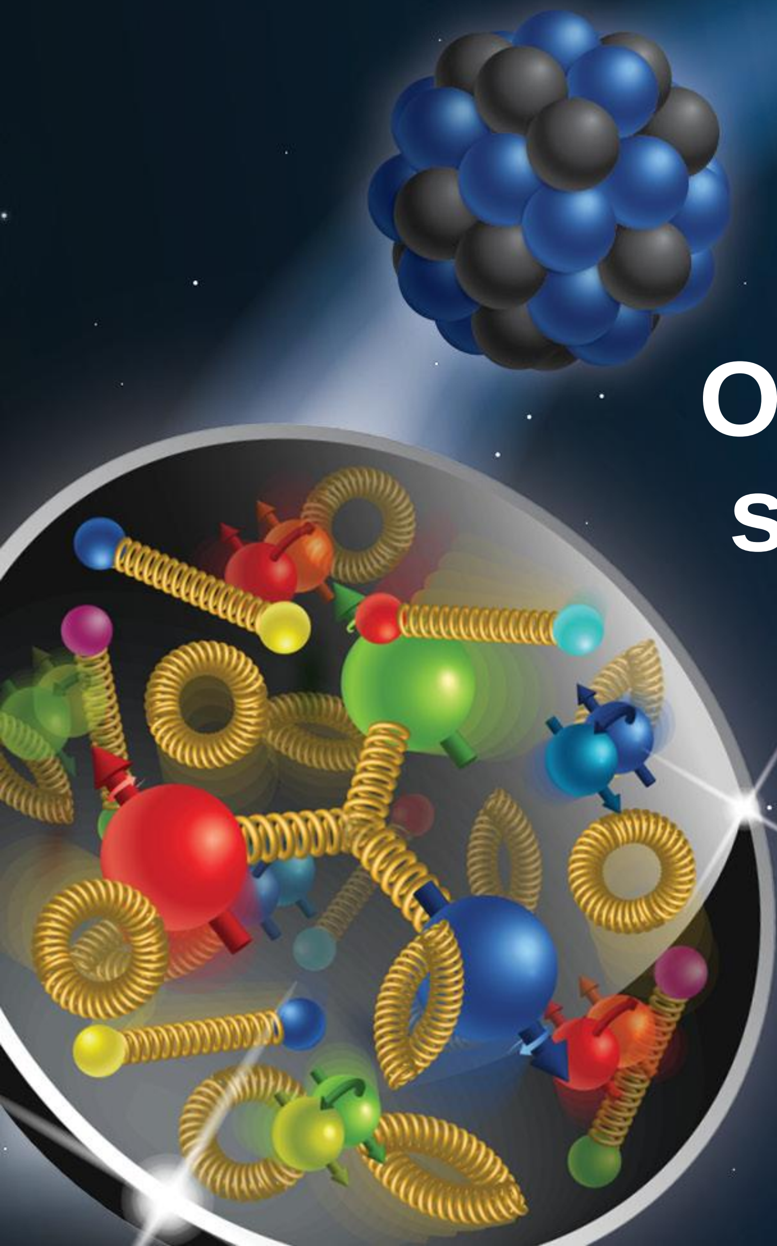


Overview of the EIC RF system and synergies with FCC-ee

R. Rimmer (Jlab)

On behalf of the EIC RF team

FCC week, June 29, 2021

Electron-Ion Collider

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

Outline

- Overview of EIC
- SRF systems overview
  - ESR
  - HSR
  - Crabbing
  - RCS
  - High energy electron cooling
  - Polarized electron injector
- Notable challenges
- Critical component R&D
  - FPC
  - HOM absorbers
  - RF power
- Conclusions

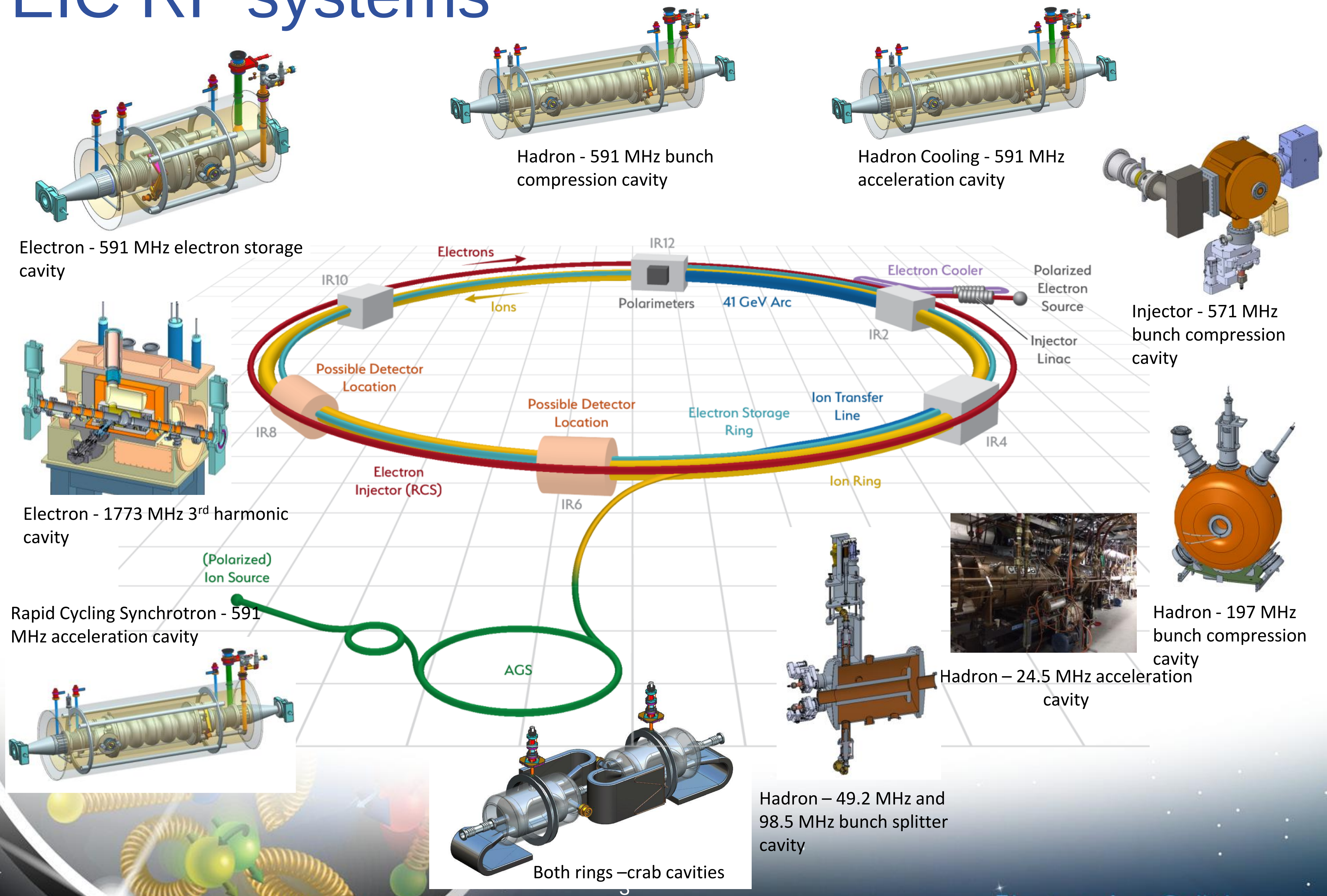
Synergies with FCC highlighted in green

See also:

AN OVERVIEW OF RF SYSTEMS FOR THE EIC

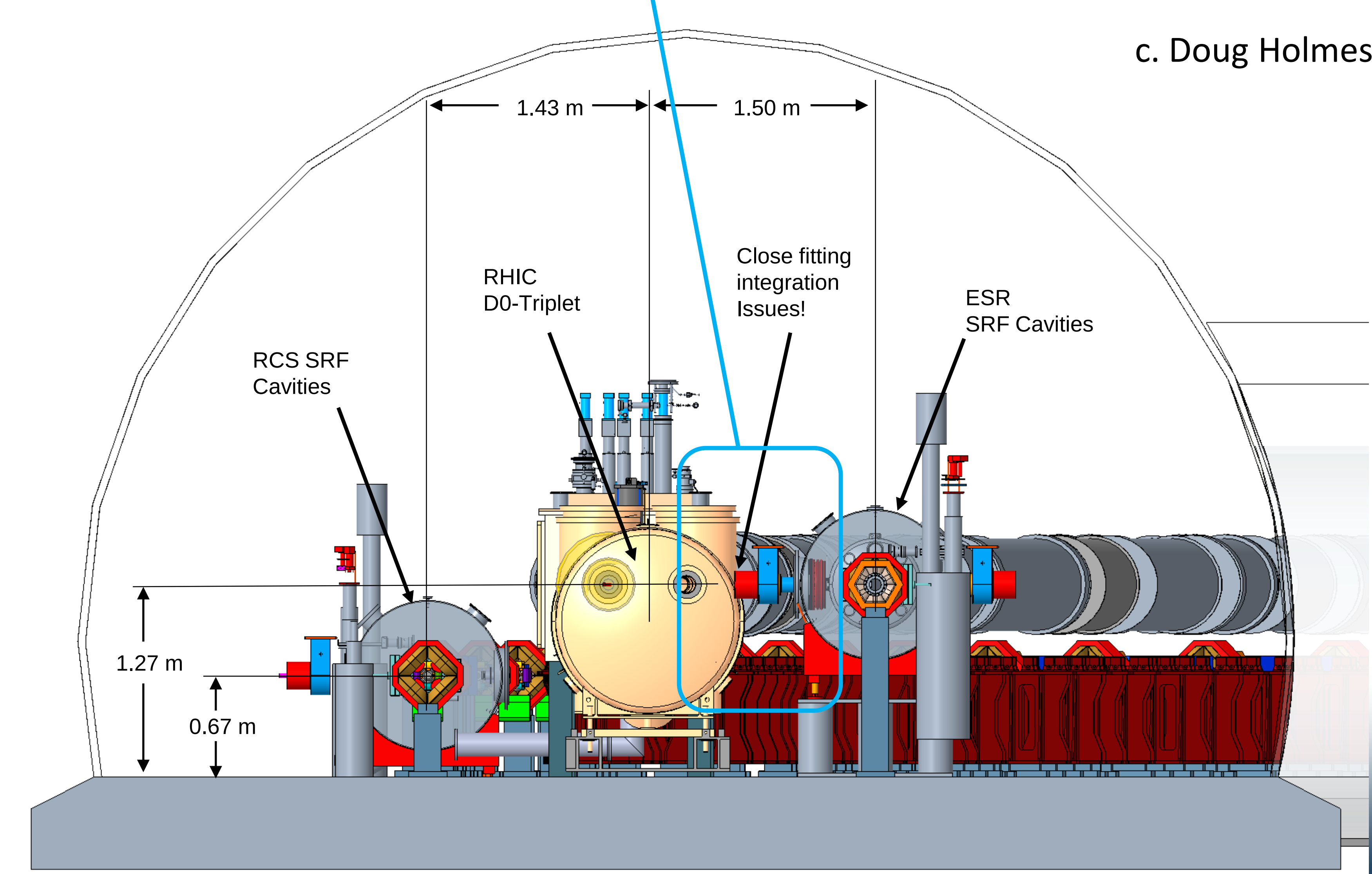
R.A. Rimmer et. al., MOPAB385 IPAC21

EIC RF systems

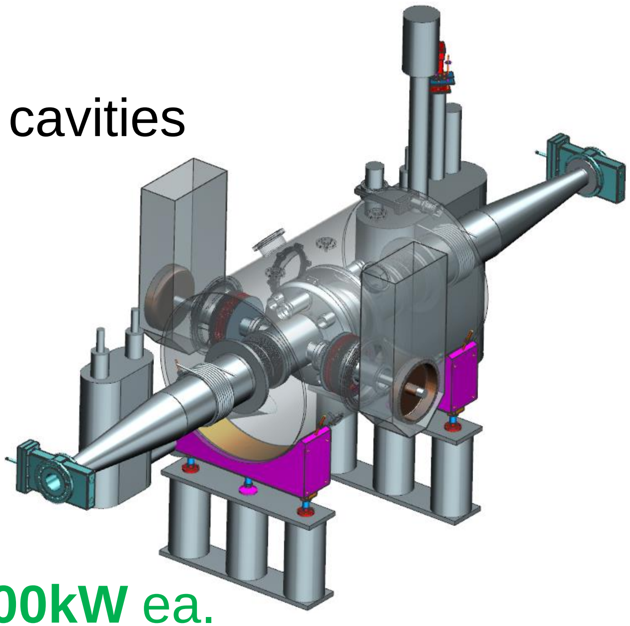


IR-10 Tunnel: Cryomodule Space Allocation

- Space constraints will contribute to the challenge for the integrated coupler/cryomodule design.



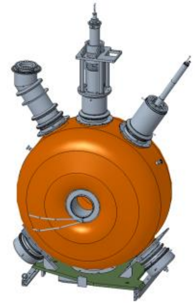
ESR RF system



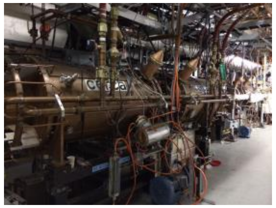
- Up to **68 MV** using 17 new **591 MHz** 1-cell SRF cavities
  - maintain 1% Bucket height from 5-18 GeV
- Naturally short bunch length ~1cm
- **10MW** maximum beam power
- ~**40 kW** HOM power per cavity
- **2.5A** maximum current
- Two fundamental power couplers per cavity, ~**400kW** ea.
- Strong beam loading requires large detuning frequency (~revolution frequency), advanced RF controls.
- Transient beam loading will be significant.
- At lower energy we can use reverse-phasing method, reducing detuning frequency and transient modulation.

HSR RF system

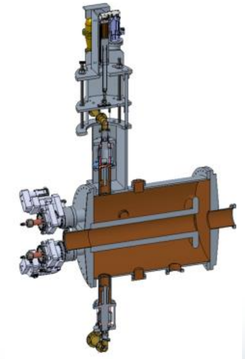
- Keep existing 6 MV 6x197 MHz NCRF system
- Re-tune existing 2x 28 MHz system to 24.6 MHz
- Add 2x 49.2MHz and 2x 98.5MHz NCRF for binary bunch splitting
- Add **20 MV 591 MHz** SRF system
- Up to **1A** beam, up to 1160 bunches
- Optimum detuning for reactive power (like LHC)
- Beam loading transient and collective effects studies started



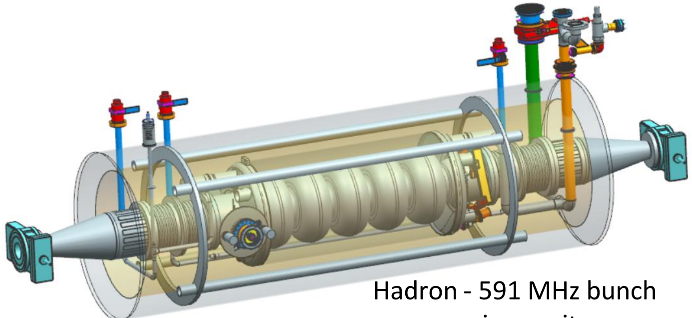
Hadron - 197 MHz bunch compression cavity



Hadron – 24.5 MHz accelerat cavity



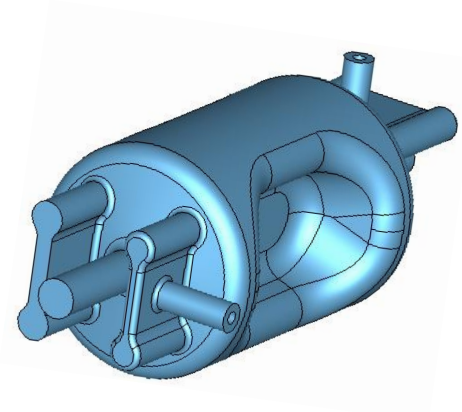
Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity

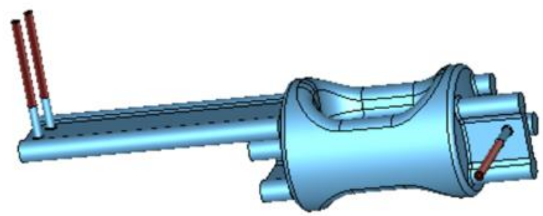


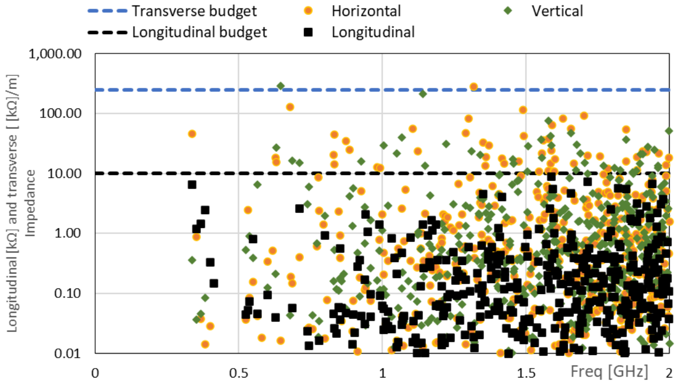
Hadron - 591 MHz bunch compression cavity

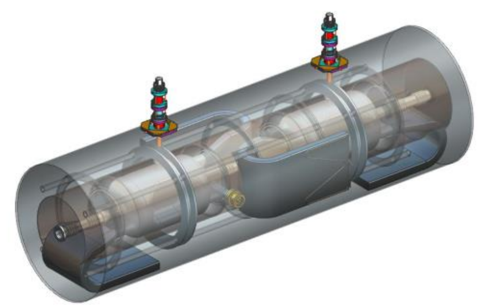
Crabbing Systems

- New SRF crabbing systems for both rings
- Large voltage needed for **25 mRad** crossing angle
- ESR system **394 MHz 2.9 MV** each side
- HSR system **197 MHz 34 MV** each side
    - Need second harmonic for **linearization**
- IR 6 total **8x 197 MHz** cavities, **6x 394 MHz** cavities
- RFD type selected for both rings
- HOM damping optimization ongoing
- Noise and RF dynamics studies needed





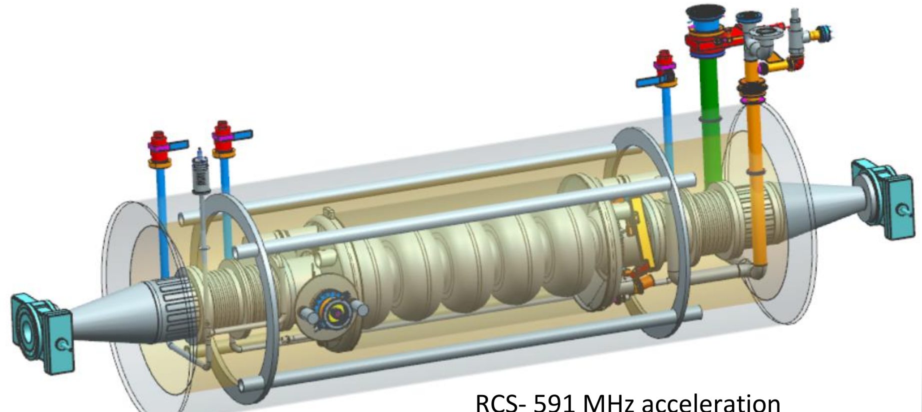




Binping Xiao, J. R. Delayen, Subashini De Silva, Z. Li, R. Rimmer, S. Verdu-Andres, Qiong Wu, WEPCAV014, SRF 2021

RCS

- Requires rapid acceleration of one or two high charge bunches per cycle for full energy injection
- **3x 591 MHz 5-cell** cavities, same as HSR and ERL
- Bunch merging to achieve peak bunch charge
- Harmonic injection kicker into RCS
- Fast kickers for injection into ESR



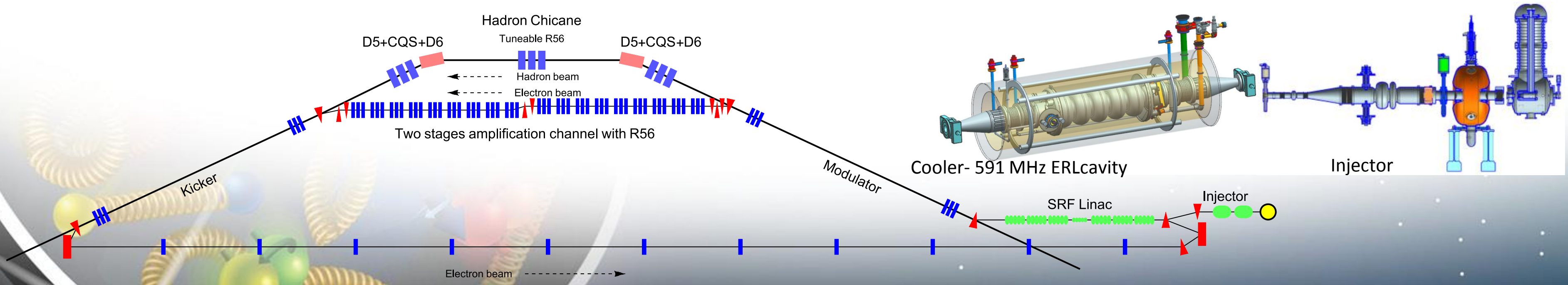
RCS- 591 MHz acceleration cavity

Harmonic kicker cavity

High energy electron cooling

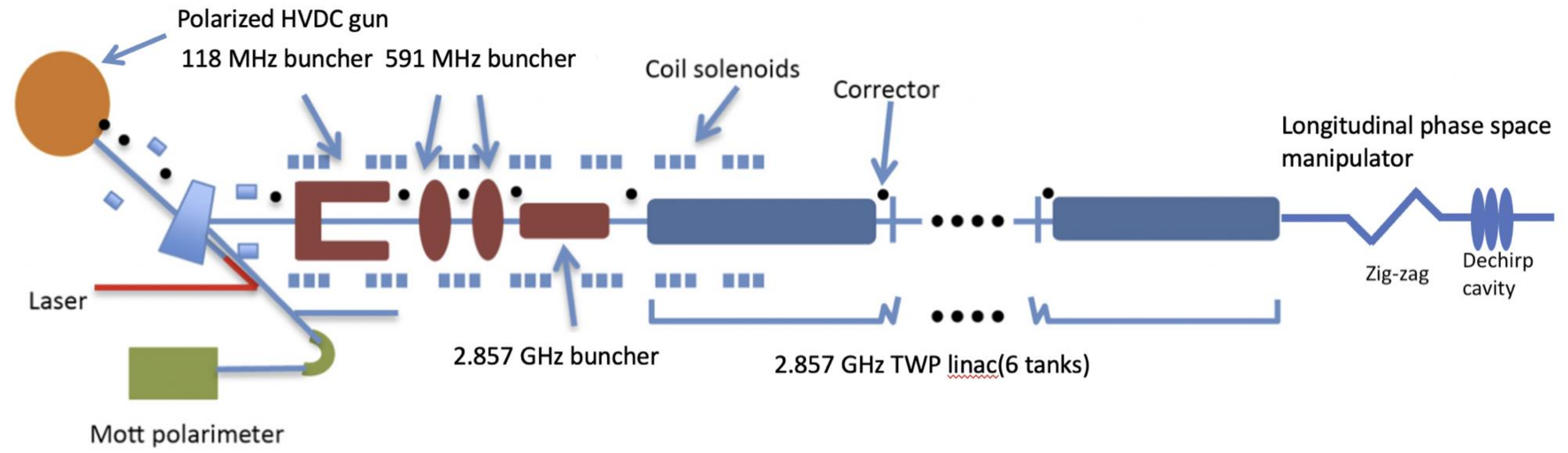
- Single Pass **150 MeV ERL**, 98.5 MHz bunch frequency
- **8 x 591 MHz, 5-cell** elliptical + **1.77 GHz** third harmonic
- Maximum 180 MV installed voltage, Eacc **15.8 MV/m**
- 8 x 591 MHz, **65 kW CW**, SSA RF Power Amplifiers
- **1 nC** per bunch, **~100 mA** single pass current (like FCC-eh)
- Injector: DC photocathode gun, 197 MHz buncher, 591 MHz acceleration, 1.77 GHz linearizer.

