

High-Energy High-Luminosity Electron-Ion Collider eRHIC

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Center for Accelerator Science and Education

2012 Workshop

Exploring QCD frontiers:
from RHIC and LHC to EIC

Stellenbosch, South Africa



January 30 to February 3, 2012
STIAS Conference Center

Topics Include:

saturation and its measurement; parton densities, nuclear spin and angular momentum, and generalized and transverse parton distribution functions; constraints on initial energy-density formation and connecting initial conditions to hydrodynamics in heavy ion collisions

Local Organizers:

J. Cleymans
A. Hamilton
W.A. Horowitz (chair)
A. Peshier
Z. Vilekazi
H. Weigert (co-chair)

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Thomas Jefferson National Accelerator Facility



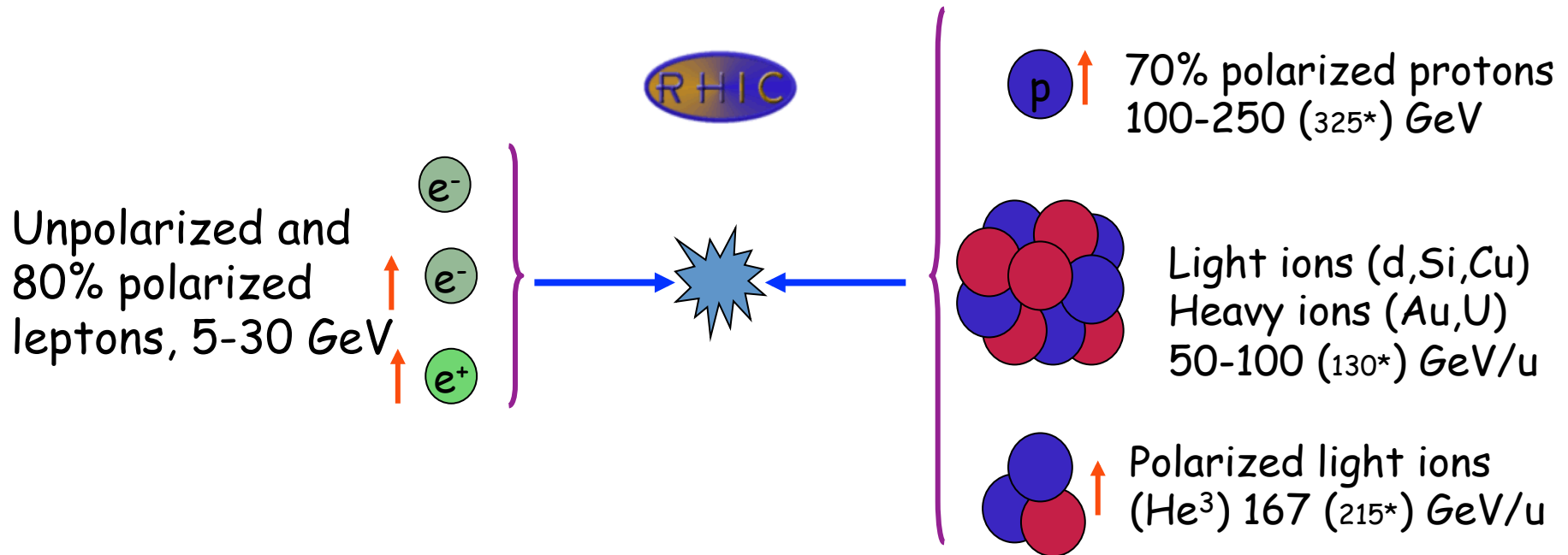
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V.N. Litvinenko, International Workshop on Electron-Ion Collider Physics
Stellenbosch Institute for Advanced Study, South Africa, February 3, 2012

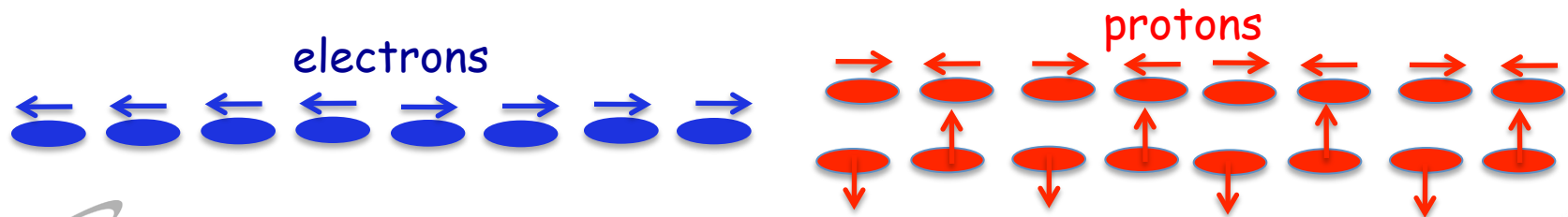
eRHIC: QCD Facility at BNL

Add electron accelerator to the existing \$2B RHIC



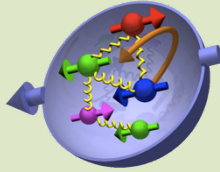
Center of mass energy range: 30-175 GeV

Any polarization direction in lepton-hadrons collisions



Most Compelling Physics Questions

spin physics

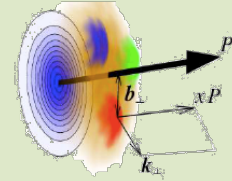


what is the polarization of gluons at small x where they are most abundant

what is the flavor decomposition of the polarized sea depending on x

determine quark and gluon contributions to the proton spin at last

imaging

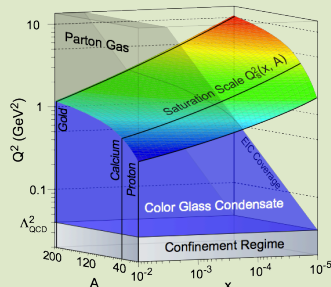


what is the spatial distribution of quarks and gluons in nucleons/nuclei

understand deep aspects of gauge theories revealed by k_T dep. distr'n

possible window to orbital angular momentum

physics of strong color fields



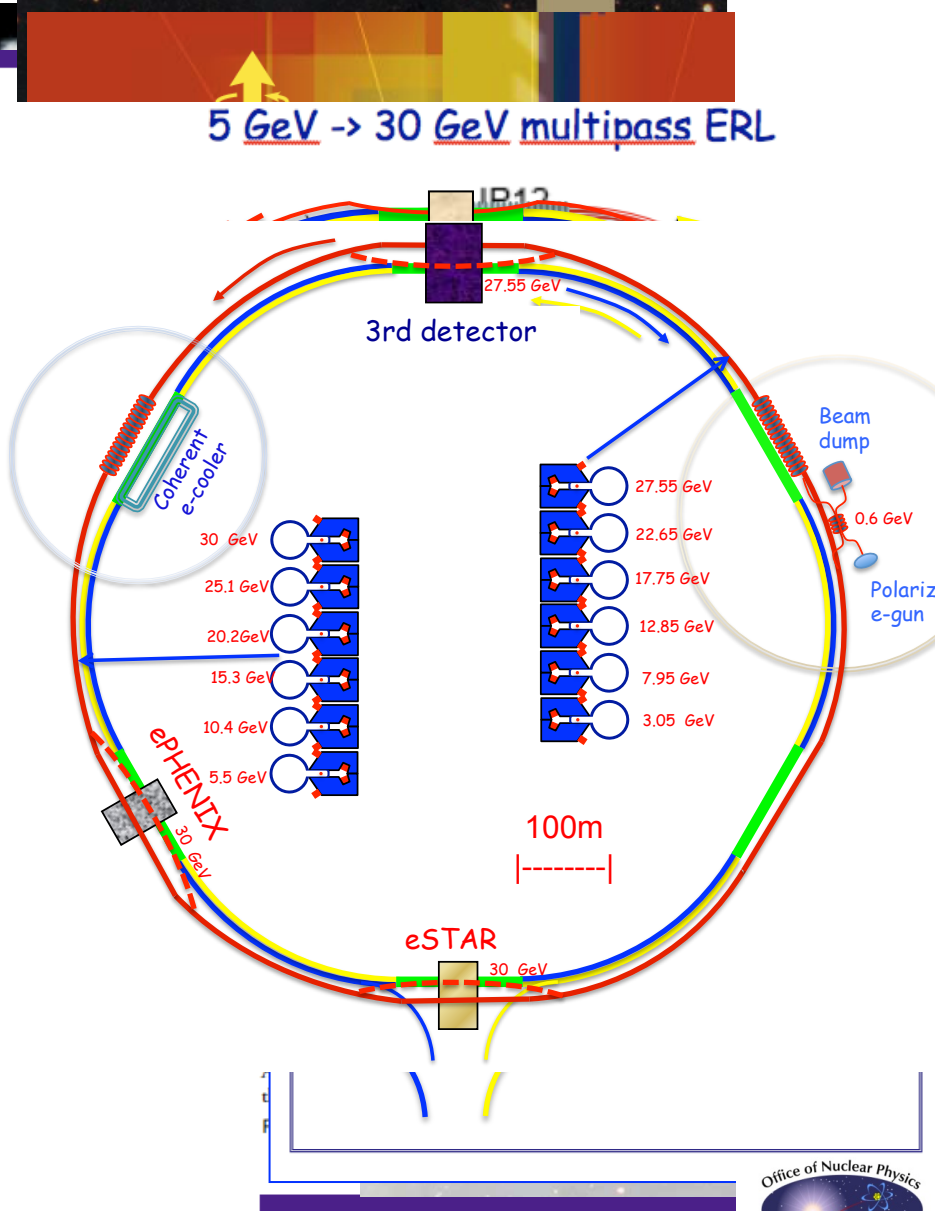
understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation

how do hard probes in eA interact with the medium

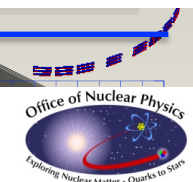
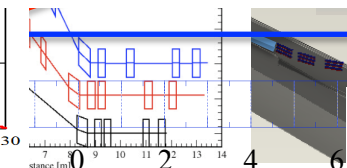
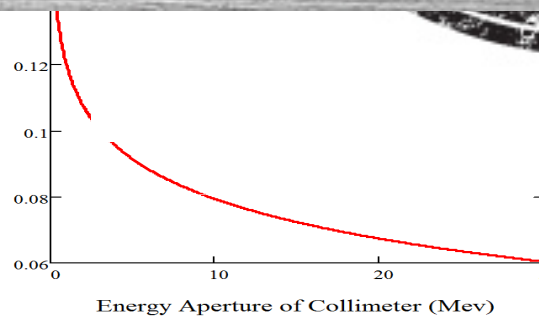
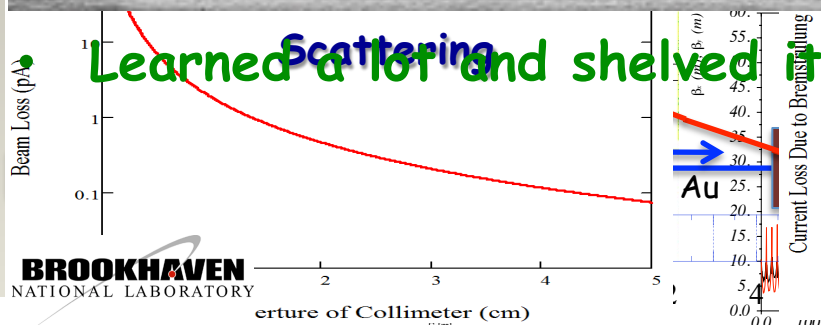
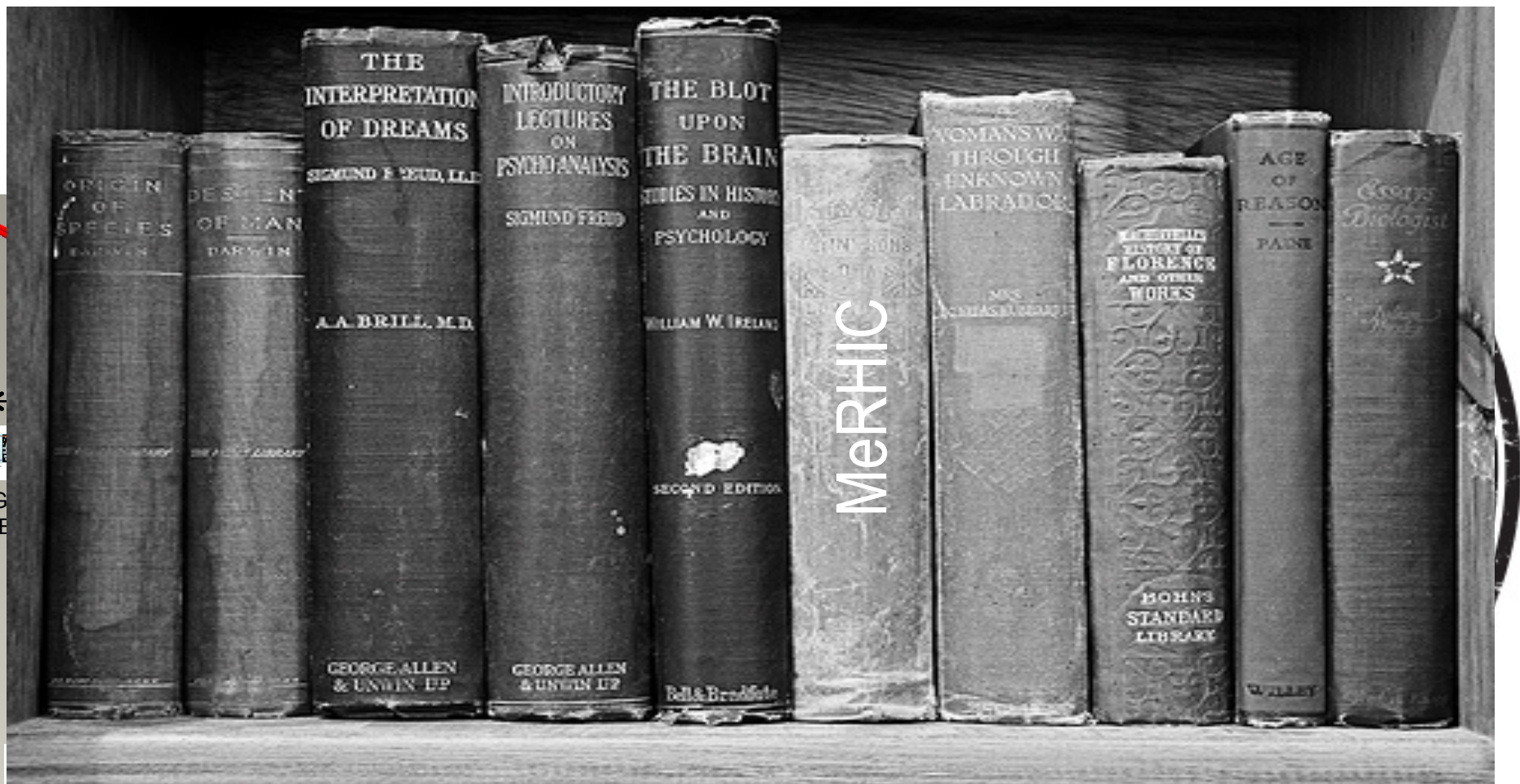
quantitatively probe the universality of strong color fields in AA, pA, and eA

