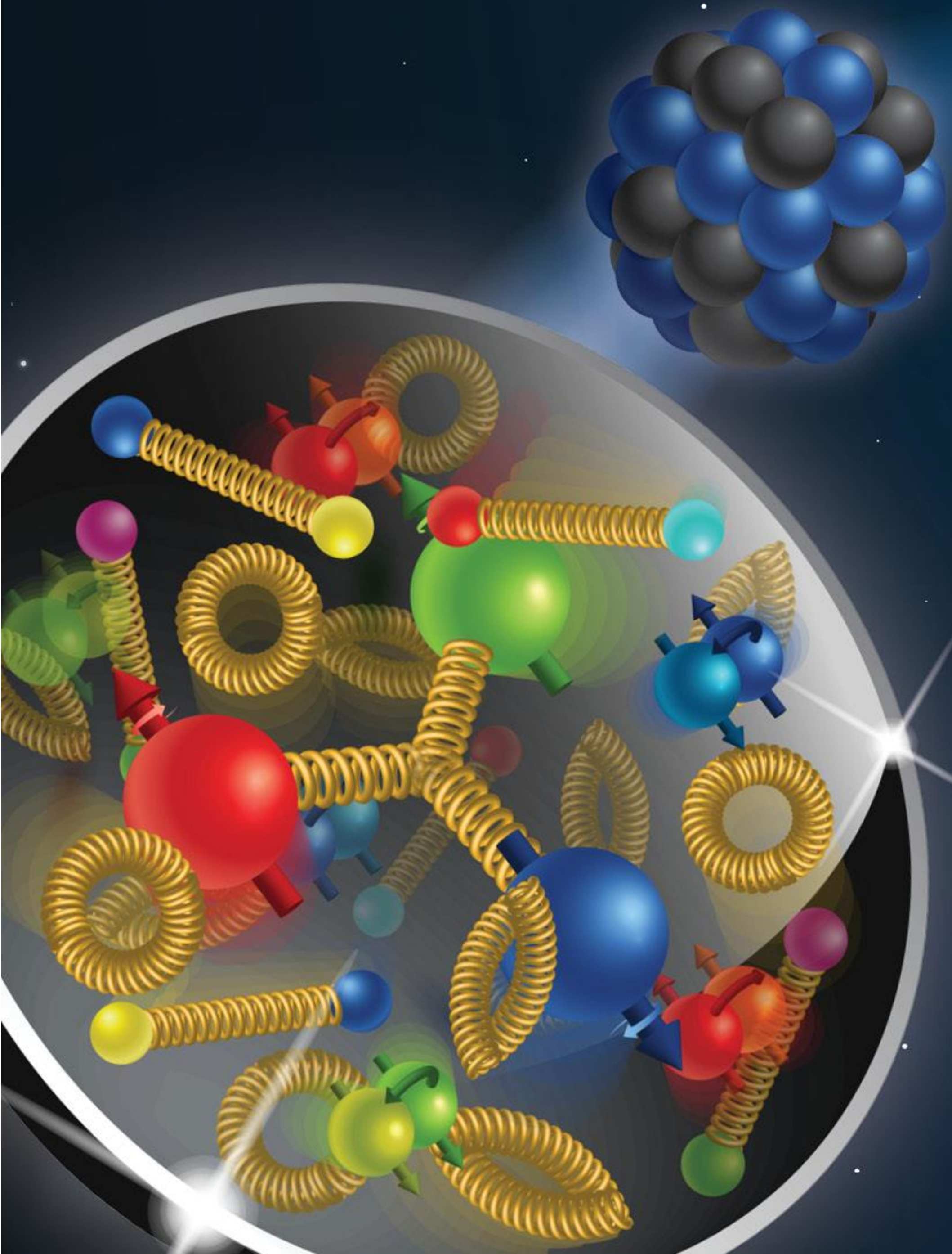


Electron-Ion Collider RF Systems

Kevin Mernick
for the EIC LLRF Team

October 10, 2022

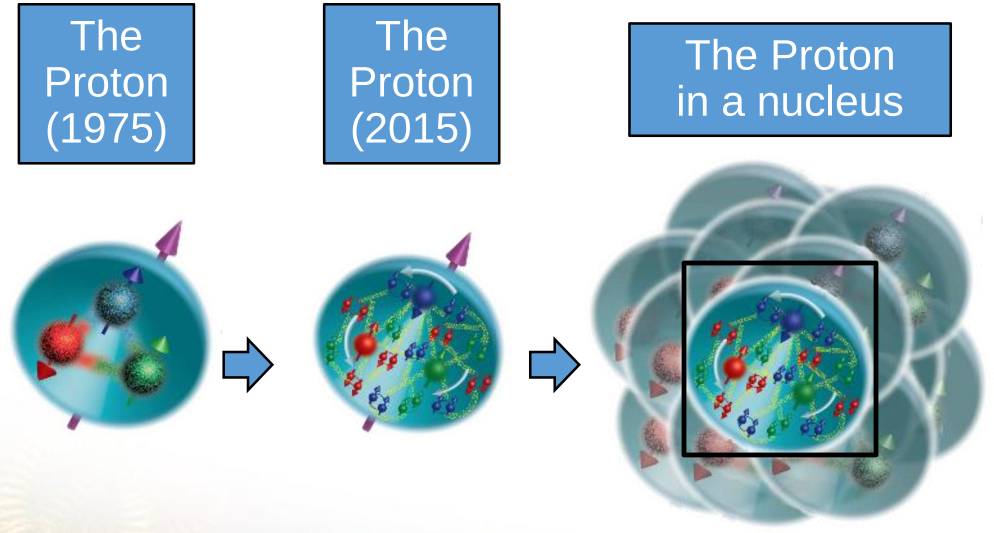
Low Level RF Workshop 2022
9-13 Oct 2022, Brugg-Windisch, Switzerland

Electron-Ion Collider

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

EIC Science Overview

Brookhaven National Laboratory (BNL) is the host site for the future Electron-Ion Collider (EIC), a unique high-energy, high-luminosity polarized collider that will be one of the most challenging and exciting accelerator complexes ever built. The EIC will be a discovery machine, providing answers to long-elusive mysteries of matter related to understanding the origin of mass, structure, and binding of atomic nuclei that make up the visible universe. The design and construction of the EIC is a partnership between BNL and Thomas Jefferson National Accelerator Facility (TJNAF / JLab).



The visible mass of matter in our universe – the atoms and molecules that constitute the galaxies, planets, and life itself – is made up of a dynamic substructure of quarks bound together by force-carrying gluons in complex systems internal to the protons and neutrons of atomic nuclei. An understanding of how the properties of matter originate from the deeply fundamental constituents of QCD is the primary goal of nuclear physics and the central motivation for polarized electron-proton and electron-ion collisions at the Electron-Ion Collider (EIC).

An EIC can uniquely address three profound questions about nucleons — neutrons and protons, and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

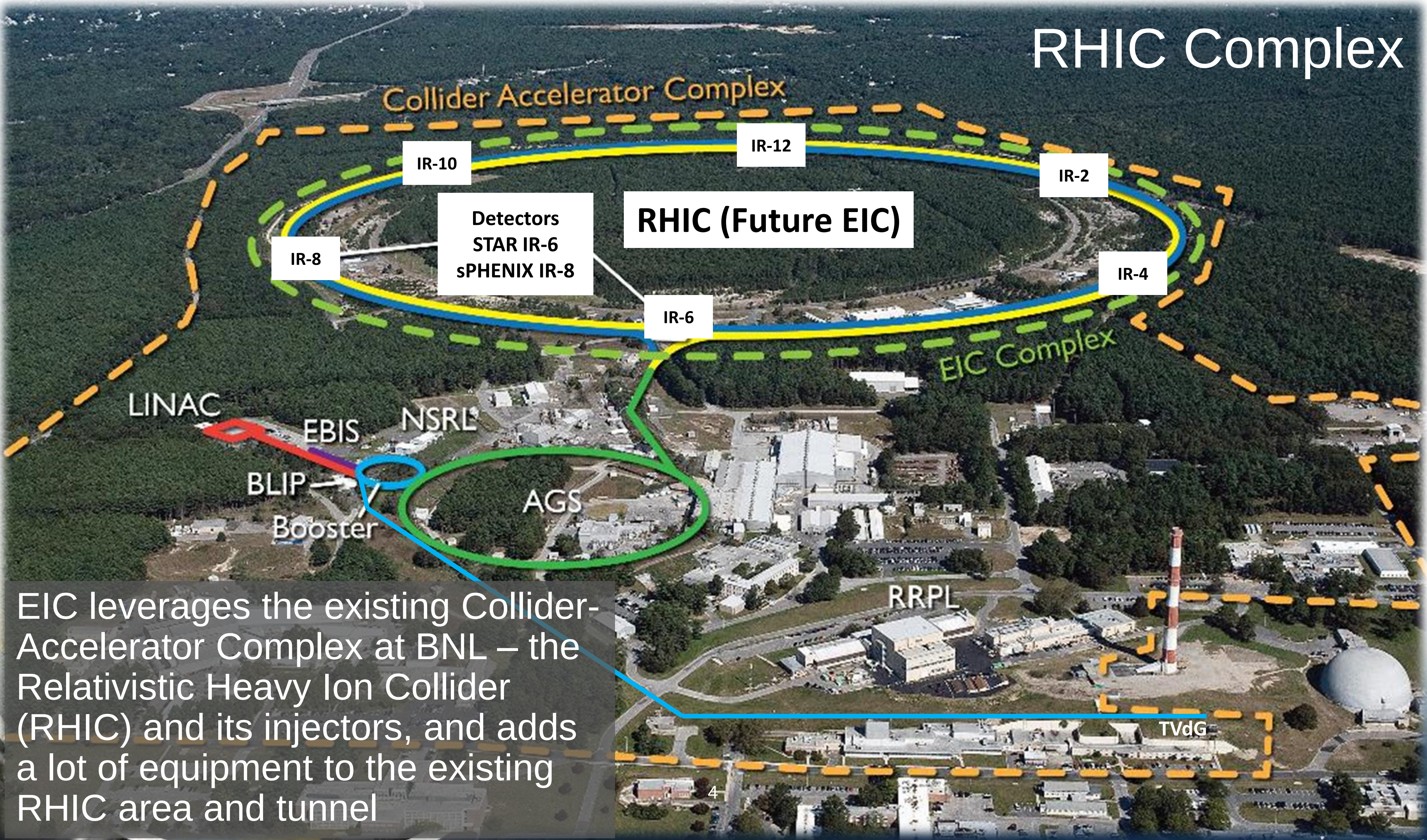
-- Electron Ion Collider Conceptual Design Report

