Office of Science
U.S. DEPARTMENT OF ENERGY

CASE
Center for Accelerator Science and Education

eRHIC and MeRHIC

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Inputs on Physics from BNL EIC task force, E.-C.Aschenauer, T.Ulrich A.Cadwell, A.Deshpande, R.Ent, W.Gurin, T.Horn, H.Kowalsky, M.Lamont, T.W.Ludlam, R.Milner, B.Surrow, S.Vigdor, R.Venugopalan, W.Vogelsang

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Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

This is review of talks given yesterdays

11:10-11:30 MeRHIC design, Vadim Ptitsyn

11:30-11:50 Polarized electron gun for MeRHIC, X. Chang

11:50-12:10 MeRHIC injection system, D. Kayran

12:10-12:30 Superconducting RF for eRHIC, Ilan Ben-Zvi

13:30-13:50 eRHIC/MeRHIC lattice and IR, Dejan Trbojevic

13:50-14:15 Beam dynamics in MeRHIC and eRHIC, Mike Blaskiewicz

14:15-14:30 Polarization in MeRHIC and eRHIC, Mei Bai

14:30-14:50 Beam-Beam effects in MeRHIC and eRHIC, Y. Hao

14:50-15:10 MeRHIC IR & detector, J. Beebe-Wang

15:10-15:30 Engineering challenges & solutions for MeRHIC, Joe Tuozzolo

Slides are on the web – please see them for details

Conclusions first

- RHIC collides hadrons from polarized protons to U with energies 2.5 GeV/u to 250 GeV/u
- Collider beam physics laws assert that with any given beam and IR parameters, a linac-ring collider outperforms a ring-ring collider
- RHIC is the only high energy polarized proton collider with polarization control of each individual bunch. ERL has full spin transparency and allows high-frequency change of the spin direction. There is no beam-beam induced electron beam depolarization in eRHIC.
- We developed detailed technical design and cost estimate for the first stage of eRHIC, called MeRHIC
- We developed a clear staged pass toward full energy high luminosity, $L>10^{34}$ sec^{-1} cm^{-2}, eRHIC, based on the experience from hadron and lepton-hadron colliders
- eRHIC R&D is focused on:
  - (a) Single cathode and Gatling polarized electron guns
  - (b) Compact SRF linacs with HOM damping
  - (c) Multi-pass high average current ERLs
  - (e) Small gap magnets and vacuum chambers
  - (f) Coherent electron cooling

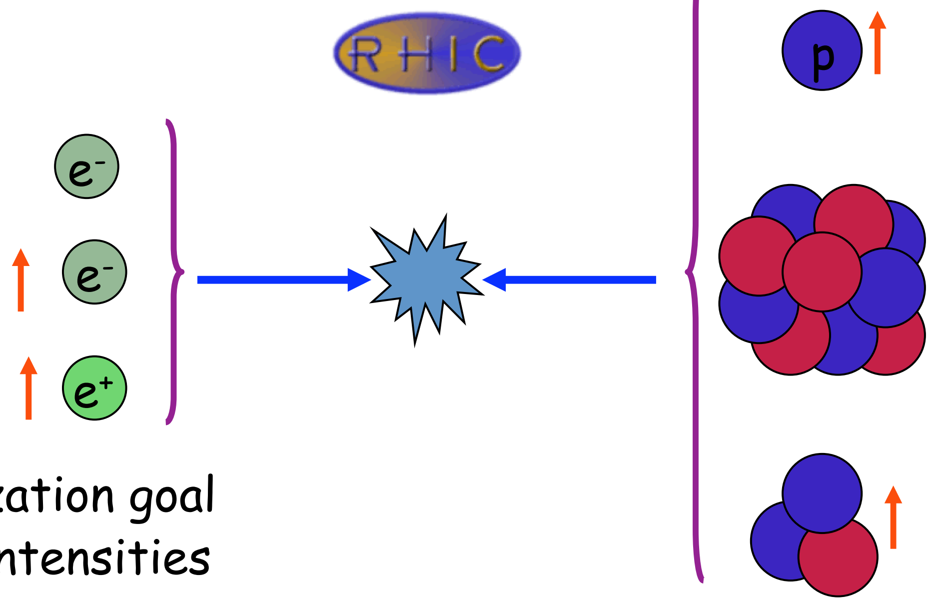
Content

- What is eRHIC
- eRHIC staging
- MeRHIC design
- IP developments
- R&D program for eRHIC
- Costs

eRHIC Scope -QCD Factory

Electron accelerator

RHIC



Unpolarized and polarized leptons 4-20 (30) GeV

70% beam polarization goal
Positrons at low intensities

Polarized protons
25↓ 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

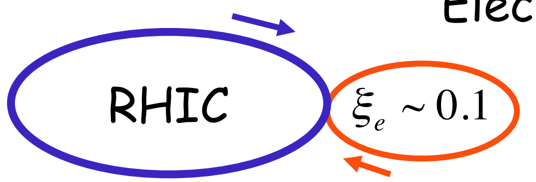
Center mass energy range: 15-200 GeV

eA program for eRHIC needs as high as possible energies of electron beams even with a trade-off for the luminosity: 20 GeV is absolutely essential and 30 GeV is strongly desirable

2007 Choosing the focus: ERL or ring for electrons?

- Two main design options for eRHIC:
  - Ring-ring:

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

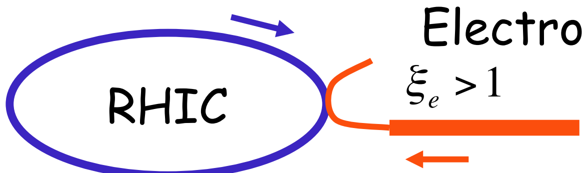


Electron storage ring

  - Linac-ring:

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

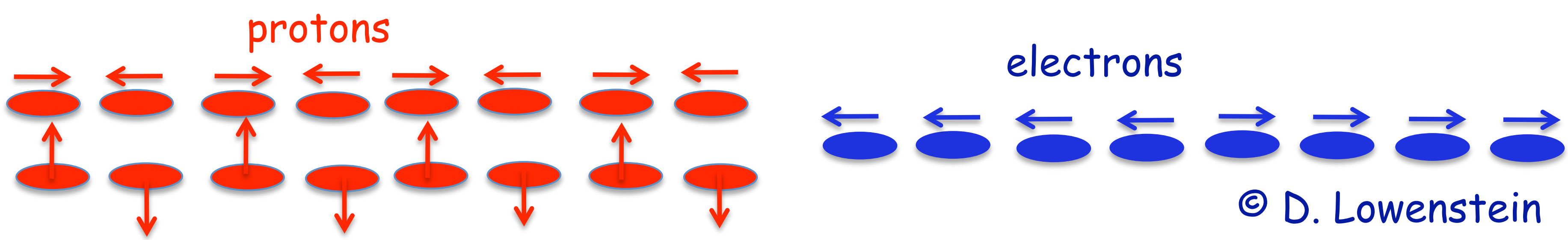
Electron linear accelerator



Natural staging strategy

✔ L x 10

Additional advantage of linac-ring - removing systematic errors



It is built-in feature of the linac-ring eRHIC: we can arbitrary select polarization of individual bunches

a) In RHIC this is already implemented by injection scheme (ion source) for protons
b) In eRHIC ERL electron polarization is reversible by switching helicity of the laser photons

It is impossible in ring-ring EIC

2008: Staging of eRHIC

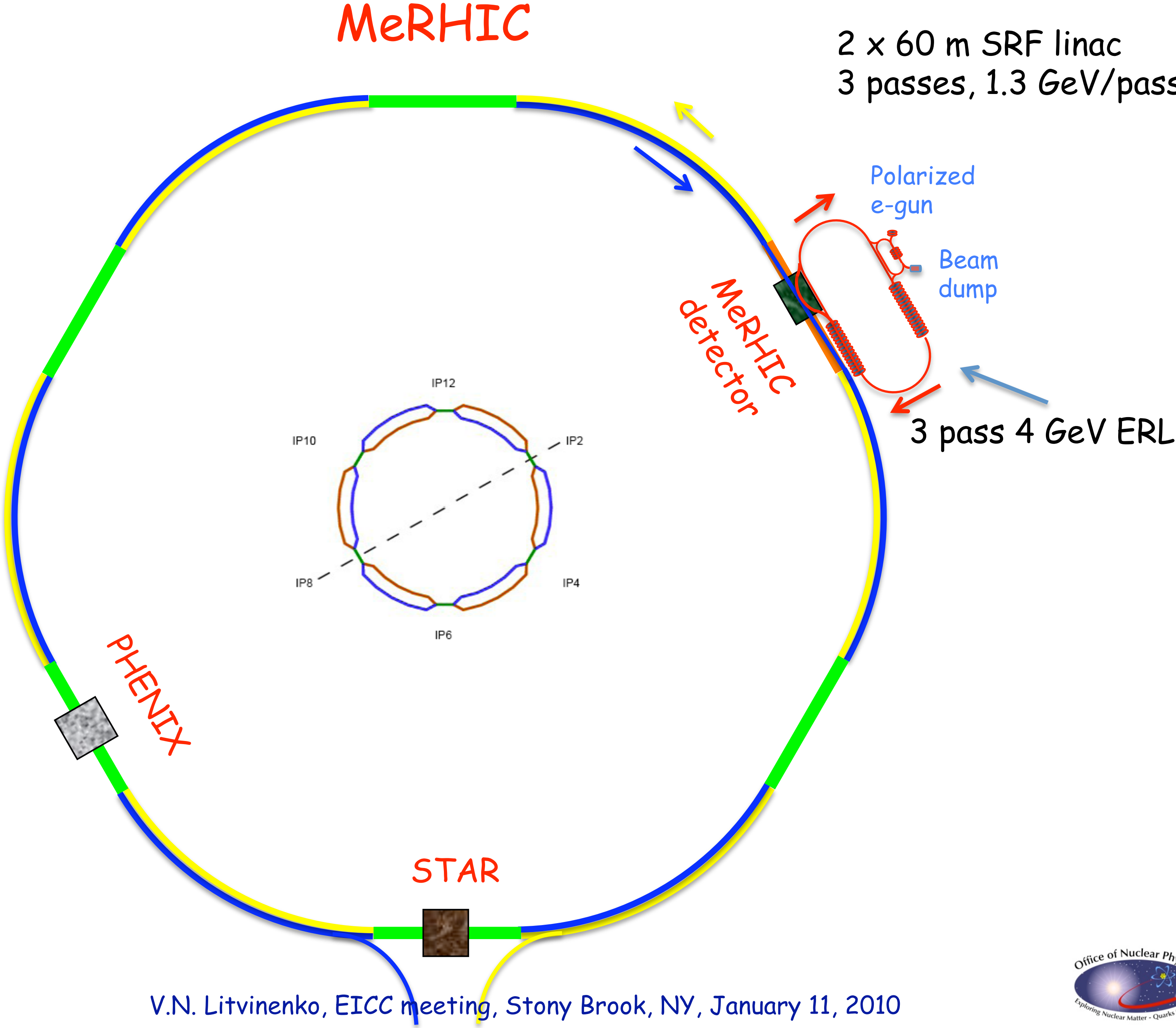
- **MeRHIC**: Medium Energy eRHIC
  - Both Accelerator and Detector are located at IP2 of RHIC
  - 4 GeV e^- x 250 GeV p (63 GeV c.m.), L ~ 10^{32}-10^{33} cm^{-2} sec^{-1}
  - 90% of hardware will be used for HE eRHIC
- **eRHIC, High energy and luminosity phase,** inside RHIC tunnel

Full energy, nominal luminosity

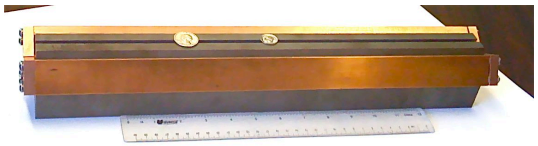
  - Polarized 20 GeV e^- x 325 GeV p (160 GeV c.m), L ~ 10^{33}-10^{34} cm^{-2} sec^{-1}
  - 30 GeV e x 120 GeV/n Au (120 GeV c.m.), ~1/5 of full luminosity
  - and 20 GeV e x 120 GeV/n Au (120 GeV c.m.), full liminosity
- **eRHIC up-grades – if needed**
  - Higher luminosity
  - Higher hadron energy

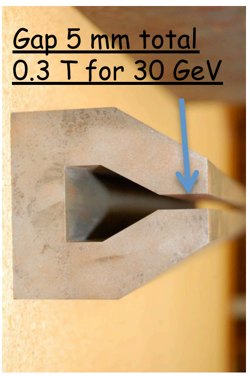
4 GeV e x 250 GeV p - 100 GeV/u Au

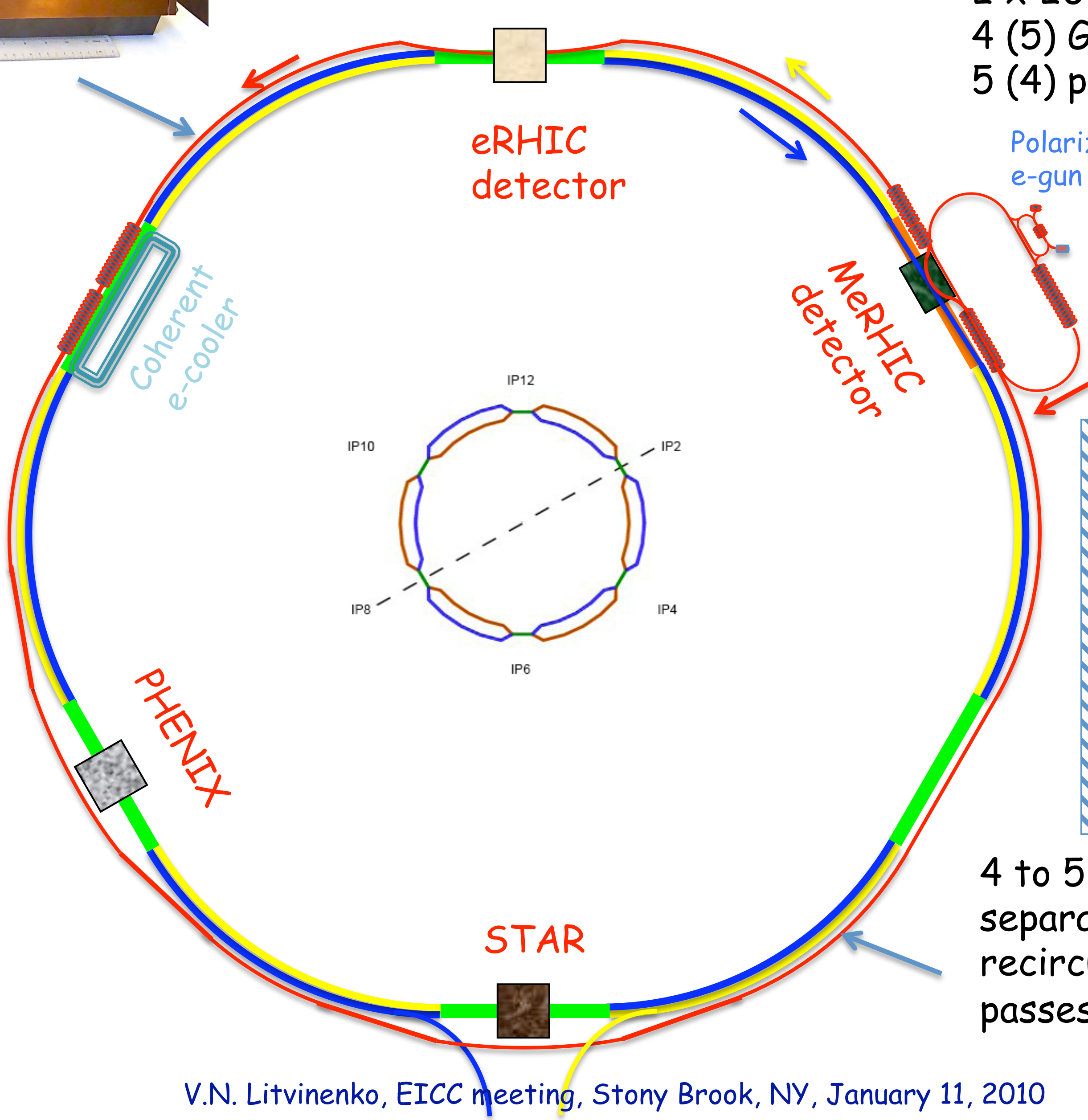
MeRHIC

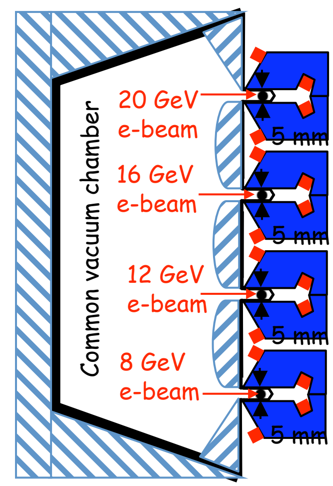


10 to 20 GeV e x 325 GeV p – 130 GeV/u Au eRHIC









2 x 200 m SRF linac
4 (5) GeV per pass
5 (4) passes

Possibility of 30 GeV low current operation

4 to 5 vertically separated recirculating passes

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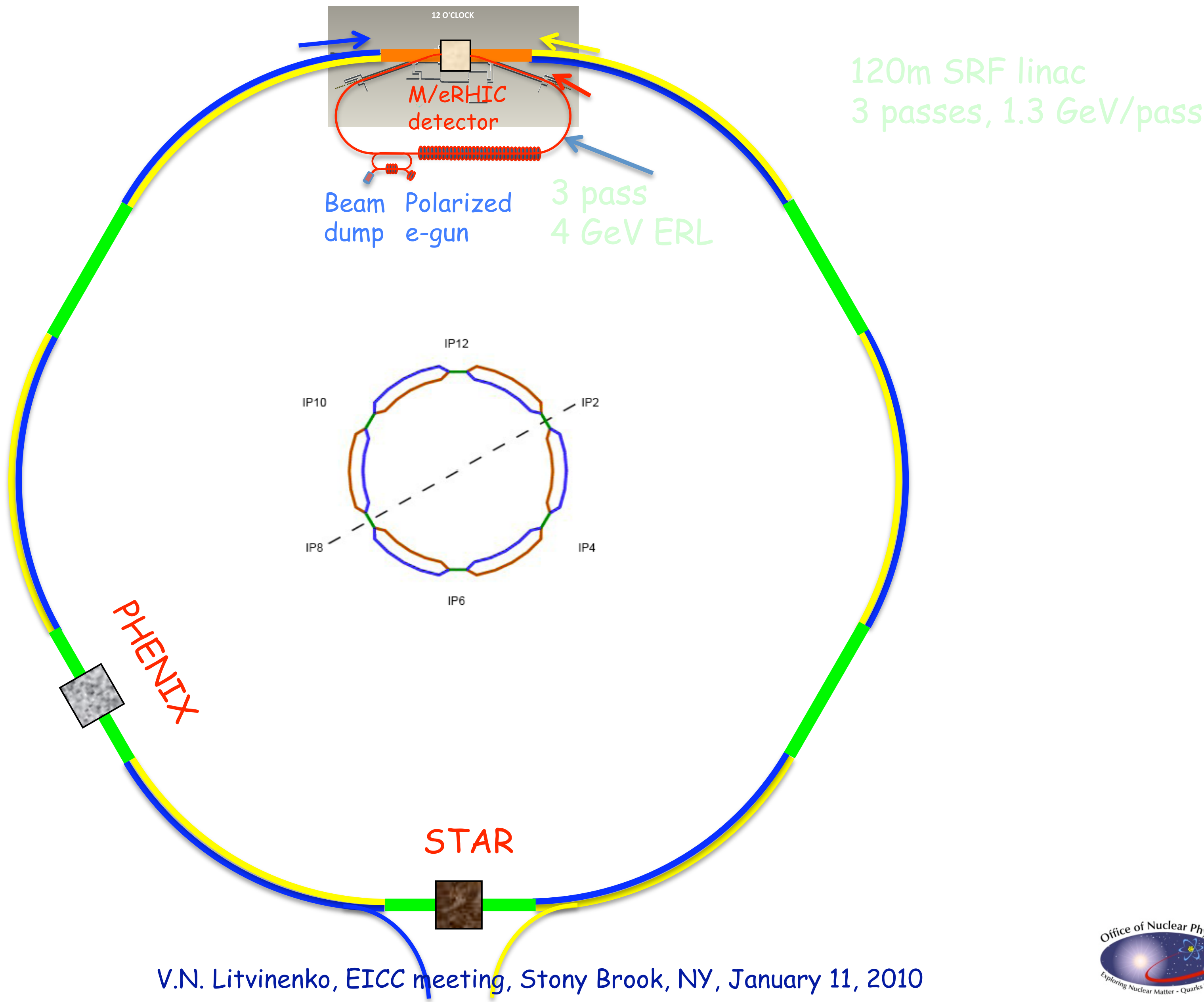
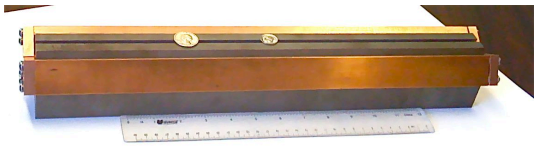
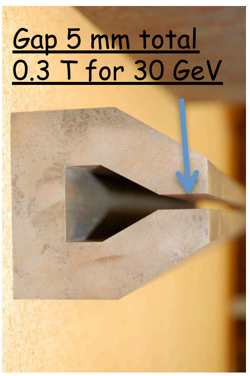
4 GeV e x 250 GeV p – 100 GeV/u Au

