eRHIC

the Planned Electron-Ion Collider at Brookhaven

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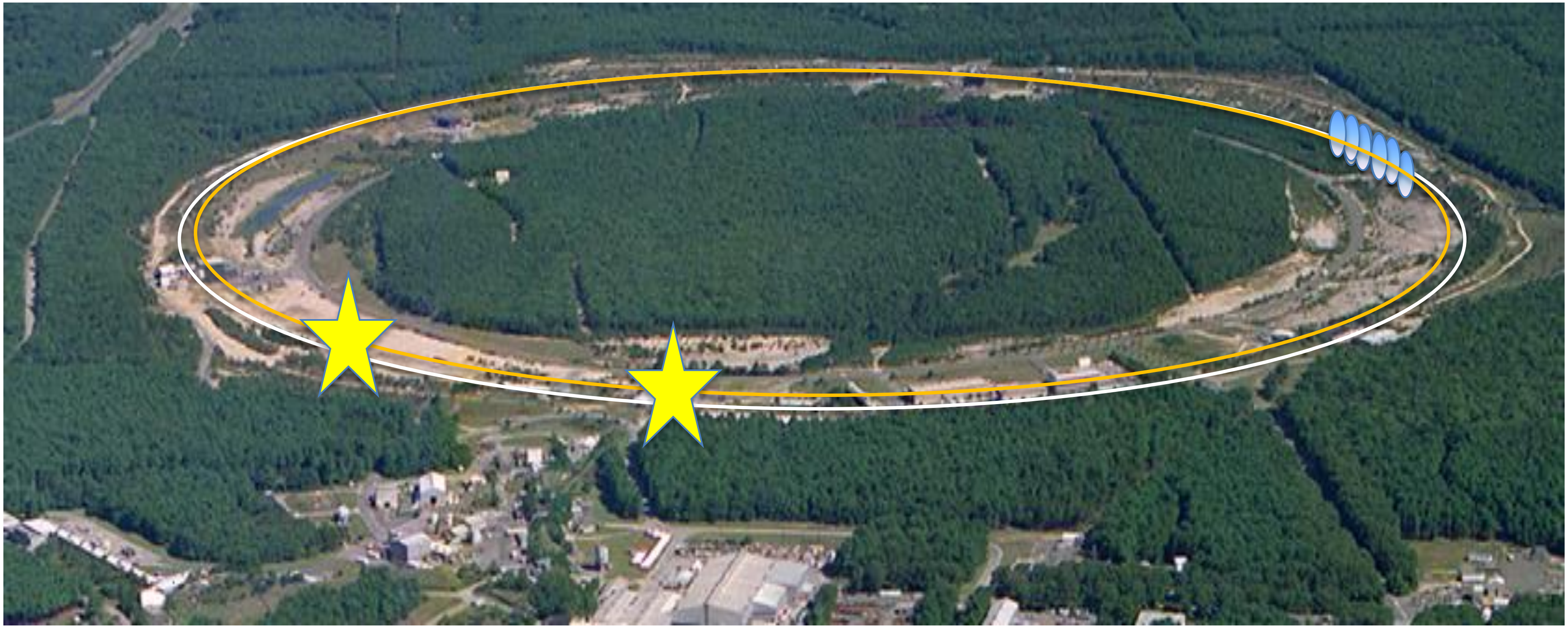


Outline

- Science
- eRHIC Overview
- Electron Source
- Recirculating Energy Recovery LINAC
- FFAG Recirculation Lattice
- Coherent Electron Cooling
- Space Charge Compensation
- Time scale
- Challenges
- Ring-Ring-Solution

Science the Electron Ion Collider

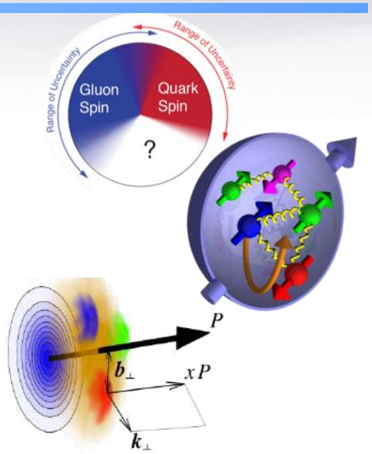
eRHIC will be based on the science results of
RHIC including quark-gluon plasma
and
HERA with particular emphasis on low-x physics, the 3d structure of nucleons and nuclei and the origin of the nucleon spin

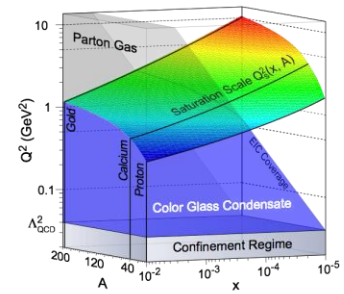
Topics:

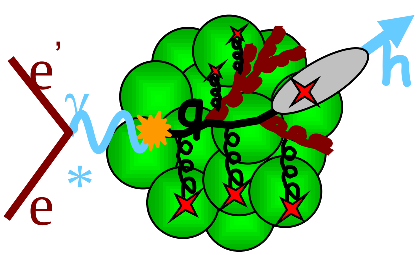
- Clarification of the origin of the proton spin
- How is the spin structure function related to gluon density, confinement
- Approach the regime of saturation of the gluon density for small x (using kinematic advantage of heavy ions compared to protons
- Measuring gluon density at small t (large b) and clarify the role of gluon density distribution for confinement

Questions to be answered by an Electron Ion Collider

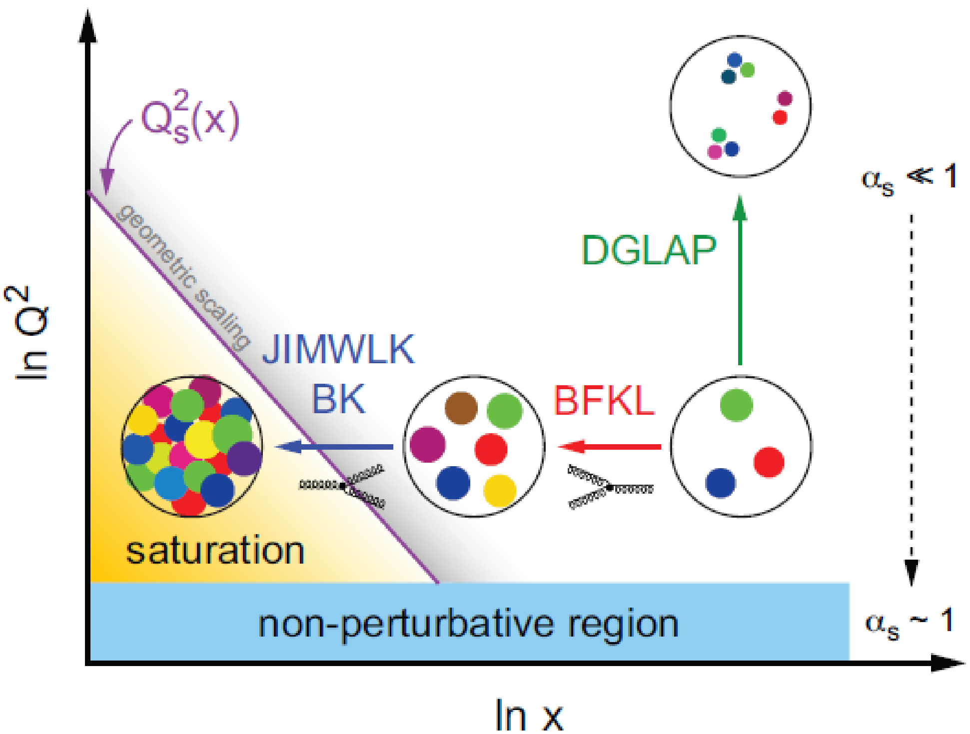
- **How is the spin of the proton constructed by its building blocks**
- **How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?** How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction?
- **What is the role of the orbital motion of sea quarks and gluons in building up the nucleon spin?**
- **Where does the saturation of gluon densities set in?** Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?
- **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?** How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

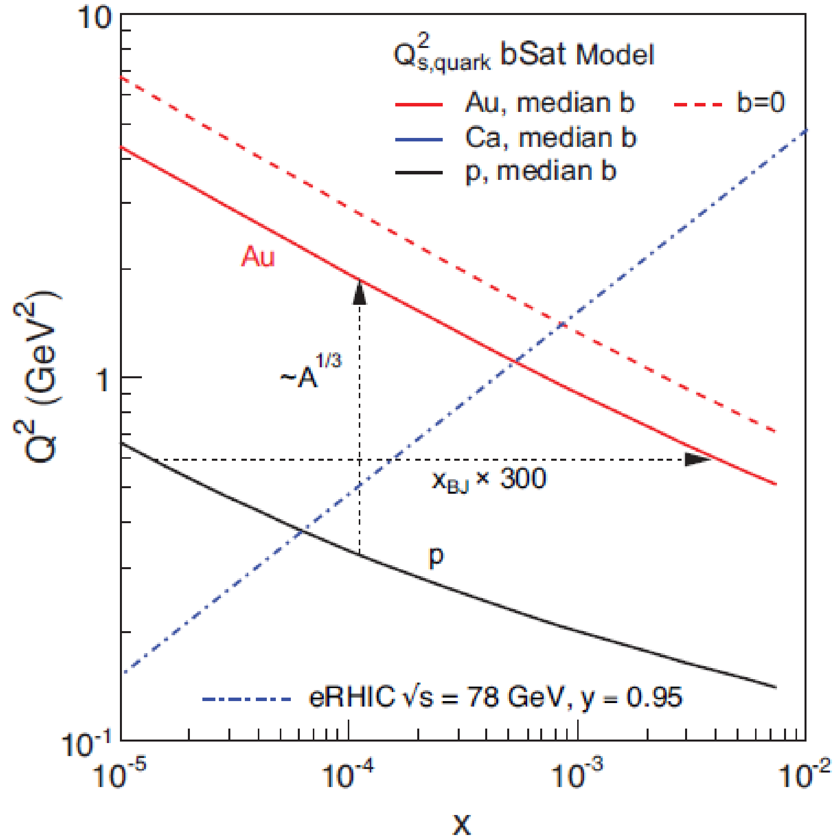






Physics of High Gluon Densities and Low-x in Nuclei





Top Level EIC Requirements

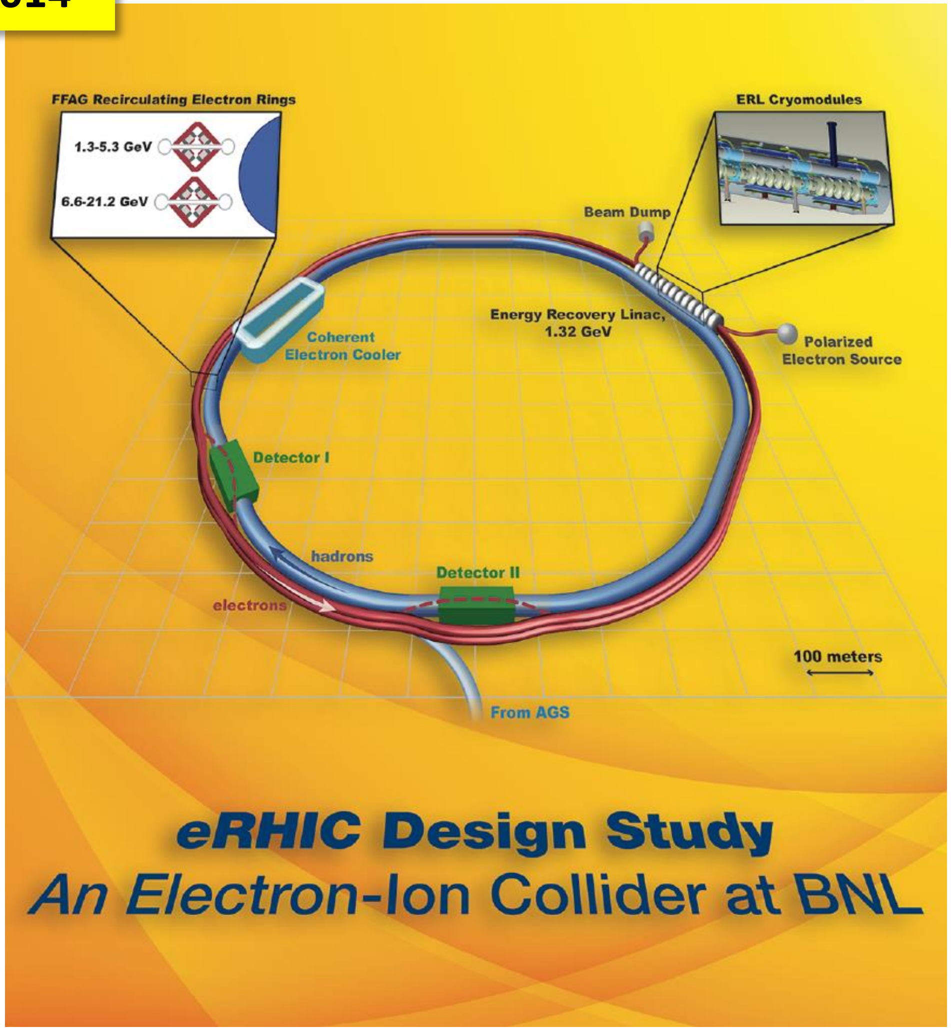
- High Luminosity: $10^{33}cm^{-2}s^{-1} < L < 10^{34}cm^{-2}s^{-1}$
- Average Luminosity ≈ to Peak Luminosity
- High Hadron and Electron Beam Spin Polarization $70\% < P < 80\%$
- Large Detector Acceptance
- Small Hadron Beam Emittance, no Halo for Near Beam Detectors

Electron Ion Collider at BNL

2014

First ideas in 2001, Ilan Ben-Zvi et al

Ben-Zvi, I. Kewisch, J. Murphy and S. Peggs, Accelerator Physics Issues in eRHIC, Nuclear Instruments and Methods in Physics Research **A463**, 94 **(2001)**



eRHIC Team

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Technical Concepts Investigated

- <u>Ring-Ring solution:</u>

Electron Storage Ring in the RHIC tunnel, 10-20 GeV electrons in up to 50 mA collide with Hadron beams in RHIC

Maximum luminosity maximal $10^{33}cm^{-2}s^{-1}$

70% Electron Beam Polarization (Sokolov Ternov)

Not developed since ~2005

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

- <u>ERL Based Solution:</u>

Up to 50mA Electrons accelerated in a multi-turn LINAC to up to 20 GeV collide with RHIC Hadron Beams, then decelerated with energy recovery

80% electron polarization

Luminosity up to several $10^{34}cm^{-2}s^{-1}$

Many different scenarios considered since early 2000's

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

Latest solution based on FFAG lattice (2 rings) for returning beam for acceleration/deceleration up to 32 turns, 1.3GeV 422 MHz superconducting Linac for acceleration/deceleration, 844 MHz system to make up for synchrotron radiation losses,

Advantages and Challenges of ERL based eRHIC w.r.t. Ring Ring solution

Advantage: Luminosity limited by Electron Beam Disruption Effects rather than beam-beam tuneshift, luminosities in the range of 10^{34} s^{-1} cm^{-2} become possible

Advantage: High lepton beam polarization of 80% easier to achieve in a LINAC

Caveat: Need high power CW polarized gun➔ novel Gatlin Gun, short cathode lifetime

Disadvantage: Lepton Beam intensity stronger limited by synchrotron radiation due to multi-turn and over bending in FFAG lattice

Challenge for both Ring-Ring and Ring LINAC

- Need extremely high **incoherent 6-D** damping for the Hadron Beam to achieve small emittance and large Luminosity and near beam detection

