Progress of the EIC Superconducting RF Systems

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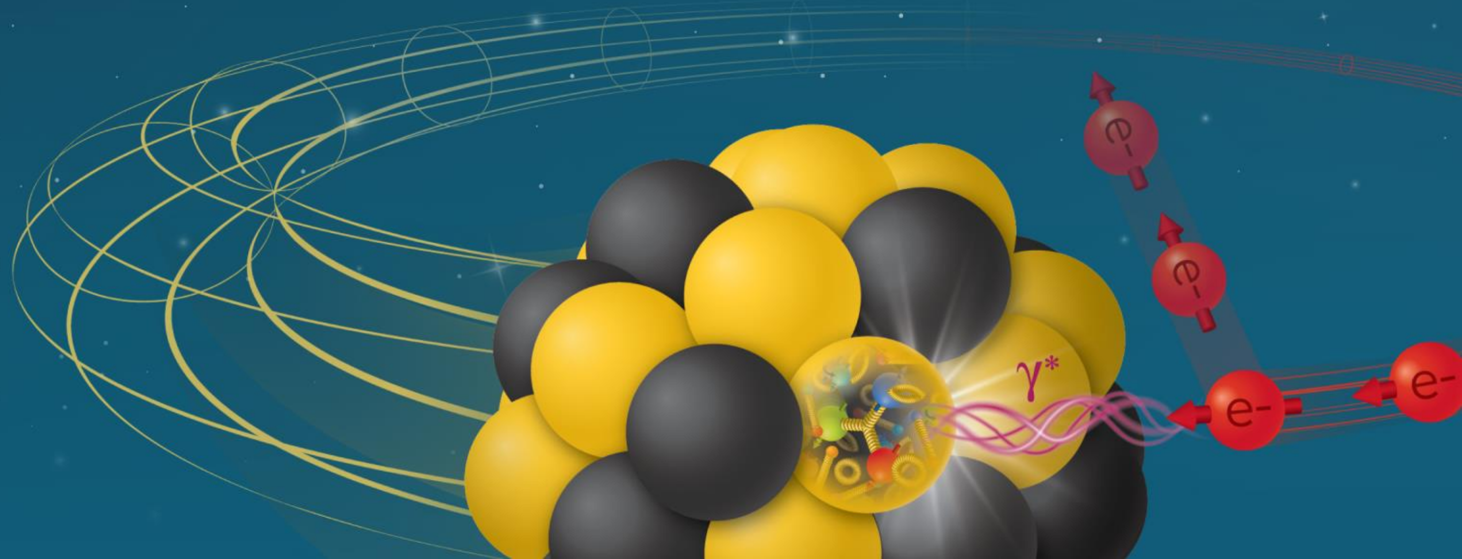
Electron-Ion Collider



The Electron-Ion Collider – *Motivation*

Evolving understanding of the Proton has shown great progress…

Still, our understanding of visible matter's mass and proton spin does not add up

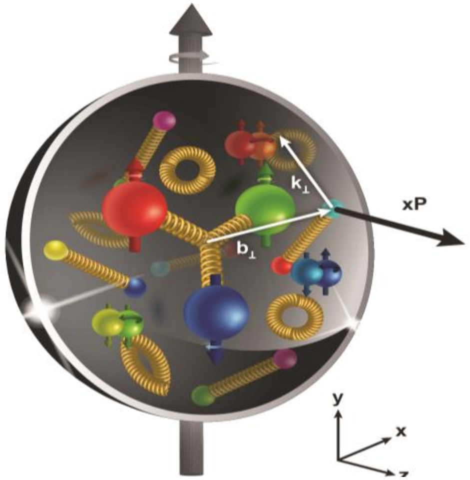
https://www.bnl.gov/eic/

The Electron-Ion Collider – *Compelling Science*

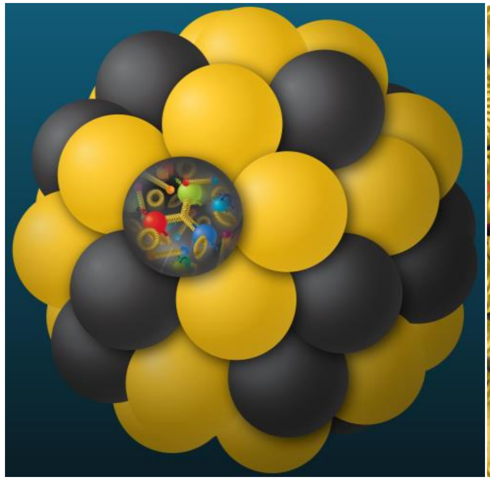
Compelling EIC Scientific Case built over decades (U.S. National Academy Report)

How do quarks, gluons, and orbital angular momentum contribute to proton spin?

