

# eRHIC Accelerator Design

*V. Ptitsyn for the eRHIC design team*



# eRHIC: QCD Facility at BNL

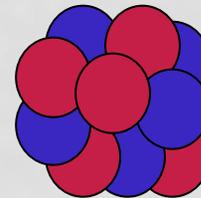
Add an electron accelerator to the existing \$2.5B RHIC including existing RHIC tunnel and cryo facility



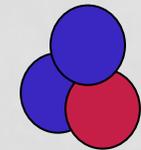
Unpolarized and 80% polarized electrons:  
15.9 GeV  
(6.6 – 21.2 GeV)



70% polarized protons  
25 - 250 (275\*) GeV



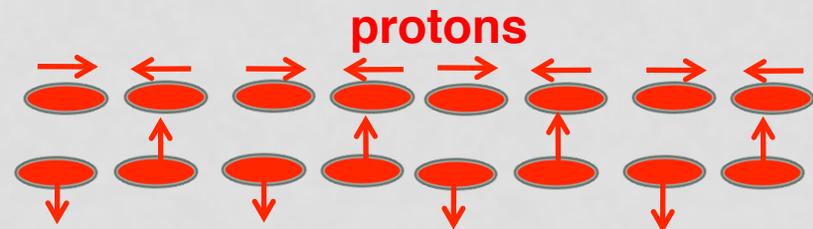
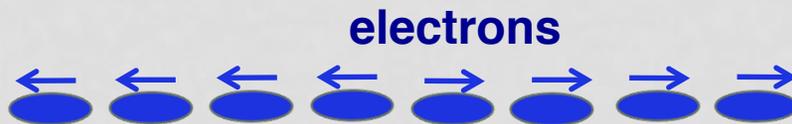
Light ions (d, Si, Cu)  
Heavy ions (Au, U)  
10 - 100 (110\*) GeV/u



Pol. light ions (He-3)  
17 - 167 (184\*) GeV/u

**Center-of-mass energy range: 30 – 145 GeV**

**Any polarization direction in electron-hadron collisions**



\* It is possible to increase RHIC ring energy by 10%

# Design choices

$L_{\text{peak}}$   
 $\text{cm}^{-2}\text{s}^{-1}$

$\sim 5 \cdot 10^{31}$

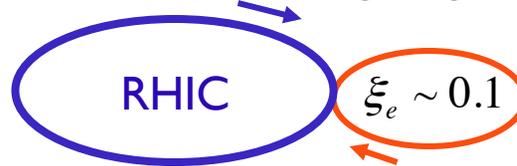
$\sim 4 \cdot 10^{32}$

up to  $1.5 \cdot 10^{34}$

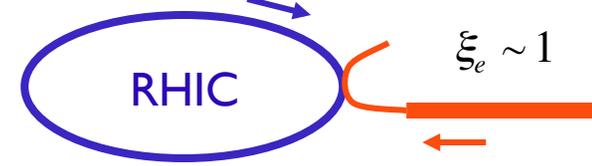
HERA



eRHIC ring-ring



eRHIC linac-ring



Compared with HERA  
eRHIC will have:

- Polarized proton and  $^3\text{He}$
- Heavy ion beams
- Wide variable center-of mass energy range
- Considerably higher luminosity

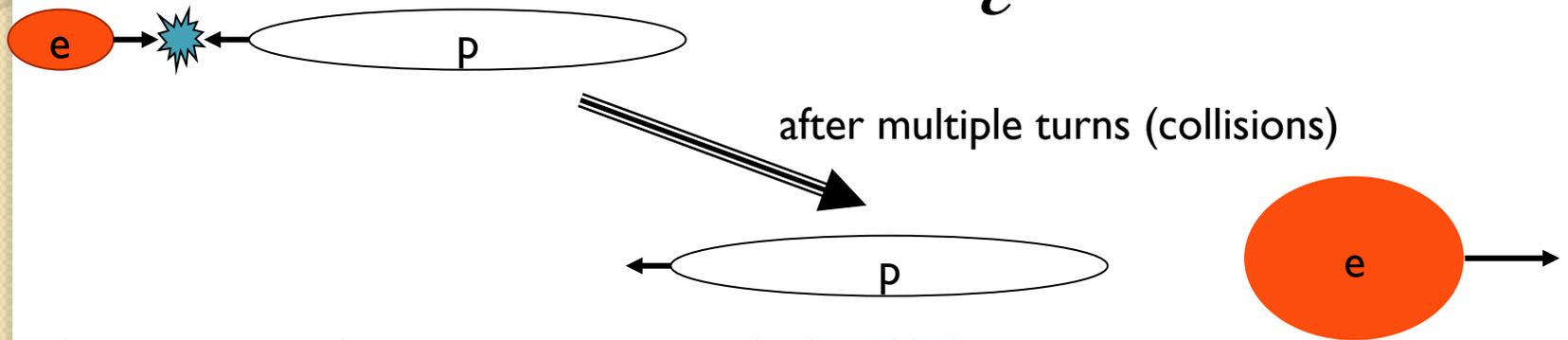
- 10 GeV storage ring
- ZDR in 2004
- Fundamental luminosity limits:
  - Beam-beam
  - SR power loss (total and per m)

- Large allowed beam-beam on electrons
- Electron energy beyond 10 GeV
- Simple energy staging by increasing the linac length
- No e-polarization issues with spin resonances

