……

Still under discussion:

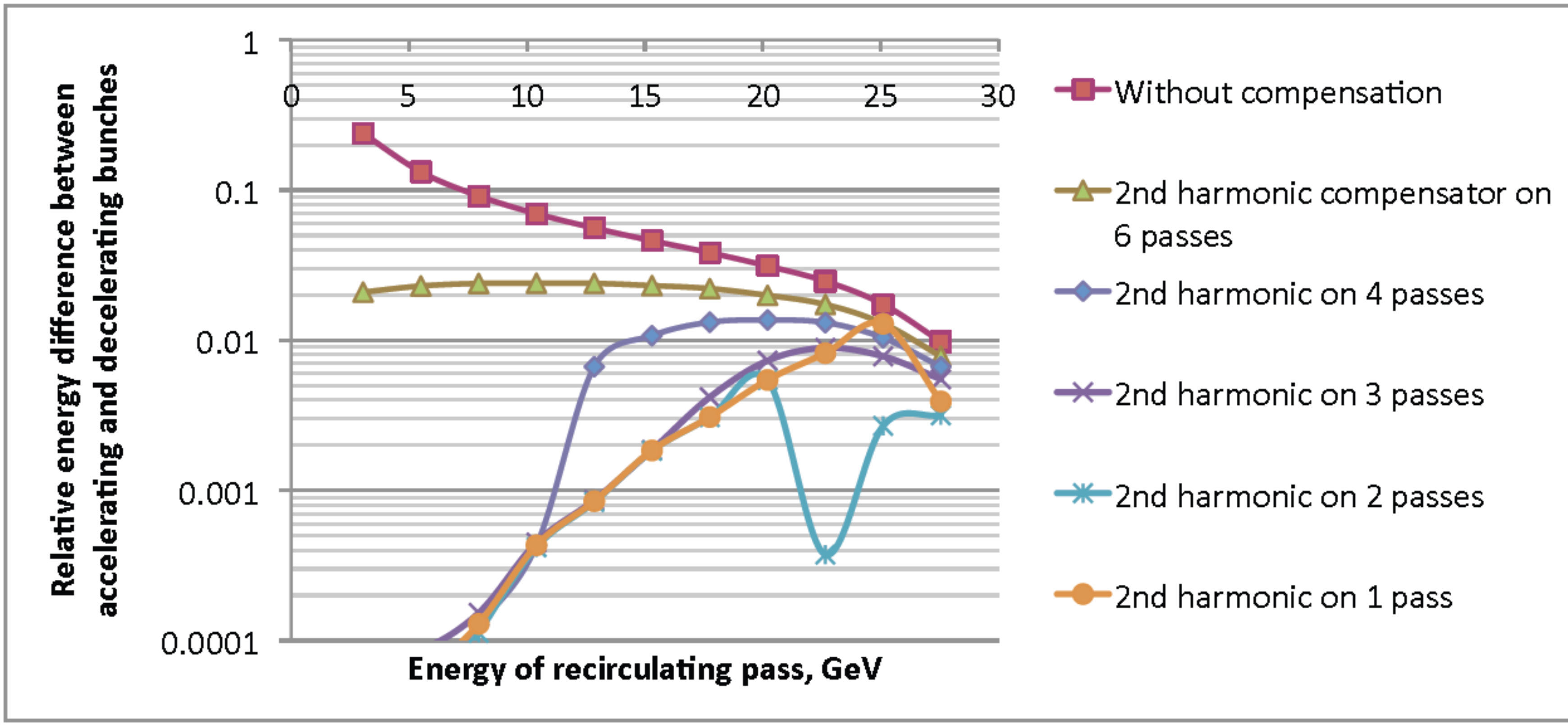
- How small can be the electron beam pipe gap?
- De-bunching and reduction of the energy spread of the electron beam at the dump.
- Length of the electron bunches and the need for harmonic cavities
- Detailed beam dynamics with CeC
- Effect of crab cavities on beam dynamics…

Magnets inventory

5 mm gap except 10 mm gap for low energy (<1/4 E_{max}) passes

Total number of dipoles in arcs:	#B2	#BV	#QF	#QD	#QF3	#QD3	#AD1	#AD2	#QD1	#QC1	
B2 → 1.20 m	1008										
QF → 0.40 m			288								
QD → 0.45 m				436							
QF3 → 0.90 m					288						
QD3 → 0.80 m						288					
INTERACTION REGION only for 30 GeV:											
Total number of vertical dipoles:											
B2 → 1.2 m long	56										
BV → 2.5 m long		21									
Total number of quads:											
QF → 0.40 m			8								
QD → 0.45 m				12							
QF3 → 0.90 m					8						
QD3 → 0.80 m						8					
Two STRAIGHT SECTIONS (12&4):											
QD → 0.45 m				118							
QF →			120								
Splitter and Combiner											
AD1 → 4.0 m							4				
AD2 → 4.0 m								4			
QD1 → 1.0 m									10		
QC1 → 1.0 m										10	
Bypasses 6&8 o'clock											
B2 → 1.20 m	168										
QD → 0.45 m				78							
QF → 0.40 m			55								
QF3 → 0.90 m					28						
QD3 → 0.80 m						32					
Pass #1 0.6 → 5.5 GeV		1176		459	636	316	320	4	4	10	10
Pass #2 5.50 → 10.4	1176		459	636	316	320	0	4	10	10	
Pass #3 10.4 → 15.3	1176		459	636	316	320	0	4	10	10	
Pass #4 15.3 → 20.2	1176		459	636	316	320	0	4	10	10	
Pass #5 20.2 → 25.1	1176		459	636	316	320	0	4	10	10	
Pass #6 25.1 → 30.0	1064	21	416	570	296	296	0	4	10	10	
Total number	**6944**	**21**	**2711**	**1206**	**1876**	**1896**	**4**	**24**	**60**	**60**	→ 14,781 elements

Loss budget for 6 pass scheme



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Main Accelerator Challenges for eRHIC

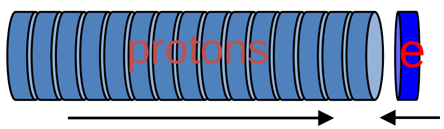
In red –increase/reduction beyond the state of the art

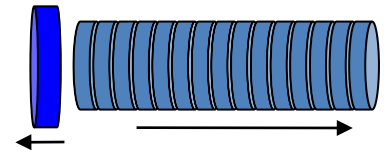
Polarized electron gun - 10x increase
Coherent Electron Cooling – New concept
Multi-pass SRF ERL 5x increase in current 30x increase in energy 3 x in # of passes
Crab crossing New for hadrons
Polarized ^{3}He production
Understanding of beam-beam affects New type of collider
β^*=5 cm 5x reduction
Feedback for kink instability suppression Novel concept

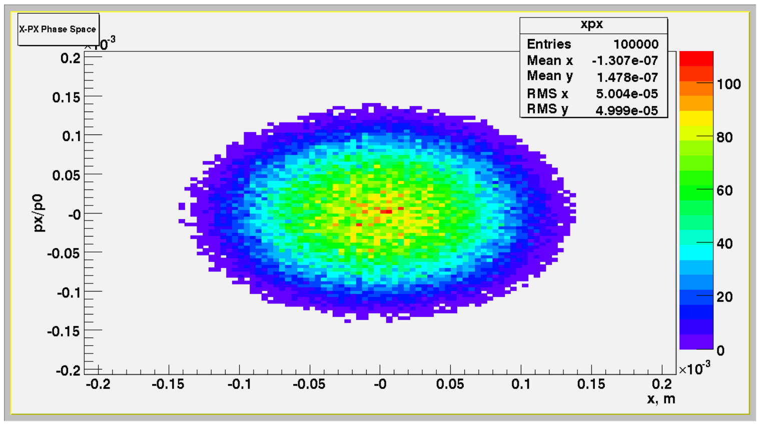
Major modification to RHIC

Modification to IR straights
Coherent Electron Cooling
6MV, 704 MHz RF system
Copper layered beam pipe
Crab cavities
Upgraded injection kickers (for 166 bunch operation)
Various Feedbacks, including that for kink instability suppression

