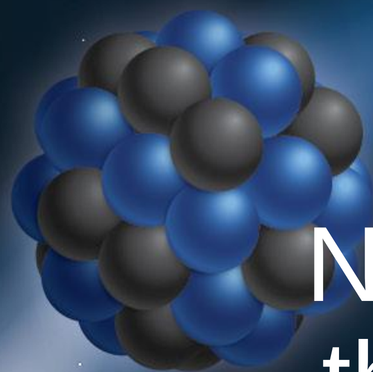
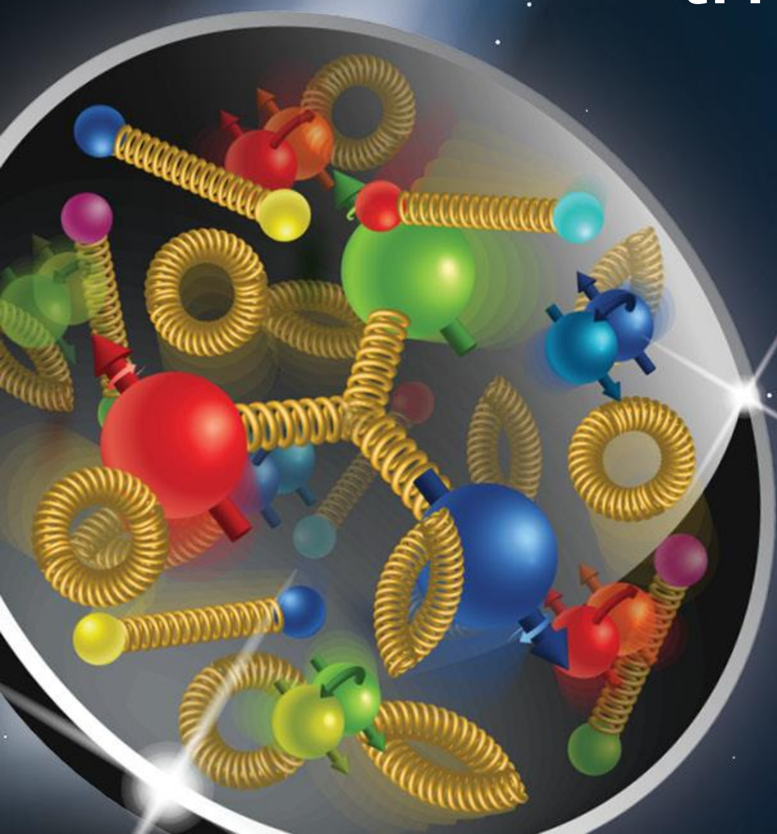


NP Accelerator Needs at the Dawn of the EIC Era



2021 SBIR STTR Exchange Meeting

August 18, 2021

Andrei Seryi,

Jefferson Lab Associate Director for Accelerator Operations and R&D

EIC Associate Director for Accelerator Systems and International Partnership

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY | Jefferson Lab | U.S. DEPARTMENT OF ENERGY | Office of Science

Overview

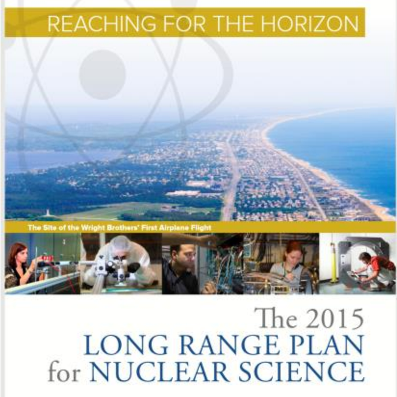
- Electron-Ion Collider
- EIC Design overview
- EIC systems and technologies
  - Ion sources
  - Rings
  - SC RF & power
  - Magnets
  - Instrumentation
  - Polarized guns
- CEBAF future outlook
- SC RF CMs
  - FE & Particulates control
- Possible energy upgrade
  - FFA & permanent magnets
- New SRF materials
- New approaches
- AI/ML techniques

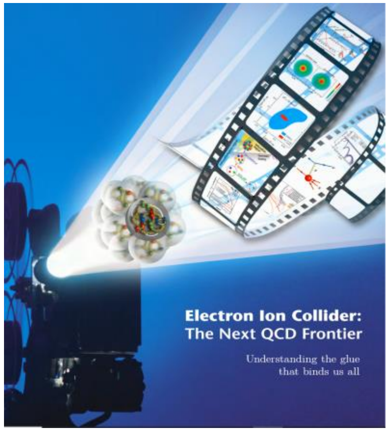
With many thanks to EIC Project colleagues for materials for this presentation, and with thanks to CEBAF colleagues for the corresponding slides

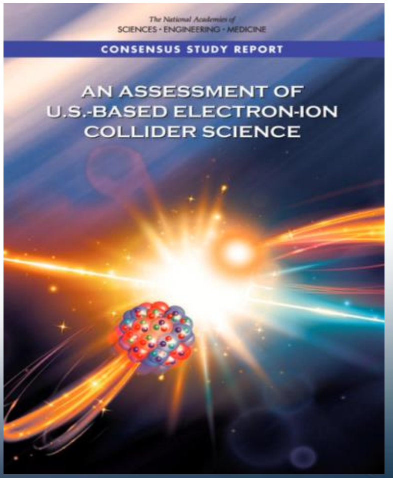
EIC Requirements

- EIC Design Goals
  - High Luminosity: $L=(0.1\text{-}1)\cdot 10^{34} cm^{-2} sec^{-1}$, need 10 -100 fb^{-1}
  - Collisions of highly polarized e and p (and light ion) beams with flexible spin patterns of bunch structure: 70%
  - Large range of center of mass energies: E_{cm} = (20-140) GeV
  - Large range of Ion Species: protons – Uranium
  - Ensure Accommodation of a second IR
  - Large detector acceptance
  - Good background conditions (hadron particle loss and synchrotron radiation in the IR)

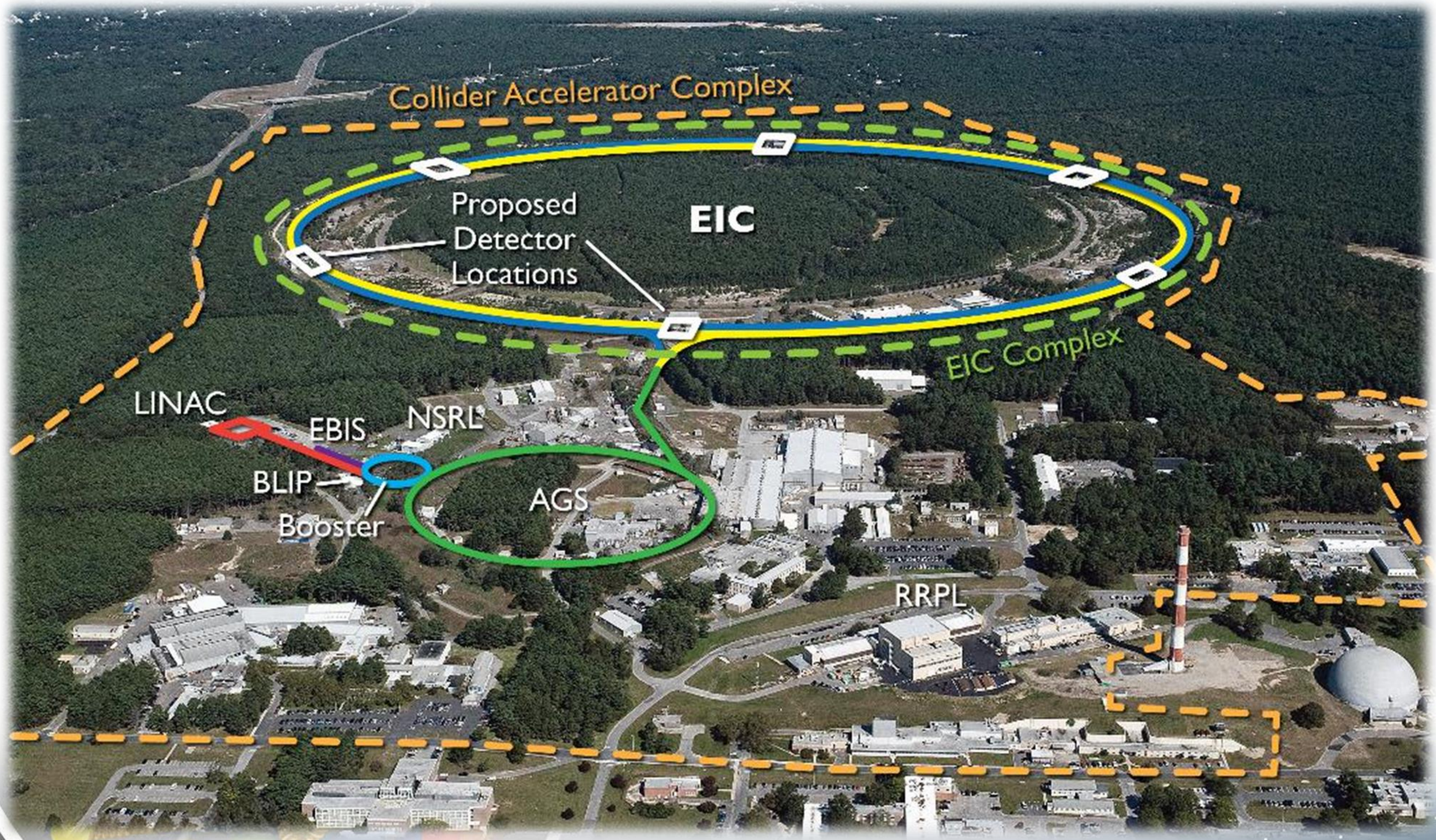
- Goals match or exceed requirements of Long-Range Plan & EIC White Paper, endorsed by NAS
- EIC Design meets or exceeds goals and requirements





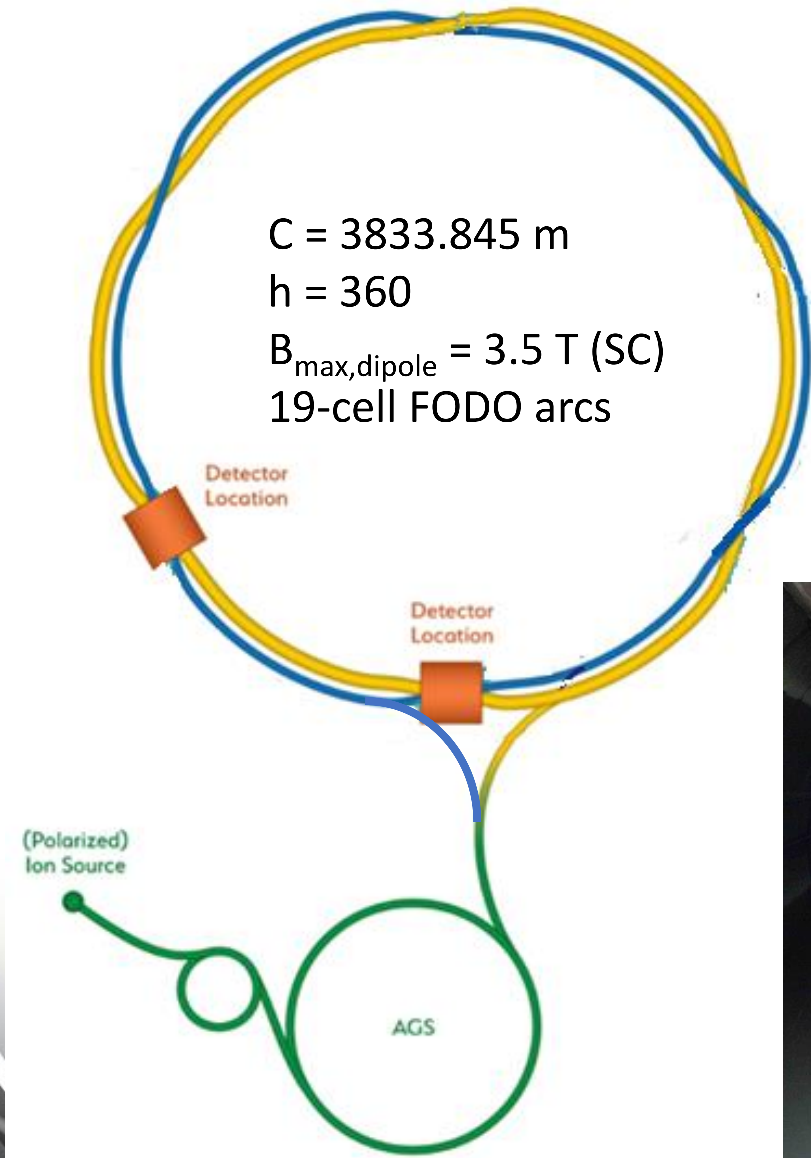


EIC Design Overview



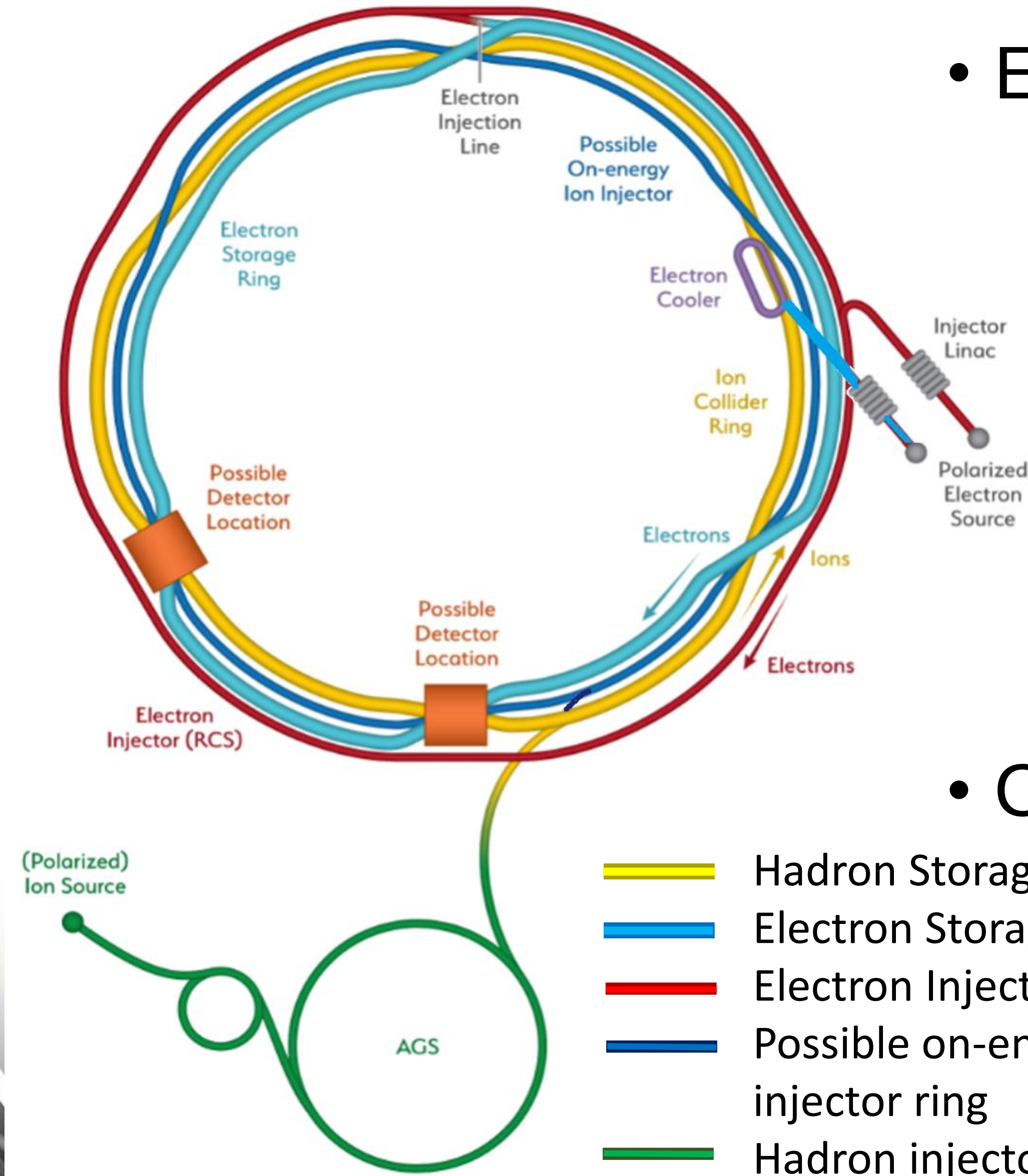
EIC CDR: https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