# Limitations of ring-ring concepts

## 1. Beam-beam effects

$$\xi_e \sim \frac{N_p}{\epsilon} < 0.08$$



Limits beam intensities, beam transverse sizes and achievable luminosity

## 2. Difficulties of maintaining the beam polarization.

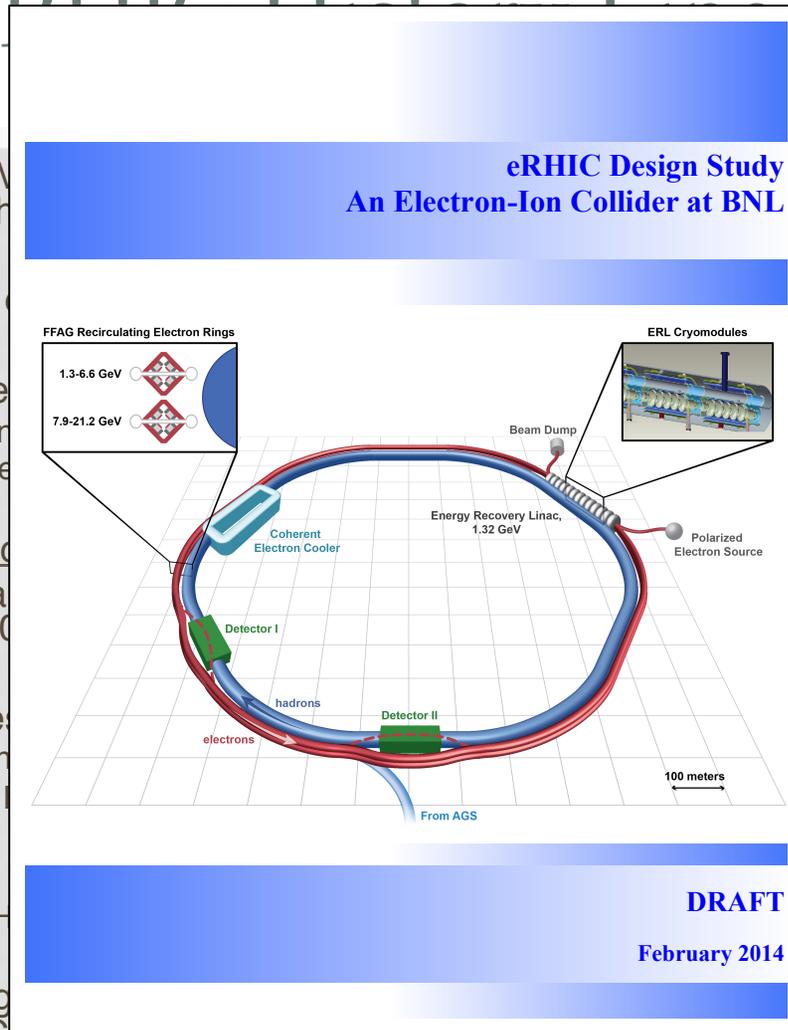
*the beam polarization can be destroyed by so-called spin resonances when magnetic field perturbations are in the resonance with the spin precession rate*

# eRHIC History Line

- I. Ben-Zvi, J. Kewisch, J. Murphy, S.Peggs, “Accelerator Physics Issues in eRHIC”, Nuclear Instrumentations and Methods in Physics Research A 463 (2001), p.94.
- eRHIC ZDR (the ring-ring design with  $L \sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ ; ERL linac-ring as backup) (2004).
- ERL-based eRHIC with separated re-circulating passes
  - $L \sim 10^{34} \text{ cm}^{-2} \text{ s}$ , high hadron beam intensity, upgrades in hadron ring, Space Charge Compensation
  - Energy staging. First stage eRHIC: 4-5 GeV electron machine.
- 2012-2013: Work on cost optimized machine design.
- Bottom-up cost estimate and optimization: minimal cost first stage (5 GeV) eRHIC with separated re-circulating passes: \$530 mln. (detector(s) not included).
- FFAG re-circulating passes + permanent magnets
  - construction and operational cost savings
  - No energy staging. Using FFAG passes widens the energy reach at moderate cost.
- 10 GeV FFAG design has been evaluated by Machine Advisory Committee (Nov. 2013) :  
”The MAC congratulates the eRHIC design team for its ingenious and novel use of the FFAG concept.”
- First draft of “eRHIC Design Study” report includes the Accelerator Design Chapter presenting main features of 21 GeV eRHIC FFAG design.

# eRHIC II: Final Design

- I. Ben-Zvi, J. Kewisch, J. M. ... Instrumentations and Meth...
- eRHIC ZDR (the ring-ring ...)
- ERL-based eRHIC with se...
  - $L \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , high hadron...
  - Energy staging. First stage...
- 2012-2013: Work on cost of ...
- Bottom-up cost estimate a... re-circulating passes: \$530...
- FFAG re-circulating passe...
  - construction and operation...
  - No energy staging. Using I...
- 10 GeV FFAG design has... "The MAC congratulates the eRH...
- First draft of "eRHIC Design... features of 21 GeV eRHIC FFAG design.



eRHIC", Nuclear  
 backup) (2004).

Compensation

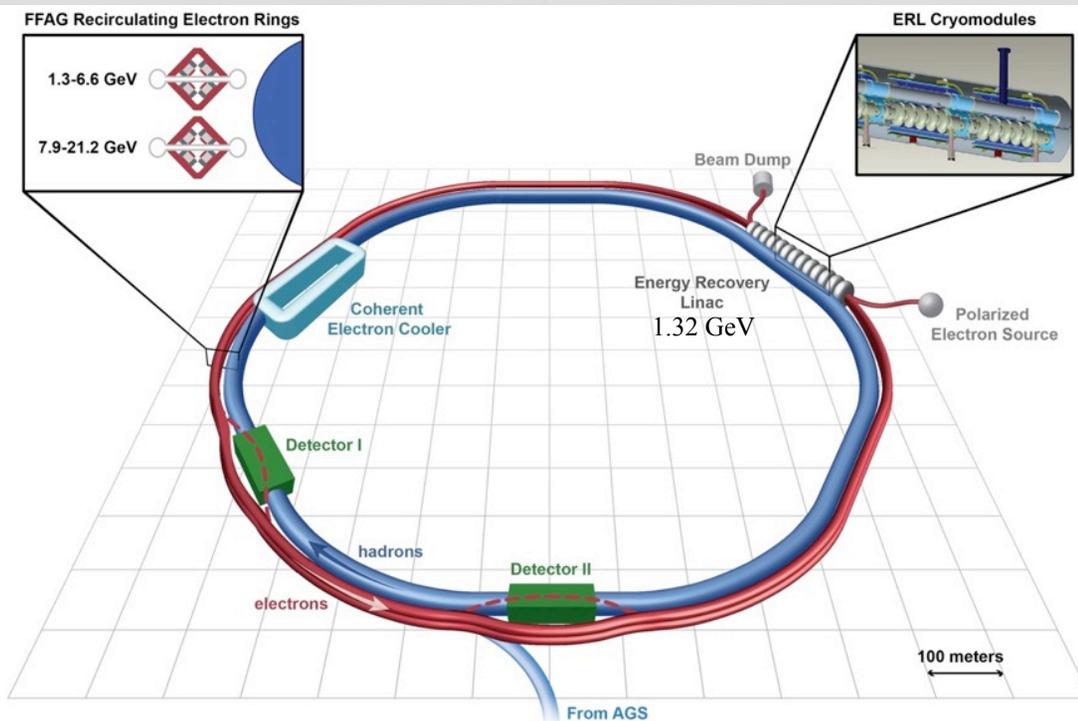
eRHIC with separated

(Nov. 2013) :  
 AG concept."