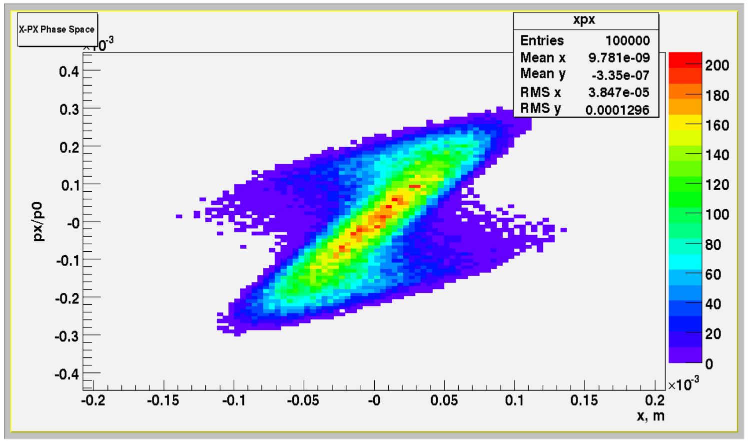
Beam Disruption



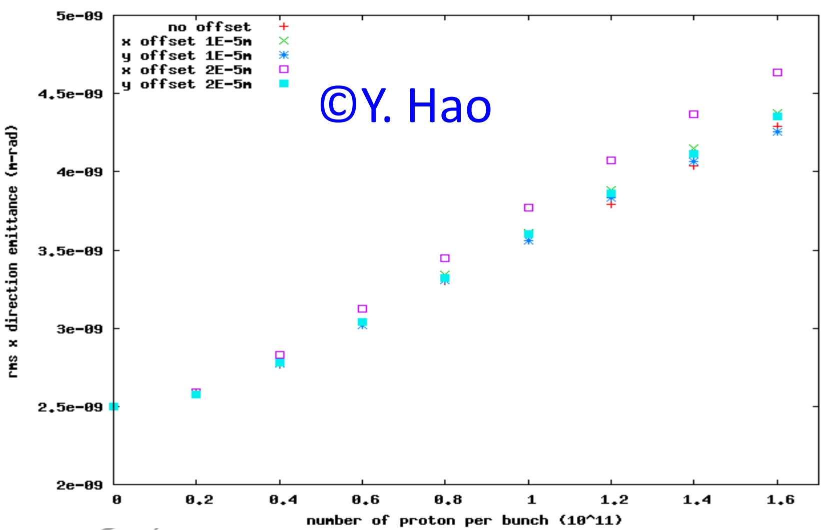


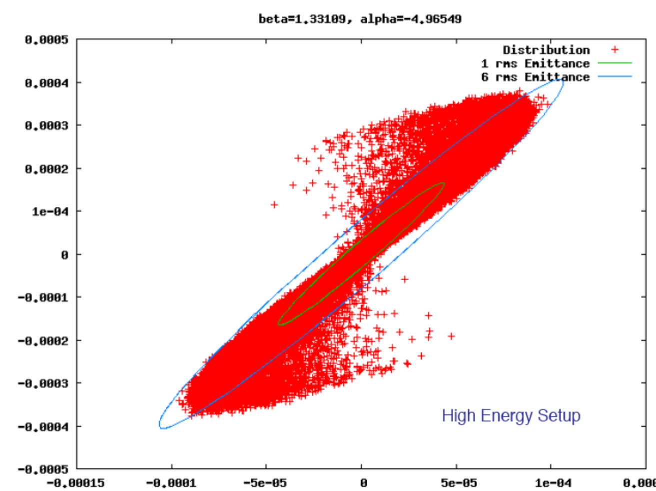


Interaction



Optimized





eRHIC developments

http://www.bnl.gov/cad/eRhic/

At PAC'11

- eRHIC – 10 papers
- CeC – 5 papers
- BNL's R&D ERL – 14 papers
- Polarized e-gun – 5 papers
- Beam dynamics in eRHIC – 3 papers
- And more – see PAC'11 proceedings

June 15: Energy losses and energy loss compensator comparisons. (V. Ptitsyn)

June 8: Synchrotron Radiation in IR electron line. (J. Beebe-Wang)

June 1: Frequency matching. (V. Ptitsyn), Delay line at 4 o'clock. (N. Tsoupas)

May 25: Wall Roughness. (A. Fedotov), eRHIC Accelerator Design Wiki. (V. Ptitsyn)

May 18: Energy loss compensation: 2nd harmonic cavities. (V. Ptitsyn), Crab crossing. (V. Litvinenko)

May 11: Towards White Paper. Planning. (V. Ptitsyn)

April 27: Crab cavities: locations and parameters. Revision. (N. Tsoupas), Energy loss compensation: 2nd harmonic cavities. (V. Ptitsyn)

April 20: Do we need crab cavities for the electron beam? (Y. Hao), Crab cavities: locations and parameters. (N. Tsoupas)

April 13: Energy loss compensation schemes. (V. Ptitsyn), Update on the IR electron beam optics. (J. Beebe-Wang)

April 6: Splitter design: two linacs versus one linac scheme. (N. Tsoupas), Update on the kink instability study. (Y. Hao)

March 23: Staging. (V. Ptitsyn)

March 16: CSR: results and comparison with calculations. (V.N. Litvinenko), Recirculating pass magnets: parameters and numbers. (D. Trbojevic)

March 9: Update on beam-beam studies. (Y. Hao), Energy spread compensation with mini-linac. (V. Ptitsyn)

March 2: Ion trapping. (Y. Hao), Electron injector status. (D. Kayran)

February 16: Electron circumference and bunch pattern. (V.Ptitsyn), IR: particle propagation. (D. Trbojevic)

February 09: Why do we need high beam energies for e-p. (E. Aschenauer), The importance of higher CME for eA physics at eRHIC. (T. Ullrich)

February 2: New eRHIC layout. (V.N. Litvinenko), Longitudinal transfer simulations. (V. Ptitsyn)

January 26: Electron by-pass lines. (N. Tsoupas)

January 19: IR top energy electron beamline. (J. Beebe-Wang), e-p and e-Au luminosities at different collision energies. (V. Ptitsyn)

January 05: Electron passes in IRs and straight sections. (N. Tsoupas), IR design status. (D. Trbojevic)

http://www.c-ad.bnl.gov/pac2011/proceedings/html/sessi0n.htm

eRHIC Luminosity in e-p

Reaching high luminosity:

- high average electron current (50 mA = 3.5 nC * 14 MHz)
  - energy recovery linacs; SRF technology
  - high current polarized electron source
- cooling of the high energy hadron beams (Coherent Electron Cooling)
- β*=5 cm IR with crab-crossing

Polarized (and unpolarized) e (80%) –p (70%) luminosities in 10^{33} cm^{-2} sec^{-1} units

Limiting factors:

- hadron $\Delta Q_{sp} \leq 0.035$
- hadron $\xi \leq 0.015$
- polarized e current ≤ 50 mA
- SR power loss ≤ 8 MW

	Protons				
Electrons	E, GeV	100	130	250	*325**
	5	0.62 (3.1)	1.4 (5)	9.7	*15*
	10	0.62 (3.1)	1.4 (5)	9.7	*15*
	20	0.62 (3.1)	1.4	9.7	*15*
	30	0.12	0.28	1.9	*3*

***** *If this energy can be reach in RHIC***

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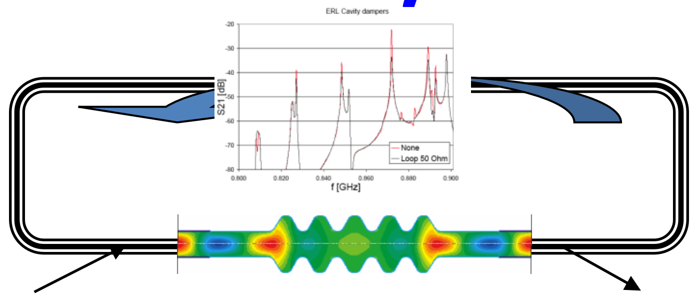
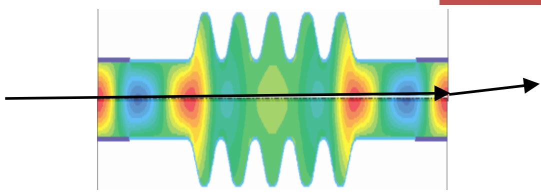
TBBU stability (©E. Pozdeyev)

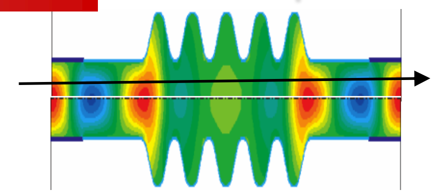
- HOMs based on R. Calaga's simulations/measurements
- 70 dipole HOM's to 2.7 GHz in each cavity
- Polarization either 0 or 90°
- 6 different random seeds
- HOM Frequency spread 0-0.001



