BROOKHAVEN NATIONAL LABORATORY

Accelerator Physics of an ERL-based Polarized Electron-Ion collider

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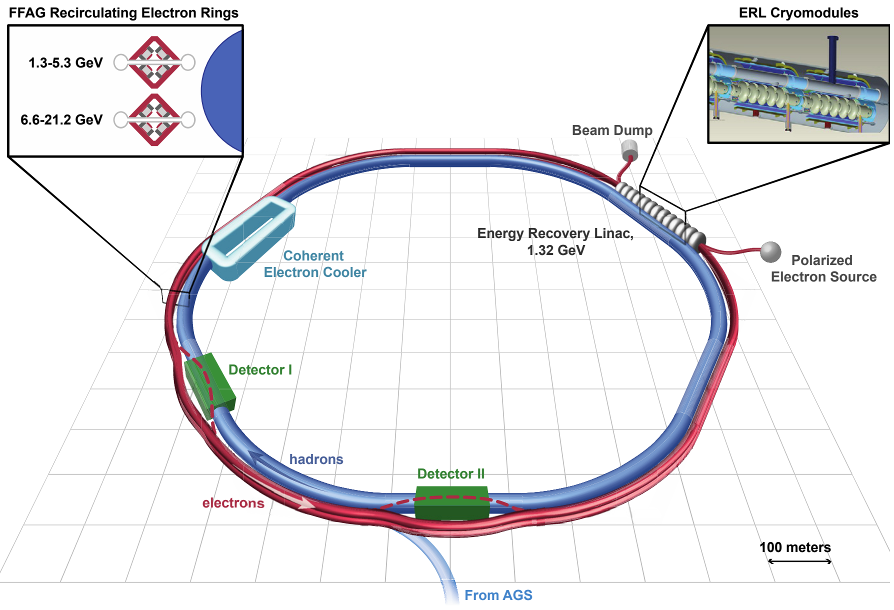
U.S. DEPARTMENT OF ENERGY | Office of Science

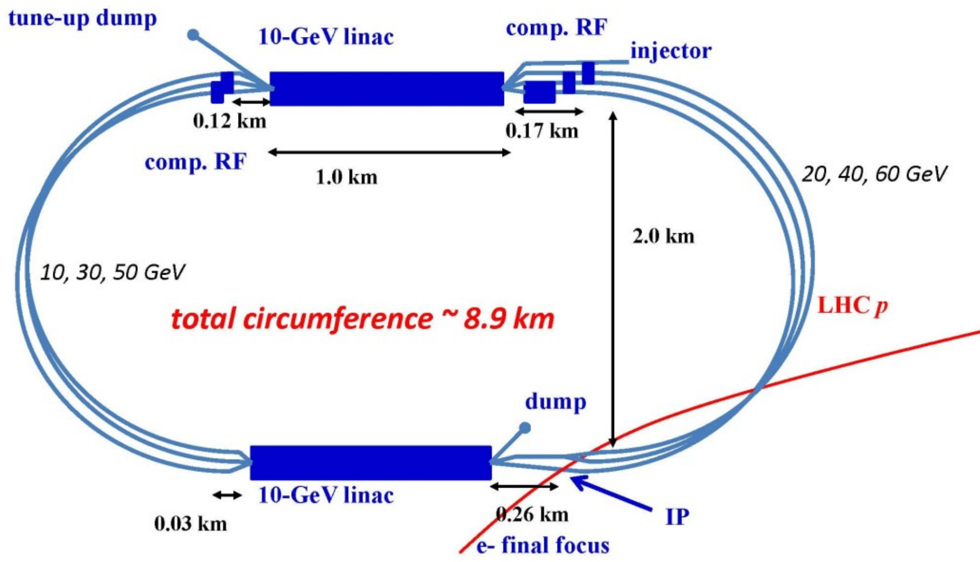
ERL based EICs

- eRHIC @ BNL
  - RHIC provides ion
    - Polarized proton (up to 250/275 GeV) and light ion (up to 167/184 GeV)
  - A new multi-pass ERL in the RHIC tunnel to provide polarized electrons (1.3-21.2 GeV)
- LHeC @ Cern
  - Proton/Ion in LHC (7TeV)
  - ERL with two linacs provides 60GeV polarized electron beam

Layouts

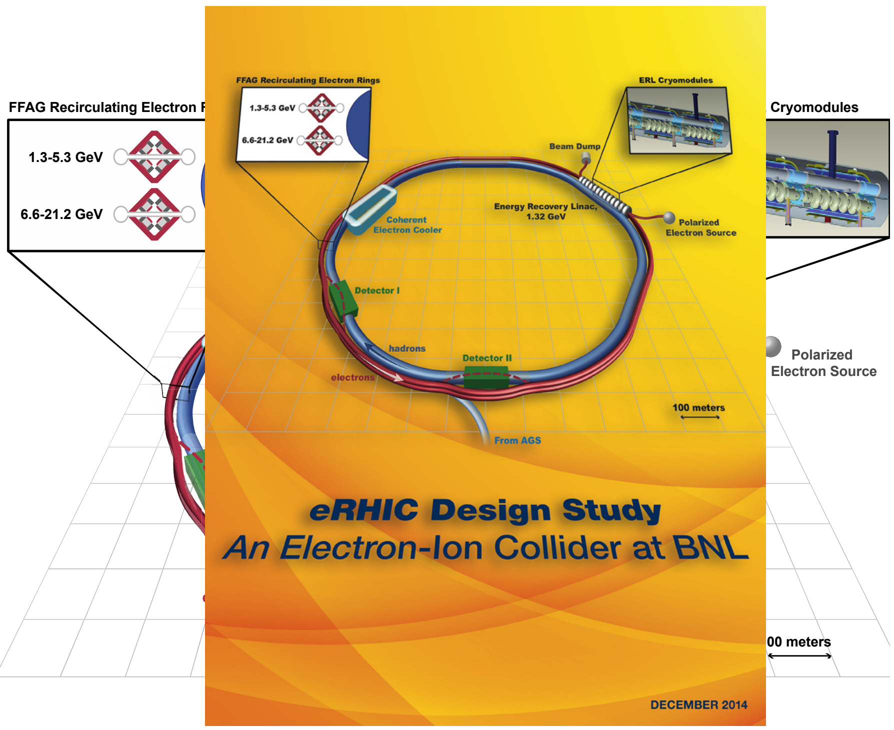


FFAG Recirculating Electron Rings
1.3-5.3 GeV
6.6-21.2 GeV
ERL Cryomodules
Beam Dump
Energy Recovery Linac, 1.32 GeV
Polarized Electron Source
Coherent Electron Cooler
Detector I
Detector II
hadrons
electrons
100 meters
From AGS



tune-up dump
10-GeV linac
comp. RF
injector
0.12 km
0.17 km
comp. RF
1.0 km
20, 40, 60 GeV
2.0 km
10, 30, 50 GeV
total circumference ~ 8.9 km
LHC p
dump
10-GeV linac
0.03 km
0.26 km
IP
e- final focus

Layouts



FFAG Recirculating Electron Rings
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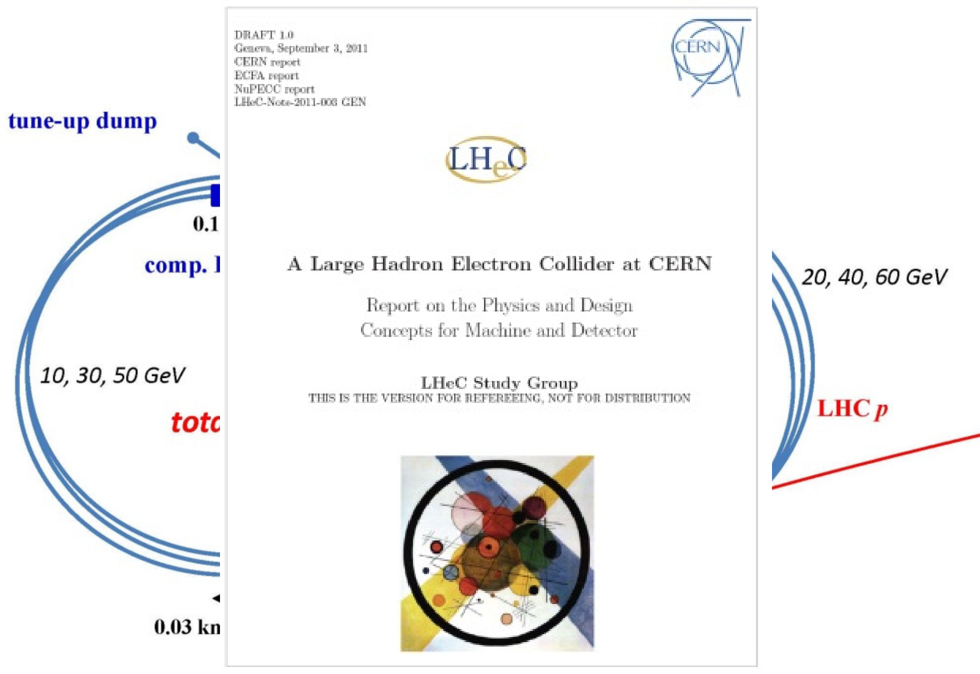
100 meters
From AGS
eRHIC Design Study
An Electron-Ion Collider at BNL
DECEMBER 2014



tune-up dump
0.1
comp. l
10, 30, 50 GeV
totc
0.03 kn
20, 40, 60 GeV
LHC p
DRAFT 1.0
Geneva, September 3, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-003 GEN
CERN
LHeC
A Large Hadron Electron Collider at CERN
Report on the Physics and Design
Concepts for Machine and Detector
LHeC Study Group
THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

Why ERL based?

- ERL based EIC removes the beam-beam limitation on the electron beam, since electron bunch collides only once with the ion bunch. → **Higher Luminosity.**
- **Spin Transparency**
- **Compact and Cost-Effective**
- **Low e-beam power @ dump**

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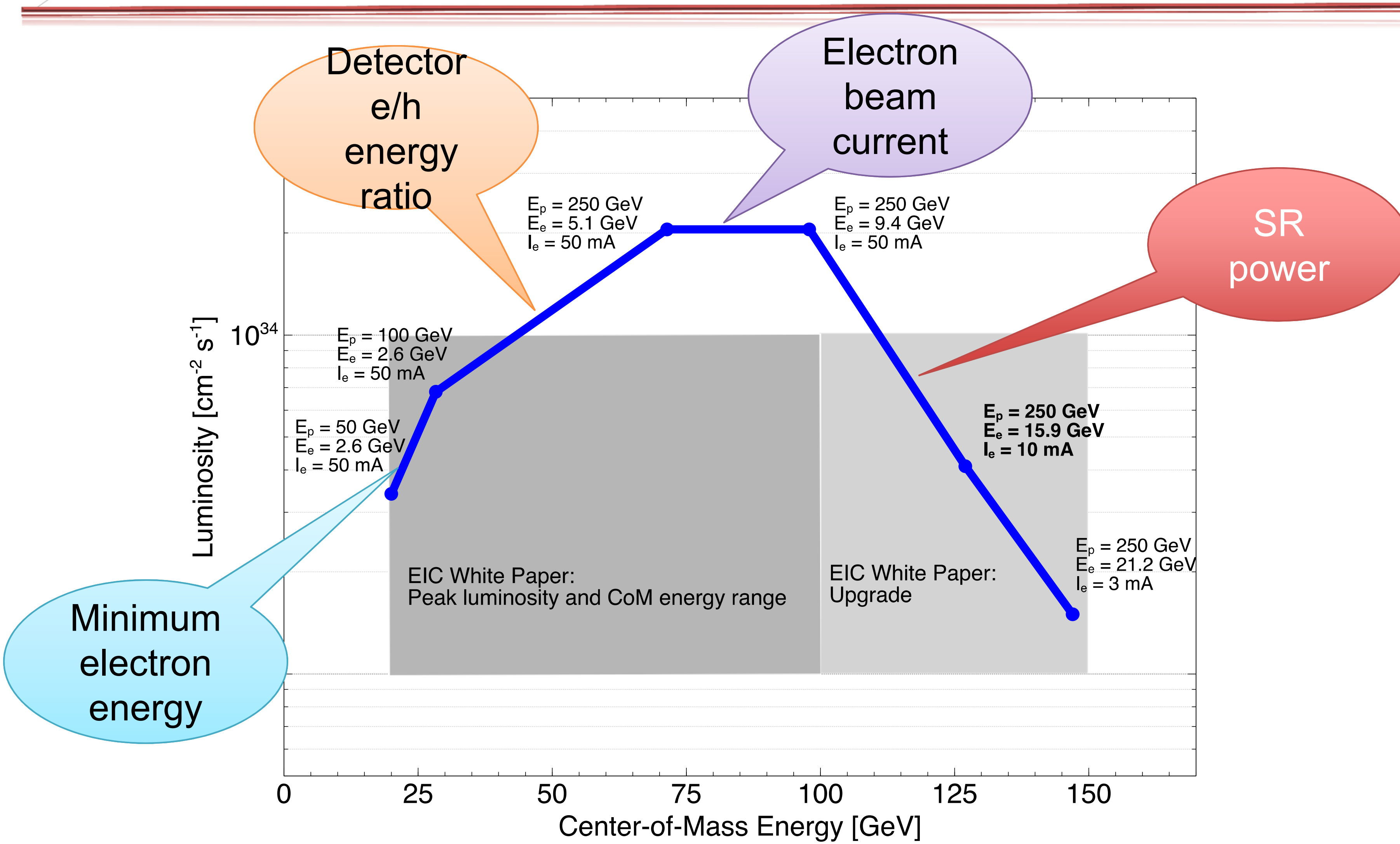
Parameter Table

