Machine Design Progress and Options at BNL:

eRHIC and MeRHIC

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

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18004

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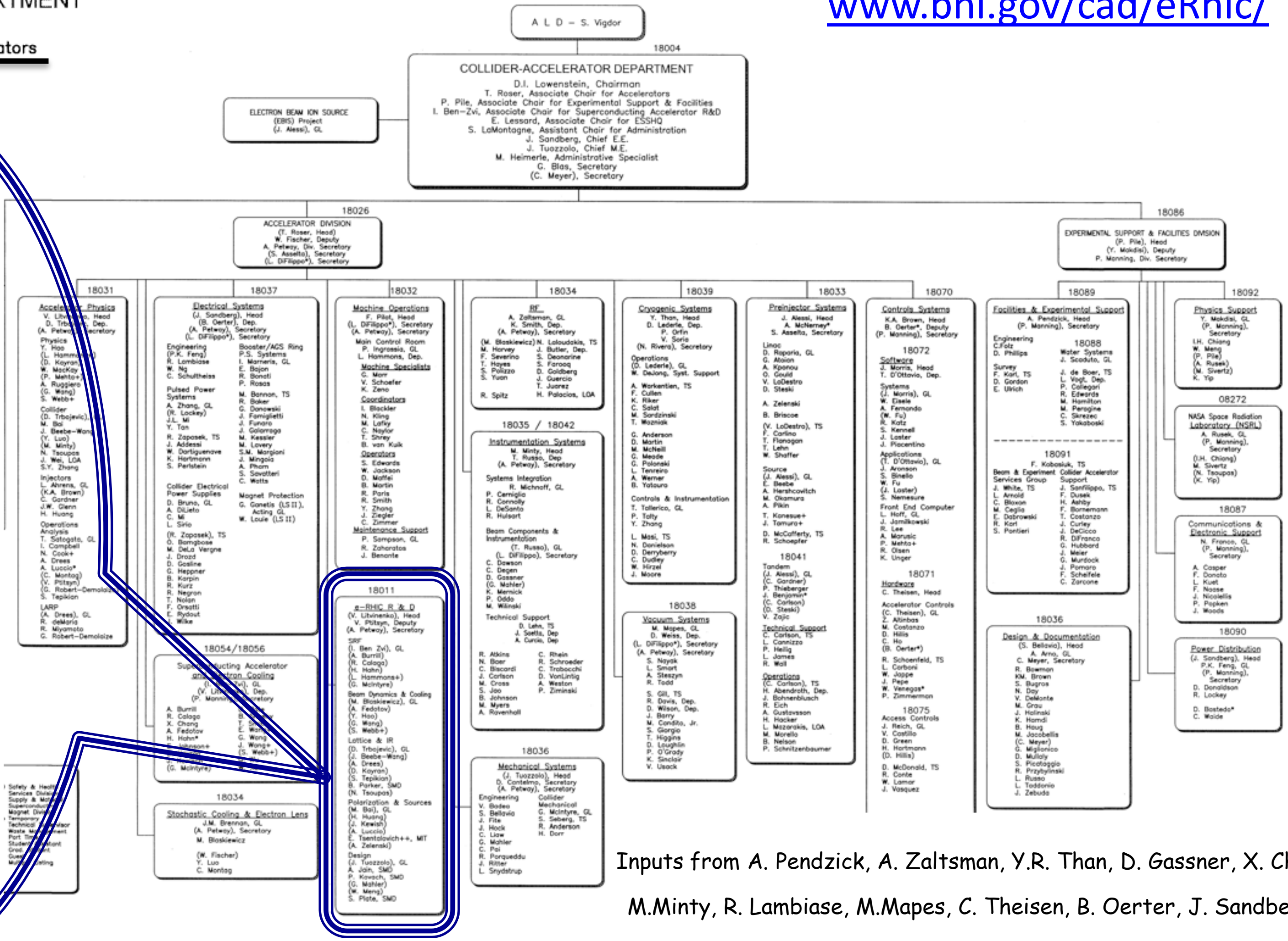
www.bnl.gov/cad/eRhic/



Inputs from A. Pendzick, A. Zaltsman, Y.R. Than, D. Gassner, X. Chang, M.Minty, R. Lambiase, M.Mapes, C. Theisen, B. Oerter, J. Sandberg, K. Mirabella, R. VanWormer

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, ….

Conclusions first

- Collider beam physics laws assert that with any given beam and IR parameters, a linac-ring collider outperforms a ring-ring collider
- 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 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*

We prepared for tomorrow following topics on MeRHIC design

- MeRHIC design –Vadim Ptitsyn
- Beam dynamics –Yue Hao
- Engineering challenges and solutions –Andrew Burrill

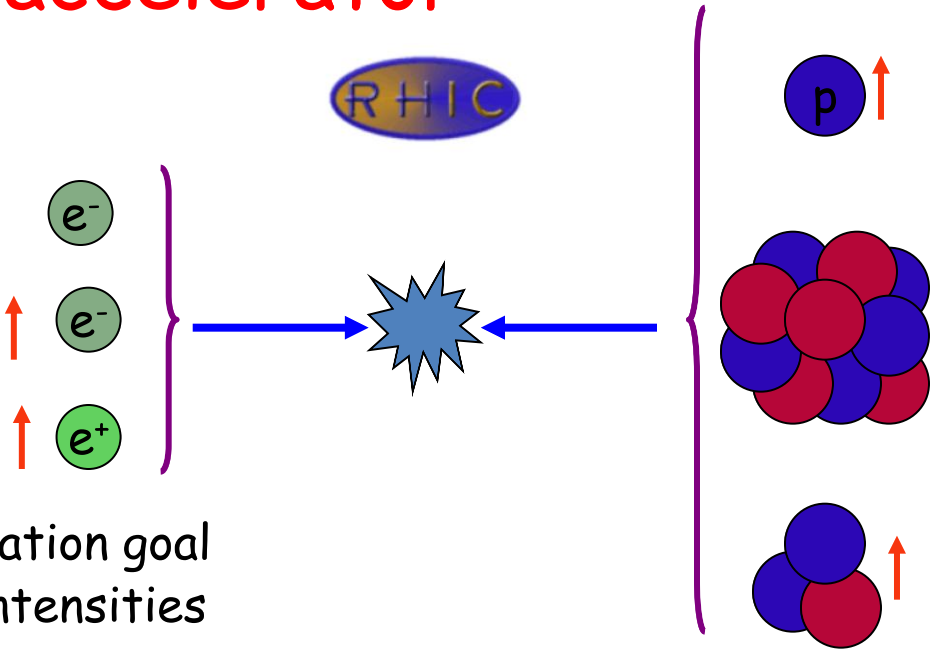
Content

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

eRHIC Scope -QCD Factory

Electron accelerator

RHIC



Polarized protons
$_{25}\downarrow$ 50-250 (325) GeV

Unpolarized and
polarized leptons
4-20 (30) GeV

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

70% beam polarization goal
Positrons at low intensities

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

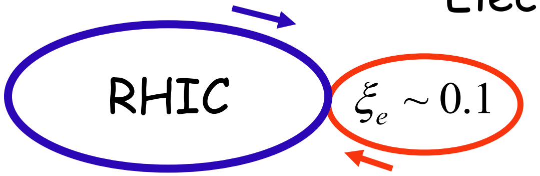
Center mass energy range: 15-200 GeV

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:

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

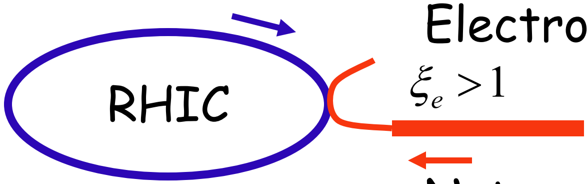


Electron storage ring

✓

  - 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

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**

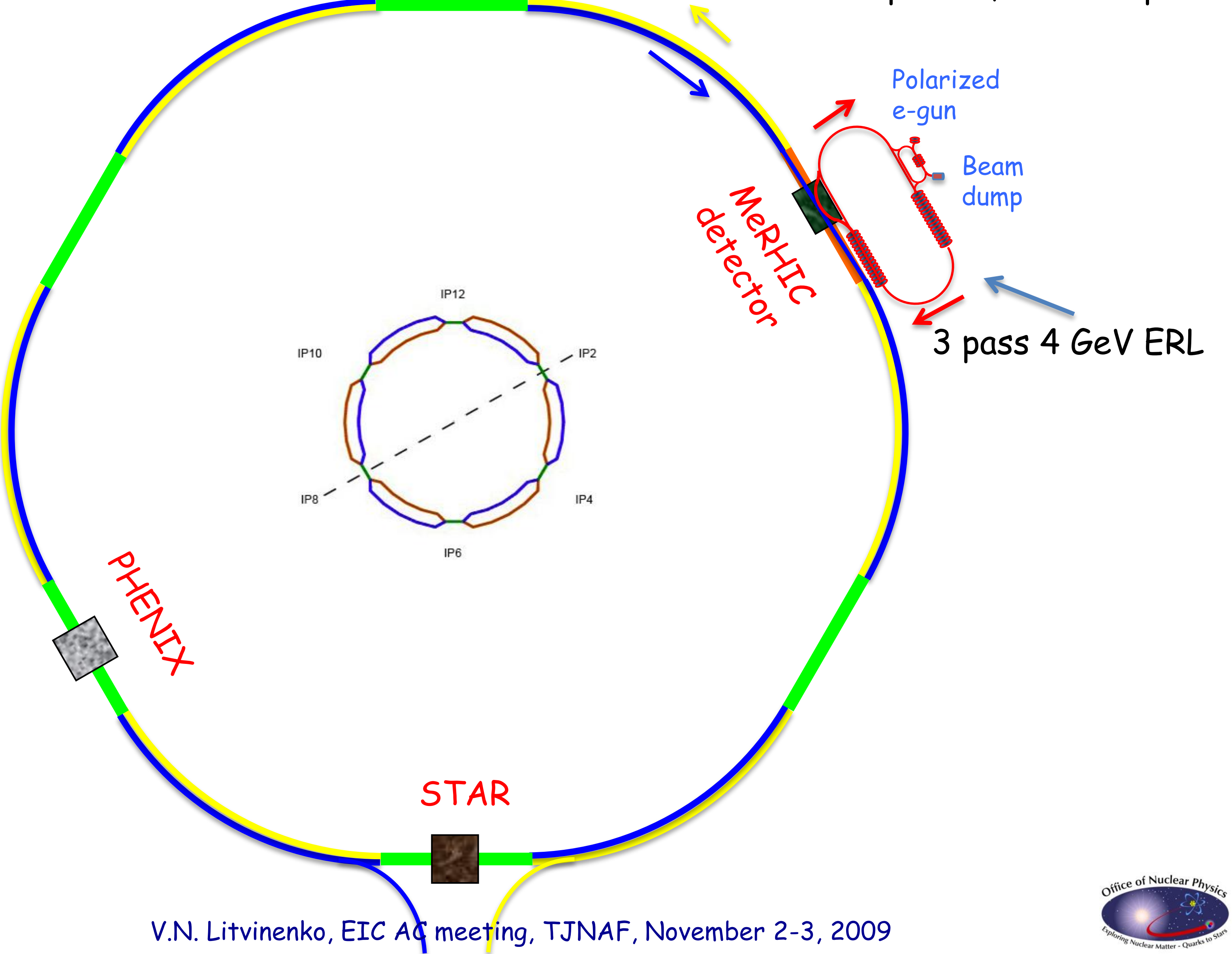
Staging of eRHIC:
Re-use, Beams and Energetics

- **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**

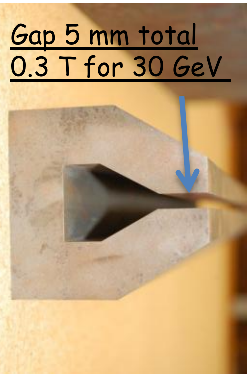
4 GeV e x 250 GeV p – 100 GeV/u Au

MeRHIC

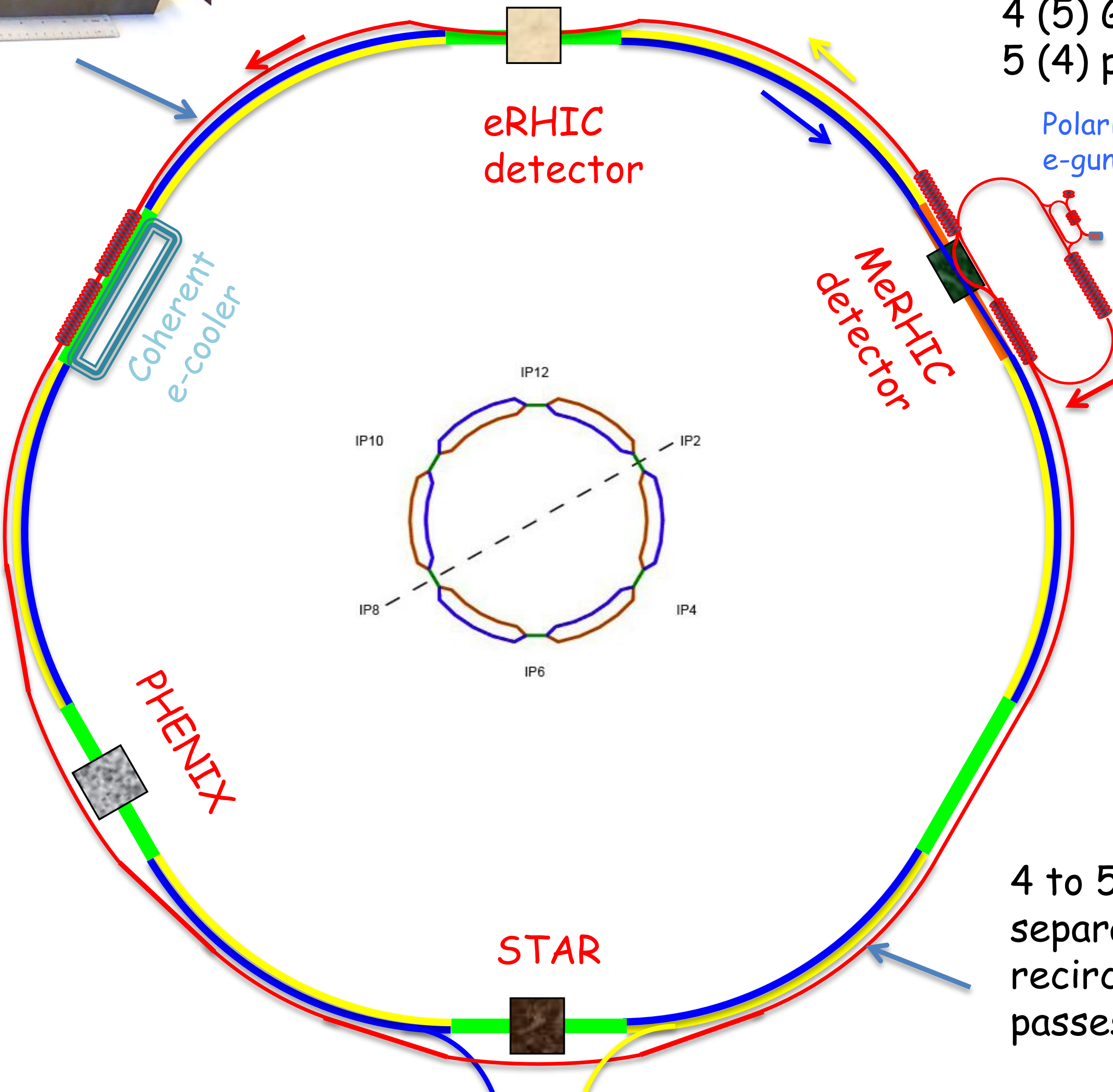
2 x 60 m SRF linac
3 passes, 1.3 GeV/pass



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

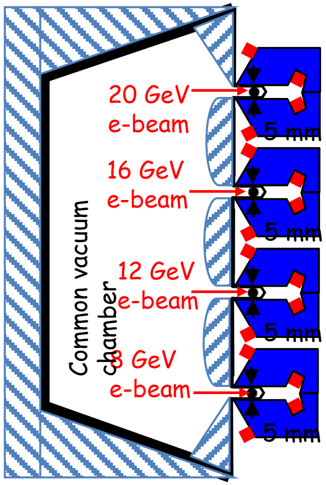


2 x 200 m SRF linac
4 (5) GeV per pass
5 (4) passes



Polarized e-gun

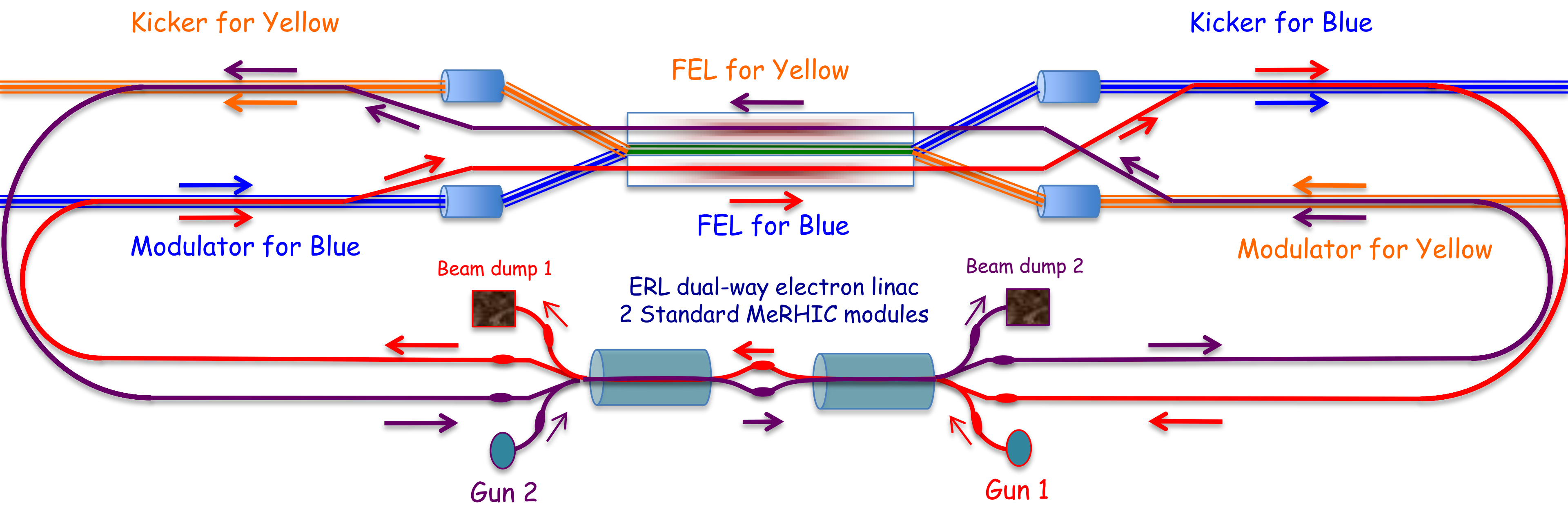
Beam dump



Possibility of 30 GeV low current operation

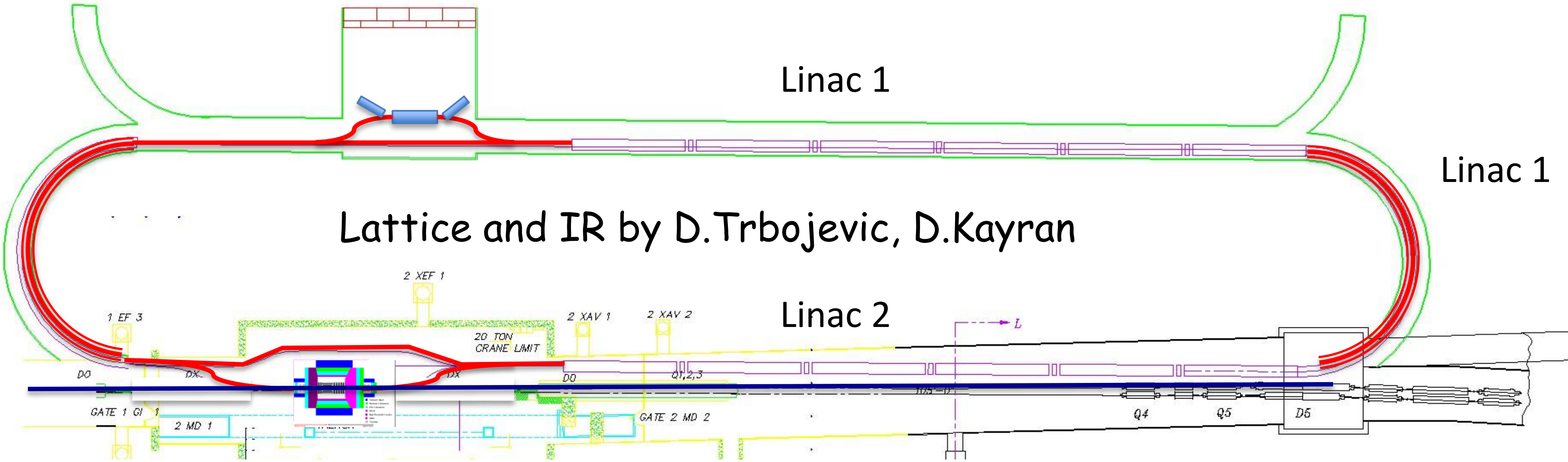
4 to 5 vertically separated recirculating passes

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



E_p, GeV	γ	$E_{e,}$ MeV
100	106.58	54.46
250	**266.45**	**136.15**
325	346.38	177.00

