EIC RHIC Updates

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EIC Accelerator Collaboration Workshop
October 7-9, 2020

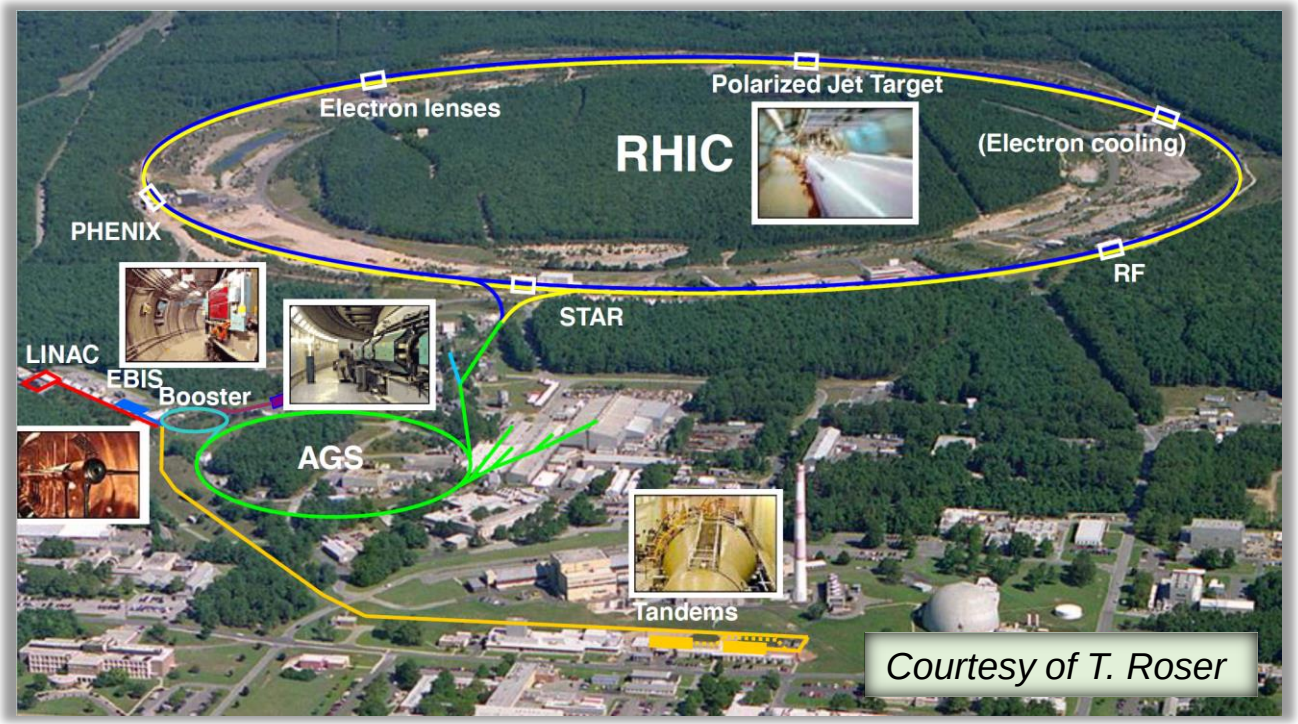
Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

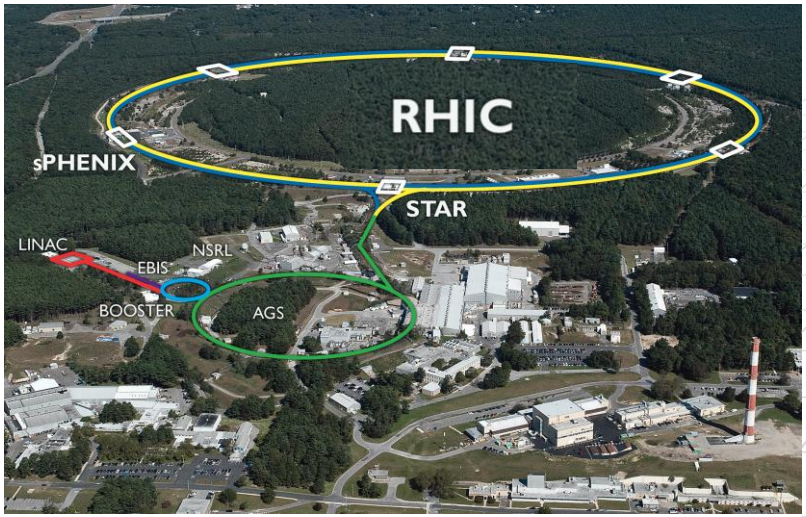
On the shoulders of giants

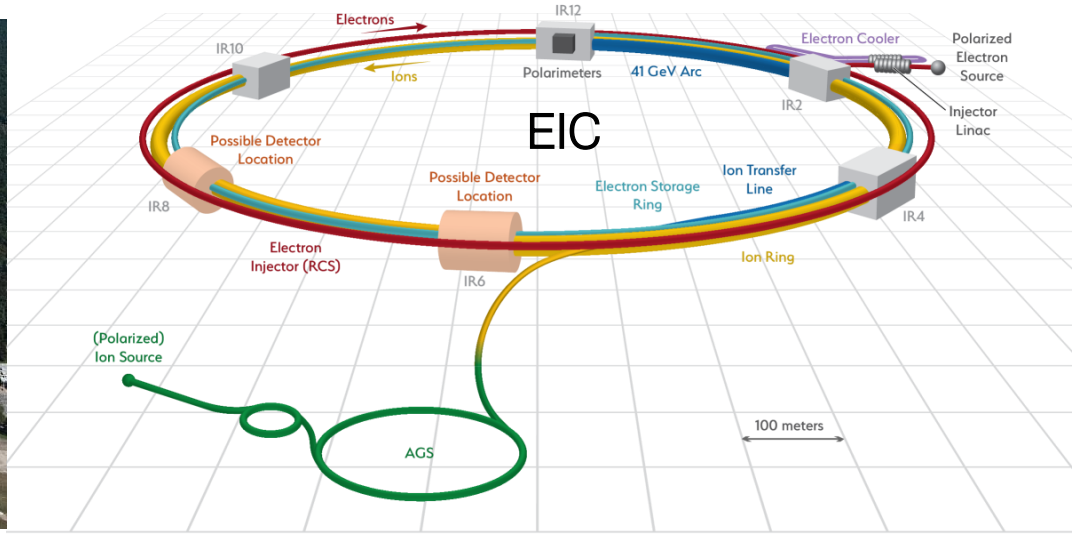


The Relativistic Heavy Ion Collider – RHIC

- Hadron accelerator and collider consisting of **two independent rings**.
- Operated with **wide range of beam energies** (3.85 to 100 GeV/u for Au and 255 GeV for protons) and **particle species** (p↑, Au,U,…)
- **Operating since 2000** with **outstanding performance**, showcasing max. L_{pk} of 7×10^{32} /cm^2/s per IP during ion-ion collisions (x40 higher than design) and proton polarization of 55% average.
- Injectors also provide beams for **unique applications**.

Existing RHIC accelerator complex will be re-used for EIC





- **Yellow RHIC ring** will be used **for EIC hadron beam**.
- **Two arcs of Blue RHIC ring** (12-2 and 4-6 o'clock) used as **EIC hadron beamlines**; **one arc as a cryoline** (2-4 o'clock). Most of remaining Blue ring components stay in tunnel.
- On-going **upgrade of ion source EBIS** will provide capability of **polarized ^{3}He**.
- Present **injector chain** will be **entirely re-used**. (EBIS, Linac, Booster, AGS)
- An **electron ring** will be added to the tunnel to complete the **Electron-Ion Collider**.

Existing RHIC accelerator complex will be re-used for EIC

Parameter	proton		Au ion	
	EIC design	RHIC demonstrated	EIC design	RHIC demonstrated
Energy [GeV/nucleon]	275	255	110	100
Particle per bunch [10^{10}]	20	22.5	0.1	0.22
RMS norm. emit., h/v [μm]]	5.9/2.5	3.1/3.1	2.0/2.0	2.0/2.0
BB parameter, h/v [10^{-3}]	$+15/+10^{\dagger}$	$-18/-18^{\dagger}$	+11/+4	−4/−4
RMS long. emittance [10^{-3}eV·s]	110	55	0.2	0.27
RMS bunch length [cm]	6	55	18	35
RMS $\Delta p/p$ [10^{-4}]	6.8	1.7	10	7.7
Polarization [%]	70	55	—	—

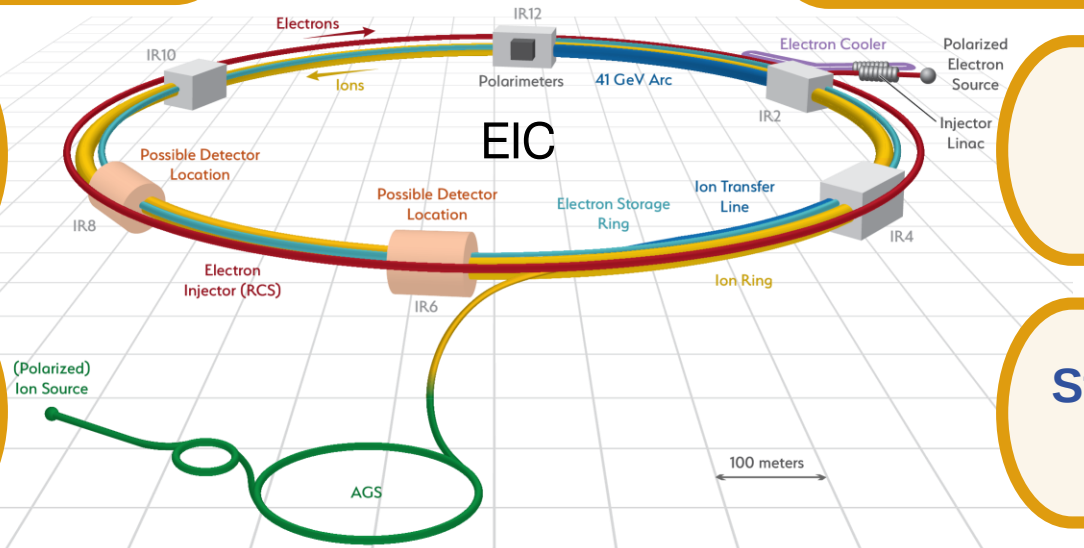
Courtesy of W. Fischer (from CDR)