➔ Need coherent electron cooling: Brilliant idea but yet to be demonstrated

➔ Space Charge Tune shift of Hadron beam up to 0.4; needs compensation,

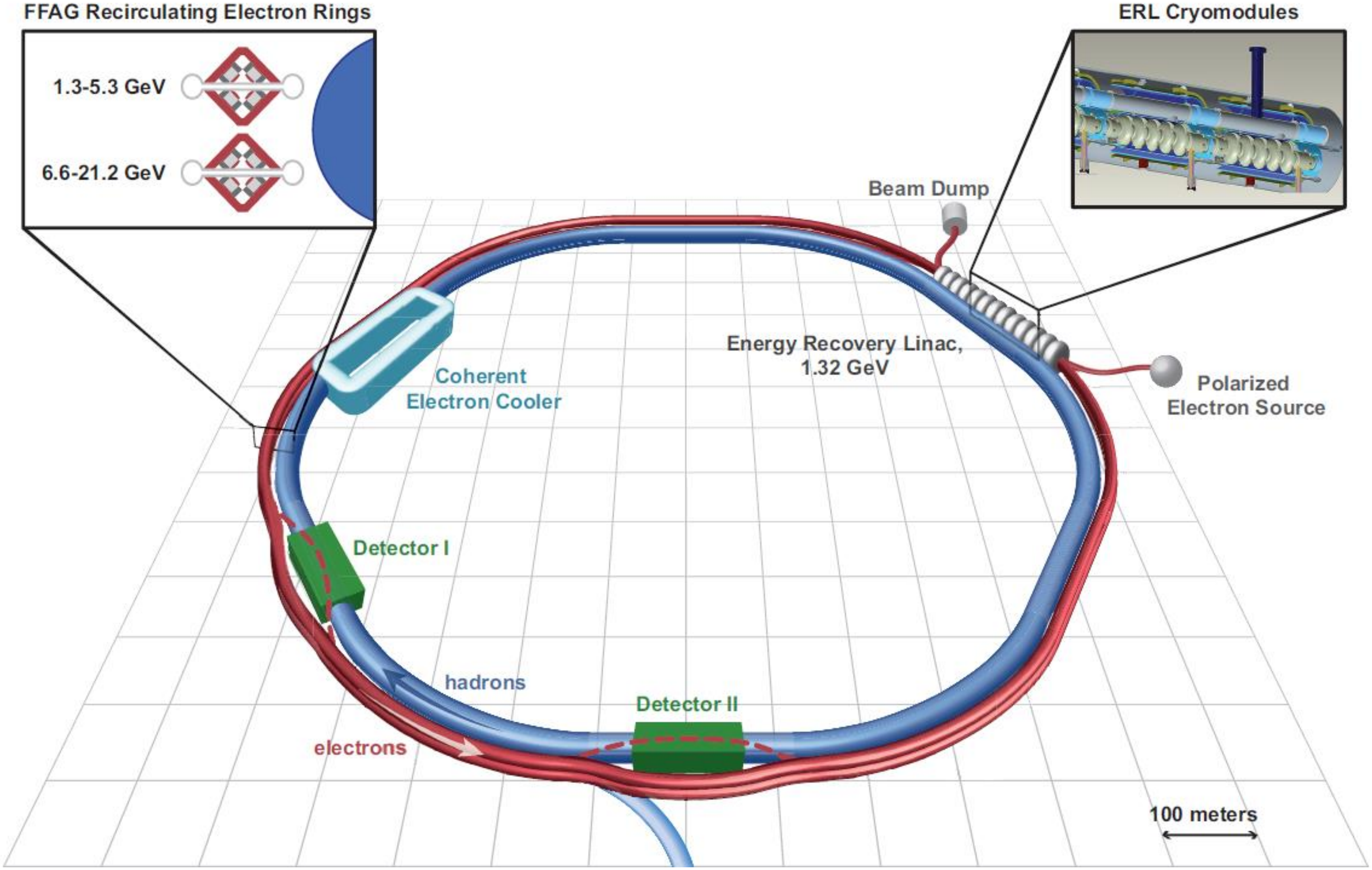
Proposed mitigation: space charge compensation by collinear electron beam in straights

issues with nonlinear resonances and dynamic aperture

- IR layout with large **crossing angle** (10mrad) requires crab cavities for both beams

➔ CRITICAL DESIGN GOALS APPEAR TO BE MORE LIKELY ACHIEVABLE WITH LINAC-RING

Overview eRHIC LINAC RING COLLIDER



Features and Challenges ERL based EIC

- Polarized Electron Source
- FFAG recirculation pass for ERL (up to 16 acceleration turns)
- Energy losses and energy spread
- Multi-pass-ERL: BBU, Ion trapping, fast ion instability
- Ring-Linac-high luminosity collision scheme, beam-beam effects, Advanced hadron cooling
- Large acceptance Low-beta interaction region, crossing angle, Crab-Crossing
- Design and dynamic aperture optimization for Hadrons

Luminosity

$$L = f_c \gamma_h \xi_h \frac{Z N_h}{\beta^* r_h} H_{hg} H_p$$

<u>Limitations:</u>

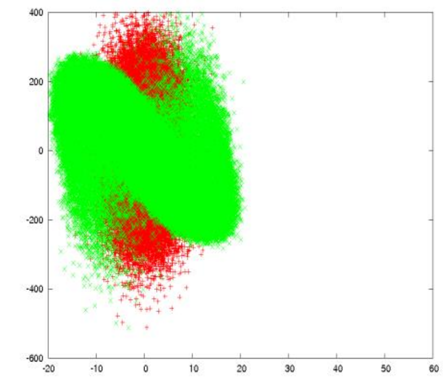
- Polarized Electron Average current 50mA
- Minimum β^* of 5cm (electrons, hadrons)
- Hadron Space charge tune-shift < 0.08
- Electron Beam Synchrotron Radiation power < 3 MW

<u>Note</u>: *Limits are not achieved simultaneously*

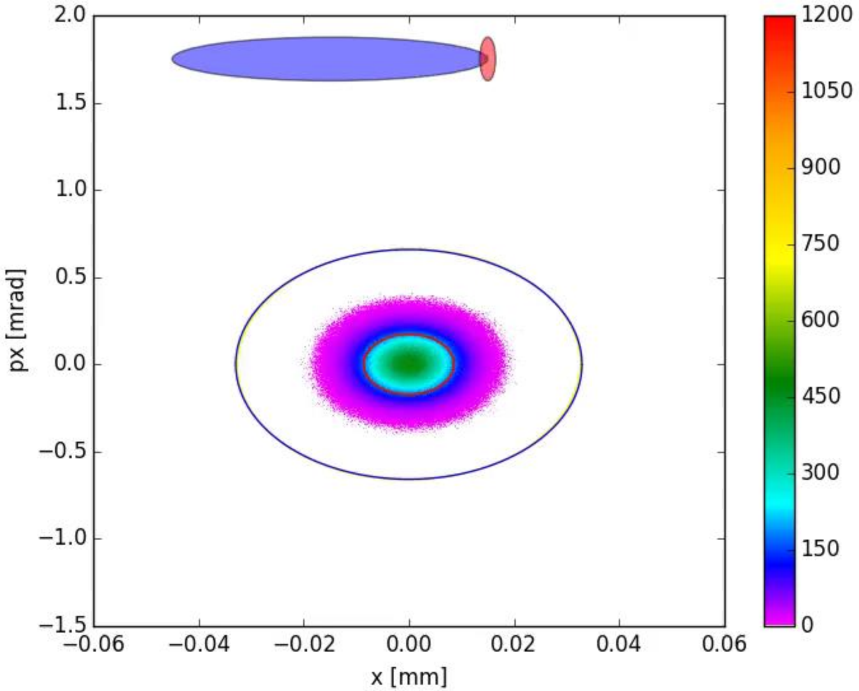
Note: e beam disruption is not considered a limitation

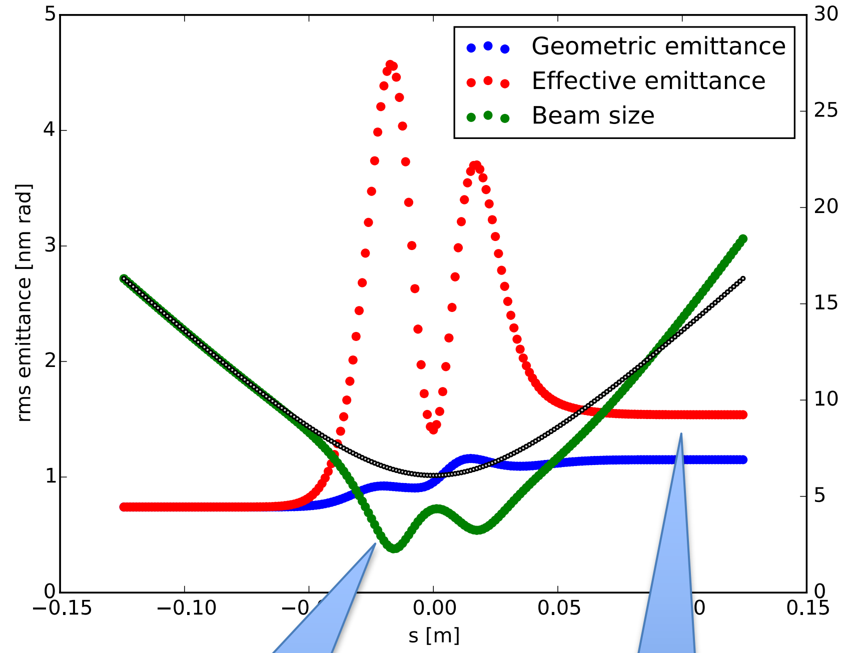
disruption parameter $D_{x,y} = \sigma_z / f_{x,y}$, where $f_{x,y}$ is the focal length

$$D_x = \frac{2 N r_e \sigma_z}{\gamma \sigma_x (\sigma_x + \sigma_y)} \qquad D_y = \frac{2 N r_e \sigma_z}{\gamma \sigma_y (\sigma_x + \sigma_y)}$$



Beam-Beam Effect, Electron Disruption





Curtesy Yuan Hao

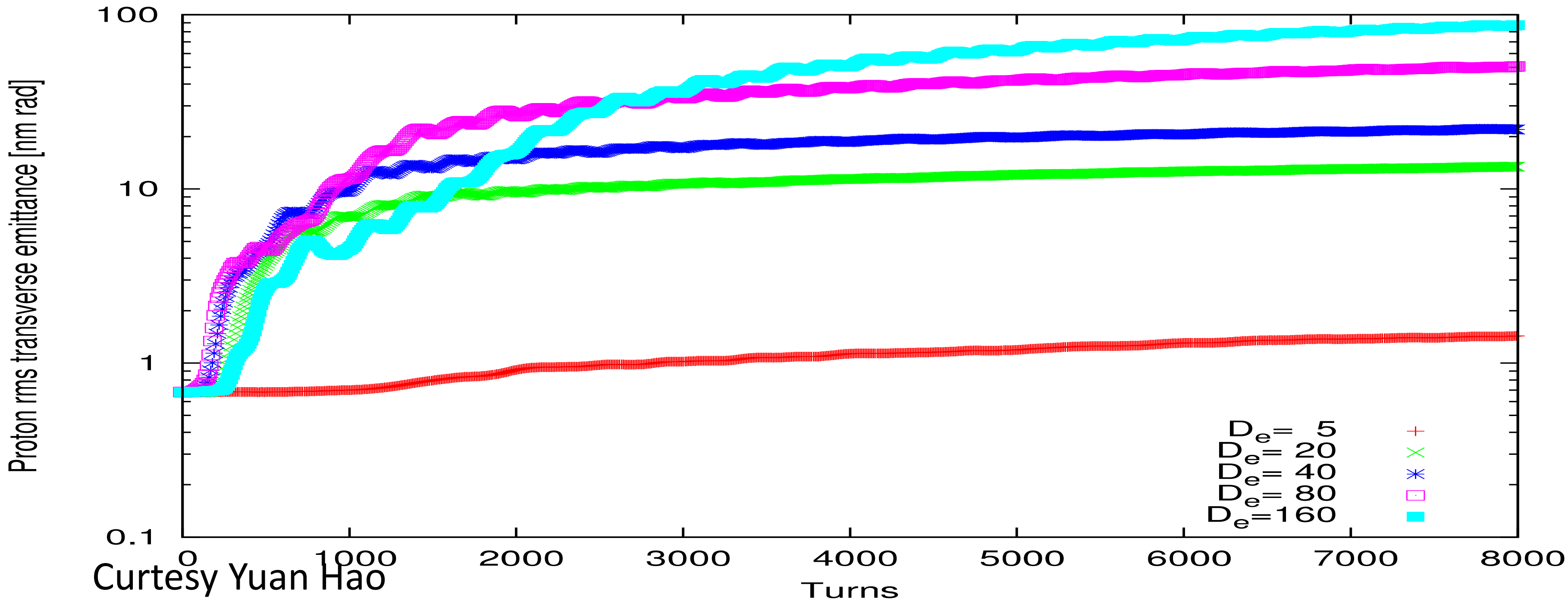
Pinch effect
L=3.3E33➔
L=4.9E33

Mismatch
and
disruption

Beam-Beam Effect: Kink Instability

Kink Instability:
Coherent equivalent of the incoherent disruption.
Initial offsets before collisions grow unstably during interaction with
Which causes emittance growth of the Ion beam.

Kink instability suppression, with disruption parameter 36, requires a pickup-kicker feedback system. Simulation shows the required bandwidth is 50-300 MHz



Curtesy Yuan Hao

e-p Parameter Table

Parameters	eRHIC	
	e	p
Energy (GeV)	15.9	250
Bunch spacing (ns)	106	
Intensity, 10^{11}	0.07	3.0
Current (mA)	10	415
rms norm. emit. (mm-mrad)	23	0.2
$\beta_{x/y}^*$ (cm)	5	5
rms bunch length (cm)	0.4	5
IP rms spot size (μ m)	6.1	
Beam-beam parameter		0.004
Disruption parameter	36	
Polarization, %	80	70
Luminosity, $10^{33}cm^{-2}s^{-1}$	4.9	

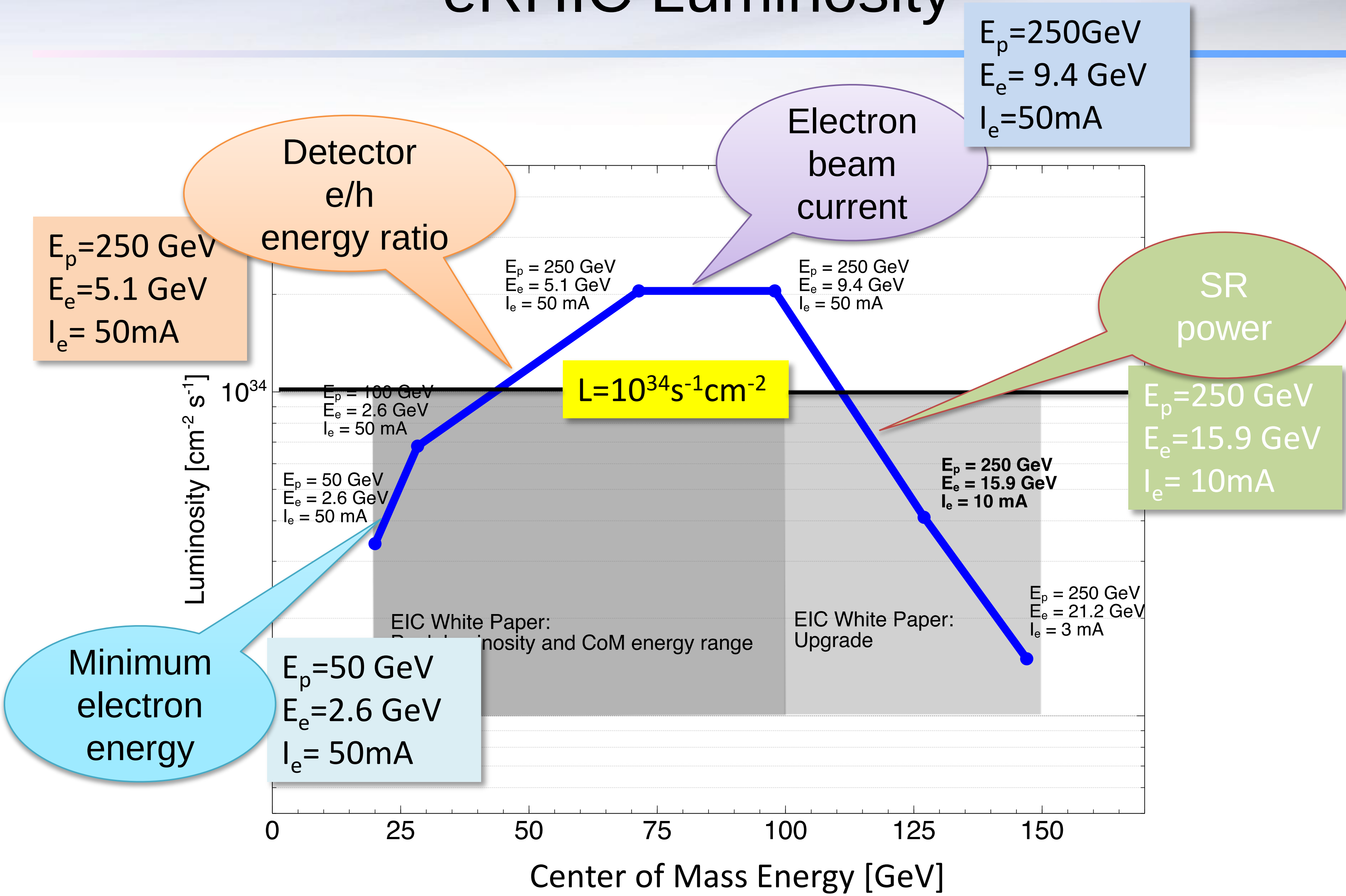
eRHIC Parameters

A final parameter list has not yet been established. This is an example of a consistent set

	e	p	$^{2}He^{3}$	$^{79}Au^{197}$	$^{92}U^{238}$
Energy, GeV	20 (30)	325	215	130	130
CM energy, GeV		161	131	102	102
		(197)	(161)	(125)	(125)
Number of bunches/distance between bunches	74 nsec	166	166	166	166
Bunch intensity (nucleons) ,10^{11}	0.24 (.05)	2	3	5	5
Bunch charge, nC	3.8 (0.4)	32	32	32	32
Beam current, mA	50 (10)	420	420	420	420
Normalized emittance of hadrons , 95% , mm mrad		1.2	1.2	1.2	1.2
Normalized emittance of electrons, rms, mm mrad		23 (34)	35 (52)	57 (85)	57 (85)
Polarization, %	80	70	70	none	none
rms bunch length, cm	0.2	4.9	4.9	4.9	4.9
β*, cm	5	5	5	5	5
Luminosity per nucleon, $cm^{-2}s^{-1}$	1.46×10^{34} (0.29×10^{34})				