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



Linac 1

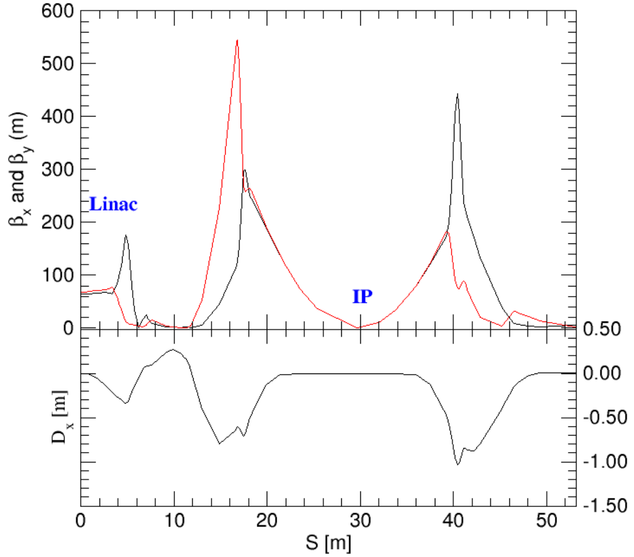
Linac 1

Lattice and IR by D.Trbojevic, D.Kayran

Linac 2

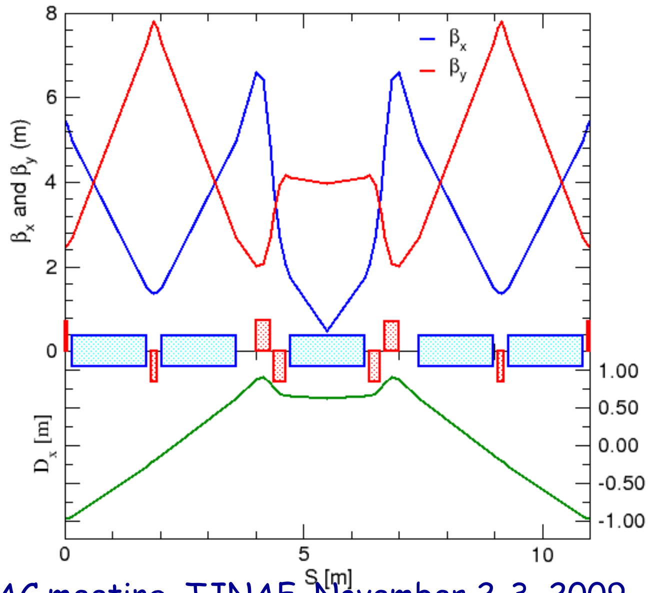
Interaction Region

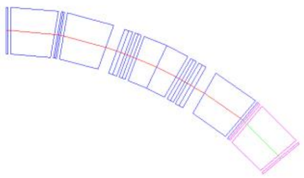
β^*=0.5 m - total length 53 m



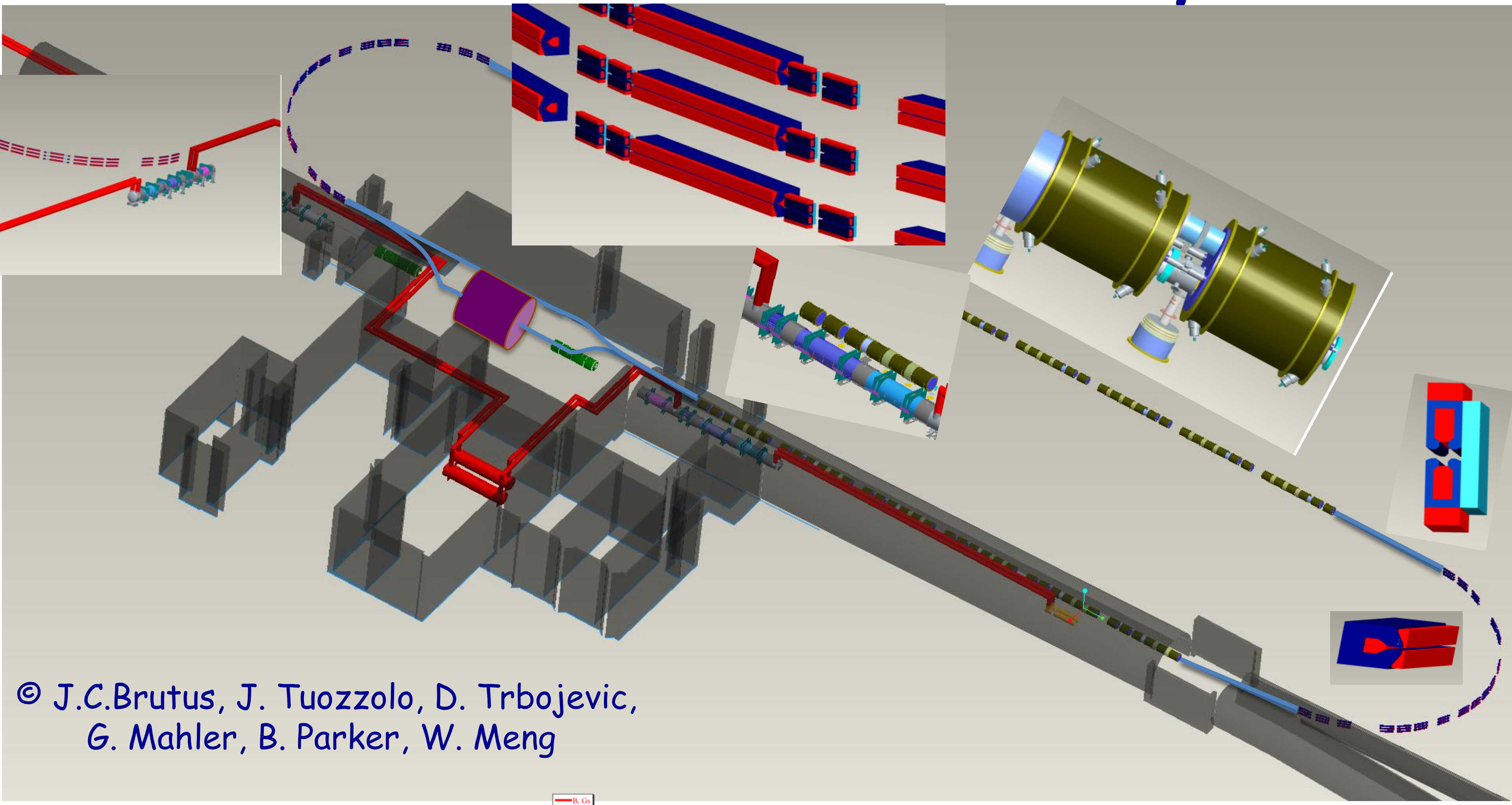
4 GeV Arcs with the Flexible Momentum Compaction Lattice

Total lenght 11 m





MeRHIC in IR 2: 3D layout



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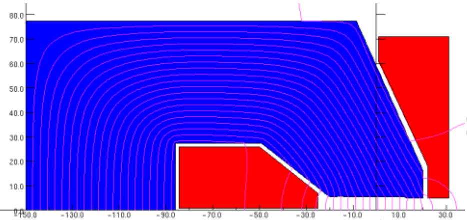
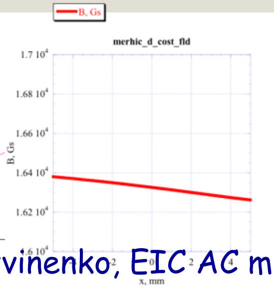
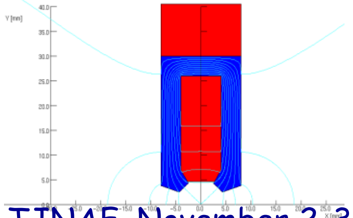
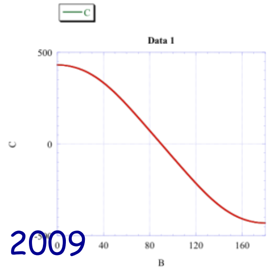






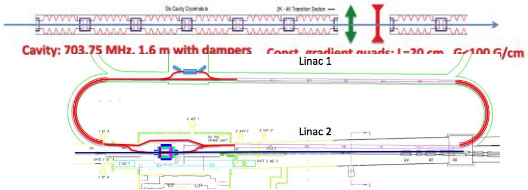


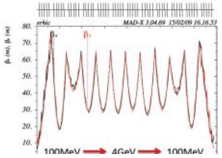
Myriad of beam dynamics issues were studied for MeRHIC
No show-stoppers !

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

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

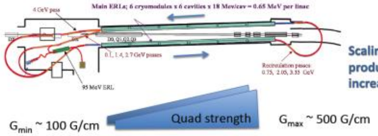
Linac design with const. grad quads (current baseline)





- Bunch: Q_b=5 nC, σ_z=2mm
- E_{inj}/E_{max} = 100MeV / 4GeV
- 3 acc./decel. passes
- N cavities = 72 (total)
- L module/period = 9.6 / 11.1m
- E_f = 18.0 MeV/cav
- ⟨dE/ds⟩ ~ 10 MeV/m

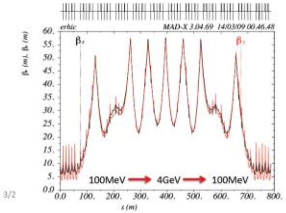
Scaled gradient solution



Scaling gradient with energy produces more focusing and increases BBU threshold

G_{min} ~ 100 G/cm

G_{max} ~ 500 G/cm



Scaled linac is work in progress

3/2

3

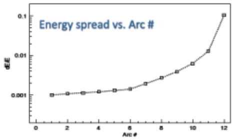
Beam losses

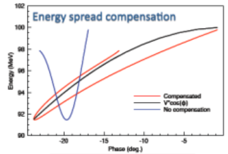
- **Touschek**
  - Total loss beyond ±6 MeV is 200 pA.
  - Small but, maybe, not negligible. We will look more carefully.
- **Scattering on residual gas (elastic)**
  - Total loss beyond 1 cm aperture at 100 MeV is 1 pA
  - Negligible
- **Bremsstrahlung on residual gas**
  - Total loss beyond ±6 MeV is < 0.1 pA
  - Negligible

(A. Fedotov, G. Wang)

Energy spread and its compensation

	δE (MeV)
RF	0.17%
Cavity Wakes	8.9
Synch. Rad. (4•rms)	1.35
Resistive Wall	0.45
CSR	> 0.001
Total	10.7





100 MeV: 9 MeV -> 2 MeV
200 MeV: 9 MeV -> 3 MeV

r, MAC

Beam-Beam: kink instability

Without Landau damping, the beam parameters are above the threshold of kink instability for proton beam. Proper energy spread and chromaticity is needed to suppress the emittance growth.

To avoid strong head-tail instability:

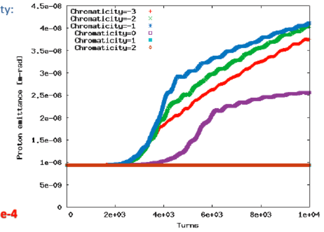
$$\frac{a\beta}{8\nu_s} < 1$$

$$a = \frac{\sigma_{pz}}{2f_p f_z} = \frac{N_p N_e r_p r_e \sigma_{pz}}{2\sigma_{px}^2 \sigma_{ex}^2 \gamma_p \gamma_e}$$

Not Cooled MEeIC case

$$\frac{a\beta}{8\nu_s} \sim 2.5$$

Chromaticity of 1 and dE/E of 5e-4 Suppress the instability

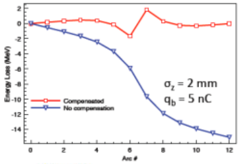


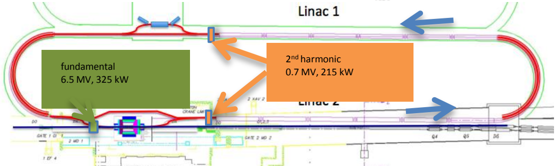
(Yue Hao)

3/24/09 E. Pozdeyev, MAC 10

Energy loss and its compensation

- **Total energy loss: 15.5 MeV**
  - Linac cavities: 6.5 MeV (0.54 MeV/linac)
  - Synch. radiation: 8.8 MeV
  - RW: 0.15 MeV, CSR: negligible
- **Total power loss: 765 kW**
- **Energy difference in arcs (max)**
  - Before compensation: 2%
  - After compensation: 0.06%



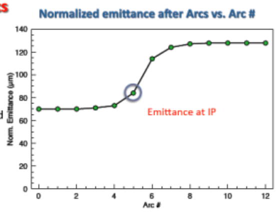


Transverse emittance growth

Synchrotron Radiation in Arcs

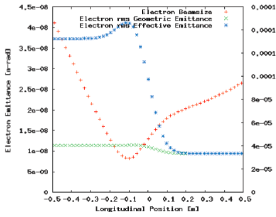
$$\delta\varepsilon = \frac{55 r_c \hbar c}{48\sqrt{3} mc^2}\gamma^5 \int_L \frac{H}{\rho^3} ds$$

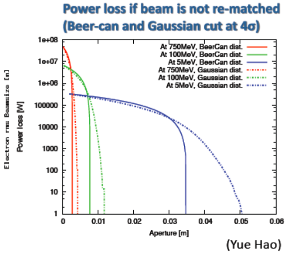
- H function of 3.35 GeV arc is used
- H function and bending radius assumed the same for all arc



Transverse breakup due to short range wakes ("banana" effect):
Work in progress

Beam-Beam: electron beam disruption


Emittance growth in collision


Power loss if beam is not re-matched (Beer-can and Gaussian cut at 4σ)

(Yue Hao)

- Growth of r.m.s. emittance is small. However, mismatch is large.
- Re-matching section might be required
- Re-m elect

3/24/09

Summary and plans

- **Main Linac design has been developed**
  - Constant gradient: weak identical quads, similar arcs, sufficiently high BBU threshold (250 mA)
  - Scaled gradient: higher BBU threshold (900 mA)
- **Beam physics: no show stoppers so far**
- **Things to do:**
  - Continue work on compact HOM dampers
  - Explore other energy spread suppression techniques (Cornell?)
  - "Banana effect" (transverse BBU due to short range wakes)
  - Ions and ion clearing (electrodes?)
  - Requirements on noise in electron beam with realistic spectrum
  - Analysis of optics errors and nonlinearities is in progress
- **Improve accuracy of estimates, simulations.**
- **Experimental studies, if possible (BNL ERL, BNL ATF, JLab FEL, etc.)**

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ERL spin transparency at all energies

Bargman, Mitchel,Telegdi equation

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

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

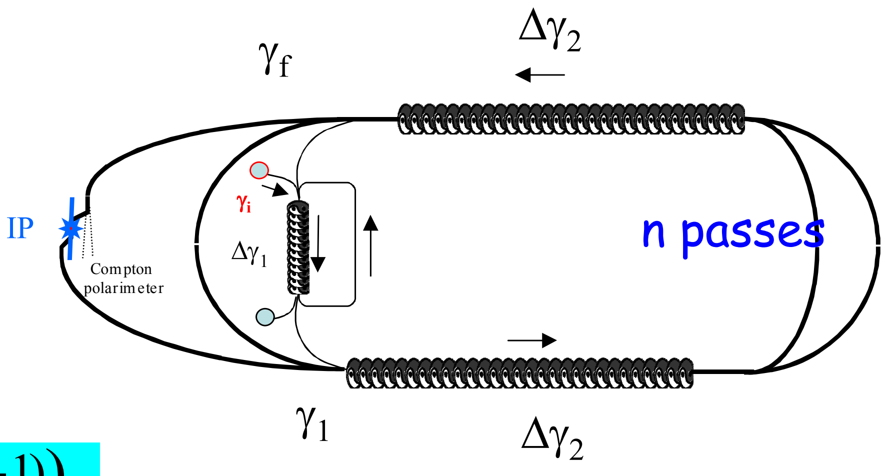
$$\hat{\mu} = \frac{g}{2}\frac{e}{m_o}\hat{s} = (1+a)\frac{e}{m_o}\hat{s}; \qquad \nu_{spin} = a\cdot\gamma = \frac{E_e}{0.44065[GeV]}$$

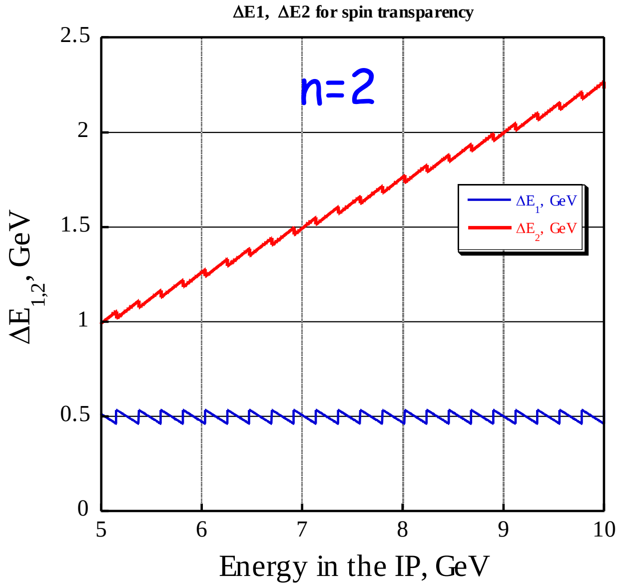
$$\Delta\varphi = a\cdot\gamma\theta$$

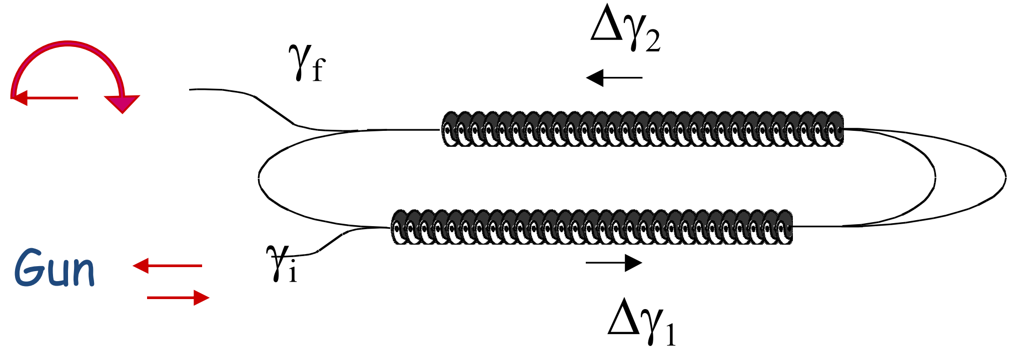
Total angle $\varphi = \pi a\cdot\left(\gamma_i(2n-1)+n(\Delta\gamma_1\cdot n+\Delta\gamma_2(n-1)\right)$

Has solution for all energies!

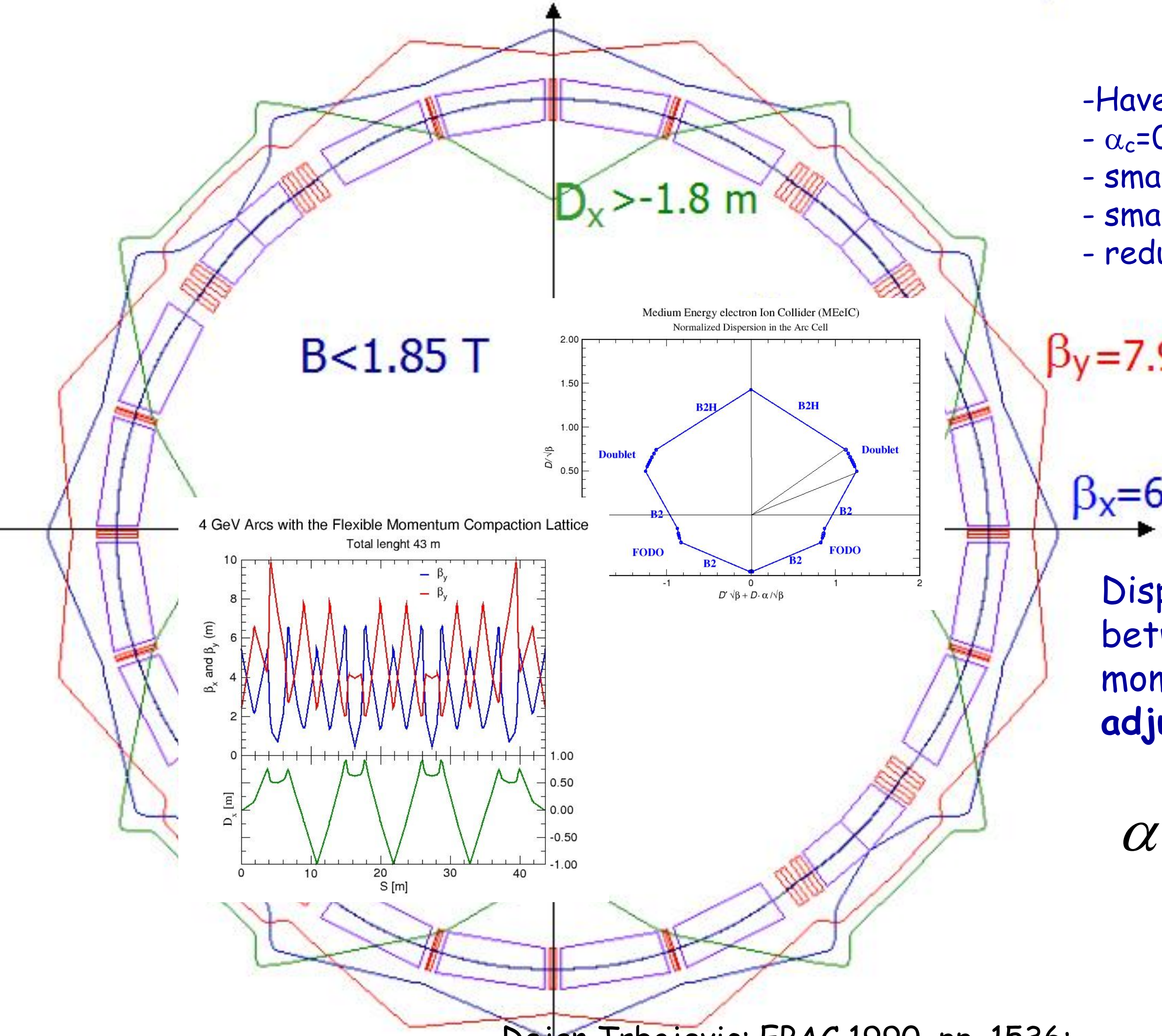
$$\begin{cases} \gamma_i + 2\cdot(\Delta\gamma_1+\Delta\gamma_2) = \gamma_f \\ a\cdot\left(\gamma_i(2n-1)+n(\Delta\gamma_1\cdot n+\Delta\gamma_2(n-1)\right) = N \end{cases}$$







Methods and solutions: asynchronous arcs



Goals:

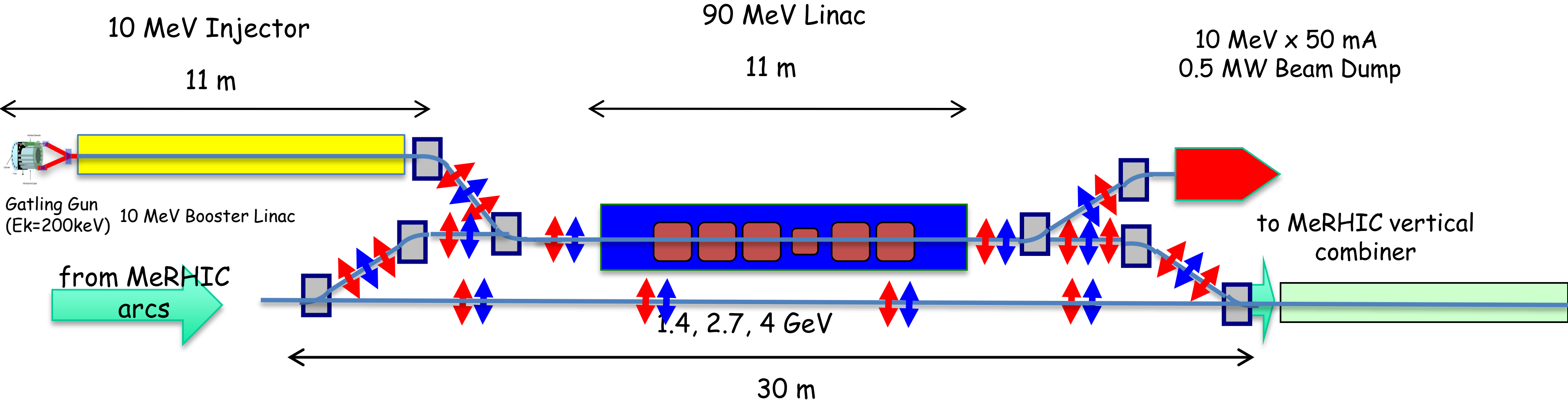
- Have a good packing factor
- α_c=0 or $M_{5,6}$=0
- small dispersion
- small betatron functions
- reduce cost of civil construction

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.”

