ERL 2011
the 50th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

ERLs in the High Energy and Nuclear Physics

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Conclusions

- Energy recovery linacs would play major role in future High Energy and Nuclear Physics facilities
  - They could be used as electron beam accelerator of choice in high-energy high-luminosity electron-hadron colliders (eRHIC, LHeC)
  - They could be used as drivers for Coherent Electron Cooling of hadron beams boosting luminosity 10- to 50–fold in high energy hadron and electron-hadron colliders (RHIC, LHC, eRHIC, LHeC)
  - ERL can be an excellent candidate for high luminosity ILC
  - ERL is considered as potential candidate as injector into conventional electron cooler for ELIC
  - ERLs can be also excellent choice to drive intense gamma-ray sources for Nuclear Physics and RIA-type facilities – both as e-beam drive and provider of photons
- ERL progress is modest, but the potential is exceptional
- New ideas on how to extend ERL energy into 0.1-1 TeV range emerging

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Content

- What changed in 6 years?
- Bread-and-Butter applications of ERLs
  - Conventional Electron Cooling, γ-ray sources…
- High
  - e
- Nev … RLs
- Con

Wednesday 19 October 2011

10:00 Applications of high-brightness gamma-rays from ERLs - Takehito Hayakawa (*JAEA*)

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Office of Nuclear Physics — Exploring Nuclear Matter - Quarks to Stars

• What changed in 6 years?

ERLs in High Energy and Nuclear Physics

Ilan Ben-Zvi and Vladimir Litvinenko

Collider-Accelerator Department
Brookhaven National Laboratory

Acknowledgements:
The large BNL teams working on electron cooling and eRHIC
MIT collaborators
Lia Merminga and JLab ELIC team

R&D Topics

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

ERL'2005 I. Ben-Zvi & V. Litvinenko, March 19, 2005 NATIONAL LABORATORY

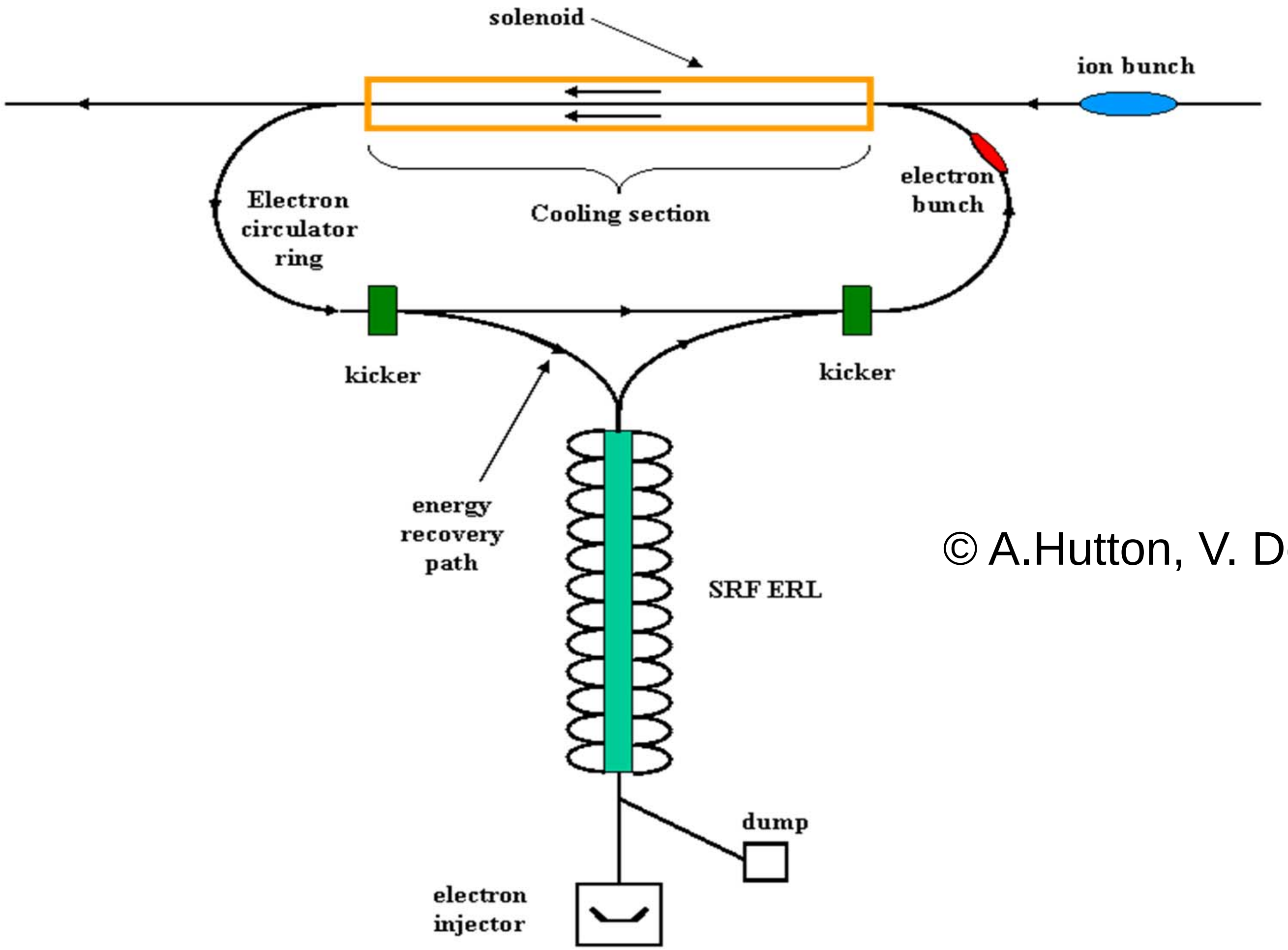
- Excellent scientific developing for a high luminosity, polarized electron-ion collider.
- JLab design: luminosities 10^{33} up to nearly 10^{35} (cm^{-2} sec^{-1}), for electron-light ion collisions at 20 to 65 GeV CM.
- BNL-MIT design: luminosities 10^{33} up to nearly 10^{34}, electrons with any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

Conclusions

ERL role in ELIC

ERL Circulator e-Cooler

(for delivering a 3A CW electron beam)



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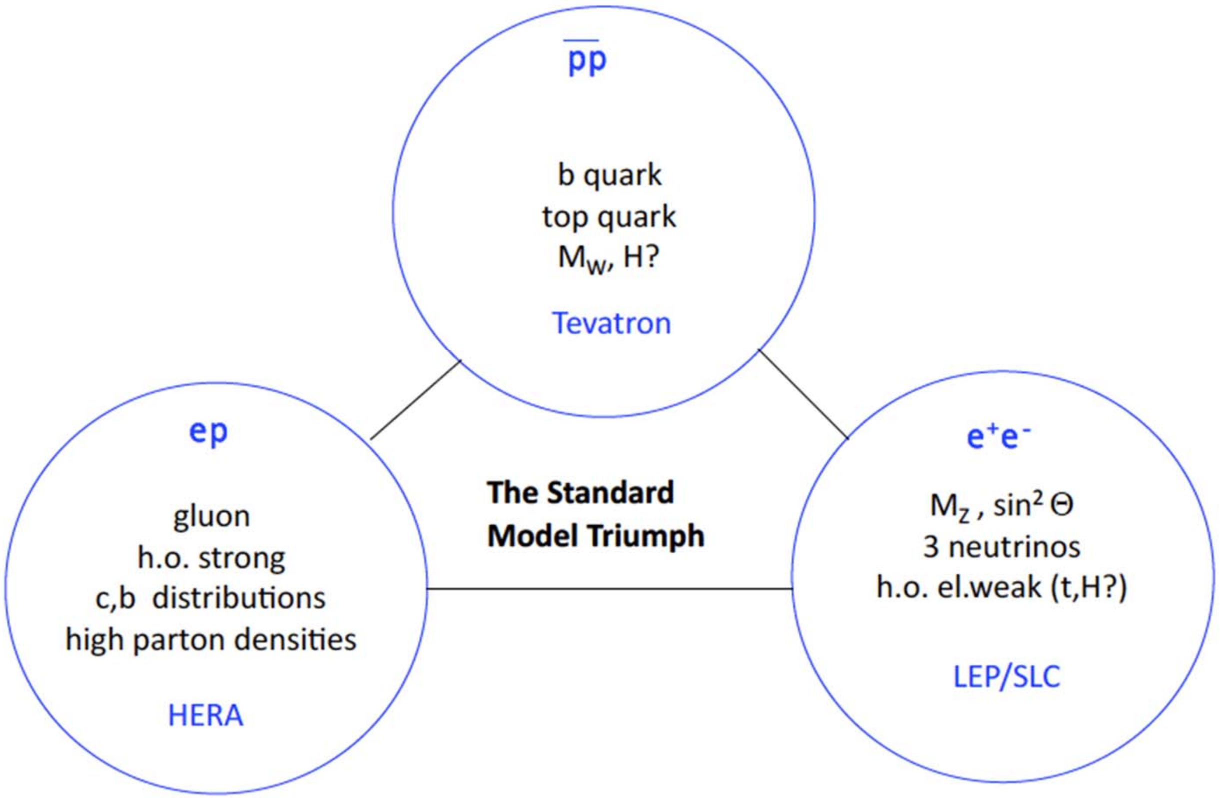
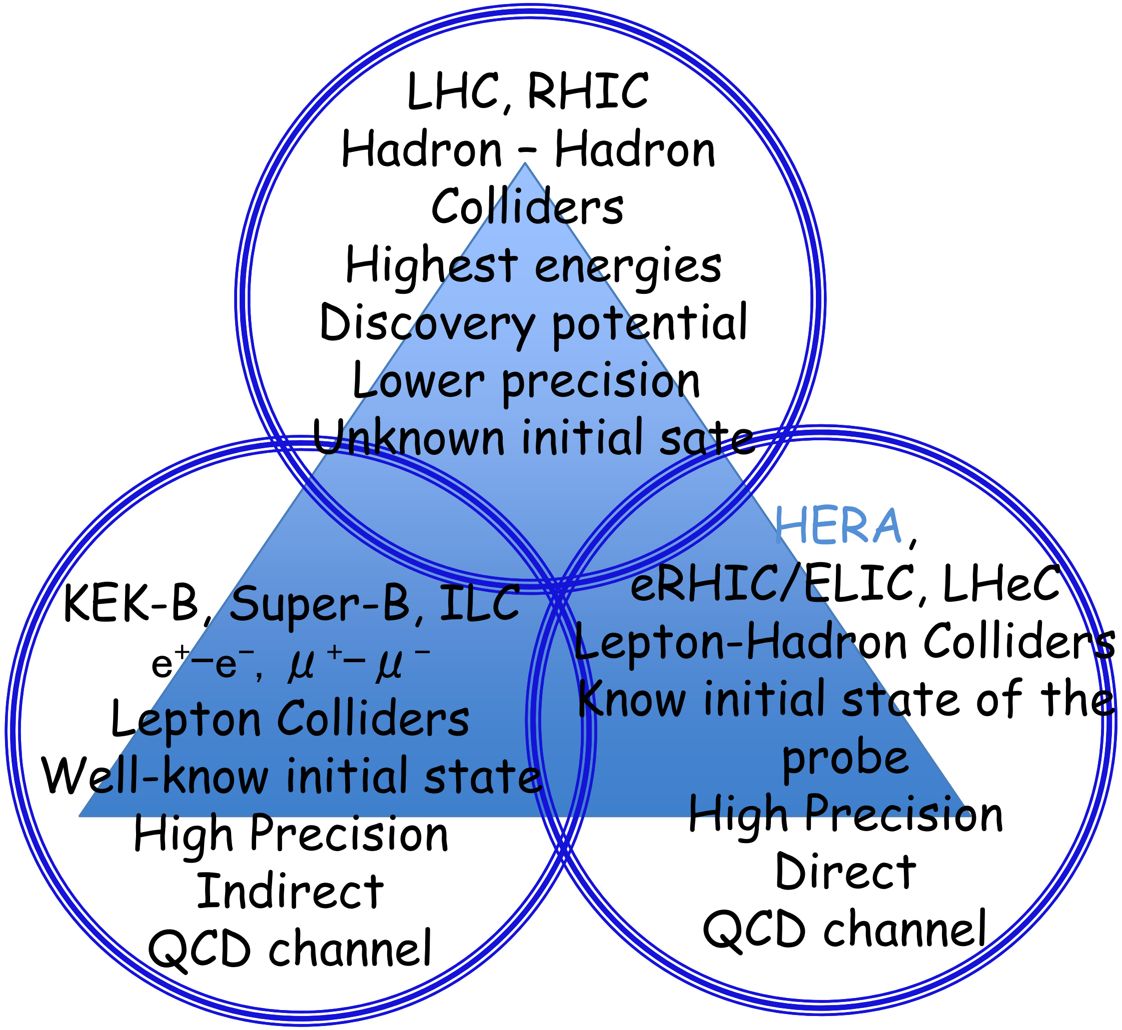
The Fermi Scale [1985-2010]



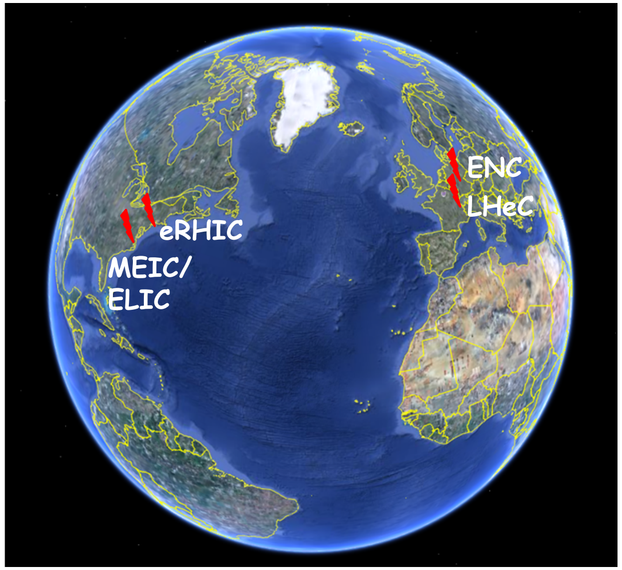
Colliders for Fundamental Physics

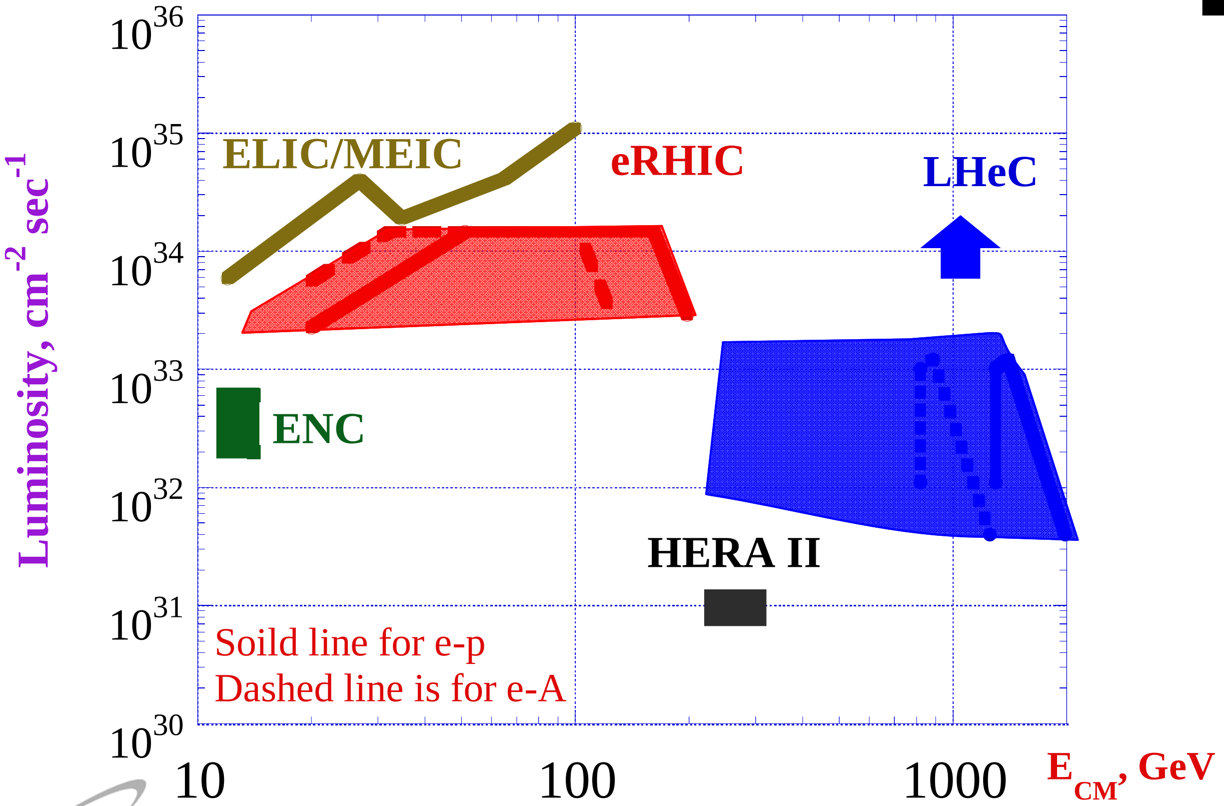


Accelerator physicist point of view

Energy Reach and Luminosities of future electron-hadron colliders

$$E_{CM} \cong \sqrt{4E_eE_h}$$





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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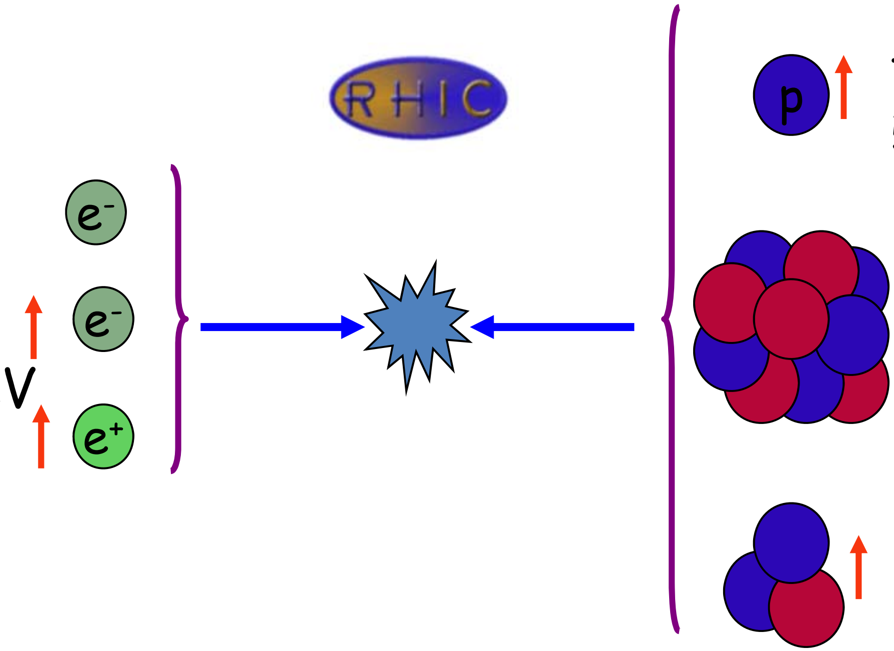
eRHIC: QCD Facility at BNL

