LOW LEVEL 2025 RADIO FREQUENCY Workshop

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Overview of EIC RF Systems

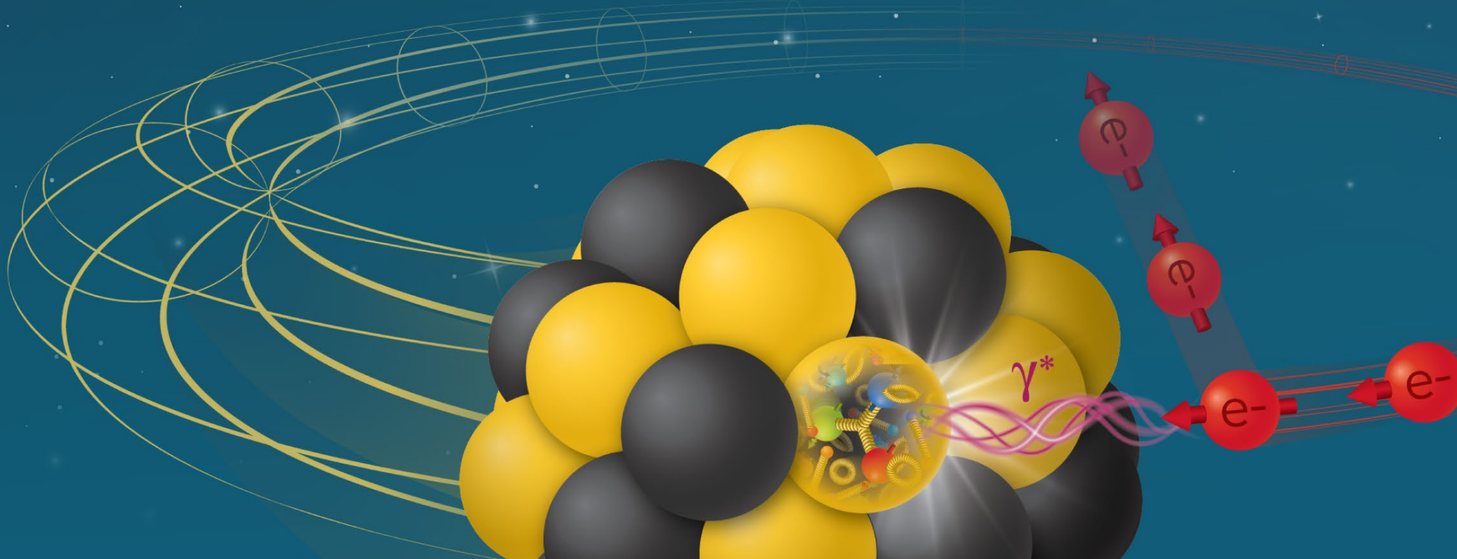
Geetha Narayan

For EIC RF Controls Team

October 13, 2025

This work was supported by the EIC Project and the U.S. Department of Energy, Contract DE-SC0012704

Electron-Ion Collider

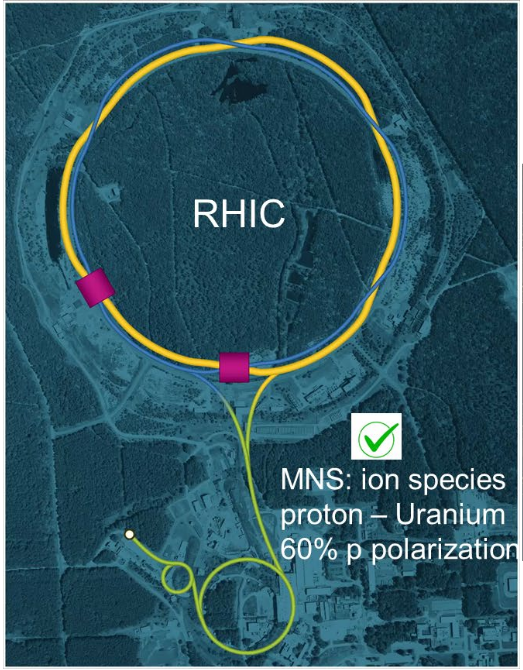


Introduction

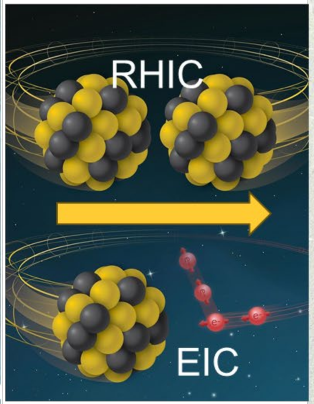
EIC is a unique, high-energy, high-luminosity, polarized beam collider that will be one of the most challenging and exciting accelerator complexes ever built - **only new collider in the next decades.**

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

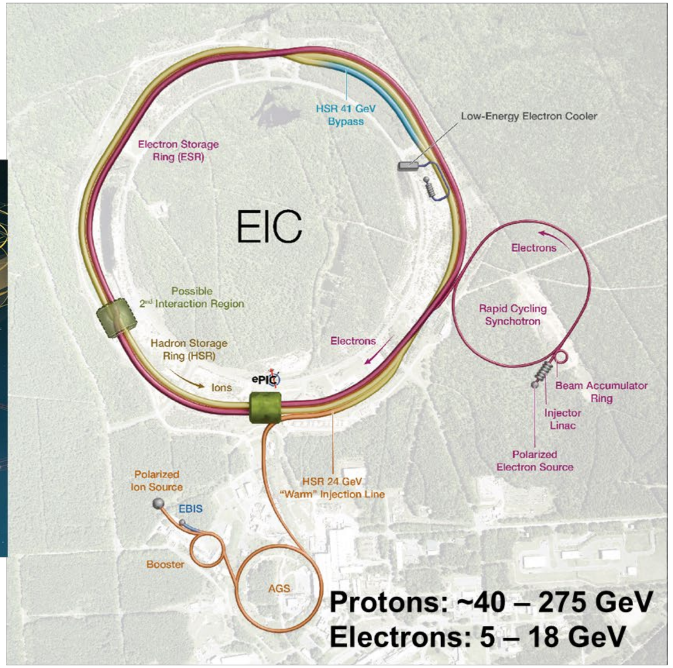
U.S. DEPARTMENT of ENERGY | Office of Science — Brookhaven National Laboratory — Jefferson Lab



From RHIC to EIC*



Facility built at Brookhaven National Laboratory



* Not to scale

"The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."
(National Academy of Sciences, 2018)

EIC Parameters

Design Goals:

- High Luminosity:

  $L = 10^{33} – 10^{34} cm^{-2} sec^{-1}$
- **Highly Polarized Beams:**

  70% (electrons, protons, light ions)
- Large Center of Mass Energy Range:

  E_{cm} = 20 – 140 GeV
- **Large Ion Species Range:**

  Protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Possibility to implement a Second Interaction Region (IR)

Key Accelerator Concepts:

- Ribbon-like (flat) hadron beam

  (11:1 transverse emittance & beam size ratio)
- **Large crossing angle** (25 mrad)
- Beam-beam limits for both beams