From RHIC to the EIC: RHIC



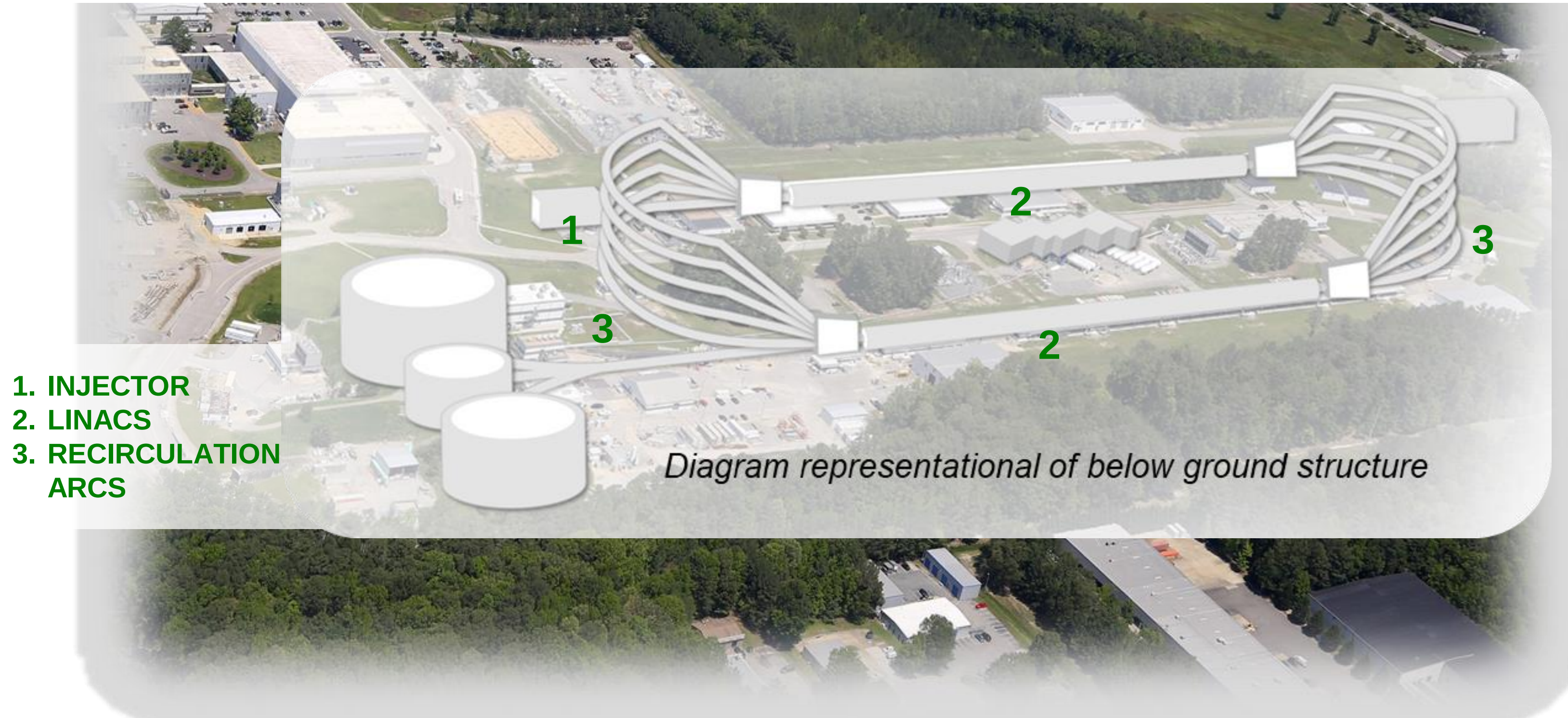
- Existing RHIC facility
  - Hadron collider (h=360)
  - 6-100 GeV/u ions
  - 100-250 GeV polarized protons
  - Two independent rings
    - Asymmetric operations include e.g. d-Au collisions
- Constructed 1990-2000
- Will operate to ~2025

From RHIC to the EIC: EIC



- Electron-Ion Collider
  - Lepton-hadron collider
  - Add electron storage ring
  - Add electron injectors
    - Full-size rapid-cycling synchrotron
  - Add "strong" electron cooling (ERL and insertion)
  - Add new detector
- Construction 2023-2030

CEBAF – nuclear physics research tool



CEBAF - a superconducting high-energy electron particle accelerator

Oversubscribed with NP experiments for >decade into the future and plans for upgrade are in development

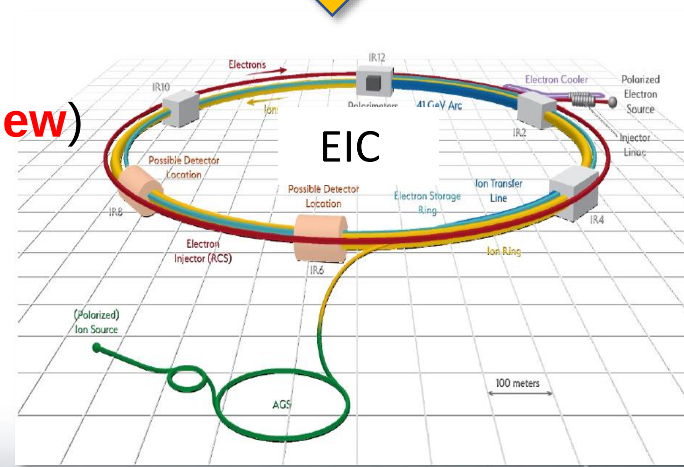
CEBAF capabilities

- CW electron beam
- E_{max} = 12 GeV
- I_{max} = 90 μA
- Pol_{max} ~ 90%
- 4 halls running simultaneously

EIC Design Overview

Design based on **existing RHIC Complex**
RHIC is well maintained, operating at its peak

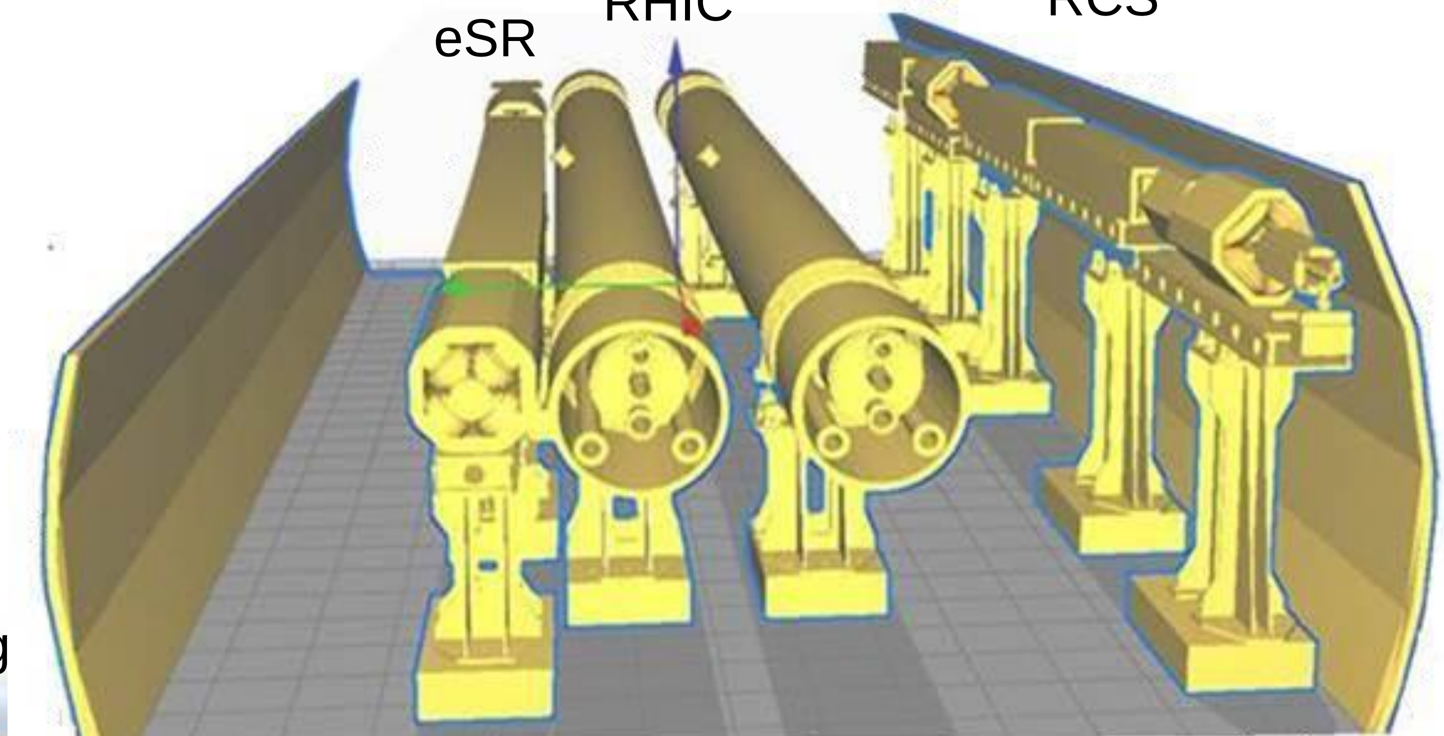
- **Hadron storage Ring (RHIC Rings) 40-275 GeV** (existing)
    - 1160 bunches, 1A beam current (3x RHIC)
    - bright vertical beam emittance 1.5 nm
    - strong cooling (coherent electron cooling)
- **Electron storage ring 2.5–18 GeV** (new)
    - many bunches,
    - large beam current, 2.5 A ➔ 9 MW S.R. power
    - S.C. RF cavities
    - Need to inject polarized bunches
- **Electron rapid cycling synchrotron 0.4- 18GeV** (new)
    - 1-2 Hz
    - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (new)
    - L = $10^{34}cm^{-2}s^{-1}$
    - Superconducting magnets
    - 25 mrad Crossing angle with crab cavities
    - Spin Rotators (longitudinal spin)
    - Forward hadron instrumentation



Tunnel Cross Section

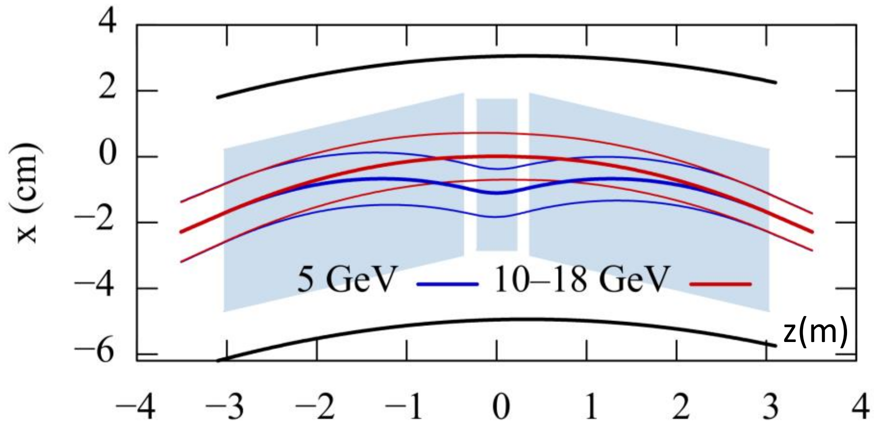
All accelerators fit into the existing tunnel

Need several new equipment buildings



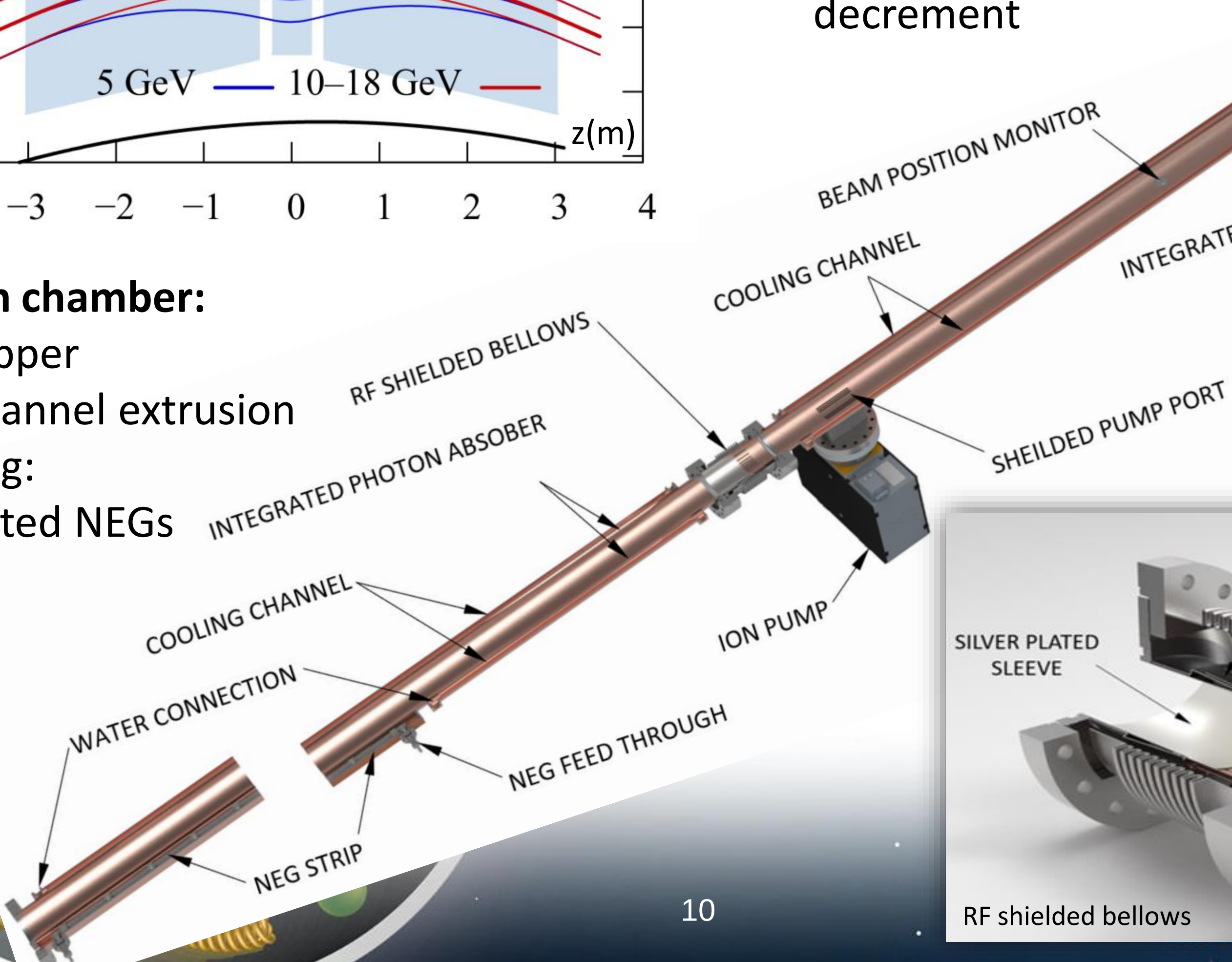
Electron Storage Ring

ESR super-bend: arc dipoles split into 3 segments

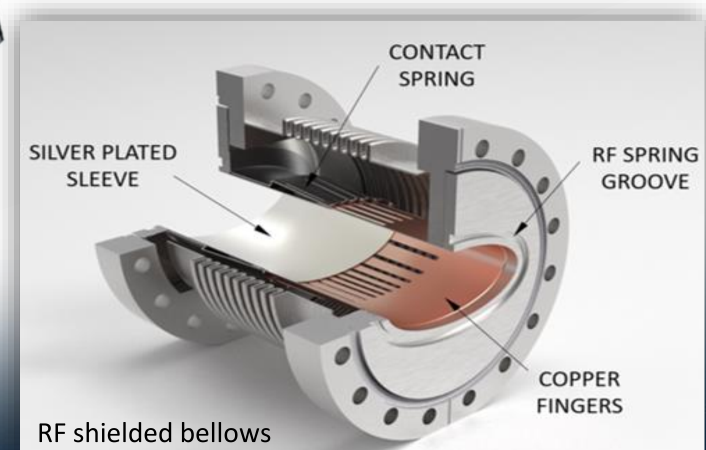


Above 10 GeV, all segments powered uniformly to reduce SR power
At 5 GeV, short center dipole provides a reverse bend to increase damping decrement