Add electron accelerator to the existing $2B RHIC

Unpolarized and
80% polarized
leptons, 5-30 GeV



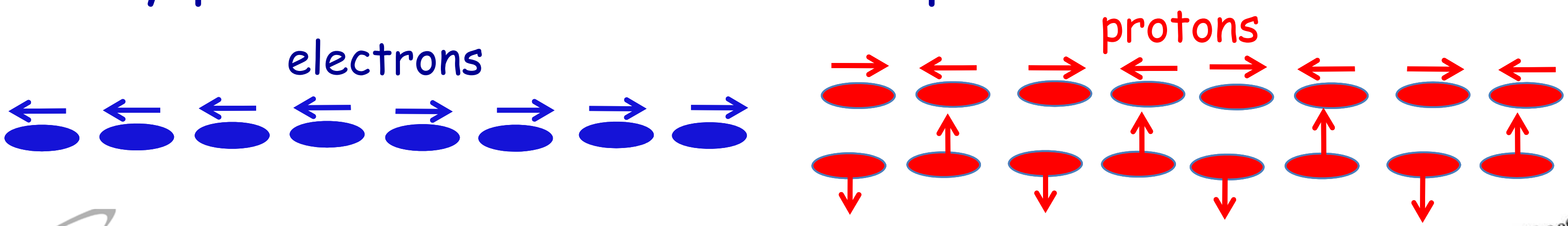
70% polarized protons
50-250 (325) GeV

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

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

Center of mass energy range: 30-200 GeV

Any polarization direction in lepton-hadrons collisions



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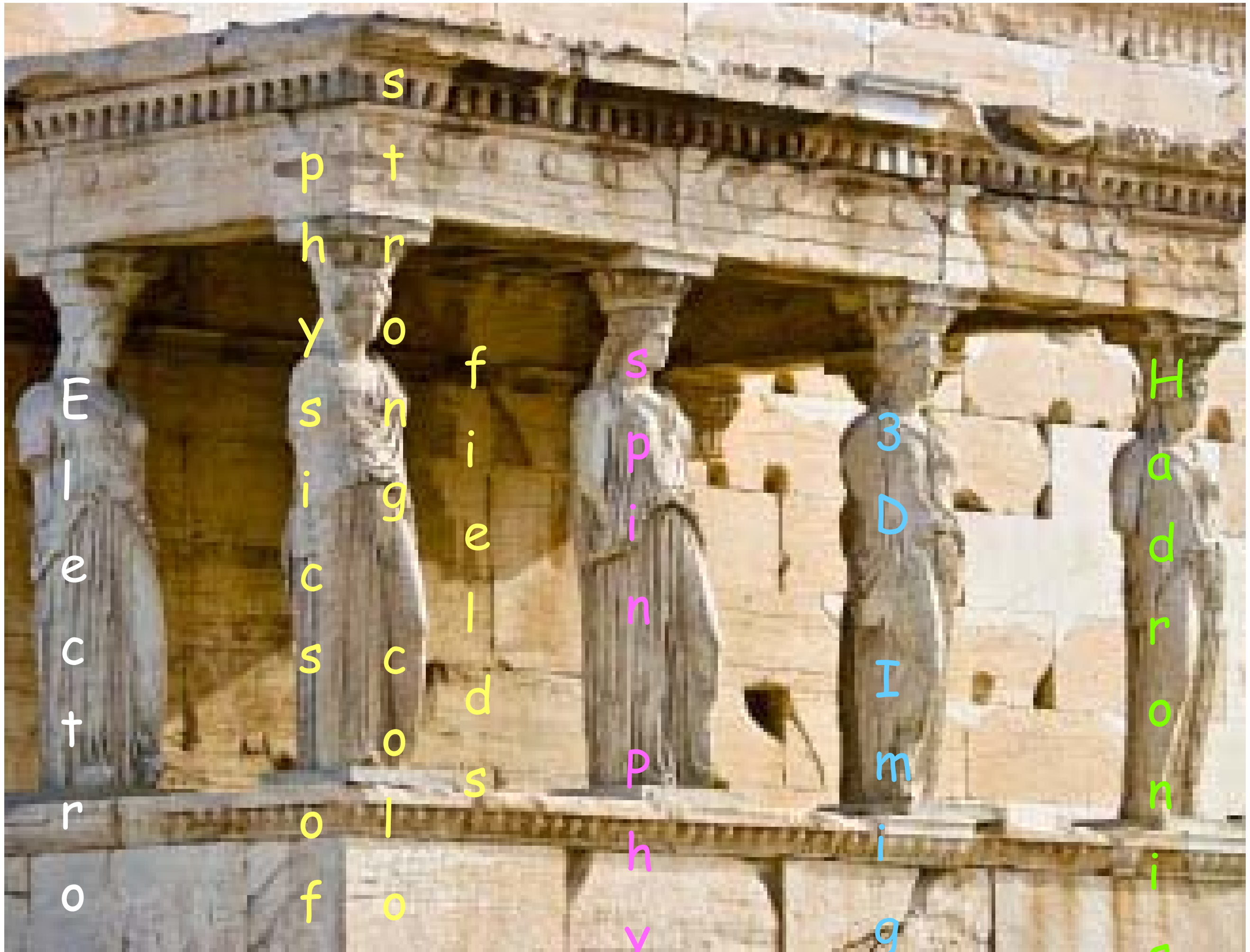
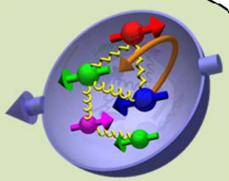
The Pillars of the EIC Physics program



Wide physics program with high requirements on detector and machine performance

Most Compelling Physics Questions

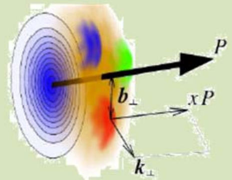
spin physics



- 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

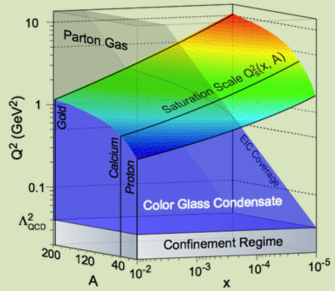


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- understand deep aspects of gauge theories revealed by k_T dep. distr'n

possible window to orbital angular momentum

physics of strong color fields

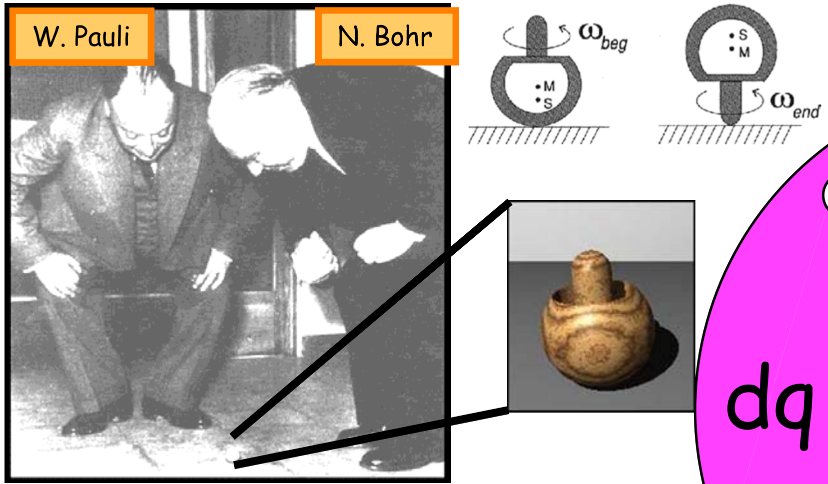
quantitatively probe the universality of strong color fields in AA, pA, and eA

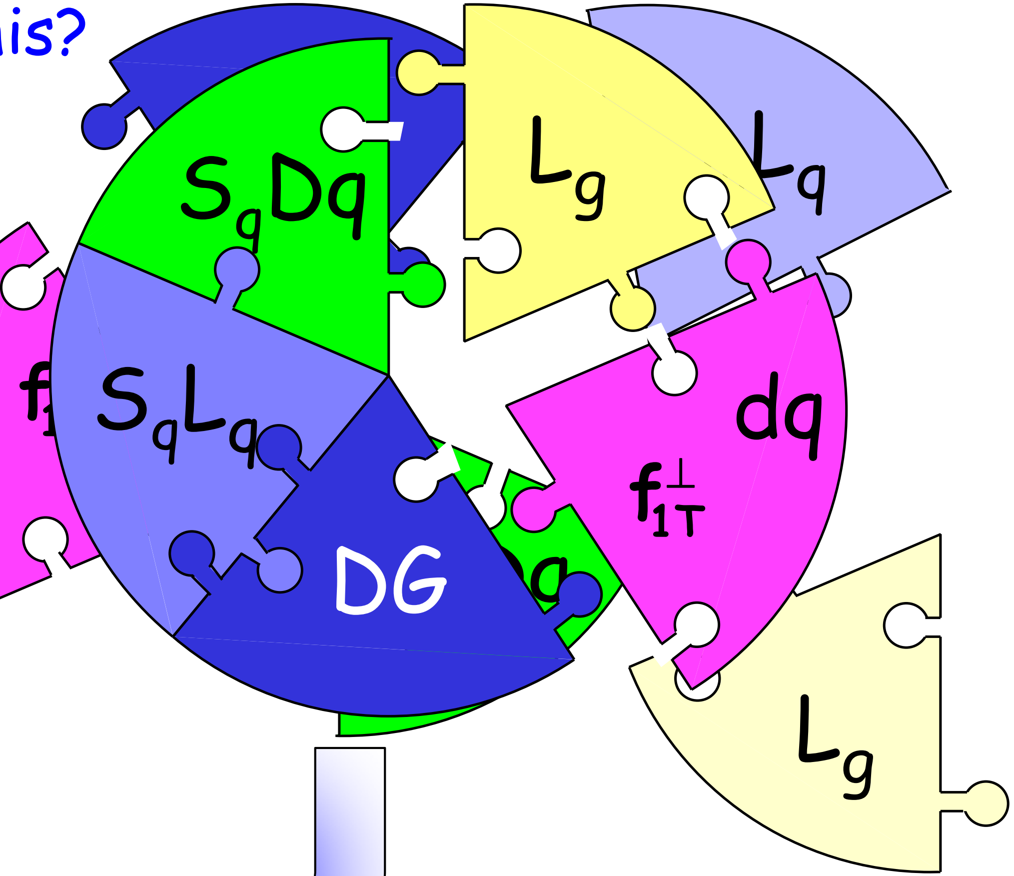


- understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- how do hard probes in eA interact with the medium

Important to understand hadron structure: Spin

Is the proton spinning like this?





"Helicity sum rule"

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2} \middle| J^z_{QCD} \middle| P,\frac{1}{2} \right\rangle = \underbrace{\sum_q \frac{1}{2} S^z_q}_{\text{total u+d+s quark spin}} + \overbrace{S^z_g}^{\text{gluon spin}} + \underbrace{\sum_q L^z_q + L^z_g}_{\text{angular momentum}}$$

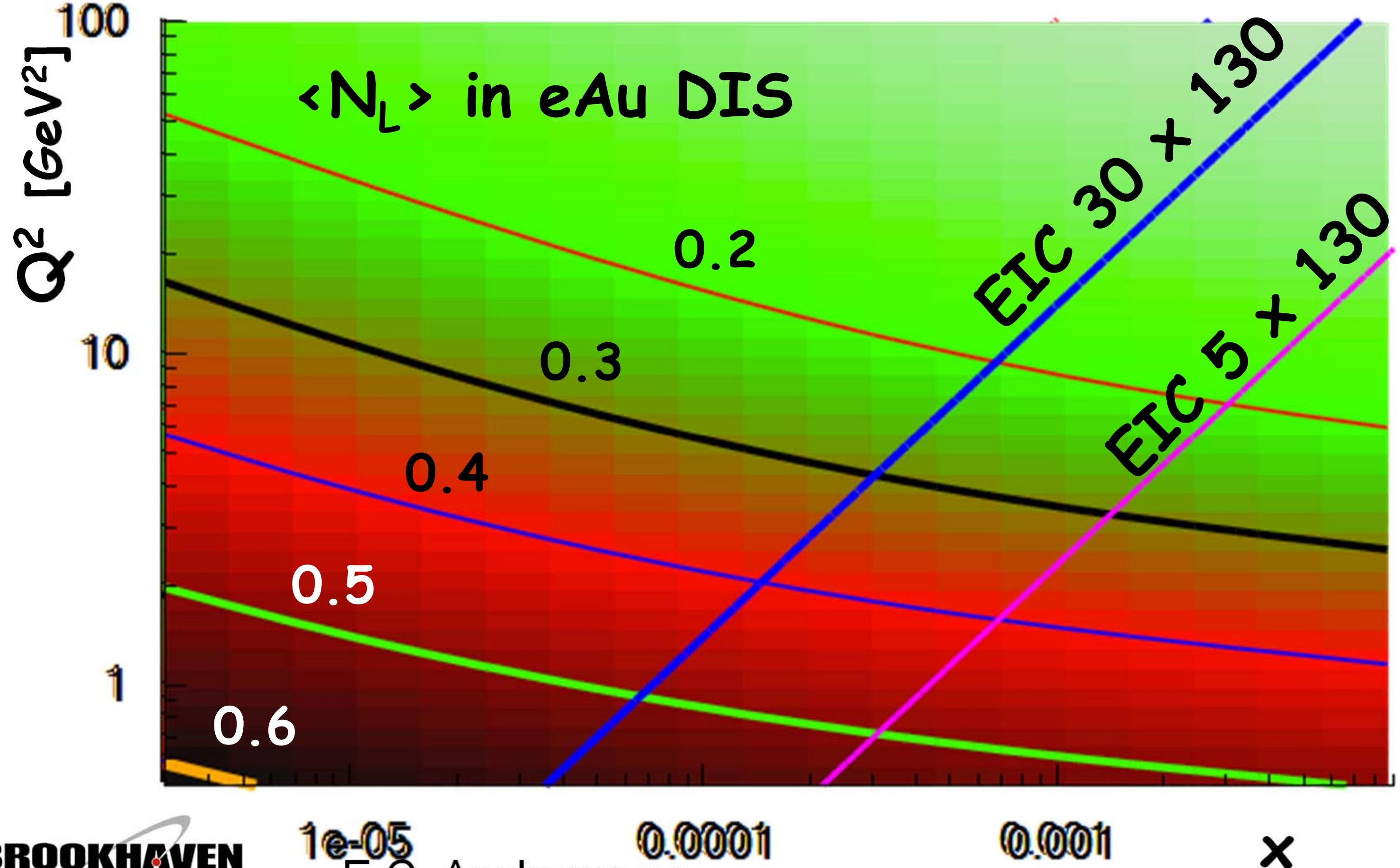
Where do we go with solving the "spin puzzle" ?