EIC Design Goals

EIC Project Design Goals

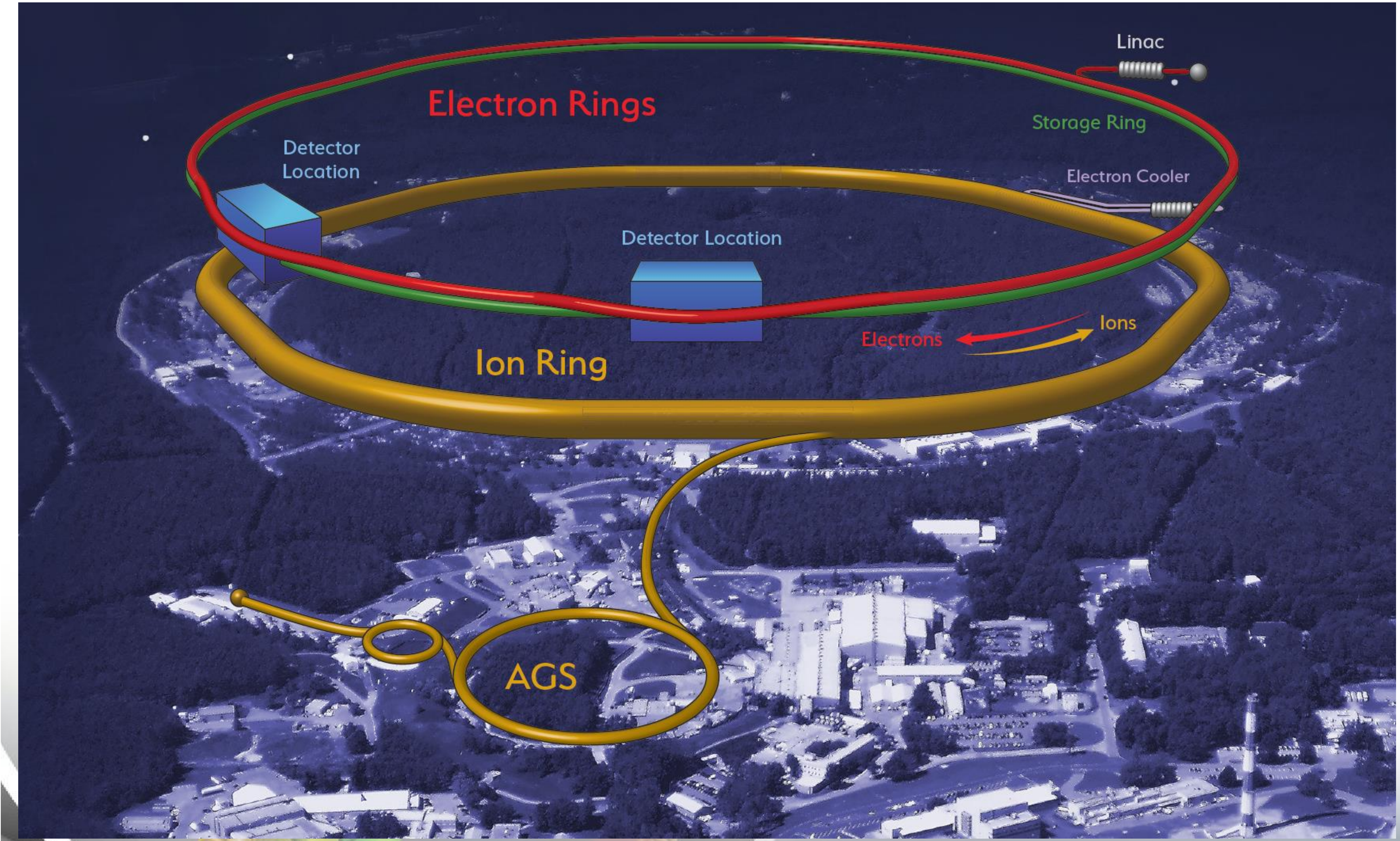
- High Luminosity: L= 10^{33} – 10^{34} $cm^{-2}s^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
  - Electrons, protons, light ions (deuterons, ^3He)
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
  - Electrons: 5 – 18 GeV
  - Protons: 41 – 275 GeV, Heavy Ions: 41 – 110 GeV/n
- Large Ion Species Range: Protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

RHIC Complex



EIC leverages the existing Collider-Accelerator Complex at BNL – the Relativistic Heavy Ion Collider (RHIC) and its injectors, and adds a lot of equipment to the existing RHIC area and tunnel

RHIC → EIC

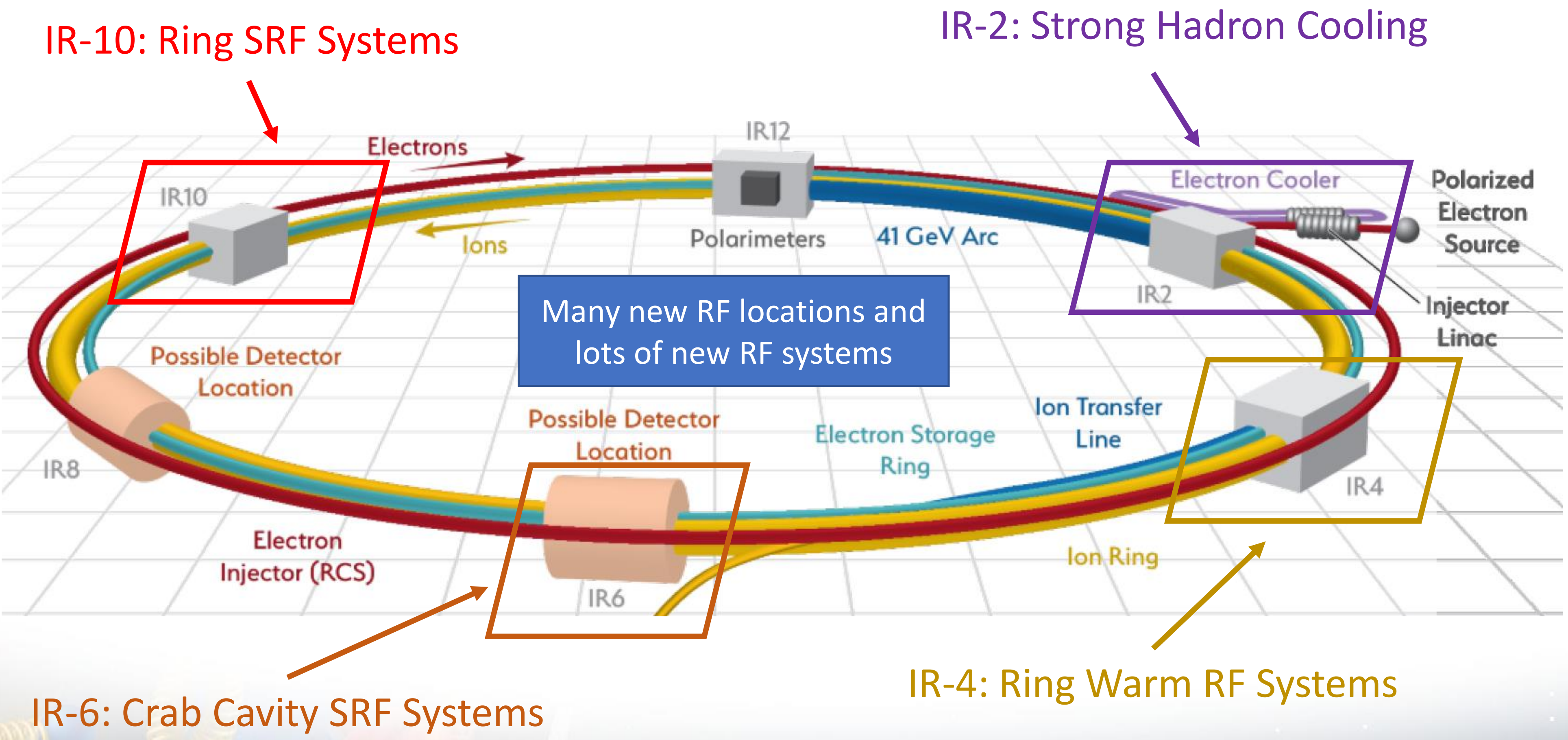


Reconfigure existing two RHIC rings into one Hadron Storage Ring (HSR)

Add:

- 400 MeV e- injection linac
- 5 – 18 GeV e- Rapid Cycling Synchrotron (RCS)
- 5 – 18 GeV Electron Storage Ring (ESR)
- 150 MeV e- ERL for Strong Hadron Cooling (SHC)
- New detector interaction region(s) with crab cavities for both beams