"The accelerator design progress for EIC strong hadron cooling", E. Wang et. Al., TUPAB036 Proc. IPAC21, Brazil.



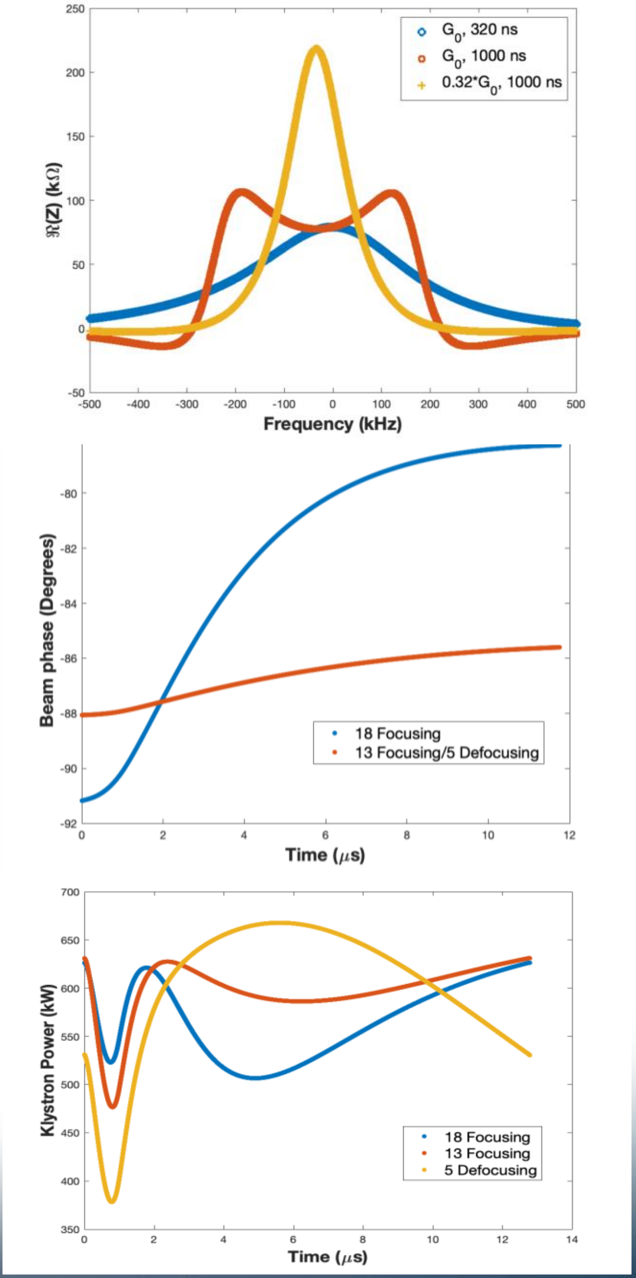
Polarized electron injector

- 350 kV DC photocathode gun
- 118 MHz buncher
- 591 MHz buncher
- 2856 MHz SLAC-type linac to 400 MeV
- 1182 MHz de-chirper



Notable challenges

- High currents
  - HOM power, BBU, RF stability, resonant heating
- High bunch charge
  - Single bunch instabilities, wakefields, CSR, resistive wall heating
- High beam power
  - RF power, couplers, collimators
  - Gap transients
- Crabbing
  - High voltage, HOMs, linearity, synchronization, noise

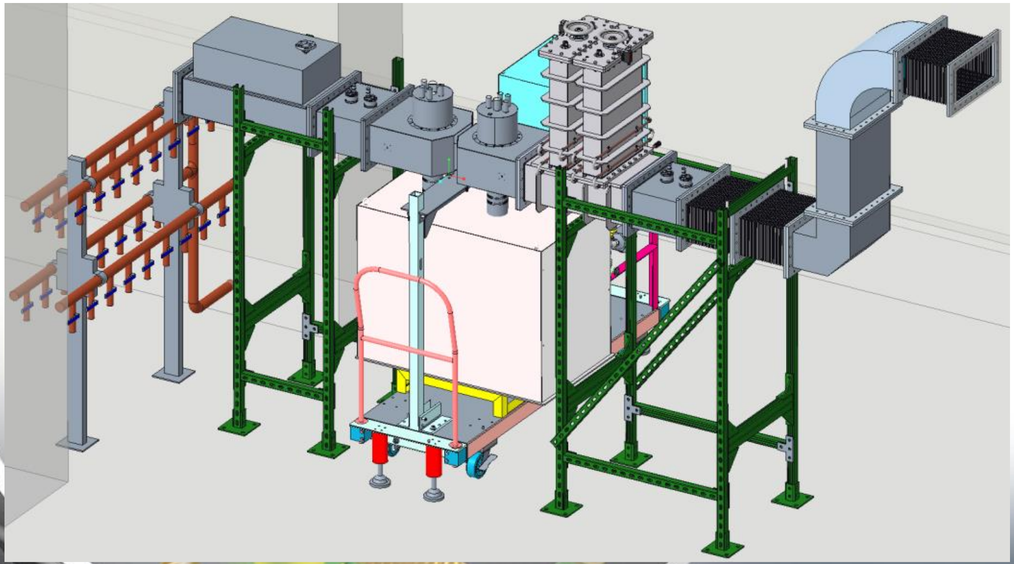


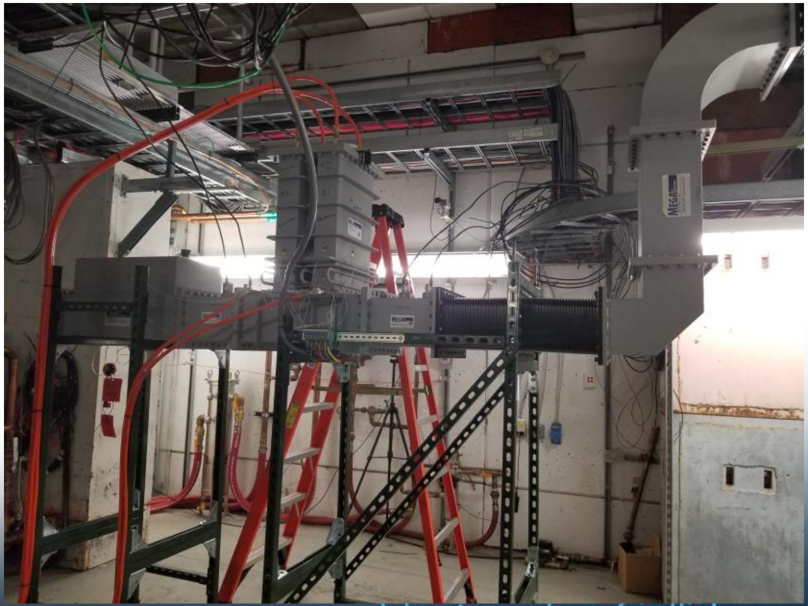
simulations of the RF system-beam interaction in the EIC electron ring

Critical component R&D

EIC FPC: 400 kW CW, Variable Q_{ext} Couplers

- EIC will use new fixed 500 kW CW coupler design.
- Vary Q_{ext} x10 using adjustable waveguide tuner section.
- Initial funding by BNL LDRD
- Now on project funds.