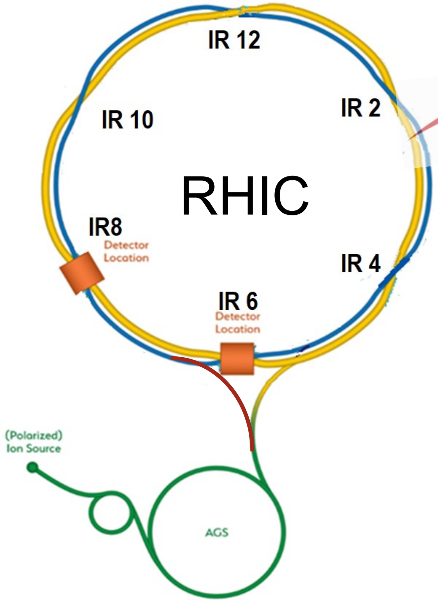
  (0.1 e/ 0.01 p)
- Spin preservation from source to collisions (protons and electrons)
- **Very high bunch intensities and circulating beam currents** (1 A (p), 2.5 A (e))
- High quality beams with preserved emittance:

  Low energy cooling (p)

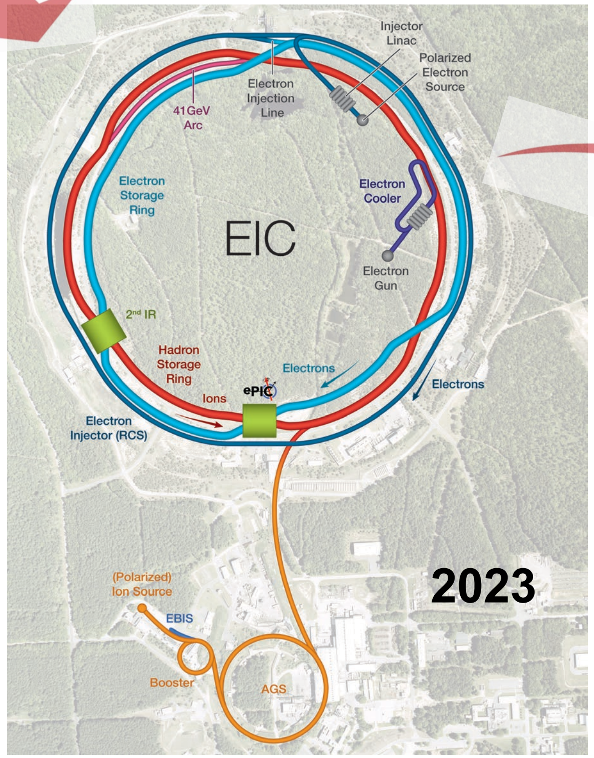
  \+ Stochastic cooling (ions)
- Upgrade path: high-energy hadron cooling at collisions

EIC Design Evolution

Hadron Storage Ring comprised of “Blue” and “Yellow” RHIC arcs



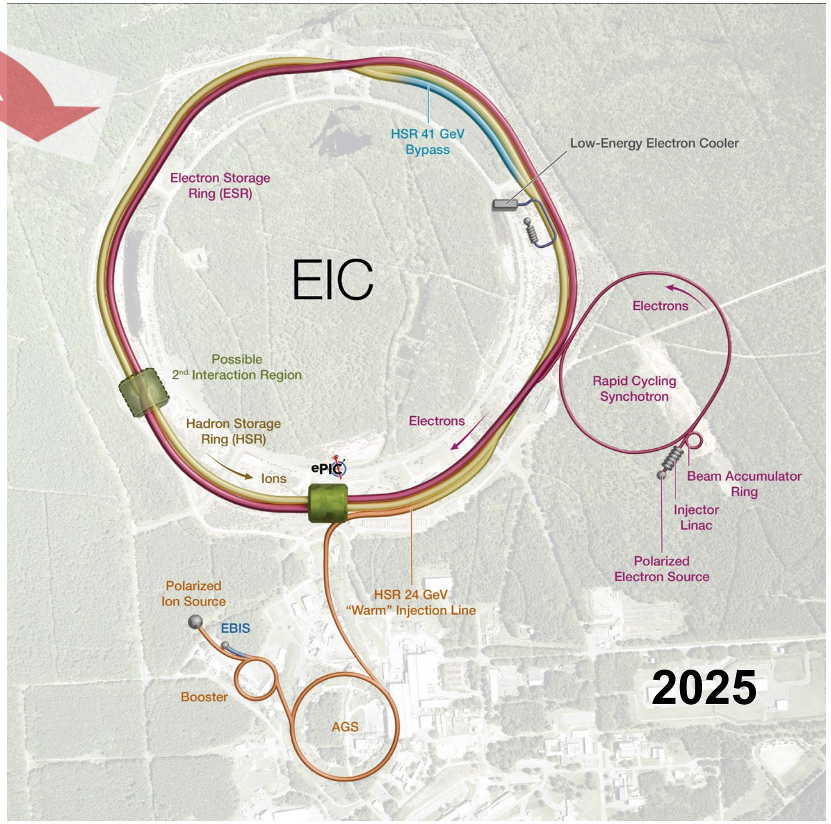
Electron complex to be installed in existing RHIC tunnel



▪ LLRF Workshop 2022
Electron-Ion Collider RF Systems, K. Mernick

Major EIC scope changes since 2023:

- New electron injector chain
  - RCS outside the RHIC tunnel
  - Beam Accumulator Ring (BAR)
- No strong Hadron Cooling (SHC)
  - Add Low Energy Electron Cooling (LEC)
  - Stochastic cooling (SC) under consideration