100 MeV Pre Accelerator ERL



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

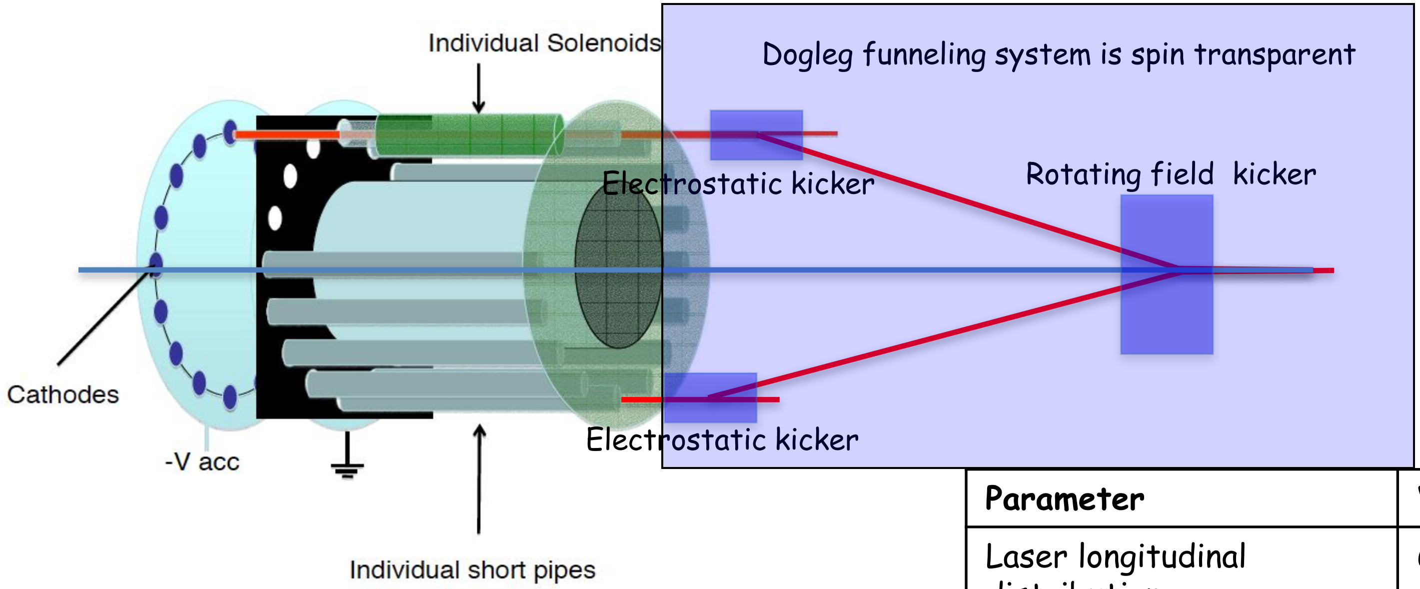
Pre-accelerator ERL:
One pass
Energy gain 90 MeV
Einj & Eextr=10 MeV
Emax =100 MeV

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

Gatling Gun*)

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



~ 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

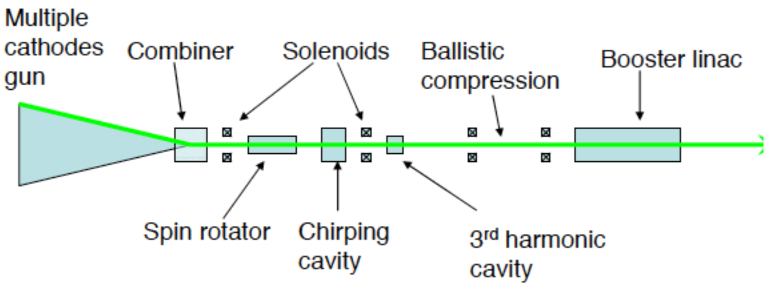
Parameter	**Value**
Laser longitudinal distribution	Gaussian
Bunch length at cathode	0.5nS [FWHM]
Laser transverse distribution	Uniform
Laser spot diameter	8mm
Bunch charge	5nC
Accelerating voltage	200kV
Cathode-anode gap	3cm
Integrated solenoid field	2.1kG-cm

Polarized e-beam injector

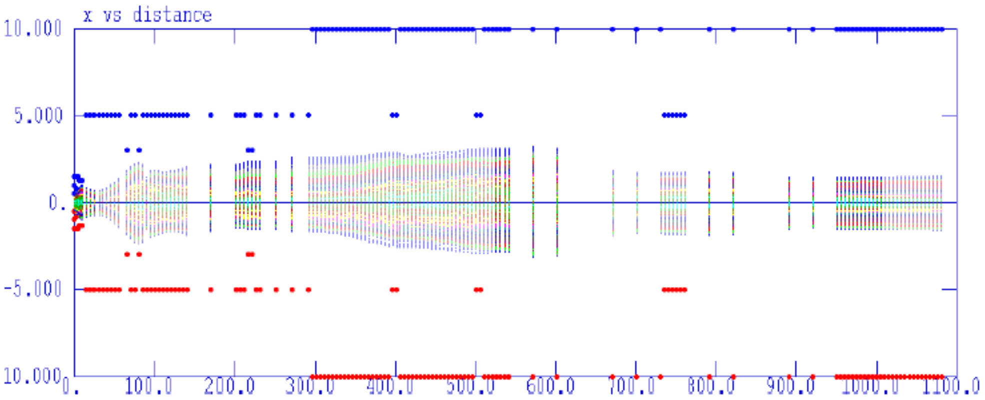
Meeic electron injector design

Xiangyun Chang, Ilan Ben-Zvi, Yue Hao, Jorg Kewisch, Vladimir Litvinenko,
Eduard Pozdeyev, Vadim Ptitsyn, Gang Wang, et al.

Injector layout



Envelope vs. Z



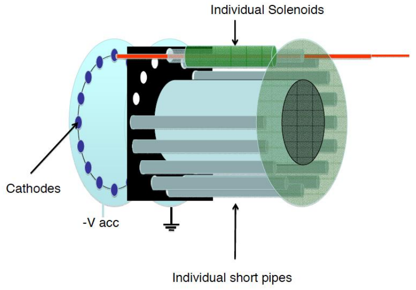
Voltage: 200kV

Laser parameters: transverse uniform with R_{MAX}=4mm
longitudinal Gaussian with σ_L=250ps (FWHM=500ps)
Bunch charge = 5nC/bunch

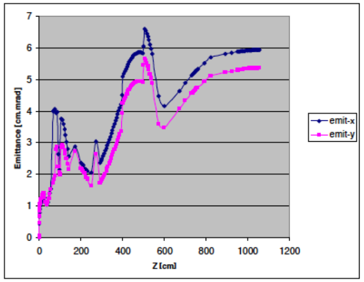
Chirping cavity & Booster linac frequency: 112MHz

Energy after booster linac: 10MeV

rms dE/E at exit: 1%



Emittance

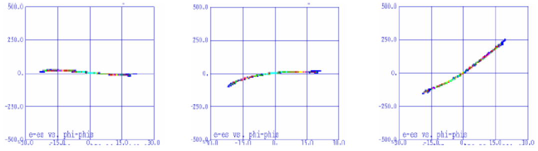


Emittance-X: 60mm.mr

Emittance-Y: 54mm.mr

These emittances can be easily reduced to below 50mm.mr!

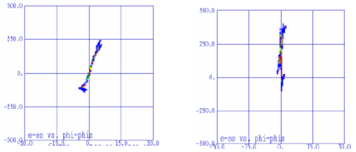
Longitudinal phase space



Before chirping cav.
E=200keV

After chirping cav.
E=790keV

After 3rd harmonic cav.
E=630keV

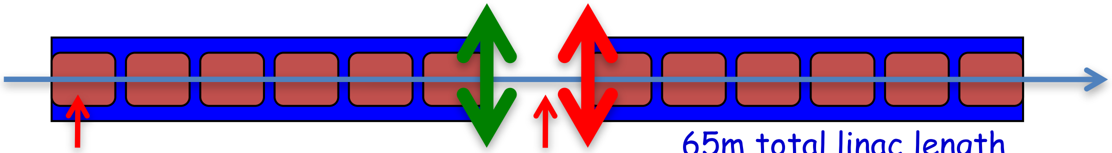


Before Linac. E=630keV

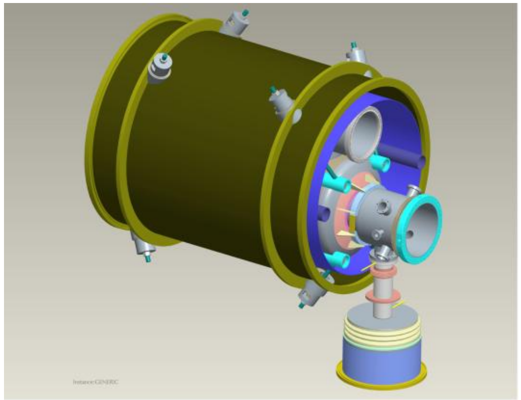
After linac. E=10MeV

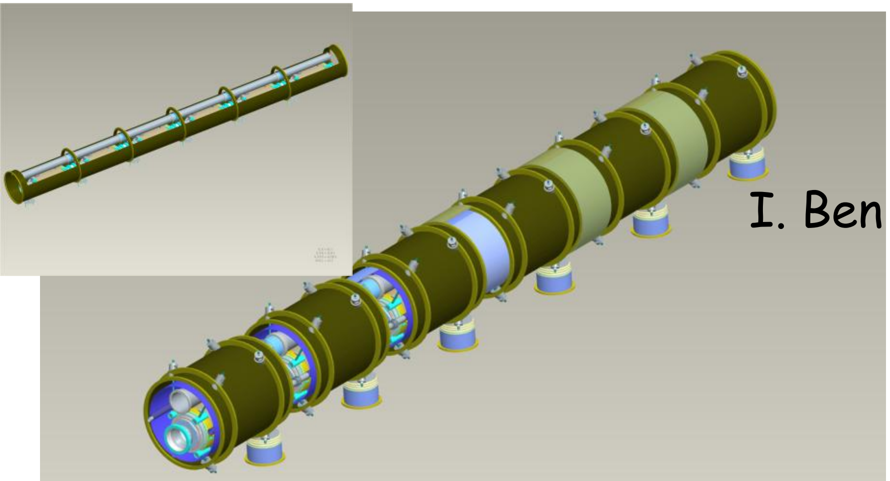
1. Bunch length is 2.8mm including all the particles.
2. Dropping off small amount of the "bad" particles the bunch length will be even smaller. So do the transverse emittances.

MeRHIC Linac Design



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

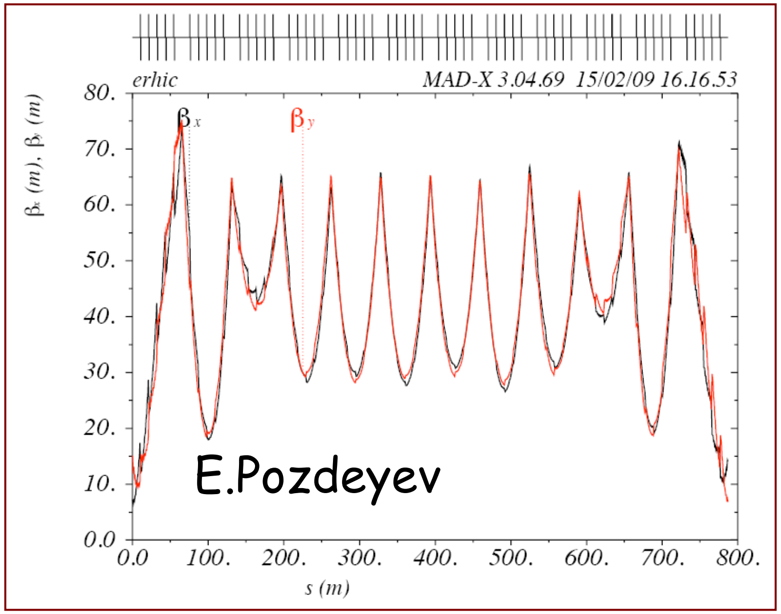




I. Ben Zvi

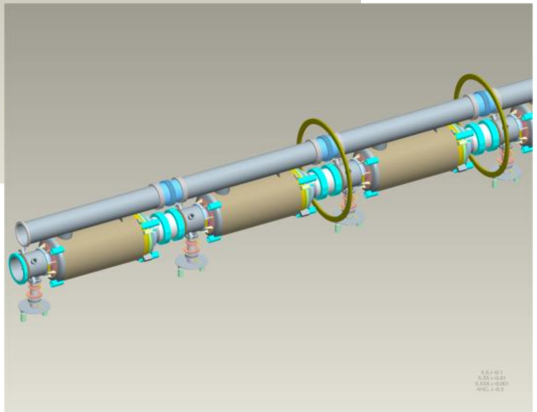
Based on BNL SRF cavity with fully suppressed HOMs
Critical for high current multi-pass ERL

100 MeV → 4 GeV → 100 MeV



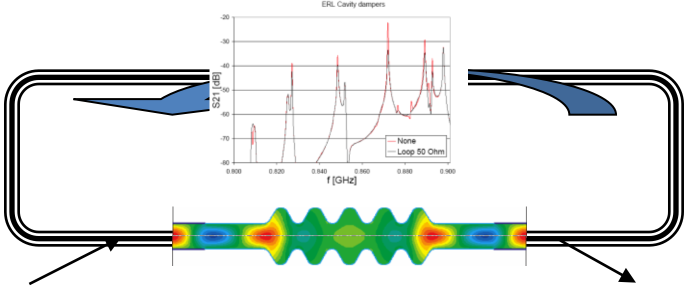
E.Pozdeyev

Current breakdown of the linac
- N cavities = 6 (per module)
- N modules per linac = 6
- N linacs = 2
- L module = 9.6m
- L period = 10.6 m
- E_f = 18.0 MeV/m
- ⟨dE/ds⟩ = 10.2 MeV/m



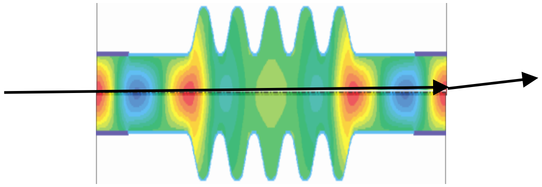
TBBU stability (©E. Pozdeyev)

- 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

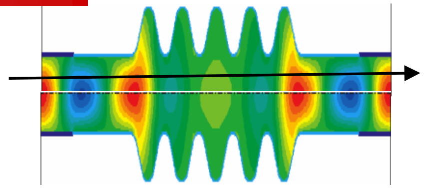


Excitation process of transverse HOM

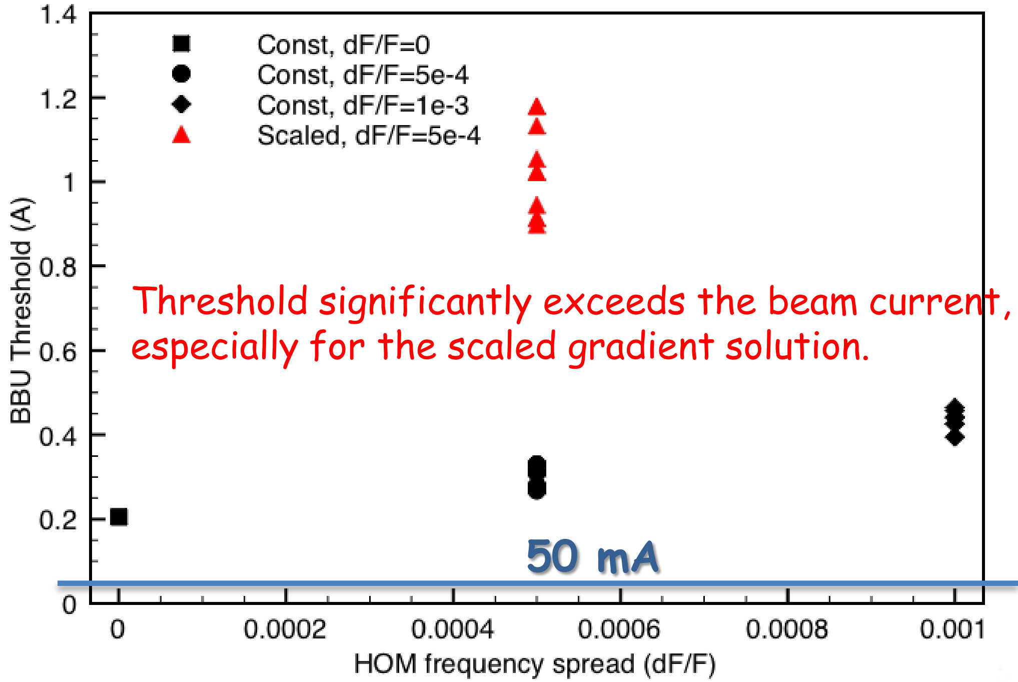
Simulated BBU threshold (GBBU) vs. HOM frequency spread.