Brief history of eRHIC

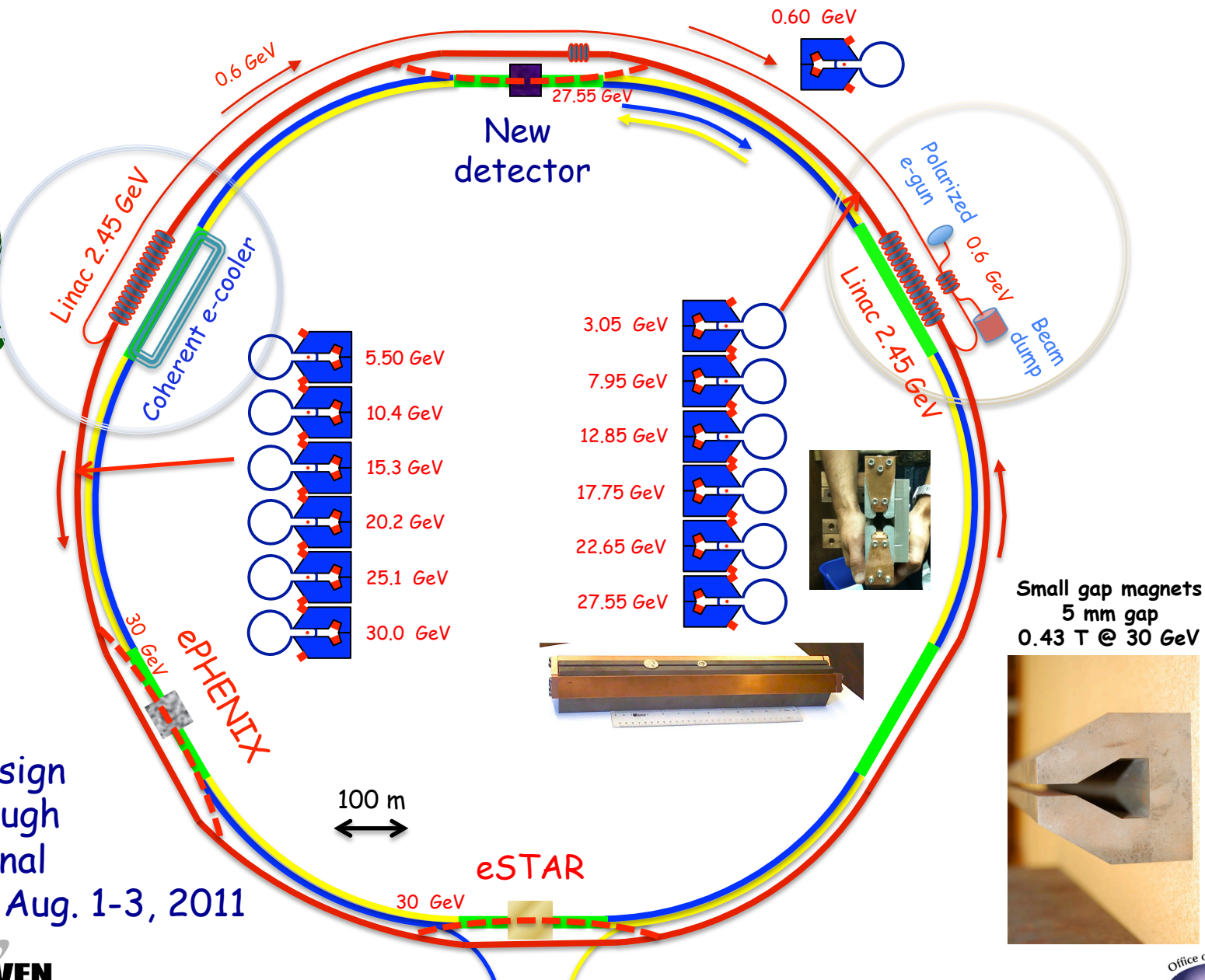
- First eRHIC paper, 2000, S.Peggs et al., ~300 pages, 1999-2000 @JACoW, ~30 Phys. Revs, ~60 NIMs....
- First White Paper on eRHIC/EIC, 2002
- 2003, eRHIC appears in DoE's "Facilities for the Future Sciences. A Twenty-Year Outlook"
- "eRHIC Zeroth Order Design Report" with cost estimate for Ring-Ring, 2004
- 2007 - after detailed studies we found that linac-ring (LR) has ~10-fold higher luminosity - LR became the main option
- 2008 - first staging option of eRHIC
- In 2009 - completed technical design, dynamics studies and cost estimate for MeRHIC with 3 GeV ERL
- Present - returned to the cost-effective (**green**) all in tunnel high-luminosity eRHIC design with staging electron energy from 5 GeV to 30 GeV



MeRHIC - 2007/2008



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



eRHIC design went through the external review on Aug. 1-3, 2011

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 $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
 - ◆ 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 $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$ level and not all energies of hadrons could be used in the collisions

eRHIC beam parameters and luminosity

	e	p	$^2\text{He}^3$	$^{79}\text{Au}^{197}$	$^{92}\text{U}^{238}$
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 for(e & hadrons)	5	5	5	5	5
Luminosity per nucleon, $\times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$		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 adjusted the same at energy of electrons from 5GeV to 20 GeV

e-beam current and luminosity fall as E_e^{-4} at electron energy $>20 \text{ GeV}$ (Sync.Rad)

eRHIC Luminosity in e-p

Reaching high luminosity:

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

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

Limiting factors:

- hadron $\Delta Q_{sp} \leq 0.035$
- hadron $\xi \leq 0.015$
- polarized e current $\leq 50 \text{ mA}$
- SR power loss $\leq 7 \text{ MW}$

	Protons				
	E, GeV	100	130	250	325
Electrons	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

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)
- $\beta^*=5$ cm IR with crab-crossing

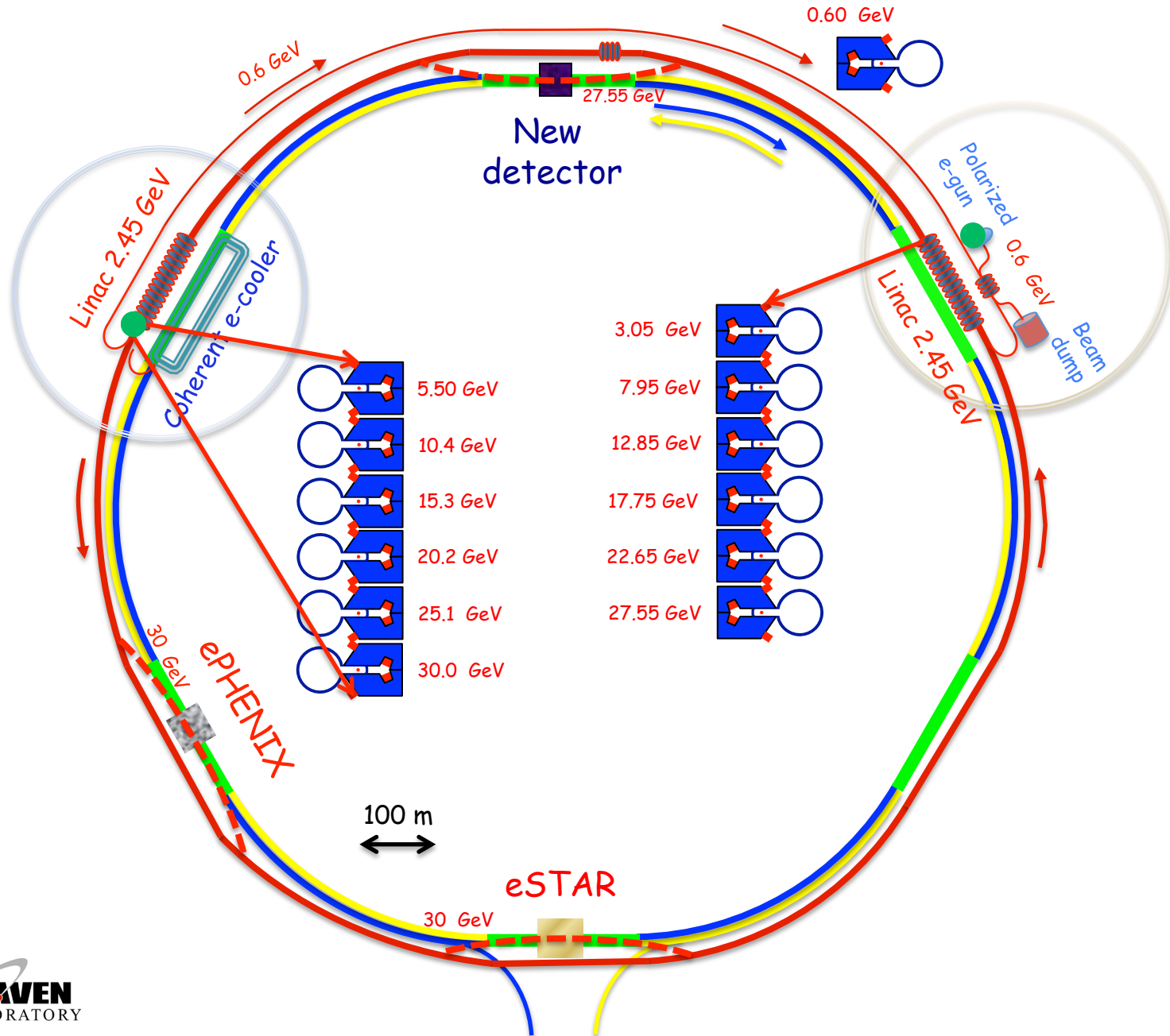
e-A luminosities in $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ units