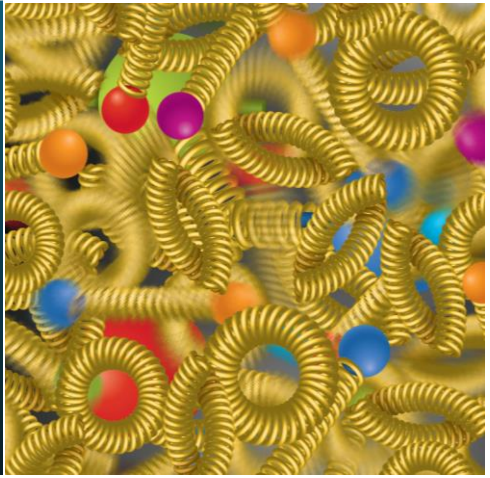
Does the mass of visible matter emerge from quark-gluon interactions?



How can we understand QCD dynamics and the relation to confinement?



How do quark-gluon interactions create nuclear binding?



Does gluon density in nuclei saturate at high energy?

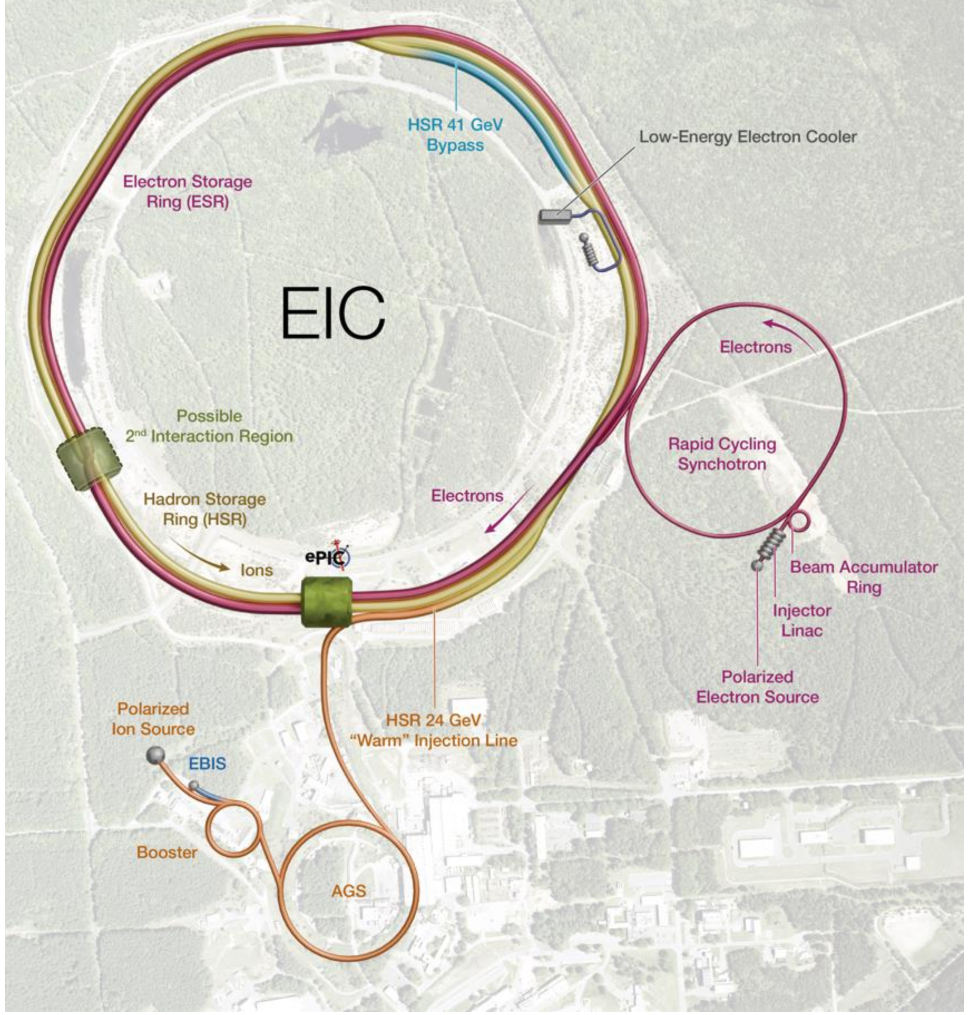
EIC will be the only operating particle collider in the U.S. and
– maybe? – the only large collider to be built in the world in the next 10 years.

The Electron Ion Collider – *Facility Performance*

High Luminosity:	$L = 10^{33} – 10^{34}\ cm^{-2}\ s^{-1}$
Highly Polarized Beams:	70%
Large Center-of-Mass Energy Range:	E_{cm} = 20 – 140 GeV
Large Ion Species Range:	Protons – Uranium
Possibility to include a Second Interaction Region (IR)	
Large Detector Acceptance, Good Background Conditions	

Versatile. Relevant. Challenging!