Gluon saturation in eA DIS

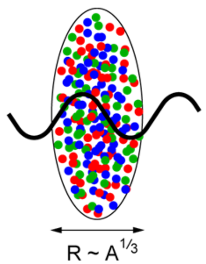
quantitative estimates

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

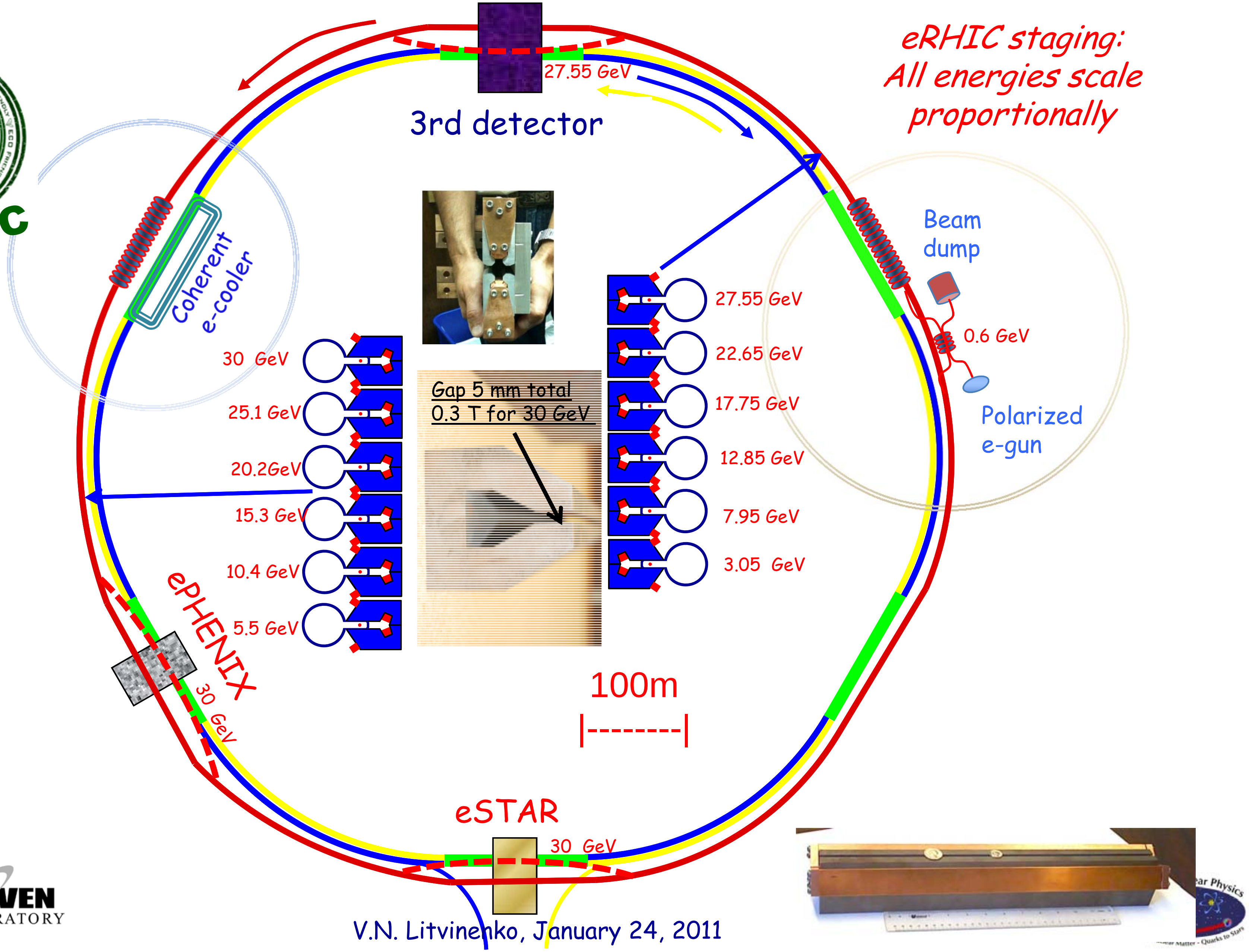


saturation effects in eA benefit from nuclear oompf

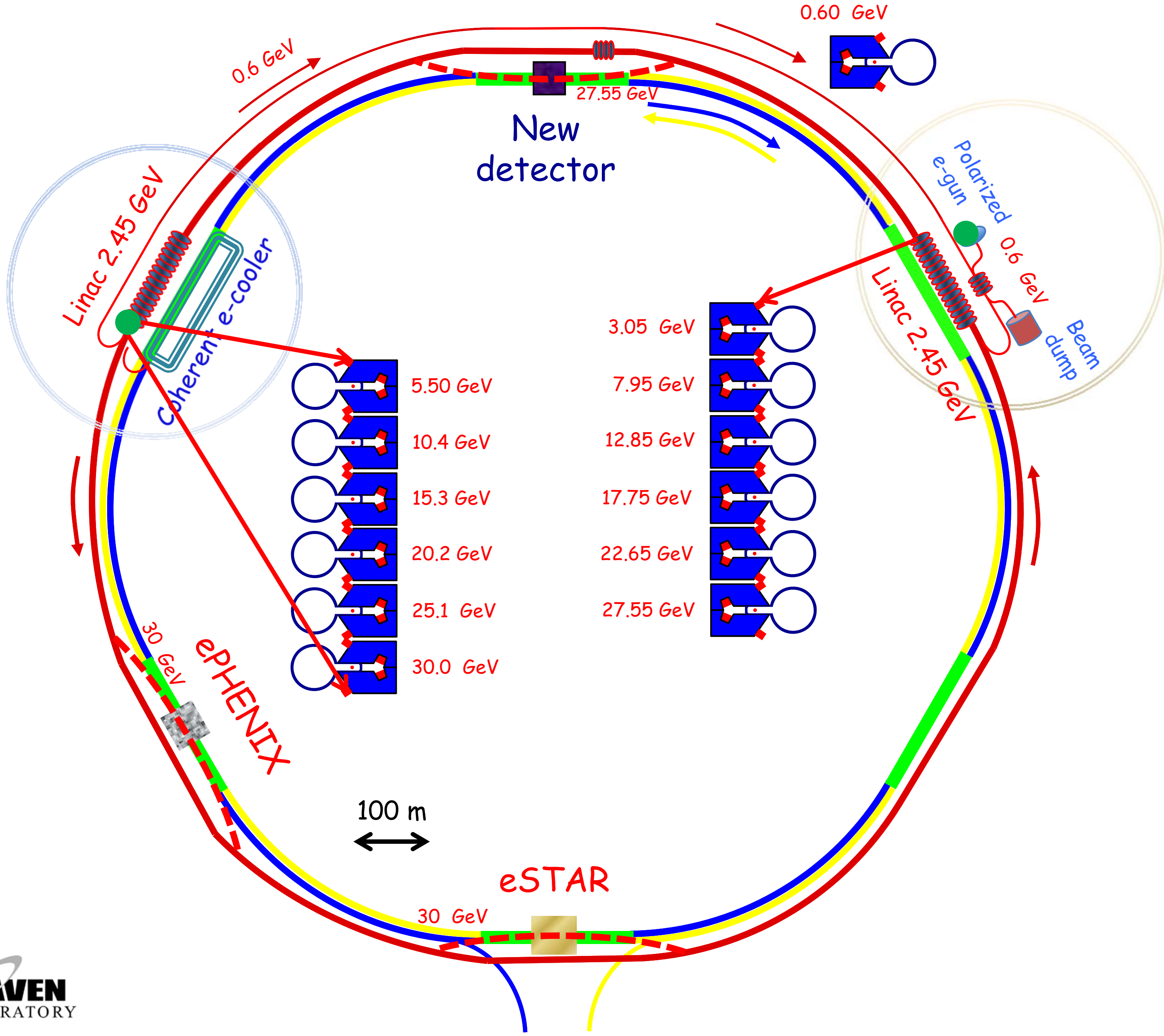


$$Q^2_{s,p} = A^{1/3} Q^2_{s,A}$$

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



e-beam in ERL



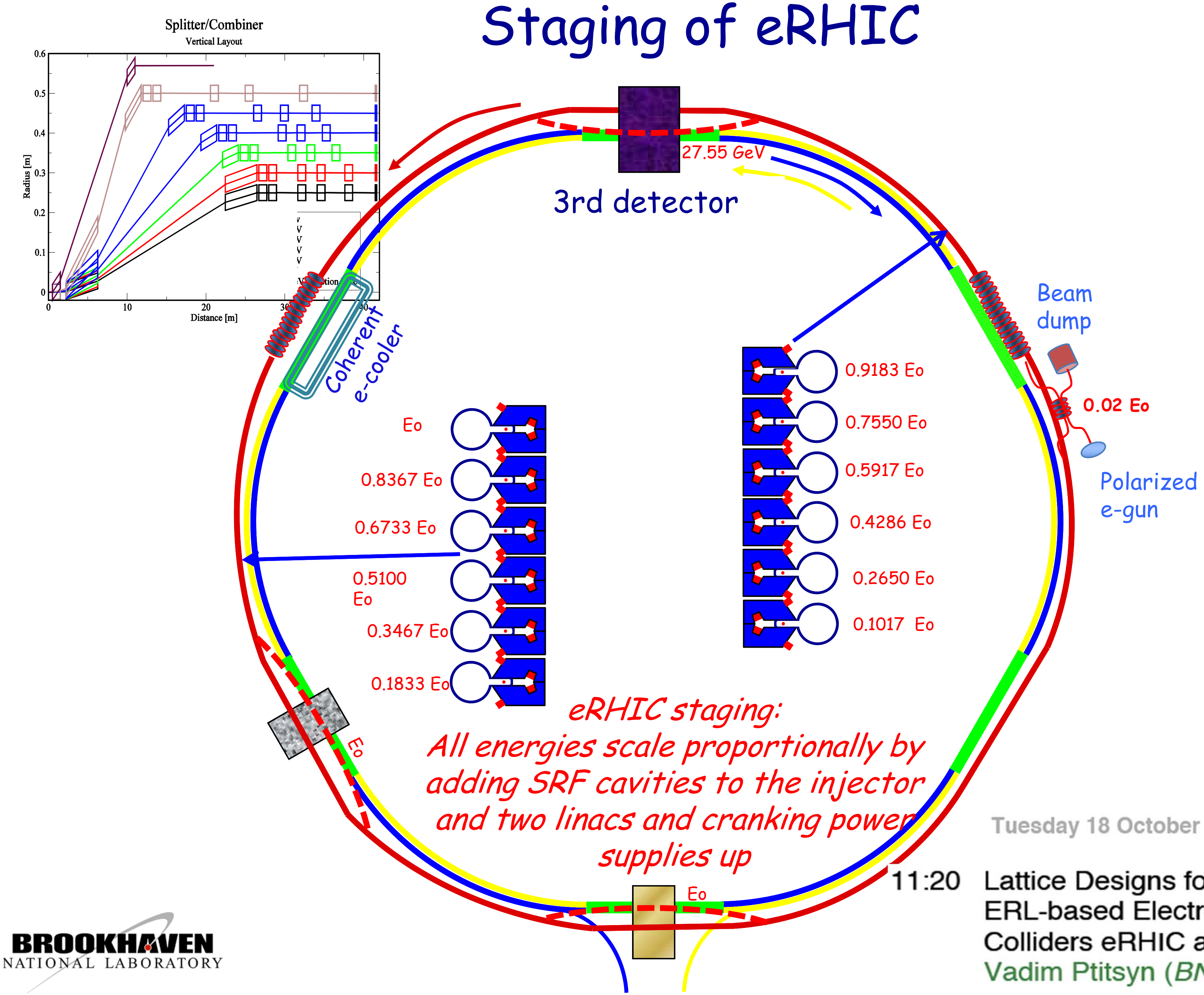
0.60 GeV
0.6 GeV
27.55 GeV
New detector
Linac 2.45 GeV
Coherent e-cooler
Polarized e-gun
0.6 GeV
Beam dump
Linac 2.45 GeV
3.05 GeV
5.50 GeV
7.95 GeV
10.4 GeV
12.85 GeV
15.3 GeV
17.75 GeV
20.2 GeV
22.65 GeV
25.1 GeV
27.55 GeV
30.0 GeV
30 GeV
ePHENIX
100 m
eSTAR
30 GeV

eRHIC luminosity

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

Hourglass effect is included

Staging of eRHIC



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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11:20 Lattice Designs for the Future ERL-based Electron Hadron Colliders eRHIC and LHeC - Vadim Ptitsyn (*BNL*)

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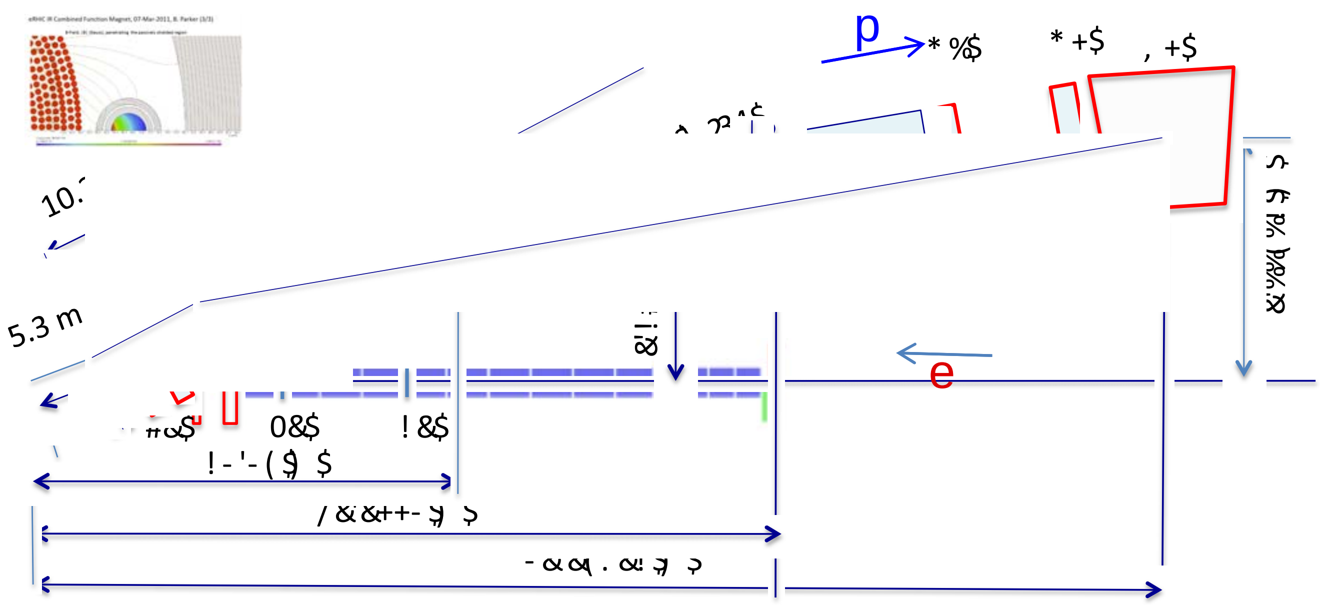
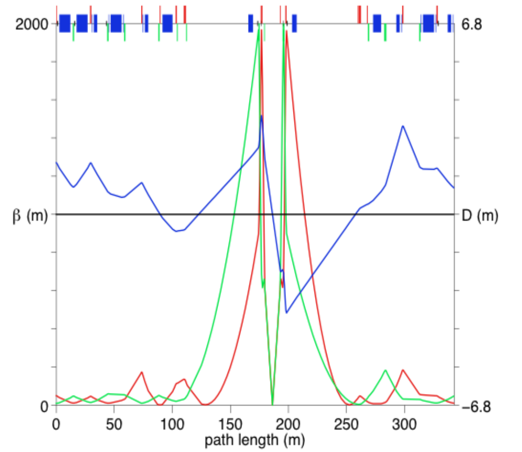
eRHIC high-luminosity IR with β^*=5 cm



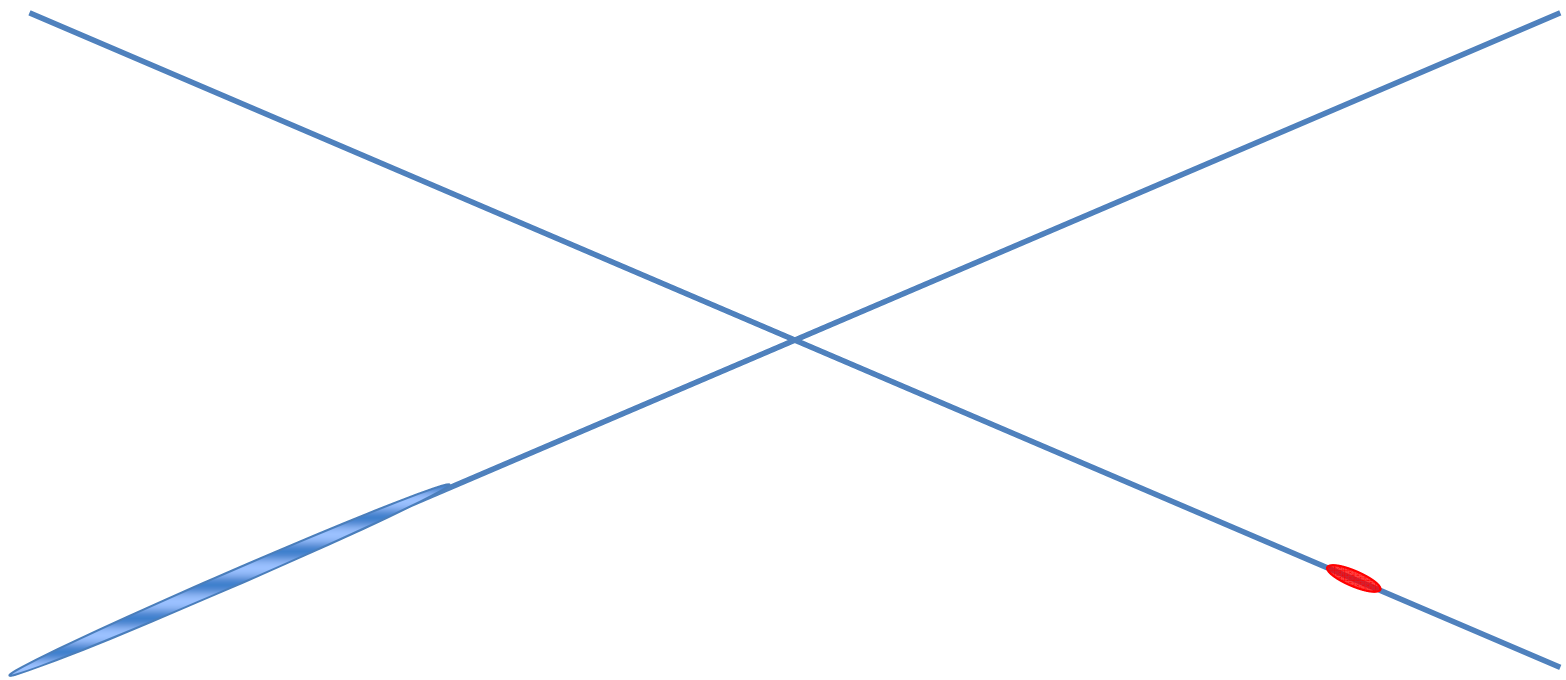
Proton beam lattice



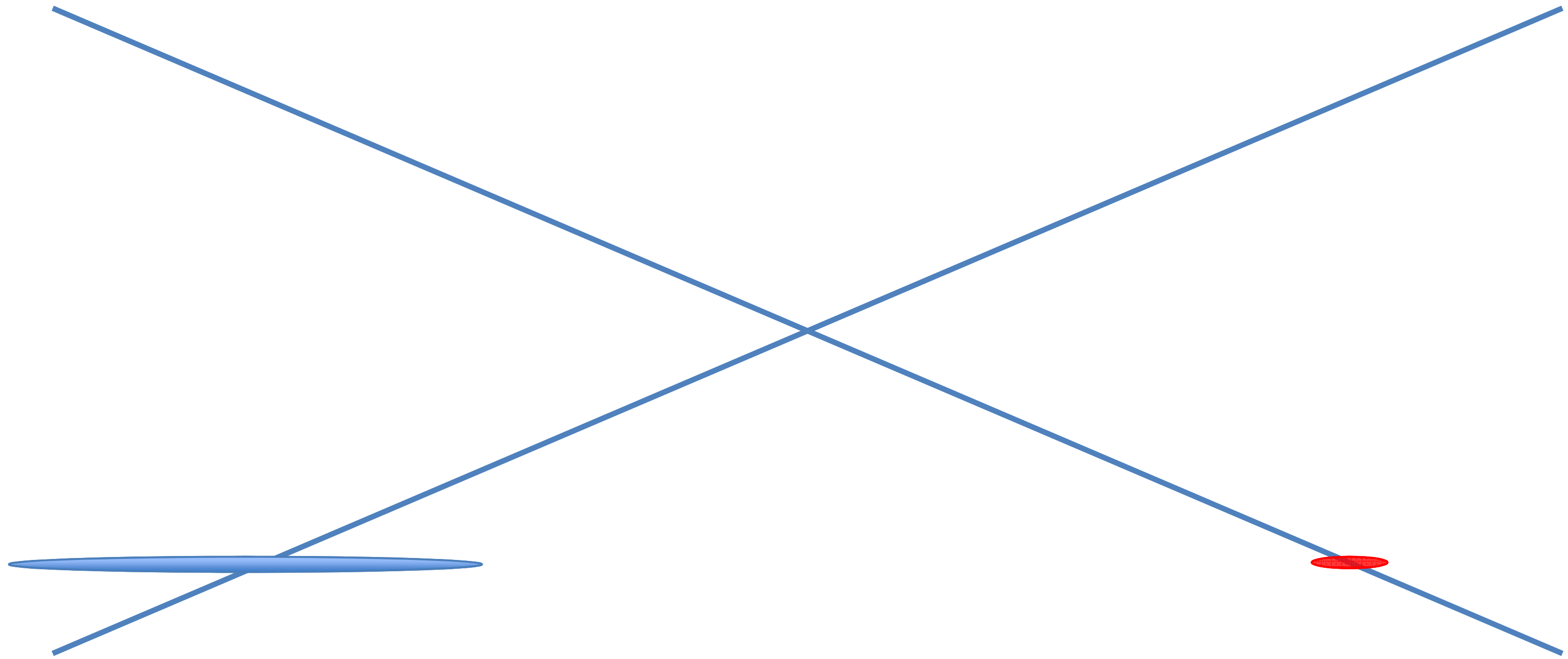
- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb_3Sn focusing magnets
- Arranged free-field electron pass through the hadron triplet magnets
- Integration with the detector: efficient separation and registration of low angle collision products
- Gentle bending of the electrons to avoid SR impact in the detector

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

"No crabbing"



"Ideal crabbing"



Mini-Workshop About eRHIC

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WG3

11:00 Superconducting RF for Energy Recovery Linacs of eRHIC - Sergey Belomestnykh (*BNL*)

WG2: Non-LS Design Issues

11:20 Lattice Designs for the Future ERL-based Electron Hadron Colliders eRHIC and LHeC - Vadim Ptitsyn (*BNL*)

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WG4 & WG5

11:00 BNL Energy Recovery Linac Instrumentation - David Gassner (*BNL*)

WG2: Beam Dynamics Issues (until 12:30) (KEK

11:40 Wakefields and Energy Spread for the eRHIC ERL - Alexei. V. Fedotov (*BNL*)

12:00 Transverse BBU Studies for eRHIC at Different Top Energy Settings - Dmitry Kayran (*BNL*)

BI
NAT

Thursday 20 October 2011

WG1

11:00 Progress at BNL Towards Development of Efficient, Robust Photocathodes for High Average Current Operation - Triveni Rao (*BNL*)

WG2/WG5(Beam Loss Issues)

13:30 Beam-Beam Effects in an ERL-based Electron-Ion Collider - Vadim Ptitsyn (*BNL*)

13:50 Intra-beam Scattering and its Application to ERL - Alexei V. Fedotov (*BNL*)

WG3

14:00 Development of antenna-type HOM couplers at BNL - Sergey Belomestnykh (*BNL*)

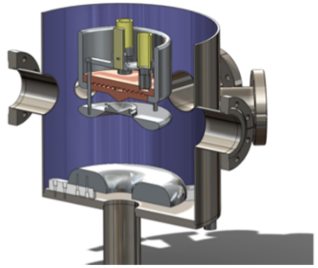
16:15 Fundamental power couplers for the ERL prototype SRF gun at BNL - Sergey Belomestnykh (*BNL*)

R&D highlights

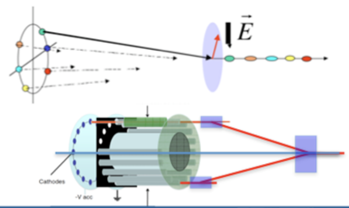
- Polarized gun for e-p program – **LDRD at BNL + MIT**
- Development of compact magnets - **LDRD at BNL, *ongoing***
- SRF R&D ERL – ***ongoing***
- Beam-beam effects, beam disruption, kink instability suppression, etc.
- Polarized He^3 source
- Coherent Electron Cooling including PoP – **plan to pursue**