Chapter presenting main

# Cost-Effective eRHIC Design

- ✧ Up to 21.2 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV polarized protons and 100 GeV/n HI RHIC beams
- ✧ Single collision of each electron bunch allows for large disruption, giving high luminosity and full electron polarization transparency
- ✧ Use 2 FFAG magnet strings in RHIC tunnel to transport up to 16 beams
- ✧ Considered permanent magnet design for FFAG lattice magnets
- ✧ Cool hadron beam 10-fold in all directions using coherent electron cooling (CeC) at reduced intensity of hadron beam
- ✧ IR design with  $\beta^* = 5$  cm using SC magnet technology and crab-crossing scheme
- ✧ Average polarized electron current of 50 mA



Design provides full luminosity ( $> 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ ) up to 15.9 GeV and reduced luminosity up to 21.2 GeV

# eRHIC beam parameters and luminosities

|   | e    | p     | ${}^3\text{He}^{2+}$ | ${}^{197}\text{Au}^{79+}$ |
|---|------|-------|----------------------|---------------------------|
| Energy, GeV   | 15.9 | 250   | 167                  | 100                       |
| CM energy, GeV  |      | 122.5 | 81.7                 | 63.2                      |
| Bunch frequency, MHz                                      | 9.4  | 9.4   | 9.4                  | 9.4                       |
| Bunch intensity (nucleons), $10^{11}$                     | 0.33 | 0.3   | 0.6                  | 0.6                       |
| Bunch charge, nC  | 5.3  | 4.8   | 6.4                  | 3.9                       |
| Beam current, mA  | 50   | 42    | 55                   | 33                        |
| Hadron rms norm. emittance, $\mu\text{m}$                 |      | 0.27  | 0.20                 | 0.20                      |
| Electron rms norm. emittance, $\mu\text{m}$               |      | 31.6  | 34.7                 | 57.9                      |
| Beta*, cm (both planes)                                   | 5    | 5     | 5                    | 5                         |
| Hadron beam-beam parameter                                |      | 0.015 | 0.014                | 0.008                     |
| Electron beam disruption                                  |      | 2.8   | 5.2                  | 1.9                       |
| Space charge parameter                                    |      | 0.006 | 0.016                | 0.016                     |
| rms bunch length, cm                                      | 0.4  | 5     | 5                    | 5                         |
| Polarization, %   | 80   | 70    | 70                   | none                      |
| Peak luminosity, $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ |      | 1.7   | 2.8                  | 1.7                       |

$$L = f_c \xi_h \frac{\gamma_h}{\beta_h^*} \frac{ZN_h}{r_h} H_{hg} H_p$$

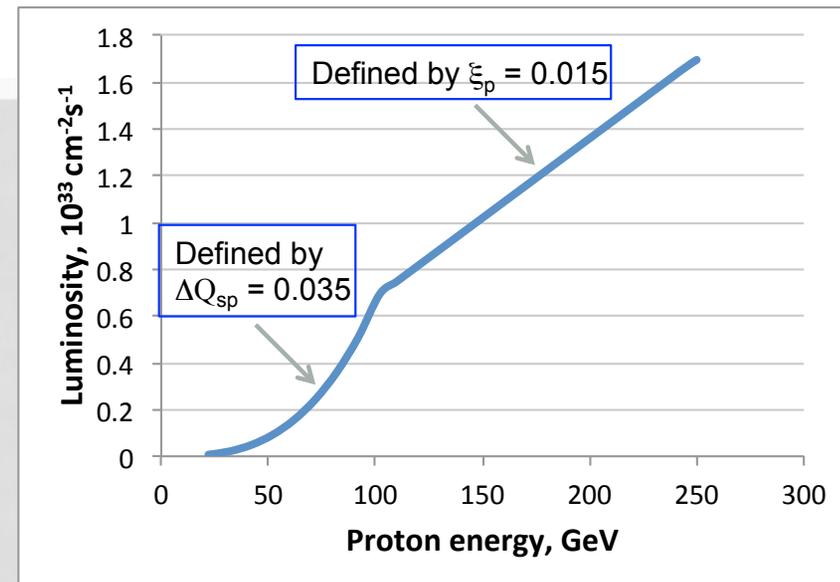
# eRHIC beam parameters and luminosities

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| <p><b><u>Future luminosity upgrade</u></b></p> <p>The proton beam intensity is only at ~15% of present level.</p> <p>Open path to the moderate cost luminosity upgrade the future by increasing the hadron beam intensity (by an order of magnitude) and related hadron ring improvements:</p> <p><i>copper coating of beam pipe, beam diagnostics upgrade, RF system upgrade</i></p> <p><b>Luminosity above <math>10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math> can be reached</b></p> |      |       |                      |                           |
| Polarization, %   | 80   | 70    | 70                   | none                      |
| Peak luminosity, $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$   |      | 1.7   | 2.8                  | 1.7                       |

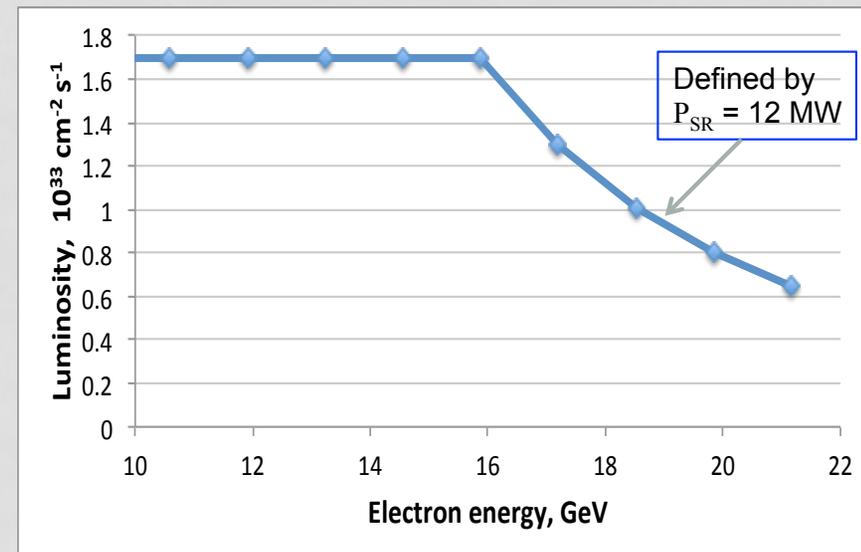
$$L = f_c \xi_h \frac{\gamma_h}{\beta_h^*} \frac{ZN_h}{r_h} H_{hg} H_p$$