Excitation process of transverse HOM

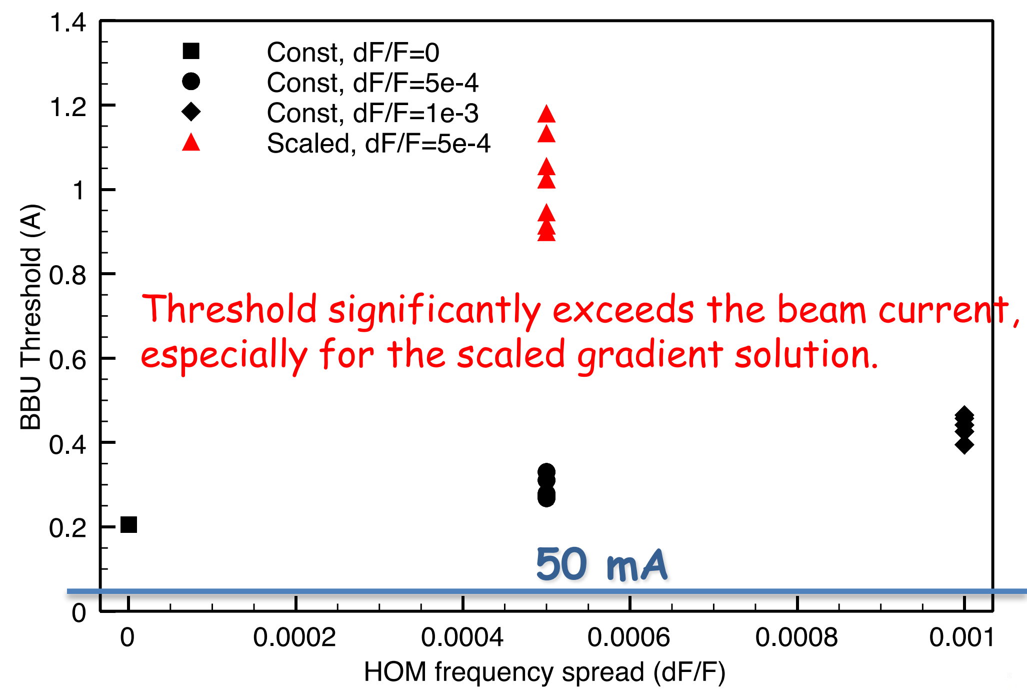


$$\begin{bmatrix} x \\ x' \end{bmatrix}_{return} = \begin{bmatrix} m11 & m12 \\ m21 & m22 \end{bmatrix} \times \begin{bmatrix} 0 \\ x' \end{bmatrix}_{comming}$$



Simulated BBU threshold (GBBU) vs. HOM frequency spread.

F (GHz)	R/Q (Ω)	Q	(R/Q)Q
0.8892	57.2	600	3.4e4
0.8916	57.2	750	4.3e4
1.7773	3.4	7084	2.4e4
1.7774	3.4	7167	2.4e4
1.7827	1.7	9899	1.7e4
1.7828	1.7	8967	1.5e4
1.7847	5.1	4200	2.1e4
1.7848	5.1	4200	2.1e4



eRHIC Luminosity in e-A

Reaching high luminosity:

- high average electron current
  - energy recovery linacs; SRF technology
  - high current polarized electron source
- cooling of the high energy hadron beams (Coherent Electron Cooling)
- β^*=5 cm IR with crab-crossing

Limiting factors:

- hadron $\Delta Q_{sp} \leq 0.035$
- hadron $\xi \leq 0.015$

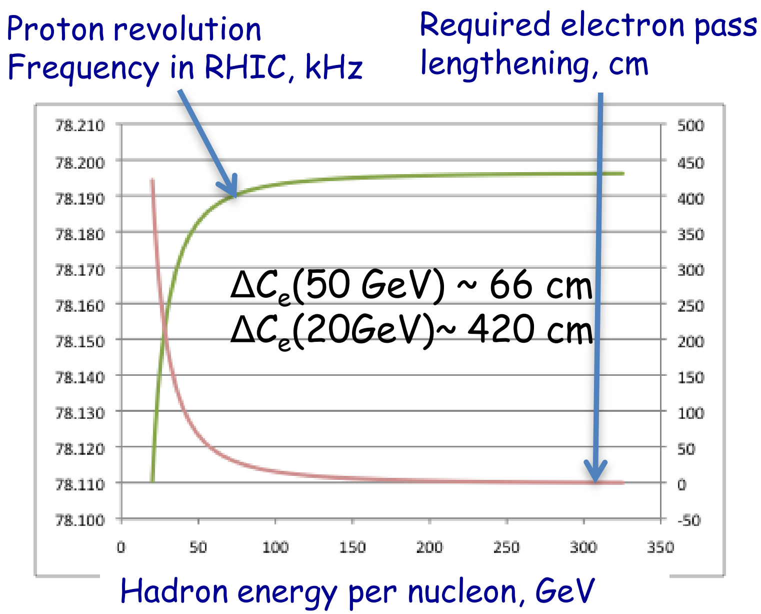
-SR power loss ≤ 8 MW

e-A luminosities in 10^{33} cm^{-2} sec^{-1} units

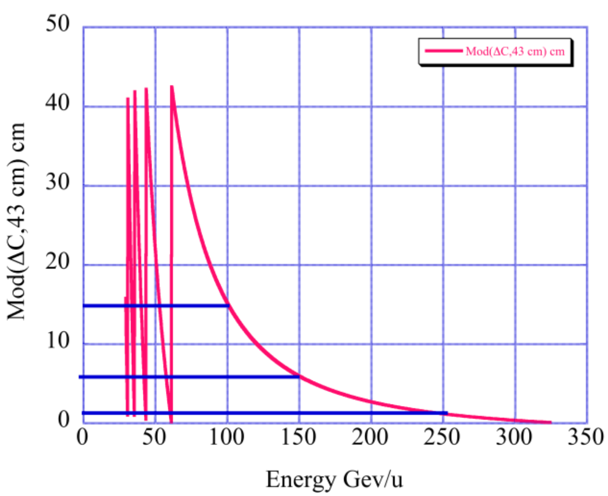
	Au ions				
Electrons	E, GeV	**50**	**75**	**100**	***130****
	5	2.5	8.3	11.4	***18***
	10	2.5	8.3	11.4	***18***
	20	0.49	1.7	3.9	*8.6*
	30	0.1	0.34	0.77	*1.7*

***** If this energy can be reach in RHIC***

Electron-hadron frequency matching & Lumi sharing



- In eRHIC electrons are ultra-relativistic ($\gamma_e \geq 10^4$) but they are colliding with barely relativistic ($\gamma_h \sim 10^2$)
- It means that rep-rate of the hadron changes with there energy and in ring-ring scenario it would require to change the circumference of the ring
- In ERL-based eRHIC case the condition is easier to satisfy – we can switch harmonic ratio between the hadron beam hadron beam rep-rate and SRF frequency, i.e. skipping a bucket
- We plan to select few top energies (e.g. 325, 250, 150 & 100 GeV/u) and have the pass length adjusted using two straight section bypasses. Maximum path-length change required in this case is only 15 cm and can be accommodated in one straight.
- It is important to note that this condition would not satisfy centered collisions in more than one IR – i.g. passing time through the center of other IR could be of by as much as 20-40 cm
- It is not a problem! Since eRHIC would operate in luminosity sharing mode, only ONE IR will have collision at any moment. Thus, we can share eRHIC luminosity between in real time in any desirable ratio (i.e. 0.87 : 0.12: 0.01 is possible)



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$$L\&0+\%235A+ f_{rev\_e} = \frac{m_e n_p}{h_e} f_{rev\_p} = \frac{9000}{h_e} f_{rev\_p}$$