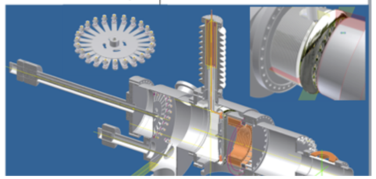
Main technical challenge is 50 mA CW polarized gun: we are building two versions

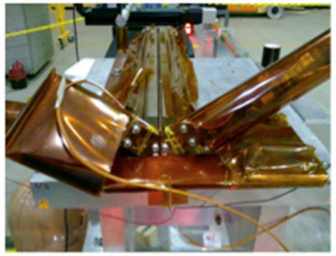
Single large size cathode



Gatling gun

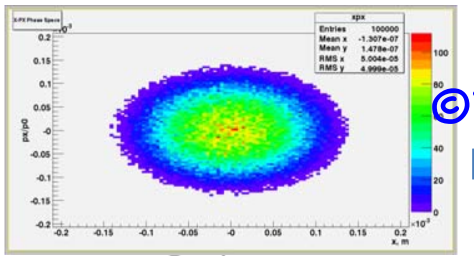






Gap 5 mm total
0.3 T for 30 GeV

©, G. Mahler, W. Meng, A. Jain, P. He, Y Hao



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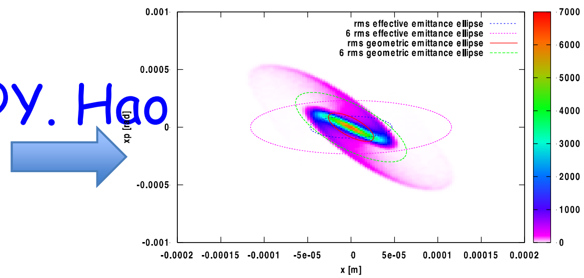
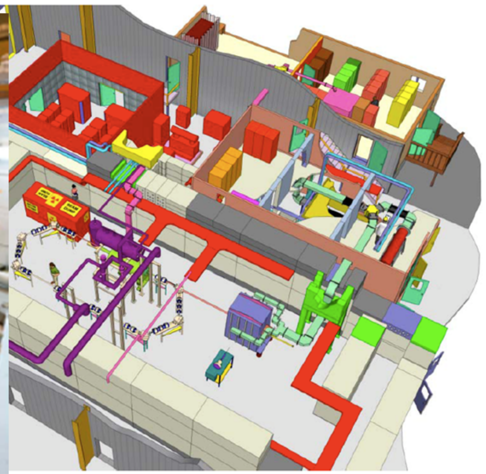
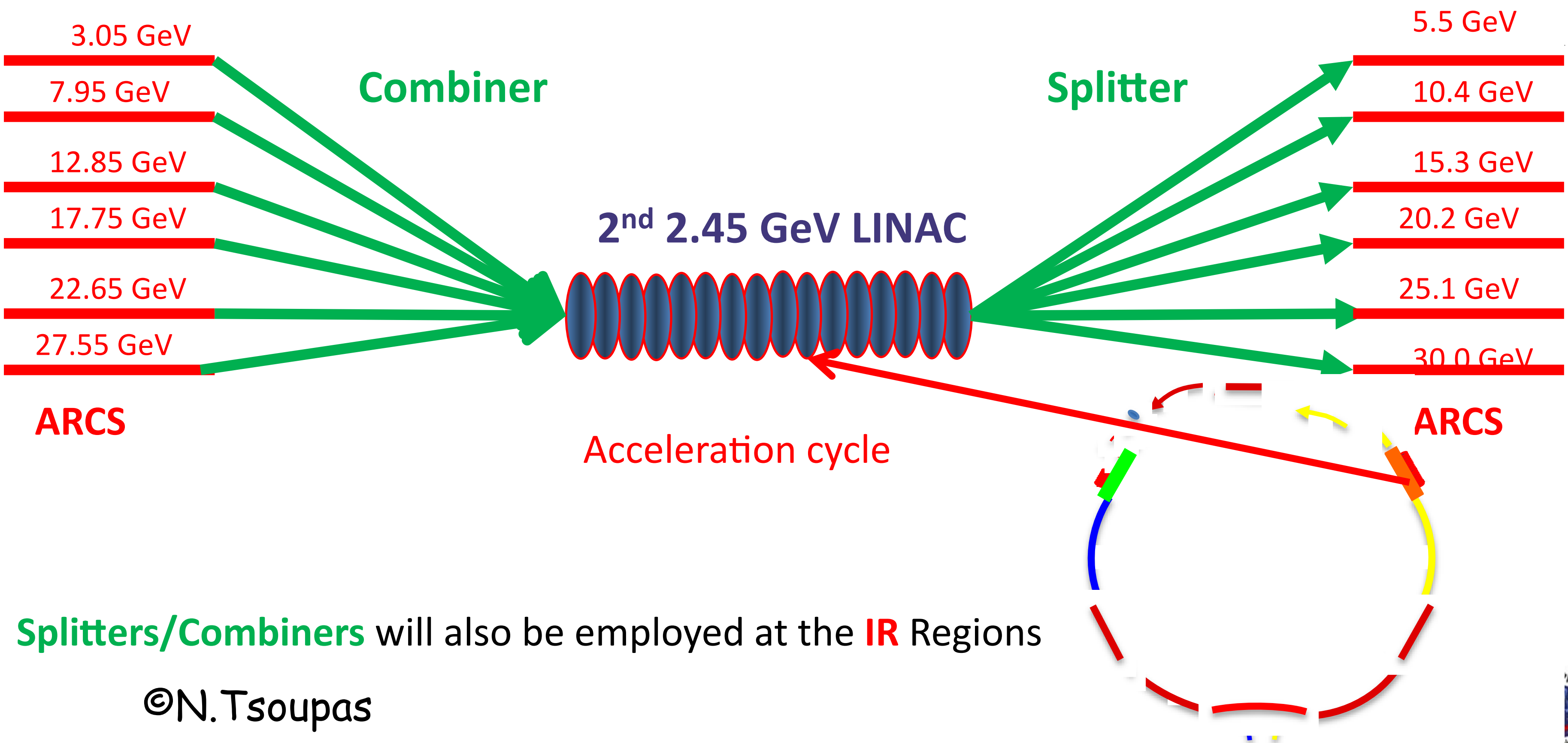




Schematic diagram of the Combiner/Splitter
2nd LINAC at 2 o' clock (Acceleration cycle)

It is the system of the beam lines which **Combines** the beams of the **ARCS** into the **LINAC** or **Splits** the beams exiting the **LINAC** into the **ARCS**



Splitters/Combiners will also be employed at the **IR** Regions

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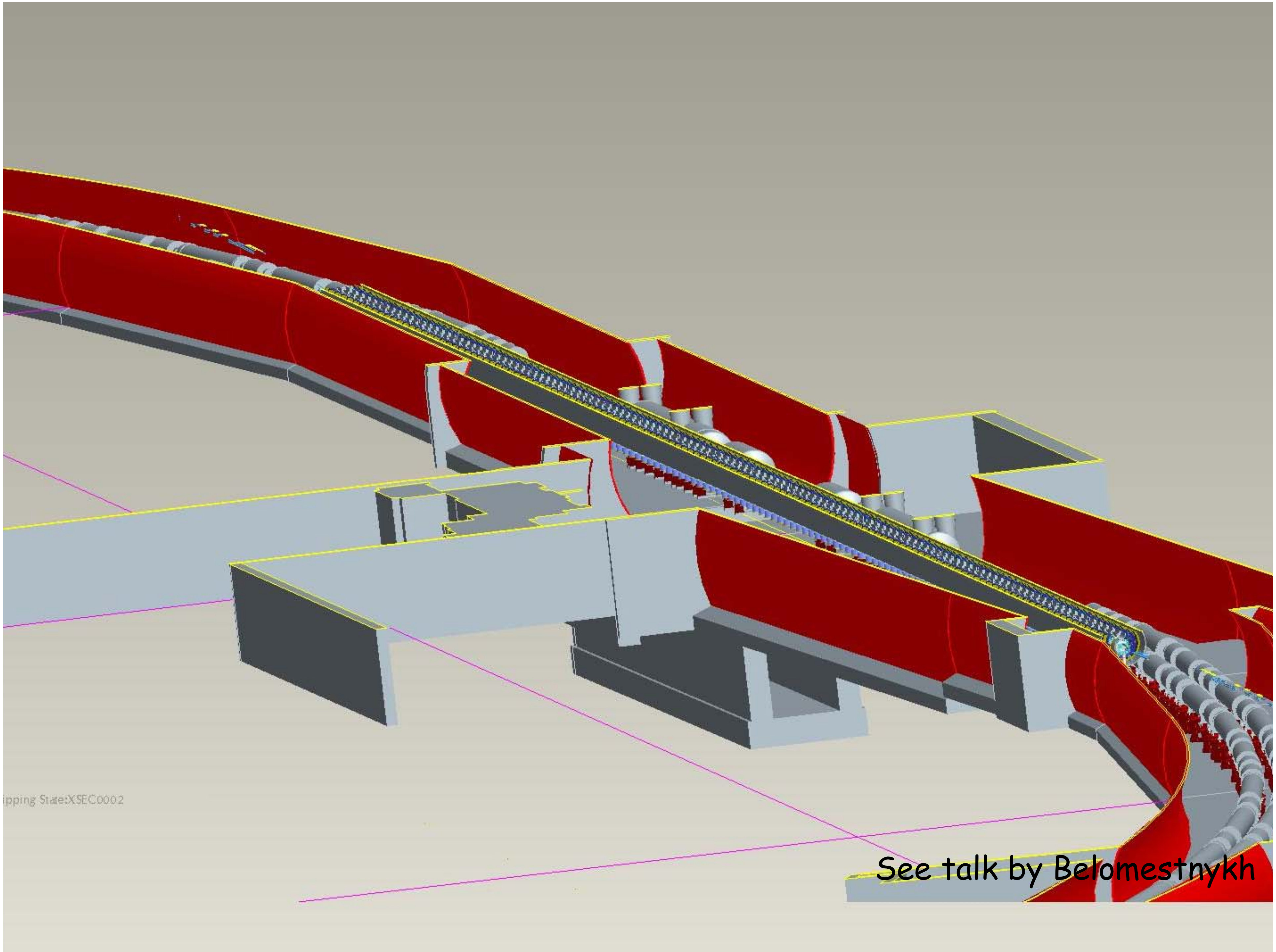


See talk by Belomestnykh

Beam dynamics studies (eRHIC)

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

The issues presently under investigation:

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

See talks by Kayran and Fedotov

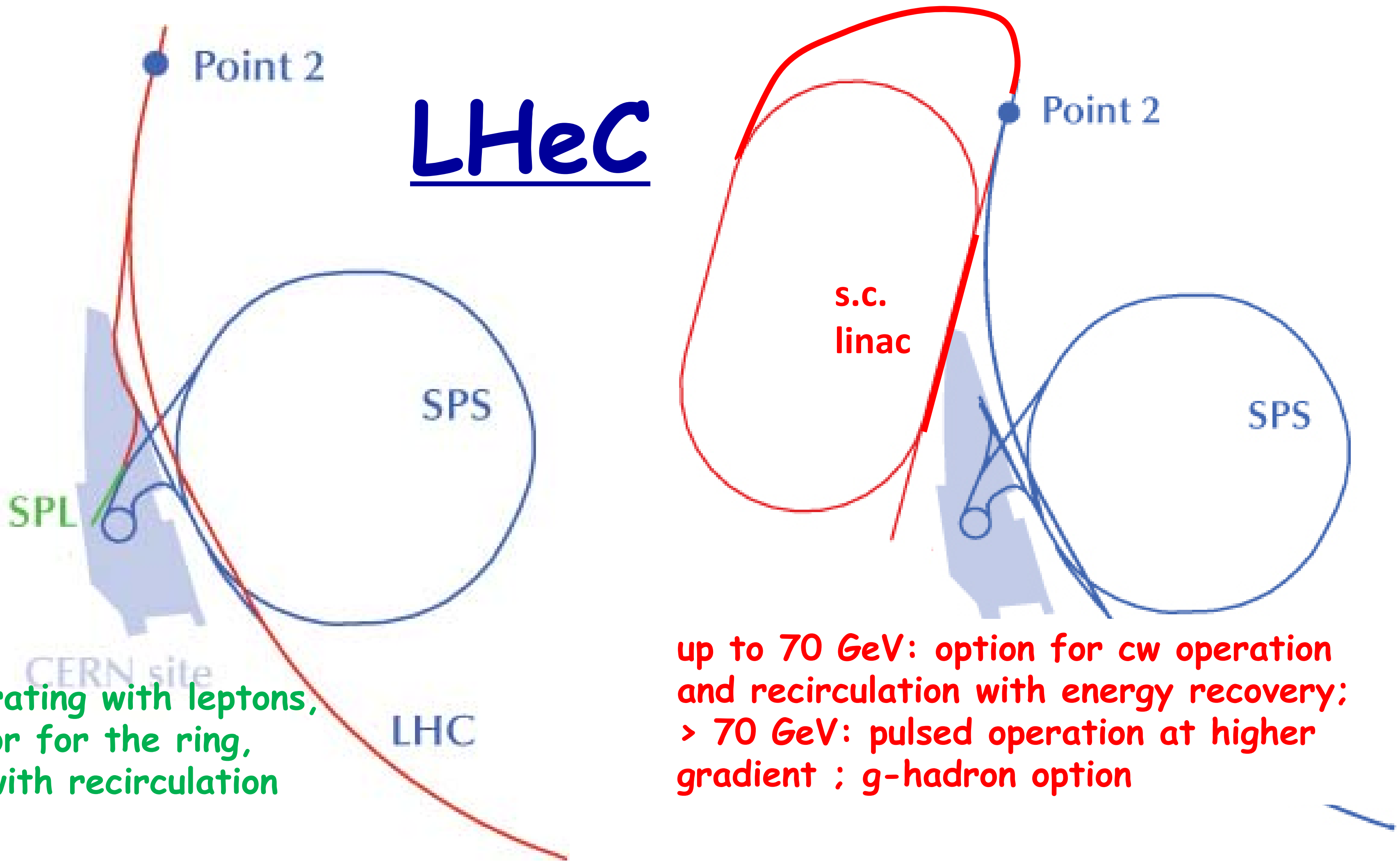
Main Accelerator Challenges

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 ^{3}He production
	Understanding of beam-beam affects New type of collider
	β*=5 cm 5x reduction
	Multi-pass SRF ERL 3-4x in # of passes
	Feedback for kink instability suppression Novel concept

Option 1: "ring-ring" (RR) e-/e+ ring in LHC tunnel

Option 2: "ring-linac" (RL)



SPL, operating with leptons, as injector for the ring, possibly with recirculation

up to 70 GeV: option for cw operation and recirculation with energy recovery; > 70 GeV: pulsed operation at higher gradient ; g-hadron option

© F. Zimmermann

Luminosity constraints

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LHC 7-TeV *p* beam parameters

	$N_{b,p}$	T_{sep}	$\varepsilon_p \gamma_p$	$\beta^*_{p,min}$
LHC phase-I upgrade	**1.7x10^{11}**	**25 ns**	**3.75 μm**	**0.25 m**
LHC phase-II upgrade ("LPA")	**5x10^{11}**	**50 ns**	**3.75 μm**	**0.10 m**

p and *e* beams matched at collision point

Ring emittance >> Linac emittance

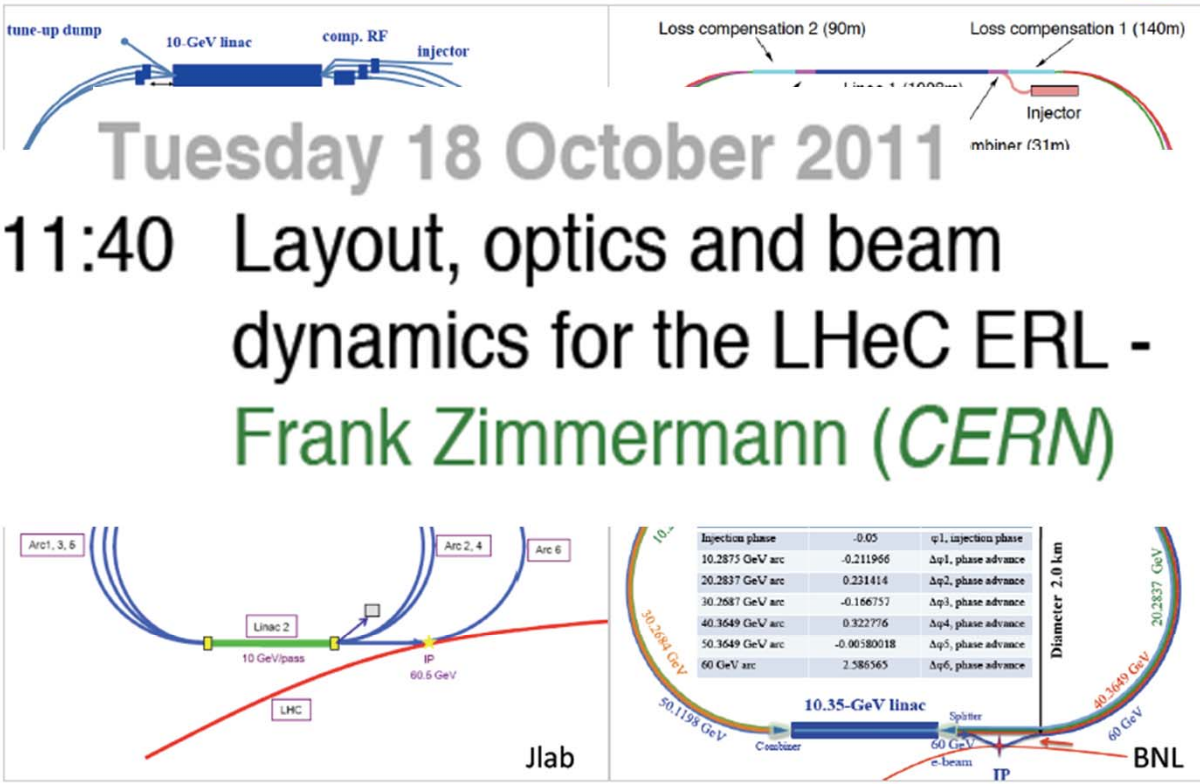
Ring has larger IP beam divergence + hourglass effect
→ larger β^* for ring

Ring SR power = Linac beam power & cryo power
= electrical power set to 100 MW
linac has much lower current

LHeC – TeV scale eH collider

ERL
for
LHeC

60 GeV Energy Recovery Linac



Two 10 GeV energy recovery Linacs, 3 returns, 720 MHz cavities

Tuesday 18 October 2011

11:40 Layout, optics and beam dynamics for the LHeC ERL - Frank Zimmermann (*CERN*)

Table 1: Parameters of the RR and RL Configurations

	Ring	Linac
electron beam		
beam energy E_e	60 GeV	
e^- (e^+) per bunch N_e [10^9]	20 (20)	1 (0.1)
e^- (e^+) polarisation [%]	40 (40)	90 (0)
bunch length [mm]	10	0.6
tr. emittance at IP $\gamma\epsilon^e_{x,y}$ [mm]	0.58, 0.29	0.05
IP β function $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12
beam current [mA]	131	6.6
energy recovery intensity gain	–	17
total wall plug power	100 MW	
syn rad power [kW]	51	49
critical energy [keV]	163	718
proton beam		
beam energy E_p	7 TeV	
protons per bunch N_p	$1.7 \cdot 10^{11}$	
transverse emittance $\gamma\epsilon^p_{x,y}$	3.75 μm	
collider		
Lum e^-p (e^+p) [10^{32}cm^{-2}s^{-1}]	9 (9)	10 (1)
bunch spacing	25 ns	
rms beam spot size $\sigma_{x,y}$ [μm]	30, 16	7
crossing angle θ [mrad]	1	0
$L_{eN} = A\ L_{eA}$ [10^{32}cm^{-2}s^{-1}]	0.3	1

Both the ring and the linac are feasible and both come very close to the desired performance. The pleasant challenge is to soon decide for one.