Parameters	eRHIC		LHeC	
	e	p	e	p
Energy (GeV)	15.9	250	60	7000
Bunch spacing (ns)	106		25	
Intensity, 10^{11}	0.07	3.0	0.01	1.7
Current (mA)	10	415	6.4	860
rms norm. emit. (mm-mrad)	23	0.2	50	3.75
$\beta_{x/y}^{*}$ (cm)	5	5	12	10
rms bunch length (cm)	0.4	5	0.06	7.6
IP rms spot size (μ m)	6.1		7.2	
Beam-beam parameter		0.004		0.0001
Disruption parameter	36		6	
Polarization, %	80	70	90	None
Luminosity, $10^{33} cm^{-2} s^{-1}$	4.9		1.3	

eRHIC, Luminosity

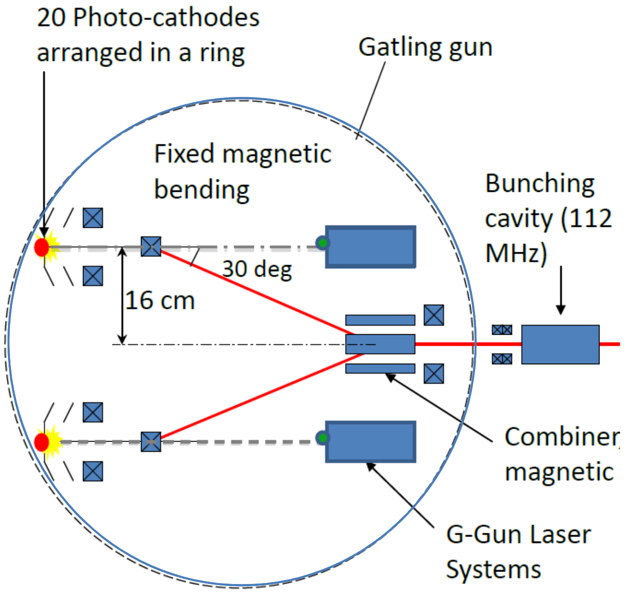


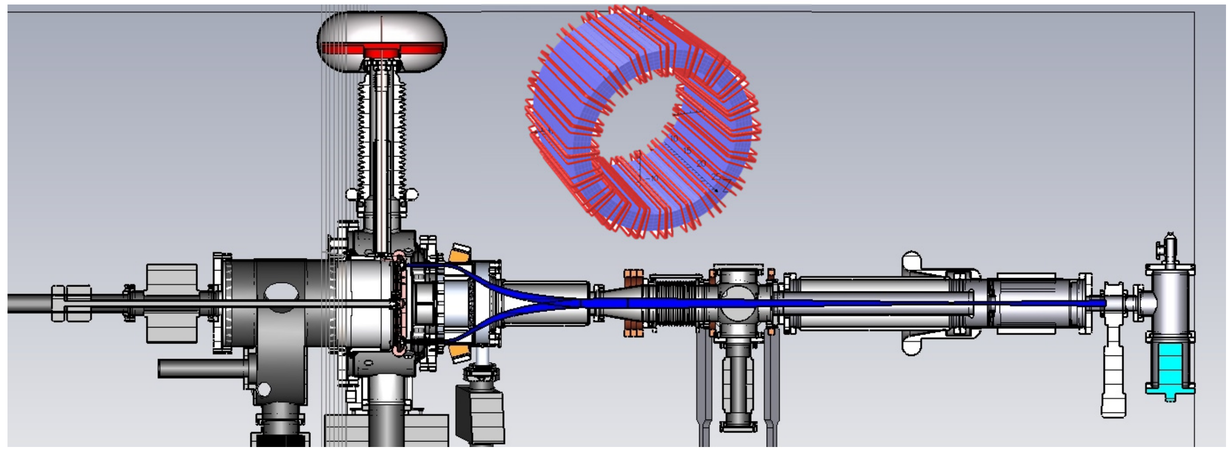
AP in ERL based EIC

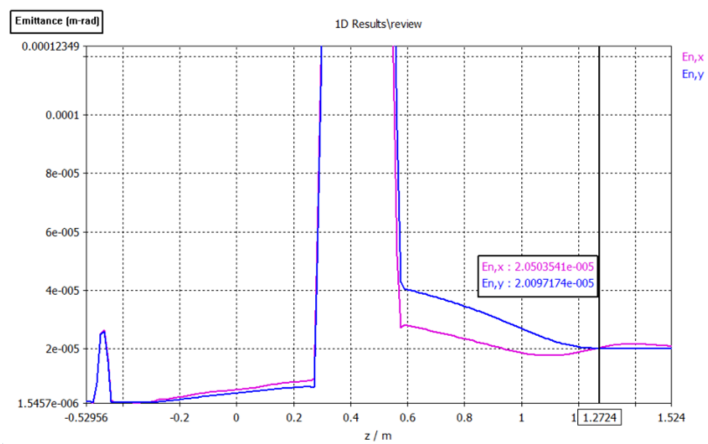
- Polarized Electron Source
- FFAG recirculation pass for ERL
- Energy losses and energy spread
- Beam dynamics --- Multi-pass-ERL
  - BBU, Ion trapping, fast ion instability
- Beam dynamics --- Linac-ring collision scheme
  - Special beam-beam effect
- Synchronization

- Advanced hadron cooling
- Low-beta interaction region and Crab-Crossing
  - Design and dynamic aperture optimization

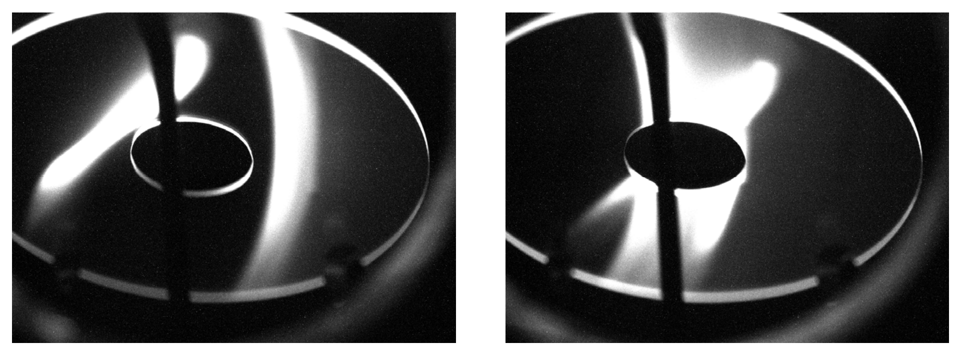
Polarized e Source







First beam detected by the YAG screen.



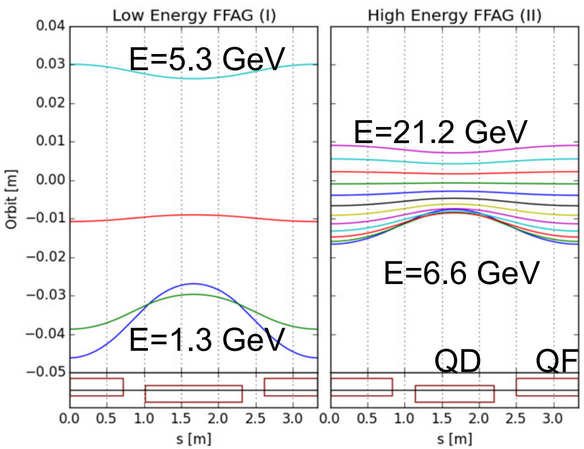
FFAG pass, I

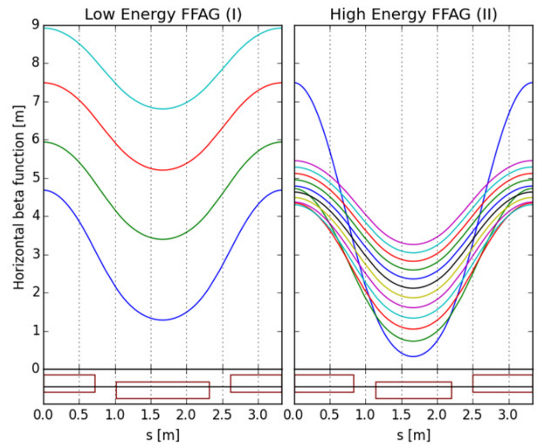
- Linear Fixed Field Alternating Gradient (FFAG) lattice with permanent magnets is adopted for the ERL recirculation passes to reduce the cost.
- Linear magnetic field,

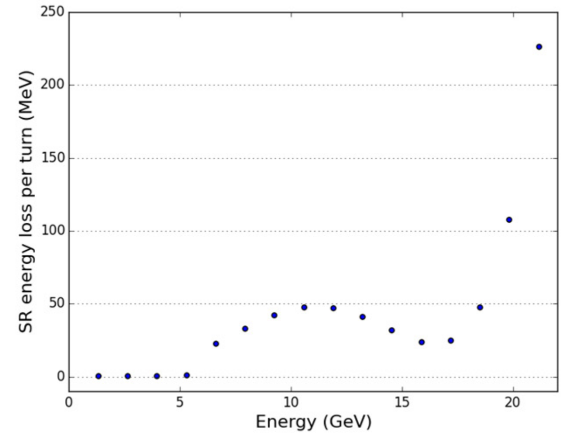
$$B(x) = B_0 + Gx \qquad B(x) = G(x + x_0)$$

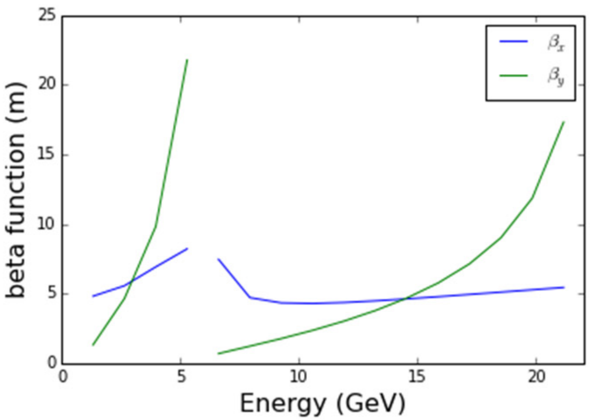
  - strong focusing -> Small dispersion -> large energy range
  - Change quad offset to guide the beam
- Only two FFAG-lines is required for 16 energies, optimized for:
  - Minimized total SR power
  - Orbit offsets, optics/tunes/chromaticity for each energy