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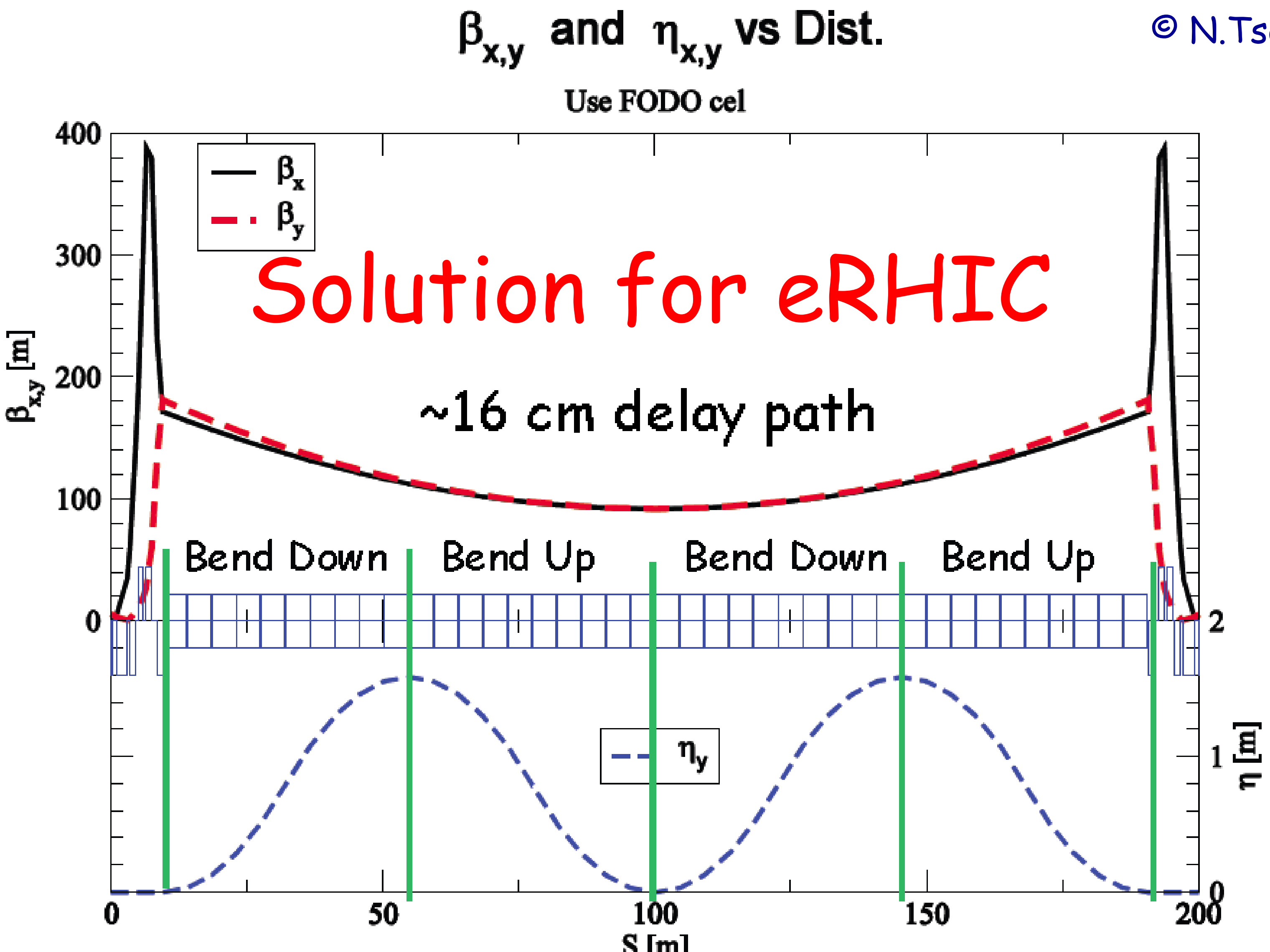
Beam optics of the 4 o'clock Delay Line

Dipoles only

© N.Tsoupas



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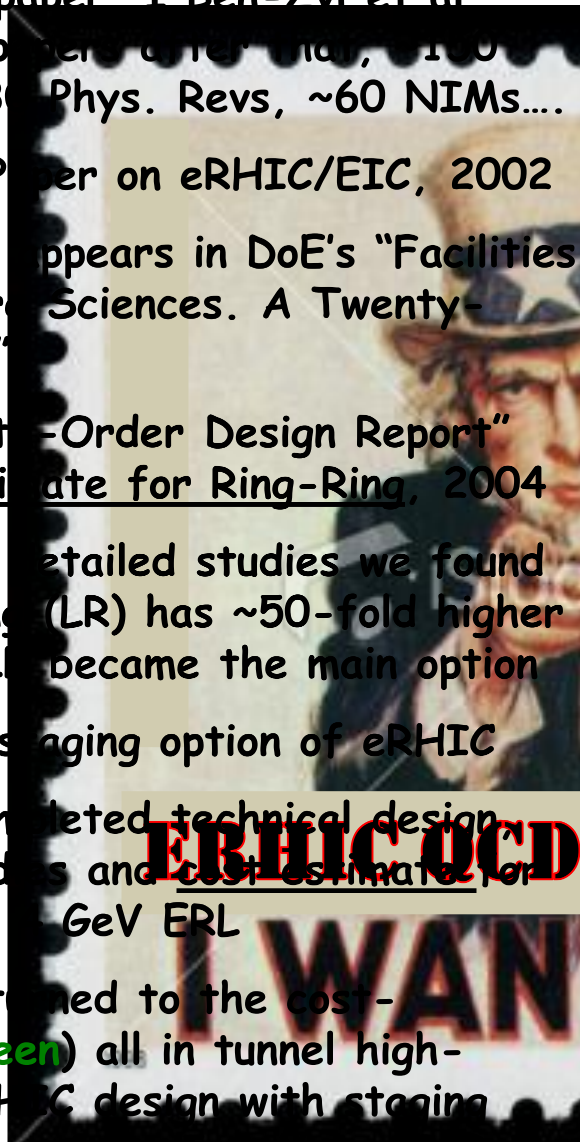
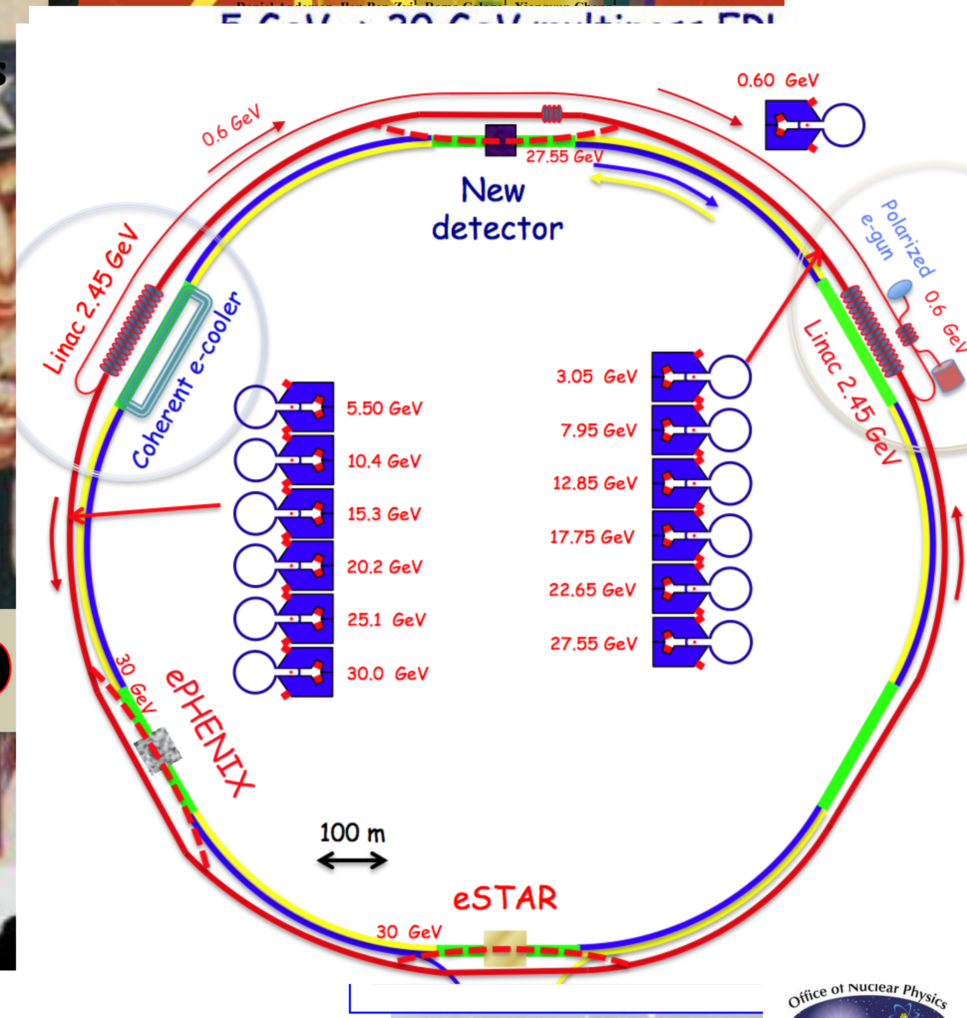
Brief history of eRHIC

- First eRHIC paper, I. Ben-Zvi et al 2001, ~300 p… @JACoW, ~3… Phys. Revs, ~60 NIMs….
- First White P…er on eRHIC/EIC, 2002
- 2003, eRHIC …ppears in DoE's "Facilities for the Futur… Sciences. A Twenty-Year Outlook"
- "eRHIC Zerot…-Order Design Report" with cost esti…ate for Ring-Ring, 2004
- 2007 – after …etailed studies we found that linac-rin… (LR) has ~50-fold higher luminosity – L… became the main option
- 2008 – first s…aging option of eRHIC
- In 2009 – co…leted technical design, dynamics stud…s and cost estimate for MeRHIC with … GeV ERL
- Present – ret…ned to the cost-effective (green) all in tunnel high-luminosity eRH…C design with staging electron energy from 5 GeV to 30 GeV