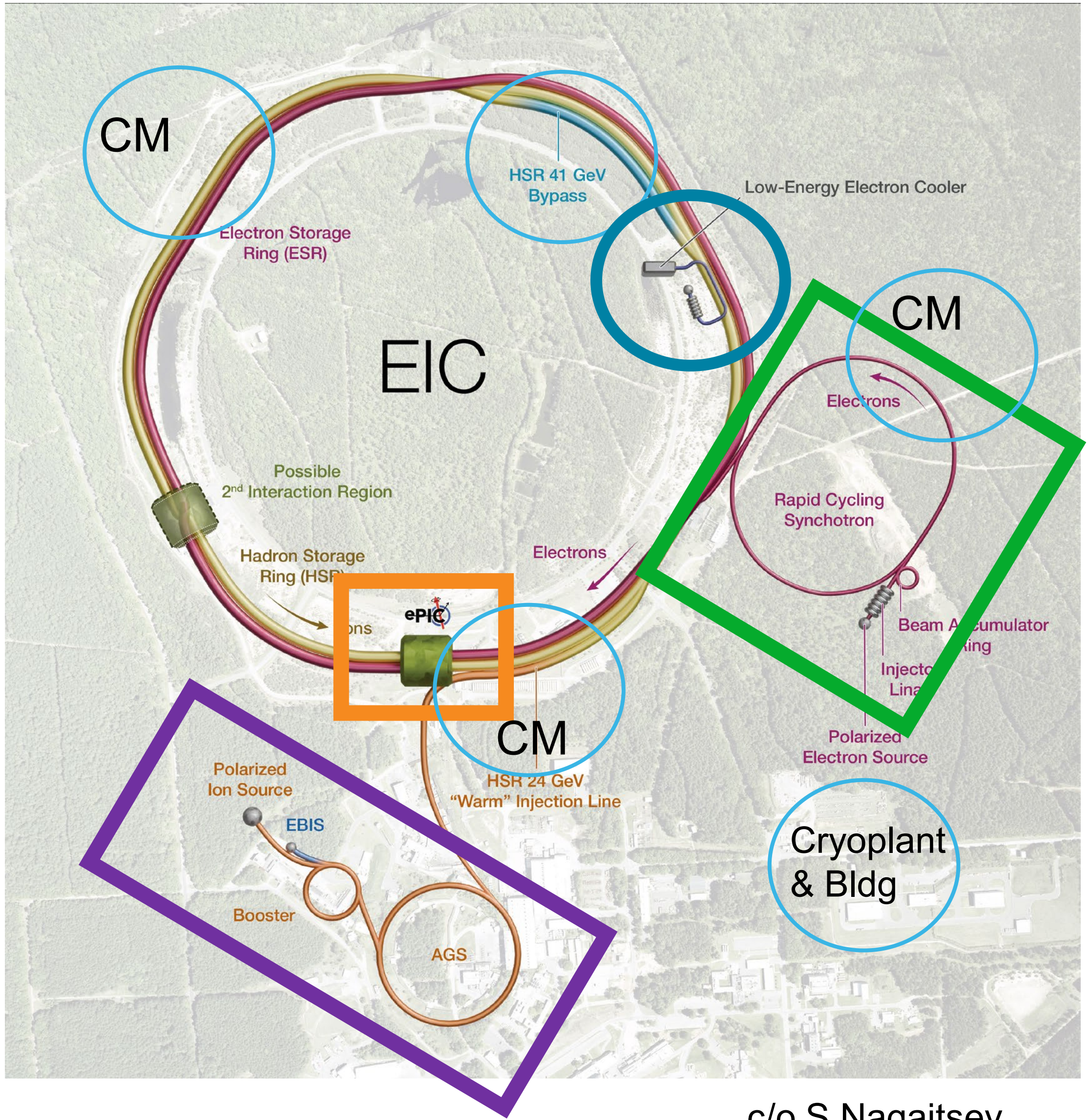
EIC Facility

Existing Accelerator Scope

- ✓ Polarized ion/proton sources
- ✓ Ion injection and acceleration systems (Linac, Booster, AGS)

New Scope

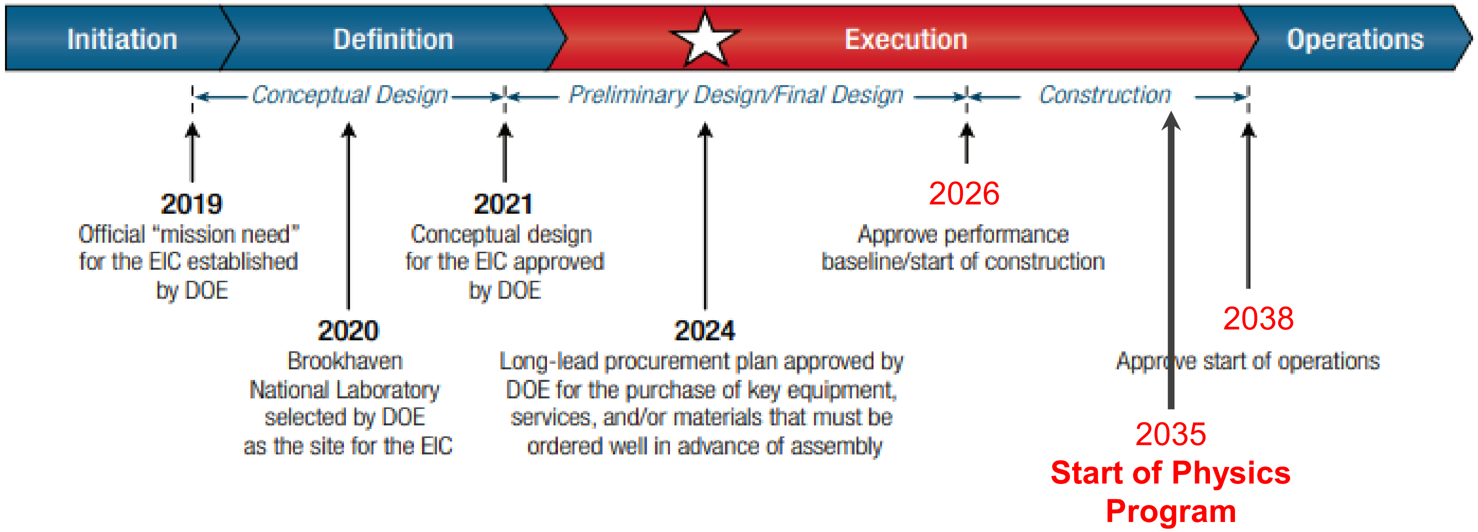
- UPGRADE Hadron Storage Ring (40, 100 – 275 GeV)
- NEW Electron Pre-Injector (750 MeV Linac)
- NEW Electron Rapid Cycling Synchrotron (0.75 GeV – Top Energy)
- NEW Electron Storage Ring (5 GeV – 18 GeV)
- NEW Interaction Region, Provision for a 2nd
- NEW Hadron Injection Cooling System
- NEW General Purpose Collider Detector



c/o S.Nagaitsev

Project Milestones

- ❖ **The EIC facility is planning to start construction in 2026 following the conclusion of RHIC operations at the end of 2025**



c/o L. Lari Sep 2025

IR06 ESR and HSR Crab Cryomodule layout

c/o K. Hamdi

Subproject Strategy

❖ **The EIC Project is proposing a staged approach to proceed as soon as possible into construction and operations.**

Initial Science Program Scope	**polarized e-** 7nC / bunch 5 – 10 GeV **polarized p** 100 – 250 GeV **nuclear beams** 100 GeV/u	**Accelerator Storage Rings (ASR)**	• **Hadron Storage Ring (HSR) modifications up to 250 GeV for protons** • **Electron Storage Ring (ESR) up to 10 GeV** • **Infrastructures to accommodate EIC needed services.**
		Detector (DET)	• **ePIC Detector** **- Including Detector Solenoid Magnet and return Flux & installation.** **- Auxiliary detector systems are included.**
		Interaction Region (IR)	• **Interaction Region including the SC magnets** • **197 MHz crab cavities** • **machine protection systems.**
		Electron Injectors (EIN)	• **Electron Injectors incl. the LINAC** • **Beam Accumulator Ring (BAR)** • **Rapid Cycling Synchrotron (RCS) up to 10 GeV and related infrastructure.**
Full Scope	**polarized e-** 28nC / bunch 18 GeV **polarized p** 275 GeV **nuclear beams** 110 GeV/u	**Energy and Luminosity Ramp-up (ELR)**	**Accelerator scope required to increase Energy and Luminosity incl. up to 18GeV e^- (RCS SRF & Cryo)** • **394 MHz crab cavities** • **41 GeV by-pass** • **Low Energy e^- Cooler** • **ESR and HSR RF power supplies**

Beam Scenarios & RF

		High Lumi		High Ecm	
		e-	p+	e-	p+
CoM Energy	(GeV)	105		140	
Luminosity	($cm^{-2}\,s^{-1}$)	$\sim 10^{34}$		$\sim 10^{33}$	
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)	60	7	60	7

c/o S. Verdu' Andres

High luminosity drives the choice of:

- Small beam size, combined with crossing angle ⇒ crab cavities are required

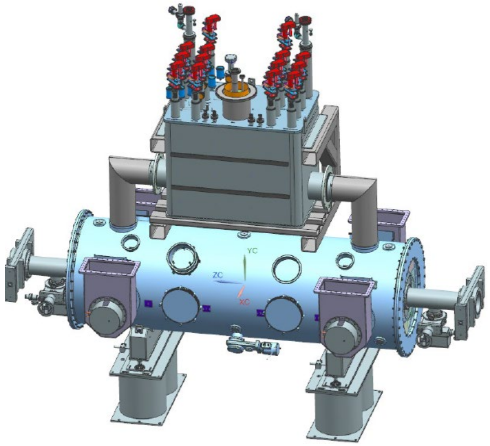
High intensity leads to:

- impedance issues, transient beam loading ⇒ tight RF control requirements (ESR main, crabs)
- high power handling ⇒ high power FPC (ESR)