Aerial view of the RHIC Accelerator Complex with EIC diagram superposed



The Electron Ion Collider – *The Accelerator*

- Reuse injection system and parts of the Relativistic Heavy Ion Collider (RHIC) for Hadron Storage Ring (HSR)
- Add Electron Storage Ring (ESR) to the RHIC tunnel
- High luminosity Interaction Region (IR)
  - Crab cavities (local scheme)
- Major recent EIC scope changes:
  - New electron injector chain (Apr. 2025 Review)
    - RCS outside the RHIC tunnel
    - New Beam Accumulator Ring (BAR) concept
    - New Tunnel and "bigger" LINAC and BAR buildings
  - No Strong Hadron Cooling (SHC) needed
    - Add Low Energy Electron Cooling (LEC) (Apr. 2025 Review)
    - Stochastic Cooling (SC) under consideration

Aerial view of the RHIC Accelerator Complex with EIC diagram superposed

Facility built at Brookhaven National Laboratory

The Electron Ion Collider – *Beam Scenarios & RF*

		High Lumi		High E_{cm}	
		e-	p+	e-	p+
CoM Energy	(GeV)	105		**140**	
Luminosity	(cm^{-2} s^{-1})	**~10^{34}**		~10^{33}	
Energy	(GeV)	10	275	**18**	275
No. bunches		**1160**	1160	290	290
Bunch charge	(nC)	**28**	11	10	30
Beam Current	(A)	2.5	1	0.23	0.69
Bunch length	(rms mm)	**7**	60	7	60

High luminosity drives the choice of:

- Small beam size, combined with crossing angle, imposes use of ⇒ crab cavities
- High intensity leads to:
  - impedance issues, transient beam loading ⇒ tight RF control requirements (ESR/HSR main, crabs)
  - high power handling ⇒ high power FPC (ESR)

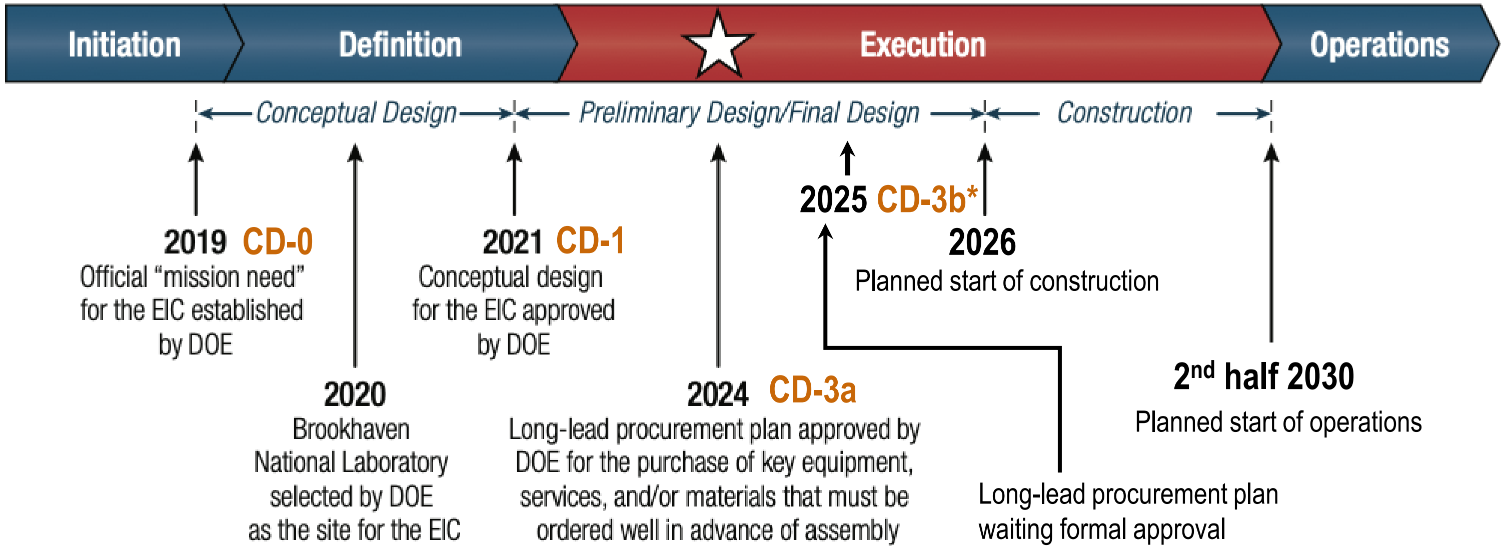
The Electron Ion Collider – *The Project*

A DOE project to be delivered by a special partnership between BNL and JLab

U.S. DEPARTMENT of ENERGY | Office of Science — Brookhaven National Laboratory — Jefferson Lab

Steady progress:

DOE Critical Decision (CD) gateways



The EIC Project is proposing a staged approach to move as soon as possible into construction and operations. While science progresses, we plan to continue construction to meet Mission Needs.

RF Systems in the EIC

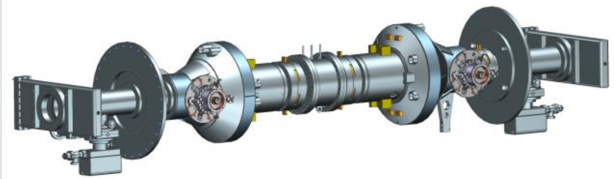
The Project is pre-CD2 and in the design phase. Many systems are still developing.