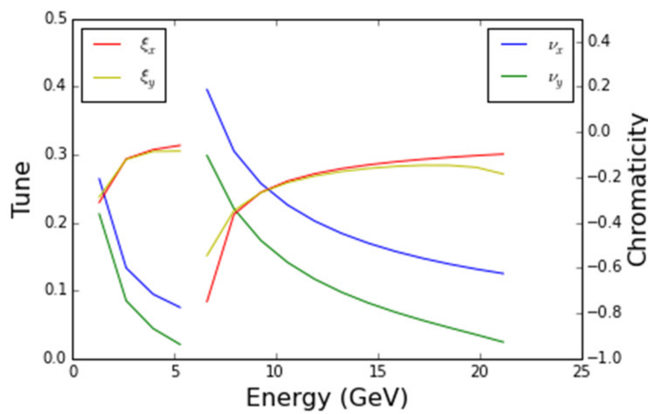
FFAG pass, II

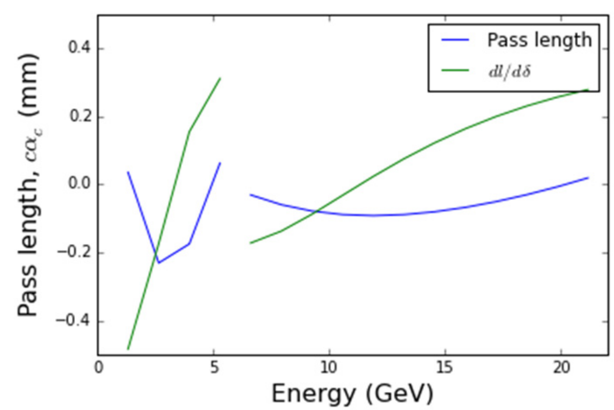

Low Energy FFAG (I)
High Energy FFAG (II)
Orbit [m]
s [m]
E=5.3 GeV
E=21.2 GeV
E=6.6 GeV
E=1.3 GeV
QD
QF


Low Energy FFAG (I)
High Energy FFAG (II)
Horizontal beta function [m]
s [m]


SR energy loss per turn (MeV)
Energy (GeV)

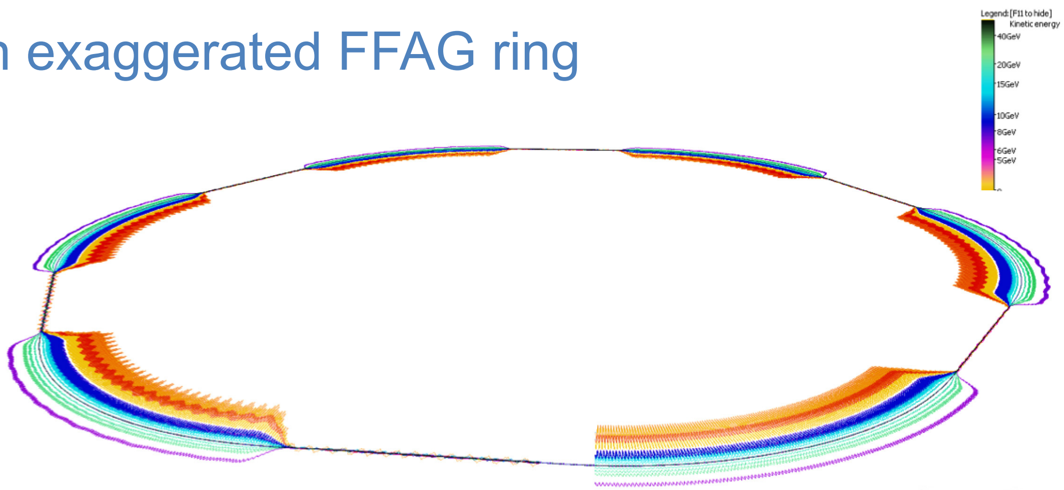

beta function (m)
Energy (GeV)
β_x
β_y


Tune
Chromaticity
Energy (GeV)
ξ_x
ξ_y
ν_x
ν_y


Pass length, $c\alpha_c$ (mm)
Energy (GeV)
Pass length
$dl/d\delta$

FFAG pass, III

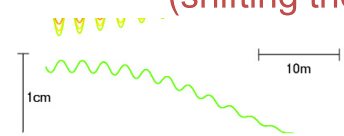
An exaggerated FFAG ring

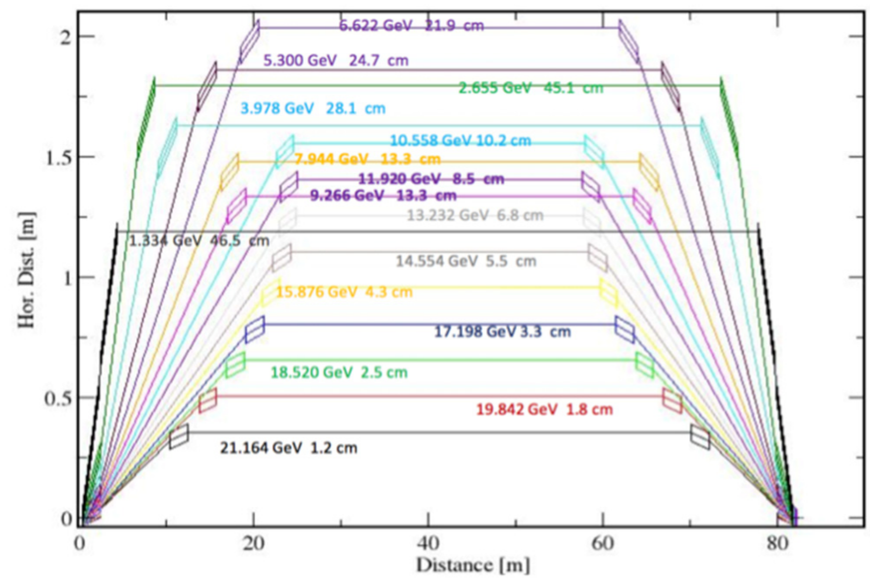


Arcs transition to

- Straight
- Detector Bypass

Orbits in Transition section (shifting the quads)

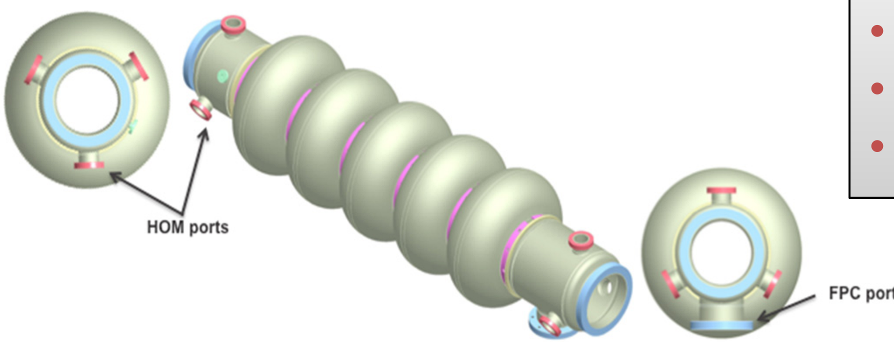




Spreader and Combiner is needed to connect with linac:

- Position and Optics matching
- Time of flight adjustment
- ‘Anchor’ for orbit correction

SRF cavity and HOM



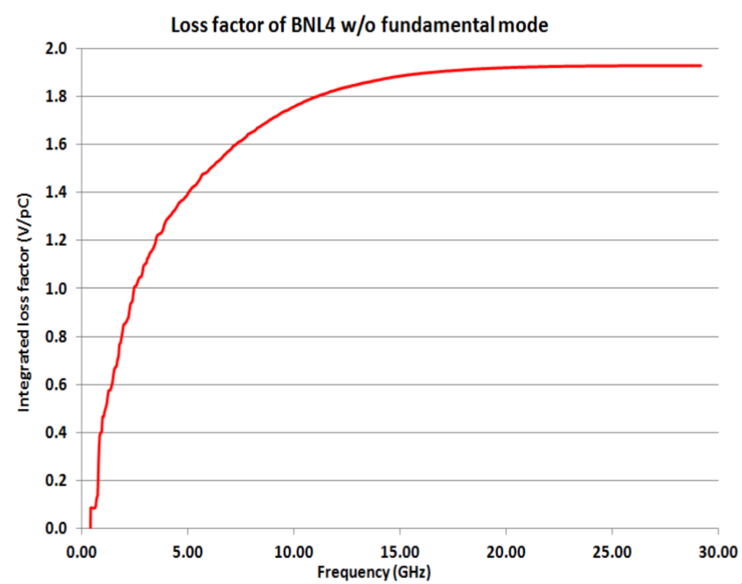
- Lower f->better BBU
- Lower f->longer bunch->less loss factor
- Lower f-> less RF loss

BNL3, 704 MHz SRF cavity

BNL4, 422MHz SRF cavity

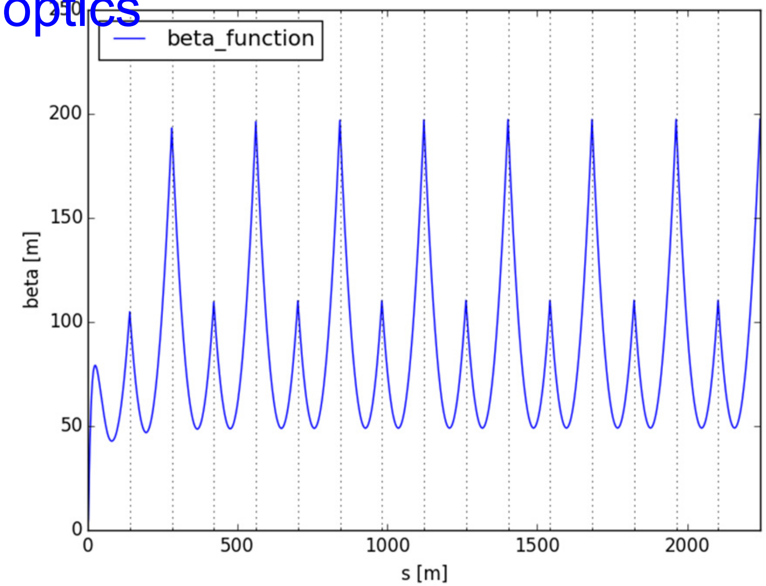
HOM power is the largest challenge in designing SRF cavity for eRHIC.

- 7.8 KW per cavity, for 50 mA, 8-pass ERL
- Current R&D effort is aiming on beam-pipe damping of the high frequency HOM power



BBU in eRHIC

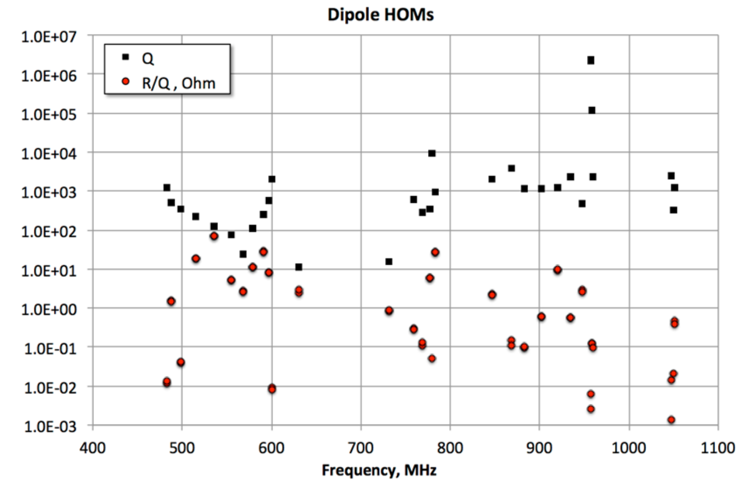
Linac optics



The beta function in the linac for 16 passes.
The horizontal and vertical optics are identical.
The grid lines separates the optics of each pass.