V. Litvinenko

eRHIC Luminosity

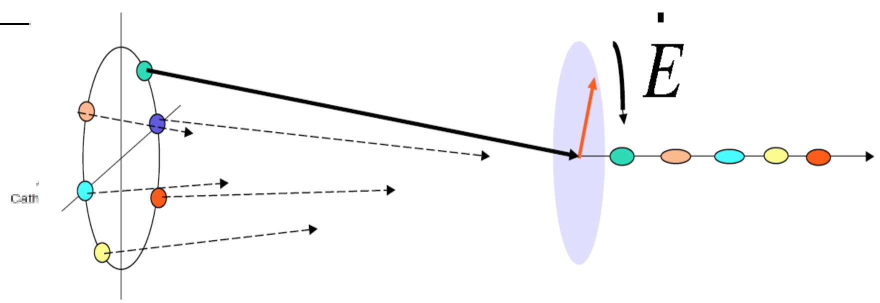


Electron Source

High Average Current (up to 50mA), high repetition rate (10 MHz) photo injector

- eRHIC uses CW electron current. 9.4 MHz bunch repetition rate
- Design average current:
  - Up to 10 GeV: 50 mA
  - Above 10 GeV: scaling down: 10 mA at 15.9 GeV, 3.5 mA at 21.2 GeV
- Polarized electron source: photoemission, very dedicated cathode technology (strained GaAs, superlattice mutlilayer cathode, up to 90% polarization; QE up to 1%, 780-850 nm laser)
  - Limiting factor: cathode lifetime (ion bombardment; 10^{-12} Torr vacuum required)
- Present state-of-the-art: JLab polarized source
  - CEBAF operation: 100-200 μA
  - Source studies: few mA demonstrated

eRHIC: multi-cathode Gatling gun (20 cathodes, up to 2.5 mA from each cathode)



Multi-Cathode Source

Properties:

- high-current polarized electron gun up to 50 mA average current
- More than 80% electron spin polarization

Main Issue: Short cathode lifetime due to high average current

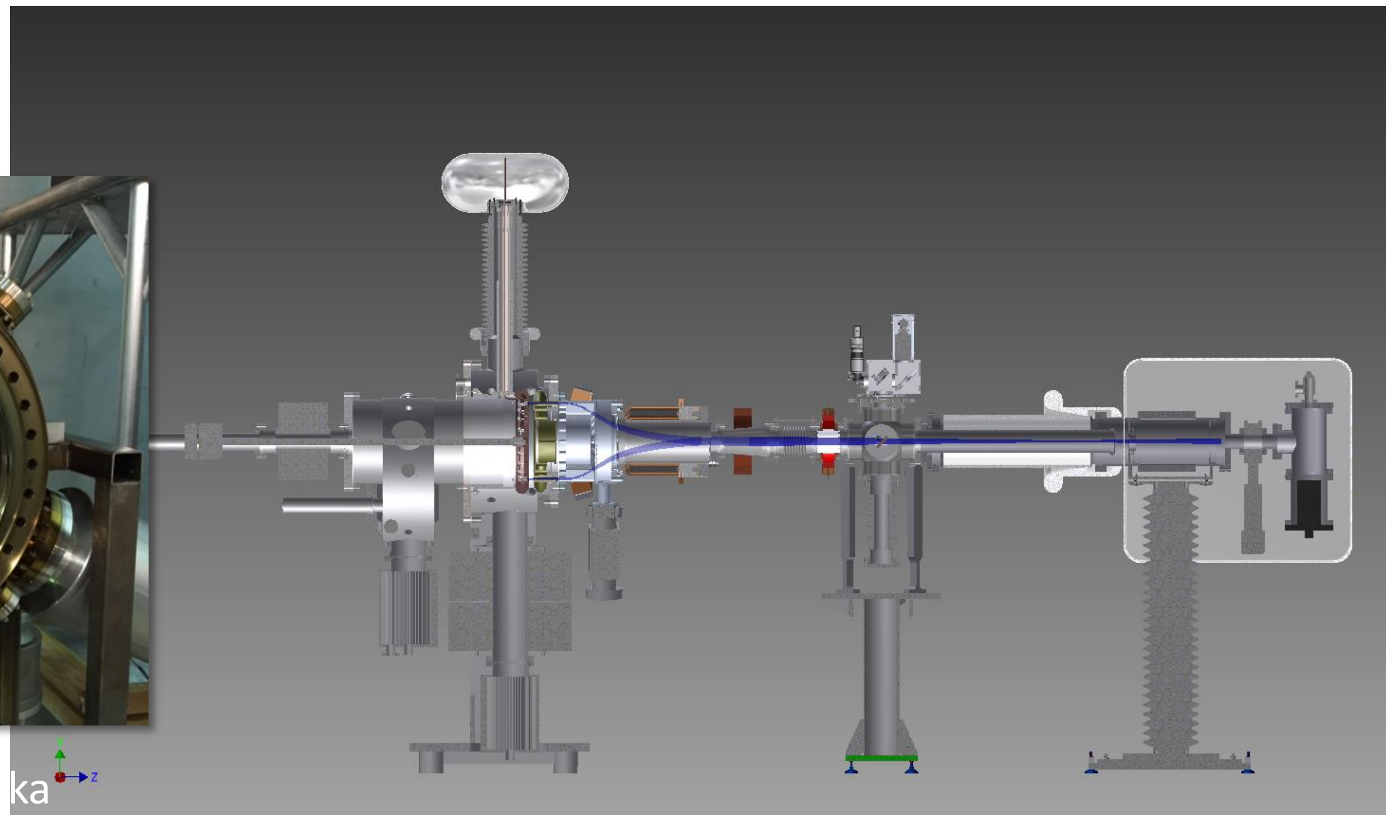
Solution: Multiple Photo Cathode Gun with Funneling beams

Expected Results:

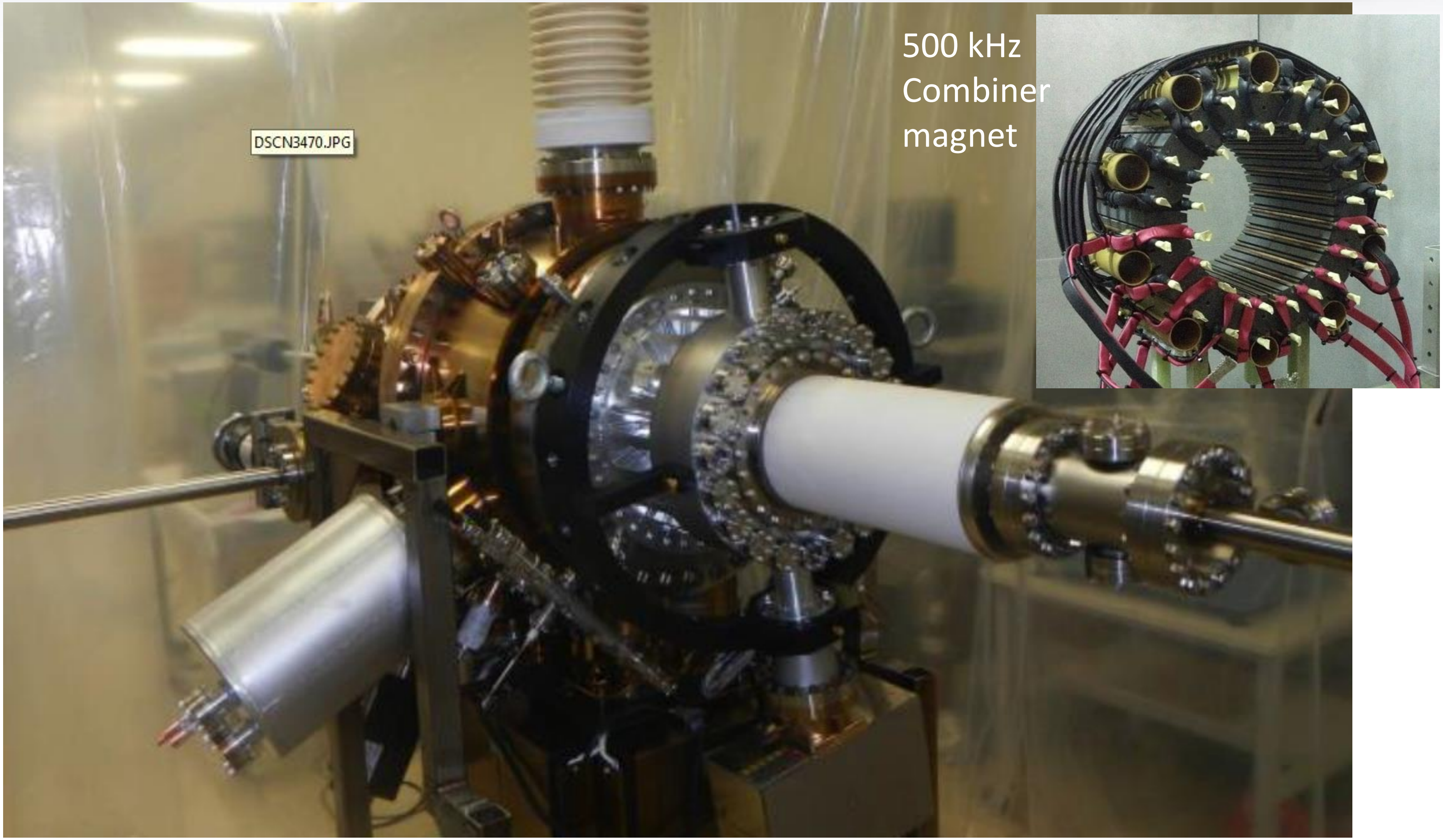
- High Bunch charge: 5.3 nC at 450KHz
- State of the art charge lifetime = 1000 C @ 2.5mA
- 50 mA distributed over 20 cathodes ➔ 765 C Charge lifetime needed ! Two guns needed
- For high energy eRHIC operation 10 mA distributed over 20 cathodes = 0.5mA per cathode for one week = 153 C Charge lifetime needed ! One gun needed for one week turn over
- Lower current will extend two gun use up to 17 days and easily allows cathode exchange within a 14 day maintenance window.
- High polarization: Obtained by using novel structures of GaAs photocathodes
- GaAs: Established and widely used source of polarized electrons
- Super lattice GaAs: More than 80% polarization.

Status of the R&D

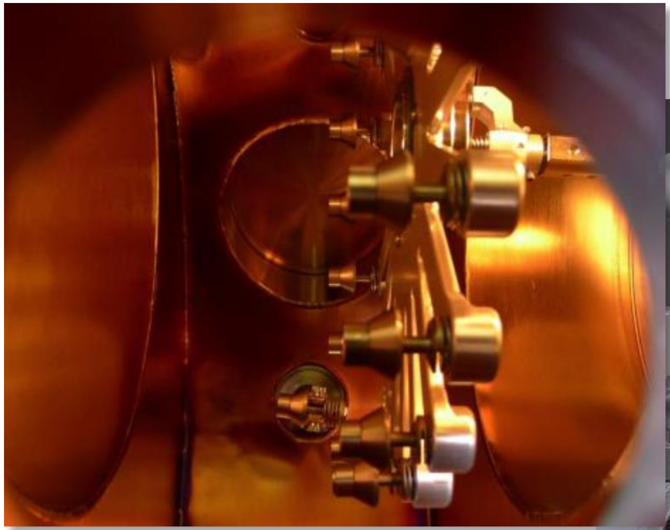
- Cathode development based on work at JLAB and MIT
- Prototype Gatling Gun has been built at Stangenes Industries
- Test with two cathodes successful, 150 C life expectations in reach
- Final assembly in Stonybrook University in progress

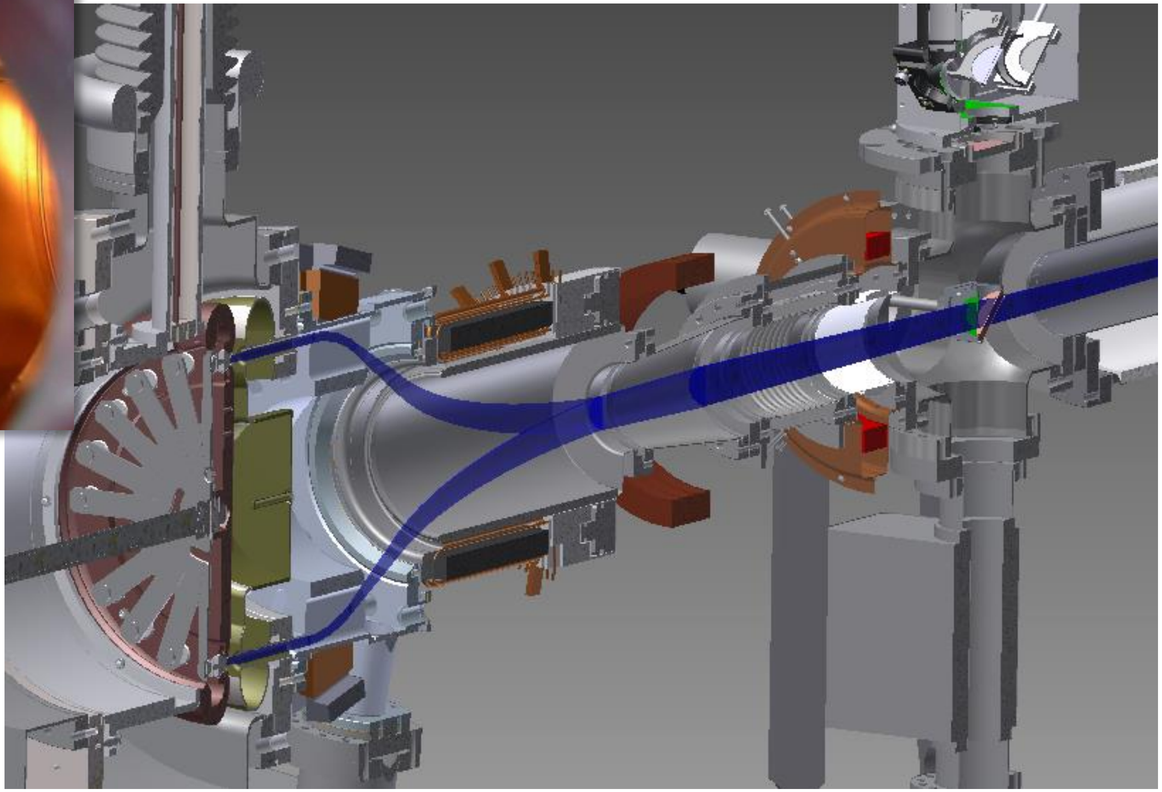


Gatlin Gun Prototype



Multiple Cathods



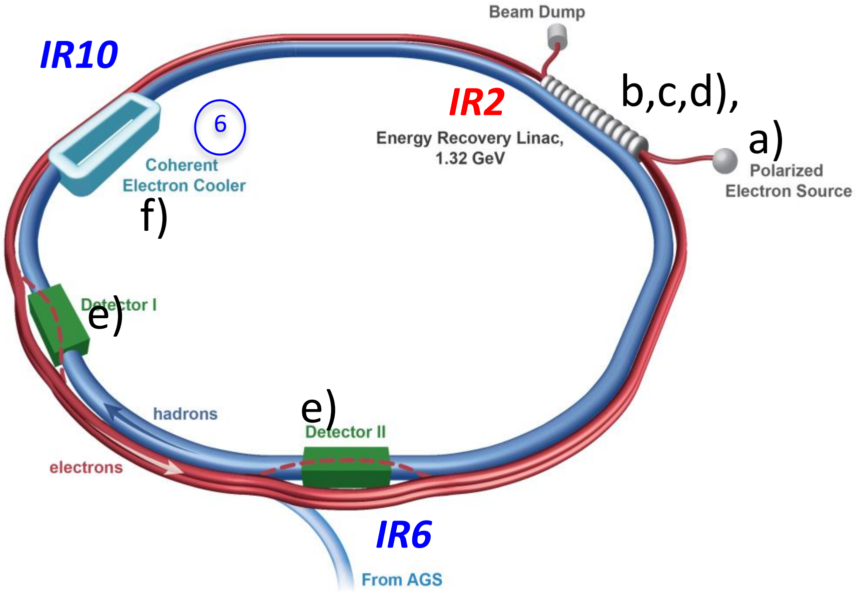


eRHIC Superconducting RF Systems

a) **12MeV Injector,** 84.5 MHz & 253 MHz quarter wavelength bunchers, 3-cell 422MHz booster cavity

b) **Main Linac** 1.322 GeV, 422MHz, up to 32 passes, 42 5-cell cavities @18.5MV/m

c) **Energy loss replacement:** 844 MHz 6 2-cell cavities, 2.4MW
d) **5th harmonic RF**, 2.1GHz 8 5-cell cavities 18.7 MV/m energy spread compensation
e) **Crab cavities** hadrons 225MHz, electrons 676 MHz
Hadron system with Including 2nd and 3rd harm for linearization (4+2+1 cavities
f) **ERL for CeC**
84.5MHz QWR gun 26 QWR cavities 84.5 +9 QWR @ 253MHz