IR10

Electron Storage Ring (ESR) & Hadron Storage Ring (HSR)

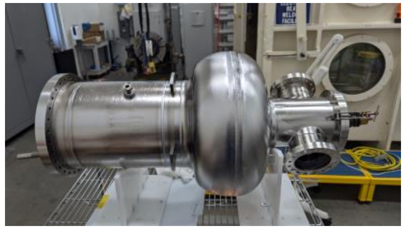
591 MHz 800 kW 2 K 1-Cell 2-Cavity Cryomodules

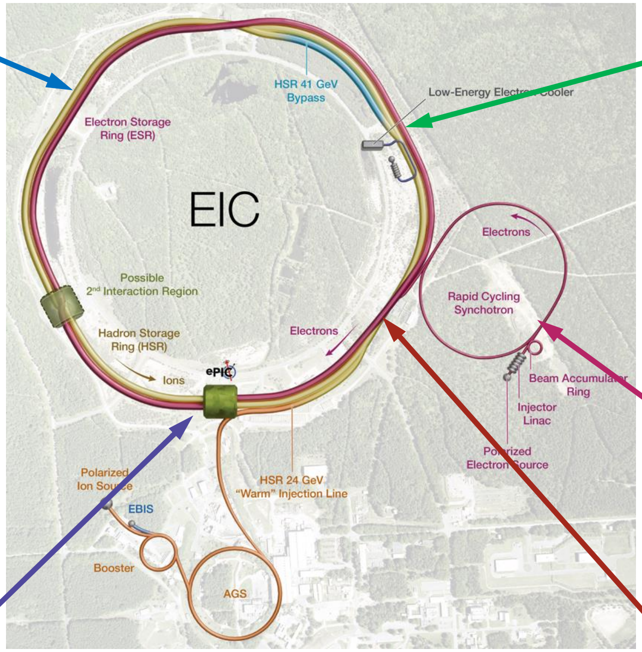
ESR = 9 CMs and HSR = 3 CMs



400 kW Amplifier

591 MHz 1-cell prototype

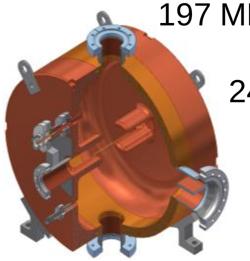




IR02

Low-Energy electron Cooler (LEC)

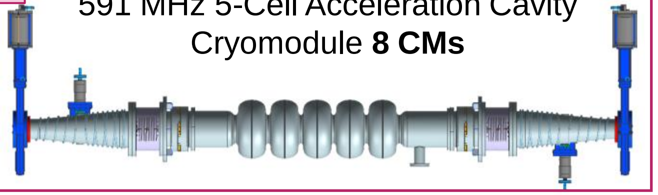
197 MHz NCRF 1-cell Acceleration Cavity
591 MHz NCRF Correction Cavity
24 MHz NCRF Compensation Cavity
591 MHz Deflecting Cavity



RCS

Rapid Cycling Synchrotron (RCS)

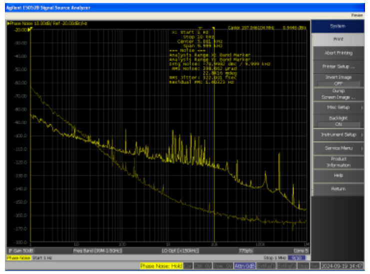
591 MHz 5-Cell Acceleration Cavity Cryomodule **8 CMs**



IR06

197 MHz & 394 MHz Crab System

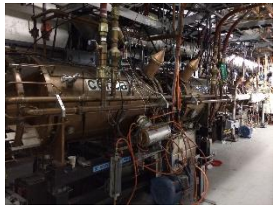
Per IP	HSR (#Cav/#CM)	ESR (#Cav/#CM)
197 MHz	8/4	–
394 MHz	4/4	2/2



EIC LLRF DAC Clock for Crab Cavities

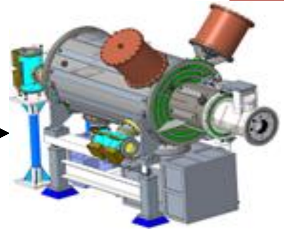
IR04

Hadron Storage Ring (HSR)

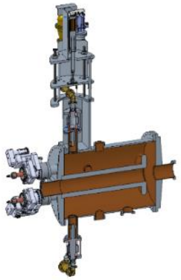


RHIC – 28 MHz acceleration cavity

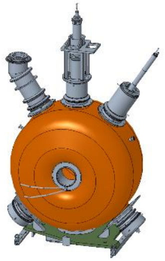
↔



HSR – 24.6 MHz Accelerating Cavity



HSR – 49.2 MHz and 98.5 MHz bunch splitter cavities



HSR – 197 MHz bunch compression cavity

Emergent scope not listed.

