# High-energy high-luminosity electron-hadron collider

# eRHIC design

Vladimir N. Litvinenko for eRHIC team
Brookhaven National Laboratory, Upton, NY, USA
Stony Brook University, Stony Brook, NY, USA
Center for Accelerator Science and Education

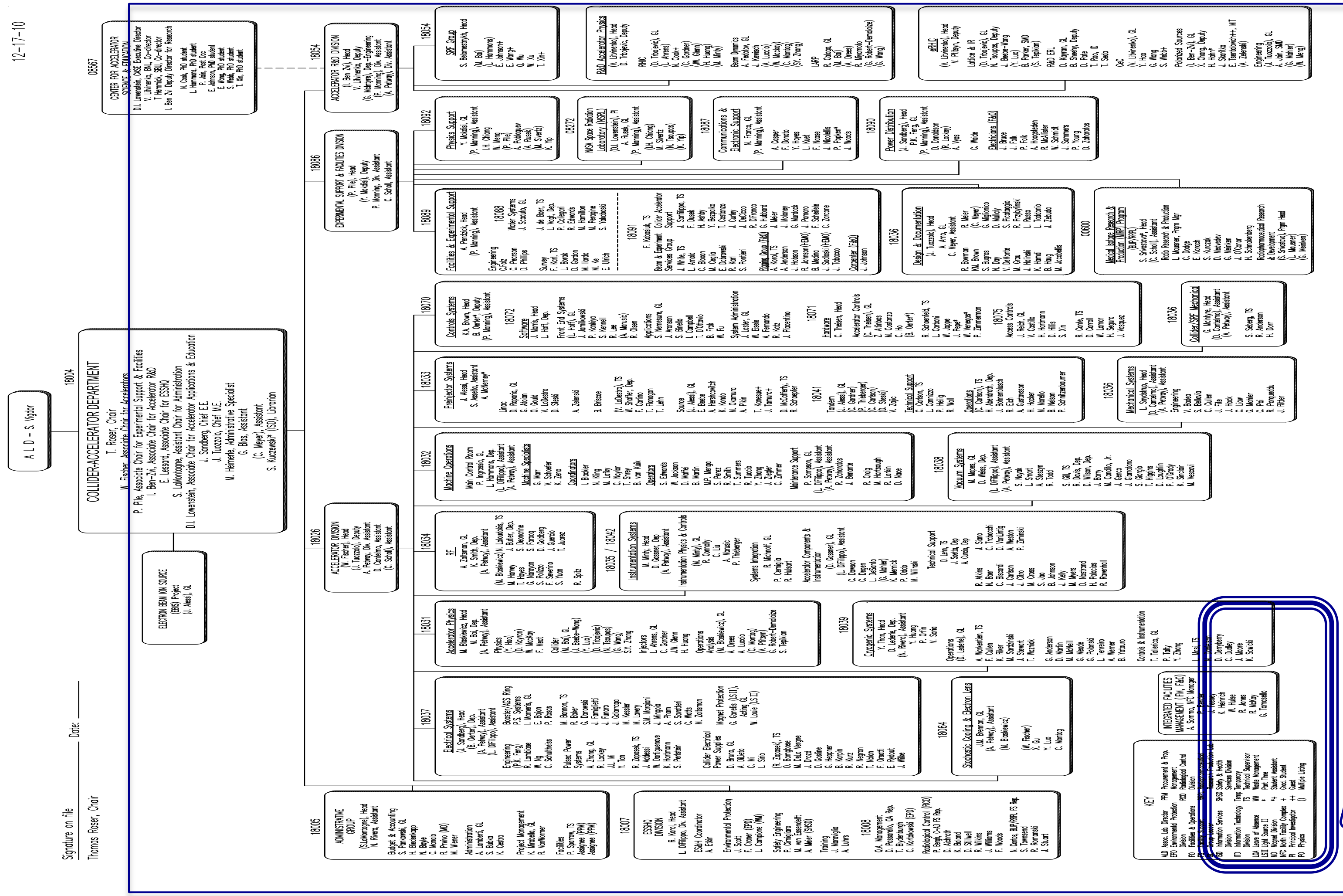
# Conclusions



- Our focus is on high-energy high-luminosity all-in-tunnel eRHIC
  - We took advantage of recent advances in super-conducting quadrupole technology to reduce designed $\beta^*$ to 5 cm and to boost eRHIC top luminosity above $10^{34}$ $cm^{-2}$ $sec^{-1}$
  - Following success of KEK-B with crab-crossing we accommodated this approach into new IR layout
- We are completing technical design and cost estimate for the eRHIC including all staging (5 GeV -> 30 GeV). We plan to
  - Complete eRHIC design in two weeks
  - External accelerator design review on August 1-3, 2011
  - Complete & review cost estimate in Fall of 2011
- eRHIC R&D progresses in:
  - (a) Single cathode and Gatling polarized electron guns
  - (b) Compact SRF linacs with HOM damping & SRF crab-cavities
  - (c) Multi-pass high average current ERLs
  - (e) Small gap magnets and vacuum chambers
  - (f) Coherent electron cooling
  - (g) Beam-beam effects

# Materials are from eRHIC R&D group and EIC task force





www.bnl.gov/cad/eRhic/

**eRHIC**
(V. Litvinenko), Head
V. Ptitsyn, Deputy

**Lattice & IR**
(D. Trbojevic), GL
N. Tsoupas, Deputy
J. Beebe–Wang
(Y. Luo)
B. Parker, SMD
(S. Tepikian)

**R&D ERL**
D. Kayran, GL
B. Sheehy, Deputy
D. Pate
T. Rao, ID
T. Seda

**CeC**
(V. Litvinenko), GL
Y. Hao
G. Wang
S. Webb+

**Polarized Sources**
(I. Ben–Zvi), GL
X. Chang, Deputy
H. Hahn*
J. Skaritka
E. Tsentalovich++, MIT
(A. Zelenski)

**Engineering**
(J. Tuozzolo), GL
A. Jain, SMD
(G. Mahler)
(W. Meng)

+ S.Belomestnykh, M. Blaskiewicz, R. Calaga , X.Chang , D.Gassner , L.Hammons, H.Hahn , P. He , W.Jackson , E. Johnson, J.Kewisch ,
G.McIntyre, M.Minty , A.Pikin , E.Pozdeyev, T.RoserY.Than, Q.Wu, W.Xu , A.Hutton, M.Poelker, G.Krafft, R.Rimmer
Inputs on Physics from BNL EIC task force lead by E.-C. Aschenauer, T. Ulrich http://www.eic.bnl.gov/taskforce.html, A.Cadwell, A.Deshpande,
R. Ent, T. Horn, H. Kowalsky, M. Lamont, T.W. Ludlam, R. Milner, B. Surrow, S.Vigdor, R. Venugopalan, W.Vogelsang, ….

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

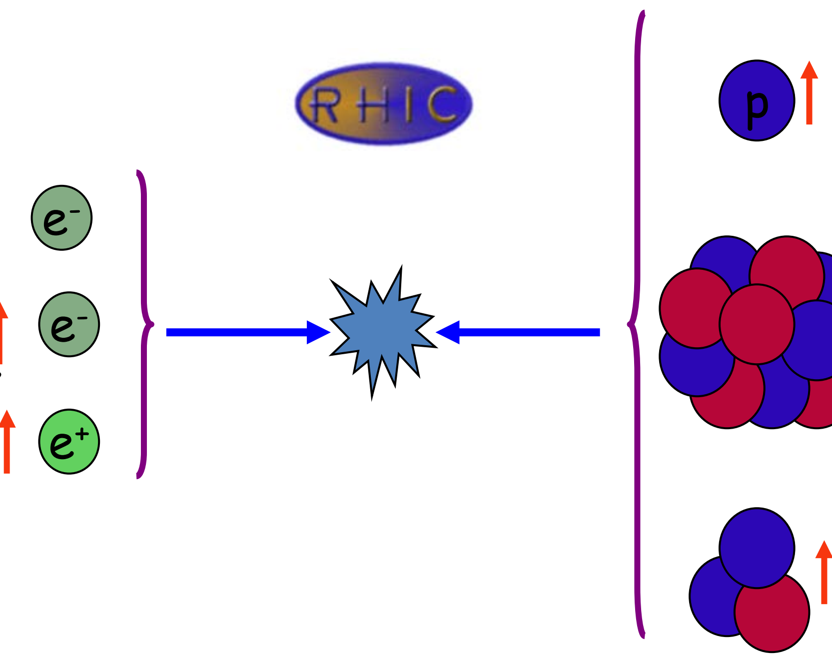
# Content

- Evolution of eRHIC concept
- eRHIC staging
- IP developments
- Accelerator challenges for eRHIC

# eRHIC: QCD Facility at BNL

## Add electron accelerator to the existing $2B RHIC

Unpolarized and
80% polarized
leptons, 5-30 GeV

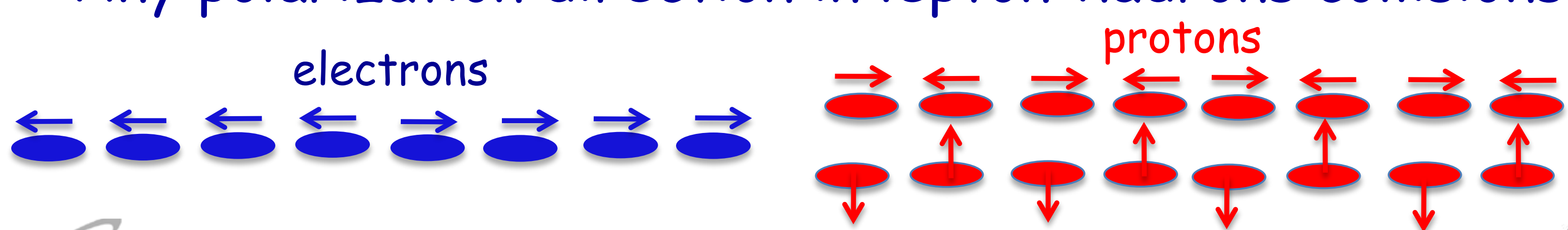



70% polarized protons
50-250 (325) GeV

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

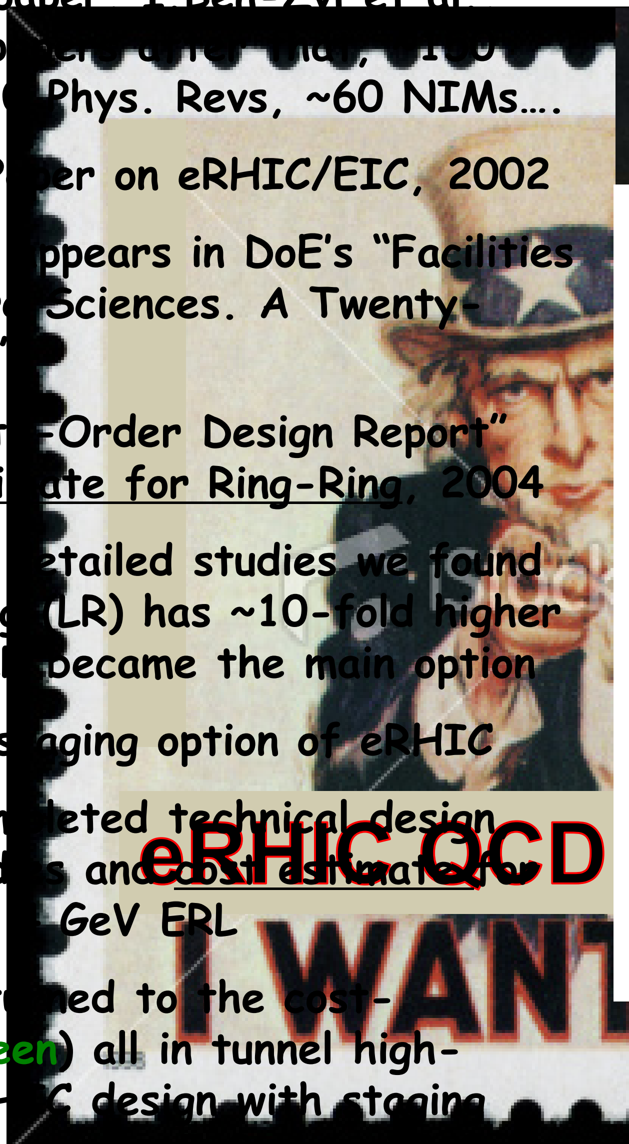


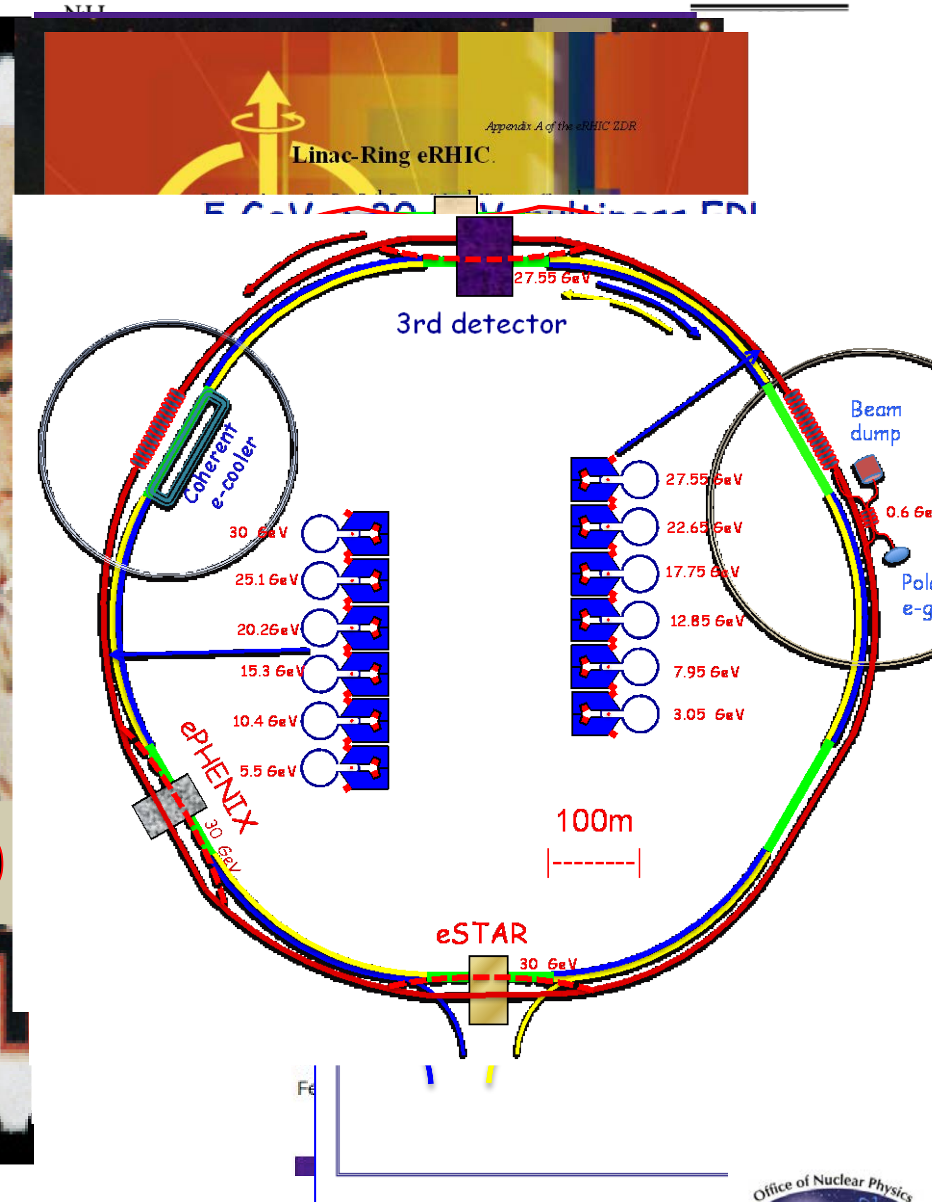

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

# Brief history of eRHIC

- First eRHIC paper, I.Ben-Zvi et al., 2001, ~300 papers after that, ~180 @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 4 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