Vacuum chamber:
OFE Copper
Multichannel extrusion
Pumping:
distributed NEGs



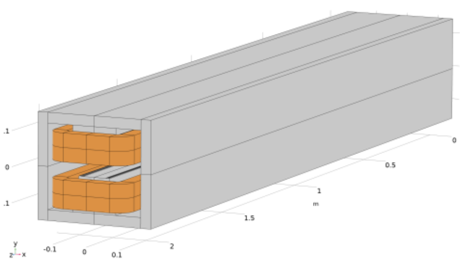
RF Bellows



RF shielded bellows

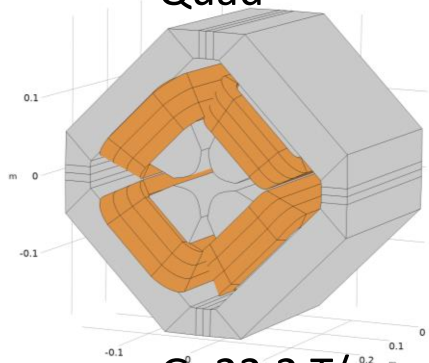
Magnets RCS & ESR

Dipole



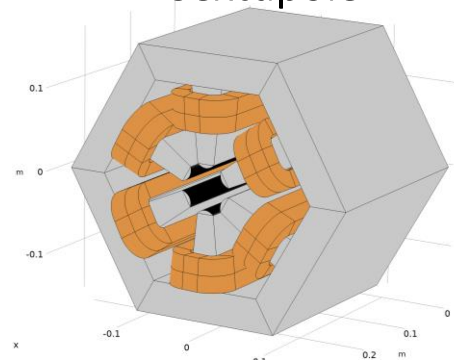
B=0.234T

Quad



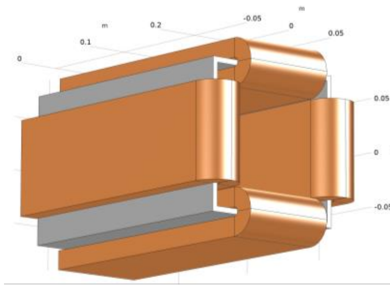
G=22.2 T/m

Sextupole



G_s=280 T/m^2
(63mT at 15mm)

Corrector



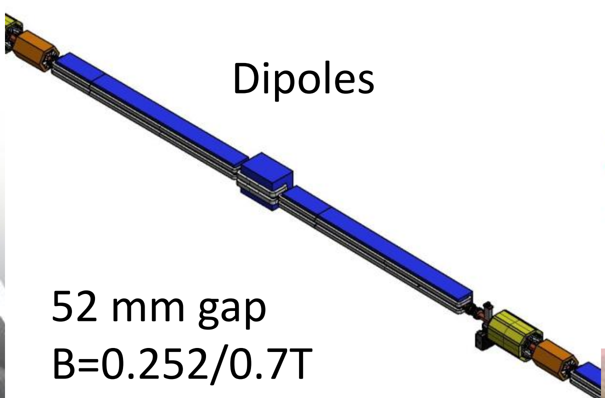
B_{dipole}=6.5 mTm

RCS: ramp rate 0.1s, duty factor 1Hz, field quality 1E-3

Close to 3000 magnets of various types. Magnetic field measurements. Ways for efficient ways to correct field quality if bulk production is for reduced specs. Exploring.

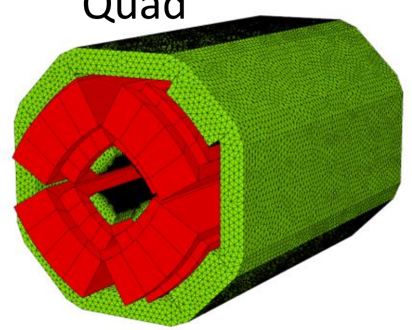
ESR: DC water cooled, for 5,10 or 18 GeV, field quality 1E-4

Dipoles



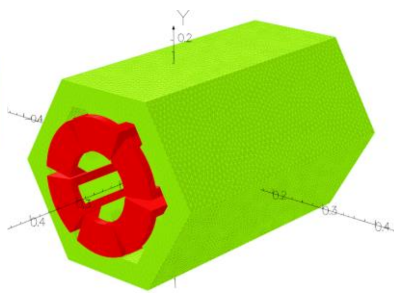
52 mm gap
B=0.252/0.7T

Quad



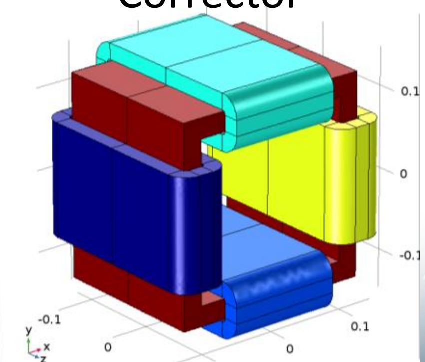
74 mm aperture
G=18T/m

Sextupole



80 mm aperture
G_s=360T/m^2
(81mT at 15mm)

Corrector



150 mm aperture
B_{dp}=6mTm

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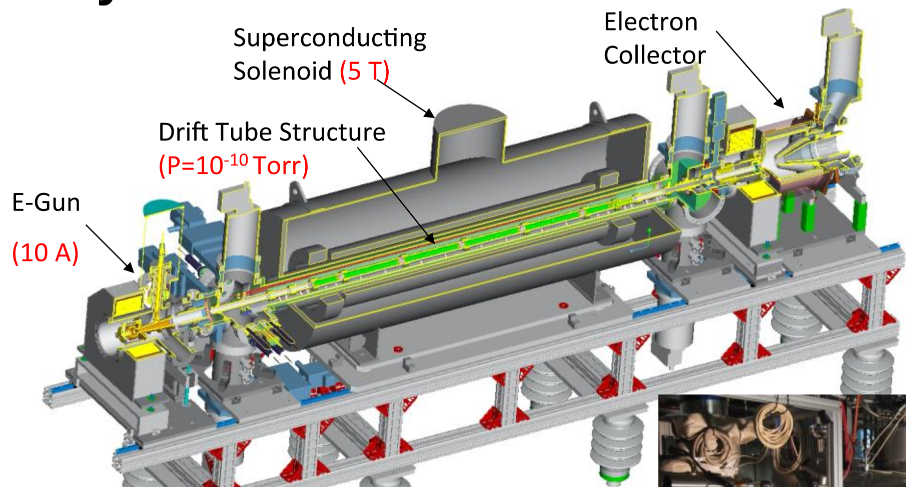
Ion source

- Ions from He to U have been already generated in the Electron-Beam-Ion-Source ion source (EBIS), accelerated and collided in RHIC
- EBIS can generate any ion beam from ^{3}He to U for the BNL EIC
- Existing EBIS provides the entire range of ion species from He to U in sufficient **quality** and **quantity** for the EIC

<u>Ion Pairs</u>
<u>in the RHIC Complex</u>

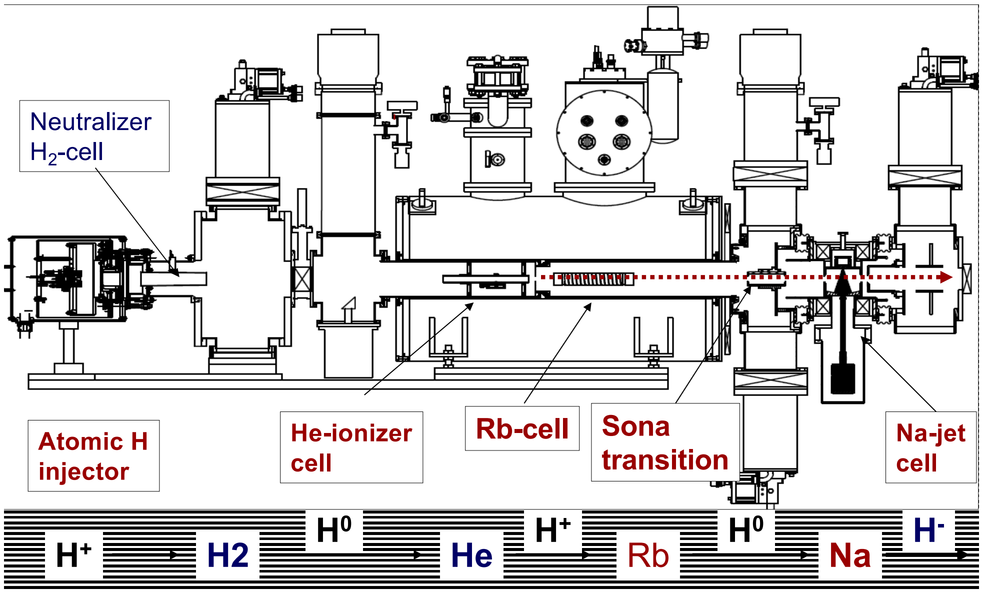
Zr-Zr, Ru-Ru	(2018)
Au-Au	(2016)
d-Au	(2016)
p-Al	(2015)
h-Au	(2015)
p-Au	(2015)
Cu-Au	(2012)
U-U	(2012)
Cu-Cu	(2012)
D-Au	(2008)
Cu-Cu	(2005)



Parameter		RHIC EBIS
Max. electron current	I_{el}=	10 A
Electron energy	E_{el}=	20 keV
Electron density in trap	j_{el}=	575 A/cm^2
Length of ion trap	L_{trap}=	1.5 m
Ion trap capacity	Q_{el}=	1.1x10^{12}
Ion yield (charges)	Q_{ion}=	5.5x10^{11} (10 A)
Yield of ions Au^{32+}	$N_{Au^{32+}}$=	3.4x10^9

$$N = \kappa * I_e * L_{trap} * E_e^{-0.5}$$

Optically pumped polarized ion source (OPPIS)



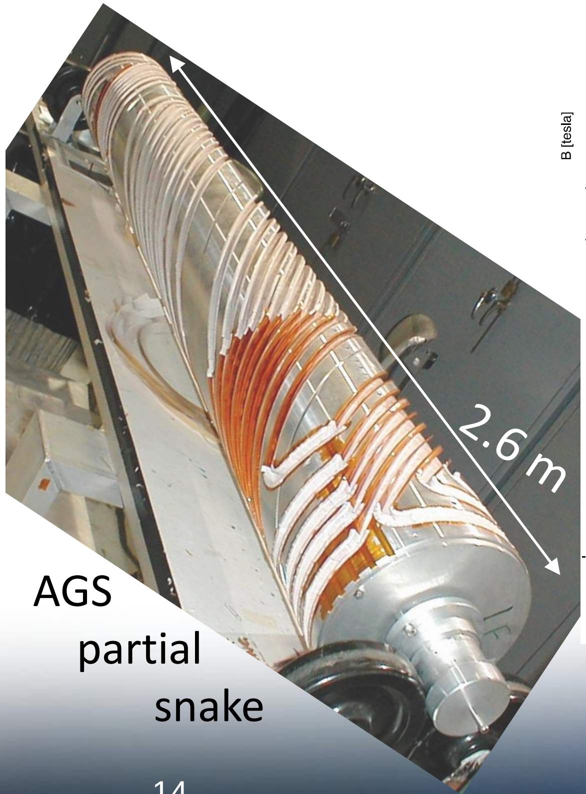
- Used for RHIC p↑+p↑ program from 2000
- Protons pickup polarized electrons in an optically pumped Rb vapor cell
- Electron polarization of H atoms is transferred to protons in a magnetic field reversal region (Sona-transition)
- H^- ions are produced then by passing through Na-cell
- Polarized protons are obtained by charge exchange injection of H^- into the Booster
- Several upgrades and modifications over years increasing polarization and intensity

up to 84% polarization
reliably 0.5 - 1.0 mA (max 1.6 mA)
up to 1 · 10^{12} H^-/pulse polarized H^- ions

EIC Hadron Polarization

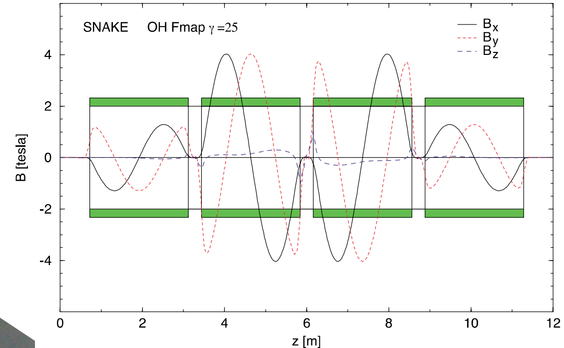
- Existing p Polarization in RHIC achieved with “Siberian snakes”
- RHIC near term improvements: proton polarization 60% → 80%
- ^{3}He polarization of >80% measured in source
- 80% polarized ^{3}He in EIC will be achieved with six “snakes”
- Acceleration of polarized Deuterons in EIC 100% spin transparent
- Need tune jumps in the hadron booster synchrotron

Electron beam ion source EBIS with polarized ^{3}He extension

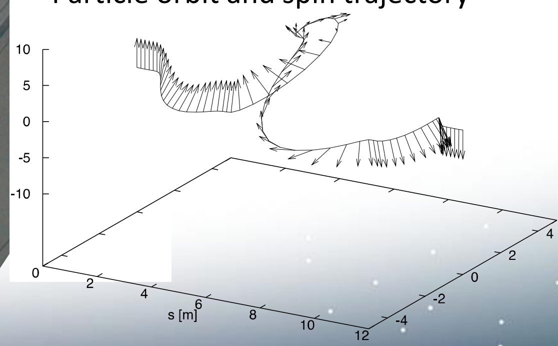


AGS partial snake

Magnet field in Snake

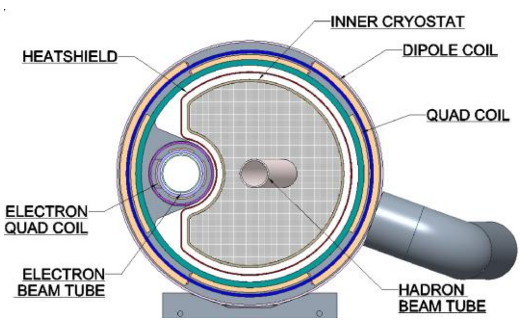


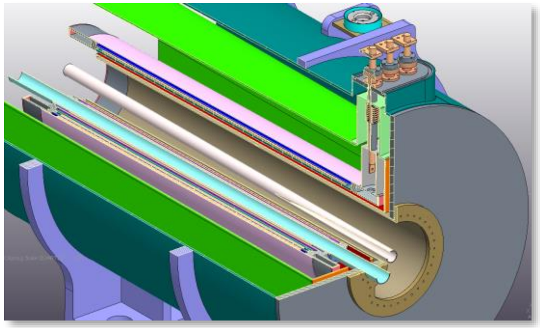
Particle orbit and spin trajectory

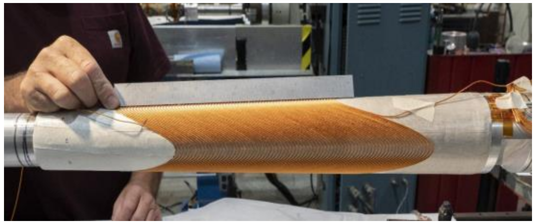


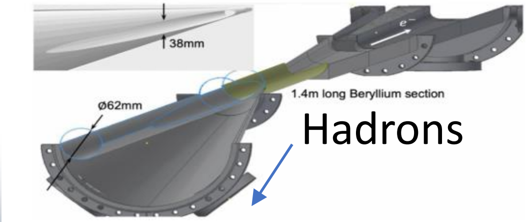
Interaction Region

- Beams collide at the collision point (IP) in the center of the Interaction region (IR)
- Complex IR Design
    - provides sufficient space for detector and detection of forward scattered particles
    - defines the collision orbits with a crossing angle of 25 mrad,
    - establishes focusing of the beam at the IP but avoiding extensive local chromaticity generation,
    - employs complex superconducting magnets with novel but-prototyped magnet technology
    - contains a low impedance vacuum system
    - accommodates crab cavities for hadrons and electrons with correct beam optics
    - accommodates spin rotators
    - fits inside the existing straight sections
    - provides favorable condition for luminosity measurements and auxiliary detectors









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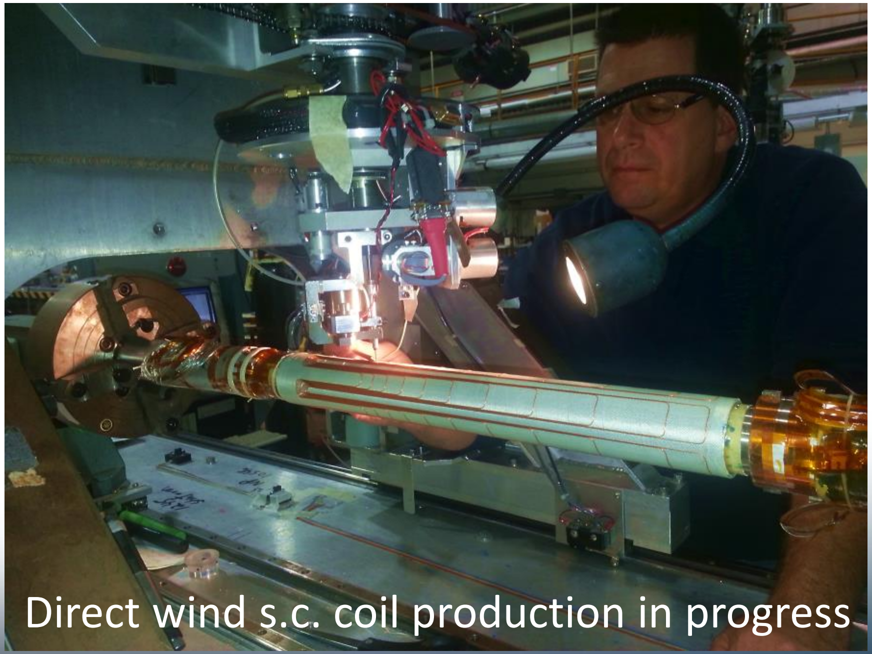
EIC IR Magnet Needs