# Luminosity versus Beam Energy

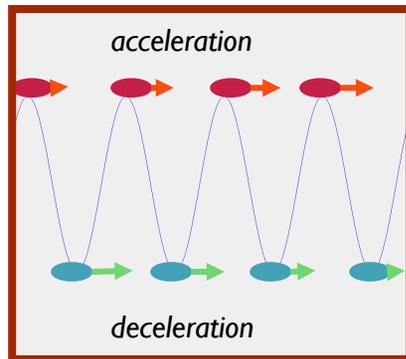
- Luminosity versus hadron beam energy
  - For 15.9 GeV electron energy or less
  - Limited by hadron beam-beam parameter above 100 GeV and space charge below 100 GeV



- Luminosity versus electron beam energy
  - Limited by maximum SR power of 12 MW above 15.9 GeV



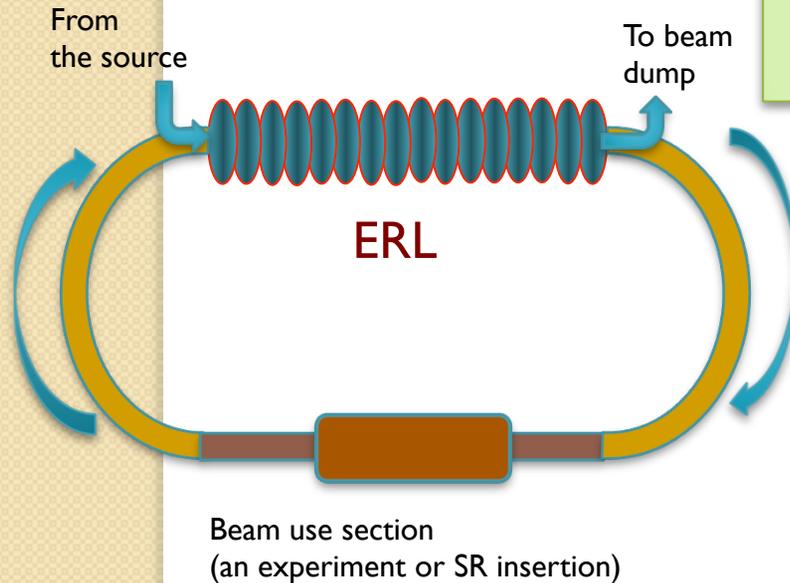
# Energy-Recovery Linacs



Electron beam passes the ERL at least two times:

- First time, in accelerating phase of electric field. The electron acquires the energy from the RF cavities of the linac.
- Second time, in decelerating phase of the electric field. The energy taken from decelerated electrons can be reused for acceleration of other electron bunches.

Energy recycling!



In eRHIC the beam can pass the linac up to 32 times !  
(16 accelerating passes and 16 decelerating passes)

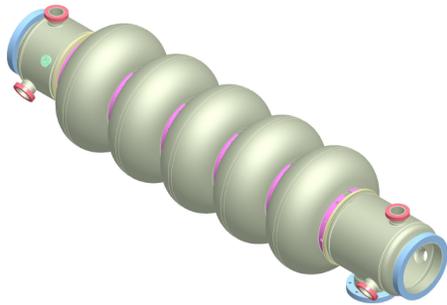
**Power balance:**

$$P_{\text{tot}} = P_{\text{beam\_acceler}} - P_{\text{beam\_deceler}} + P_{\text{loss}}$$

~ 750 MW in eRHIC

~ 12 MW (mostly SR)

# Superconducting RF Cavities



703.75 MHz 5-cell cavity designed in BNL for high current applications

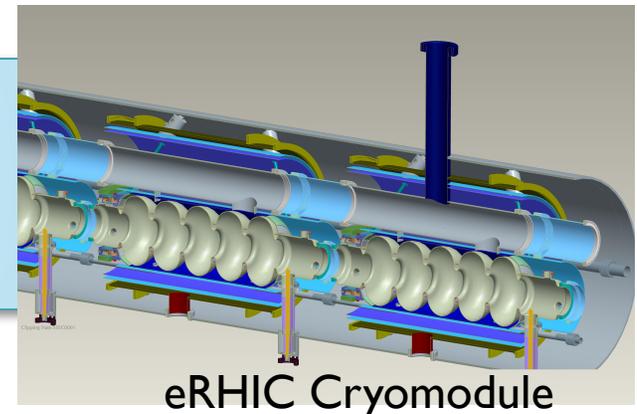
The EM field power is dissipated in the RF cavity walls because of the resistivity:  $P_{\text{loss}}$  is unacceptably large even for copper cavities ( $\sim$ tens of MW total for eRHIC).

The superconducting technology has to be used. Material: Niobium (Nb) at 2K.

*Present eRHIC design uses 422 MHz SRF cavities in main linac as well as higher frequency cavities for beam energy loss and energy spread compensation*

State-of-the-art cavity and cryomodule design:

- maintain the fundamental mode of EM field
- minimize and provide effective damping for High Order Modes of EM field (higher frequencies)



eRHIC Cryomodule

# NS-FFAG approach for eRHIC

- Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) approach is used for eRHIC recirculation passes. It can transport large energy range.
- eRHIC FFAG cell is comprised of two quadrupoles (F & D) whose magnetic axes are shifted horizontally with respect to each other by an offset  $\Delta$ .

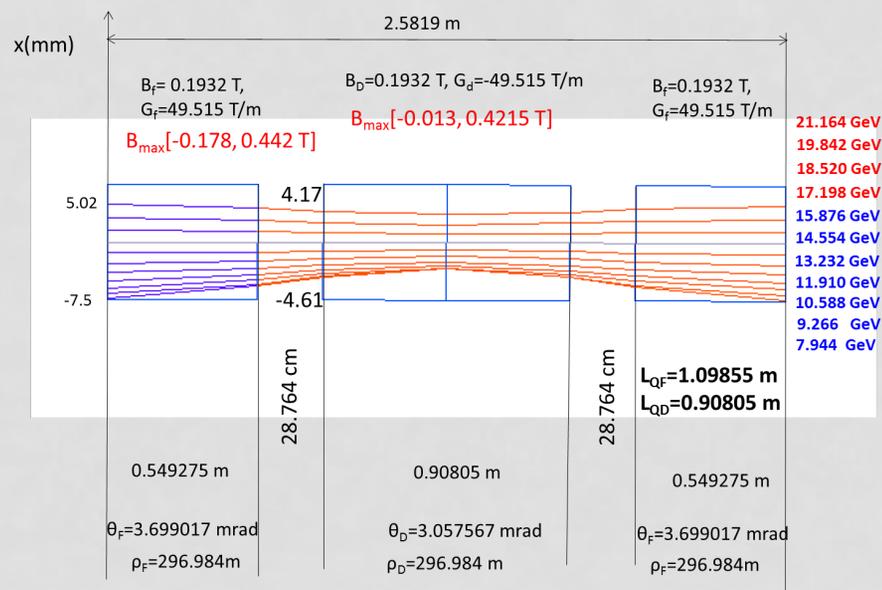
It can be considered as *strongly focusing, bent FODO cell*