Challenges to RF Systems

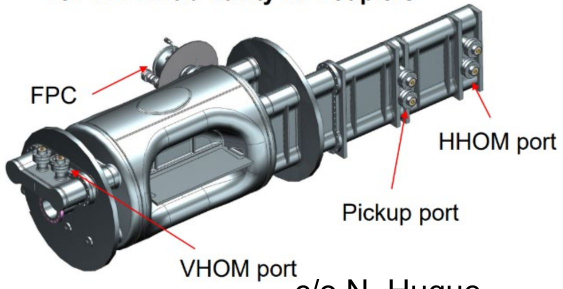
EIC System	Notable Challenges
RCS	1. Accurate control of SRF cavities in a dynamically ramping accelerator ring 2. Achieve precise swap-out injection into the ESR
ESR + HSR Store Systems	1. Demanding RF feedback requirements to reduce cavity impedance 2. Very strong transient beam loading generated by beam abort gap
ESR Store	1. Reverse Phase Mode (as used in KEKB) is planned to mitigate transient beam loading
HSR NCRF	1. Bunch-split which maintains longitudinal emittance 2. Requires appropriate transient beam loading compensation
HSR Energy Ramp	High current, MHz level tuning, and precise control at every injection
Crabs	1. Fundamental crab mode can drive strong transverse instabilities 2. High-gain RF feedback required to reduce effective cavity impedance by ~2500 (68 dB) 3. One-Turn Delay Feedback (OTFB) required to further reduce impedance at betatron side bands for additional factor of 10 (20 dB) 4. Low noise injected by fundamental crab mode can limit luminosity lifetime leading to tight RF noise requirements 5. Accurate control of crabbing vs un-crabbing fields from multiple cavities 6. Requires cavity to cavity amplitude and phase control with cavities at different location 7. Long term drift compensation and beam-based feedback are essential

591 MHz 1-cell Cryomodule



c/o J. Matalevich

197 MHz Crab Cavity w/ Couplers

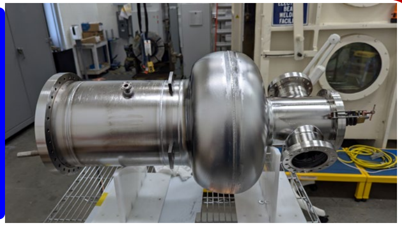


c/o N. Huque

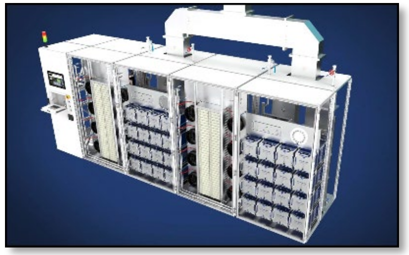
c/o M. Blaskiewicz EIC Tech Design Review 2023
c/o T. Mastoridis BNL-222748-2022-TECH

EIC RF Systems Distribution

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

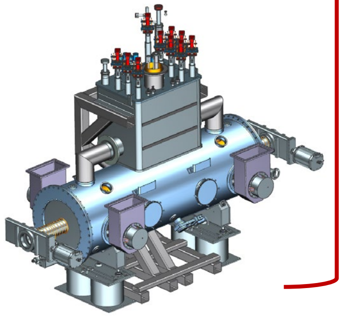


400 kW Solid State Amplifier



Electron Storage Ring & Hadron Storage Ring – IR10

591 MHz 800 kW 2 K
1-Cell Cavity Cryomodules
ESR = 9 CMs, 18 Cav
HSR = 3 CMs, 6 Cav

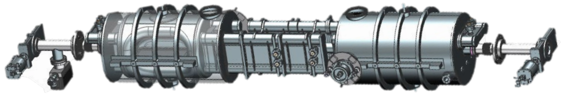


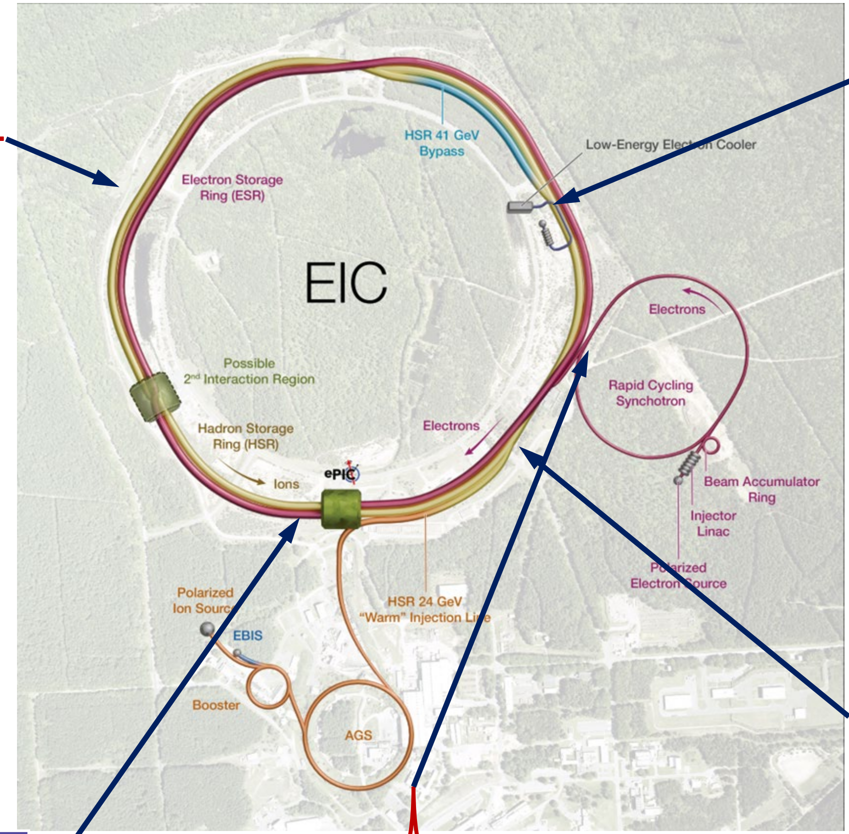
New LLRF clocking scheme reduces phase noise for 197 MHz RF

Frequency Source	Integrated Jitter, 1 Hz – 10 kHz BW
RHIC 197 MHz Low Level Source	318.557 fs
Newly Developed 197 MHz Low Level Source	49.665 fs

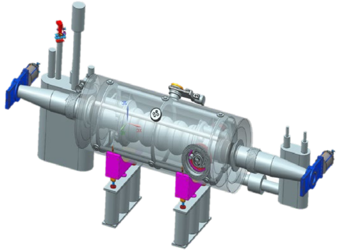
Crab Cavities (per IR)	HSR (Cavities/CMs)	ESR (Cavities/CMs)
197 MHz	8/4	–
394 MHz	4/4	2/2

IR06



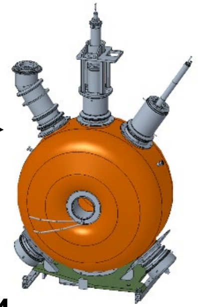


RCS
591 MHz 5-Cell Cavity Cryomodules

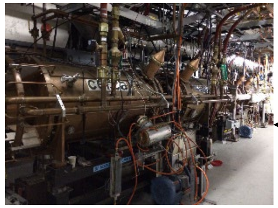


c/o: Zack Conway

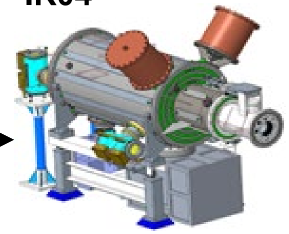
Low-Energy Cooler- IR02
197 QWR NCRF,
591 NCRF,
24 MHz NCRF,
591 MHz Deflecting Cavity



