# eRHIC Ring-Ring Design Strategy

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On behalf of the eRHIC Ring-Ring Design Team

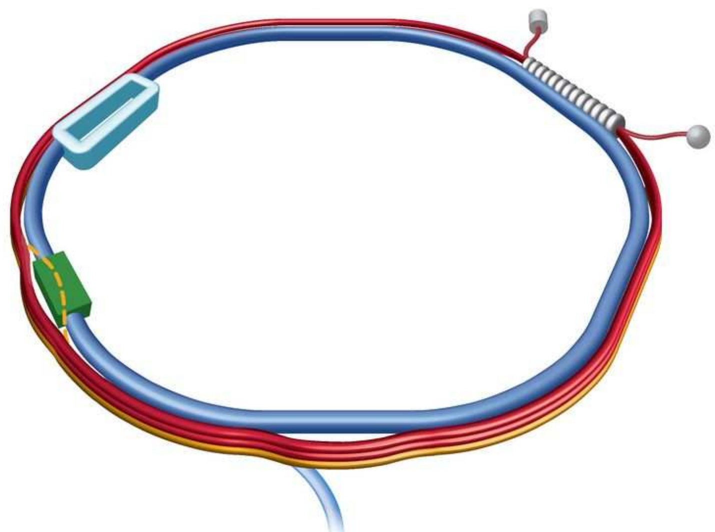
BNL eRHIC Advisory Committee, July 11, 2016

# The Charge

The machine design should aim to cover the parameters listed in the Long Range Plan:

- CM energy: 20 - 100 GeV; possibly upgradable to 140 GeV
- Luminosity: $0.1 - 1 \times 10^{33}$; upgradable to $1 - 10 \times 10^{33}$ with modest upgrades depending on R&D progress for ion cooling
- Frequent changes to the spin-sign assignment of the electron beam as determined by the Physics requirements
- Beam divergencies at the IR not exceeding the experimental requirements

# Design overview



- Electron storage ring with 10 GeV, upgradeable to 20 GeV
- 330 bunches per ring
- High intensity ($3.1 \cdot 10^{11}$) electron bunches, 1.35 A electron current
- Flat proton emittances, 4.7 $\mu$m hor., 1.8 $\mu$m vert.
- Moderate proton bunch intensities, $1.5 \cdot 10^{11}$
- Full energy polarized electron injector

# Interaction region

- Interaction region has undergone a major revision

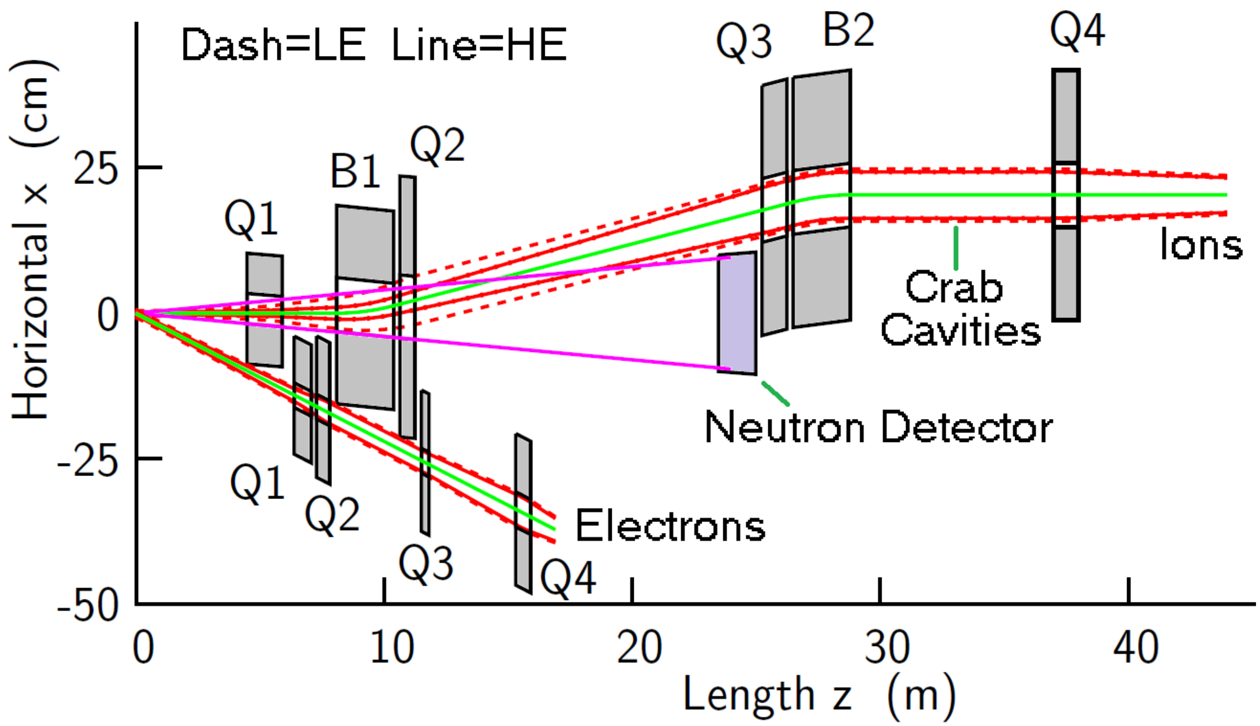
- Previous "Baseline" design had hadron doublet at 32 m from the IP, requiring large apertures and causing large chromaticities

- Adopted new IR design with actively shielded hadron magnets at 4.5 m

- Luminosity upgrades do not require rebuilding this new IR

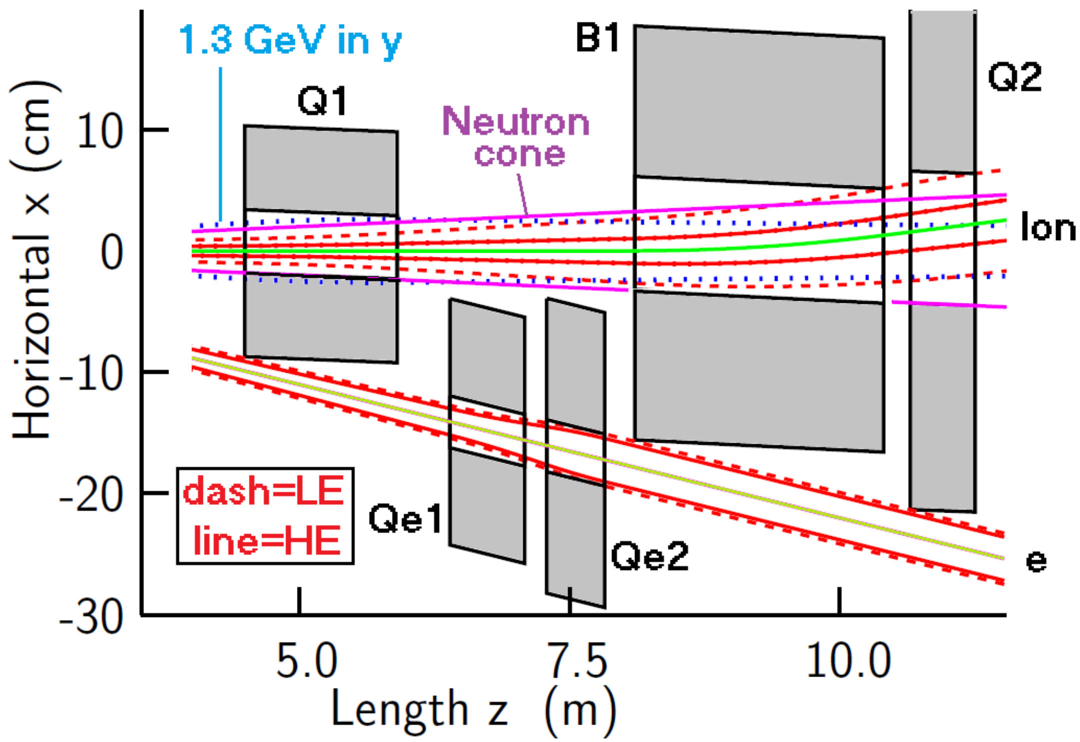
- Developed new set of beam parameters consistent with this IR design