EIC RF Layout



EIC Parameters

Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34

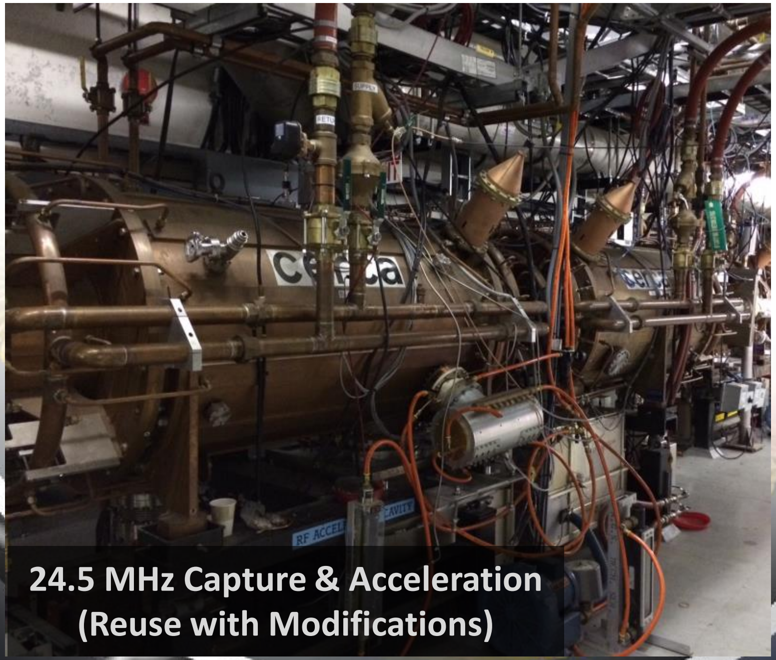
Proton current increases from ~300 mA in 111 bunches in RHIC
to 1 A in 290 bunches (at injection) or 580/1160 bunches (after split)

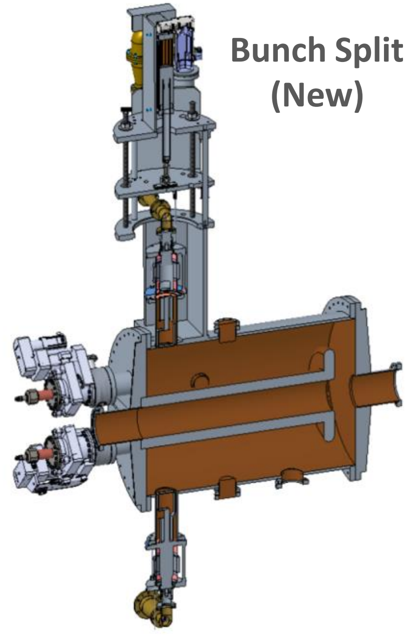
EIC compared to other large electron/positron accelerators

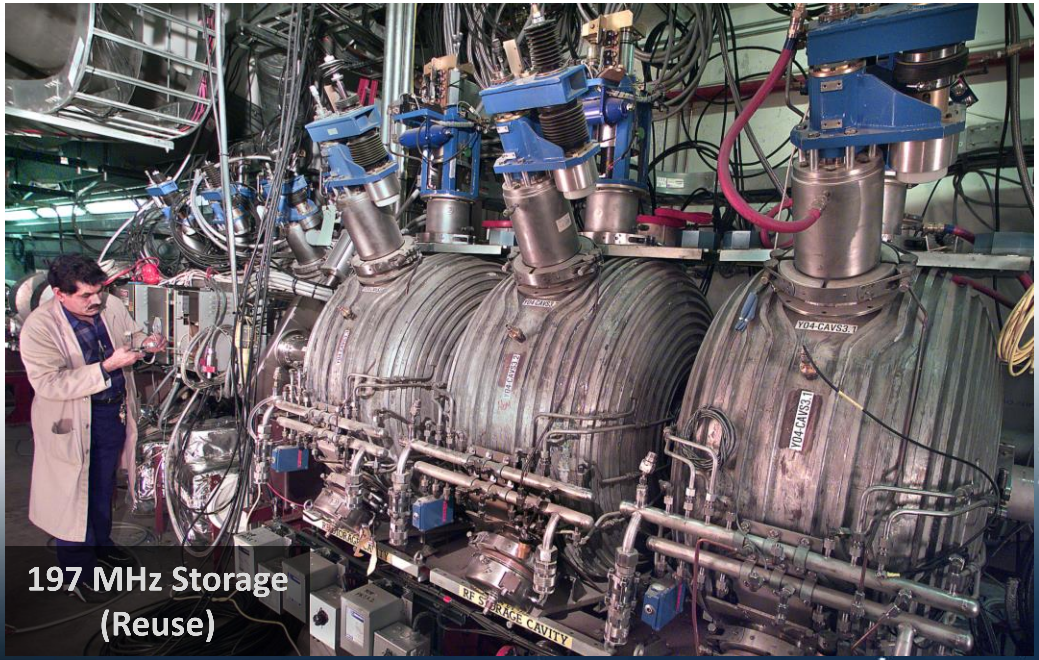
Parameter	CESR-B	PEP-II LER/HER	KEKB LER/HER	EIC
Circumference C [m]	768	2200	3000	3834
Number of bunches N_b	36	1588	1584	1160 (580)
Beam current I [A]	0.365	2.45/1.55	1.3/1.6	2.5
Bunch intensity N_e [10^{10}]	16.2	7.0/4.4	5.0/6.2	15 (30)
Beam-beam parameter ξ_e	0.062	0.064/0.055	0.12/0.1	0.1
Transv. damp. decr. δ [10^{-4}]	1.1	1.8/2	2.5	1.25

Hadron Storage Ring RF Systems

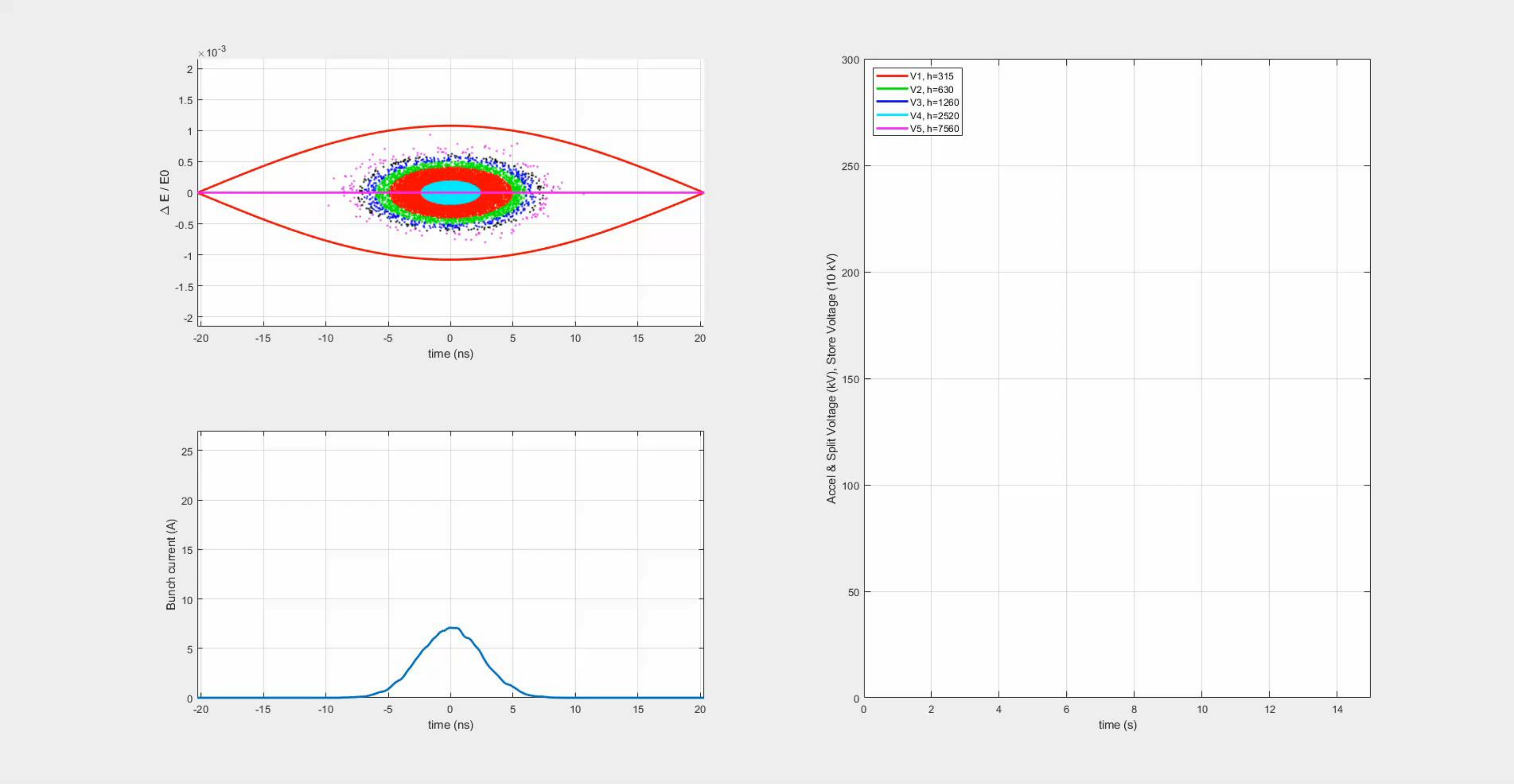
Freq [MHz]	Type	Quantity	Function	Notes
24.6	Copper, QWR	2 - 4	Capture / Accelerate	Modify existing RHIC 28 MHz
49.2	Copper, QWR	2	Bunch Split 1	New
98.5	Copper, QWR	2	Bunch Split 2	New
197	Copper, Reentrant	7	Storage	Existing
591	SRF, 5 cell (or SRF, 2 cell)	1 (or 2?)	Storage	New


24.5 MHz Capture & Acceleration
(Reuse with Modifications)


Bunch Split
(New)


197 MHz Storage
(Reuse)

HSR Bunch Splitting



- Perform two consecutive 1:2 bunch splits
- Compress bunches with higher frequency storage RF systems
- 5 total RF systems with 1 : 2 : 4 : 8 : 24 harmonic relationship

HSR Circumference Adjustment

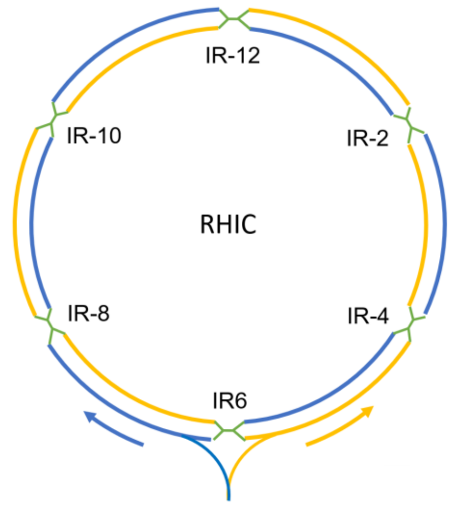
- The revolution period of the hadrons and electrons must match exactly.
- The electrons are ultrarelativistic ($1 - \beta < 5 \times 10^{-9}$). The hadrons are not.
- Need to adjust hadron path length to compensate. At 100 GeV and 275 GeV use a radial shift. At 41 GeV, the larger change requires routing beam through an inner arc rather than an outer arc.
- Acceleration and bunch splitting will be done at the nominal radius, then the magnets and RF frequency will be adjusted to apply the radial shift.