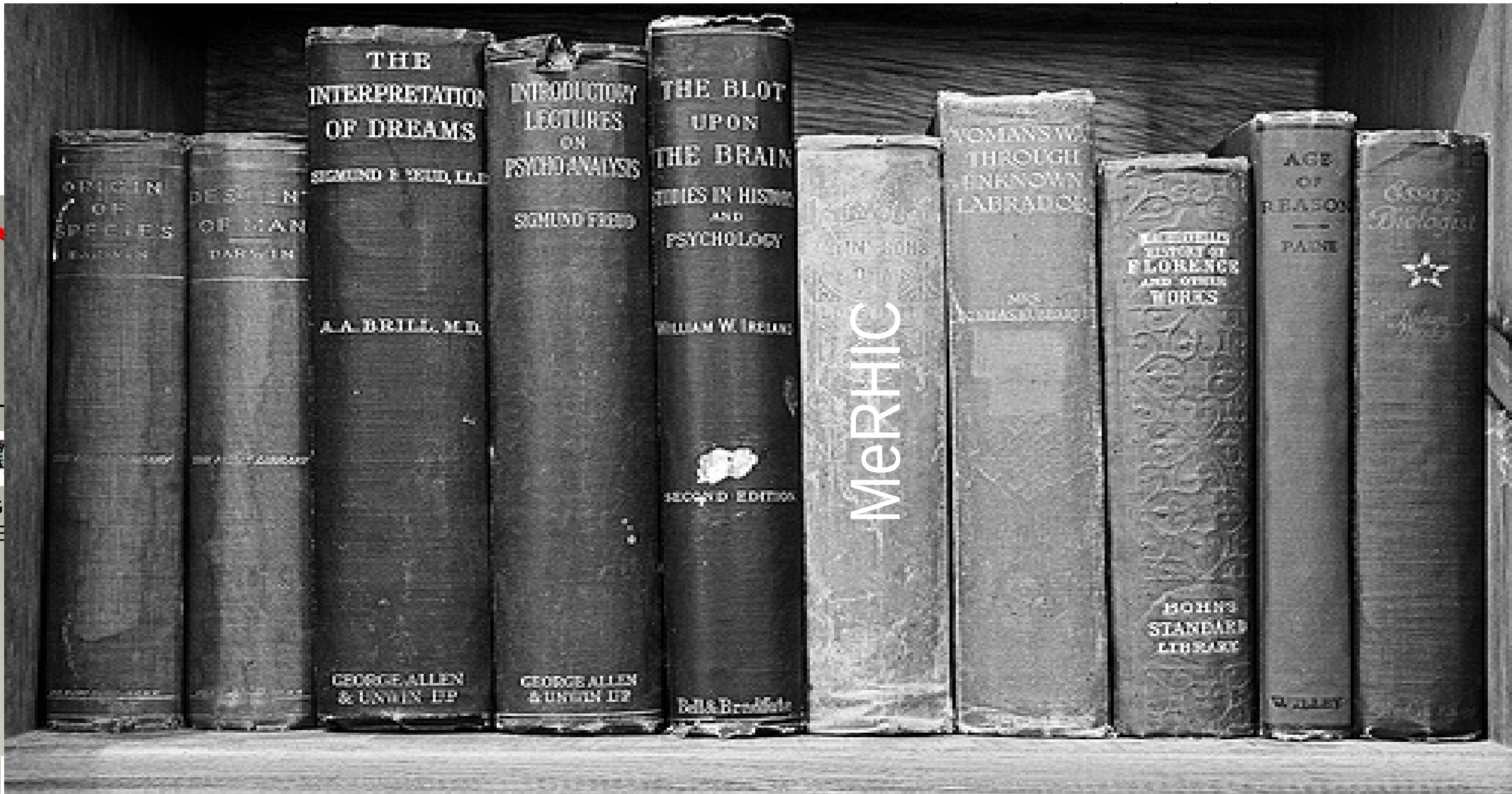



BROOKHAVEN NATIONAL LABORATORY

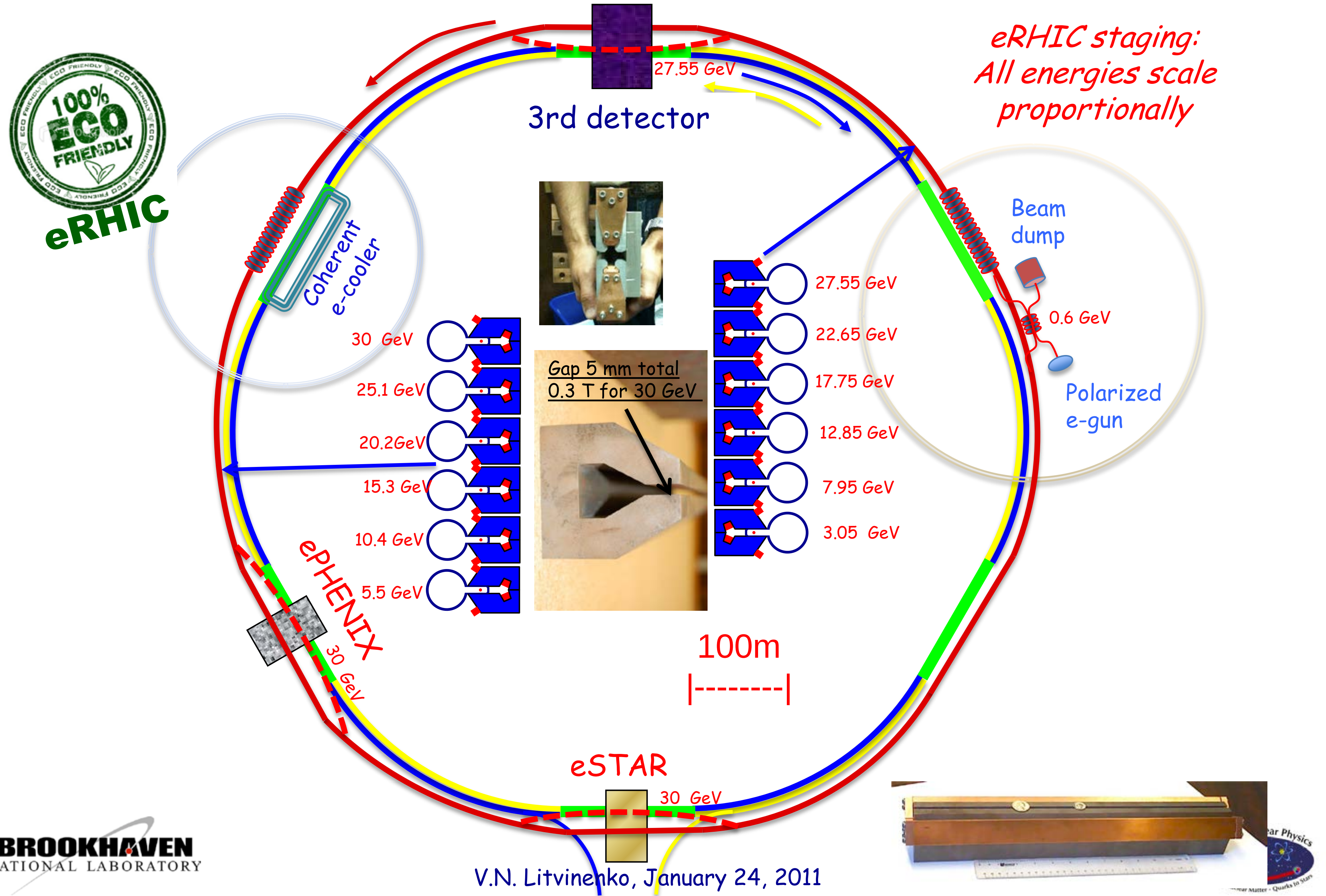
Office of Nuclear Physics

# MeRHIC – 2007/2008




- Learned a lot and shelved it

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



# 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

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

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 |

Limiting factors:

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

# 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 $10^{33}$ $cm^{-2}$ $sec^{-1}$ 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

# 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)

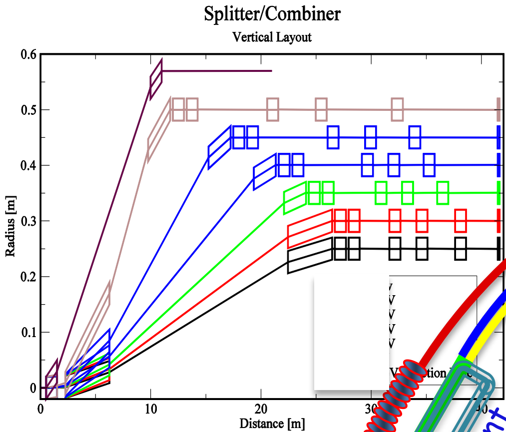
January 19: IR top energy electron beamline. (J. Beebe-Wang), e-p and e-Au luminosities at different collision energies. (V. Ptitsyn)

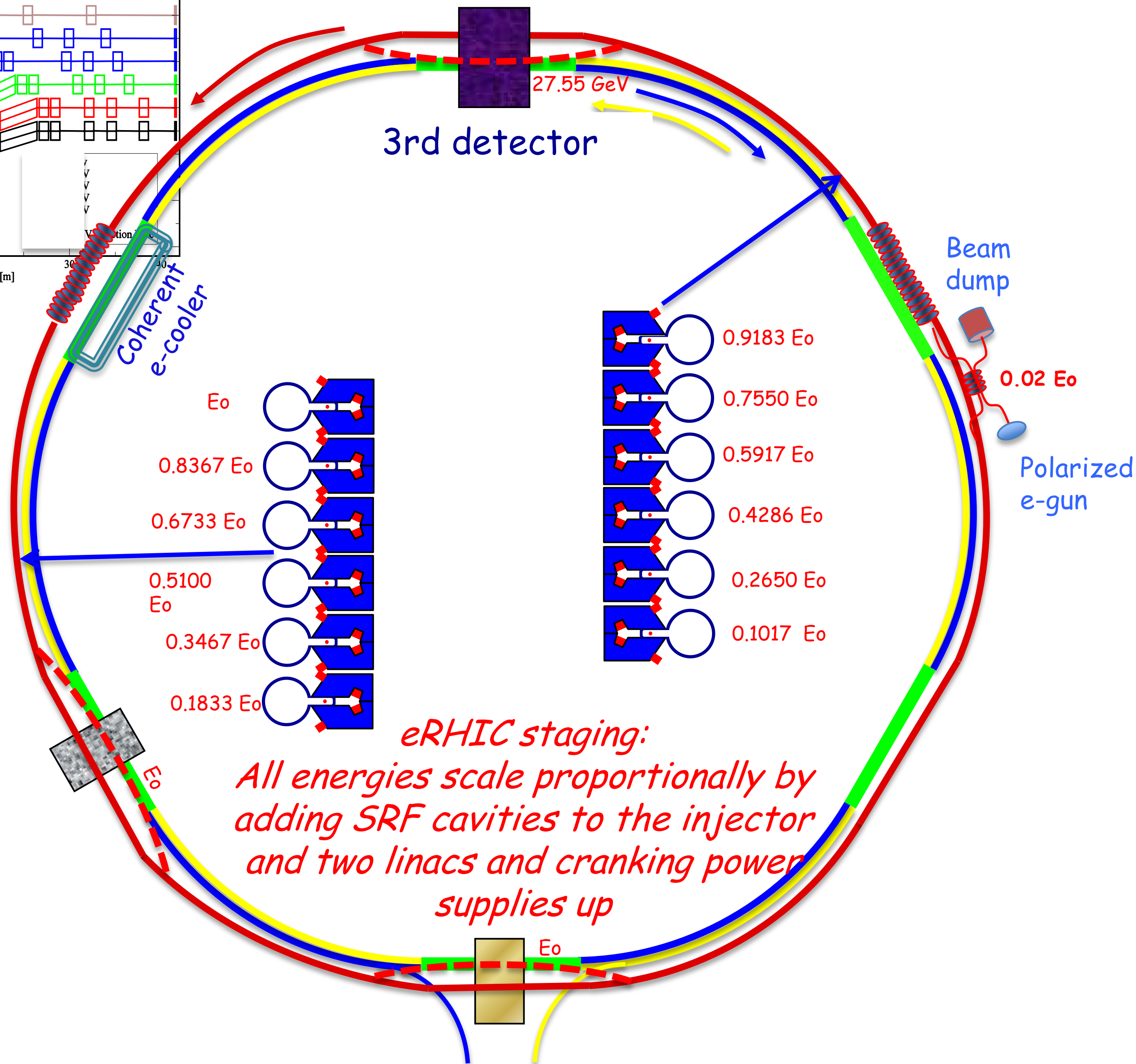
January 05: Electron passes in IRs and straight sections. (N. Tsoupas), IR design status. (D. Trbojevic)



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

# Staging of eRHIC

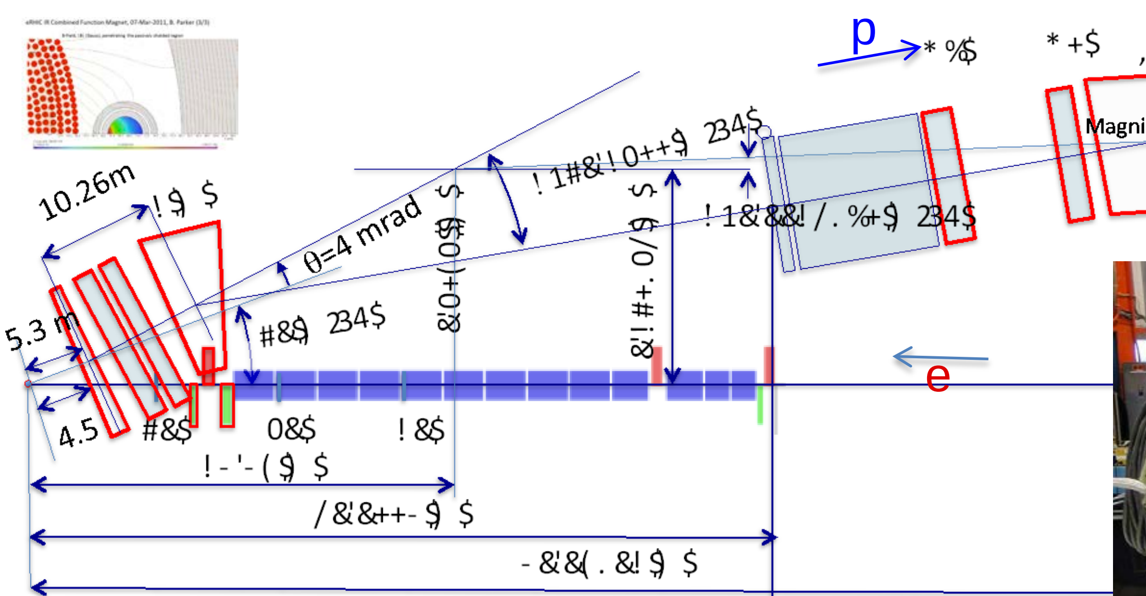


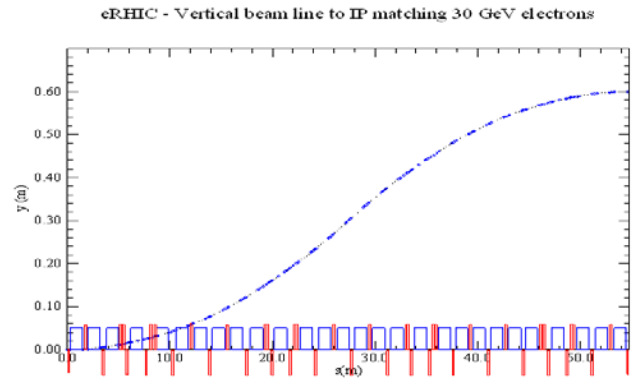



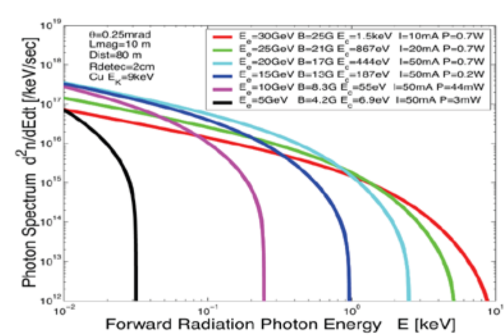

| E/Eo |
|---|
| 0.0200 |
| 0.1017 |
| 0.1833 |
| 0.2650 |
| 0.3467 |
| 0.4283 |
| 0.5100 |
| 0.5917 |
| 0.6733 |
| 0.7550 |
| 0.8367 |
| 0.9183 |
| 1.0000 |