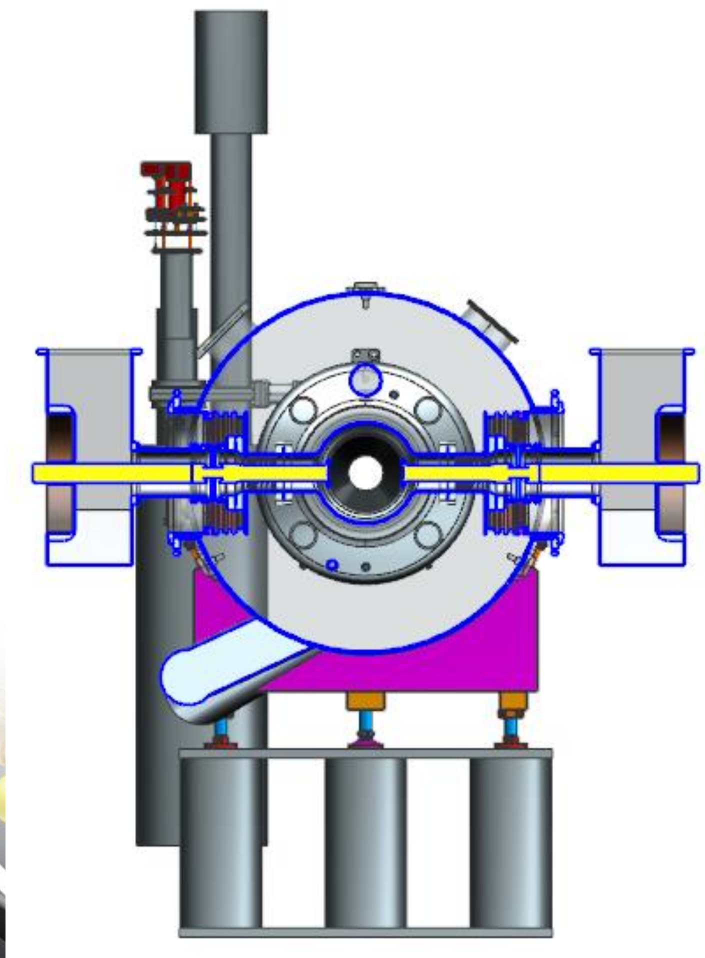


Courtesy Wencan Xu

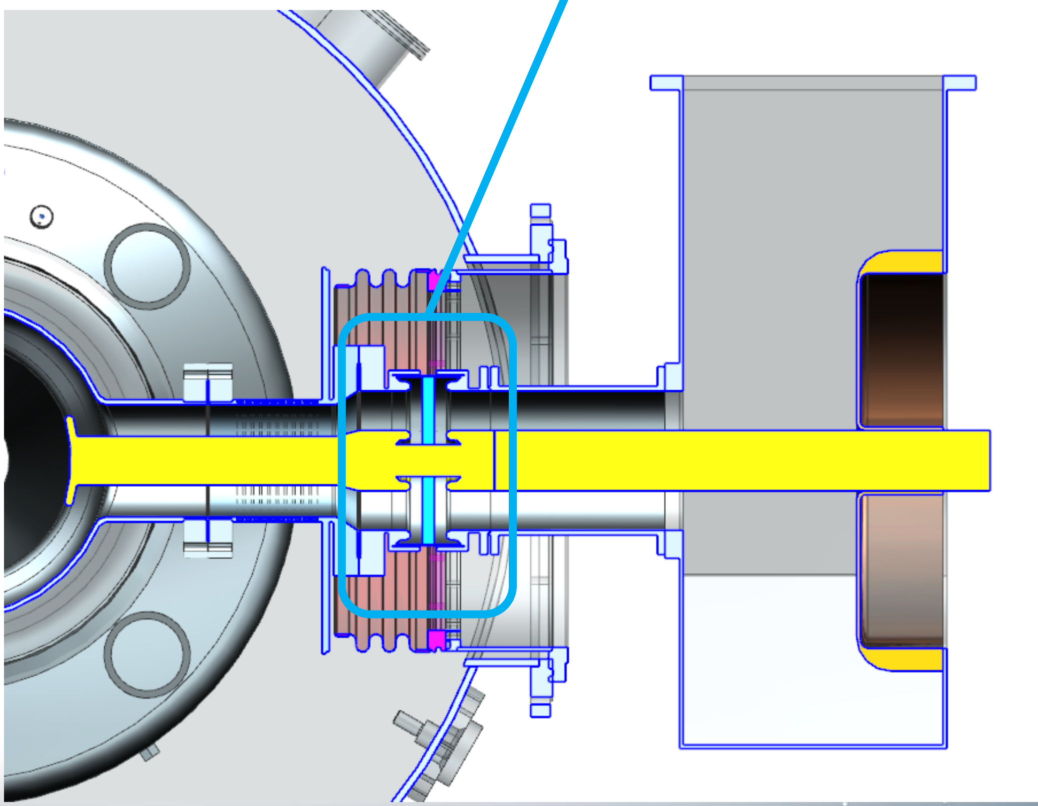
ESR Cavity/Cryomodule Concept with 500 kW Fixed Coupler

- Coupler is an evolution from the KEK / SNS / BNL high power fixed coupler design
- Goals: High power, broadband and physically robust window

End view of the cryomodule, cut on the mid-plane of the couplers. Courtesy: Jim Henry, F. Marhauser.



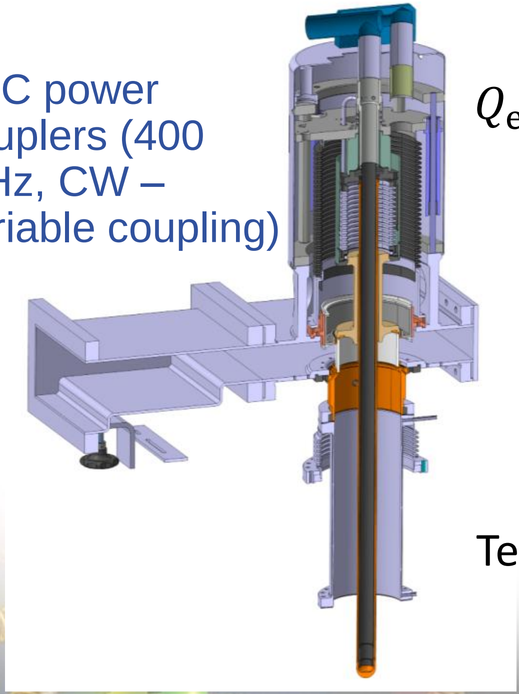
Zoom of one coupler. Pringle position set for minimum Q_{ext}. Ceramic in detuned-short position. Courtesy: Jim Henry.



FCC-ee FPC needs:

- Power need at FCC-ee Z-pole: 1 MW/single-cell cavity.
- FCC baseline: use 2x 500 kW power couplers (LHC-type)
- R&D towards 1 MW CW power couplers is only starting
- Complication: to use the same 4-cell cavities in FCC-ee "WW" and FCC-ee "ZH", the coupling must be changed.

LHC power couplers (400 MHz, CW – variable coupling)



Q_{ext} variable by a factor 20.

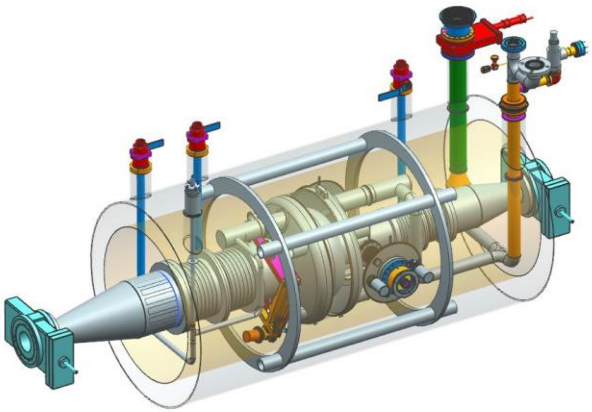
Tested up to 500 kW CW forward.