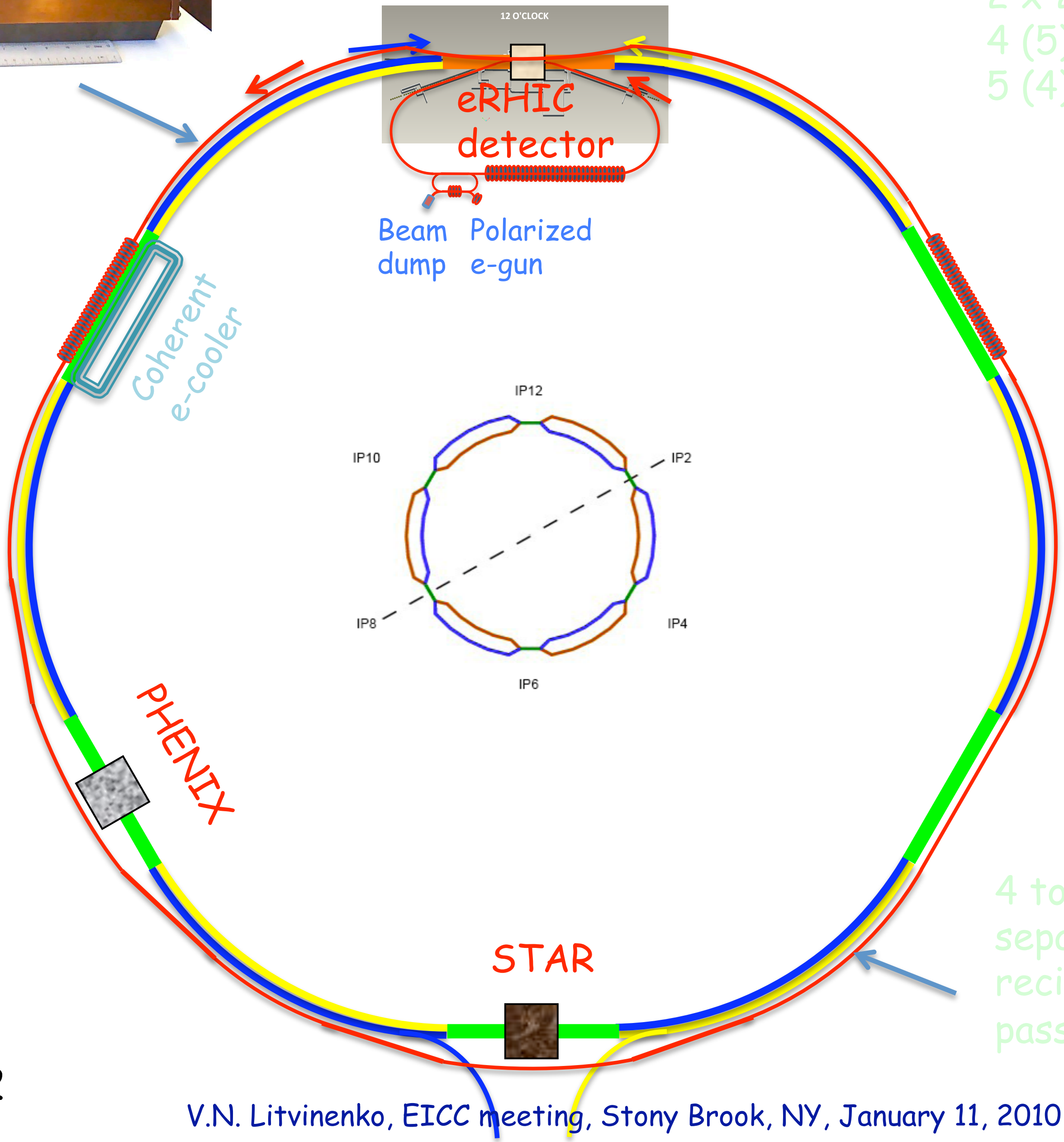
MeRHIC



10 to 20 GeV e x 325 GeV p – 130 GeV/u Au
eRHIC







2 x 200 m SRF linac
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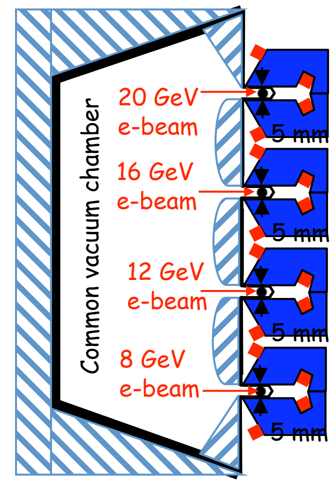
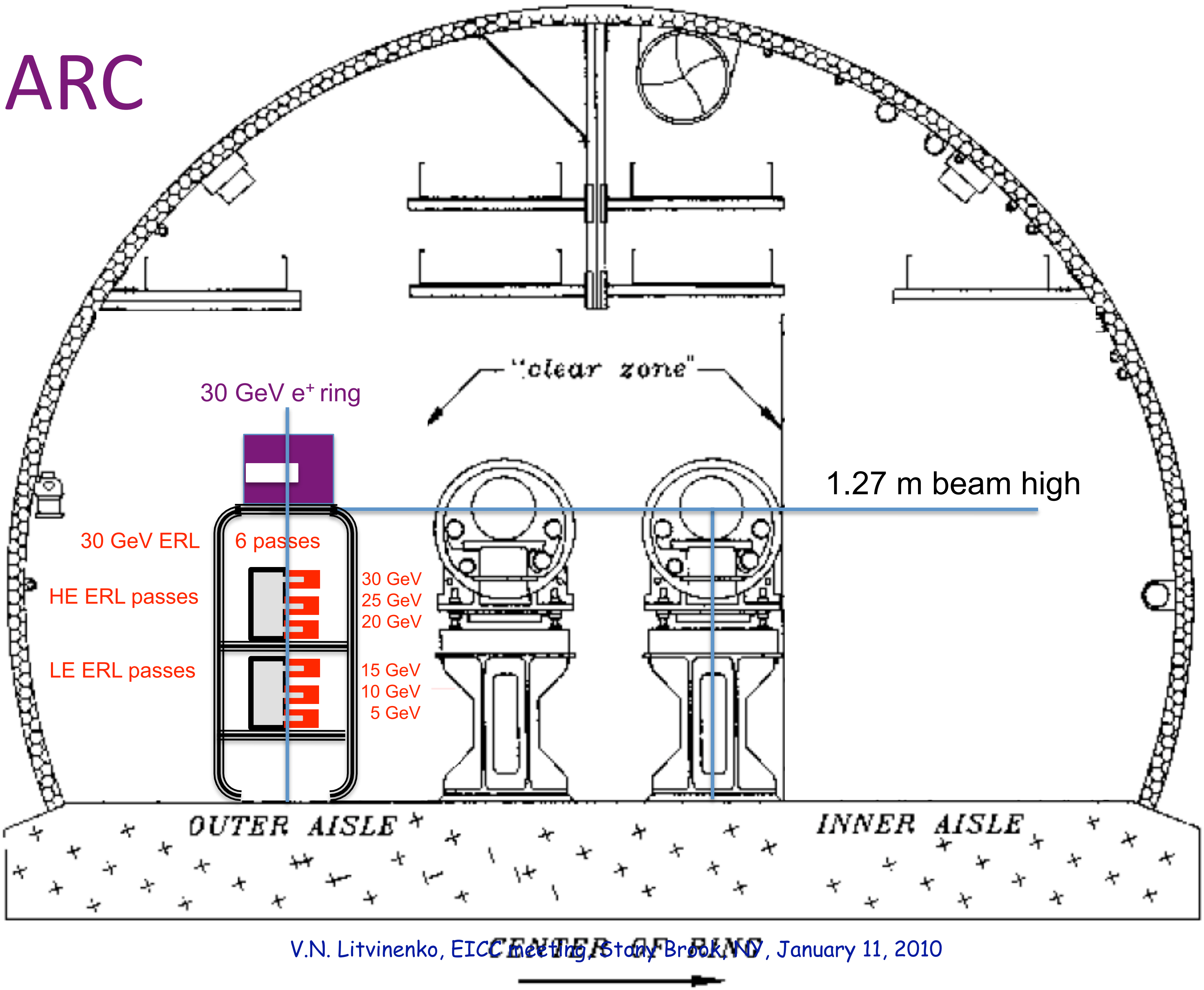


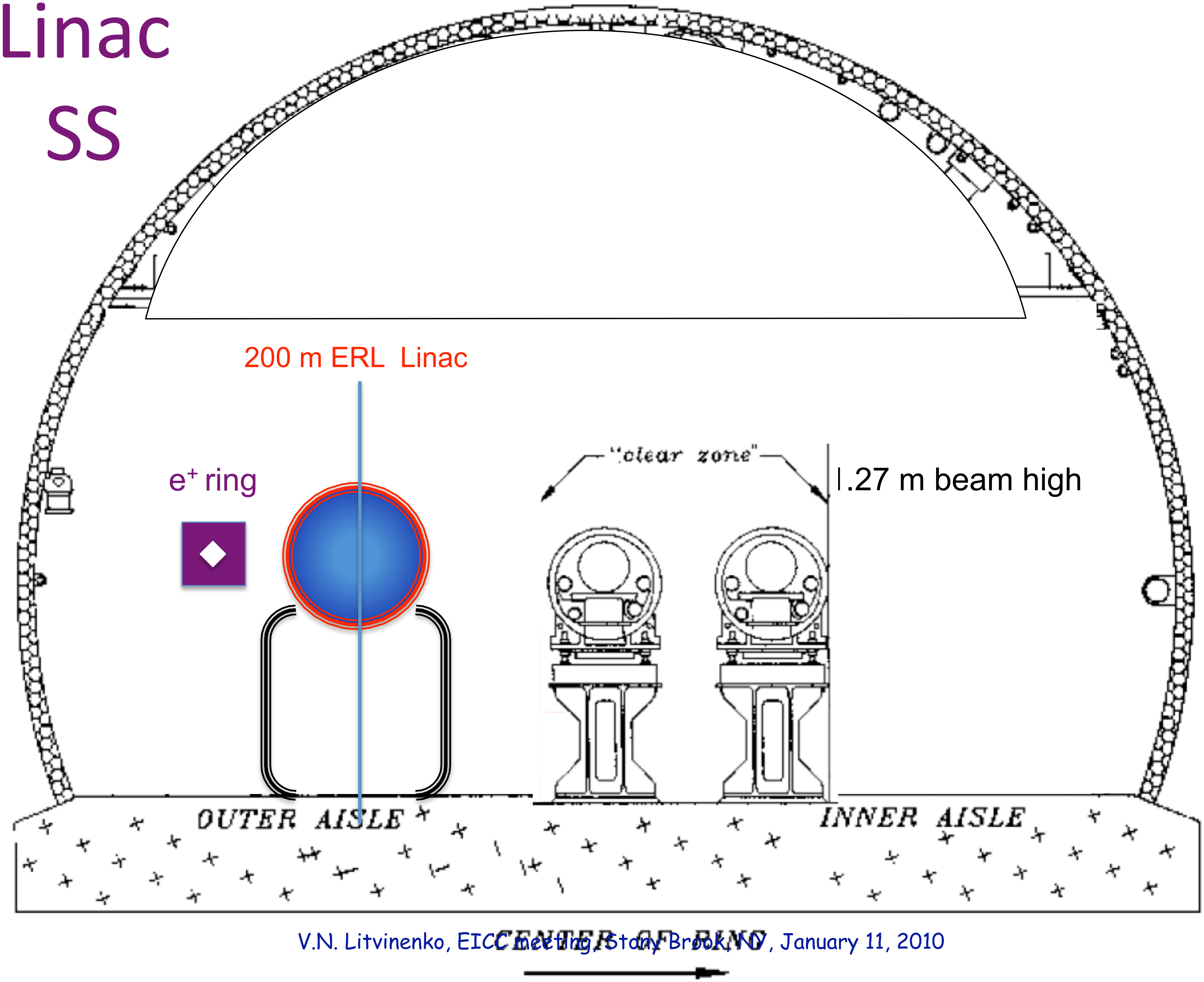
Possibility
of 30 GeV
low current
operation

4 to 5 vertically
separated
recirculating
passes

ARC


"clear zone"
30 GeV e+ ring
1.27 m beam high
30 GeV ERL
6 passes
HE ERL passes
LE ERL passes
30 GeV
25 GeV
20 GeV
15 GeV
10 GeV
5 GeV
OUTER AISLE
INNER AISLE
CENTER OF RING

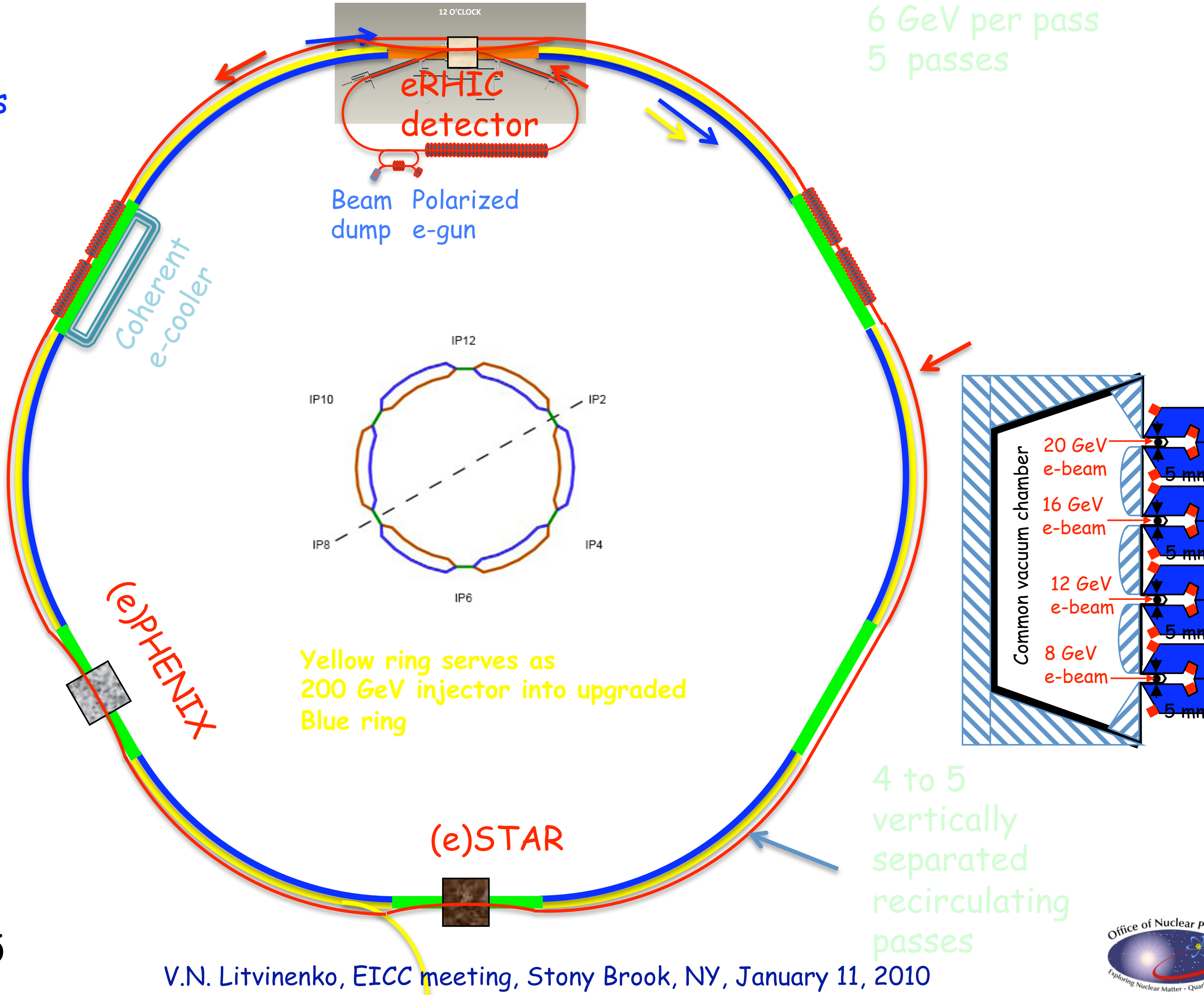
Linac SS


200 m ERL Linac
e+ ring
"clear zone"
1.27 m beam high
OUTER AISLE
INNER AISLE
CENTER OF RING

30 GeV e x 800 GeV p – 320 GeV/u U

eRHIC II

POSSIBLE
FUTURE
Up-grade:
New LHC-class
SC DIPOLE
magnets
in Blue ring



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V.N. Litvinenko, EICC meeting, Stony Brook, NY, January 11, 2010

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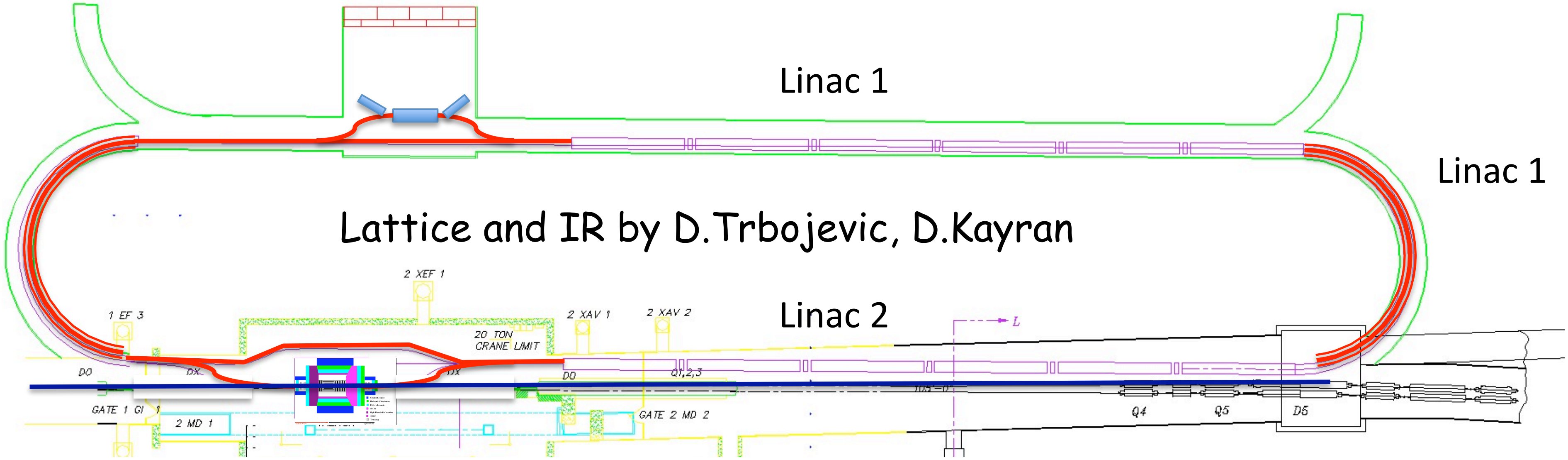
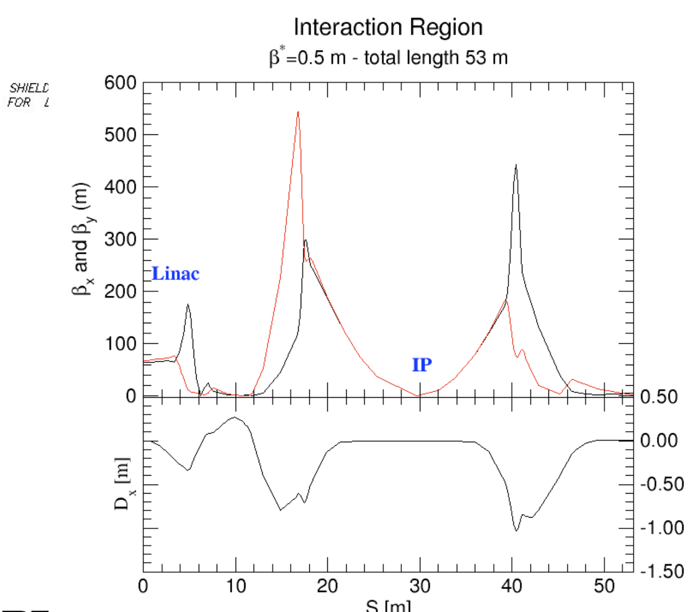
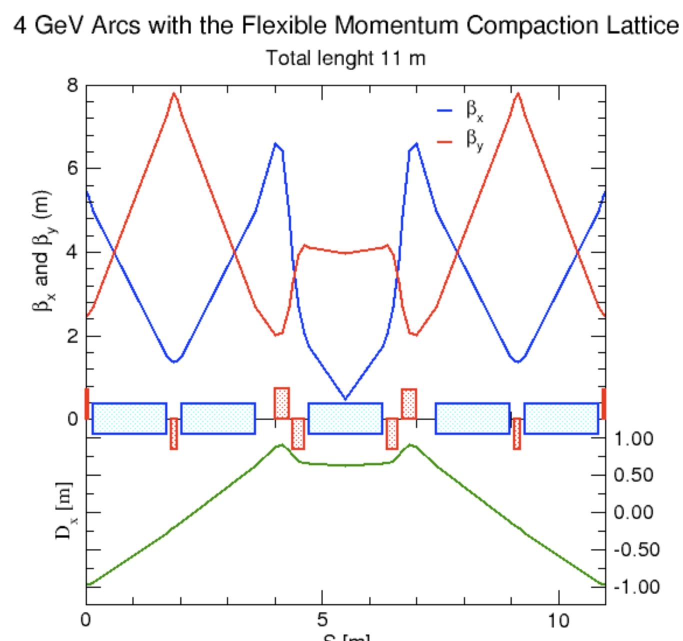
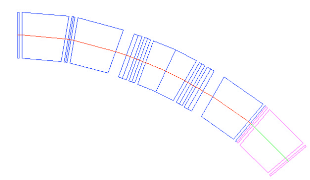
MeRHIC with 4 GeV ERL at 2 **o'clock** IR of RHIC

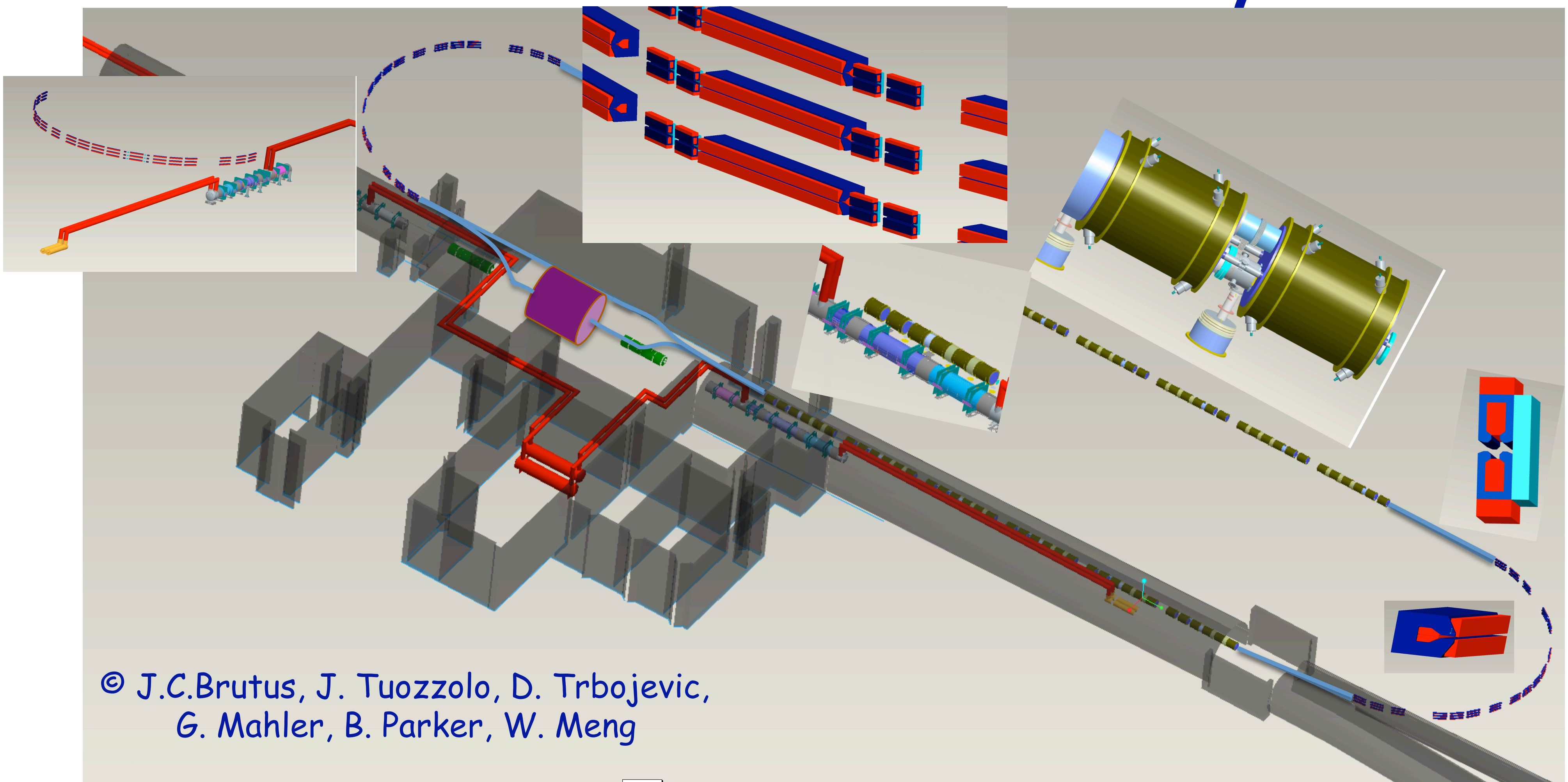




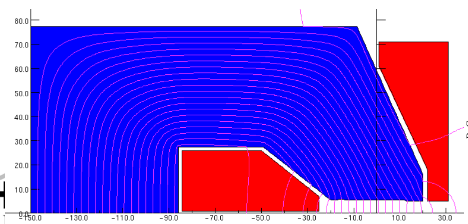


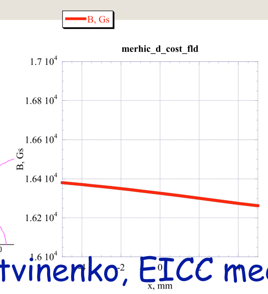


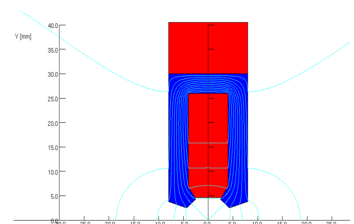
MeRHIC in IR 2: 3D layout

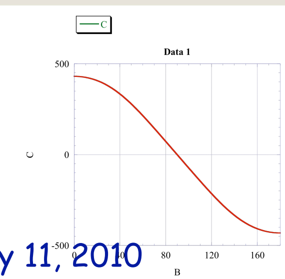


© J.C.Brutus, J. Tuozzolo, D. Trbojevic,
G. Mahler, B. Parker, W. Meng

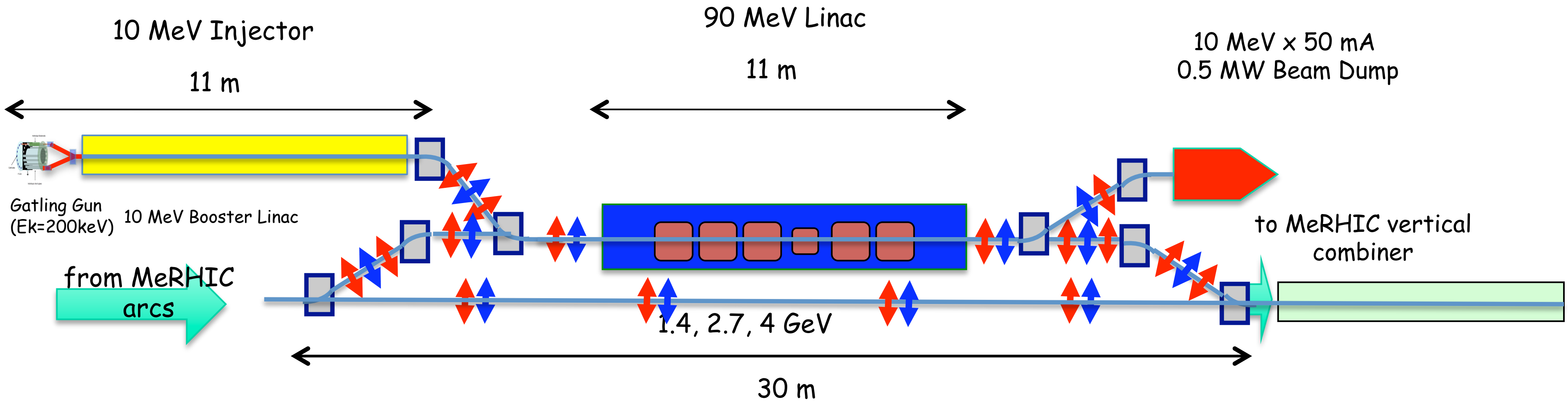








100 MeV Pre Accelerator ERL



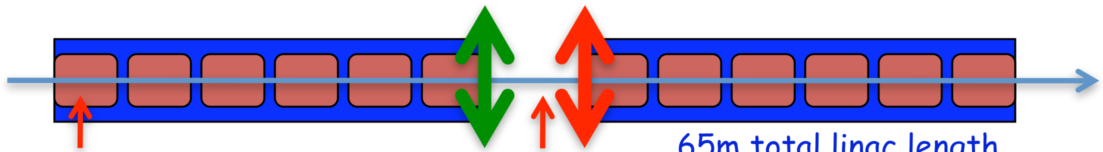
Injector Parameters
Polarized Gun (200kV)
Cathode GaAs,
Laser 780nm
Emax= 10 MeV
Iavr =50 mA,
Q per bunch =5nC