BROOKHAVEN NATIONAL LABORATORY

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



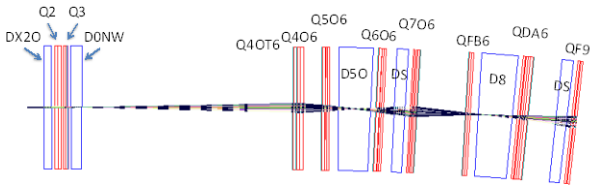



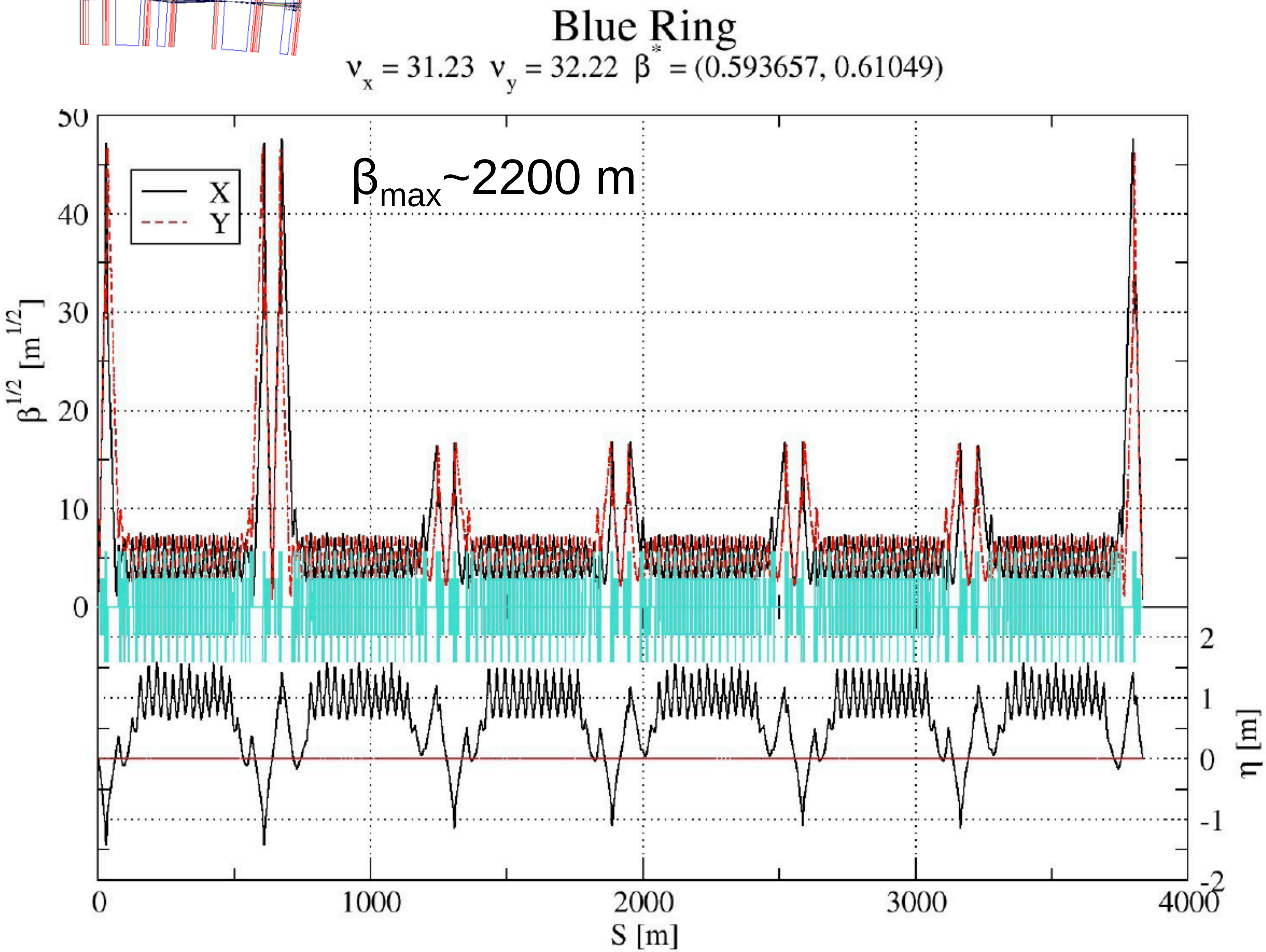

New eRHIC Ideas Page 1

- 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

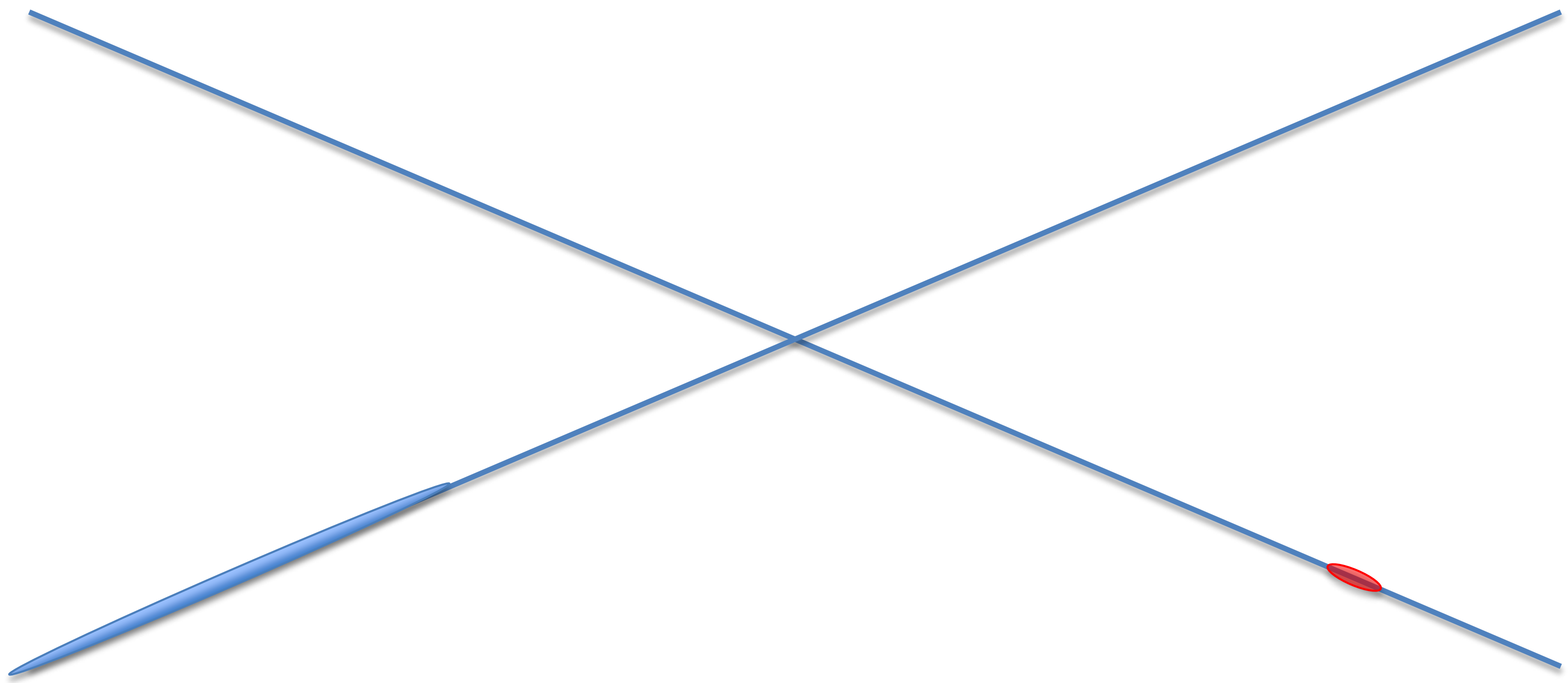


Q2
Q3
DX2O
D0NW
Q4OT6
Q4O6
Q5O6
Q6O6
Q7O6
D5O
DS
QFB6
QDA6
D8
QF9
DS

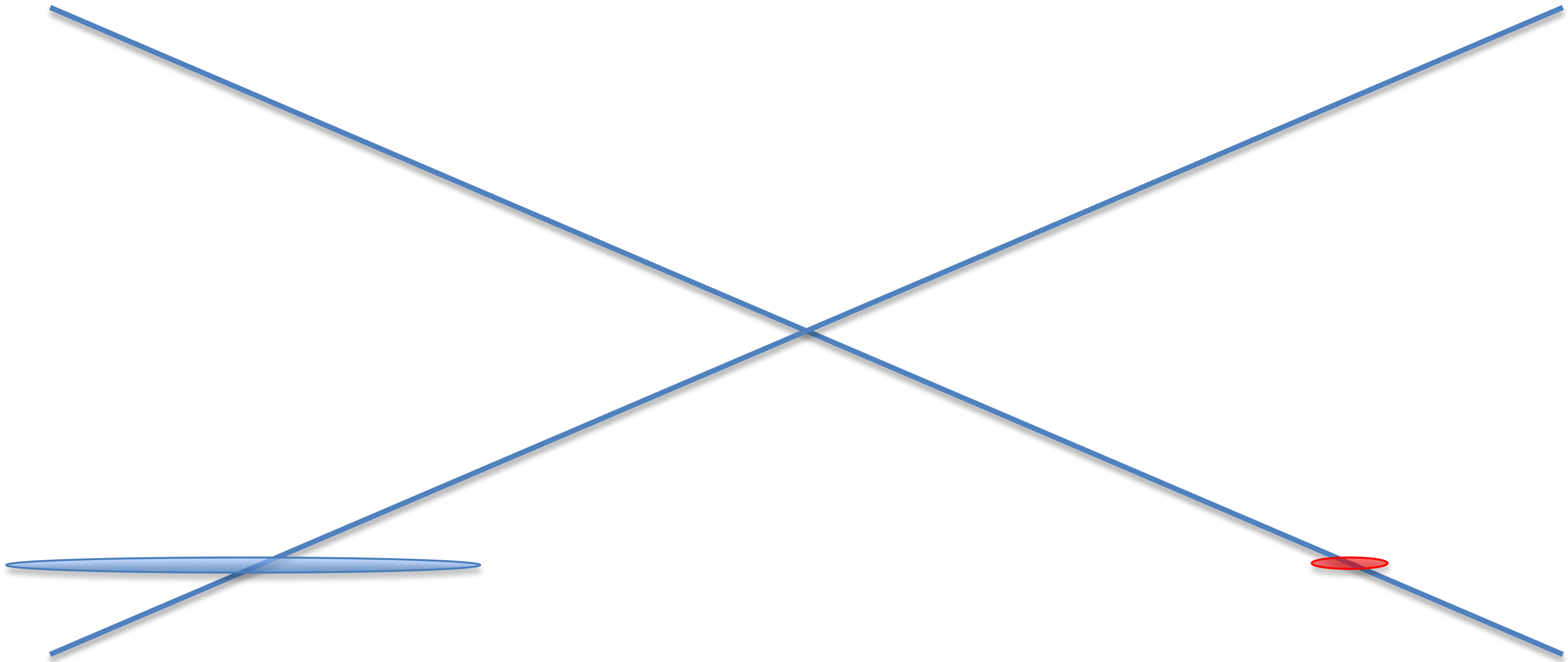



Blue Ring
$\nu_x = 31.23$ $\nu_y = 32.22$ $\beta^* = (0.593657, 0.61049)$
$\beta_{max}$~2200 m
X
Y
$\beta^{1/2}$ [$m^{1/2}$]
η [m]
S [m]
0
10
20
30
40
50
1000
2000
3000
4000
2
1
0
-1
-2

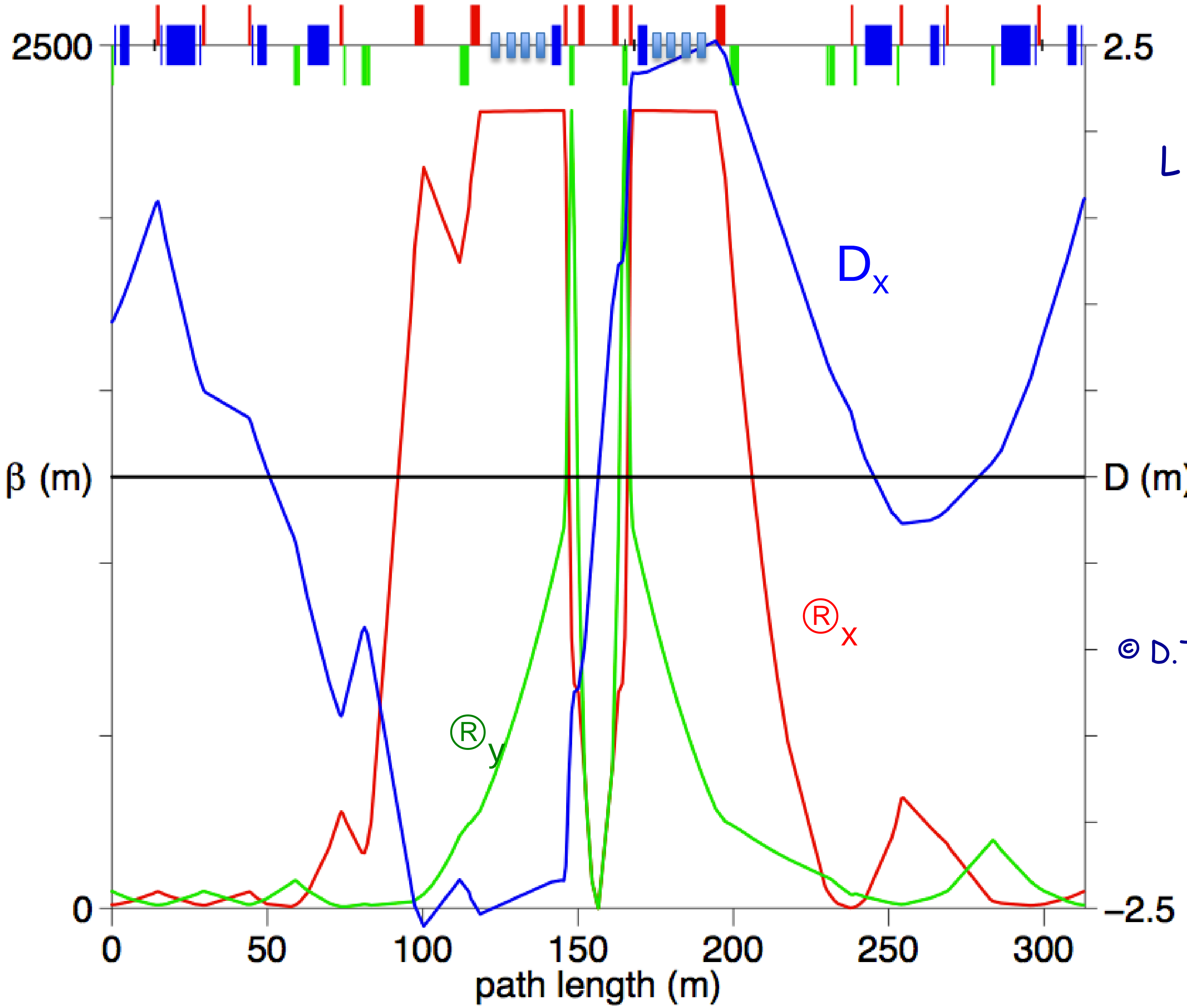
# "No crabbing"



# "Ideal crabbing"



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

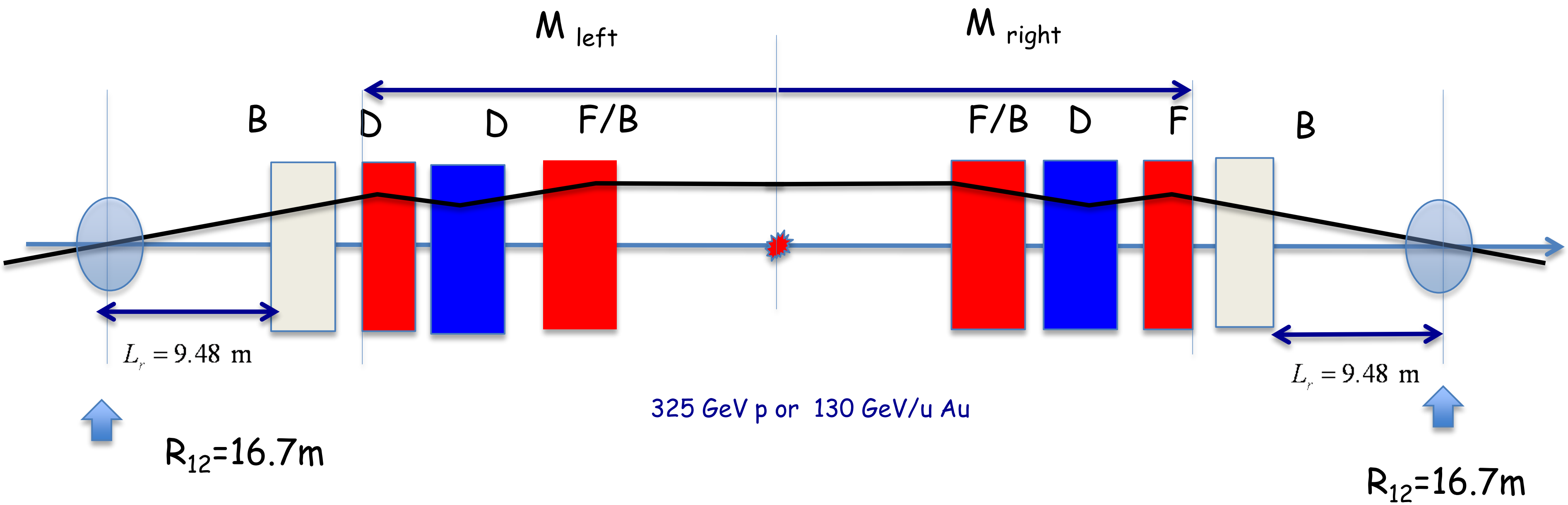



L triplet=4.5 m

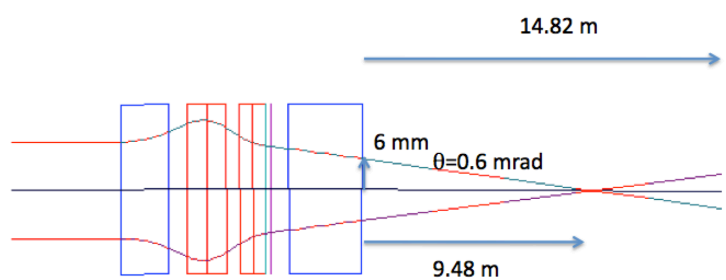
© D.Trbojevic

# RHIC lattice

Fresh from the press by
Dejan Trbojevic



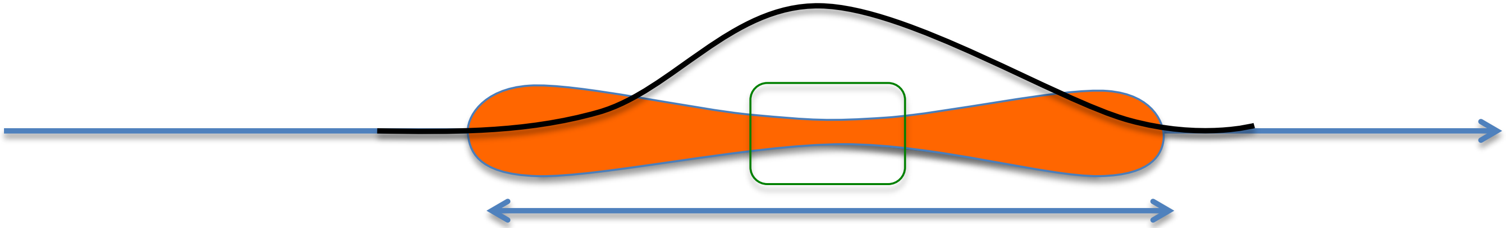

$$V_{\perp}[MV] \cong 15.5 \cdot \frac{E_p[GeV]}{325} \lambda_{rf}[m]$$



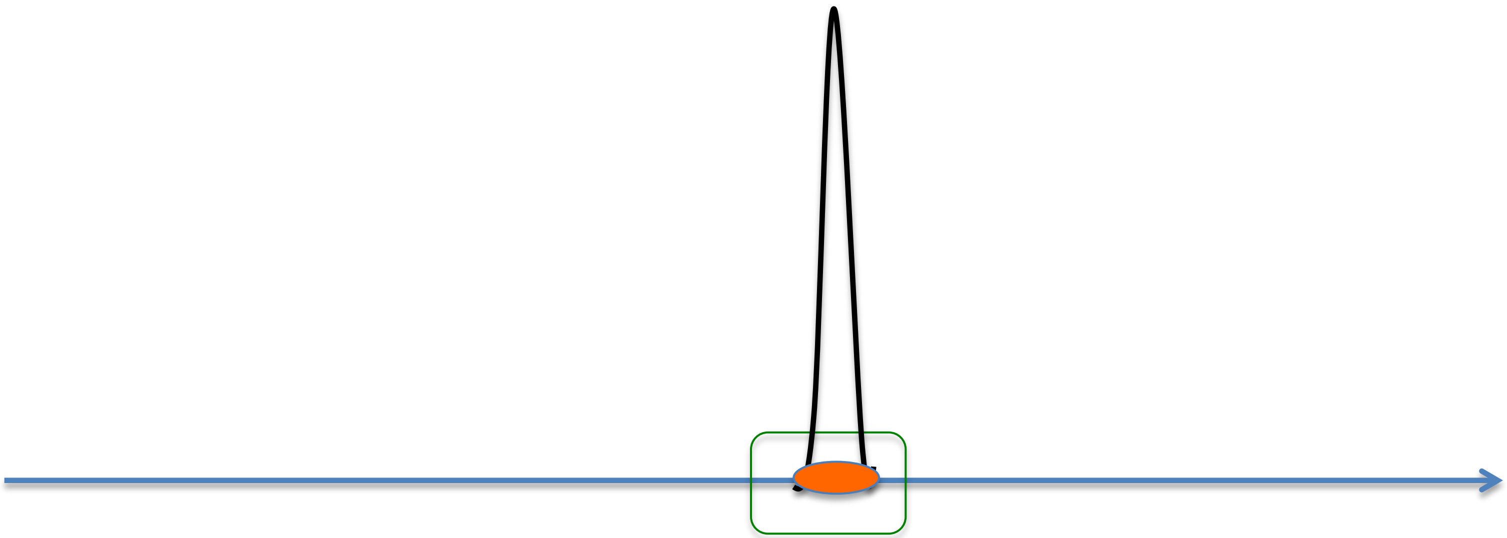

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics

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




**All requires very short hadron bunches**




BROOKHAVEN NATIONAL LABORATORY
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