*Small quadrupole offsets bend the beams adiabatically if bend radius is much larger than cell length*

- Orbit and optics dependence on the energy can be accurately found in paraxial approximation

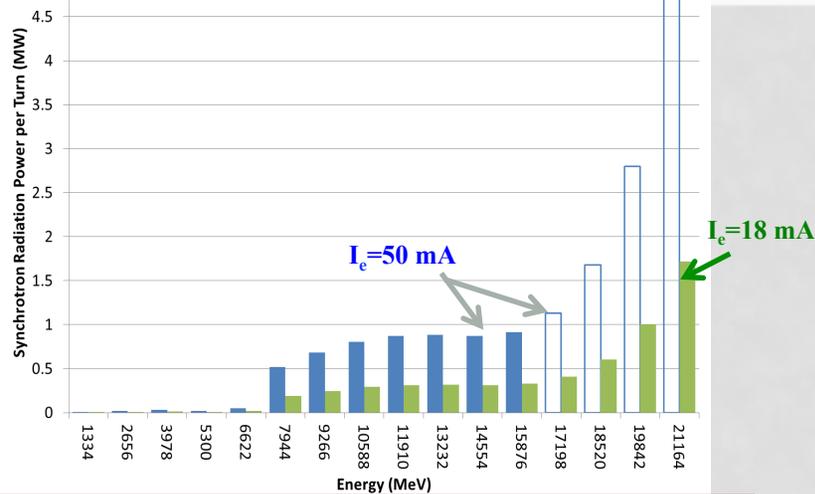
## High energy FFAG cell

© D.Trbojevic



# Synchrotron Radiation Effects

## SR power loss per recirculation pass



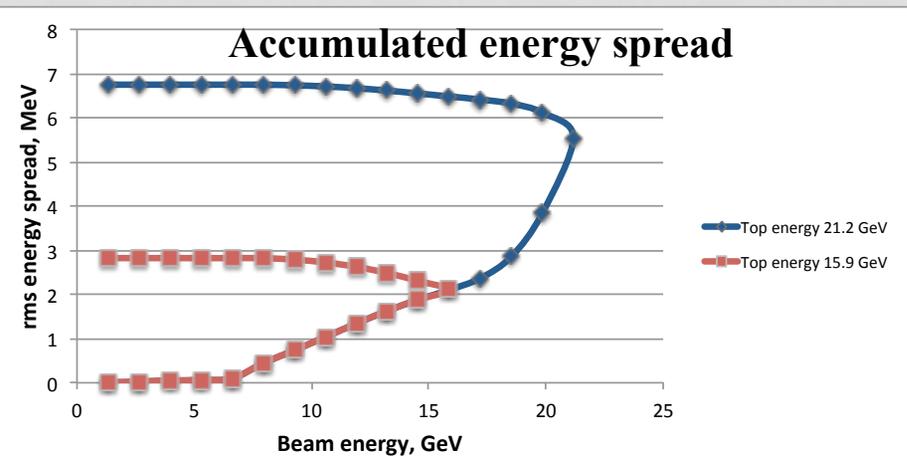
**Total SR power 12 MW:**  
 operation at 15.9 GeV top energy  $\rightarrow$  50 mA  
 operation at 21.2 GeV top energy  $\rightarrow$  18 mA

Energy loss and energy spread are compensated by high harmonic SRF cavities

FFAG lattice was thoroughly optimized on several factors:

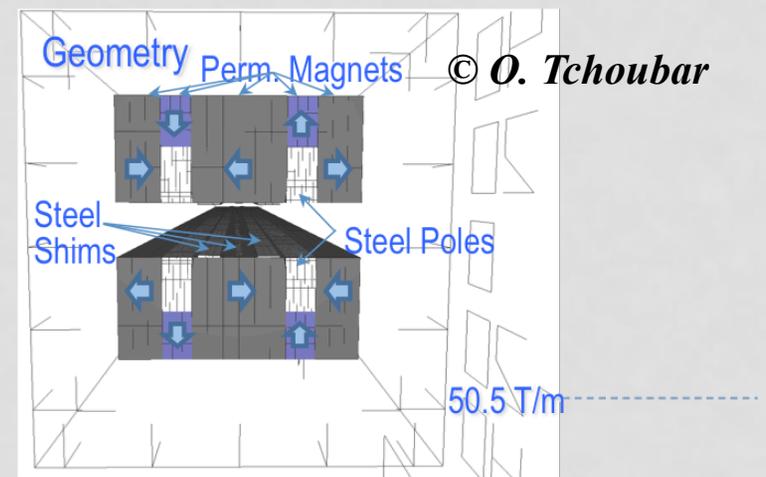
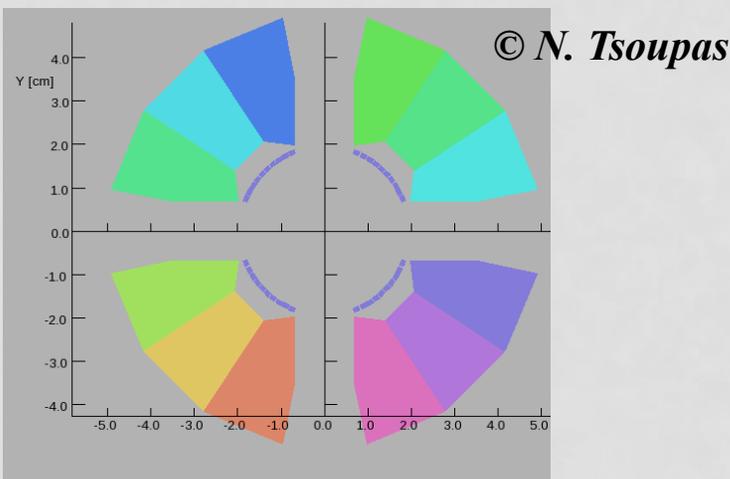
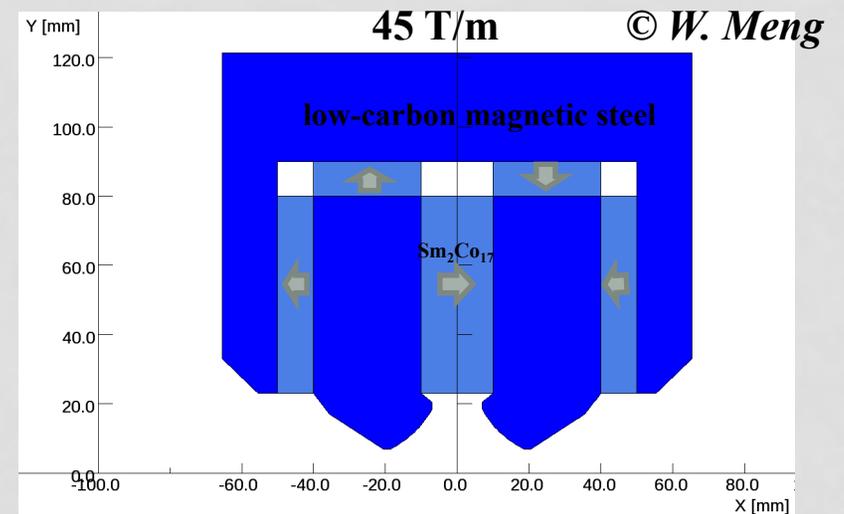
- energy acceptance
- orbit spread
- time-of-flight spread
- synchrotron radiation power