Eight Key Updates of the RHIC Hadron Rings Towards EIC

Injection System Upgrade

Beam Instrumentation Upgrade

Path Length Variation, Energy Upgrade



Vacuum Chamber Update

Interaction Regions

Strong Hadron Cooling

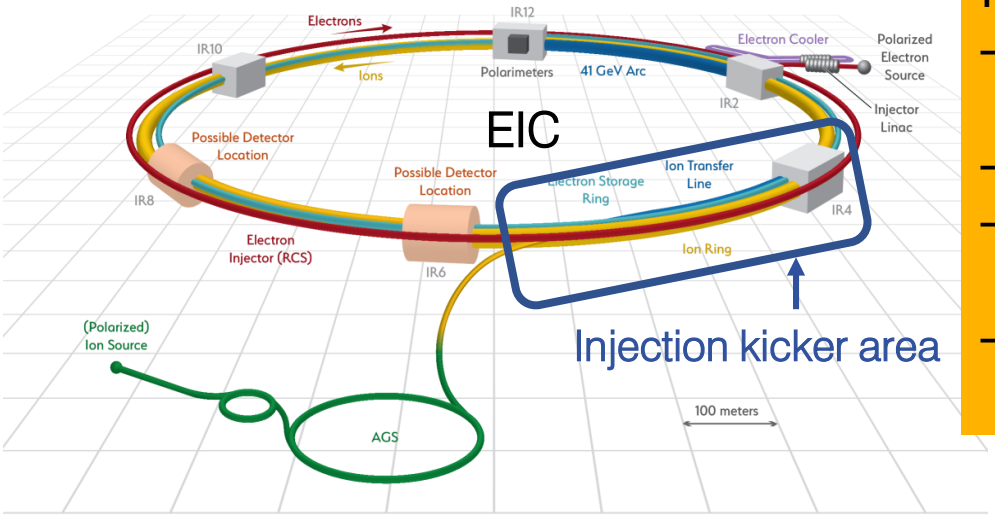
Additional Snakes

Hadron Ring RF Systems

L2 Manager: Vadim Ptitsyn

Transfer Line & Injection Upgrade

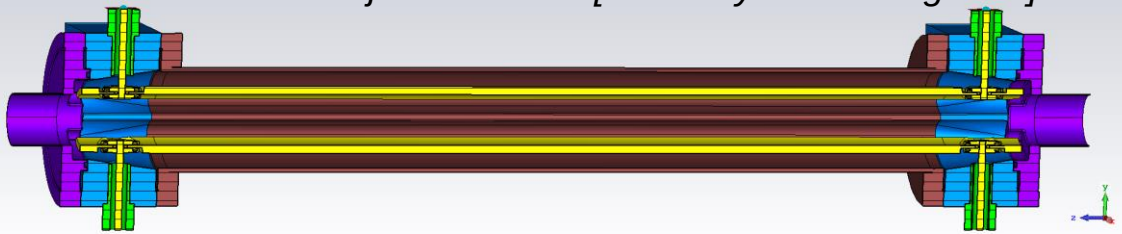
Tripling **number of bunches** requires **longer injection kicker insertion (**~20m)
→ not enough space for this system in presently used injection area at 5 o'clock.



Required **modifications**:

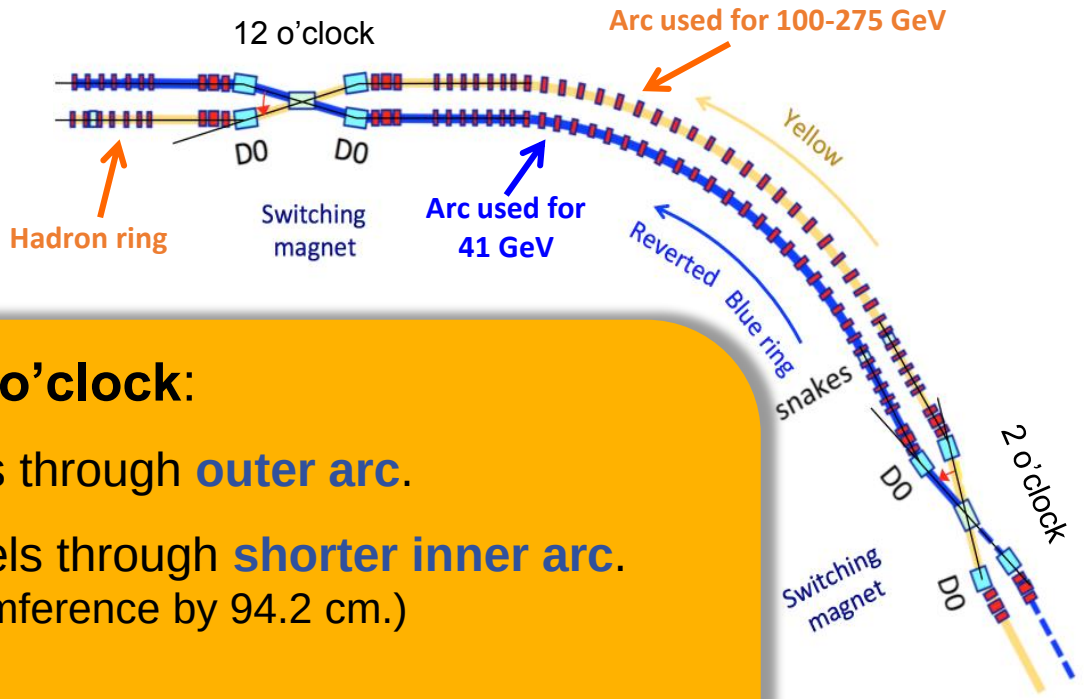
- Beam transported to IR4 area through inner Blue arc.
- AtR Y-line for transfer into Blue 6-4 arc
- 4 o'clock transfer line and injection kicker system
- Blue 6-4 arc SC bus connections and power supplies

Cross section of injection kicker [Courtesy of M. Sangroula]



POC: Nick Tsoupas

Path Length Variation to Synchronize Electrons and Hadrons at Different Energies



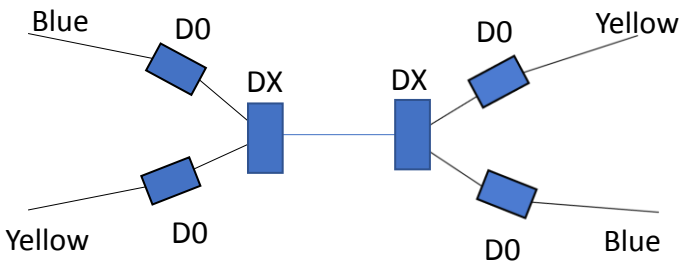
Required **modifications in 12-2 o'clock**:

- **100-275 GeV** hadron beam travels through **outer arc**.
- Slower **41 GeV** hadron beam travels through **shorter inner arc**. (Effectively shortens hadron ring circumference by 94.2 cm.)
- Modifications of **power supply bus connections** at 2 and 12 o'clock valve boxes.
- New **power supplies** for inner arc and D0 magnets.
- Two additional **warm "switching" magnets** to deviate 41 GeV beam

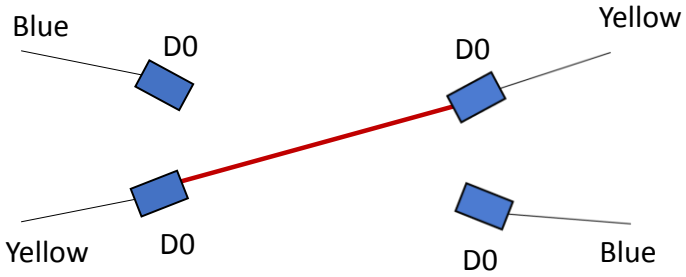
POC: Steve Peggs

Energy upgrade: from 260 to 275 GeV

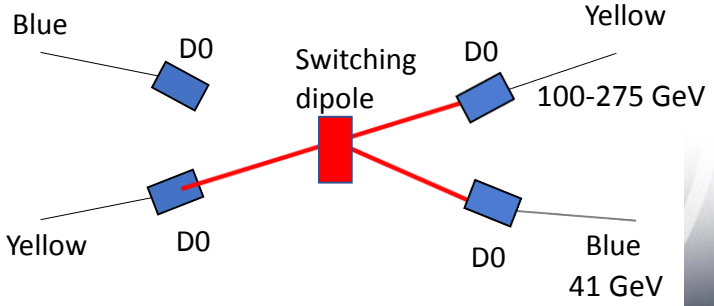
Schematic of IR crossing in the present RHIC