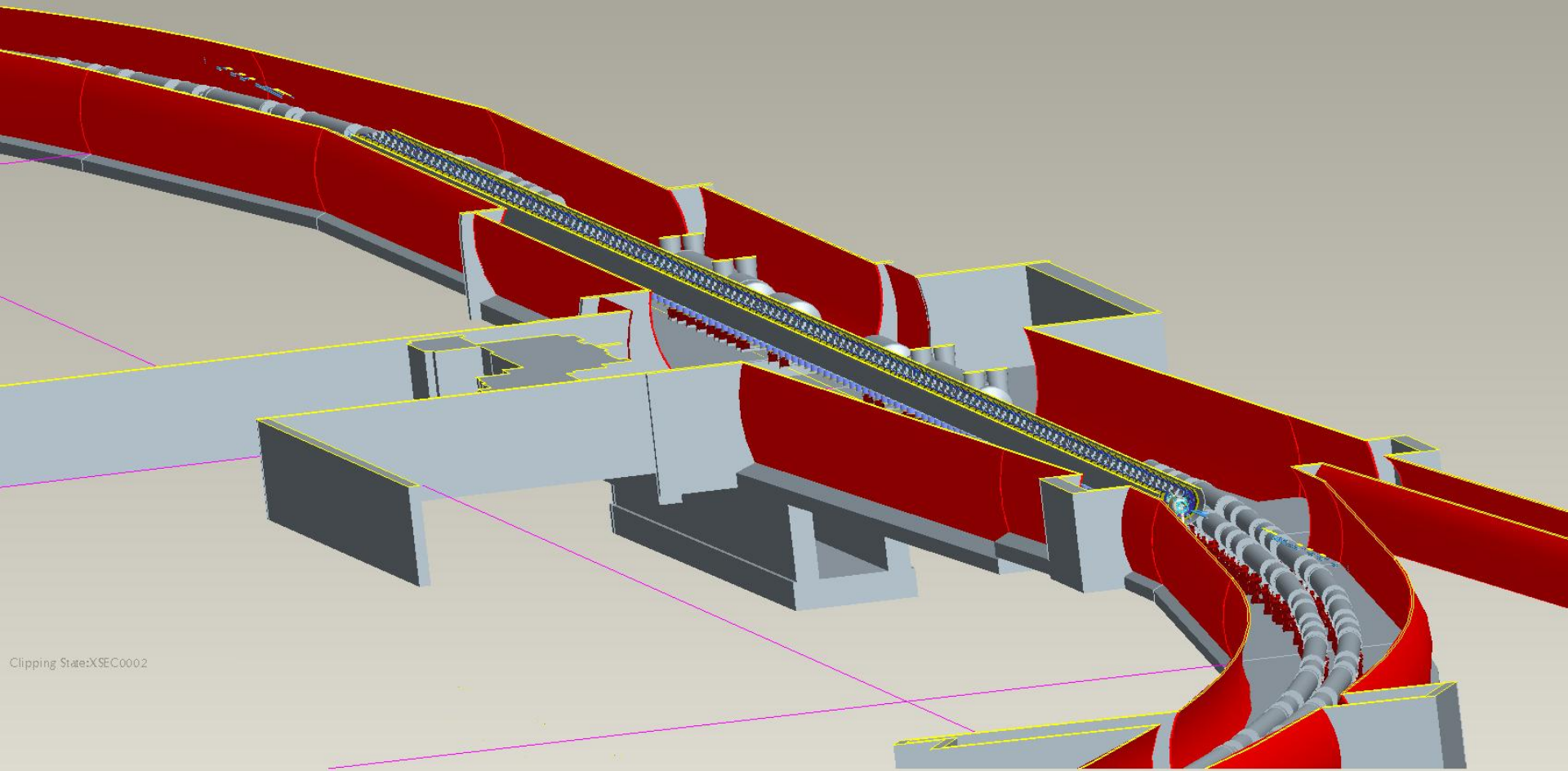
Limiting factors:

- hadron $\Delta Q_{sp} \leq 0.035$
- hadron $\xi \leq 0.015$
- SR power loss $\leq 7 \text{ MW}$

	Au ions				
	E, GeV	50	75	100	130
Electrons	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

e-beam in ERL



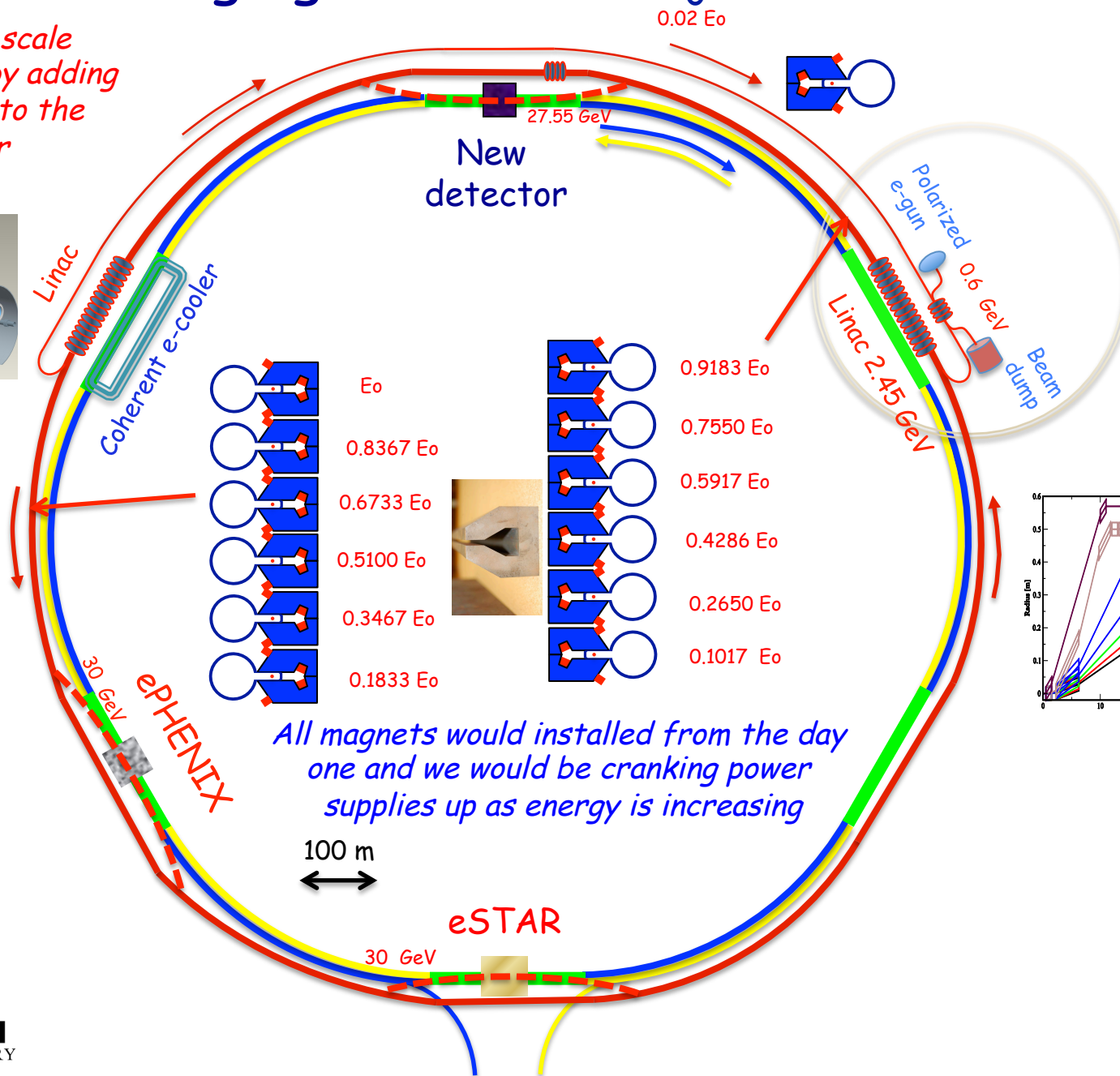
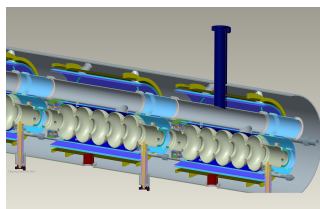


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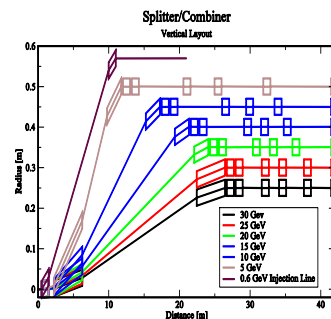
Staging of eRHIC: $E_0 : 5 \rightarrow 30 \text{ GeV}$

E/E_0
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

All energies scale proportionally by adding SRF cavities to the injector



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

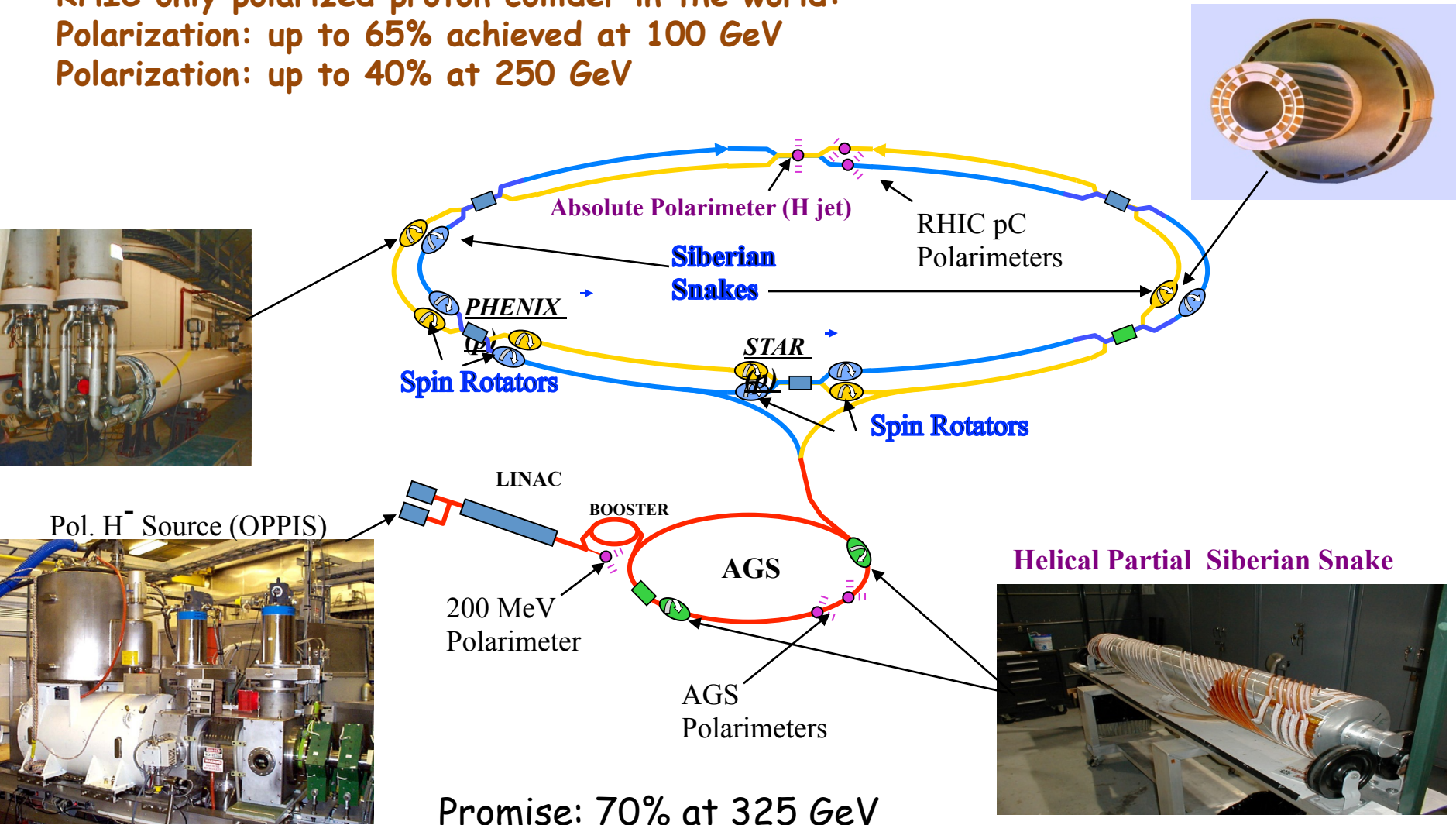


eRHIC: polarized protons

RHIC only polarized proton collider in the world:

Polarization: up to 65% achieved at 100 GeV

Polarization: up to 40% at 250 GeV



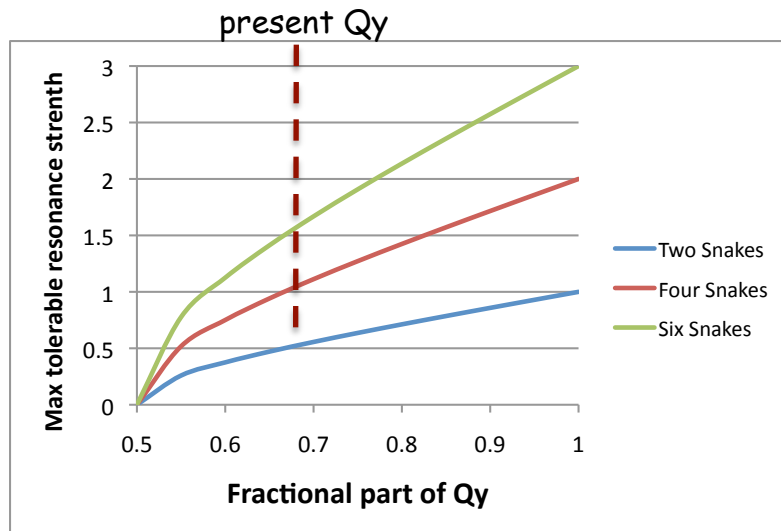
Promise: 70% at 325 GeV

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:

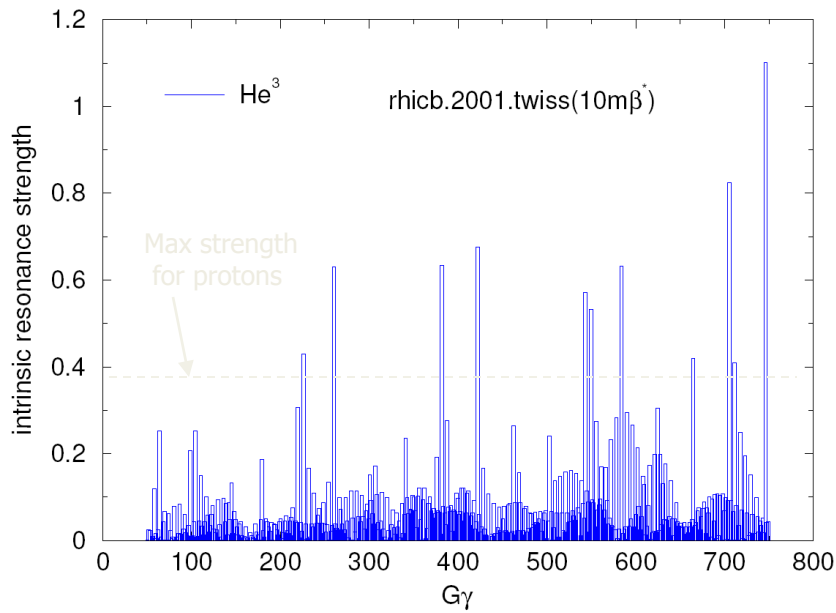
- AGS: jump quads improved considerably the slope of the polarization dependence on the bunch intensity
- RHIC: betatron tunes placed further away from the 0.7 higher-order spin resonance and the vertical realignment of all magnets led to better polarization transmission on the ramp