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



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



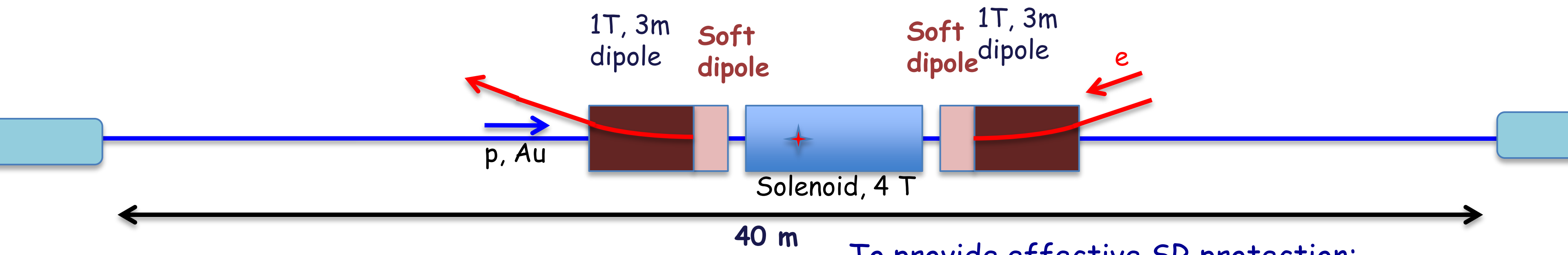
Threshold significantly exceeds the beam current, especially for the scaled gradient solution.

eRHIC IR developments

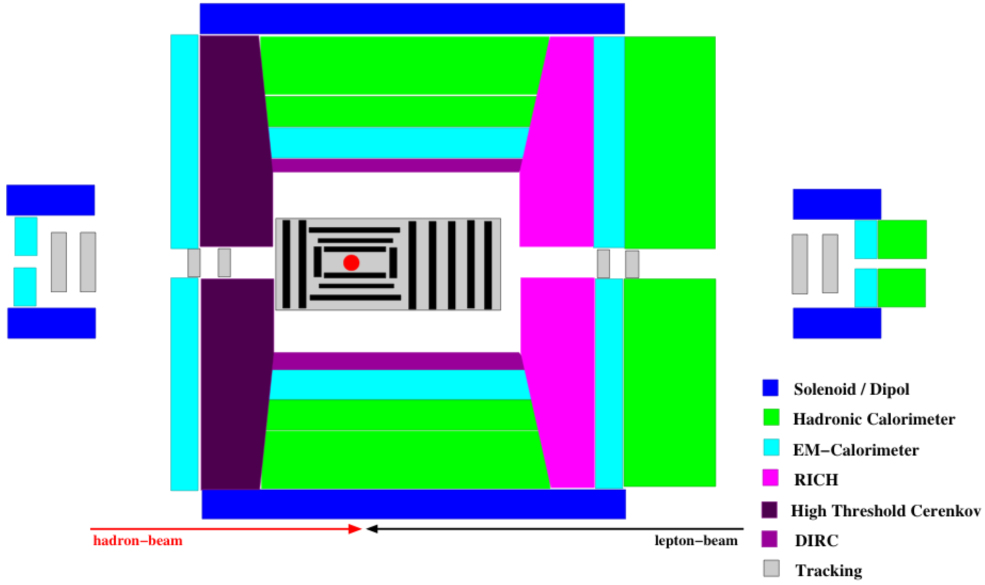
- **eRHIC IR lattice is design in direct communication with EIC task-force and with inputs from EIC collaboration**
- **Main boundary conditions on present IR designs – our main priority**
  - There should be no magnetic elements (except dipole magnets used for EIC physics!) of both electron and hadron 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
    - C) no – **zilch!** - hard X-rays in the detector
  - No – **Zilch!** – hard X-ray 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 integrated into a detector (aka BarBar)**
- **CeC can compress hadron bunch lengths to few cm and β* ~ 5 cm or even shorter are possible in such IR – few possible scenarios are under consideration. This IR can bring eRHIC luminosity well above 10^{34}.**

Integrated IR design
MeRHIC 4 GeV e x 250 GeV p/100 GeV Au

Remove DXes – 40 m to detect particles scattered at small angles



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



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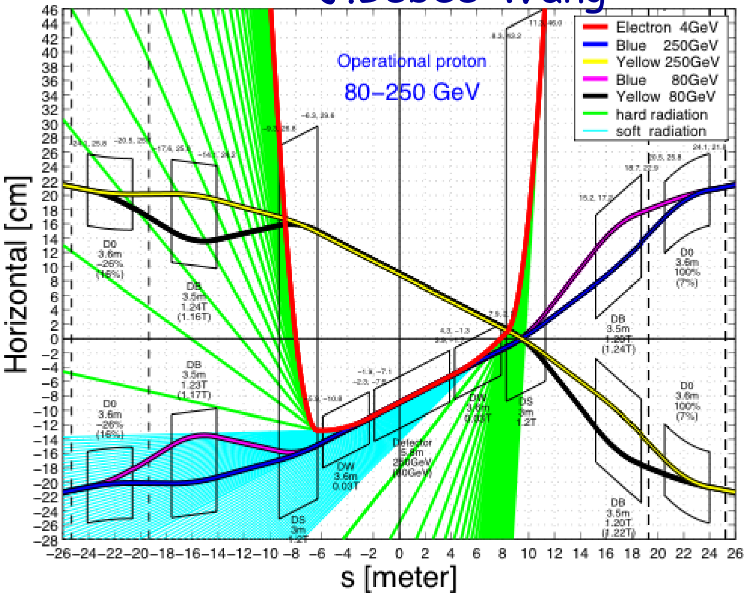
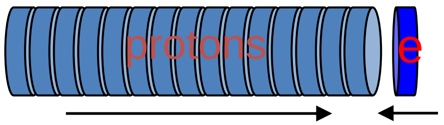
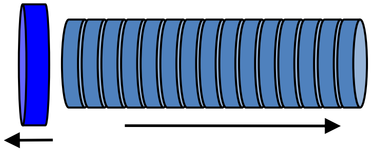
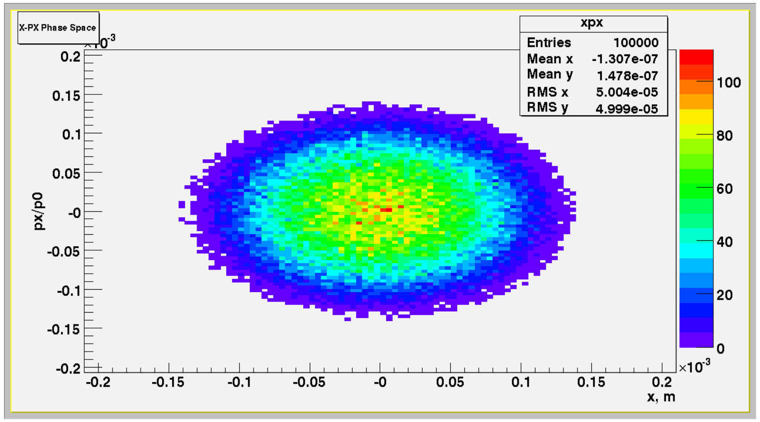


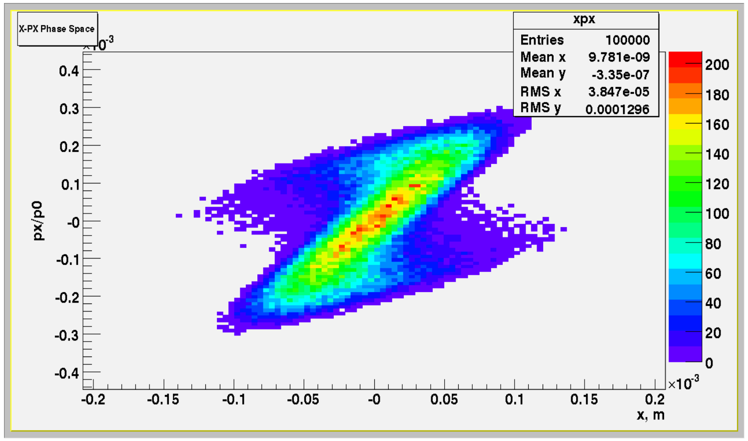
Beam Disruption



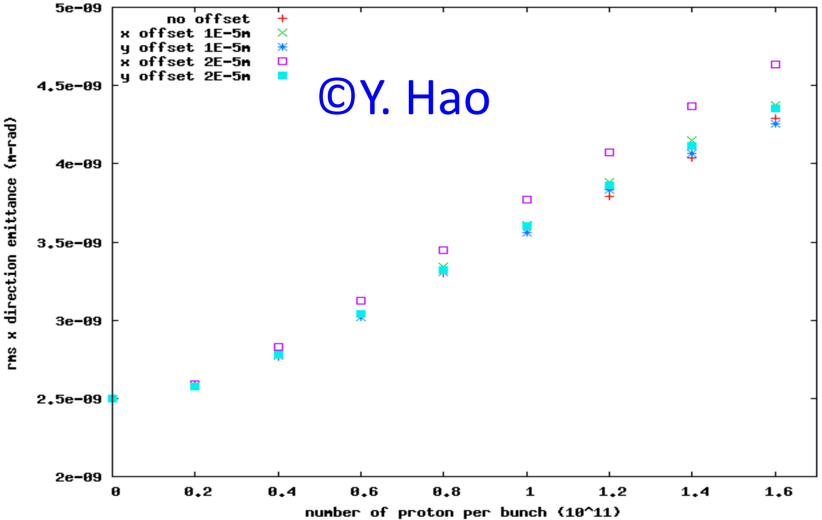




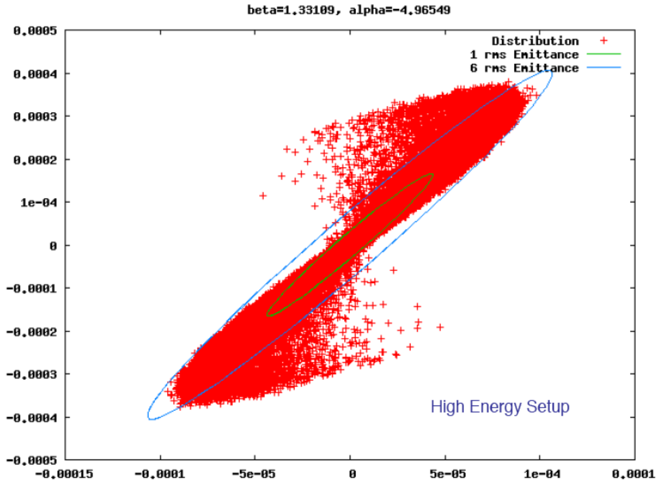
Interaction



Optimized

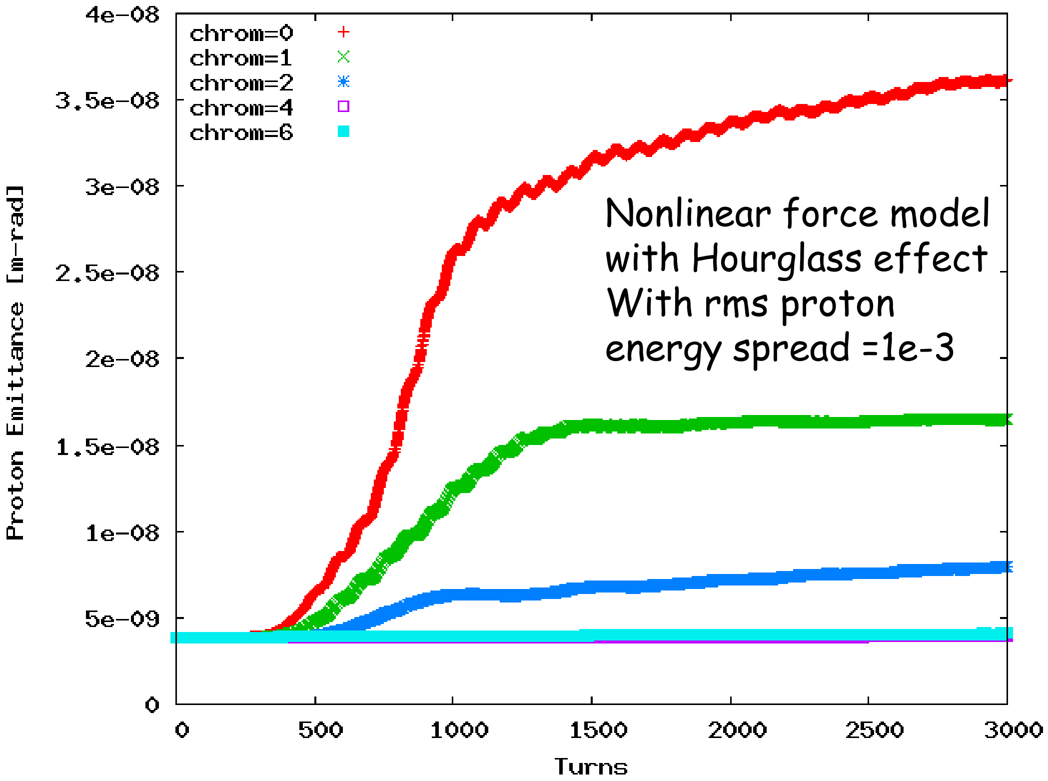


©Y. Hao

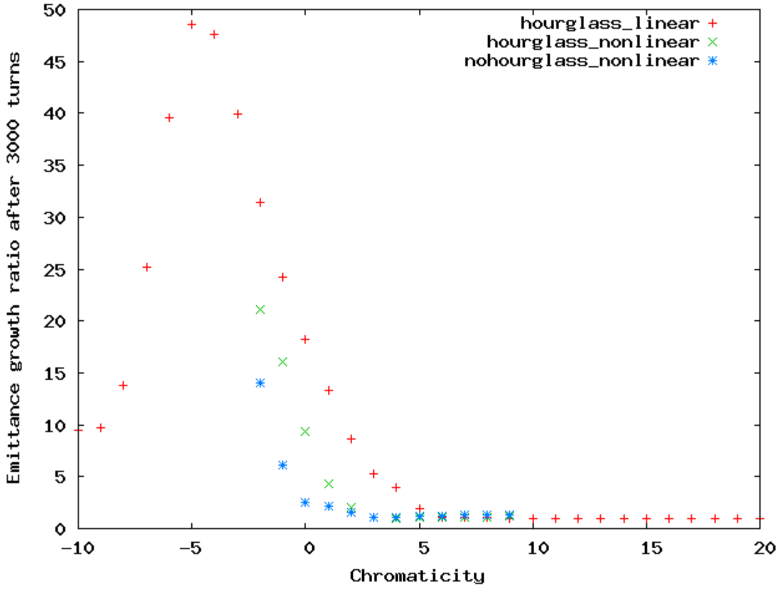


High Energy Setup

Suppression of kink instability



Nonlinear force model with Hourglass effect With rms proton energy spread =1e-3



The optimum chromaticity is around $\xi = +4$ © Y. Hao

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

eRHIC parameters

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

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

Using only to of JLab assumptions for ELIC

micro-beta*, traveling RF focusing ,
on a paper, 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 50
(from 25 cm to 0.5 cm)
boost luminosity by a factor of fifty

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	2.5
Polarization, %	70	80
rms bunch length, cm	4.9	0.2
β^*, cm	0.5	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	25	25
Luminosity, × 10^{35}, $\text{cm}^{-2}\text{s}^{-1}$	0.028	

eRHIC's assumptions

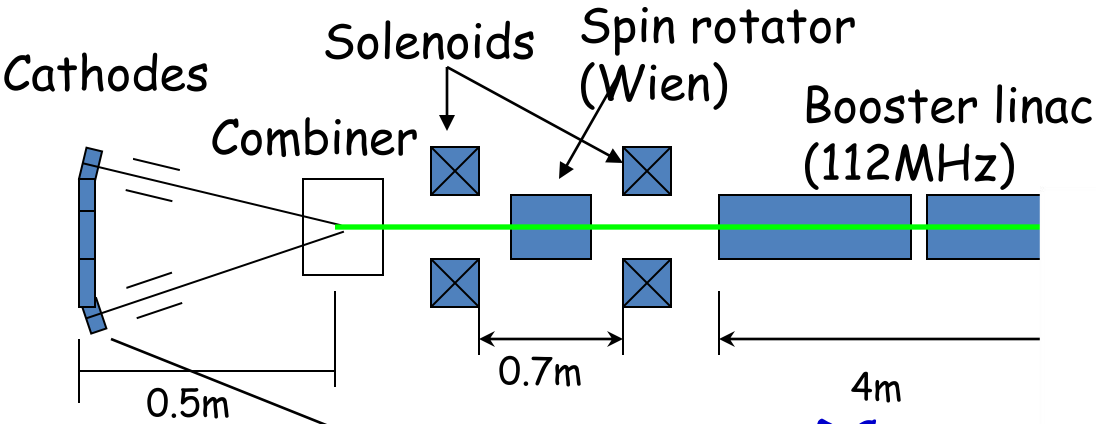
are based on beam optics for HE hadron colliders such as RHIC, HERA, Tevatron, LHC

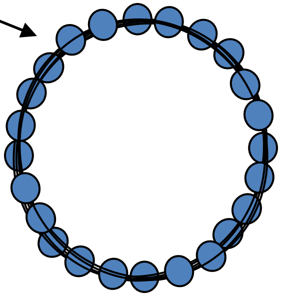
We have potential for future up-grades beyond capabilities of present day colliders: increase intensities of electron and proton bunches about 2 fold, the rep-rate 2 fold and reduce beta* 5 fold – total up to 20 fold increase in luminosity.

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

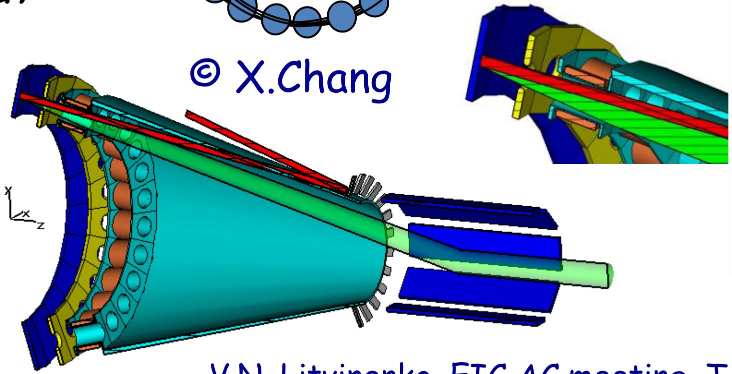
Main technical challenge is 50 mA CW polarized gun: we are building it





Based on demonstrated current technology developed at JLab

DC gun with 24 cathodes



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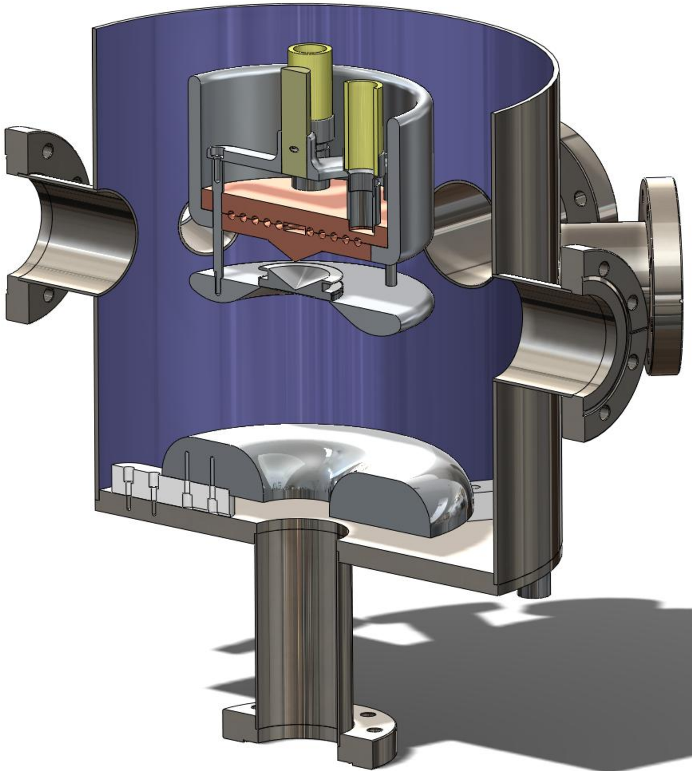
Single cathode DC gun



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Coherent Electron Cooling (CeC)

At a half of plasma oscillation

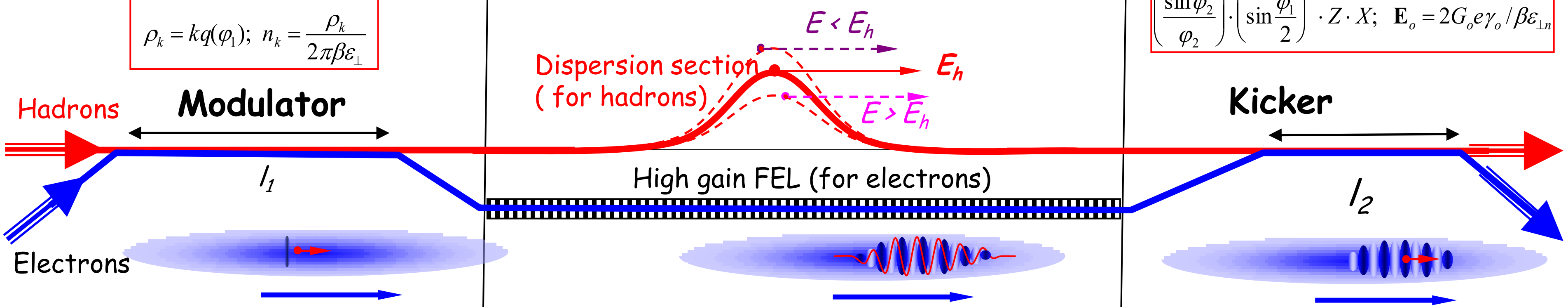
$$q_{\lambda_{FEL}} \approx \int_0^{\lambda_{FEL}} \rho(z)\cos(k_{FEL}z)dz$$

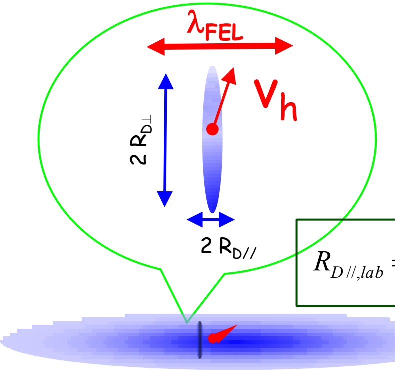
$$\rho_k = kq(\varphi_1);\; n_k = \frac{\rho_k}{2\pi\beta\varepsilon_\perp}$$

Dispersion

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

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





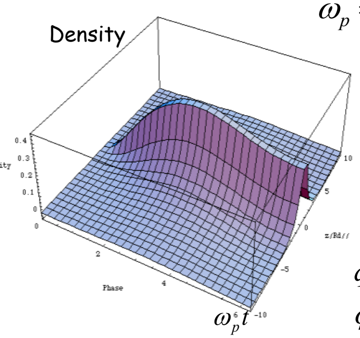
Debay radii

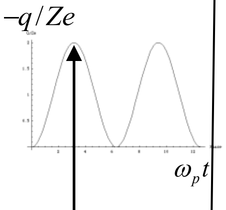
$$R_{D\perp} >> R_{D//}$$

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

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

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



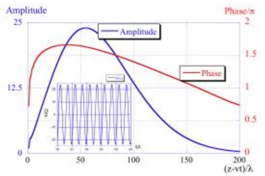


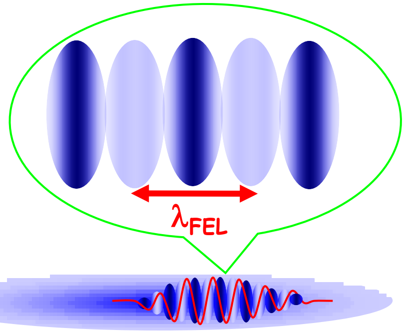
$$q = -Ze\cdot(1-\cos\varphi_1)$$

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

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

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

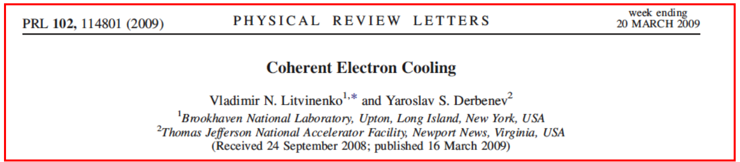




$$\lambda_{fel} = \lambda_w\left(1+\langle\vec{a}_w^2\rangle\right)/2\gamma_o^2$$