Schematic of IR crossing in eRHIC IR8, IR10 and IR4



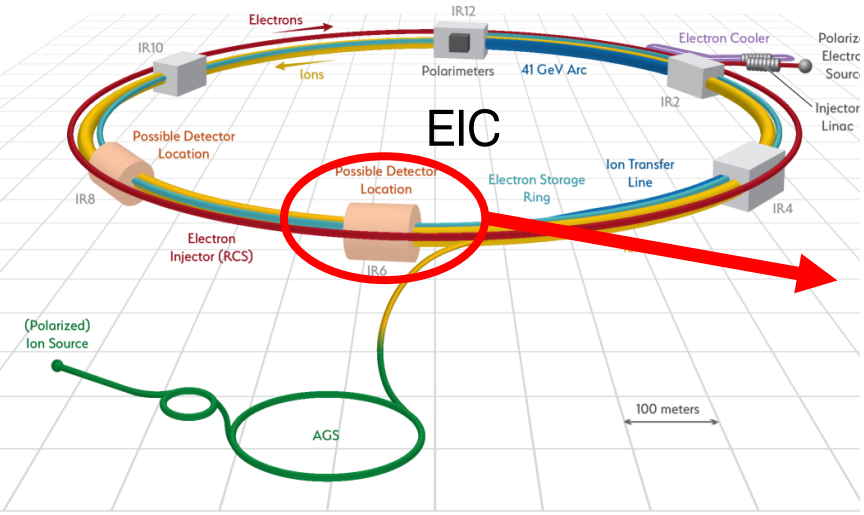
Schematic of IR crossing in eRHIC IR12 and IR2

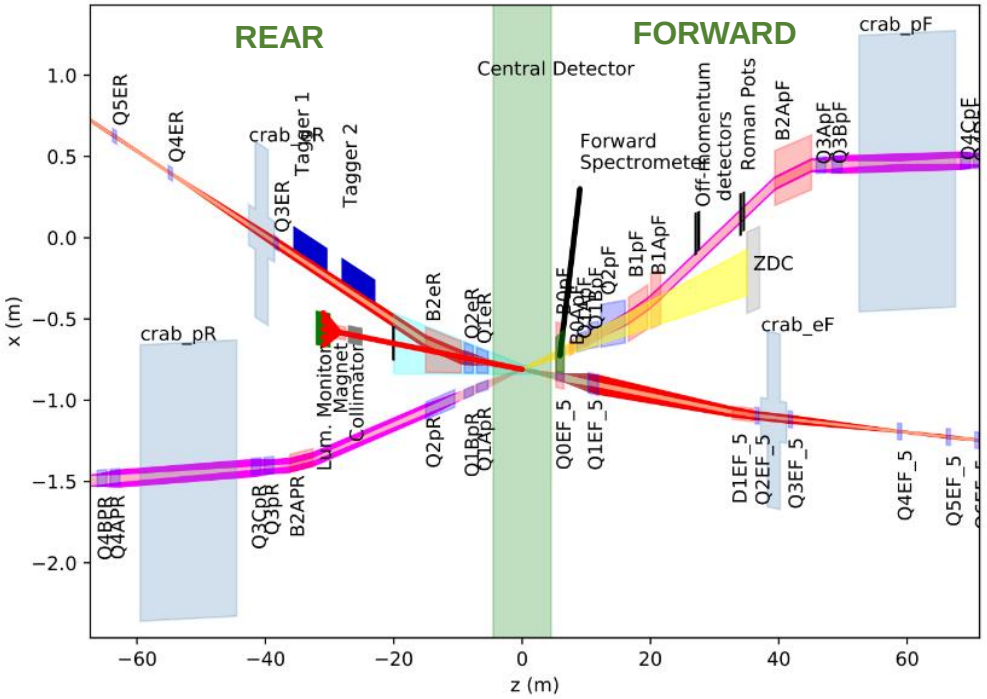


- Present **RHIC proton energy limited to 260 GeV by DX** separator magnets, **to be removed** for EIC.
  (In the center of each straight section.)
- Arc magnets could ultimately go 30% higher in field. However, trying to **avoid additional PS upgrade costs and required quench training**, we **limit the energy increase** in EIC **to 275 GeV**.

POC: Vadim Ptitsyn

Interaction Region for Detector





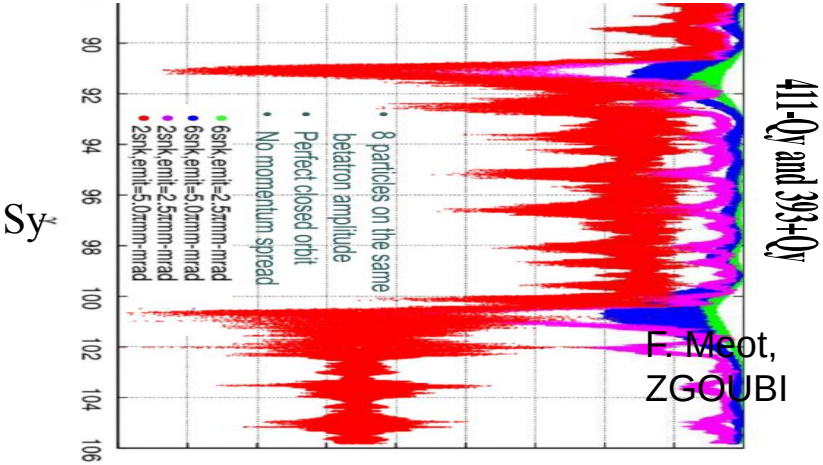
- Possible IR location: IP6
- Need to **match existing hadron ring lattice with new IR**.
- **Most** of IR **magnets** will be **new**, **some SC** (all NbTi; three main types: 9 direct wind magnets, 6 collared magnets, 1 special magnet + tapered double helix); **others warm**.
- The IR also **hosts crabs and spin rotators**, and will precise new **beam instrumentation**.

POC: Holger Witte

Additional Snakes for Successful Acceleration of He-3

He-3 polarization preservation simulations show that **number of Snakes must be increased from present 2 to 6 for successful acceleration of He-3** over the full energy range. It will eliminate also **weak depolarization of p↑** seen in RHIC.

Crossing strongest spin resonances in RHIC



F. Meot, ZGOUBI

To add 4 Siberian Snakes to Yellow ring:

- Use the 2 Blue Siberian Snakes
- Sort the helical dipoles from the Blue Spin Rotators by their helicity and recombine them to make another pair of Snakes

+/- indicate the magnet helicity

H1	H2	H2	H1
+	-	+	-

The RHIC **Spin Rotator** consists of four helical magnets **with alternate helicity**.

H1	H2	H2	H1
+	+	+	+

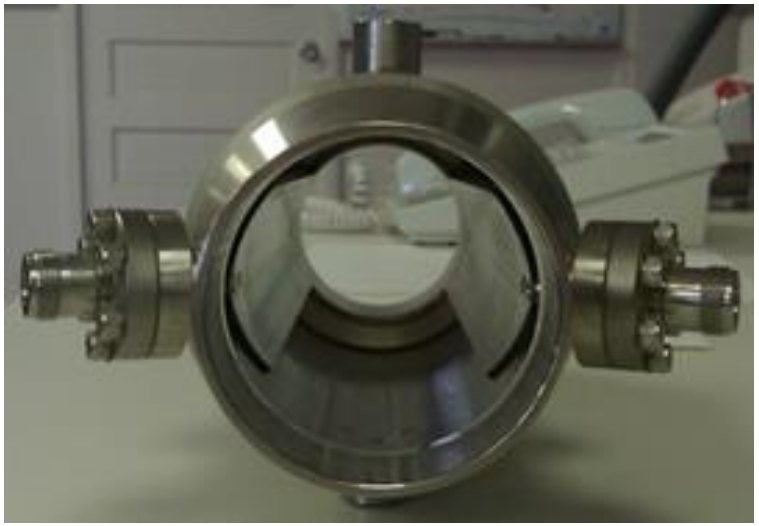
The RHIC **Siberian Snake** consists of four helical magnets, **all having the same helicity**.

POC: Vadim Ptitsyn

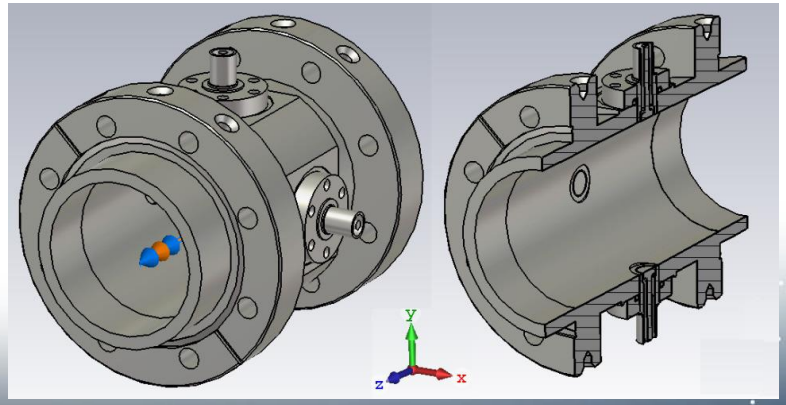
Beam Instrumentation Upgrade for High Beam Current

Beam Position Monitor Upgrade:

1. **Present stripline BPMs cannot be used** at EIC peak current values and large orbit radial shifts, because of BPM **cable heating issues**.
2. Manufacture **sleeves to shield** present BPMs in the entire Yellow ring and in Blue 2-12 sextant. [279 BPMs]
3. Procure and test **new button BPMs** and produce BPM-bellows assemblies ready for the installation.
   [203 single plane and 76 dual plane BPMS. 710 cold SiO2 insulated cables.]
4. Upgrade **BPM electronics**: from old IFE to next generation V301 boards.