Pre-accelerator ERL:
One pass
Energy gain 90 MeV
Einj & Eextr=10 MeV
Emax =100 MeV

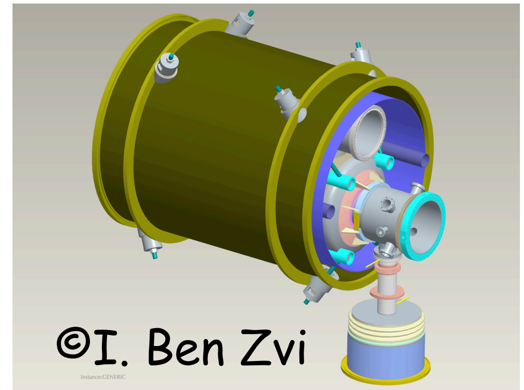
eBeam parameters :
E=100 MeV
Iavr=50 mA
Ipeak=500 A
Reprate = 9.8 MHz
Emittance =70 mm-mrad
Banchlength = 3 mm
dE/E = 1E-3

© D. Kayran

MeRHIC Linac Design



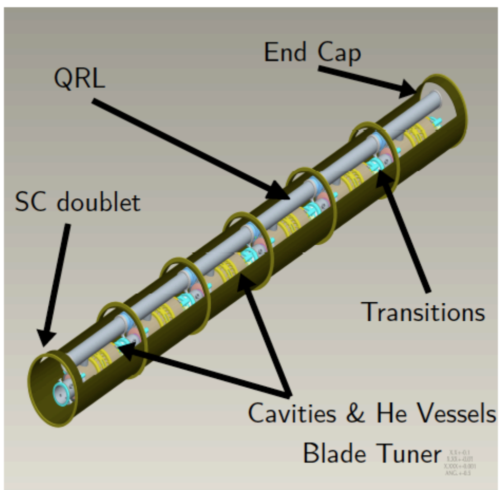
65m total linac length
All cold: no warm-to-cold transition



Based on BNL SRF cavity with fully suppressed HOMs
Critical for high current multi-pass ERL

Preliminary Cryomodule

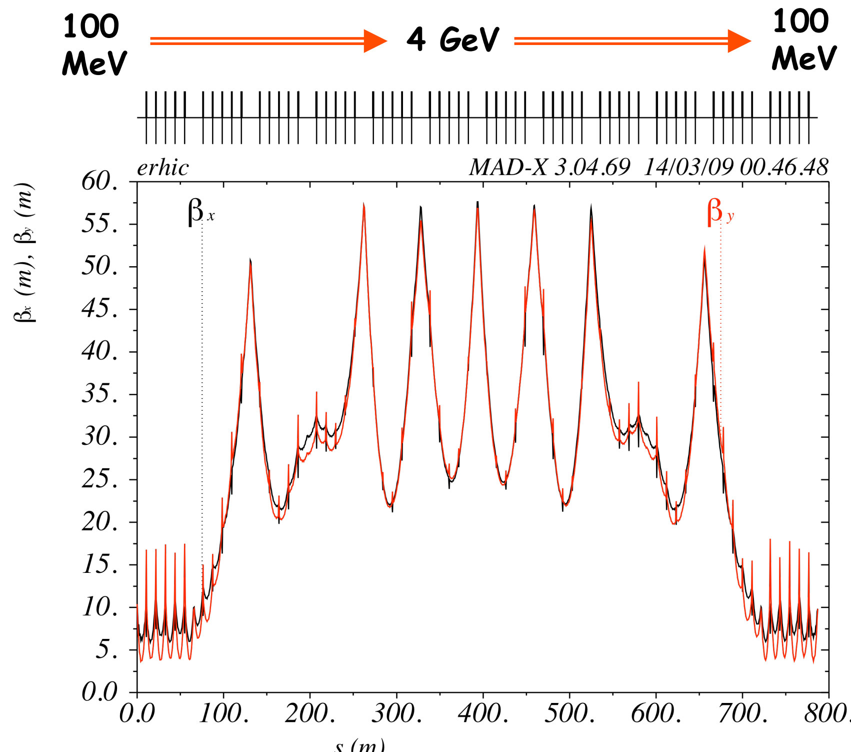
©George Mahler



String assembly of multiple cavities. Heat shielding and top covers removed for clarity.

Breakdown of the eRHIC Cryomodule

- N cavities = 6 (but can 4-8)
- Module length = 9.6 m
- L period = 10.6 m
- E_{acc} = 18.0 MV/m
- dE/ds = 10.2 MeV/m



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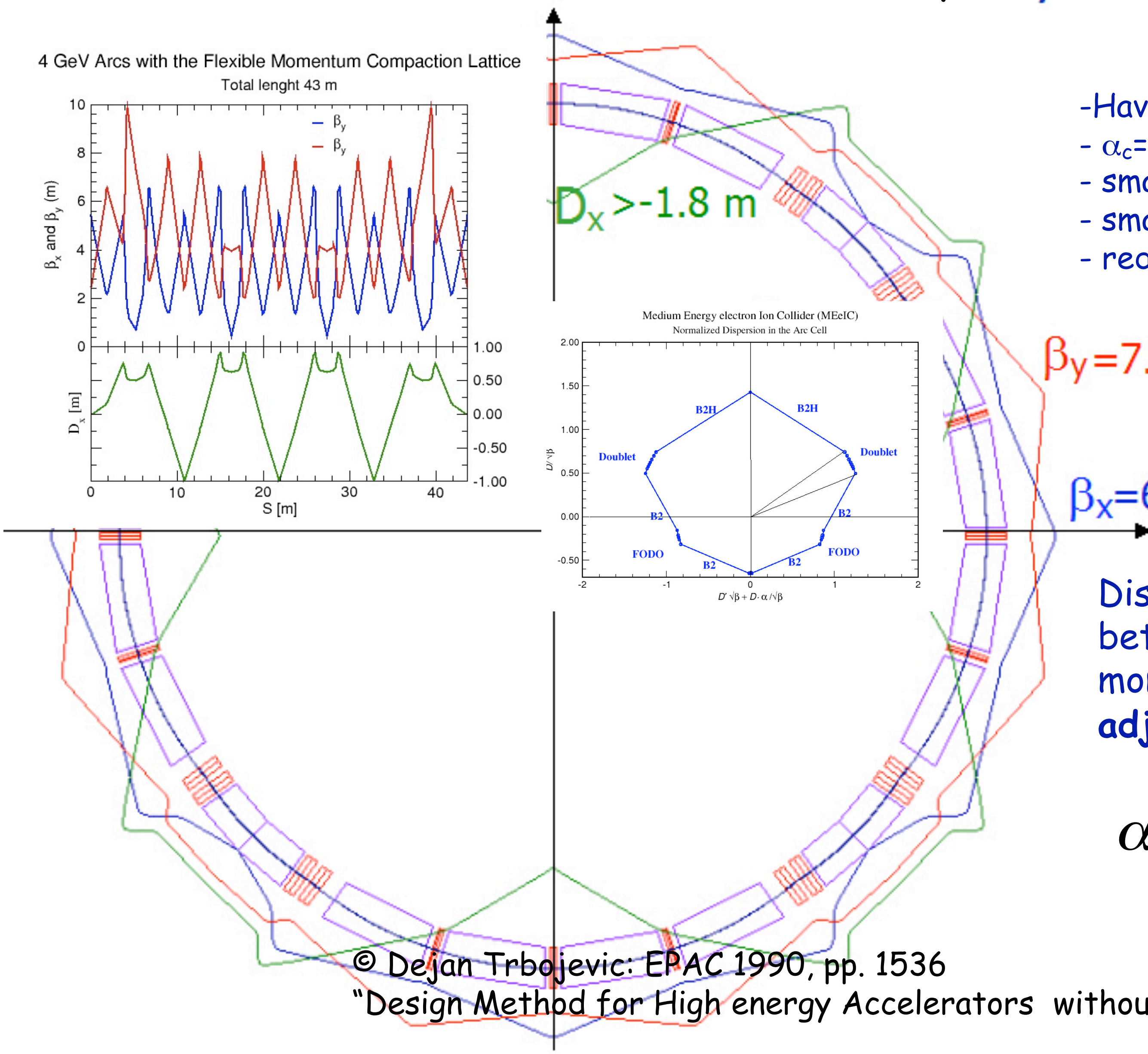
Methods and solutions: asynchronous arcs



Goals:

-Have a good packing factor
- $\alpha_c=0$ or $M_{5,6}=0$
- small dispersion
- small betatron functions
- reduce cost of civil construction

Dispersion function oscillates between ±1.8 m and the momentum compaction is **adjustable**:

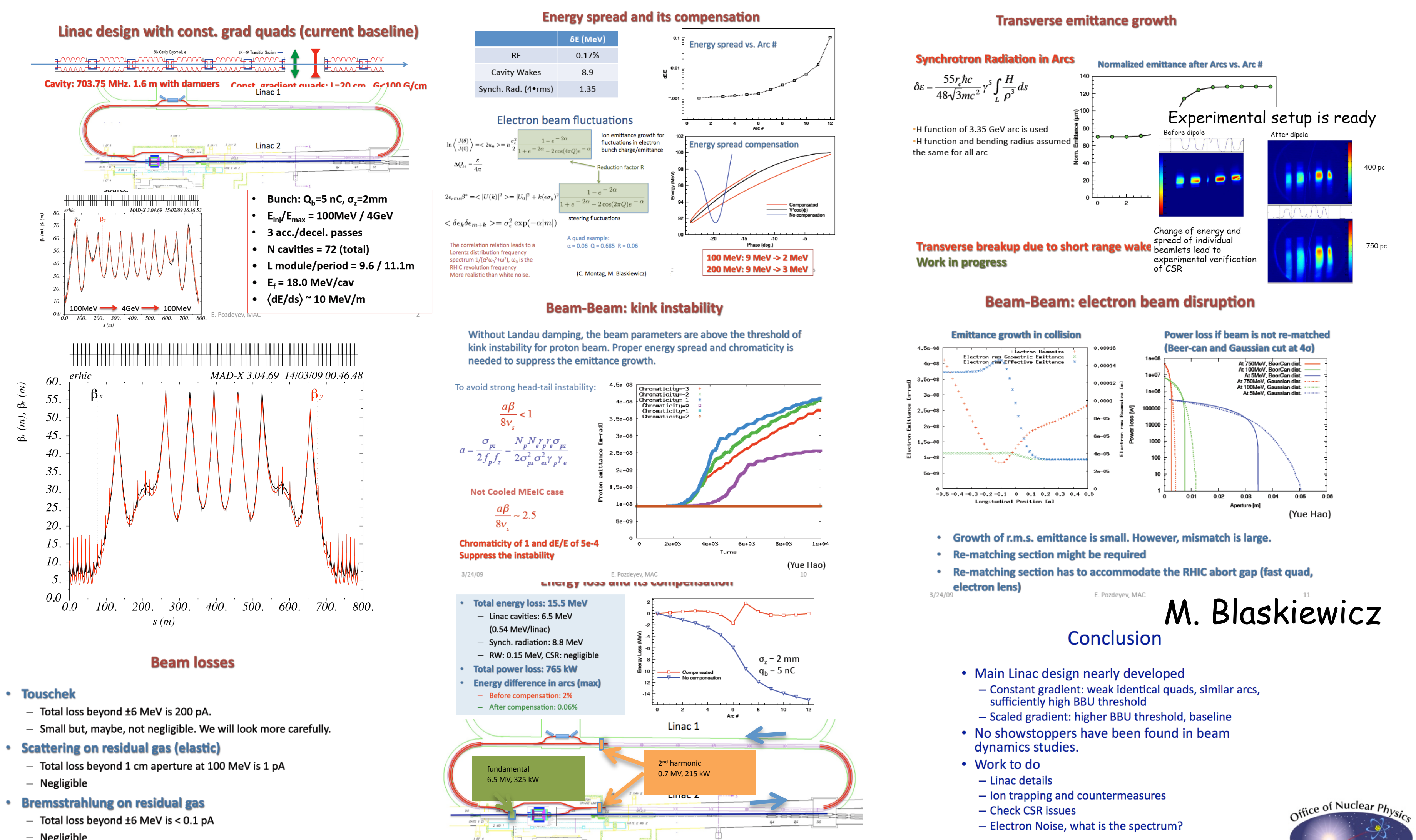
$$\alpha = \frac{1}{C_o}\int \frac{D}{\rho}\,ds \approx 0$$

© Dejan Trbojevic: EPAC 1990, pp. 1536
"Design Method for High energy Accelerators without Transition Energy."

Myriad of beam dynamics issues were studied for MeRHIC No show-stoppers !

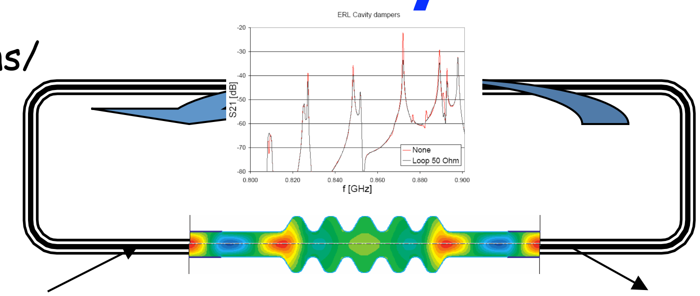
Majority of these findings were reported at MAC meeting in March 2009

Main finding – we could operate main SRF linacs without 3rd harmonics

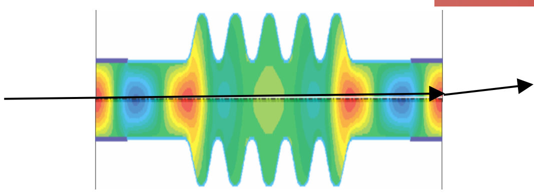


TBBU stability (©E. Pozdeyev)

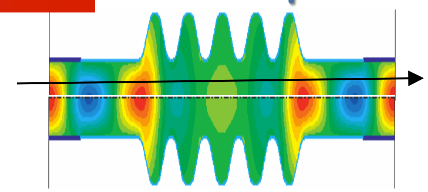
- HOMs based on R. Calaga's simulations/ measurements
- 70 dipole HOM's to 2.7 GHz in each cavity
- Polarization either 0 or 90°
- 6 different random seeds
- HOM Frequency spread 0-0.001



Excitation process of transverse HOM

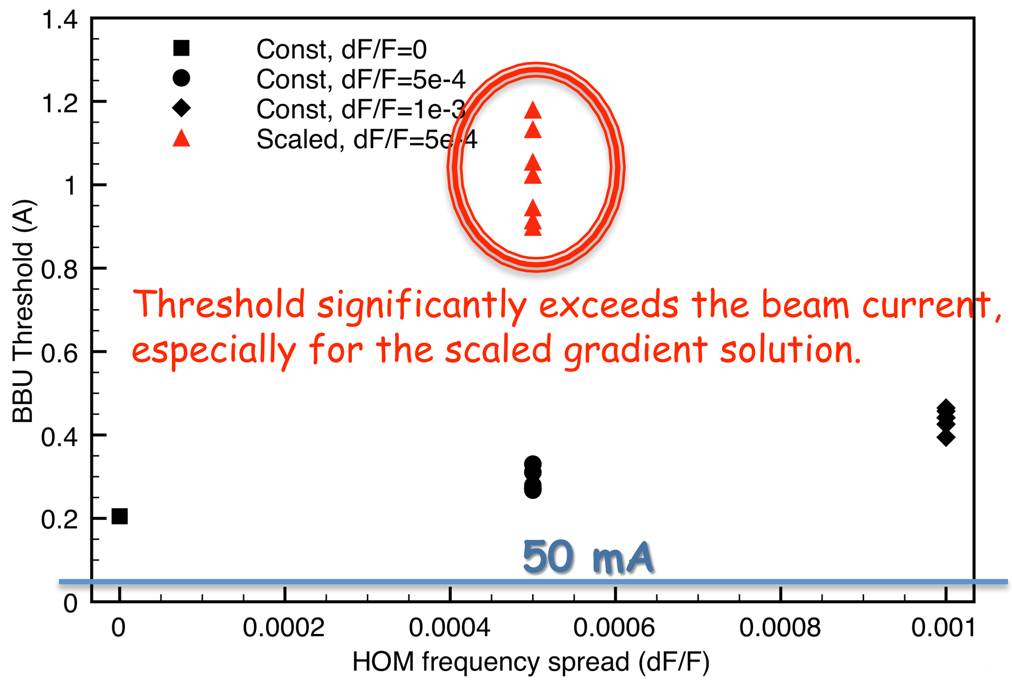


$$\begin{bmatrix} x \\ x' \end{bmatrix}_{return} = \begin{bmatrix} m11 & m12 \\ m21 & m22 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ x' \end{bmatrix}_{comming}$$

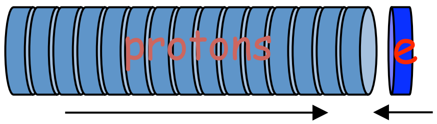


Simulated BBU threshold (GBBU) vs. HOM frequency spread.

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



e-Beam Disruption – used bunches are discarded



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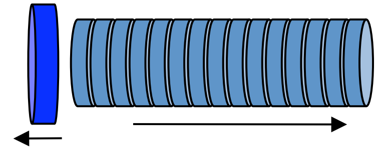
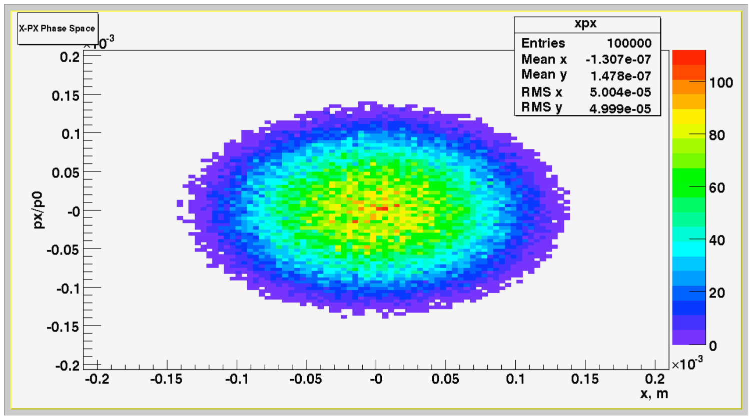
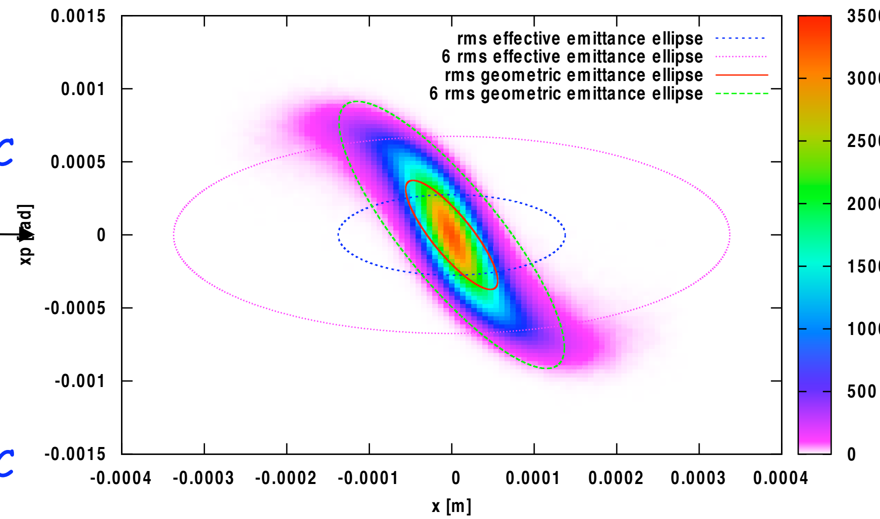
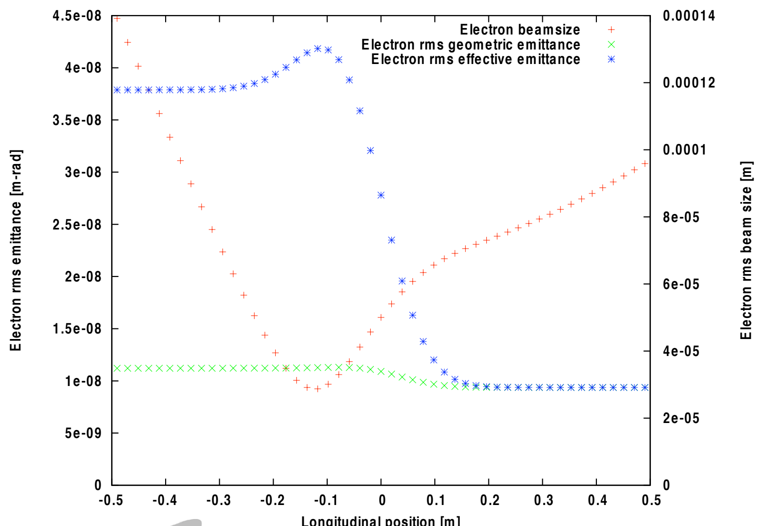