# IR layout



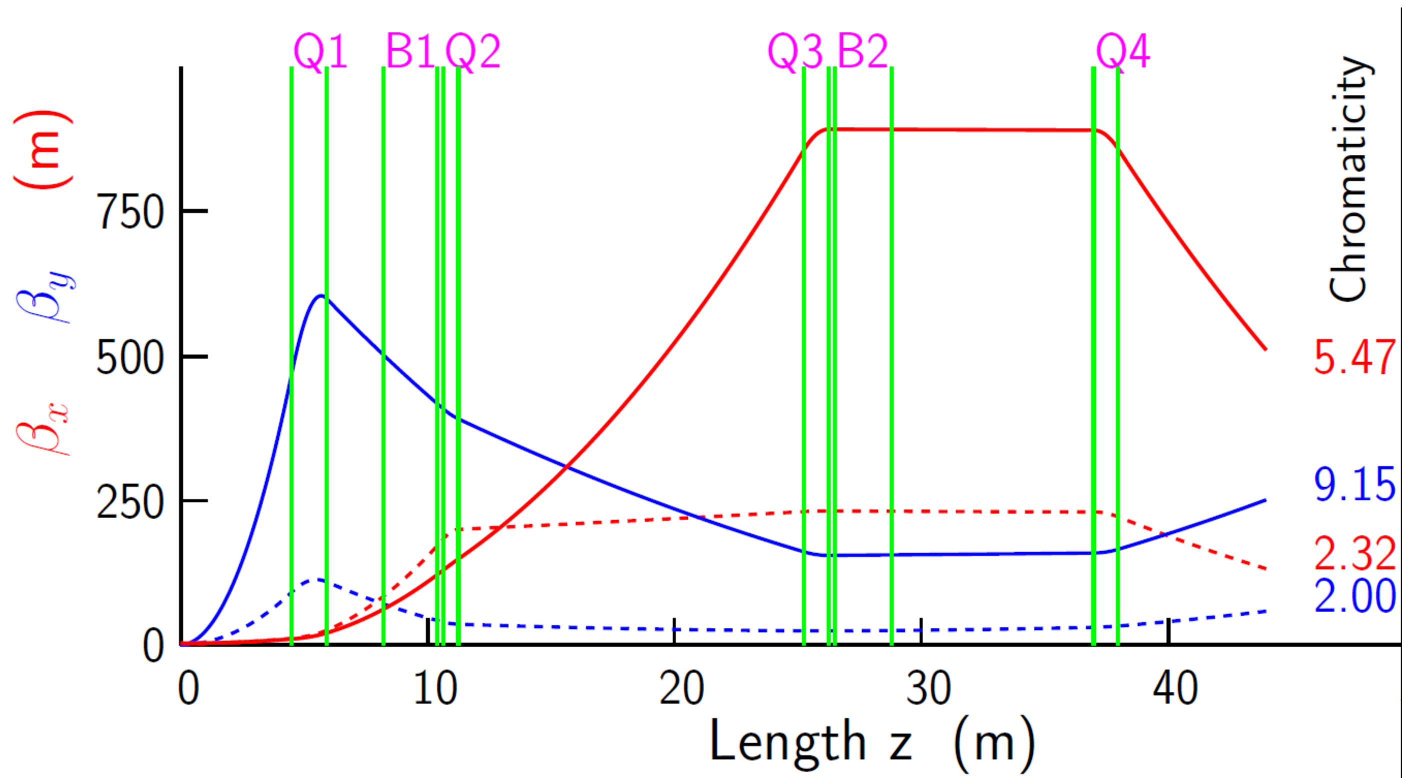

- Interleaved arrangement of electron and hadron quadrupoles
- 22 mrad total crossing angle
- Beam size in crab cavity region independent of energy - crab cavity apertures can be rather small, thus allowing for higher frequency

# Detailed view



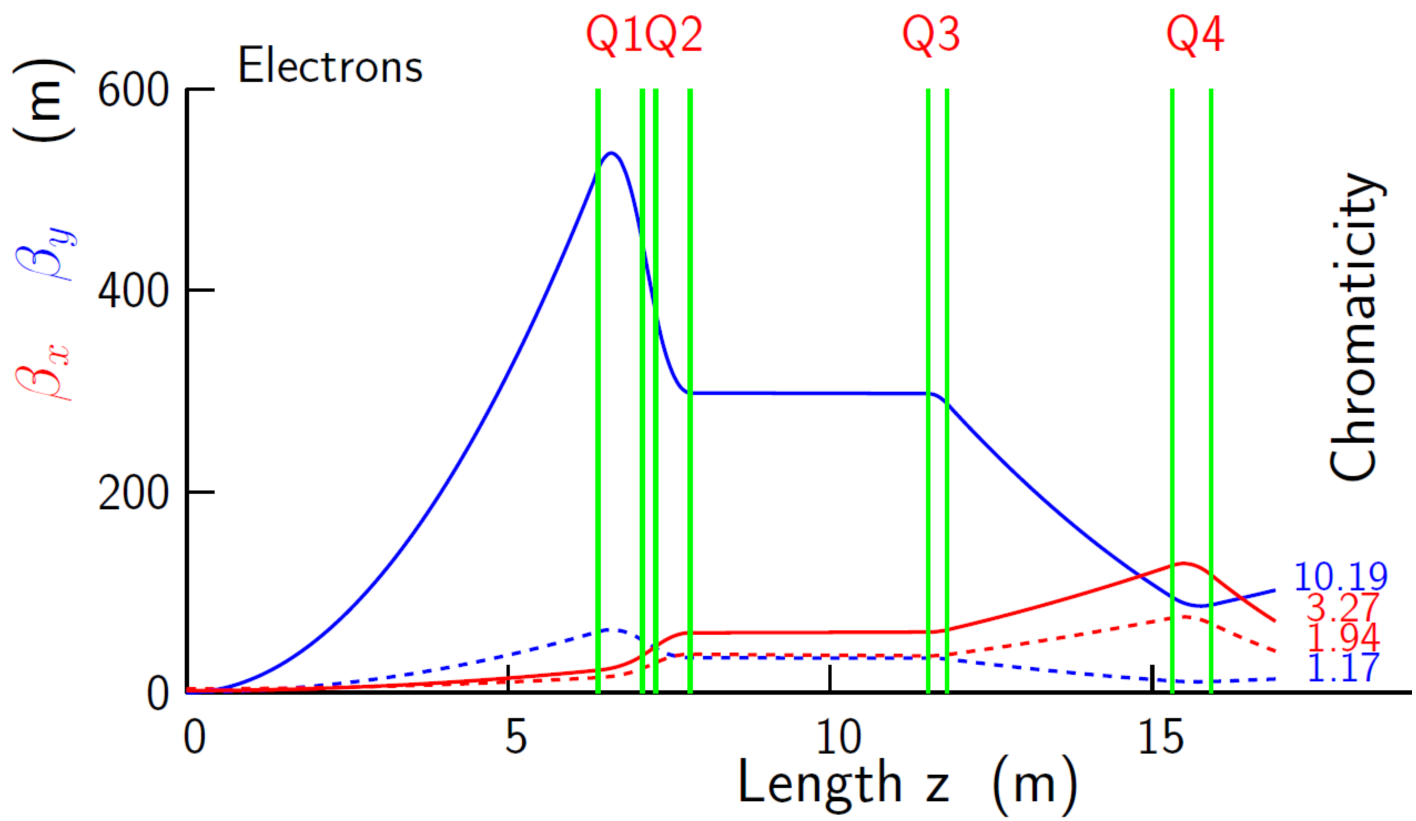

- IR magnets are "appropriately aggressive." While challenging, fundamental design parameters are consistent with previous experience
- Main risk from overall complexity, requiring carefull attention to detail to satisfy accelerator, physics and magnet production requirements

# Proton $\beta$-functions at highest and lowest energies




- Solid: 250 GeV; Dashed: 50 GeV
- Maximum $\beta$ around 850 m, keeping chromaticities small
- Beam size in crab cavities independent of energy

# Electron $\beta$-functions at highest and lowest energies




• Solid: 20 GeV; Dashed: 4.4 GeV

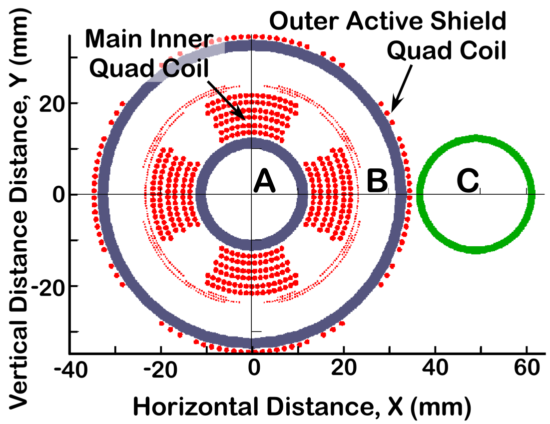
• Small chromaticities due to early focusing - corresponding number for KEKB is 38

# IR magnet parameters

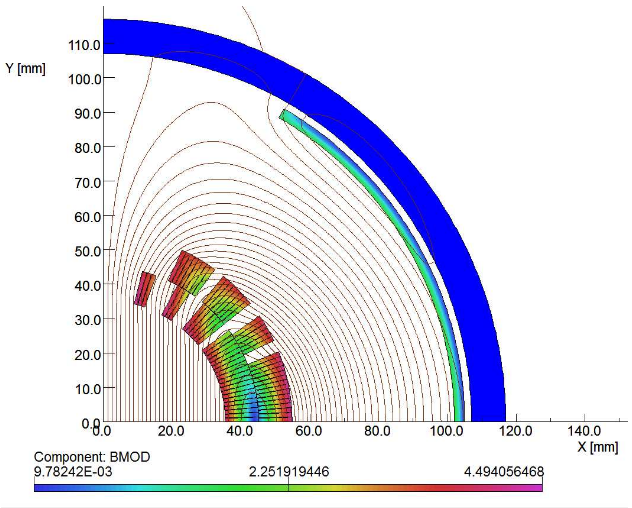
| | $s_{\text{downstream}}$ m | $L$ m | IR cm | OR cm | $B_{\text{pole}}$ T | gradient T/m |
|---|---|---|---|---|---|---|
| Q1 | 5.91 | 1.41 | 2.61 | 9.51 | 3.70 | -141.67 |
| B1 | 10.41 | 2.30 | 4.65 | 17.05 | 4.00 | 0 |
| Q2 | 11.26 | 0.60 | 5.44 | 22.44 | 1.50 | 27.50 |
| Q3 | 26.26 | 1.00 | 4.49 | 21.49 | 1.54 | 34.33 |
| B2 | 28.81 | 2.30 | 4.49 | 21.49 | -4.00 | 0 |
| Q4 | 38.00 | 0.99 | 4.47 | 21.47 | 1.42 | 31.67 |
| Qe1 | 7.09 | 0.69 | 2.14 | 10.14 | 1.08 | -50.41 |
| Qe2 | 7.83 | 0.53 | 2.15 | 12.15 | 1.23 | 57.45 |
| Qe3 | 11.83 | 0.30 | 2.14 | 12.15 | 0.57 | -26.67 |
| Qe4 | 15.93 | 0.60 | 3.02 | 16.00 | 1.01 | 33.33 |