CERN-ECFA-NuPECC:
CDR Draft (530pages) being refereed
Publish early 2012

Steps towards TDR (tentative)
-Prototype IR magnet (3 beams)
-Prototype Dipole (1:1)
-Develop Cavity/Cryomodule
-Civil Engineering, …

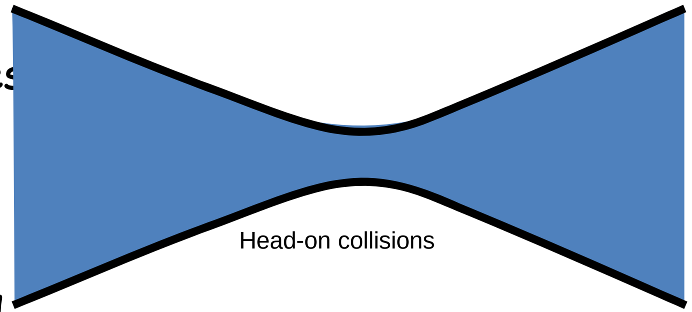
Build international collaborations
for the accelerator and detector development. Strong links to ongoing accelerator and detector projects.

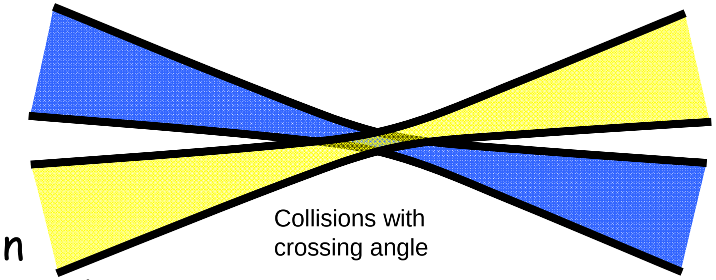
The LHC offers the unique perspective for a further TeV scale collider. The LINAC's are of about 2mile length, yet the Q^2 is 10^5 times larger than was achieved when SLAC discovered quarks. Particle physics needs pp, ll and ep.
Here is a realistic prospect to progress.

What about hadron colliders?

Collisions with large crossing angle

- Head-on collisions:
  - Luminosity loss from hour-glass effect requires shorter bunch length for smaller beta-star
  - Reducing bunch length limited by peak current and instabilities
  - Difficult to reduce beta-star without reducing emittance and momentum spread





- Large crossing-angle collisions:
  - To be beneficial needs low emittance beams (strong cooling: synchrotron rad. or CeC)
  - Separate bunches outside high luminosity region to avoid beam-beam effect from low luminosity region.
  - Reducing beam emittance back to beam-beam limit
  - Smaller emittance and shorter overlap region allows for smaller beta-star
  - For N_b/k particles colliding:

$$\frac{L}{\gamma} = \frac{1}{4\pi} k \frac{N_b/k}{\varepsilon_n} \frac{N_b/k}{\tau_b} \frac{R}{\beta^*} = \frac{1}{4\pi} \frac{N_b}{k\varepsilon_n} \frac{N_b}{\tau_b} \frac{R\gamma\sigma'^2}{\varepsilon_n} = \frac{1}{4\pi} \frac{N_b}{\varepsilon_n^0} \frac{N_b}{\tau_b} \frac{R\gamma\sigma'^2}{\varepsilon_n^0/k} = k\frac{L^0}{\gamma}$$

  - RHIC: overlap length ~ 10 cm, ε_n (95%) ~ 1 π μm , β^* ~ 10 cm → luminosity ~ x10
  - Effect of long range beam-beam?

Hadron beams need cooling

- Why Coherent Electron Cooling?
  - Stochastic cooling with 10 GHz bandwidth (read ~ cm apertures!) can not cool hadron beams with with longitudinal density ~ 10^{11}/nsec and compete with IBS
  - Traditional electron cooling could not cool high energy proton beams at TeV scale (eRHIC, RHIC, LHC) – cooling rate falls as $E^{5/2}$
  - Coherent electron cooling (i.e. stochastic cooling at optical and X-ray frequencies) has a natural scaling to be effective at high energy and promises to cool TeV proton beams under an hour
- Why ERLs are relevant ?
  - Seems to be the only suitable driver

Coherent Electron Cooling (CeC)

At a half of plasma oscillation

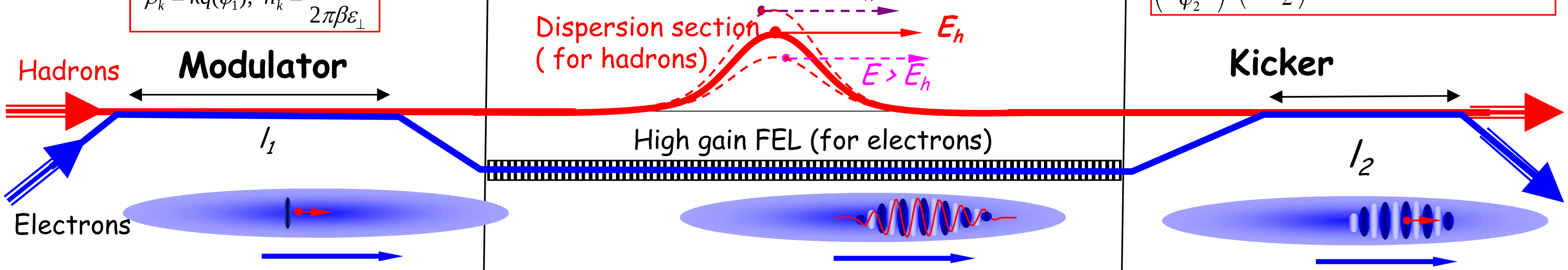
$$q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

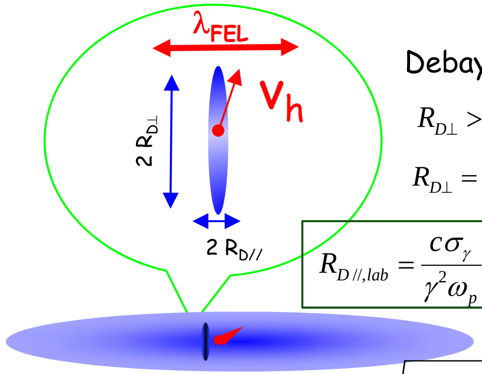
$$\rho_k = kq(\varphi_1);\ n_k = \frac{\rho_k}{2\pi\beta\varepsilon_\perp}$$

Dispersion

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

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





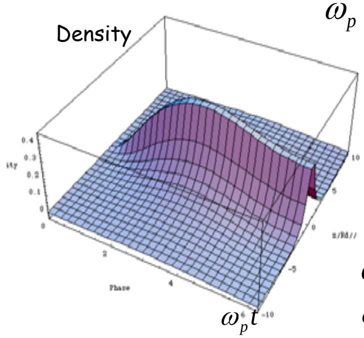
Debay radii

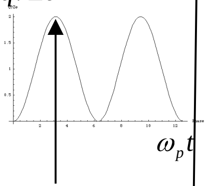
$$R_{D\perp} >> R_{D//}$$

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

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

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



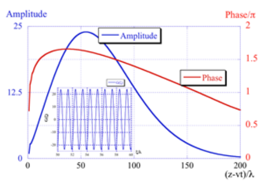


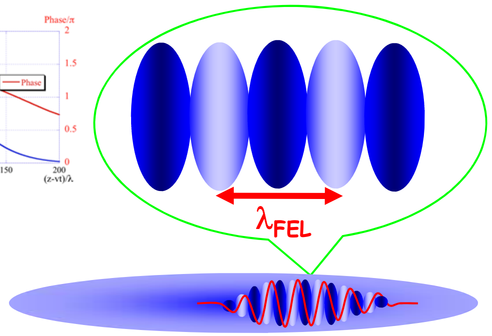
$$q = -Ze\cdot(1-\cos\varphi_1)$$

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

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

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





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

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

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

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

Coherent Electron Cooling

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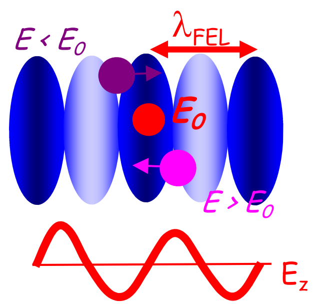
(Received 24 September 2008; published 16 March 2009)

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



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

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

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

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

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

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

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Gains from coherent e-cooling:

Coherent Electron Cooling vs. IBS

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

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

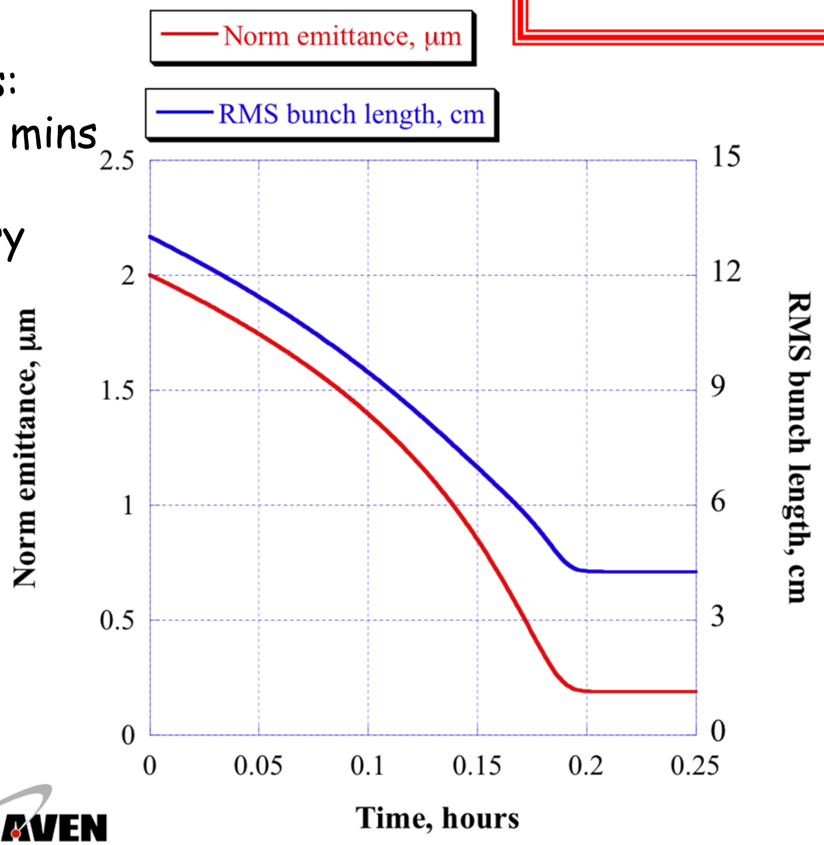
$$\frac{dS}{dt} = \frac{1}{\tau_{IBS//}} \frac{1}{X^{3/2} Y} - \frac{1-2\xi_\perp}{\tau_{CeC}} \frac{1}{X};$$

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

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

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 50 mA (10 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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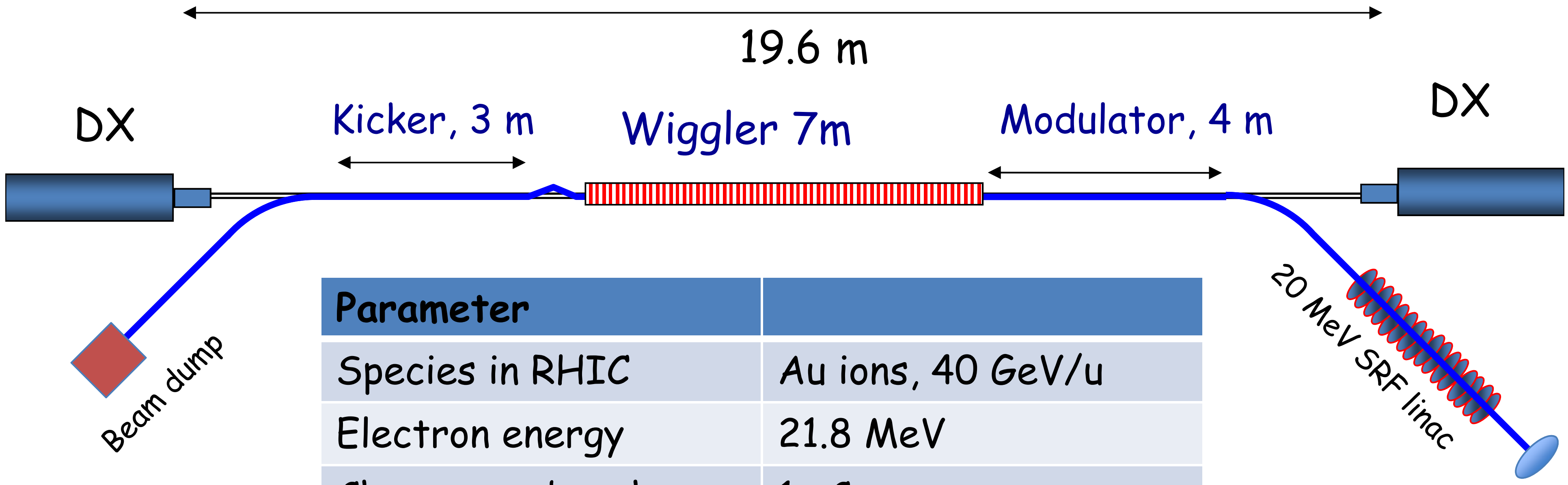
Layout for Coherent Electron Cooling proof-of-principle experiment in RHIC IR 2 Collaboration between BNL, Jlab and Tech X



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

Promise 1:
ERL can help boosting luminosity of HE hadron collider 10-fold!

What about NLC with TeV beams? or LHeC with 150 GeV e-beam?

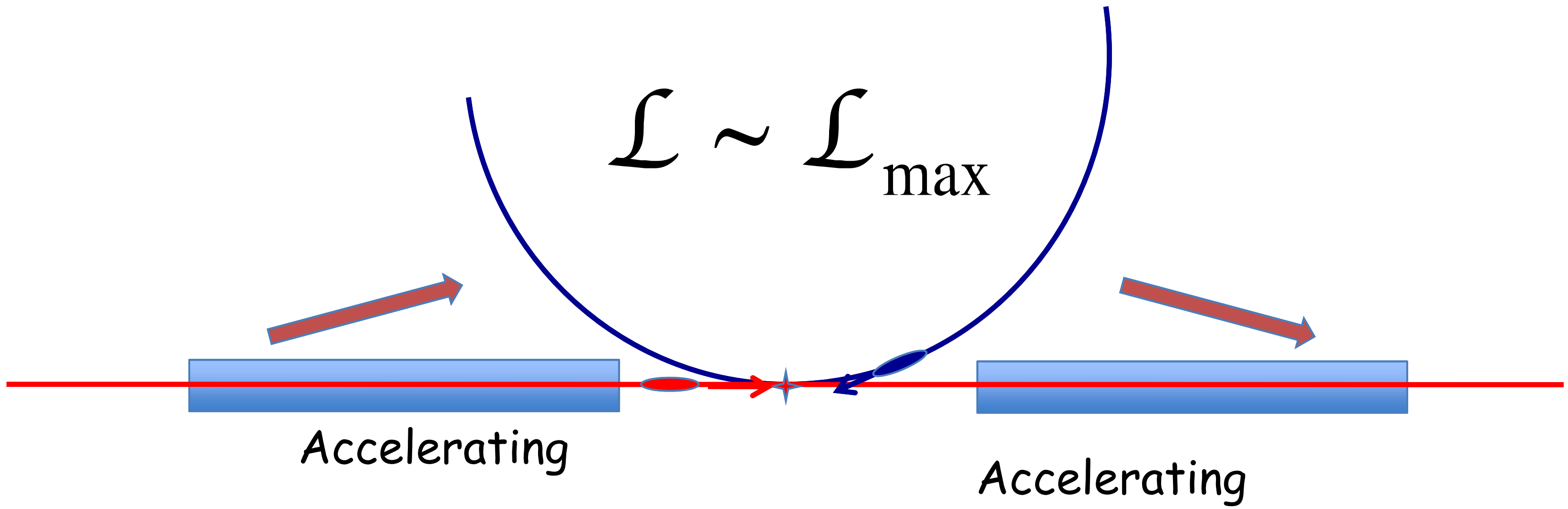
Can ERL work at such high energies where SR is the killer!

E_e^4 !!!

16-fold price of doubling the energy

10 MW for 10 mA at 30 GeV in eRHIC (3.8 km circumference)

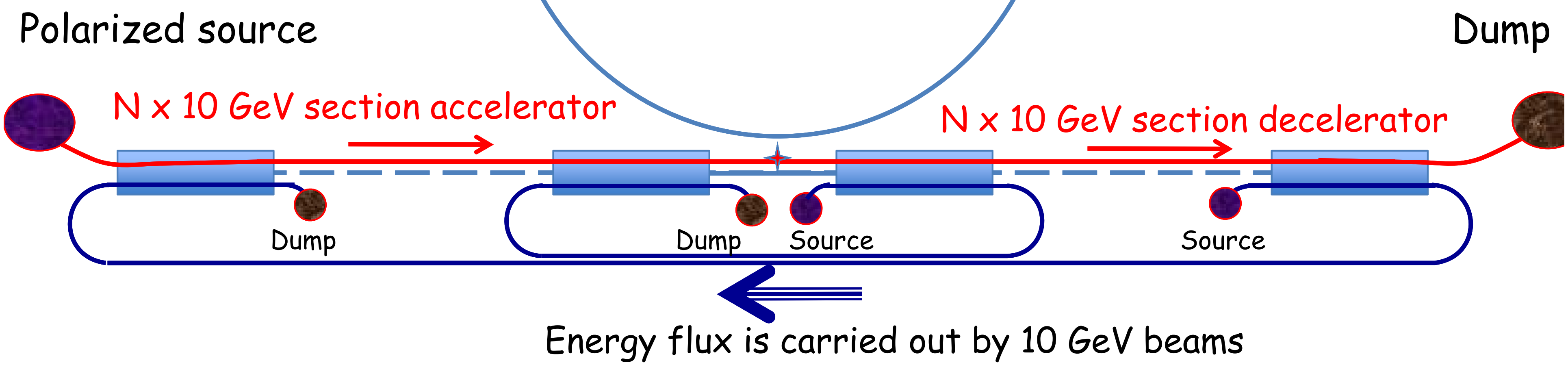
100% Energy recovery – needs 2 linacs
What to do with the energy?



e-beam current is ~ 1 A
Energy of e-beam is ~ 100 GeV
Energy to transfer ~ 100 GW
Best RF coupled do 1 MW ->

2 x 100,000 couplers, 100,000 high precision waveguides…. – simply out of this world

100% energy recovery LHeC II - E_e = 150... GeV N=15



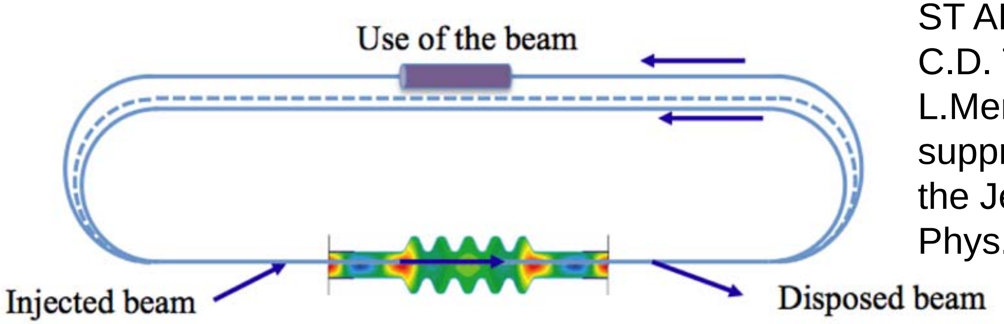
Synchrotron radiation a determined by energy of the returning beams. Losses grow linearly with the energy of the HE beam