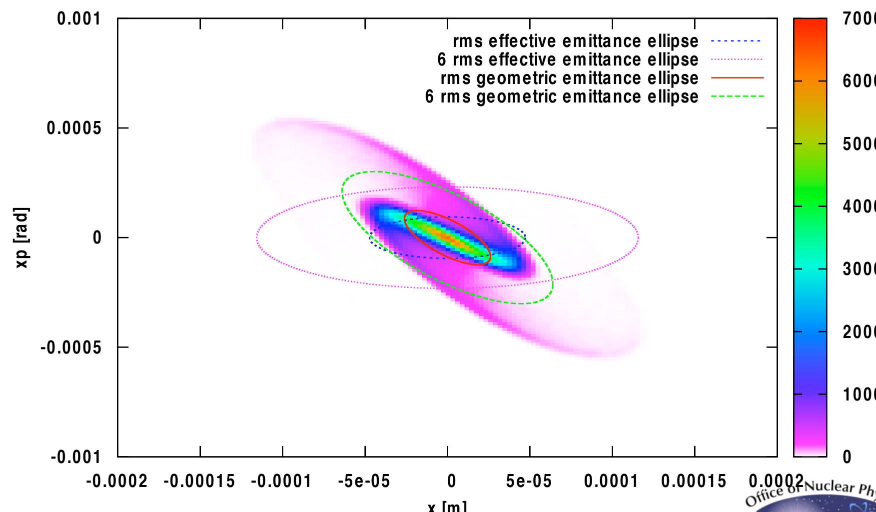


MeRHIC



eRHIC





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Suppression of kink instability

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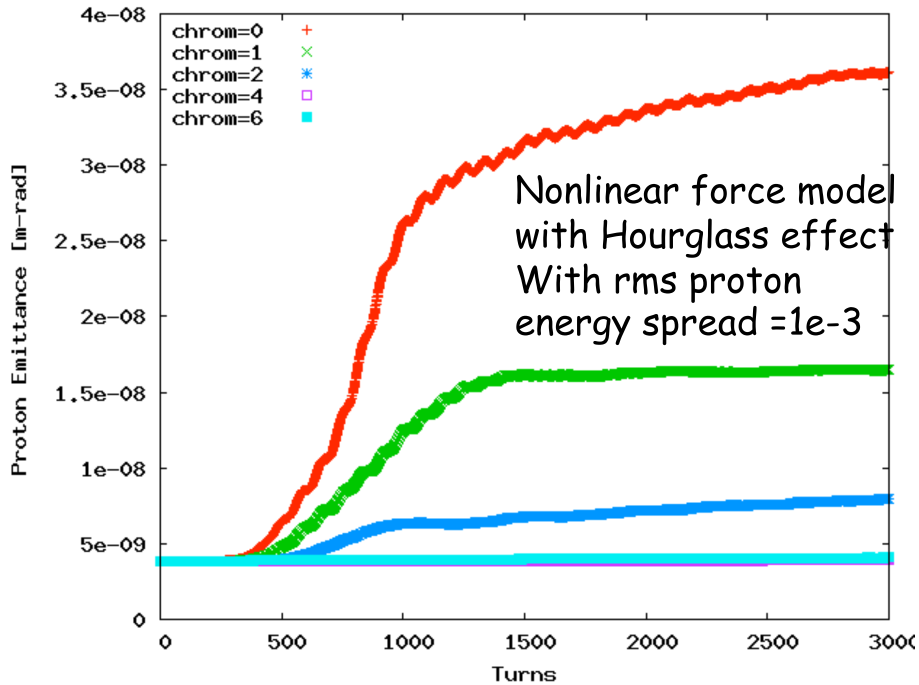
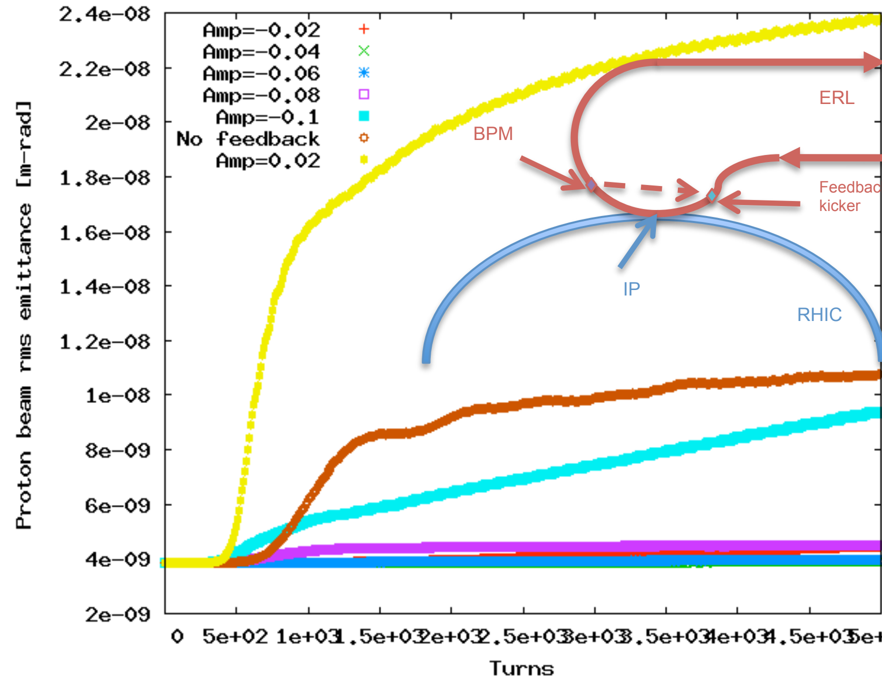


By chromaticity: ξ ~ +4



By feedback

Recent studies proved our early assumption (ZDR Appendix A) that using simple feed-back on electron beam suppress kink instability completely for all MeRHIC/eRHIC parameter ranges

Luminosity in eRHIC

	MeRHIC		eRHIC IR1		eRHIC IR2	
	p /A	e	p /A	e	p /A	e
Energy, GeV	250/100	4	325/130	20	325/130	20
Number of bunches	111	105 nsec	166	74 nsec	166	74 nsec
Bunch intensity (u) , 10^{11}	2.0	0.31	2.0	0.24	2.0	0.24
Bunch charge, nC	32	5	32	4	32	4
Beam current, mA	320	50	420	50	420	50
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.2	25	1.2	25
Polarization, %	70	80	70	80	70	80
rms bunch length, cm	20	0.2	4.9	0.2	4.9	0.2
β*, cm	50	50	25	25	5	5
Luminosity, $cm^{-2}s^{-1}$	0.1×10^{33} as is 1×10^{33} with CeC		2.8×10^{33}		1.4×10^{34}	

< Luminosity for 30 GeV e-beam operation will be at 20% level>

If we accept two of JLab assumptions for ELIC

micro-beta*, few sec e-cooling rate,

on a paper it would brings eRHIC luminosity to 1.4 x 10^{35} cm^{-2} sec^{-1}

$$L = f_c \frac{N_h N_e}{4\pi\beta^* \varepsilon}$$

Reducing β* by a factor of 10

(from 5 cm to 0.5 cm)

boost luminosity by a factor of ten

Parameters

	eRHIC with CeC	
	p / A	e
Energy, GeV	325 / 130	20
Number of bunches	166	
Bunch intensity (u) , 10^{11}	2.0	0.24
Bunch charge, nC	32	4
Beam current, mA	420	50
Normalized emittance, 1e-6 m, 95% for p / rms for e	1.2	25
Polarization, %	70	80
rms bunch length, cm	0.5	0.2
β^*, cm	0.5	0.5
Luminosity, x 10^{35}, $cm^{-2}s^{-1}$	1.4	

Parameters

	eRHIC with CeC	
	p / A	e
Energy, GeV	325 / 130	20
Number of bunches	166	
Bunch intensity (u) , 10^{11}	2.0	0.24
Bunch charge, nC	32	4
Beam current, mA	420	50
Normalized emittance, 1e-6 m, 95% for p / rms for e	1.2	25
Polarization, %	70	80
rms bunch length, cm	4.9	0.2
β^*, cm	5	5
Luminosity, x 10^{35}, $cm^{-2}s^{-1}$	0.14	

eRHIC's assumptions

are based on beam optics for HE hadron colliders
such as RHIC, HERA, Tevatron, LHC

We have potential for future up-grades beyond capabilities of present day colliders: about 2 fold increase intensities of electron and proton bunches and the rep-rate

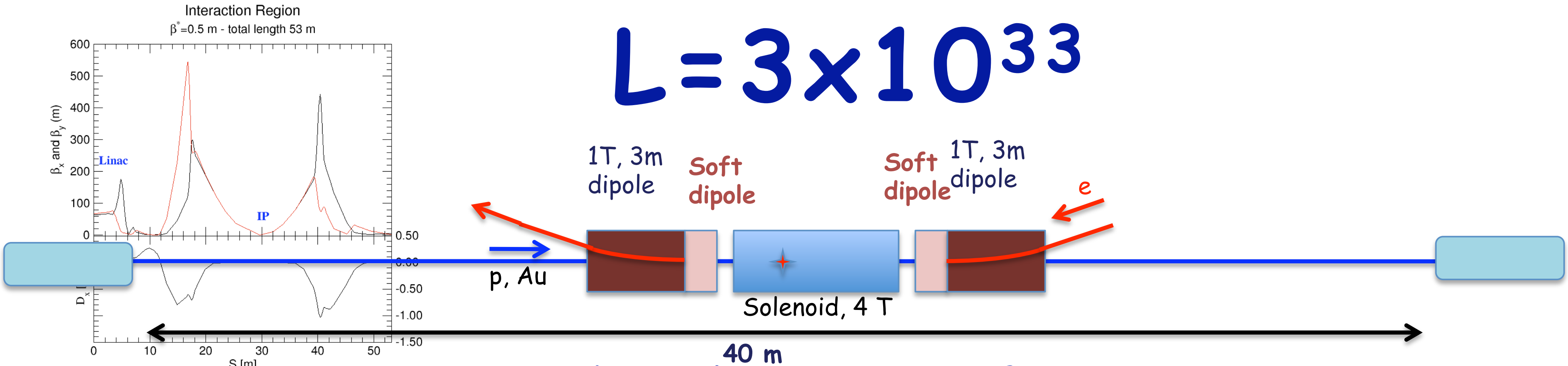
Recently we had found way to reduce beta* to 5 cm in dedicated IP basing the triplet on newly tested quadrupoles for LHC up-grade

eRHIC IR developments

- **eRHIC IR lattice is design in direct communication with EIC task-force and with inputs from EIC collaboration**
- **Main boundary conditions on present IR designs – <u>our main priority</u>**
  - There should be no magnetic elements (except dipole magnets used for EIC physics!) of both electron and hadron accelerators
  - One of the golden measurements (diffraction) required
    - A) very strong dipole next to the IP
    - B) very long element-free straight sections for excellent energy resolution
  - No hard X-rays in the detector chamber
- **This limits choice of β^* to 40 cm without CeC and to 25 cm with CeC. We found solutions to all existing demands. Focusing is not a problem in all this scenario and excellent fits are found for all cases (Tepikian for RHIC, Trbojevic of ERL).**
- **Luminosity hungry experiments may require a dedicated IR, where accelerator elements are closer to the IP**
- **CeC can compress hadron bunch lengths to few cm and β^* ~ 5 cm and shorter are possible in such IR – few possible scenarios are pursued. This IR brings eRHIC luminosity above 10^{34}.**

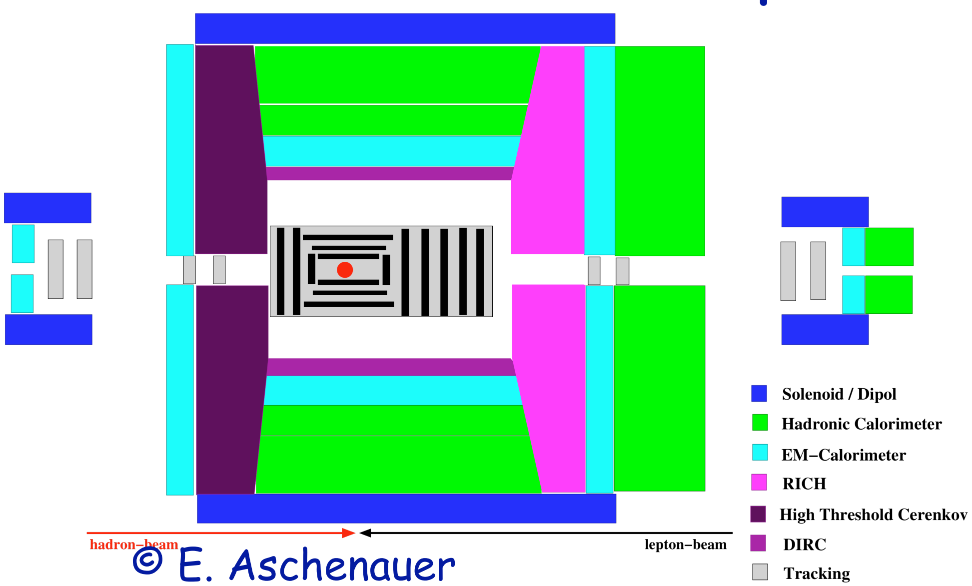
Integrated low-X IR design, β*=25 to50 cm

$L=3\times10^{33}$



First machine elements 20 m from IP

40 m to detect particles scattered at small angles



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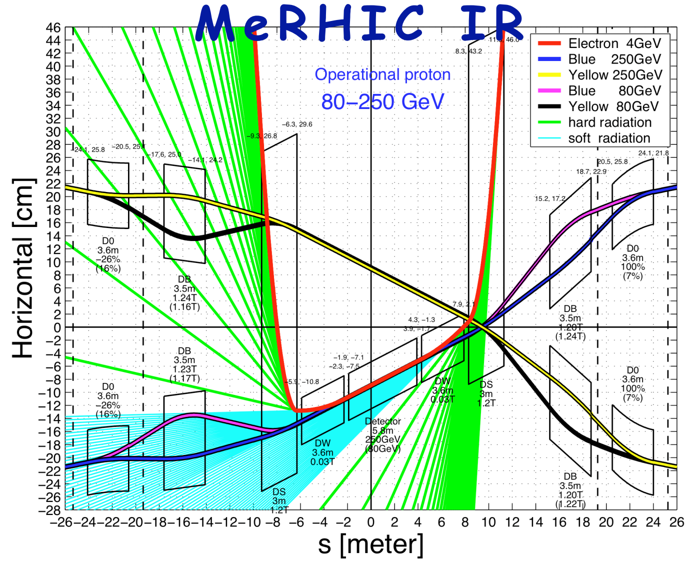
MeRHIC IR



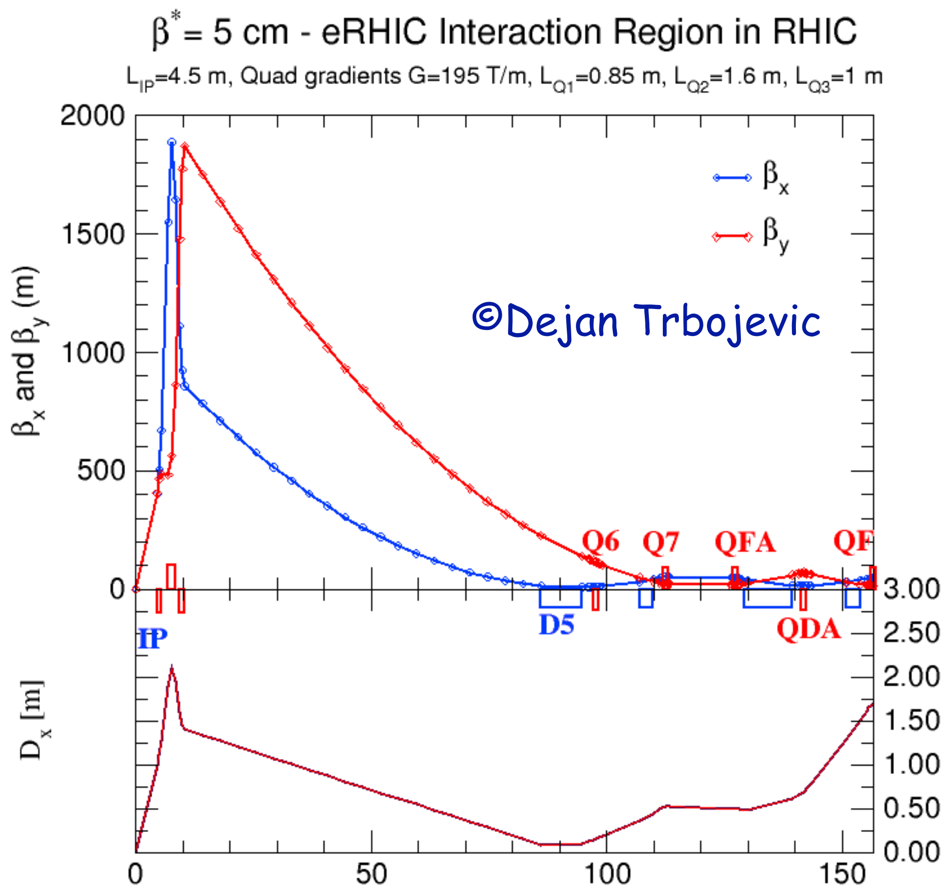
© J.Beebe-Wang

To provide effective SR protection: -soft bend (~0.05T) is used for final bending of electron beam

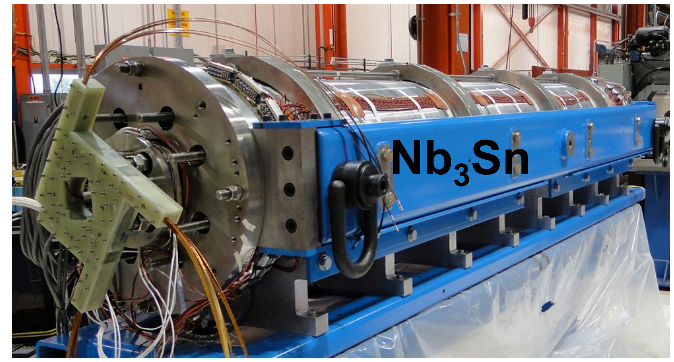
Integrated high-Q IR design, β*=5cm

First quadrupole is 4.5 m from IP

$L=1.4\times10^{34}$



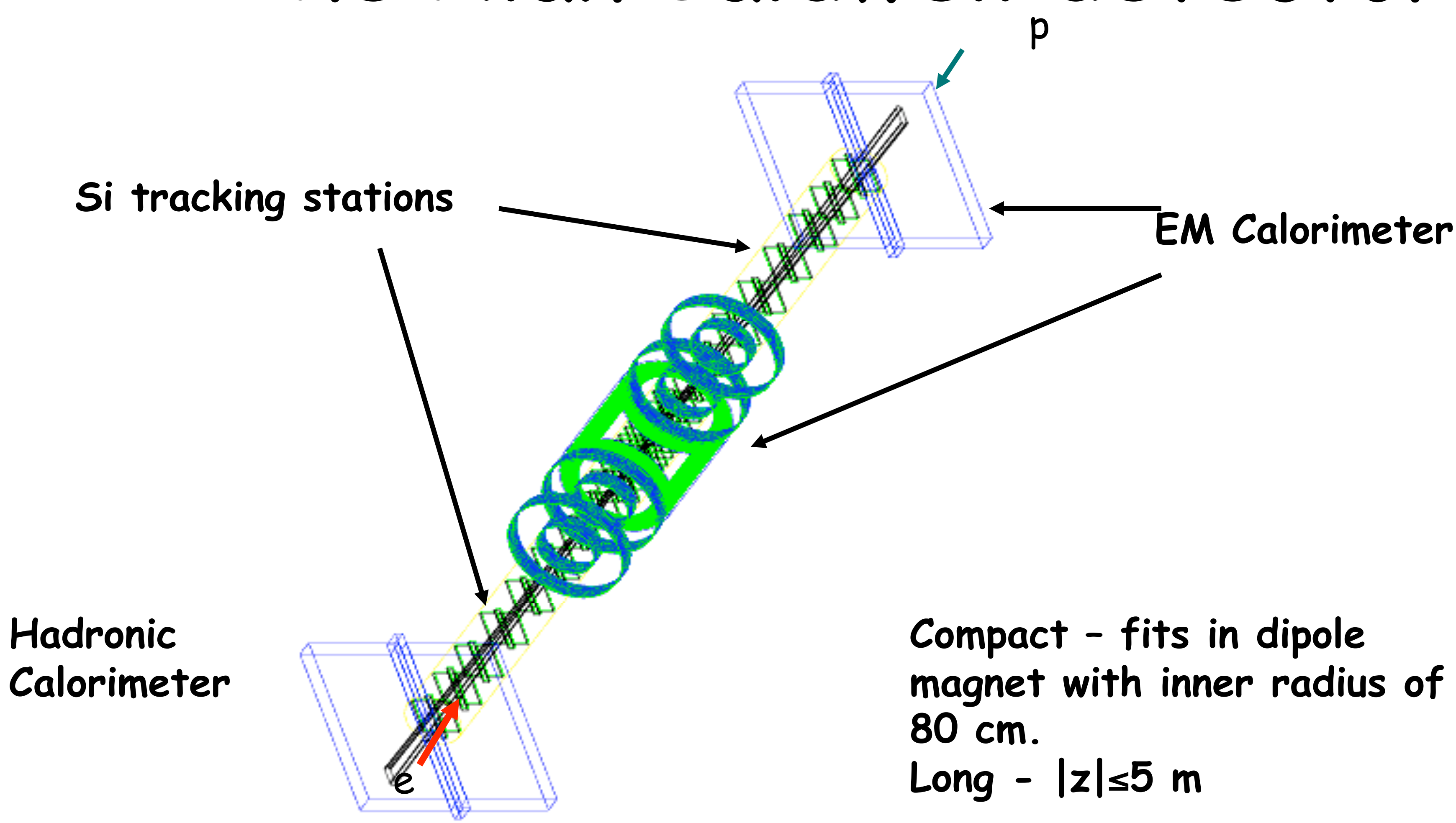

```
TRIPLET:
 GDB1  =       -197.05051  T/m
 GFB2  =        199.49689  T/m
 GDB3  =       -192.97180  T/m
```



Plan to use newly commissioned (last month!) LARP SC quads with 200 T/m gradient

May be used for luminosity hungry experiments
Will work with the Alan Caldwell detector
Or a JLab type one

The Alan Caldwell detector



Compact – fits in dipole magnet with inner radius of 80 cm.
Long - |z|≤5 m

Gains from coherent e-cooling:

Coherent Electron Cooling vs. IBS

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

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

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

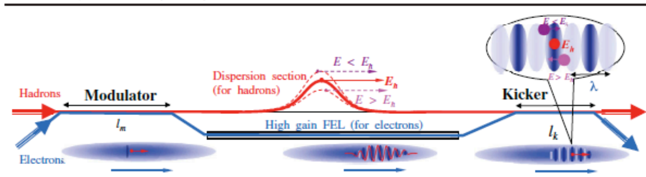


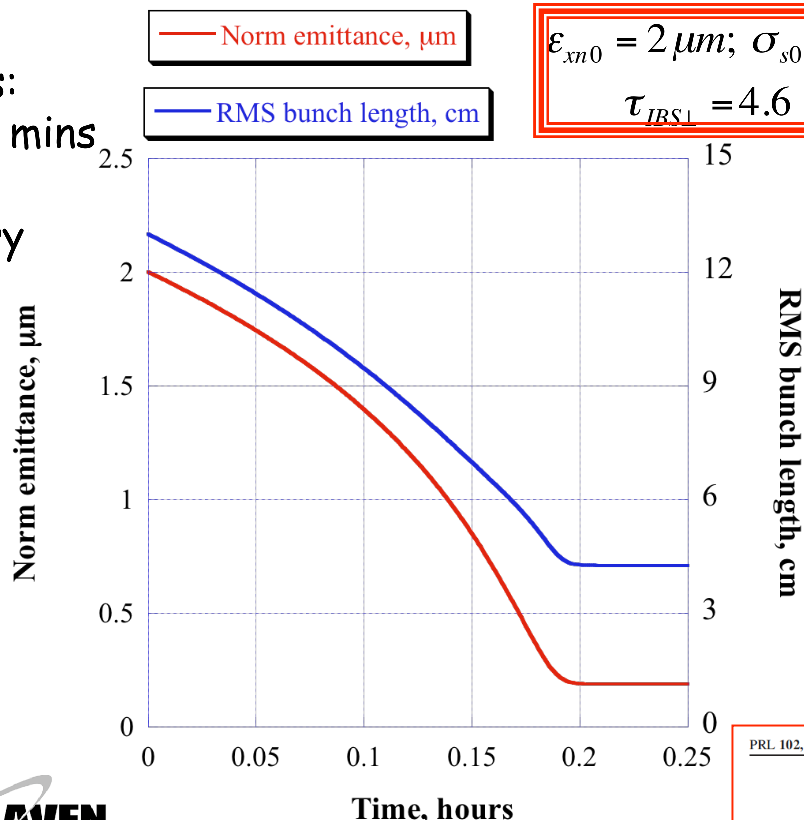
FIG. 1 (color). A general schematic of the Coherent Electron Cooler (CEC) comprising three sections: A modulator; a FEL plus a dispersion section; and, a kicker. The FEL wavelength, λ, in the figure is grossly exaggerated for visibility.