# Gains from coherent e-cooling:

## Coherent Electron Cooling vs. IBS

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

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

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

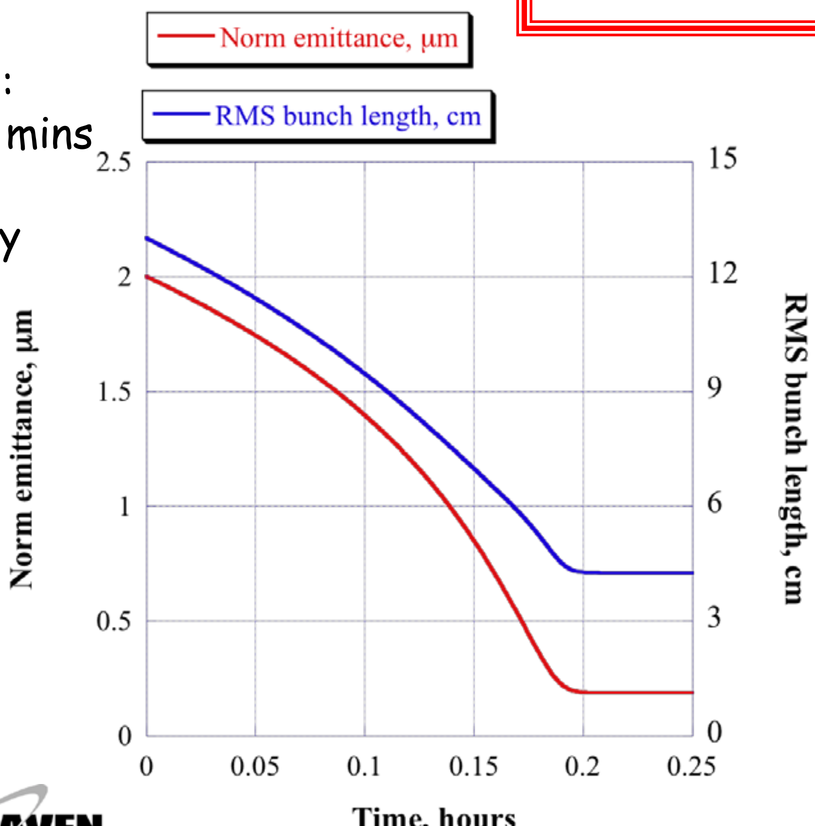
$$X=\frac{\tau_{CeC}}{\sqrt{\tau_{IBS//}\tau_{IBS\perp}}}\frac{1}{\sqrt{\xi_\perp(1-2\xi_\perp)}};\quad S=\frac{\tau_{CeC}}{\tau_{IBS//}}\cdot\sqrt{\frac{\tau_{IBS\perp}}{\tau_{IBS//}}}\cdot\sqrt{\frac{\xi_\perp}{(1-2\xi_\perp)^3}}$$

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

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

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

Dynamics:
Takes 12 mins to reach stationary point




### 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

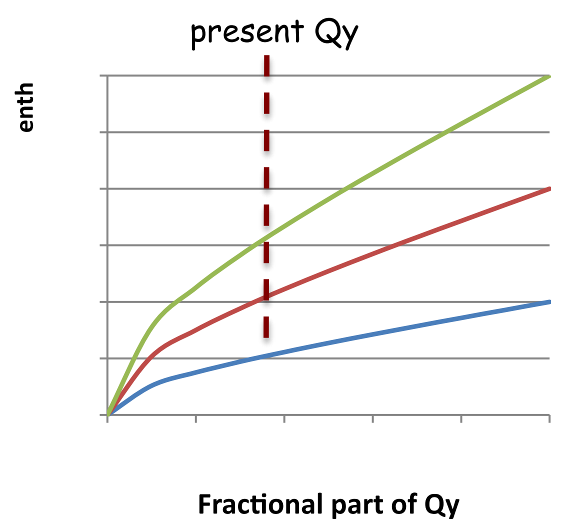
BROOKHAVEN NATIONAL LABORATORY
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

# 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

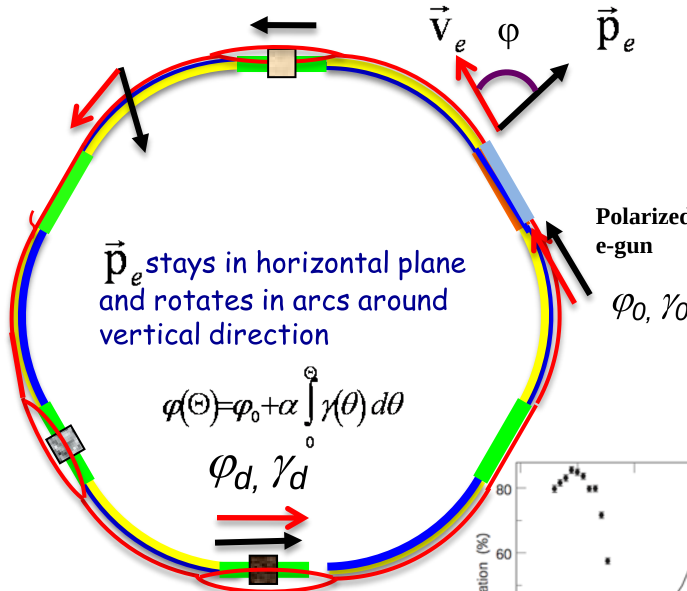
Possible future developments:

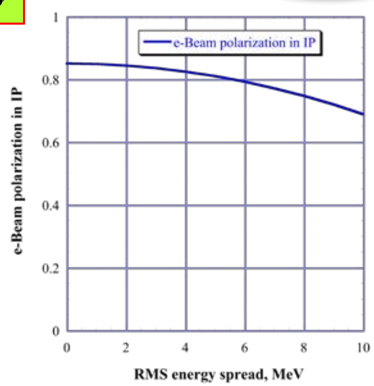
- Working point near integer (allowed by recent success of 10 Hz orbit feedback):
  - Fewer high-order spin resonances
  - Reduced strength of those resonances
- Increased number of the Snakes

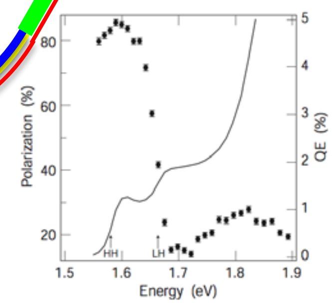
© V.Ptitsyn

# 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%



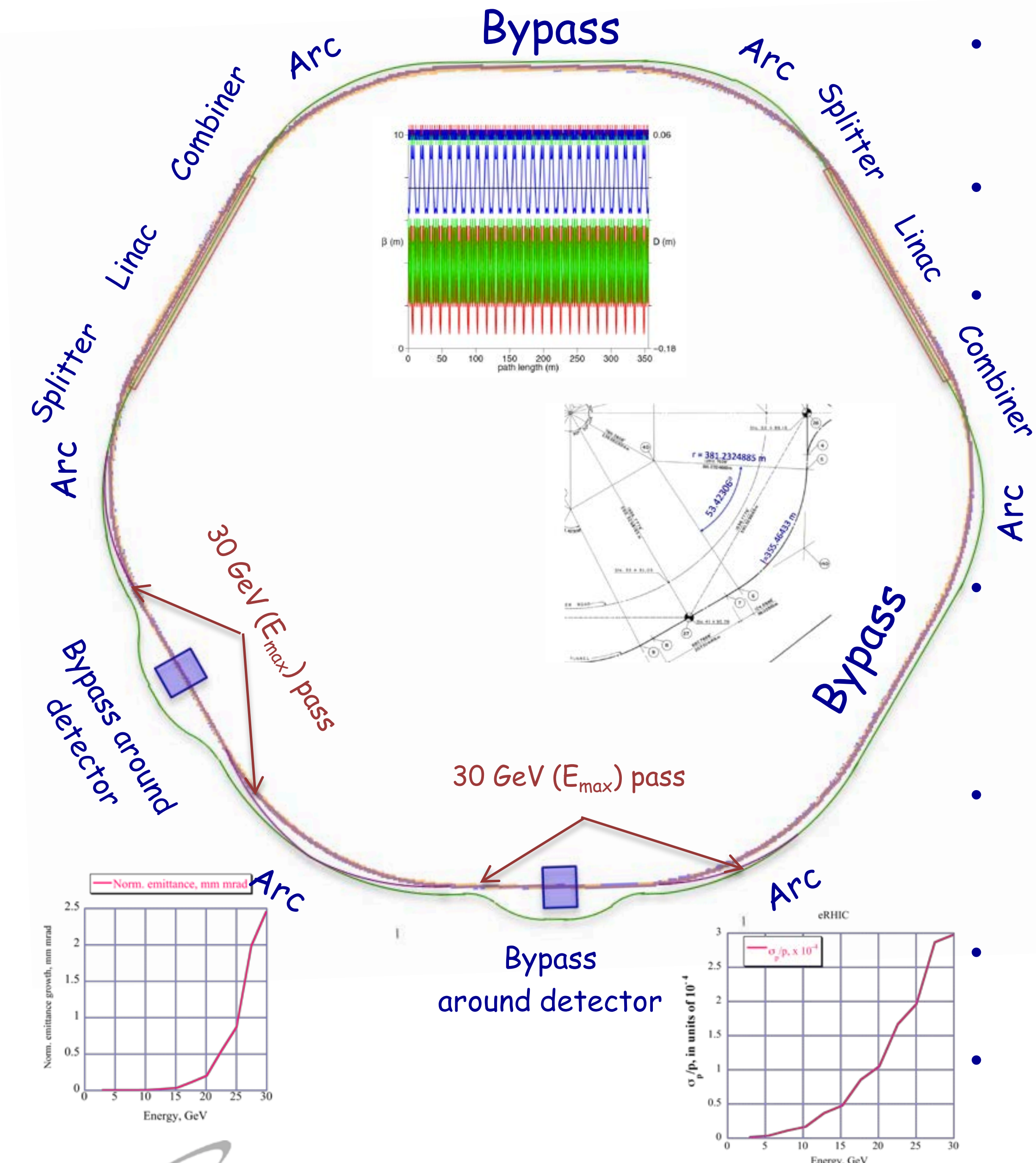

*The GaAs–GaAsP cathode achieved a maximum polarization of 92±6% with a quantum efficiency of 0.5%

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

BROOKHAVEN NATIONAL LABORATORY

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

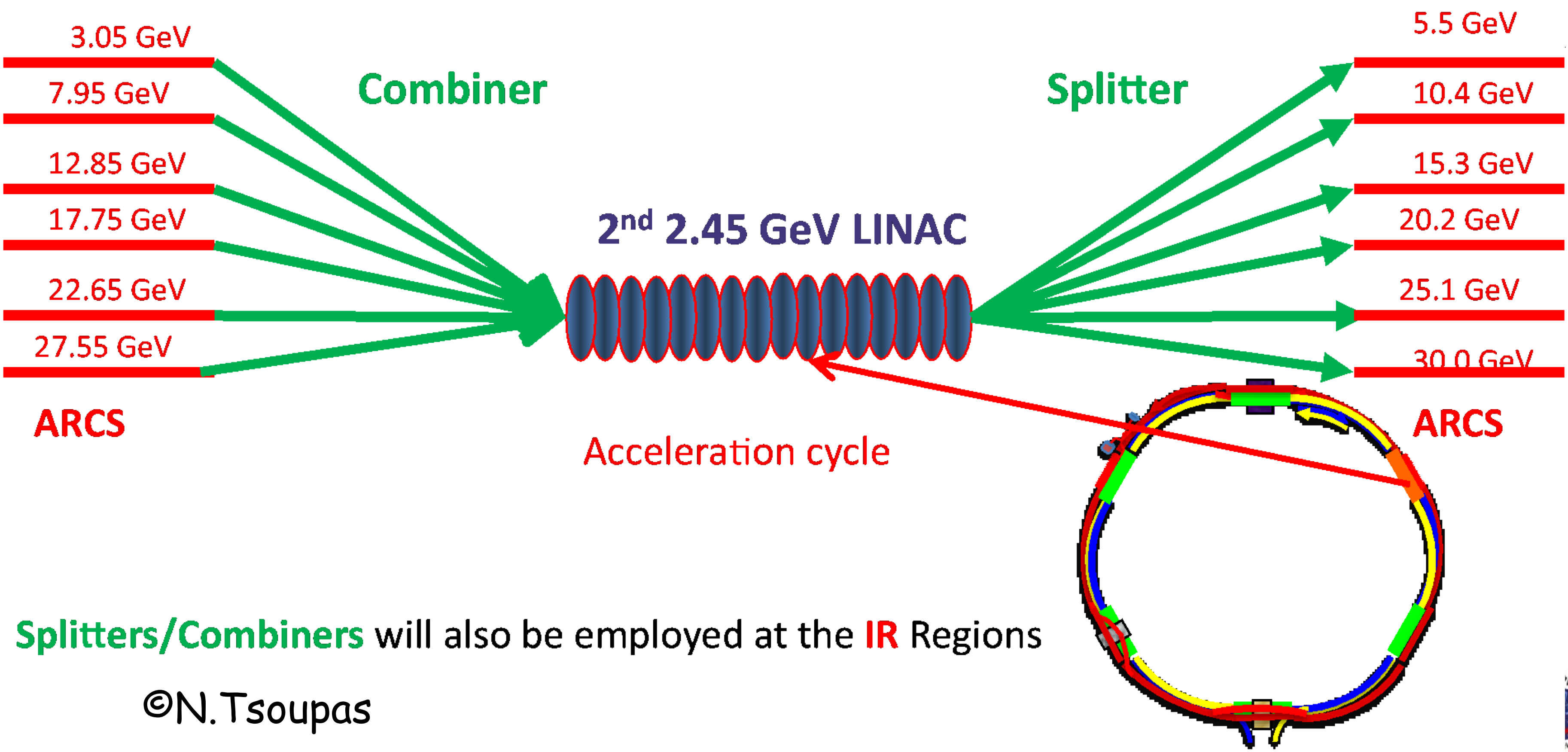
# ERL Lattice with two detectors




- 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

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

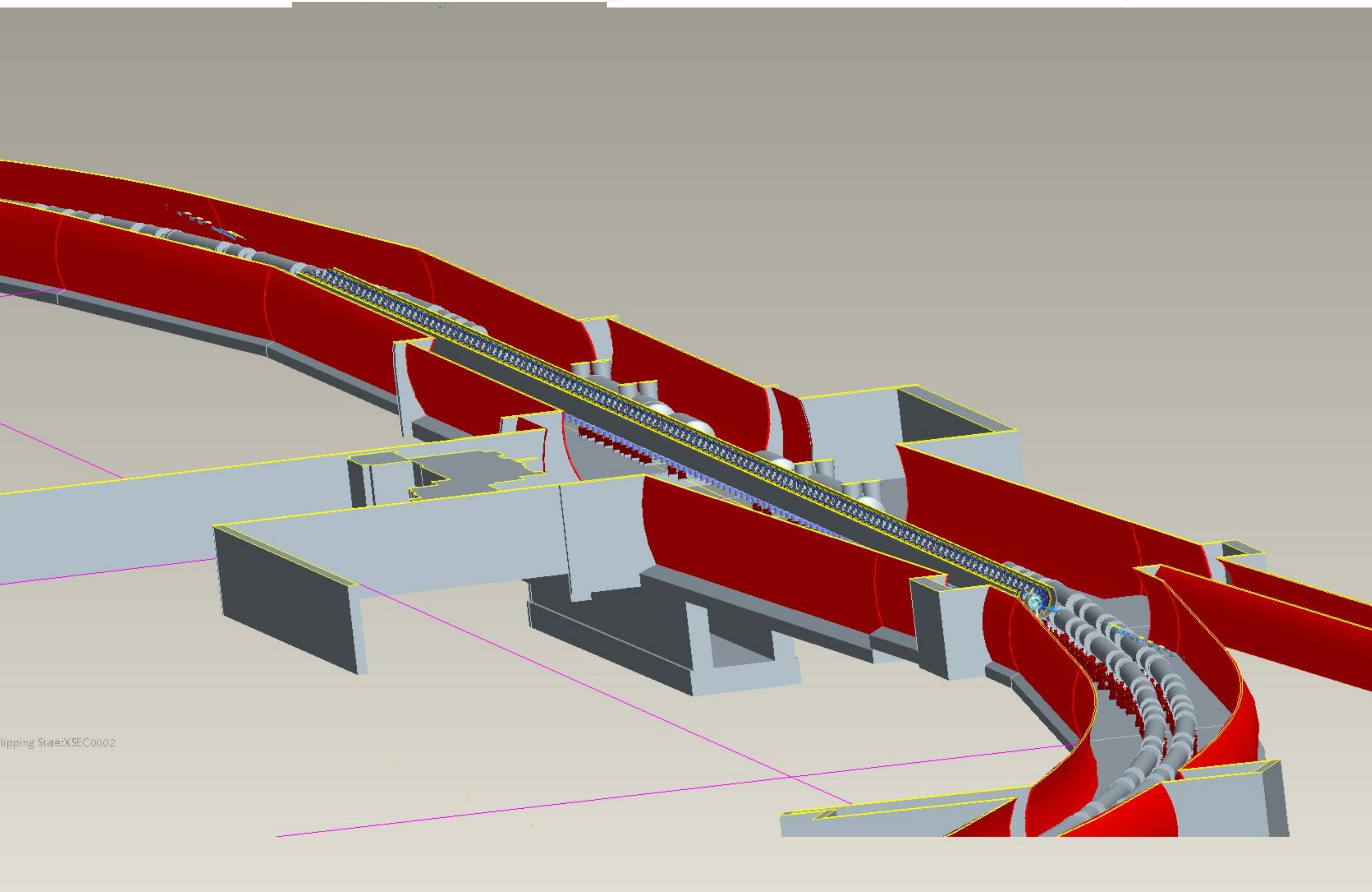
It is the system of the beam lines which **Combines** the beams of the **ARCS** into the **LINAC** or **Splits** the beams exiting the **LINAC** into the **ARCS**




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

©N.Tsoupas

# eRHIC Linac Design without and with quads





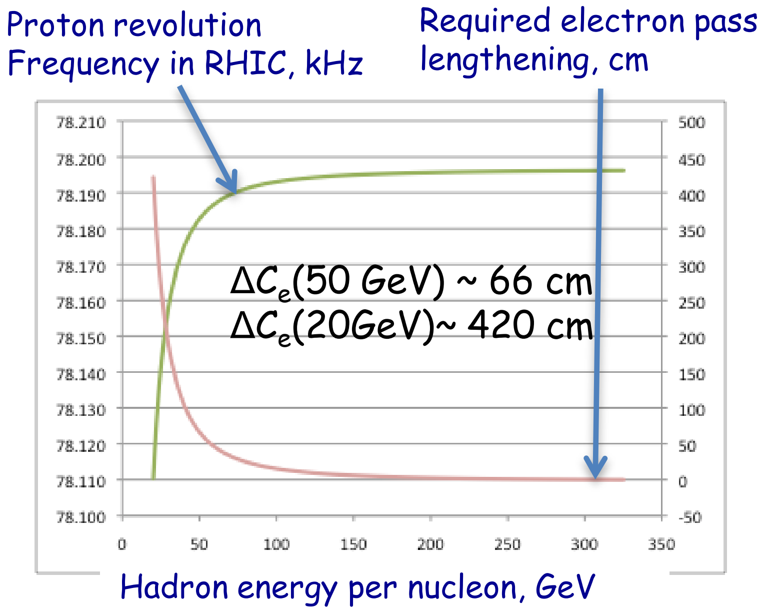

©I. Ben Zvi, , G. Mahler, H.Hahn, Y. Hao, S. Belomestnykh, W.Jackson, ….