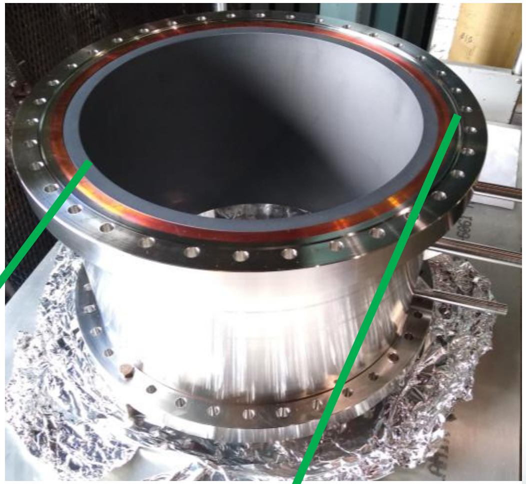
E. Montesinos

EIC High Power SIC HOM Absorber

- Requirement and challenge
  - High power (~20 kW ea.), broadband HOM dampers
  - Large size of SiC HOM damper for low frequency
- Initial LDRD program, now on project
  - Low power test on a cavity to test effective damping bandwidth
  - High power test to test the power handling capability
- Design approach:
  - Solid one-piece HOM damper, Simple shrink-fit assembly based on ANL design

ESR cryomodule concept





RF power options

Super-power klystrons

- Limited vendors, high cost, low efficiency

Combined IOT's

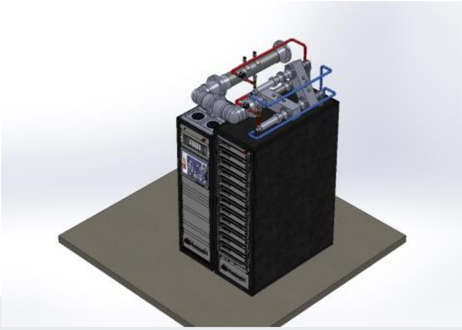
- Better efficiency, becoming obsolete

Combined SSA's

- High efficiency
- Reliability and redundancy
- Costs falling, supply growing

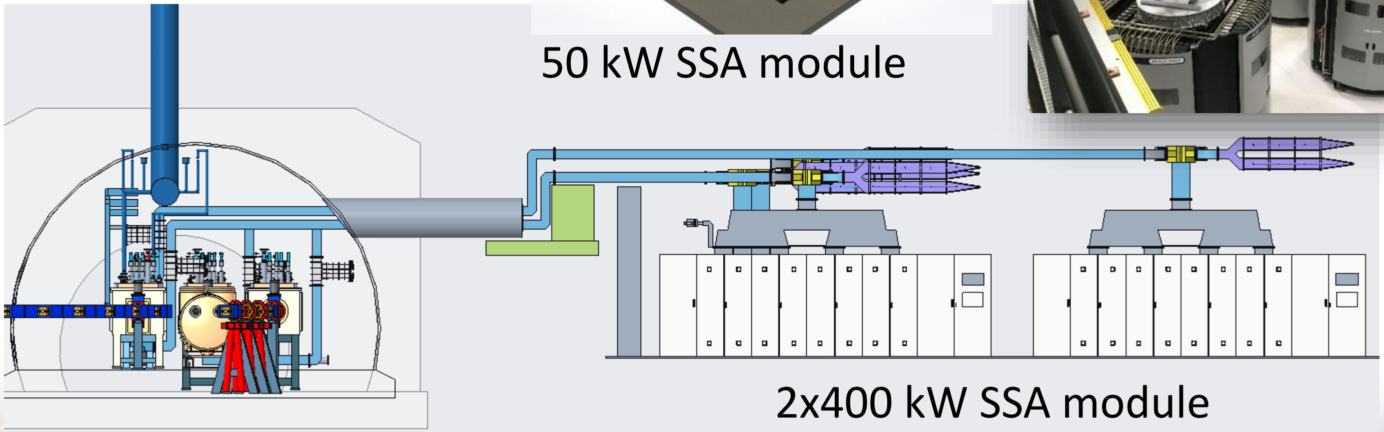
IOT

MW klystron



50 kW SSA module

SPS 200 MHz, 4.6 MW SSPA



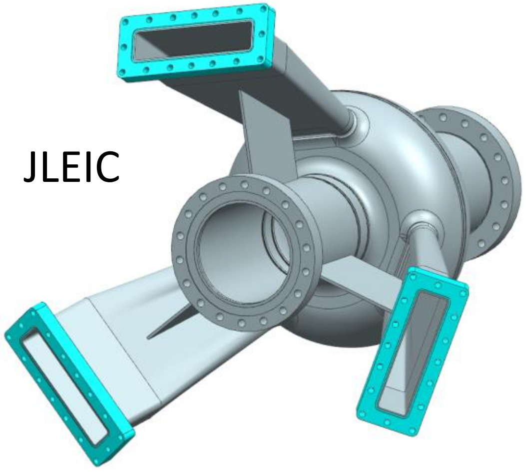
2x400 kW SSA module

Approximately 70 ft, 22m.

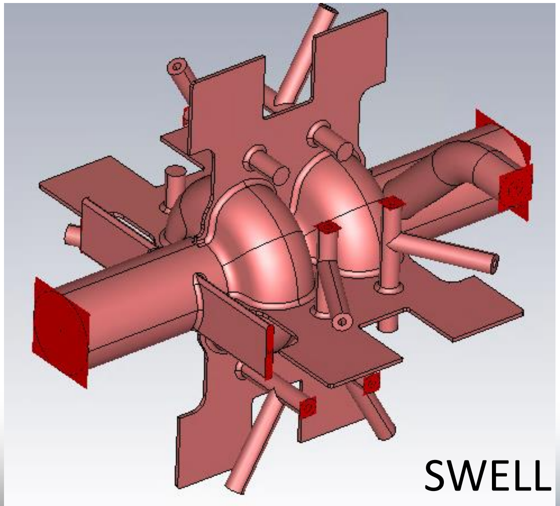
Advanced structure R&D

- Conservative baseline choices (KEK-B and LHC type)
  - Asymmetric EIC cavity under study to ease packaging
- On-cell damped JLEIC concept
  - Jlab LDRD funded
  - "Extreme" HOM damping
- CERN SWELL concept
  - Novel fabrication approach

JLEIC

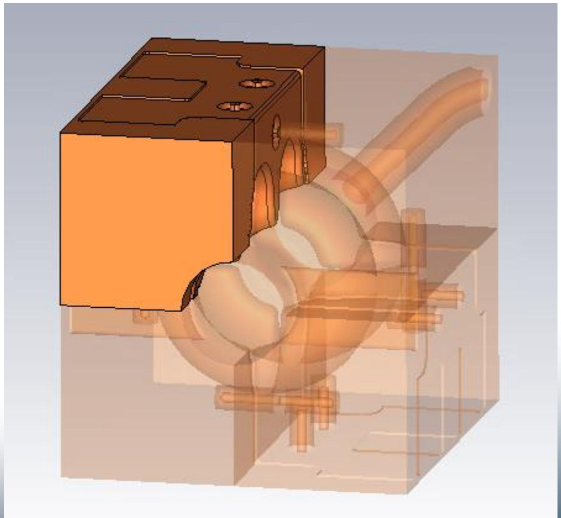


F. Marhauser et. al.



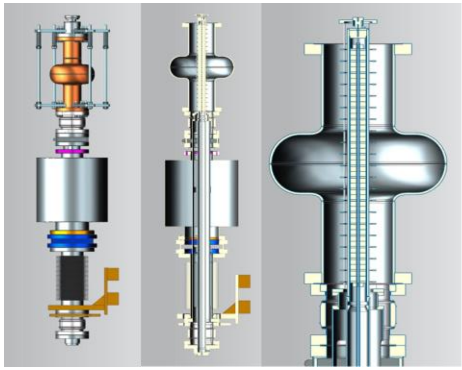
SWELL

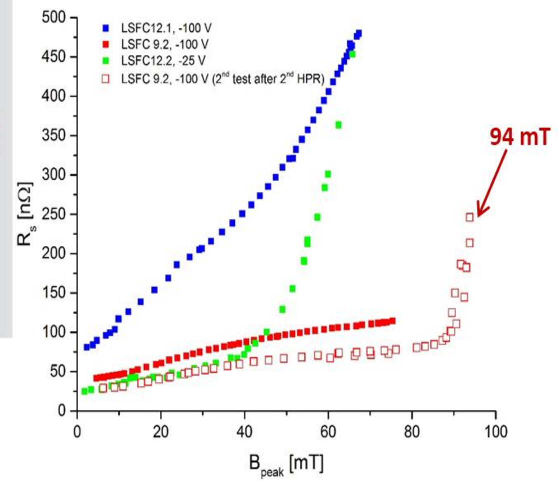
Igor Syratchev et. al.