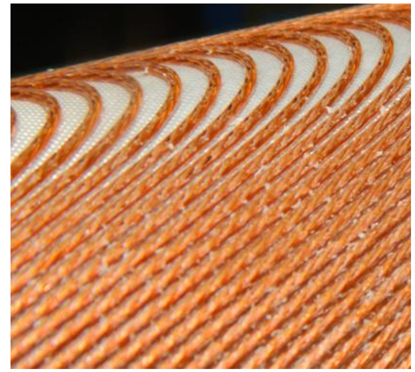
- Interaction region (IR): highly congested area
- Requires specialized magnets, which are often one-offs
- Requirements:
  - Excellent field quality
  - Robust technology
  - Space efficient
  - Cost efficient
    - Minimize tooling

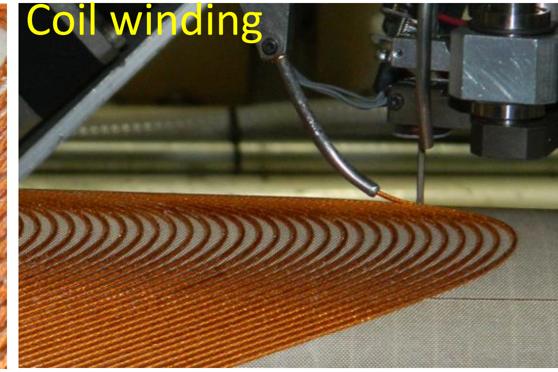


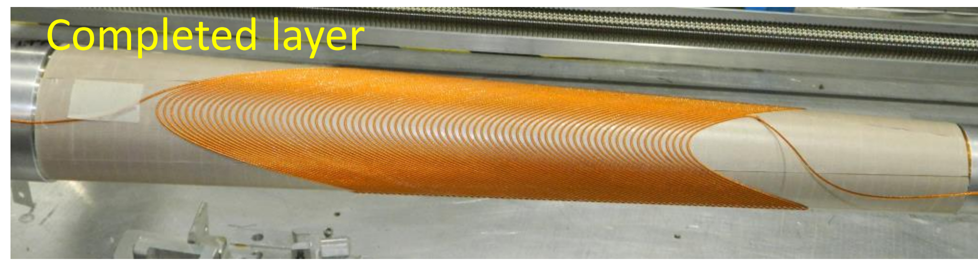
Direct wind s.c. coil production in progress

Example: Tapered Magnets

- Allows to move magnets closer to IP
  - Highly desirable
- Helps with crosstalk issues
- Implementation: double-helix or canted cosine theta (CCT)
- Excellent field quality
- No expensive tooling







Proof-of-principle demonstrator
Length: 0.45m
Gradient (centre): 45T/m (measured)
IR: 30..40mm

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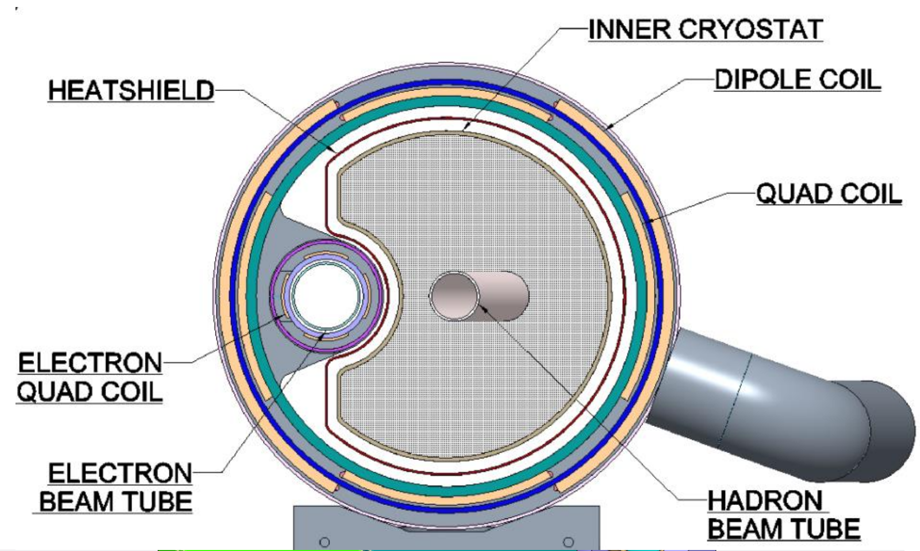
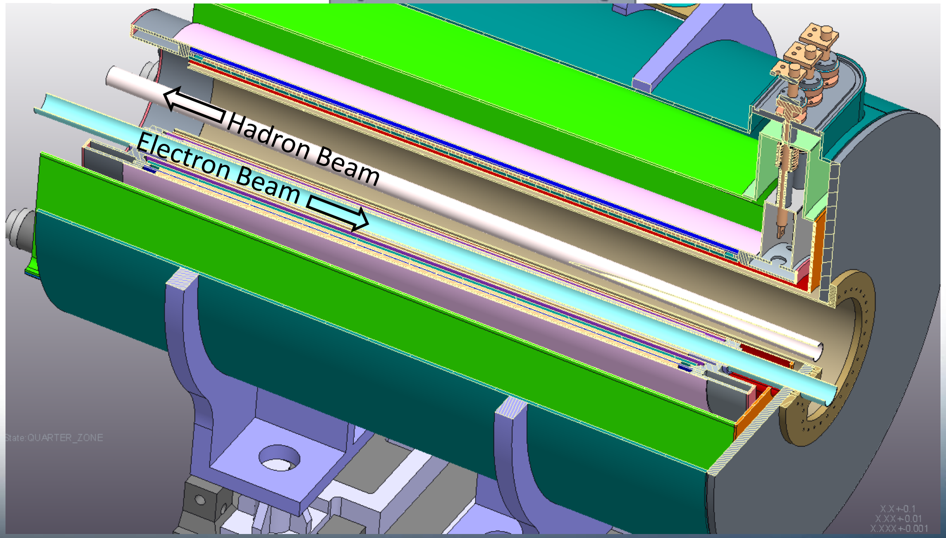
Magnetic Shielding

- Beams sharing aperture of single magnet (e.g. spectrometer magnet)
  - One beam needs to be shielded from spectrometer field (~1-2T)
  - Sometimes need additional multipole field (e.g. quadrupole)





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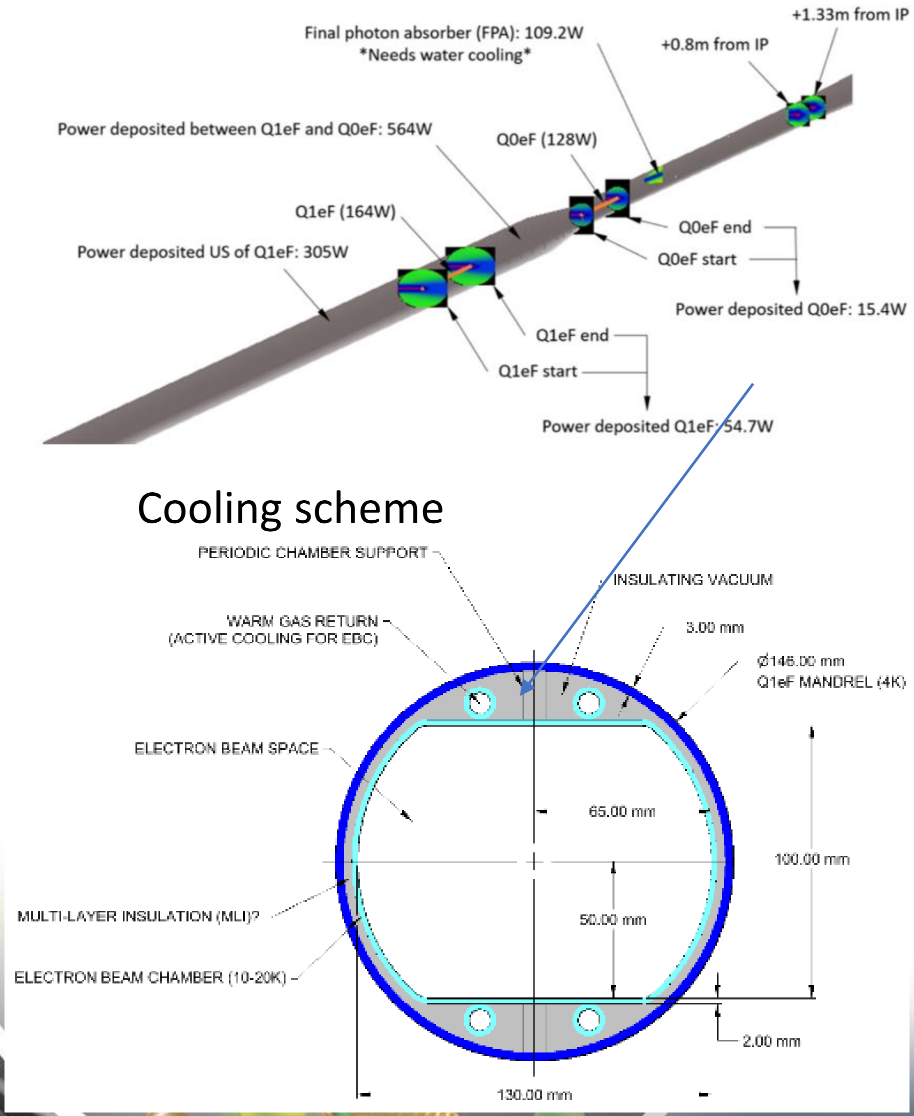
Space Efficient Cooling Methods



- Challenge: synchrotron radiation (several 100W over ~1m) hitting beampipe inside superconducting magnets
- Needs to be cooled
- Sought are innovative solutions how to cool this
  - Not much space radially – close to IP

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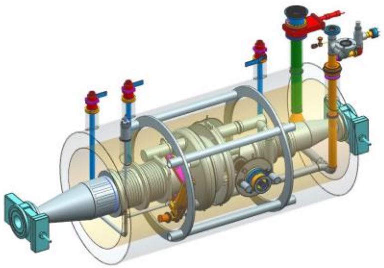
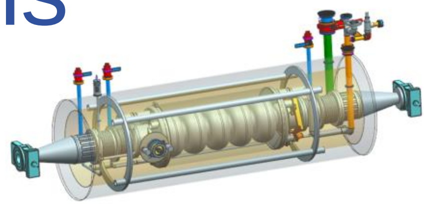
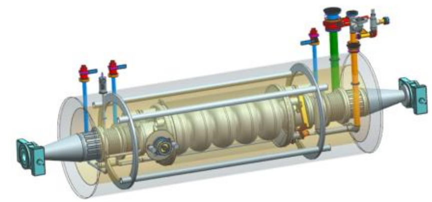
EIC RF systems



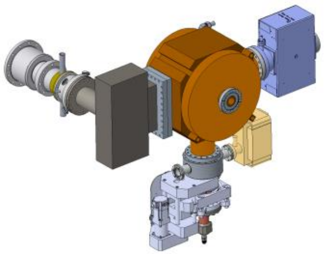
Electron - 591 MHz electron storage cavity



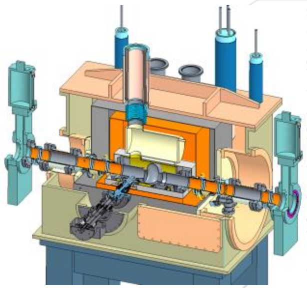
Hadron - 591 MHz bunch compression cavity



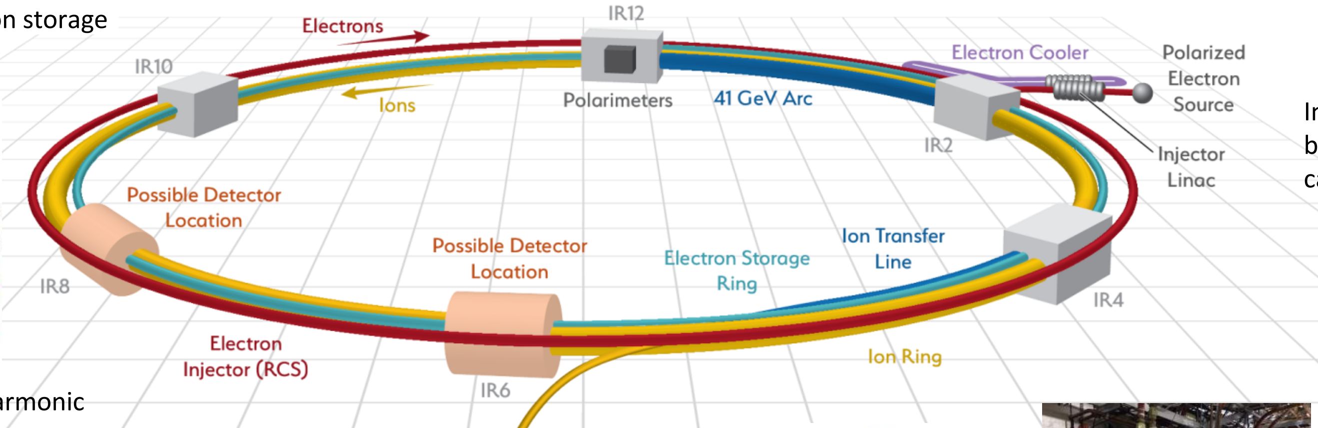
Hadron Cooling - 591 MHz acceleration cavity

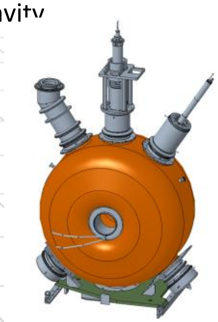


Injector - 571 MHz bunch compression cavity



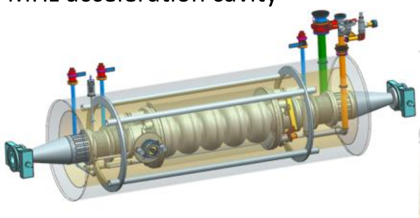
Electron - 1773 MHz 3rd harmonic cavity



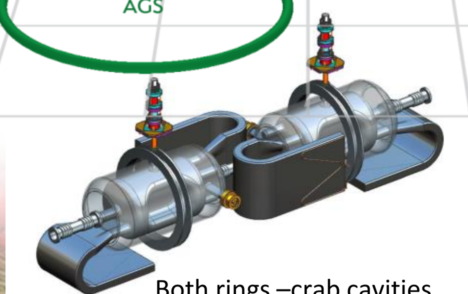


Hadron - 197 MHz bunch compression cavity

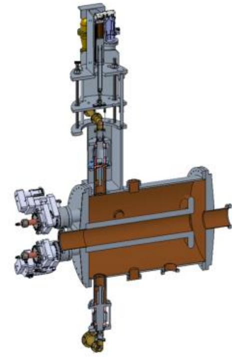
Hadron – 24.5 MHz acceleration cavity



Rapid Cycling Synchrotron - 591 MHz acceleration cavity



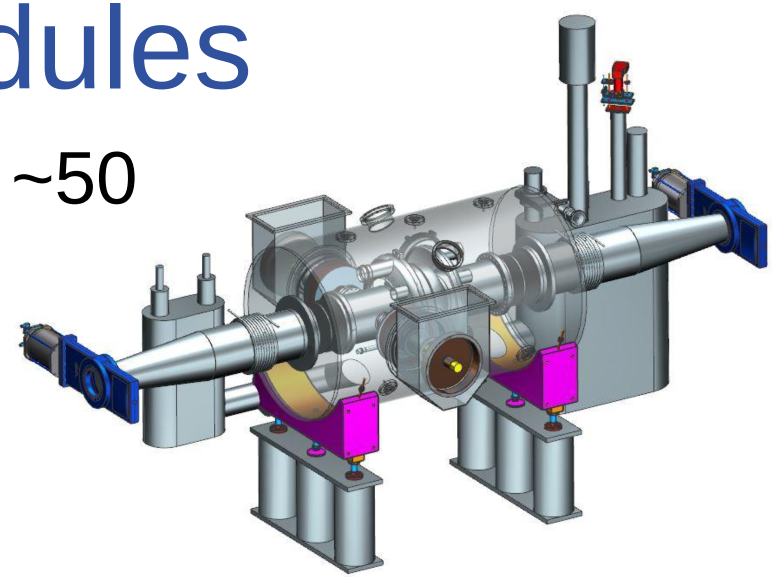
Both rings –crab cavities

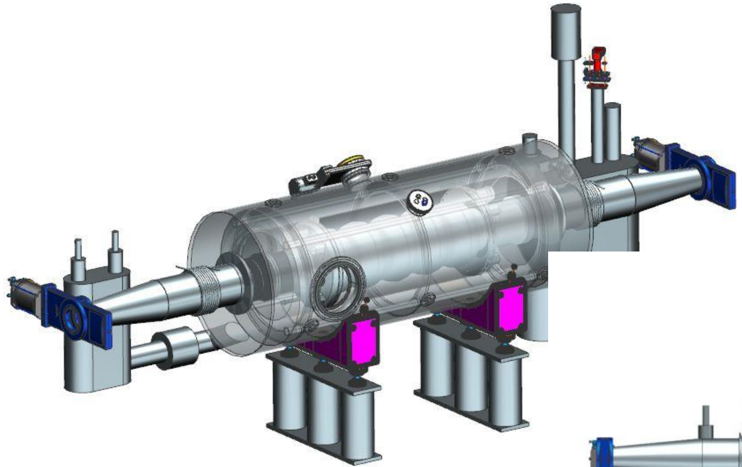


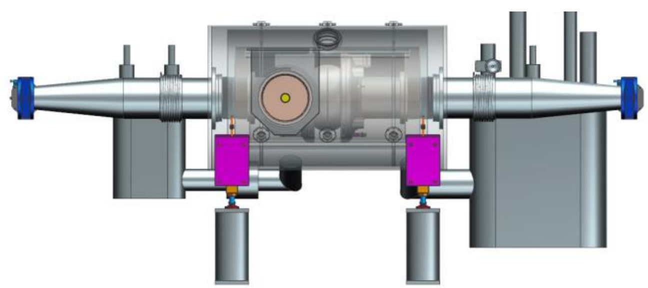
Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity

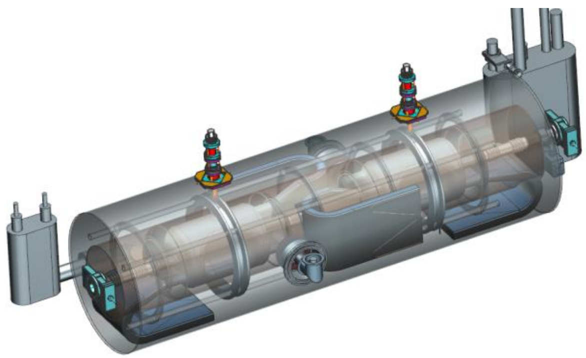
EIC SRF Cryomodules

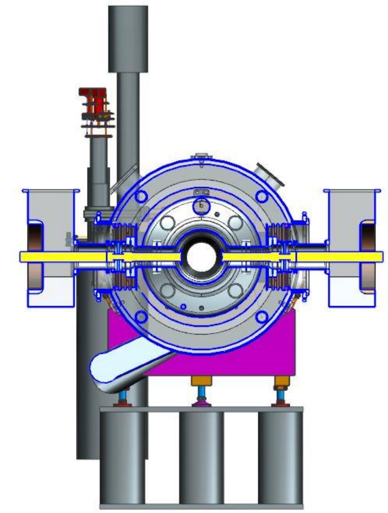
- Several types required, total ~50











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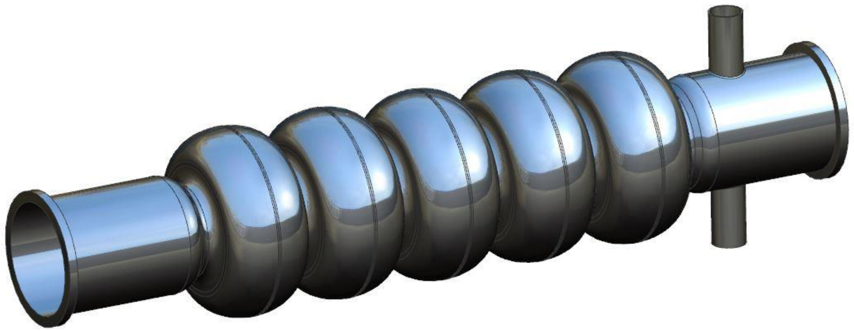
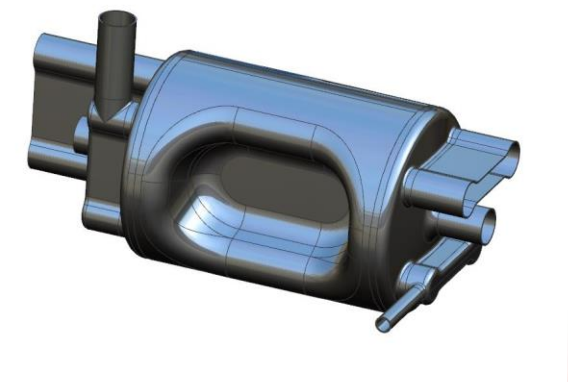
EIC SRF Cavities

- SRF cavities, 197-1773 MHz
  - High RRR, fine grain, Niobium sheet cavities
  - 5 types, 3 elliptical and 2 non-elliptical, quantities ~ 4-20
  - Build to print





Cavity Type	Freq [MHz]	Type	# Cavities
Elliptical	591	SRF, Elliptical, 1-cell	19
Elliptical	591	SRF, Elliptical, 5-cell	17
Elliptical	1773	SRF, Elliptical, 1-cell	4
Crab Cavity	197	SRF, RF Dipole (RFD)	8
Crab Cavity	394	SRF, RF Dipole (RFD)	6

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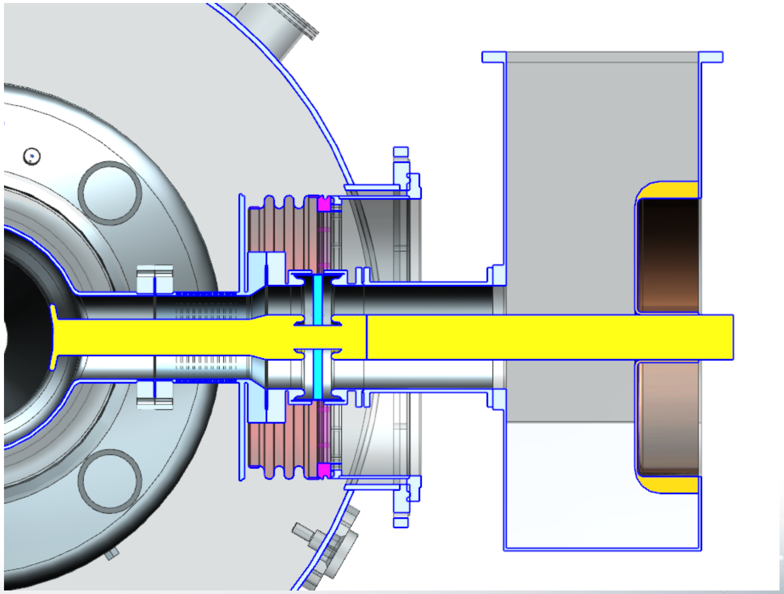
EIC SRF Power Couplers

- Fundamental Power Couplers
  - Based on existing Coaxial Couplers
  - ***Coaxial Up to 500 kW continuous wave, very high power***



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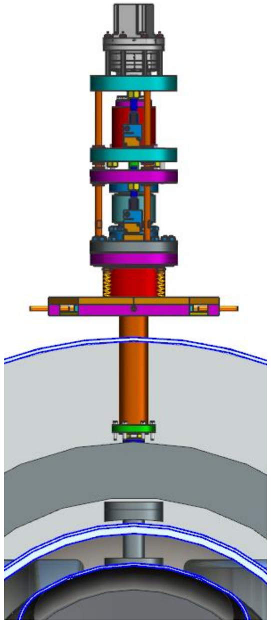
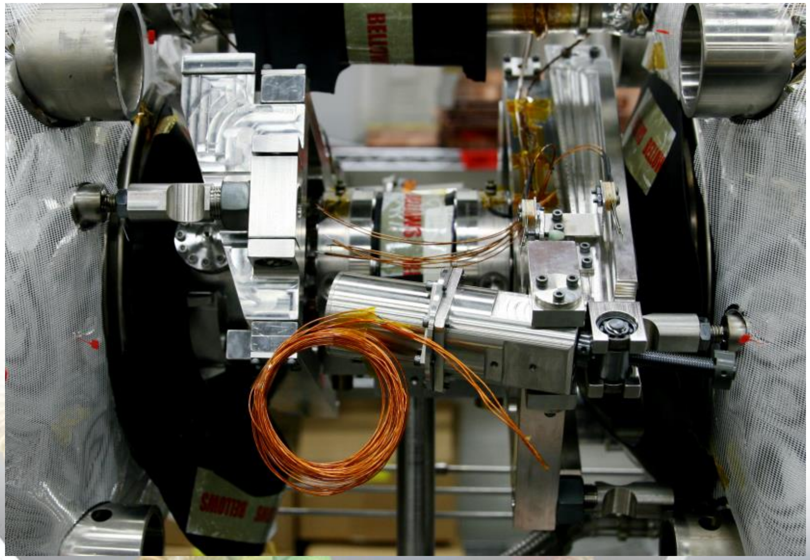
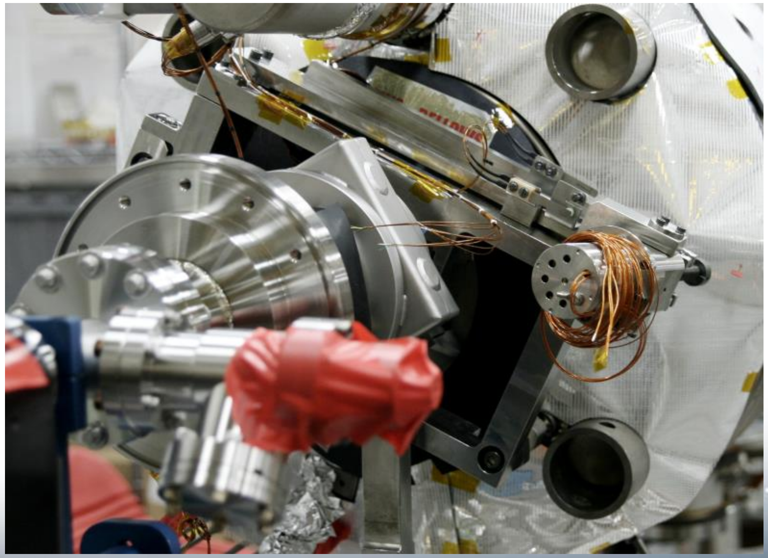
EIC SRF Cavity Tuners



- Cavity frequency tuners
  - High resolution cryogenic temperature mechanical actuators
- Stepper Motor and Piezo actuators
- ~mm range with ~nanometer resolution





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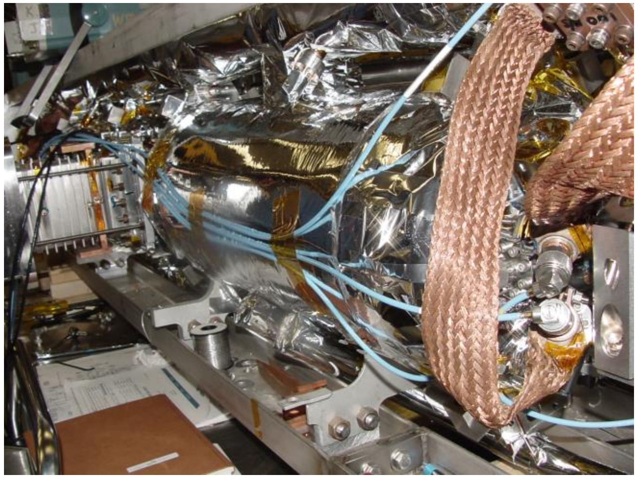
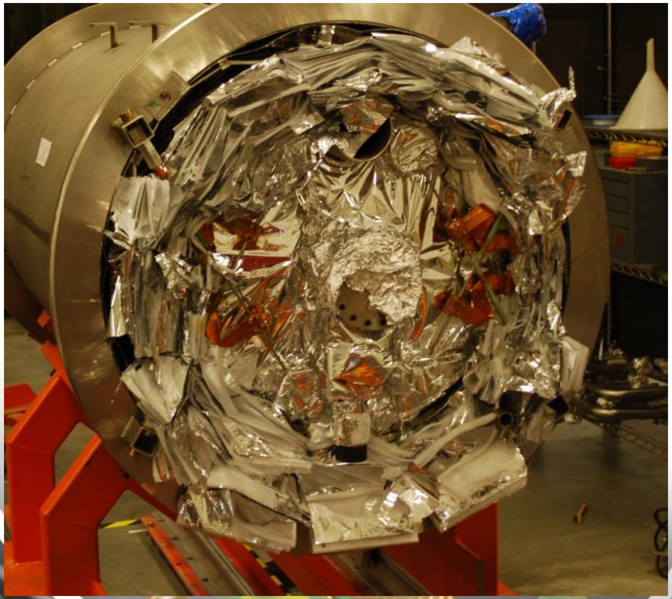
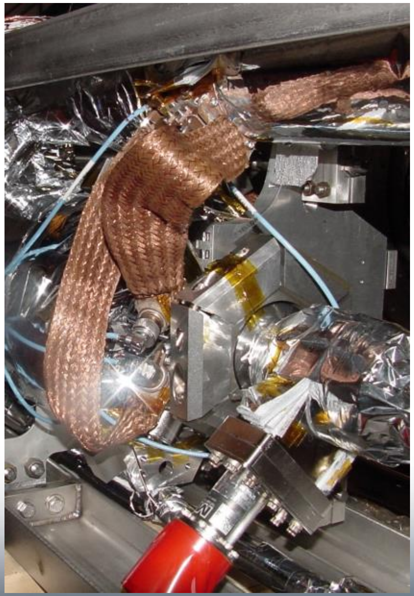
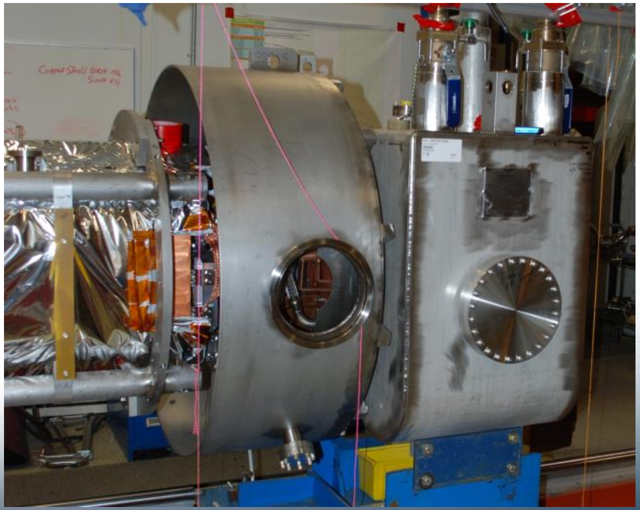
EIC SRF Cryostat Components

- Cryogenic piping, shields, and valves
  - 0.03-3 atmosphere pressure
  - 2-50 Kelvin Temperature range
  - Intermediate temperature shields
  - Shutoff and control valves
  - Heat exchanger



