eRHIC: high-energy high-luminocity electron-ion collider at BNL

- Design overview
- Performance
- Progress with eRHIC R&D & retiring technical risks
- Cost elements
- Conclusions

Vladimir N. Litvinenko
Stony Brook University

Stony Brook University

for eRHIC design team: BNL, SBU, Tech-X, BINP, Daresbury Lab, SLAC, ANL, CERN, Niowave, AES, Stangenes Industries, Transfer Engineering, Atlas Technologies, Jlab, Cornell U…

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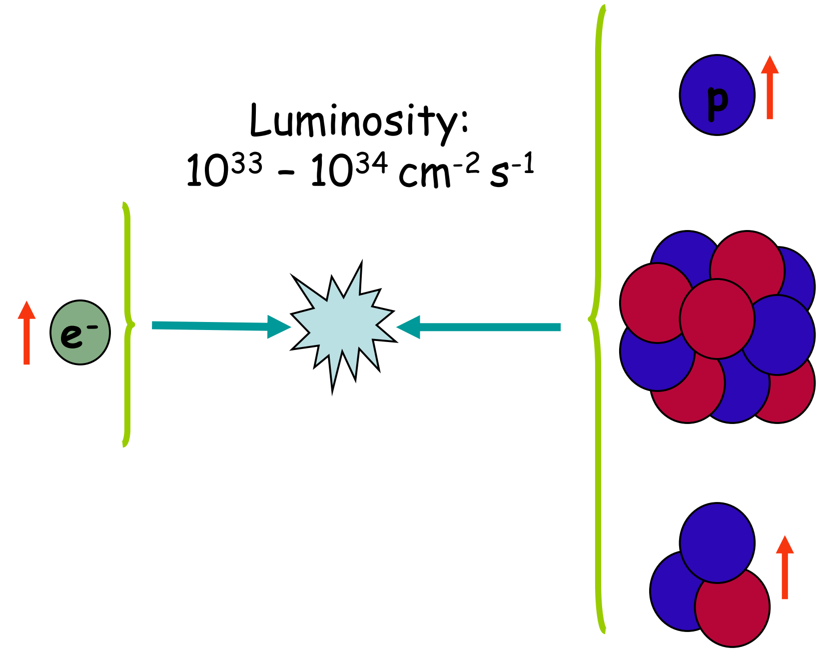
eRHIC: Electron Ion Collider at BNL

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

80% polarized electrons:
1.3 – 21.2 GeV

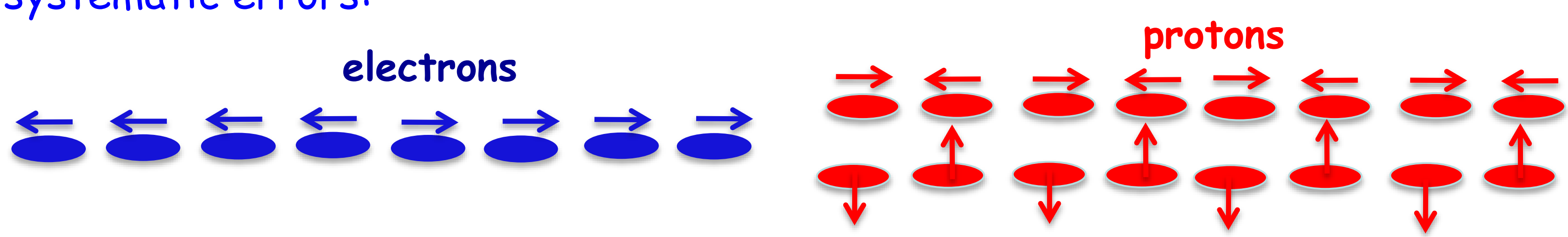


70% polarized protons
25 - 250 (275*) GeV

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

Polarized light ions (^3He) 17-167 (184*) GeV/u

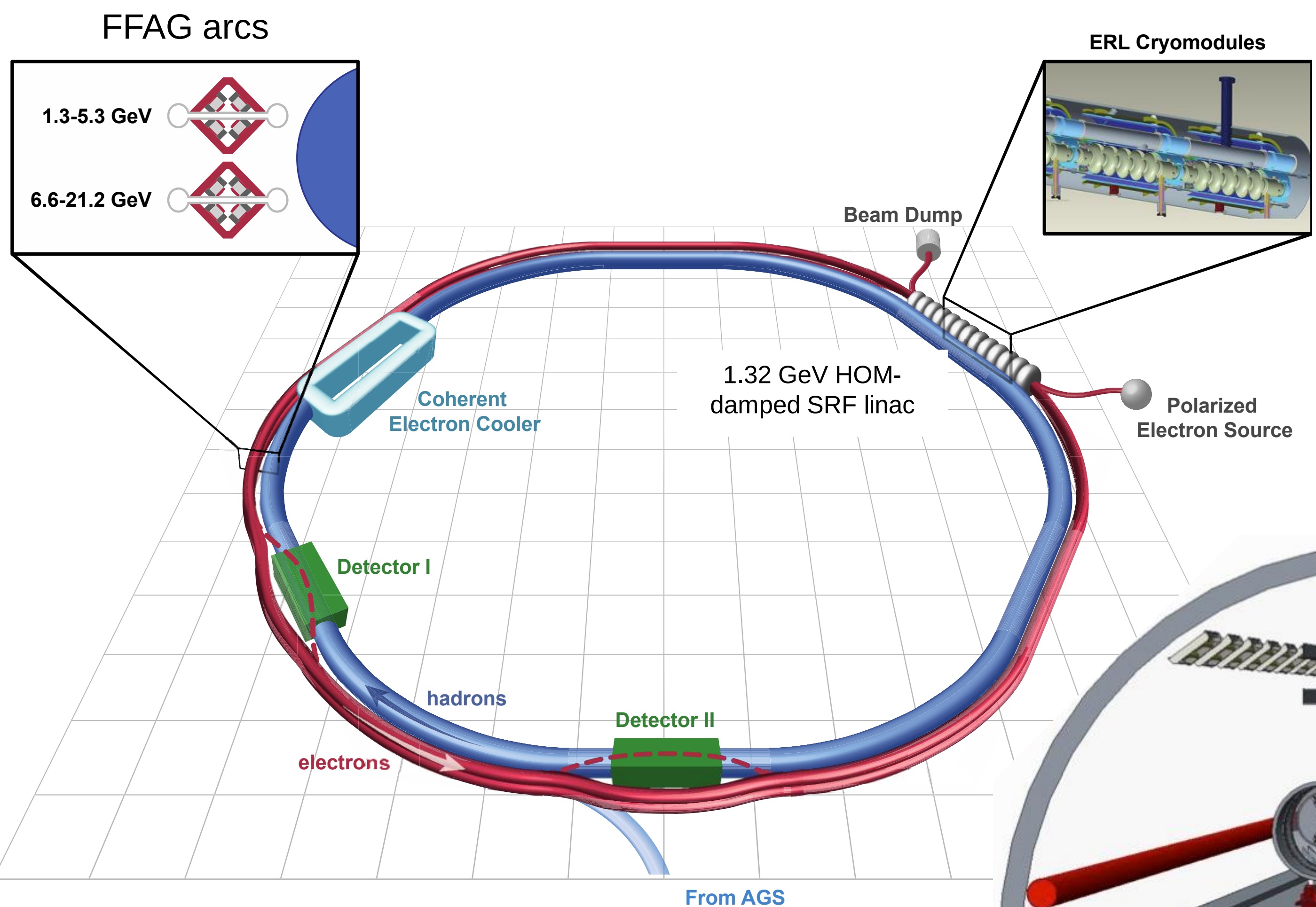
- Center-of-mass energy range: 20 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any bunch-by-bunch polarization pattern in electron-hadron collisions to reduce systematic errors:

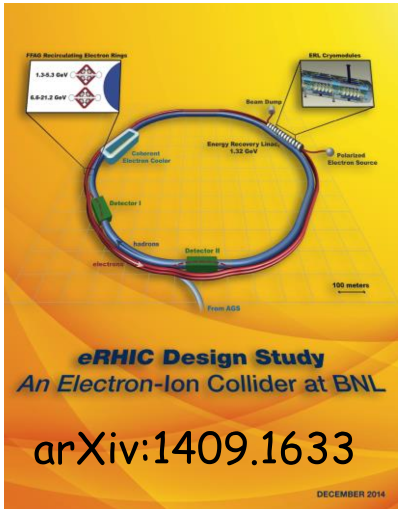


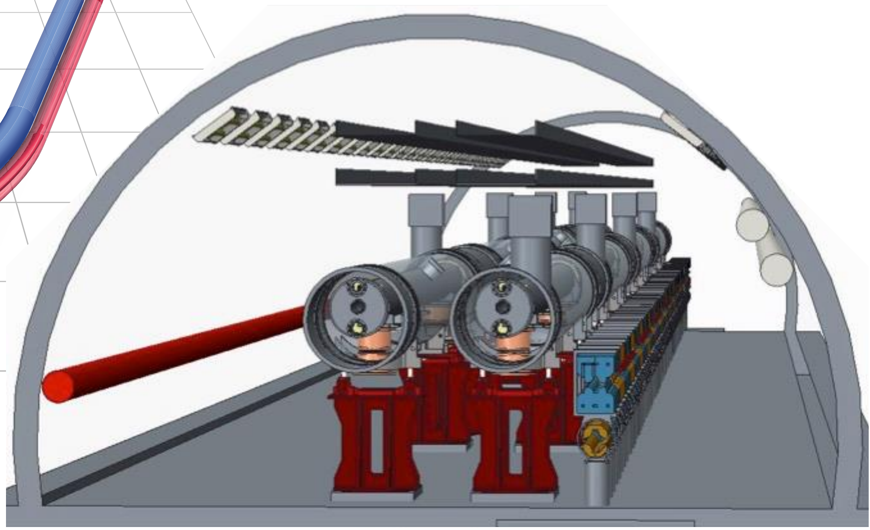
* It is possible to increase RHIC ring energy by 10%

eRHIC design

Highly advanced and energy efficient accelerator







- 4.1×10^{33} cm^{-2} s^{-1} for $\sqrt{s}$ = 126 GeV (15.9 GeV e↑ on 250 GeV p↑)

Demonstrated technology and performance supporting eRHIC design

- 250 GeV polarized proton beams with required intensity and brightness
- 100 GeV/n Au beams with the required intensity and brightness
- 100 GeV/n He-3 beams with the required intensity and brightness
- 4 mA polarized electron beam source demonstrated at JLab
- 30 mA ERL demonstrated at BINP, 10 mA ERL demonstrated JLab FEL
- High energy ERL demonstrated (CEBAF), multi-pass ERL demonstrated (BINP)
- Performance of existing HOM-damped BNL 704 MHz SRF cavity supports eRHIC ERL
- Crab cavities tested with beam at KEK
- NS-FFAG principle first demonstrated with EMMA at Daresbury, UK
- eRHIC FFAG beam-lines is based on a well-know bent FODO beam-lines, studied in depth since invention of strong focusing in late 1950s
- Permanent magnets had been successfully used for Fermilab Recycler and transport lines and as focusing elements in B-factory detectors

eRHIC design is highly cost effective

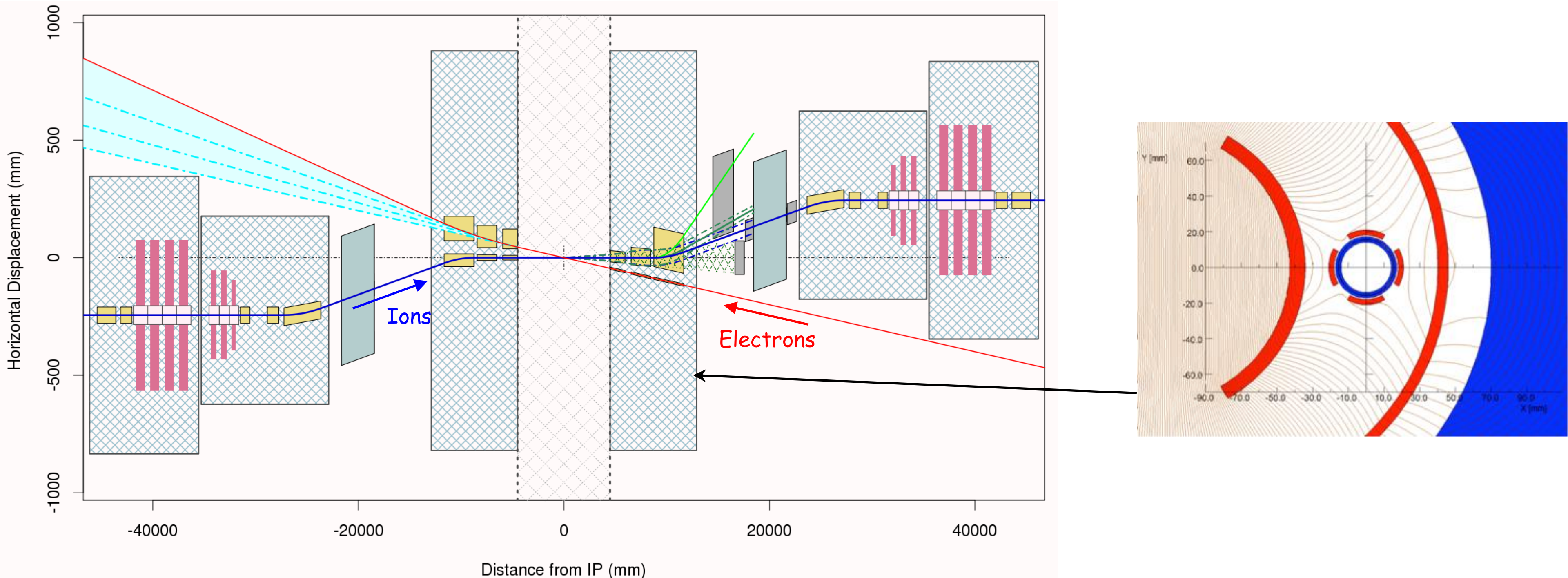
- Use of the RHIC facility for the 250 GeV hadron beam
  - The RHIC facility replacement value is about FY15 $2.5B
- Use of the existing RHIC tunnel, detector buildings and cryo-facility
  - Very limited need for civil construction
- Use an Energy Recovery Linac (ERL) for the 21.2 GeV electron beam
  - Without ERL up to 500 MW of RF power would be needed
- Recirculate electron beam multiple times to reduce size of CW SRF Linac to 1.32 GeV
  - 16 times reduction of Linac cost
- Use two Fixed Field Alternating Gradient (FFAG) arcs to transport 16 different beam energies around the RHIC tunnel.
  - 8 times reduction of magnet, vacuum system, instrumentation cost
- Use permanent magnets for electron recirculation arcs
  - Eliminate need for power supplies, power supply buildings, magnet cooling
- Bright hadron beam allows for low electron beam intensity and low synchrotron radiation power
  - Greatly reduced need for RF power for energy loss compensation

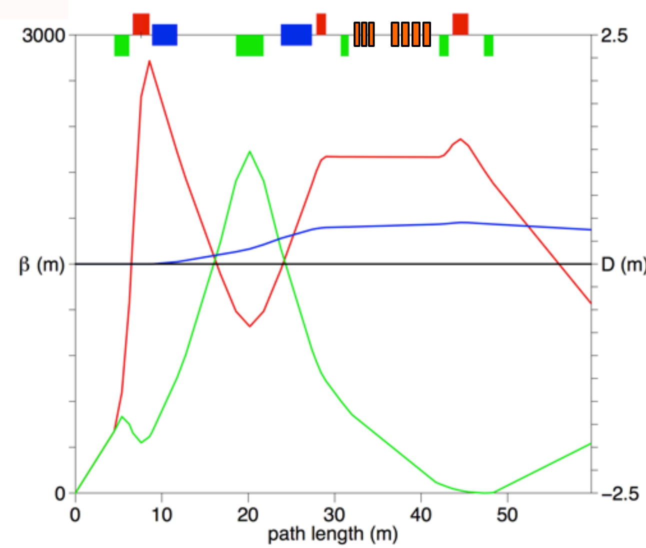
eRHIC TPC cost elements

#	WBS	eRHIC	FY15 M$ Burdened				
			Burdened Labor	Burdened Material	Cont. $	Total	Cont. %
#	1.1	Civil Construction/Infrastructure	7.3	40.8	18.9	**67.0**	39%
#	1.2	Cryogenic Systems	12.2	47.5	16.0	**75.7**	27%
#	1.3	CW SRF Linac	23.4	69.6	36.8	**129.8**	40%
#	1.4	RF Power Amplifiers and LLRF	3.2	47.9	15.6	**66.7**	30%
#	1.5	Magnets	22.8	66.7	27.7	**117.3**	31%
#	1.6	Vacuum	9.9	45.3	11.0	**66.2**	20%
#	1.7	Magnet PS	3.1	31.6	11.5	**46.1**	33%
#	1.8	Instrumentation	13.8	23.2	10.0	**47.0**	27%
#	1.9	Controls	9.8	7.3	5.4	**22.4**	31%
#	1.10	Electron Injector and Abort	8.8	16.1	8.4	**33.3**	34%
#	1.11	RHIC Modifications	6.7	6.2	4.0	**17.0**	31%
#	1.12	Commissioning/Pre-Operations	6.9	7.8	4.3	**18.9**	29%
#	1.13	Project Management/Control	21.3	2.4	4.7	**28.4**	20%
#	1.14	Project R&D	10.0	5.4	4.6	**20.0**	30%
		TPC Total	**159.3**	**417.7**	**178.9**	**755.9**	**31%**