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

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

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



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

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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Coherent Electron Cooling

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

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Challenges and Advantages

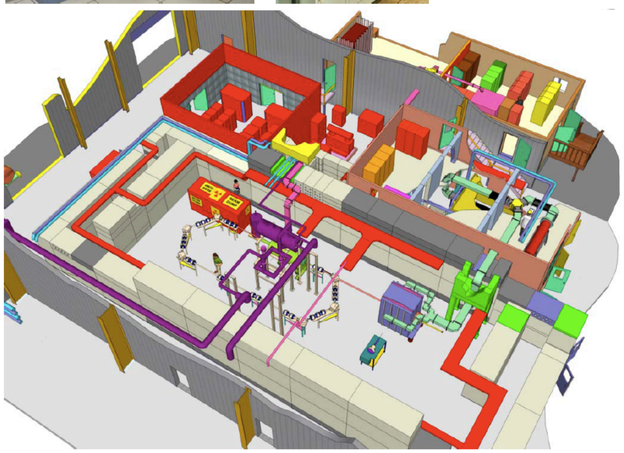
- **Main Challenge – 50 mA polarized gun for e-p program**
- Main advantage – RHIC
  - Unique set of species from d to U
  - The only high energy polarized proton collider
  - Large size of RHIC tunnel (3.8 km)
- Main limitation
  - Ion cloud limits the hadron beam intensity

R&D ERL

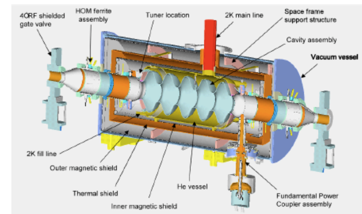
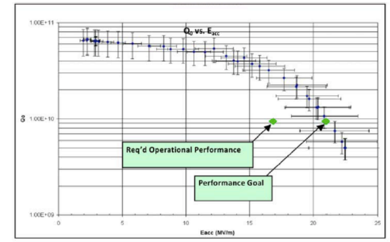
Status of the R&D ERL

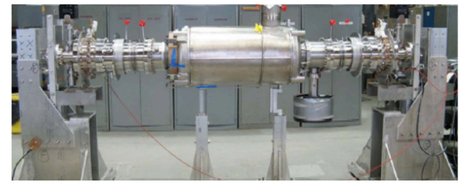
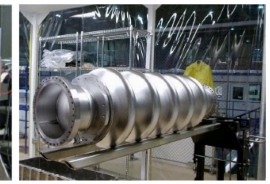
- The ERL is in an advanced stage of construction
- Beam will be generated next year
- Major systems are coming on



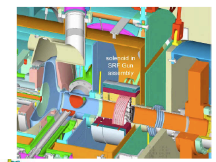
A Prototype eRHIC Cavity

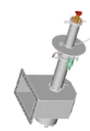
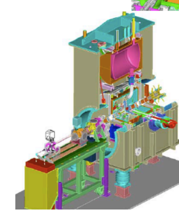



High-current SRF electron-gun

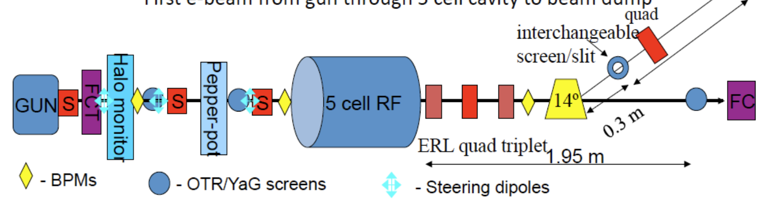
- ½ Cell SRF injector
  - Demountable cathode stalk
  - HTS Solenoid
- UHV load-lock cathode
- MW twin couplers



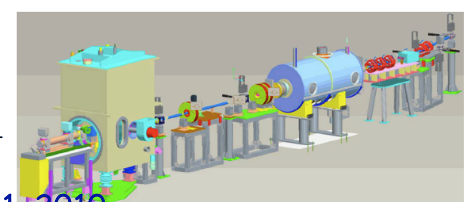



G5 Test:

First e-beam from gun through 5 cell cavity to beam dump



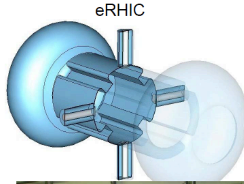
Rich program of tests:
Gun, photocathode,
emittance, halo, more…
To be followed up by full ERL

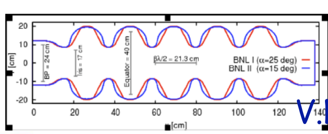


eRHIC New Cavity Design

- Reduce peak magnetic field.
- Reduce stiffness.
- Apply new ideas in HOM damping.
- Reduce fundamental at HOM couplers
- Increase real-estate gradient
- Development / measurement program

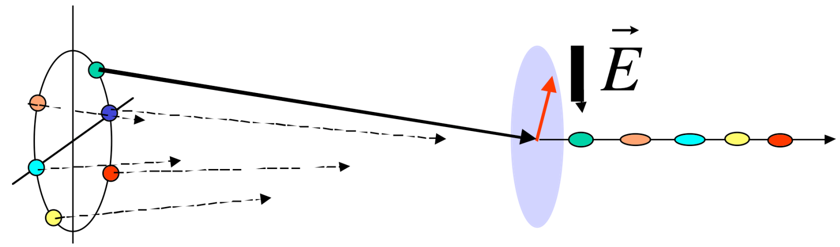
New cavity design for eRHIC



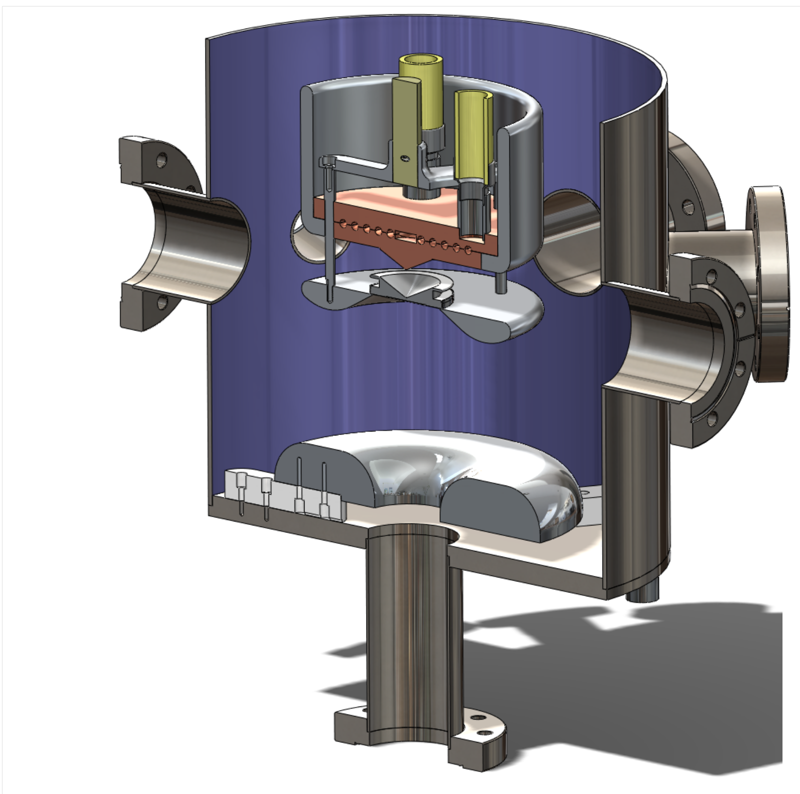


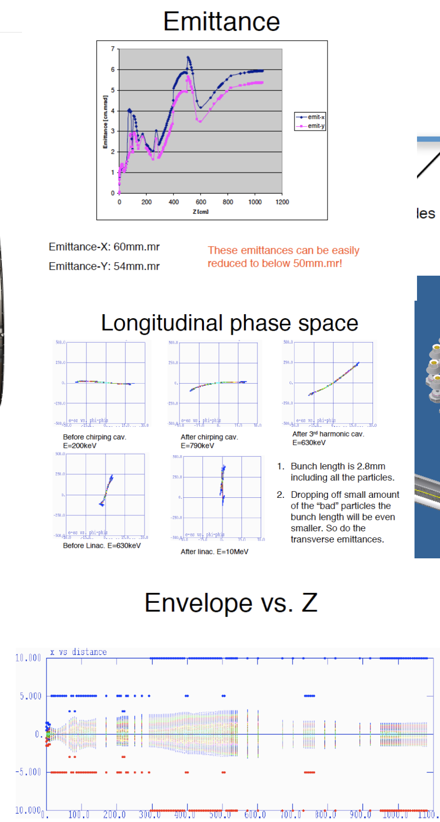
Main technical challenge is 50 mA CW polarized gun: we are building two versions

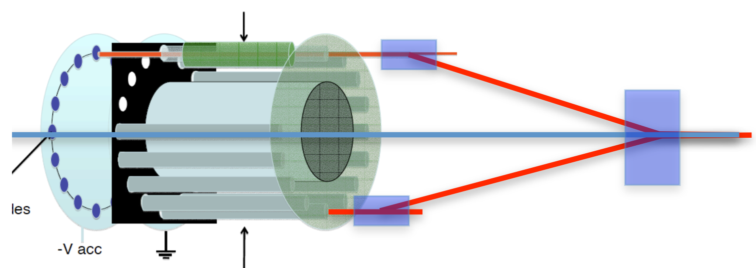
Gatling gun

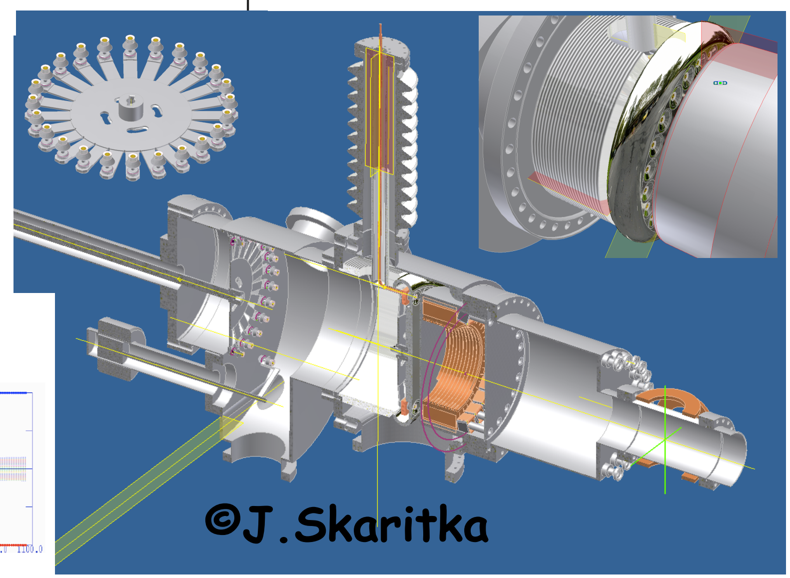


Single large size cathode









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* the Gatling gun is the first **successful** machine gun, invented by Dr. Richard Jordan Gatling.

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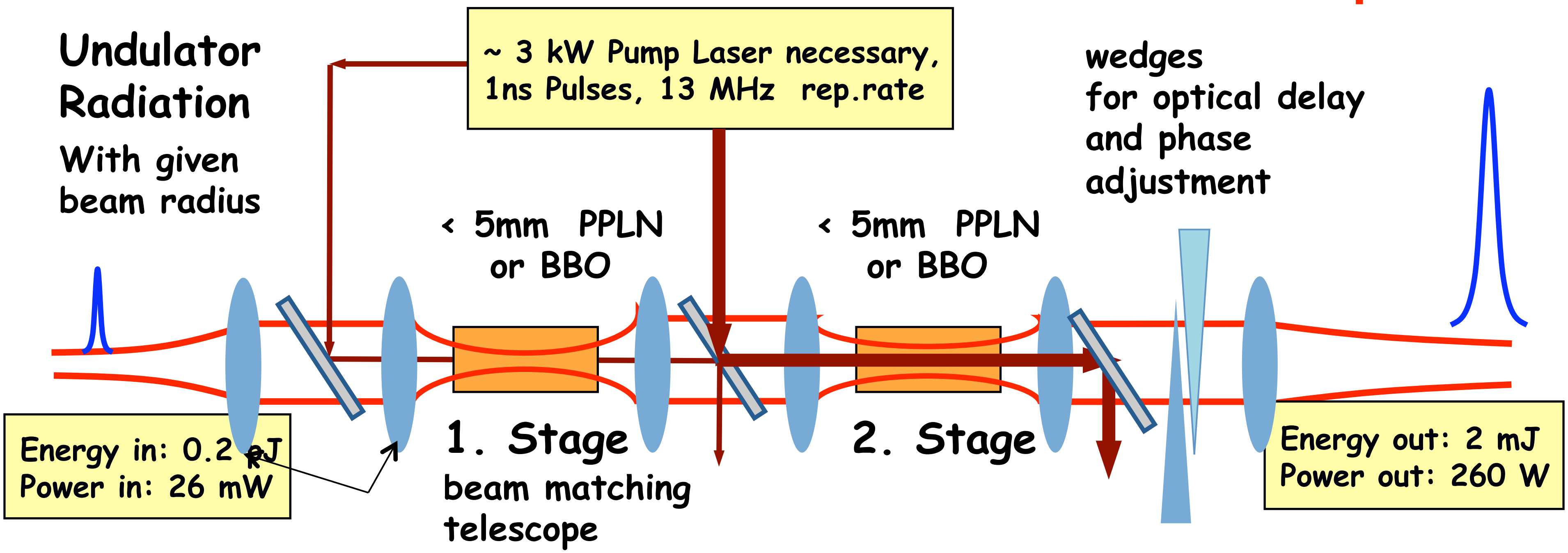
Schematic OPA layout for eRHIC OSC

$B = 10$ T; $\lambda_u = 27$ cm; $K = 0.14$; $\lambda = 2\mu m$ ©C. Tschalär MIT/Bates

250 GeV protons



Design to achieve total optical delay of < 2 cm possible

High Gain, G=10^7: Two stage amplifier necessary

1. Stage: G=10^5, 2. Stage: G=10^2

for $k = 2\pi/(2\mu m)$; $K = 0.14$; $I_i = 400$mA; $E_i = 250$ GeV

$$G \cong \frac{3}{E_i}\sqrt{\frac{P_{av}}{I_i/e}k(\alpha\hbar c)\frac{K^2}{K^2+2}} = 1.36\cdot 10^{-13}\sqrt{P_{av}/\text{Watt}}.$$

For $P_{av} = 260$W; $\bar{\delta} = 1.6\cdot 10^{-4}$; and $\upsilon = 2$:

Cooling time $\tau = T/\alpha_\varepsilon \cong 17$ minutes

VL Note – OSC works only for fixed energy of protons !

Changing energy for more then few % requires changing the SC undulator.

Coherent Electron Cooling (CeC)

At a half of plasma oscillation

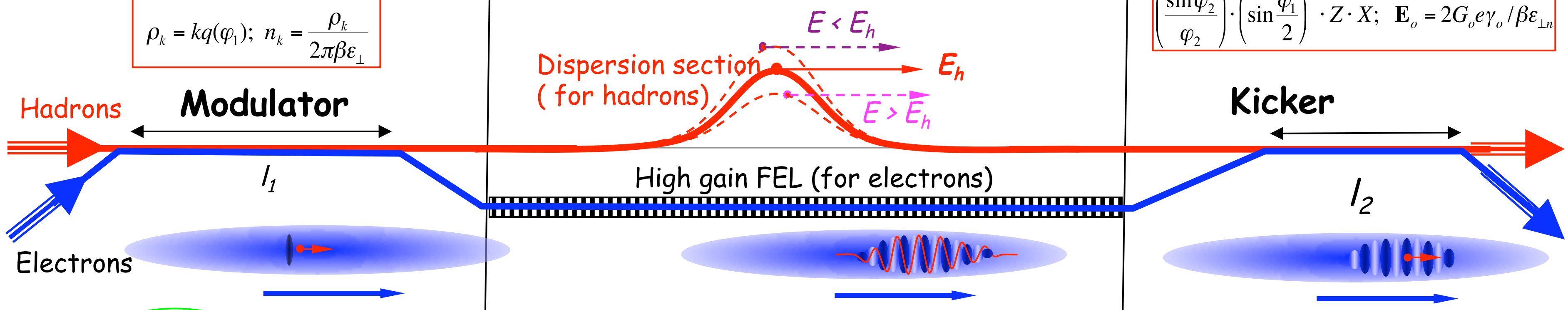
$$q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

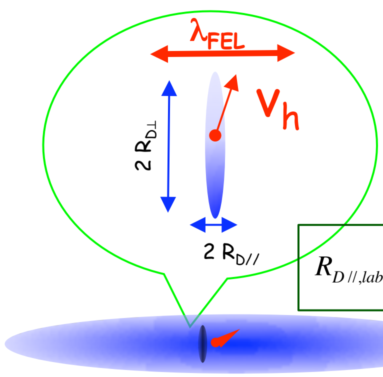
$$\rho_k = kq(\varphi_1);\ n_k = \frac{\rho_k}{2\pi\beta\varepsilon_\perp}$$

Dispersion

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

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





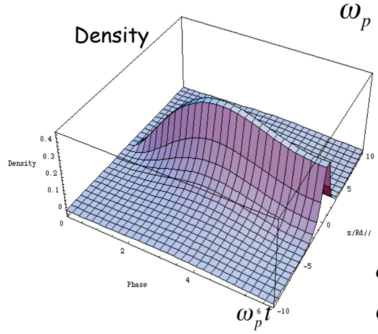
Debay radii

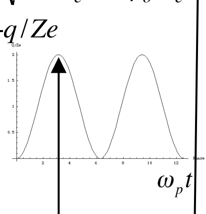
$$R_{D\perp} >> R_{D//}$$

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

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

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



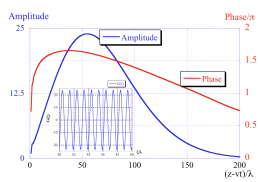


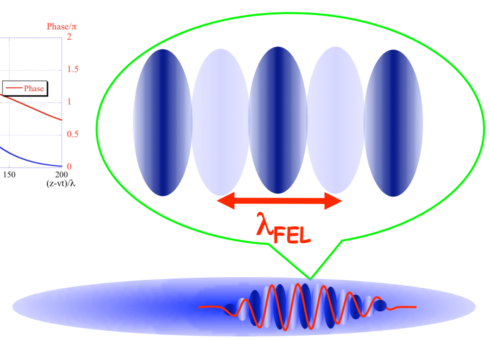
$$q = -Ze\cdot(1-\cos\varphi_1)$$

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

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

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





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

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

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

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Coherent Electron Cooling

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

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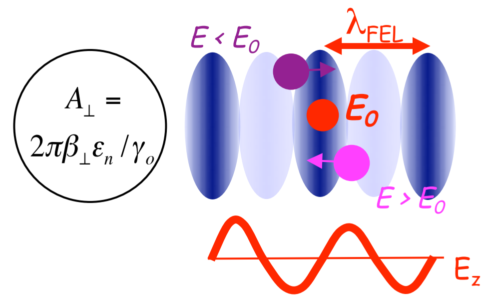

$$k_{FEL} = 2\pi/\lambda_{FEL};\ k_{cm} = k_{FEL}/2\gamma_o$$

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

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

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

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

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

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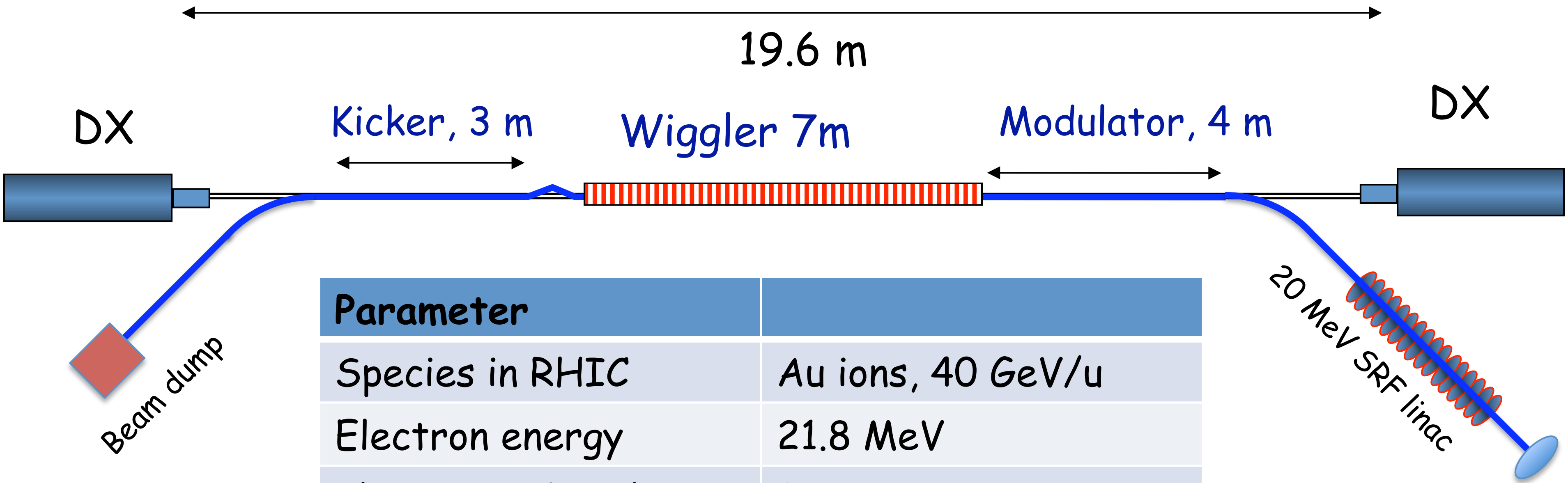
Possible layout for Coherent Electron Cooling proof-of-principle experiment in RHIC IR

Collaboration with JLab: R.Rimmer, G.Krafft, Ya.Derbenev

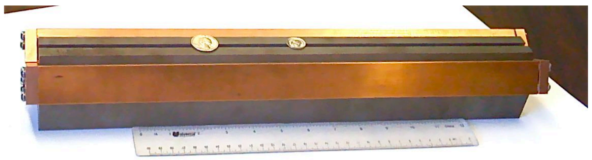


Parameter	
Species in RHIC	Au ions, 40 GeV/u
Electron energy	21.8 MeV
Charge per bunch	1 nC
Train	5 bunches
Rep-rate	78.3 kHz
e-beam current	0.39 mA
e-beam power	8.5 kW