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

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

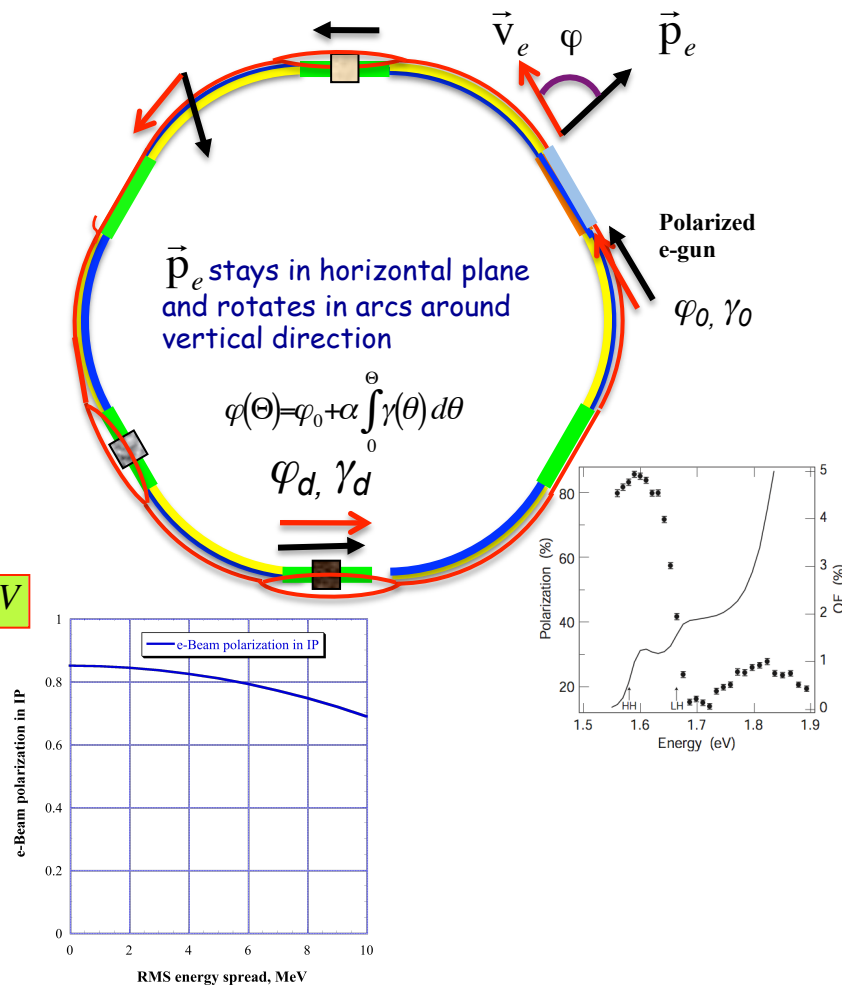
- Larger G factor than for protons
- RHIC Siberian snakes and spin rotators can be used for the spin control, with less orbit excursions than with protons.
- More spin resonances. Stronger resonance strength.
- Spin dynamics at the acceleration in the injector chain and in RHIC has to be studied.



	$^3\text{He}^{+2}$	p
$m, \text{ GeV}$	2.808	0.938
$G=(g-2)/2$	-4.18	1.79
$E/n, \text{ GeV}$	16.2-166.7	24.3 - 325
γ	17.3 - 177	25.9 - 346
$ G\gamma $	72.5 - 744.9	46.5 - 477.7

Electron polarization in eRHIC

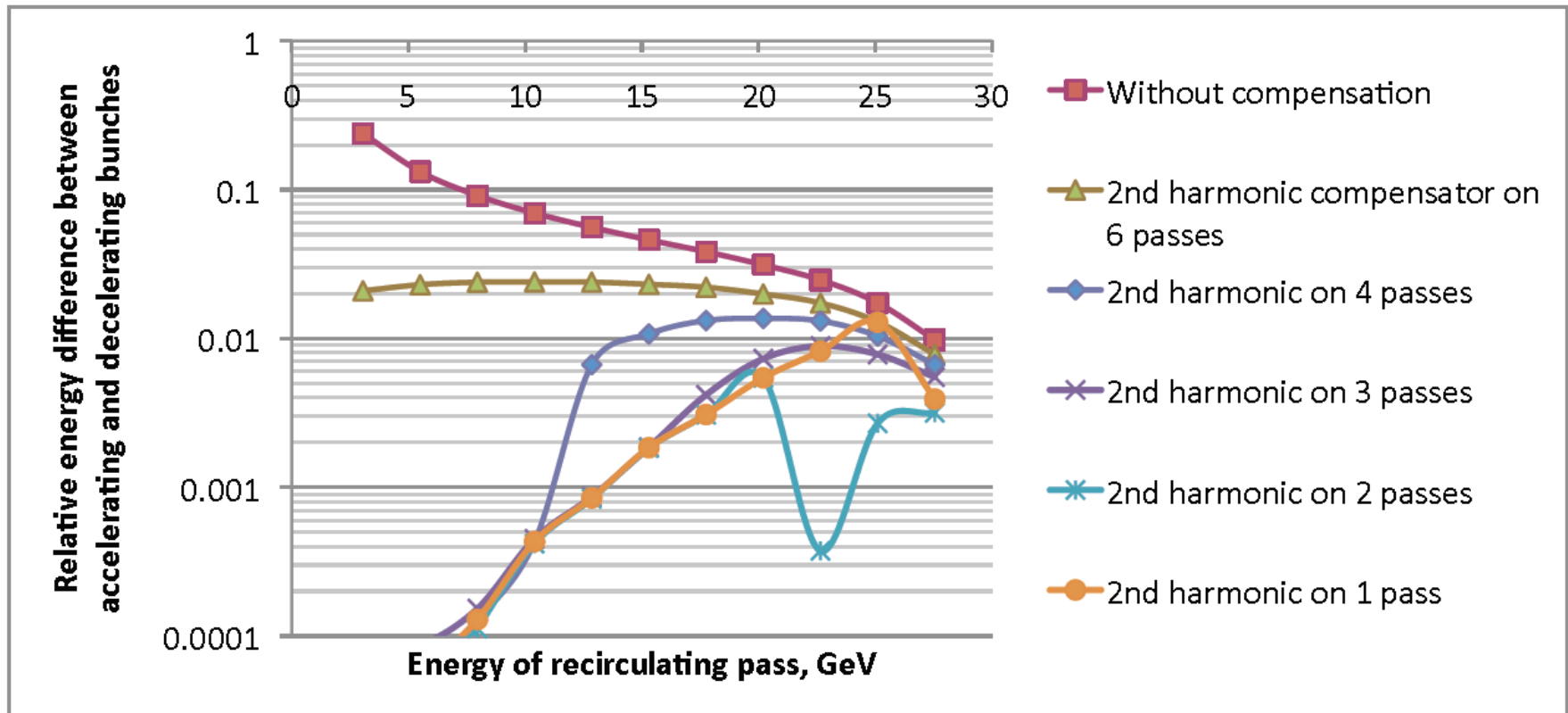
- Only longitudinal polarization is needed in the IPs
- High quality longitudinally polarized e-beam will be generated by DC guns with strained-layer super-lattice GaAs-photocathode
- Direction of polarization will be switch by changing helicity of laser photons in and arbitrary bunch-by-bunch pattern
- 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: $E_e = N \cdot 0.07216 \text{ GeV}$
- 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%



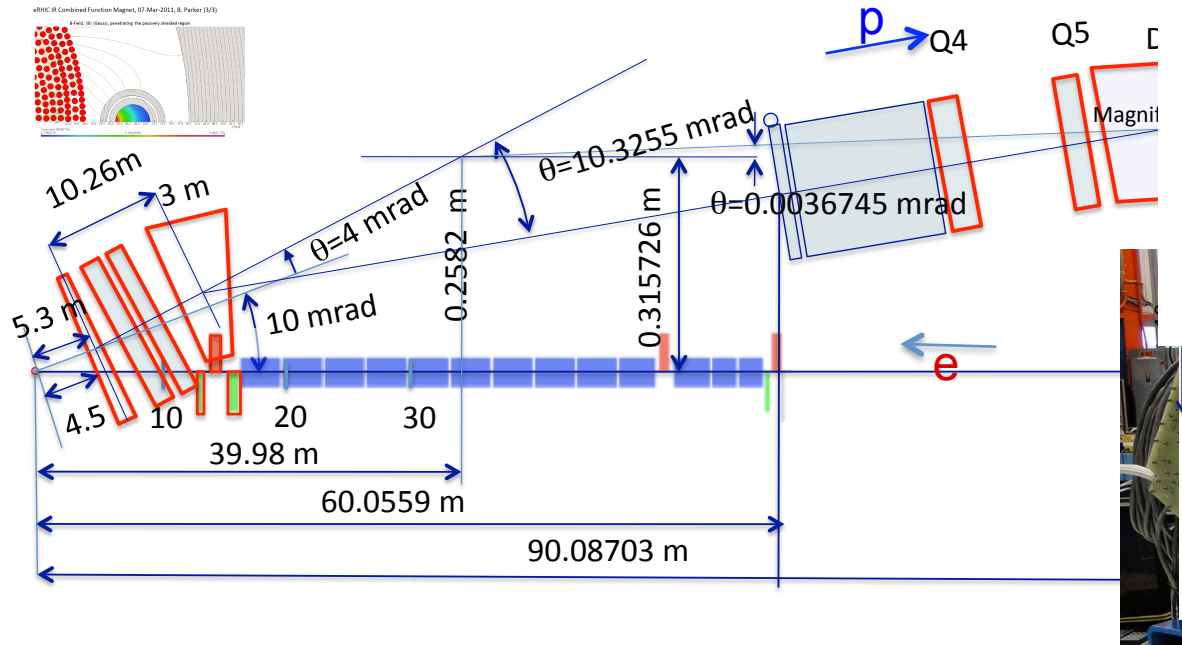
***The GaAs-GaAsP cathode achieved a maximum polarization of $92 \pm 6\%$ with a quantum efficiency of 0.5%**

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

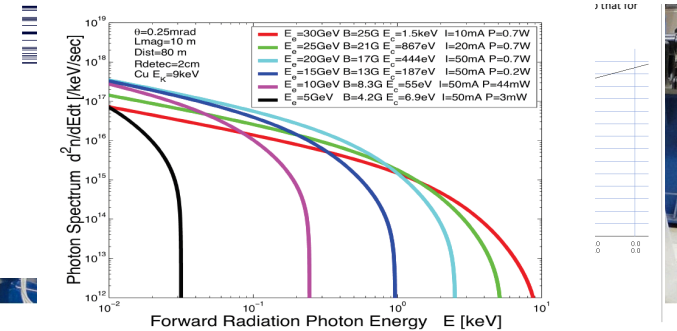
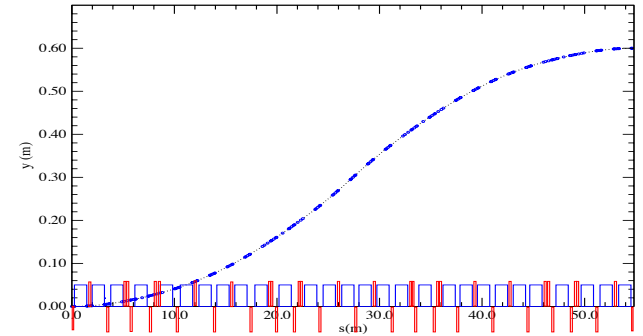
Loss budget for 6 pass scheme



eRHIC high-luminosity IR with $\beta^*=5$ cm



eRHIC - Vertical beam line to IP matching 30 GeV electrons

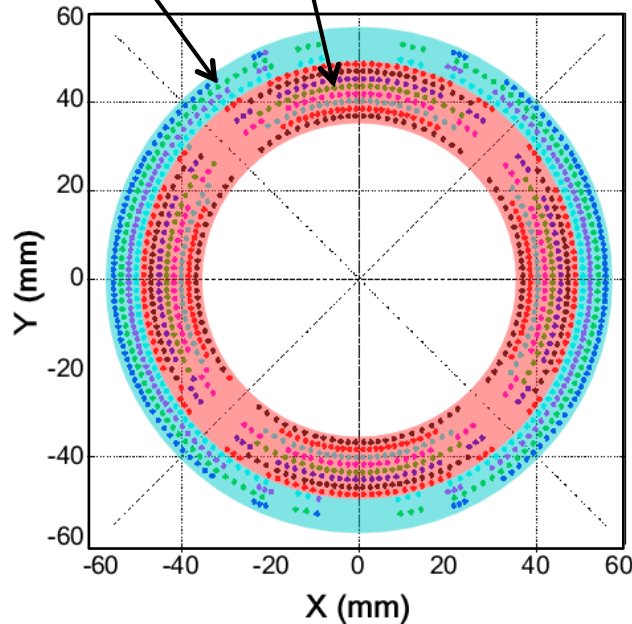


- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb₃Sn focusing magnets
- Arranged free-field electron pass through the hadron triplet magnets
- Integration with the detector: efficient separation and registration of low angle collision products
- Gentle bending of the electrons to avoid SR impact in the detector