- Full bottom-up cost and contingency estimate of eRHIC conceptual design
- WBS elements 1.1 to 1.11 all include PED, construction, assembly, and installation
- Based on extensive experience from RHIC, RHIC upgrades, NSLS II, and also information from other projects (Cryo: FRIB, CEBAF 12 GeV; CW SRF Linac: FRIB, LCLS II, CEBAF 12 GeV; Magnets: FNAL Recycler)
- Based on EIC costing review: doubled project R&D to $40M to retire all technical risks before FY19/20 construction start -> eRHIC TPC = $776M

eRHIC high-luminosity IR with β^* = 5 cm

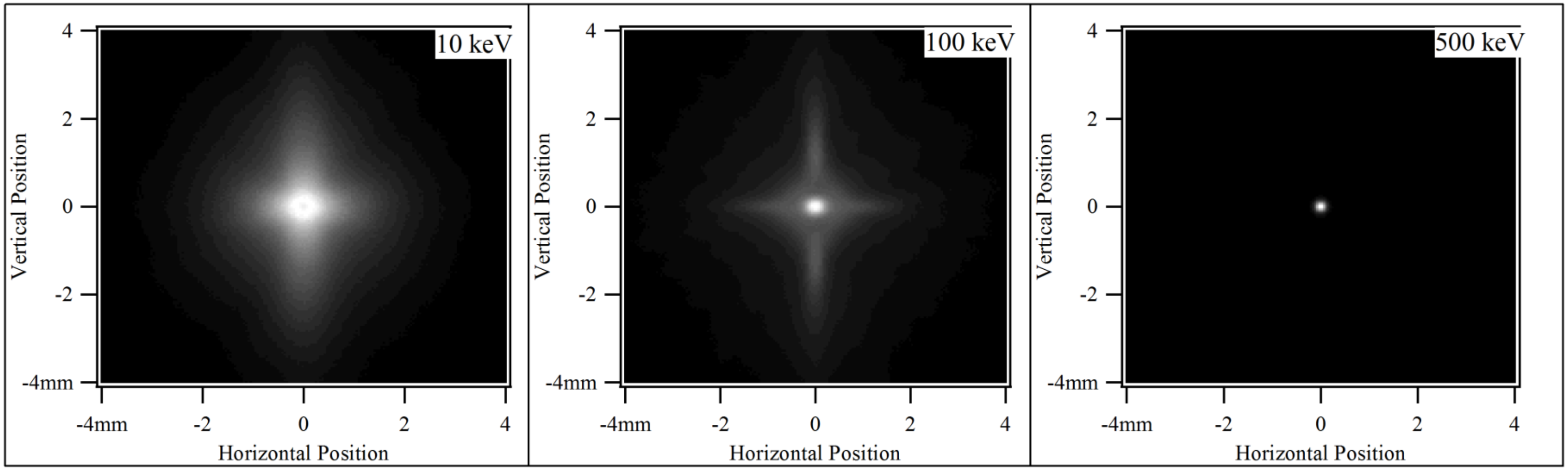




- 10 mrad crossing angle and crab-crossing
- 90 degree lattice and beta-beat in adjacent arcs to reach β^* of 5 cm with good dynamic aperture
- Final focus doublet and dipole with large aperture for forward collision products and with field-free passage for electron beam
- Only soft bends of electron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

Low e-beam current and crossing angle provide for a very low X-ray back-ground in IR

Photon flux @ eRHIC IP

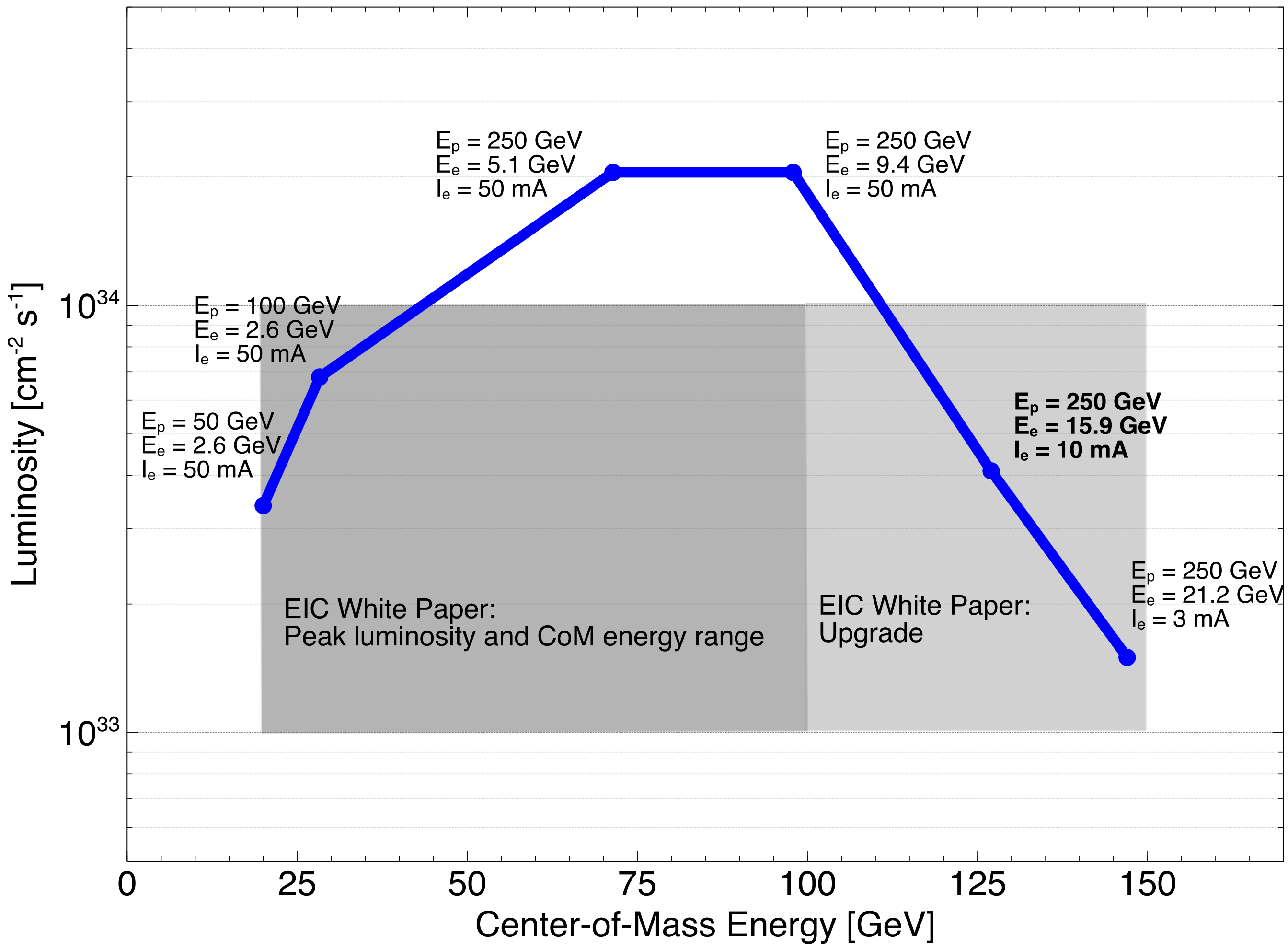


Total power is about 40 W and practically all high energy photons will propagate through IR without hitting the walls of vacuum chamber.

SR would be absorbed far from the detector to reduce the back-scattered photons and neutrons.

We have all tools in hands, including GEANT4, for simulating the IR background when the detector/IR is finalized.

eRHIC peak luminosity vs. CoM energy



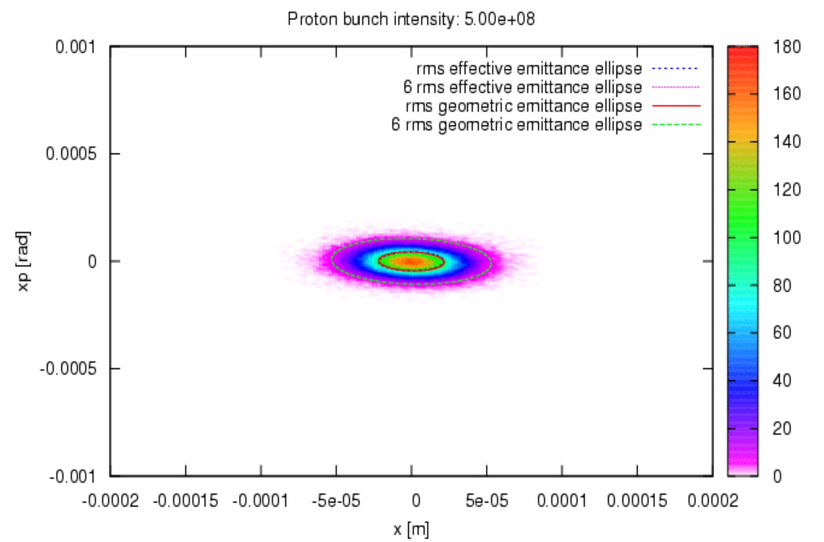
- eRHIC design covers whole Center-of-Mass energy range, including “White Paper Upgrade”
- Small beam emittances and IR design allows for full acceptance detector at full luminosity
- Detailed parameters for E_p=250GeV, E_e=15.9GeV, I_e=10mA are in the next slide

eRHIC parameters for nominal operating energies

	e	p	$^{2}He^{3}$	$^{79}Au^{197}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		126	103	80
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.07	3.0	3.0	3.0
Bunch charge, nC	1.1	48	32	19.6
Beam current, mA	10	415	275	165
Hadron rms normalized emittance, 10^{-6} m		0.2	0.2	0.2
Electron rms normalized emittance, 10^{-6} m		23	35	58
β*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter		0.004	0.003	0.008
Electron beam disruption		36	16	6
Space charge parameter		0.08	0.08	0.08
rms bunch length, cm	0.4	5	5	5
Polarization, %	80	70	70	none
Peak luminosity, 10^{33} cm^{-2}s^{-1}		4.1	2.8	1.7

High luminosity with a Linac-Ring collider

- For Linac-Ring collider the single collision of electron bunch removes the limitation of the beam-beam effect of the high energy hadron beam on the lower energy electron beam
- Can reach high luminosity with high intensity, low emittance hadron beam, relatively low collision frequency and intensity electron beam
- Disruption of electron beam by hadron beam is large, but emittance growth is limited to below a factor of two in all cases. The used beam can be fully energy recovered without losses.
- Need strong hadron beam cooling (10 times in transverse and longitudinal direction) for highest luminosities, small vertex distribution, and small forward divergence
  - Small forward divergence is critical for physics case
- Novel cooling method:
  - Coherent electron Cooling (CeC)
  - Required performance demonstrated in extensive simulations
  - Proof-of-Principle test underway at RHIC

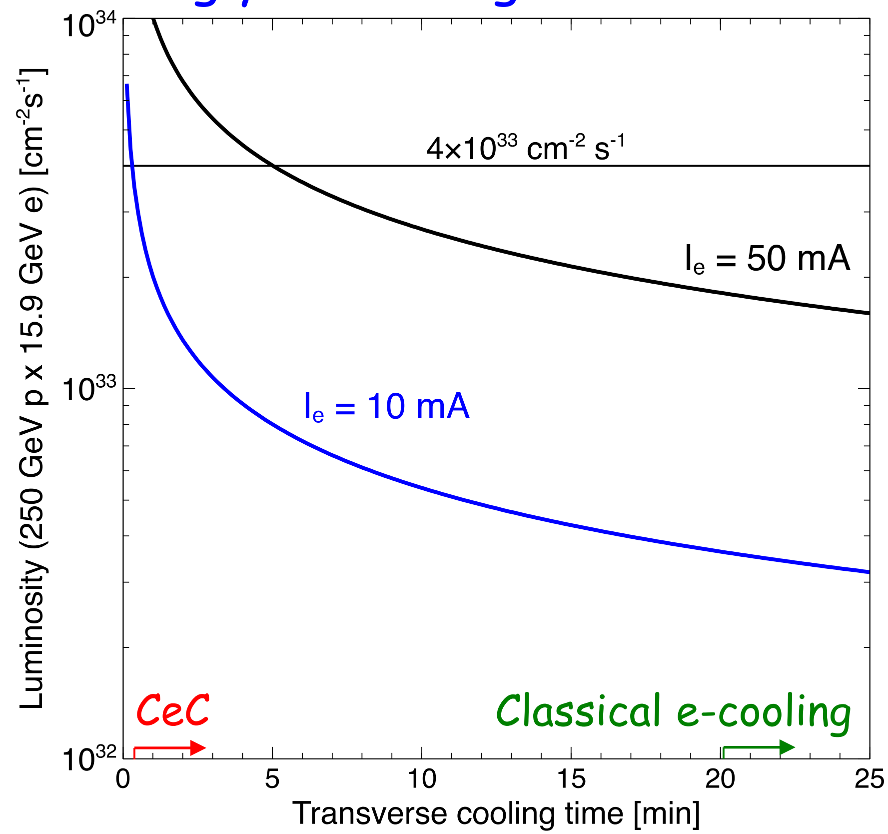


Main performance risk: fast hadron cooling

- At maximum luminosity (4×10^{33} $cm^{-2}\,s^{-1}$) the transverse IBS growth time of 250 GeV proton beam (3×10^{11} ppb, 0.2 mm, 5 cm bunch length) is about 20 seconds
- Only CeC with enhancements such as micro-bunching and with a 50mA, 125 MeV electron beam can reach this cooling time
- However, luminosity doesn't depend strongly on cooling time

$$L \propto t_{cool}^{-4/7}$$

- Less efficient cooling up to 5 minute cooling time can be fully compensated with increased eRHIC electron current (50 mA)
- Enhanced classical electron cooling with 3 A, 125 MeV electron beam, as being developed at JLab, can support ~ 20 minutes cooling time or ~ 2×10^{33} $cm^{-2}\,s^{-1}$ with 50 mA electron current.



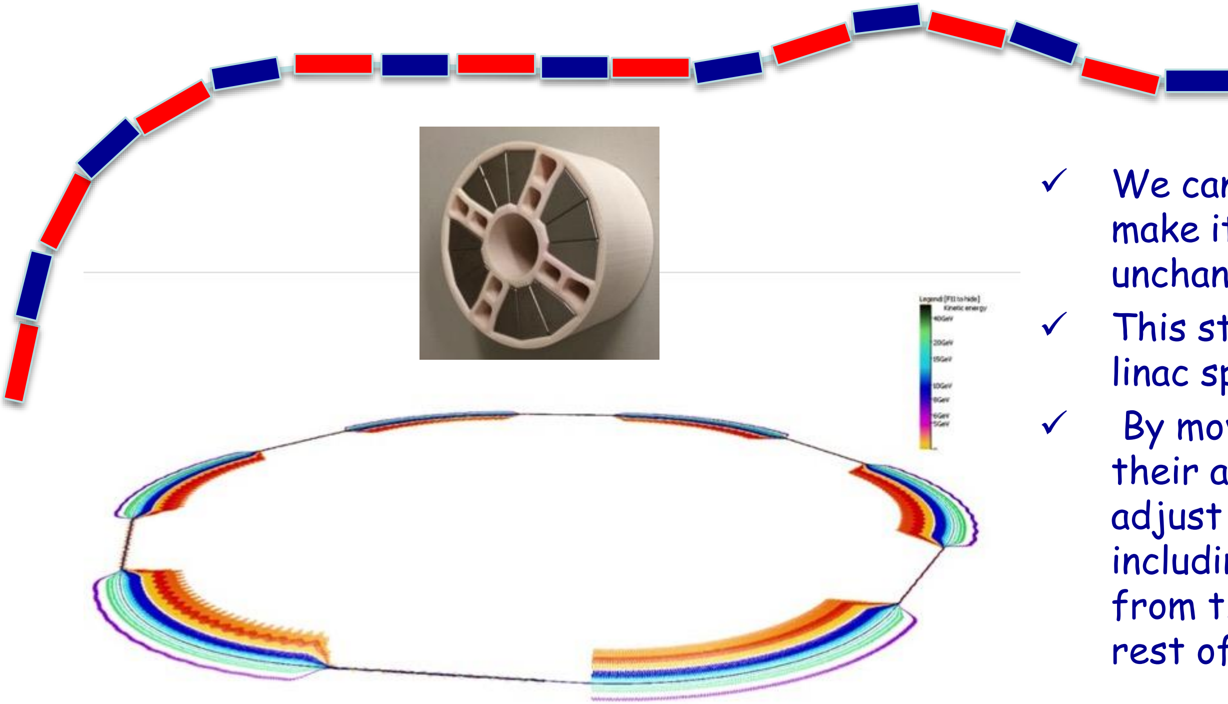
Accelerator technologies in eRHIC design (I)

- RHIC with beams from heavy ions to polarized proton beams – well established and proven technology
  - Upgrade to six snakes will use standard technology established at C-AD
  - Production and acceleration of polarized ^{3}He ions in RHIC accelerator chain is in progress
- DC polarized electron gun combining beams from multiple cathodes
  - Current from a single cathode of 4 mA was demonstrated at Jlab
  - A combiner magnet has been designed and prototyped [PR STAB 14, 092001 (2011)]
  - The gun generated first test beam and is undergoing commissioning at Stony Brook University
- 12 MeV pre-accelerator is based on a standard SRF and room-temperature electro-magnet technology
- Splitters and combiners are based on a standard electro-magnet technology and do not present any technical risk
- eRHIC FFAG beam-lines are a well-know bent FODO beam-lines, studied in depth since invention of strong focusing. While being unusual, technologically they are not a risk. All necessary analytical and simulations tools are available
- Permanent magnets are extensively used in modern accelerators: from undulators in multiple light sources, final focusing in B-factories and FERMI-lab recycler ring.
  - Studies are underway to determine radiation resistance of the permanent magnets at RHIC
  - If necessary, electromagnets can be used instead of permanent magnets
- Superconducting magnets developed for eRHIC IRs are based on the tested technologies at Superconducting Magnet Division at BNL

Accelerator technologies in eRHIC design (II)

- eRHIC's ERL is based on HOM-damped SRF cavities
  - Two prototype cavities had been manufactured, reached their design operational parameters in vertical tests. The first is undergoing commissioning as part of the high current BNL's R&D ERL
  - Full scale Cu prototype demonstrated all simulated features of the HOM damping (which is up to three orders of magnitude better than the competing schemes). We used TBBU codes successfully benchmarked against JLab ERL to verify stable performance of the eRHIC ERL
  - BNL's is commissioning 2 SRF cavities with goal of demonstrating the key parameters
- eRHIC's crab cavities
  - KEK demonstrated successful operation of crab cavities in electron-positron collider
  - The prototype crab cavity had been manufactured in collaboration with CERN and reached its designed parameters in vertical test. Will be tested with hadron beam in SPS (CERN)
- Coherent electron Cooling (CeC) is untested technology and Linac-Ring beam-beam effects are also a novelty
  - A CeC proof-of-principle system is under the final stage of construction. 20 MeV CW linear accelerator will generate electron beam, which will be used for experiments verifying performance of traditional and advanced CeC schemes as well as linac-ring collisions
  - It also will be used to measure performance of a traditional electron cooling with a bunched electron beam - as a back-up option for eRHIC
- **In short: current eRHIC R&D is addressing all technical risks in eRHIC design with goal to retire them within 2-3 years. Further R&D would be needed for value engineering**

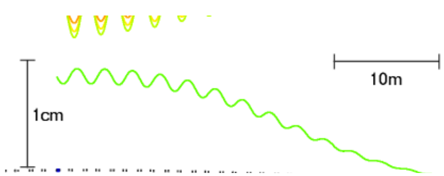
Bent FODO beam-line accommodating multiple energy beams – it is called FFAG

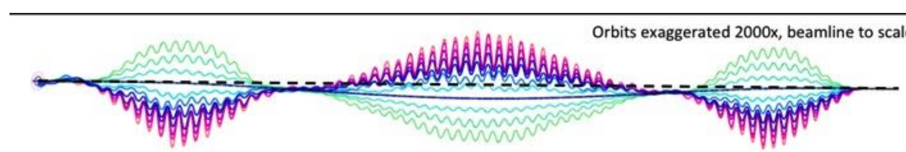


- ✓ We can bend and turn the FODO line, or make it straight – the $\beta_{x,y}$ and $\alpha_{x,y}$ stay unchanged;
- ✓ This string must be continuous from the linac splitters to linac combiners;
- ✓ By moving quads horizontally (or moving their axis using dipole trims) one can adjust all orbits to a desirable pattern, including separating a single energy beam from the rest of the pack and passing the rest of the beams around the detector