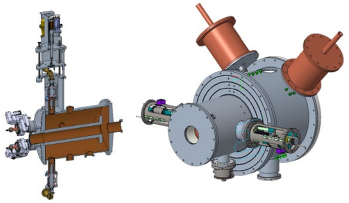
HSR NCRF – IR04



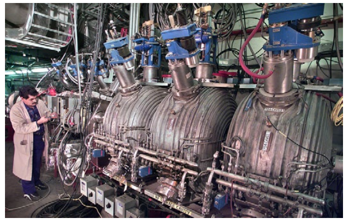
RHIC – 28 MHz acceleration cavity (Modify and Reuse)



24.6 MHz Capture & Accel Cavity

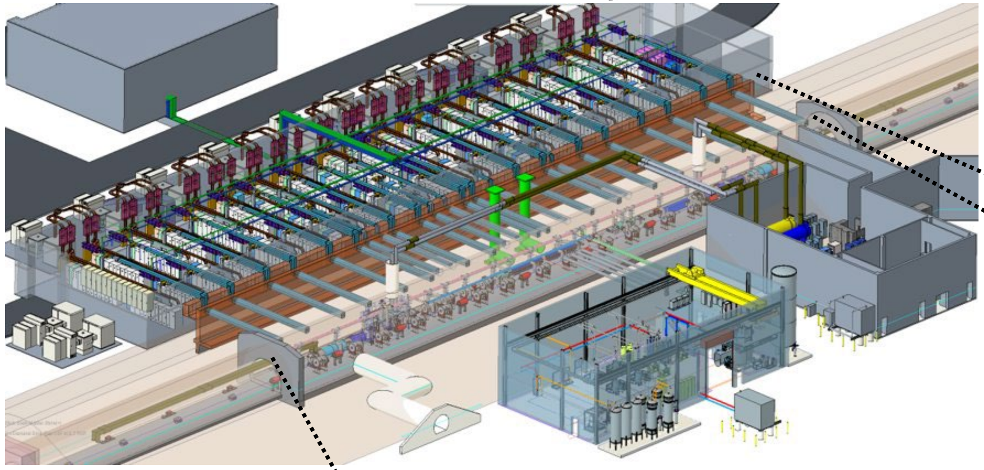


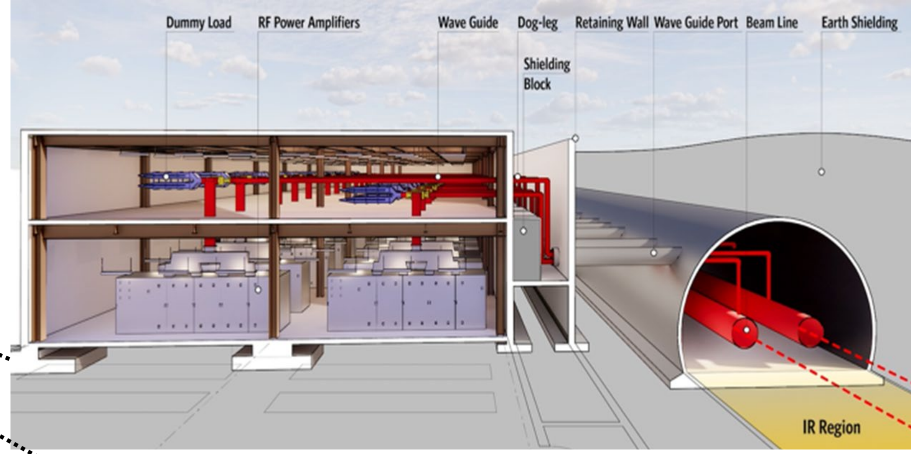
Bunch Splitting (New)
49.2 MHz NCRF
98.5 MHz NCRF

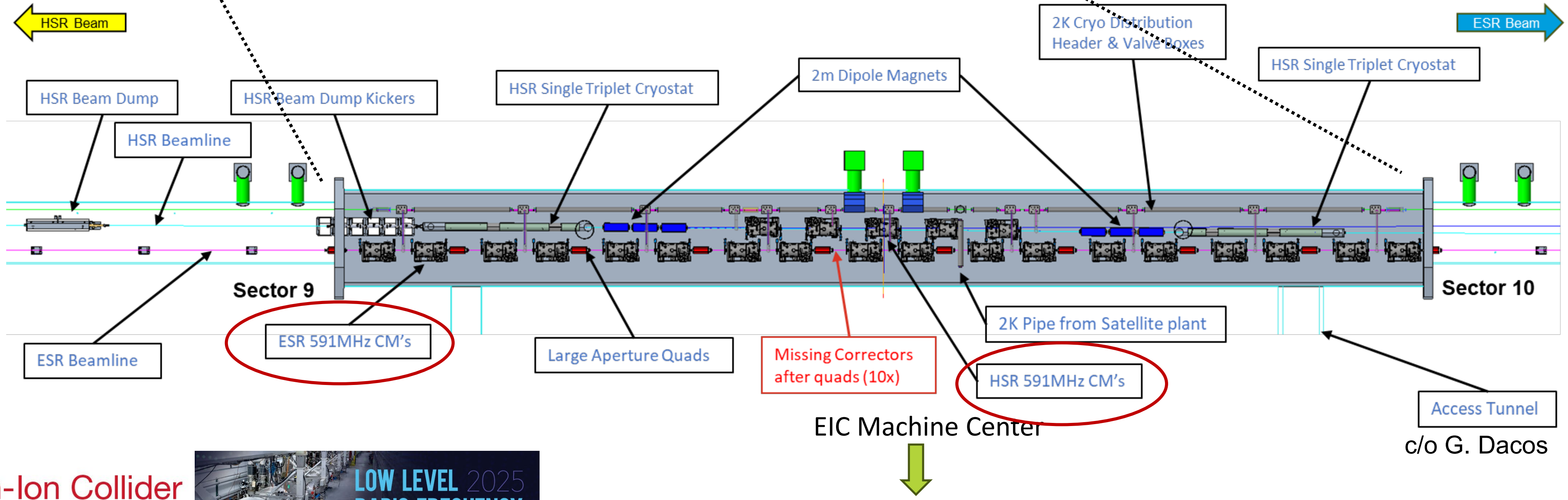


RHIC – 197 MHz NCRF capture & acceleration cavity (Reuse)