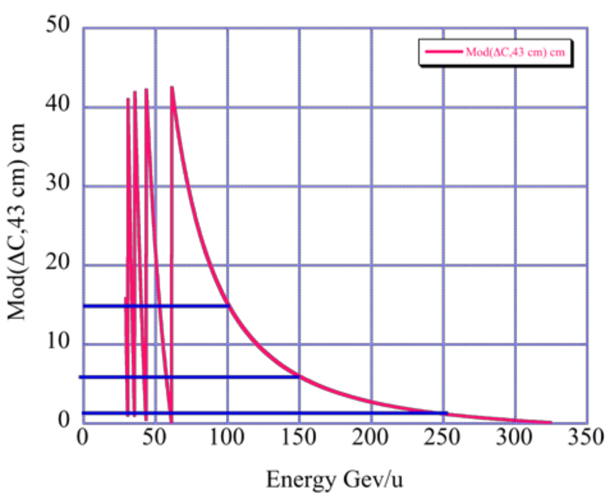
# Magnets inventory

## 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 | |

# 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.e. 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)

$$f_{rev\_e} = \frac{m_e n_p}{h_e} f_{rev\_p} = \frac{9000}{h_e} f_{rev\_p}$$

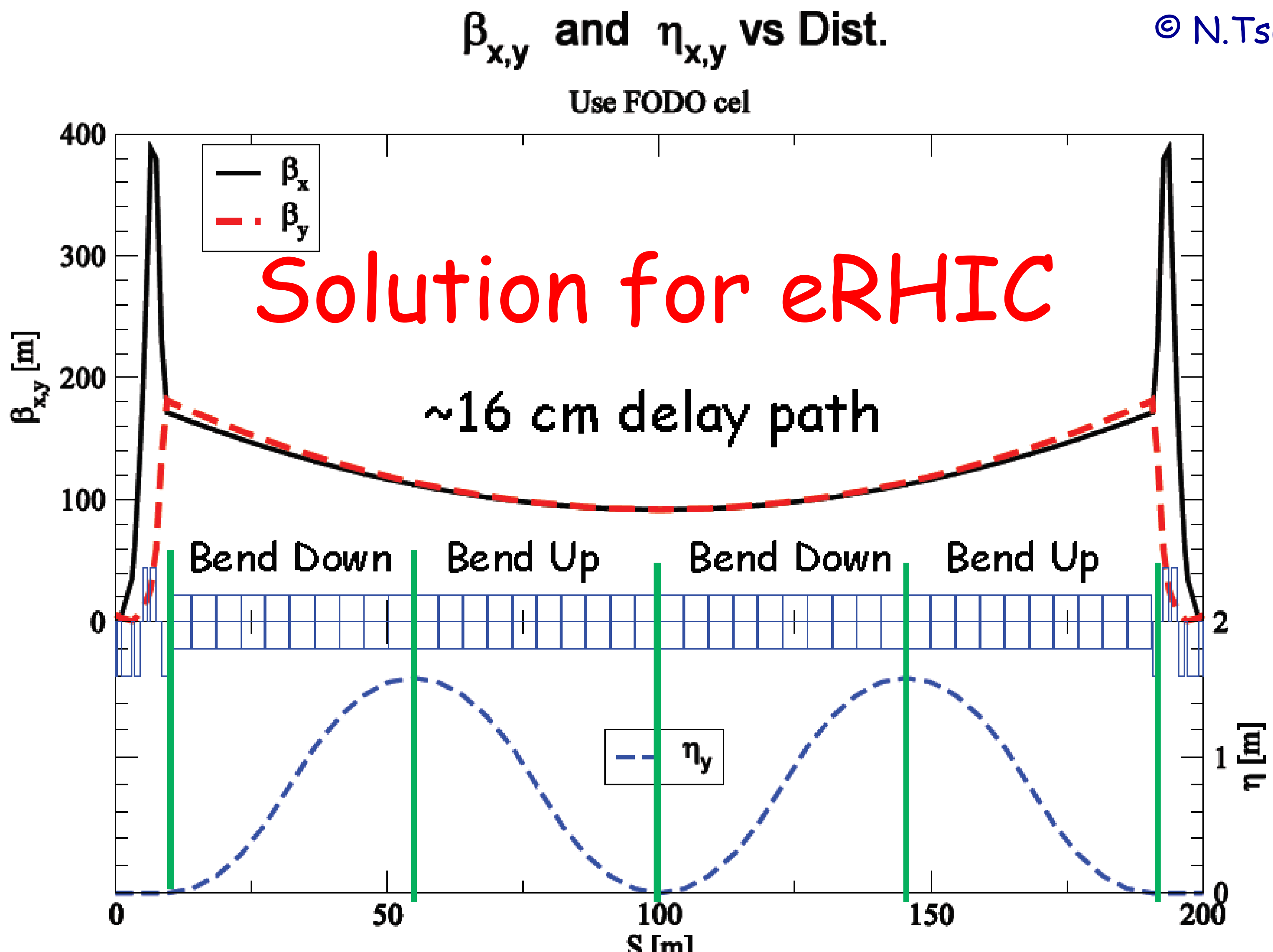
BROOKHAVEN NATIONAL LABORATORY

© V.Ptitsyn, V.Litvinenko

# Beam optics of the 4 o'clock Delay Line

## Dipoles only

© N.Tsoupas



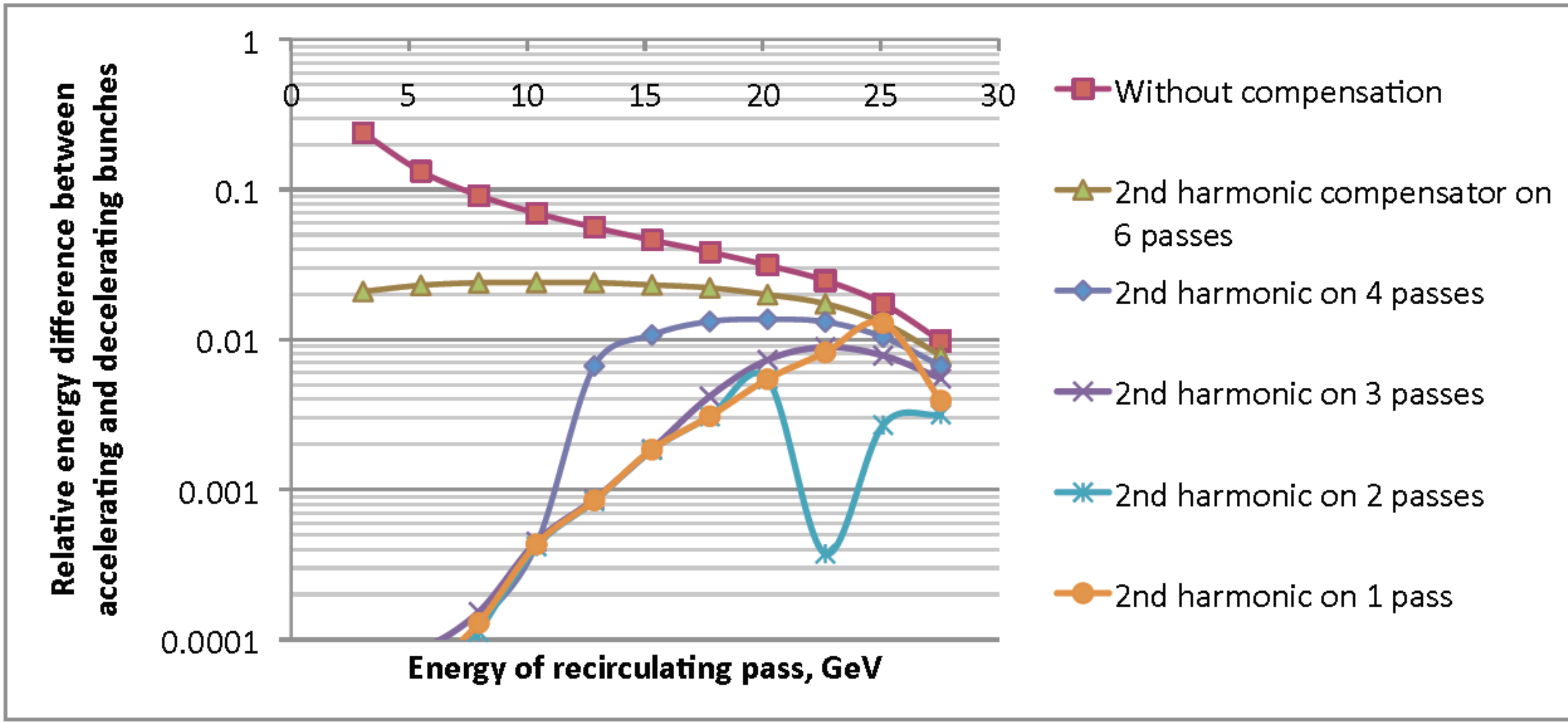
# Beam dynamics studies

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

# Loss budget for 6 pass scheme



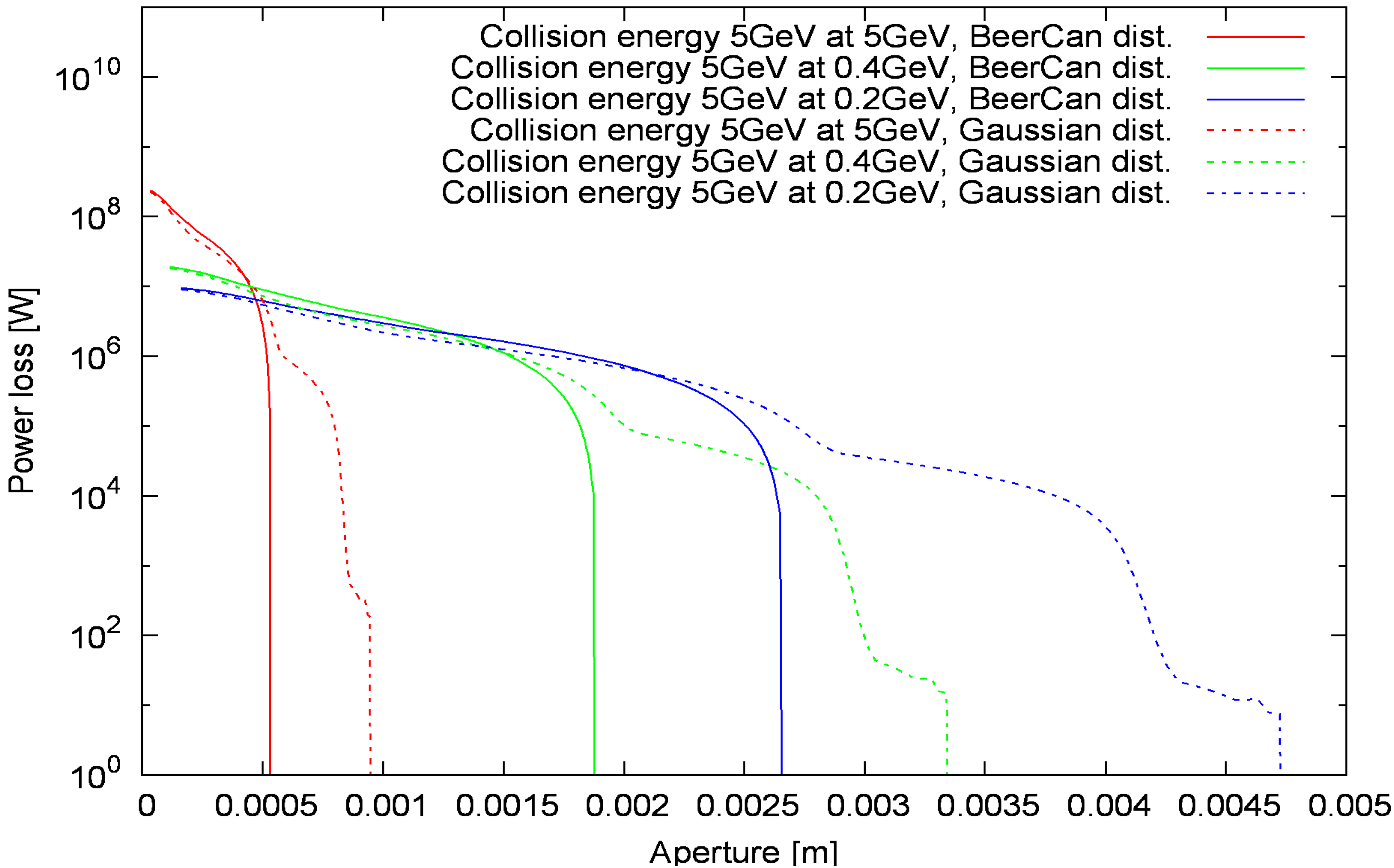

© V.Ptitsyn

BROOKHAVEN NATIONAL LABORATORY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

# Beam disruption and Aperture








Y.Hao, V.Ptitsyn

# 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<br>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 |
| | β*=5 cm 5x reduction |
| | Multi-pass SRF ERL 3-4x in # of passes |
| | Feedback for kink instability suppression Novel concept |

BROOKHAVEN NATIONAL LABORATORY

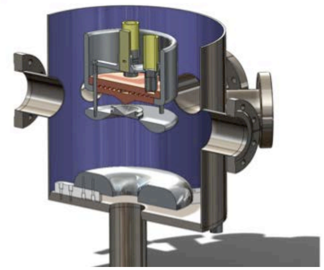
Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

# eRHIC R&D highlights

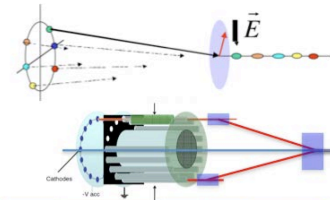
- Polarized gun for e-p program – **LDRD at BNL + MIT**
- Development of compact magnets - **LDRD at BNL, ongoing**
- SRF R&D ERL – **ongoing**
- Beam-beam effects, beam disruption, kink instability suppression, etc.
- Polarized $He^3$ source
- Coherent Electron Cooling including PoP – **plan to pursue**

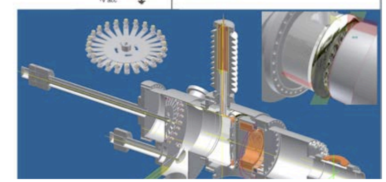
Main technical challenge is 50 mA CW polarized gun: we are building two versions