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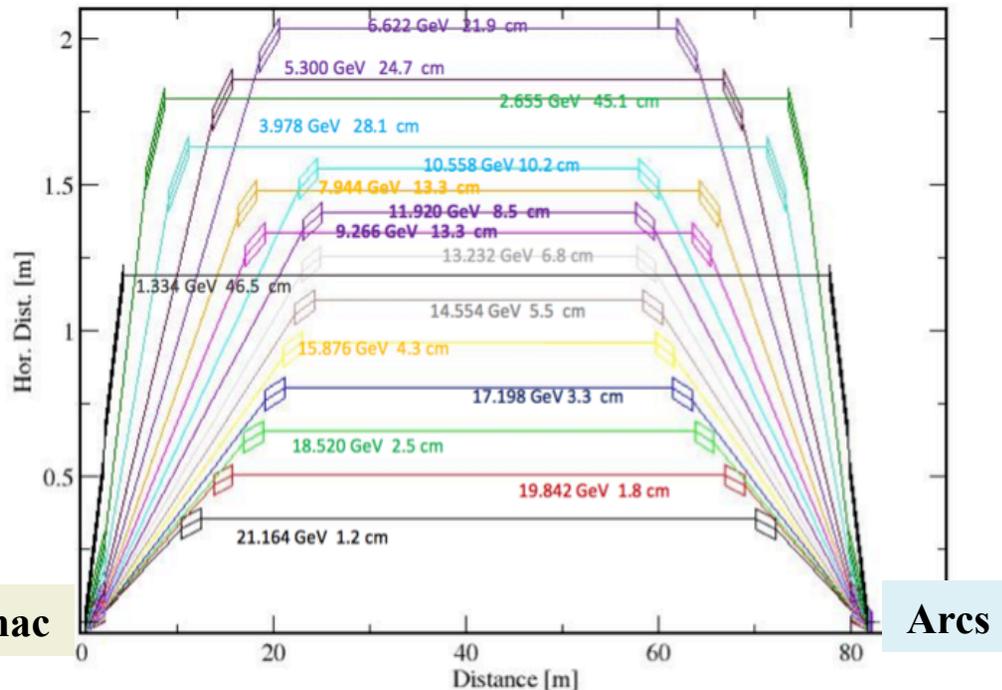
# Permanent Magnet Designs

- ✧ FFAG lattice can be realized with permanent magnets
- ✧ Expected construction and operational cost savings
- ✧ Expected field quality (after shimming)  $\sim 10^{-3}$
- ✧ SmCo: acceptable  $B_r$ , good temperature stability, exceptional radiation resistance



# Beam Spreader and Combiner

© N. Tsoupas

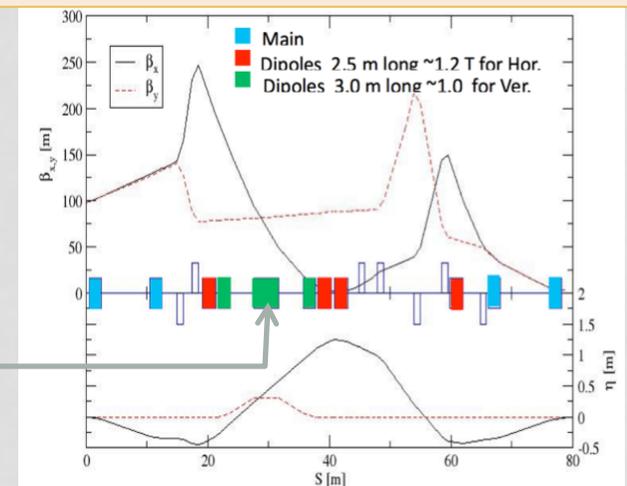


Linac

Arcs

- Placed on either side of the linac to separate/combine the 16 beams with different energies between FFAG arcs and CW Linac
- Match optical function from the arc to the linac
- Ensure isochronous one turn transport:  
*path length and  $R_{56}$  corrections*
- Betatron phase advance adjusters

- ✧ 15 cm horizontal separation between individual lines
- ✧ Some of the lines are folded into the vertical plane to reduce path length difference
- ✧ Vertical magnet chicanes are used for pathlength correction