SRF Systems in the EIC

	System	Frequency (MHz)	Cavity Type	Installed voltage per cavity (MV)	#Cavities per cryomodule	#Cavities: 10 GeV, 7 nC (Phase I)	#Cavities: 10 GeV, 28 nC; 18 GeV, 7 nC (Phase II)	RF Power (kW / FPC)	#FPC (per cavity)
ACCELERATION	ESR	591	1-cell	3.4	2	6	→ 18	380	2
	HSR	591	1-cell	3.4	2	6	6	70	2
	RCS	591	5-cell	20	1	2	→ 8	70	1
CRAB	HSR	197	RFD	8.5	2	8 per IR	8 per IR	75	1
	HSR	394	RFD	–2.4	1		→ 4 per IR	35	1
	ESR	394	RFD	2.9	1		→ 2 per IR	35	1

- All 2 K Nb cavities. RCS SRF system will be operated at 4K in Phase I.
- ESR and HSR 591 MHz SRF systems use the same design, with small variations to the FPC antenna.
- Same 394 MHz crab design for HSR and ESR.

ESR 591 MHz SRF System

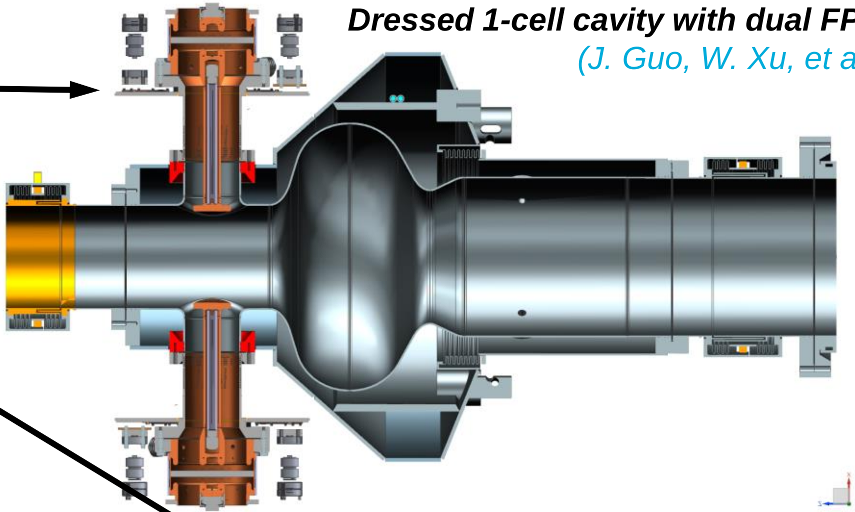
Highest power and highest voltage appear at different beam scenario (high Luminosity and high Ecm)

Assume 18 cavities, 2 FPC per cavity		10 GeV		18 GeV	
Beam current	(A)	2.5		0.23	
Synchrotron radiation power	(MW)	8.8		8.4	
HOM power per cavity	(kW)	33.5		1.0	
Total power loss	(MW)	9.37		8.4	
Power per cavity	(kW)	520		466	
Power per FPC	(kW)	344	→ **400**	307	with 20% overhead + 10% transmission loss
dE per turn	(MeV)	3.5		37	
Total voltage	(MV)	20.3		61.5	
Voltage per cavity	(MV)	1.2		3.4	
Peak E	(MV/m)	13		37	< **40**
Peak B	(mT)	24.7		70	< **80**

GOAL

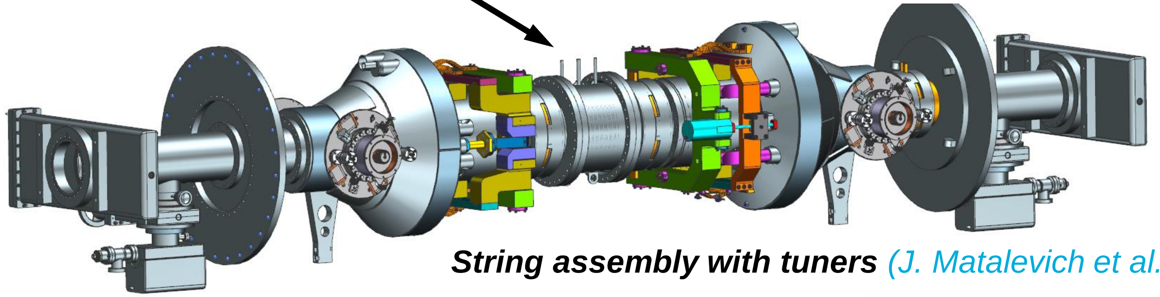
ESR 591 MHz Single-Cell 2-Cavity Cryomodule

- Each single-cell cavity powered by two 400 kW CW disk-type coaxial Al_2O_3 window fundamental power couplers
- The two cavities in a cryomodule are connected by large beam pipe hosting room-temperature SiC beam line absorber