- Cold masses to be installed in shared vacuum vessel
- Inner radii determined by maximum $10\sigma$ proton, $15\sigma$ electron size over entire energy range
- Outer radii determined by space available between beams
- Developed conceptual designs for the most challenging magnets

# IR magnets







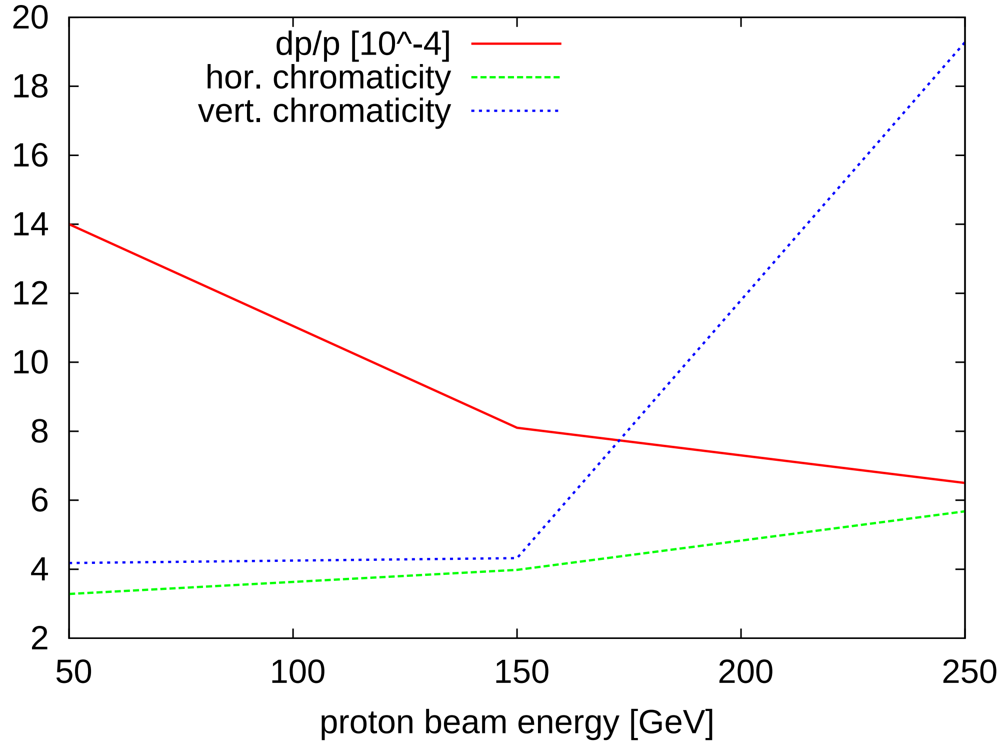

- Prototype for actively shielded quadrupole already exists as part of ILC work
- Actively shielded dipole has been designed conceptually

# Proton beam parameters for Baseline

| | | eRHIC | RHIC |
|---|---|---|---|
| $N_b$ | | 330 | 110 |
| max. $N_p$ | $[10^{11}]$ | 1.5 | 2.5 |
| $\epsilon_N$ hor./vert. | [$\mu$m] | 4.7/1.8 | 2.5/2.5 |
| min. $\sigma_s$ | [cm] | 8 | 20 |
| max. $\Delta p/p$ | $10^{-4}$ | 14 | 5 |
| min. $\beta_p^*$ | [cm] | 4.4 | 60 |
| max. $\hat{\beta}_p$ | [km] | 0.9 | 3 |
| min. $\tau_{\mathrm{IBS}}$ | [h] | 7.3 | 4.8 |
| max. $\mathcal{L}$ | $[10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}]$ | 1.7 | |

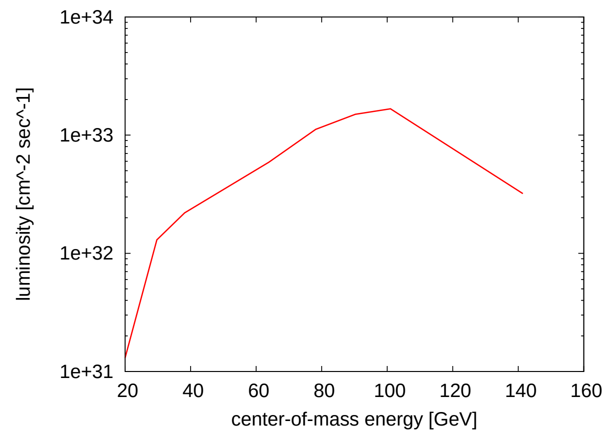
- Only most extreme parameters are listed - complete list in Backup Slides
- Proton emittances can be achieved by slight shaving (vertical, 25 percent reduction) and noise injection (horizontal) - long IBS growth time requires no cooling whatsoever while ensuring high average luminosity
- Necessary decoupling required for flat beams demonstrated at RHIC during 31.2 GeV d-Au run

# Proton IR chromaticities and momentum spread




- Very low IR chromaticity at low energy where dp/p is large
- High energy IR chromaticity comparable to present RHIC
- Off-momentum dynamic aperture expected to be sufficient - to be confirmed by tracking

# Luminosity vs. $\sqrt{s}$




- $1.7 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ peak luminosity with 10 GeV electrons, 250 GeV protons, including hourglass, crab crossing, and abort gap
- Luminosity above $1 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ for 70 GeV $< \sqrt{s} <$ 100 GeV
- Electron energy 5 GeV or higher, as suggested by detector designers, except for lowest energy point at $\sqrt{s} = 20$ GeV
- Lowest energy assumes no radiation damping for 2 GeV electrons. Could be improved with aggressive superbends at expense of wide magnets. Alternative: 5 GeV electrons on 20 GeV protons, requiring large bypasses for circumference adjustment

# Electron polarization

- Self-polarization not viable below 20 GeV due to long Sokolov-Ternov time - need a full-energy polarized electron injector

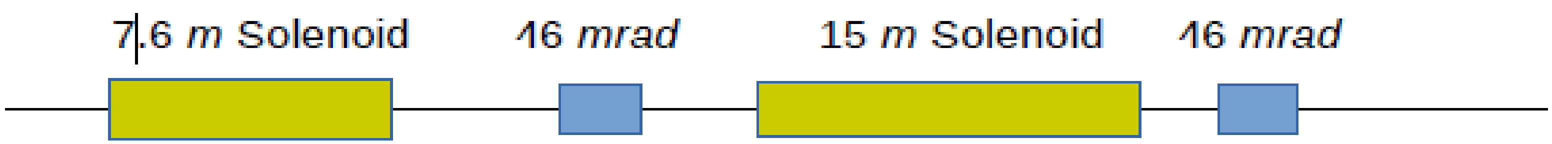
- Experiments require arbitrary spin patterns

- Inject bunches with required spin direction (up or down), and replace faster than Sokolov-Ternov

- 1 Hz injector cycle replaces each individual of the 360 bunches in 6 min

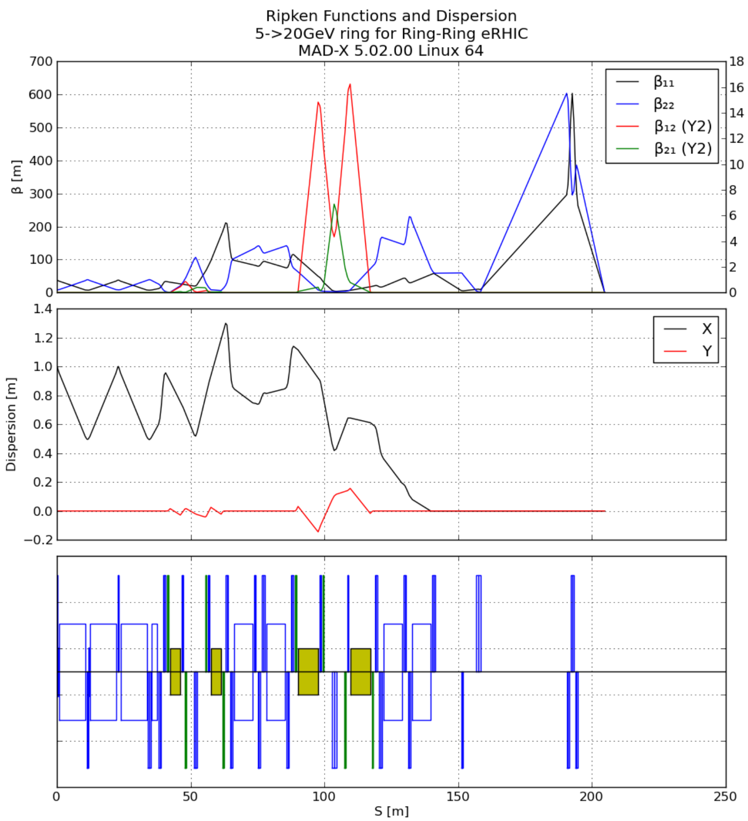
## Spin rotators

- Electron spin rotators will be based on solenoids with subsequent bends




- Proper setting of the two solenoids provides longitudinal polarization at all energies, 5-20 GeV
- Maximum solenoid field 7 T