Mirror symmetry is assumed between linac passes.
Initial twiss parameter is chosen to minimize the beta function.

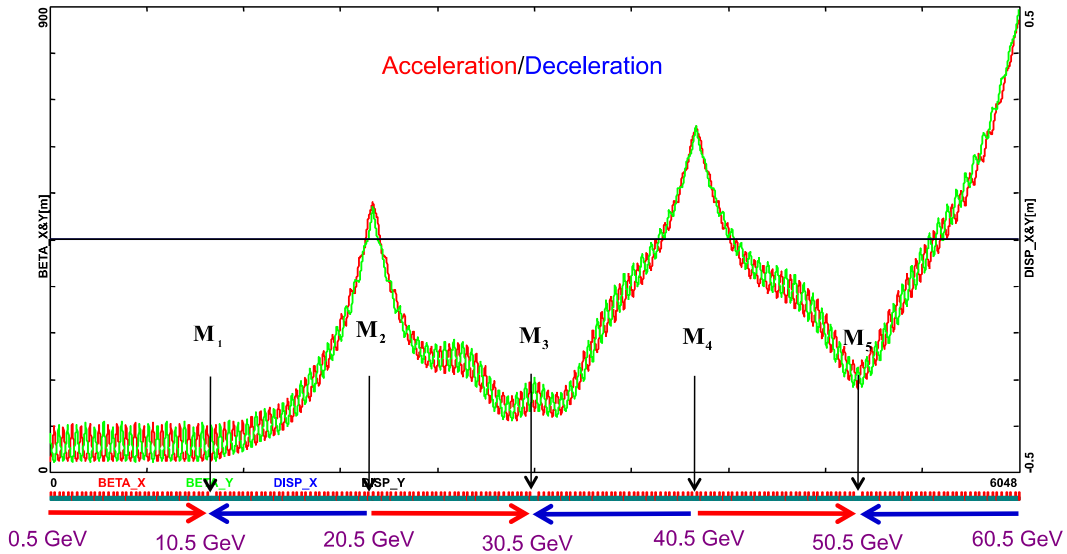
Quality factors and *R/Q*'s of the dipole HOM of 422 MHz cavity (BNL3 scaled).



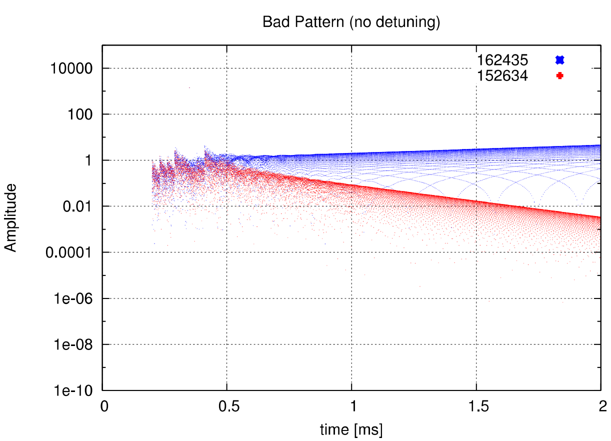
Multipass beam-breakup source current thresholds for 16 pass operation (simulation results)

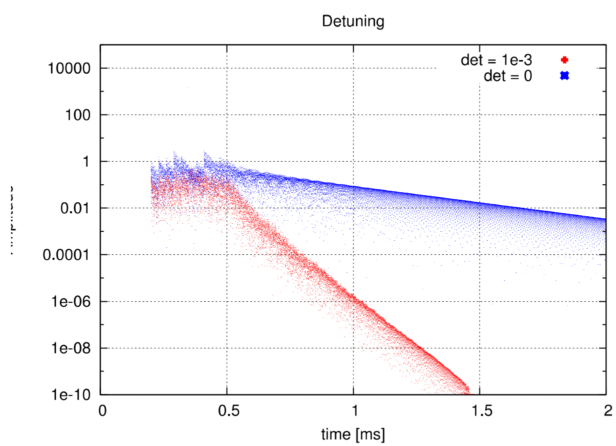
Δf/f (rms)	Current Threshold (mA)
0	53
5e-4	95
1e-3	137
3e-2	225
1e-2	329

BBU in LHeC



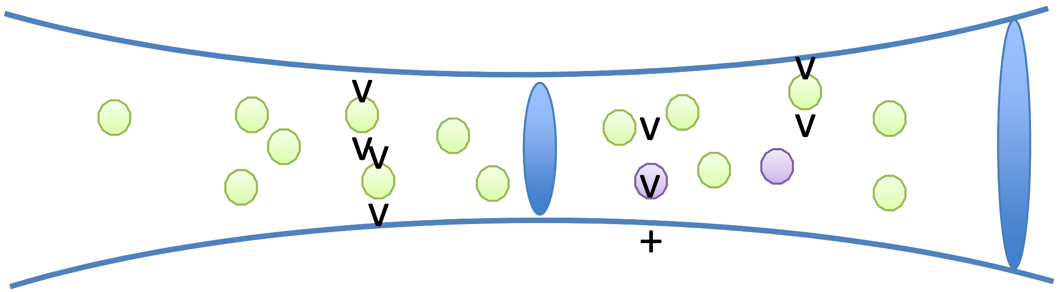
#	f [GHz]	A [V/C/m²]	Q
1	0.9151	9.323	1e5
2	0.9398	19.095	1e5
3	0.9664	8.201	1e5
4	1.003	5.799	1e5
5	1.014	13.426	1e5
6	1.020	4.659	1e5
7	1.378	1.111	1e5
8	1.393	20.346	1e5
9	1.408	1.477	1e5
10	1.409	23.274	1e5
11	1.607	8.186	1e5
12	1.666	1.393	1e5
13	1.670	1.261	1e5
14	1.675	4.160	1e5
15	2.101	1.447	1e5
16	2.220	1.427	1e5
17	2.267	1.377	1e5
18	2.331	2.212	1e5
19	2.338	11.918	1e5
20	2.345	5.621	1e5
21	2.526	1.886	1e5
22	2.592	1.045	1e5
23	2.592	1.069	1e5
24	2.693	1.256	1e5
25	2.696	1.347	1e5
26	2.838	4.350	1e5



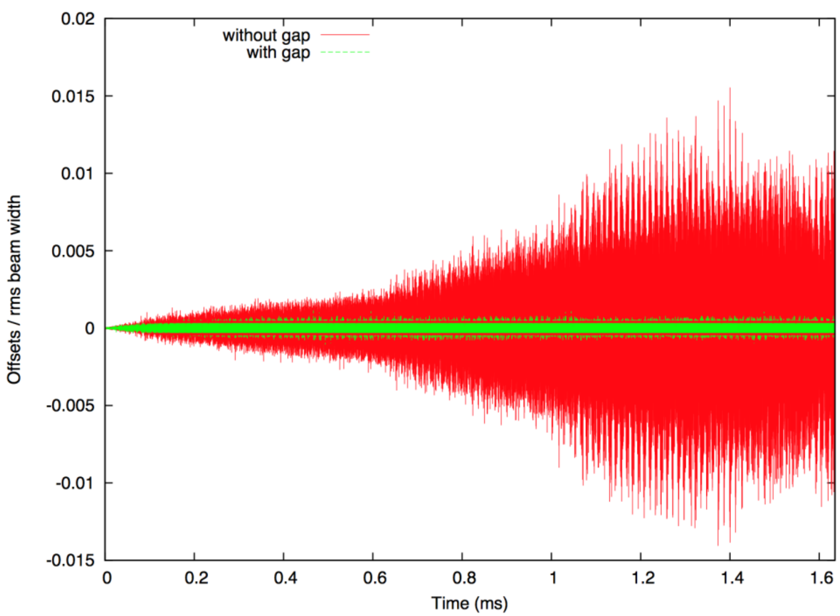


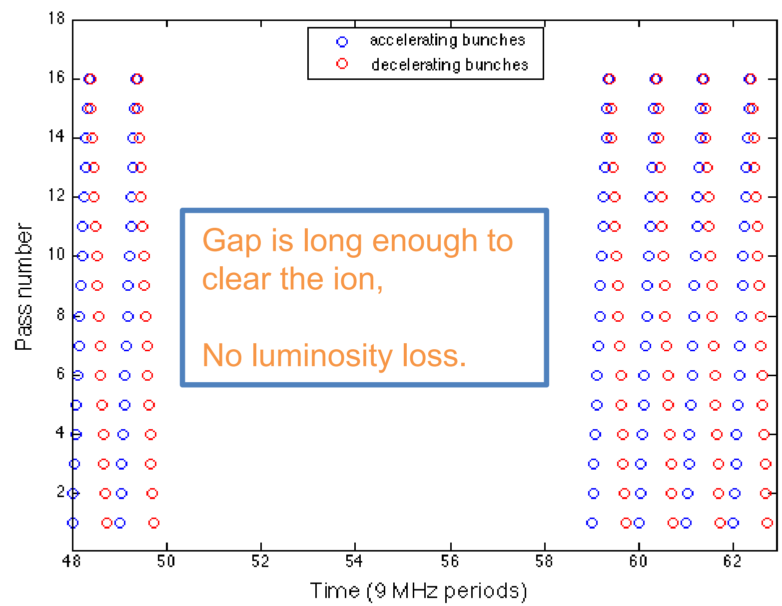
@Dario Pellegrini, Alex Bogacz

Ion effects



- Ion trapped in linac, neutralization
- Fast ion instability, beam transverse offset

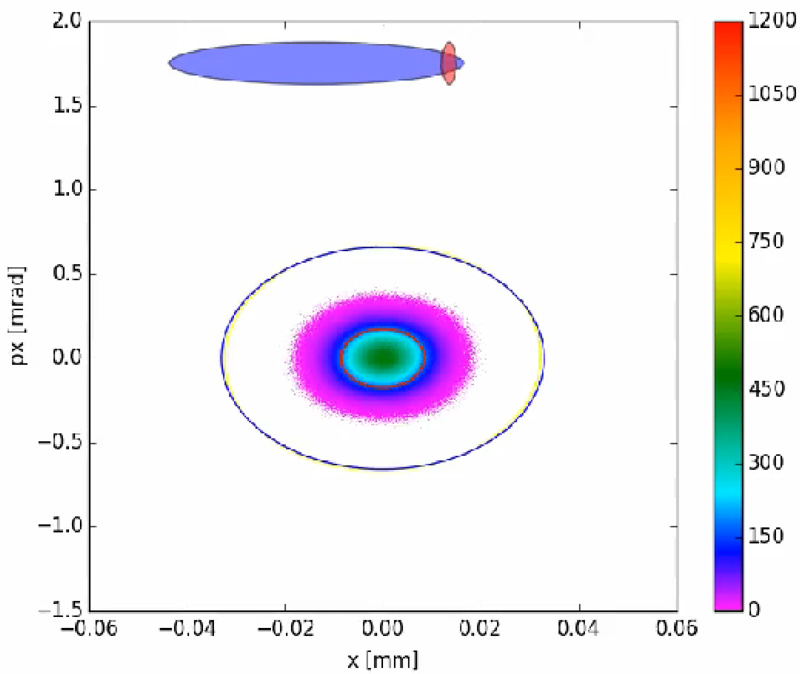


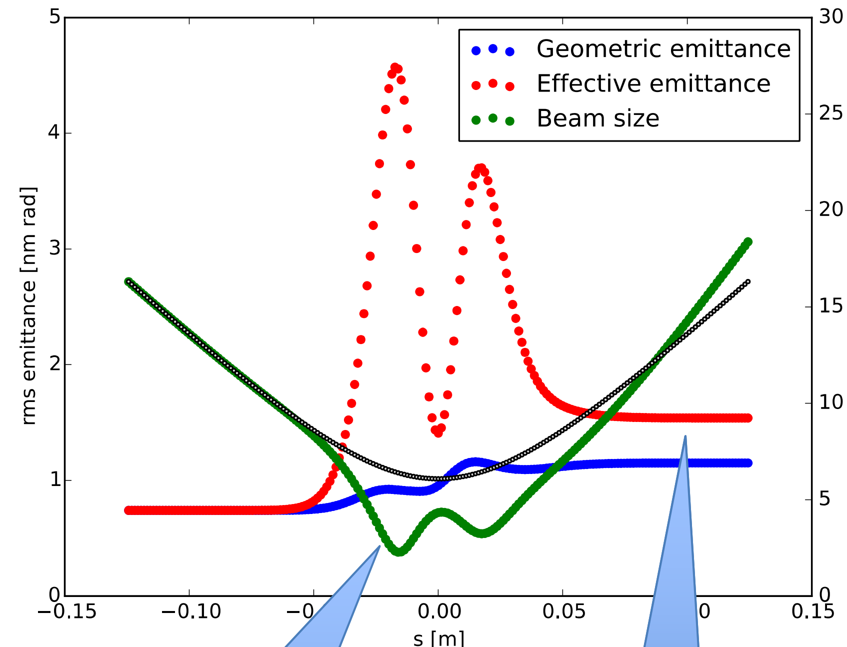


Gap is long enough to clear the ion,

No luminosity loss.