Putting all beams onto a single trajectory for a straight section

Bypass around the detector



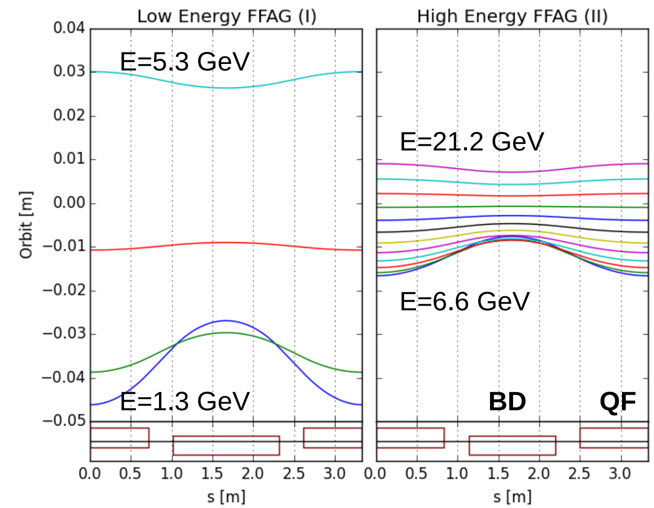


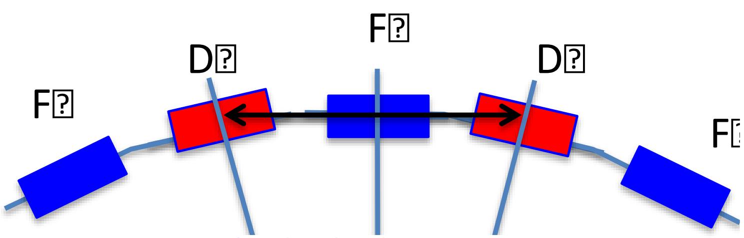
Deviation from a center-line trajectory is shown
Orbits are exaggerated 200x

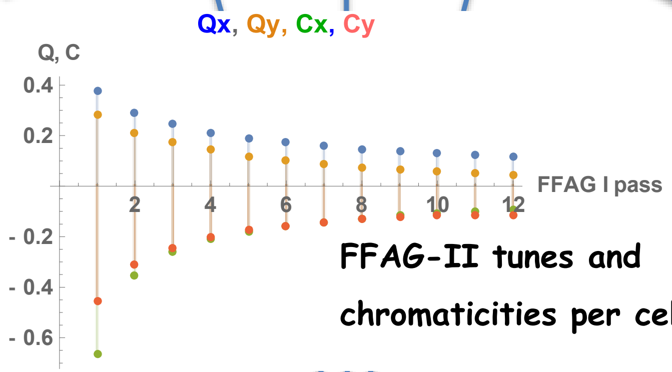
eRHIC (FFAG) FODO Lattice Parameters

Cell parameters of both FFAGs

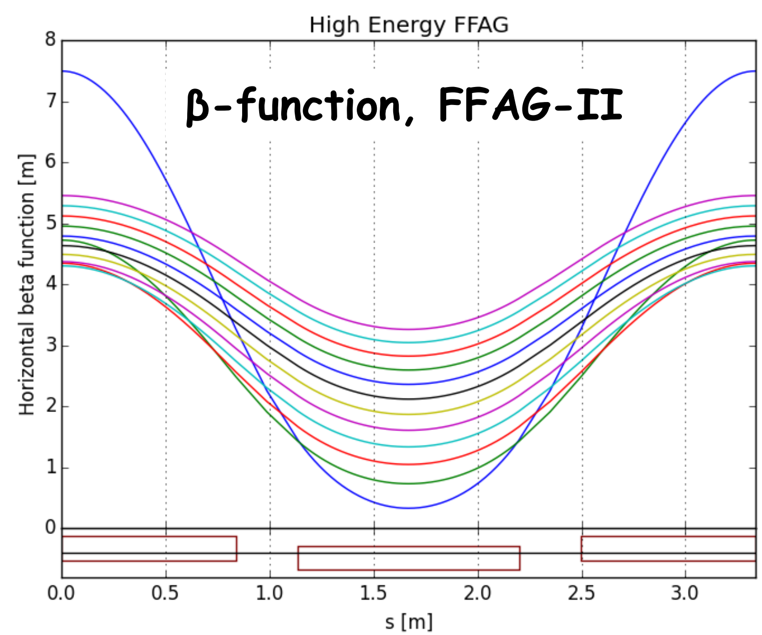
Element	Length (m)	Gradient (T/m)	Offset (mm)
All Drifts	0.3		
BD (Low)	1.3	3.5	-13.3
QF (Low)	1.44	-3.5	13.3
BD (High)	1.68	23.3	-8.2
QF (High)	1.06	-30	8.2





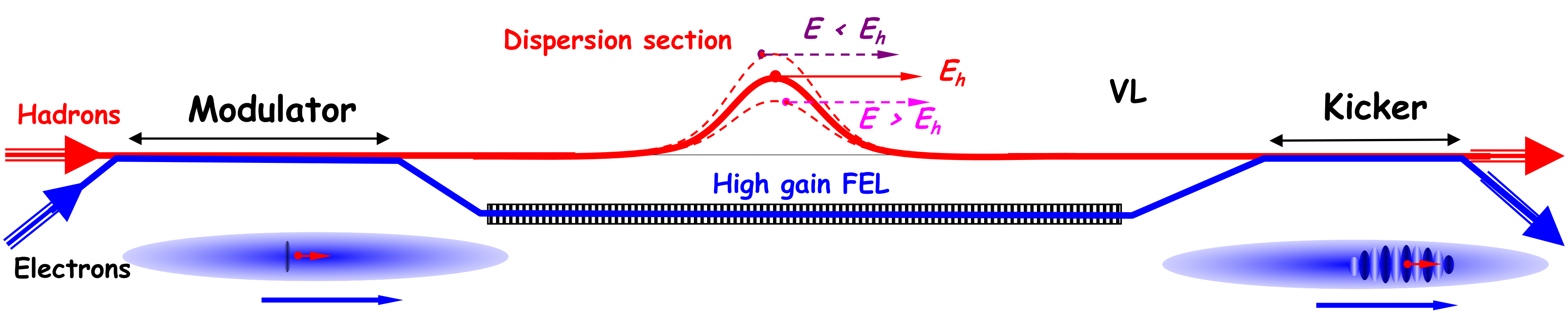


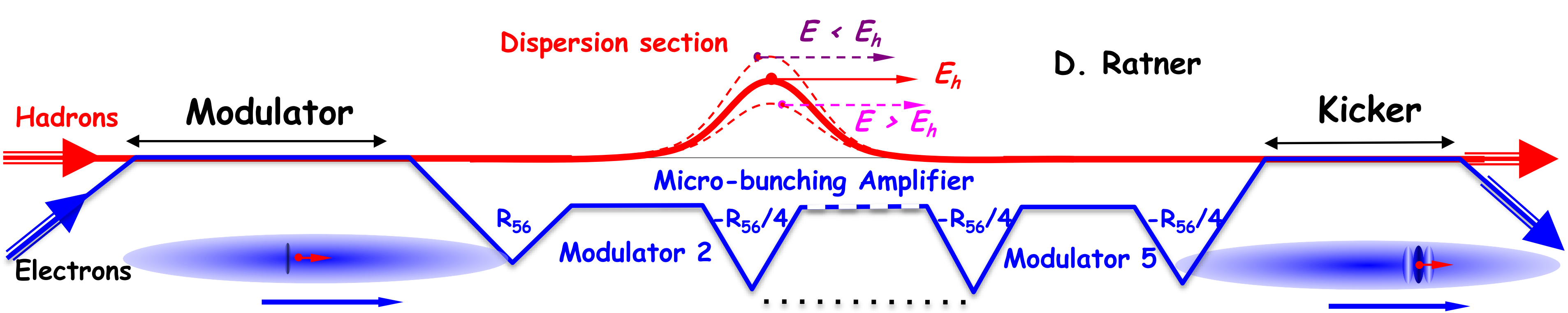
FFAG-II tunes and chromaticities per cell



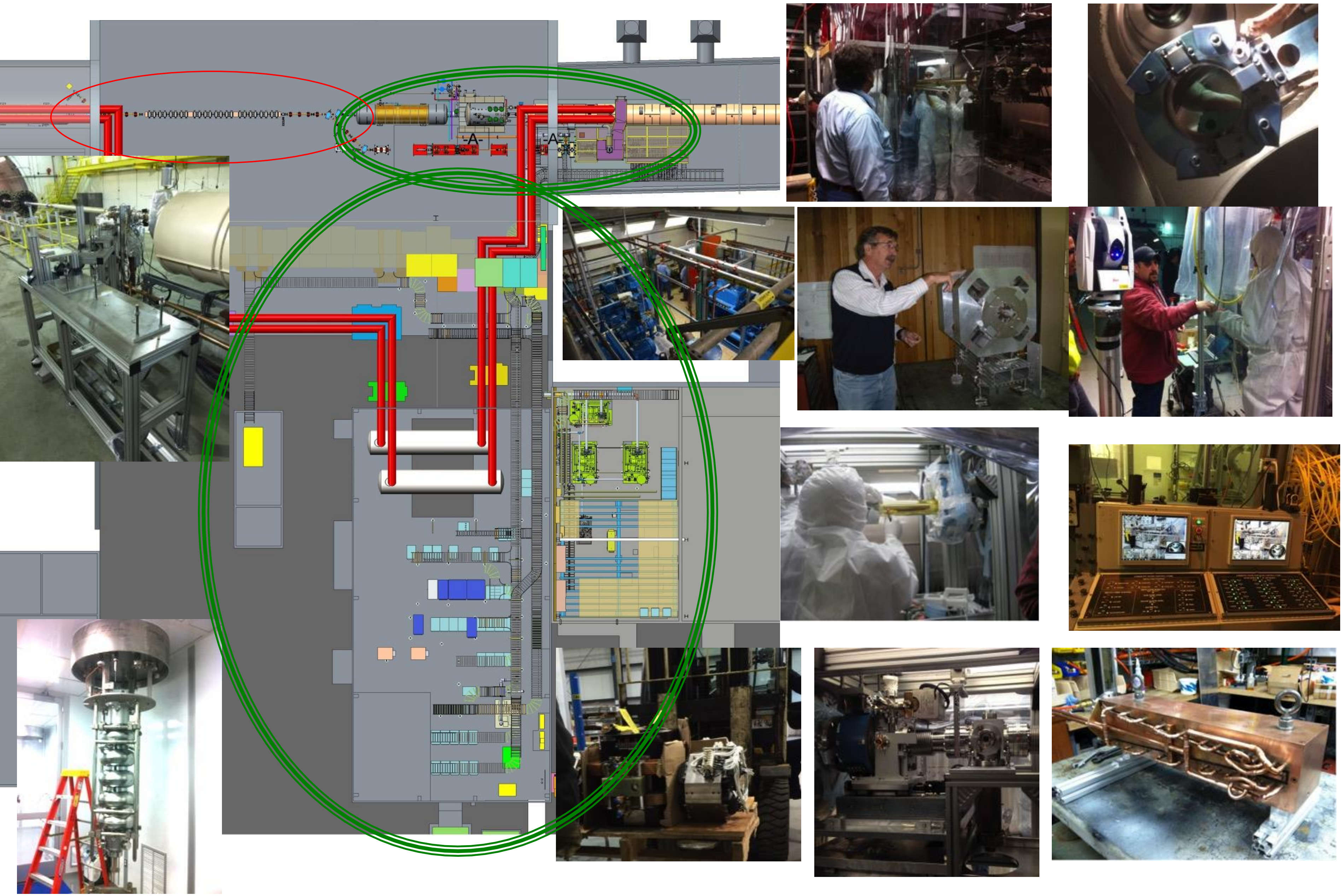
Coherent electron Cooling

- EL version was developed by V. Litvinenko and Y. Derbenev [PRL102, 114801(2009)]; micro-bunching amplifier proposed by D. Ratner [PRL 111, 84802 (2013)]
- CeC is a very high bandwidth (~ 10 - 100 THz) stochastic cooling using electron beam as the pick-up, the amplifying medium, and as the kicker
- Made possible by high brightness electron beams and FEL technology
- Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (2016)
- Micro-bunching amplifier test also planned with same set-up



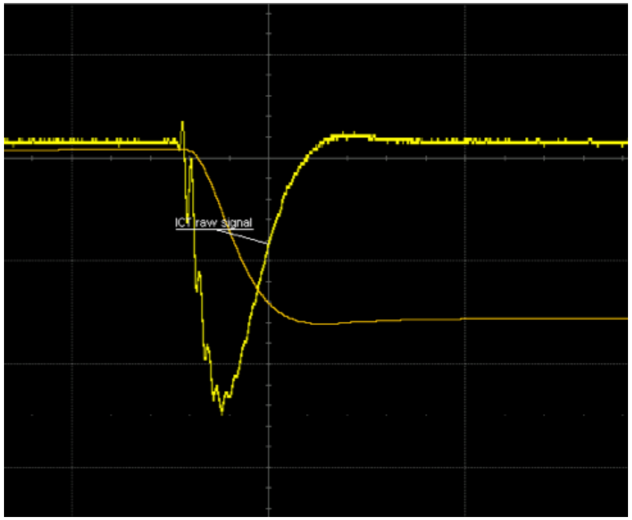


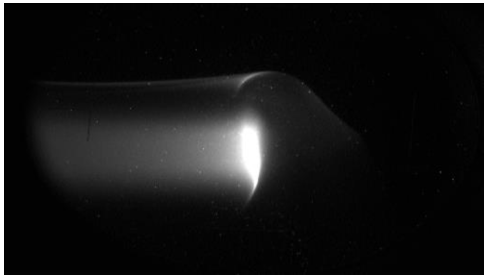
Progress with CeC Proof-of-Principle Experiment

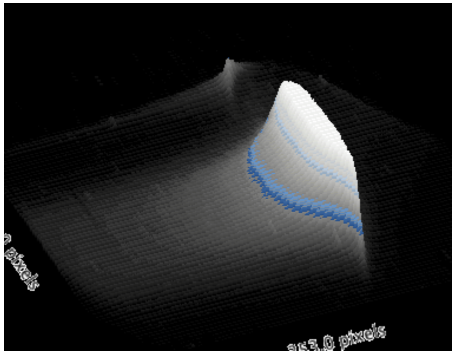


First beam from 112 MHz SRF laser-drivem e-gun June 2015

- 1.6-1.7 MeV (kinetic energy) in CW mode
- Laser generated CW e-Beam with 3 nC @ 5 kHz
- 2 MeV in pulse mode
- 25 MV/m at photocathode



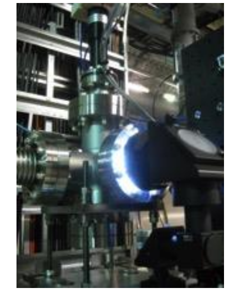


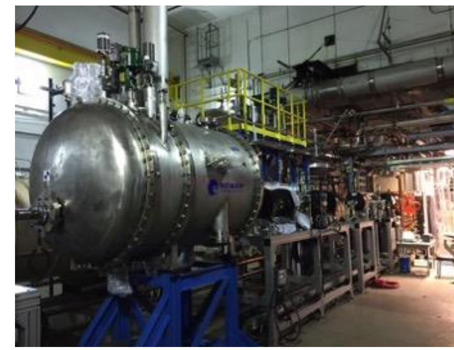


Milestones reported to DoE NP Q3 FY15

Demonstrating operation of 112 MHz SRF gun with 3 nC charge per bunch,
1.6 to 1.7 MeV kinetic energy in CW mode and above 2 MeV in pulsed mode.
Production of high QE photocathodes for 112 MHz SRF gun.
Receiving helical wiggler system for CeC PoP FEL amplifier
Completion of the 704 MHz SRF linac cryo-module at NioWave Inc.
Completing the low energy transport beam line and its control system.

Assembling the rest of CeC – Summer 2015



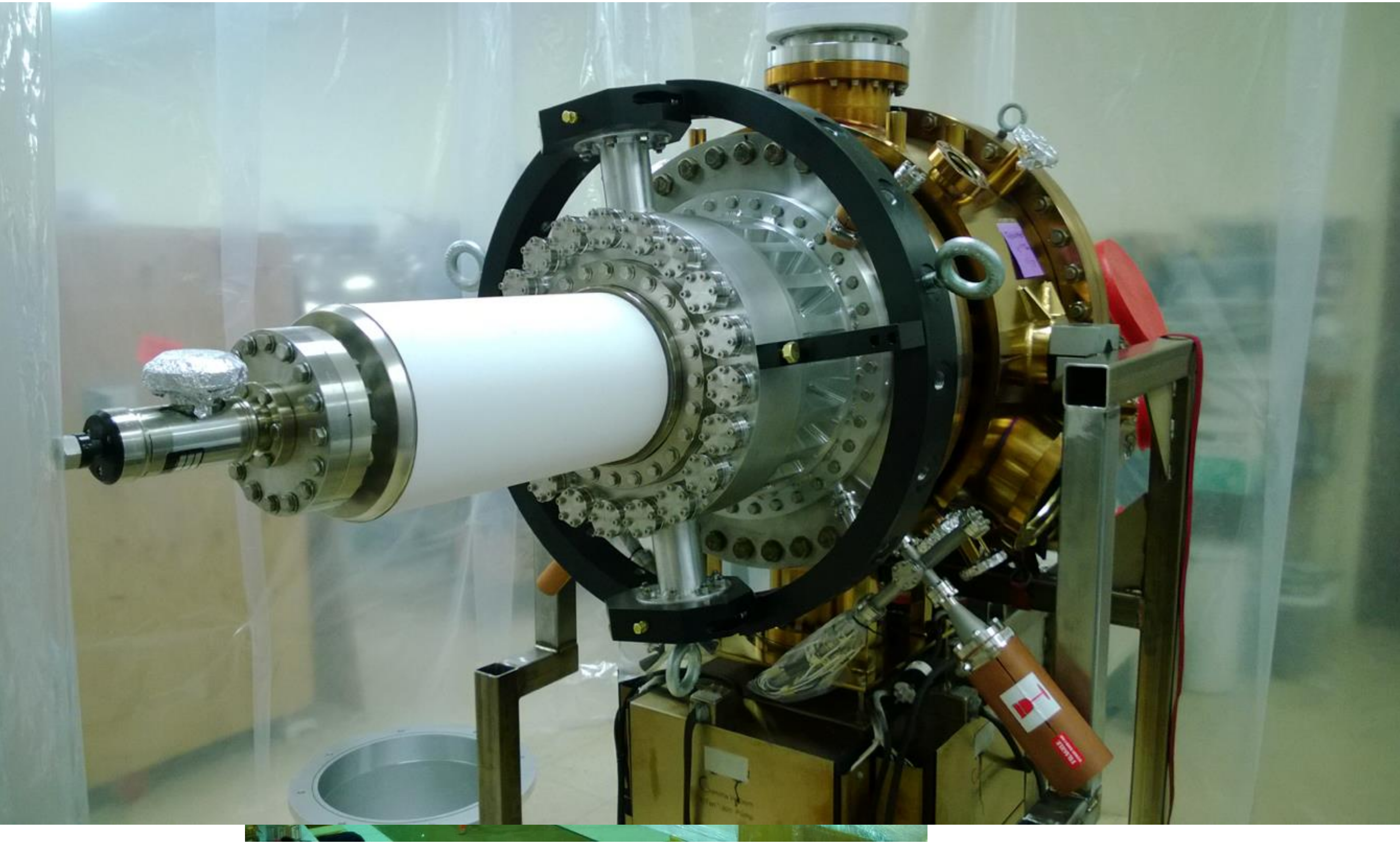


Schedule

Delivery of 704 MHz linac to BNL	V	30-Jul-15
Assembling and tuning helical wigglers	V 1/3	15-Aug-15
Install 704 MHz in RHIC tunnel	x	15-Nov-15
Install helical wigglers in RHIC tunnel	x	01-Dec-15
CW laser is commissioned	x	01-Dec-15
Beam diagnostics is intalled		15-Dec-15
Optical diagnostics is installed		15-Dec-15
Complete CeC beam-line	**X**	**15-Dec-15**