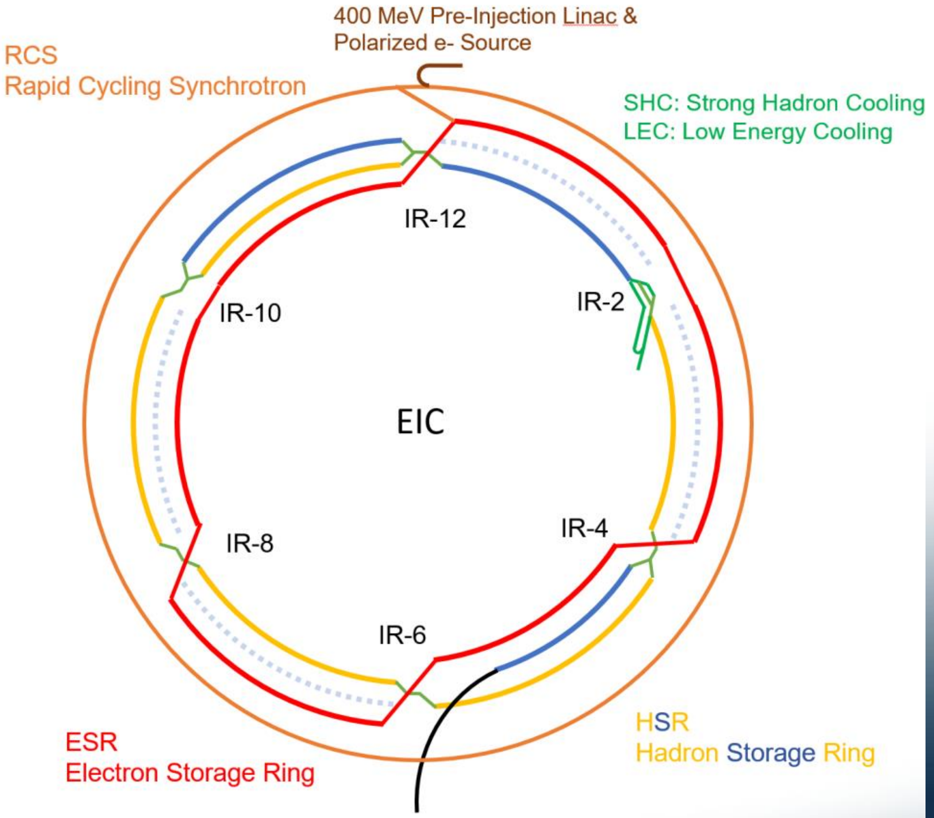
With nominal circumference

Proton Energy (GeV)	$1 - \beta$	ΔT_{rev} (ps)
41	2.62E-04	3031.3
100	4.40E-05	244.3
275	5.82E-06	-244.3

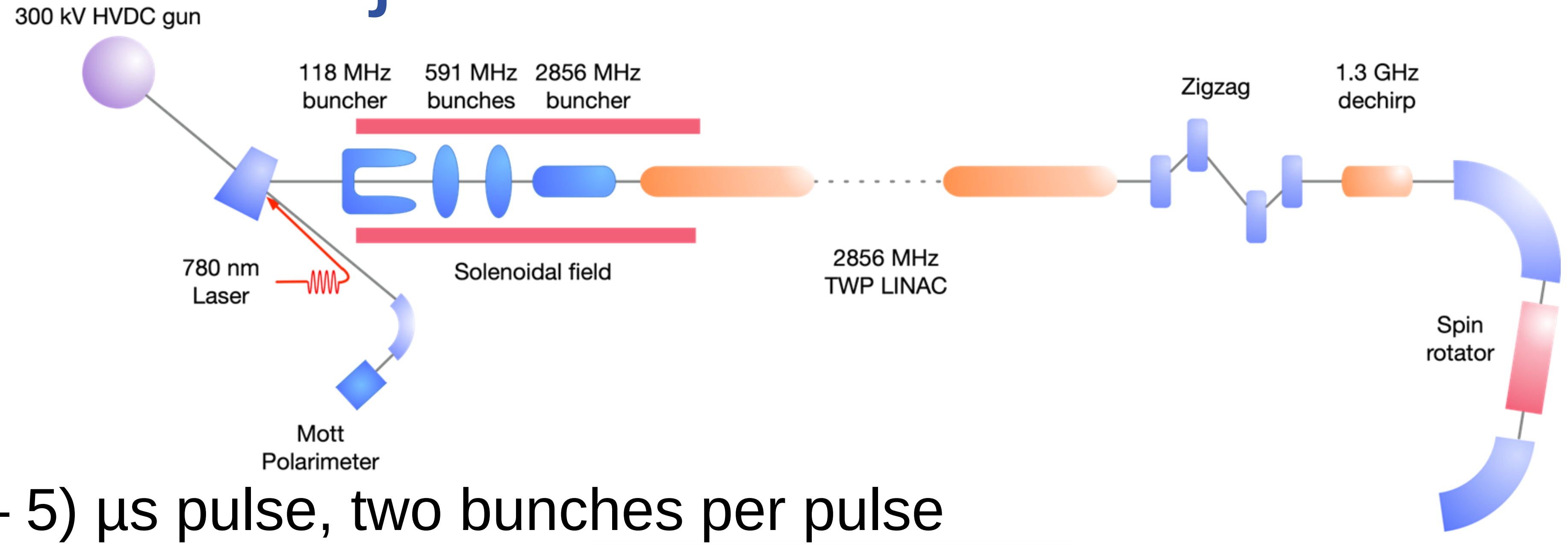
With circumference adjustment

Proton Energy (GeV)	ΔC (mm)	ΔT_{rev} (ps)
41	-908.53	-0.3E-3
100	-73.23	-3.7E-3
275	73.23	-0.5E-3





400 MeV Injection Linac



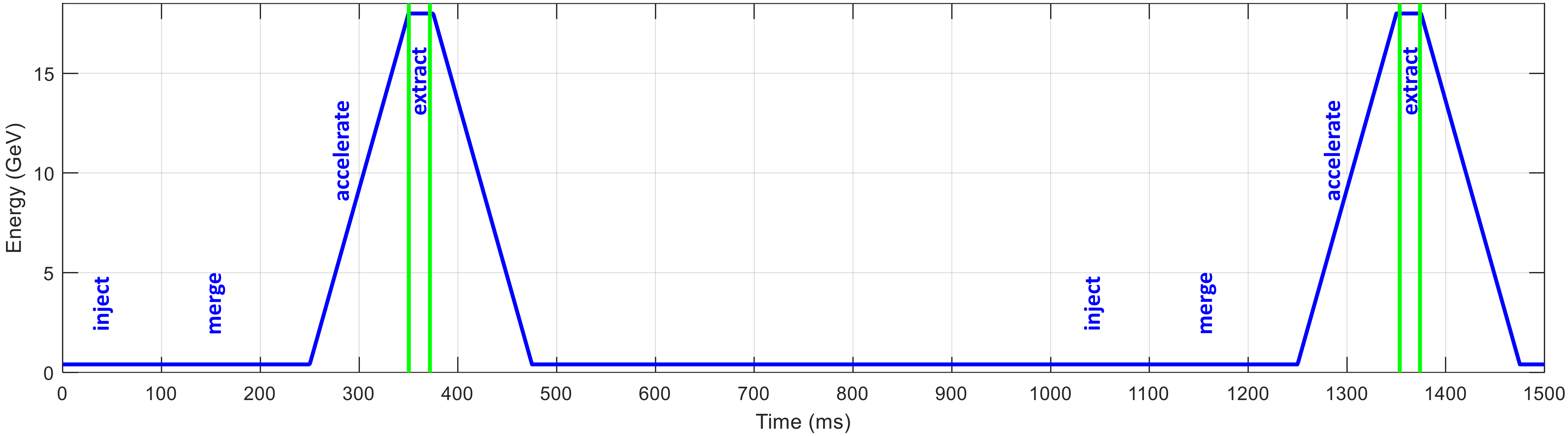
- Few (3 – 5) µs pulse, two bunches per pulse
- All frequencies are harmonics of $24 \times f_{rev\_RCS}$ (1.87 MHz)
  - 118 MHz, 591 MHz, 2856 MHz bunchers
  - 2856 MHz linac
  - 1298 MHz dechirp for bunch stretching
- Project plans this as a turnkey procurement (including LLRF cavity controllers)
- EIC LLRF provides frequency reference(s) and timing/trigger signals

Rapid Cycling Synchrotron RF Systems

Freq [MHz]	Type	Quantity	Function
591	SRF, 5 cell	3	Main RF
295.5	Copper, Reentrant	2	Bunch Merge 1
147.75	Copper, Reentrant	1	Bunch Merge 2