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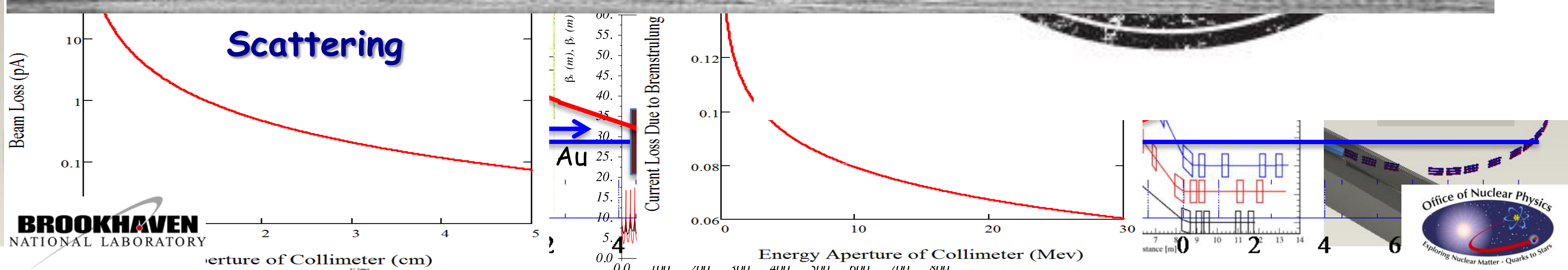
MeRHIC – 2007/2008



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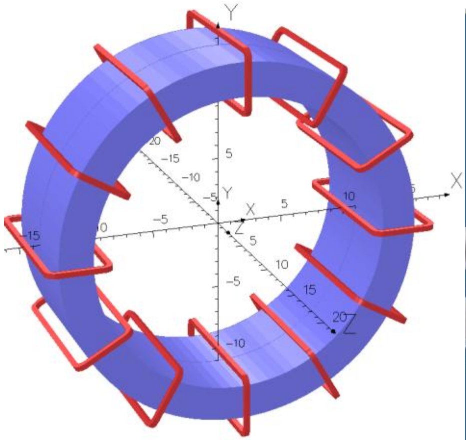
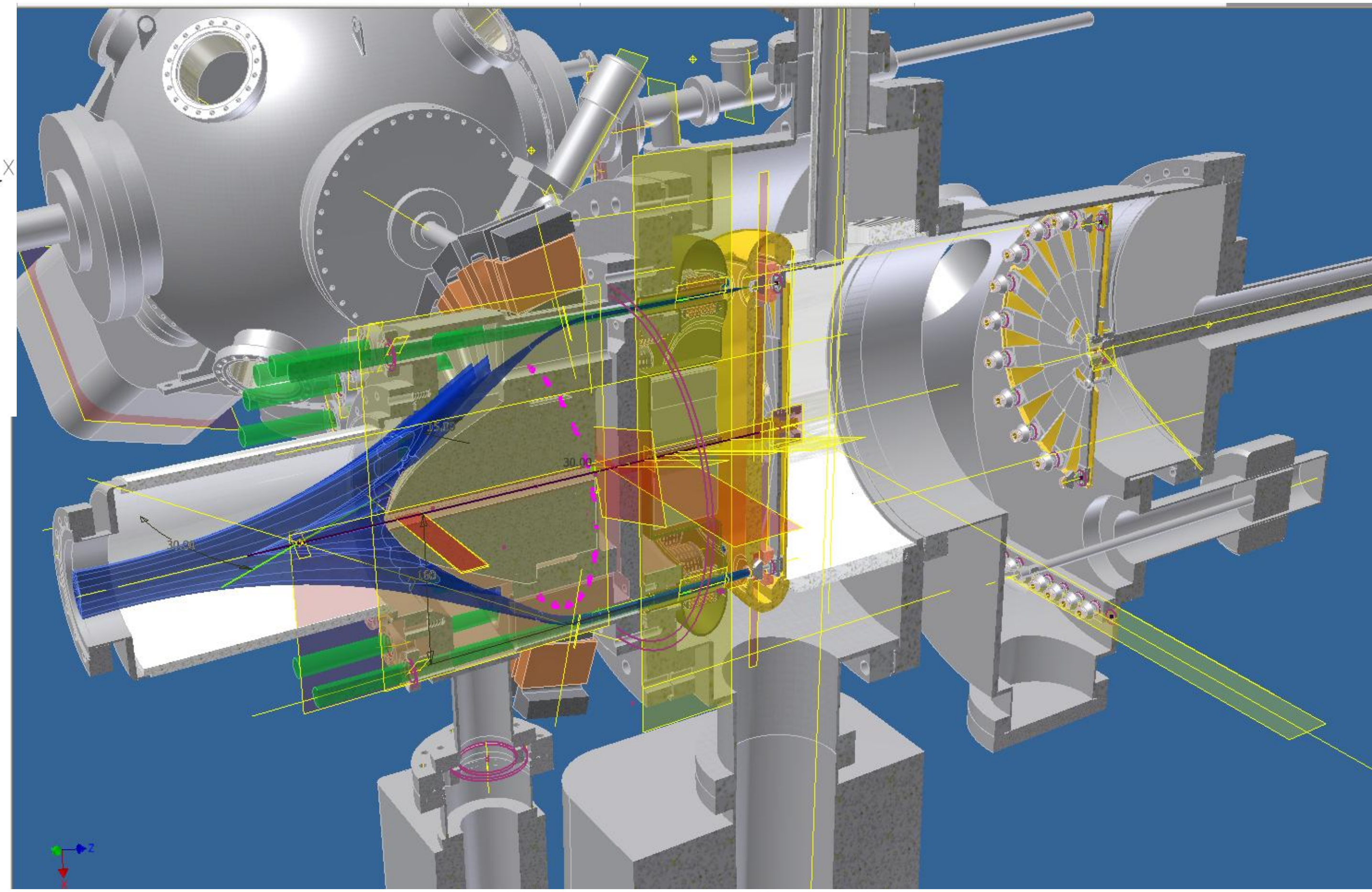
LDRD on EIC Polarized Electron Gun





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. Post doc with cathode preparation expertise will arrive in one month. A Stony Brook Ph.D. student got started on the project.

Coherent Electron Cooling (CeC)

At a half of plasma oscillation

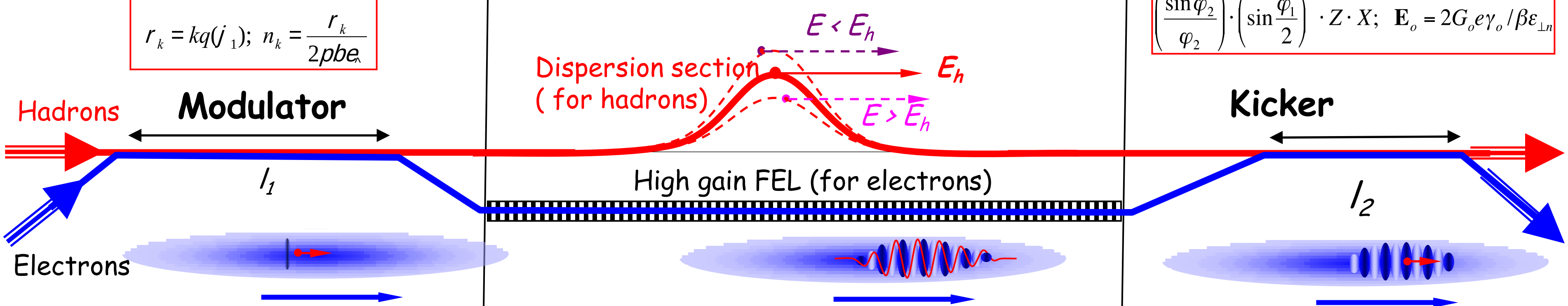
$$q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL} z)\,dz$$

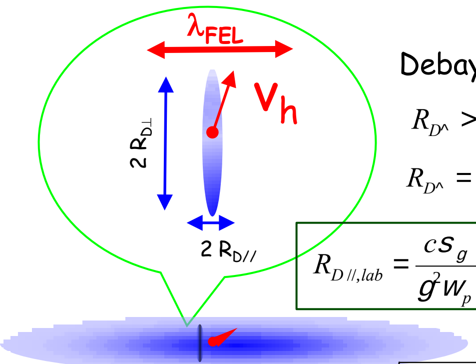
$$\rho_k = kq(\varphi_1);\quad n_k = \frac{\rho_k}{2\pi\beta\varepsilon_\perp}$$

Dispersion

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

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





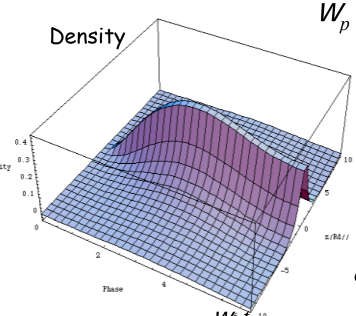
Debay radii

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

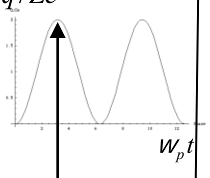
$$R_{D\perp} = \frac{c\gamma\sigma_{\theta e}}{\omega_p}$$