Commissioning	Milestones		
SRF cavities cold	x	15-Feb-16	Has to be sinchroniozed with RHIC crun
Complete cavity conditioning	**X**	**15-Mar-16**	
Generating fist beam	**X**	**01-Apr-16**	Assuming that SRF gun is working with photocathode pack
Measuring beam parameters	X	15-Apr-16	
Propagate beam to the beam dump	x	01-May-16	
Test co-propagation with ion beam	**X**	**15-May-16**	
Demonstrate FEL amplification	**X**	**01-Jun-16**	
First cooling attempt	**X**	**01-Jul-16**	Dedicated 5 days of running, dates have to be adjusted to the end of the RHIC run

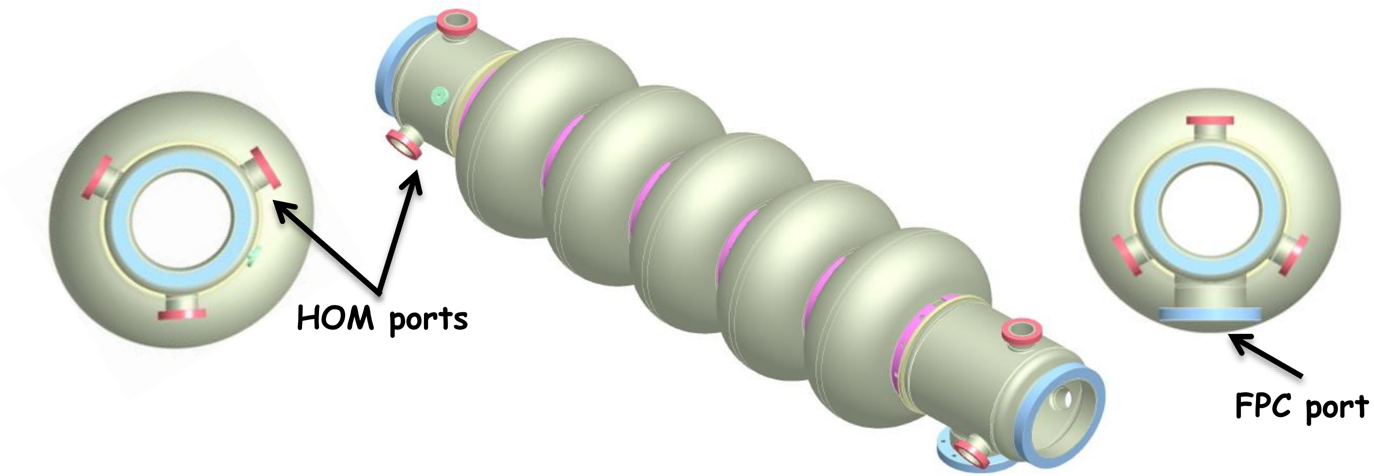
Polarized Gatling electron gun

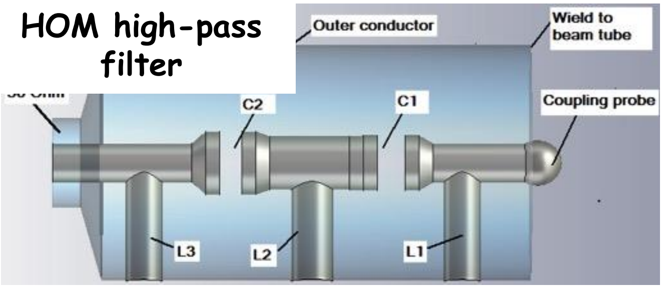


- It is real hardware under the test

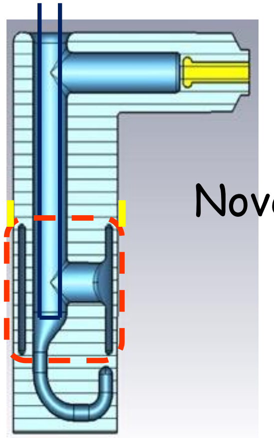
SRF Cavity R&D

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

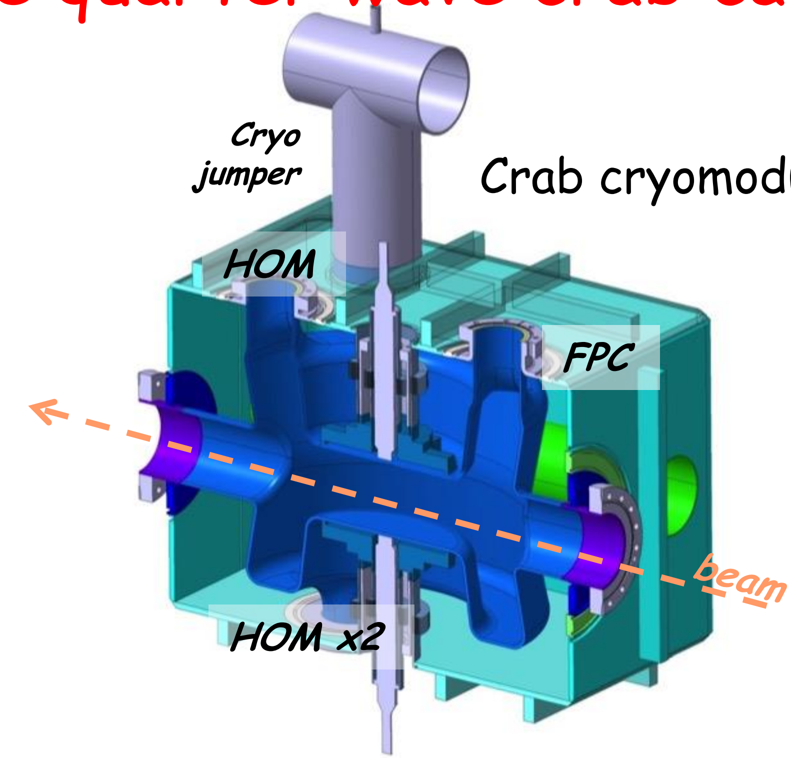


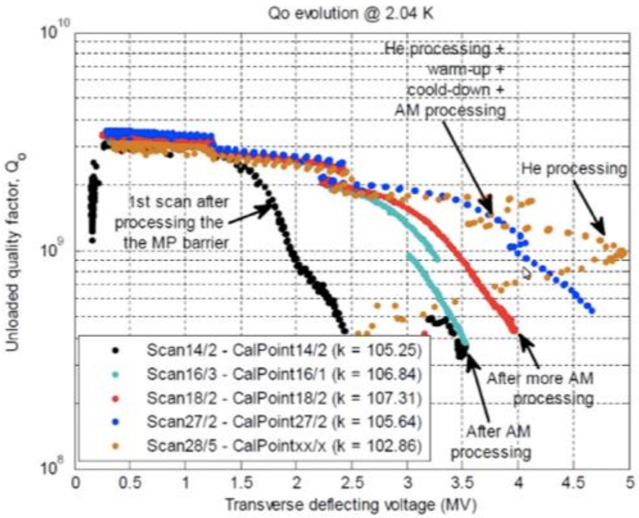


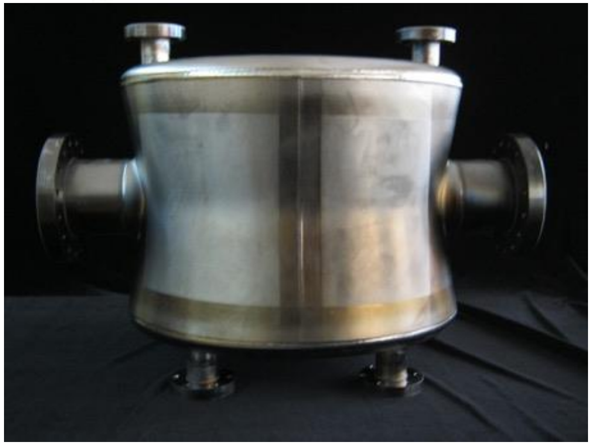
LARP funded BNL's double quarter wave crab cavity



Novel HOM dampers







Proof-of-principle reached designed performance

Test at SPS (CERN) should start in 2017

Summary

- Linac-ring design of eRHIC with highly cost-effective design reaches high luminosity (> 10^{33} cm^{-2} s^{-1}) from 20 to 145 GeV CM
- Uses existing RHIC facility for heavy ion and polarized proton beam ($2.5B replacement value) and existing RHIC tunnel, detector buildings and cryo-facility.
- Extensive R&D is under way on fast hadron cooling (Coherent electron Cooling) and high current polarized electron source (Gatling Gun). We expect to retire all critical technical risks in time for start of eRHIC construction (FY19/20)
- Cost estimate: FY15$ 776M (one high luminosity IR with crab crossings, 2nd IR available, detector cost separate).
- We are carefully looking into all options, including the ERL-ring as the main option and ring-ring design as a back-up option. We are also considering various pathways of reducing technical risks while keeping cost under control.

Credits: eRHIC design & R&D team

BNL: *Z.* Altinbas, E.C.Aschenauer, S.Belomestnykh, I.Ben-Zvi, D. Beavis, M. Blaskiewicz, S.Brooks, C.Brutus, T.Burton, A.Fedotov, C.M. Folz, D.Gassner, H. Hahn, Y.Hao, J. Jamilkowski, Y.Jing, F.X. Karl, D.Kayran, R. Lambiase, C.Liu, Y.Luo, G.Mahler, M.Mapes, G.McIntyre, W.Meng, F.Meot, T.Miller, M.Minty, P. Orfin, B.Parker, A. Pendzick, I.Pinayev, V.Ptitsyn, T. Rao, T.Roser, , J. Sandberg, B. Sheehy J.Skaritka, K. Smith, L. Snydstrup, R. Than, O.Tchoubar, P.Thieberger, D.Trbojevic, N.Tsoupas, J.Tuozzolo, E.Wang, G.Wang, D. Weiss, M. Willinski, Q.Wu, W.Xu, A. Zaltsman

Stony Brook University/CASE: A. Elizarov, V.N. Litvinenko, C.Marques, O.Rahman E. Riehn, M.Ruiz-Oses, T. Xin, Y. Wu

BINP, Novosibirsk, Russia: V.V. Anashin, T.V. Bedareva, M.A. Kholopov, A. Krasnov, A.M. Semenov, O. Shevchenko, P. Vobly

Niowave, Lansing, MI: C. Boulware, T. Grimm, R. Jecks, N. Miller

AES, Medford, NY: M.D. Cole, A.J. Favale, D. Holmes, J. Rathke, T. Schultheiss, A.M. Todd

Tech-X, Bolder Co*:* G.I. Bell, J.R. Cary, K. Paul, I.V. Pogorelov, B.T. Schwartz, A. Sobol, S.D. Webb

Stangenes Industries, Palo Alto, CA*:* C. Yeckel, R. Miller, M. Stangenes, K. Thompson

Transfer Engineering, Fremont, CA*:* M. Ackeret, J. Pietz, L. Neverida

Atlas Technologies, Pt. Townsend, WA: D. Bothel, J. Bothel, T. Casey

Thermionics NW, Pt. Townsend, WA*:* K. Coates

STFC, Daresbury, Warrington, UK: P. McIntosh, A.Moss, A. Wheelhouse

SLAC: D. Ratner, V. Yakimenko

ANL: P.N. Ostroumov and team

Jlab: M Pielker

MIT: E. Tsentalovich

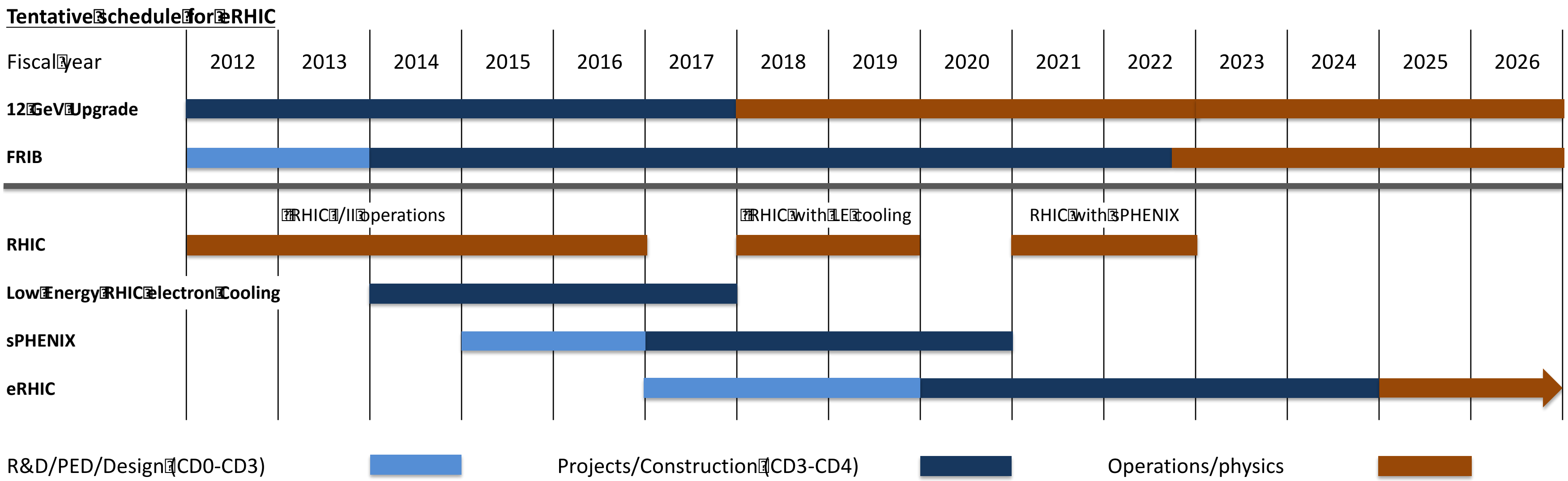
CERN: R. Calaga, S. Verdu-Andres

eRHIC is too cute
… that it almost a felony not to build it.
Is not it?

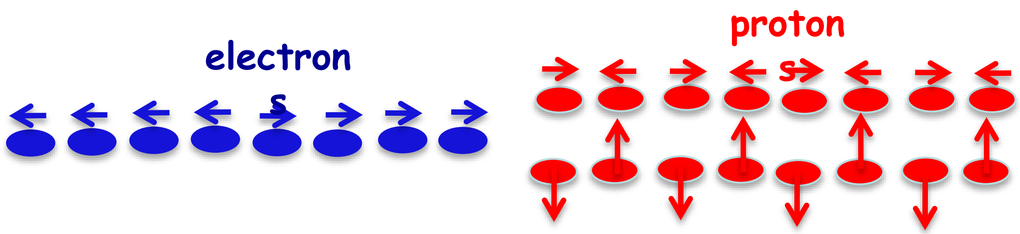
Thank you for your attention

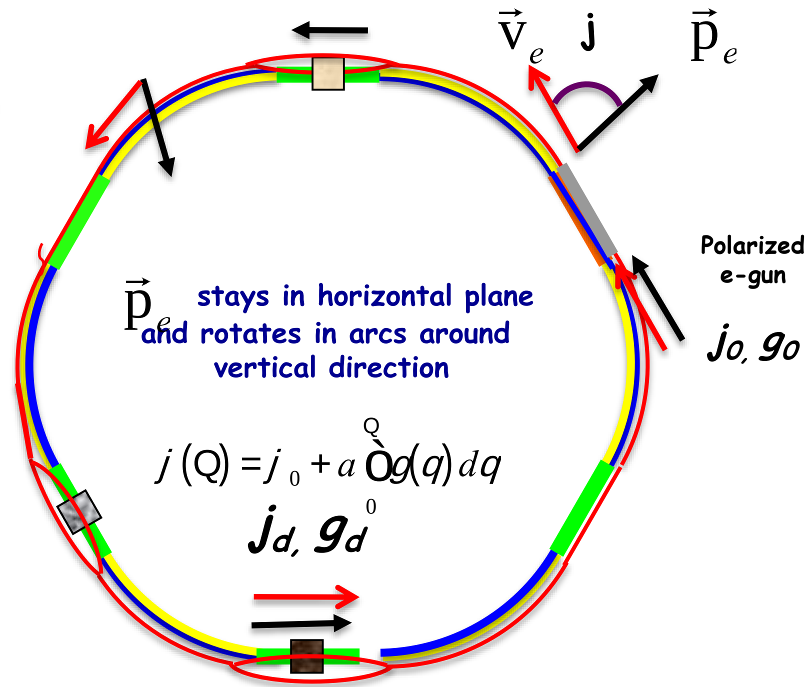
Back-up slides

RHIC and possible eRHIC schedule

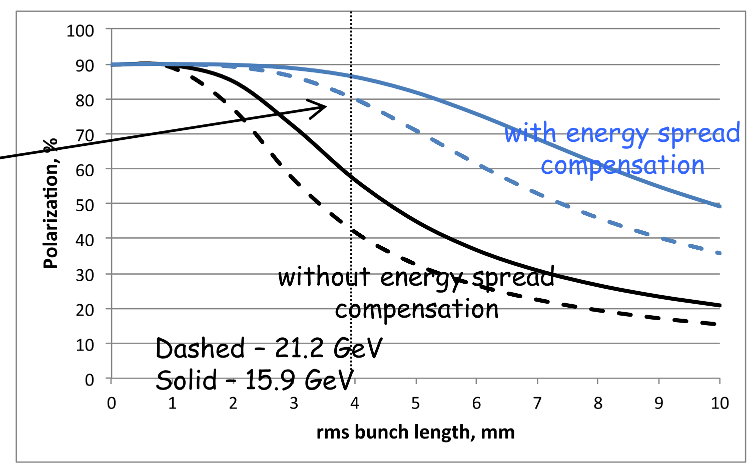


Electron Polarization in eRHIC





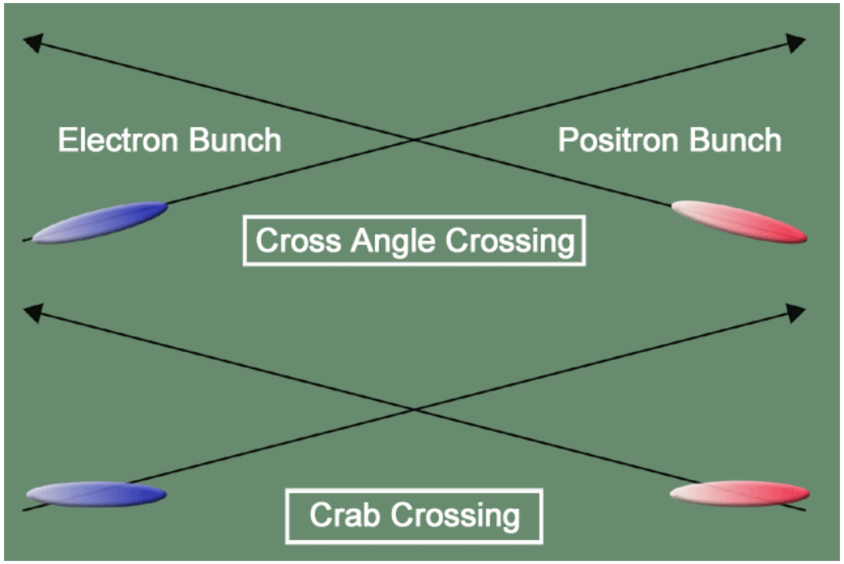
- 90% longitudinally polarized e-beam from DC gun with polarization sign reversal by changing helicity of laser photons.
- Only longitudinal polarization is needed in the IPs. eRHIC avoids lengthy spin rotator insertions. Cost saving.
- The linac energy choice of 1.322 GeV enables longitudinal polarizations at two detectors (IP8 and IP6).
- To achieve 80% polarization up to 21.2 GeV SRF 5th harmonic cavities (2.1 MHz) are used for the energy spread reduction.