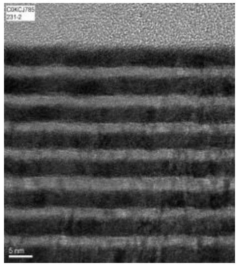


Alternative materials

- Thin film Nb on copper (HIPIMS)
  - Significant cost savings at 197 MHz or 394 MHz
- Multilayers (Nb, NbN, NbTiN)
- Nb_3Sn
  - Potential for high Qo at 4K
- HTS?
  - In time for FCC perhaps?

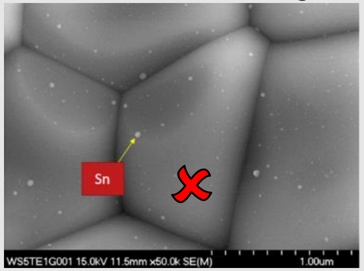


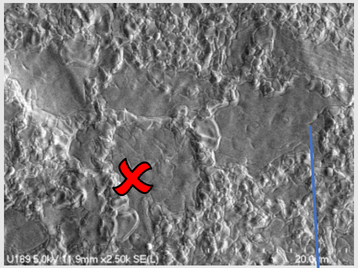




PI: Anne Marie Valente Feliciano

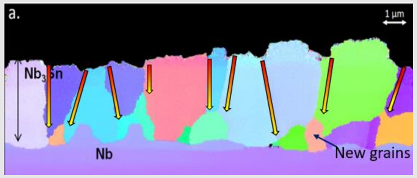
Research to understand the fundamental growth mechanism of Nb_3Sn linked with RF performance

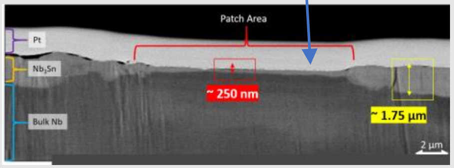


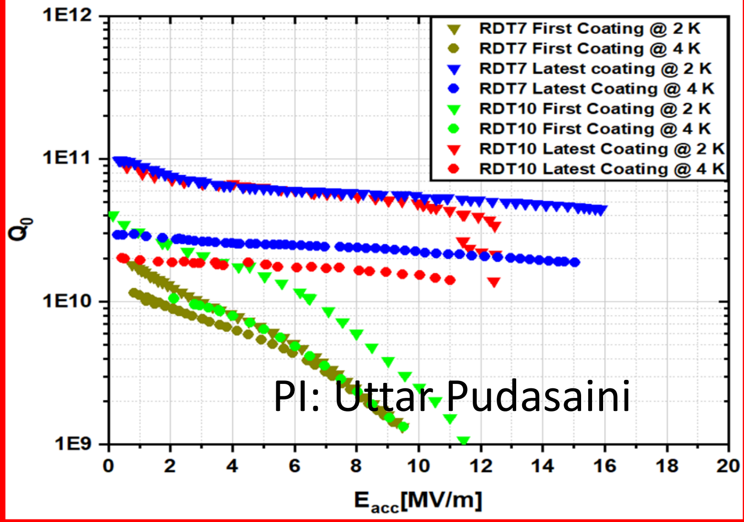


Grain-boundary diffusion primarily controls thin-film growth. Patchy regions lack grain boundaries resulting in thin regions.

Factors contributing to Q-slopes in Nb_3Sn cavities







PI: Uttar Pudasaini

Conclusions

- EIC project is making good progress
- Pushing the state of art on many frontiers
- RF systems being developed as an integrated set
- High degree of modularity in design
- Many challenges ahead and **much synergy with FCC**

Thank You For Your Attention!

Work supported by Brookhaven Science Associates, LLC under DOE Contract No. DE-SC0012704, by Jefferson Science Associates under contract DE-SC0002769, and by SLAC under Contract No. DE-AC02-76SF00515.

Back up

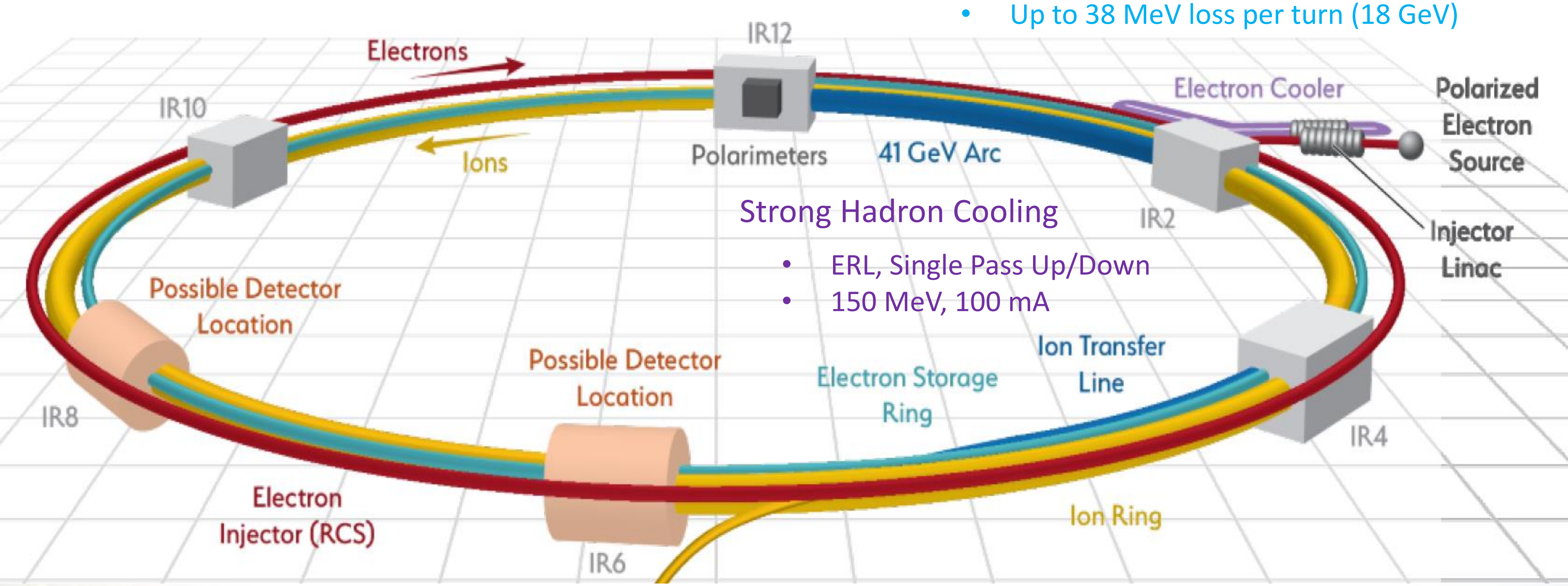
Introduction to EIC at BNL

Hadron Ring based on RHIC

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

ESR: new 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)



Strong Hadron Cooling

- ERL, Single Pass Up/Down
- 150 MeV, 100 mA

IR Crab Cavities

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

RCS: new Rapid Cycling Synchrotron

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

EIC ESR frequency comparison

	394	591	788
#cells (eSR)	14	17	32
#Amplifiers (eSR)	14	17	16
impedance	least	Acceptable (?)	most
Est. HOM power (kW)	264	580*	704
3H freq	1182	1773	2364 (1572 2^{nd}?)
Comments:	Synergy with LHC/FCC	Synergy with FCC-ee? (SWELL?)	Synergy with PERLE/FCC
size	Large. New cavity, cryostat, infrastructure	Large but fits in most Jlab infrastructure and modular cryostat	Fits in cryostat and infrastructure
transients	least	acceptable	most
Max bunch rate (MHz)	394	197	788