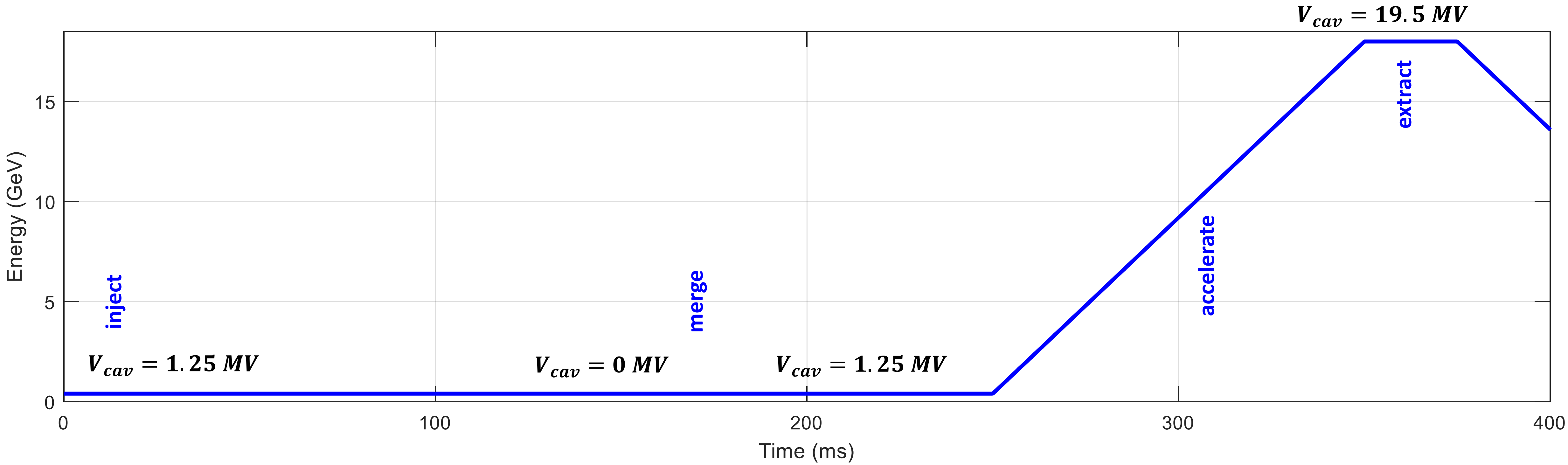
- Injection of 4 linac pulses with 2 bunches per pulse
- 4 : 2 : 1 bunch merge at 400 MeV to get two 28 nC bunches
- Accelerate from 400 MeV to 18 GeV in 100 ms
  - For 5 GeV and 10 GeV, shorter ramp with the same rate
- Transfer two bunches to ESR
- Machine cycle repeats at 1 Hz
  - Constant replacement (due to depolarization) of all bunches in ESR takes < 5 minutes at 18 GeV, ~10 minutes at lower energies

RCS Machine Cycle



- Acceleration rate is 2.2 MeV/turn
- Synchrotron radiation losses are negligible at low energies, but reach 39.5 MeV/turn at 18 GeV
- Cavity voltage changes significantly through the cycle

RCS Main Cavities Voltage Requirement

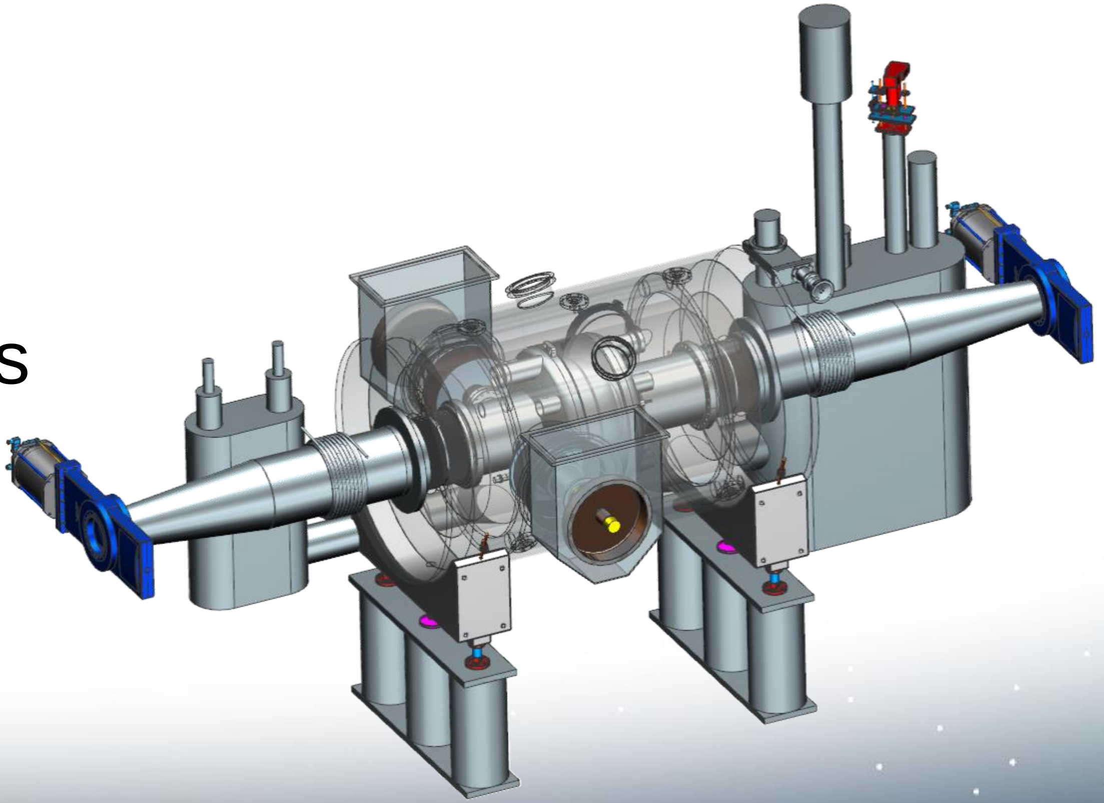


- Total voltage is 3x individual cavity voltage shown here
- 591 MHz system voltage goes to 0 during the merge
- Fast Lorentz detuning compensation is new for us

Electron Storage Ring RF Systems

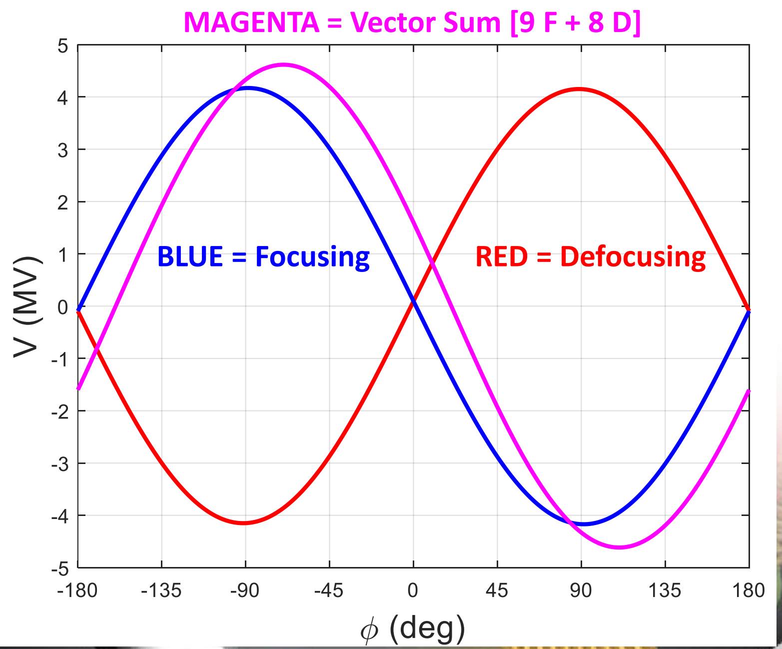
Freq [MHz]	Type	Quantity	Function
591	SRF, 1 cell	17	Main RF

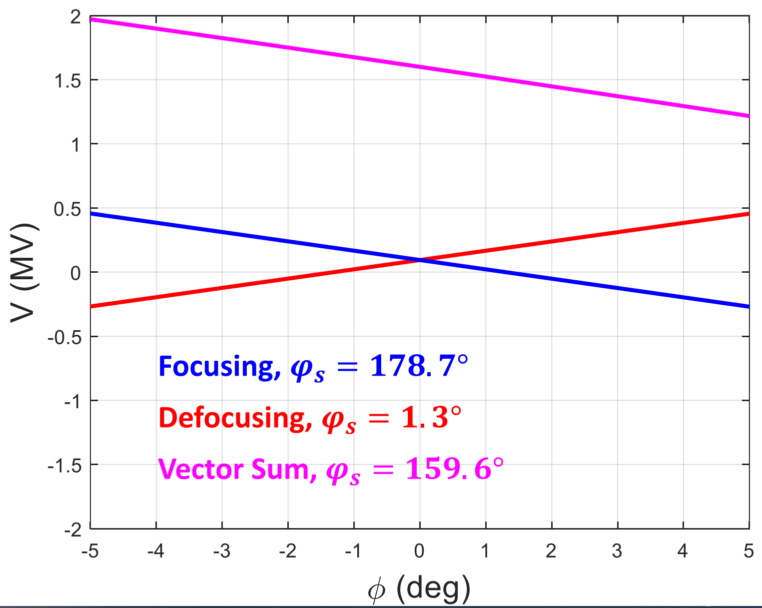
- ESR RF system sized based on synchrotron radiation power
  - 10 GeV: 2.5 A @ ~4 MeV/turn = 10 MW
  - 18 GeV: 0.25 A @ ~40 MeV/turn = 10 MW
- Cavity design driven by beam dynamics
  - Low R/Q
  - Dual 500 kW power couplers
  - Dual SiC high power broadband beamline HOM absorbers (~20 kW each)