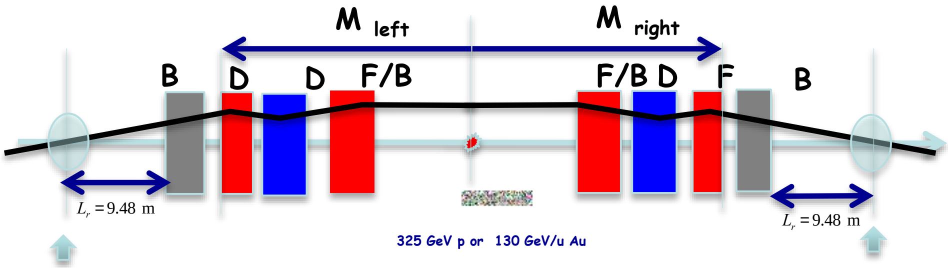


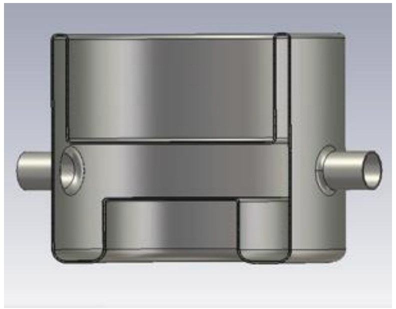
Why crab-crossing?

- We have to separate colliding beams.
- To avoid synchrotron radiation by 30 GeV electrons in the IR – one of serious backgrounds at HERA, we can not use separating dipoles.
- To separate beams without applying magnetic field, we need a crossing angle
- This also allows bringing the hadron triplet closer to the IR – hence lower β*
- Crossing angle reduces luminosity ~100-fold
- The crabbing (tail up, nose up) is needed to restore luminosity

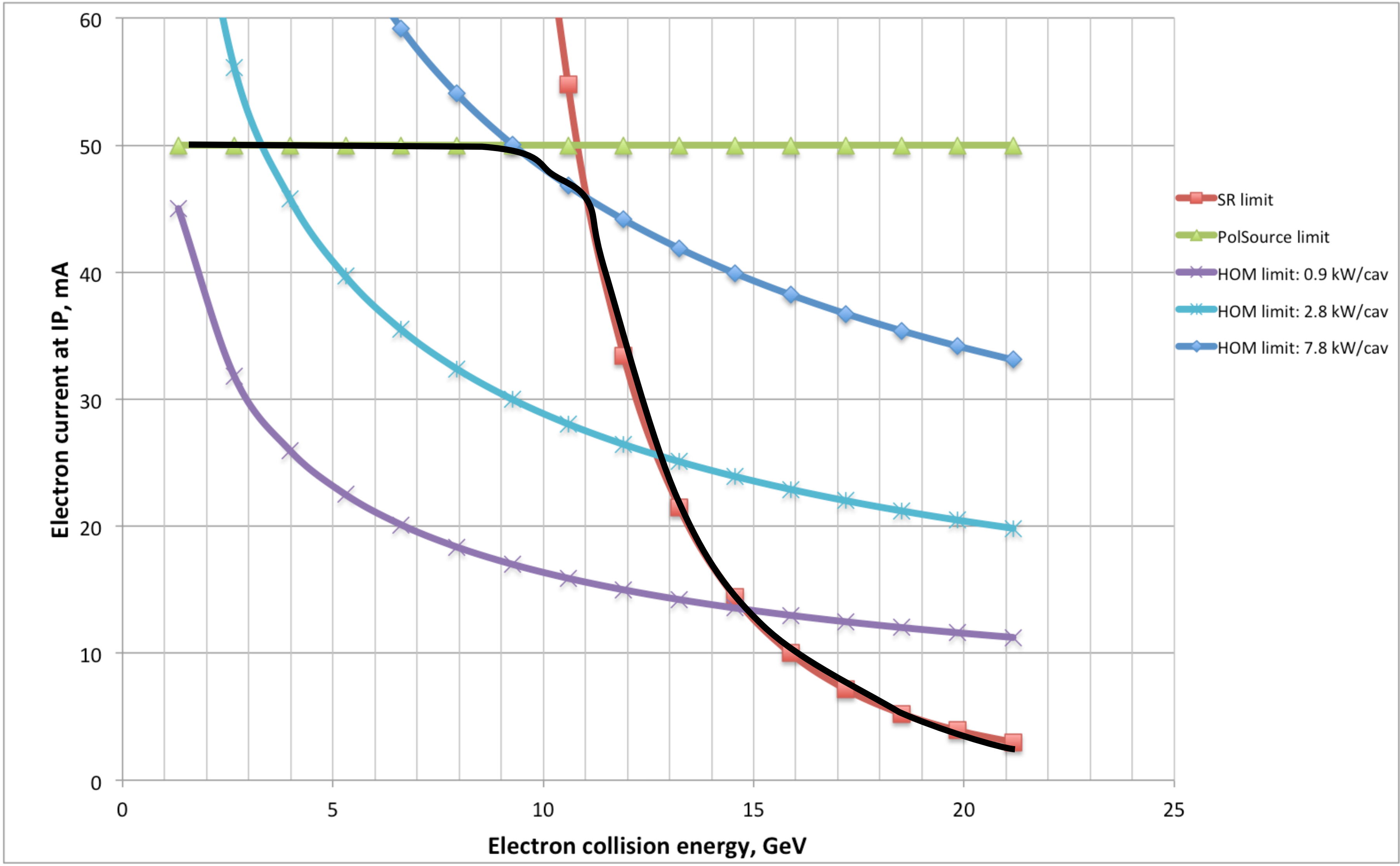
Idea Introduced by R. B. Palmer SLAC PUB 4832





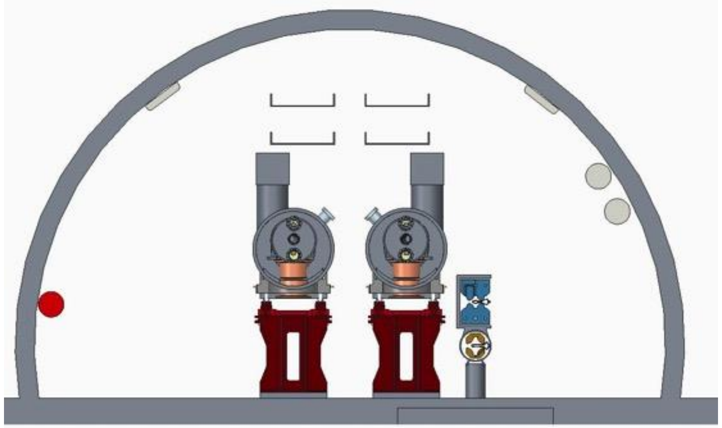


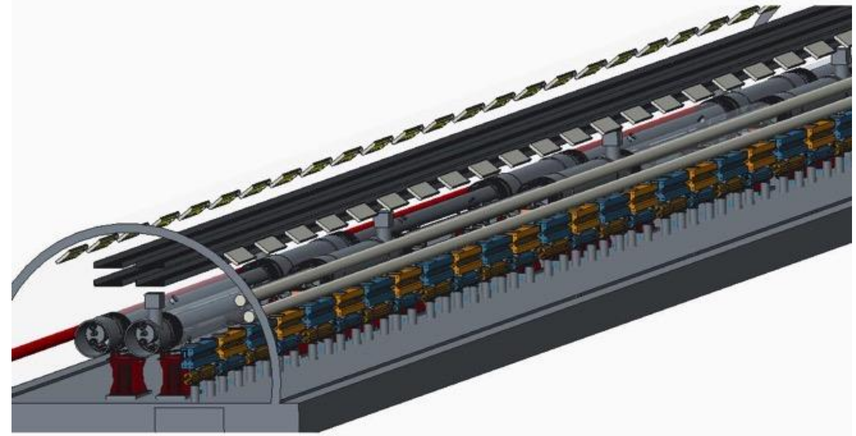
16 kW HOM power was demonstrated in KeK SRF system



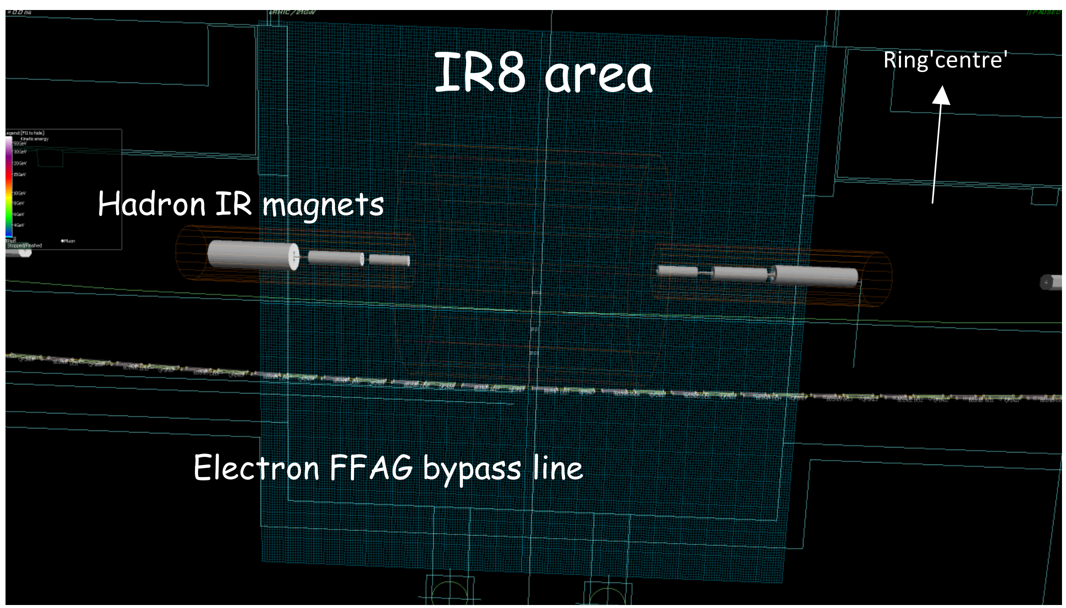
FFAG Recirculation Beamlines in RHIC Tunnel

Vertically stacked electron FFAG beamlines in arc tunnel area

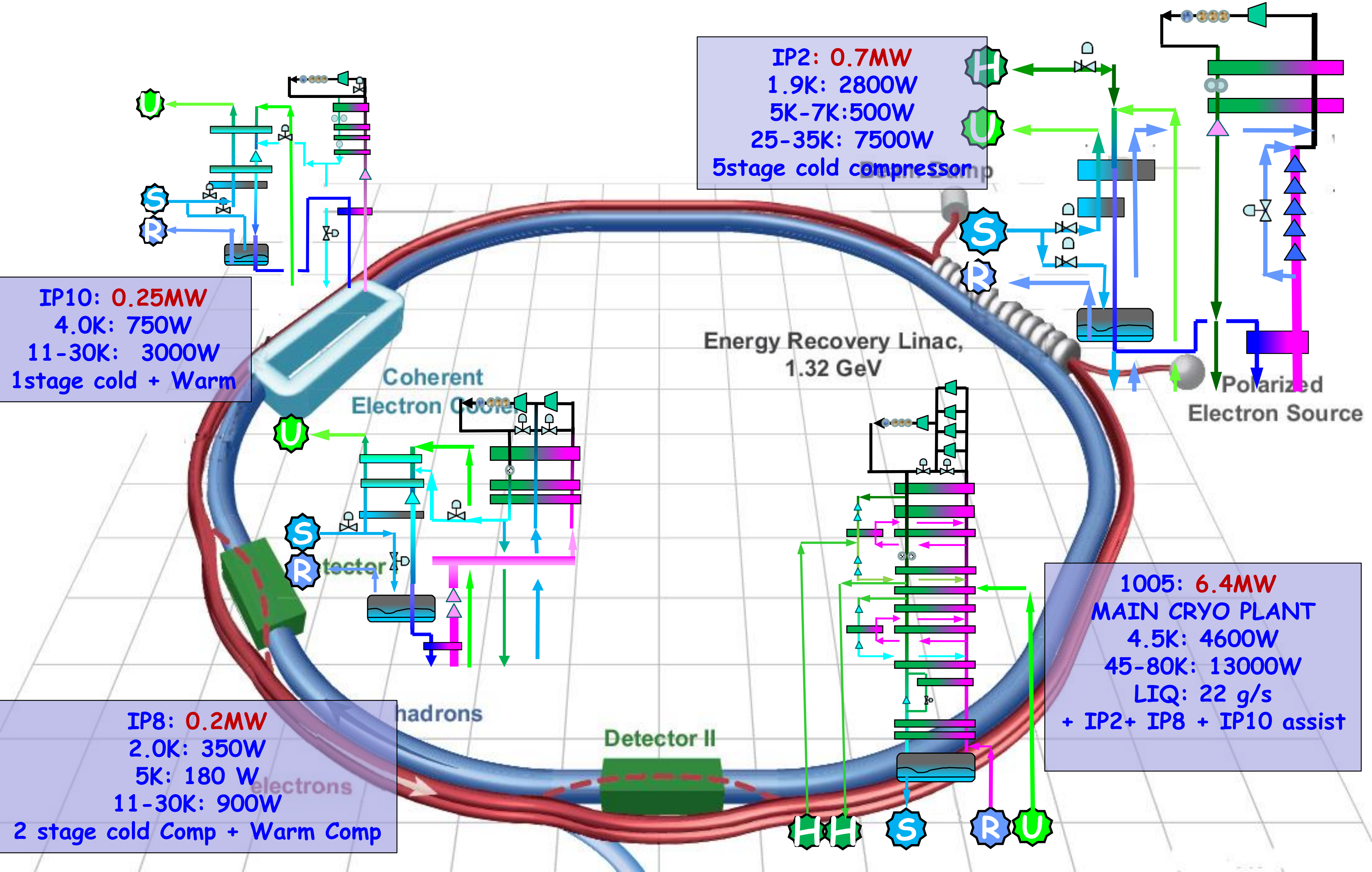




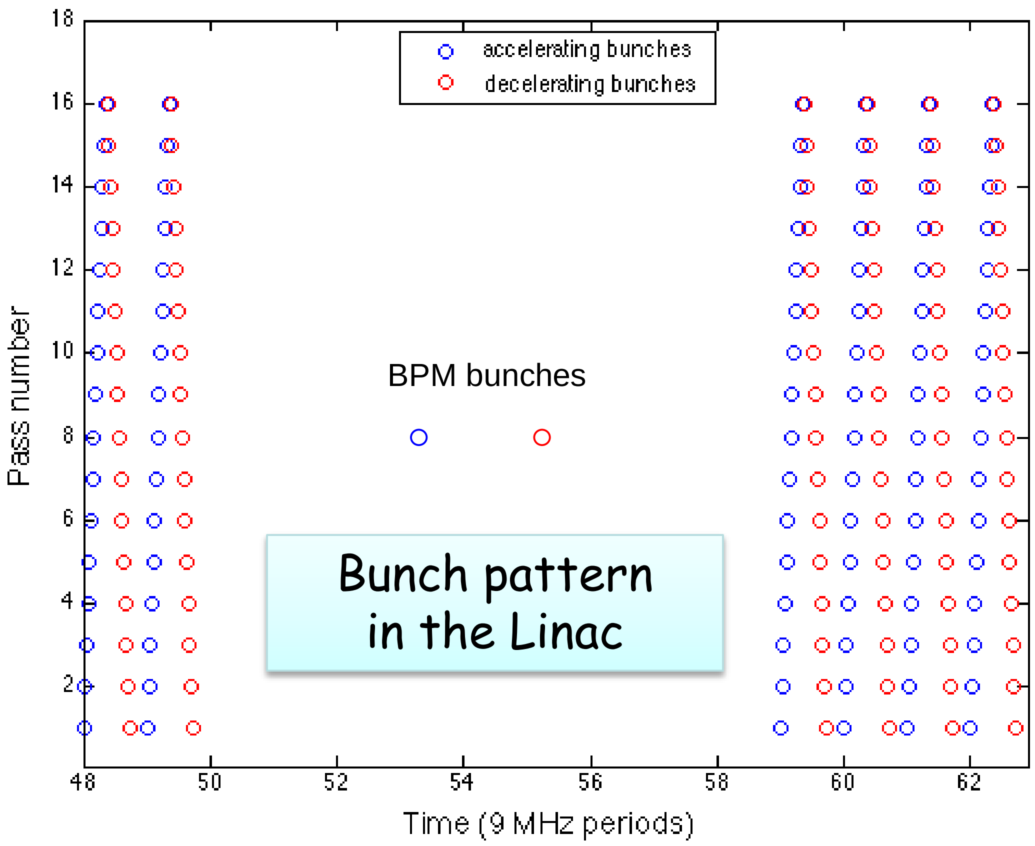
No modifications of tunnel walls is required to accommodate the detector bypass