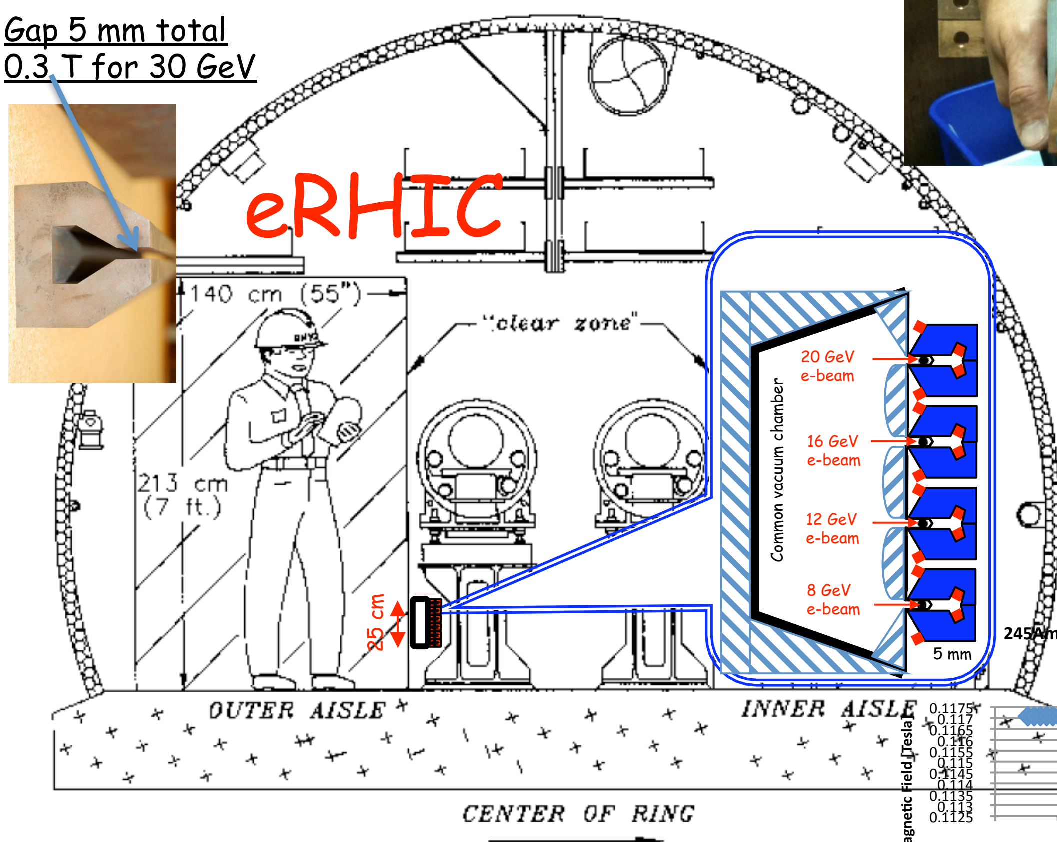
eRHIC loop magnets: LDRD project

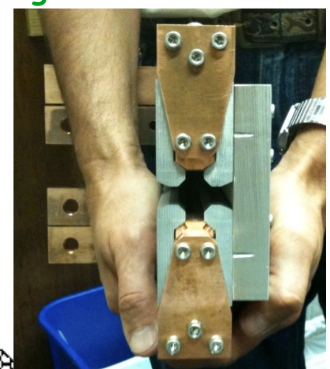
- Small gap provides for low current, low power consumption magnets
  - -> low cost eRHIC
  - Dipole prototype is under tests
  - Quad and vacuum chamber are in advanced stage

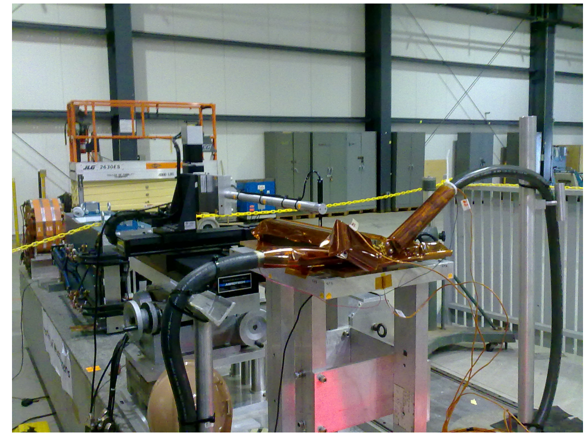
©, G. Mahler, W. Meng, A. Jain, P. He, Y.Hao

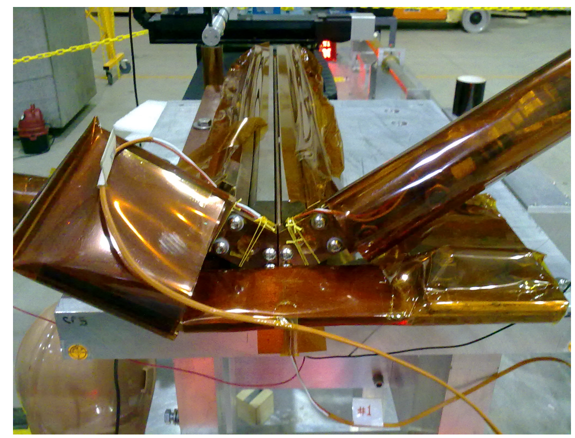


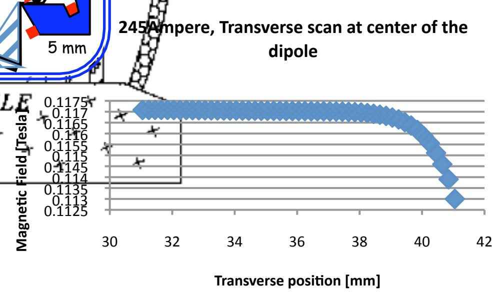
Gap 5 mm total
0.3 T for 30 GeV

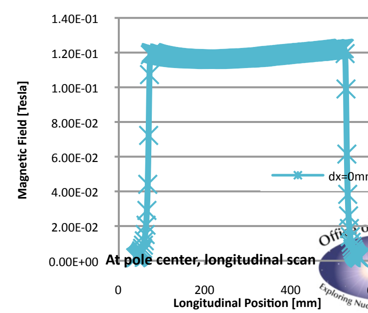












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Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

eRHIC

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eRHIC targeted LDRD projects

- **Accelerator:**
  - Proof of principle for a gatling gun polarized electron source

    PI: Ilan Ben-Zvi
  - Laser development for polarized electron source

    PI: Treveni Rao
  - Undulator development for coherent electron cooling

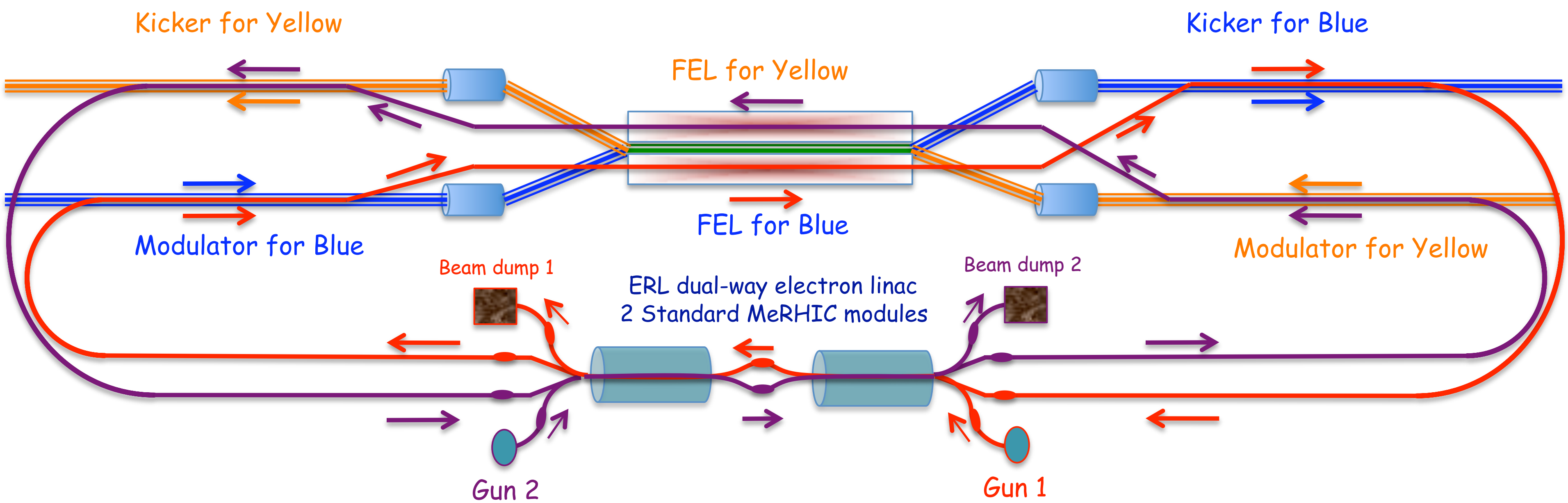
    PI: Vladimir Litvinenko

Conclusions

- RHIC collides hadrons from polarized protons to U with energies 2.5 GeV/u to 250 GeV/u
- Collider beam physics laws assert that with any given beam and IR parameters, a linac-ring collider outperforms a ring-ring collider
- RHIC is the only high energy polarized proton collider with polarization control of each individual bunch. ERL has full spin transparency and allows high-frequency change of the spin direction. There is no beam-beam induced electron beam depolarization in eRHIC.
- We developed detailed technical design and cost estimate for the first stage of eRHIC, called MeRHIC
- We developed a clear staged pass toward full energy high luminosity, $L>10^{34}$ sec^{-1} cm^{-2}, eRHIC, based on the experience from hadron and lepton-hadron colliders
- eRHIC R&D is focused on:
  - (a) Single cathode and Gatling polarized electron guns
  - (b) Compact SRF linacs with HOM damping
  - (c) Multi-pass high average current ERLs
  - (e) Small gap magnets and vacuum chambers
  - (f) Coherent electron cooling

Back-up

Possible layout in RHIC IP of CeC driven by a single linac – **<u>to boost polarized pp- luminosity</u>**



E_p, GeV	γ	E_e, MeV
100	106.58	54.46
250	**266.45**	**136.15**
325	346.38	177.00

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eRHIC R&D

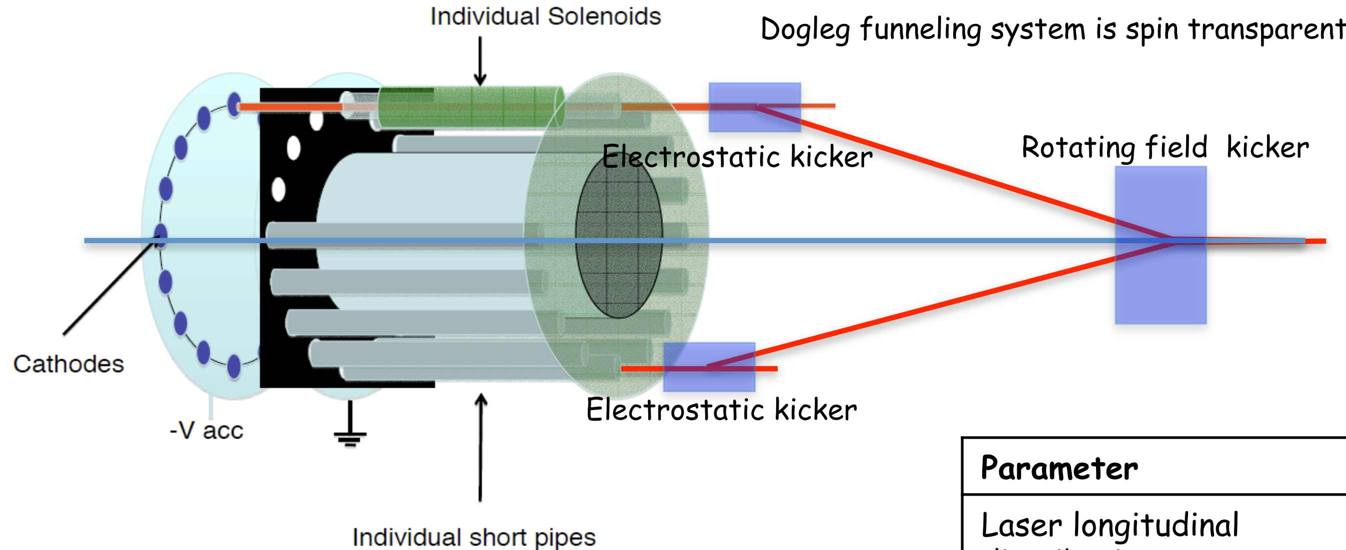
- Polarized gun for e-p program
- Development of compact recirculating loop magnets
- R&D ERL
- Compact eRHIC SRF with HOM damping
- Coherent Electron Cooling including PoP
- Polarized He^3 source

Resources in FY 2009

• Administrative -	1
• Scientists (include. 2 PhD students) -	8
• Professionals –	3
• Technicians –	4
• **Total** -	**16**

Gatling Gun*)

To be updated & combine with the next slide



~ 50 mA from injector is needed.
State of the art electron polarized source is 1 mA.

The multi cathode to reduce load on a single cathode can be used

Parameter	Value
Laser longitudinal distribution	Gaussian
Bunch length at cathode	0.5nS [FWHM]
Laser transverse distribution	Uniform
Laser spot diameter	8mm
Bunch charge	5nC
Accelerating voltage	200kV
Cathode-anode gap	3cm
Integrated solenoid field	2.1kG-cm

Progress with eRHIC

- Continued:
  - Development of R&D ERL
  - Small gap magnets
  - Understanding and suppression of kink instability
  - Simulation of electron beam disruption in the collision
  - Simulations of the beam-beam effects on hadron beam
- New developments
  - MeRHIC lattice and cost estimating
  - eRHIC staging and cost estimate
  - Coherent electron cooling for RHIC pp and eRHIC
  - Compact spreaders and combiner
  - Effects of wake-fields on beam energy loss and beam quality
  - Synchrotron radiation effects
- Publications on eRHIC-related accelerator R&D
  - About 25 papers in last year including one Phys. Rev . Lett.

eRHIC parameters

	MeRHIC		eRHIC with CeC		eRHIC II 8T RHIC	
	p /A	e	p /A	e	p / A	e
Energy, GeV	250/100	4	325 / 125	20	800 / 300	20
Number of bunches	111		166		166	
Bunch intensity (u) , 10^{11}	2.0	0.31	2.0	0.24	3.0	0.24
Bunch charge, nC	32	5	32	4	32	4
Beam current, mA	320	50	420	50	630	50
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.2	25	1	10
Polarization, %	70	80	70	80	70 (?)	80
rms bunch length, cm	20	0.2	4.9	0.2	4.5	0.2
β^*, cm	50	50	25 (5)	25 (5)	25 (5)	25 (5)
Luminosity, x 10^{33}, $cm^{-2}s^{-1}$	0.1 -> 1 with CeC		2.8 (14)		17 (85)	

< Luminosity for 30 GeV e-beam operation will be at 20% level>

RHIC

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MeRHIC parameters for e-p collisions

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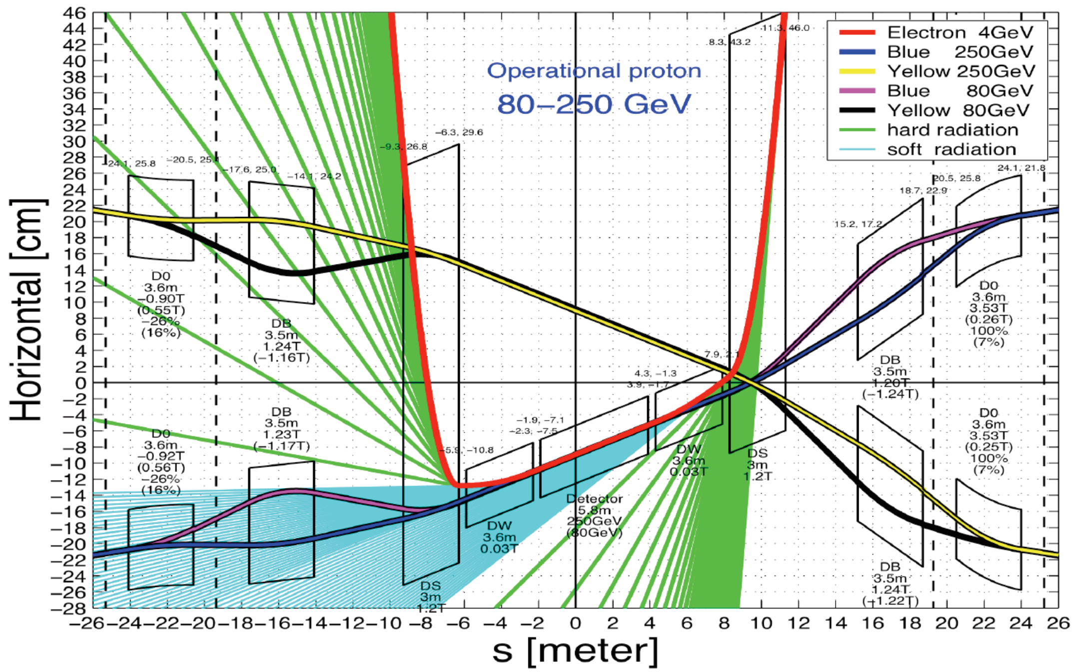
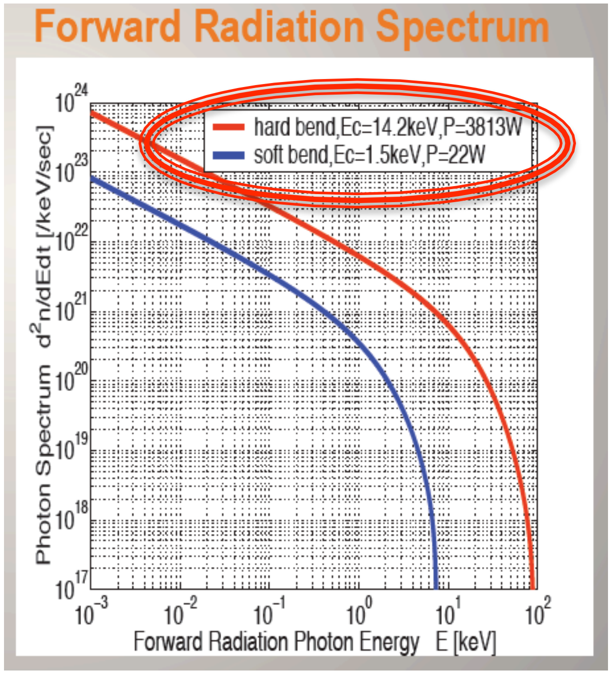
	not cooled		With cooling	
	p	e	p	e
Energy, GeV	250	4	250	4
Number of bunches	111		111	
Bunch intensity, 10^{11}	2.0	0.31	2.0	0.31
Bunch charge/current, nC/mA	32/320	5/**50**	32/320	5/**50**
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.5	7.3
rms emittance, nm	9.4	9.4	0.94	0.94
beta*, cm	50	50	50	50
rms bunch length, cm	20	0.2	5	0.2
beam-beam for p /disruption for e	1.5e-3	3.1	0.015	7.7
Peak Luminosity, 1e32, $cm^{-2}s^{-1}$	**0.93**		**9.3**	

Luminosity for light and heavy ions is the same as for e-p if measured per nucleon!

IR without DXes: 5-fold flexibility for hadron energy

J. Beebe-Wang, E.-C. Aschenauer





- 40 cm β^* and 40 m element free space
- Integrated 5.8 m long 4 T solenoid
- First indication that it is good layout for diffraction physics
- There is enough flexibility in the layout to accommodate main detector needs

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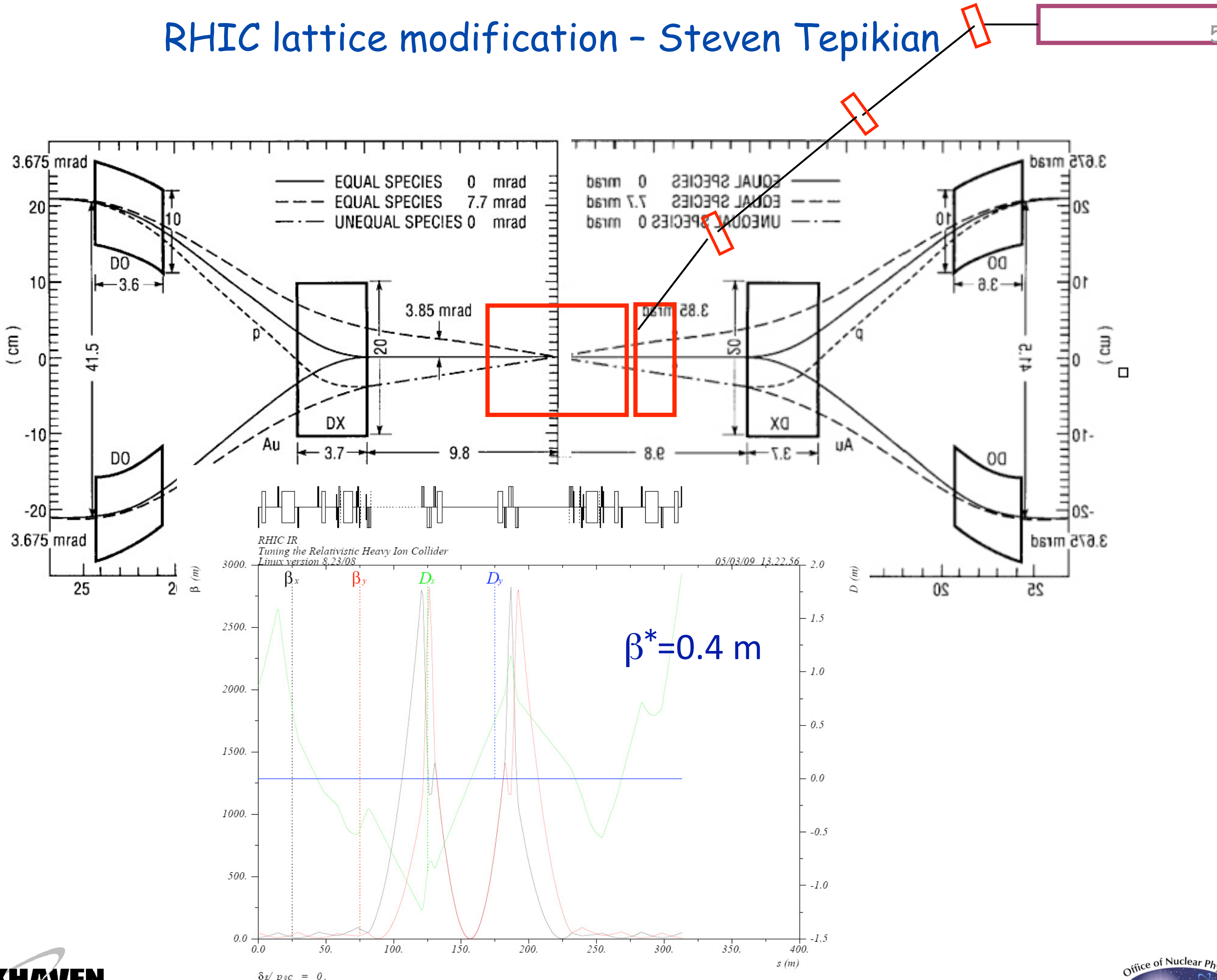
RHIC lattice modification – Steven Tepikian



ERL spin transparency at all energies

Bargman, Mitchel, Telegdi equation

$$\frac{d\hat{s}}{dt} = \frac{e}{mc}\hat{s}\times\left[\left(\frac{g}{2}-1+\frac{1}{\gamma}\right)\vec{B} - \frac{\gamma}{\gamma+1}\left(\frac{g}{2}-1\right)\hat{\beta}\left(\hat{\beta}\cdot\vec{B}\right) - \left(\frac{g}{2}-\frac{\gamma}{\gamma+1}\right)\left[\vec{\beta}\times\vec{E}\right]\right]$$

$$a = g/2-1 = 1.1596521884\cdot 10^{-3}$$

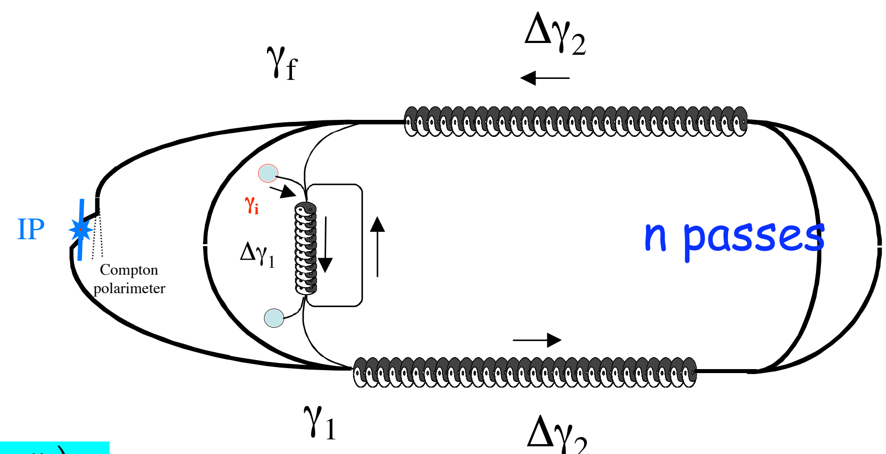
$$\hat{\mu} = \frac{g}{2}\frac{e}{m_o}\hat{s} = (1+a)\frac{e}{m_o}\hat{s}; \qquad \nu_{spin} = a\cdot\gamma = \frac{E_e}{0.44065[GeV]}$$