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

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

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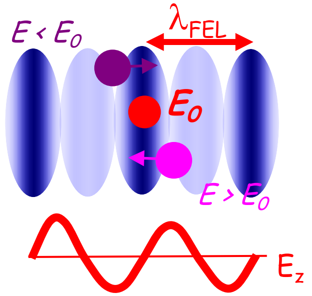
(Received 24 September 2008; published 16 March 2009)

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



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

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

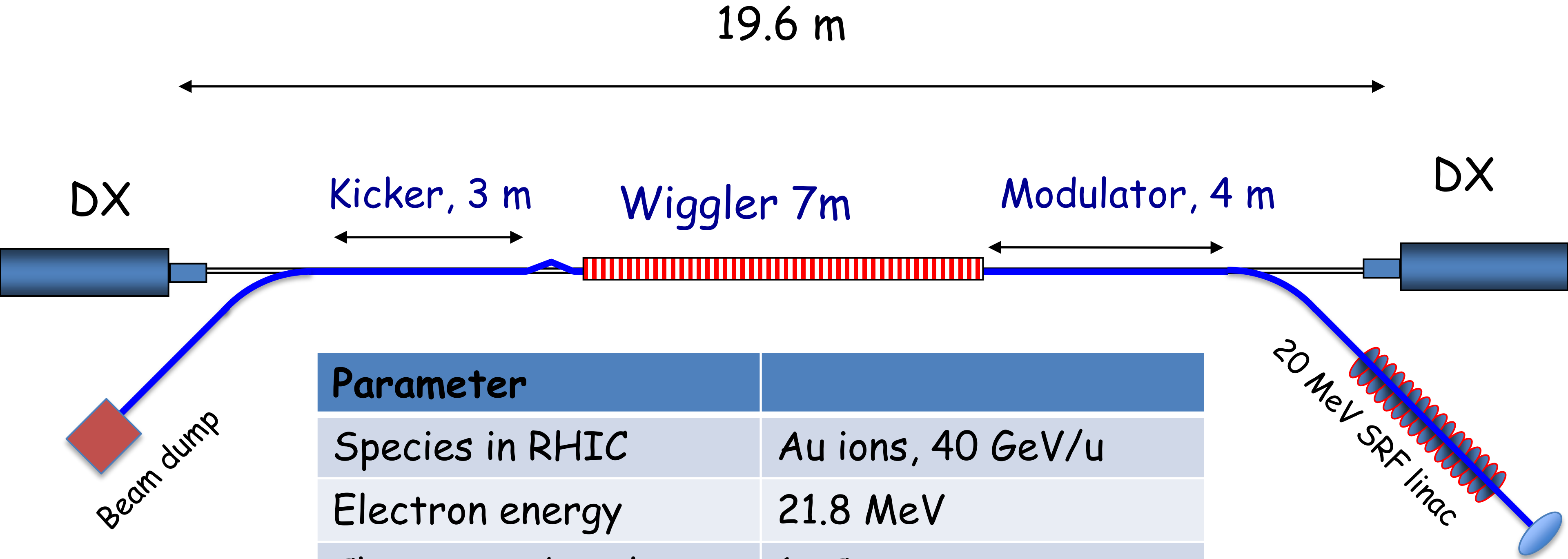
$$\Delta\varphi = 4\pi en \Rightarrow \varphi = -\varphi_0\cdot\cos(k_{cm}z)$$

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

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

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

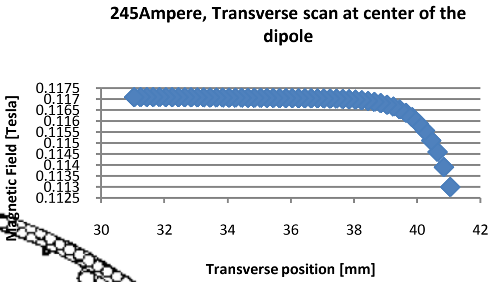
Possible layout for Coherent Electron Cooling proof-of-principle experiment in RHIC IR



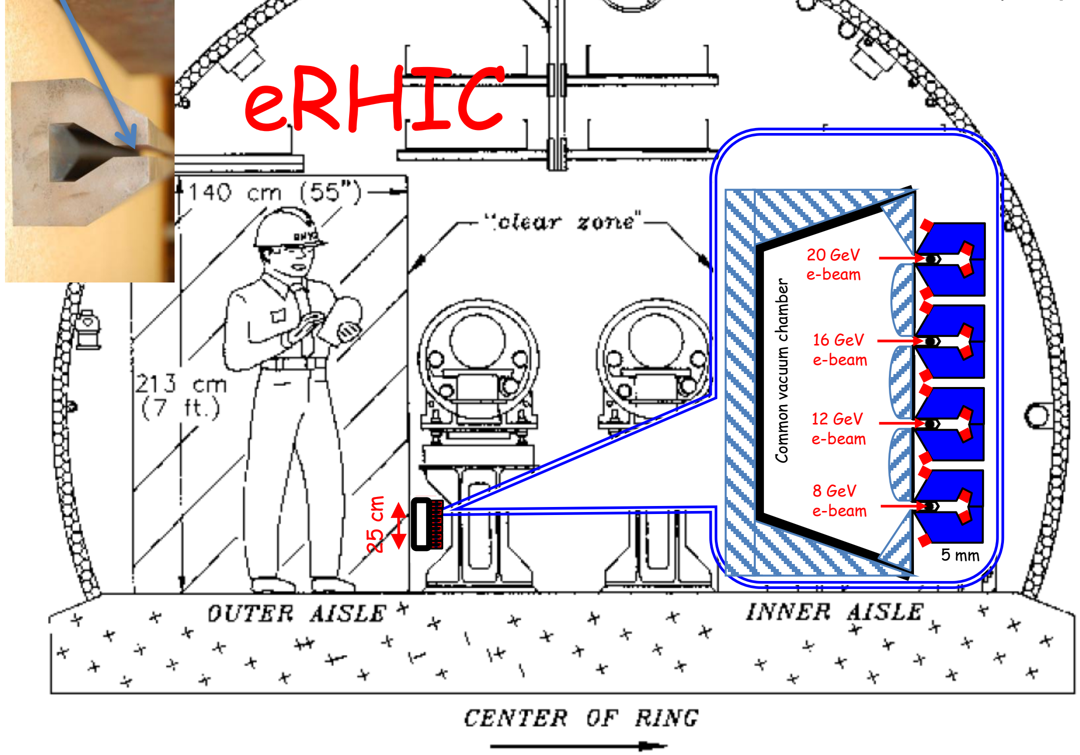
Parameter	
Species in RHIC	Au ions, 40 GeV/u
Electron energy	21.8 MeV
Charge per bunch	1 nC
Train	5 bunches
Rep-rate	78.3 kHz
e-beam current	0.39 mA
e-beam power	8.5 kW

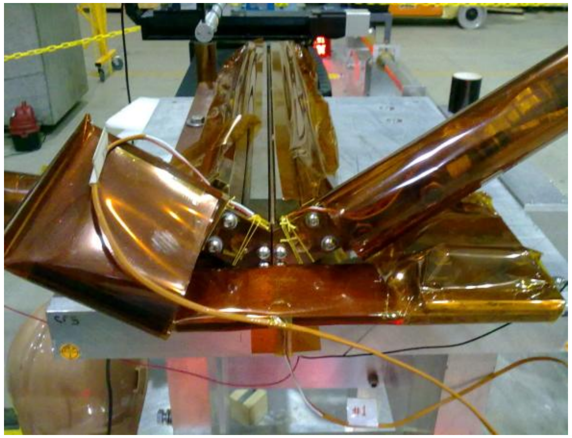
eRHIC loop magnets: LDRD project

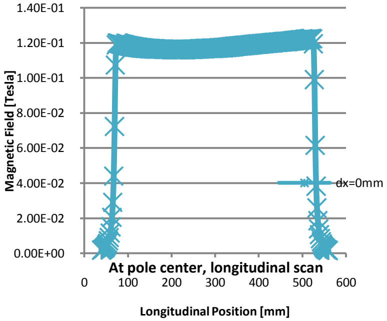
- Small gap provides for low current, low power consumption magnets
  - -> low cost eRHIC
  - Dipole prototype is under tests
  - Quad and vacuum chamber are in advanced stage



Gap 5 mm total
0.3 T for 30 GeV







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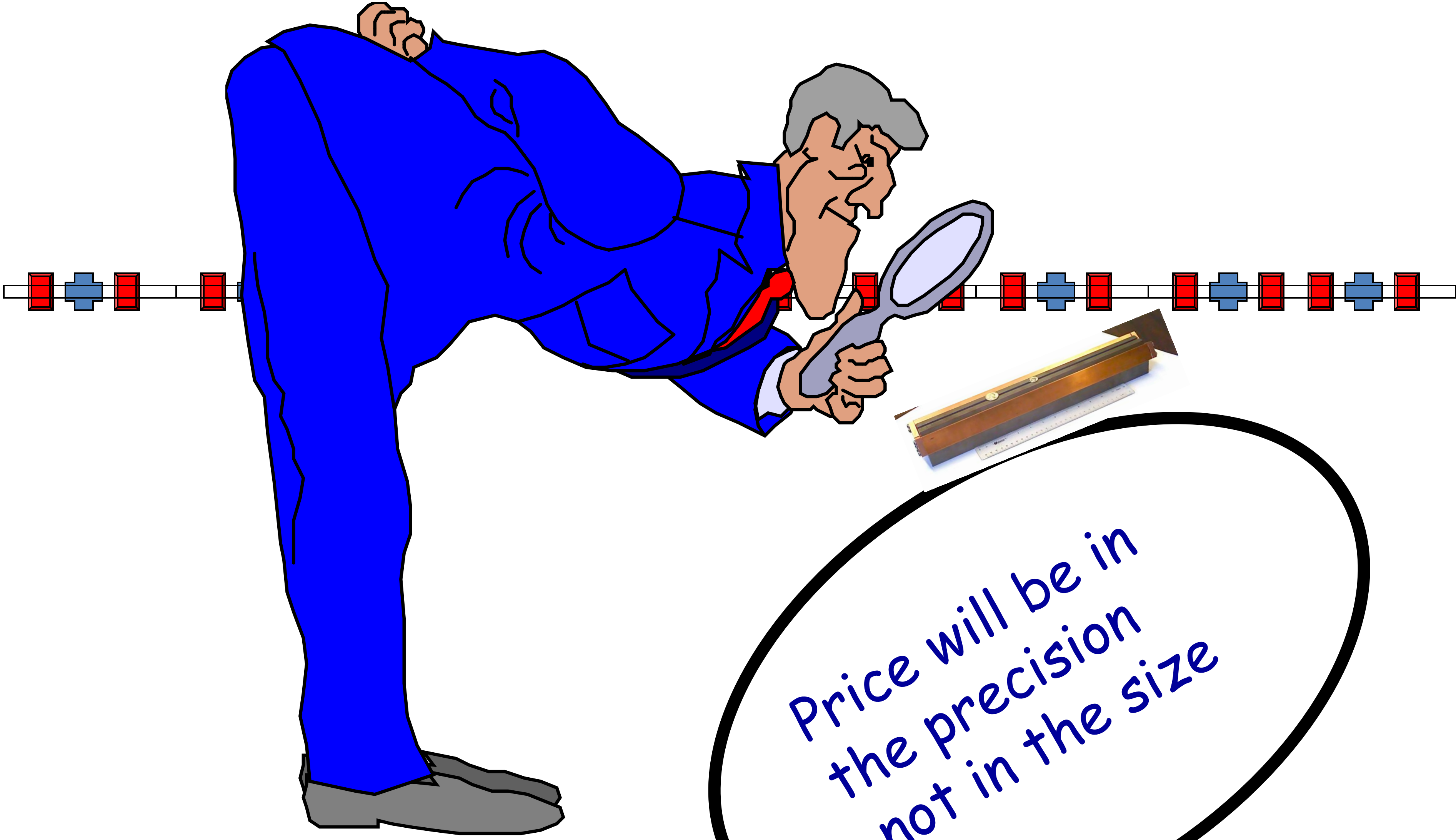
eRHIC



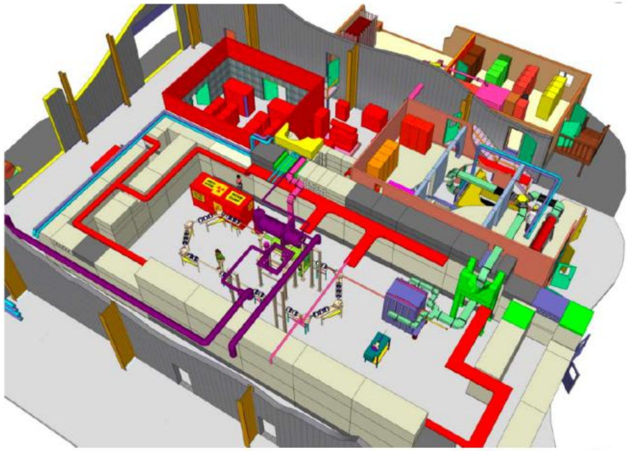
Price will be in the precision not in the size

R&D ERL

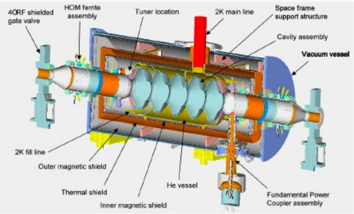
Status of the R&D ERL

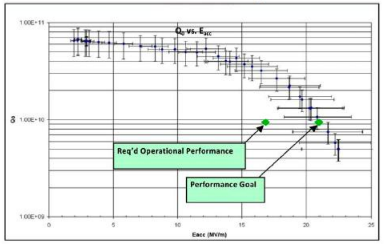
- The ERL is in an advanced stage of construction
- Beam will be generated next year
- Major systems are coming on

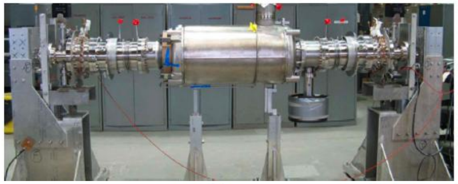


A Prototype eRHIC Cavity



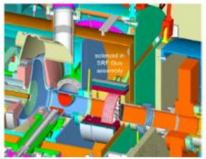


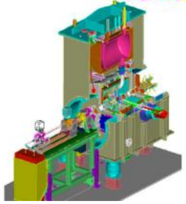



© I. Ben Zvi

High-current SRF electron-gun

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

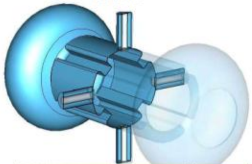


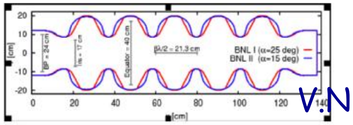



eRHIC New Cavity Design

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

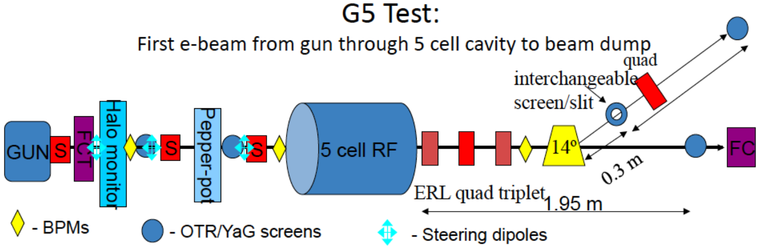
New cavity design for eRHIC



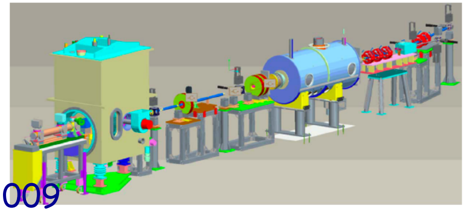


G5 Test:

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



Conclusions

- **Collider beam physics laws assert that with any given beam and IR parameters, a linac-ring collider outperforms a ring-ring collider**
- **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 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*

We prepared for tomorrow following topics on MeRHIC design

- MeRHIC design – Vadim Ptitsyn
- Beam dynamics – Yue Hao
- Engineering challenges and solutions – Andrew Burrill

Back-up

eRHIC R&D (more in T.Roser's presentation)

- 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**

eRHIC targeted LDRD-proposals

- 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
  - polarized ^{3}He source development
    PI: Anatoli Zelenski

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.

Gains from coherent e-cooling:

Coherent Electron Cooling vs. IBS

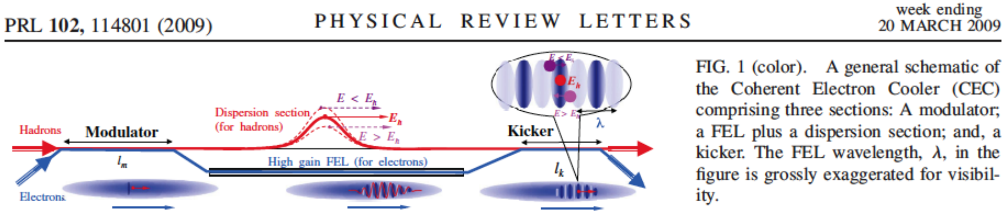

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FIG. 1 (color). A general schematic of the Coherent Electron Cooler (CEC) comprising three sections: A modulator; a FEL plus a dispersion section; and, a kicker. The FEL wavelength, λ, in the figure is grossly exaggerated for visibility.

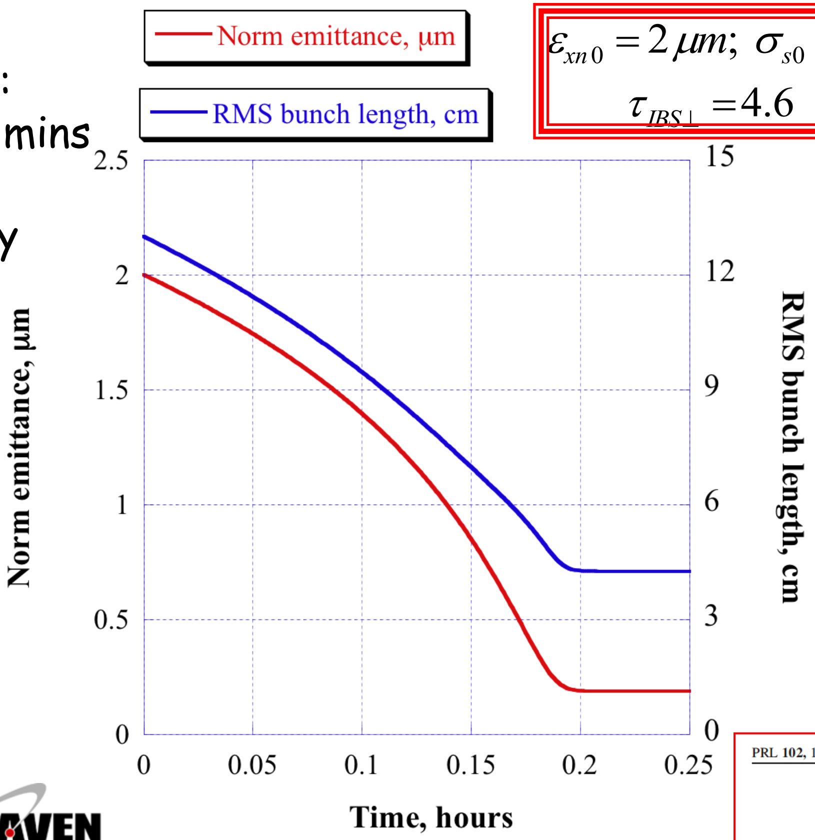
$$X=\frac{\varepsilon_x}{\varepsilon_{xo}};\ S=\left(\frac{\sigma_s}{\sigma_{so}}\right)^2=\left(\frac{\sigma_E}{\sigma_{sE}}\right)^2;$$

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

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

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

Dynamics:
Takes 12 mins to reach stationary point



$$\varepsilon_{xn0}=2\,\mu m;\ \sigma_{s0}=13\ cm;\ \sigma_{\delta 0}=4\cdot 10^{-4}$$

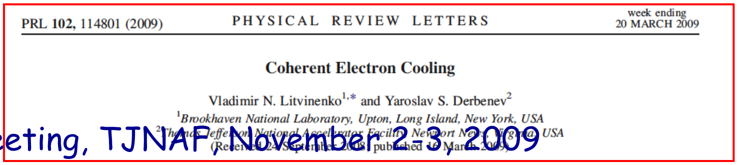
$$\tau_{IBS\perp}=4.6\ \ hrs;\ \tau_{IBS//}=1.6\ \ hrs;$$