Existing stripline BPM (above) will be shielded; button BPMs (below) will be installed adjacent



POC: David Gassner

Beam Instrumentation Upgrade for High Beam Current

Other instrumentation upgrades:

- **Instrumentation for the new hadron injection transfer line** (IR6 to IR4): 2 Current transformers, 6 Profile Monitors, 6 BPMs, 10 BLMs
- **Wall Current Monitor** - replace by a wider band electro-optical WCM pick-up that can resolve the 6 cm rms (150ps) proton bunch length
- **Ionization Profile Monitors** (includes higher voltage bias to improve performance)
- Multi-use **Stripline kickers**: H & V Tune meter kicker, Longitudinal damper, Injection damper, Gap cleaner
- **Base-band Tune system** (BBQ)
- **HF Schottky and LF Schottky**
- **Collimators**
- **Head-Tail Pick-up**

All upgraded hadron ring beamline components include **improved impedance**.

POC: David Gassner + Angelika Drees

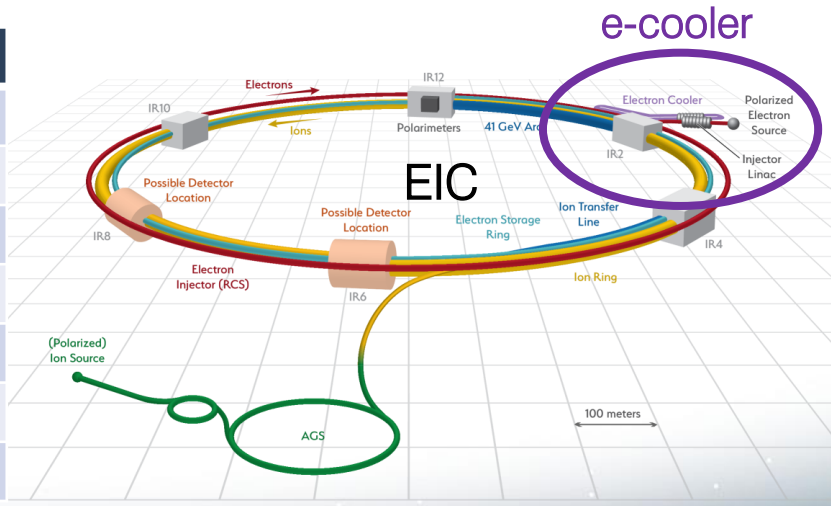
Strong Hadron Cooling for High Luminosity

High lumi requires small beam size and small beam size requires small emittance.

Reduction of the hadron beam emittance beyond what can be naturally provided, particularly a strongly reduced vertical emittance, is needed to reach the EIC luminosity goal of **$L = 10^{34}cm^{-2}s^{-1}$**

⇒ Strong Hadron Cooling needed to produce the small emittance and against IBS

E-Cooler Parameters	Value
e-beam energy [MeV]	150
e-beam normalized emittance [mm-mrad]	2.8
e-beam energy spread	10^{-4}
RMS beam size[mm]	0.7
Average electron beam current [mA]	120
e-beam bunch charge [nC]	1
Cooling time [min]	50



POC: Erdong Wang

Vacuum Chamber Update

With the present RHIC beam pipe (stainless steel):

1) **Higher intensity, shorter bunches** of EIC lead to large **resistive-wall heating**

	Species	E (GeV/u)	M	N (10^9 ppb)	I_{ave} (A)	σ_z (m)	P' (W/m)*
RHIC	p↑	255	111	197	0.27	0.6	0.05
RHIC	$^{197}Au^{79+}$	9.8	111	1.85	0.20	0.3	0.08
EIC	p↑	275	290	198	0.72	0.06	4.03
EIC	$^{197}Au^{79+}$	110	1160	0.5	0.57	0.07	0.62

2) **Higher intensity, short bunch spacing** of EIC beam lead to **e-cloud buildup**

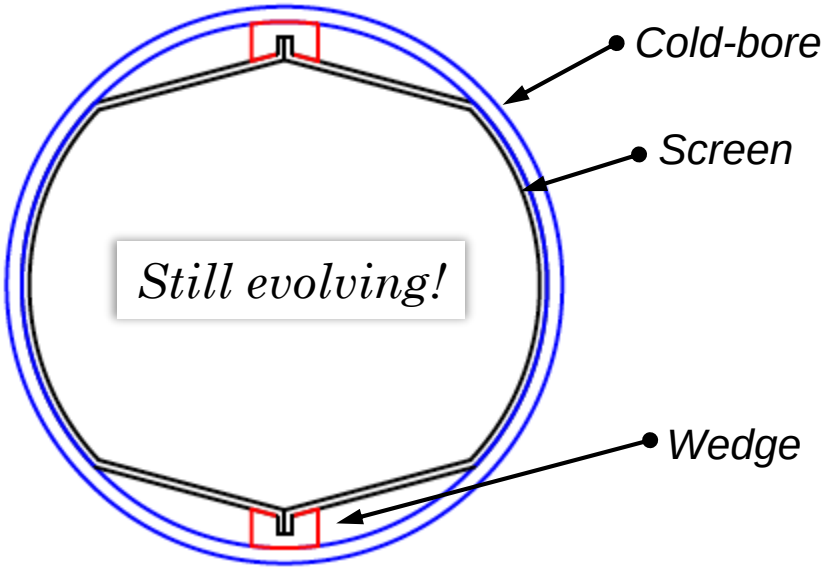
- RHIC experienced first e-cloud in 2001. Different mitigations implemented.
- No evidence of e-cloud in warm beam pipes where NEG was applied.
- PyECLOUD shows e-cloud builds up in the EIC Hadron Ring for SEY > 1.1. Scrubbed stainless steel (current RHIC pipes) has SEY ~ 1.35.

⇒ Install **amorphous-carbon coated copper screens** into existing beam pipe, mirroring solution developed for LHC

- High electrical conductor like copper …to reduce RW heating
- Low-SEY material like amorphous carbon (a-C) …to mitigate e-cloud

Vacuum Chamber Update

⇒ Install **amorphous-carbon coated copper screens** into existing beam pipe



Cold-bore beam pipe - SS316LN, I.D. 69 mm

Screen

- *OFHE copper-clad austenitic stainless steel*
- *deposited 100 nm amorphous carbon layer*
- *cooled by contact to 4.55K cold bore*
- *perforations for vacuum pumping at cold bore*

Wedge

Challenges:

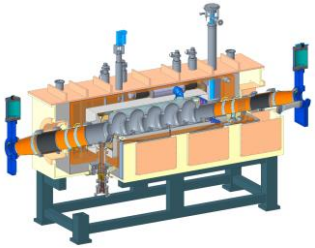
- Design screen with **minimal impact to aperture** that can be **installed** through vacuum chamber of 10 m-long RHIC dipoles **with large 45 mm sagitta.**
- Provide **amorphous carbon** film with **good adherence, reduced coating time.**
- Ensure **low impedance, adequate mechanical, vacuum and thermal stability**.

Thanks to N. Kos, V. Baglin, P. Costa-Pinto, M. Taborelli, P. Chiggiato, L. Prever-Loiri, E. Todesco, G. Willering, I. Aviles-Santillana, A. Gallifa-Terricabras, O. Capatina (CERN), R. Zwaska, R. Ainsworth (FNAL) for useful discussions

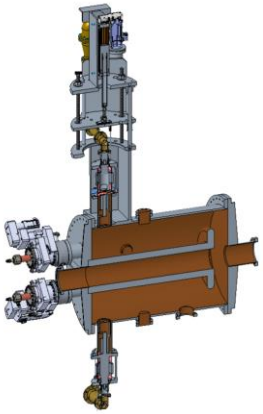
POC: Silvia Verdú-Andrés

Hadron Ring RF Systems

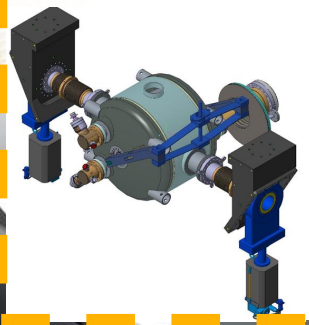
NEW SYSTEMS



Two 591 MHz SRF for **bunch compression to 6 cm rms** bunch length. Same as RCS and SHC ERL cavities.



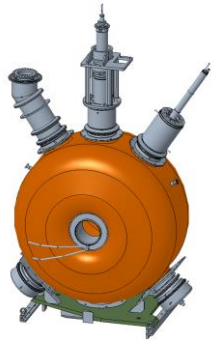
49 MHz & 98 MHz NCRF cavities for two-step **splitting** of hadron bunches **from 290 to 1160 after acceleration**.



Eight 197 MHz and four 394 MHz SRF crabs for reestablishing **head-on collision** in 25 mrad x-angle. Several valid cavity types under consideration: DQW, RFD, WOW.

MODIFY/REUSE EXISTING SYSTEMS

Two 28 MHz NCRF cavities in Yellow ring tuned to 24.5 MHz. Power amplifiers will be reused.



Twelve 197 MHz NCRF cavities from Blue and Yellow RHIC rings together with their power amplifiers, to increase **total voltage**.

POC: Kevin Smith

Hadron Ring RF Systems

Notable challenges:

- **High currents** (up to 1 A): *HOM power, RF stability, heating*
- **High bunch charge** (up to 20e10 ppb): *single bunch instabilities, wakefields, heating*
- **High beam power**: *RF power, couplers, collimators; gap transients*
- **Crabbing**: high voltage, HOMs, linearity, synchronization, noise
- **Variety of filling patterns**: *abort gaps, filling, bunch splitting*

Work in progress:

- **Beam loading transient and collective effects** studies started; focus on understanding stability margins and mitigation efforts if needed.
- Design of **197 MHz crab** with improved HOM impedance
- Evaluating **RF power** options
- Starting to think about **cavity production phase and facility requirements**

POC: Kevin Smith

Summary and Overview

- RHIC is a **solid backbone to build upon** the future EIC.
- **Eight key updates** were identified, involving a **broad variety of systems** that require the implication of experts **in multitude of disciplines**.
- There exist **challenges and R&D opportunities, an ambitious project,** as well as **synergies** with work for LHC, HL-LHC, LCLS-II and with accelerators currently under study: *sufficient strong motivations to join forces.*

"None of us is as smart as all of us"

Ken Blanchard

Let's collaborate!