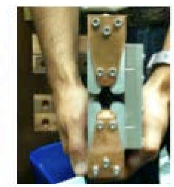
Single large size cathode



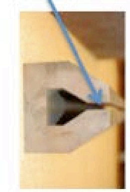
Gatling gun



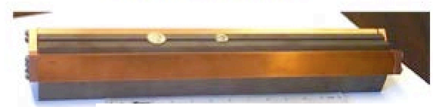



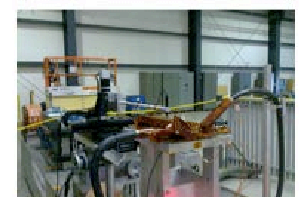


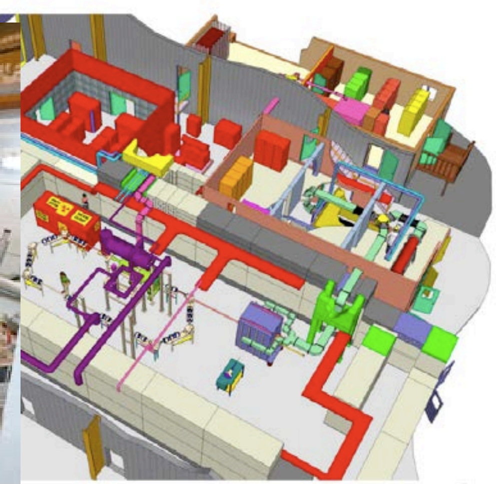
Gap 5 mm total
0.3 T for 30 GeV

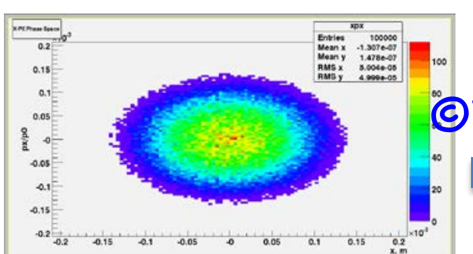


©, G. Mahler, W. Meng, A. Jain, P. He, Y Hao

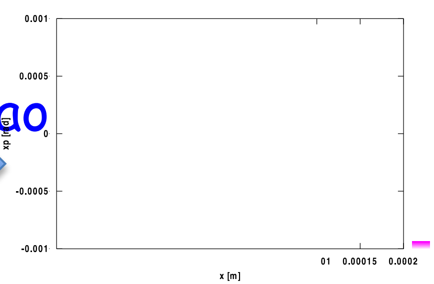









©Y. Hao



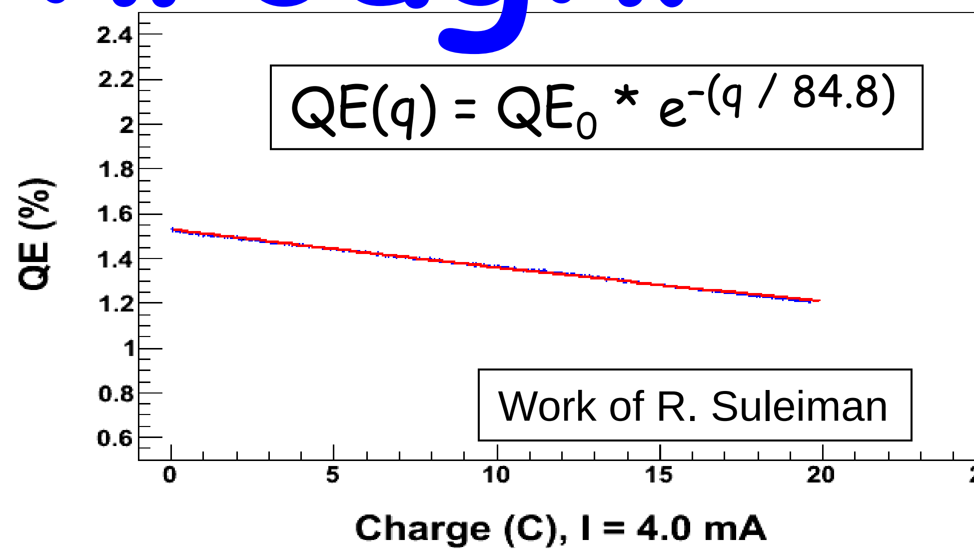

BROOKHAVEN
NATIONAL LABORATORY

# 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 |
| [illegible] 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




$QE(q) = QE_0 * e^{-(q / 84.8)}$

© J. Grames, JLab http://www.c-ad.bnl.gov/pac2011/proceedings/papers/weods3.pdf

# Coherent Electron Cooling (CeC)

## At a half of plasma oscillation

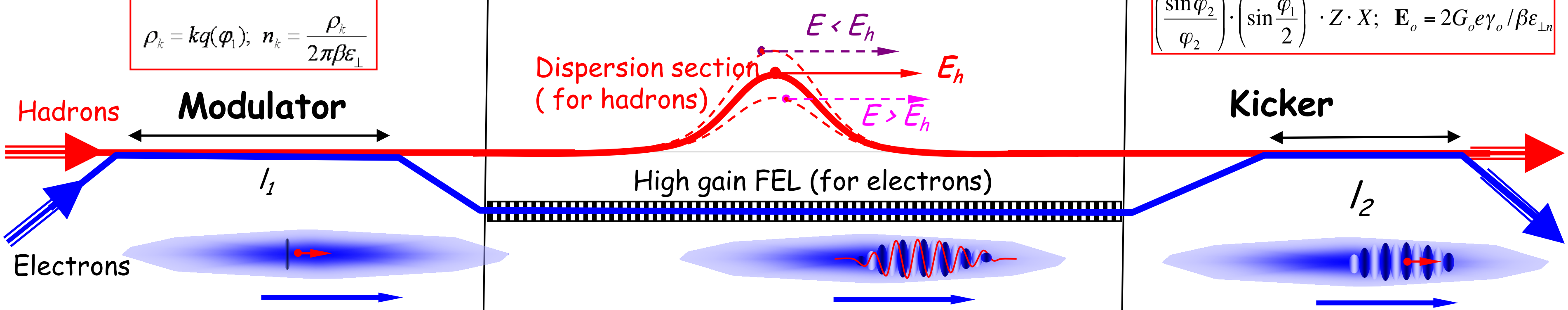
$$q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL} z)\,dz$$

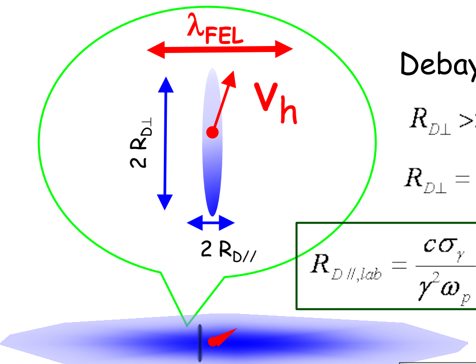
$$\rho_k = kq(\varphi_1);\; n_k = \frac{\rho_k}{2\pi\beta\varepsilon_\perp}$$

## Dispersion

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

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



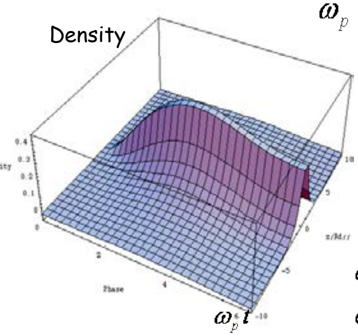

Debay radii

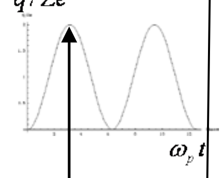
$$R_{D\perp} >> R_{D//}$$

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

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

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



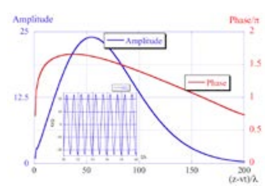



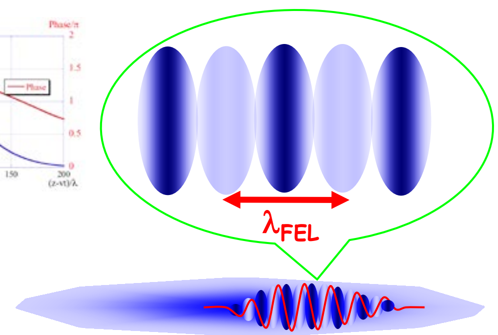

$$q = -Ze\cdot(1-\cos\varphi_1)$$

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

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

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




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

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

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

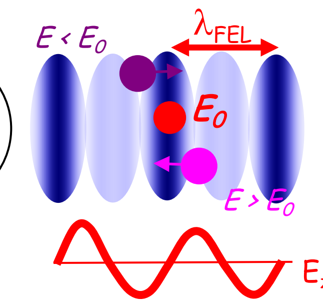
PRL 102, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

**Coherent Electron Cooling**

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]

[1]Brookhaven National Laboratory, Upton, Long Island, New York, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA
(Received 24 September 2008; published 16 March 2009)

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




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

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

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

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

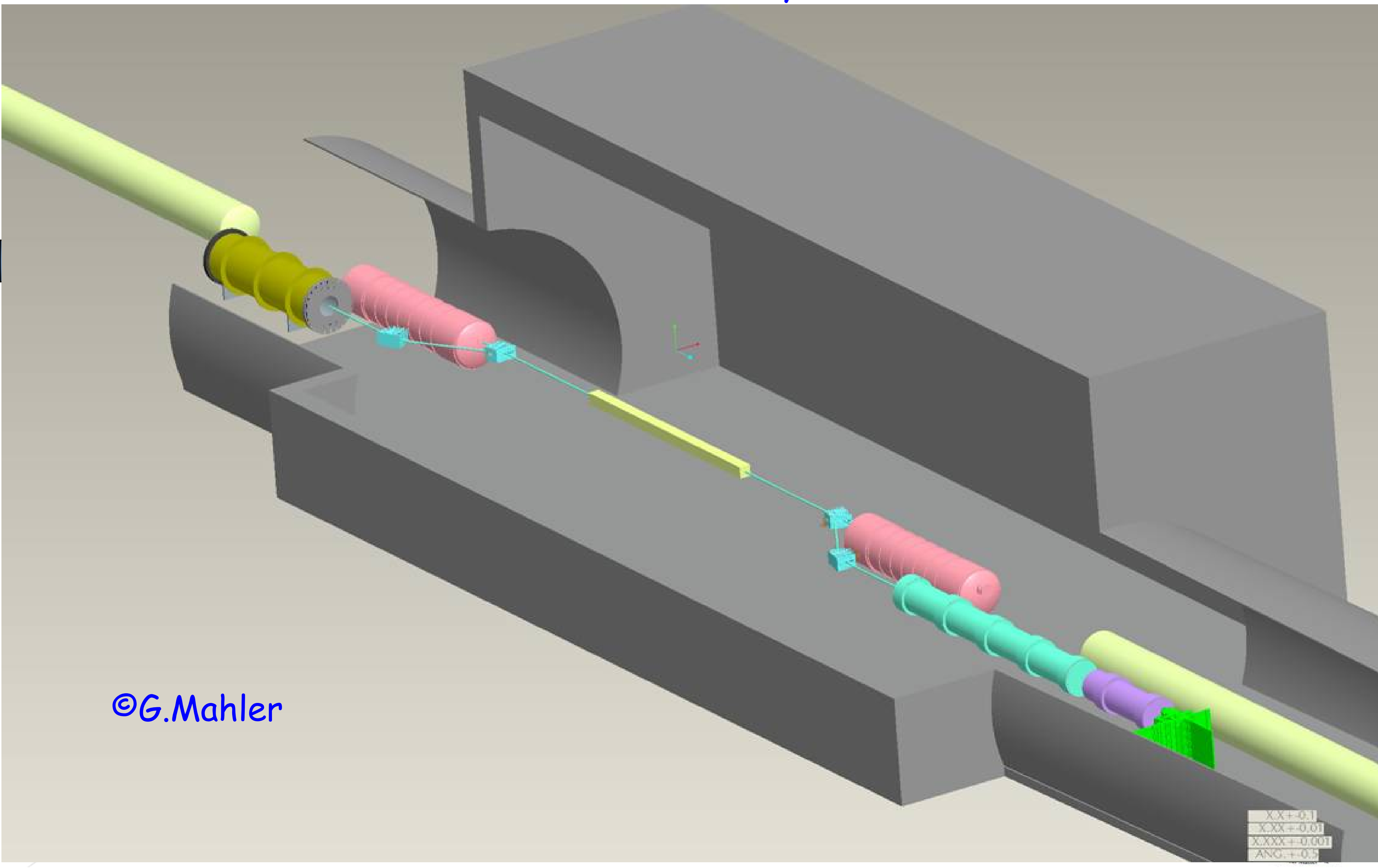
$$\mathbf{E}_o = 2G_o\gamma_o\frac{e}{\beta\varepsilon_{\perp n}}$$

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

BROOKHAVEN NATIONAL LABORATORY

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

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



**Tomorrow, 2:00 p.m.**

**Plenary Session I, Thursday, June 23, 2011**

**Machine R&D for eRHIC, by *Dmitry Kayran***

**Friday 8:50 a.m.**

**Plenary Session II, June 24, 2011**

**Possibilities for maintaining *AA* and pp capabilities in parallel with eRHIC**

***by Vadim Ptitsyn***

# Conclusions

- Our focus is on high-energy high-luminosity all-in-tunnel eRHIC
  - We took advantage of recent advances in super-conducting quadrupole technology to reduce designed $\beta^*$ to 5 cm and to boost eRHIC top luminosity above $10^{34}$ $cm^{-2}$ $sec^{-1}$
  - Following success of KEK-B with crab-crossing we accommodated this approach into new IR layout
- We are completing technical design and cost estimate for the eRHIC including all staging (5 GeV -> 30 GeV). We plan to
  - Complete eRHIC design in two weeks
  - External accelerator design review on August 1-3, 2011
  - Complete & review cost estimate in Fall of 2011
- eRHIC R&D progresses in:
  - (a) Single cathode and Gatling polarized electron guns
  - (b) Compact SRF linacs with HOM damping & SRF crab-cavities
  - (c) Multi-pass high average current ERLs
  - (e) Small gap magnets and vacuum chambers
  - (f) Coherent electron cooling
  - (g) Beam-beam effects

……………

page | discussion | view source | history

# Main Page

navigation

- Main page
- Community portal
- Current events
- Recent changes
- Random page
- Help

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

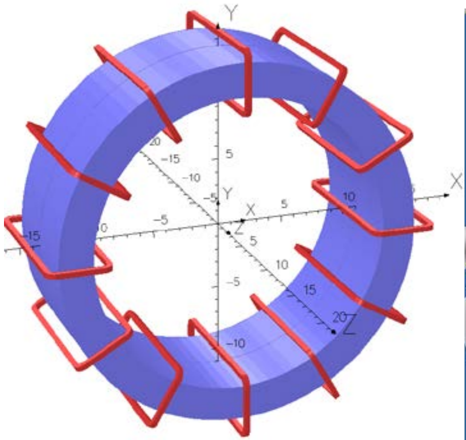
**Ion Beam**

- 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

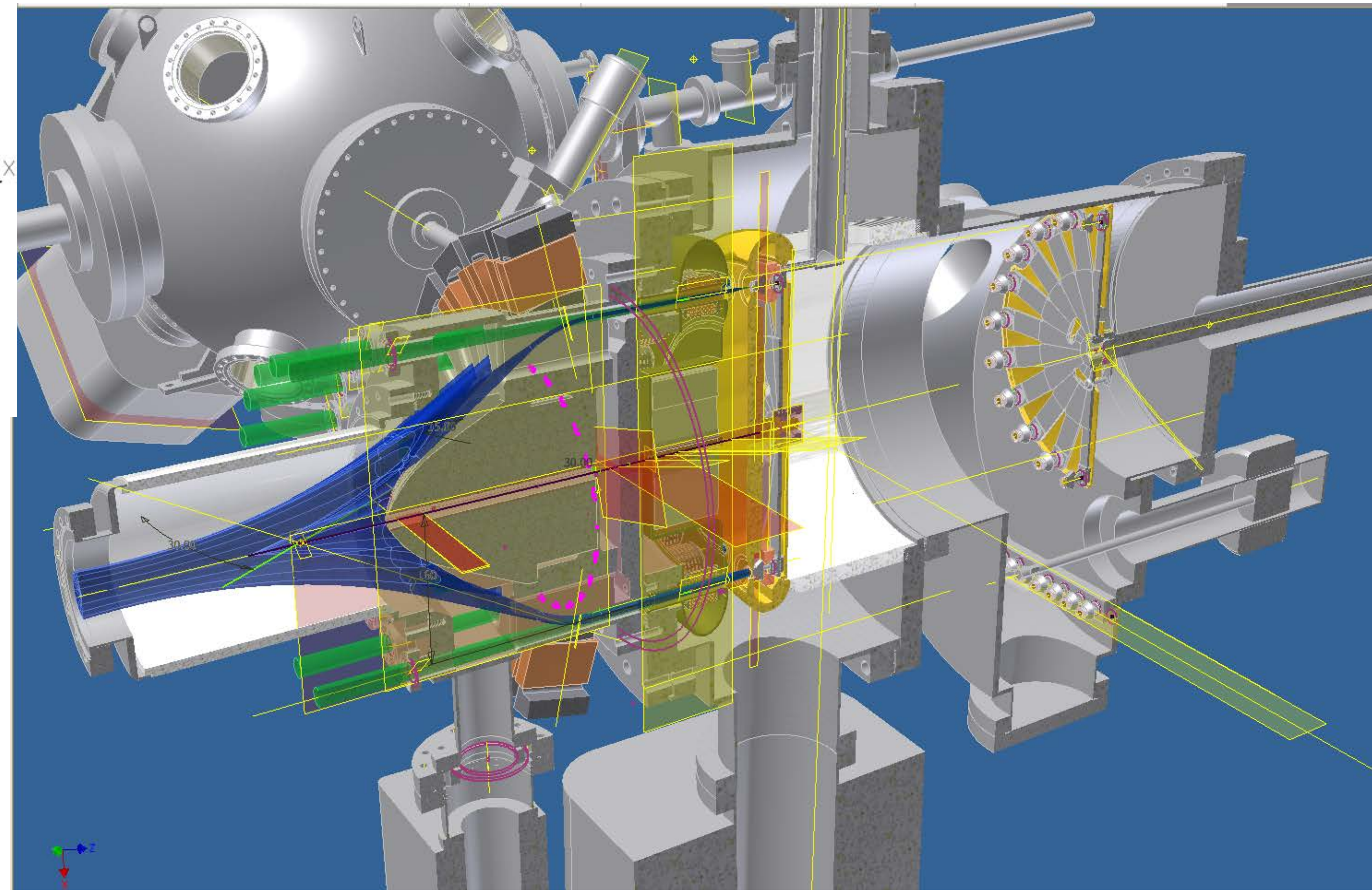
**Interaction Region**

- 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)

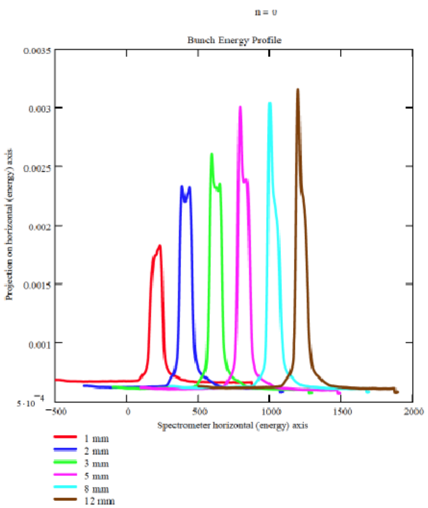


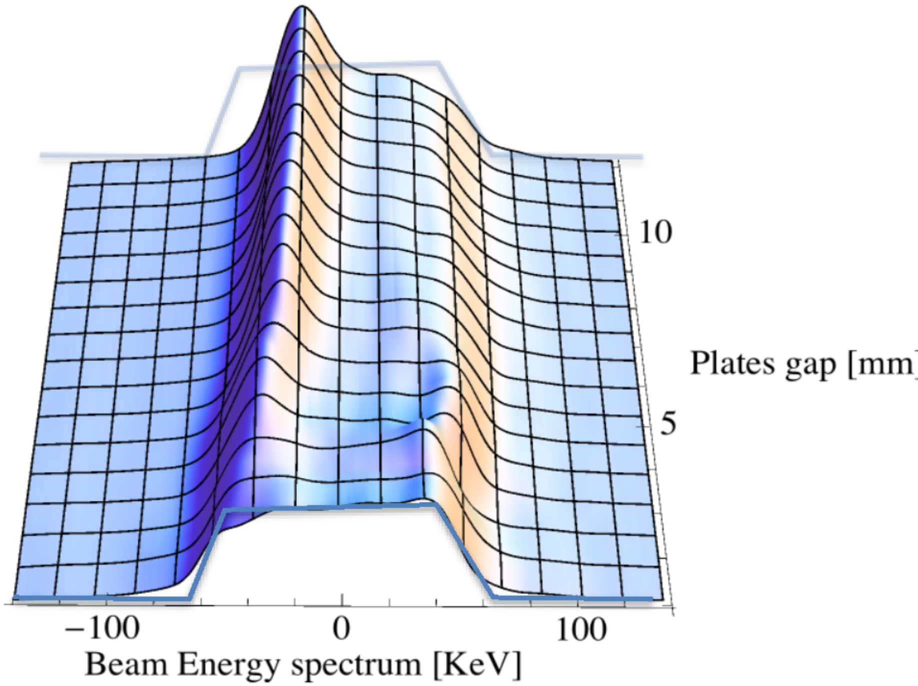
Sectioned view of the gun: Green –indicate Laser, Blue- indicate electron beam paths. Near center is the cathode shroud and anode, and to the right is the cathode magazine. The cathode preparation chamber can be seen on upper left.