Beam-Beam Effect, Electron Disruption

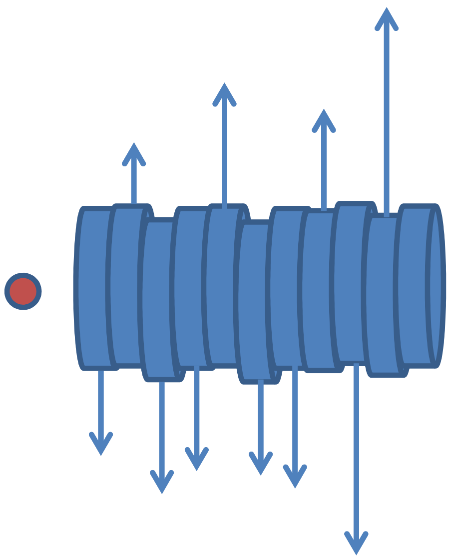


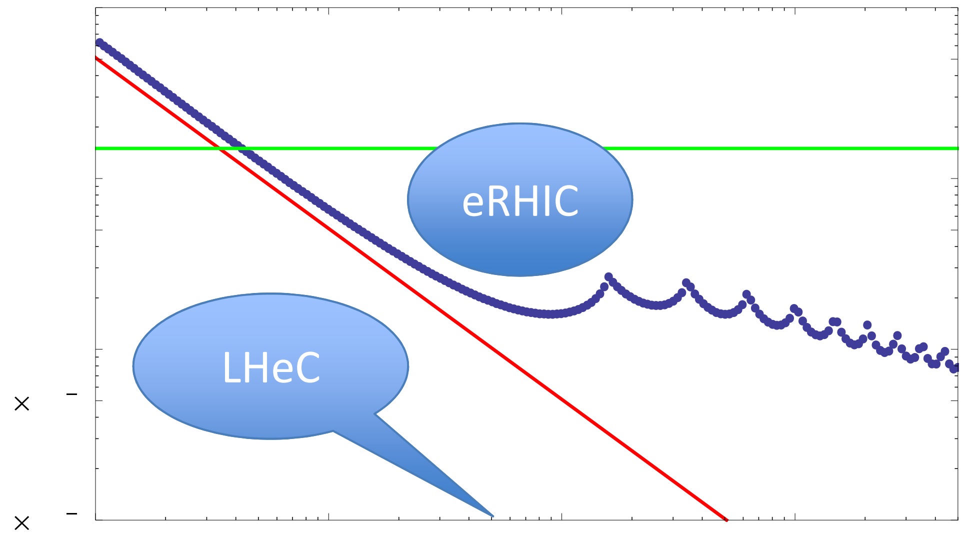


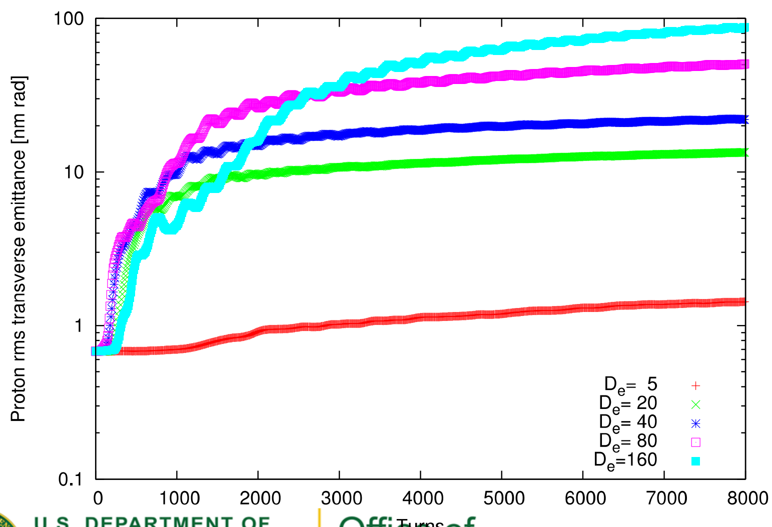
Pinch effect
3.3->4.9e33

Mismatch
and
disruption

Beam-Beam effect
Kink instability



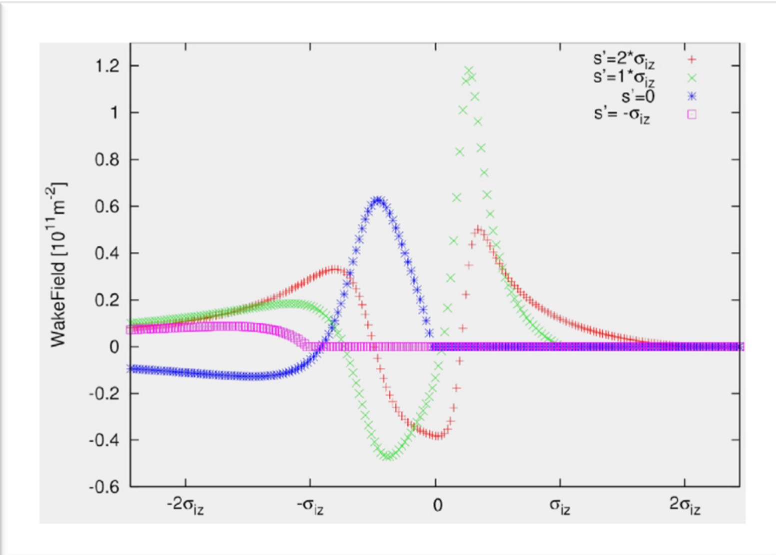


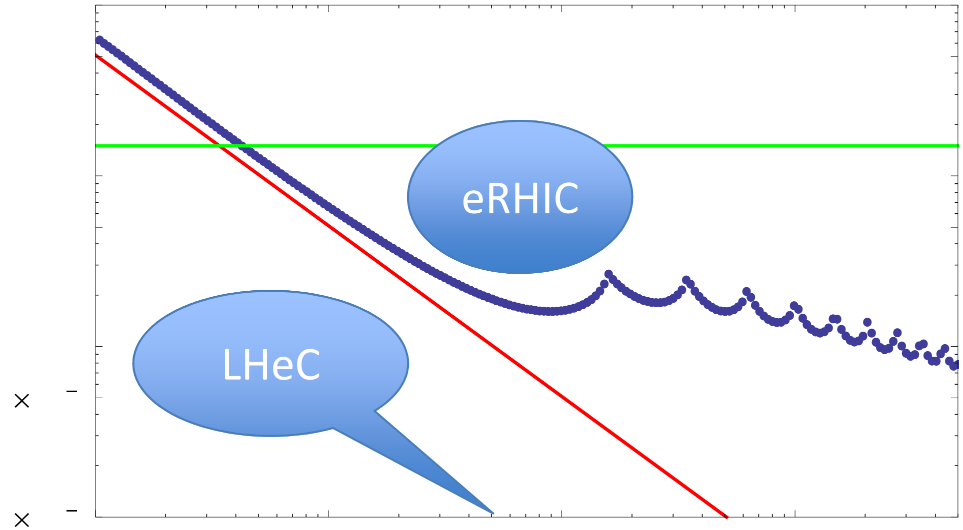


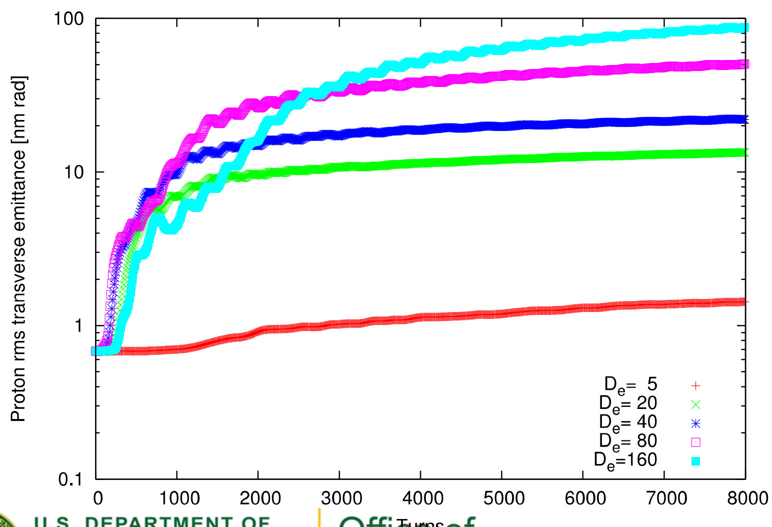
Kink instability suppression, with disruption parameter 36, requires a pickup-kicker feedback system.

Simulation shows the required bandwidth is 50-300 MHz.

Beam-Beam effect
Kink instability





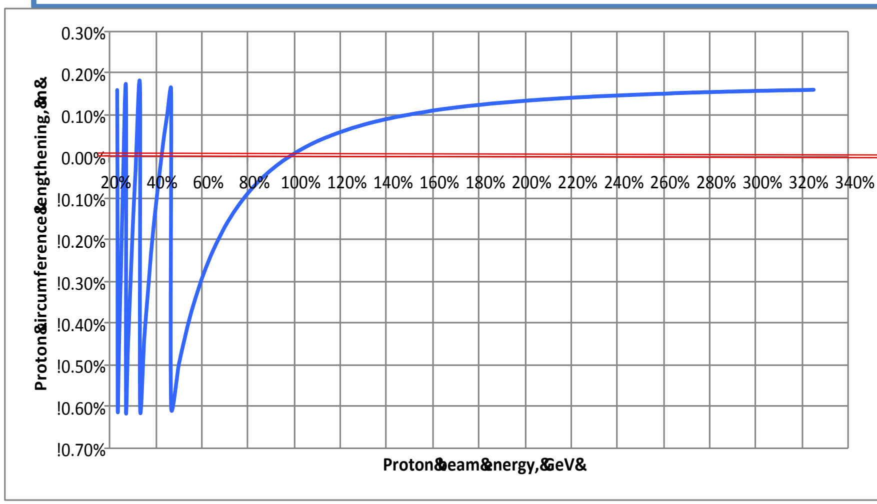


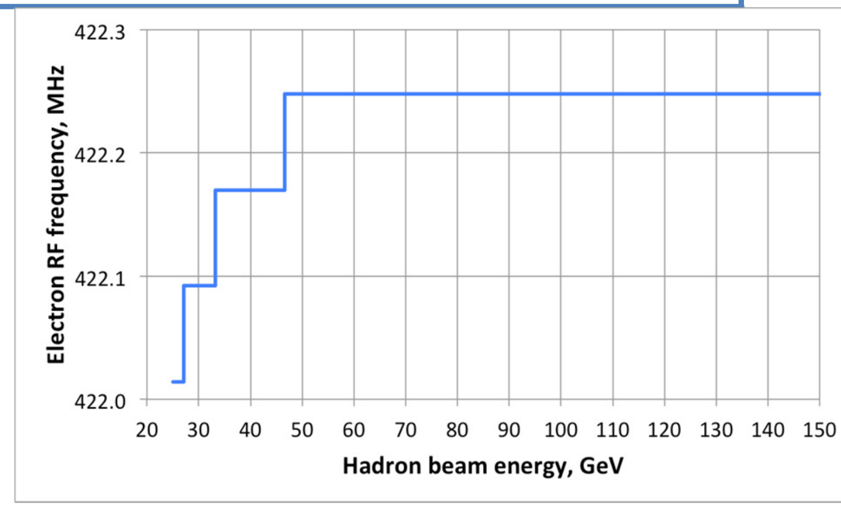
Kink instability suppression, with disruption parameter 36, requires a pickup-kicker feedback system.