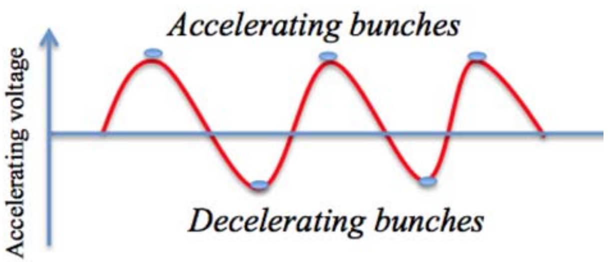
Should work both for LHeC II and NLC

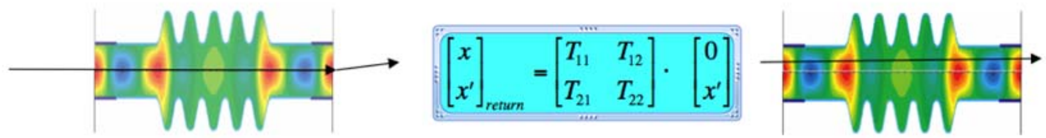
TBBU!
A killer of effective ERLs

It is believed that for a given Q*R/Q and spread of the HOM, the TBBU threshold is inverse proportional to number of ERL passes squared

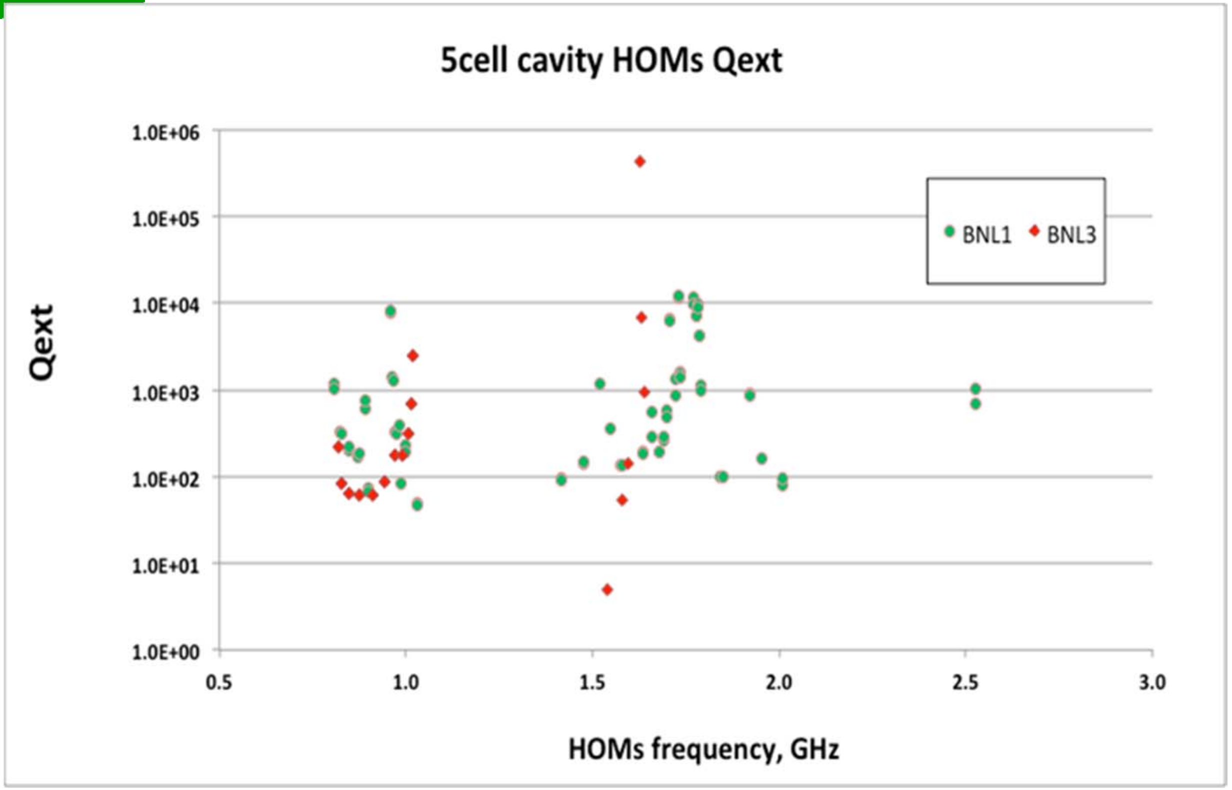
G.H. Hoffstaetter and I.V. Bazarov, “Beam-breakup instability theory for energy recovery linacs”, Phys. Rev. ST AB 7, 054401 (2004)
C.D. Tennant, K.B. Beard, D.R. Kouglas, K.C. Jordan, L.Merminga, E.G. Pozdeyev, “First observations and suppression of multipass, multibunch beam breakup in the Jefferson Laboratory free electron laser upgrade”, Phys. Rev. ST AB 8, 074403 (2005)







HOMs used for BBU



Comparison of BNL1 and BNL3 dipole HOM's

BNL1

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

BNL3

F (GHz)	R/Q (Ω)	Q	(R/Q)Q
1.01E+09	30.6	313.0	9562.7
1.01E+09	30.5	313.0	9551.2
1.63E+09	1.0	6730.0	7030.9
1.02E+09	7.7	693.0	5328.8
1.02E+09	7.6	693.0	5301.0
9.11E+08	67.2	61.1	4108.1
9.11E+08	67.1	61.1	4101.6
9.90E+08	22.7	176.0	3991.7

BBU simulation results

For simulation:

- 28 dipole HOMs are used for BNL3 and 70 HOMs for BNL1
- HOM Frequency spread 0-0.01
- Two different set of phase advances per each arc.

Challenges
Exist both for eRHIC
and LHeC ERLs
See talks
By Kayran and
Zimmerman

N

Chromatic ERL Arcs

- ✓ The driver of the TBBU is the displacement of the beam in a RF cavity caused by a kick in another cavity, i.e. $T_{12}(s_1/s_2)$.
- ✓ Strong focusing ERL arcs (such as eRHIC) have very large natural chromaticity ~ 100
- ✓ It means that in combination with reasonable energy spread, there is exponential suppression of whole beam response

$$f(\delta)=\frac{1}{\sqrt{2\pi}\sigma_\delta}\exp\left(-\frac{\delta^2}{2\sigma_\delta^2}\right) \qquad \phi=2\pi C$$

$$\langle T_{12}\rangle=\frac{\langle x(s)\rangle}{x'}=\exp\left(-\frac{(\phi\sigma_\delta)^2}{2}\right)\cdot \mathrm{w}_{io}\mathrm{w}_o\left(\cos(\psi_o-\pi/2)-\frac{\upsilon\phi\sigma_\delta^2}{\mathrm{w}_o}\sin(\psi_o-\pi/2)\right)$$

V.N. Litvinenko, Chromaticity and beam stability in energy recovery linacs, in press

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Do not use sextupoles in ERL and enjoy extra stability and multi-pass economy

$$\left\langle T_{12} \right\rangle \propto \exp\left(-\frac{(\phi\sigma_{\delta})^2}{2} \right) \cdot T_{12}(\max)$$

$$I_{th}(chromatic) \propto \exp\left(\frac{(\phi\sigma_{\delta})^2}{2} \right) \cdot I_{th}(achromatic)$$

Assuming a strong focusing lattice for return loops, similar to that designed for eRHIC electron-hadron colliders the loop's chromaticity can be $C(s) \sim {}''300$ and $''(s) \sim 2\#10^3$. Then for a beam with RMS energy spread of 0.2% the response $\left\langle T_{12} \right\rangle$ will be suppressed 3,000 fold, and according to formula (2) the threshold for TBBU instability will increase about 3,000 fold.

Conclusions

- Energy recovery linacs would play major role in future High Energy and Nuclear Physics facilities
  - They could be used as electron beam accelerator of choice in high-energy high-luminosity electron-hadron colliders (eRHIC, LHeC)
  - They could be used as drivers for Coherent Electron Cooling of hadron beams boosting luminosity 10- to 50–fold in high energy hadron and electron-hadron colliders (RHIC, LHC, eRHIC, LHeC)
  - ERL can be an excellent candidate for high luminosity ILC
  - ERL is considered as potential candidate as injector into conventional electron cooler for ELIC
  - ERLs can be also excellent choice to drive intense gamma-ray sources for Nuclear Physics and RIA-type facilities – both as e-beam drive and provider of photons
- ERL progress is modest, but the potential is exceptional
- New ideas on how to extend ERL energy into 0.1-1 TeV range emerging

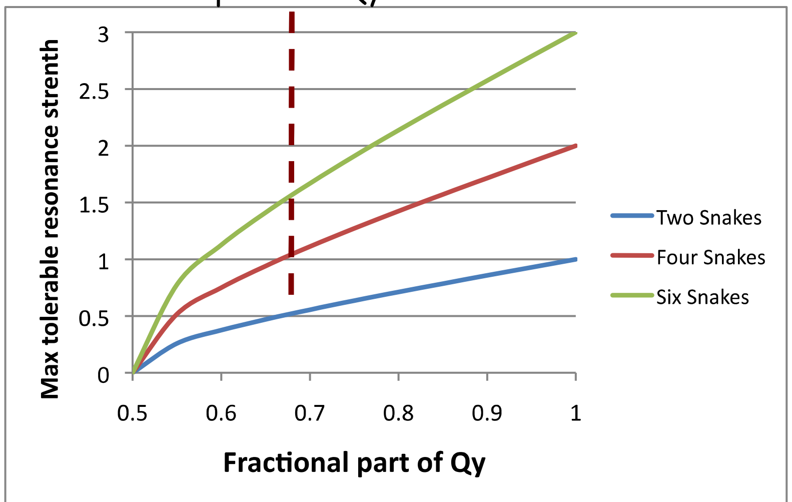
R&D ERL test facility

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

© V.Ptitsyn

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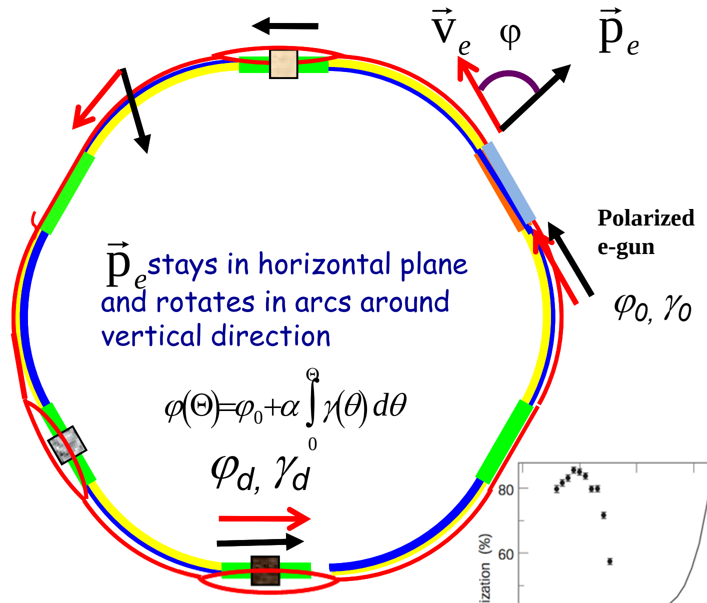
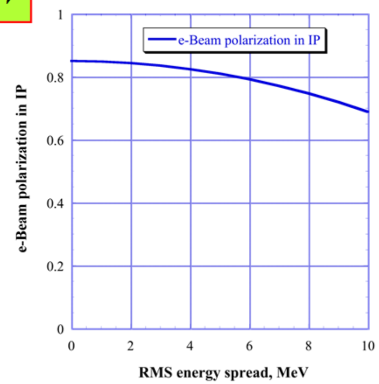
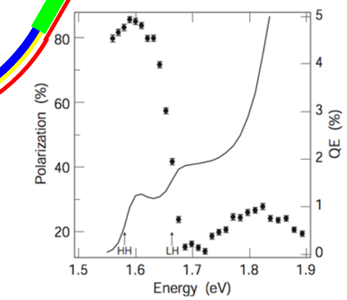
Electron polarization in eRHIC

- 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: $E_e = N \cdot 0.07216\,GeV$
- 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)

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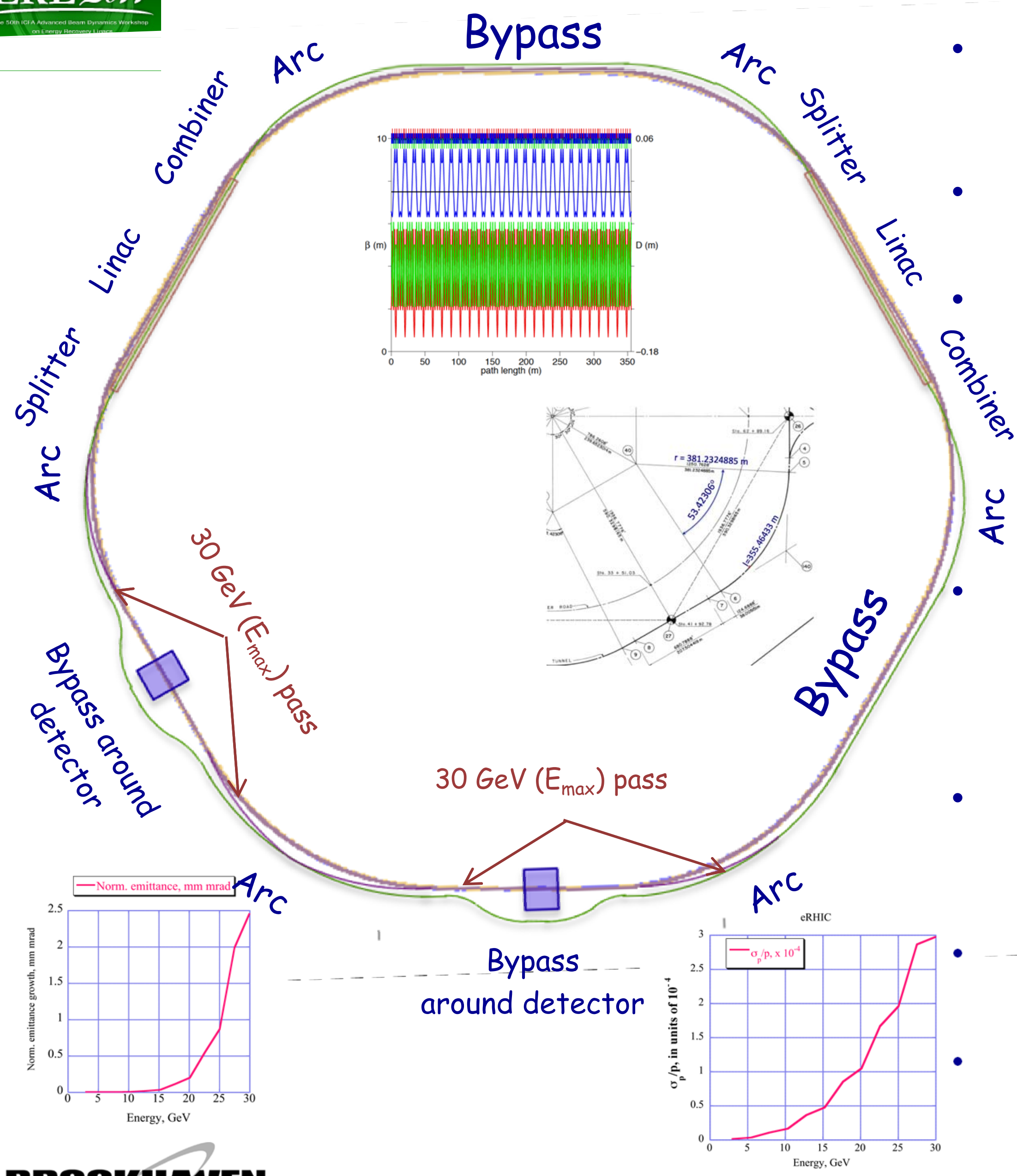
ERL Lattice with two detectors



- 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

D. Trbojevic

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- Random page
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Contents [hide]

Welcome to eRHIC Accelerator Design Wiki

http://www.cadops.bnl.gov/eRHIC/erhicWiki/index.php/Main_Page

Design Documents

- eRHIC White Paper.

Design items:

Overview

- Physics requirements
- Accelerator concept and staging
- Main beam parameters and luminosities

Electron Accelerator

- Design concept overview
- Time Structure
  - Frequency matching
  - Bunch pattern
- Injector System
  - Polarized electron source
  - 10 MeV Injector
  - 600 MeV pre-accelerator
- Lattice
  - Arcs
  - Splitters/mergers
  - Detector bypasses
  - Straight sections
  - Main linacs
  - Path lengthening
- SRF
  - Main linacs
  - Energy loss compensator
  - Energy spread compensator
  - Crab-cavities
- Beam Dynamics
  - Energy loss and energy spread
    - Synchrotron radiation
    - Resistive wall
    - Cavity wakes
    - Pipe roughness
    - Total energy loss budget and compensation
    - Energy spread compensation
  - Transverse emittance
  - Electron beam disruption by beam-beam interactions
  - Ion trapping
  - Beam Breakup
    - Multipass beam breakup
    - Single pass beam breakup
  - Beam lifetime
- Beam polarization and polarimetry
- Beam loss and machine protection

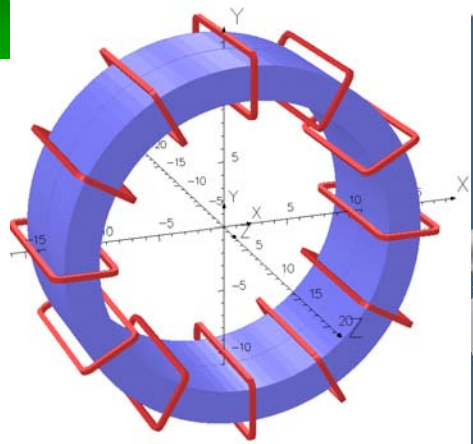
Ion Beam

- Beam parameters
- Coherent Electron Cooling
- Beam Dynamics
  - Coherent instabilities and their control
  - Beam-beam effects
    - Kink instability
    - Effect of electron beam parameter fluctuations
    - Interplay with space-charge and choice of the working point
- Beam polarization and polarimetry