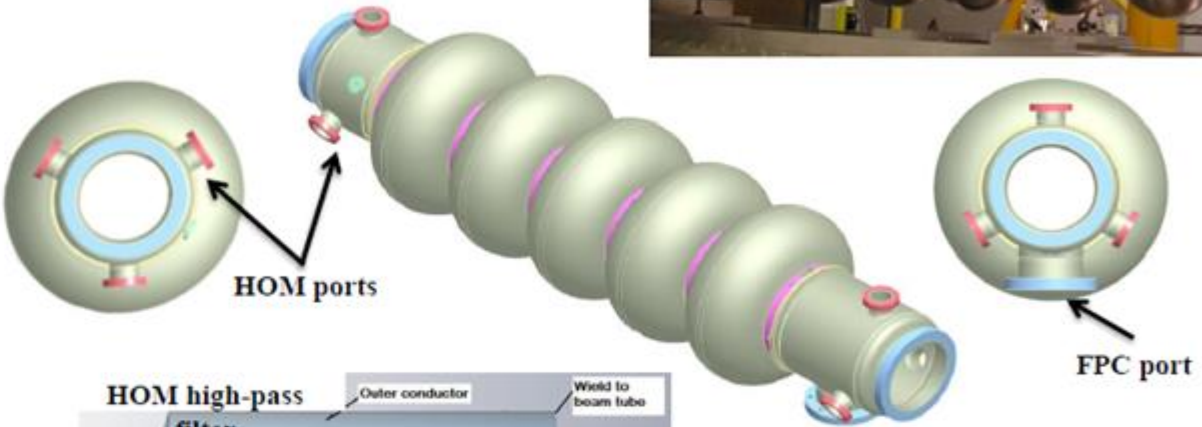


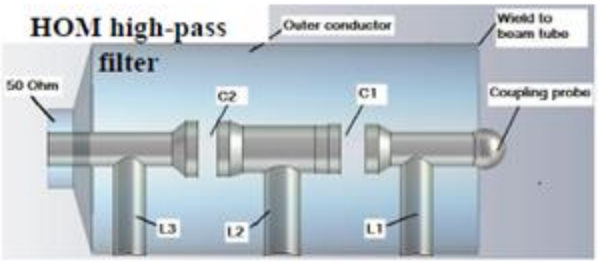
Main LINAC Parameters

Energy gain	1.32 GeV
Bunch length	4 mm rms
Bunch repetition frequency	9.38 MHz
Number of RF buckets per RHIC revolution	120
Number of RF buckets filled	111
RF frequency	422.3 MHz
Number of SRF cavities	42
Linac fill factor	0.60
Cavity type	elliptical, 5-cell
Accelerating gradient	18.4 MV/m
Operating temperature	1.9 K
Cavity intrinsic Q factor at operating gradient	$5 \cdot 10^{10}$
Peak resonant frequency detuning due to microphonic noise	6 Hz
Q_{ext} of FPC	$3.5 \cdot 10^{7}$
Peak RF power per cavity	30 kW
Total heat load at 1.9 K	2 kW
Maximum HOM power per cavity	7.8 kW

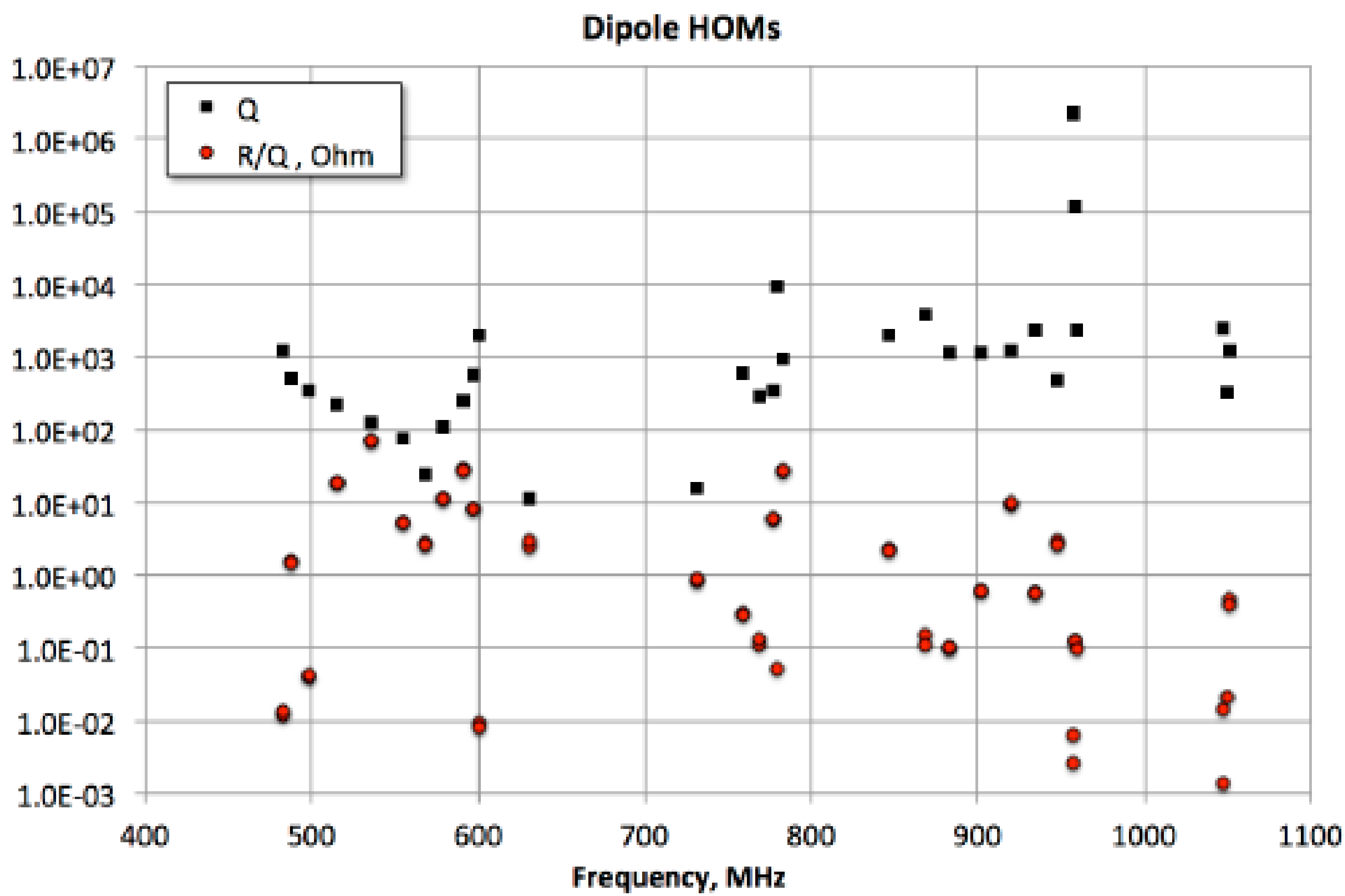
Main ERL Superconducting RF

- The main SRF linac will utilize five-cell 422 MHz cavities, scaled versions of the BNL3 704 MHz cavity developed for high current linac applications.
- Stability considerations require cavities with highly damped HOMs.

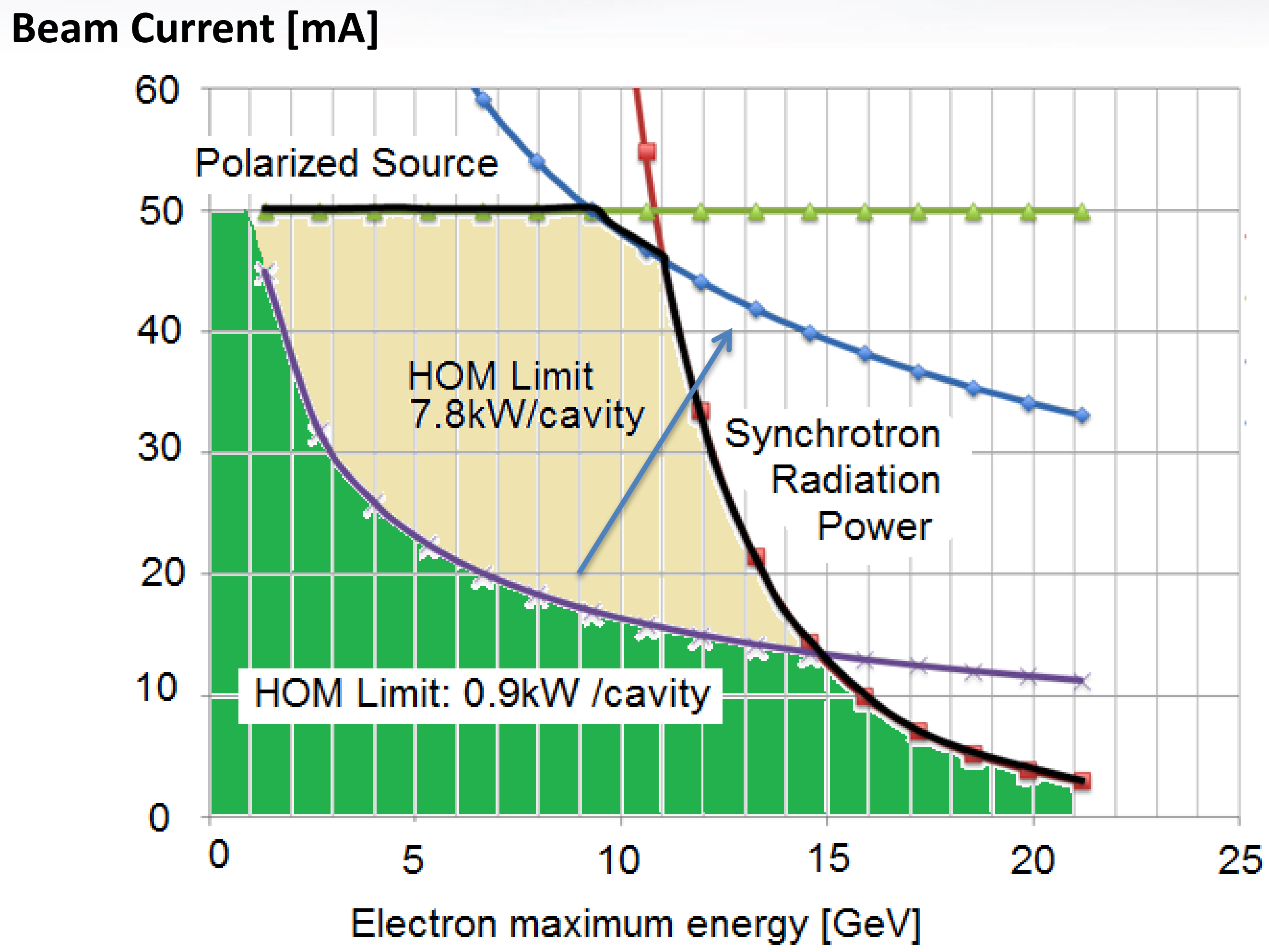




Scaled HOMs from 703 MHz Cavity



Electron Beam Current Limitation



R&D for Waveguide based HOM couplers for 7.8kW/cavity in progress

Furthermore HOM frequency spread considered to mitigate BBU

HOM Power and BBU Mitigation: 422 MHz

Large HOM power main challenge for eRHIC SC ERL RF Design

- 7.8 KW per cavity, for 50 mA, 8-pass ERL
- HOM power coupler: wave guide approach
- Some effort is aiming on beam-pipe damping of the higher frequency HOM power

RF Frequency Optimization

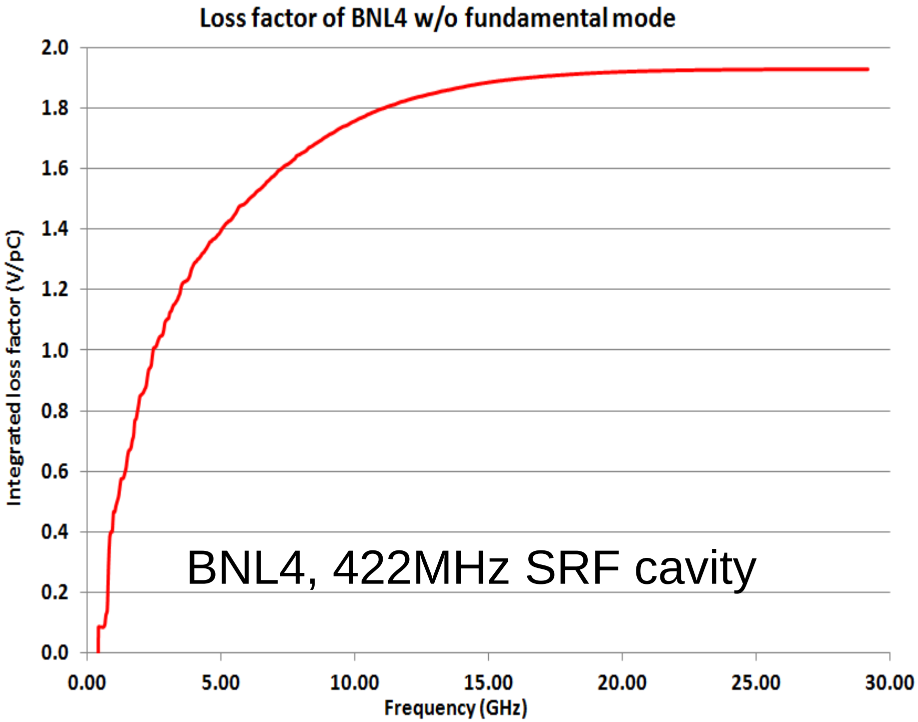
<u>Higher Frequency</u>

- higher gradient, less construction cost

Lower frequency

- less BBU
- longer bunch, less loss fact
- less RF loss

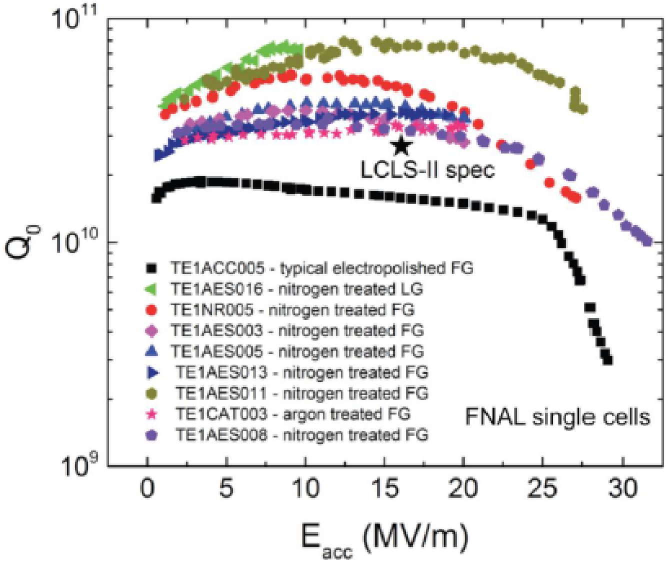
➔ **After several iterations: 422 MHz**

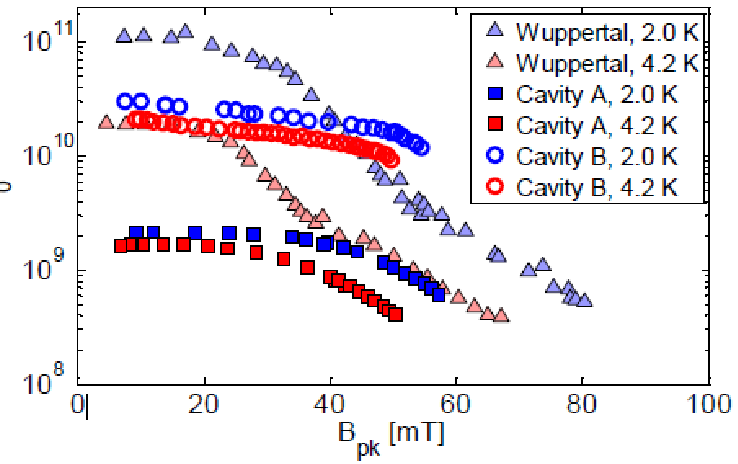


4.2 K main ERL LINAC Operation

R&D underway at several laboratories to operate at 4.2K

- 4.2K operation instead of 2K through improvements in SRF surface properties of cavities.
- Potential saving in refrigeration system of 24 M$ as well as a reduction in operating cost.
- Two recent advances in SRF make this possible:
  - Nitrogen doping
  - Nb_3Sn surface
- Work done only at 1.3 GHz so far
- We plan to test these approaches at 422 MHz. We will seek collaboration with other laboratories.