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

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



$-q/Ze$

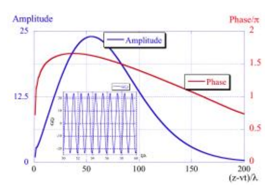


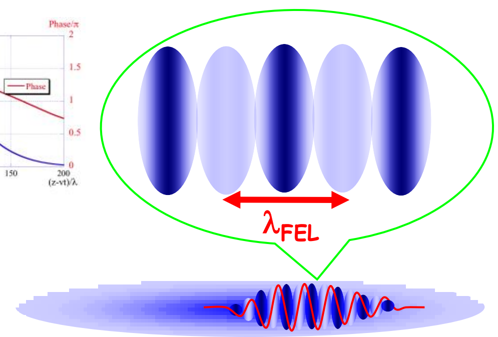
$$q = -Ze\cdot(1-\cos\varphi_1)$$

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

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

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

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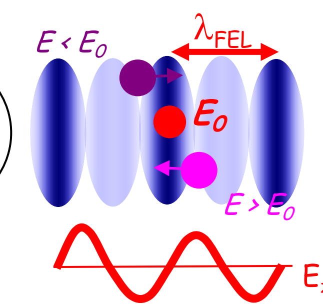
[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA
(Received 24 September 2008; published 16 March 2009)

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



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

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

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

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

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

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

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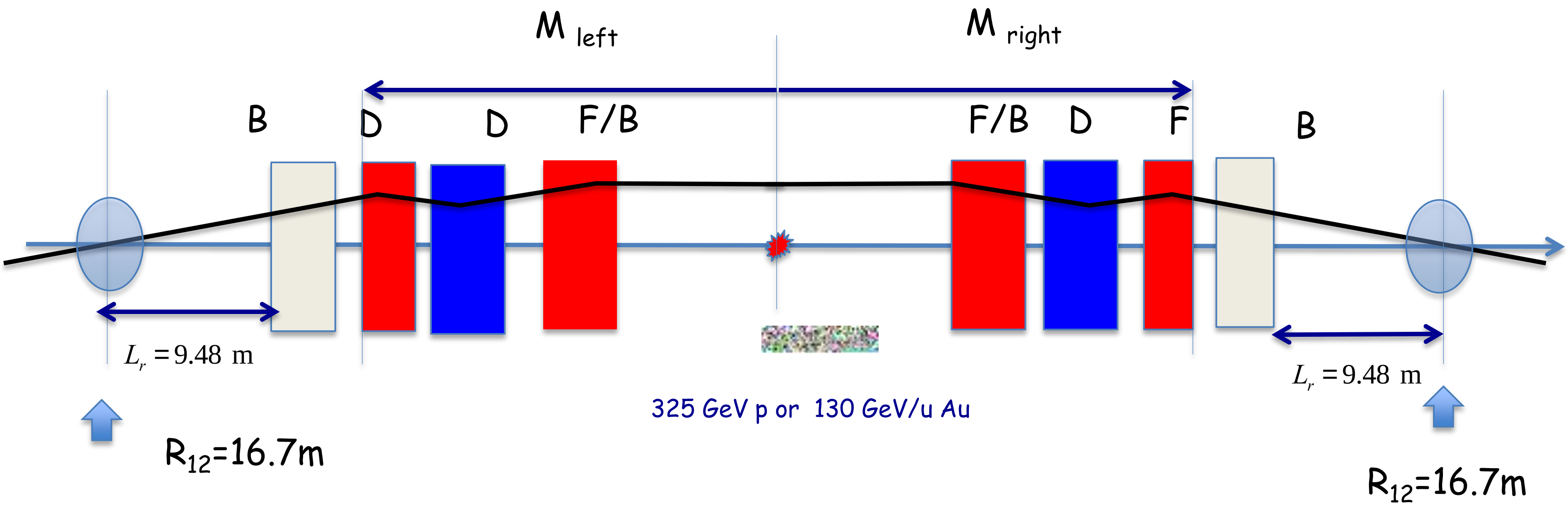
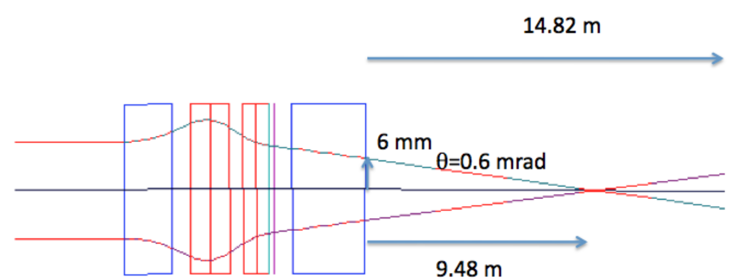
RHIC lattice

Fresh from the press by Dejan Trbojevic

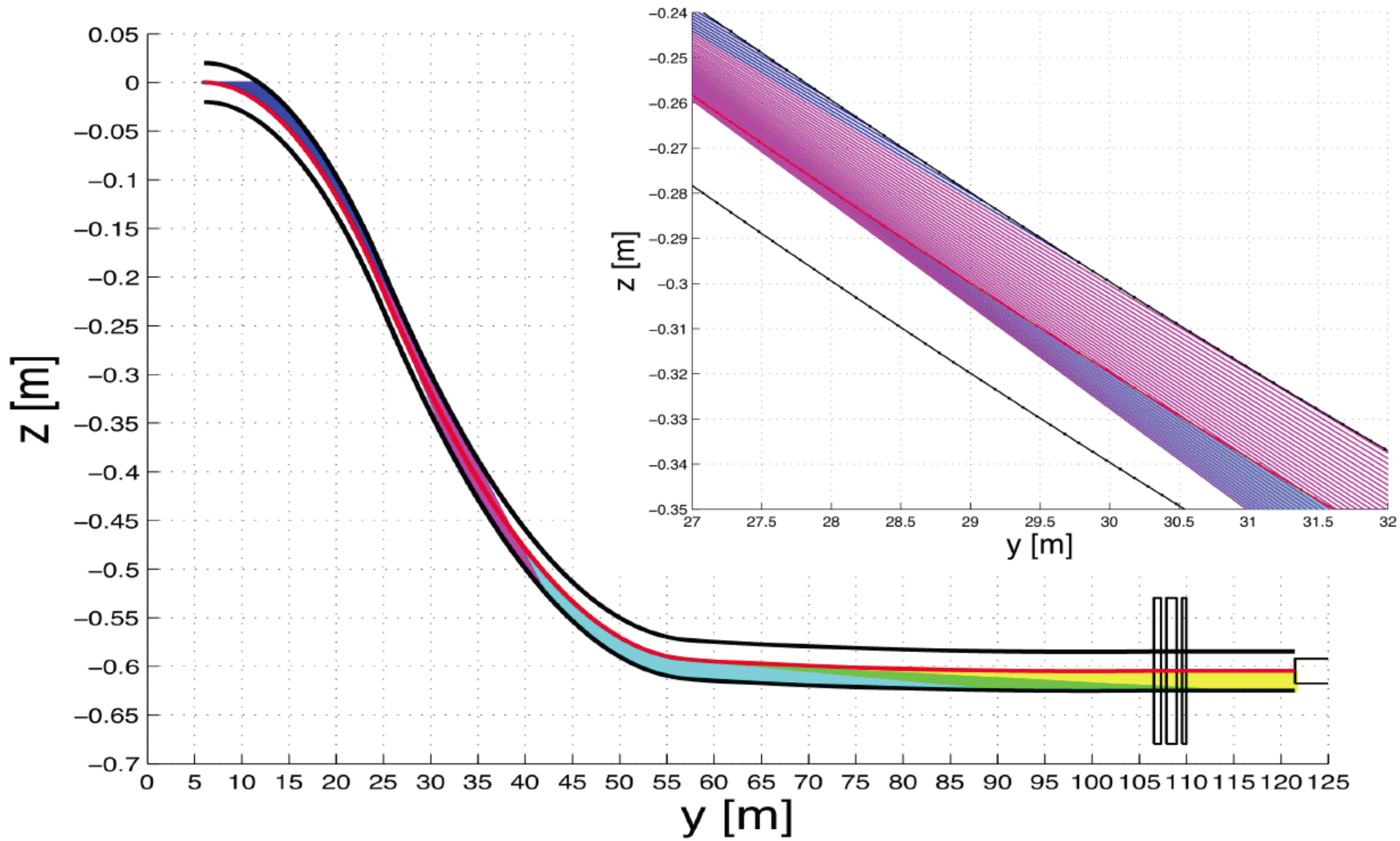


$$V_{\wedge}[MV] \approx 15.5 \times \frac{E_p[GeV]}{325} / \lambda_{rf}[m]$$



Direct Synchrotron Radiation onto Absorbers

The electron beam line from arc to IP



Basic concept of the adjustable momentum compaction lattice $M_{5,6} = 0$

The inhomogeneous equation of the dispersion function *D* has two solutions: one without dipoles present (=0) and one with the dipoles = 1/ρ