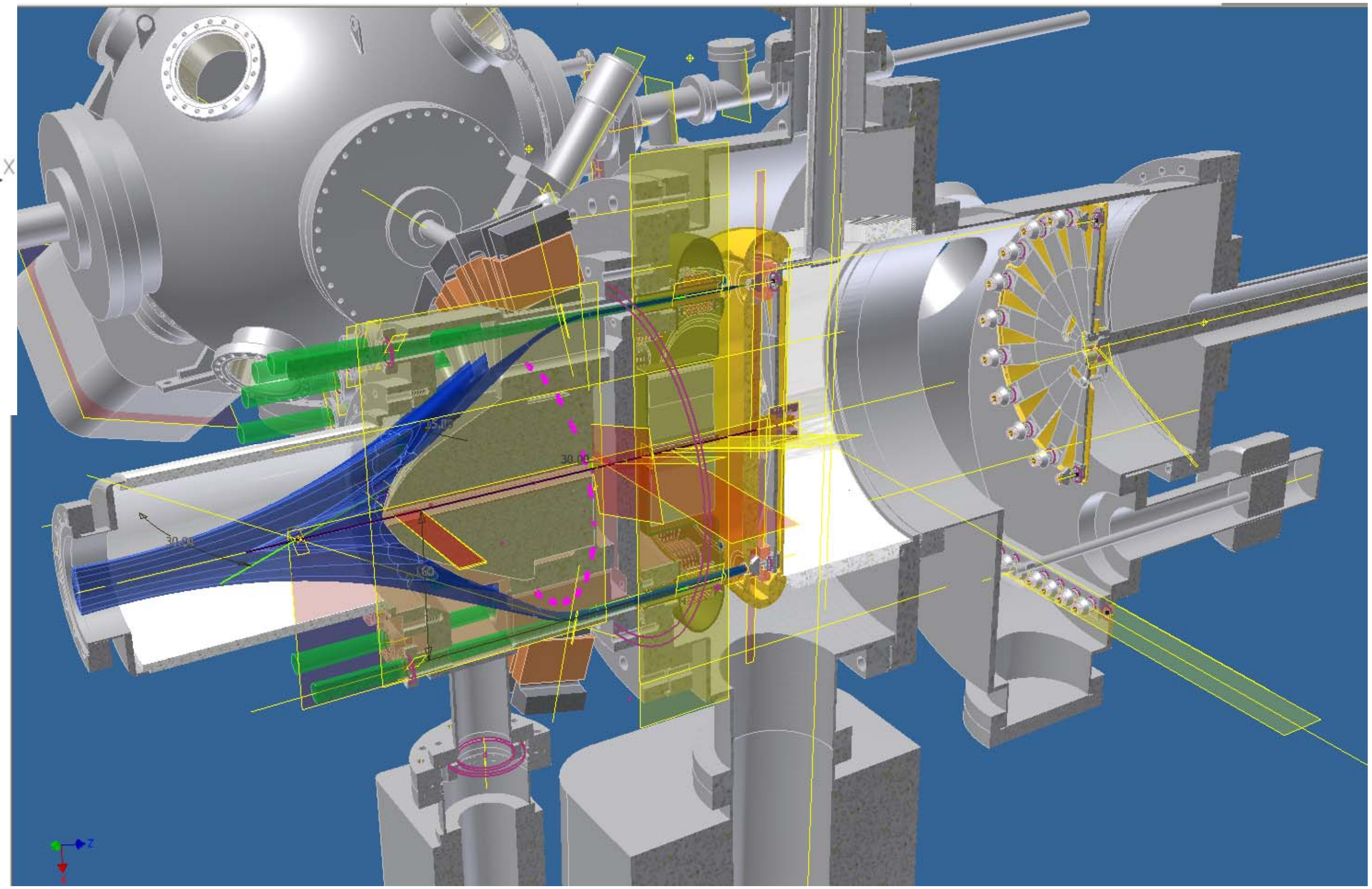
Interaction Region

- Overview
- Proton lattice and magnets
- Electron Beamline
- Synchrotron radiation protection and detector background issues
- Crab-Crossing
- Proton spin rotators

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

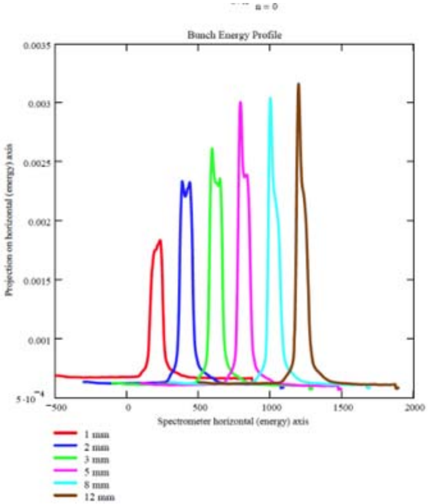


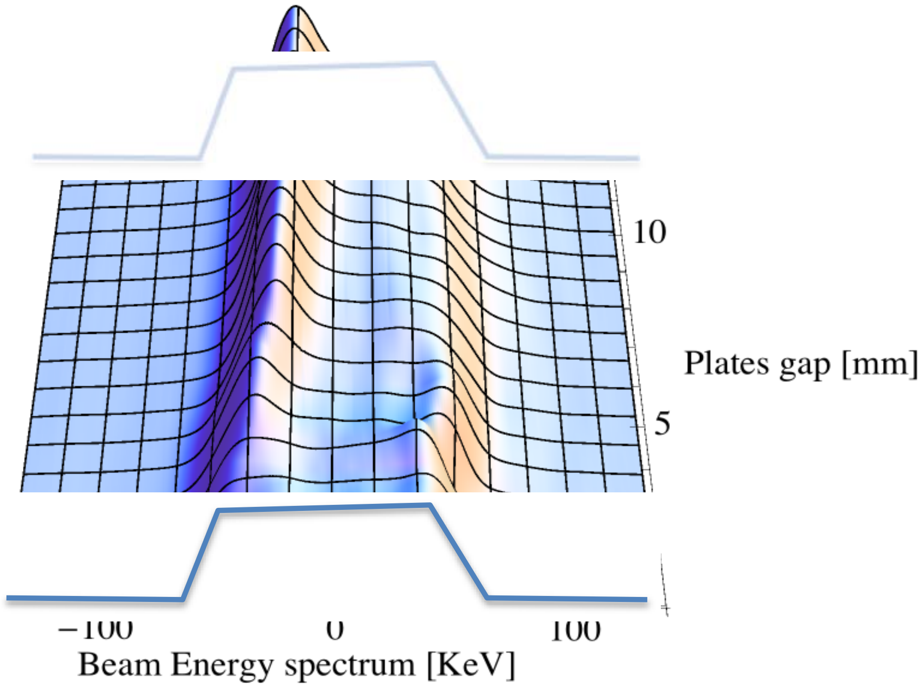
Sectioned view of the gun: Green –indicate Laser, Blue- indicate electron beam paths. Near center is the cathode shroud and anode, and to the right is the cathode magazine. The cathode preparation chamber can be seen on upper left.

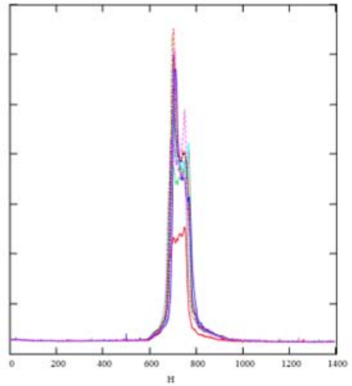


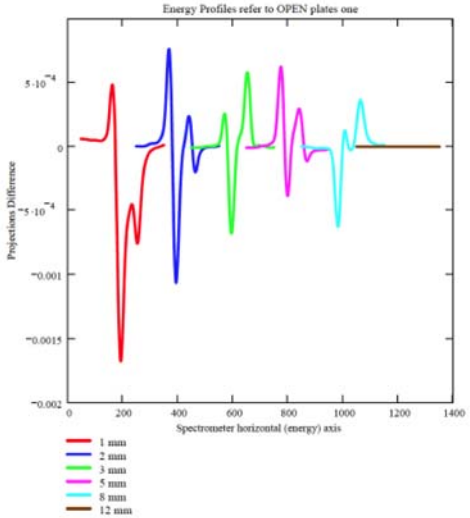
Current 2-D simulation results are very close to our goals. Detailed mechanical design has been done. Most components have been ordered. 3D tracking is in progress. Post doc with cathode preparation expertise will arrive in one month. A Stony Brook Ph.D. student got started on the project.

Summary of experimental results



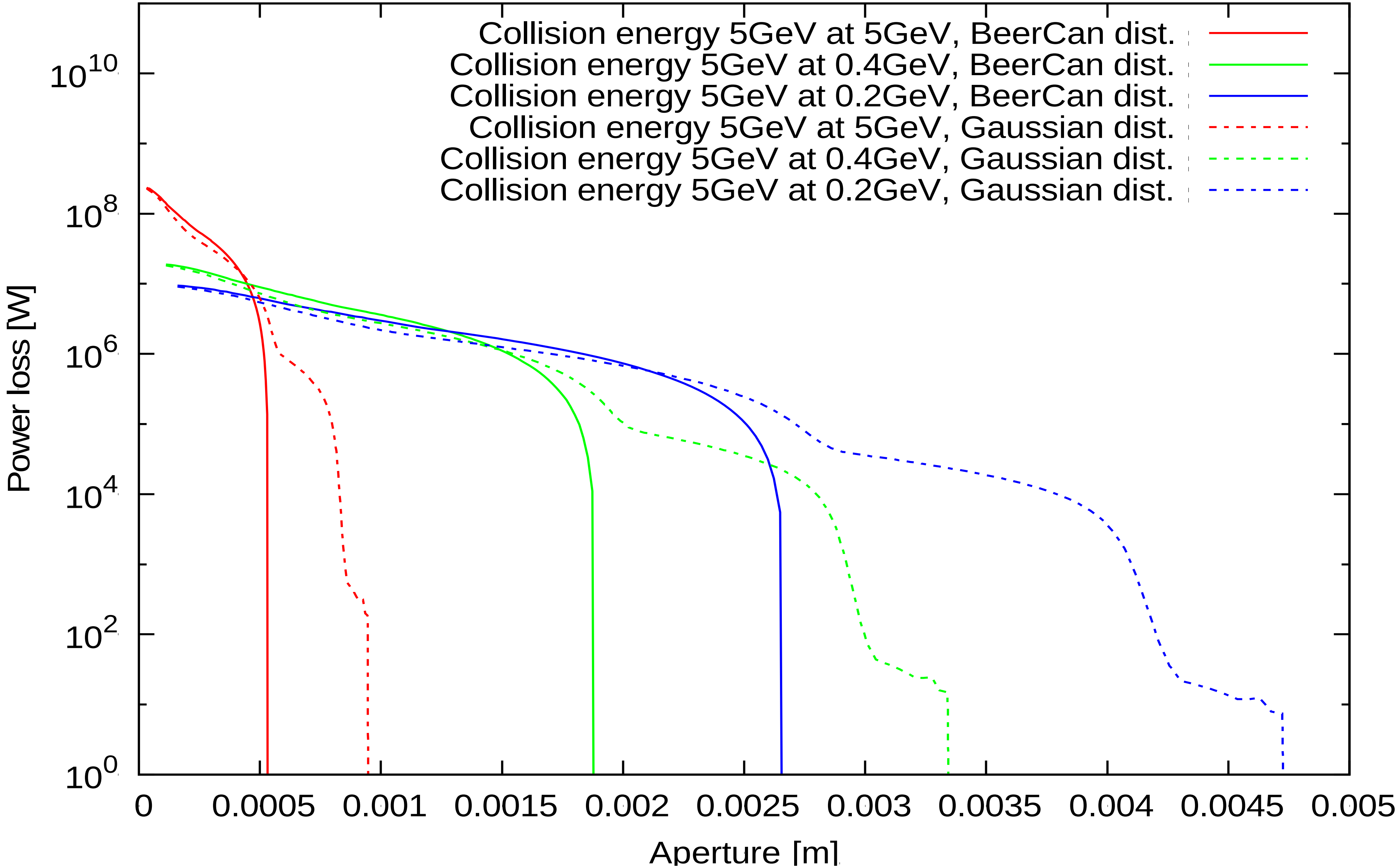






With closed gap the distribution is close to that from the HE slit – opening gap increases the distortions

Beam disruption and Aperture



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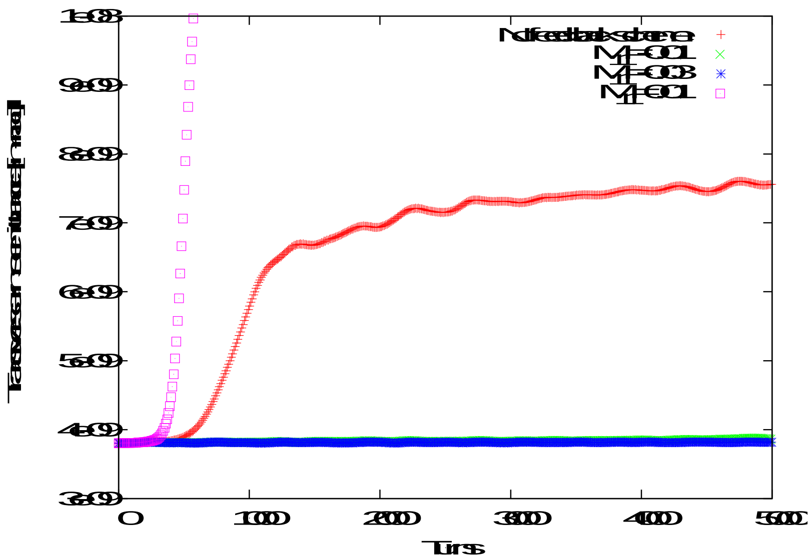
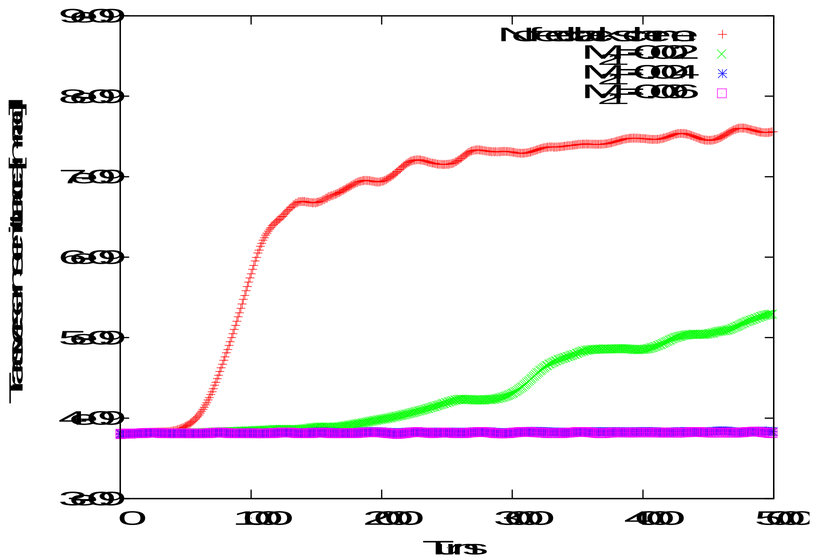
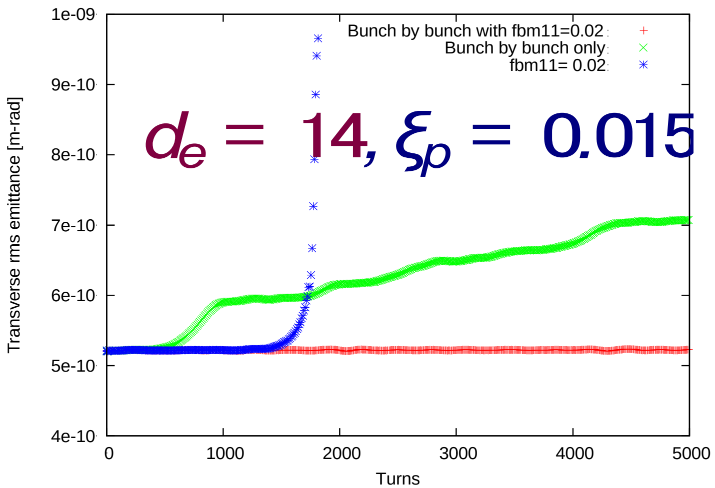
The Feedback Scheme

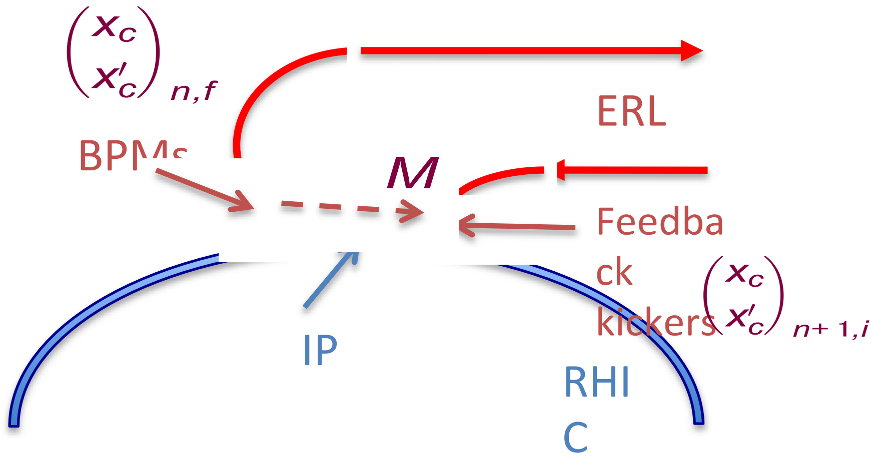
Beam-Beam Parameters: $d_e = 5.7,\ \xi_p = 0.015$







$d_e = 14,\ \xi_p = 0.015$



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

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

eRHIC Beam Loss Due To Beam-Gas Scattering

(Bremsstrahlung & Elastic Scattering)

Cross Section For Elastic Scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{Z_i^2}{4} r_e^2 \left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4\left(\frac{\theta}{2}\right)}$$

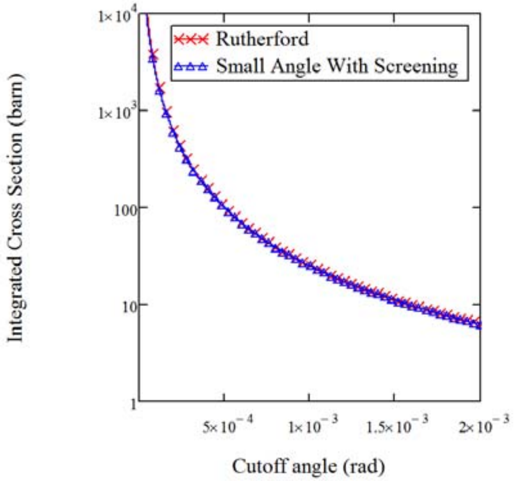
$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} \left[1-\beta^2 \sin^2\left(\frac{\theta}{2}\right)\right]$$

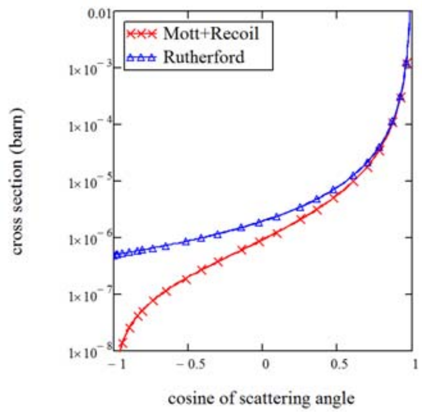
$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott+Recoil} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{1+\sin^2(\theta/2)\frac{m_e \gamma \beta^2}{M_{nuclei}}}$$

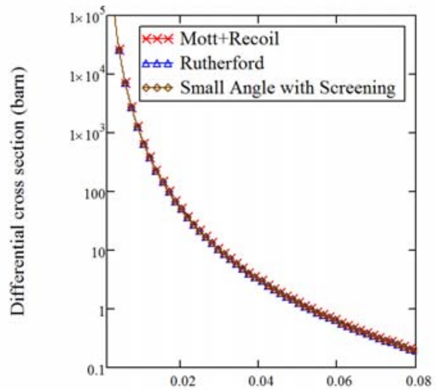
$$\left(\frac{d\sigma}{d\Omega}\right)_{\theta<<1+screening} = 4Z_i^2 r_e^2 \left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\left(\theta^2+\theta_{\min}^2\right)^2}$$

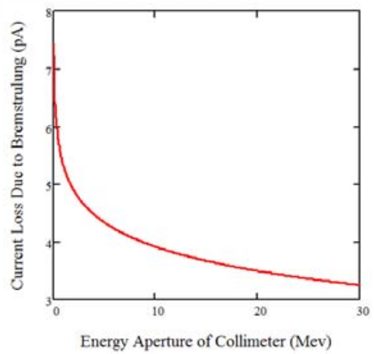
$$\theta_{\min} = \frac{\hbar}{pa} \approx \frac{Z^{1/3}}{192}\frac{m_e c}{p} \approx \frac{2.6\times 10^{-6}}{p(Gev)}$$

$$\theta_{\max} = \frac{\hbar}{pR} \approx \frac{Z^{1/3}}{192}\frac{m_e c}{p} \approx \frac{0.138}{p(Gev)}$$



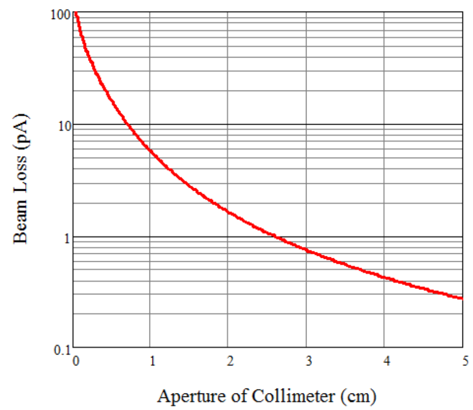






Depending on transverse aperture, beam loss due to elastic collision varies from 0.27 to 5.68pA (5mm - 1cm) under the present model.