IBS in RHIC for eRHIC, 250 GeV, $N_p=2\cdot10^{11}$
Beta-cool, ©A.Fedotov

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

This allows

a) keep the luminosity as it is
b) reduce polarized beam current down to 25 mA (5 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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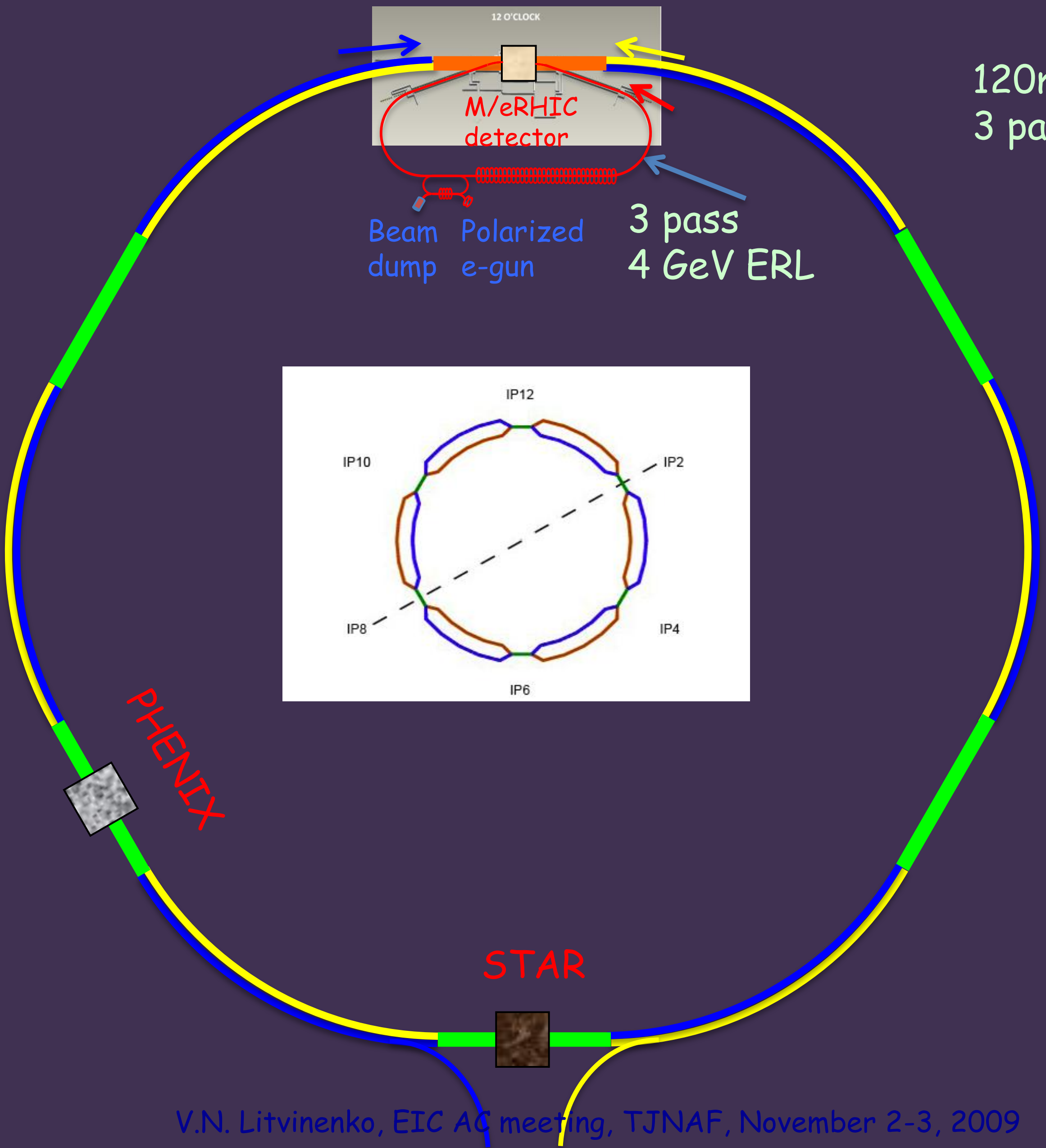
Coherent Electron Cooling

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)

4 GeV e x 250 GeV p – 100 GeV/u Au

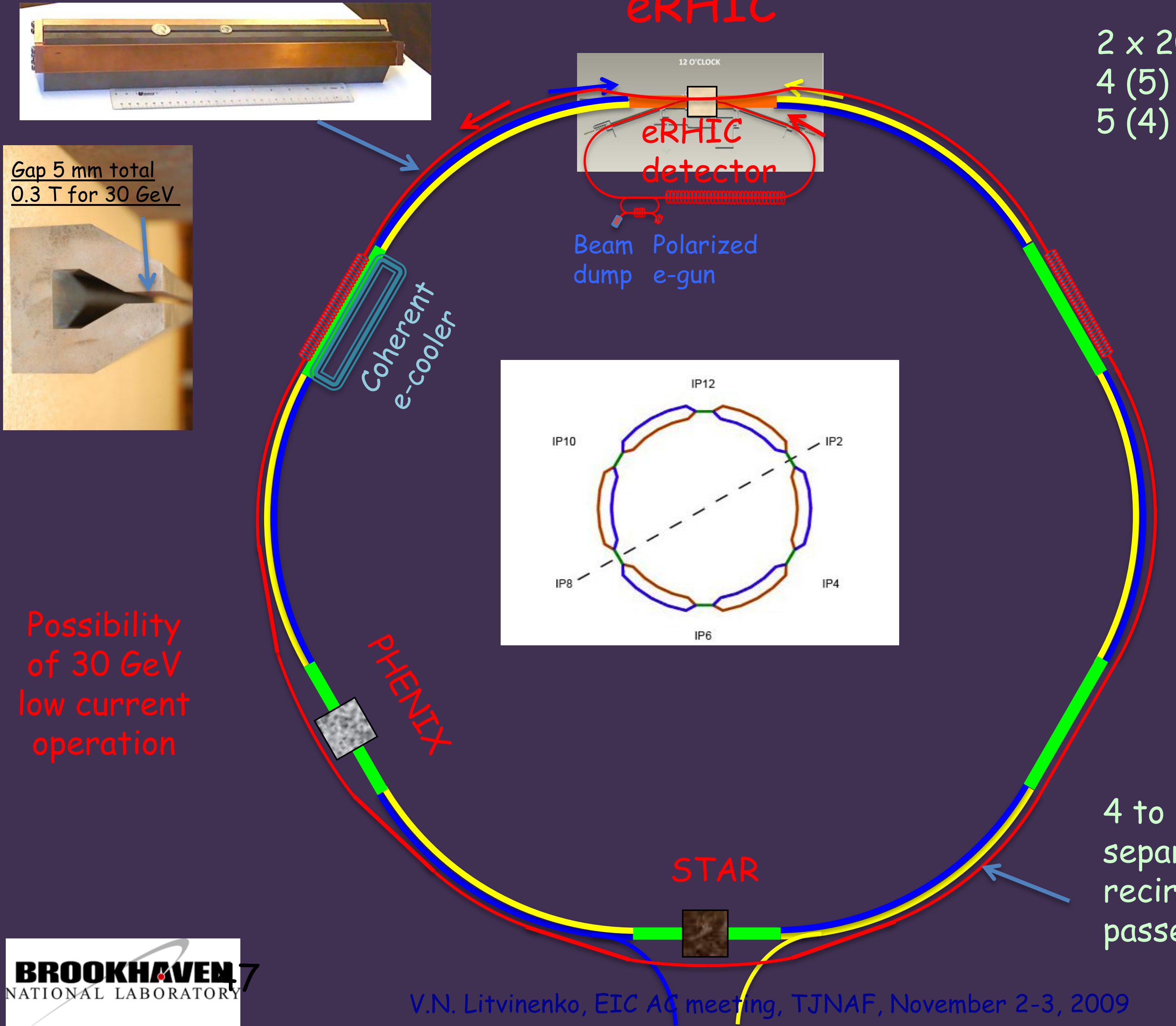
MeRHIC



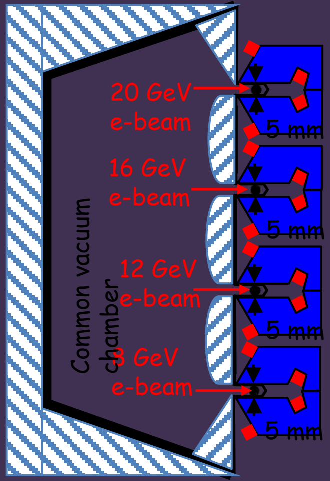
120m SRF linac
3 passes, 1.3 GeV/pass

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



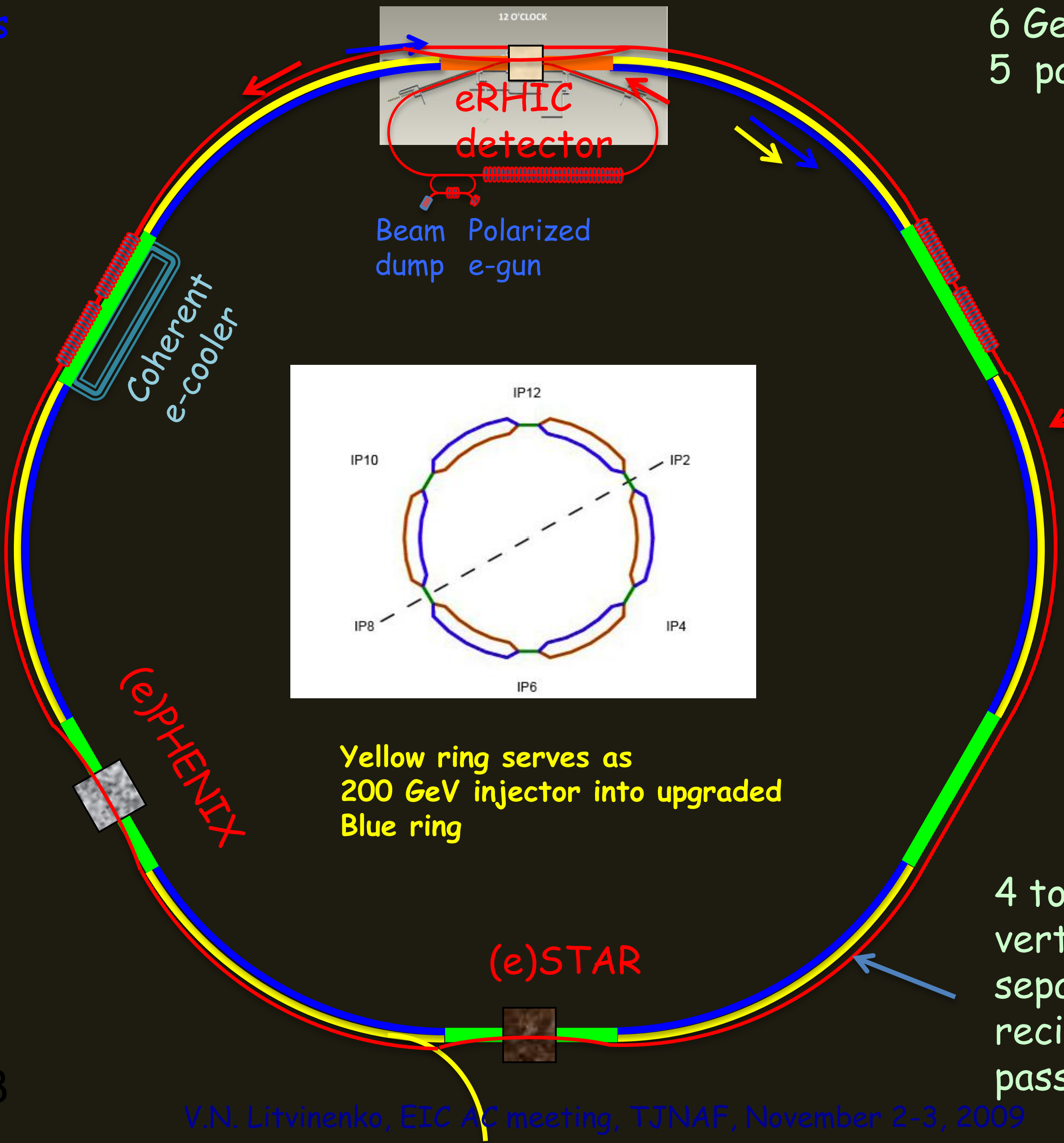
4 to 5 vertically separated recirculating passes

30 GeV e x 800 GeV p – 320 GeV/u U

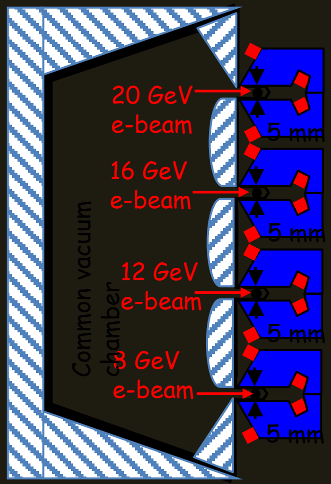
eRHIC II

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

3 x 200 m SRF linac
6 GeV per pass
5 passes



Yellow ring serves as
200 GeV injector into upgraded
Blue ring



4 to 5
vertically
separated
recirculating
passes

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>

MeRHIC parameters for e-p collisions

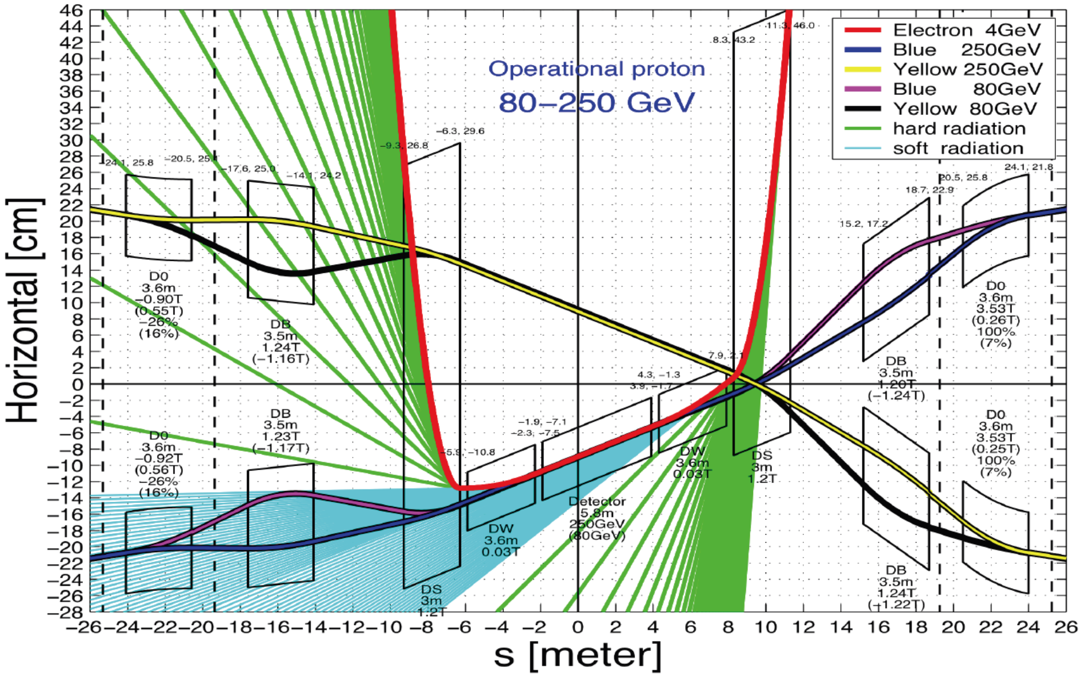
© V.Ptitsyn

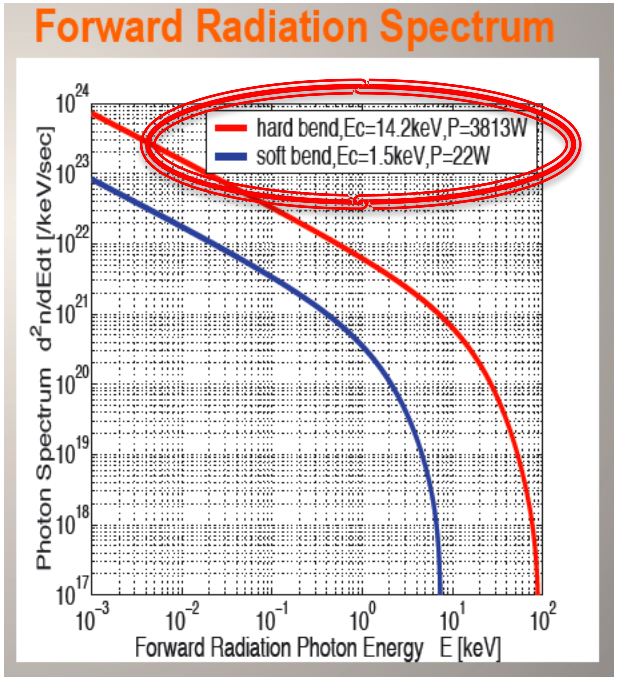
	not cooled		With cooling	
	p	e	p	e
Energy, GeV	250	4	250	4
Number of bunches	111		111	
Bunch intensity, 10^{11}	2.0	0.31	2.0	0.31
Bunch charge/current, nC/mA	32/320	5/**50**	32/320	5/**50**
Normalized emittance, 1e-6 m, 95% for p / rms for e	15	73	1.5	7.3
rms emittance, nm	9.4	9.4	0.94	0.94
beta*, cm	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

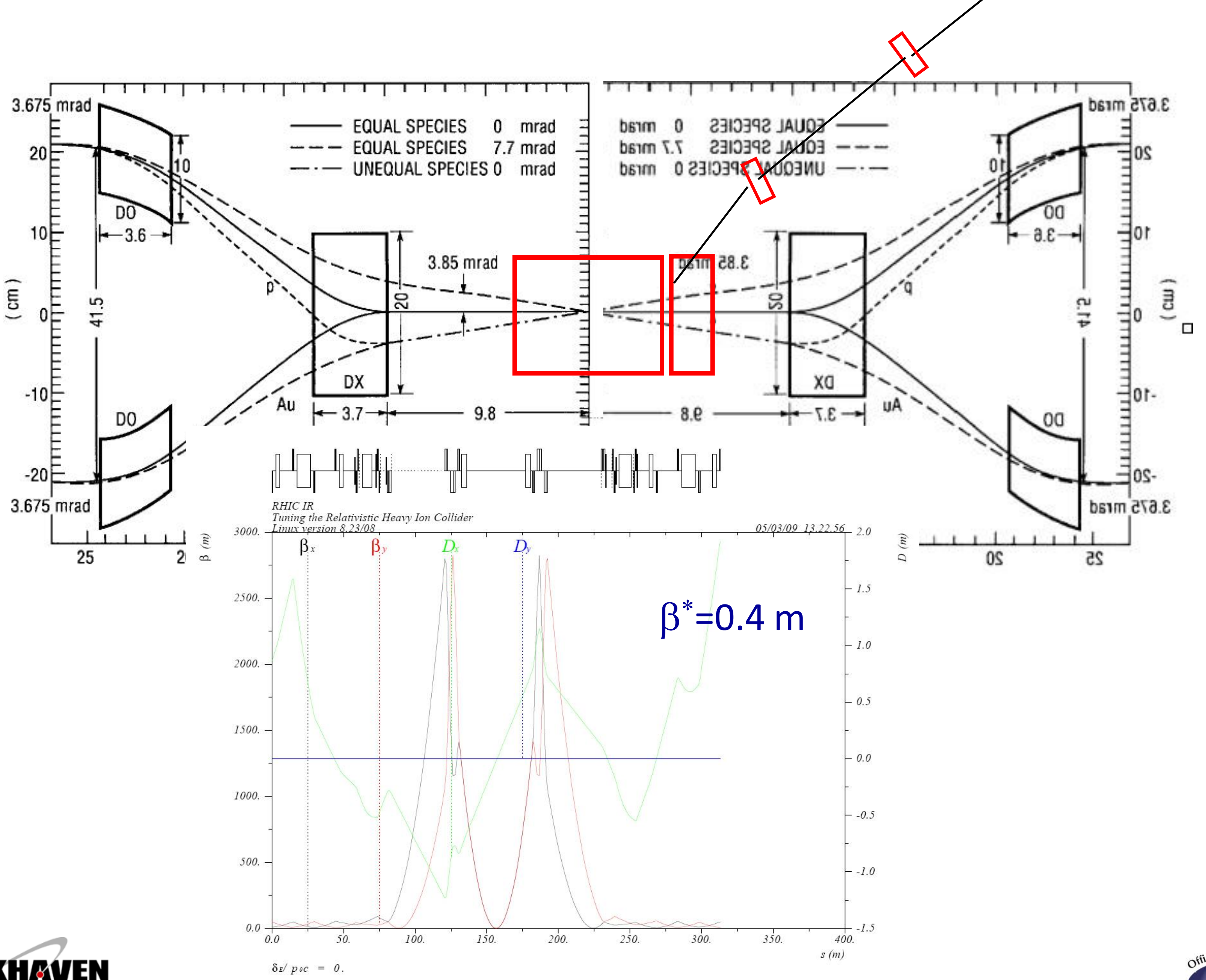
J. Beebe-Wang, E.-C. Aschenauer





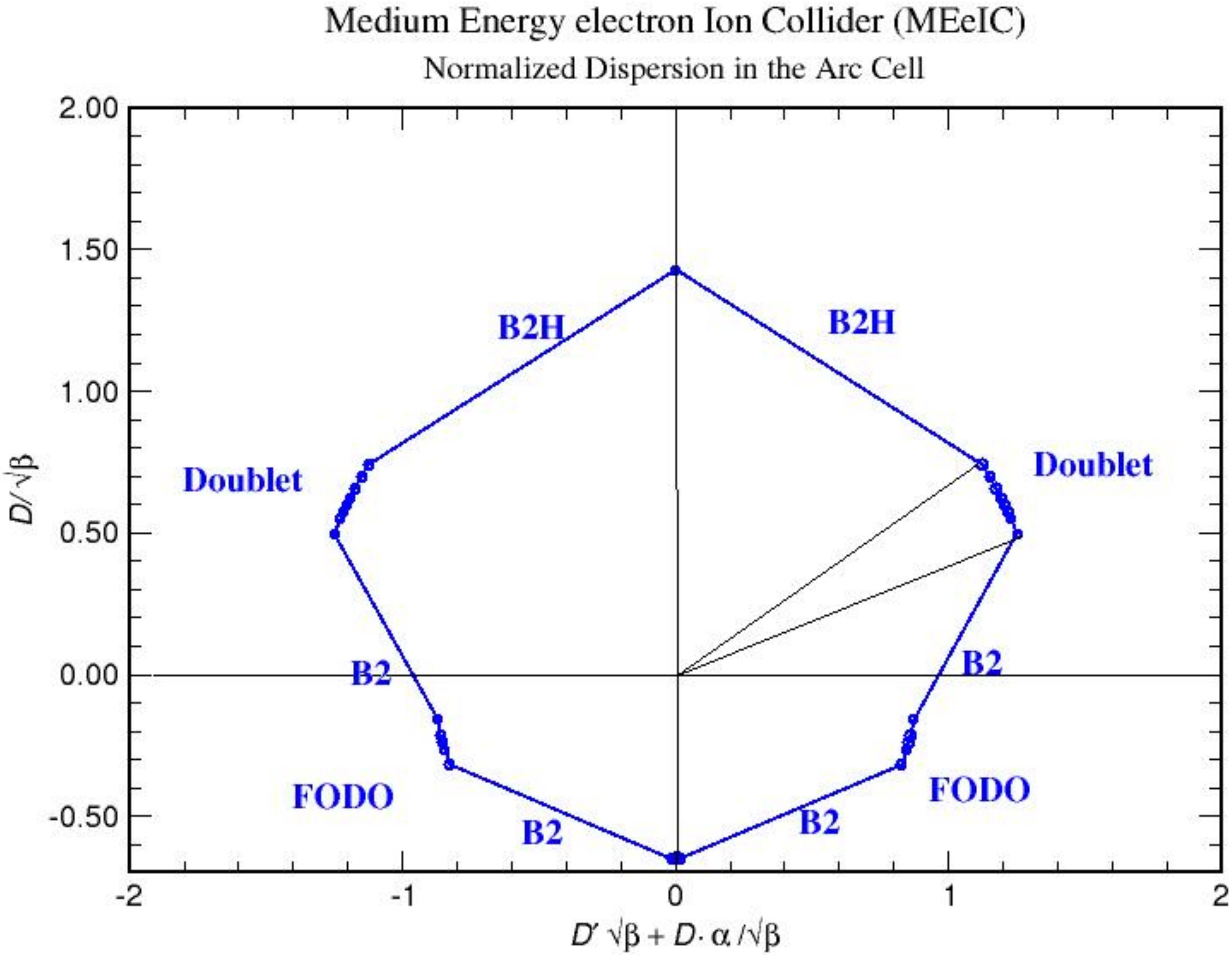
- **40 cm β* and 40 m element free space**
- **Integrated 5.8 m long 4 T solenoid**
- **First indication that it is good layout for diffraction physics**
- **There is enough flexibility in the layout to accommodate main detector needs**