# Optics design of interaction region straight with spin rotators




- Complete integrated design with dispersion suppressor, coupling compensation, low-$\beta$ section, and matching into arc

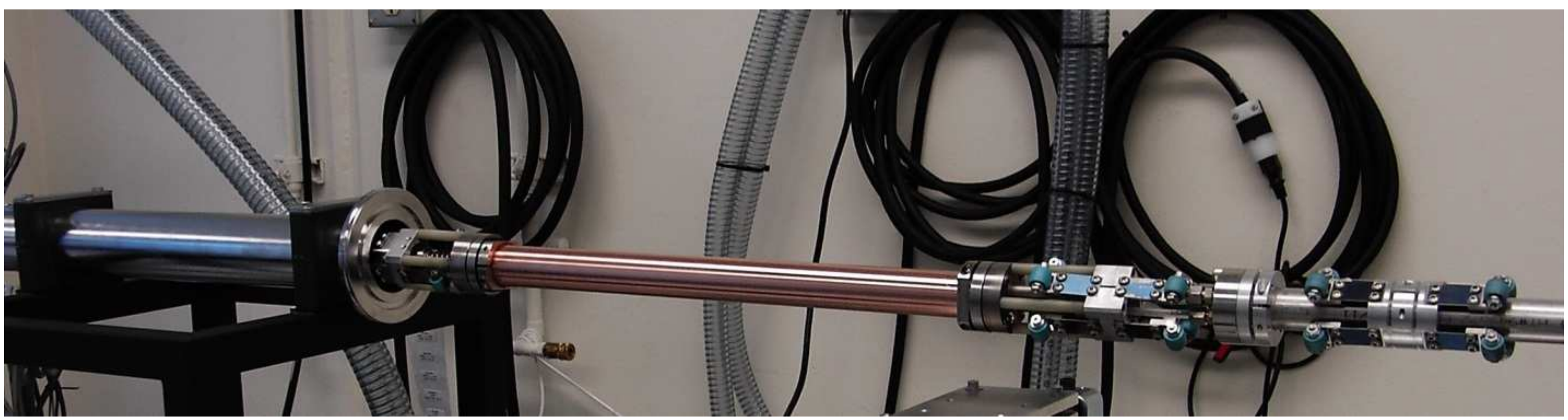
# In-situ beam pipe coating

• In-situ beam pipe coating of an entire machine has never been done, but successful coating of 20 m combination of cold-bore RHIC tubing & bellows having room temperature conductivity 85% of solid copper was achieved.

• The required baseline performance of $\approx 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ can still be achieved based on 180 bunches - heat load from ohmic losses for uncoated stainless steel pipes is 0.85 W/m

• Backup options:

- Weave copper wire cage (or ribbons) during deposition; copper deposition adds to conductivity and acts as a glue
- Folded cage insertion opens like umbrella with disengaging opening mechanism



- RHIC cryo capacity limit corresponds to heat load of 0.5-1 W/m from resistive wall and electron cloud

- Using a resistivity of $2.7 \cdot 10^{-8}\,\Omega \cdot$ m (room temperature copper - at 4 K it's 100 times better), 360 proton bunches with $N = 1.5 \cdot 10^{11}$/bunch and $\sigma_s = 8$ cm generate 0.37 W/m - well below the limit

- Caveat:
  Increase in effective resistivity due to magneto-resistance - to be quantified by putting a copper resonator in a high field magnet and measuring the change in $Q$ as function of magnetic field. Resonator capable of operating at cryogenic temperatures is about to be setup
  Heat load from electron clouds still needs to be evaluated

- Could use mole to add layer of amorphous carbon to reduce SEY for e-cloud if necessary. E-cloud simulation results for Cu-coated eRHIC are slightly better than for present LHC with 25 nsec, $1.2 \cdot 10^{11}$ (Details in Backup Slides)

- Estimated time to coat full ring: 120 days in 3 shifts

- eRHIC construction may be only opportunity for coating

# Crab cavities

- Short, wide proton bunches and low $\beta$ in crab cavity location allow for high RF cavity frequency - 336 MHz (similar to LHC prototype)

- Higher frequency requires less voltage - need up to 8 MV at 336 MHz

- Geometric effect of adding a second harmonic is negligible (2 percent), indicating that beam dynamics is likely unaffected

- According to simulations, electrons likely need crab cavities, too. Could copy KEKB crab cavity design

# Beam-beam

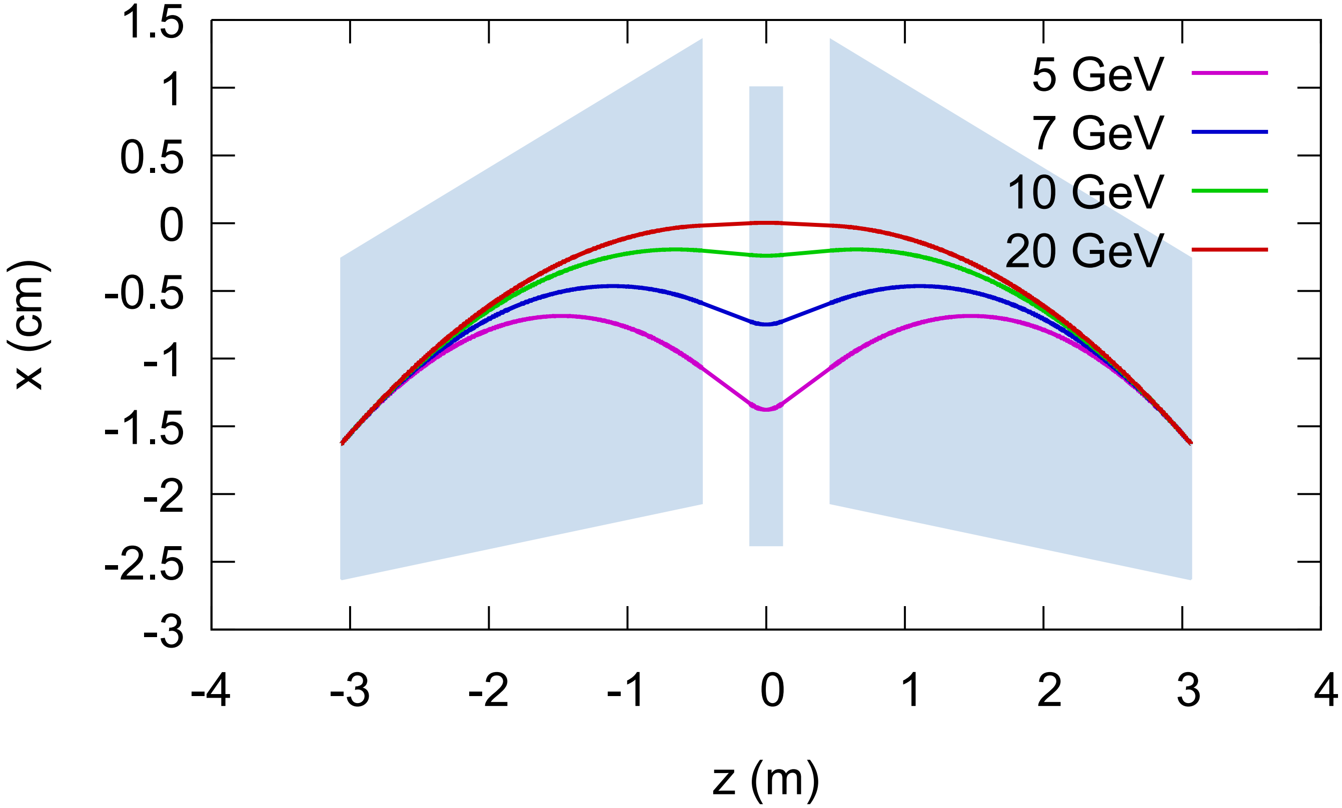
- Electron and proton beam-beam parameters have been achieved in $e^+e^-$ colliders and RHIC, resp.

- Effect of crab crossing with long (up to 13 cm),flat proton bunches on both beams needs to be studied in weak-strong simulations - in progress

- Effect of electron bunch replacement - with or without accumulation - on proton emittance to be studied using RHIC electron lens and simulations

- Strong-strong simulations to study coherent beam-beam, kink instability in collaboration with LBNL. Preliminary studies show no sign of kink instability

# Superbends




Short, sharp bends to increase damping decrement at low energies, thus allowing high electron beam-beam parameter $\xi = 0.1$