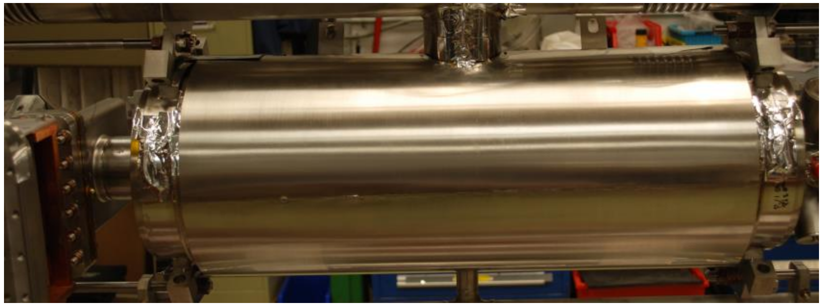


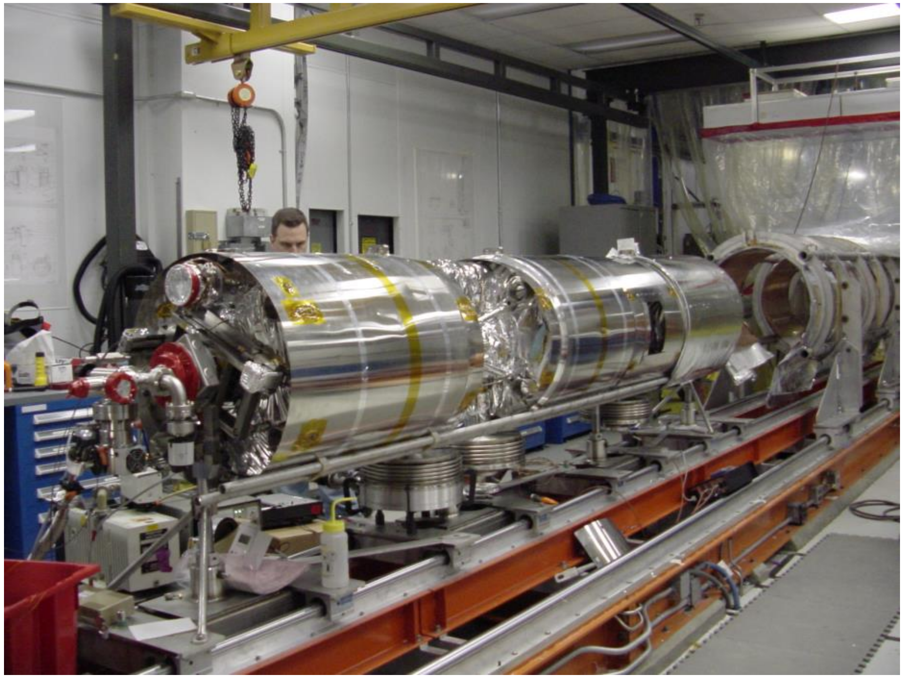




EIC SRF Cryostat Components

- Magnetic Shielding
  - High permeability warm and cryogenic shields





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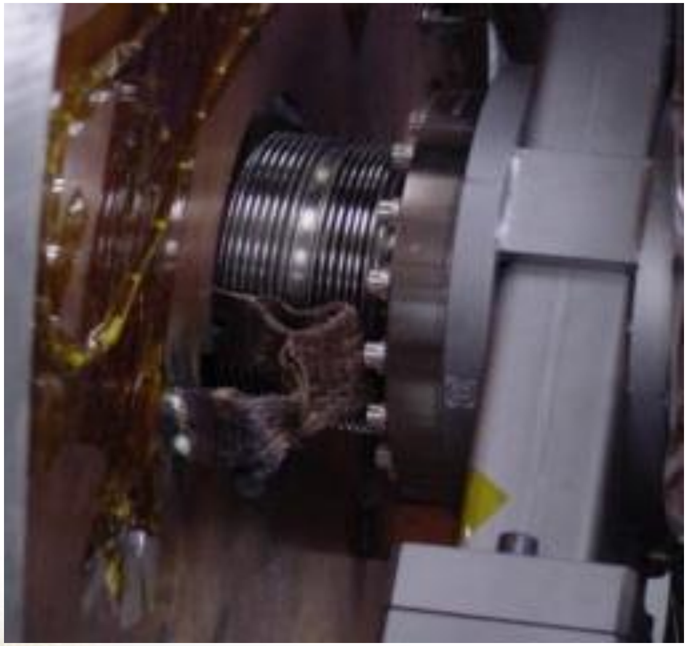
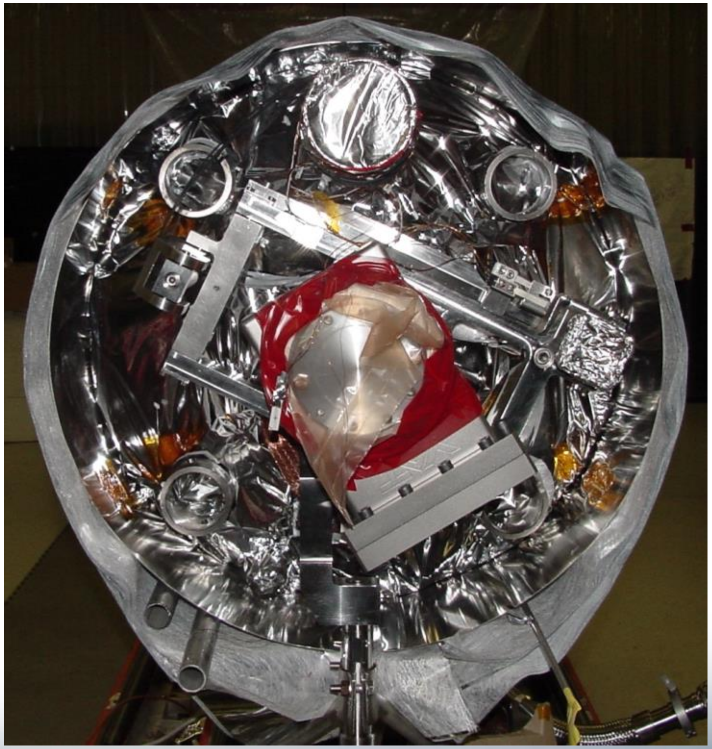
EIC SRF Cryostat Components

- Vacuum components
  - Warm Beamline RF absorbers
  - Valves, Pipes, Bellows, Instrumentation





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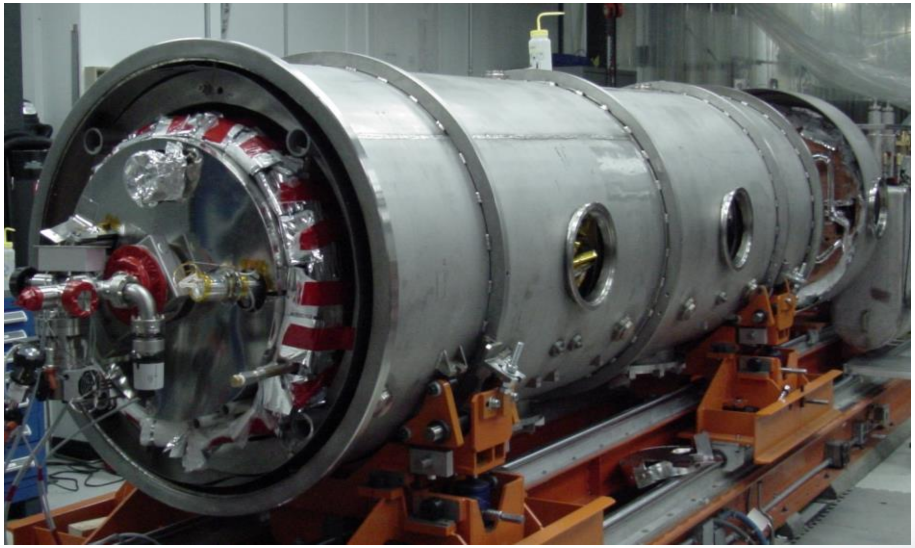
EIC SRF Cryostat Components

- Stainless Steel vacuum vessels
  - Large cylindric vessels
    - ~40 in diameter, 120 in long, with multiple ports and interface features



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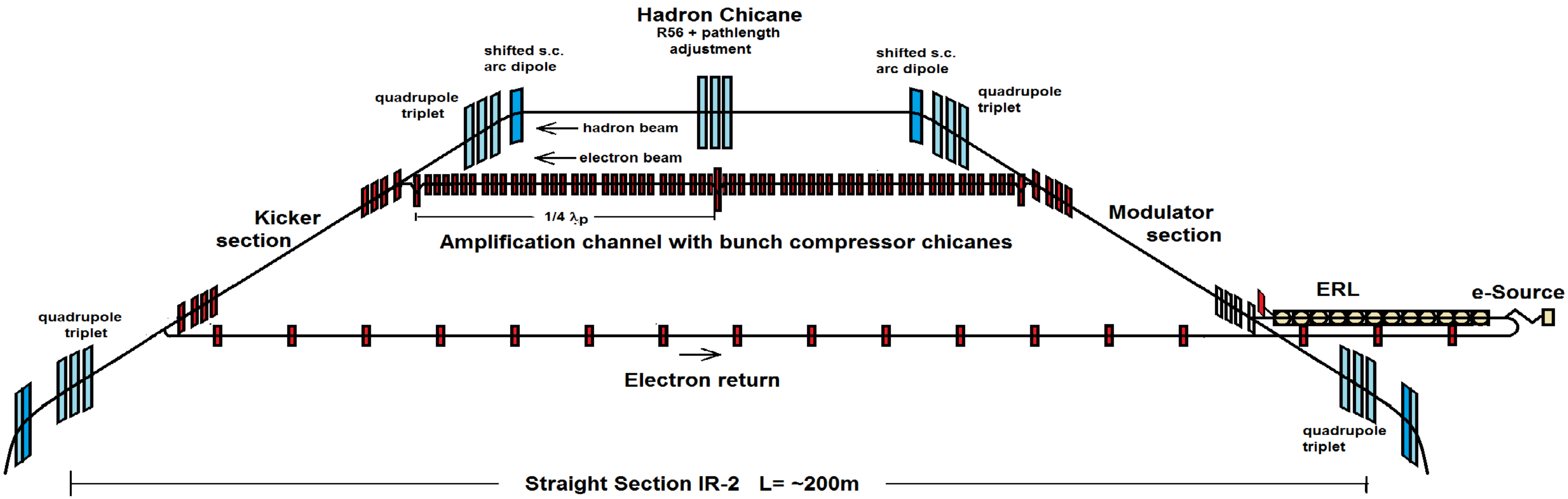
RF Power – Solid State Amplifiers, etc.

591 MHz Very High Power Solid State	400 kW CW
591 MHz Moderate Power Solid State	<100 kW CW
Low to Mid Frequency, Small production Solid State 49, 98, 148, 197, 296 MHz, 30-80 kW SS	
High Frequency, Small production SS	1773 MHz CW 20 kW
Vacuum Tube Amplifiers 24.6 MHz CW Tetrode 150 kW 197 MHz CW Tetrode 90 kW	
Circulators and Dummy Loads for above	
Waveguides, High Power Couplers, etc..	

EIC Strong Hadron Cooling

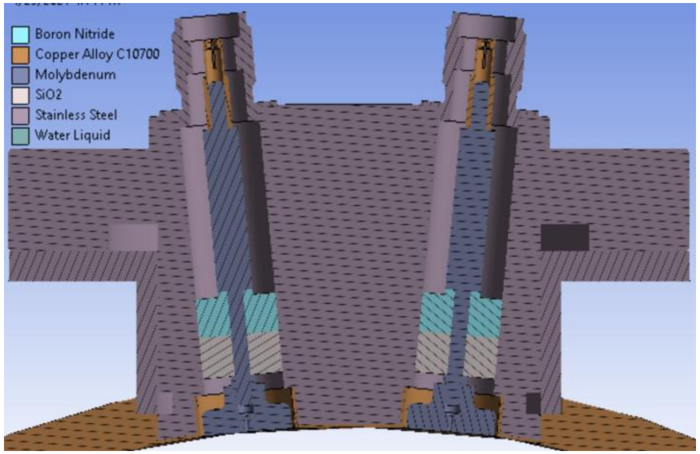
Coherent Electron Cooling with μ-bunching amplification

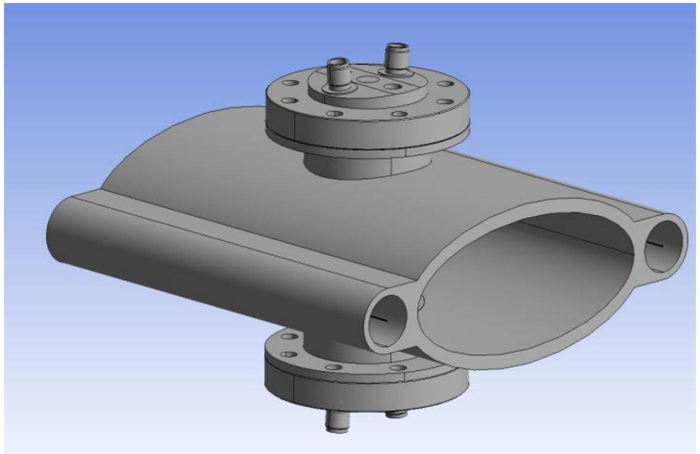


- The EIC cooler requires up to 150 MeV electron beams with average electron beam current of ~100 mA => 15 MW
- Requires use/design of a world-class SRF **energy-recovery linac** (ERL)
- Electron/hadron beams separate and rejoin each other
  - Adjustable R_{56} for electrons to tune amplification
- Electron source/accelerator must be **extremely "quiet"** (no substructure)
  - avoid amplification of "shot noise", electron beam structure not from hadrons

Instrumentation

- Large variety! Some examples:
- SHC area:
  - Instrumentation that ensure the electron-hadron longitudinal alignment to within 1 micron (even ~300nm) at the SHC kicker region ➔ the need for nondestructive radiation based longitudinal profile measurement
- Other instrumentation with a degree of novelty:
  - The electro-optical longitudinal bunch length monitor
  - New HF Schottky detector
  - New ionization profile monitors: higher voltage bias, and higher density MCP to improve performance





ESR BPM pick-up models

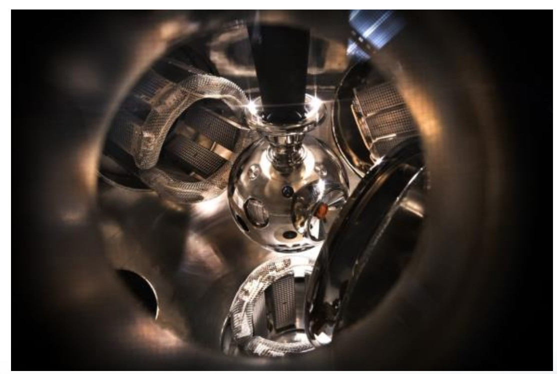
J. Bellon
C. Hetzel
D. Gassner

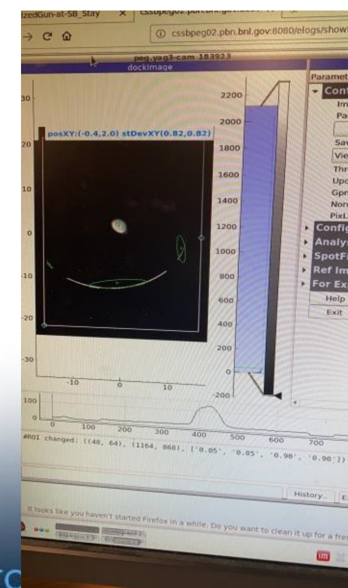
Electron Injector Complex

- **Electron Injector consists** of:
  - polarized electron source (existing, photo cathode Strained GaAs SLAC/JLAB design),
  - 400 MeV s-band injector LINAC (similar to NSLS-II Linac)
  - spin transparent Rapid Cycling Synchrotron (RCS)
- **RCS:** Fast cycling synchrotron, 384, 3.84m dipoles, Q,S,C

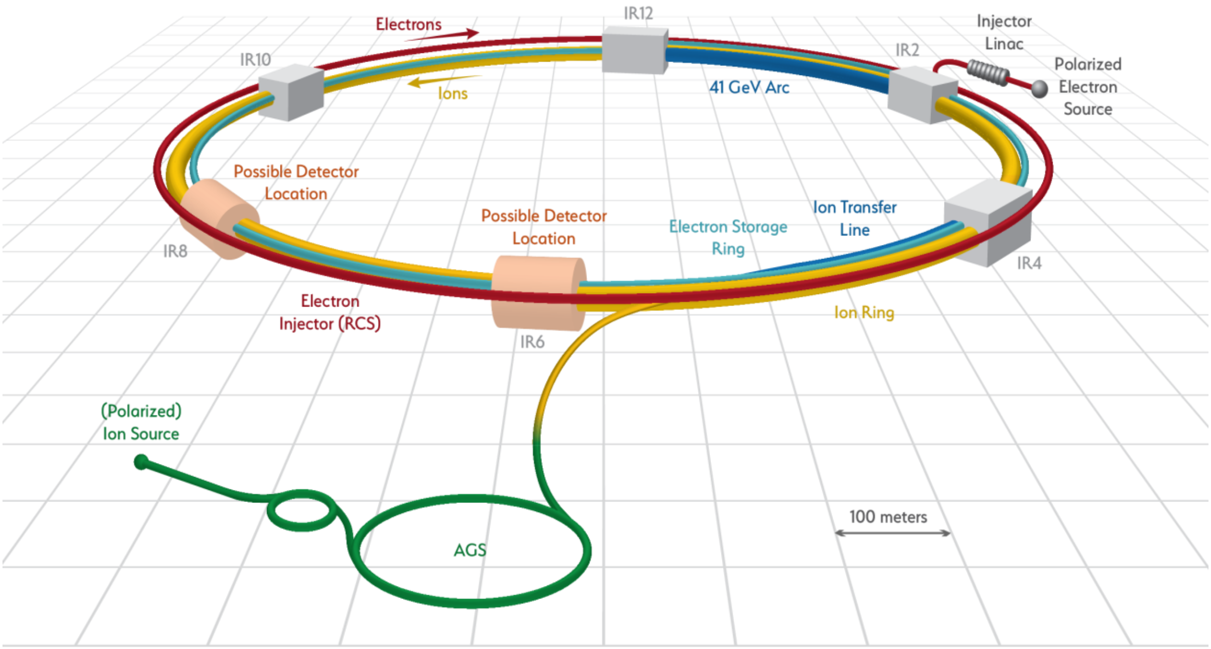
Gun and experimental hall
Pics: Courtesy J. Skaritka