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

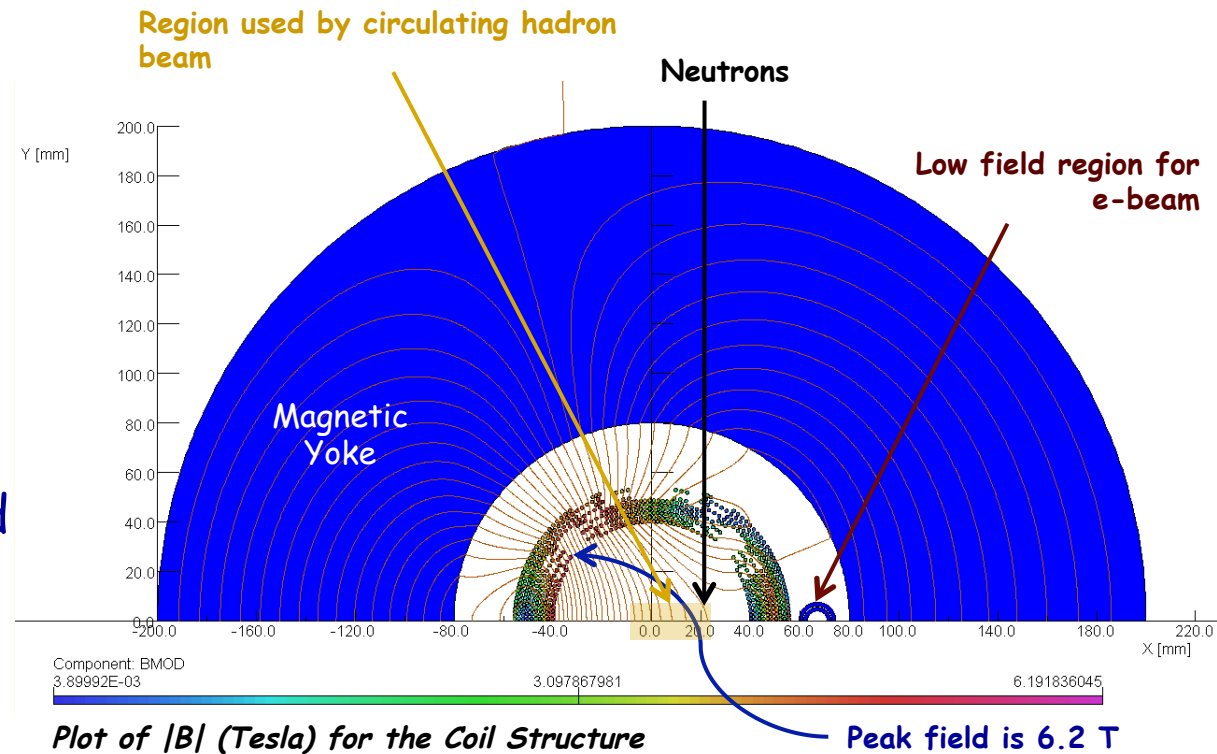
Design Details for First IR Magnet

Dipole & Quadrupole Coil Sets

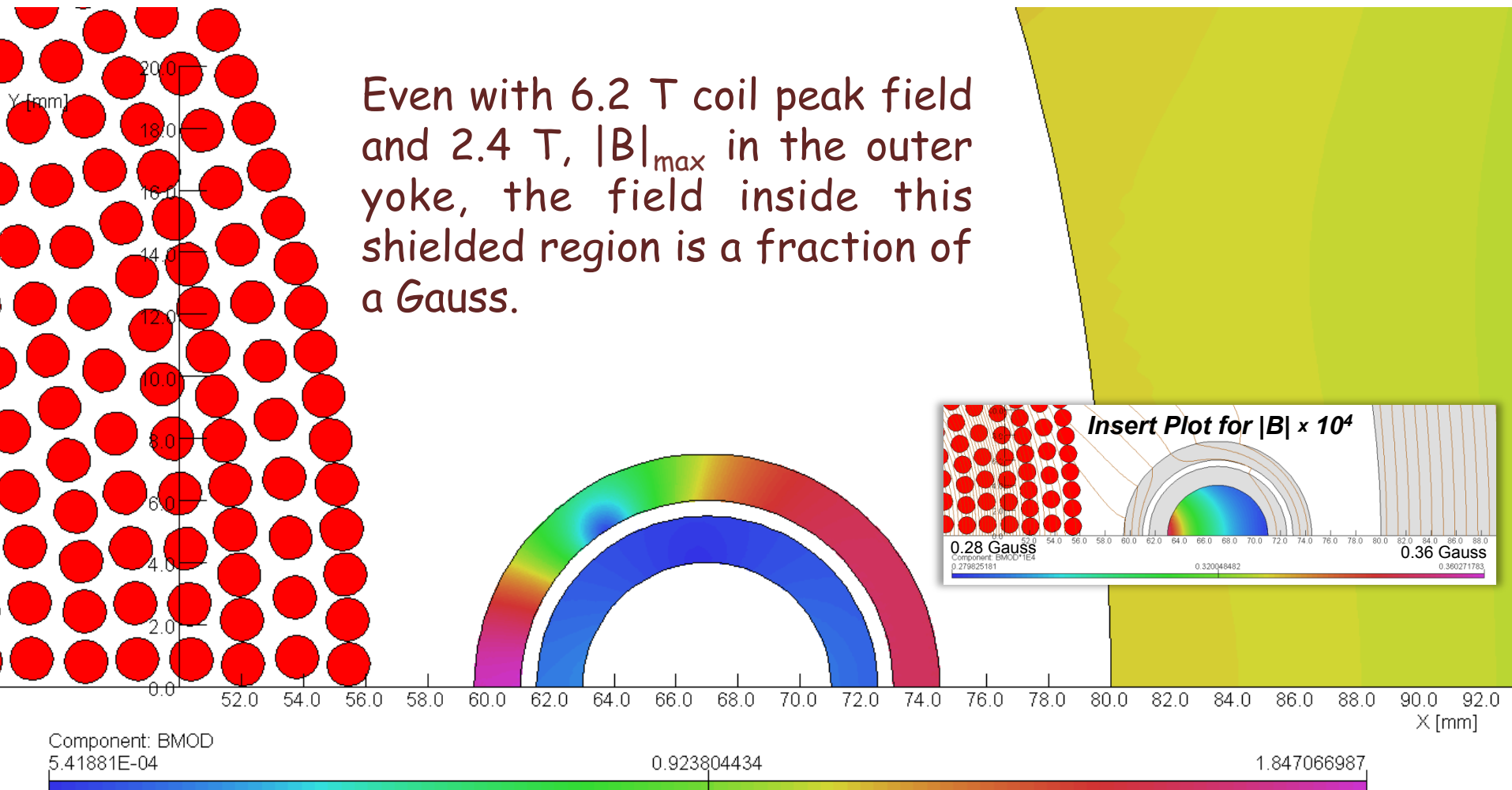


- Magnet structure is aligned with e-beam.
- Magnet offset is optimized for neutrons, circulating beam and early analysis for off-momentum charged particle measurement.

$B_0 = 2.701 \text{ T}$
 Gradient = -85.74 T/m and
 $L_{\text{mag}} = 1.95 \text{ m}$



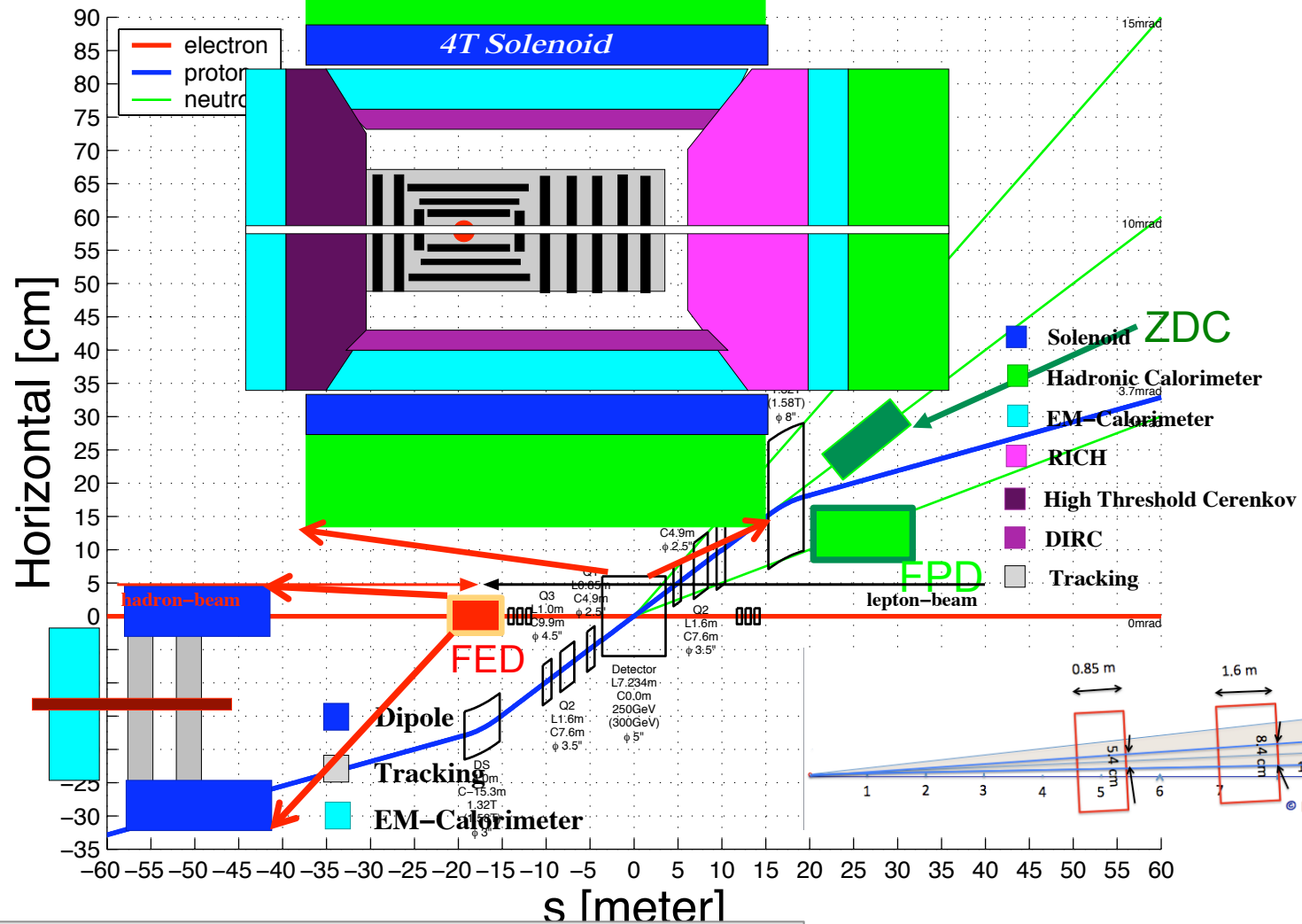
Reduced Field Region for e-



Plot of $|B|$ (Tesla) for the Yoke and Two Layer Shield Structure

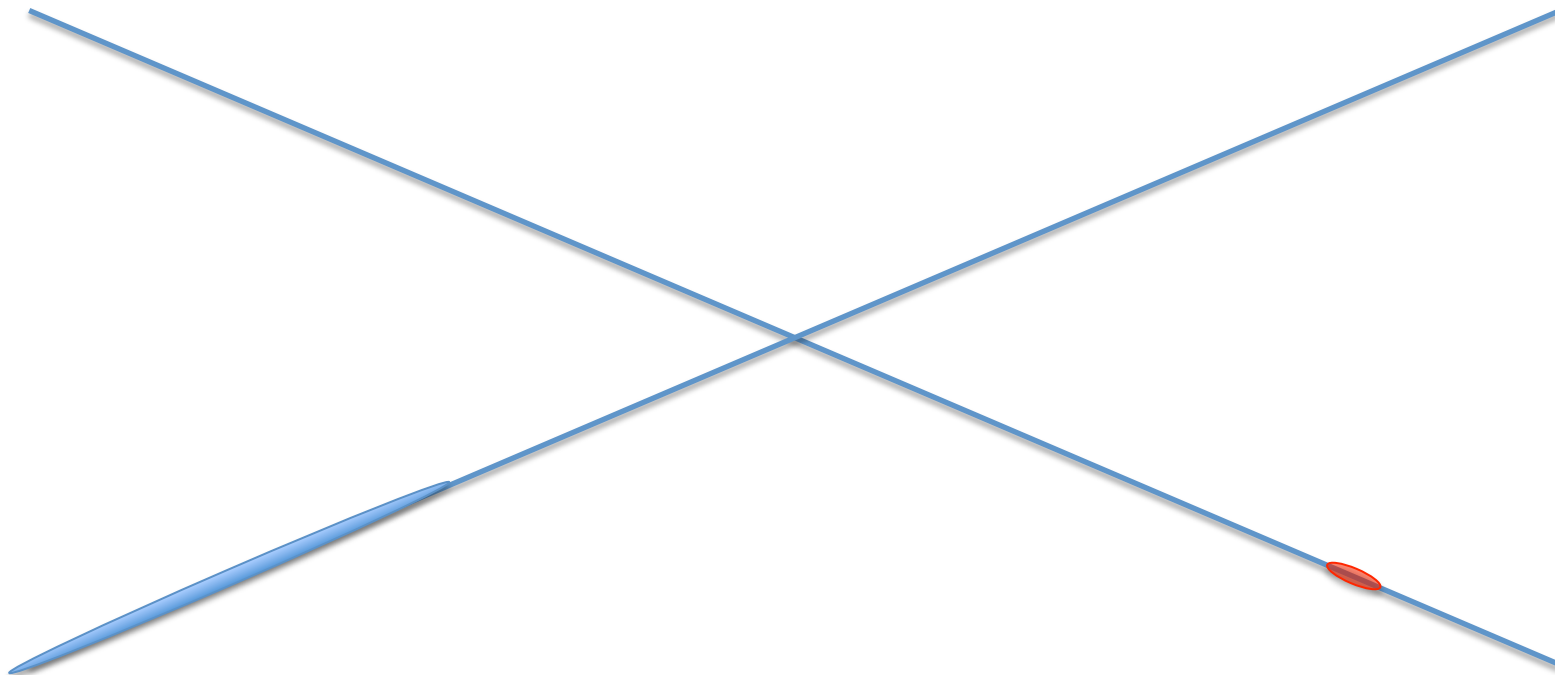
"eRHIC IR Magnet Designs," Brett Parker, BNL-SMD