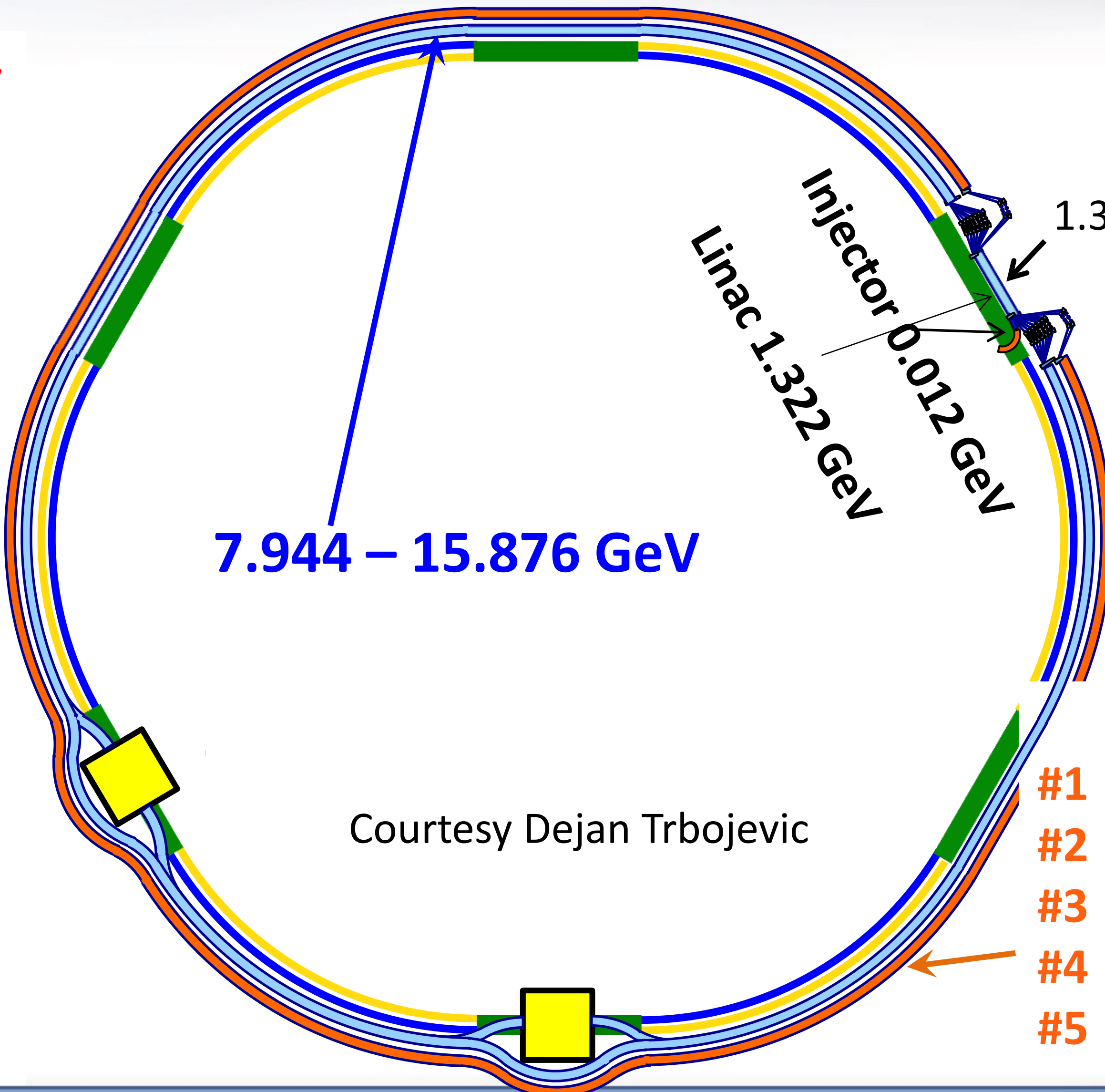
eRHIC FFAG Lattice Design Study

Parameter	Low-Energy FFAG	High-Energy FFAG
Energy range 5 x in energy	1.334 – 6.622 GeV	7.944 – 21.164 GeV
Energy ratio	4.96×	2.66×
Turns (1.322GeV linac)	5	11
Synchrotron power	0.26MW @ 50mA	9.8MW @ 21.2 GeV, 18mA 10.2MW @ 15.9 GeV, 50mA
TOF range (path length range over whole turn)	54.7ppm (12cm)	22.4ppm (5cm)
Drift space	28.8cm	28.8cm
Tune range	0.036 – 0.424	0.035 – 0.369
Orbit range (quad aperture)	31.3mm (r_{max} = 23.6mm)	12.6mm (r_{max} = 9.1mm)
Max |B| on orbit	0.227 T	0.451 T
Max quad strength	9.986 T/m	49.515 T/m

Courtesy Dejan Trbojevic

NS-FFAG Layout of the eRHIC

Option #2 Energy
10 mA
Linac 1.322 GeV
#1 7.944 GeV
#2 9.266 GeV
#3 10.588 GeV
#4 11.910 GeV
#5 13.232 GeV
#6 14.554 GeV
#7 15.876 GeV
#8 17.198 GeV
#9 18.520 GeV
#10 19.842 GeV
#11 21.164 GeV

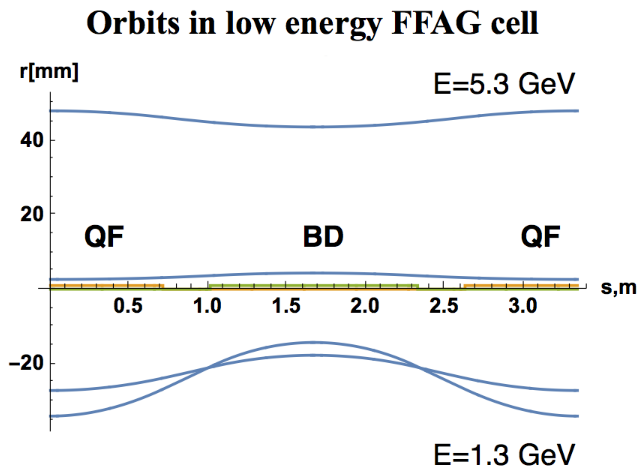


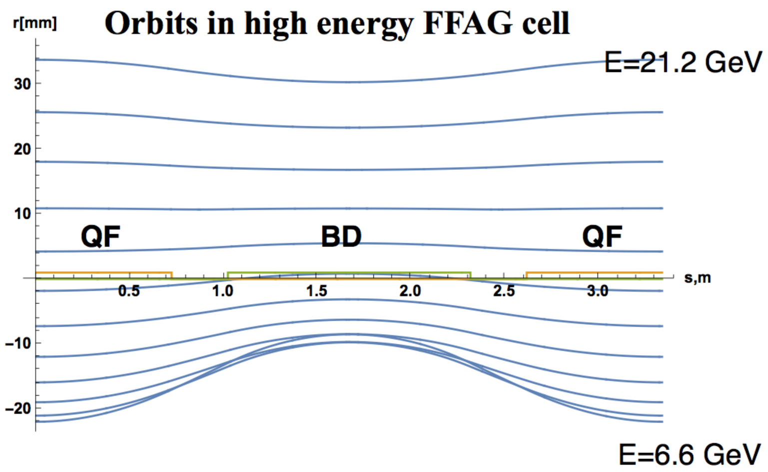
Energy
#1 1.334 GeV
#2 2.565 GeV
#3 3.978 GeV
#4 5.300 GeV
#5 6.622 GeV

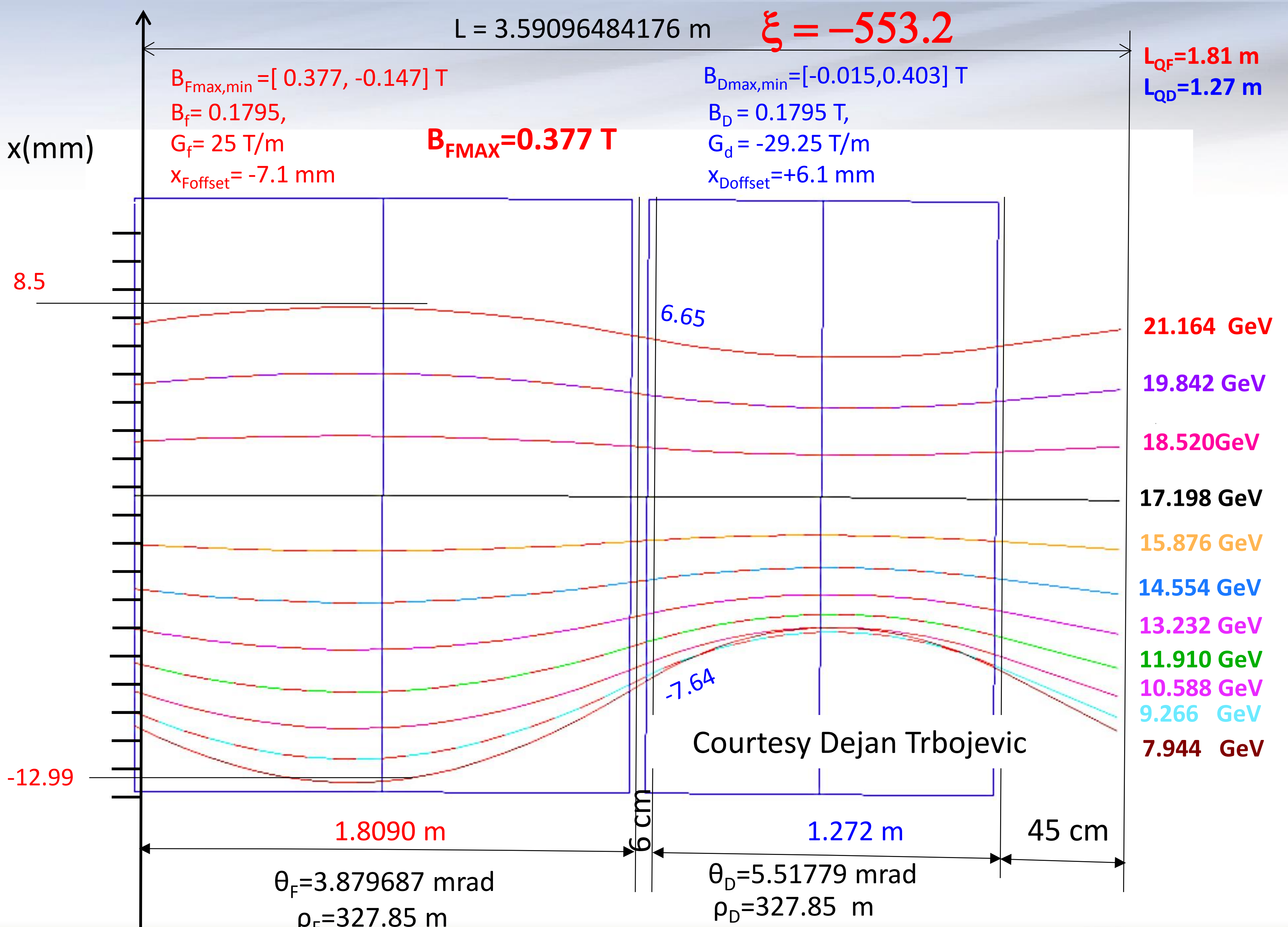
Linear FFAG Approach for eRHIC

- Linear Fixed Field Alternating Gradient approach is used for eRHIC recirculation passes to transport beams of large energy range in a same beamline.
- eRHIC FFAG cell is comprised of two quadrupoles (QF & BD) whose magnetic axes are shifted horizontally with respect to each other by an offset Δ . It is *strongly focusing, bent FODO cell.*
- Orbit and optics dependence on the energy can be accurately found in paraxial approximation
- eRHIC utilizes two FFAG beamlines stacked vertically

Courtesy Dejan Trbojevic

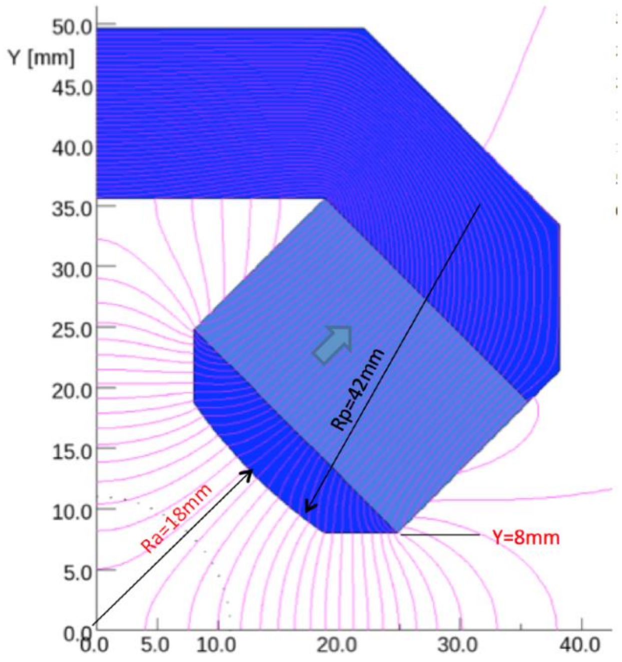


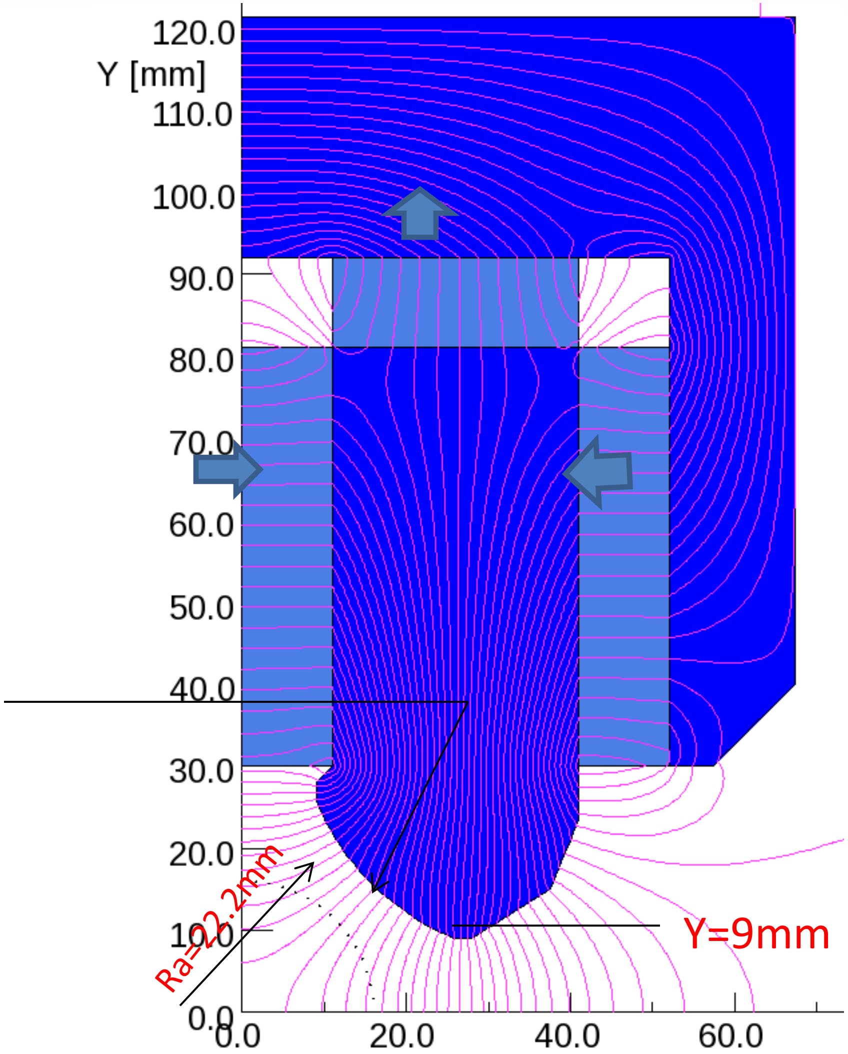




L = 3.59096484176 m
ξ = −553.2
L_QF=1.81 m
L_QD=1.27 m
B_Fmax,min =[0.377, -0.147] T
B_f= 0.1795,
G_f= 25 T/m
x_Foffset= -7.1 mm
B_FMAX=0.377 T
B_Dmax,min=[-0.015,0.403] T
B_D = 0.1795 T,
G_d = -29.25 T/m
x_Doffset=+6.1 mm
x(mm)
8.5
6.65
-7.64
-12.99
21.164 GeV
19.842 GeV
18.520GeV
17.198 GeV
15.876 GeV
14.554 GeV
13.232 GeV
11.910 GeV
10.588 GeV
9.266 GeV
7.944 GeV
Courtesy Dejan Trbojevic
1.8090 m
6 cm
1.272 m
45 cm
θ_F=3.879687 mrad
ρ_F=327.85 m
θ_D=5.51779 mrad
ρ_D=327.85 m