Simulation shows the required bandwidth is 50-300 MHz.

Synchronization

RHIC ion beam is not ultra relativistic. Eg. 25 GeV <->250 GeV, 7e-4 time of flight difference. Solution: harmonic jump to reduce the path length adjustment.



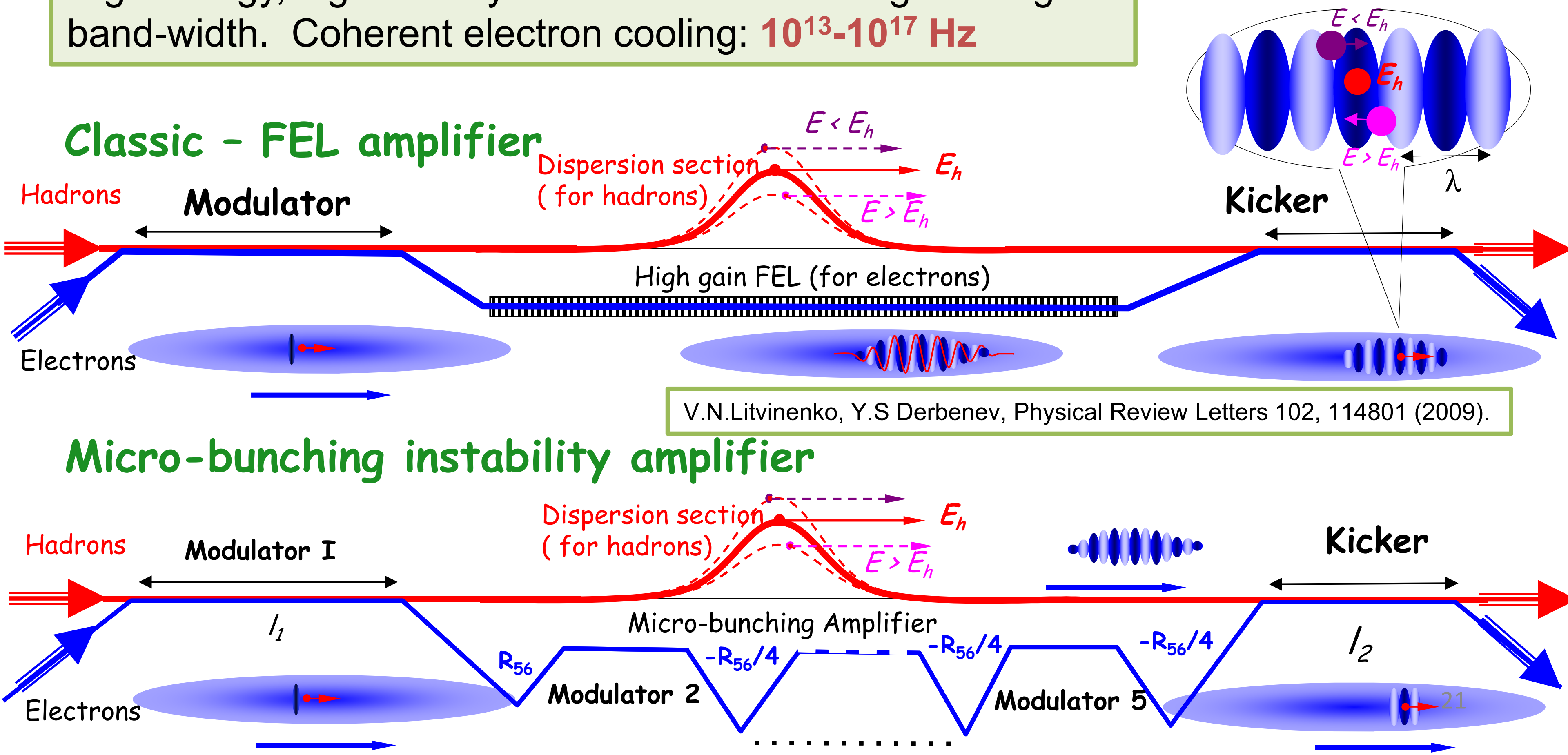


16 cm will guarantee continuous energy change 100-250 GeV. ongoing accelerator experiments at RHIC aims on radius shift +/- 1.27cm.

Individual ion energies below 50 GeV can be realized by harmonic jump. Advantage of ERL based EIC, no instability involved.

Advanced Cooling for ion beam

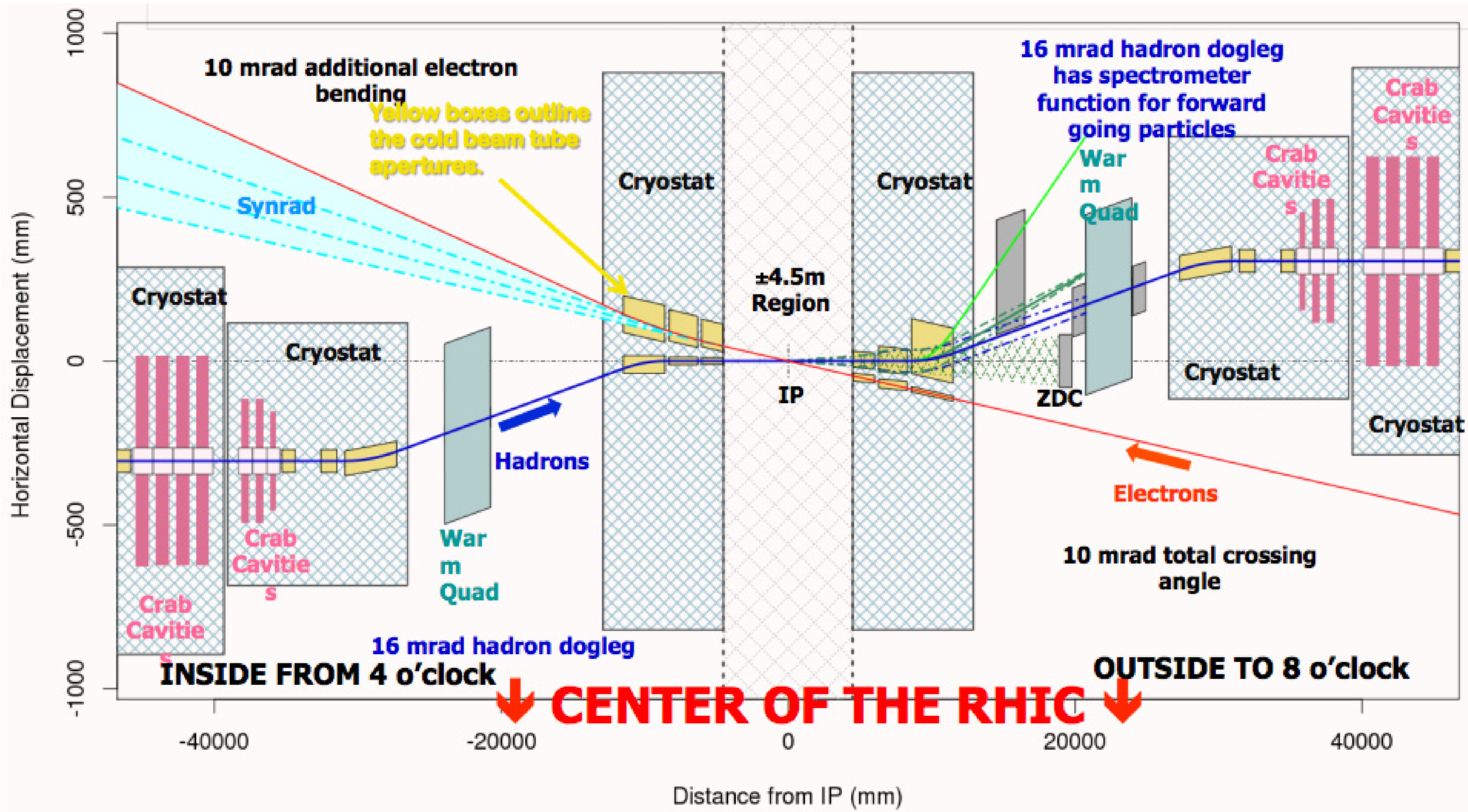
High energy, high density ion beam need cooling with high band-width. Coherent electron cooling: **10^{13}-10^{17} Hz**



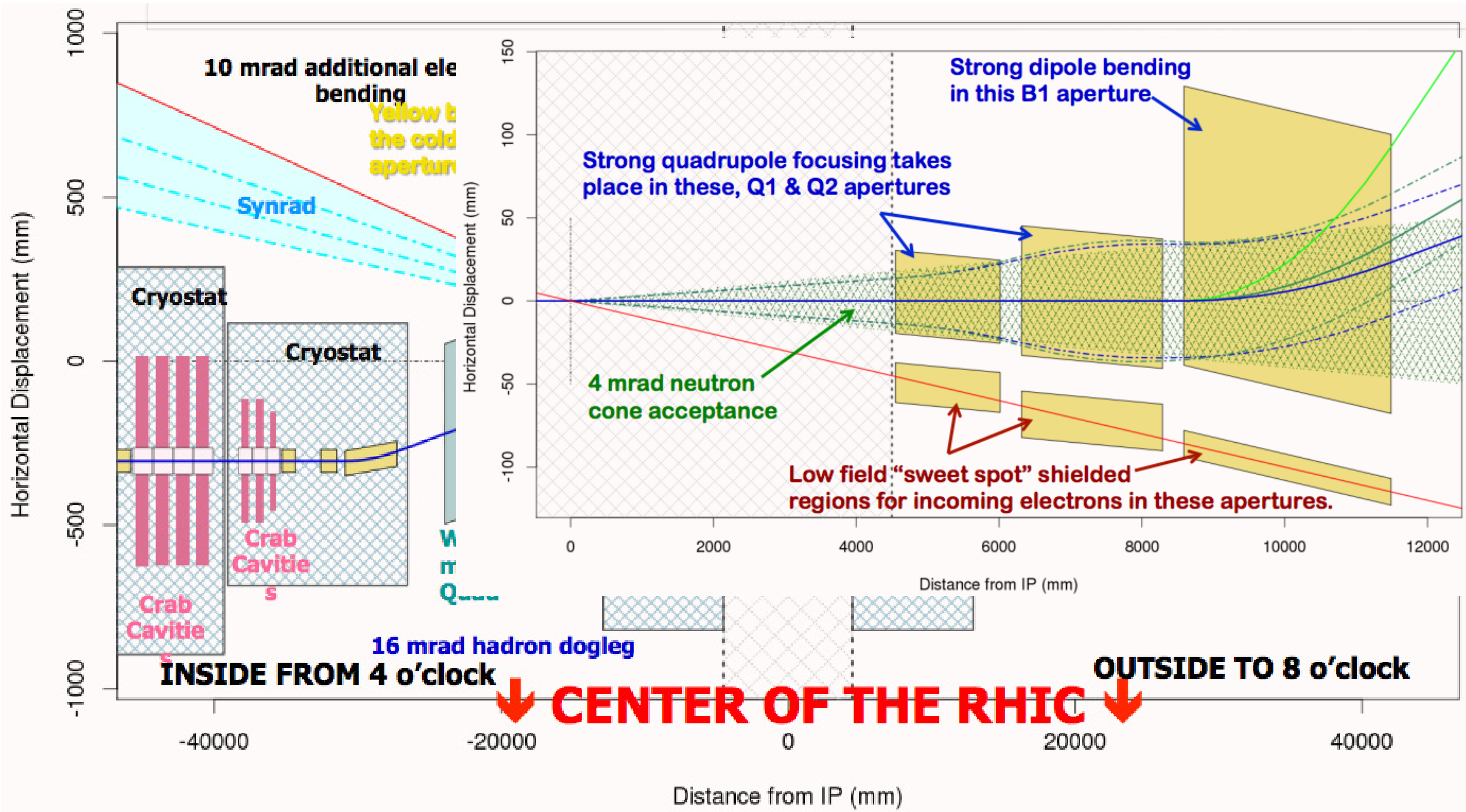
V.N.Litvinenko, Y.S Derbenev, Physical Review Letters 102, 114801 (2009).