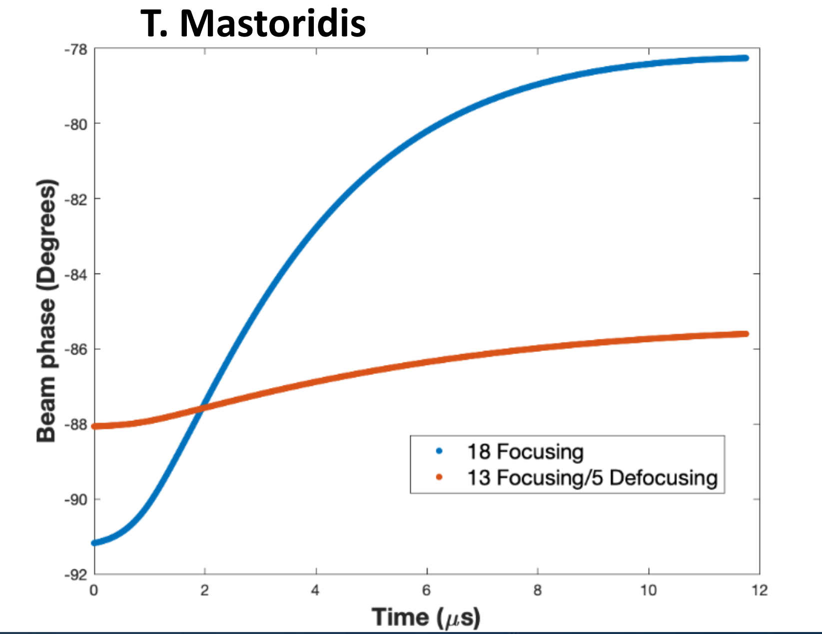


ESR RF-Beam Interaction

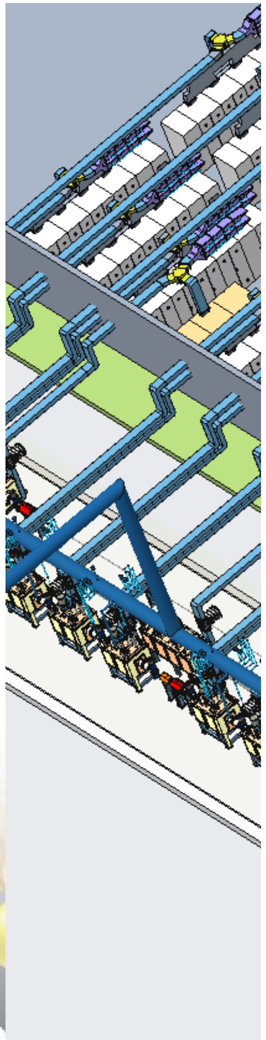
- High current operation at low required voltage
  - Transient beam loading (driven by 1 μs beam gap)
  - Large detuning
- Planning RF focus/defocus to counteract
  - All cavities provide same in-phase voltage (accelerating power to beam)
  - Some cavities reverse the quadrature voltage (defocus vs focus)
  - Raises RF voltage on all cavities – reduced detuning and beam loading, also reduces required range of Q_{ext}
- Feedback to reduce cavity impedance, with “gap feedforward” to reduce P_{fwd}

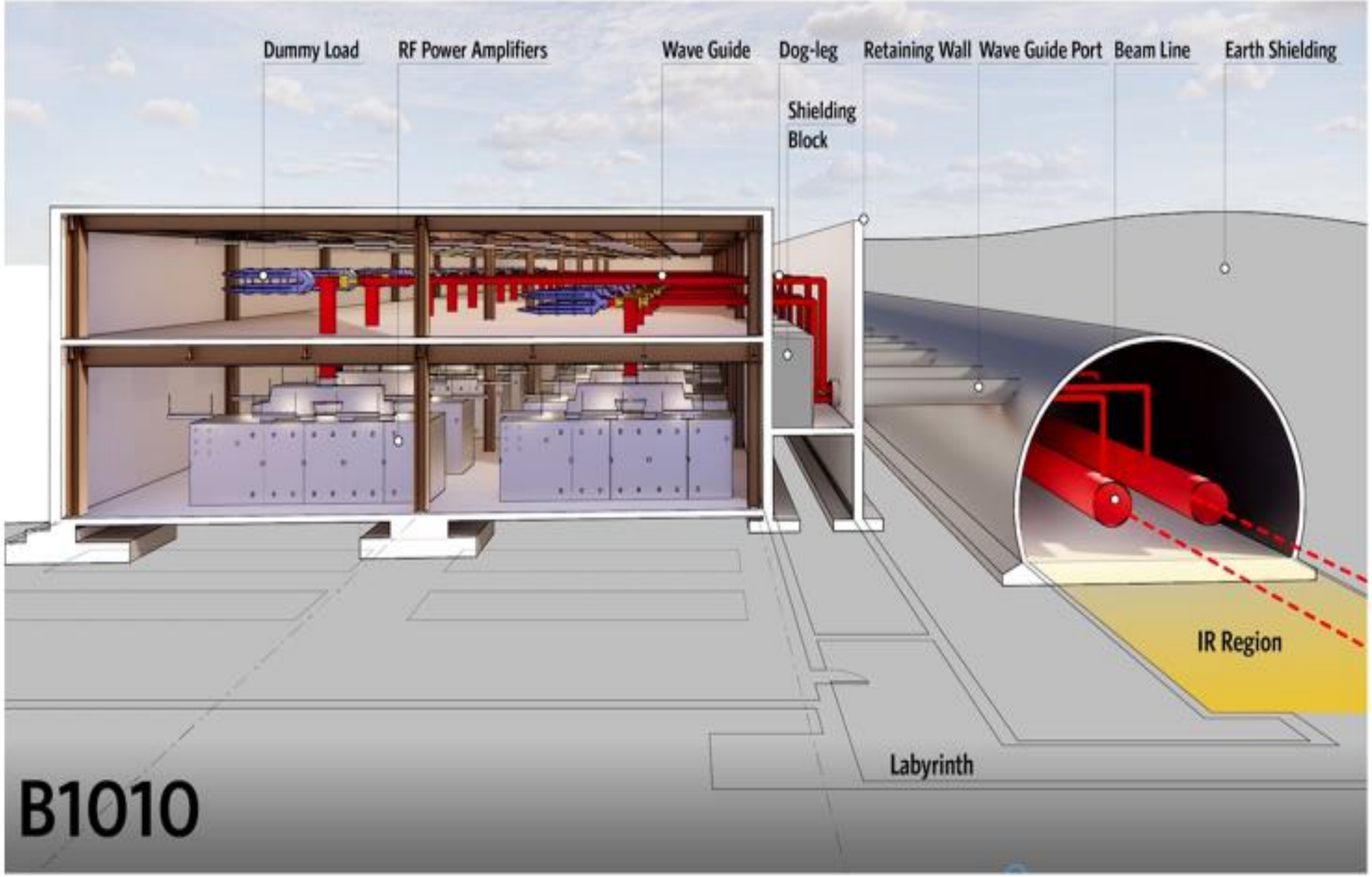






1010 RF Support Building





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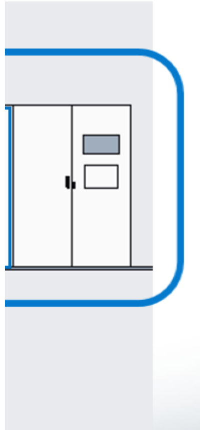
irculators,



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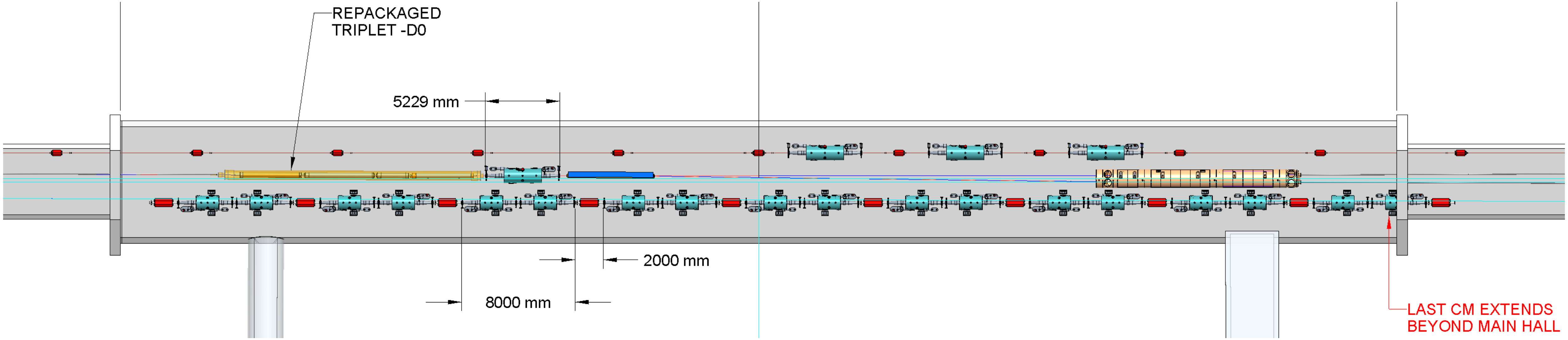
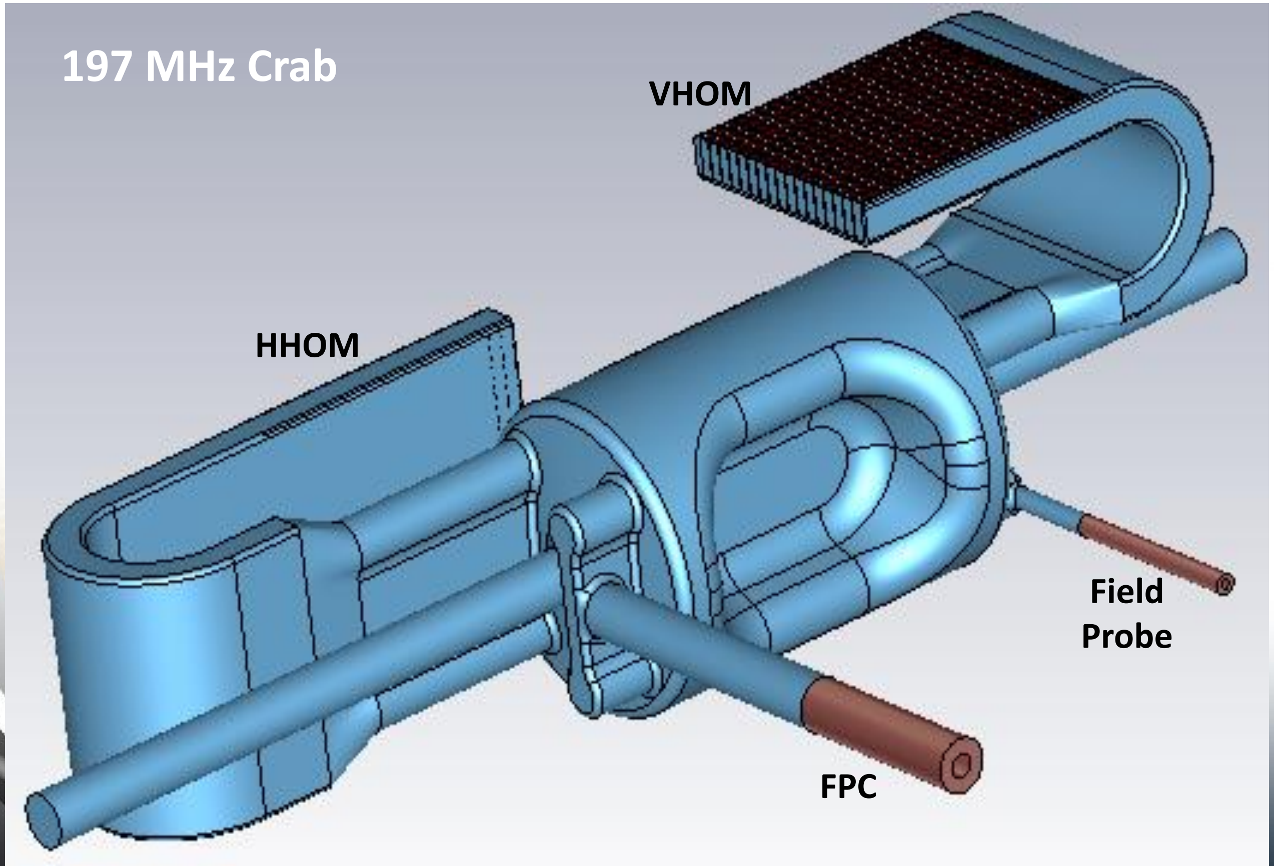
IR10 Tunnel Layout