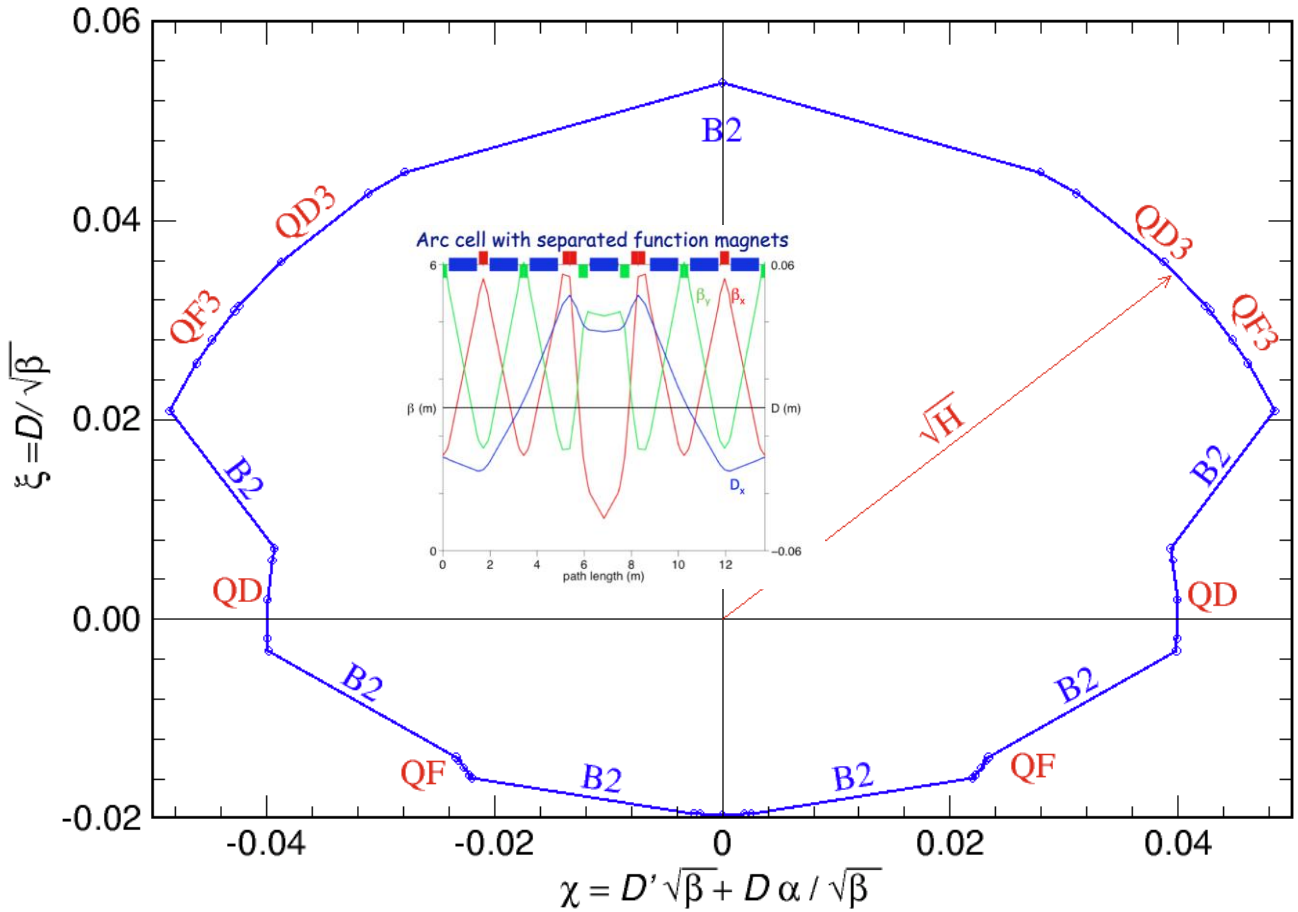
$$D'' + kD = \begin{cases} = 0 \\ = 1/\rho \end{cases}$$