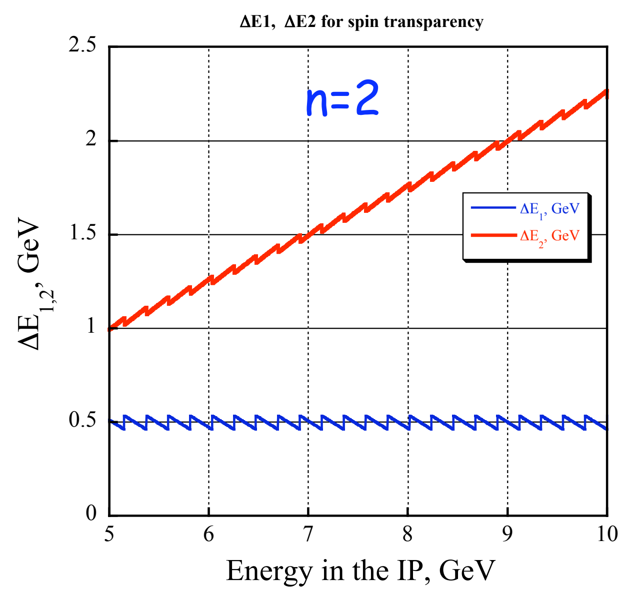
$$\Delta\varphi = a\cdot\gamma\theta$$

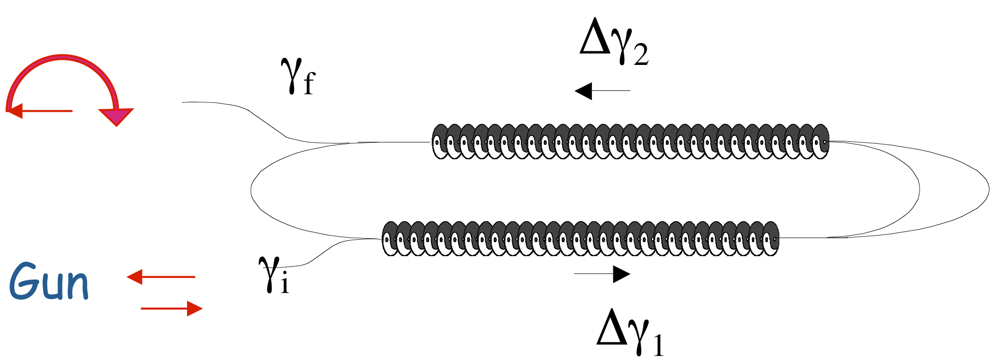
Total angle $\varphi = \pi a\cdot\left(\gamma_i(2n-1) + n(\Delta\gamma_1\cdot n + \Delta\gamma_2(n-1)\right))$

Has solution for all energies!

$$\begin{Bmatrix} \gamma_i + 2\cdot(\Delta\gamma_1+\Delta\gamma_2) & = \gamma_f \\ a\cdot\left(\gamma_i(2n-1) + n(\Delta\gamma_1\cdot n + \Delta\gamma_2(n-1)\right)) & = N \end{Bmatrix}$$







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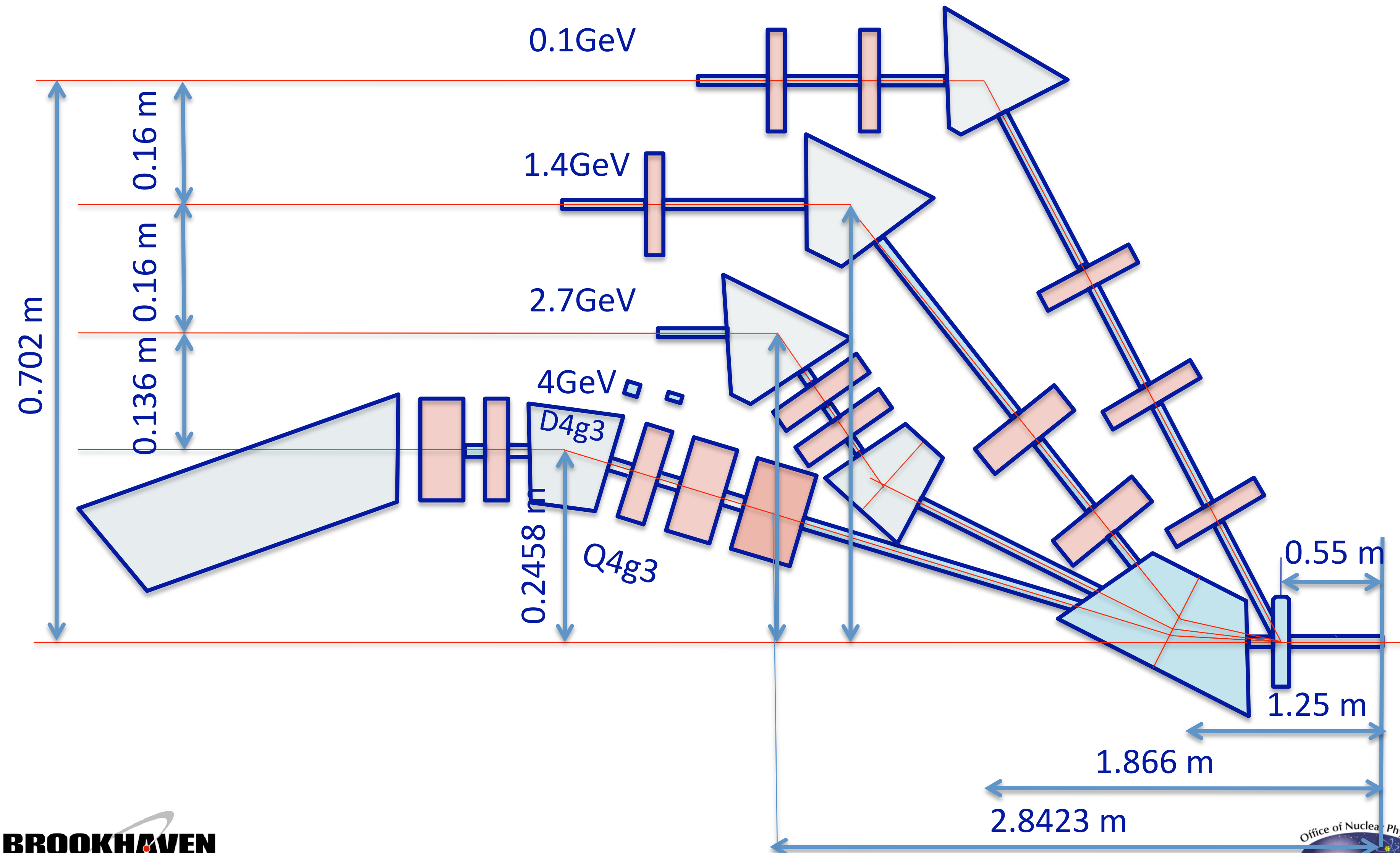
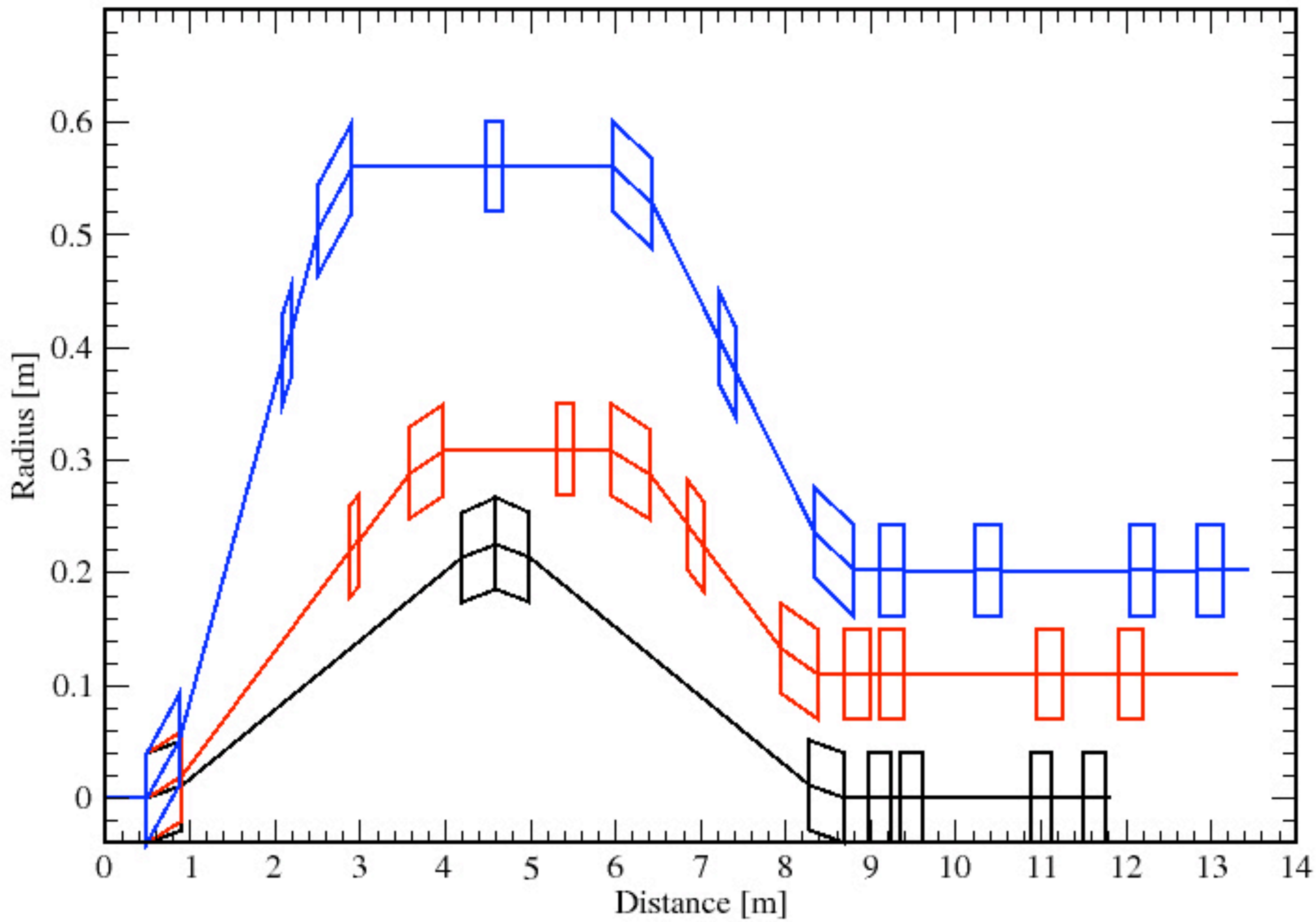
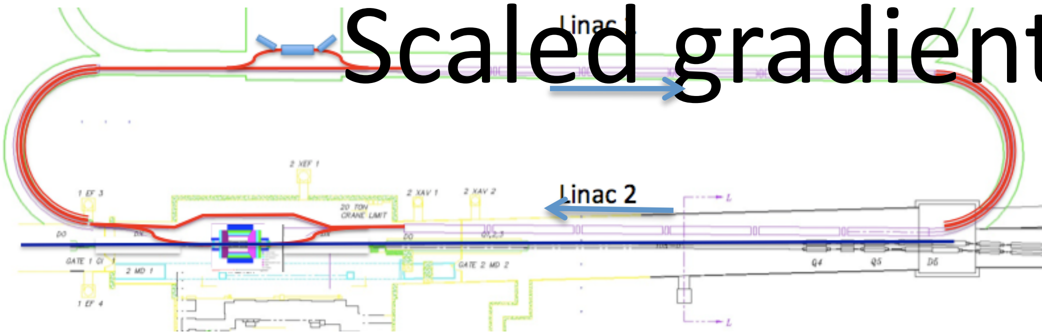
Switchyard at the linac



Vertical splitters – 3.35 GeV, 2.05 GeV, and 0.75 GeV



Scaled gradient solution

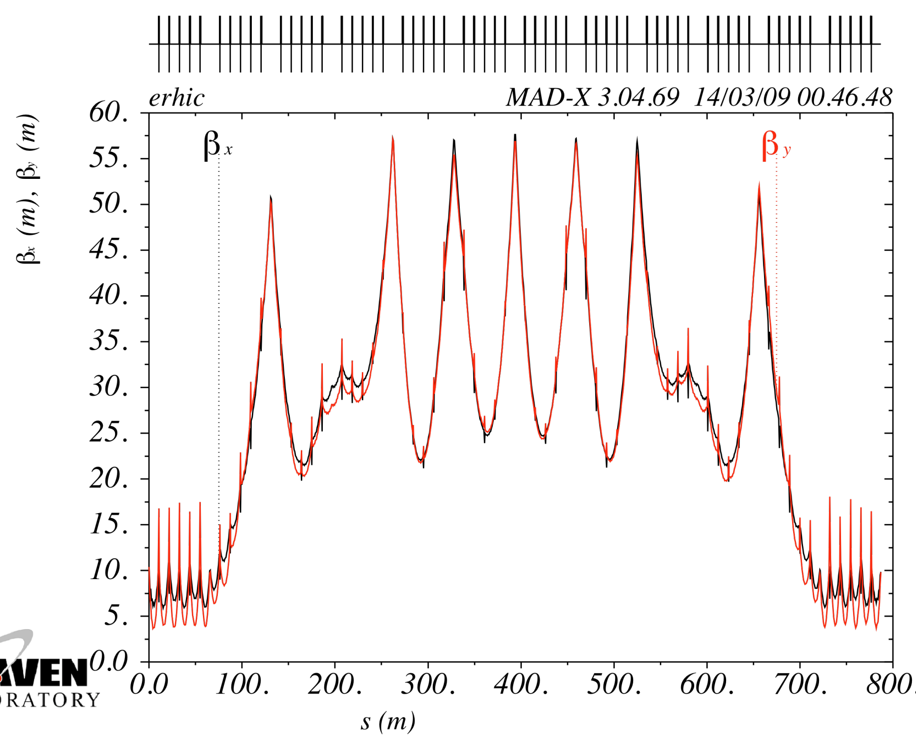


Scaling gradient with energy produces more focusing and increases BBU threshold

G_{min} ~ 100 G/cm

Quad strength

G_{max} ~ 500 G/cm



Matching scaled linac to arcs is in the works

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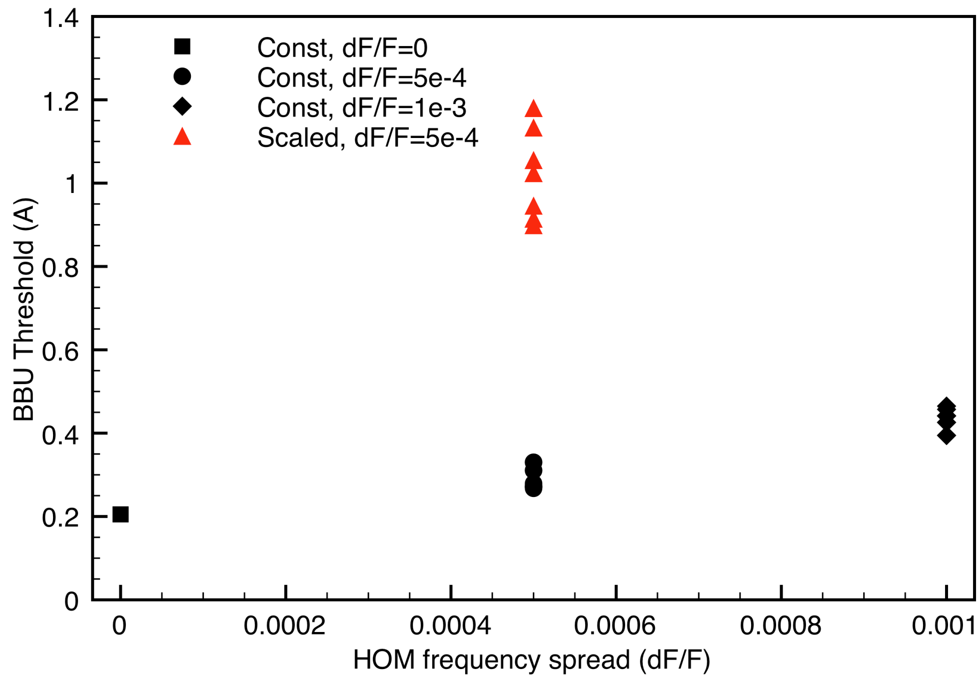
BBU simulations

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

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

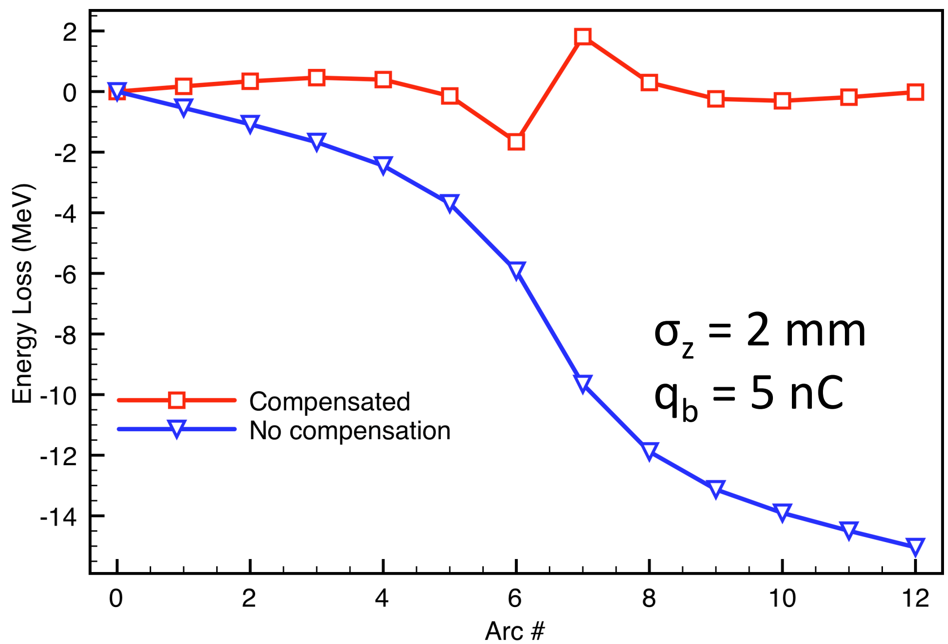
Simulated BBU threshold (GBBU) vs. HOM frequency spread. Beam current 50 mA

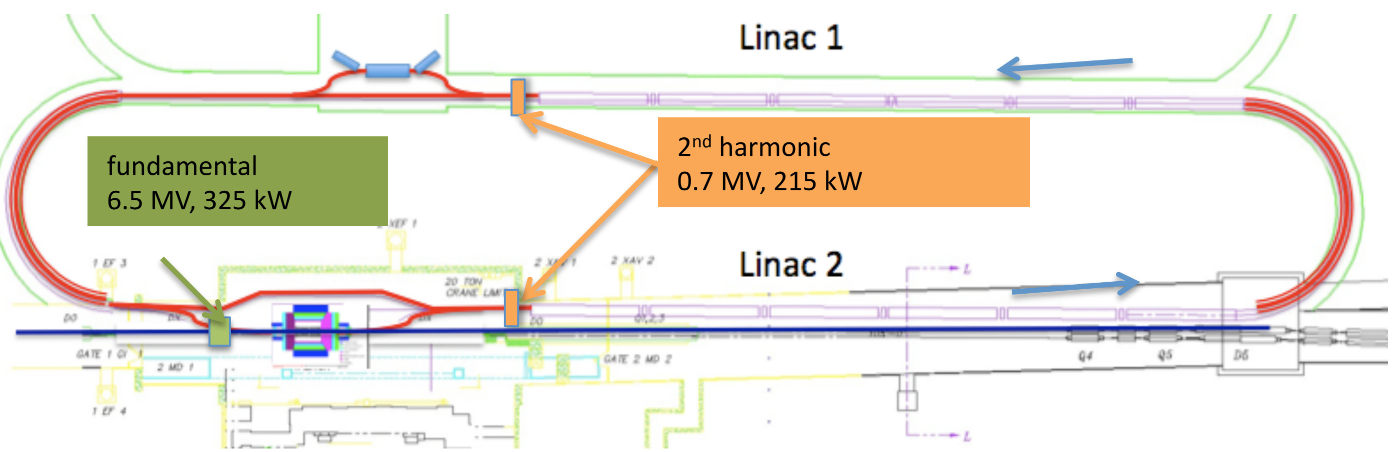


Threshold significantly exceeds the beam current, especially for the scaled gradient solution.