eRHIC Cryogenic System



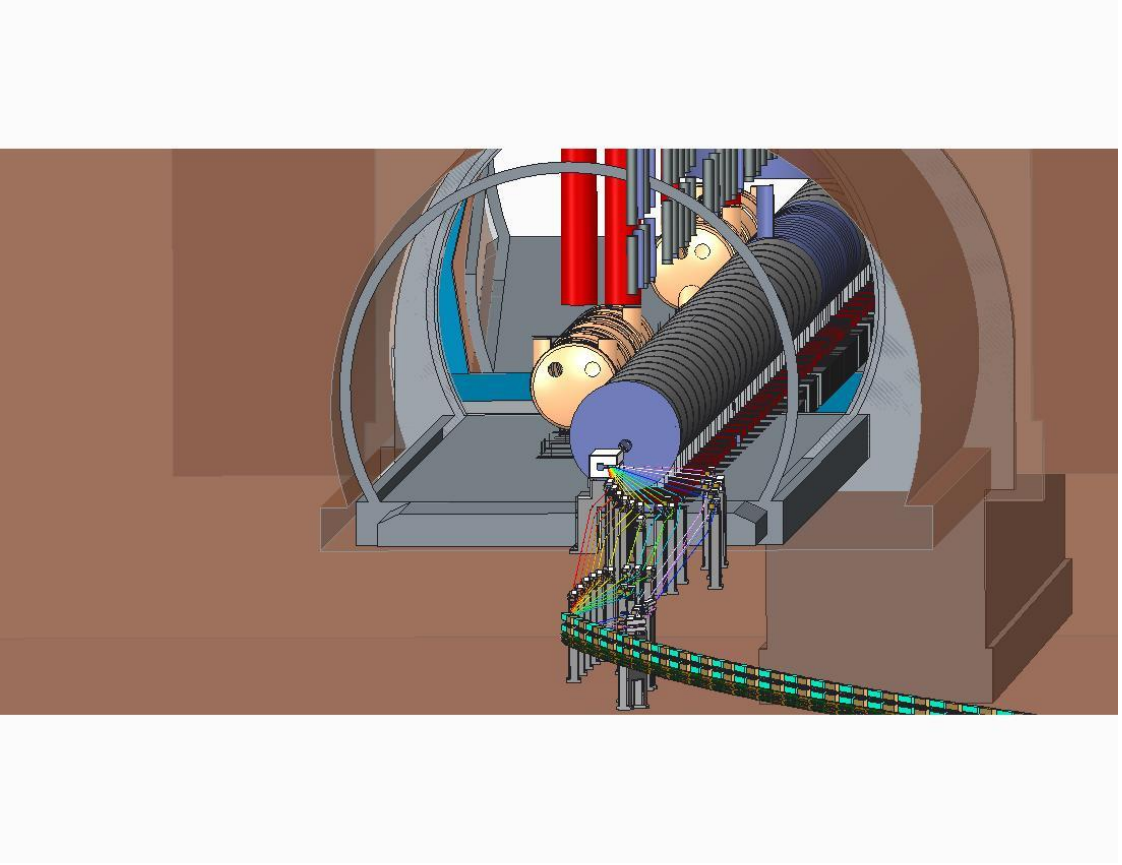
e-Beam Bunch Pattern

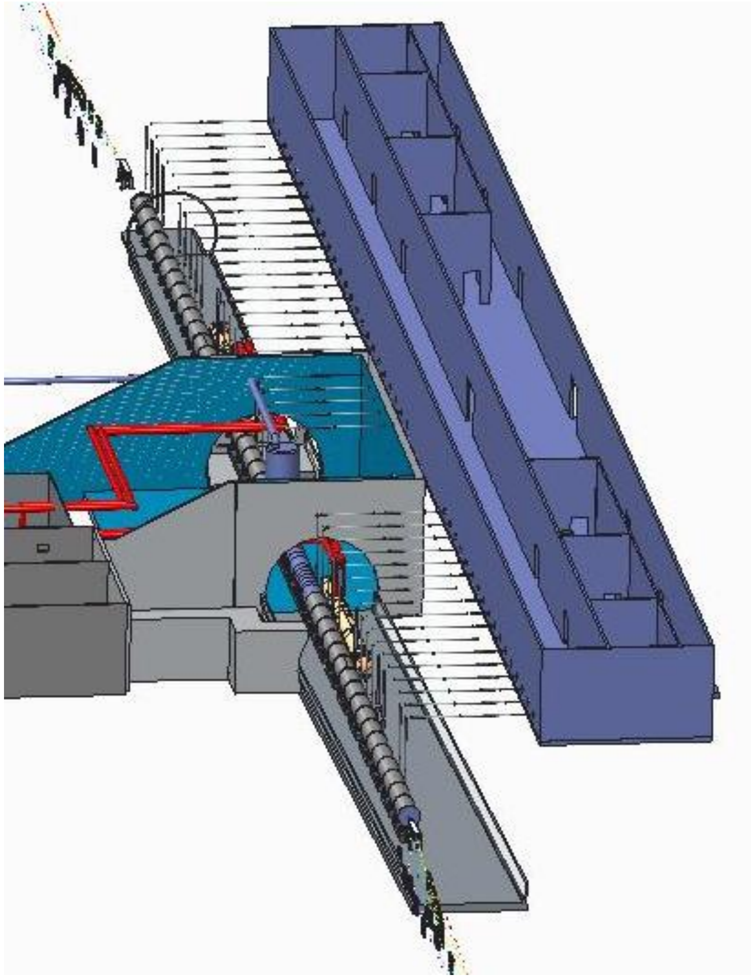


- The bunch pattern is defined by the length of electron circumference.
- Presently one RF bucket shift between the bunches. Half-bucket shift at the top energy pass.
- ~ 900 ns gap to eliminate ion accumulation
- For orbit measurements of individual passes: bunches in the gap are introduced. *Every 16 RHIC revolution periods inject one bunch into the gap.*

Main Linac and Separator Layouts at 2 o'clock area

Both main SRF linac and the separator can be fit in the available space at 2 o'clock tunnel area.

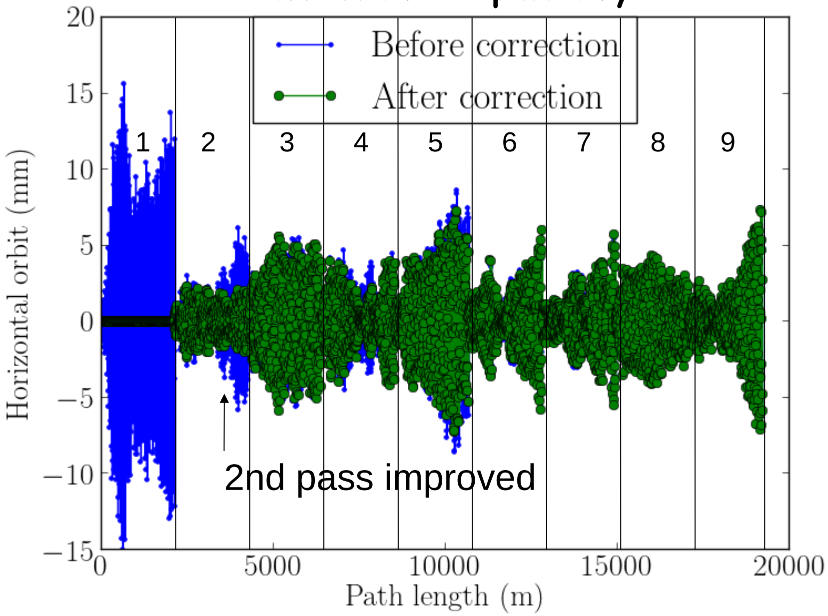




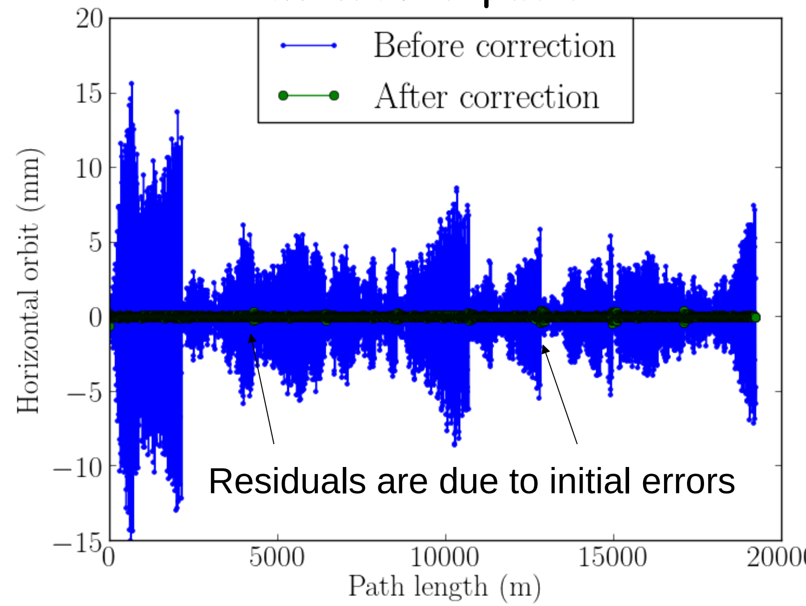
Orbit Control in a FFAG Beamline

- Multiple energies go through the same dipole correctors
- Studied both 1st pass steering and the simultaneous correction of multiple passes in the presence of misalignments and errors.
- Concluded that efficient correction can be done with:
  - one BPM (double-plane button pick-up) per two FFAG cells; 1066 BPMs total
  - dipole corrector every other magnet (H-correctors in QF, V-correctors in BD) 2132 H and 2132 V dipole correctors in total

Correction: 1st pass only



Correction: all passes



Pre-project R&D to mitigate technical risk

- Prototyping of Gatling Gun polarized electron source (BNL LDRD, DOE NP mid-term accel. R&D)
  - First beam from two cathodes in one gun, prototype supports full tests with 20 cathodes
- Coherent electron Cooling (DOE NP COMP, BNL PD)
  - CeC PoP in 2016 using 40 GeV/n Au beams in RHIC; micro-bunching technique test also possible
  - Same set-up allows test of e-p collisions with high disruption parameter
- High average current ERL to support operation with high current e-beam (NAVY, DOE NP mid-term accel. R&D)
  - Results from test-ERL in 2015/16
- Development of high gradient crab cavities for HL-LHC upgrade (LARP)
- Development of polarized He-3 underway in collaboration with MIT (DOE NP mid-term accel. R&D)
- 422 MHz elliptical 5-cell cavity (BNL LDRD)
  - Test of 4 K operation with N_2 doping
- Possible multi-pass ERL beam dynamics studies at BINP ERL, CEBAF, or a future Cornell multi-pass test-ERL

eRHIC on-project R&D

- Value engineering:
  - R&D on application of novel developments in SRF (nitrogen doping, possibly Nb_3Sn coating) at 422 MHz for allowing 4K instead of 2K operation of main linac
  - R&D on 4K operation of QW crab cavities
  - R&D on fast, high-power reactive tuning of SRF cavities, to reduce required RF power amplifiers
  - Explore use of elliptical cavities for CeC ERL.
  - R&D on high-efficiency RF amplifiers (multi-beam IOTs, solid-state amplifiers)
  - Optimize cost of FFAG arcs (permanent magnets, correction schemes, instrumentation)
  - Optimize cost of cryomodules.
- Prototypes:
  - Prototype eRHIC FFAG permanent magnets and section with 2 FODO cells including correction elements
  - Prototype Linac main cavities, energy loss, and energy spread cavities and cryo-modules
  - Prototype CeC ERL cavities and cryo-module

Main cost drivers

- CW SRF Linacs
  - 140 m long 1.32 GeV Linac with 20 MeV energy loss compensation and 53 MeV energy spread compensation
    - *Total for elliptical cavities, cryo-modules and RF: TPC cost $122.9M*
  - 50 m long 52 MeV Linac with 6 MeV energy spread compensation for CeC
    - *Total for quarter-wave cavities, cryo-module and RF: TPC cost $50.2M*
- FFAG arcs
  - 4264 permanent magnet quadrupoles, each with two electrically powered correctors and one dual plane BPM for every 4 magnets
    - *Total, incl. corrector and PS, vacuum chamber and BPMs: TPC cost $175.0M Average cost per magnet: TPC cost $41.2k*
- Spreader/combiner beamlines on either side of main linac
  - Each with 16 beam lines with total of 218 magnets
    - *Total, incl. vacuum chamber, BPMs, PS: TPC cost $35.2M*

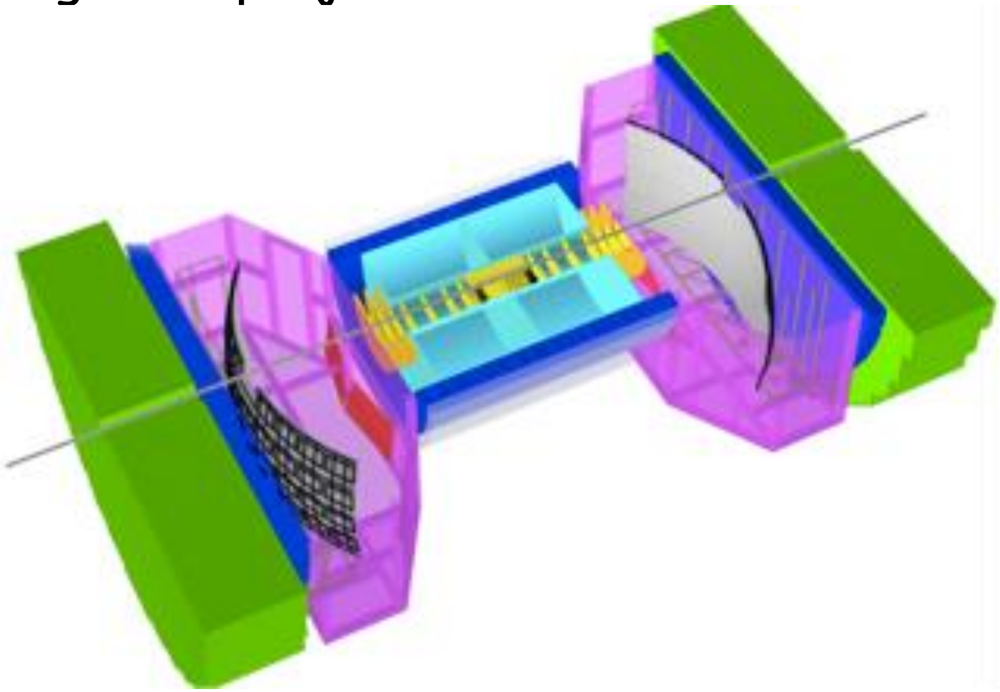
Progress with eRHIC R&D and retiring of eRHIC technical challenges

Sample V

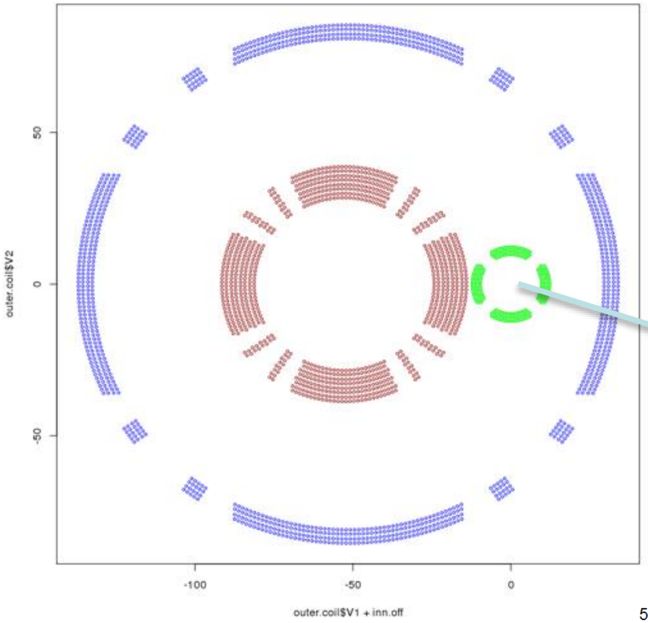
Crab cavities

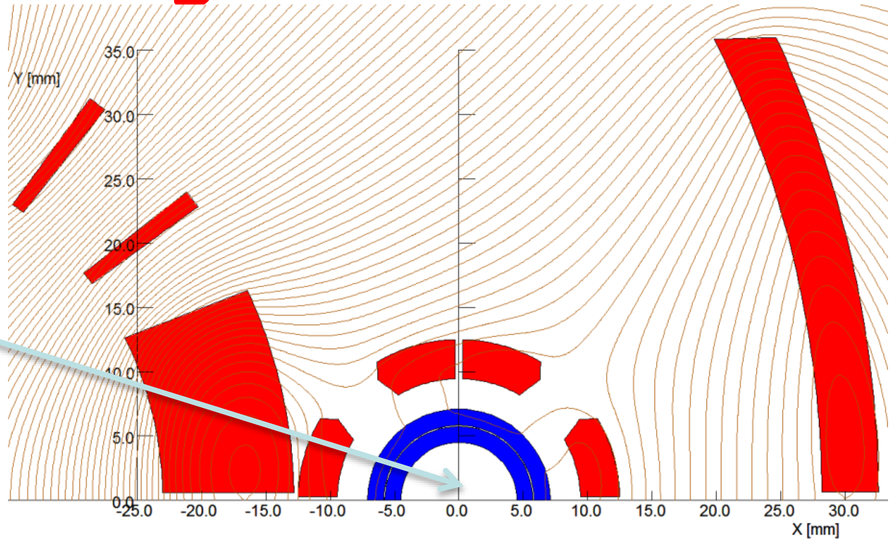
Initial eRHIC detector

- eRHIC TPC includes one high luminosity interaction region, a second high luminosity IR is available
- An initial eRHIC detector is not included in eRHIC TPC, although detector halls and infrastructure exist from RHIC
- Initial eRHIC detector will use detector elements from the existing RHIC detectors
- Additional equipment cost for an initial eRHIC detector is estimated to be about FY15$ 100M with large off-project contributions expected