A detector integrated into IR

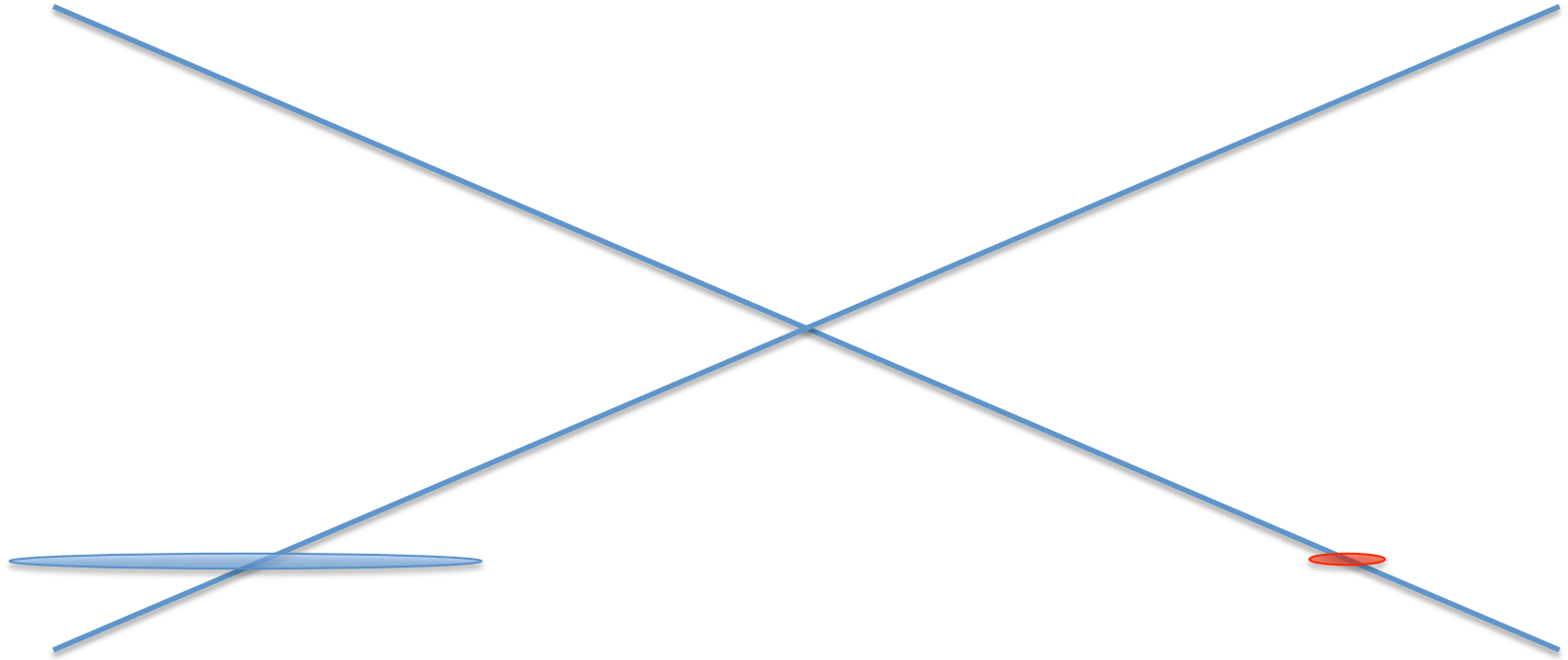


- Dipoles needed to have good forward momentum resolution
 - Solenoid no magnetic field @ $r \sim 0$
- DIRC, RICH hadron identification $\rightarrow \pi, K, p$
- high-threshold Cerenkov $\rightarrow$ fast trigger for scattered lepton
- radiation length very critical $\rightarrow$ low lepton energies

"No crabbing"



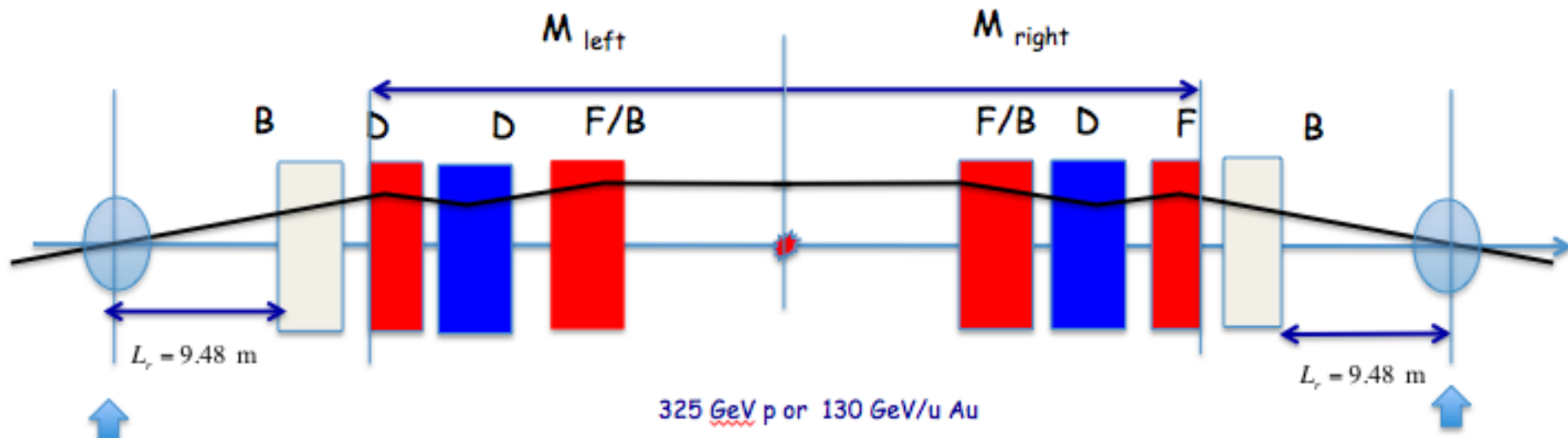
"Ideal crabbing"



Invented at BNL, pioneered at KEK's B-factory

RHIC lattice

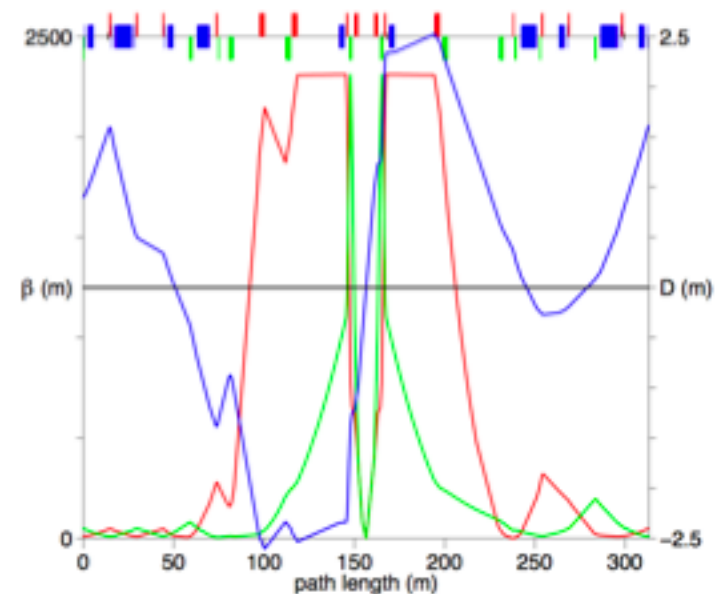
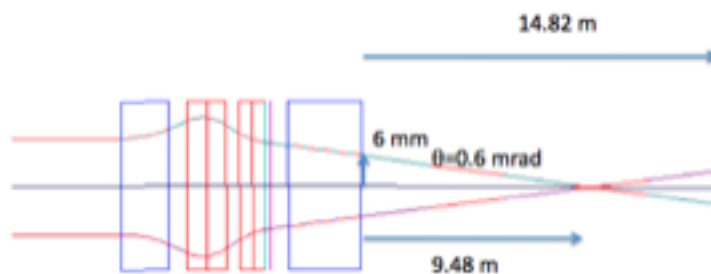
Dejan Trbojevic



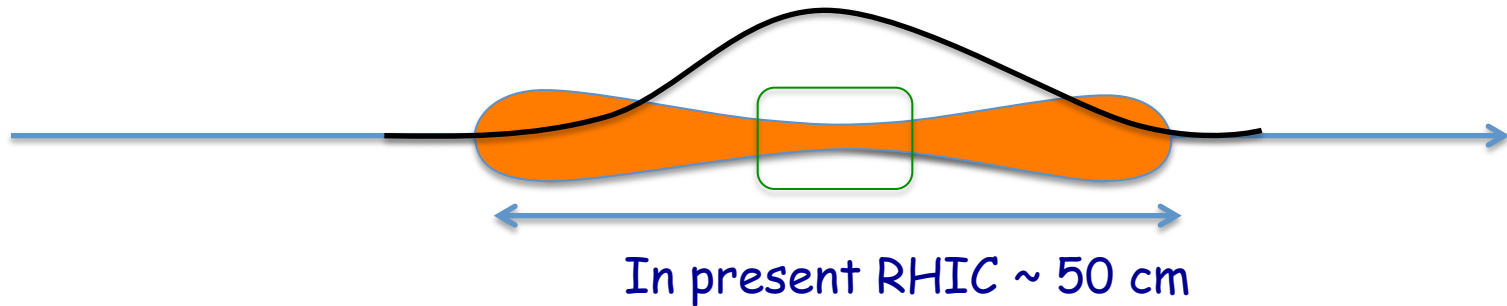
$$R_{12} = 16.7 \text{ m}$$

$$V_{\perp} [\text{MV}] \cong 15.5 \cdot \frac{E_p [\text{GeV}]}{325} \lambda_{rf} [\text{m}]$$