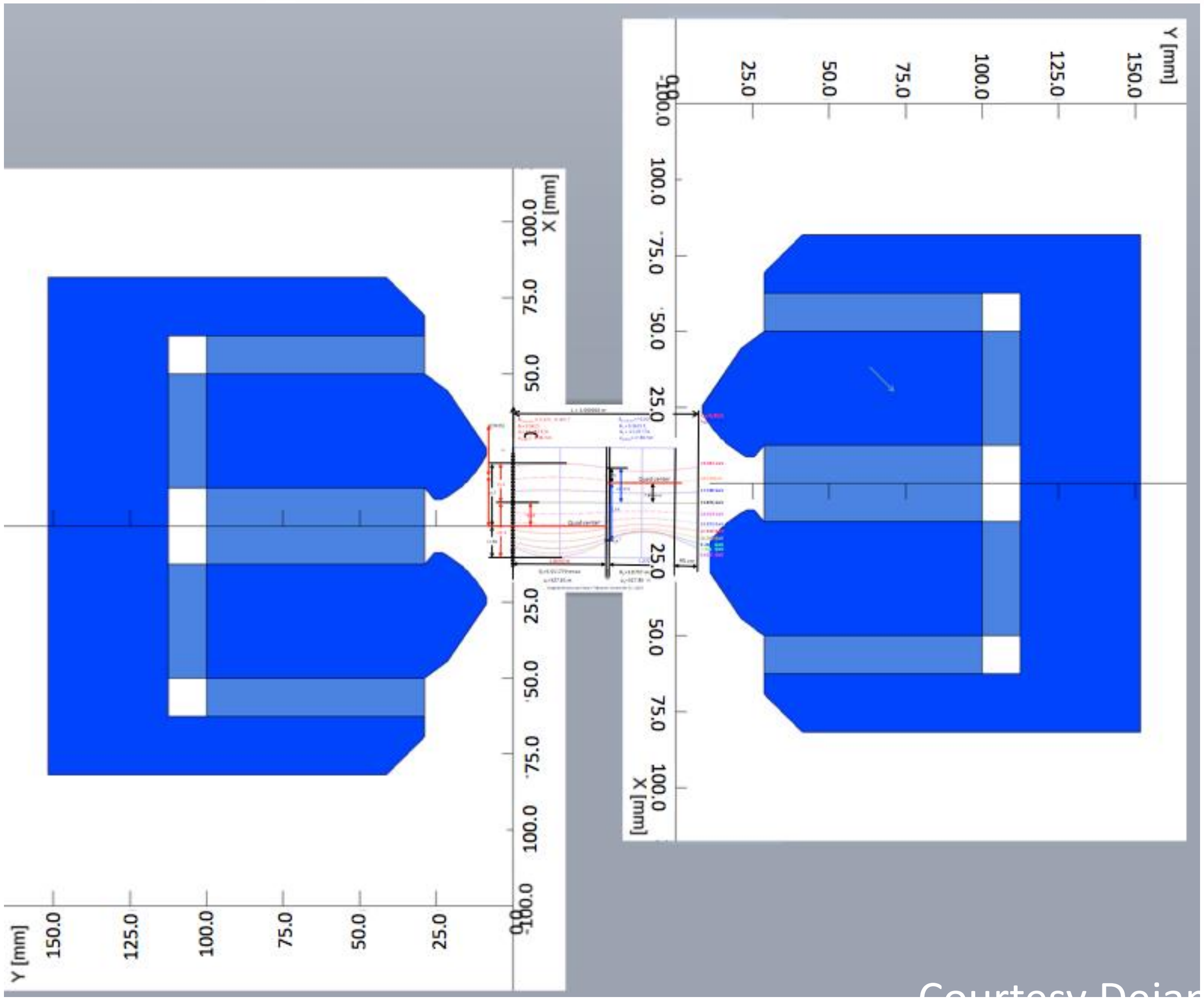
Magnet for the Lattice





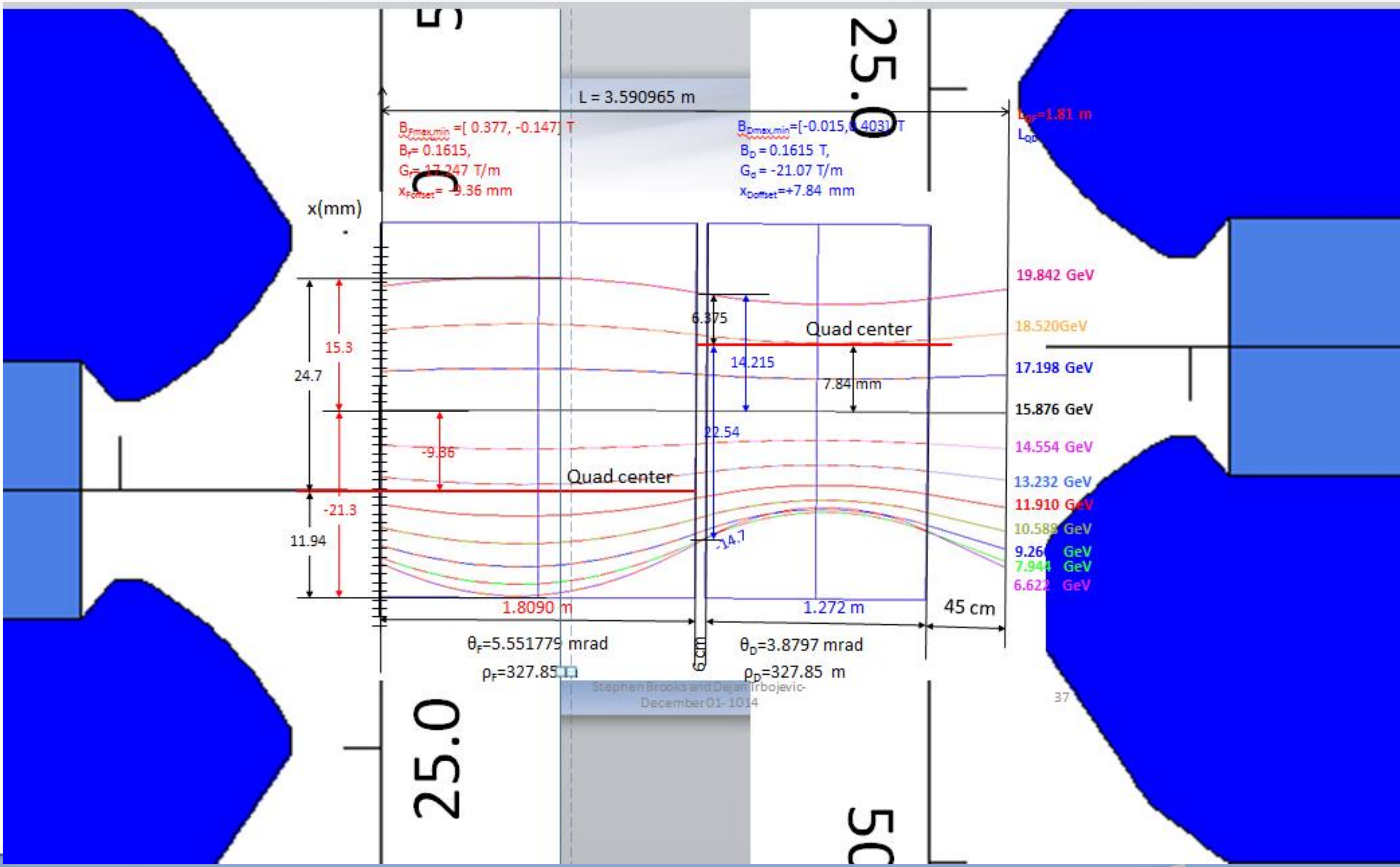
Courtesy Dejan Trbojevic

High Energy FFAG

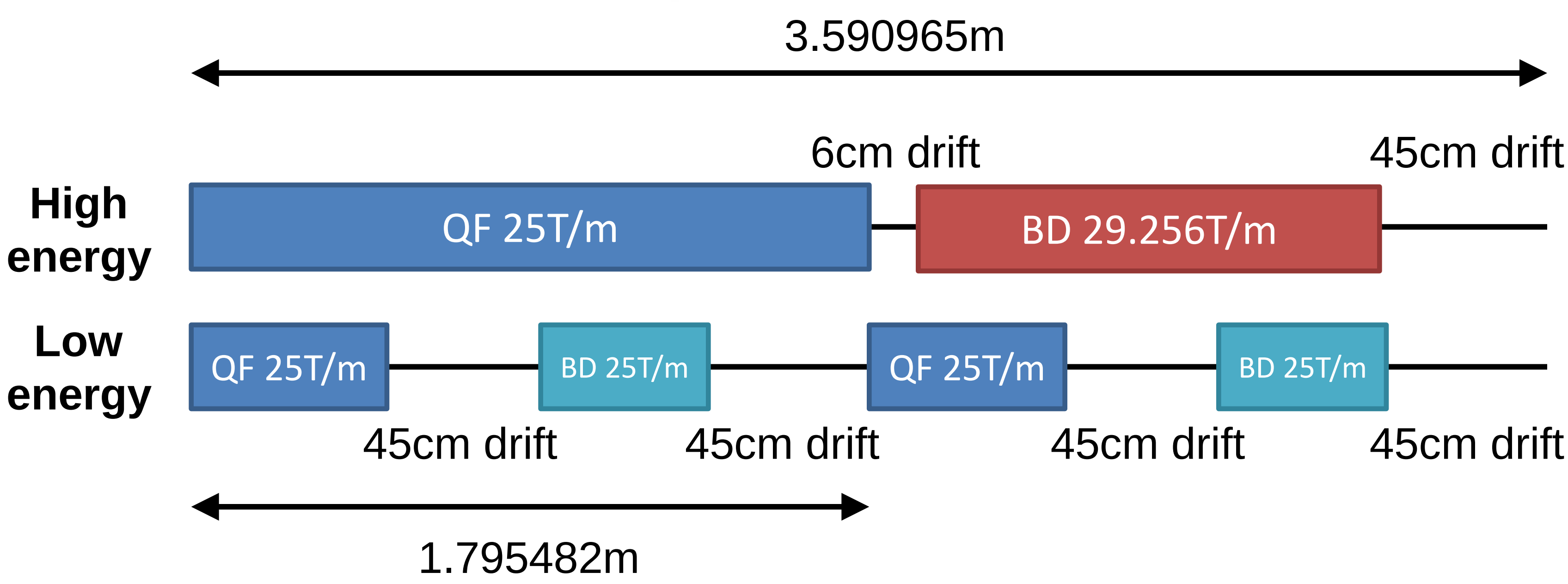


Courtesy Dejan

Low Energy FFAG



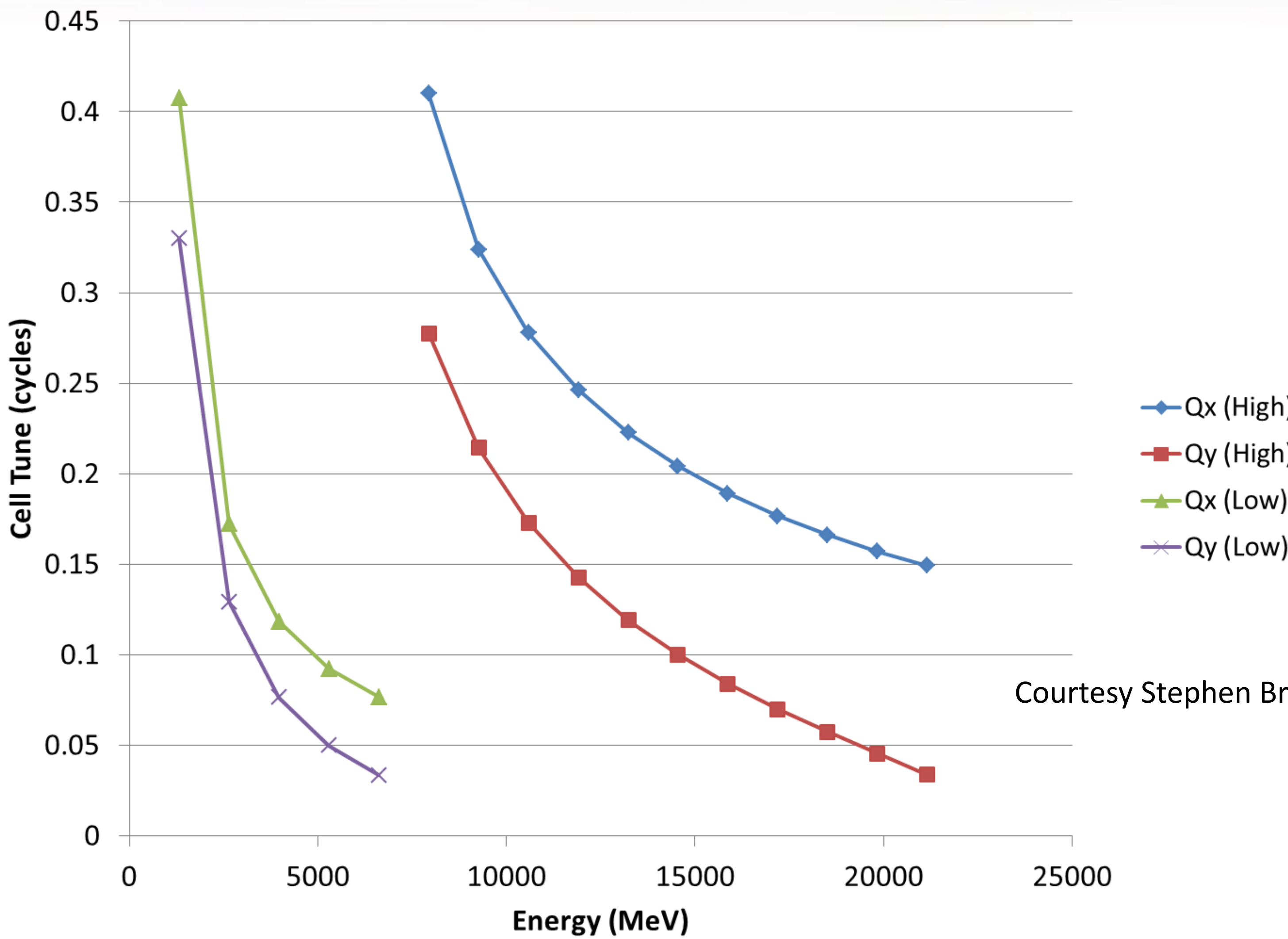
FFAG Cell Stacking



- Angle/length will be tweaked to exact number of cells per turn when hadron ring and FFAG physical positioning is chosen

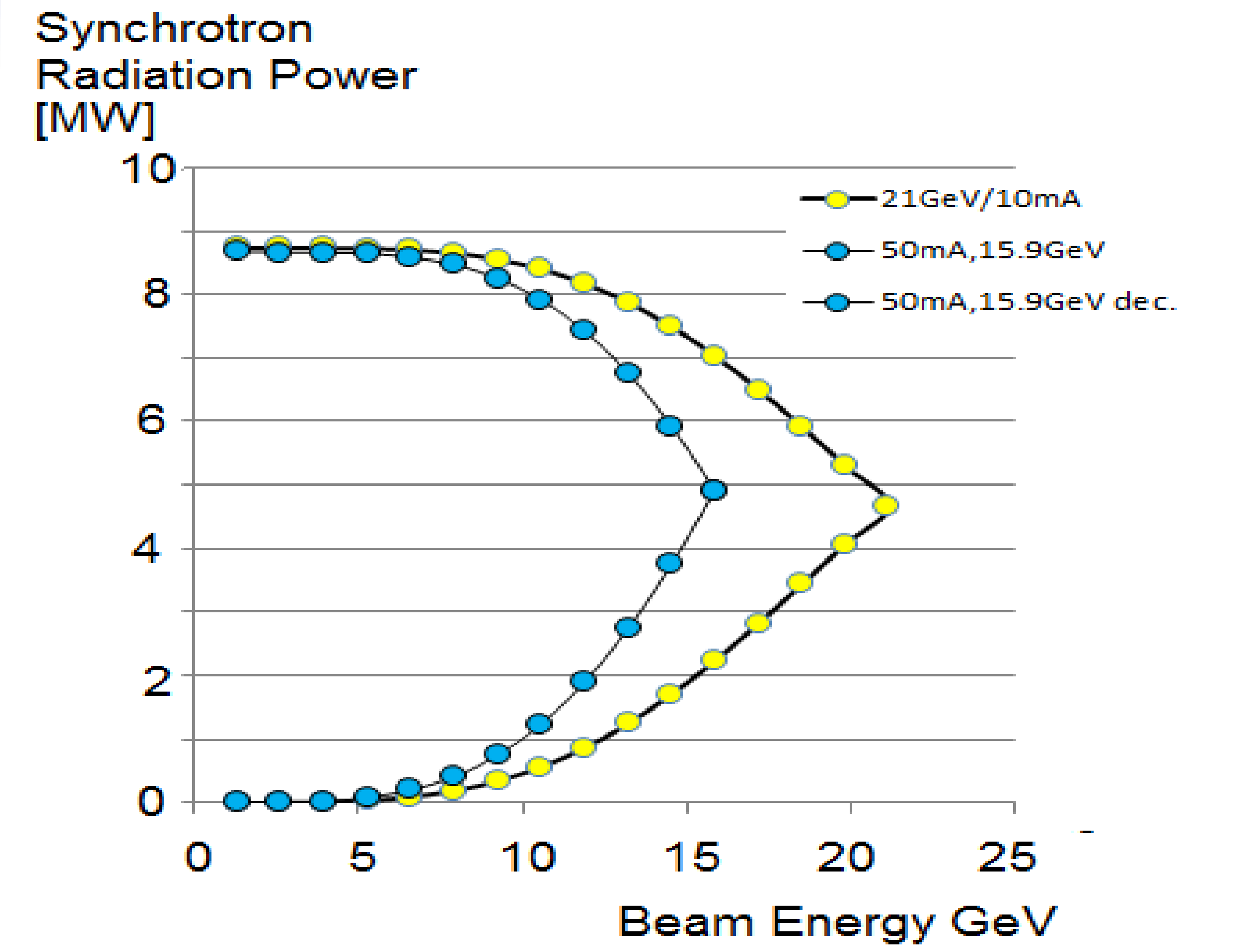
Stephen Brooks, eRHIC FFAG meeting

Betatron Phase Advance per Turn (“Tunes”)