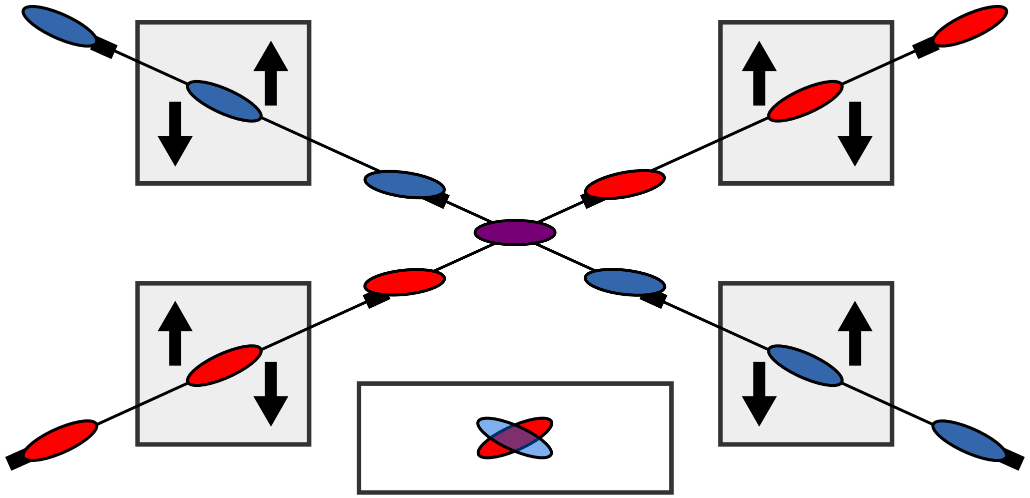
- ESR on bottom (ring inside), HSR middle, RCS top (outside)
- Tunnel layout includes
  - 18 ESR cavities
  - 1 HSR cavity
  - 3 RCS cavities
  - HSR switchyard for IR10-IR12 inner/outer arc

Crab Cavity RF Systems

Freq [MHz]	Type	Quantity	Function
197	SRF, RF dipole	8	HSR fundamental
394	SRF, RF dipole	4	HSR linearization
394	SRF, RF dipole	2	ESR fundamental



Crab crossing utilizes a transverse head-tail kick to maximize beam overlap and collision luminosity with a crossing angle

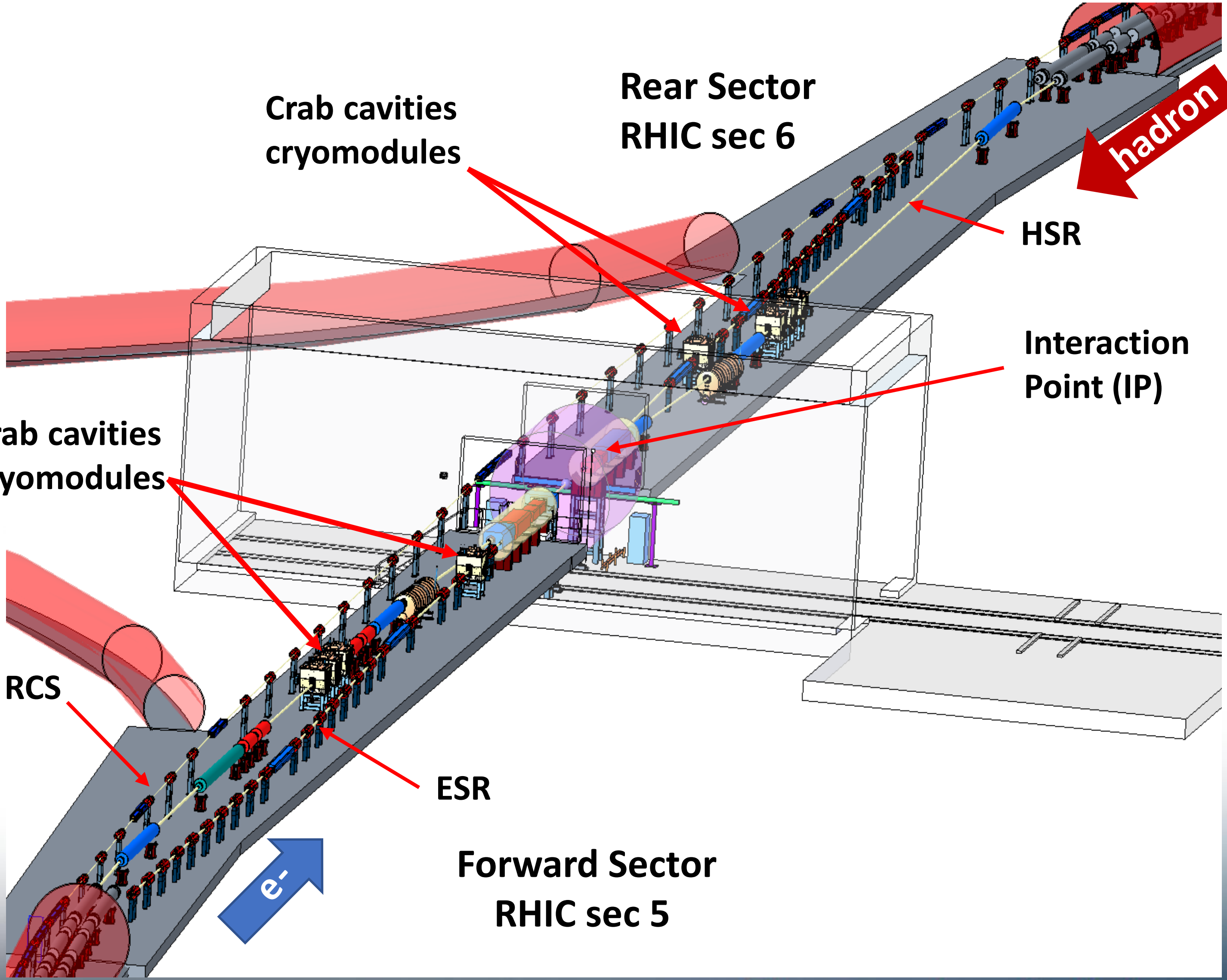


IR6 Layout

Interaction region includes

- IR magnets (focusing)
- Spin rotators
- Matching magnets (to arcs)
- Crab cavities
- Snakes (spin preservation)

The interaction region extends about ±130 m in both directions to achieve the required conditions for an experimental detector



Crab Cavity Challenges

- RF Noise causes transverse emittance growth
- Transient beam loading effects on beam position and amplifier P_{fwd}
- Impedance reduction for transverse instability control

Large crossing angle of 25 mrad (compared to HL-LHC 0.6 mrad) exacerbates these issues

Noise driven emittance growth (T. Mastoridis)

P. Baudrenghien, T. Mastoridis, "Transverse emittance growth due to RF noise in the High-Luminosity LHC Crab Cavities", Phys. Rev. ST Accel. Beams 18, 101001, October 2015

Machine parameters **Bunch length dependence** **RF noise**

$$\frac{d\epsilon_n}{dt} = N_{cavities}\beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 \left\{e^{-\sigma_\phi{}^2}\left[I_0\left[\sigma_\phi{}^2\right] + 2\sum_{l=1}^{\infty} I_{2l}\left[\sigma_\phi{}^2\right]\right]\right\} \sum_{k=-\infty}^{\infty}\int_{-\infty}^{\infty} S_{\Delta\phi}\left[(k \pm \nu_b)f_{rev}\right]\rho(\nu_b)\,d\nu_b$$

$$= N_{cavities}\beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 C_{\Delta\phi}(\sigma_\phi)\frac{2\sigma_{\Delta\phi}^2}{f_{rev}}$$

$$= \frac{1}{N_{cavities}\beta*}\left[\left(\frac{ec\theta_{cc} f_{rev}}{4\omega_{RF}}\right)^2\right] C_{\Delta\phi}(\sigma_\phi)\frac{2\sigma_{\Delta\phi}^2}{f_{rev}}$$