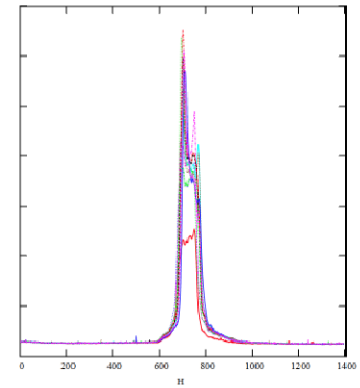


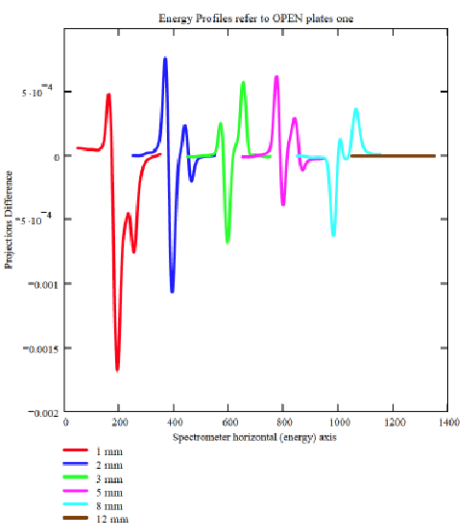
**Current 2-D simulation results are very close to our goals. Detailed mechanical design has been done. Most components have been ordered. 3D tracking is in progress. Post doc with cathode preparation expertise will arrive in one month. A Stony Brook Ph.D. student got started on the project.**

# Summary of experimental results





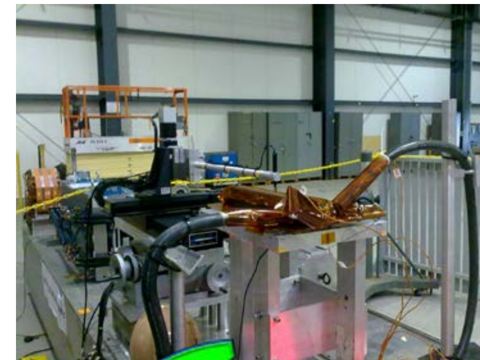

With closed gap the distribution is close to that from the HE slit – opening gap increases the distortions

BROOKHAVEN NATIONAL LABORATORY

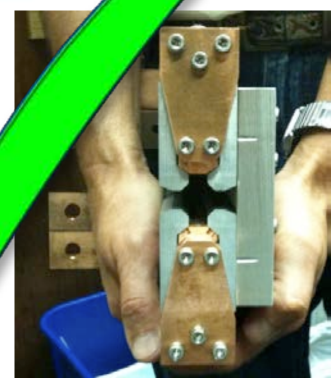
© M.Fedurin, V.Yakimenko, V.Litvinenko, A.Fedotov, D.Kayran,

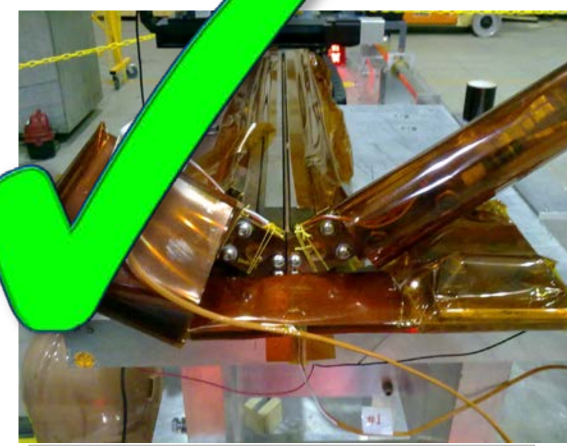
# LDRD: Development of Small Gap Magnets

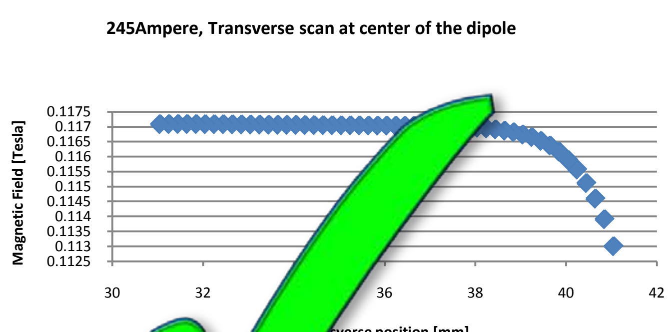
- Small gap provides for low current, low power consumption magnets
  - -> **low cost eRHIC**
  - Dipole prototype satisfy our reqs !!!
  - Fab. Technique used for quads did not satisfy our reqs
    - –but pawed the way to better fabrication technique

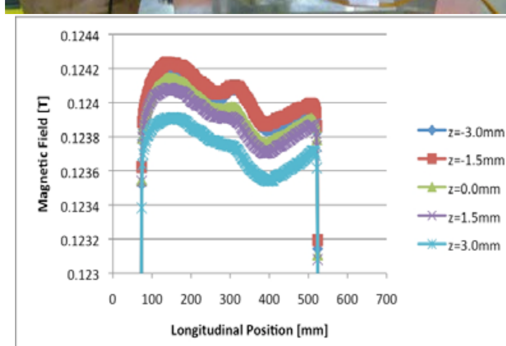


Gap 5 mm total
0.3 T for 30 GeV





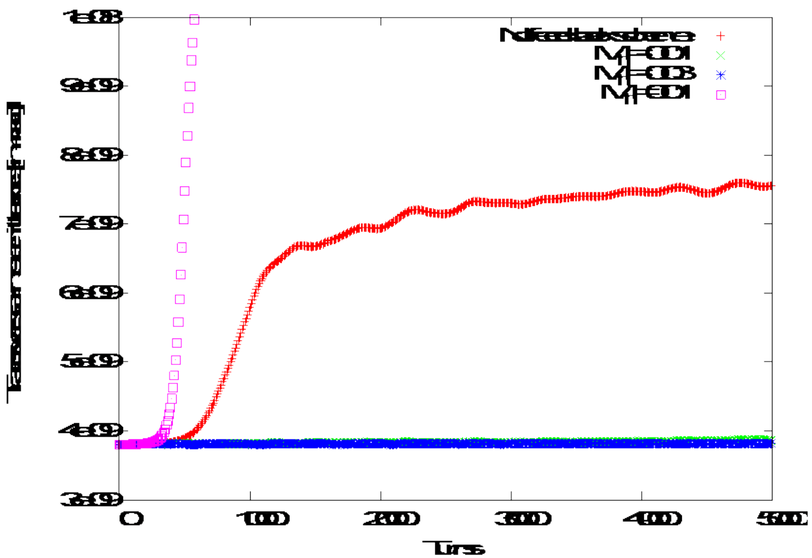


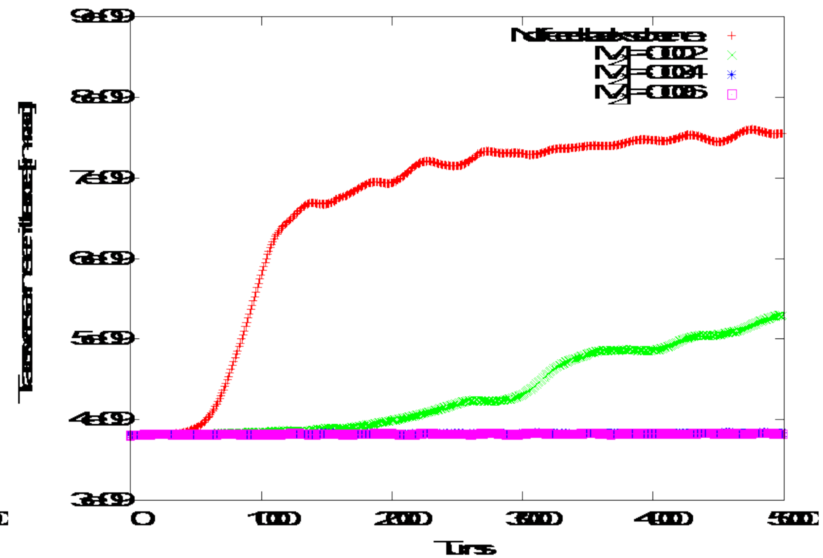




BROOKHAVEN NATIONAL LABORATORY

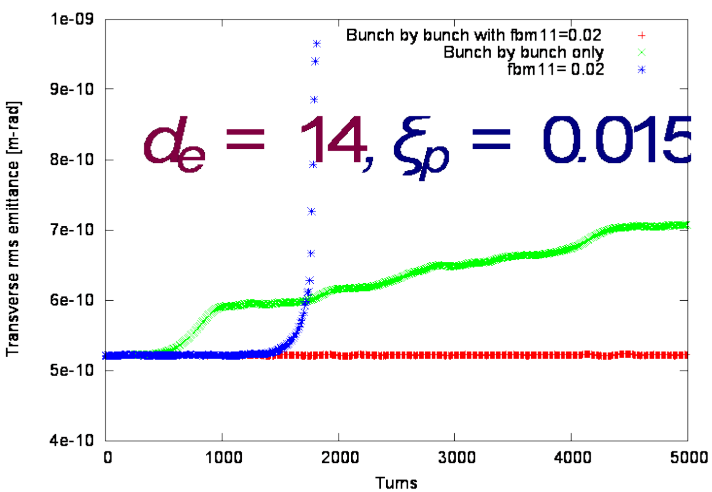
# The Feedback Scheme

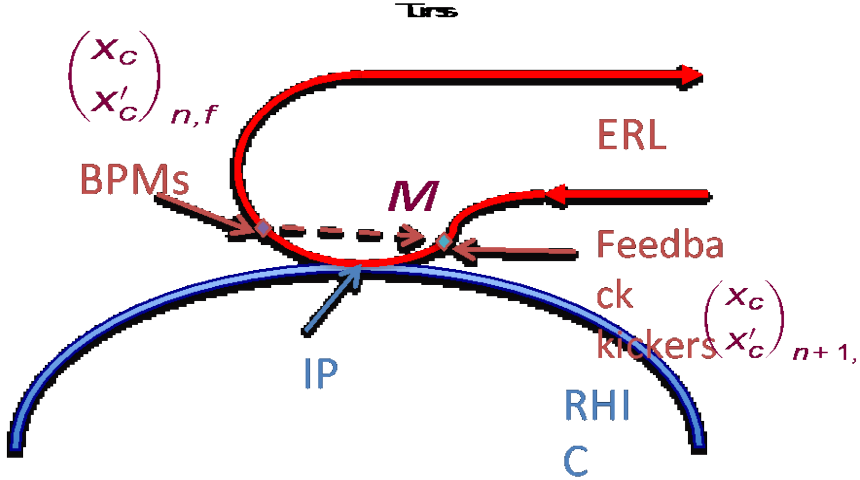
Beam-Beam Parameters: $d_e = 5.7, \xi_p = 0.015$





$d_e = 14, \xi_p = 0.015$



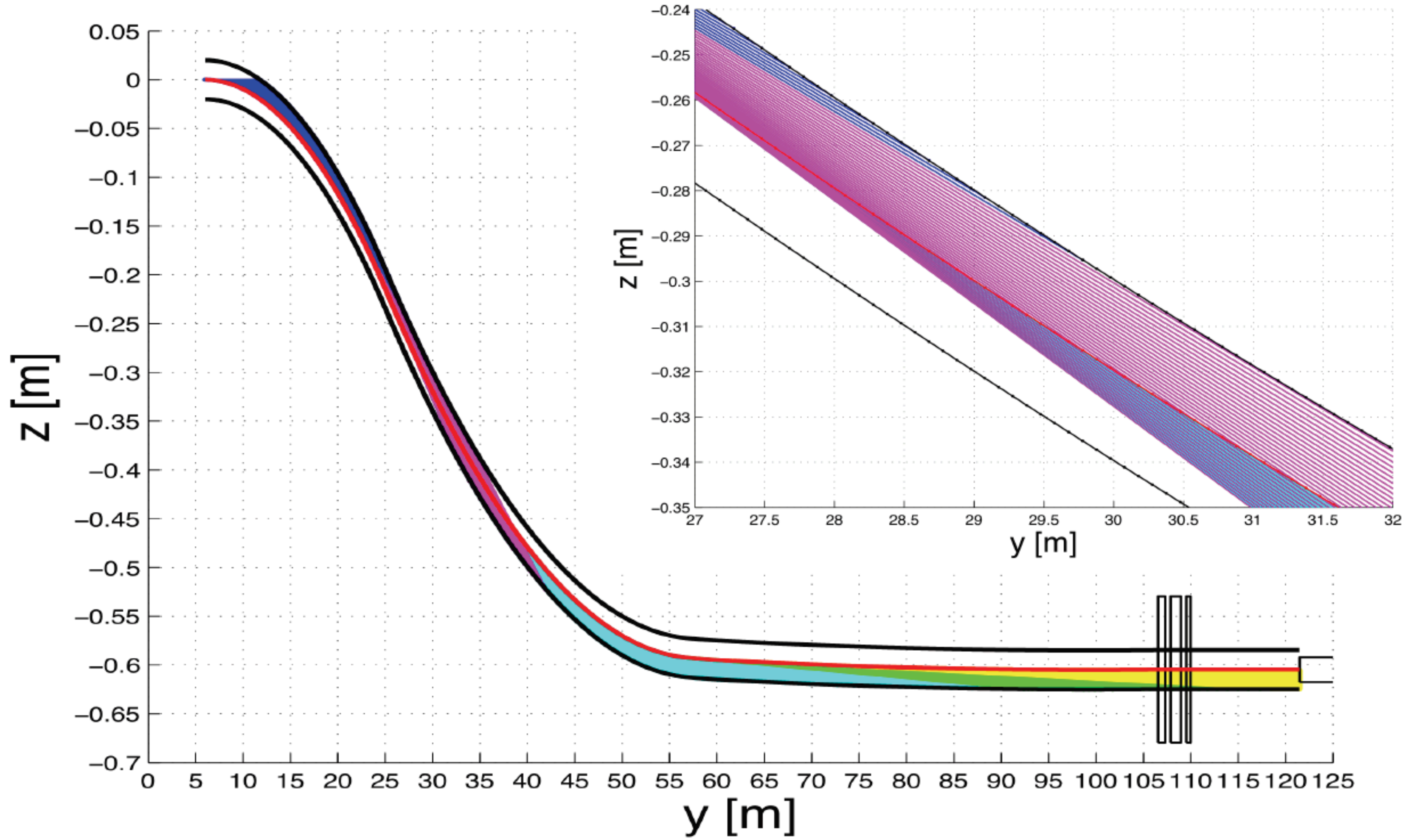




Y.Hao, V.N.Litvinenko, V.Ptitsyn

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

# Direct Synchrotron Radiation onto Absorbers

## The electron beam line from arc to IP



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

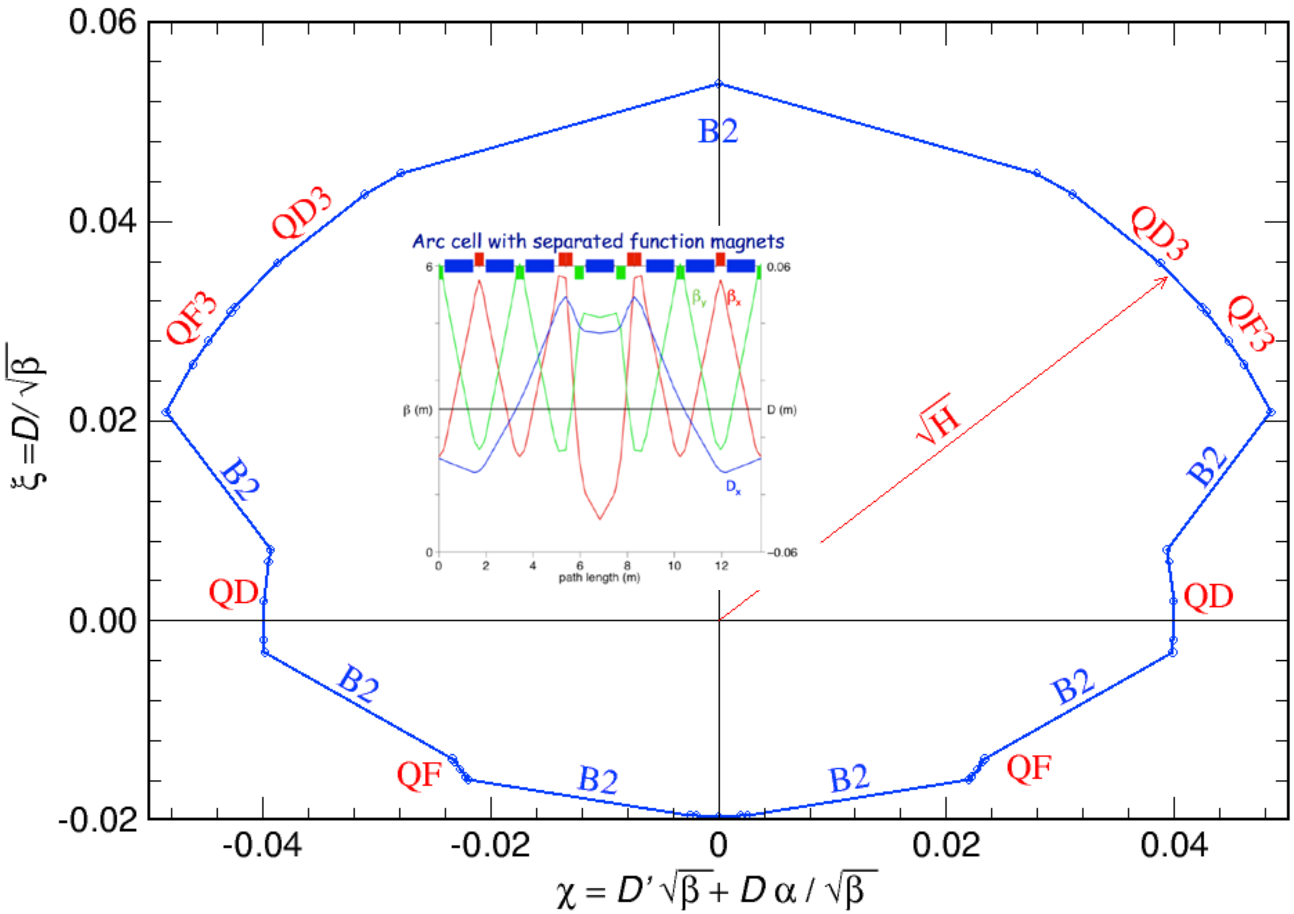
The inhomogeneous equation of the dispersion function *D* has two solutions: one without dipoles present (=0) and one with the dipoles = 1/ρ