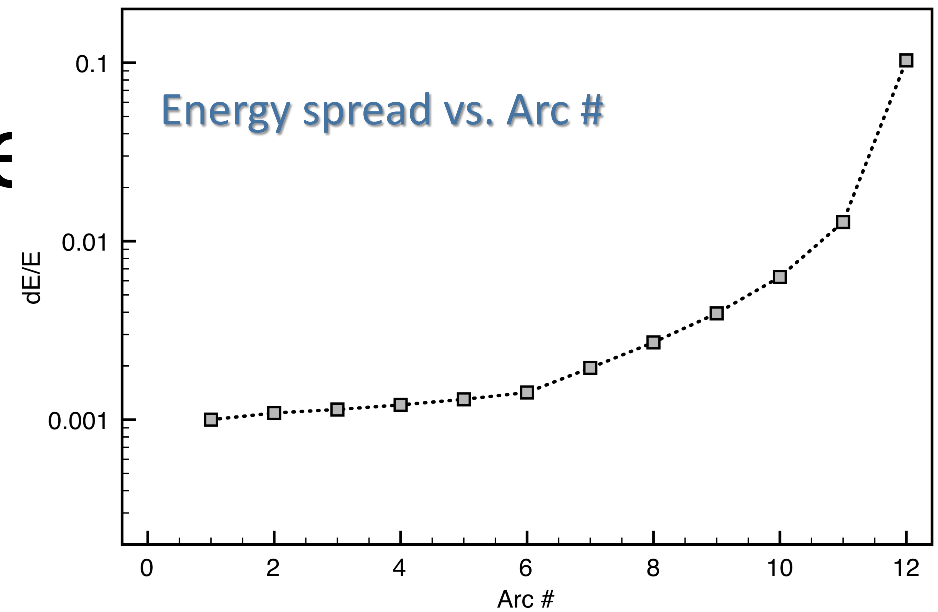
Energy loss and its

- Energy loss
  - Linac cavities: 0.54 MeV/linac. (6.5 MeV total)
  - Synch. radiation: 8.8 MeV total
  - CSR: negligible
- Total power loss: 765 kW
- Energy difference in arcs (max)
  - Before compensation: 2%
  - After compensation: 0.06%

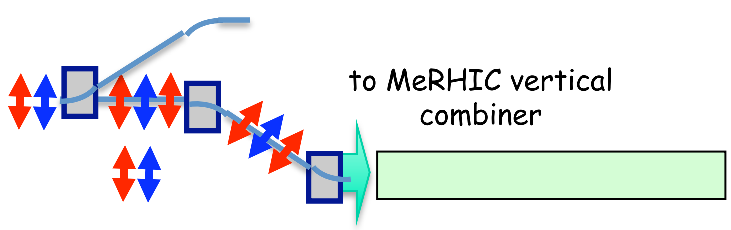


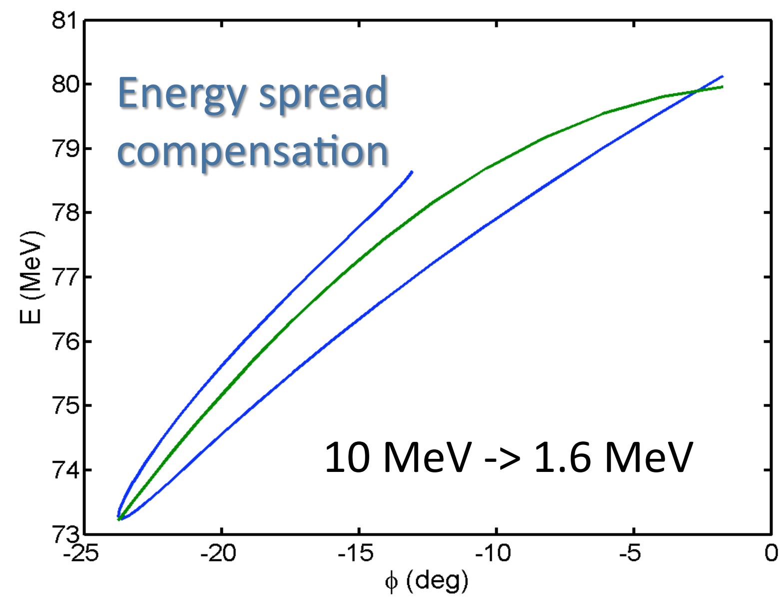


	δE (MeV)
RF	0.17%
Cavity Wakes	8.9
Synch. Rad. (4•rms)	1.35
Resistive Wall	small
CSR	small
Total	10.25



Dog-leg with
M56=15 cm, M566=125 cm^2





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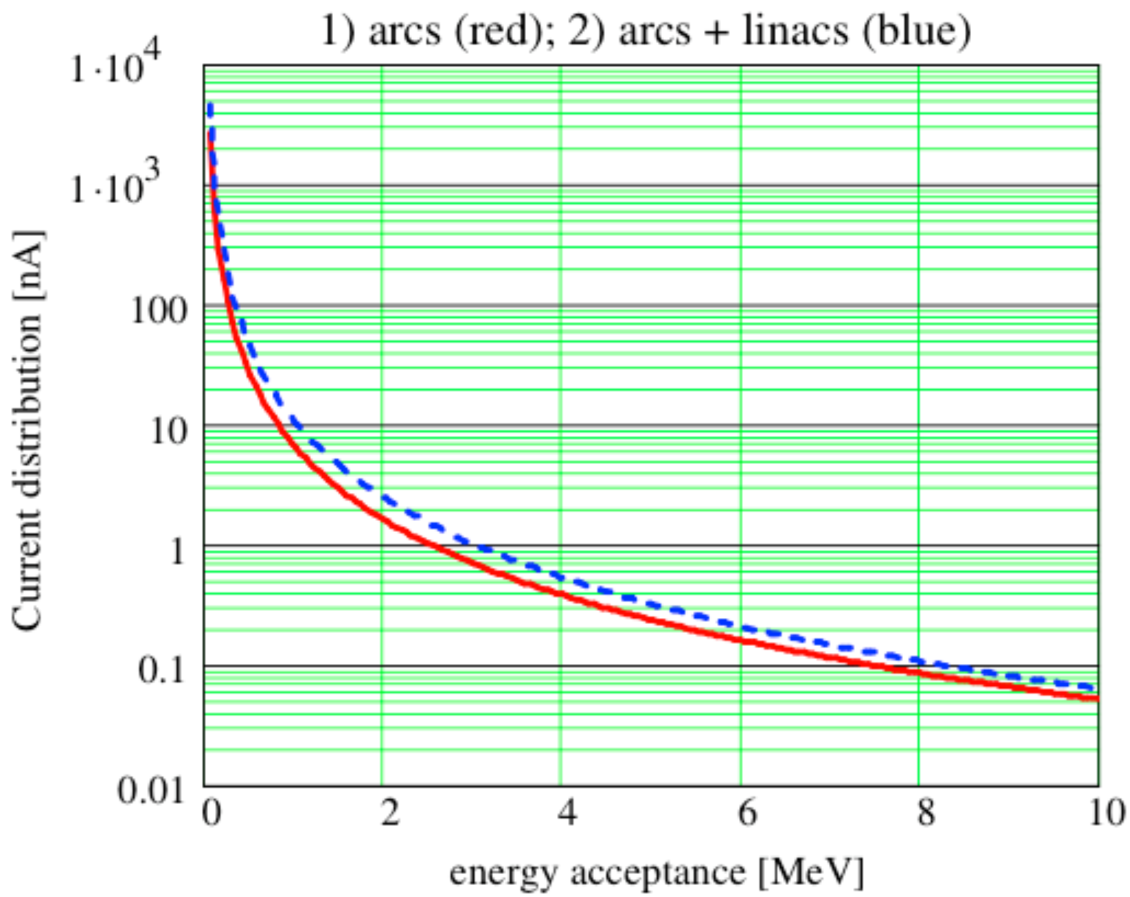
Beam losses: Touschek

Total beam loss beyond given energy aperture



Not a large problem but not negligible

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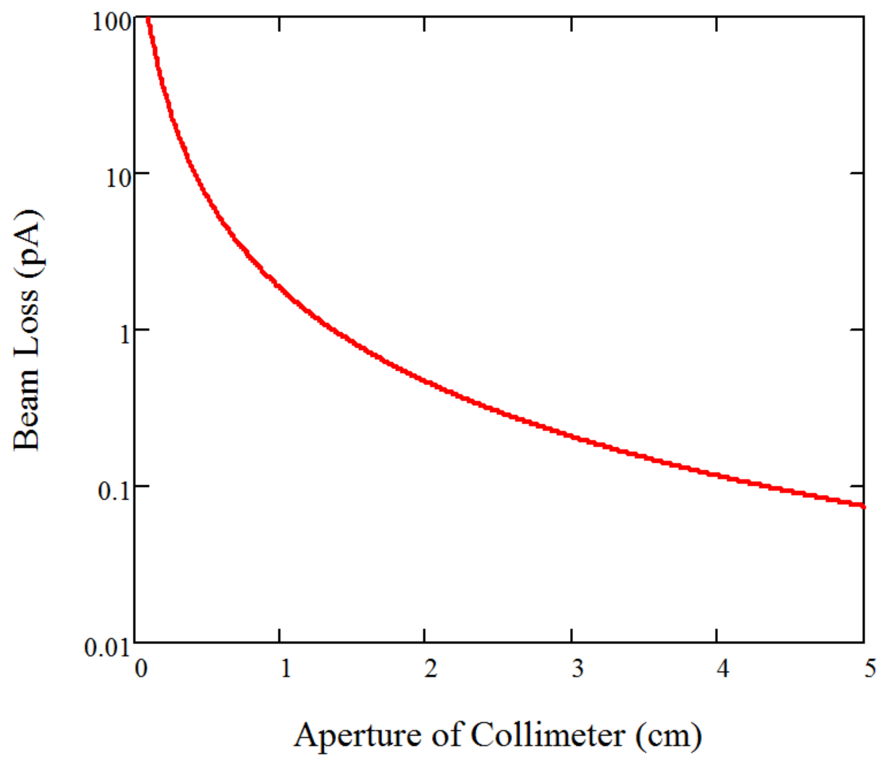
Beam losses: Collisions with residual gas

Scattering

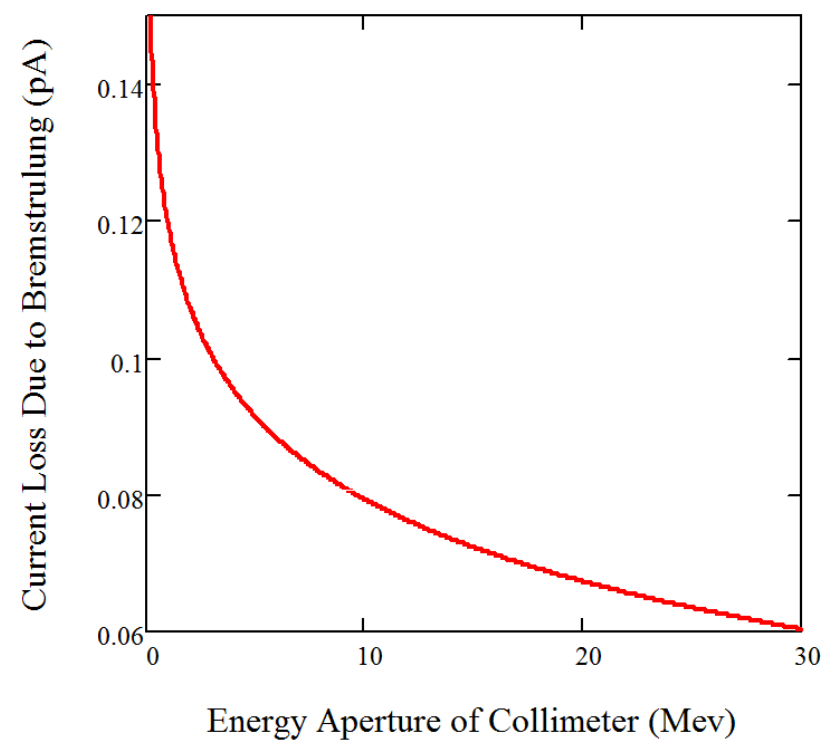
Losses beyond aperture at 100 MeV



Small, can be neglected

Bremsstrahlung

Losses beyond energy aperture



Small, can be neglected

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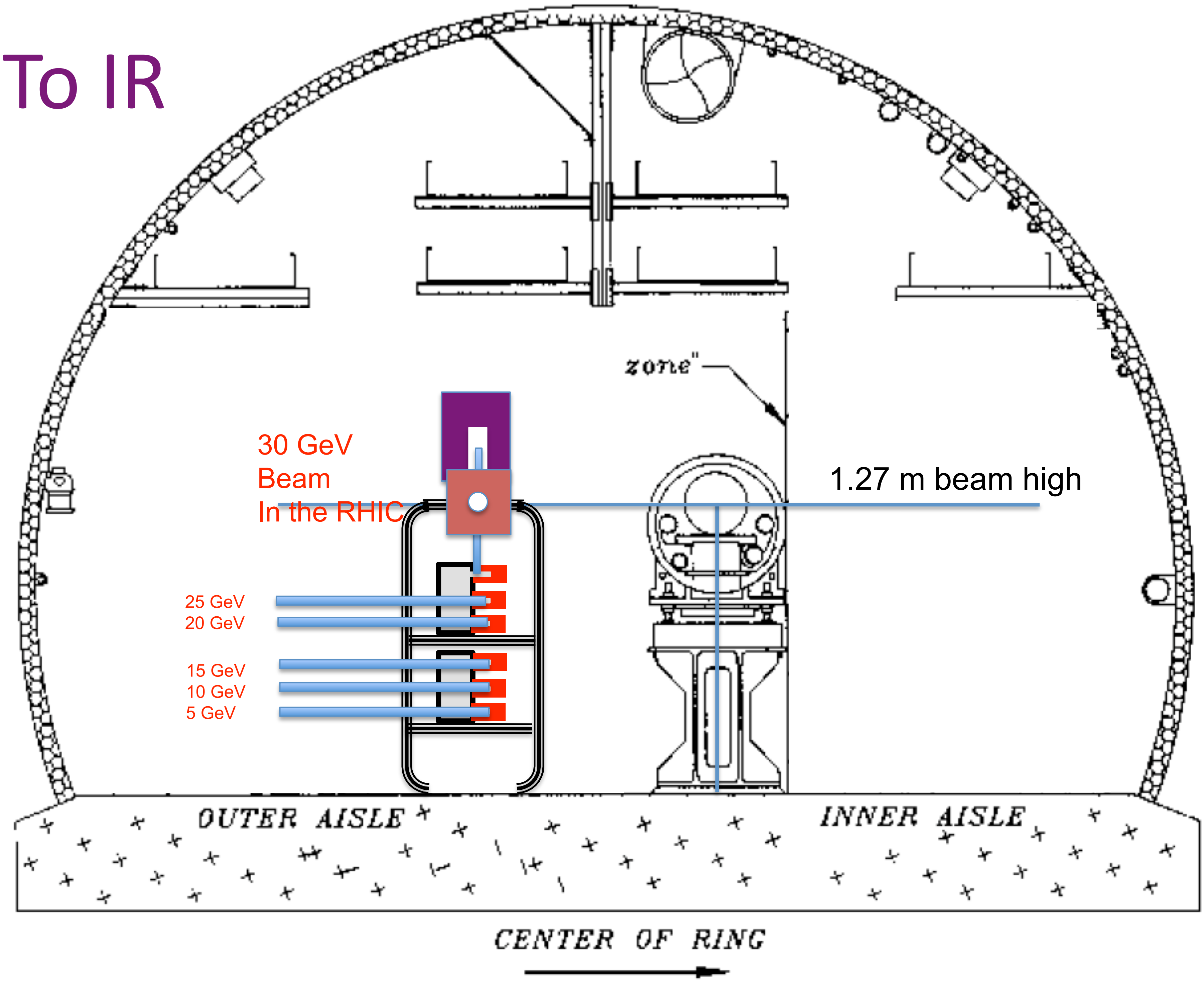
To IR



zone"
30 GeV
Beam
In the RHIC
1.27 m beam high
25 GeV
20 GeV
15 GeV
10 GeV
5 GeV
OUTER AISLE
INNER AISLE
CENTER OF RING

Staging of eRHIC: Re-use, Beams and Energetics

- **MeRHIC**: Medium Energy electron-Ion Collider
  - > 90% of ERL hardware will be use for full energy eRHIC
  - Possible use of the detector in eRHIC operation
- **eRHIC – High energy and luminosity phase**
  - **Based on present RHIC beam intensities**
  - With coherent electron cooling requirements on the electron beam current is 50 mA
  - 20 GeV, 50 mA electron beam losses 4 MW total for synchrotron radiation.
  - 30 GeV, 10 mA electron beam loses 4 MW for synchrotron radiation
  - Power density is <2 kW/meter and is well within B-factory limits (8 kW/m)
- **eRHIC upgrade(s) if needed**

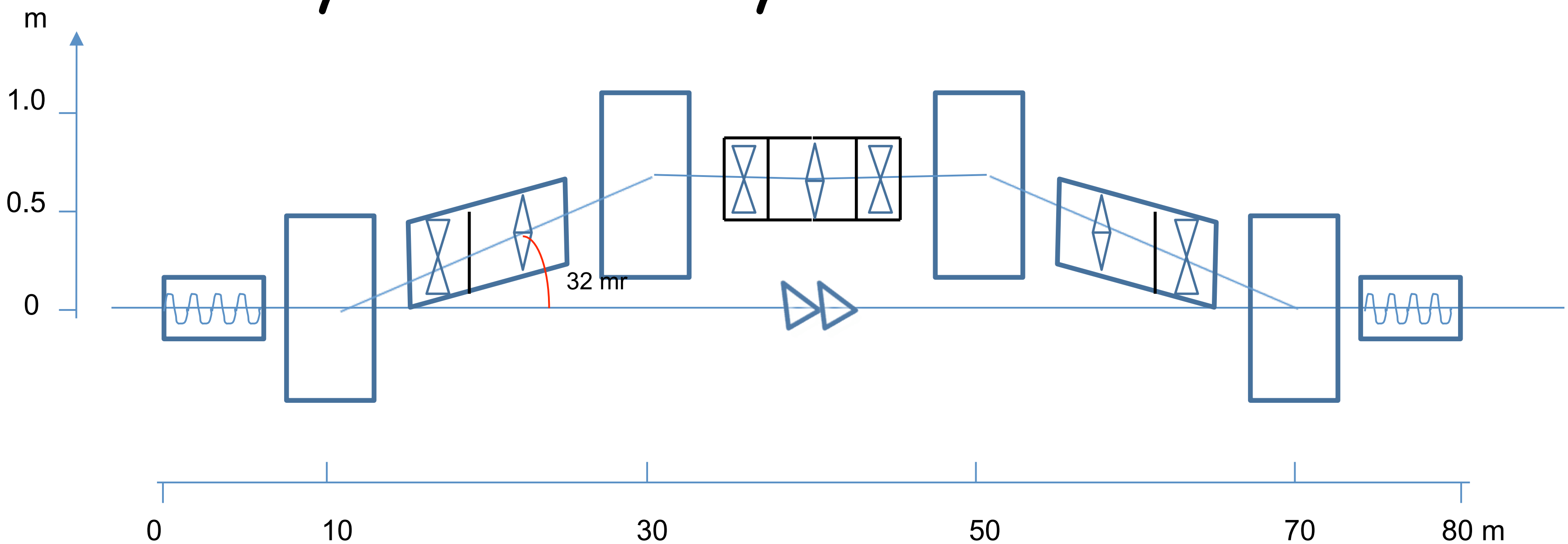
OSC Bypass for RHIC

OPA is fast: Input-output delay = $L_{crystal}/c \leq$ 20mm

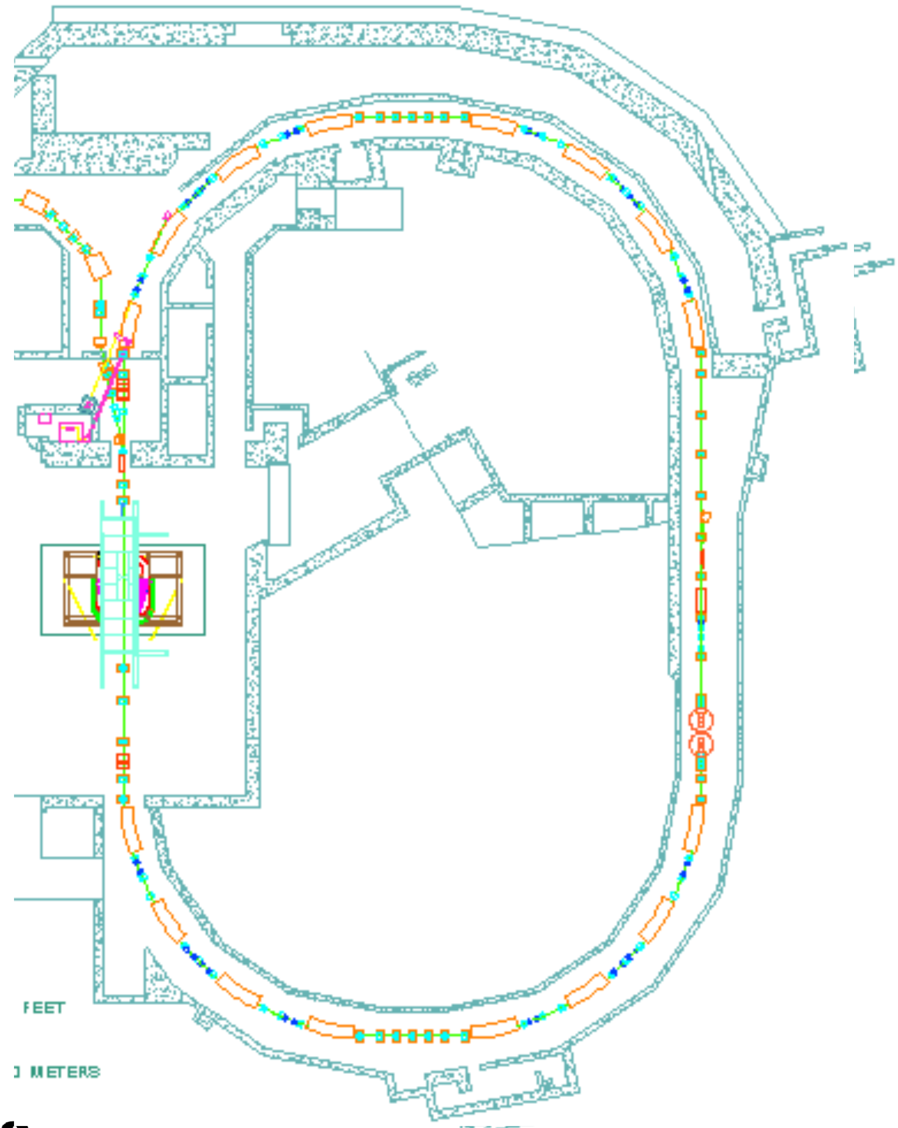
$\Delta\ell = 20$ mm

→allows small-angle (32mrad) bypass with

→relaxed tolerances for field and position accuracy and stability

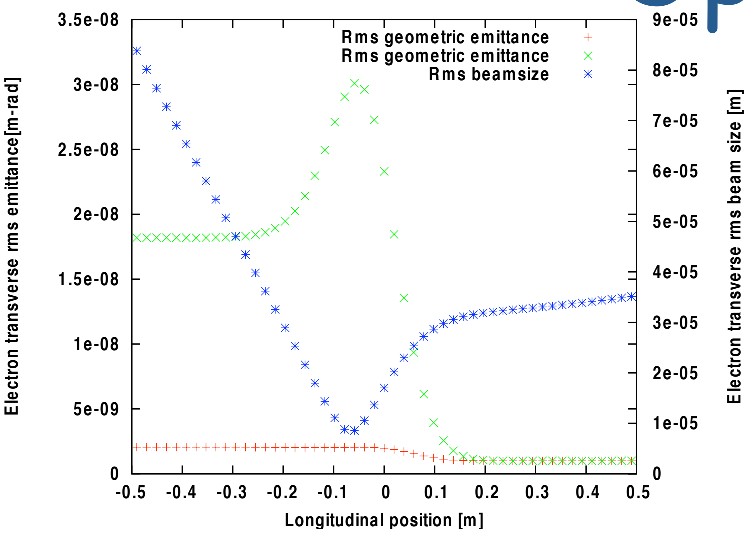


Bates OSC Experiment: Layout

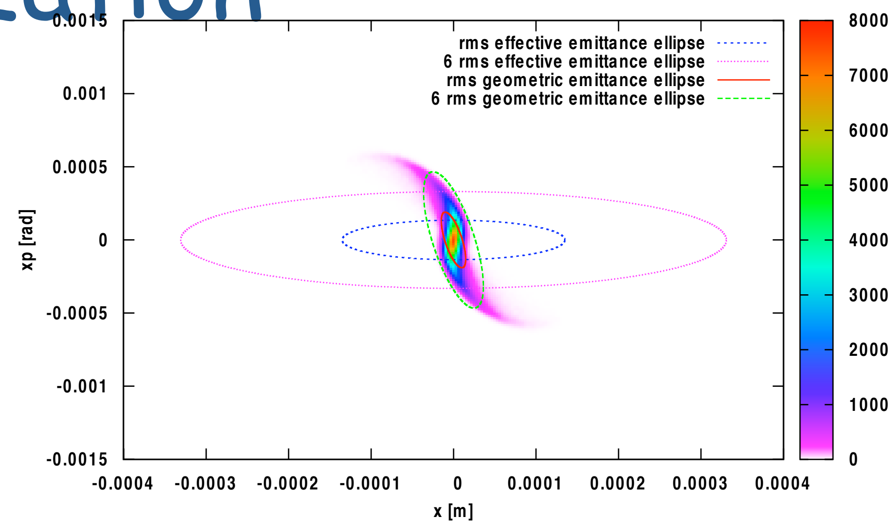


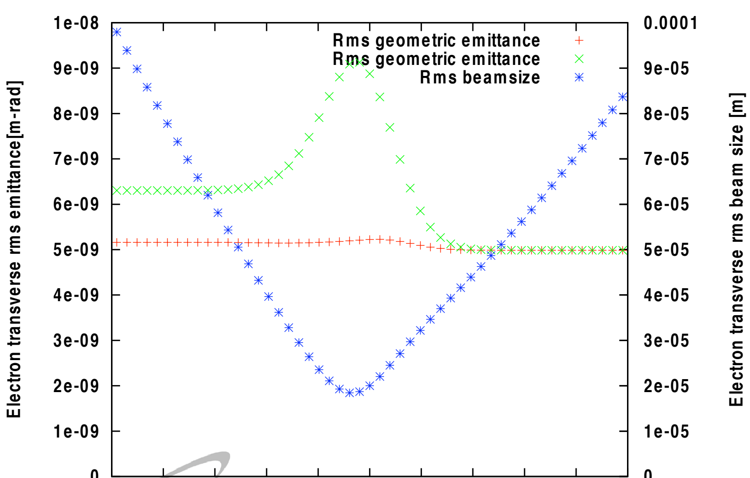
- Distinguish OSC from damping due to synchrotron radiation
  - Low energy electrons
  - Large dipole bend radius
- Long straight sections desirable for OSC apparatus
- South Hall Ring, e^- storage ring
  - Full energy injection at 300 MeV
- Dedicated use of South Hall Ring for first OSC demonstration
  - Design tolerances consistent with existing technology
  - Optimize for SHR environment

Disruption for eRHIC Optimization



β*= 1m
Emittance: 1nm-rad





β*= 0.2m
Emittance: 5nm-rad