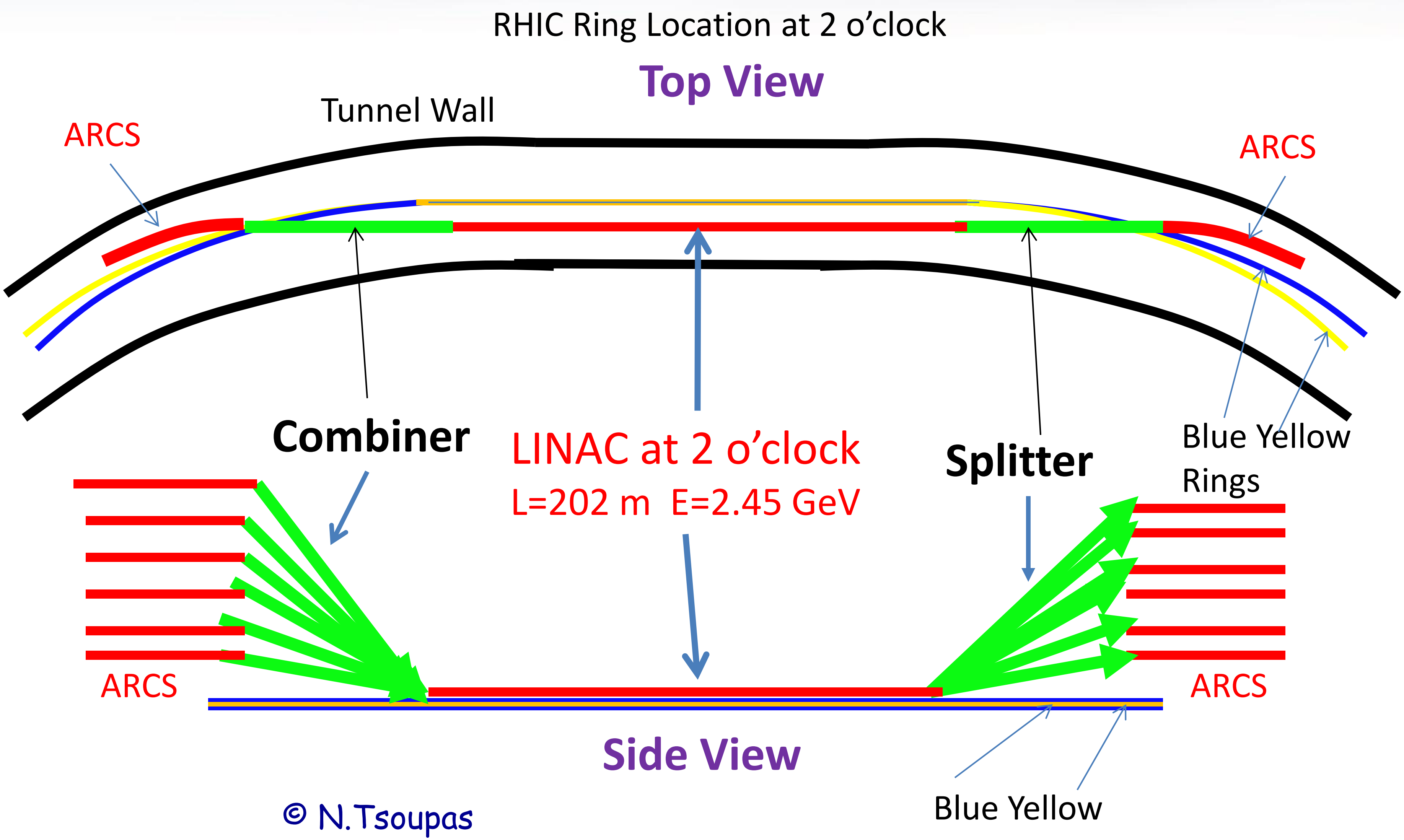


Courtesy Stephen Brooks

Synchrotron Radiation Power



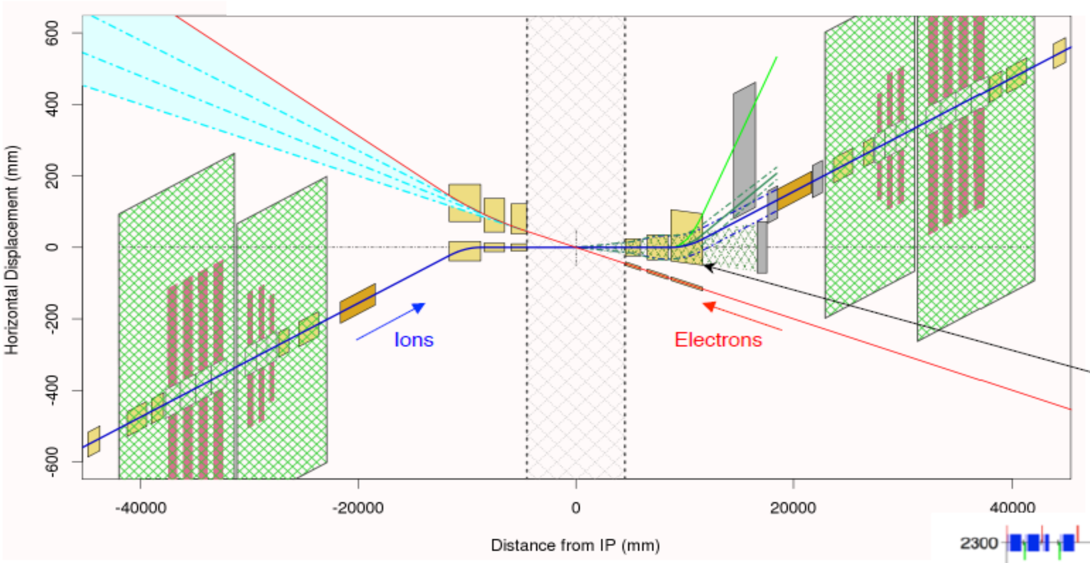
Splitter/Combiner in Relation to the RHIC Ring



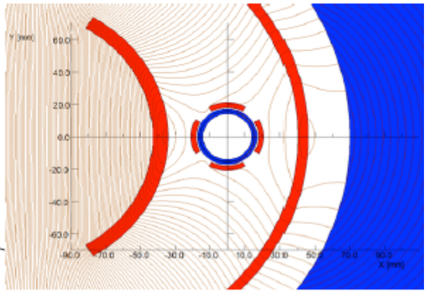
Interaction Region

IR design driven by

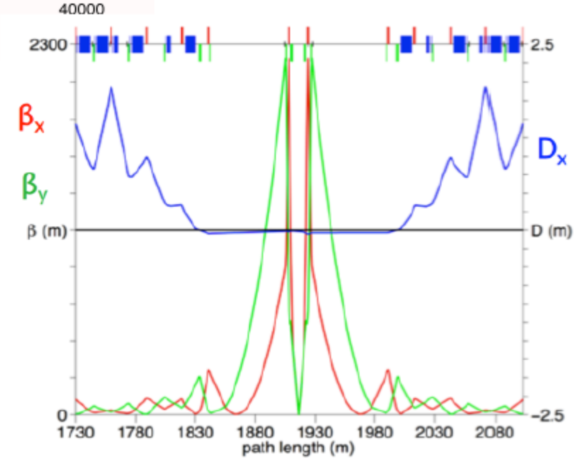
- acceptance needs for near-beam detection and forward Neutron detection
- Avoid synchrotron radiation from beam separation
- Dipole field at IP not considered because of use of existing detector (Star)



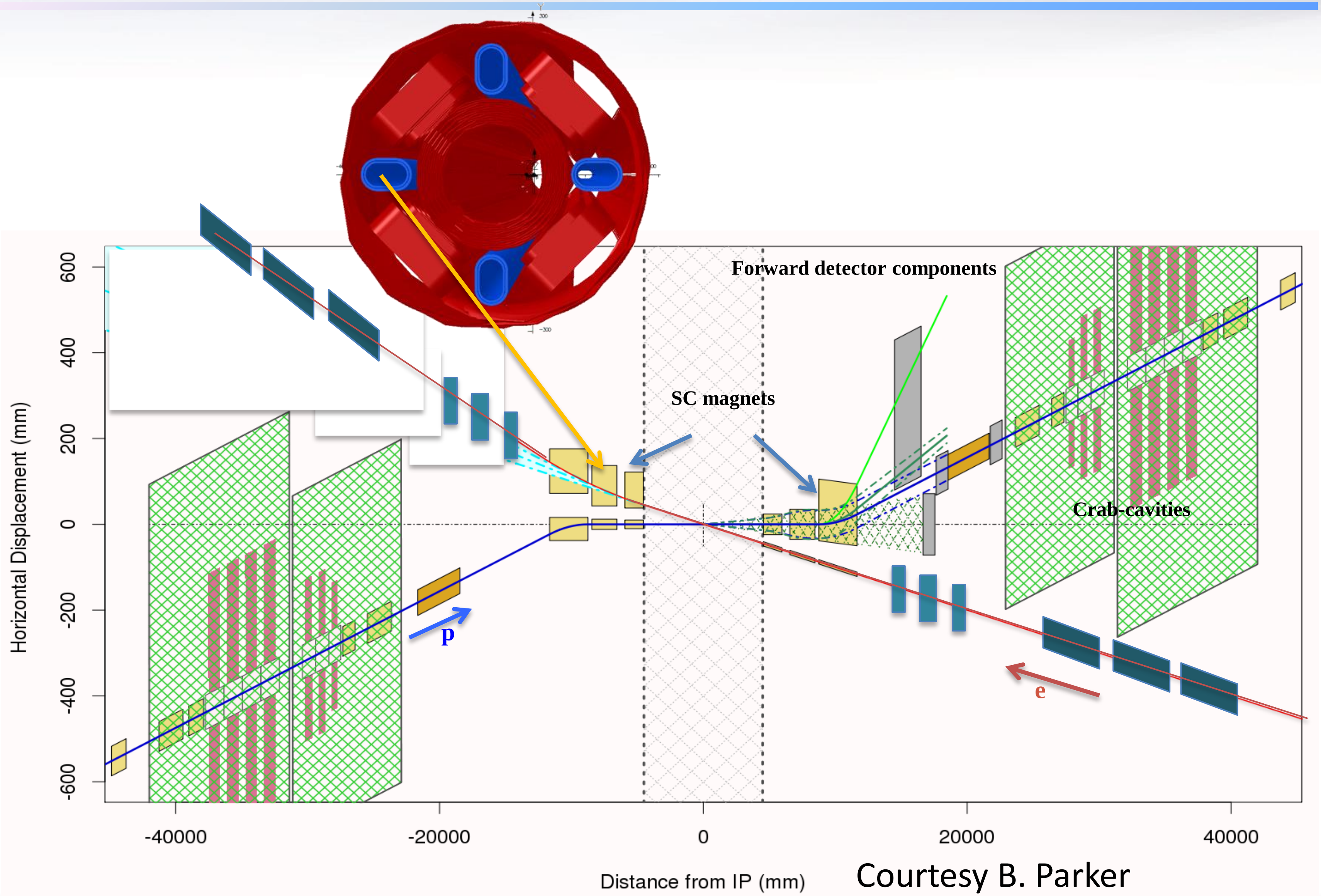
β* = 5 cm



- 10 mrad crossing angle and crab-crossing
- 90 degree lattice and beta-beat in adjacent arcs to reach beta* of 5 cm with good dynamic aperture
- Combined function triplet with large aperture for forward collision products and with field-free passage for electron beam
- Only soft bends of electron beam within 60 m upstream of IP

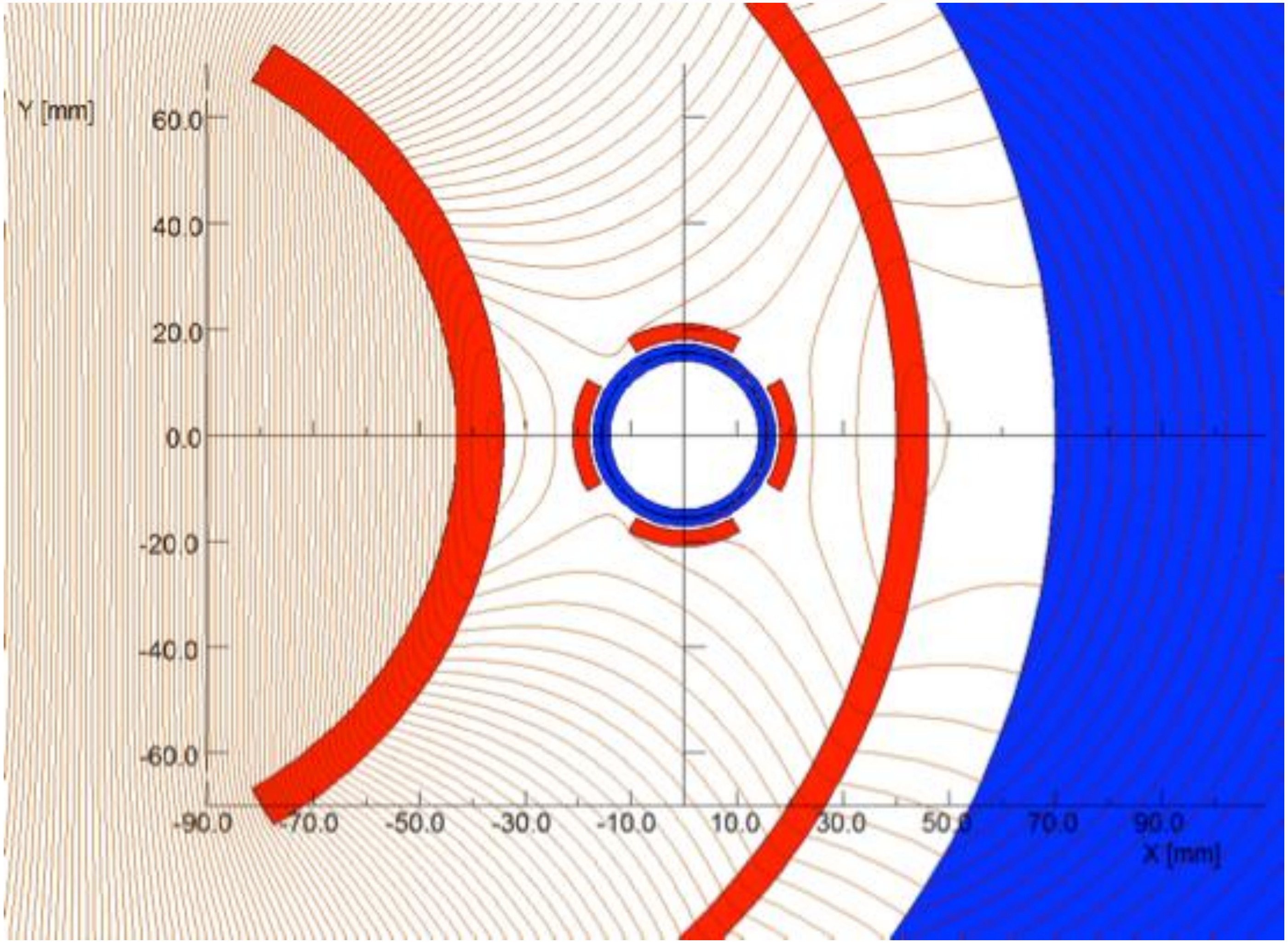


IR Design



Courtesy B. Parker

Electrons passing the Hadron Low Beta Lenses

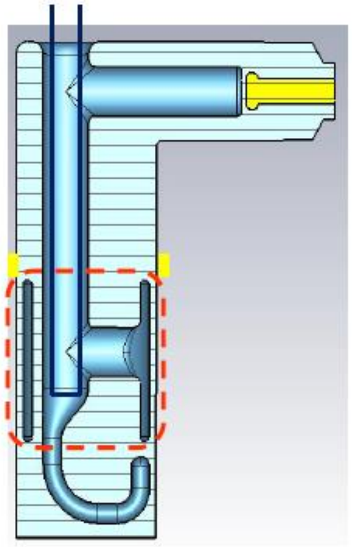


Crab Cavities

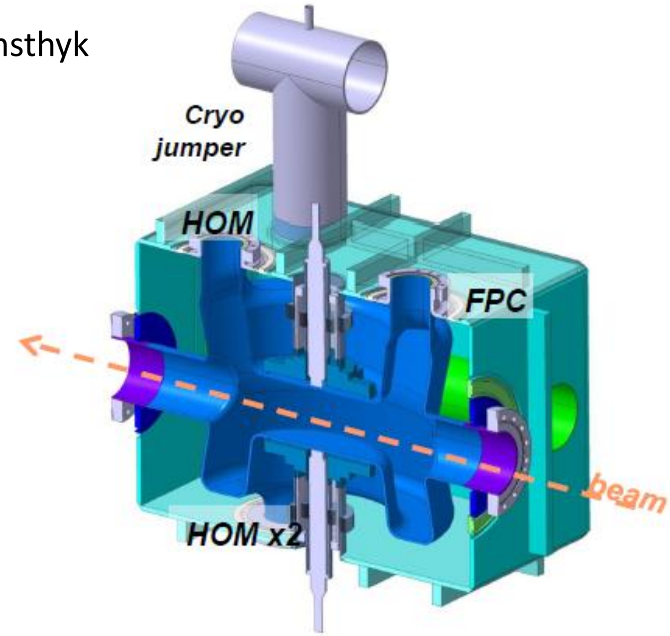
Large Crossing Angle of 10 mrad

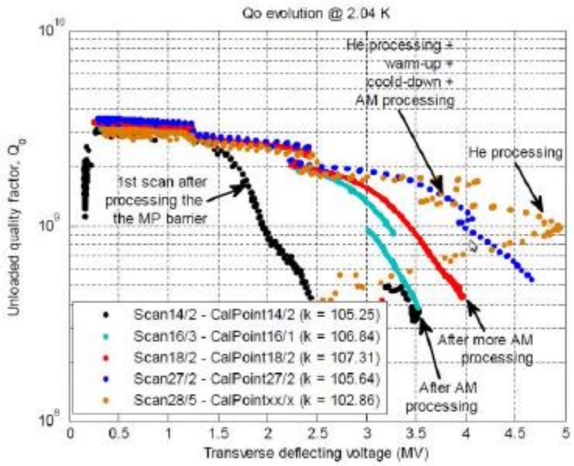
➔
Requires crab cavities for both E and Hadron beam