D. Ratner, Physical Review Letters 111, 084802 (2013).

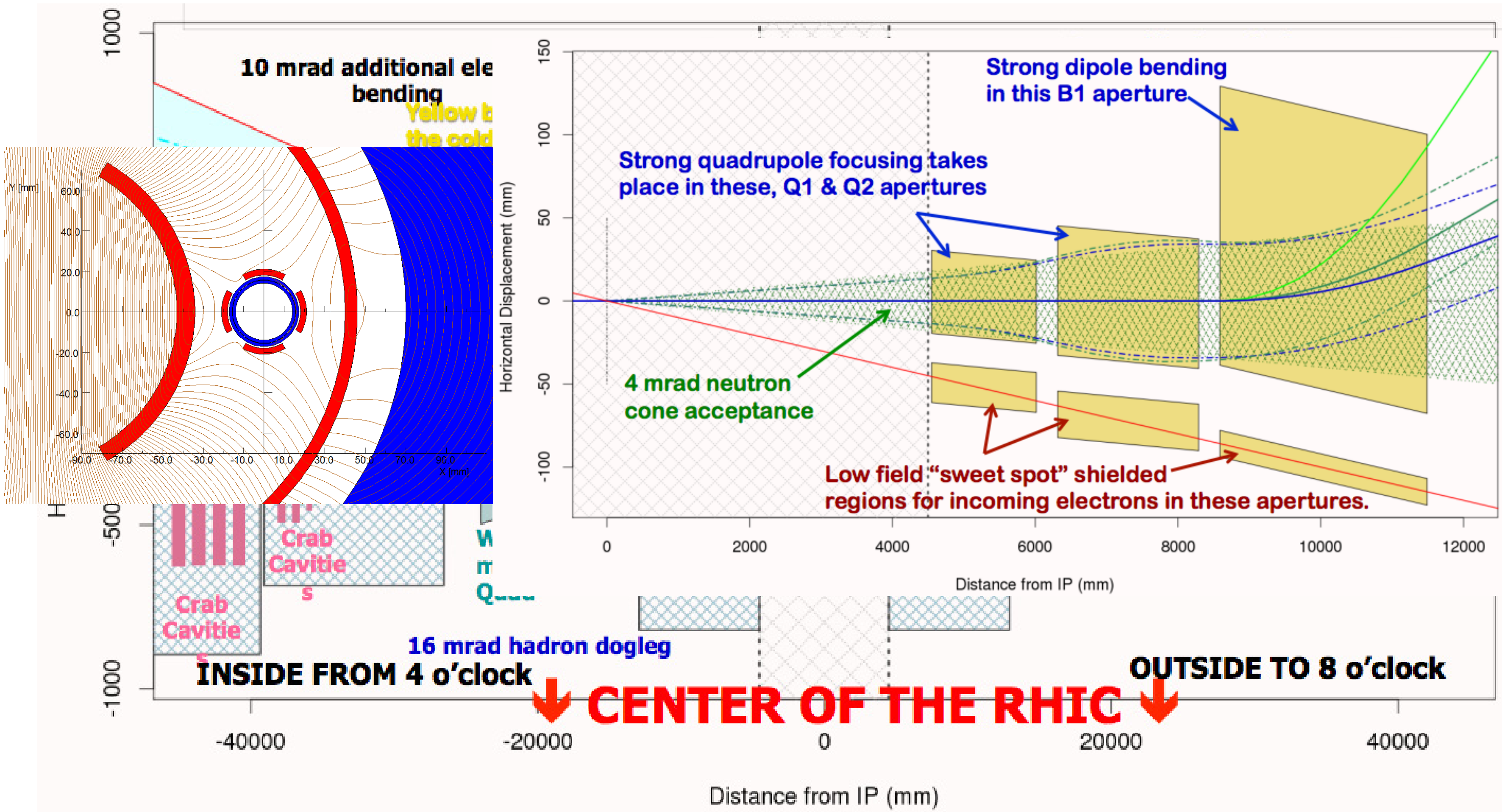
IR Design


10 mrad additional electron bending
Yellow boxes outline the cold beam tube apertures.
Synrad
Cryostat
Cryostat
Cryostat
Cryostat
±4.5m Region
IP
16 mrad hadron dogleg has spectrometer function for forward going particles
Warm Quad
Crab Cavities
Crab Cavities
Cryostat
ZDC
Cryostat
Hadrons
Electrons
Warm Quad
Crab Cavities
Crab Cavities
10 mrad total crossing angle
16 mrad hadron dogleg
INSIDE FROM 4 o'clock
OUTSIDE TO 8 o'clock
CENTER OF THE RHIC
Horizontal Displacement (mm)
1000
500
0
-500
-1000
-40000
-20000
0
20000
40000
Distance from IP (mm)

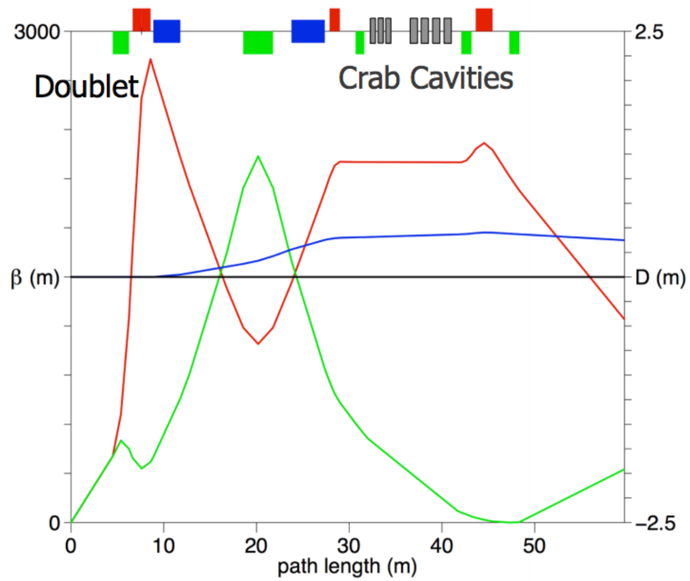
IR Design

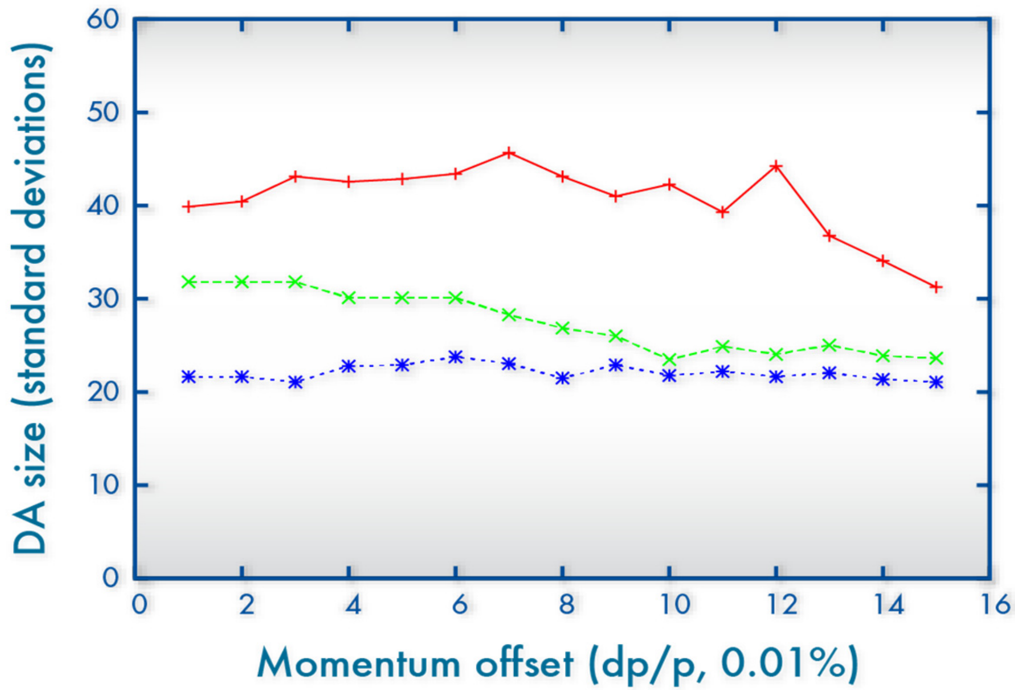

10 mrad additional ele
bending
Synrad
Cryostat
Cryostat
Crab Cavities
Crab Cavities
16 mrad hadron dogleg
INSIDE FROM 4 o'clock
CENTER OF THE RHIC
OUTSIDE TO 8 o'clock
Horizontal Displacement (mm)
Distance from IP (mm)
Strong dipole bending in this B1 aperture
Strong quadrupole focusing takes place in these, Q1 & Q2 apertures
4 mrad neutron cone acceptance
Low field "sweet spot" shielded regions for incoming electrons in these apertures.
Horizontal Displacement (mm)
Distance from IP (mm)

IR Design


10 mrad additional ele
bending
Yellow b
the cold
Y [mm]
X [mm]
Strong dipole bending in this B1 aperture
Strong quadrupole focusing takes place in these, Q1 & Q2 apertures
4 mrad neutron cone acceptance
Low field "sweet spot" shielded regions for incoming electrons in these apertures.
Horizontal Displacement (mm)
Distance from IP (mm)
Crab Cavitie s
Crab Cavitie s
16 mrad hadron dogleg
INSIDE FROM 4 o'clock
CENTER OF THE RHIC
OUTSIDE TO 8 o'clock
Distance from IP (mm)

DA of the Ion ring

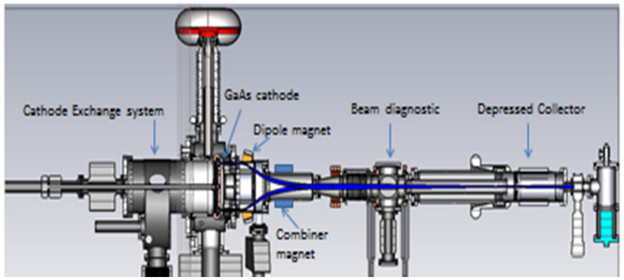




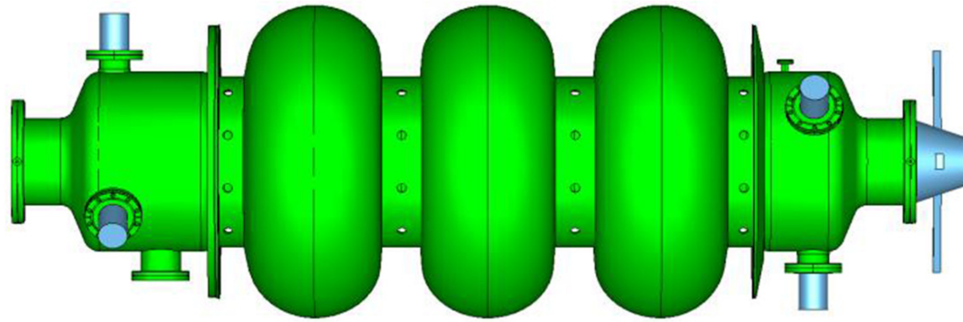
Maximize dynamic aperture by optimizing low order nonlinear driving terms and chromaticity (first and second order).