# Proton injection

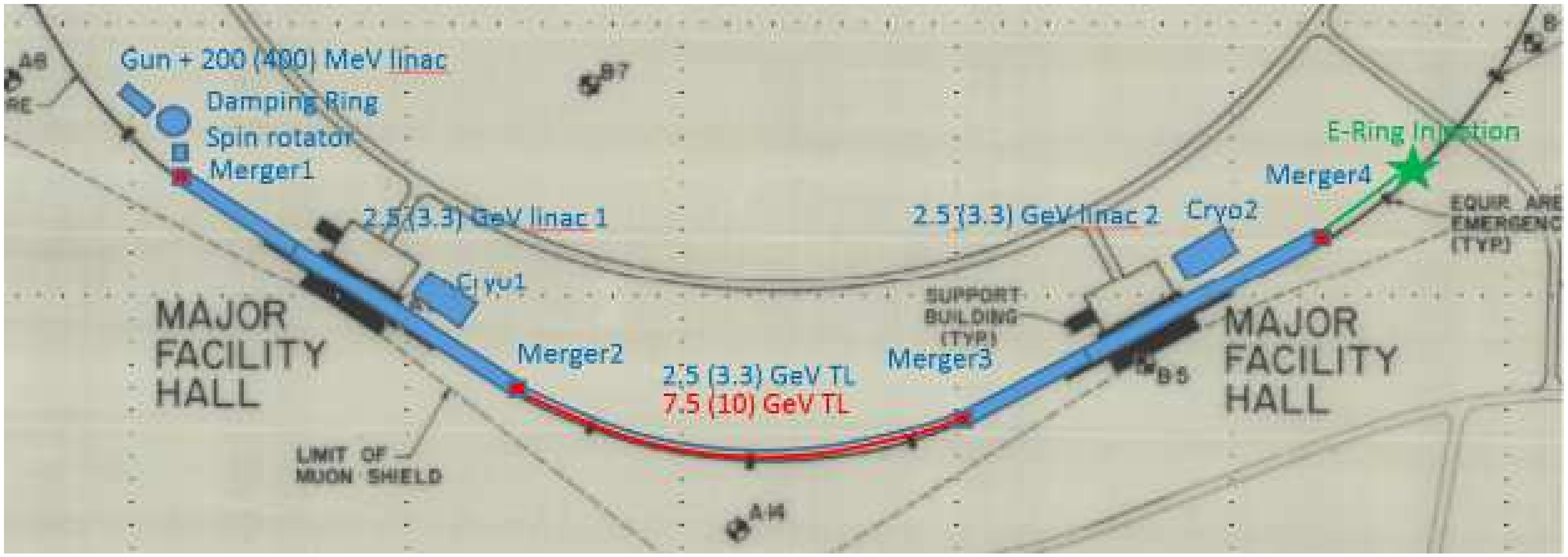
- Injecting 330 proton bunches requires new, faster injection kickers
- Full bunch length of $\tau_b = 15\,$nsec, spaced at $\tau_s = 35\,$nsec
- Strip line kickers, $L = 1.25\,$m long give rise time $\tau_r = \tau_s - \tau_b - 2L/c = 12\,$nsec
- Deflection angle $\phi = 2\,$mrad requires 16 modules for 24 GeV protons
- Total kicker length approx. 25 m
- Available space in present injection kicker location is only approx. 6 m

Solution:

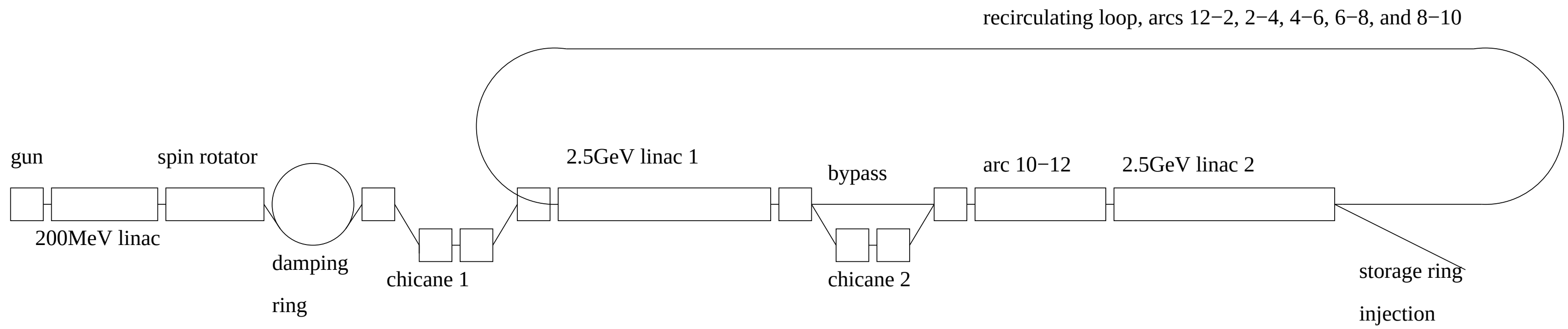
• Extend transfer line through one RHIC arc and inject in warm straight section in IR 8

• May be able to use Yellow arc as transfer line, after diode polarity flip

# Full-energy polarized electron injector




- Recirculating linac based on XFEL/LCLS-2 cryomodules
- With two 2.5 GeV linacs in two adjacent RHIC straights, one recirculation to 10 GeV
- To reach 20 GeV, add cryomodules to reach 3.3 GeV per linac, and a second recirculating loop




- Bunch replacement scheme requires acceleration of high intensity (up to $3.1 \cdot 10^{11}$, or 50 nC) bunches in injector

- Acceleration of 90 nC bunches was demonstrated at ISIR in Japan, with warm 1.3 GHz linac

- Accumulator ring at $\approx$ 250 MeV to generate high intensity bunches

- Two chicanes for bunch compression

- Investigating beam-beam effect of full energy bunch accumulation in electron storage ring in simulations as an alternative scheme. Detector background is potential concern

# Energy upgrade

Initial configuration provides electrons up to 10 GeV
Energy upgrade to 20 GeV:

- Add more RF cavities to the storage ring, for a total of $\approx$ 80 MV. This also raises the available power to 10 MW
- Extend injector linacs to raise total energy from 5 GeV to 6.6 GeV
- Add a second recirculating loop in the RHIC tunnel

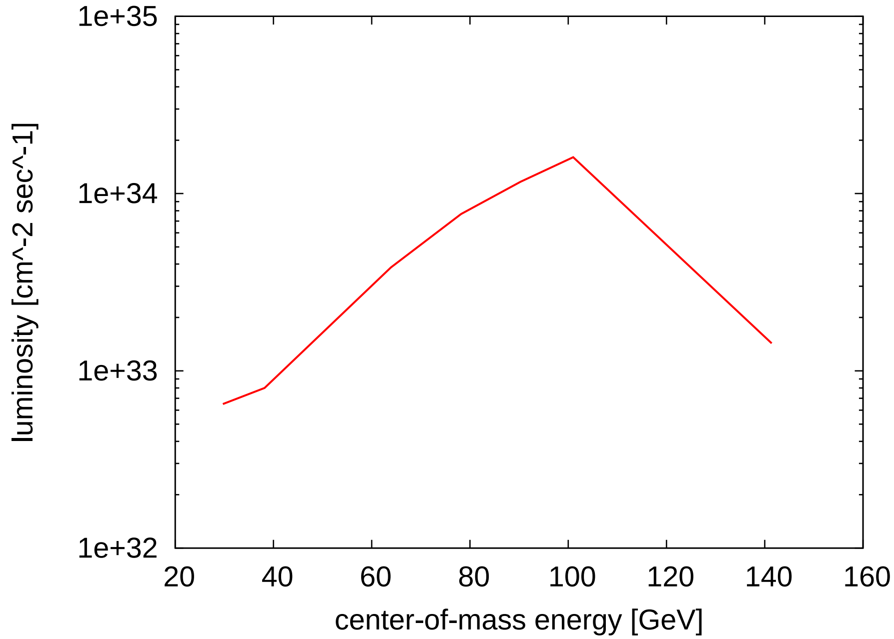
# Luminosity upgrade

- Luminosity upgrade path relies on increasing the number of bunches, and ultimately cooling
- Increasing the number of proton bunches to 660 with $1.5 \cdot 10^{11}$ - and ultimately to 1300 at half the bunch intensity - requires beam pipe coating to work
- Coating quality can be explored experimentally with baseline set-up
- As an intermediate step, 660 bunches provide peak luminosity of $3.4 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. 10 MW electron RF already in place after energy upgrade. No hardware modifications or additions needed
- Simple scaling laws suggest that a 100 m long magnetized electron cooler with 60 nC may be sufficient to achieve normalized emittances of $2.5\,\mu\mathrm{m}/0.2\,\mu\mathrm{m}$ for the Ultimate Design with $16 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ - large electron beam current, but no CeC required

- No IR geometry modifications required

- One type of IR quadrupole needs to be replaced with high gradient (170 T/m) magnet

- Ultimate peak luminosity: $16 \cdot 10^{33}\,\text{cm}^{-2}\text{sec}^{-1}$



# Risk assessment

- Crab cavities:
  High risk - absolute must in any EIC

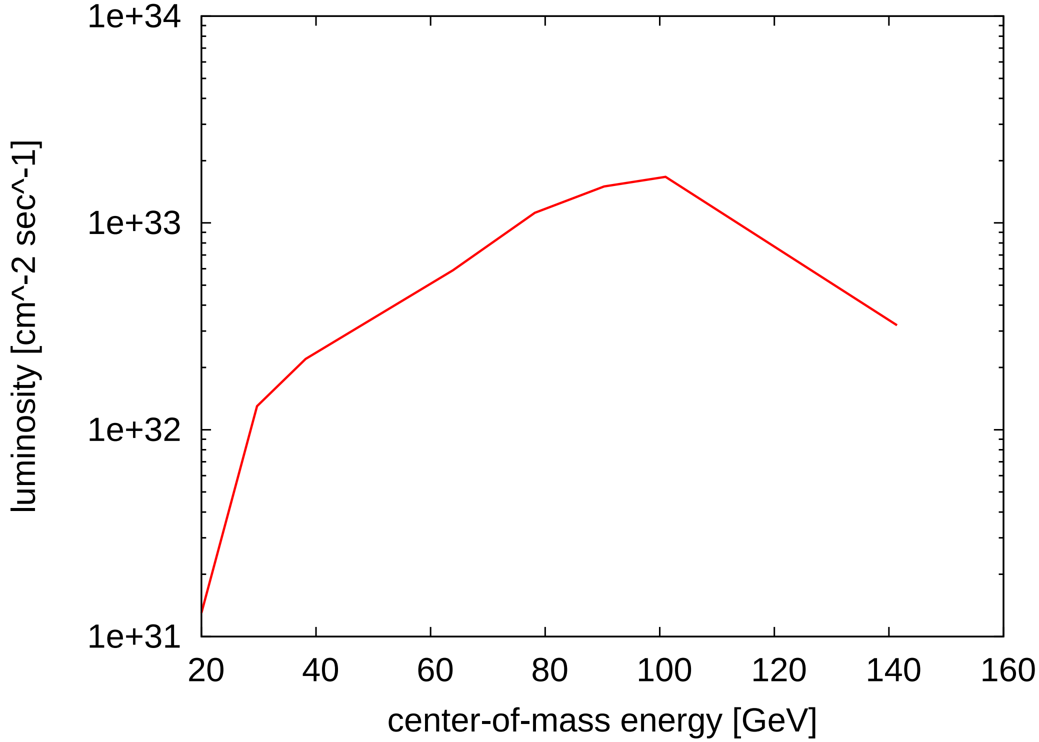
- Beam pipe coating:
  Medium risk - multiple methods under study. Could run with 180 bunches for $0.85 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ peak luminosity in case of total failure