Acknowledgements

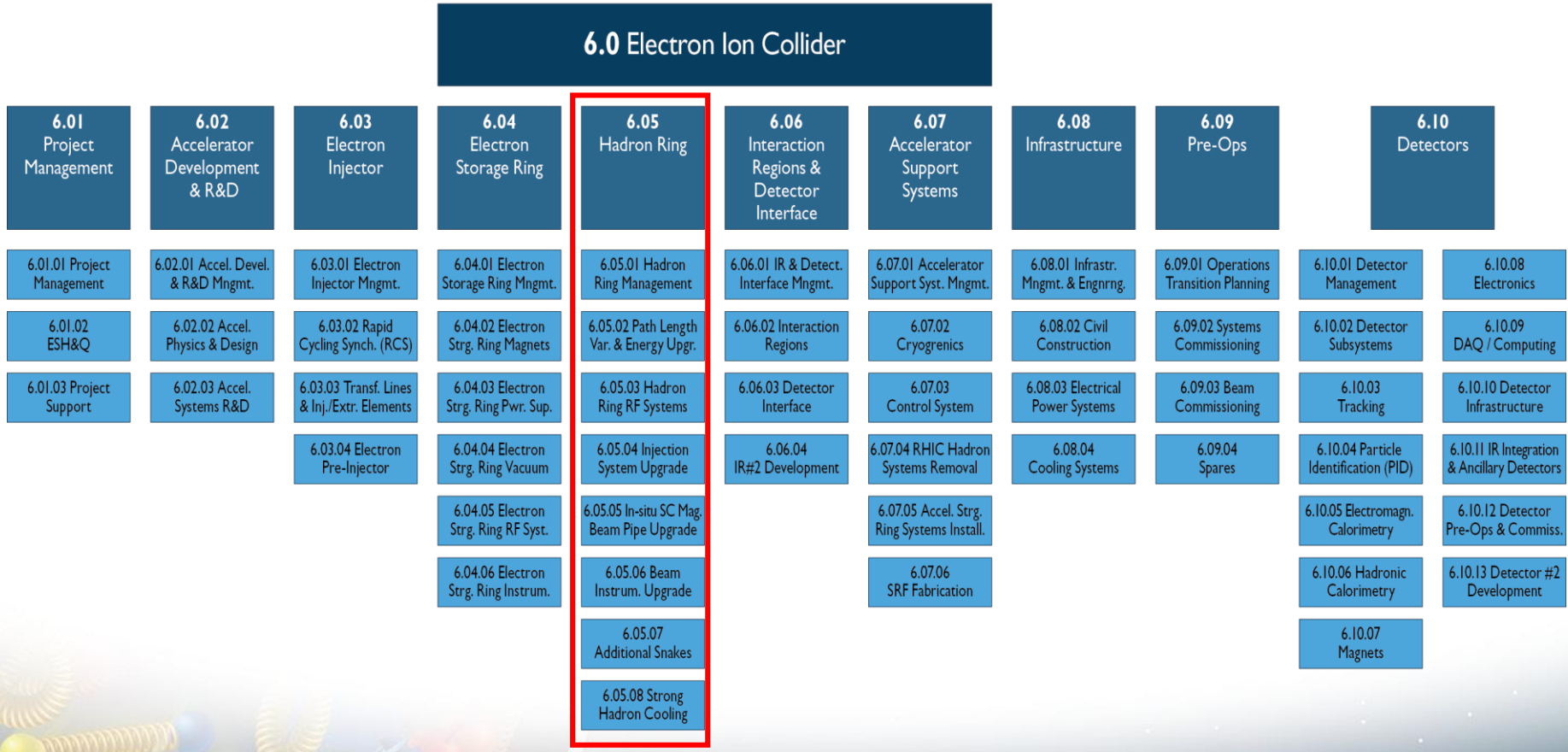
Thanks to the following colleagues for providing materials for this talk:

Vadim Ptitsyn	(EIC)
Erdong Wang	(EIC)
Kevin Smith	(EIC)
Holger Witte	(EIC)
Medani Sangroula	(EIC)
David Gassner	(EIC)
Wolfram Fischer	(EIC)
Yun Luo	(EIC)
Thomas Roser	(CAD)
Robert Rimmer	(JLab)
Themis Mastoridis	(UCLA San Luis Obispo)

…and to you for your attention!

BACK-UP SLIDES

Scope



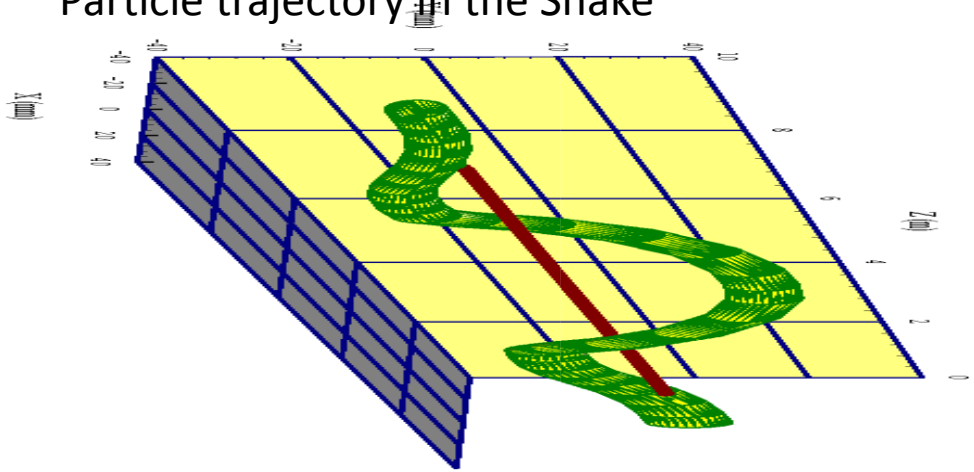
Courtesy of Vadim Ptitsyn

Siberian Snakes

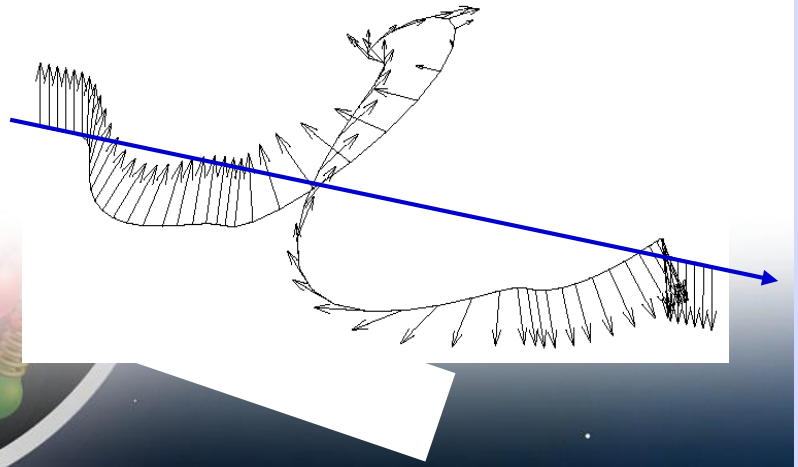
Courtesy of Vadim Ptitsyn

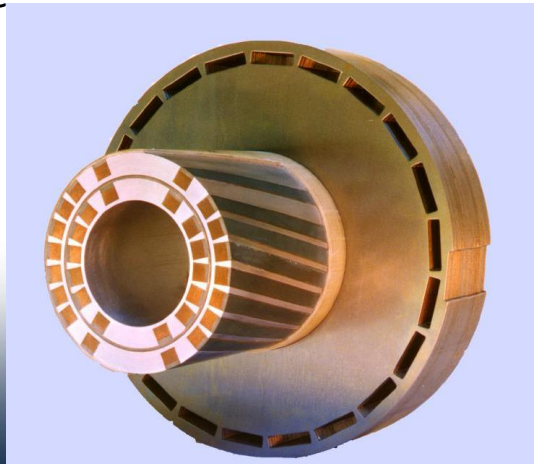
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist

Particle trajectory in the Snake



Particle and spin trajectories in the Snake





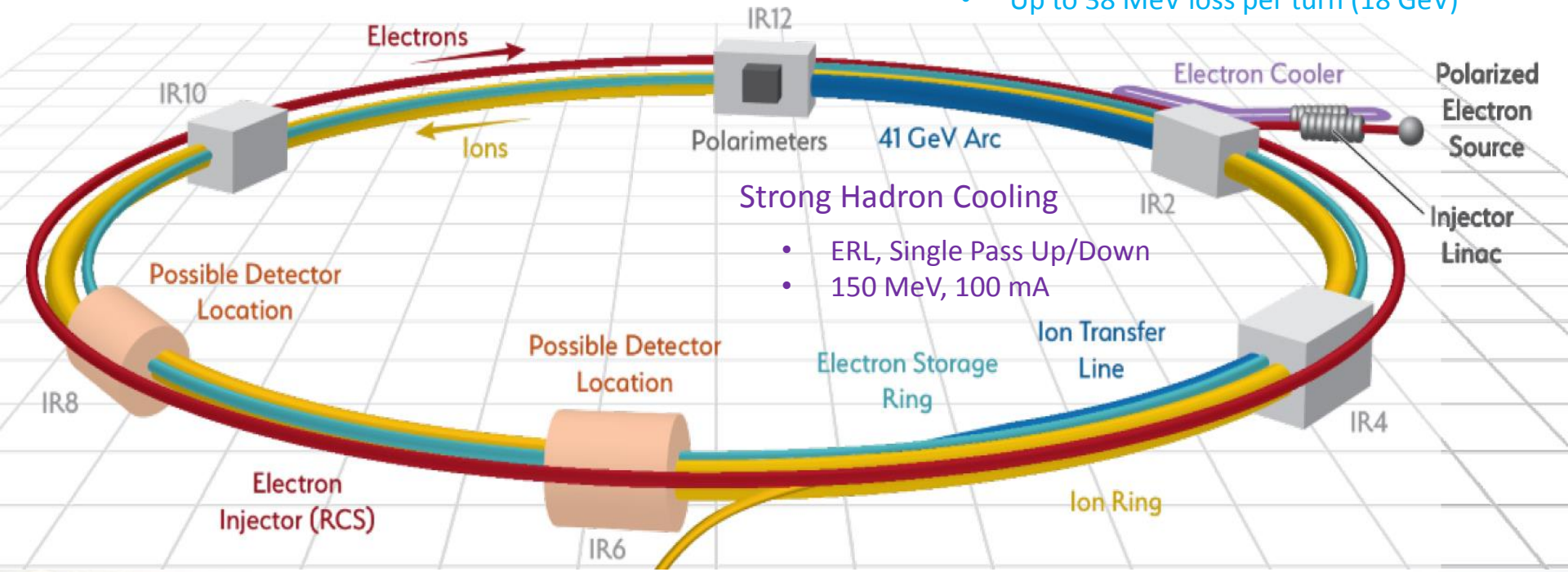
Overview of RF for EIC at BNL

RCS: Rapid Cycling Synchrotron

- 400 MeV – 18 GeV Full Energy e- Injector
- 1 Hz Repetition Rate
- 100 ms ramp
- 28 nC per bunch

eSR: electron Storage Ring

- 5 GeV – 18 GeV
- 2.5 A maximum beam current (10 GeV)
  - 1160 bunches, 28 nC per bunch
- Up to 10 MW synchrotron radiation power
- Up to 38 MeV loss per turn (18 GeV)



IR Crab Cavities

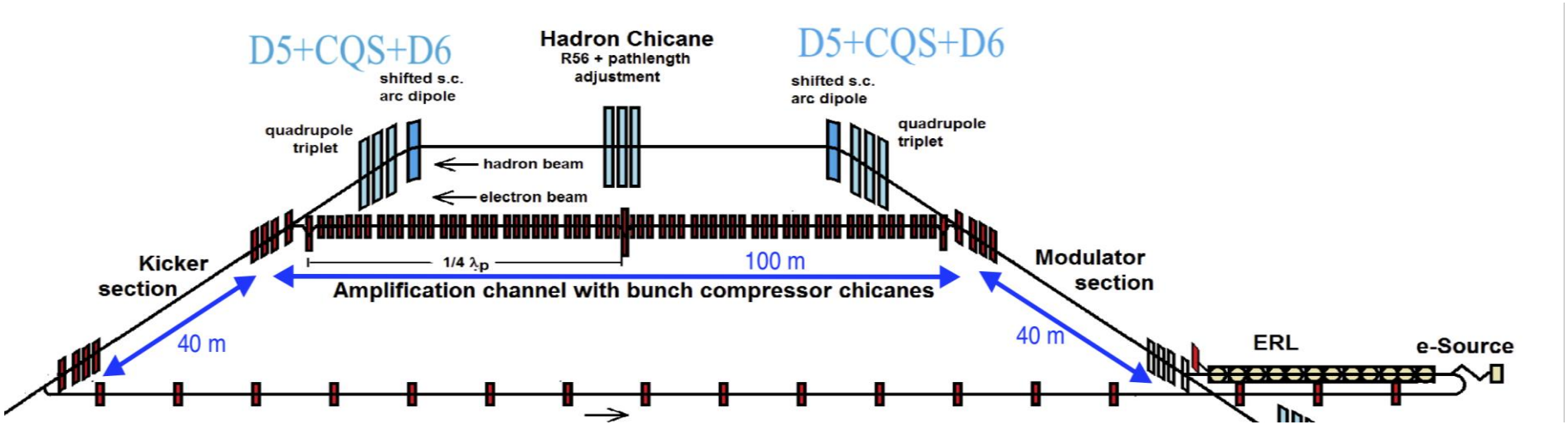
- 25 mrad crossing angle
- 8x Hadron Crab Cavities
- 6x electron Crab Cavities

Hadron Ring

- Up to 275 GeV Proton Store Energy
- 1 A maximum beam current
  - 1160 bunches, 11 nC per bunch

Strong Hadron Cooling for High Luminosity

Design based on Coherent Electron Cooling with Micro-bunched amplification

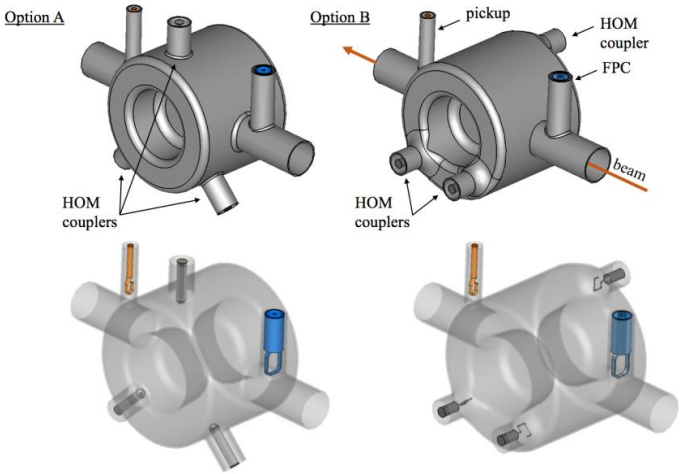


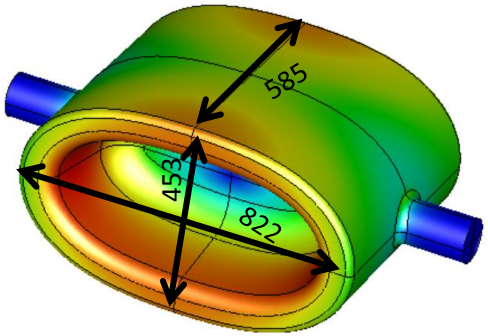
- 150 MeV electron accelerator utilizing: 120 mA injector, ERL consisting of five 591 MHz and three 1773 MHz SRF cavities; beam transfer lines, 2K cryogenics system for ERL.
- Hadron chicane for pathlength and R56 adjustment using displaced SC dipole magnets at IR2 straight section.
- Two-stage amplification section uses three chicanes and two $\lambda_p/4$ drifts
- Modulator and kicker section common for both hadron and electron beams