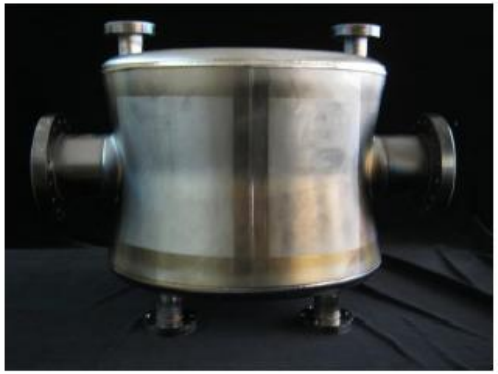
Prototypes (developed in collaboration with CERN)



Courtesy S. Belomsthyk

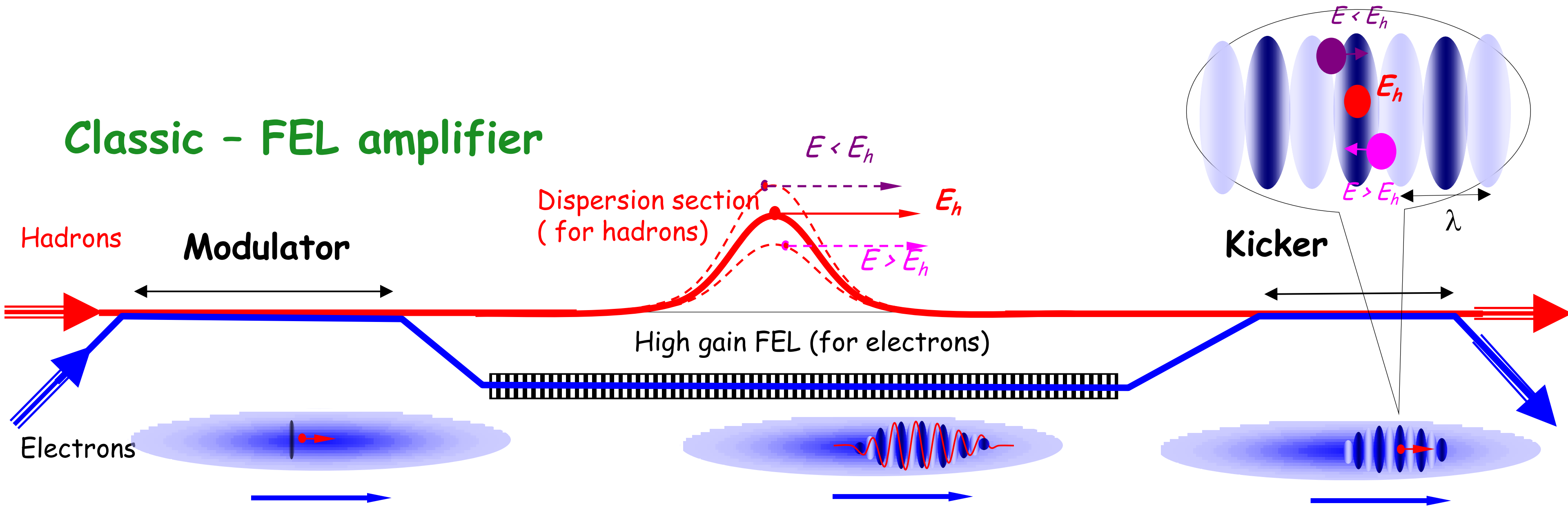






Coherent Electron Cooling

- High energy, high density ion beam need cooling with high band-width.
  BW: **10-10000 THz**



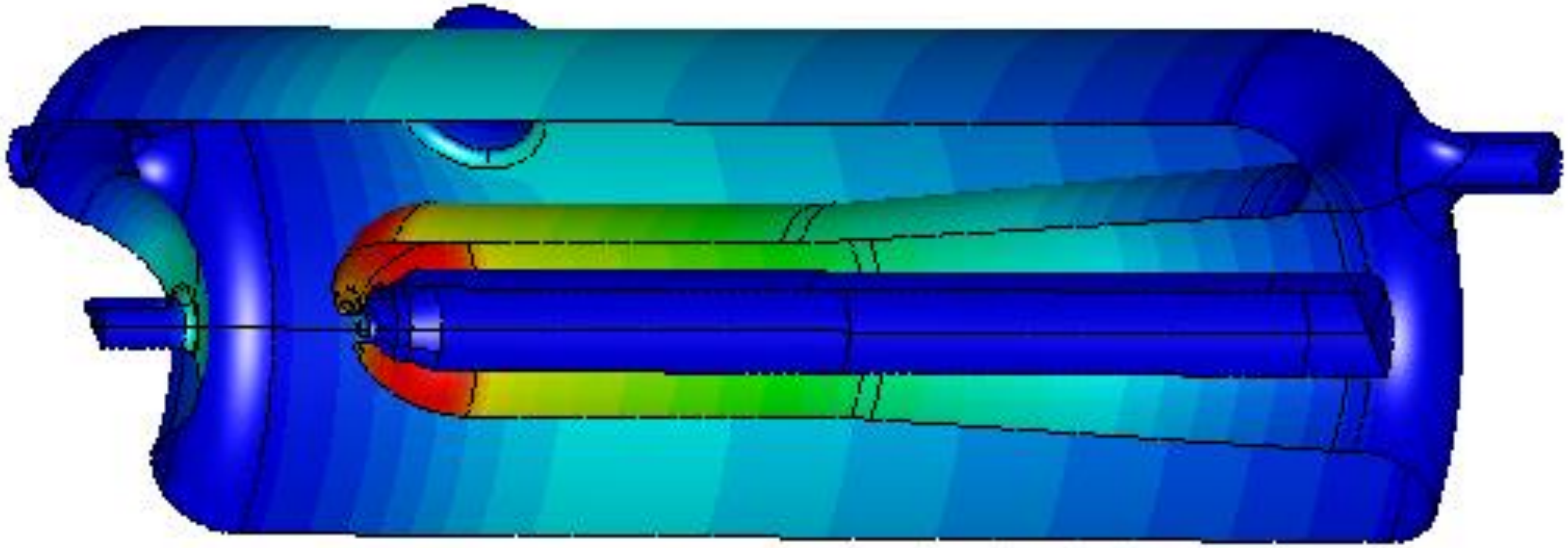
V.N.Litvinenko, Y.S Derbenev, Physical Review Letters 102, 114801 (2009).

Coherent Electron Cooling Parameters

Hadron beam			
Species	p	**Beam energy, GeV**	250
Particles per bunch	$3\ x10^{1o}$-$2\ x10^{11}$	**ε_n, mm mrad**	0.2
Energy spread	10^{-4}	**RMS bunch length, nsec**	0.27
Electron beam			
Beam energy, MeV	136.2	**Peak current, A**	50
ε_n, mm mrad	1	**RMS bunch length, nsec**	0.27
CeC			
Modulator length, m	10	**Kicker length, m**	10
FEL wiggler length, m	9	**λ_w, cm**	3
λ_o, nm	422	**a_w**	1
g, FEL gain used/max	3/44	**CeC bandwidth, Hz**	$1.1\ x\ 10^{13}$
Cooling time, hours	0.12		

CEC Erl QWR structure under development

84.5 MHz QWR buncher



Space Charge Effects

- Hadron beam cooled to 0.2 mrad mm normalized emittance experience a large space charge tuneshift of $\Delta Q = 0.4$ (at lowest Hadron energies)

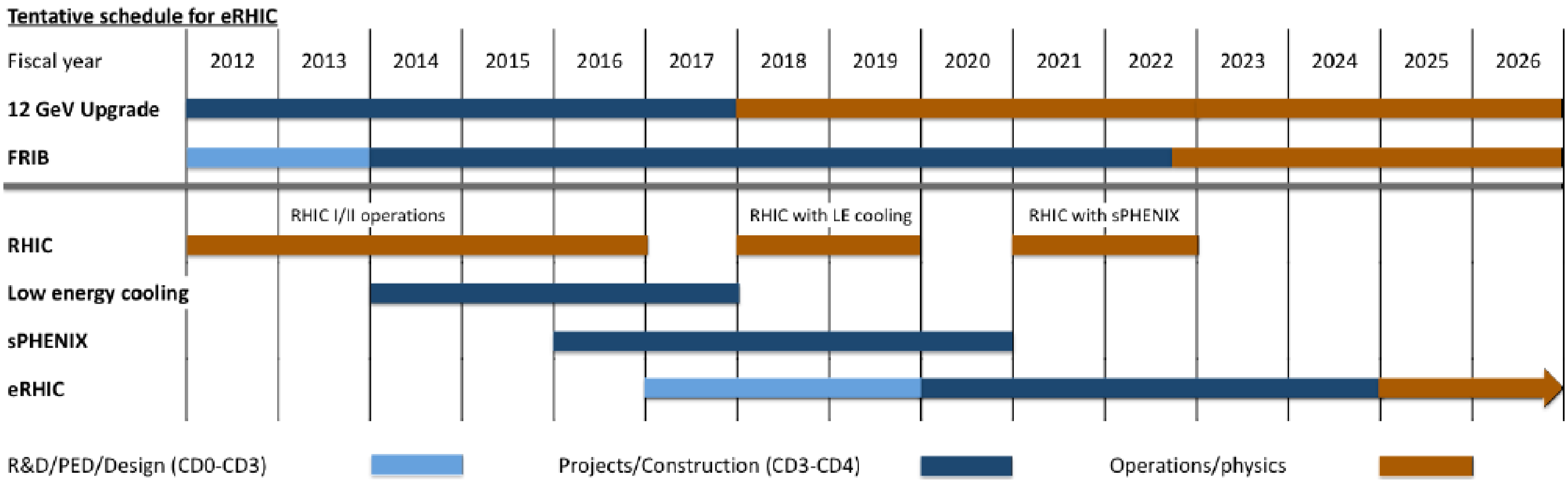
- It is almost certain that under these conditions the beam lifetime would be poor.

- It is considered to compensate the incoherent space charge tuneshift by creating an incoherent space charge force by electron beams overlapping with the hadron beam in several straight section.

- This scheme has not yet been validated. Issues are strong nonlinear forces which drive resonances due to overcompensation in a few locations

Timeline

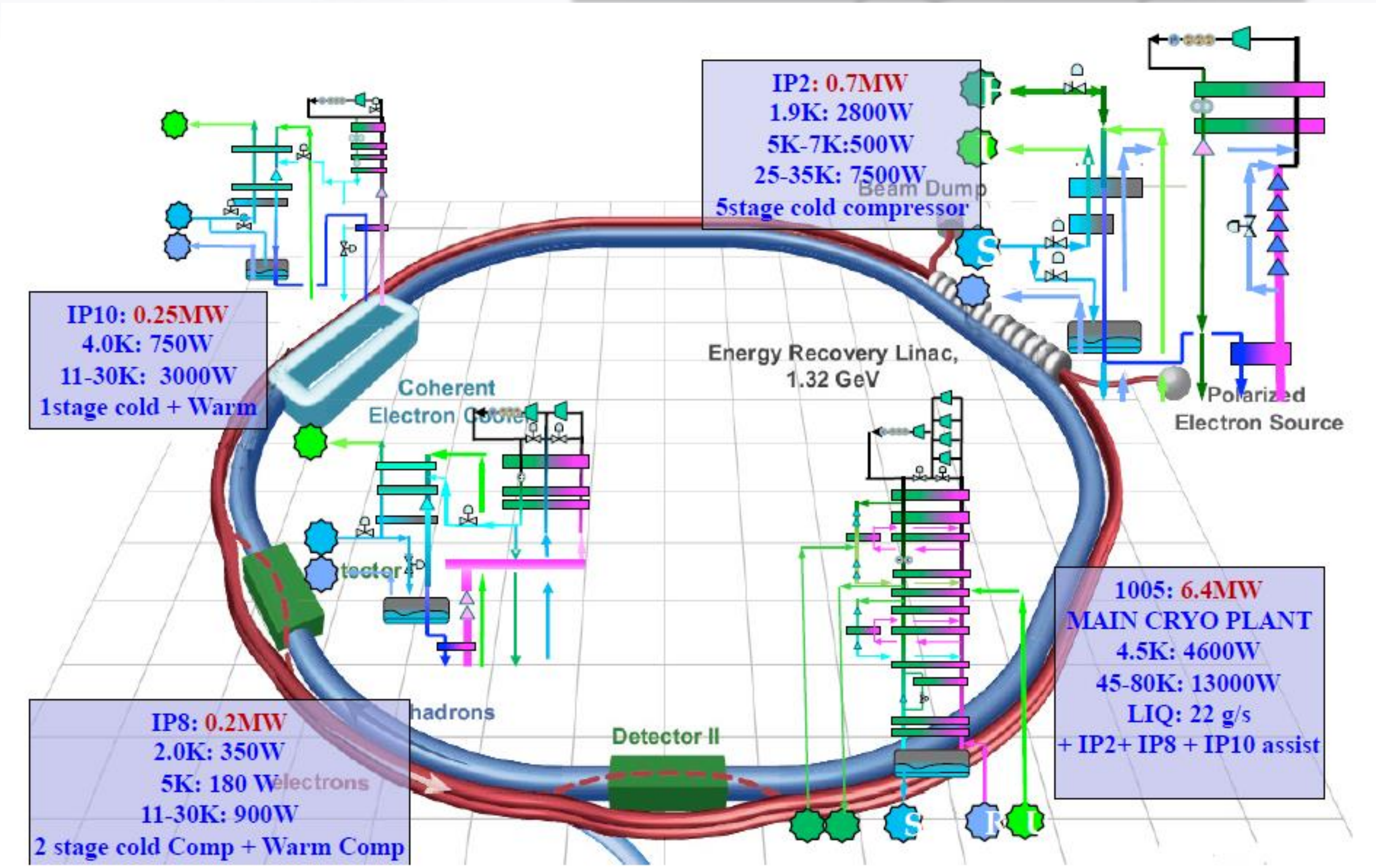
RHIC and possible eRHIC schedule



Summary

- The science scope of eRHIC is based on the results from HERA and RHIC. It is supported enthusiastically by the US nuclear physics community
- eRHIC is still at an early stage and the mission need has not yet been acknowledged by DOE, though there are indications that funding of this project is likely.
- Accelerator and Nuclear Scientists are using the time before approval to explore many technical solutions in order to achieve the very challenging eRHIC performance goals such as a luminosity in excess of $10^{34}s^{-1}cm^{-2}$
- A number of very creative solutions have been proposed and studies thoroughly.
- R&D on critical component is carried out
- A completely consistent design has not been created yet but the parameter space has been extensively explored and studies are underway to arrive at an overall consistent design.
- Some of the elements of the eRHIC design are quite advance and have not been demonstrated yet. The most intricate proposal is coherent electron cooling. A proof of principle experiment in RHIC is planned in the FY16 timeframe.
- eRHIC is an exciting but challenging proposal with many excellent ideas. This needs now to be turned into a realistic proposal with calculable technical and cost risk.

eRHIC Cryogenic System



The Science of Electron-Hadron Colliders

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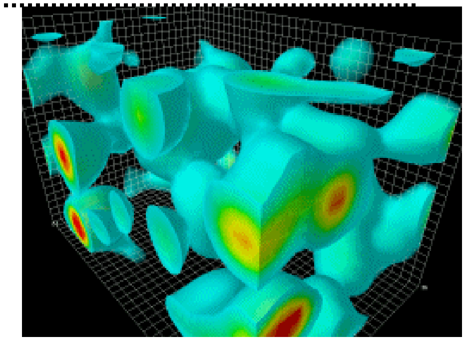
eA

High density parton matter, gluon saturation/non-linear QCD, Color-Glass-Condensate?



e↑p↑

Spin structure of the nucleon

3D Spatial Landscape of the nucleon: valence quarks → gluons and sea

Higgs physics, Super-symmetry, Beyond the Standard Model, Tera-scale physics, Substructure of quarks and leptons?

Lepton Flavor Number Violation

ep

Formation of color neutral hadrons from quarks and gluons

10   100   1000 $\sqrt{s}$ (GeV)