Disrupted beam-beam effect is calculated by electron's rms beamsize. Field error and misalignment is included.

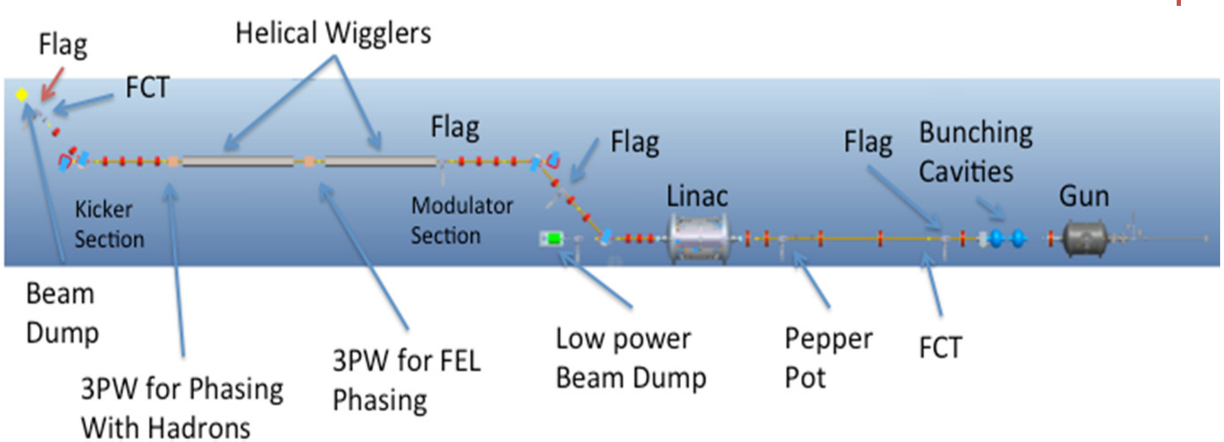
R&D projects @ BNL



High current polarized e-source

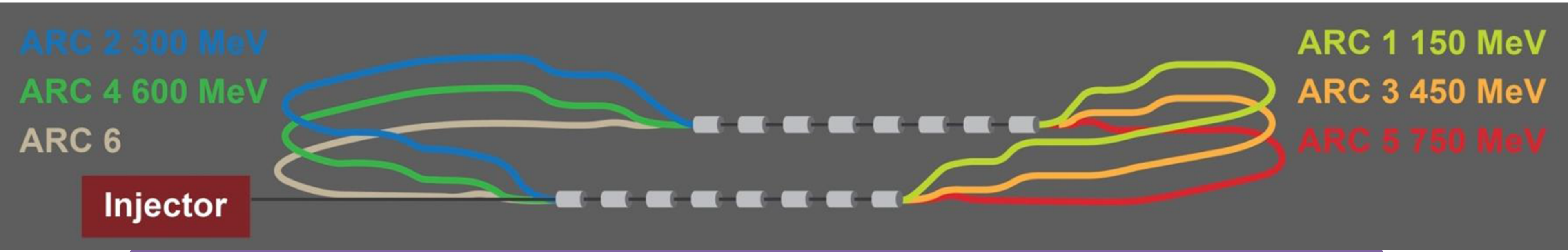


Effective HOM damping



Advanced Cooling concept
Beam-Beam study for e-I collision

LHeC ERL test facility

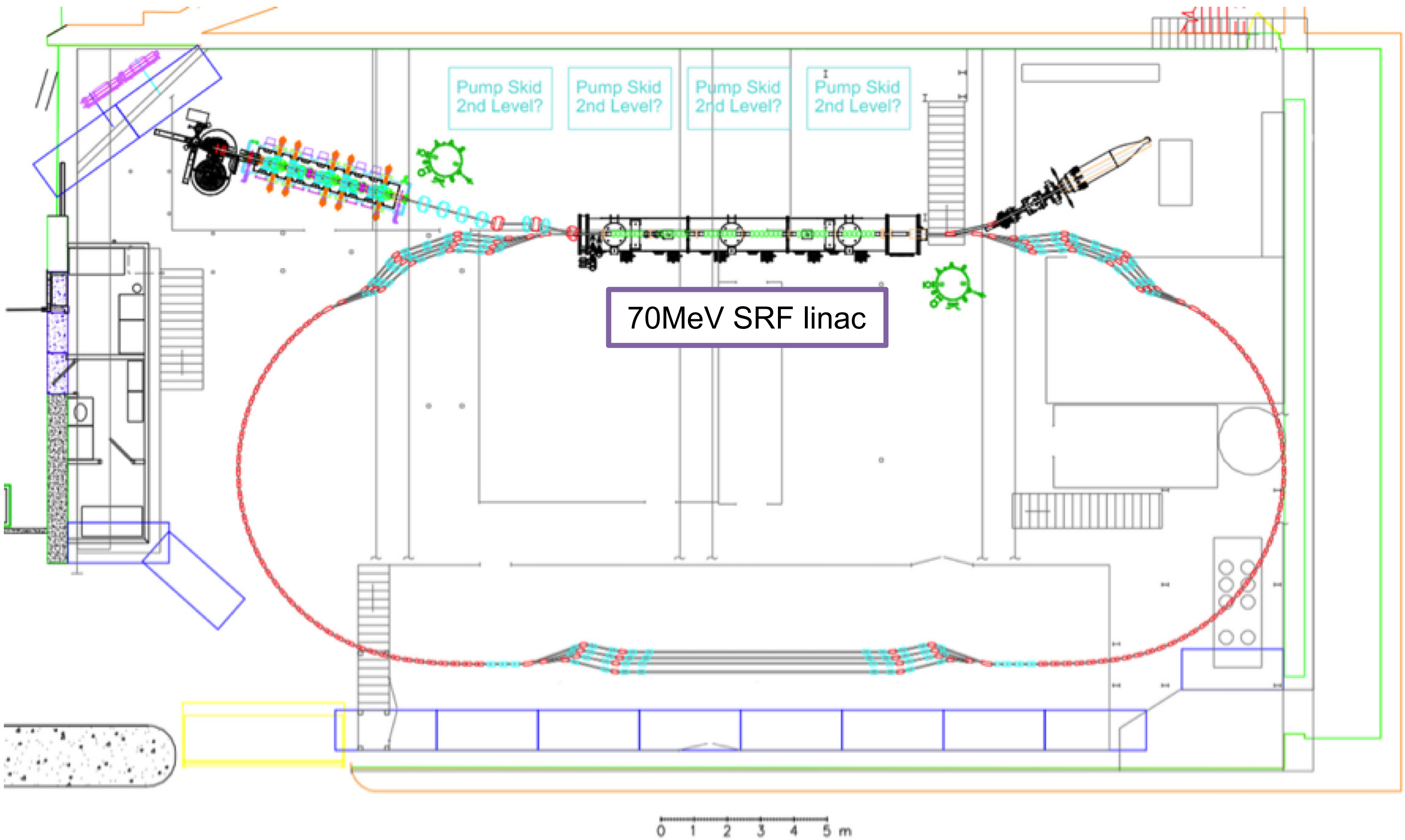


High energy multi-pass ERL, by stages

TARGET PARAMETER*	VALUE
Injection Energy [MeV]	5
Final Beam Energy [MeV]	900
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	50
Beam Current [mA]	10
Bunch Spacing [ns]	25 (50)
Passes	3

@ Alessandra Valloni

A new possibility: Cβ



Proposal: Cornell-BNL FFAG-ERL Test Accelerator (Cβ)

Summary

- ERL technology provides a pathway for a high-lumi electron ion collider.
- Specific accelerator physics challenges need to be considered. Some of them are well-studied, some are still being investigated.
- Several ongoing R&D projects, especially experimental demonstrations, will greatly reduce the design risks of ERL based EIC.

In this conference…

MOPJE066 D. Pellegrini, Single and Multi-bunch End-to-end Tracking in the LHeC
MOPJE068 D. Pellegrini, PLACET2: a Novel Code for Beam Dynamics in Recirculating Machines
MOPJE079 E. Alaniz, Tracking Studies in the LHeC Lattice

ERL : TUPTY047 D. Trbojevic, Non-Scaling Fixed Field Alternating Gradient ERL for eRHIC

: TUPWI050 C. Liu, Optics Correction for the Multi-pass FFAG ERL Machine eRHIC
: TUPWI051 C. Liu, Orbit Correction for eRHIC Lattice with Large Chromaticity
: TUPWI055 F. Meot, Chromatic Effects and Orbit Correction in eRHIC FFAG Arcs: Polarization Monitoring

: TUPWI052 F. Meot, End-to-end 9-D+SR Polarized Bunch Transport in the Energy-recovery Electron Recirculator of the eRHIC Collider

: WEPJE023 O. Rahman, Cathode Performance during Two Beam Operation of the High Current High Polarization Electron Gun for eRHIC
: WEPJE033 E. Wang, The Progress of Funneling Gun High Voltage Condition and Beam Test

: WEPJE026 J. Berg, Conceptual Design of a Quadrupole Magnet for eRHIC

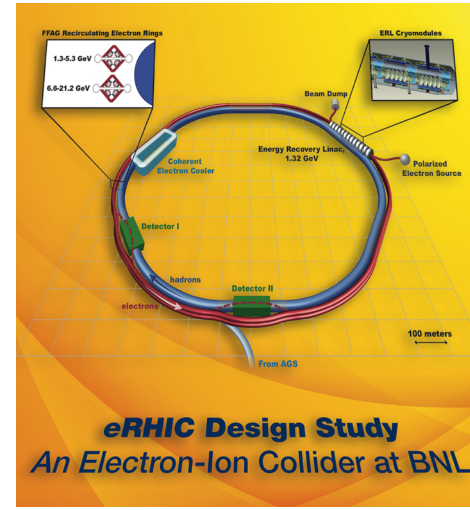
: WEPWI048 S. Belomestnykh, SRF Cavity Design for FFAG-based eRHIC Linac

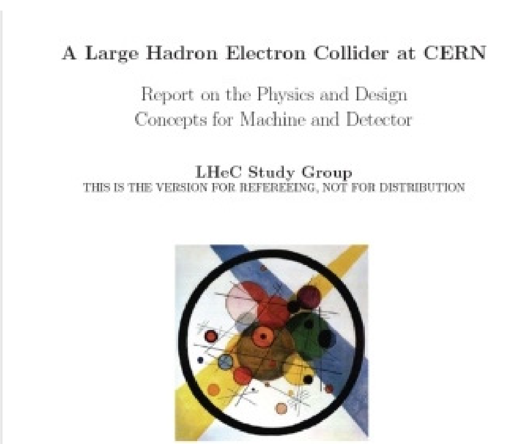
RHIC : WEAB1 V. Litvinenko, Compensating Tune Spread Induced by Space Charge in Bunched Beams
: MOPMN027 Y. Jing, Dynamic Aperture Study for eRHIC Hadron lattice
: TUPWI049, H. Huang, Polarized Proton Beam for eRHIC

Acknowledgement

eRHIC design team:

S. Belomestnykh, I. Ben-Zvi, S. Brooks, C. Brutus, A. Fedotov, D. Gassner, Y. Jing, D. Kayran, V. N. Litvinenko, C. Liu, G. Mahler, G. McIntyre, W. Meng, F. Meot, T. Miller, M. Minty, B.Parker, I. Pinayev, V. Ptitsyn, T. Roser, J. Skaritka, O. Tchoubar, P. Thieberger, D. Trbojevic, N. Tsoupas, J. Tuozzolo, E. Wang, G. Wang, Q. Wu, W. Xu





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Thank you for your attention.