- Recirculating injector linac:
  Low risk - existing, mass produced technology, but beam loading effects due to high intensity bunches need to be studied. Alternative: accumulation in storage ring if backgrounds and beam-beam allow

- Electron polarization:
  Low risk - high polarization levels have been achieved in many storage rings, including HERA with its spin rotators. Required spin matching conditions are known, and eRHIC is designed accordingly

- Dynamic aperture due to chromaticity contribution from IR:
  Low risk - could increase vertical $\beta^*$ at the price of reduced luminosity. Electron IR chromaticity 4 times smaller than in KEKB

# Summary




- Baseline design provides $1.7 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ peak luminosity

- Baseline design does not require any cooling whatsoever, and has minimum IBS growth time of 7.3 hours - long stores, high average luminosity

- Ring-ring eRHIC - and especially its luminosity upgrade - is based on many (330 - 660 - 1300) bunches, requiring copper coated beam pipes
- "Barebones" approach with only 165 bunches (no copper coating) still provides $0.85 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ peak luminosity. eRHIC construction may be only opportunity to copper coat beam pipes
- Intermediate luminosity upgrade to 660 bunches provides $3.4 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ peak luminosity, without cooling
- With 1300 bunches and magnetized cooling peak luminosity reaches $16 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ in Ultimate upgrade
- Interaction region with close-in low-$\beta$ quadrupoles requires 22 mrad crossing angle, and therefore crab cavities - as any EIC design does

# Backup Slides

# Complete parameter list for Baseline

| | E GeV | N $10^{10}$ | $\epsilon_x(\epsilon_{Nx})$ nm($\mu$m) | $\epsilon_y(\epsilon_{Ny})$ nm($\mu$m) | $\beta_x$ m | $\beta_y$ m | $\sigma_x$ $\mu$m | $\sigma_y$ $\mu$m | $\xi_x$ | $\xi_y$ | $\widehat{p}_\perp$ MeV | $\sigma_s$ cm | SR MW | lum $10^{33}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\sqrt{s}$ | 20 | | | | | | | | | | | | | |
| p | 50 | 0.8 | 87(4.7) | 33(1.8) | 2.2 | 0.22 | 439 | 85 | .015 | .014 | 99 | 13.0 | 0.0 | 0.013 |
| e | 2 | 31 | 53(236) | 11(48) | 3.7 | 0.68 | 441 | 86 | .015 | .015 | | 0.8 | 0.1 | |
| $\sqrt{s}$ | 29.7 | | | | | | | | | | | | | |
| p | 50 | 9 | 87(4.7) | 33(1.8) | 2.2 | 0.22 | 439 | 85 | .014 | .007 | 99 | 13.0 | 0.0 | 0.13 |
| e | 4.4 | 31 | 53(520) | 11(105) | 3.7 | 0.68 | 441 | 86 | .065 | .062 | | 0.8 | 0.1 | |
| $\sqrt{s}$ | 38.2 | | | | | | | | | | | | | |
| p | 50 | 15 | 87(4.7) | 33(1.8) | 2.2 | 0.22 | 439 | 85 | .014 | .007 | 99 | 13.0 | 0.0 | 0.22 |
| e | 7.3 | 31 | 53(864) | 11(175) | 3.7 | 0.68 | 441 | 86 | .065 | .062 | | 0.8 | 1.1 | |
| $\sqrt{s}$ | 63.9 | | | | | | | | | | | | | |
| p | 100 | 15 | 43(4.7) | 16(1.8) | 2.2 | 0.10 | 311 | 41 | .014 | .005 | 139 | 12.0 | 0.0 | 0.59 |
| e | 10.2 | 31 | 38(861) | 5.8(132) | 2.6 | 0.30 | 312 | 42 | .069 | .059 | | 0.8 | 4.1 | |
| $\sqrt{s}$ | 78.2 | | | | | | | | | | | | | |
| p | 150 | 15 | 29(4.7) | 11(1.8) | 2.2 | 0.07 | 253 | 28 | .015 | .004 | 171 | 10.0 | 0.0 | 1.12 |
| e | 10.2 | 31 | 31(703) | 4.7(108) | 2.1 | 0.16 | 254 | 28 | .086 | .061 | | 0.8 | 4.1 | |
| $\sqrt{s}$ | 90.3 | | | | | | | | | | | | | |
| p | 200 | 13 | 22(4.7) | 8(1.8) | 2.2 | 0.05 | 219 | 21 | .015 | .004 | 199 | 9.0 | 0.0 | 1.50 |
| e | 10.2 | 31 | 27(609) | 4(97) | 1.8 | 0.10 | 219 | 21 | .099 | .059 | | 0.8 | 4.1 | |
| $\sqrt{s}$ | 101 | | | | | | | | | | | | | |
| p | 250 | 12 | 18(4.7) | 7(1.8) | 2.8 | 0.04 | 221 | 17 | .015 | .003 | 200 | 8.0 | 0.0 | 1.67 |
| e | 10.2 | 31 | 24(555) | 4(89) | 2.0 | 0.07 | 222 | 17 | .10 | .048 | | 0.8 | 4.1 | |
| $\sqrt{s}$ | 141.4 | | | | | | | | | | | | | |
| p | 250 | 15 | 17(4.7) | 7(1.8) | 2.8 | 0.04 | 219 | 17 | .002 | .000 | 198 | 8.0 | 0.0 | 0.32 |
| e | 20.0 | 5 | 24(931) | 4(149) | 2.0 | 0.08 | 220 | 17 | .065 | .035 | | 0.8 | 9.8 | |

- Luminosity numbers account for abort gap (330 bunches instead of 360), hourglass factor, and crab crossing

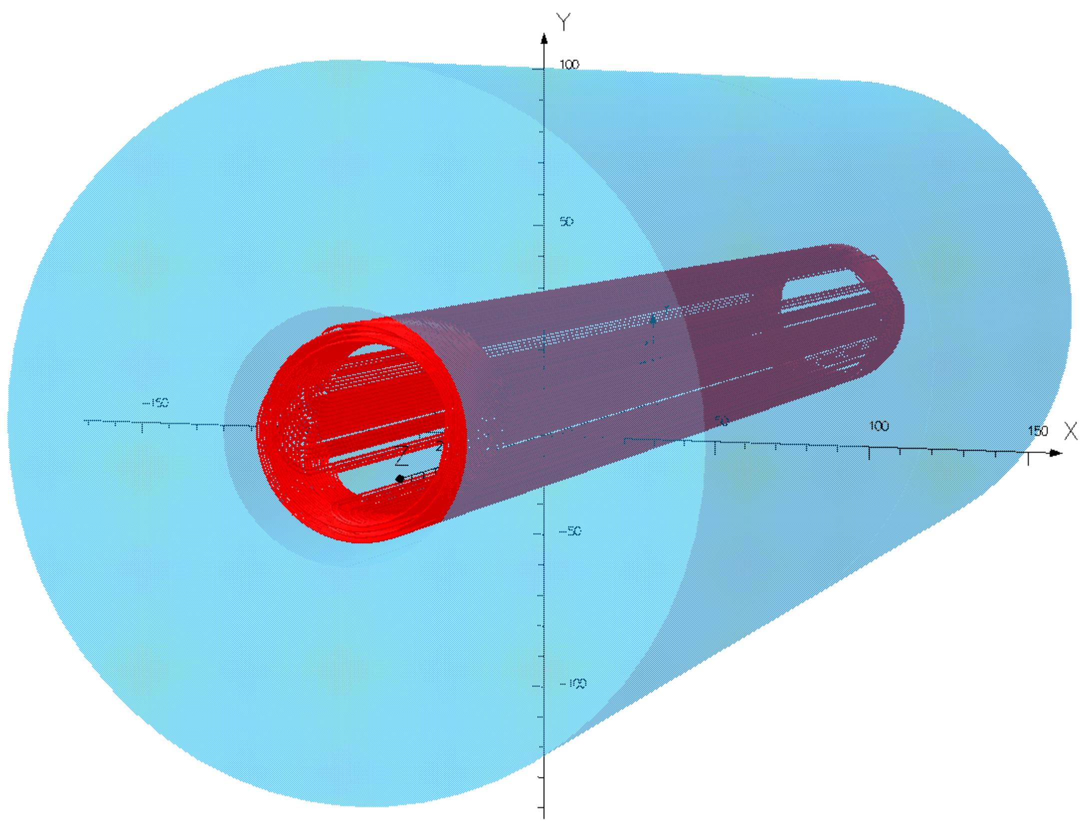
- Maximum synchrotron radiation power up to 10 GeV is 4.1 MW. 20 GeV requires 9.8 MW; increased power comes together with increased voltage need
- Lowest energy ($\sqrt{s} = 20\,\text{GeV}$) assumes no synchrotron radiation damping. Treating electrons like hadrons