RHIC lattice modification – Steven Tepikian



β^*=0.4 m

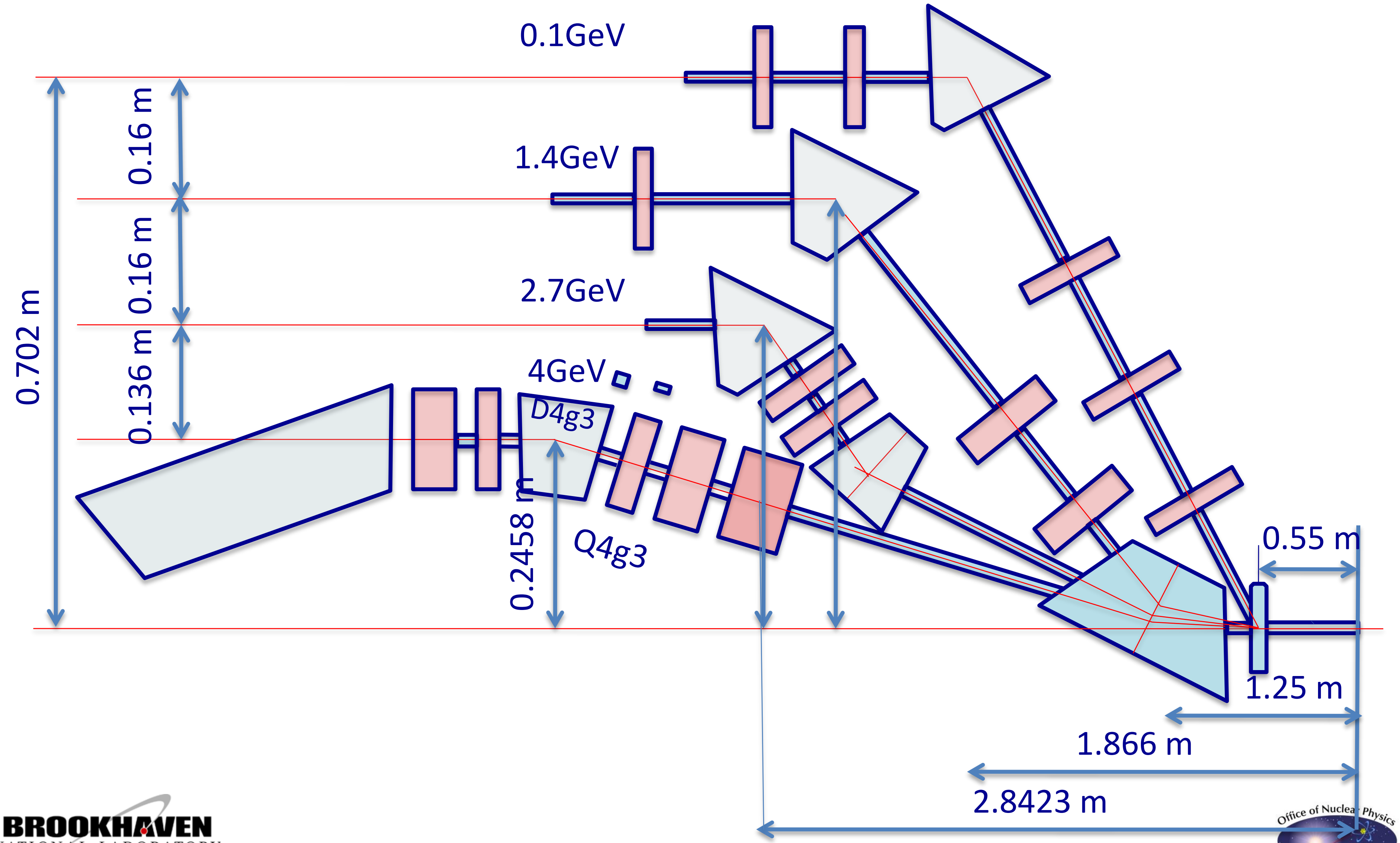
Methods and solutions: construction of the asynchronous arcs:



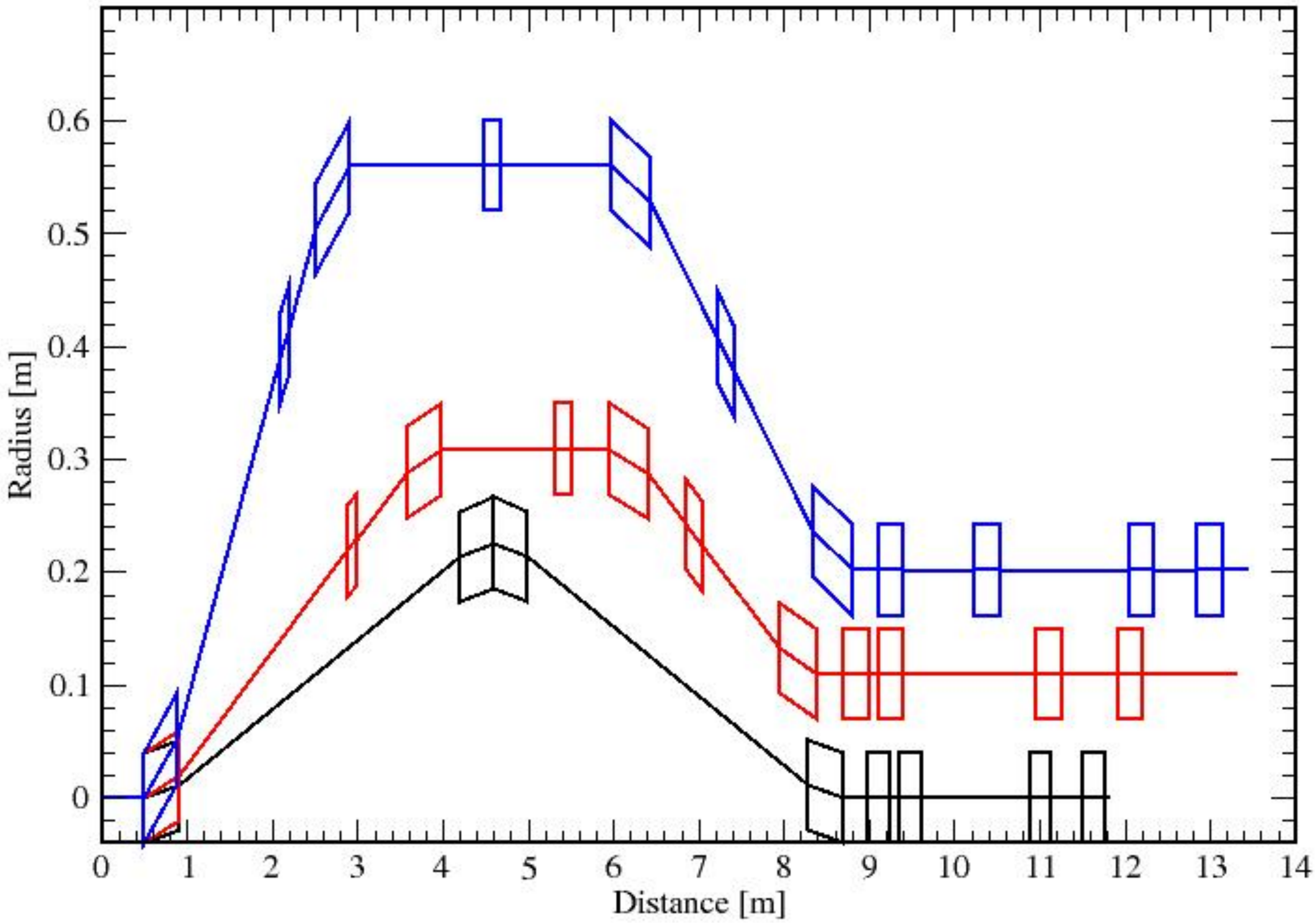
Medium Energy electron Ion Collider (MEeIC)

Normalized Dispersion in the Arc Cell

Switchyard at the linac



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



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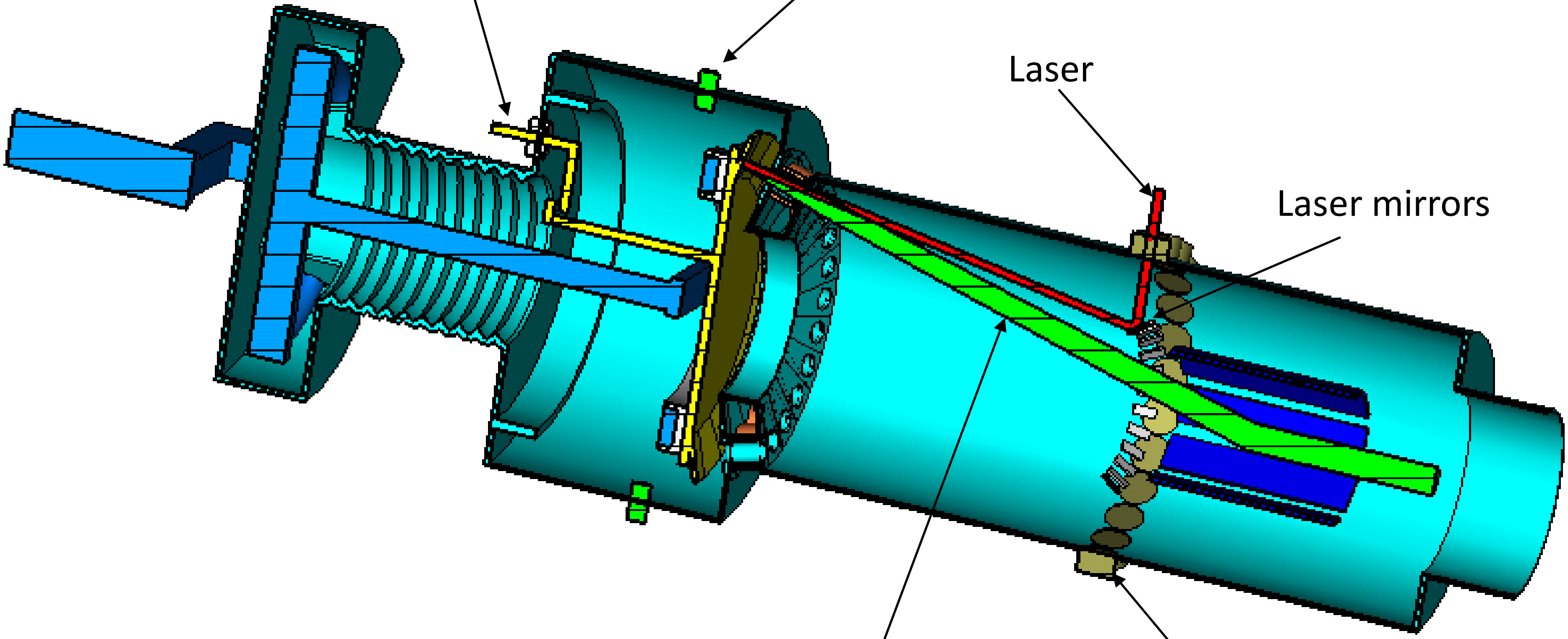


HV feedthrough

Caesiation x 6

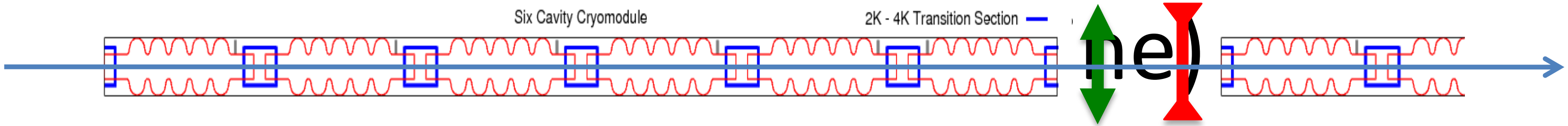
Laser

Laser mirrors

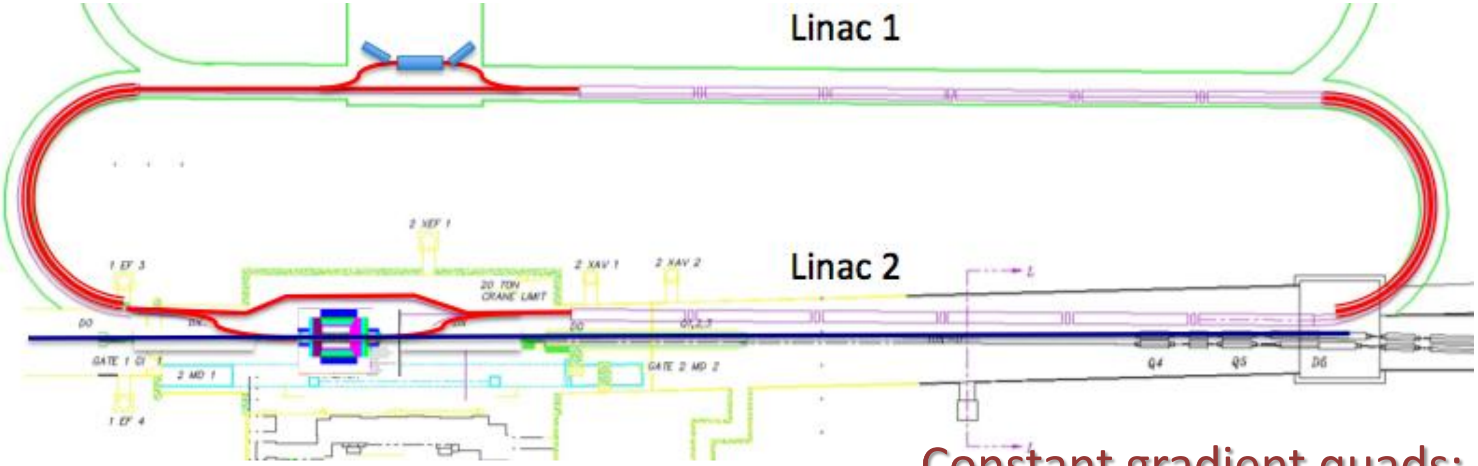
Electron Beams

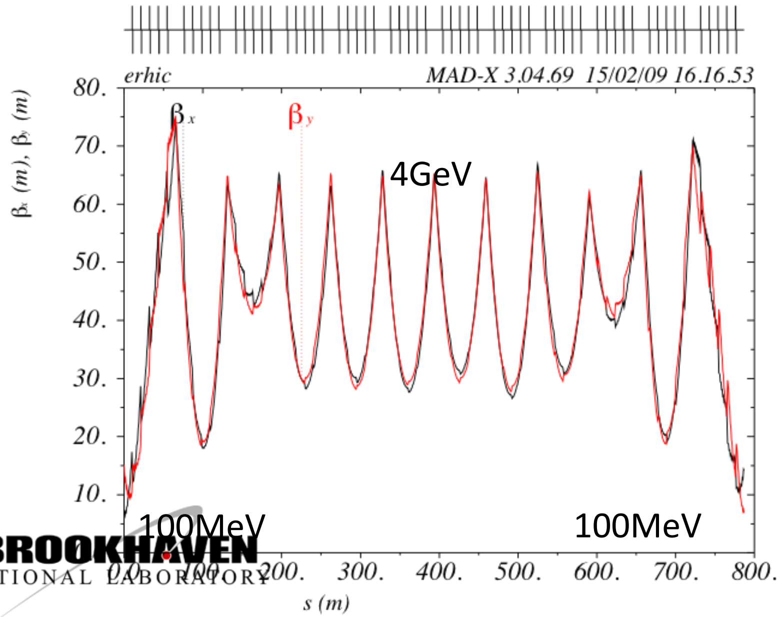
Laser windows

Linac design with const. grad quads



Cavity: 703.75 MHz, 1.6 m with dampers

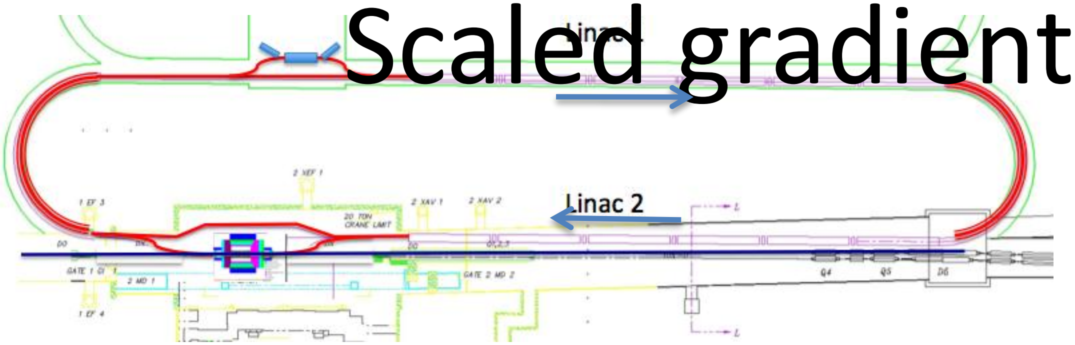




Constant gradient quads:
L=20 cm, G~100 Gauss/cm

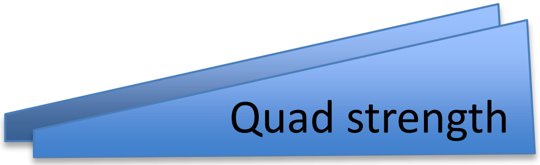
- E_{inj}/E_{max} = 100MeV / 4GeV
- 3 acc./decel. passes
- N cavities = 72 (total)
- L module/period = 9.6 / 11.1m
- E_f = 18.0 MeV/m
- ⟨dE/ds⟩ = 10.2 MeV/m