Cathode and
Gun front end



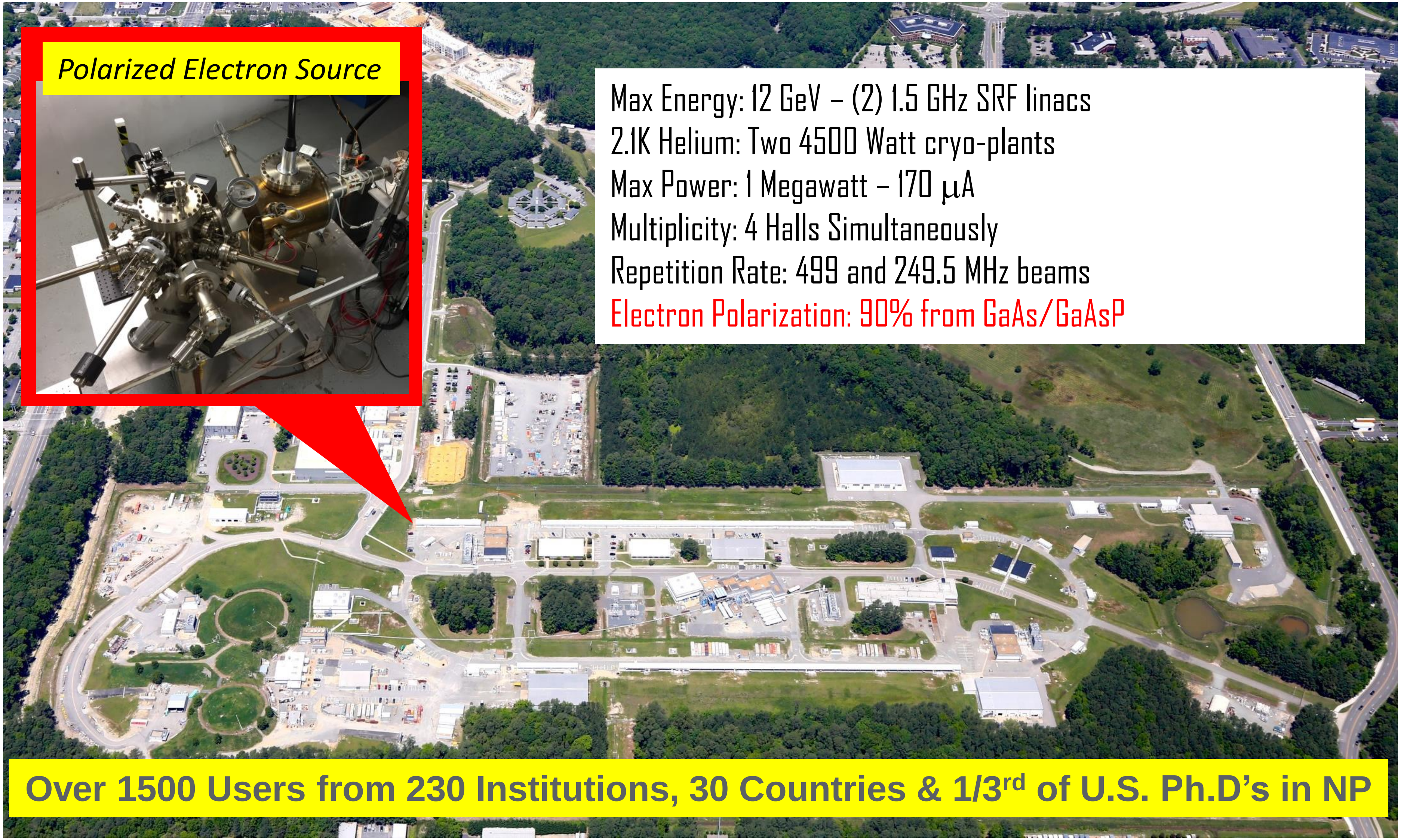


EIC and polarized beams



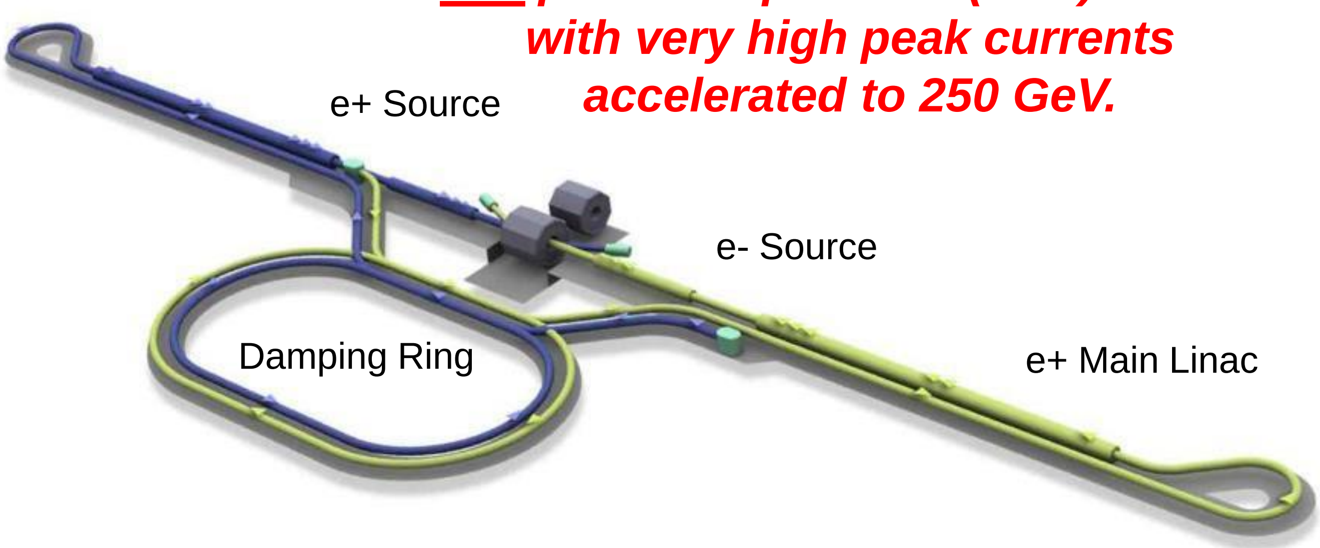
Polarized electron beams (>85%) with very high bunch charge (7 nC) from a 350 kV dc-high voltage photogun merged and accelerated to 5-18 GeV .

CEBAF polarized beams

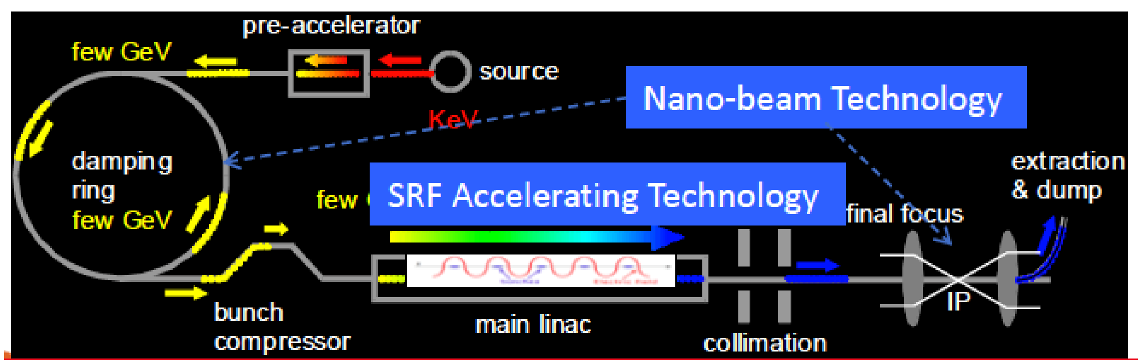


ILC 250 accelerator facility – global efforts (if approved)

ILC requires polarized electron (90%) and polarized positron (30%) beams with very high peak currents accelerated to 250 GeV.



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10 ^{10}



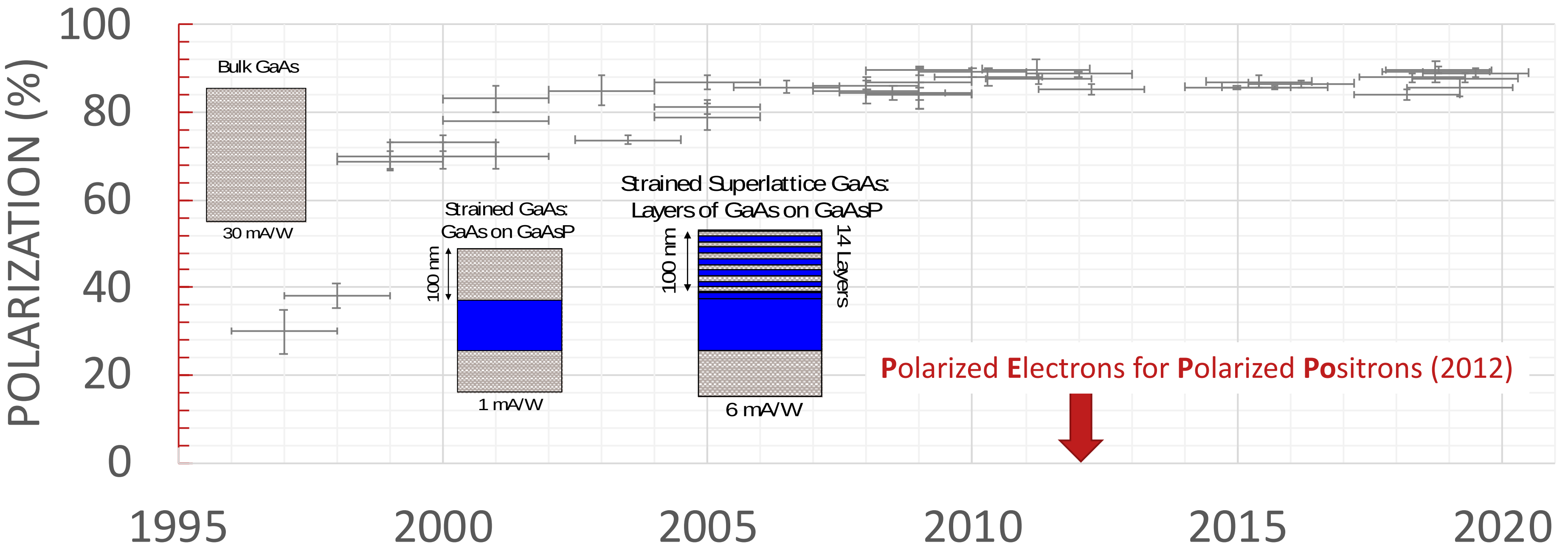
***8,000** SRF cavities will be used.*

Jefferson Lab

High Polarization GaAs Photocathodes

GaAs photocathodes have been the backbone for providing high spin polarization beams for the US DOE programs

- Parity violation experiments have driven source developments over last ~25 years
- Planned programs at EIC, Jefferson Lab and internationally at MESA (Germany) will depend on these materials
- Future facilities at the ILC (Japan) or the linac production of polarized positrons beams could as well
- Yet, there is no domestic supplier of GaAs/GaAsP SSL photocathode material



Higher Beam Voltage Photo-guns

Higher voltage polarized photo-guns are essential for future polarized beam programs

- High peak current beams required for the EIC, similarly imagined at the ILC with gun voltages >300 kV
- Higher gun voltages improve beam quality, brighter beams for more demanding Parity Violation experiments
- US suppliers of large compact doped insulators, high voltage cables and connectors needed 300-500 kV

EIC photo-gun testing at Stony Brook U.
Courtesy E. Wang

High voltage photo-gun testing at Jefferson Lab
Courtesy C. Hernandez-Garcia

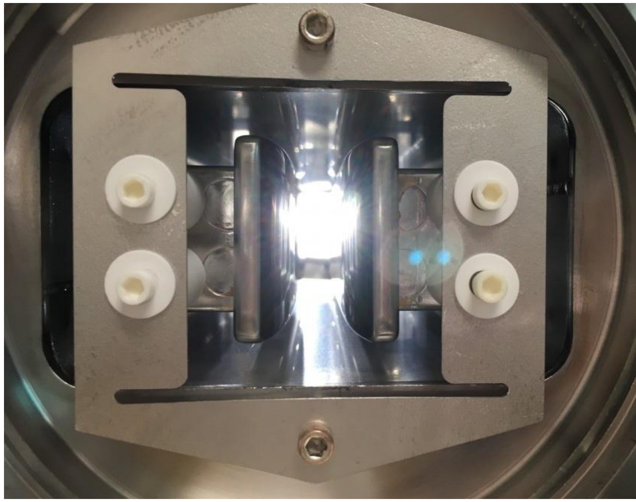
Mott Polarimetry & Spin Rotators at Electron Injectors

Polarized source capabilities and User's programs continue to push limits on low energy polarimetry & controls

- MeV energy Mott polarimetry offers rapid and precise electron polarimetry with sub-percent accuracy
- Breaking theoretical <0.5% limits is in reach, using ultra-thin sub-micron diamond targets
- Wien filters operating >5 MV/m may scale with higher gun voltages or as MeV spin correctors for PV experiments

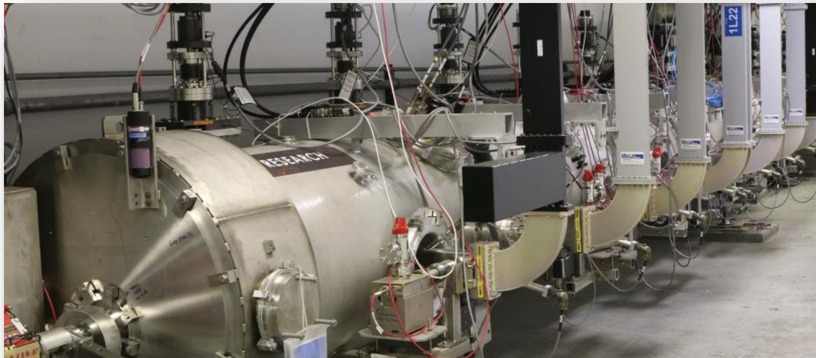
Radiative corrections limiting sub-half percent absolute accuracy may be disentangled by scattering polarized electron beams from both low-Z (e.g. C) and high-Z (e.g. Au) targets of varying thicknesses.

Wien filters originally designed for 100 kV are being imagined for with >350 keV polarized guns and to provide sub-degree control at MeV energies for parity violation experiments.



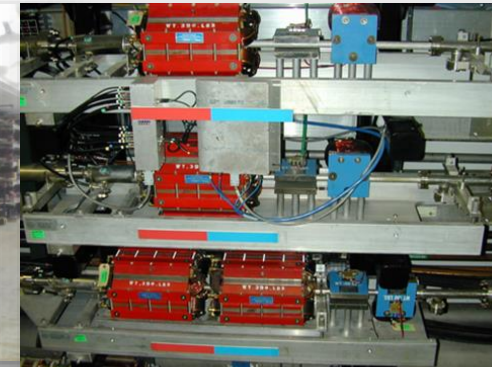
Joe Grames at al

CEBAF Accelerator – Technical Scope

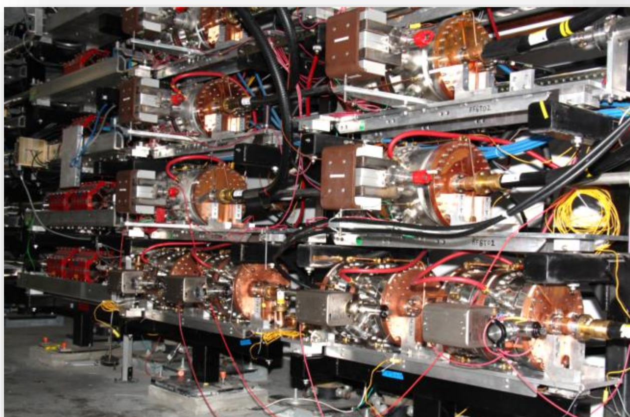


52-1/4 Cryomodules with 418 SRF Cavities to Accelerate Electrons in CEBAF

~500 Large Dipoles powered by >40 HVPS

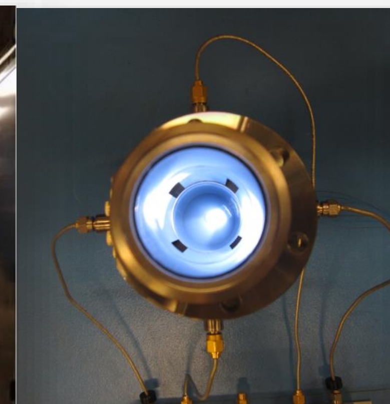


>2800 Magnets to Focus and Steer Beam



16 RF Deflectors for Extracting Beams

418 Klystrons for 52.25 Cryomodules



>800 Beam Position Monitors

High Power Exp Hall Beam Dump

- Capable of delivering 4 independent CW polarized electron beams simultaneously to experiment Halls.
- Over 7 km of beamline ~800 BPMs, 60 harps, 150 viewers, and 7 synchrotron light monitors.
- >580,000 data channels on a distributed network of over 600 local computers with 200 kHz data rate.