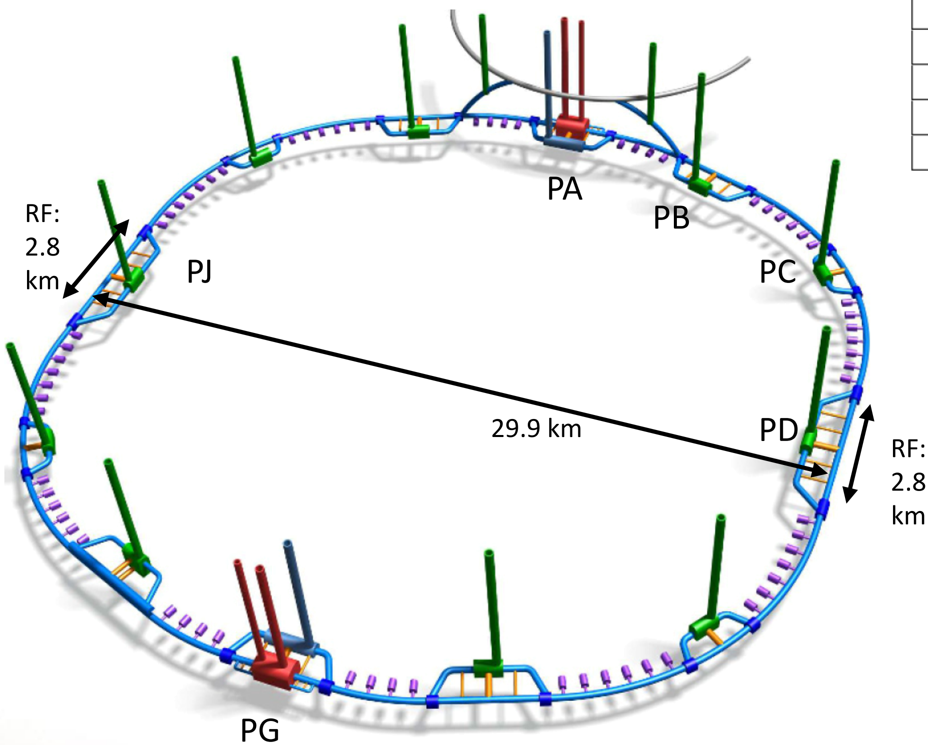
*still under optimization

EIC baseline

600 MHz option for FCC-ee?

FCC-ee RF systems

O. Brunner



Parameter	Z	WW	ZH	$t\bar{t}1$	$t\bar{t}2$
Beam Energy (GeV)	45.6	80	120	175	182.5
Beam current (mA)	1390	147	29	6.4	5.4
Number of bunches	16640	2000	328	59	48
Beam RF voltage (MV)	100	750	2000	9500	10 930
Run time (year)	4	2	3	1	4

Z	400 MHz, 1-cell, strong HOM damping! 2 MV/cavity, 1 MW/cavity!
WW	400 MHz, 4-cell, still substantial BL and HOM excitation, 1 MW/cavity
ZH	400 MHz, 4-cell cavities, 370 kW per cavity (change FPC)
$t\bar{t}$	realign 400 CMs to share them for both beams, add 800 MHz, 5-cell cavities, operated at 20 MV/m, 175 kW/cavity

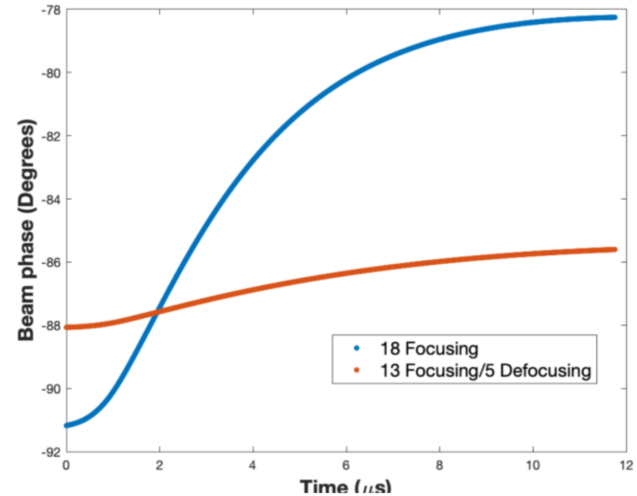
Possible candidates for 600 MHz?

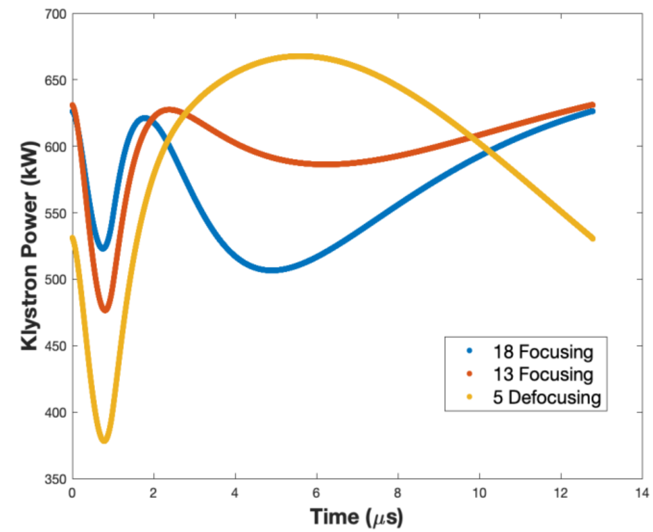
Summary of RF systems for EIC

RF System	Sub System	Freq [MHz]	Type	Location	#
Electron Storage Ring	Fundamental	591	SRF, 1-cell	IR-10	17
RCS	Fundamental	591	SRF, 5-cell	IR-10	3
Pre-Injection LINAC	Buncher 1	118	Copper, ¼ Wave	IR-2	1
	Buncher 2	591	Copper, 1-cell	IR-2	2
	De-chirper	1182	Copper LINAC	IR-2	1
	400 MHz LINAC	2856	SLAC type LINAC	IR-2	6
Hadron Ring	Capture / Accel	24.6	Copper, Quarter Wave	IR-4	2
	Bunch Split 1	49.2	Copper, Quarter Wave	IR-4	2
	Bunch Split 2	98.5	Copper, Quarter Wave	IR-4	2
	Bunch Comp. 1	197	Copper, 1-cell	IR-4	6
	Bunch Comp. 2	591	SRF, 5-cell	IR-10	1
Crab Cavity	Hadron	197 + 394	SRF, RFD	IR-6	8 + 4
	Electron	394	SRF, RFD	IR-6	2
Hadron Cooling	NC Buncher	197	Copper, 1-cell	IR-2	1
	SRF booster.	591	SRF, 1.5-cell	IR-2	1
	ERL Linac	591	SRF, 5-cell	IR-2	8
	Third Harmonic	1773	SRF, 5-cell	IR-2	4

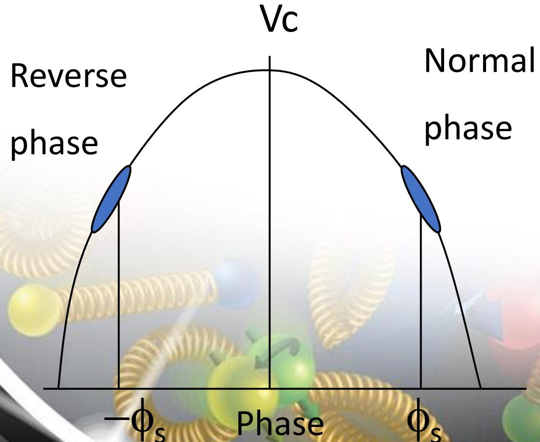
Reverse phase operation

- Also known as counter-phasing or RF FODO
- Allows keeping higher cavity stored energy for nominal bunch length at lower beam energy
- Reduces detuning angle
- Reduces range of Qext of FPC
- Reduces gap transients at low beam energy
- R and N cavities have slightly different gap transients
- R cavity reflected power increases after a beam trip





T. Mastoridis (Cal Poly)



Yoshiyuki Morita, KEK, Presentation at EIC workshop 6-9 Oct 2020 https://indico.cern.ch/event/949203/

Y. Morita et al., IPAC'10, p. 1536