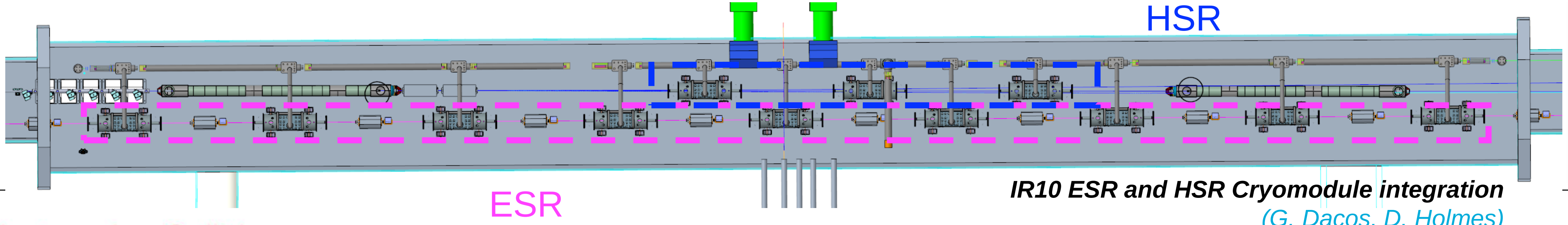
Dressed 1-cell cavity with dual FPC
(J. Guo, W. Xu, et al.)

Prototype 591 MHz single-cell cavity
(D. Savransky et al.)



String assembly with tuners *(J. Matalevich et al.)*

- Construction of First Article ESR 591 MHz CM is one of the CD-3A Long Lead Procurements



IR10 ESR and HSR Cryomodule integration
(G. Dacos, D. Holmes)

Well integrated team effort of BNL and JLab led by JLab

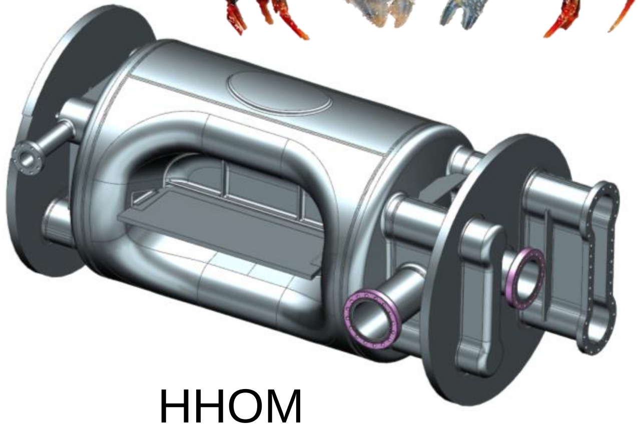
Crab Cavities

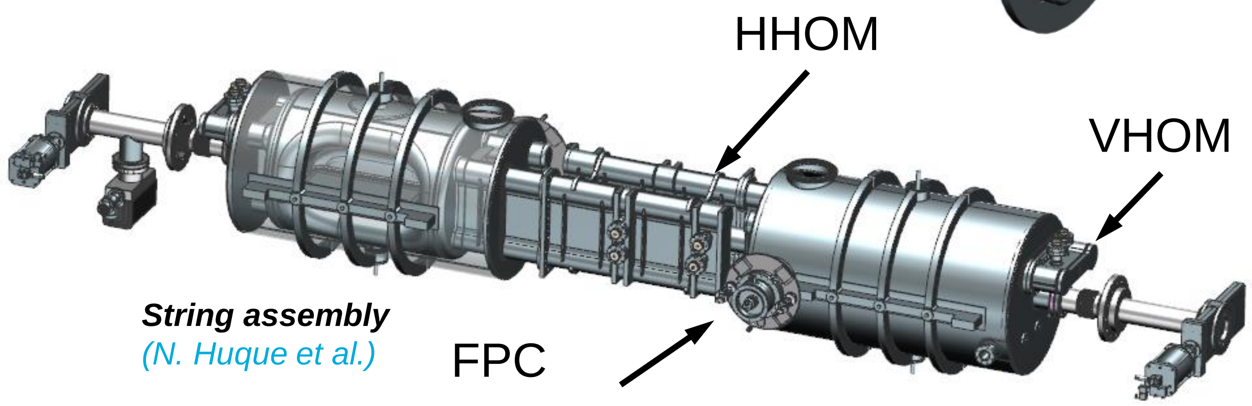
- Horizontal crabbing kick to maximize luminosity at 25 mrad crossing angle
- Limited space and high voltage required motivate the use of **compact SRF crabs** (RFD)

		HSR		ESR
Frequency	(MHz)	197	394	394
Total voltage	(MV)	33.8	-4.7	5.8
#Cavities/CM		2	1	1
#Cavities/IP		8	4	4

- Prototyping started.