IR-10 Layout with RF Support Building







c/o G. Dacos

RF Systems and Quantities

Sub-Project	RF System	Sub System Functions	Freq [MHz]	SRF / NCRF	Type	# Cavities	# CMs	PA Type	# FPCs per Cavity	Power per FPC[KW]	Voltage per Cavity (MV)	Location
ASR	Electron Storage Ring (ESR)	Accel / Store	591	SRF	1-cell	6	3	SSA	2	400	4.0	IR-10
	Hadron Storage Ring (HSR)	Capture / Accel	24.6	NCRF	QWR	4	n/a	Tetrode	1	120	0.2	IR-4
		Bunch Split 1	49.2	NCRF	QWR	3	n/a	SSA	1	120	0.2	IR-4
		Bunch Split 2	98.5	NCRF	QWR	4	n/a	SSA	1	120	0.2	IR-4
		Store 1	197	NCRF	Reentrant	8	n/a	Tetrode	1	65	1.0	IR-4
		Store 2	591	SRF	1-cell	6	3	SSA	2	35	4.0	IR-10
IR	Crab Cavities (Crab)	Hadron	197	SRF	RFD	8	4	SSA	1	75	8.5	IR-6
EIN	Rapid Cycling Synchrotron (RCS)	Accel 1 / Store	591	SRF	5-cell	2	2	SSA	1	70	20.0	IR-4
	Beam Accumulator Ring (BAR)	Fundamental	59.1	NCRF	QWR	1	n/a	SSA	1	30	0.1	IR-4
		Harmonic	tbd	NCRF	QWR	1	n/a	SSA	1	5	tbd	IR-4
	750MeV LINACfor RCS	Buncher 1	197	NCRF	Reentrant	1	n/a	tbd	1	tbd	0.4	IR-4
		Capture 1	1300	NCRF	taper	1	n/a	tbd	1	tbd	2.8	IR-4
		Capture 2	1300	NCRF	AWA LINAC	1	n/a	tbd	1	tbd	10.3	IR-4
		Accel 2	2856	NCRF	TW	14	n/a	tbd	1	tbd	60.0	IR-4
ELR	Electron Storage Ring (ESR)	Accel / Store	591	SRF	1-cell	12	6	SSA	2	400	4.0	IR-10
	Rapid Cycling Synchrotron (RCS)	Accel 1 / Store	591	SRF	5-cell	6	6	SSA	1	70	20.0	IR-4
	Crab Cavities (Crab)	Hadron	394	SRF	RFD	4	4	SSA	1	30	2.4	IR-6
		Electron	394	SRF	RFD	2	2	SSA	1	30	2.9	IR-6
	Low Energy Cooler (LEC) for HSR	Energy Compensation	24.6	NCRF	QWR	1	n/a	SSA	1	tbd	0.0	IR-2
		Accel	197	NCRF	Reentrant	16	n/a	SSA	2	80	0.9	IR-2
		Third Harmonic	591	NCRF	Reentrant	4	n/a	SSA	1	35	0.4	IR-2
		Deflecting	591	NCRF	Deflecting	1	n/a	SSA	1	3	0.1	IR-2

Frequency range:
24.6 MHz to 2.8 GHz

Total # cavities: 106

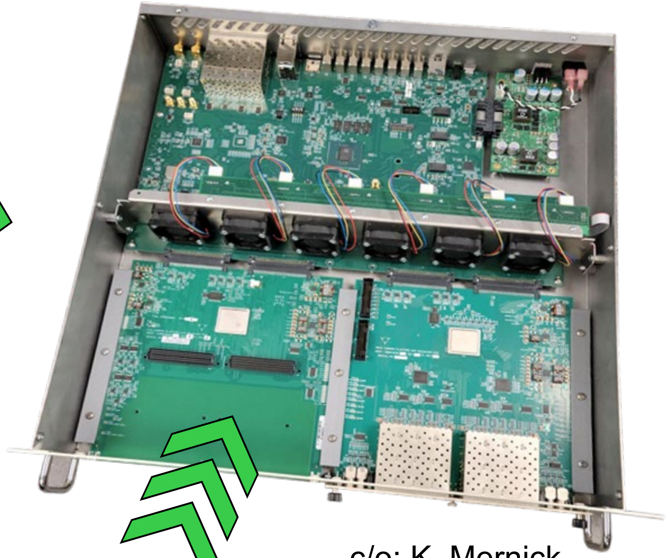
* The Project is pre-CD2
Many systems are still developing.

EIC RF Systems – RF Controls

- EIC RF Controls development is an outgrowth of decades of **RHIC LLRF** and **CEBAF LLRF** development.
  - PIP-II → Linac LLRF System
  - LCLS-II → Linac LLRF System
  - SNS → Accumulator Ring RF System
- RF Controls for the EIC
  - Synchronization of many accelerators.
  - LLRF, machine protection, monitoring, interfaces (cryogenics, vacuum, etc).
- Leveraging both teams' excellence for EIC