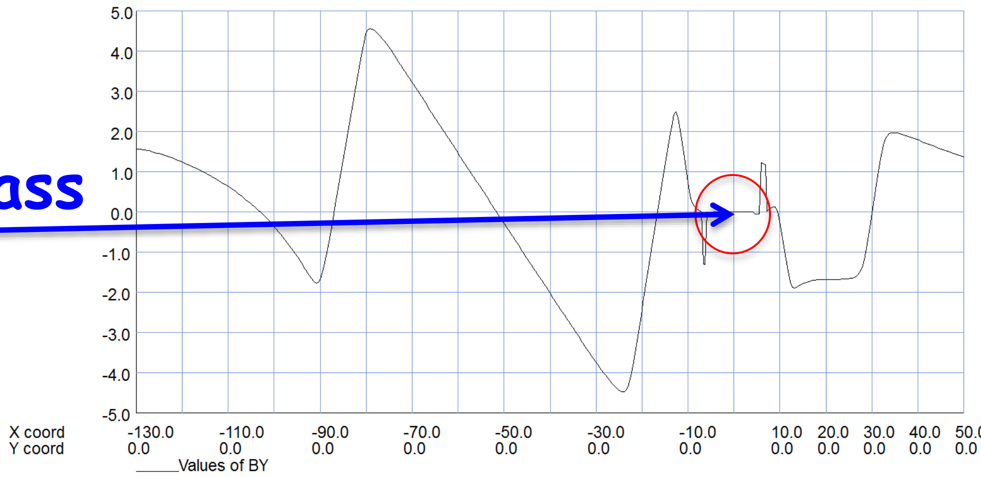


"Sweet-spot" in the heart of the IR design





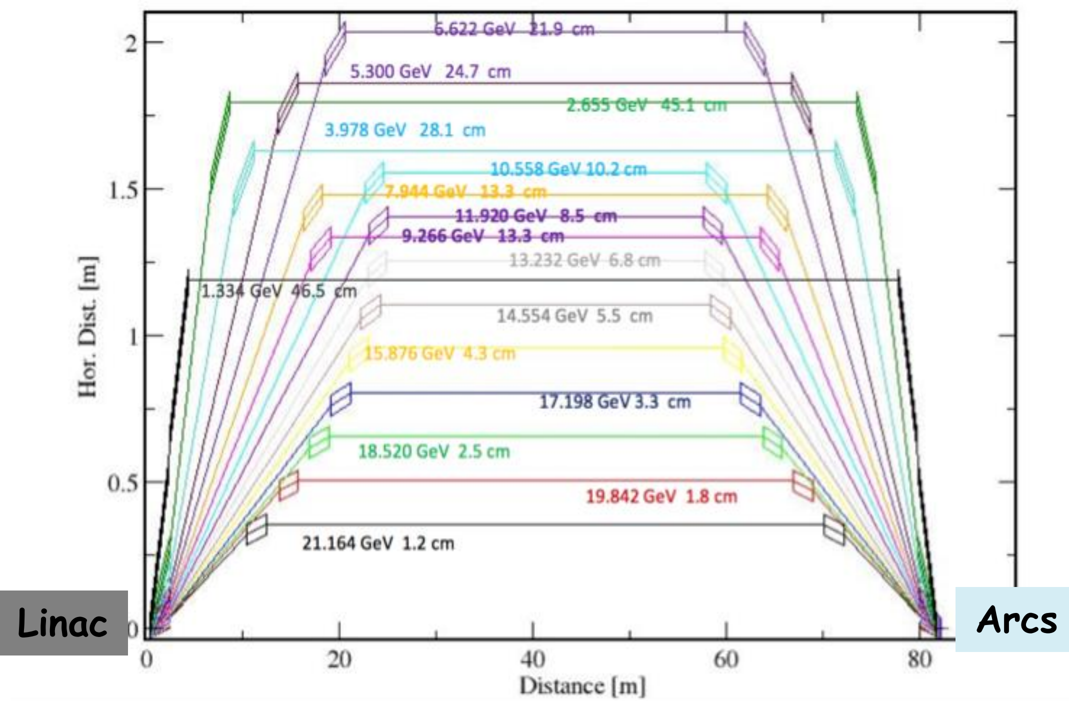
e-beam pass



® Bret Parker

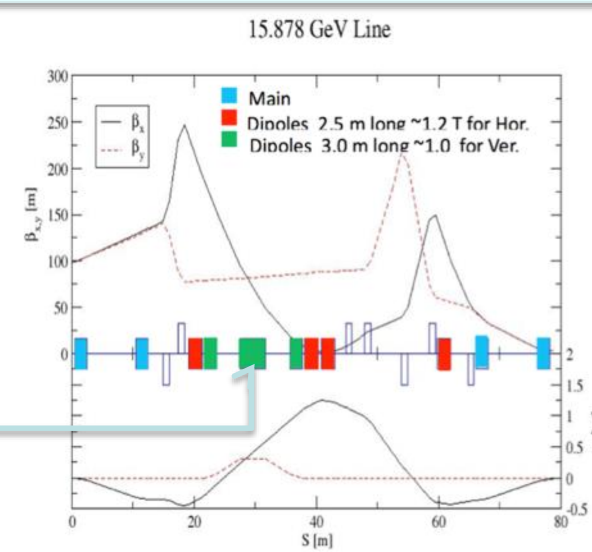
Beam Spreader and Combiner

© N. Tsoupas



- 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:

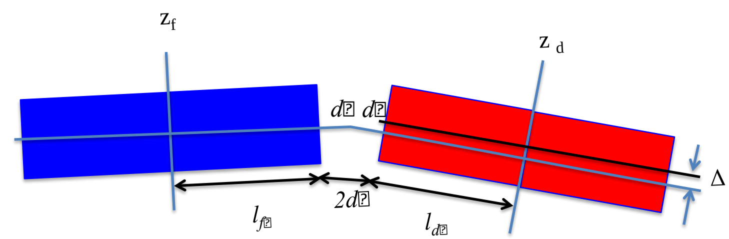
  path length and R_{56} corrections
- Betatron phase advance adjusters



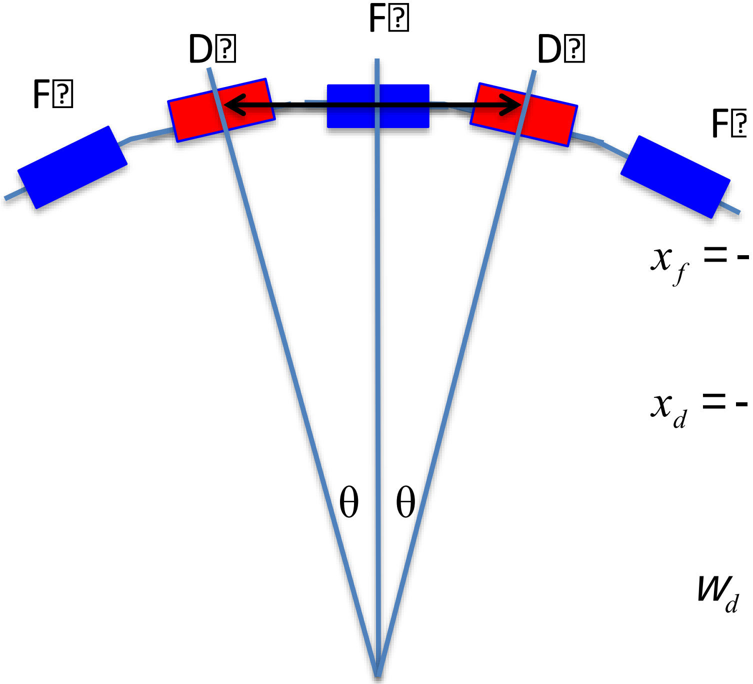
- ✧ 15 cm horizontal separation between individual lines
- ✧ Some of the lines are folded into the vertical plane to reduce path length difference
- ✧ Vertical magnet chicanes are used for pathlength correction

eRHIC FFAG arcs as a bent FODO beam-line

- An ideal eRHIC FFAG cell is comprised of two quadrupoles (F & D) whose magnetic axis are shifted horizontally with respect to each other by Δ
- Orbit dependence on the energy can be easily found in paraxial approximation
- **Everything can be done accurately and analytically – no doubt that proposed FFAG lattice would work!**



$$L=2(l_F+l_D+2d)$$



Orbit

$$x_f=-\frac{a_{xd}\theta+c_{xd}(\Delta+d\theta)}{a_{xf}c_{xd}+a_{xd}c_{xf}+2dc_{xd}c_{xf}}$$

$$x_d=-\frac{a_{xf}\theta-c_{xf}(\Delta-d\theta)}{a_{xf}c_{xd}+a_{xd}c_{xf}+2dc_{xd}c_{xf}}$$

$$a_{xf}=\cos\varphi_f;\ b_{xf}=\frac{\sin\varphi_f}{w_f};c_{xf}=-w_f\sin\varphi_f$$

$$a_{xd}=\cosh\varphi_d;\ b_{xd}=\frac{\sinh\varphi_d}{w_d};c_{xd}=w_d\sinh\varphi_d$$

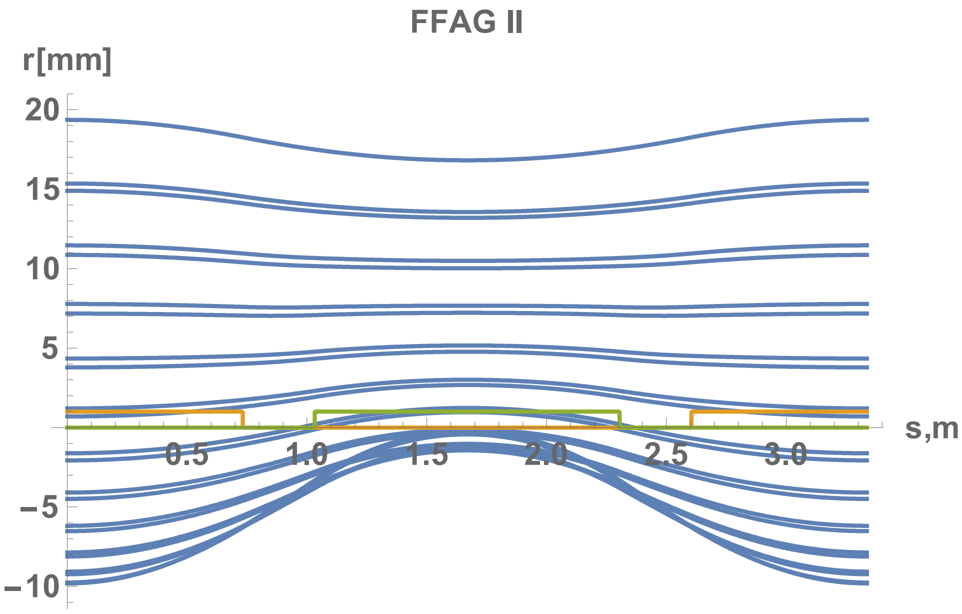
$$a_{yf}=\cosh\varphi_f;\ b_{yf}=\frac{\sinh\varphi_f}{w_f};c_{yf}=w_f\sinh\varphi_f$$

$$a_{yd}=\cos\varphi_d;\ b_{yd}=\frac{\sin\varphi_d}{w_d};c_{yd}=-w_d\sinh\varphi_d$$

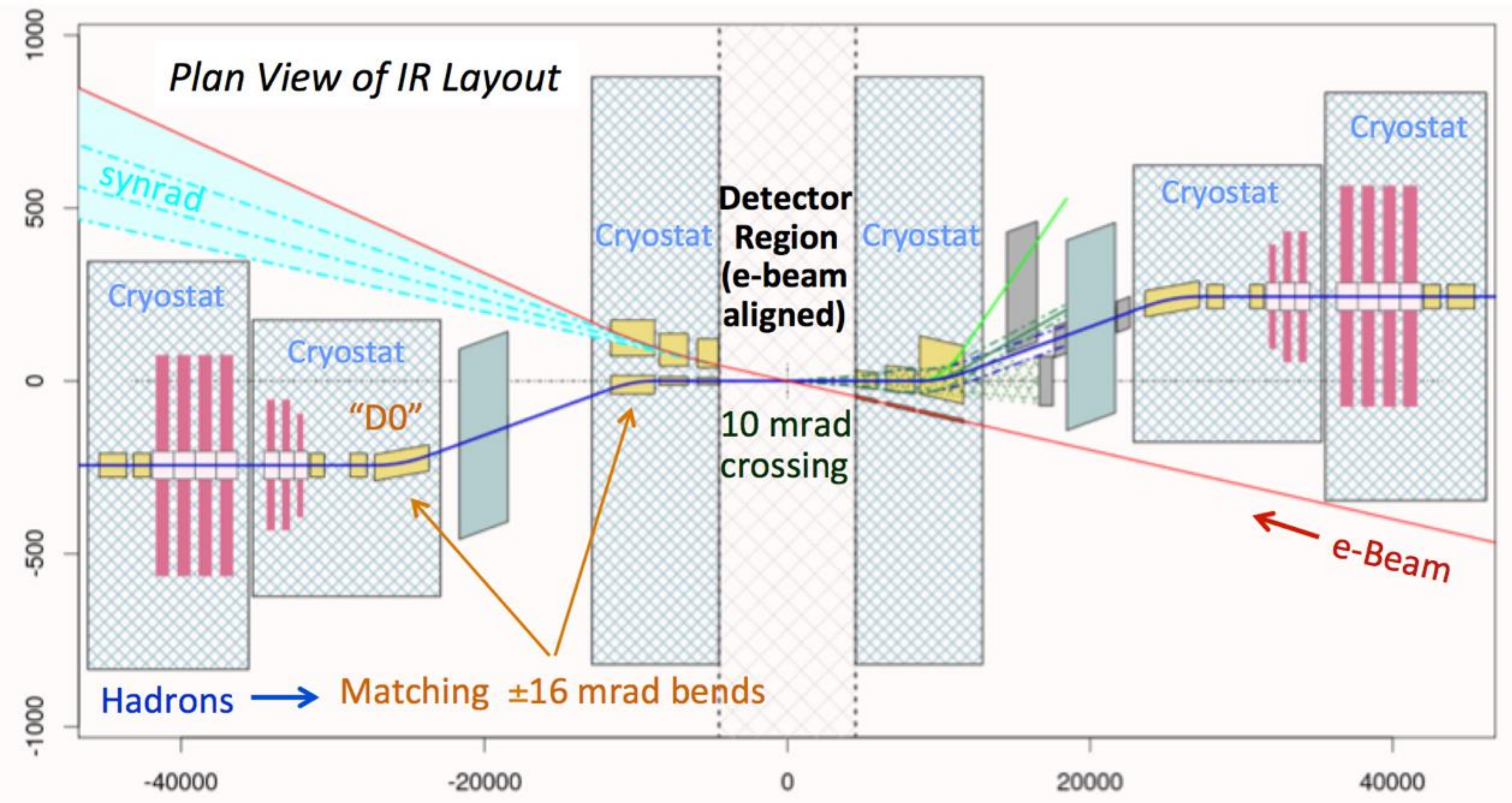
$$w_d=\sqrt{-\frac{eG_d}{pc}};w_f=\sqrt{\frac{eG_f}{pc}}. \qquad \varphi_{f,d}=w_{f,d}l_{f,d}$$

Accelerating/Decelerating Orbits

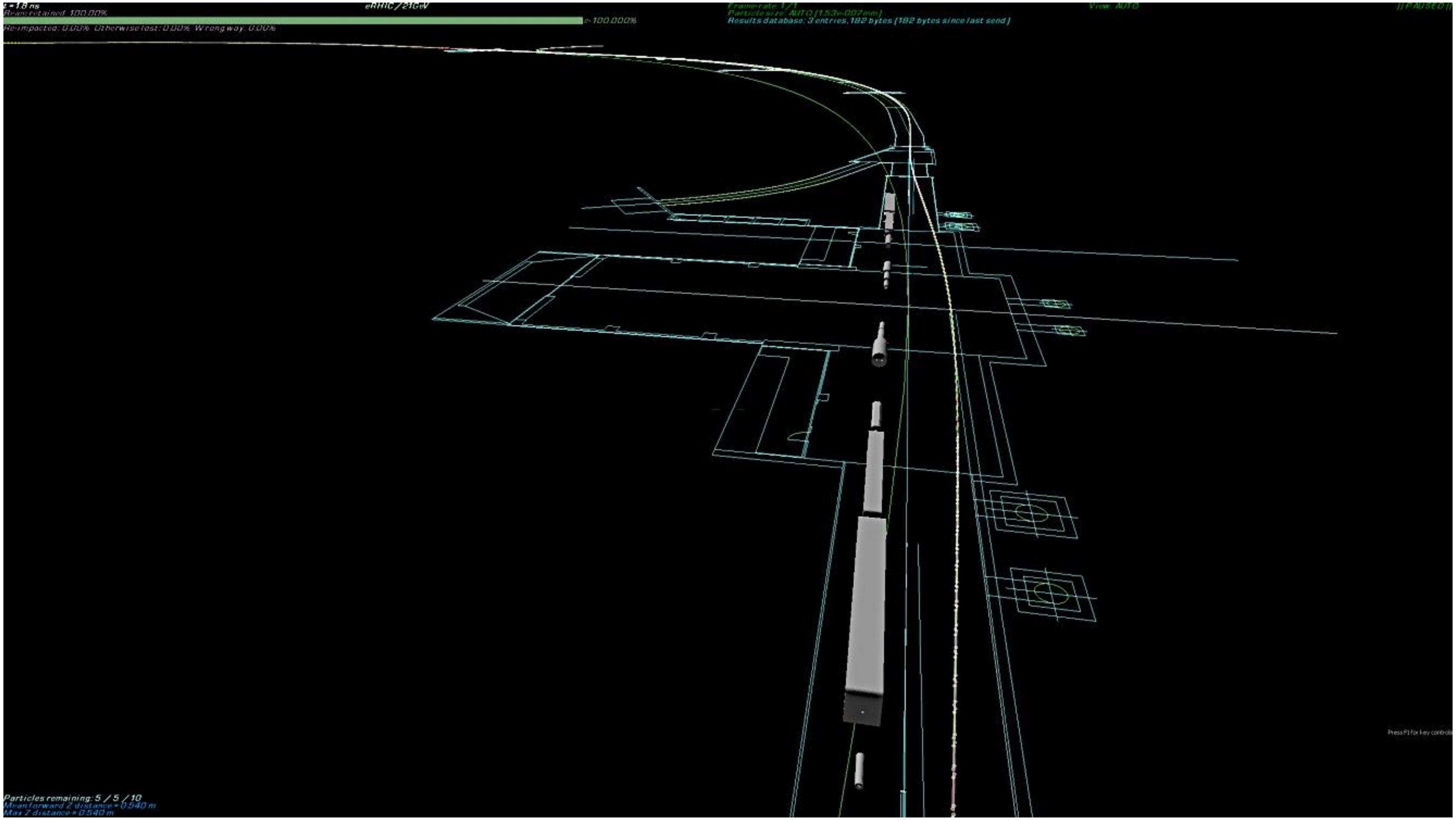
- Accelerating/Decelerating Orbits
  - Example of characteristic accelerating/decelerating orbit splits with present configuration of the energy loss compensation system. Shown for operation at 21.2 GeV top energy.