# Complete parameter list for Ultimate Design

| | E<br>GeV | N<br>$10^{10}$ | $\epsilon_x(\epsilon_{Nx})$<br>nm($\mu$m) | $\epsilon_y(\epsilon_{Ny})$<br>nm($\mu$m) | $\beta_x$<br>m | $\beta_y$<br>m | $\sigma_x$<br>$\mu$m | $\sigma_y$<br>$\mu$m | $\xi_x$ | $\xi_y$ | $\widehat{p}_\perp$<br>MeV | $\sigma_s$<br>cm | SR<br>MW | lum<br>$10^{33}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\sqrt{s}$ | 29.7 | | | | | | | | | | | | | |
| p | 50 | 3.2 | 42(2.2) | 7.4(0.4) | 1.1 | 0.11 | 215 | 28 | .015 | .011 | 97 | 8.5 | 0.0 | 0.65 |
| e | 4.4 | 15.5 | 40(393) | 2.4(24) | 1.2 | 0.34 | 216 | 29 | .037 | .080 | | 0.4 | 0.0 | |
| $\sqrt{s}$ | 38.2 | | | | | | | | | | | | | |
| p | 50 | 4.0 | 42(2.2) | 7.7(0.4) | 1.1 | 0.11 | 215 | 29 | .015 | .011 | 97 | 8.5 | 0.0 | 0.80 |
| e | 7.3 | 15.5 | 40(653) | 2.5(41) | 1.2 | 0.34 | 216 | 29 | .028 | .062 | | 0.4 | 2.1 | |
| $\sqrt{s}$ | 63.9 | | | | | | | | | | | | | |
| p | 100 | 7.0 | 22(2.3) | 4.1(0.4) | 1.1 | 0.05 | 156 | 15 | .015 | .007 | 139 | 6.0 | 0.0 | 3.83 |
| e | 10.2 | 15.6 | 30(678) | 1.4(33) | 0.83 | 0.15 | 156 | 15 | .050 | .100 | | 0.4 | 8.1 | |
| $\sqrt{s}$ | 78.2 | | | | | | | | | | | | | |
| p | 150 | 7.0 | 15(2.4) | 2.2(0.4) | 1.1 | 0.04 | 130 | 9 | .014 | .007 | 176 | 6.0 | 0.0 | 7.66 |
| e | 10.2 | 15.6 | 25(581) | 1.0(22) | 0.66 | 0.08 | 130 | 9 | .059 | .100 | | 0.4 | 8.1 | |
| $\sqrt{s}$ | 90.3 | | | | | | | | | | | | | |
| p | 200 | 6.4 | 11(2.4) | 1.4(0.3) | 1.2 | 0.03 | 115 | 6 | .015 | .006 | 197 | 5.5 | 0.0 | 11.66 |
| e | 10.2 | 15.6 | 22(503) | 0.7(16) | 0.61 | 0.05 | 116 | 6 | .063 | .100 | | 0.4 | 8.1 | |
| $\sqrt{s}$ | 101 | | | | | | | | | | | | | |
| p | 250 | 6.1 | 9.5(2.6) | 0.8(0.2) | 1.5 | 0.02 | 120 | 4 | .014 | .006 | 199 | 5.5 | 0.0 | 16.04 |
| e | 10.2 | 15.6 | 21(471) | 0.4(10) | 0.7 | 0.04 | 120 | 4 | .064 | .100 | | 0.4 | 8.1 | |
| $\sqrt{s}$ | 141.4 | | | | | | | | | | | | | |
| p | 250 | 7.4 | 10(2.6) | 0.8(0.2) | 1.5 | 0.02 | 120 | 4 | .001 | .000 | 199 | 5.5 | 0.0 | 1.43 |
| e | 20.0 | 1.2 | 21(806) | 0.5(18) | 0.7 | 0.04 | 120 | 4 | .039 | .065 | | 0.4 | 9.2 | |

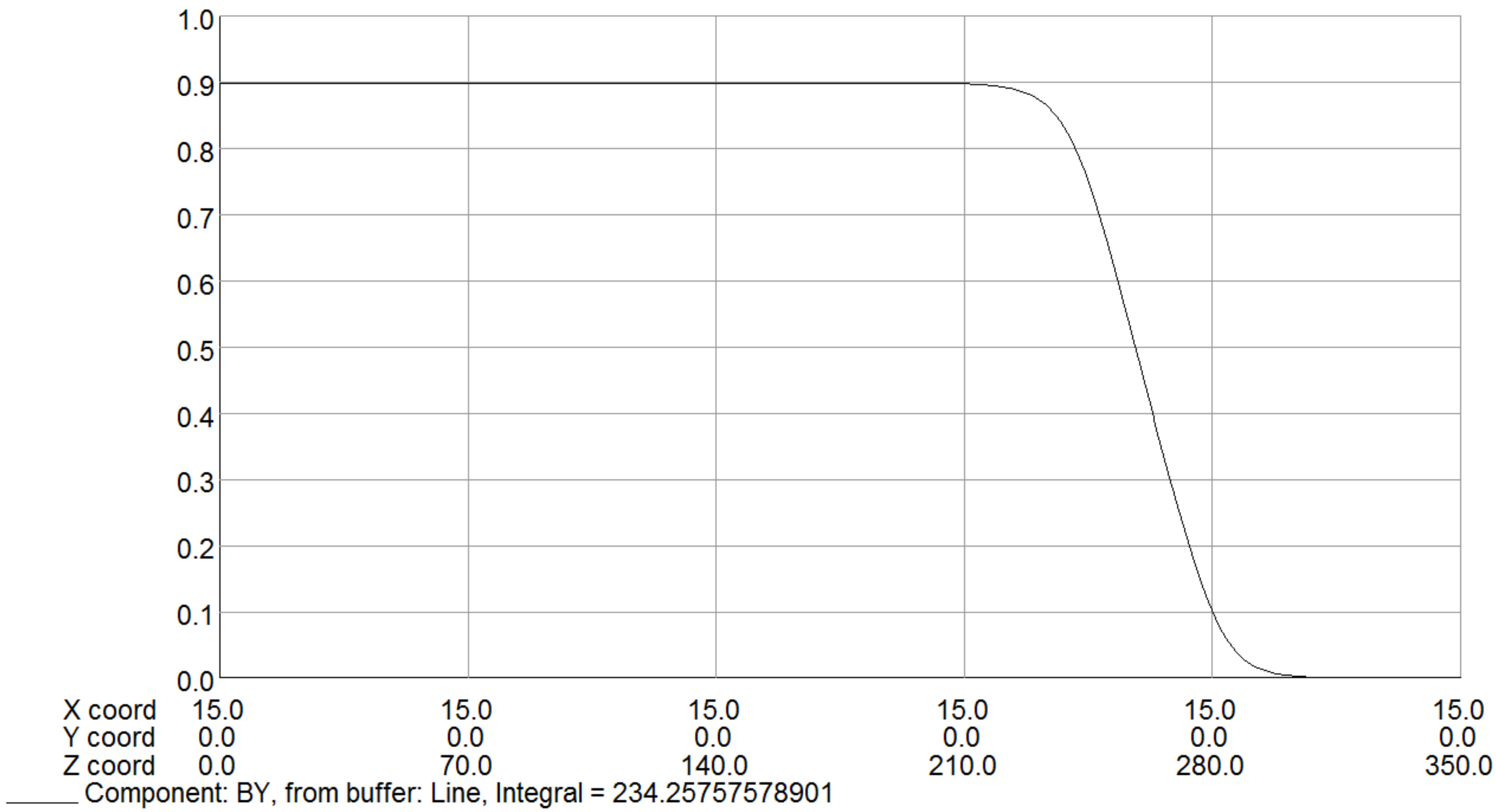
- 1300 very flat bunches plus 10 percent abort gap; hourglass, crab crossing included
- Small proton emittances require magnetized cooling, up to 60 nC in 100 m cooling section