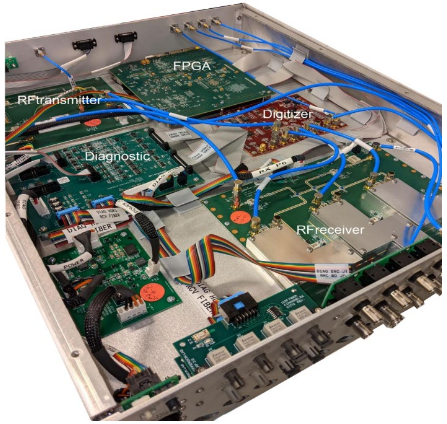
RHIC LLRF Platform

EIC Common Platform

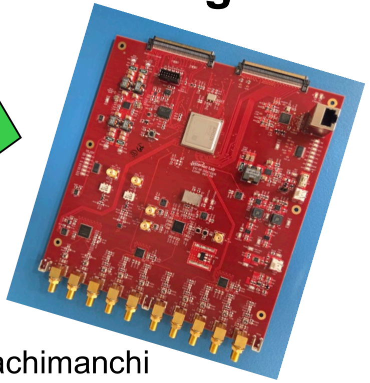


c/o: K. Mernick

JLAB LLRF Field Controller



EIC RF Digitizer

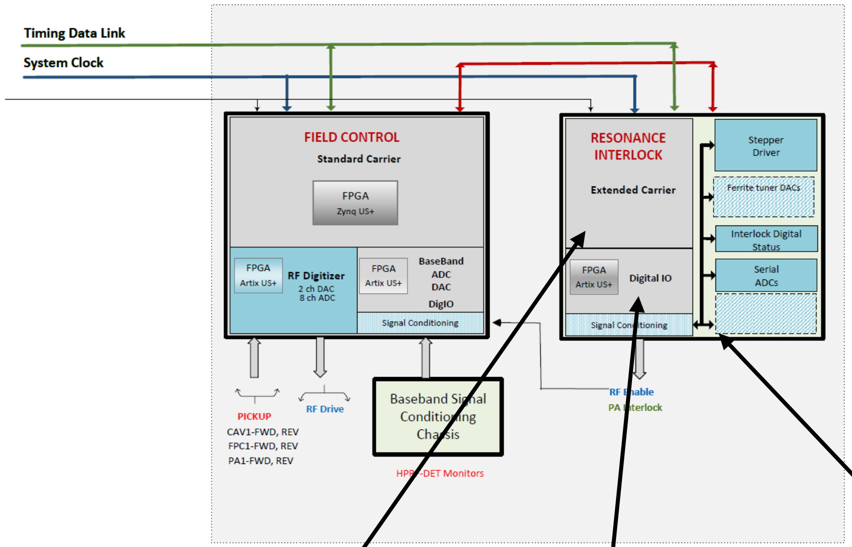


c/o: R. Bachimanchi

EIC LLRF – Modular and Scalable

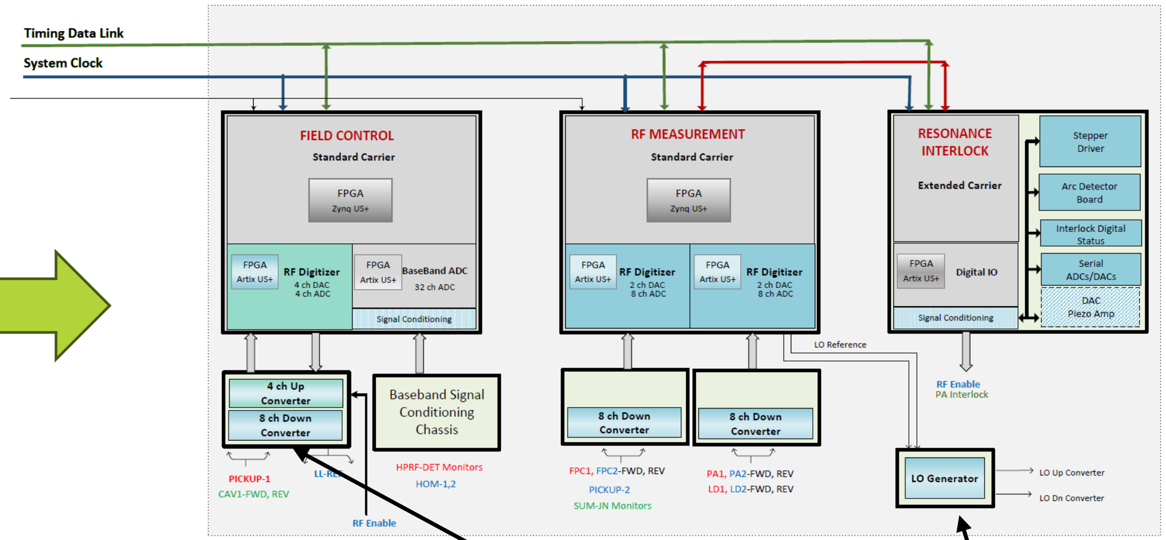
HSR 24.6 MHz
HSR 49.2 MHz
HSR 98.5 MHz

- NCRF cavities
- 1 FPC per cavity
- Direct Sampling – no up/down conversion needed
- May need controls for Ferrite Tuner

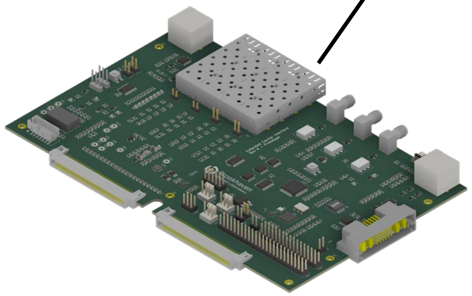


ESR 591 MHz
HSR 591 MHz
LEC 197 MHz

- SRF cryomodules - ESR & HSR
- NCRF - LEC
- 2 FPCs per cavity
- Up/down conversion required

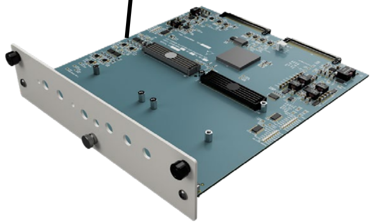


Extended Carrier



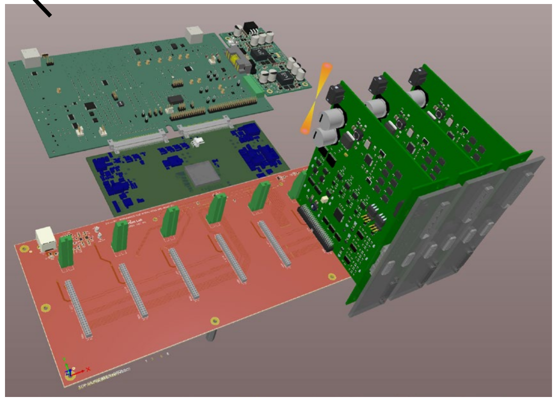
c/o S. Tajne

Digital I/O



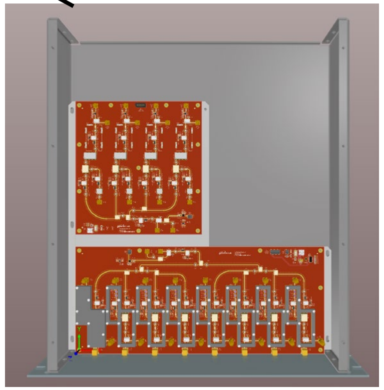
c/o K. Hernandez

Resonance and Interlock

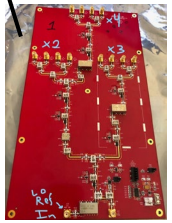


c/o J. Latshaw

4 Ch Upconverter
8 Ch Downconverter



LO Generator



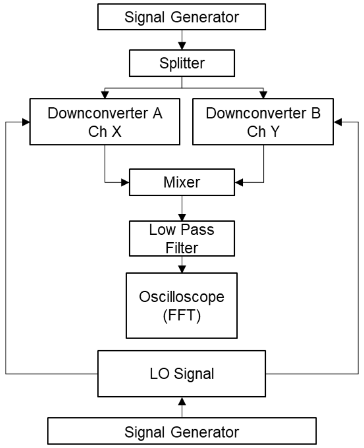
c/o J. Settle

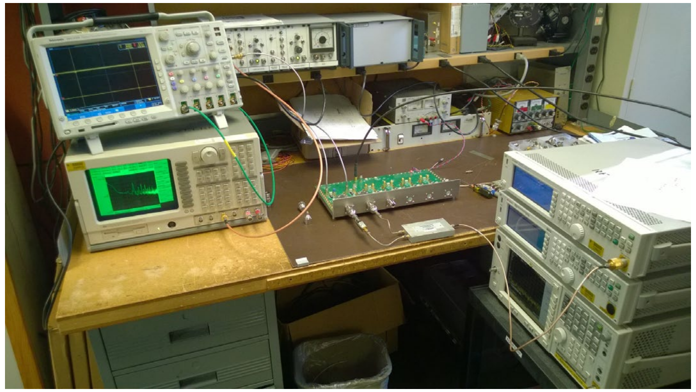
RF Controls Tests in Progress

- Analog Cavity Emulator and FPGA Cavity Simulator (BNL)
  – enabling early development of LLRF

c/o A. Singh, S. Mai

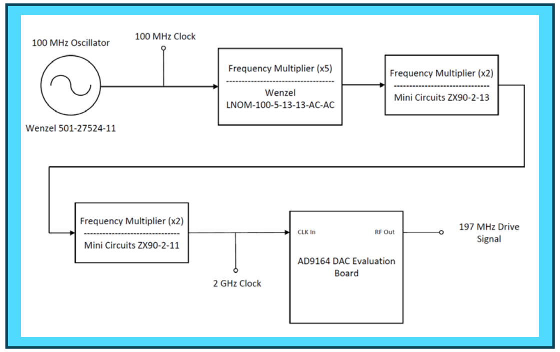
- Residual Noise Test on Analog Down Converters (JLAB)



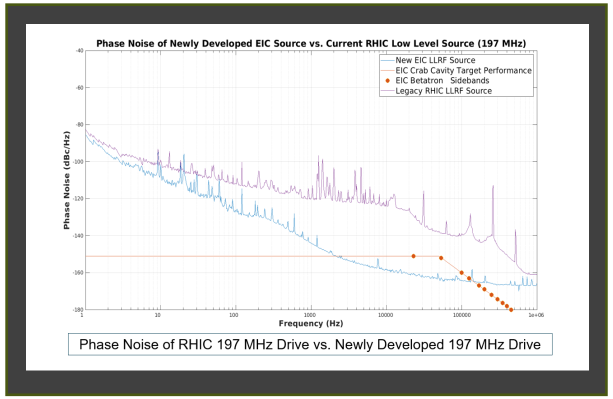


c/o J. Settle

- Evaluating AD9164 DAC @ 197MHz for Crab Cavity (BNL) requirements with an ultra-low phase noise Wenzel source