$$\chi = D'\sqrt{\beta} + D\frac{\alpha}{\sqrt{\beta}}$$

$$\xi = \frac{D}{\sqrt{\beta}}$$

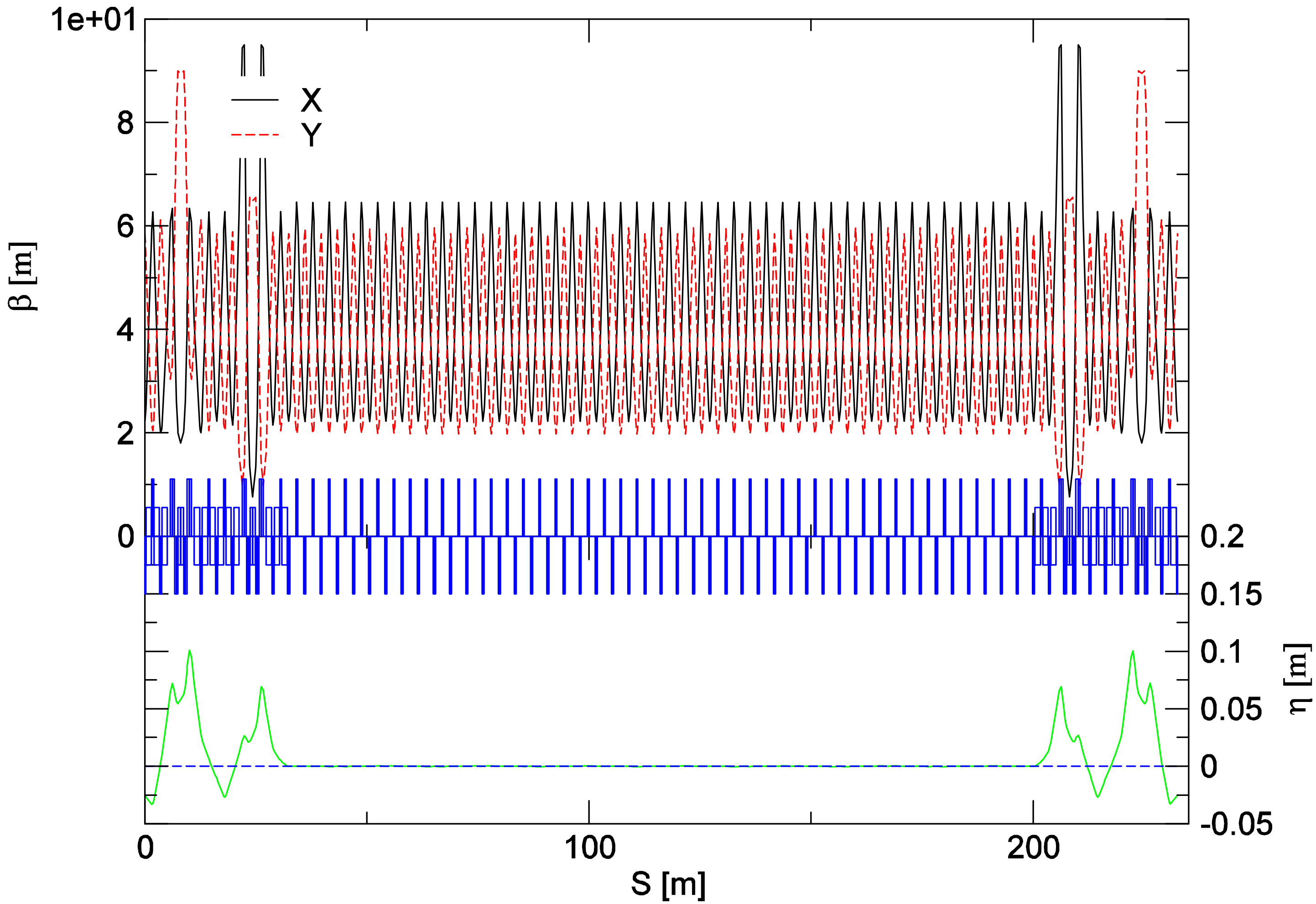
$$\xi^2 + \chi^2 = J^2 \ (if\ = 0)$$

© D. Trbojevic



D.Trbojevic et al, AIP CONFERENCE PROCEEDINGS, V. 530, (2000) p. 333

ByPass SS



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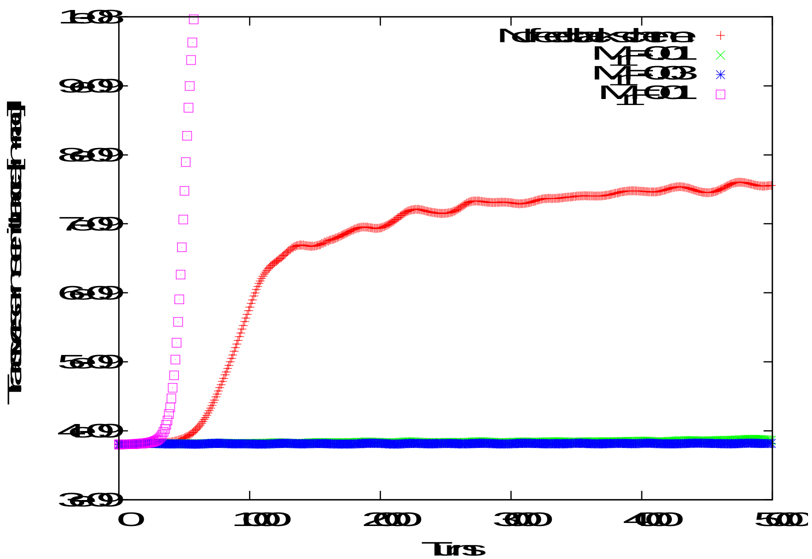
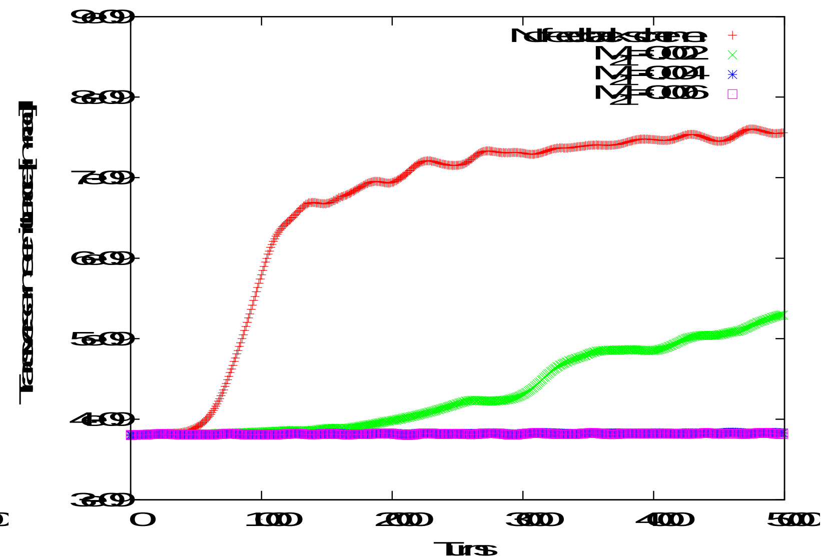
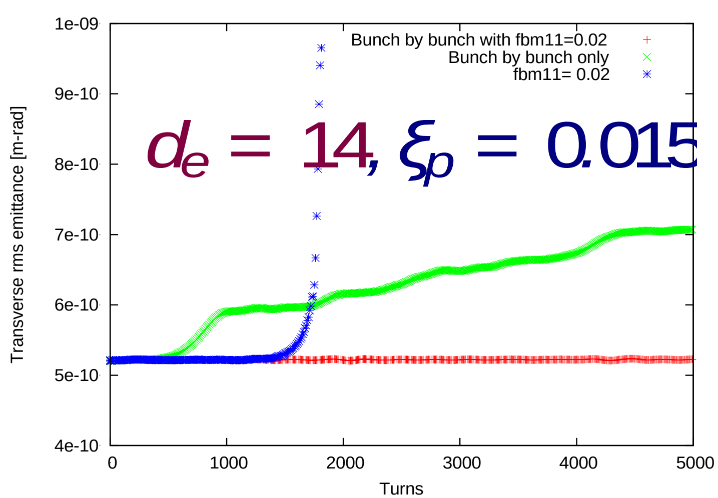
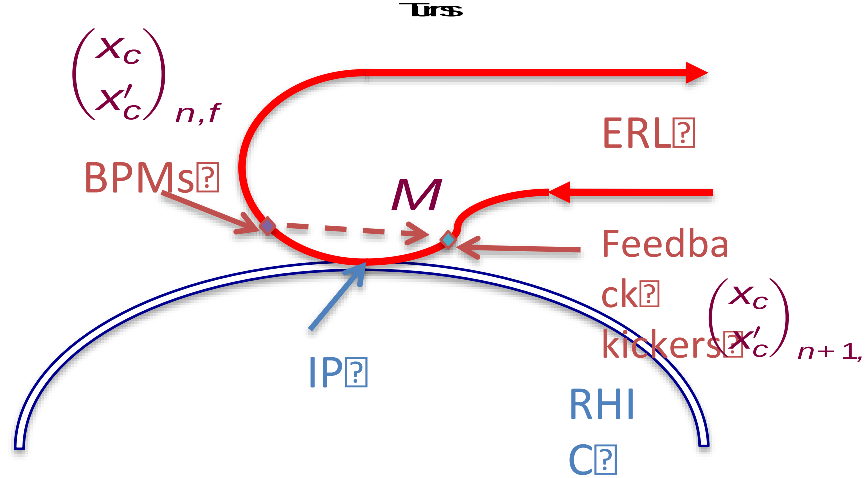
The Feedback Scheme

Beam-Beam Parameters: $d_e = 5.7, \xi_p = 0.015$



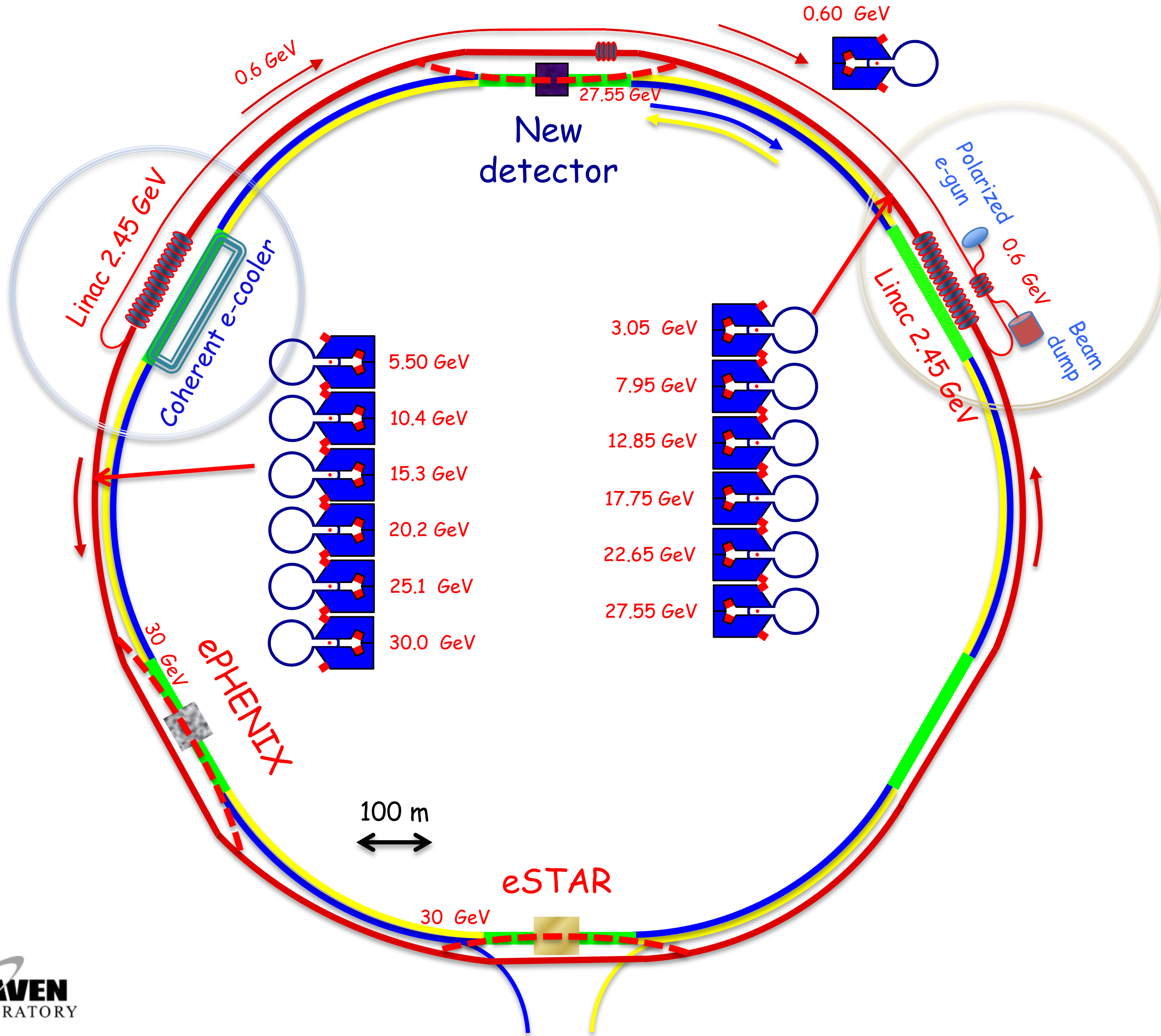






Y.Hao, V.N.Litvinenko, V.Ptitsyn

http://www.c-ad.bnl.gov/pac2011/proceedings/talks/tuoan4_talk.pdf



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