POC: Erdong Wang

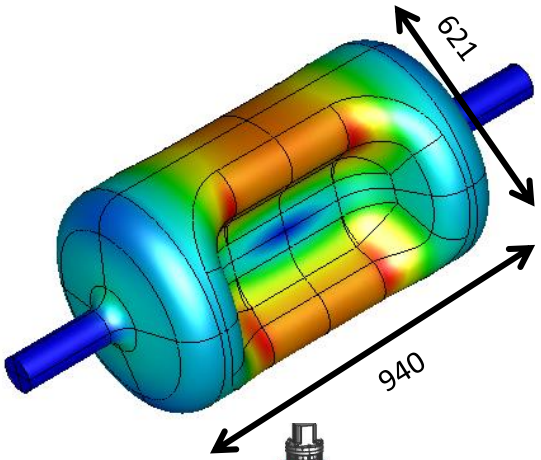
Crabbing Systems

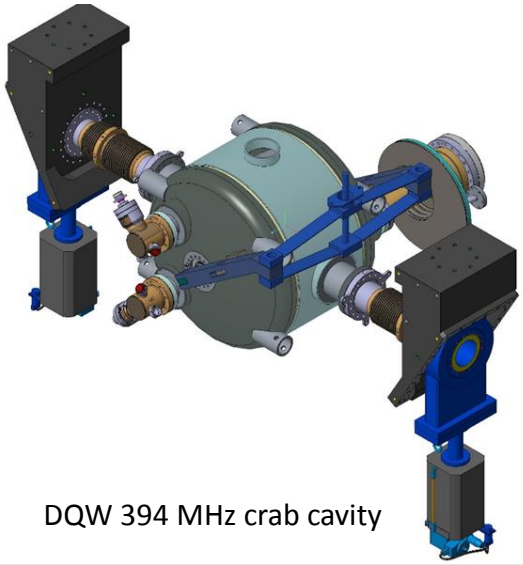
Courtesy of Kevin Smith, Robert Rimmer



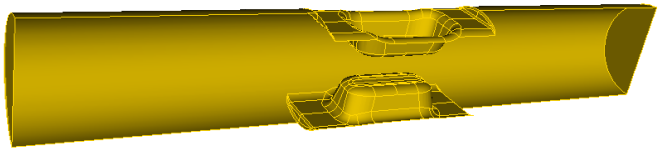


DQW 197 MHz crab cavity

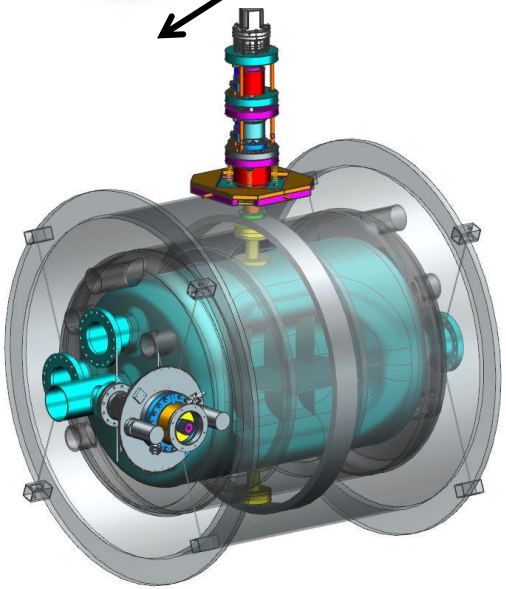




DQW 394 MHz crab cavity



"WOW" crab cavity
Courtesy: Zhenghai. Li



RFD 197 MHz crab cavity

Courtesy: Qiong Wu, Silvia Verdú-Andrés, Doug Holmes, Binping Xiao

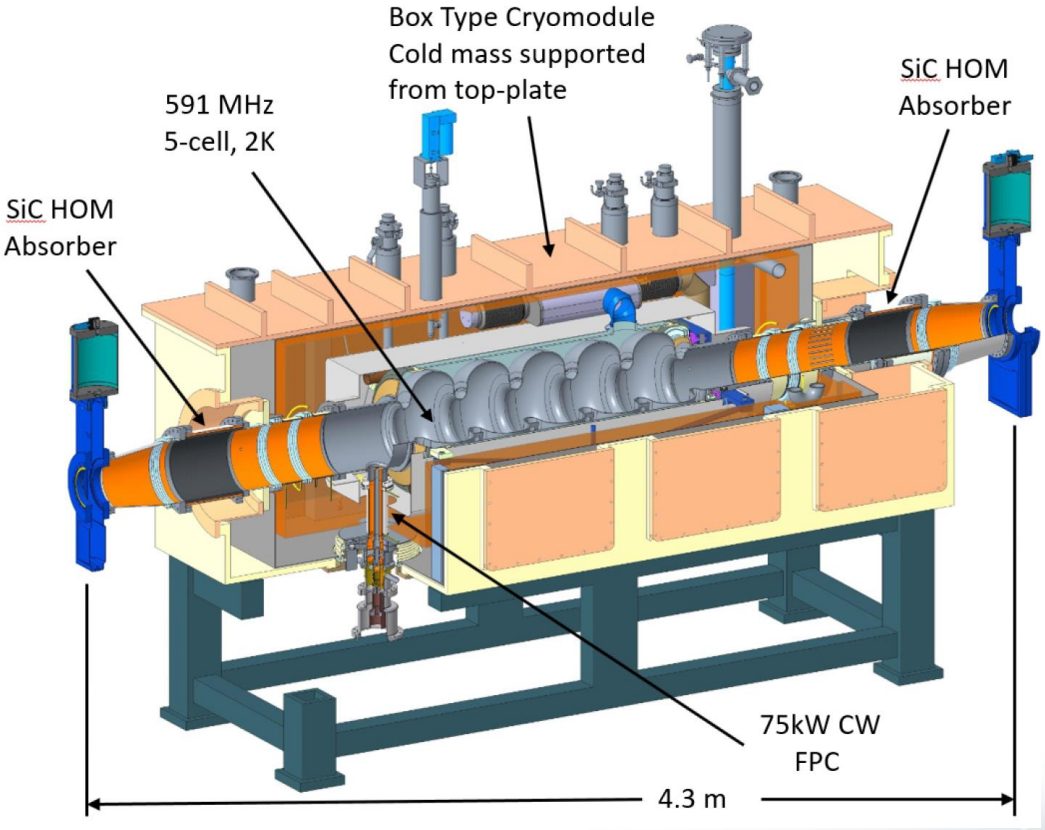
Courtesy: Suba Da Silva, HyeKyoung Park, Jean Delayen, ODU, Jim Henry Jlab.

Strong Hadron Cooling RF System Parameters and Concept

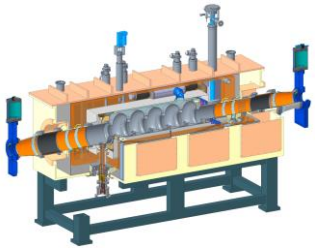
- Cryomodules
  - 9x 591 MHz, 5-cell elliptical, 2K (ERL)
  - Single cavity per cryomodule
  - Warm beamline SiC HOM absorbers
  - Maximum 180 MV installed voltage
    - E_{acc}: 15.8 MV/m
    - E_{pk}: 35.8 MV/m
    - B_{pk}: 69.7 mT
    - P_{dyn}: 32 W
  - Reusing the same design as the RCS 5-cell single cavity cryomodules.

- RF Power Amplifiers
  - 9x 591 MHz, 65 kW CW, IOT
  - Commercial transmitter units

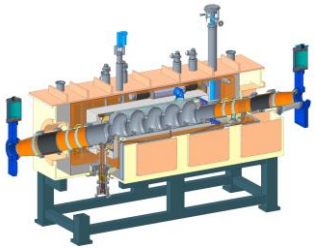
- Beam Parameters
  - Single Pass 150 MeV ERL (1 up, 1 down)
    - Maximizes beam breakup threshold current
  - 1 nC per bunch
  - 100 mA single pass current
    - 98.5 MHz bunch frequency
  - HOM power well below the 20 kW per absorber rating.



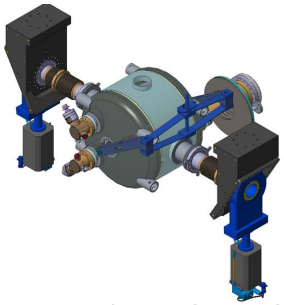
Hadron Ring RF Systems



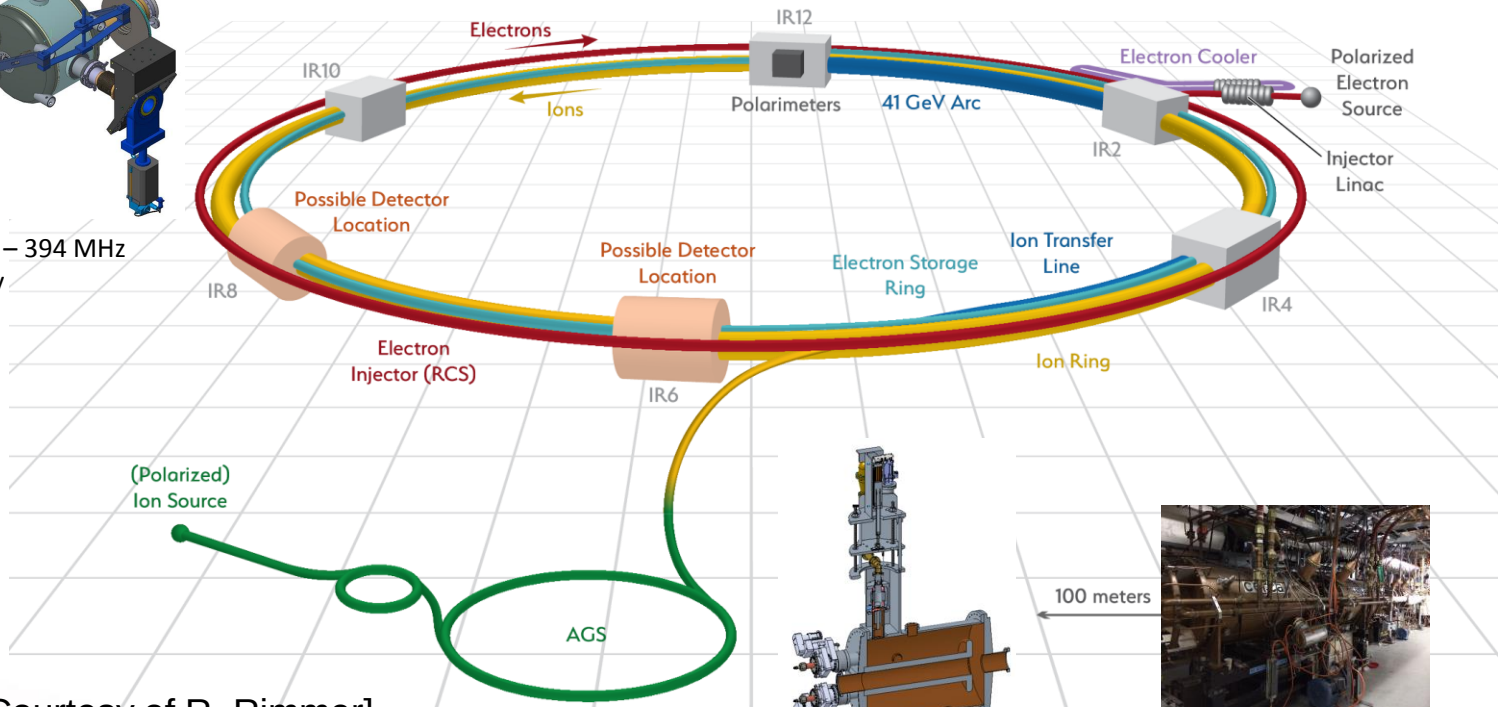
Hadron - 591 MHz
bunch compression cavity



Hadron - 591 MHz
strong hadron cooling



Both rings – 394 MHz
crab cavity



[Courtesy of R. Rimmer]