# Hadron-Electron Synchronization

**Main synchronization condition:**

**the electron and hadron bunch repetition frequencies at the collision points have to be the same:**

$$f_{be} = f_{bh}$$

**The hadron bunch frequency (at the fixed circumference) depends on the hadron energy**

**Presently accepted solution for the frequency synchronization includes:**

➤ **Hadron delay line**

*Preliminary design provides up to 16 cm path lengthening ability.*

➤ **The RF harmonic switching method;**

*Used to operate with the hadron energies <50 GeV/n*

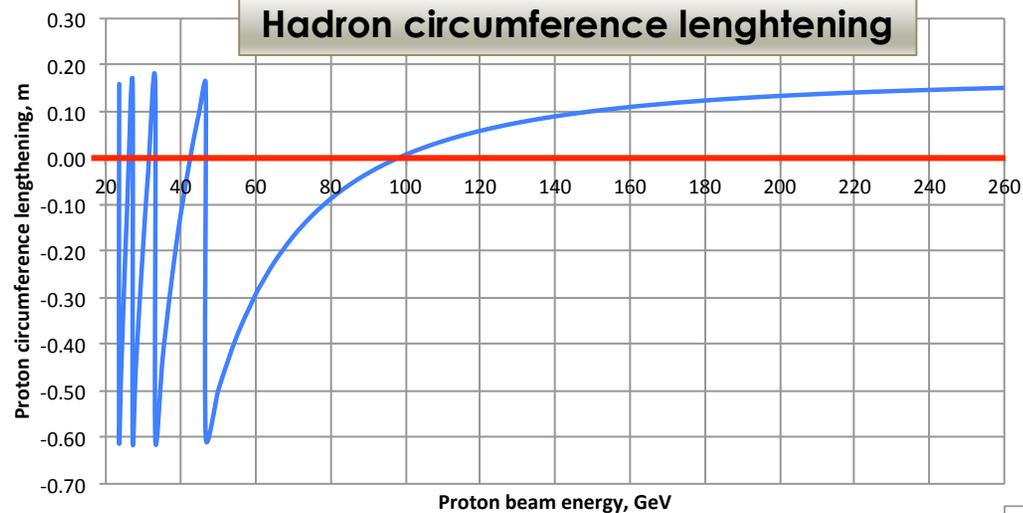
# Hadron Circumference Lengthening and Harmonic Switching

$$C_e = \frac{h_e}{5280} \frac{C_h}{\beta_h}$$

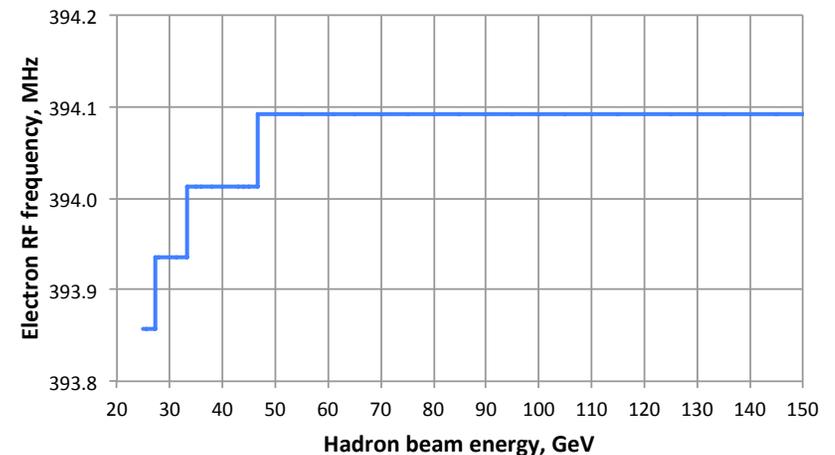
**Delay line: max 16cm**

**The operation is possible only above the red line (positive path lengthening)**

**Sharp changes corresponds to the change of electron RF harmonic ( $h_e$ )**



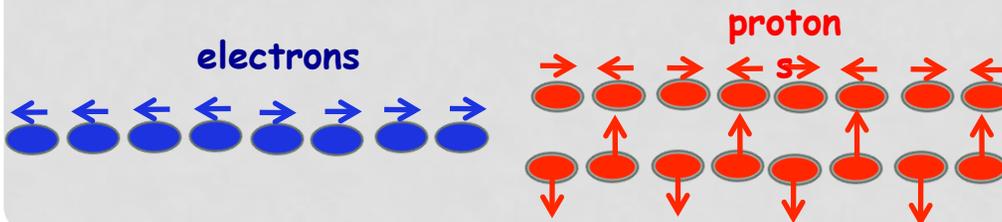
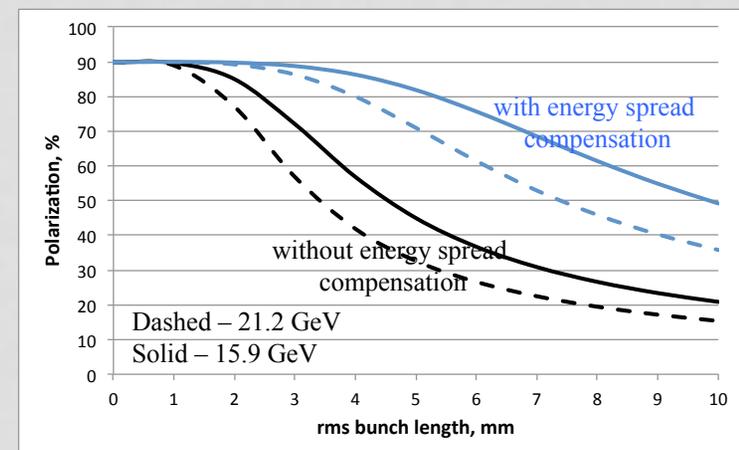
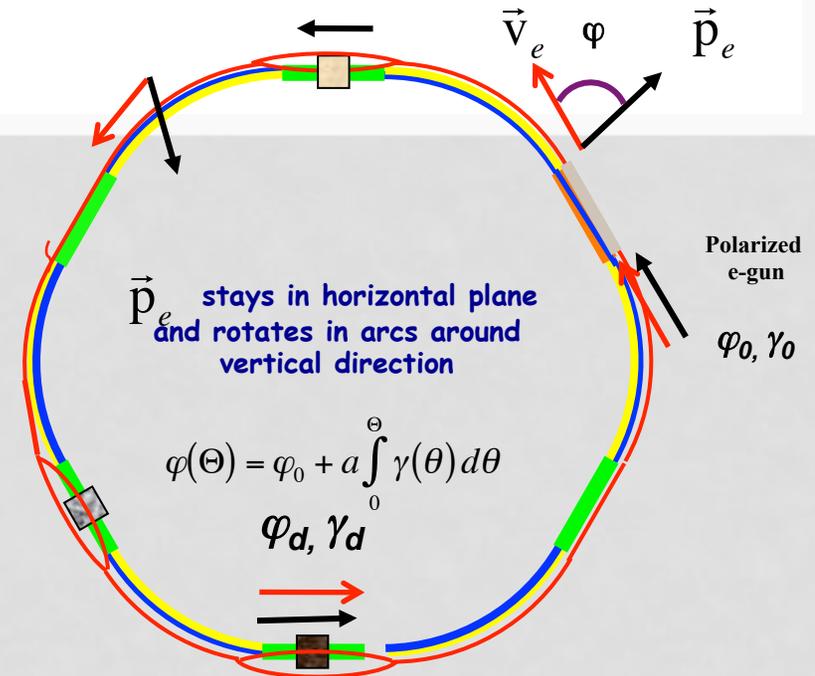
**Linac RF frequency**