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

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

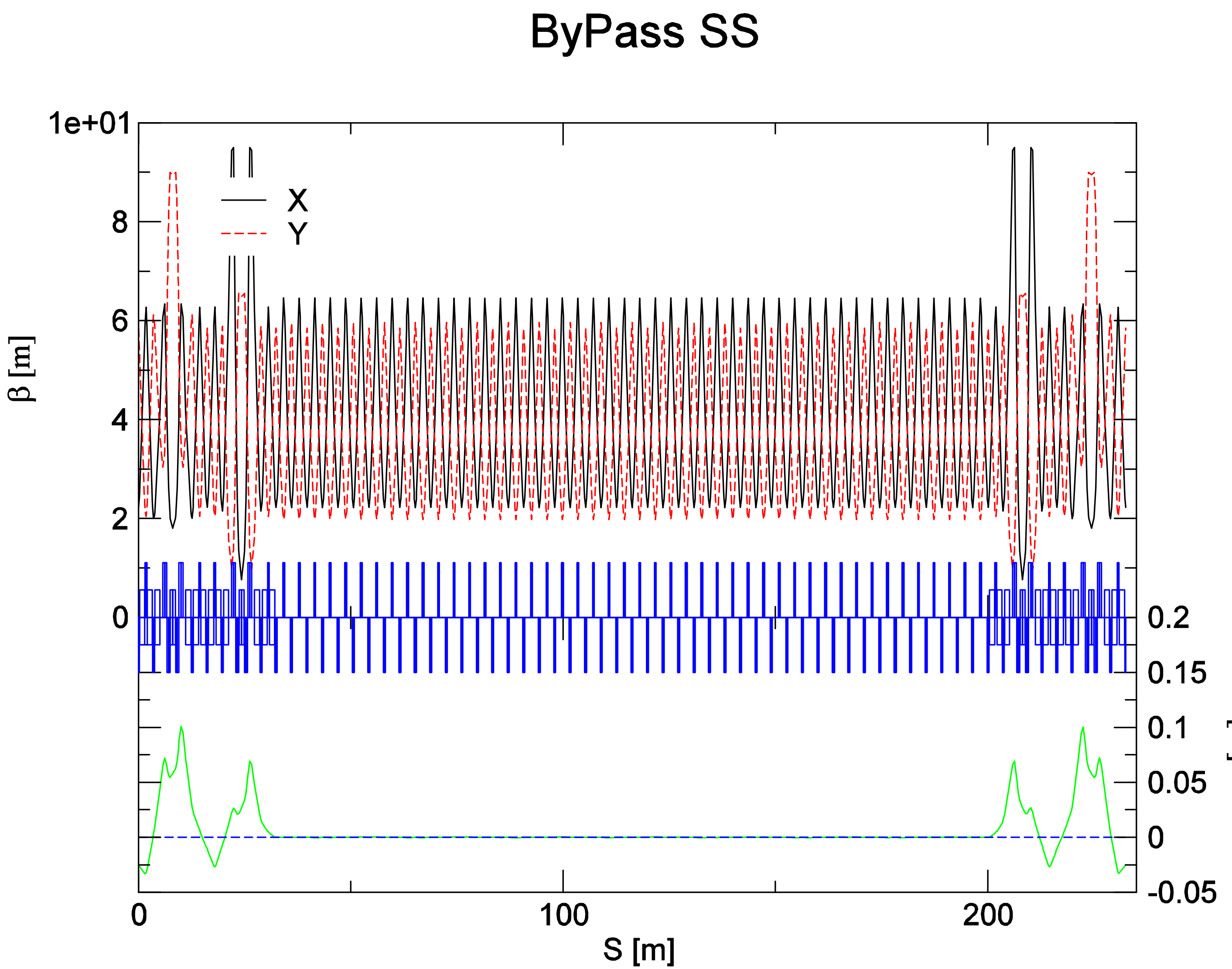
$$\xi = \frac{D}{\sqrt{\beta}}$$

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



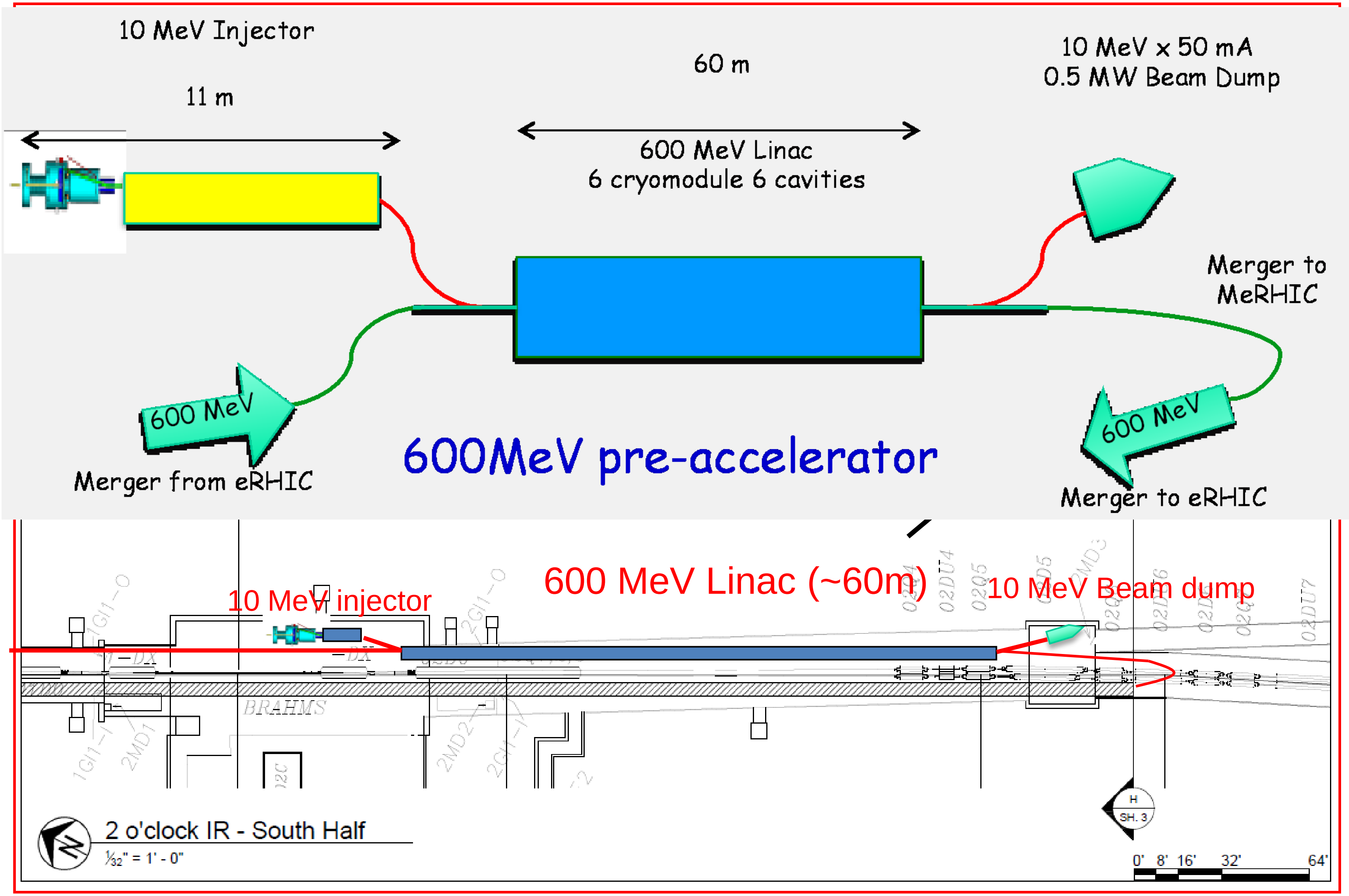

© D. Trbojevic

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




Time: Tue Jan 18 09:47:24 2011  Last file modify time: Tue Jan 18 09:46:32 2011

# eRHIC injector ERL




© D.Kayran, X.Chang

# eRHIC Beam Loss Due To Beam-Gas Scattering

(Bremsstrahlung & Elastic Scattering)

Cross Section For Elastic Scattering

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

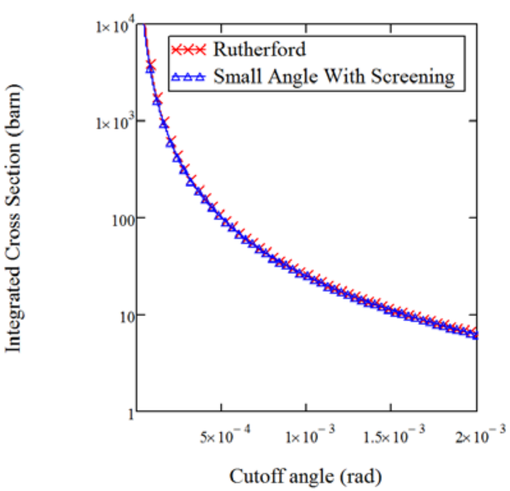
$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} \left[1 - \beta^2 \sin^2\left(\frac{\theta}{2}\right)\right]$$

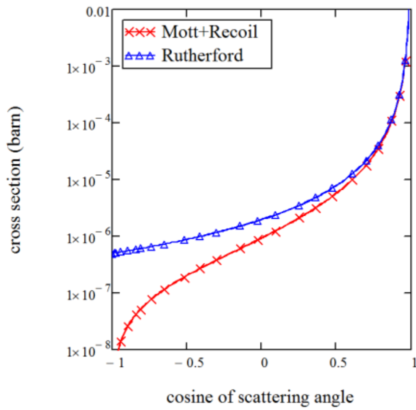
$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott+Recoil} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{1 + \sin^2(\theta/2)\frac{m_e \gamma \beta^2}{M_{nuclei}}}$$

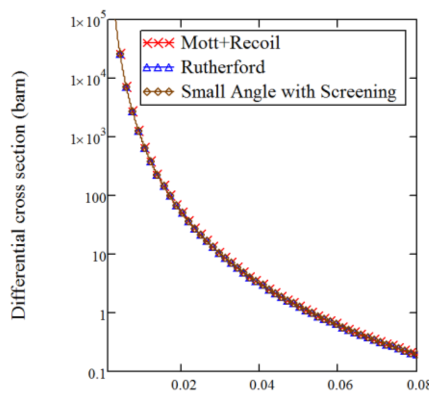
$$\left(\frac{d\sigma}{d\Omega}\right)_{\theta<<1+screening} = 4Z_i^2 r_e^2 \left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\left(\theta^2 + \theta_{min}^2\right)^2}$$

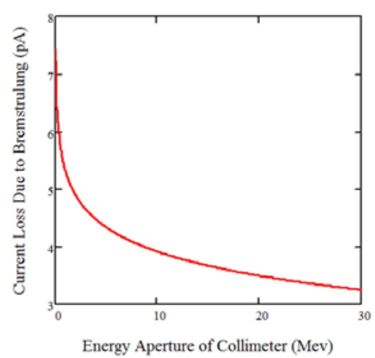
$$\theta_{min} = \frac{\hbar}{pa} \approx \frac{Z^{1/3}}{192} \frac{m_e c}{p} \approx \frac{2.6 \times 10^{-6}}{p(Gev)}$$

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



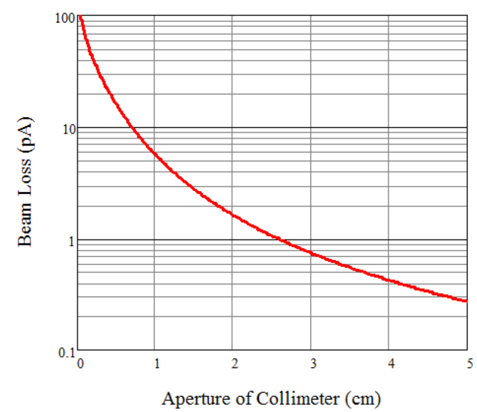




Depending on transverse aperture, beam loss due to elastic collision varies from 0.27 to 5.68pA (5mm - 1cm) under the present model.

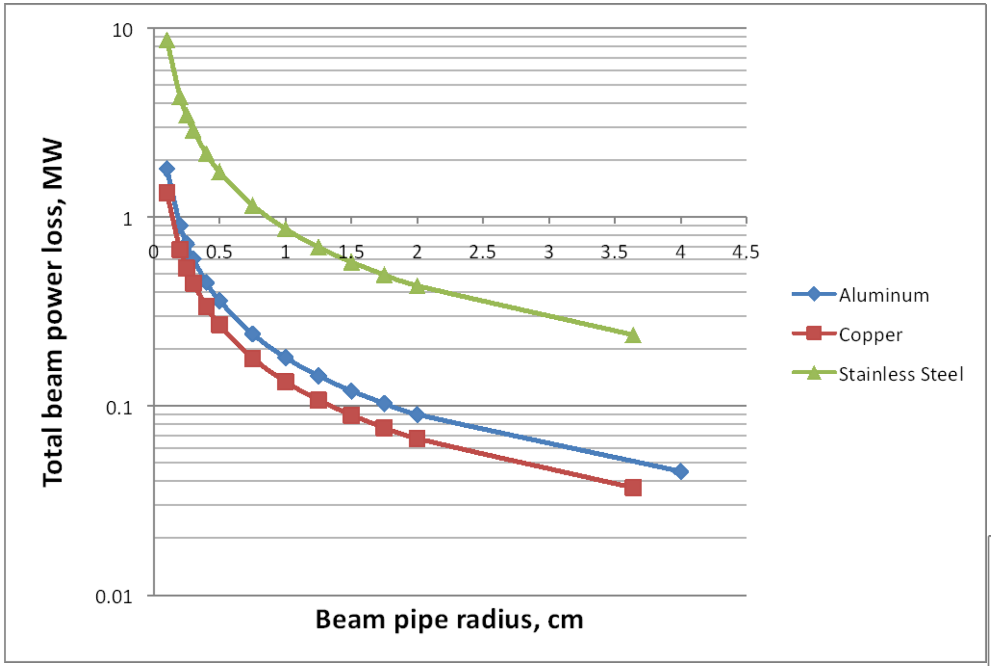
Depending on energy deviation aperture, beam loss due to bremsstrahlung varies from 3.92 to 5.32pA (10Mev/1Mev).




© Gang Wang

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

# Resistive wall wake-field

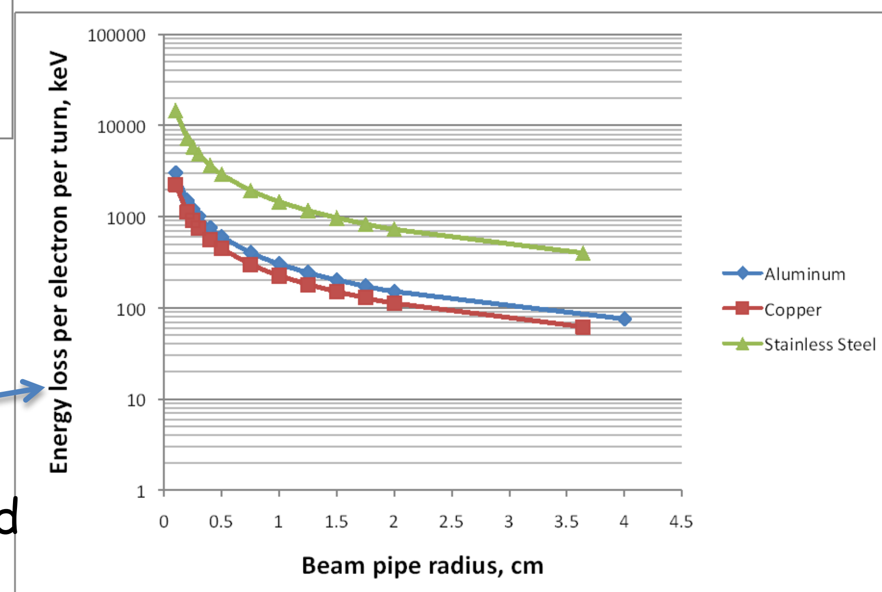



6 pass scheme
One turn: 3440 m
Bunch length: 2 mm
Bunch charge: 3.54 nC
Beam current: 50 mA

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

© V.Ptitsyn

Characterizes also
resulting energy spread




BROOKHAVEN
NATIONAL LABORATORY

# R&D ERL under construction.

## Aim: 0.5 amp CW

D. Kayran, G. McIntyre