Radio-Frequency Dipole (RFD) crab cavity *(S. De Silva, B. Xiao, Z. Li, et al.)*





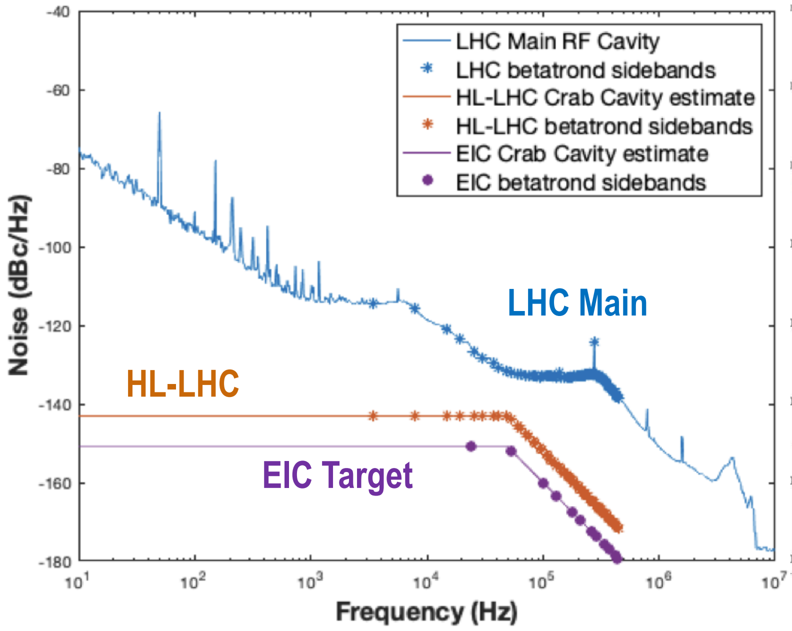
String assembly *(N. Huque et al.)*

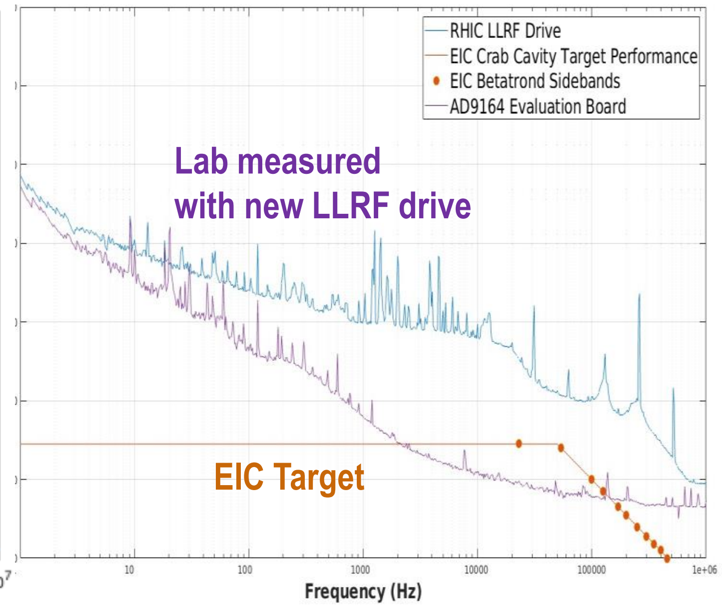
IR06 ESR and HSR Crab Cryomodule integration *(K. Hamdi)*

Crab Cavity RF Field Control

- Crab cavities have **large transverse impedance** and are at **large β locations** ⇒ fundamental crab mode can drive **strong transverse instabilities**
  - **High-gain RF feedback** required to reduce effective cavity impedance by ~2500 (68 dB)
  - **One-Turn Delay Feedback** (OTFB) required to further reduce impedance at betatron sidebands for additional x10 (20 dB)

- **Low-noise** injected into fundamental crab mode can **limit luminosity lifetime**





⇒ **Tight RF noise requirements**
- Significant progress
- On track to meet requirements

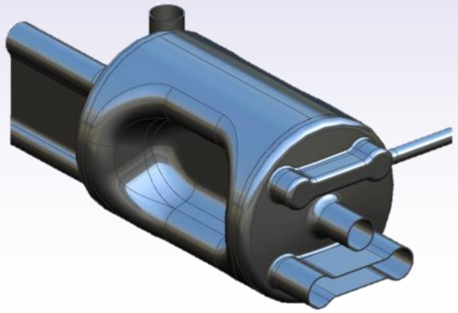
M. Blaskiewicz, T. Mastoridis, F. Severino, K. Mernick, K. Smith

Modified from Z. Conway

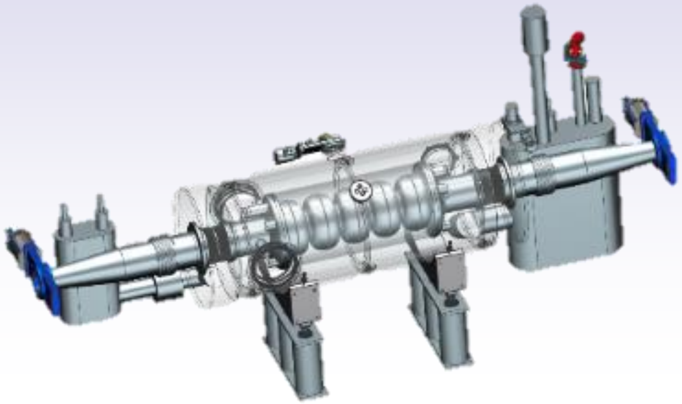
In-Kind Contributions

- The EIC Facility is envisioned as “fully international in character”.
- EIC Project In-Kind Contribution goals: **5% of the Accelerator**
- In-kind contributions from several countries are under discussion.
- For SRF Systems – draft document preparation started for:

394 MHz Crab cavity cryomodule from Canada and UK

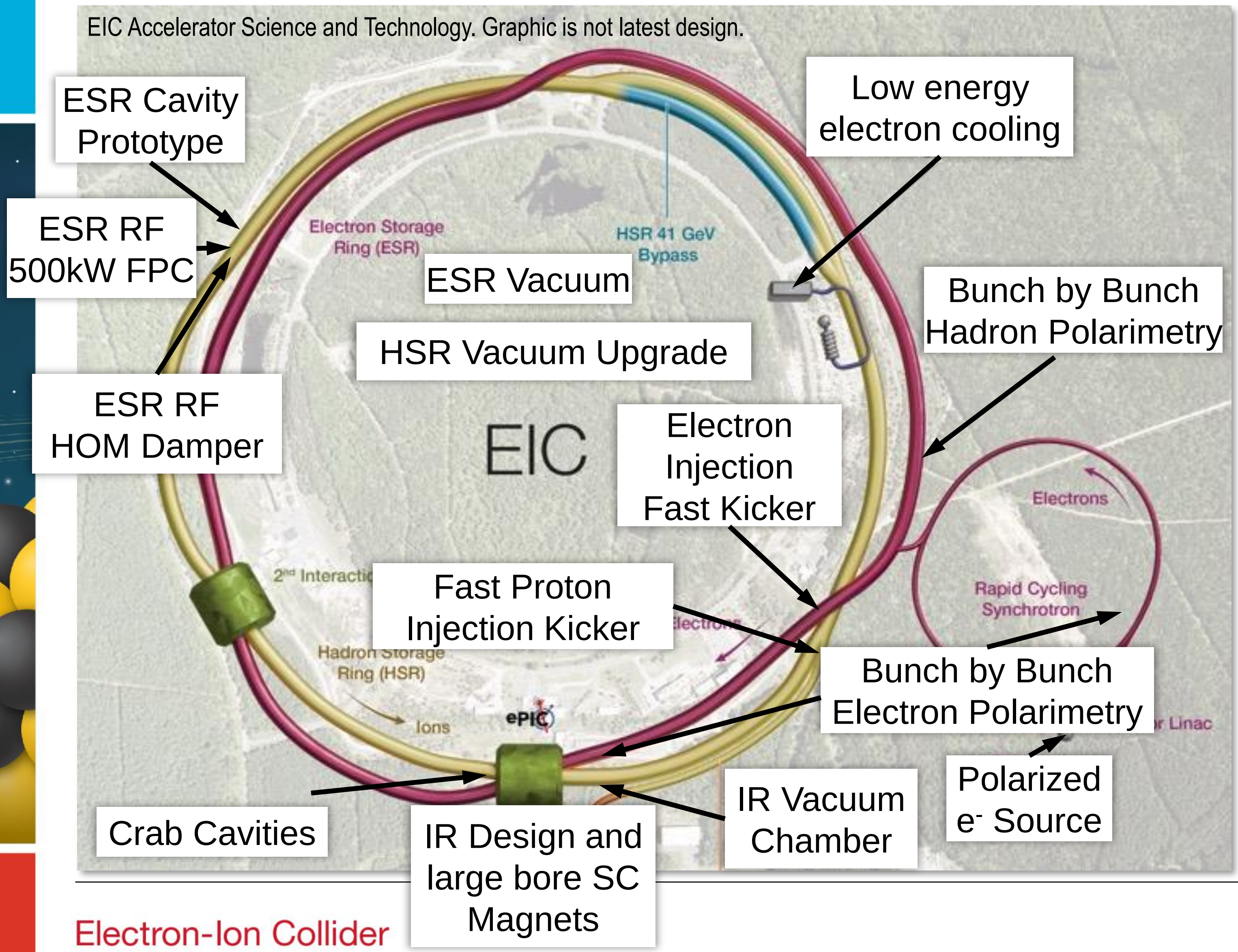


591 MHz 5-cell cavities cryomodule from France



Modified from P. Berrutti

EIC – FCC Synergies



EIC-FCC Synergies

- Operation with crossing angle
- Crab cavity design and operation
- Crab cavity low level RF control, beam loading, noise suppression …
- Beam-beam simulations and beam dynamics
- Electron cloud mitigation
- Ion sources for d to Pb
- Polarized light Ion sources, p,d, He-3
- Machine – Detector protection, collimation, beam-dump…
- Beam Instrumentation and Controls
- Beam screens and coatings
- Large bore SC magnets,
- SRF cavities

Modified from E. C. Aschenauer

Overview

- The EIC is an exciting machine that relies on cutting-edge technology.

- Some long-lead procurements have already started.

- The EIC and FCC share multiple synergies – also in RF Systems, where they also share common challenges (SRF, RF controls, crab cavities)

- Reaching design performance will take time … and many *großer Schwarzer!*

Thanks to the FCC Week 2025 Organizing Committee for the invitation and

thanks to the EIC Team for all the effort to advance the EIC Project

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