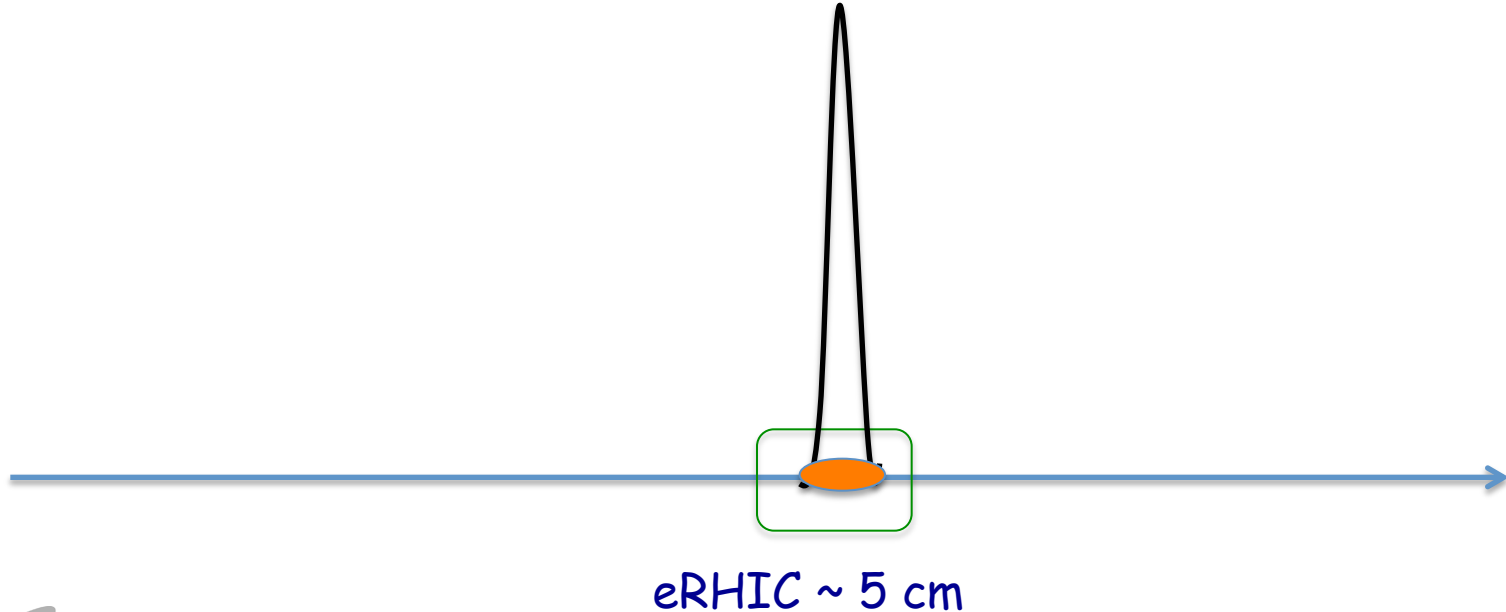
$$R_{12} = 16.7 \text{ m}$$



High luminosity (small β^*), Hourglass & Vertex cuts



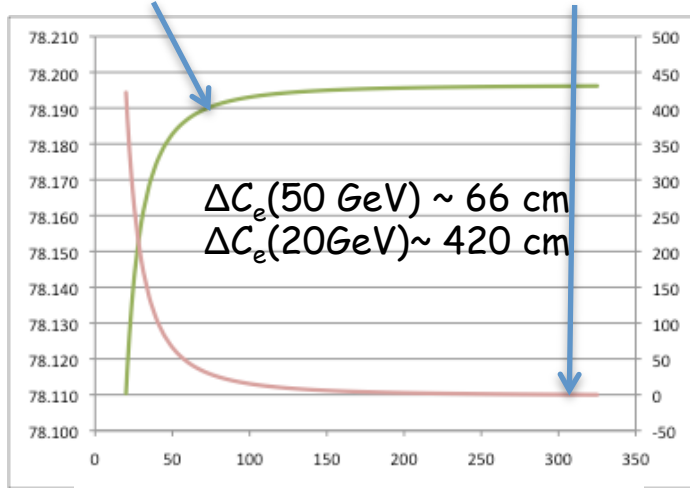
All requires very short hadron bunches



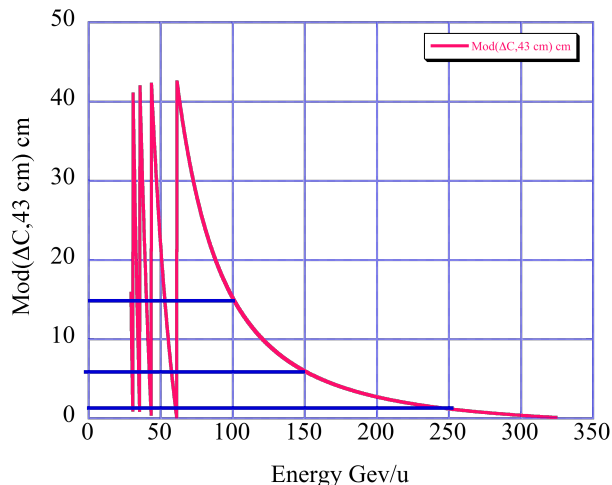
Electron-hadron frequency matching & Lumi sharing

Proton revolution
Frequency in RHIC, kHz

Required electron pass
lengthening, cm



Hadron energy per nucleon, GeV



- 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

Harmonic relations

- 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

	RF harmonic	Bunch harmonic	RF to bunch harmonic
Protons:	$f_{rf,p} = h_p f_{rev,p}$	$f_{b,p} = n_p f_{rev,p}$	$f_{rf,p} = m_p f_{b,p}$
Electrons:	$f_{rf,e} = h_e f_{rev,e}$	$f_{b,e} = f_{b,p}$	$f_{rf,e} = m_e f_{b,p}$
	$h_e \sim 8980-9020$	$n_p = 180$	$m_e = 50$

- 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)

From this: $f_{rev,e} = \frac{m_e n_p}{h_e} f_{rev,p} = \frac{9000}{h_e} f_{rev,p}$

One can change the relation between revolution frequencies using h_e

Main Accelerator Challenges

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

eRHIC at BNL

Polarized electron gun - 10x increase

Coherent Electron Cooling - New concept

Multi-pass SRF ERL
5x increase in current 30x increase in energy

Crab crossing New for hadrons

Polarized ^3He production

Understanding of beam-beam affects New type of collider

$\beta^*=5\text{ cm}$ 5x reduction

Multi-pass SRF ERL 3-4x in # of passes

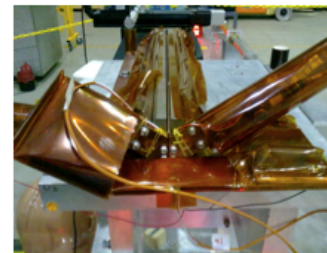
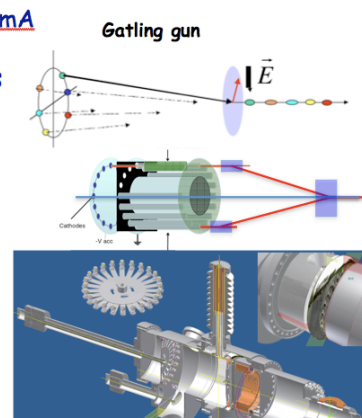
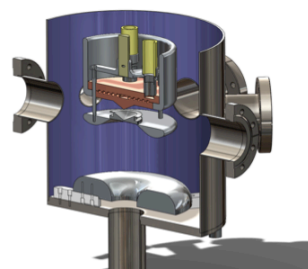
Feedback for kink instability suppression Novel concept

eRHIC R&D highlights

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

Main technical challenge is 50 mA CW polarized gun:
we are building two versions

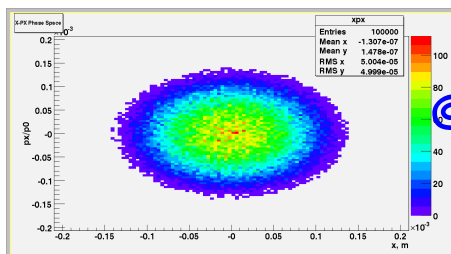
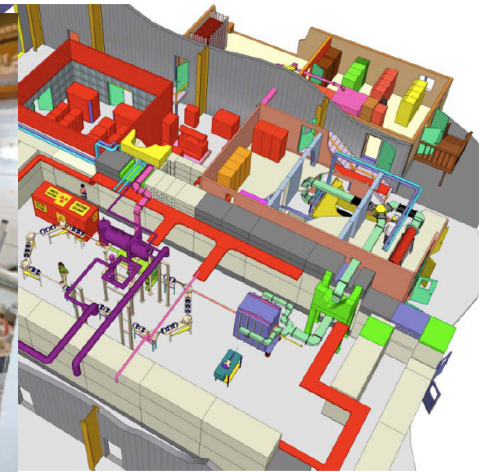
Single large size cathode



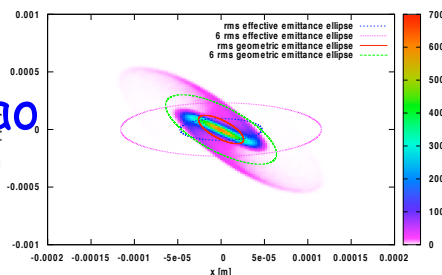
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A. Jain, P. He, Y. Hao



Gap 5 mm total
0.3 T for 30 GeV



©Y. Hao

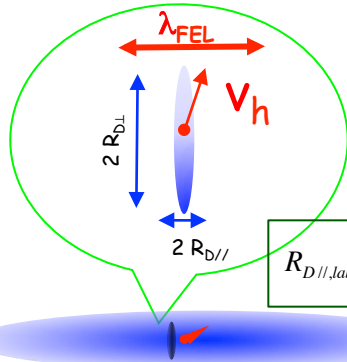
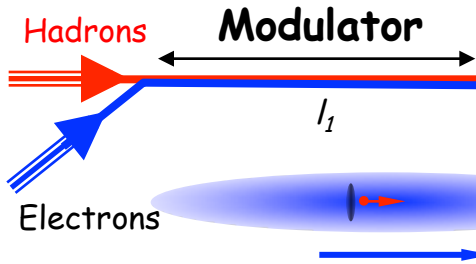


Coherent Electron Cooling (CeC)

At a half of plasma oscillation

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

$$\rho_k = k q(\varphi_1); n_k = \frac{\rho_k}{2\pi\beta\epsilon_{\perp}}$$



Debye radii

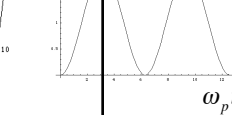
$$R_{D\perp} \gg R_{D\parallel}$$

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

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

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

$$-q/Ze$$



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

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

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

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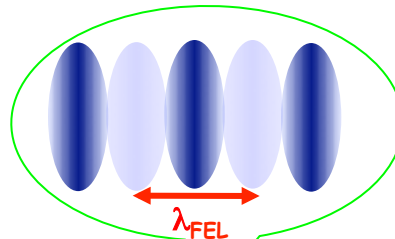
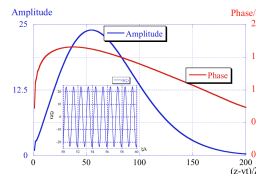
Dispersion

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



High gain FEL (for electrons)

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



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

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

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

PRL 102, 114801 (2009)

PHYSICAL REVIEW LETTERS

week ending
20 MARCH 2009

Coherent Electron Cooling

Vladimir N. Litvinenko^{1,*} and Yaroslav S. Derbenev²

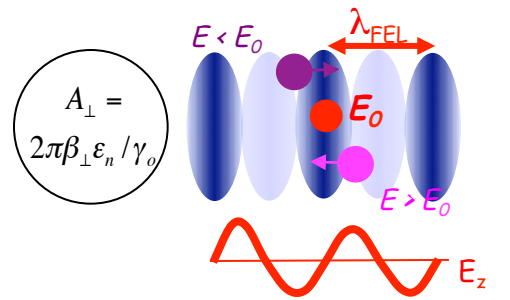
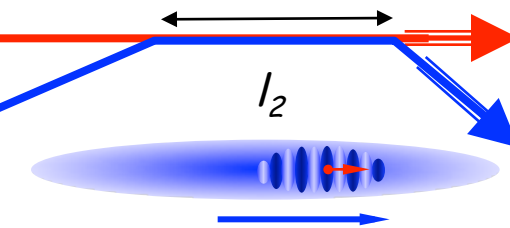
¹Brookhaven National Laboratory, Upton, Long Island, New York, USA

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

$$\Delta E_h = -e \cdot \mathbf{E}_o \cdot \mathbf{l}_2 \cdot \sin\left(k_{FEL} D \frac{E - E_o}{E_o}\right).$$

$$\left(\frac{\sin\varphi_2}{\varphi_2}\right) \cdot \left(\frac{\sin\varphi_1}{2}\right)^2 \cdot Z \cdot X; \mathbf{E}_o = 2G_o e\gamma_o / \beta\epsilon_{\perp n}$$

Kicker



$$A_{\perp} = \frac{2\pi\beta_{\perp}\epsilon_n}{\gamma_o}$$

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

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

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

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

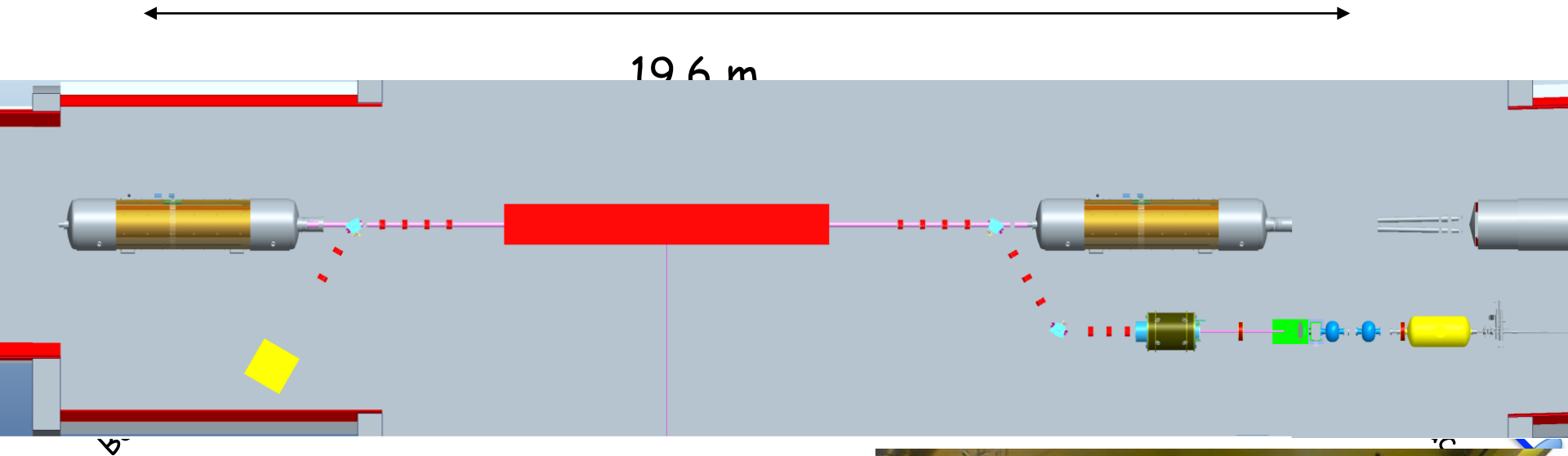
$$\mathbf{E}_o = 2G_o\gamma_o \frac{e}{\beta\epsilon_{\perp n}}$$