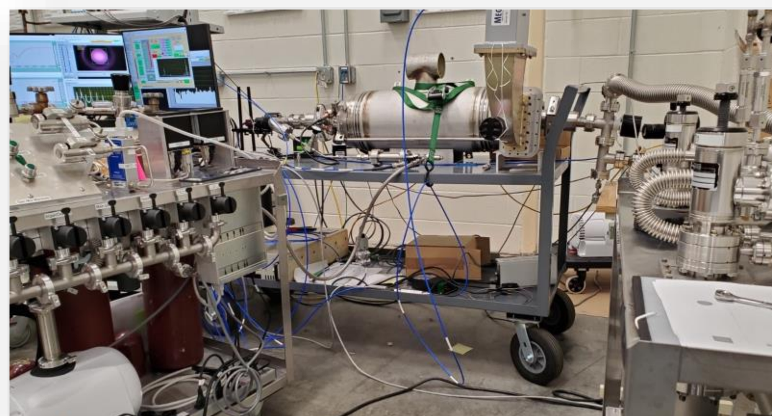
CEBAF SC RF cryomodules – field emission control

- Small particulates (metal, etc.) or thin hydrocarbon film, accumulated with time on the surface of 2K cold Nb cavities cause field emission and degradation of accelerating gradient
- Ideally – need mitigation methods that can be applied in tunnel, without CM disassembly
- Plasma Processing in development
  - Learned to establish plasma in all 7 cells
  - Processed individual cavities
  - Processed entire C100 CM taken from CEBAF
- Liquid Nitrogen Cleaning – in development. Other methods?

Refurbished C100 installed

Plasma established in all 7 cells of a C100 cavity.

Plasma Processing Gas Delivery System

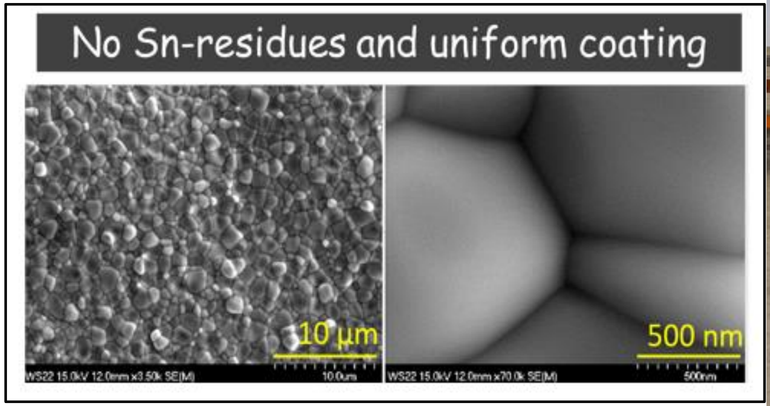


Plasma Development and Testing Lab

Tom Powers et al

New SRF materials – Nb3Sn cavities

- Active work to develop Nb3Sn coating
  - Allow to use T=4K or higher f cavities
- Challenges – uniform film, brittle material (cavity tuning)
- Will benefit CEBAF, ATLAS, FRIB, etc.
- Will allow to create more efficient and compact accelerators

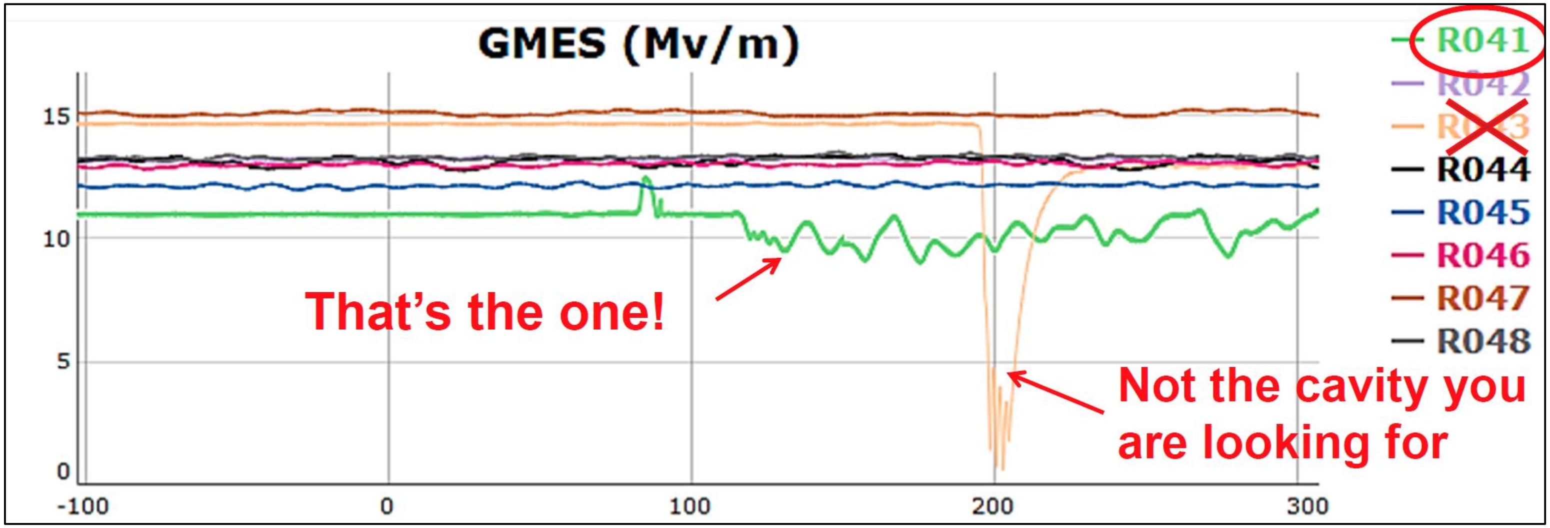


R. Rimmer, U.Pudasaini, JLAB, G. Eremeev, FNAL, et al.

C75 pair Nb3Sn coated & tested. Being re-coated

AI / ML – for CEBAF operations

- Goal – improve detection of cavity trips to maximize gradient. Eventually – to anticipate and possibly prevent trips
- Fruitful collaboration with ODU Engineering

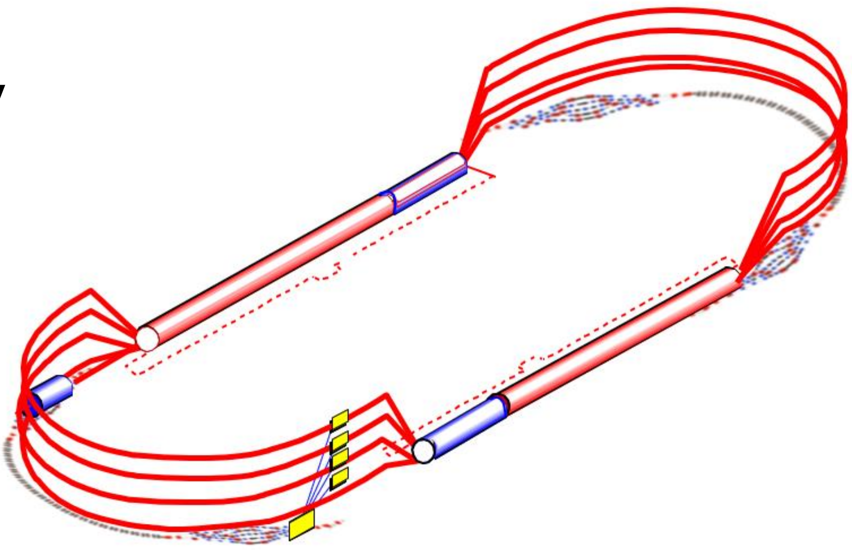


Examples of a waveform for one of the particular types of SRF cavity trips. There are ~10 types of trips, and our ML already trained to recognize most of them

Chris Tennant, et al

Potential CEBAF energy upgrade & needed technologies

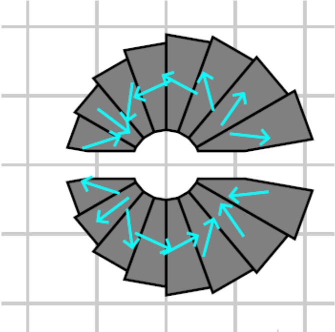
- Investigating an affordable path to upgrade CEBAF to double the energy
- Good science motivation, complementary to EIC operation
- Studying the feasibility of an FFA-based additional arc to bring the energy to 20-24 GeV in the existing tunnel
  - FFA (Fixed Field Accelerator) arcs will allow to have more passes, thus more energy
  - FFA arcs are fixed field, thus ➔
  - Exploring the option to make FFA arcs based on permanent magnets

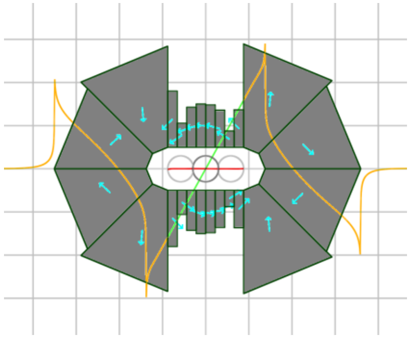


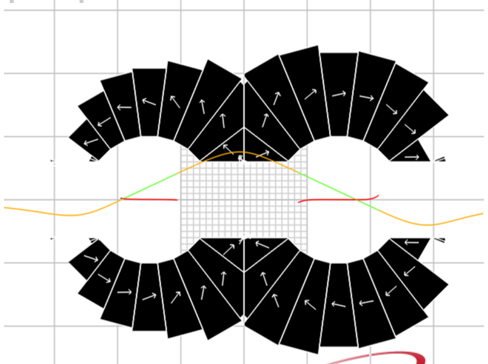
Alex Bogatcz, et al

CEBAF energy upgrade and FFA permanent magnets

- **Halbach magnet variations**
- Demonstrated (in accelerator)
  - Field tuning with iron rods
  - Combined-function magnets
- In development
  - Open midplane magnets
- Future research
  - Oval apertures
  - Multiple apertures
- For CEBAF: push gradients further



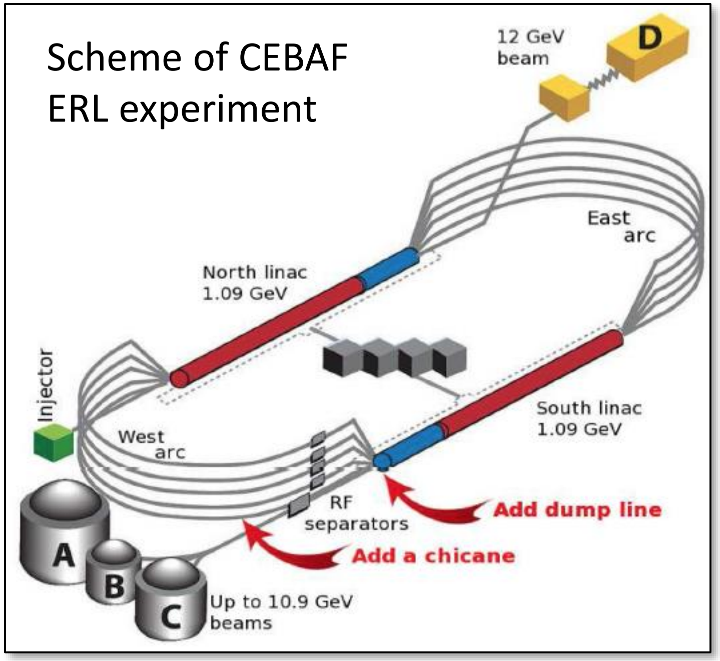




Steve Brooks (BNL), et al

Energy Recovery – the near future champion

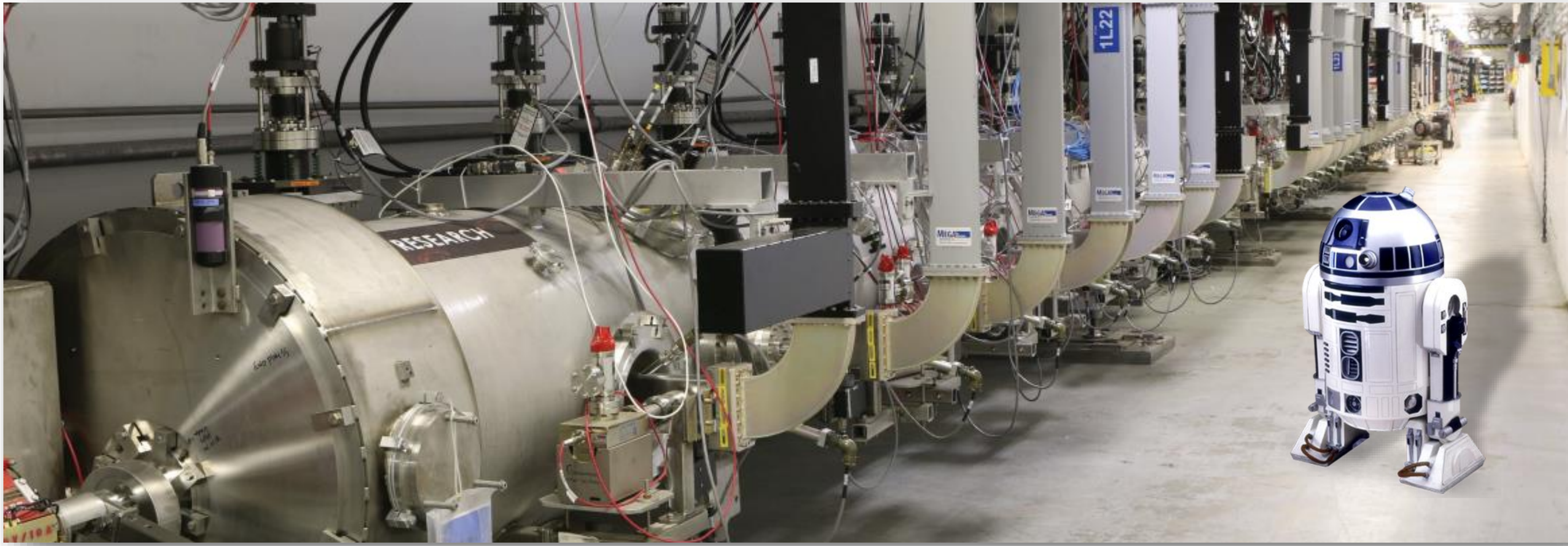
- Energy recovery is already indispensable, e.g. in existing DC electron cooling facilities (like in FNAL's 4.3 MeV e-cooler)
- EIC Strong Hadron Cooling relies on ERL
- European long range planning includes ERL as one of the key technology on its roadmap
- There are ERL-based concepts for LHeC, ILC, FCC-ee, and number of NP applications can benefit from ERLs too
- JLAB expertise:
  - GeV scale ERL, single pass, CEBAF (2003)
  - 1.3 MW circulated power ERL @LERF
- ERL experiments @ CBETA, ALICE, planned PERLE
- Next: multi-pass high-energy ERL experiment at CEBAF in plans



Scheme of CEBAF ERL experiment

800 MHz cavity built at JLAB for PERLE prototype

Remote actions during operations



- Variety of operations in CEBAF can benefit from remote robot-like instruments
  - E.g. making radiation map survey during beam operation, to find field emission hot spots, and thus optimize the gradient, and maximize longevity of accelerator equipment
  - Radiation-resistant autonomous robots

*) The image of R2B2 in the tunnel does not reflect the plan or reality and is for inspiration only

Conclusion

- The EIC's high luminosity and highly polarized beams will push the frontiers of accelerator science and technology and provide unprecedented insights into the building blocks and forces that hold atomic nuclei together
- Ongoing R&D, in the labs, and in SBIR/STTR partners, will further push the frontiers of accelerator technology, for benefits of the existing, planned, and dreamed of accelerators

Thank you for your attention!

With many thanks to EIC Project colleagues for materials for this presentation, and with thanks to CEBAF colleagues for the corresponding slides