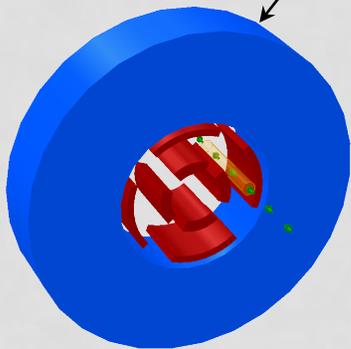
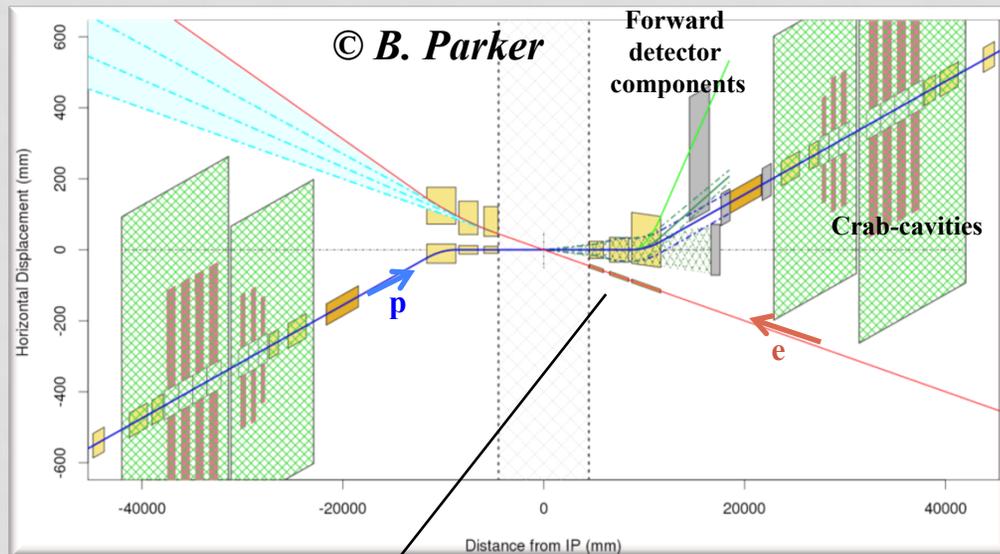
**Accessible proton energy ranges:**  
**100-250 GeV; 43-46 GeV; 31.6-33.2 GeV;**  
**26.3-27.1 GeV; 23-23.5 GeV**

# Electron Polarization in eRHIC

- 90% longitudinally polarized e-beam from DC gun with super-lattice GaAs-photocathode with polarization sign reversal by changing helicity of laser photons.
- Only longitudinal polarization is needed in the IPs.
- eRHIC avoids lengthy spin rotator insertions. Cost saving.
- Integer number of 180-degree spin rotations between the gun and IPs
- With the linac energy of 1.322 GeV the polarization is longitudinal at both experimental IPs
- To achieve 80% polarization up to 21.2 GeV harmonic cavities are used for the energy spread reduction



# Interaction Region with $\beta^* = 5 \text{ cm}$

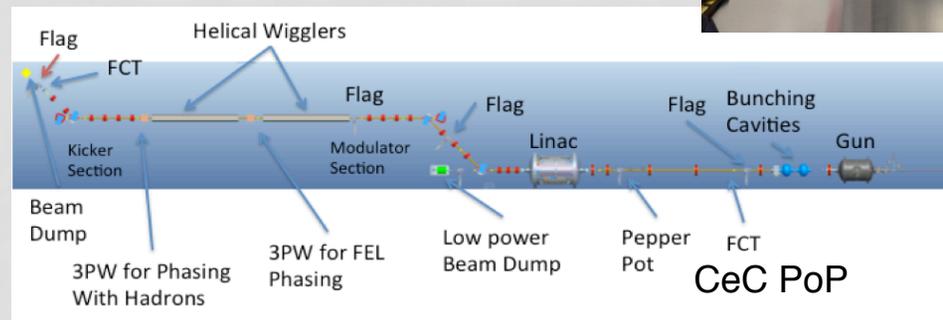
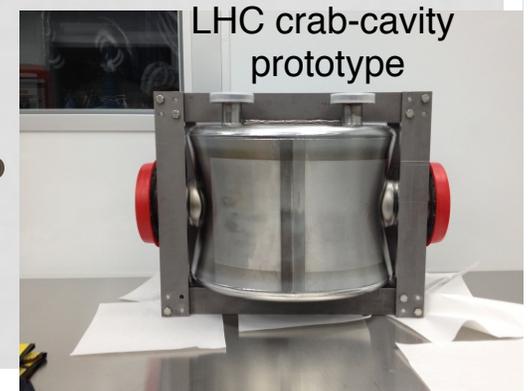
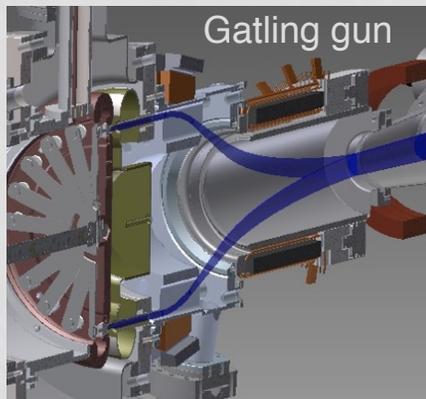


**Electron passage is arranged between SC coils of hadron magnet**

- 10 mrad crossing angle with crab-crossing
- Large enough aperture IR SC magnets for forward collision products and with field-free passage for electron beam
- Recent IR design improvements on the magnet design with electron passage and integration of detector components
- 90 degree lattice and beta-beat in adjacent arcs (ATS) to reach  $\beta^*$  of 5 cm and provide effective chromatic corrections

# eRHIC R&D and demonstration tests

- Prototyping of Gatling Gun polarized electron source
- Coherent electron Cooling PoP using 40 GeV/n Au beams in RHIC
- High average current ERL to support operation with high current e-beam
- FFAG Demo prototype
- Development of high gradient crab cavities within LARP



*For more details: Y. Hao's talk on eRHIC accelerator R&D on Tuesday*

# Summary

- The present cost-effective design of ERL-based eRHIC relies on FFAG lattice of recirculation passes and reaches high luminosity ( $> 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ ) up to 125 GeV CM energy and 145 GeV CM energy for somewhat lower luminosity.
- Studies of design issues specific for the FFAG lattice approach have not revealed showstoppers. Solutions have been found for the optimal FFAG lattice, spreader/combiner, orbit measurement and correction, ion gap formation ... .
- Several R&Ds are under way with results expected in 2014-2016
- Modest upgrades to the hadron ring would support highest luminosity ( $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ).

# Acknowledgements

for their contributions to the FFAG eRHIC Accelerator design:

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