$$30X = q/e \approx Z(1 - \cos\varphi_1)$$



Coherent Electron Cooling demonstration experiment at RHIC IR2

Goal - cool a single 40 GeV/u Au ion bunch in RHIC

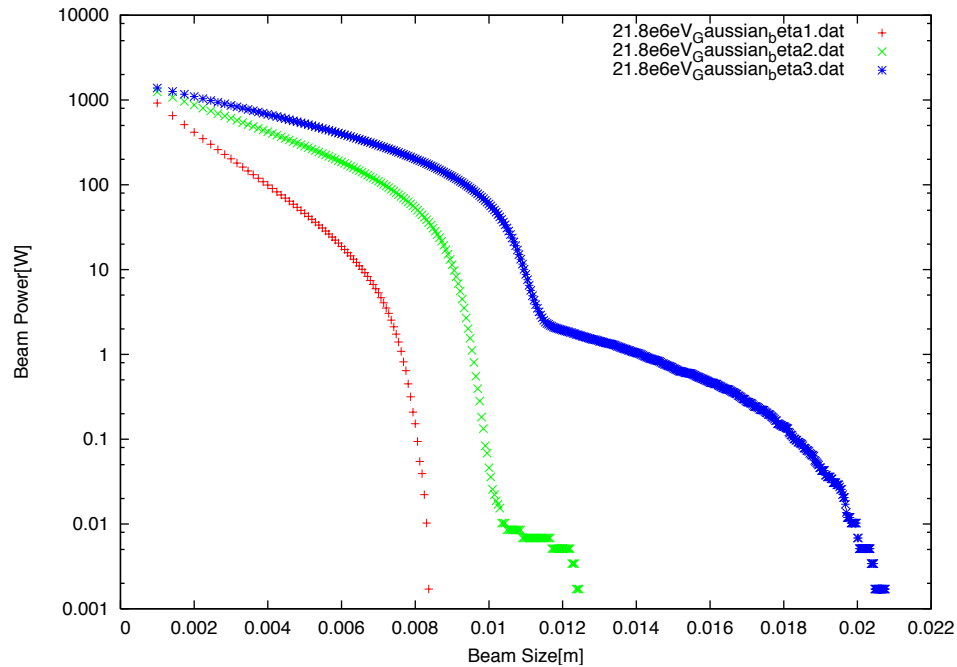


Parameter	
Species in RHIC	Au ions, 40 GeV/u
Electron energy	21.8 MeV
Charge per bunch	1 nC
Train	1 bunches
Rep-rate	78.3 kHz
e-beam current	0.078 mA
e-beam power	1.7 kW

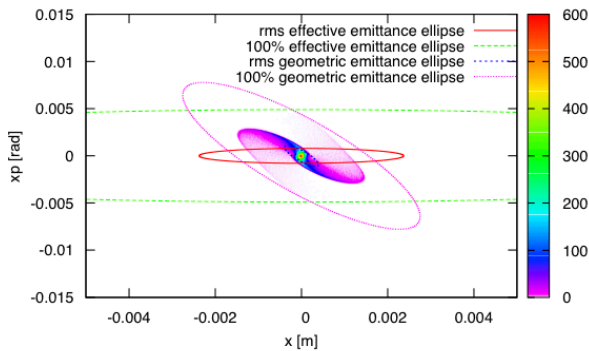


10.19.2011

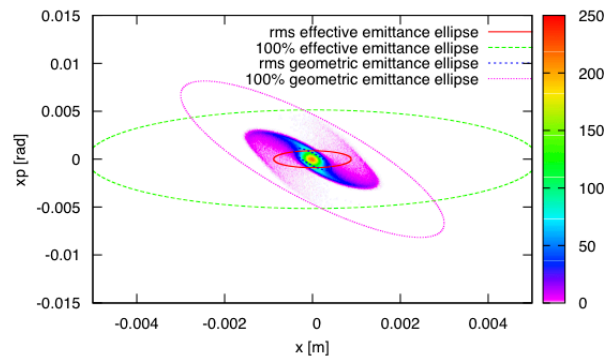
Mismatch, tuning of e beta*



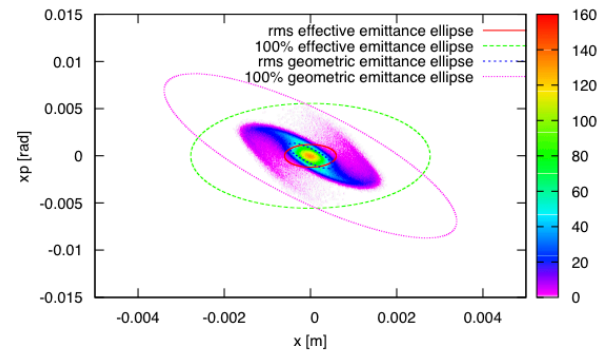
The experiment also can demonstrate the effect of mismatch due to the beam-beam interaction and its relation with the electron design optics.



$\text{Beta}^* = 3\text{m}$



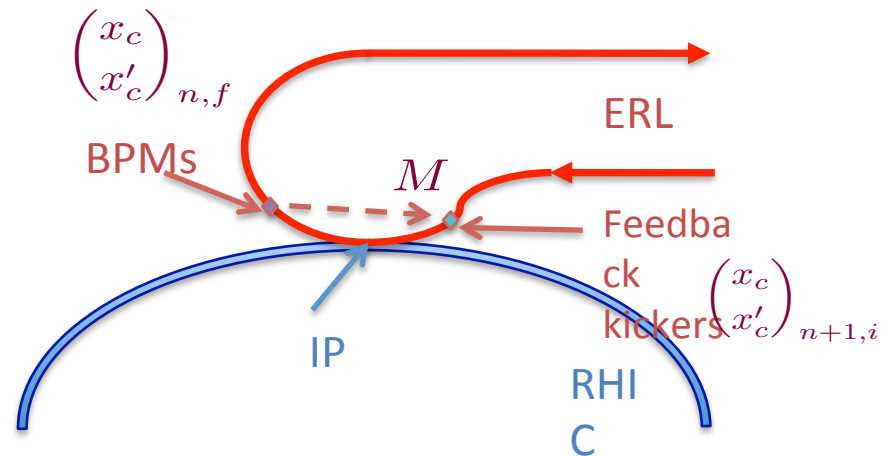
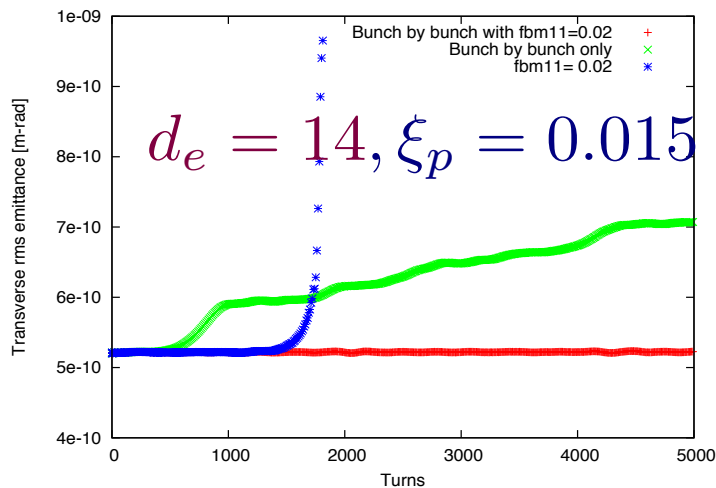
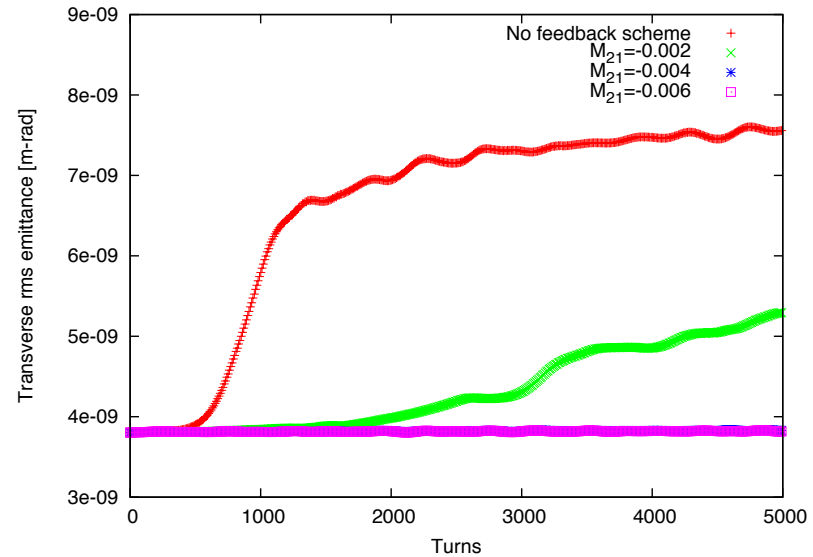
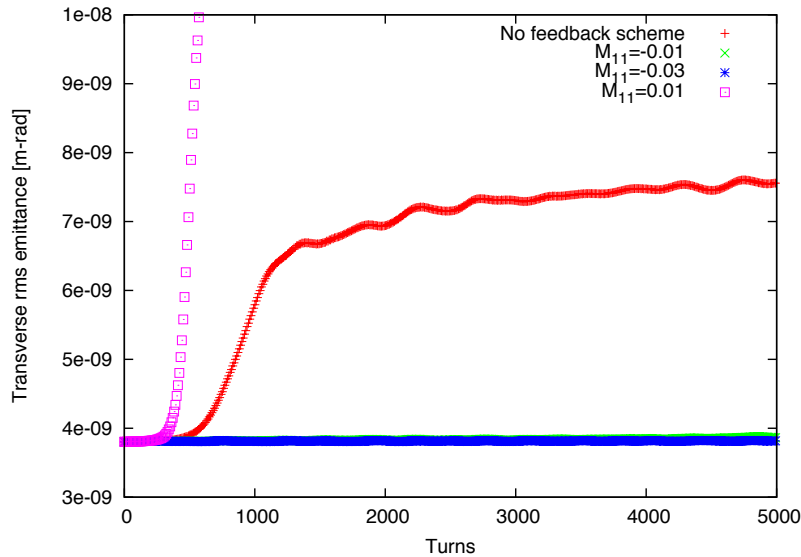
$\text{Beta}^* = 1\text{m}$



$\text{Beta}^* = 0.5\text{m}$

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

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...

August 2011 Review

- 1) Frank Zimmermann (CERN)
 - 2) Jean Delaysen (ODU)
 - 3) George Ganetis (BNL)
 - 4) Hsiao-chaun Hseuh, (BNL)
 - 5) Valery Lebedev (FNAL)
 - 6) Matt Poelker (Jlab)
 - 7) Eduard Pozdeyev (MSU/NSCL)
 - 8) Peter Wanderer (BNL)
-
- **From the report:**
 - **The committee is very impressed by the ingenious design of eRHIC. The design includes a number of outstanding and novel elements.**
 - **The committee is highly satisfied with the material presented, covering most of the relevant subjects. The committee did not see any significant holes in the concept.**
 - **Plus about 40 recommendations**

Milestones & Goals

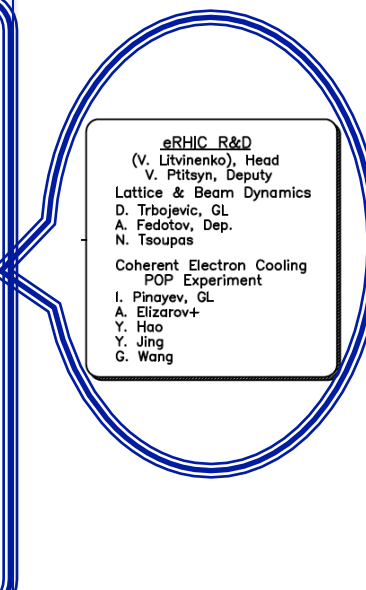
- Main milestones

- Finish eRHIC cost estimate Spring of 2012
- External review of the estimate Summer of 2012
- Address concerns of the reviews End of 2012
- Complete start-to-end eRHIC ERL simulations 2013
- Complete beam-beam simulations 2014
- Complete magnet prototyping 2015
- Demonstrate coherent e-cooling 2016-17

Summary

- eRHIC design progresses well
 - Accelerator design is completed
 - And went through the External review
 - Cost estimate is underway
 - Follow-up on the committee recommendations is in progress
- Physics of the collider is well understood
 - No show-stoppers were found
 - Many processes can be studied or simulated from first principles
- Number of novel concepts require extensive R&D
- Next 3-5 years will be critical for completing R&D and be ready for full eRHIC design

Date: _____



Credits: E. Aschenauer, J. Beebe-Wang, S. Belomestnykh, I. Ben-Zvi, R. Calaga, X. Chang, A. Fedotov, H. Hahn, L. Hammons, Y. Hao, P. He, A. Jain, E. Johnson, D. Kayran, J. Kewisch, V. N. Litvinenko, G. Mahler, W. Meng, B. Parker, A. I. Pikin, I. Payev, V. Ptitsyn, T. Rao, T. Roser, B. Sheehy, J. Skaritka, R. Than, D. Trbojevic, N. Tsoupas, J. Tuozzolo, G. Wang, Q. Wu, Wencan Xu

- Backup slides