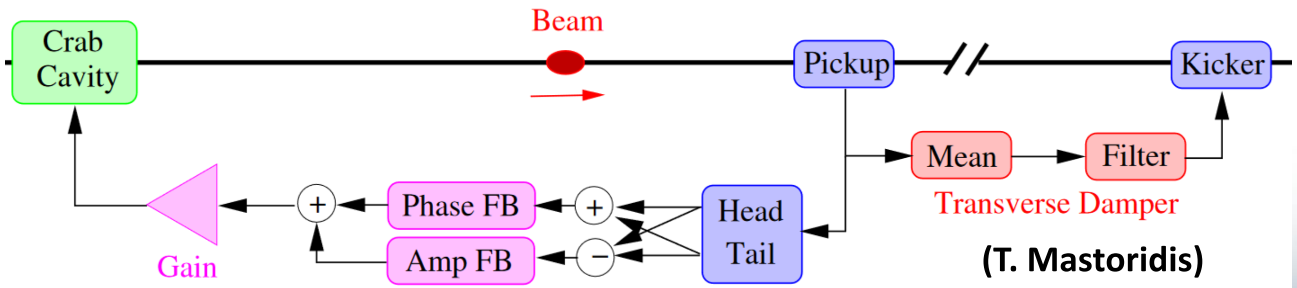
$$\frac{d\epsilon_n}{dt} = N_{cavities}\beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 \left\{e^{-\sigma_\phi{}^2}\sum_{l=0}^{\infty} I_{2l+1}\left[\sigma_\phi{}^2\right]\right\} \sum_{k=-\infty}^{\infty}\int_{-\infty}^{\infty} S_{\Delta A}\left[(k \pm \nu_b \pm \nu_s)f_{rev}\right]\rho(\nu_b)\,d\nu_b$$

$$= \frac{1}{N_{cavities}\beta*}\left[\left(\frac{ec\theta_{cc} f_{rev}}{4\omega_{RF}}\right)^2\right] C_{\Delta A}(\sigma_\phi)\frac{4\sigma_{\Delta A}^2}{f_{rev}}$$

	$\sigma_{\Delta\phi}$ (μrad)
HL-LHC	8.17
ESR 5 GeV	805
HSR 41 GeV	3.09
HSR 100 GeV	2.69
HSR 275 GeV	**1.75**

Transverse instability (M. Blaskiewicz)

We are investigating whether RF feedback and a comb filter at the betatron sidebands can give enough impedance reduction

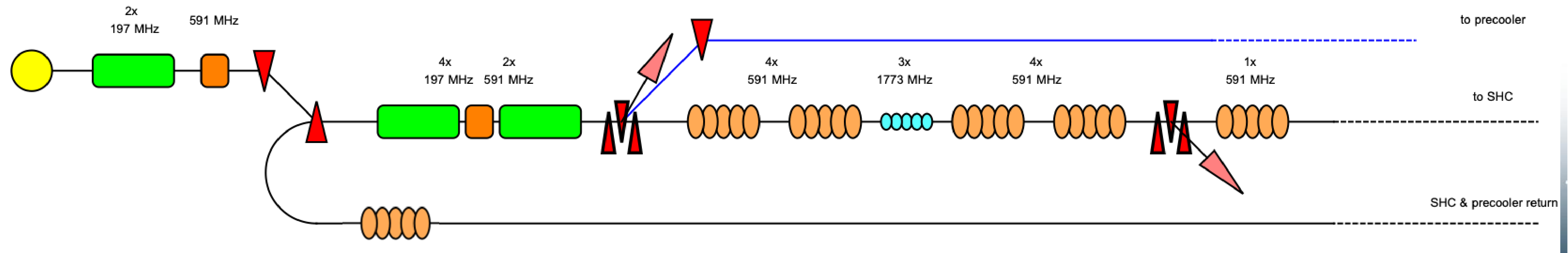


(T. Mastoridis)

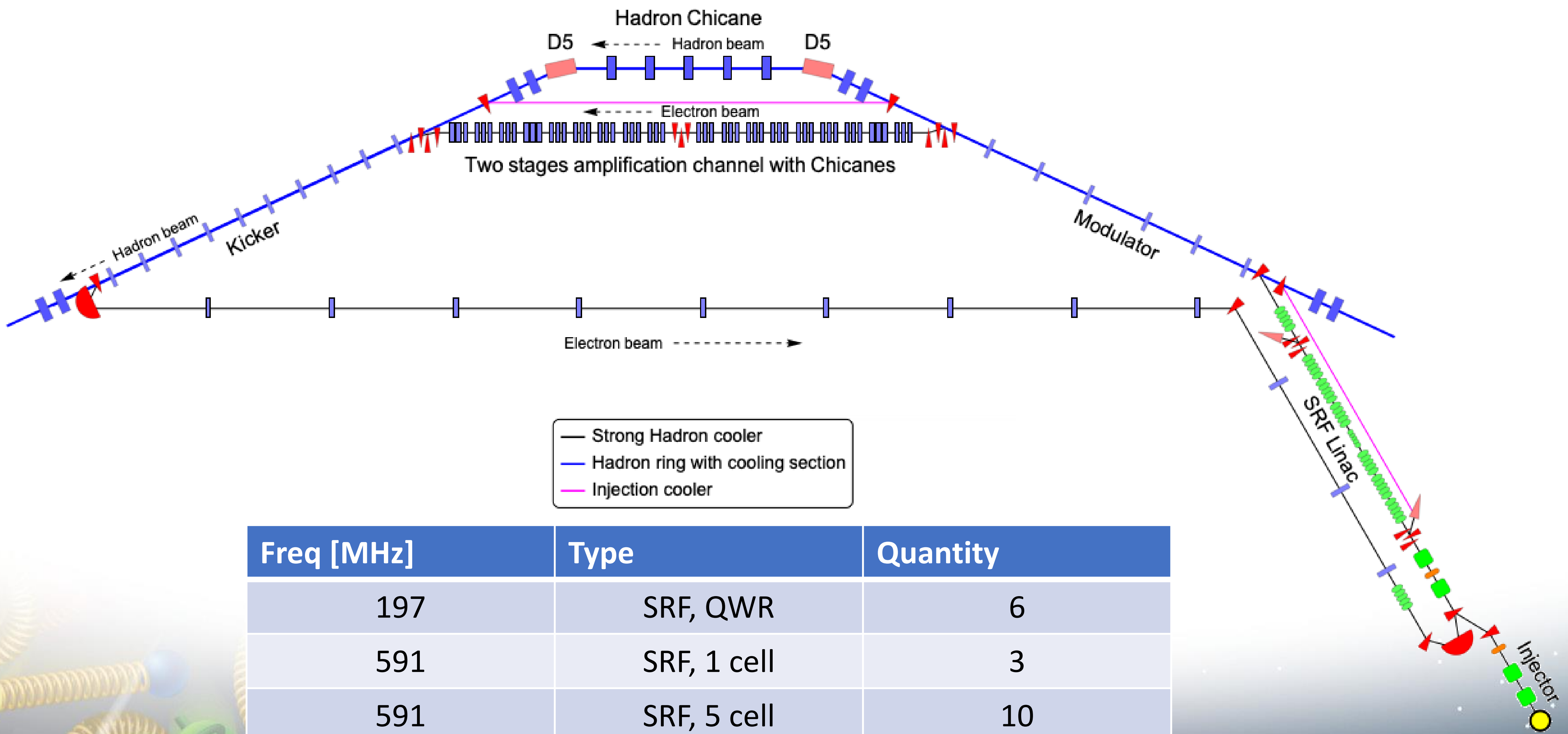
Beam based feedback also being investigated to address both the noise and stability issues

Electron Cooling ERL RF Systems

- Strong Hadron Cooling at 100 GeV and 275 GeV (coherent electron cooling)
- Injection pre-cooling at 25 GeV (using bunched beam conventional electron cooling). Also possibly used for 41 GeV
- All require $\gamma_e = \gamma_p$ ➔ electron energy 14 - 22 MeV or 54 – 150 MeV
- Required beam current is ~100 mA ➔ energy recovery linac
- Required fractional rms momentum spread < 10^{-4}



Electron Cooler Layout



Freq [MHz]	Type	Quantity
197	SRF, QWR	6
591	SRF, 1 cell	3
591	SRF, 5 cell	10
1773	SRF, 5 cell	3

EIC Cavity Summary

- 74 cavities
- 15 different types of cavities (5 HSR, 3 RCS, 1 ESR, 2 Crab, 4 ERL) – maybe only 13 if HSR, RCS and ERL all use the same 5-cell, 591 MHz
- 9 different frequencies (24.6, 49, 98, 148, 197, 295, 394, 591, 1773 MHz)
- Not including injector linac or RCS multi-harmonic injection kicker

EIC LLRF Team

Geetha Narayan[1], **Curt Hovater**[2], **Ramakrishna Bachimanchi**[2], Tom Hayes[1], Kayla Hernandez[1], **James Latshaw**[2], Themis Mastoridis[3], **Kevin Mernick**[1], Tomasz Plawski[2], Sal Polizzo[1], **Freddy Severino**[1], **Kevin Smith**[1*]

[1]BNL, [2]JLab, [3]CalPoly

Bold = attending LLRF22

Talks
Curt – JLab Lab talk (earlier)
KevinM – this talk (now)
Rama – SELAP experience at JLab (Thursday)

Posters
James – PIP-II Resonance Control
Geetha – EIC Common Hardware Platform
Freddy – EIC Common Platform Clocking

*Kevin Smith is LLRF Emeritus, EIC Deputy Technical Director