Scaled gradient solution

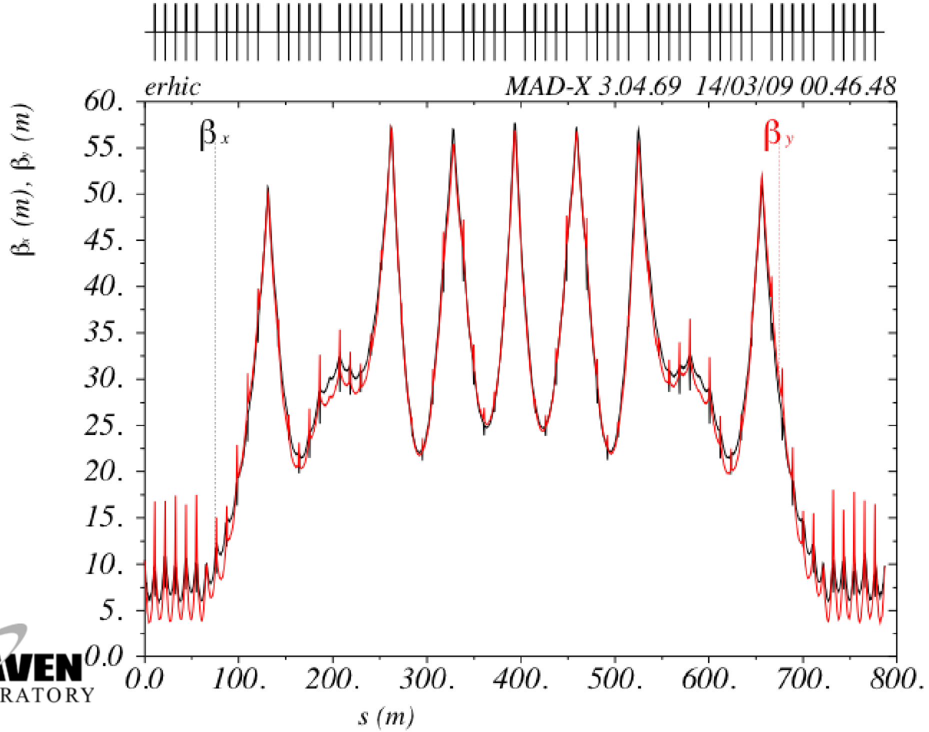


Scaling gradient with energy produces more focusing and increases BBU threshold

G_{min} ~ 100 G/cm



G_{max} ~ 500 G/cm



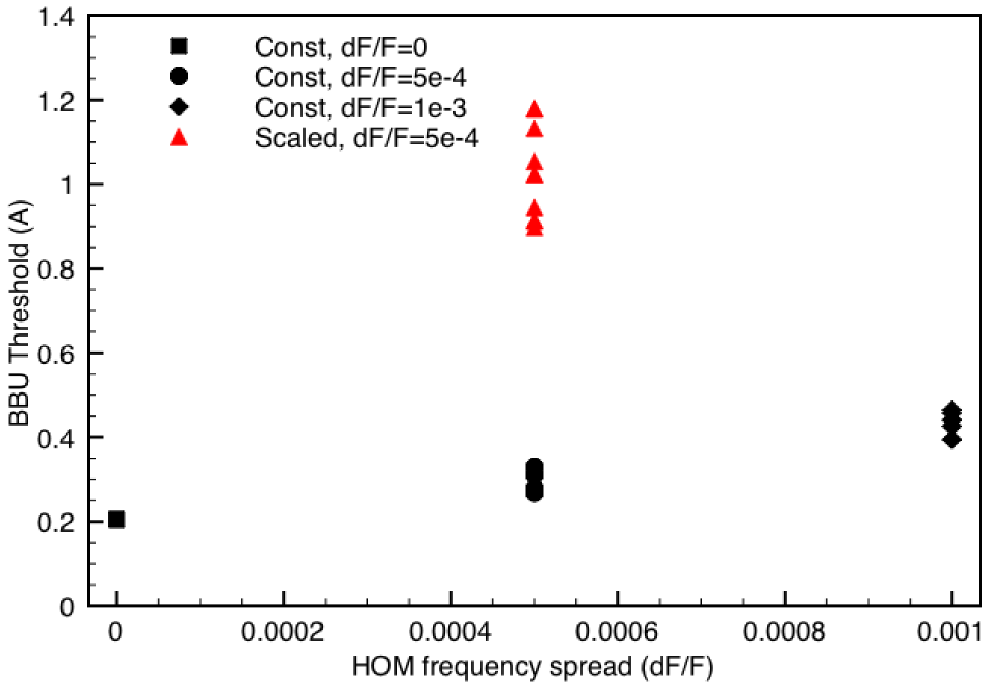
Matching scaled linac to arcs is in the works

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

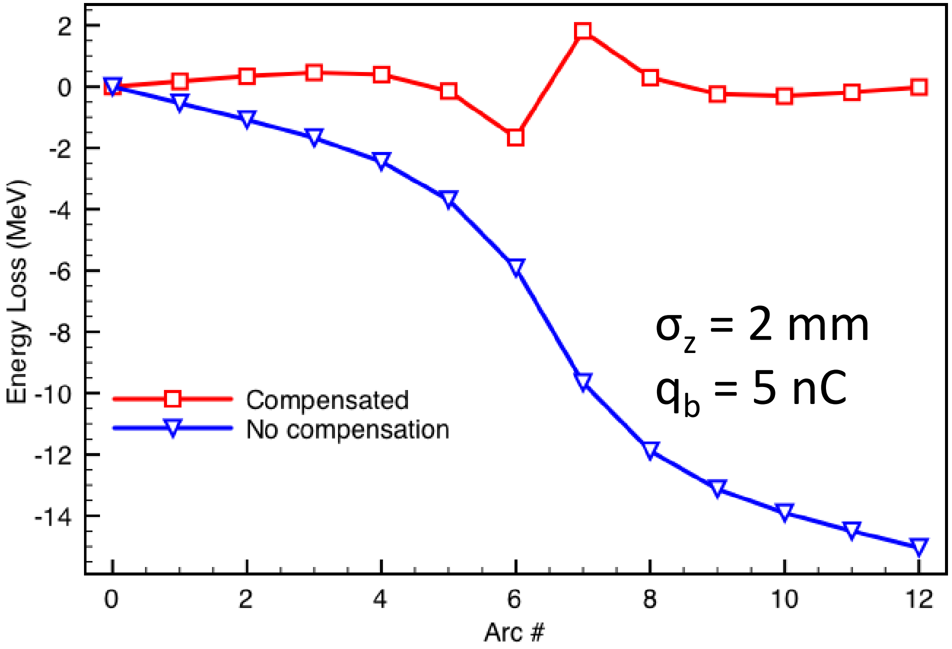


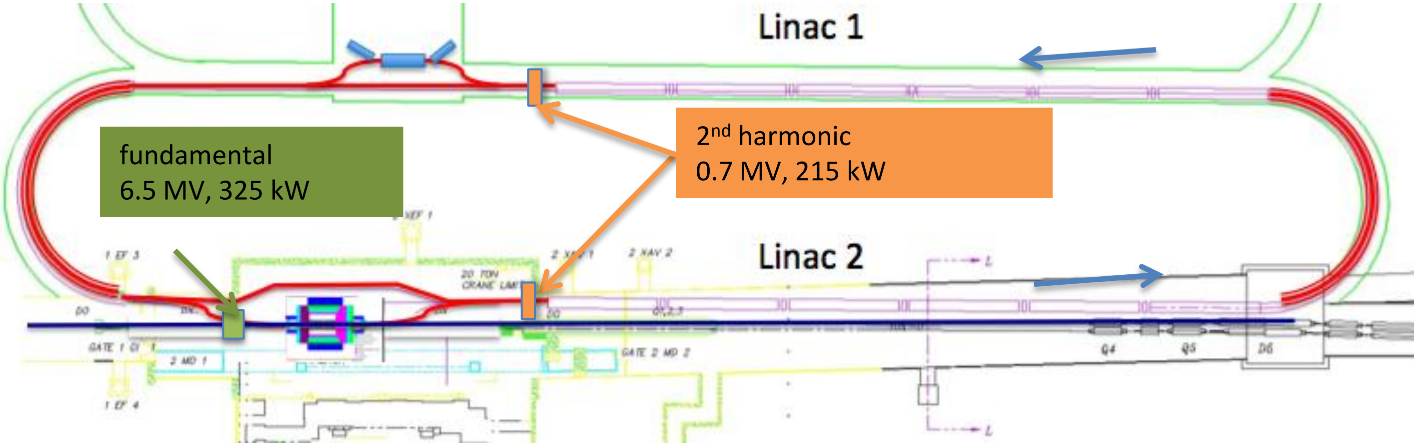
Threshold significantly exceeds the beam current, especially for the scaled gradient solution.

Energy loss and its

e

- 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%





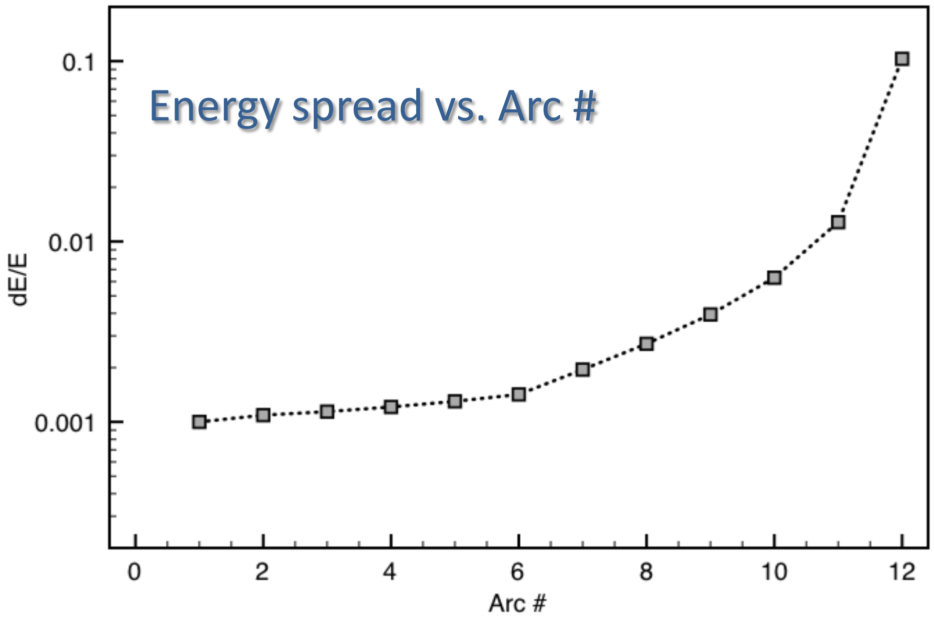
fundamental
6.5 MV, 325 kW

2^{nd} harmonic
0.7 MV, 215 kW

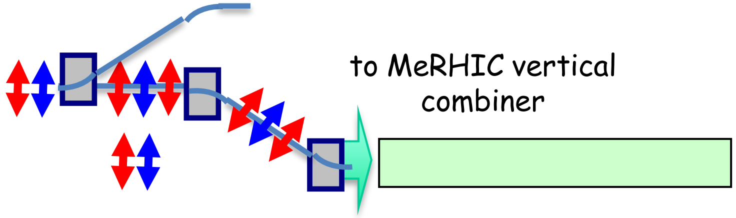
Energy spread and its

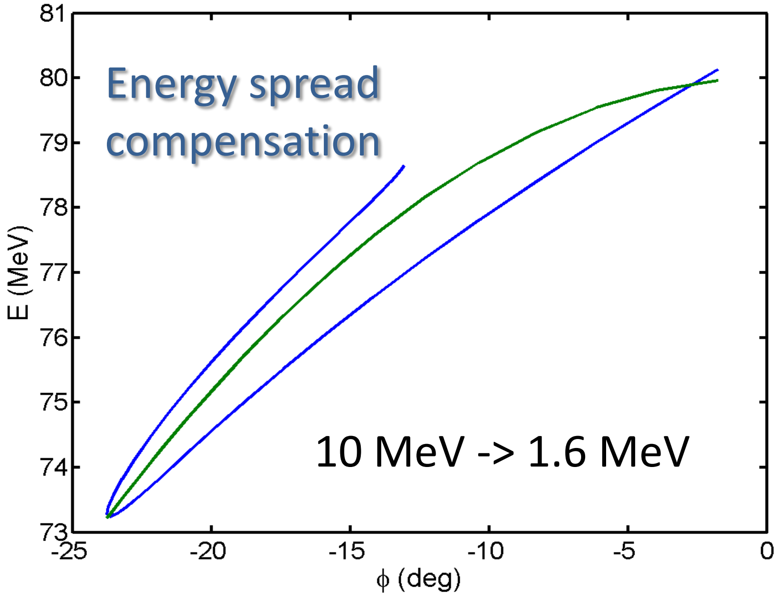
npe

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


Energy spread vs. Arc #

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

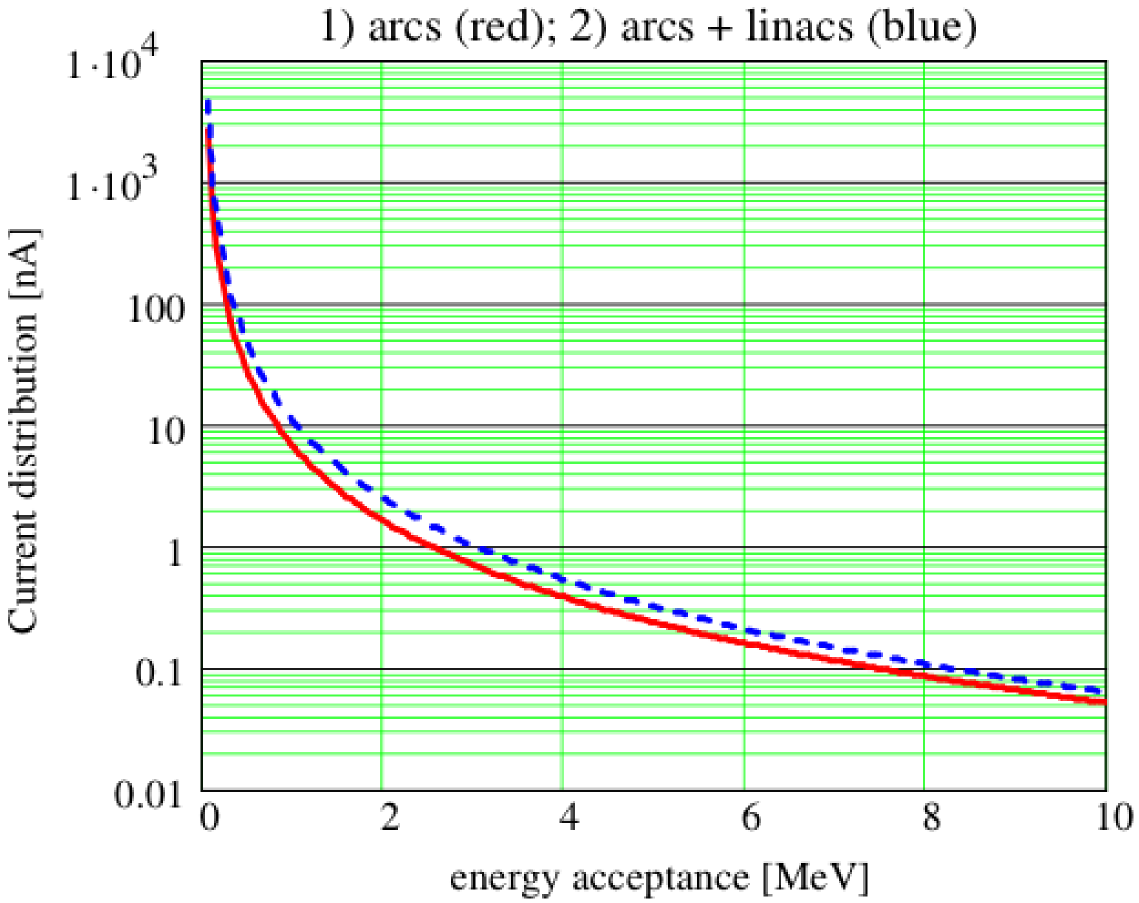



Energy spread compensation

10 MeV -> 1.6 MeV

Beam losses: Touschek

Total beam loss beyond given energy aperture

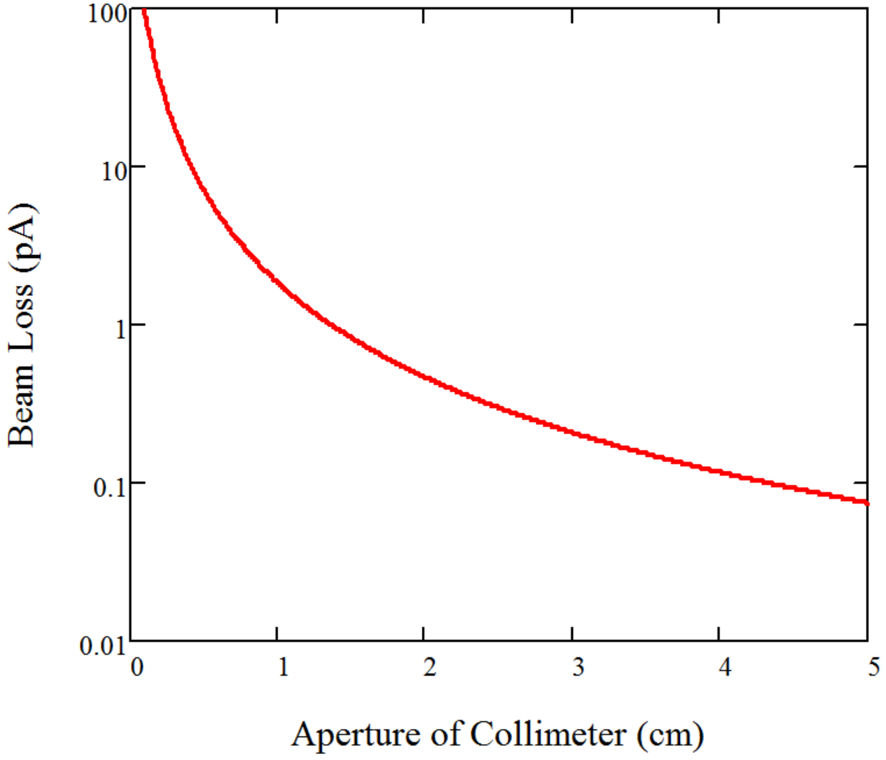


Not a large problem but not negligible

Beam losses: Collisions with residual gas

Scattering

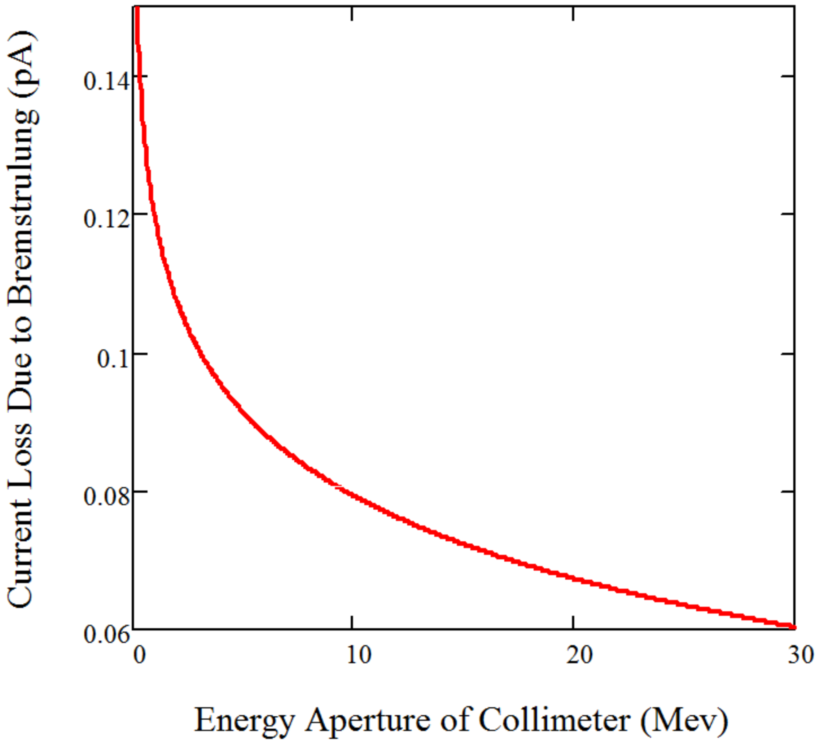
Losses beyond aperture at 100 MeV



Small, can be neglected

Bremsstrahlung

Losses beyond energy aperture

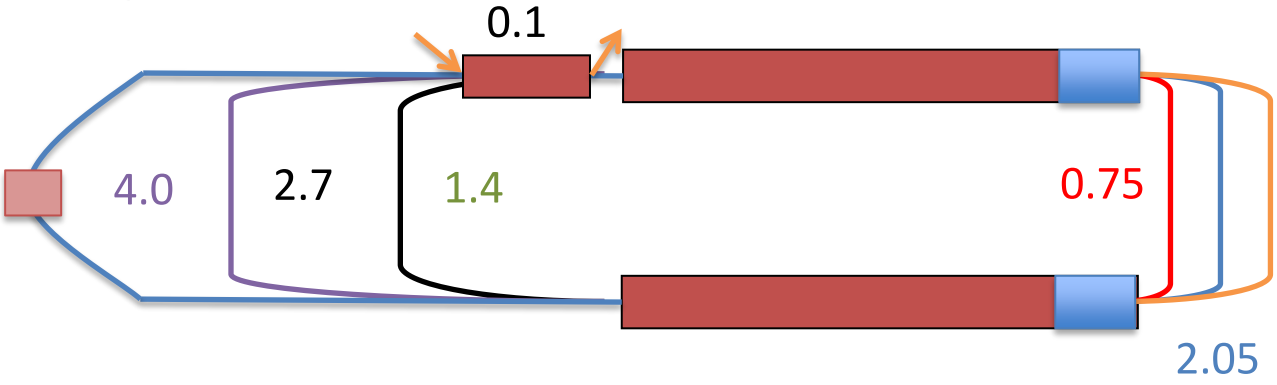


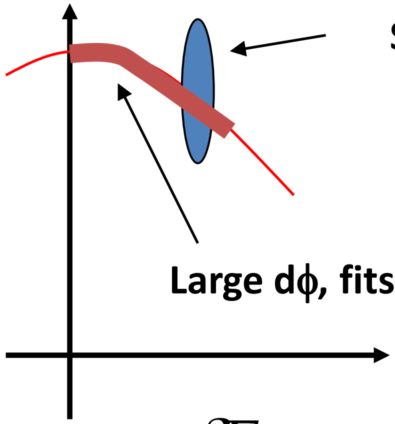
Small, can be neglected

Energy spread compensation

$$m_{56} = 15\text{ cm}$$

$$m_{566} = ?$$





Smal dφ, Large dE

Large dφ, fits the RF wave -> small dE

$$\frac{\delta E_f}{\delta E_i} = \frac{\delta \phi_i}{\delta \phi_f} = \frac{\delta \phi_i}{l_b} \bar{\lambda}_{RF}$$