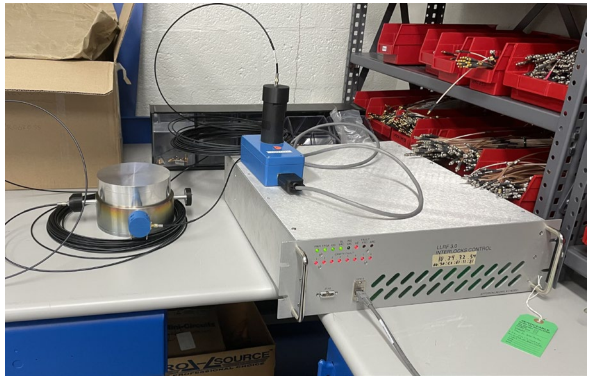
c/o F. Severino



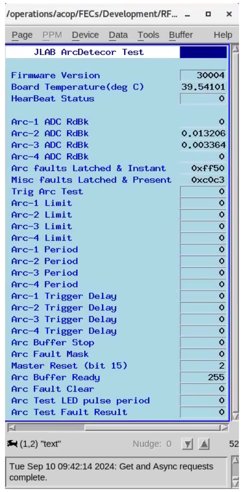
Phase Noise of RHIC 197 MHz Drive vs. Newly Developed 197 MHz Drive

c/o M. McCooey

- JLAB Arc Detector – 591MHz FPC Mockup Test (BNL & JLAB) using RHIC ADO to EPICS bridge for data monitoring and logging



c/o K. Fahey



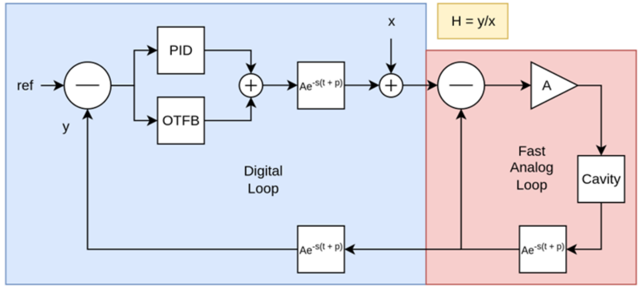
A view from RHIC APEX Studies

Goal:
Measure and compensate for transient beam loading in RHIC yellow 28MHz accelerating cavity

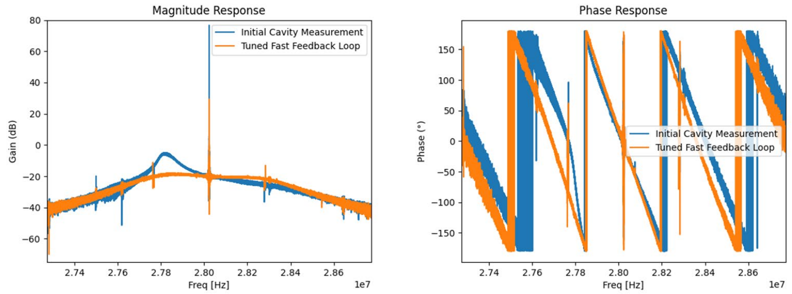
Designs under Test:
One-Turn Delay Feedback
Feed Forward compensation
Digital Network Analyzer (DNA)
Bunch-by-bunch ADC
(amplitude and phase measurement)

Date: 9/17/2025

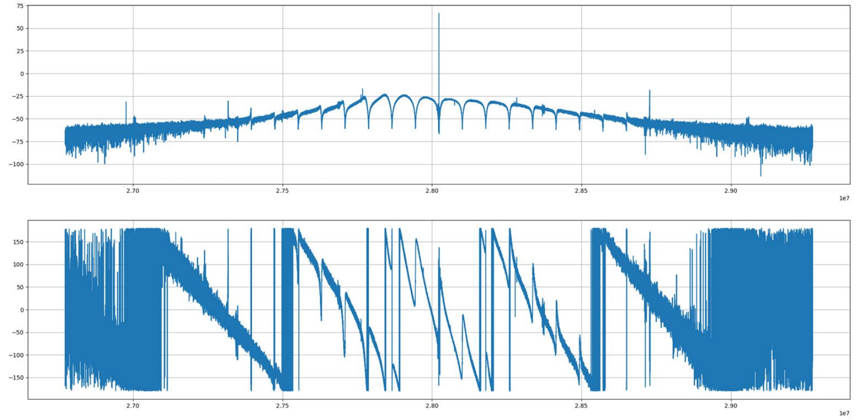
- To tune the loop, DNA is used in an iterative process, to take measurements
- Model parameters are tweaked until response fits the measurement.



- Digital Network Analyzer used to measure the System Response
  Blue -> error in analog loop
  Orange -> correction after 2.5 ns cable addition

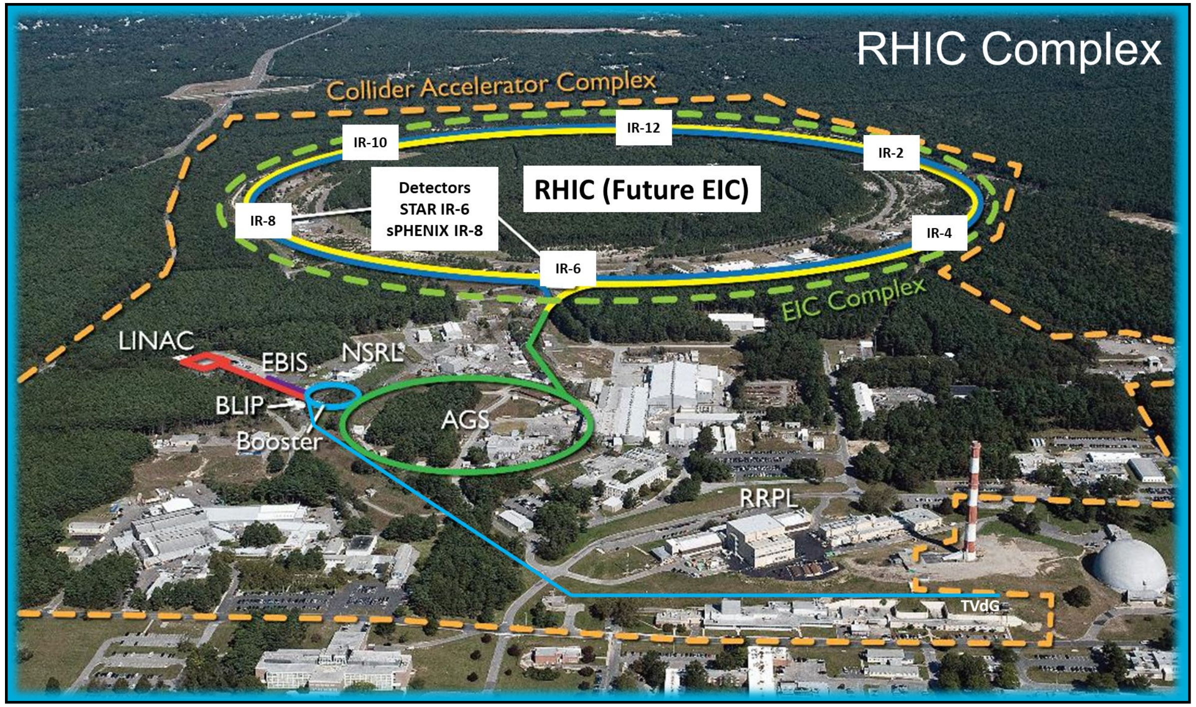


- Closed-loop system response of the 28 MHz cavity
  - PID, OTFB, and analog fast-feedback enabled
  - Up to 30 dB of gain



Celebrating 25 years of RHIC and Commencement of EIC

- C-AD and EIC Management
- Zack and Silvia (EIC RF Systems)
- C-AD and EIC LLRF Team at BNL
- JLAB LLRF Team
- Advisers and well wishers
  - Curt, Tomasz, Alex Z, KSS



And many others, whose collective efforts are turning the EIC's goal into a reality.

Thank you!