# 3D view of QE2

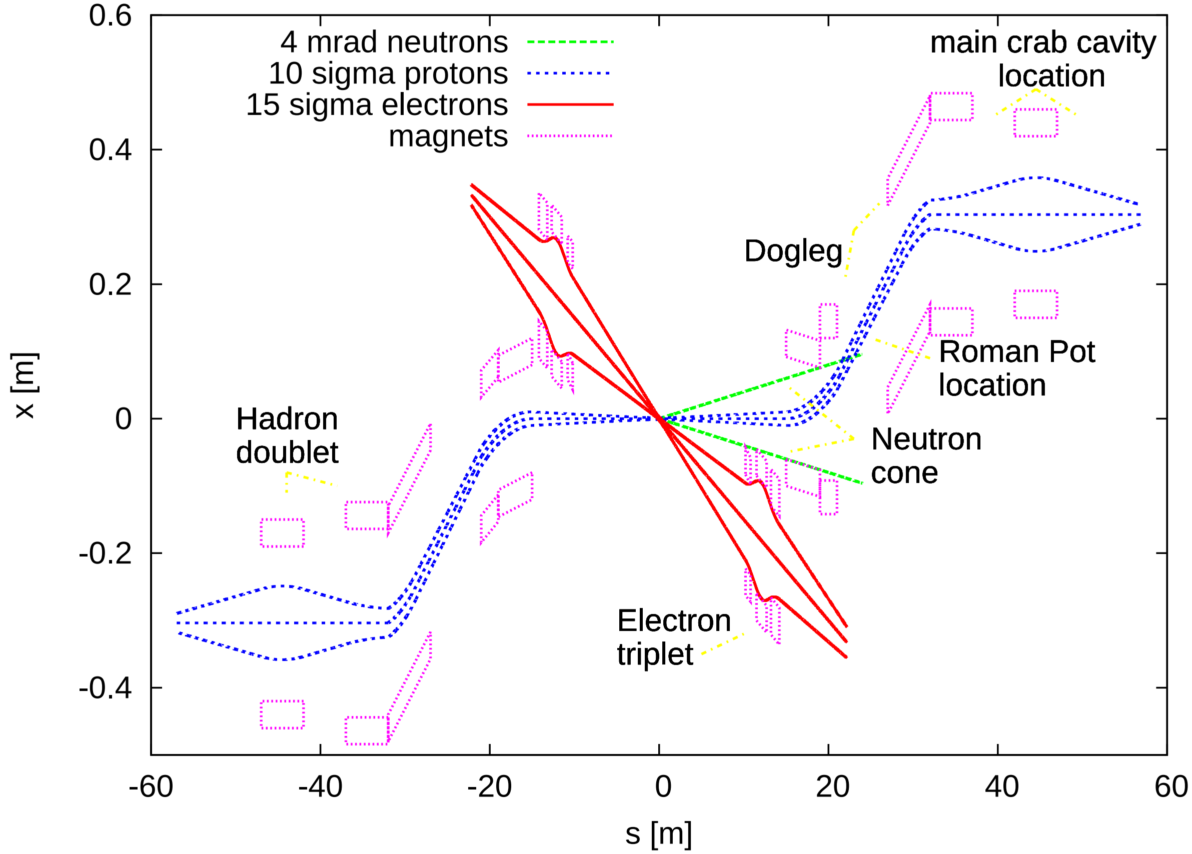



- 3 mm thick coils support tube/beam pipe, 21.5 mm inner radius
- 100 mm outer radius yoke
- 1 mm diameter standard cable
- 60 T/m

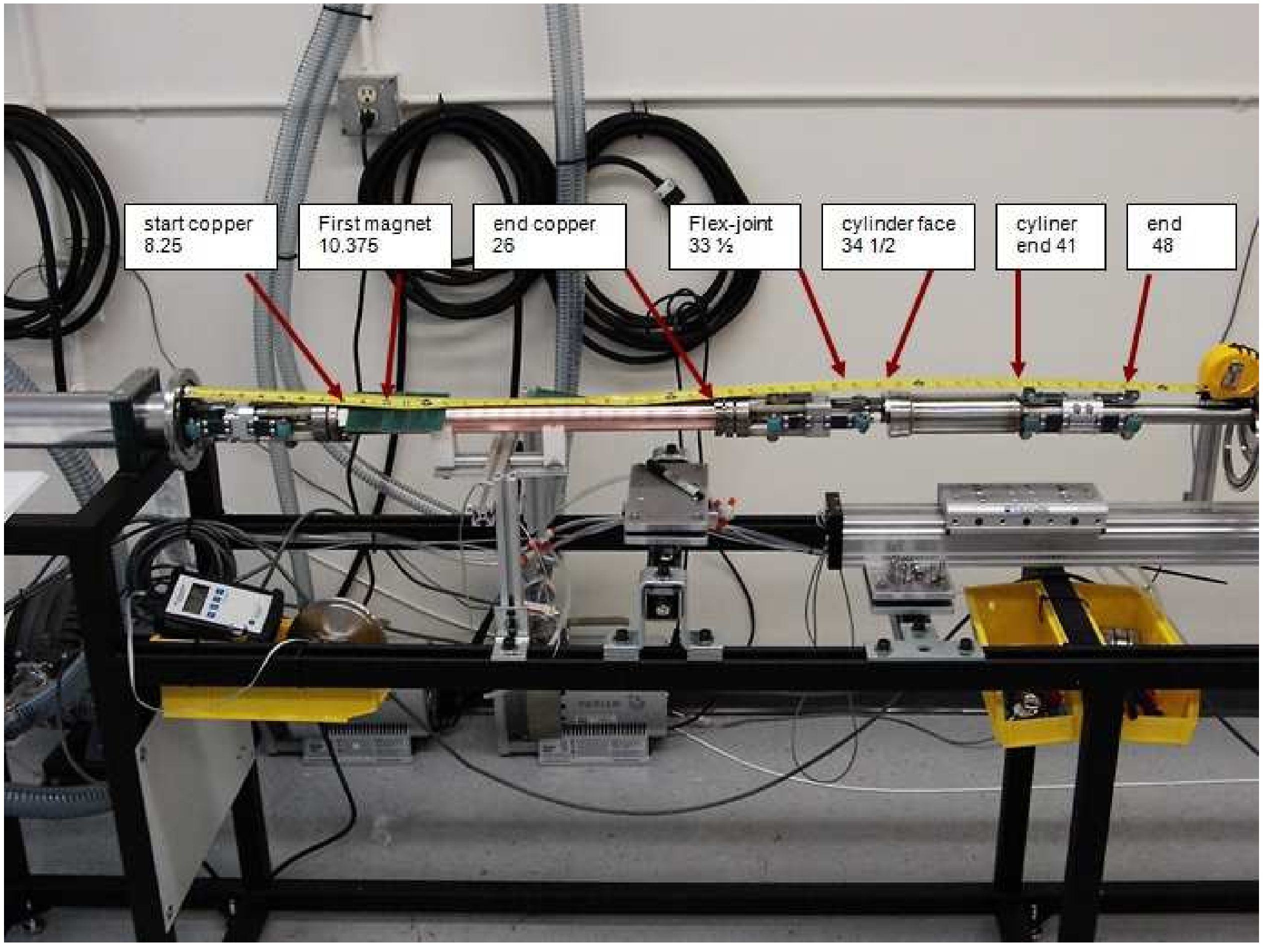
# Field in half QE2 at 15 mm



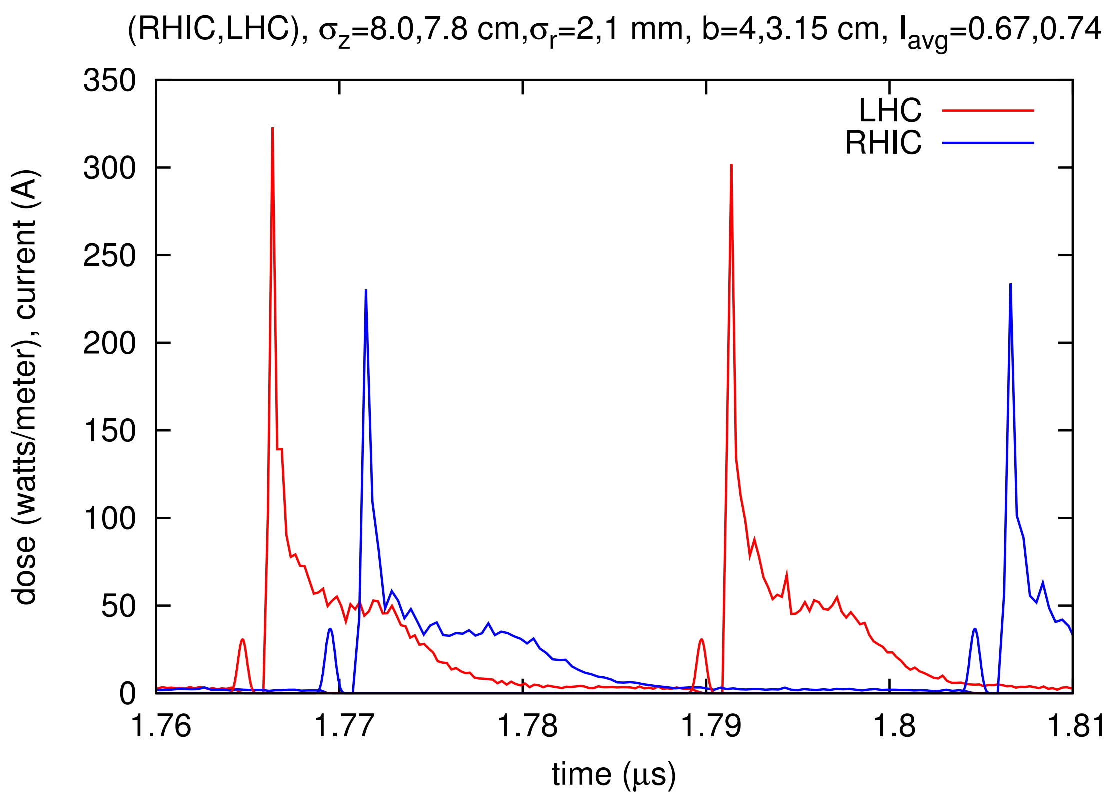
# Previous interaction region design



# Mole for in-situ beam pipe coating



# Electron cloud simulations for eRHIC and LHC




- Electron cloud power per unit length
- eRHIC fares better than present LHC in simulations