Depending on energy deviation aperture, beam loss due to bremsstrahlung varies from 3.92 to 5.32pA (10Mev/1Mev).



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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

Limiting factors:

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

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

	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

ERL 2011

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

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

Limiting factors:

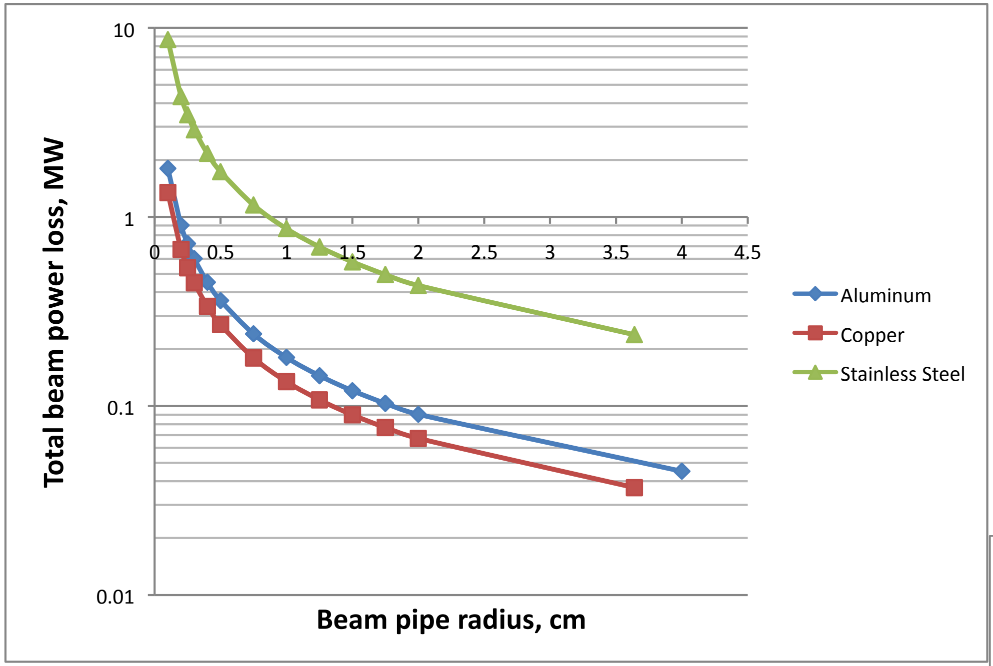
- hadron $\Delta Q_{sp} \leq 0.035$
- hadron $\xi \leq 0.015$

-SR power loss ≤ 8 MW

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics — Exploring Nuclear Matter - Quarks to Stars

Resistive wall wake-field



6 pass scheme
One turn: 3440 m
Bunch length: 2 mm
Bunch charge: 3.54 nC
Beam current: 50 mA

Reasonable choice : Al or Cu pipe,
5 mm radius (or half-gap)

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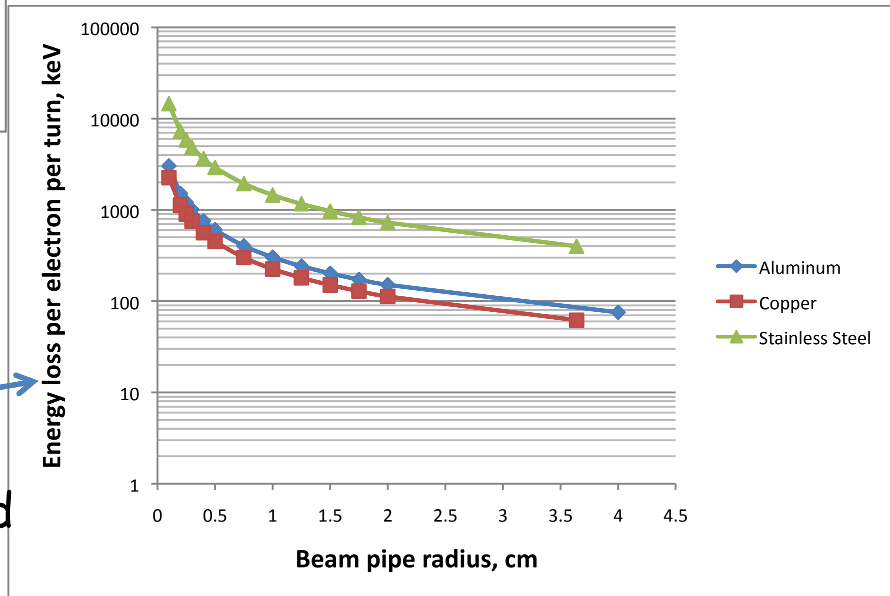
Characterizes also resulting energy spread



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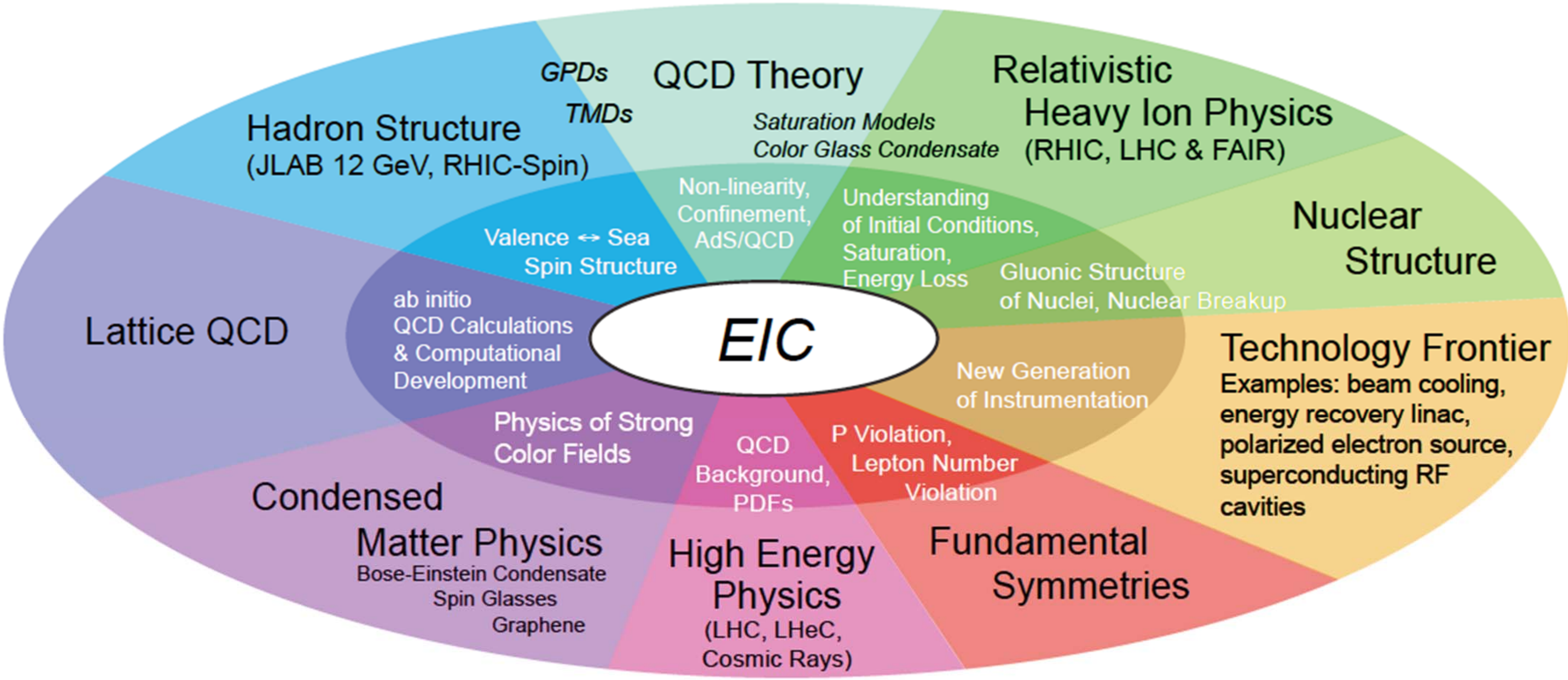
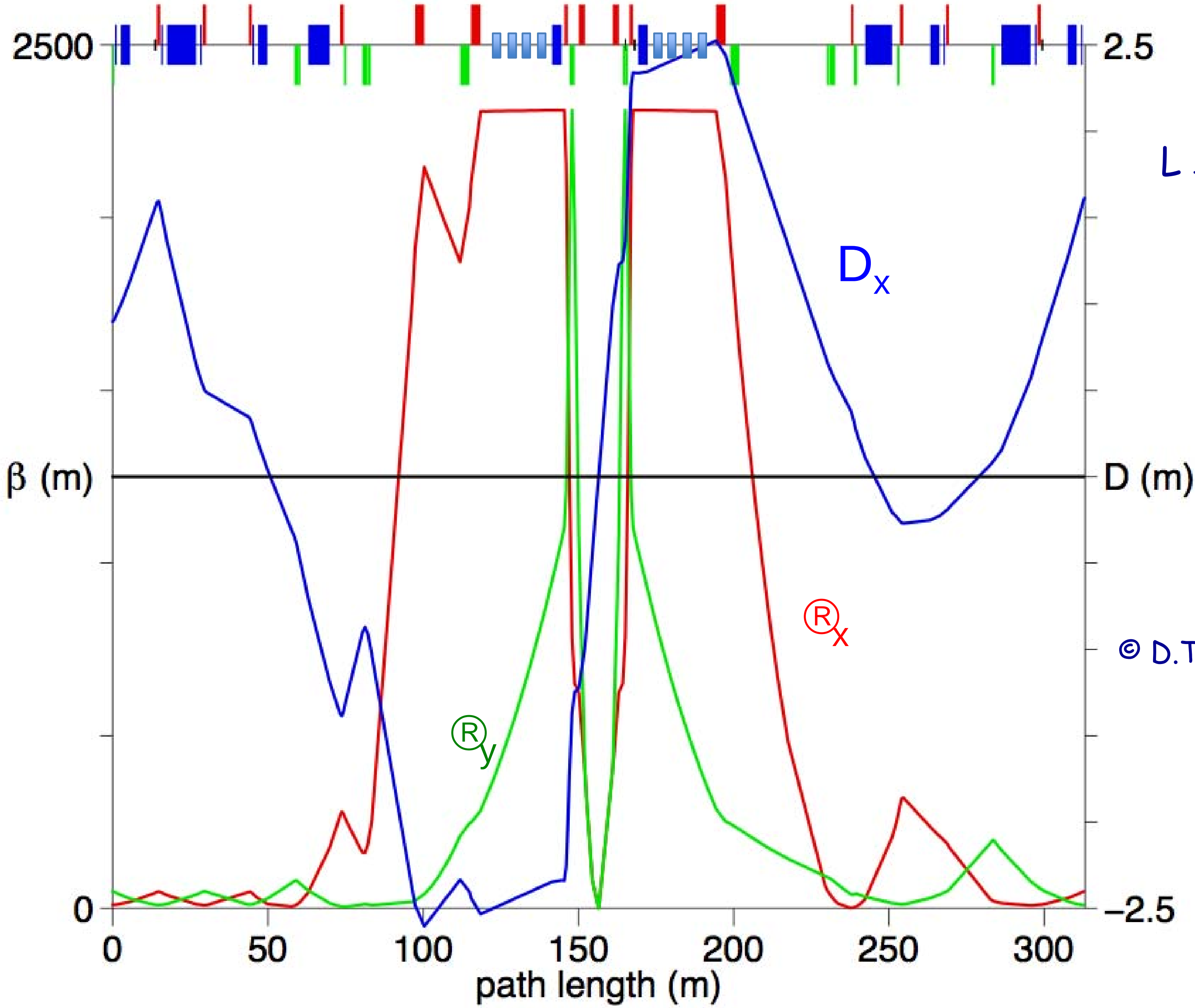
EIC Science Case

How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

The machine presents a unique opportunity for fundamental physics:



RHIC interaction region with β*= 5 cm & crab cavities



$L_{triplet}$=4.5 m

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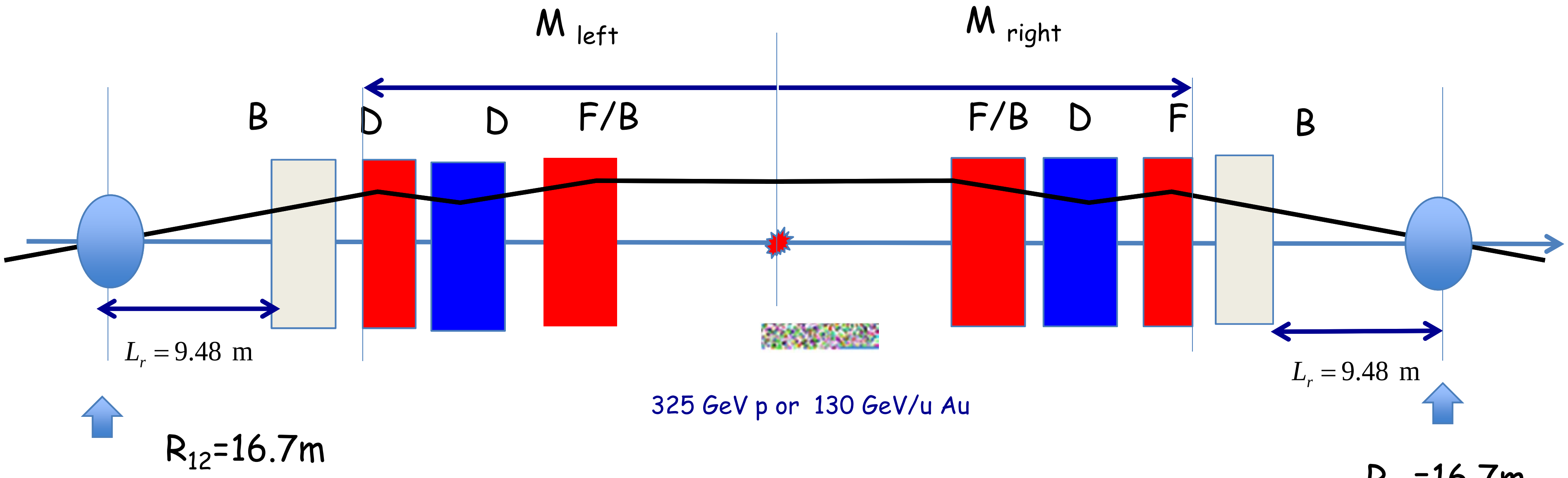
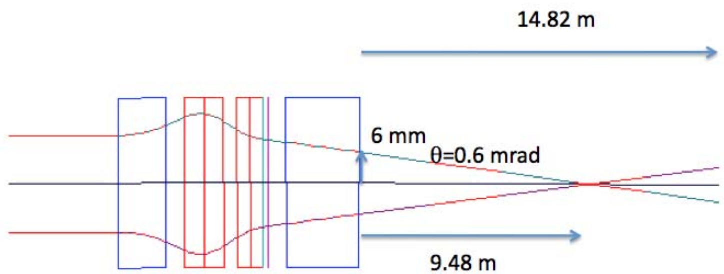
RHIC lattice

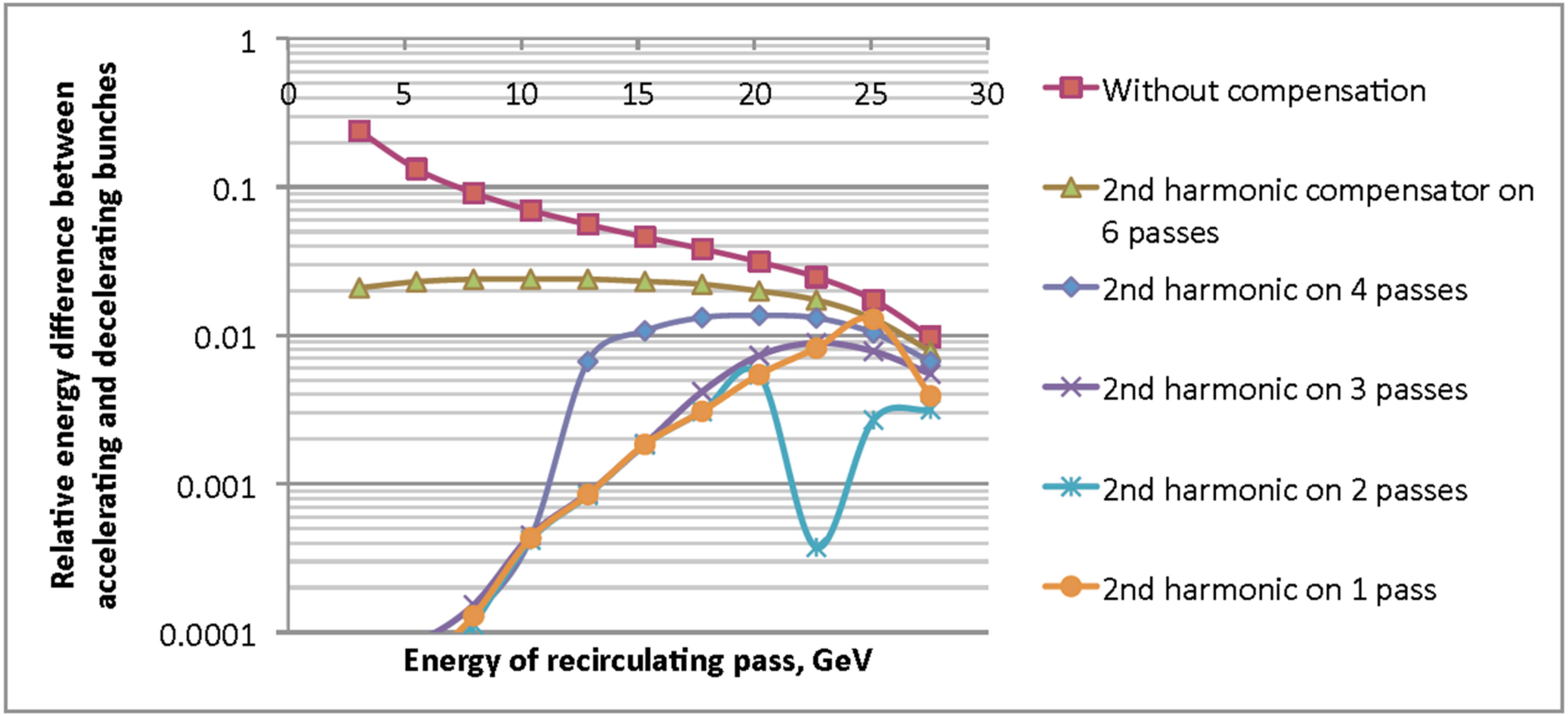
Fresh from the press by
Dejan Trbojevic



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



Loss budget for 6 pass scheme



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