Hadron – 49.2 MHz and 98.5 MHz
bunch splitter cavity

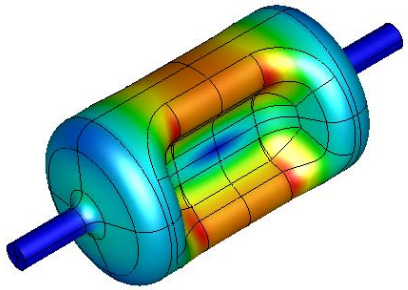
Hadron – 24.5 MHz
acceleration cavity

Hadron - 197 MHz
bunch compression
cavity

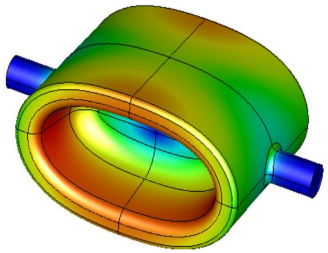
Hadron Ring RF Systems

New systems:

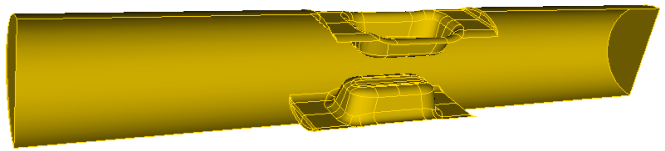
- **Two 591 MHz SRF** used for **bunch compression to 6cm rms** bunch length. Same as RCS and SHC ERL cavities.
- **49 MHz and 98 MHz NCRF** cavities for realizing two steps **splitting** of hadron bunches **from 290 to 1160 after acceleration**.
- **Eight 197 MHz and four 394 MHz SRF crabs** for reestablishing **head-on collision** in 25 mrad x-angle. Several valid cavity types under consideration: DQW, RFD, WOW.



RFD 197 MHz crab cavity [Da Silva, Park, Delayen, Henry]



DQW 197 MHz crab cavity [Verdu-Andres, Xiao]



"WOW" crab cavity *[Zhenghai Li]*

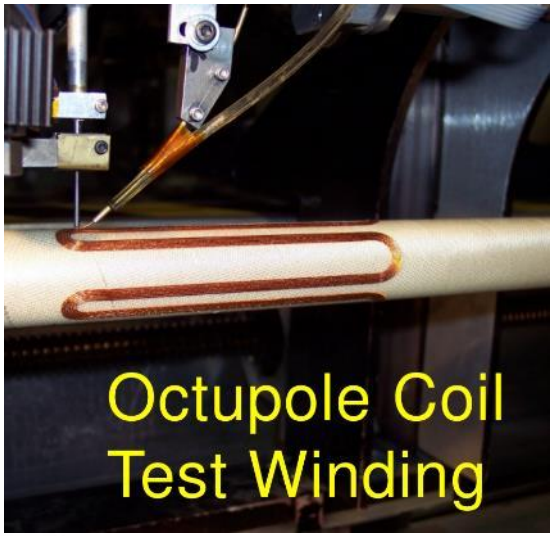
Modifications and reuse of existing systems:

- **197 MHz NCRF** cavities from Blue and Yellow RHIC rings will be re-used in EIC hadron (Yellow) ring together with their power amplifiers, in order to increase the **total voltage**. Total of 12 cavities.
- **Two 28 MHz NCRF** cavities in Yellow ring will be modified to the 24.5 MHz frequency. Power amplifiers will be reused.

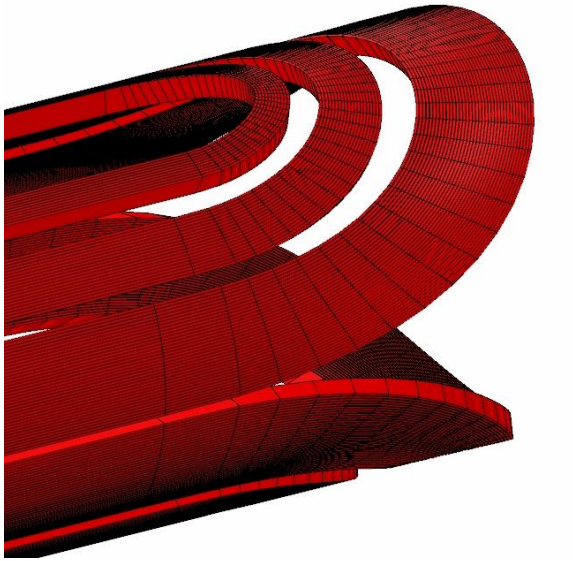
POC: Kevin Smith

IR Magnets - Overview

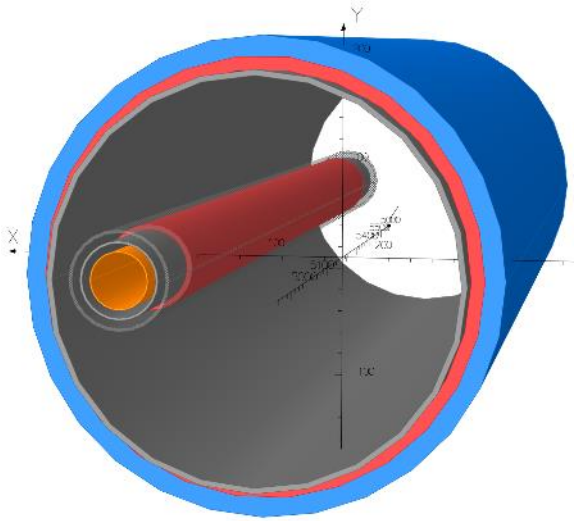
- Three groups of superconducting magnets
  - All NbTi
- (Also: normal conducting magnets, not addressed here)



9 Direct Wind Magnets (S-MD)



6 Collared Magnets

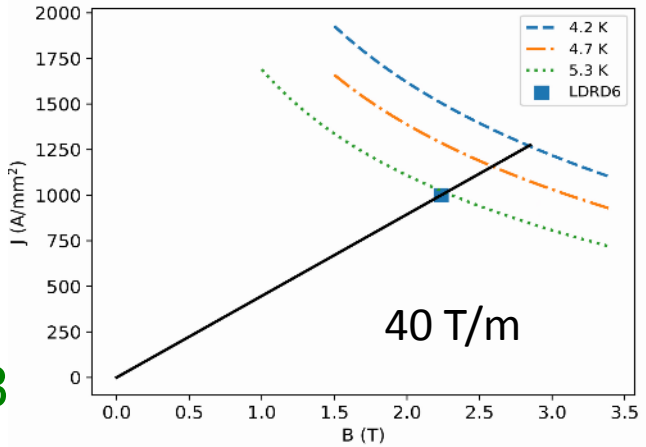


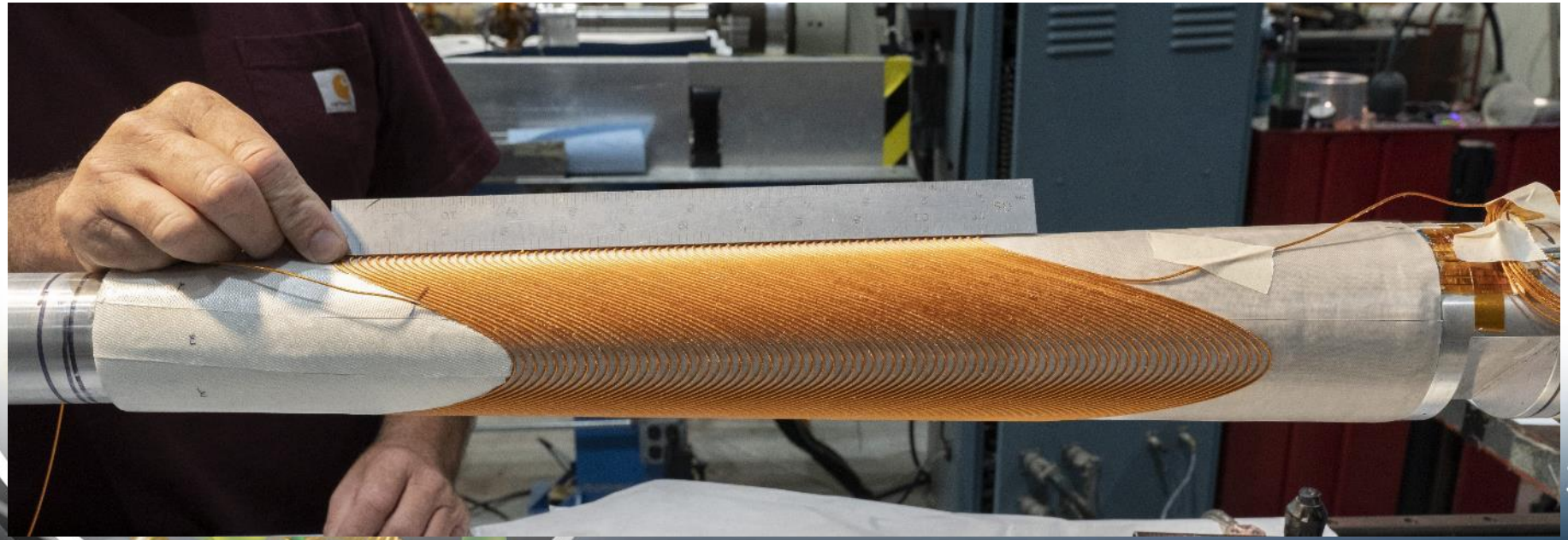
1 Special Magnet

Courtesy of Holger Witte

Tapered Double Helix Magnet

- Demonstrator presently under construction
- 4 layer coil
  - Aperture: 60..80mm
  - L=0.4m
- Compatible with direct wind process
- H. Witte et al. http://dx.doi.org/10.1109/TASC.2019.290298





Courtesy of Holger Witte