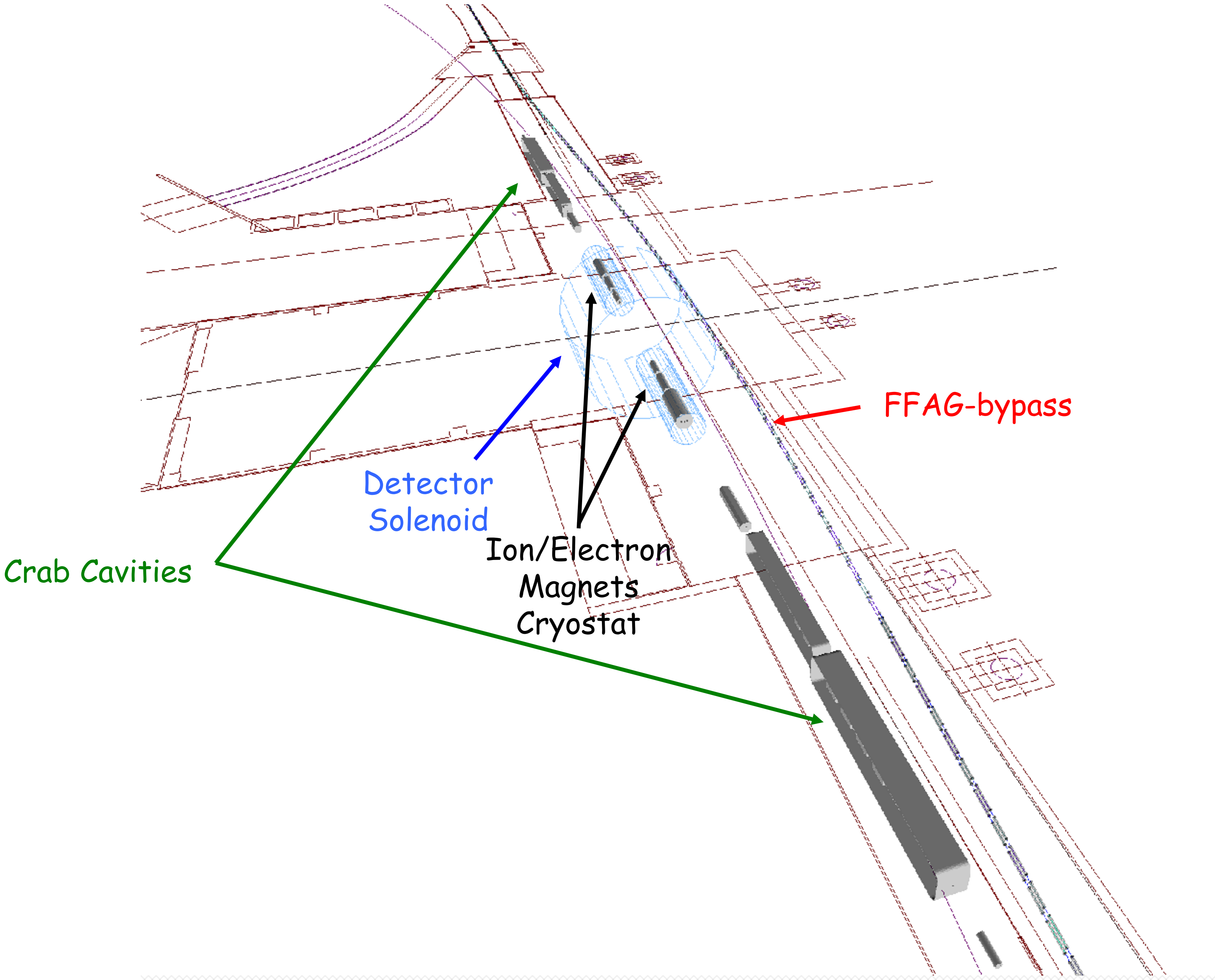
IR


Plan View of IR Layout
synrad
Cryostat
Cryostat
"D0"
Cryostat
Detector
Region
(e-beam
aligned)
10 mrad
crossing
Cryostat
Cryostat
Cryostat
e-Beam
Hadrons
Matching ±16 mrad bends
1000
500
0
-500
-1000
-40000
-20000
0
20000
40000

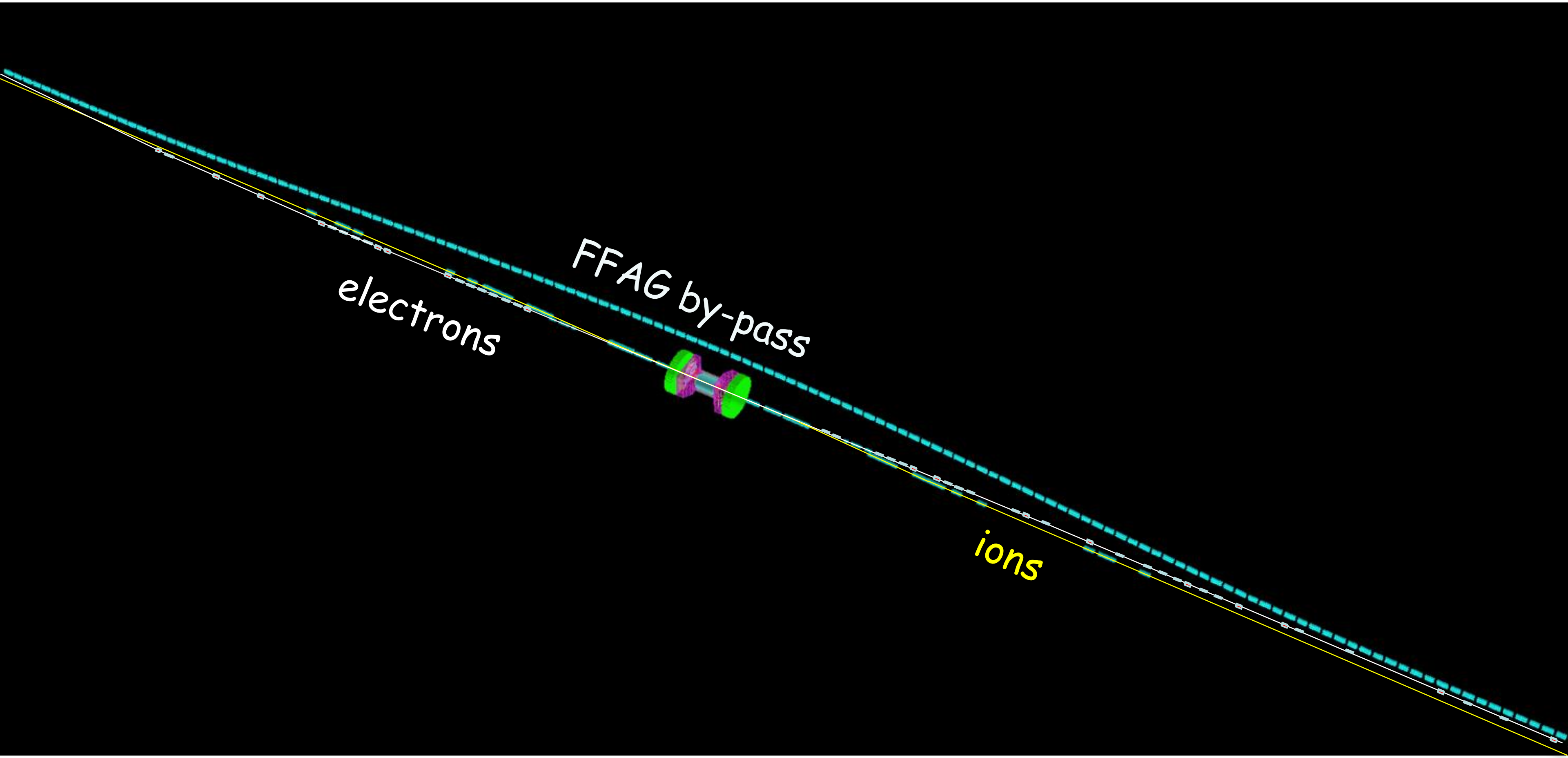
INTERACTION REGION in eRHIC

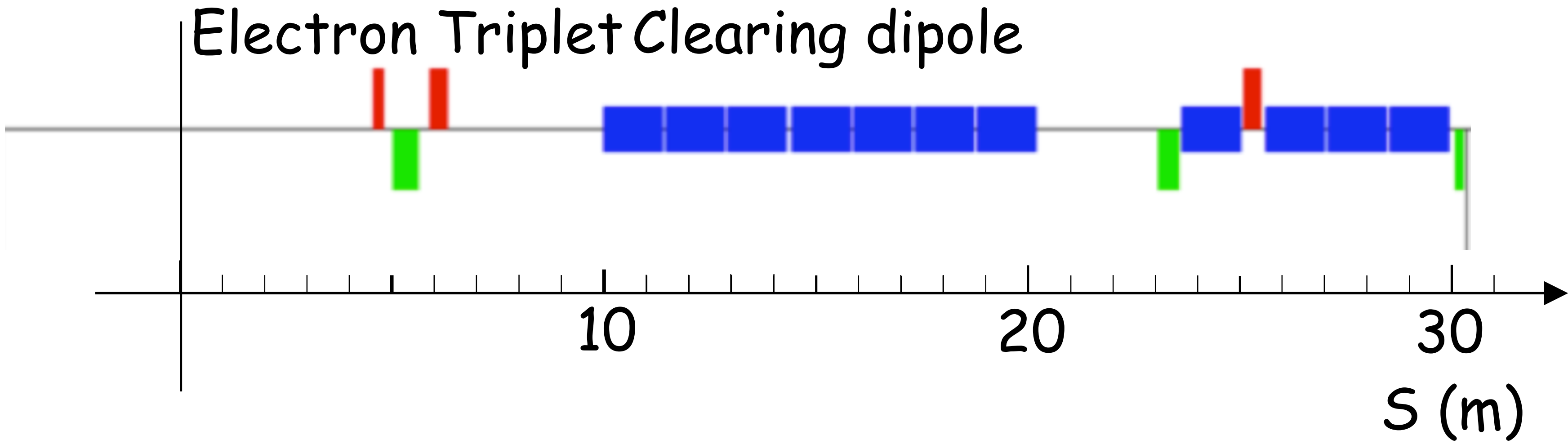


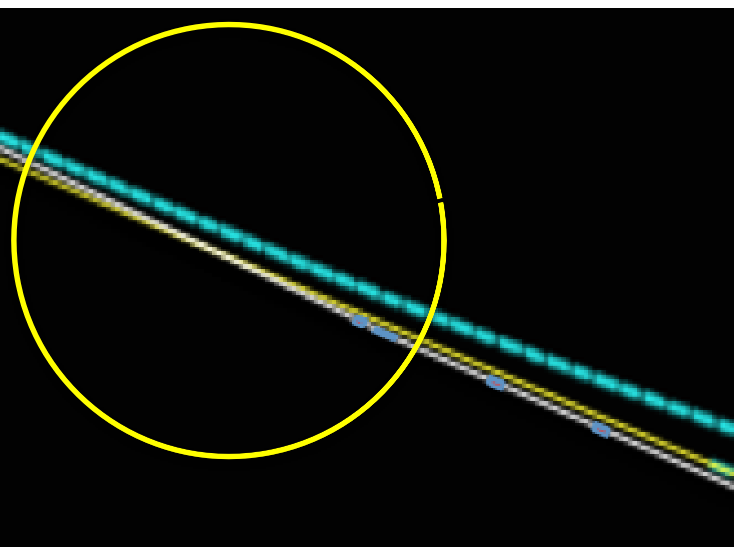
- FFAG arcs bypass the detector(s) on the outside and cross to the inside on the side of the linac.
- Electron beam line for collisions cross from outside to inside at detector and then cross back to outside after the detector.
- 180 degree phase shift in electron beam line through detector.

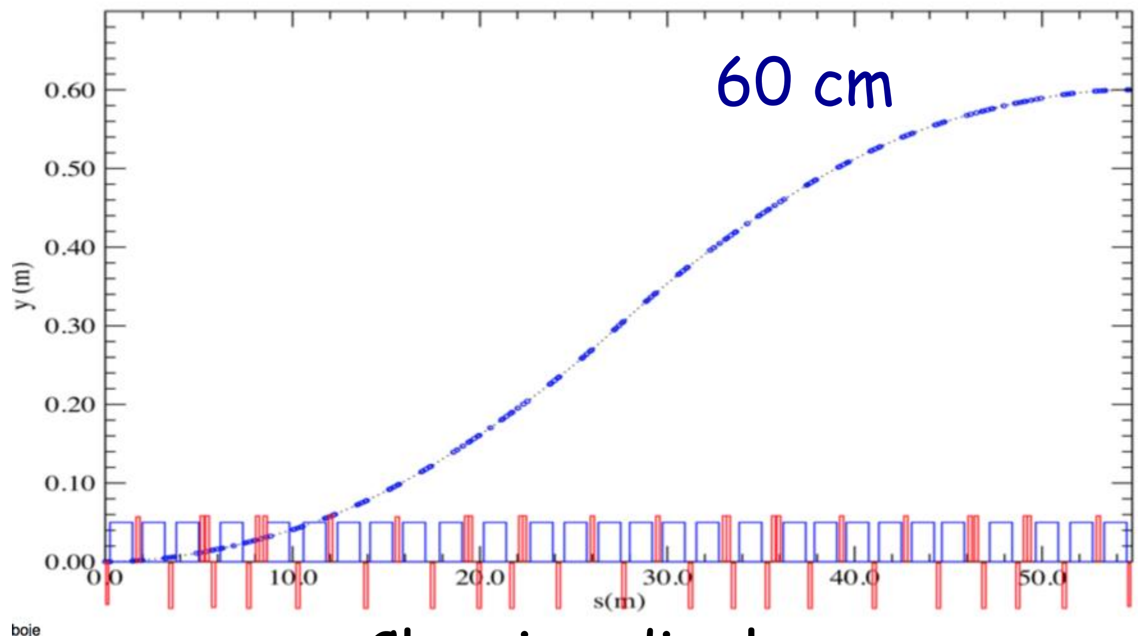


FFAG-bypass
Detector
Solenoid
Crab Cavities
Ion/Electron
Magnets
Cryostat

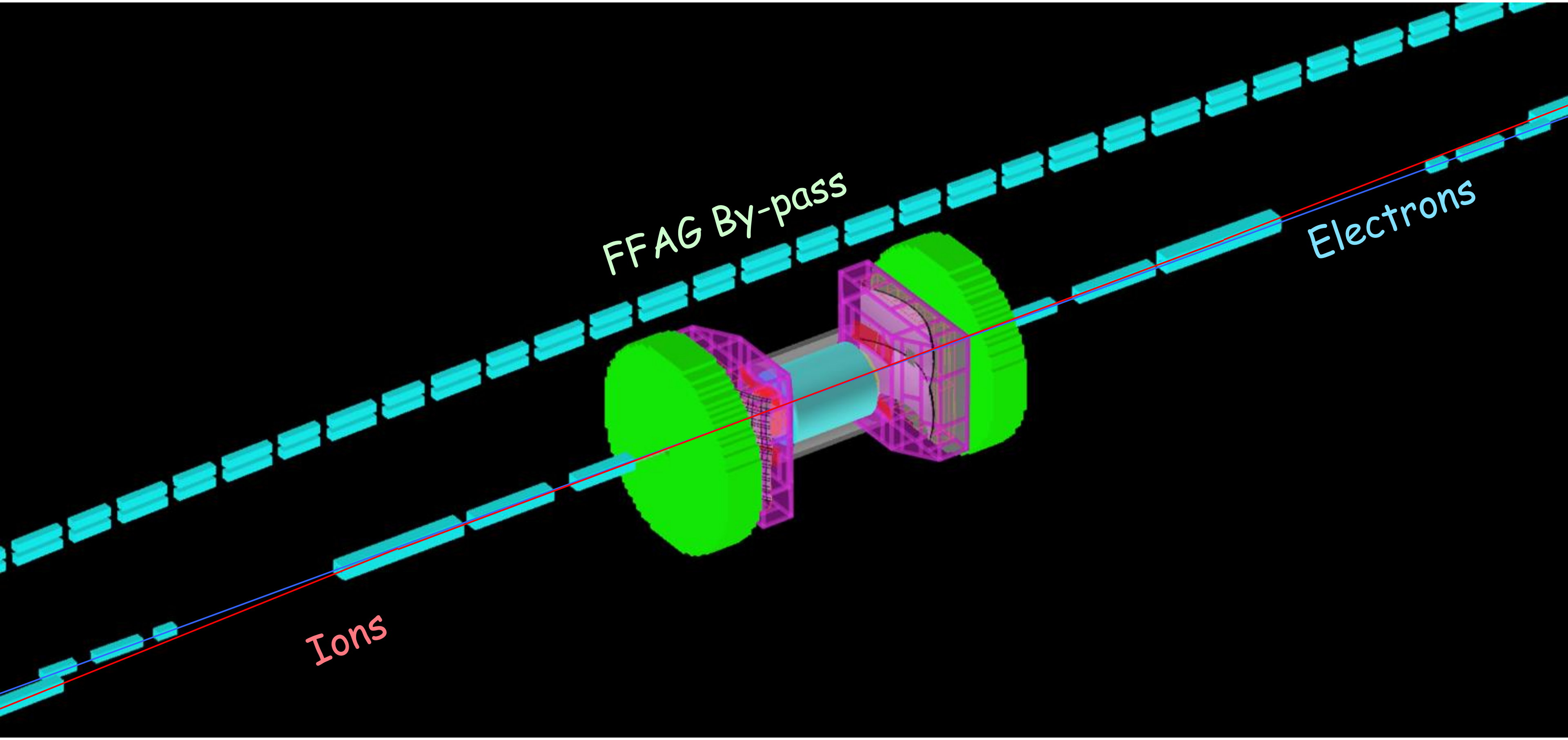

FFAG by-pass
electrons
ions







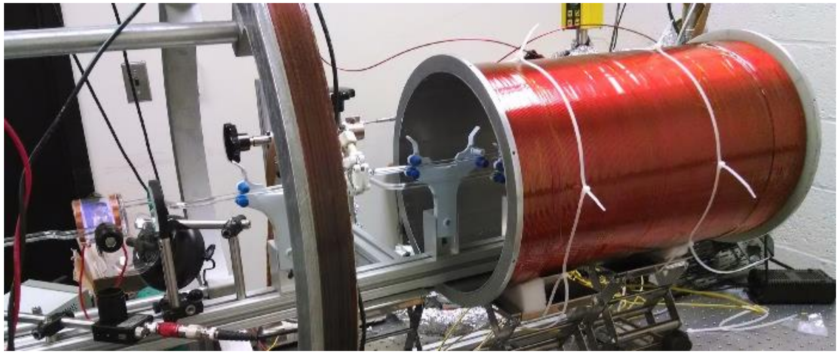
Clearing dipole


FFAG By-pass
Electrons
Ions

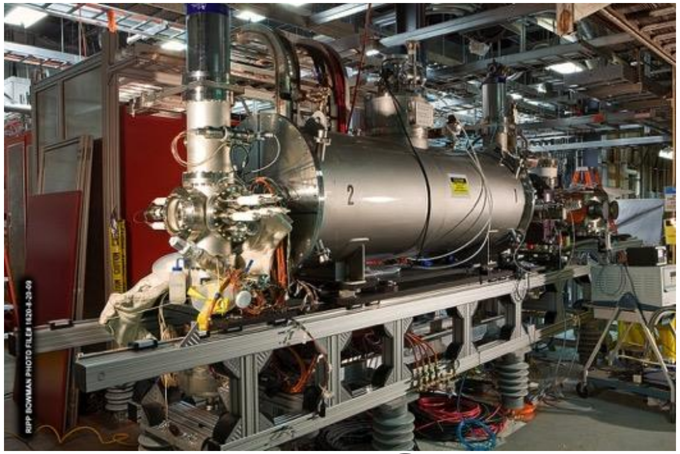
Polarized ^{3}He – MIT and BNL

- Optically pumped ^{3}He↑ source developed at MIT
  R. Milner, J. Maxwell, C. Epstein

- BNL EBIS turns ^{3}He↑ gas into beam for acceleration



MIT pumping and test cell



BNL EBIS

- **Status**

- MIT source demonstrated $P \sim 70\%$
  current tests study depolarization during transfer

- MIT source moved to BNL in 2014

- Accelerated bunches of 10^{10} unpolarized ^{3}He in AGS in 2013
  4x increase possible through additional bunch merge

- Acceleration of ^{3}He↑ in Booster/AGS/RHIC studied in simulation
  RHIC requires 6 instead of current 2 snakes (with one RHIC ring used for eRHIC, snakes and rotators from other ring can be used for additional 4 snakes)

- ^{3}He↑ polarimetry after EBIS, in AGS and RHIC to be developed