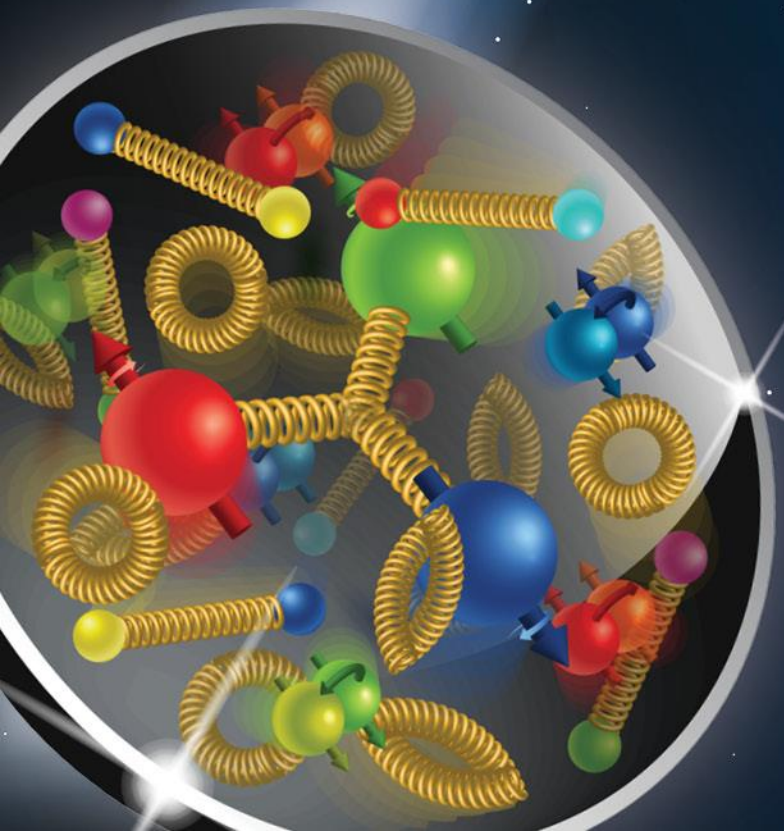

EIC SRF Systems Overview

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TRIUMF 2021 EIC Accelerator Partnership workshop

October 26-29, 2021

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- EIC RF Systems Scope Overview
- EIC SRF Cavity Types and Parameters
- EIC SRF Design Overview
- Conclusion

EIC RF Scope Overview

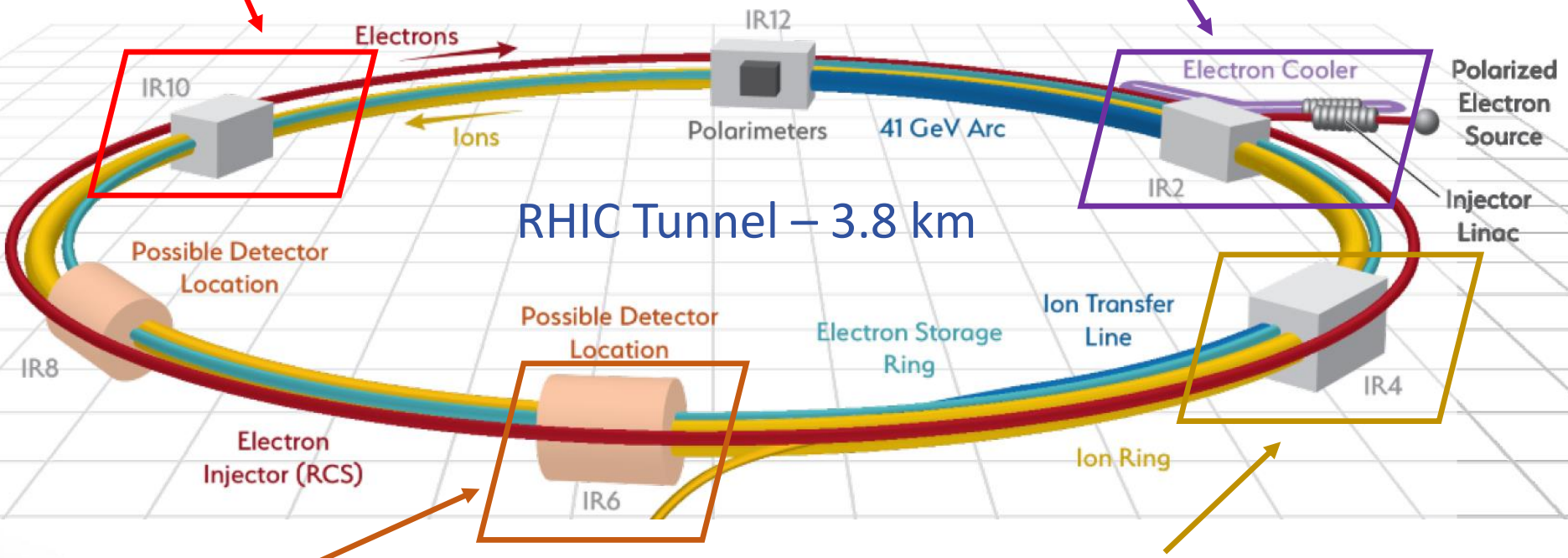
Scope Overview – EIC RF Systems (Geographical)

IR-10: SRF Systems

RCS SRF Systems
Electron Storage Ring SRF Systems
Hadron Ring Storage-2 SRF

IR-2: Strong Hadron Cooling

Energy Recovery Linac (ERL)



IR-6: Crab Cavity SRF Systems

197 MHz and 394 MHz Hadron Crab Cavity Systems
394 MHz Electron Crab Cavity Systems

IR-4: Warm RF Systems

Hadron RF Systems (Hadron SRF at IR-10)
RCS Warm RF Systems (Bunch Merging)

Scope Overview – EIC RF Systems (By Type & Number)

RF System	Sub System	Freq [MHz]	Type	Location	# Cavities
Electron Storage Ring	Fundamental	591	SRF, 1-cell	IR-10	17
Rapid Cycling Synchrotron	Fundamental	591	SRF, 5-cell	IR-10	3
	Bunch Merge 1	295	NCRF, Reentrant	IR-4 or IR-10	2
	Bunch Merge 2	148	NCRF, Reentrant	IR-4 or IR-10	1
Hadron Ring	Capture / Accel	24.6	NCRF, QWR	IR-4	2
	Bunch Split 1	49.2	NCRF, QWR	IR-4	2
	Bunch Split 2	98.5	NCRF, QWR	IR-4	2
	Store 1	197	NCRF, Reentrant	IR-4	6
	Store 2	591	SRF, 5-cell	IR-10	1
Strong Hadron Cooling ERL	Inj. Bunch Comp.	197	NCRF, Reentrant	IR-2	1
ERL Injector design remains	Inj. Booster	591	SRF, 1-cell (MB)	IR-2	1
under active development.	Inj. Booster	591	SRF, 1-cell (HB)	IR-2	1
Not detailed further today.	Inj. Linearization	1773	SRF, 1-cell (HB)	IR-2	1
	ERL Fundamental	591	SRF, 5-cell	IR-2	10
	ERL Third Harmonic	1773	SRF, 5-cell	IR-2	3
Crab Cavity	Hadron	197	SRF, RFD	IR-6	8 (4 CM)
	Hadron/Electron	394	SRF, RFD	IR-6	6

Scope Overview – EIC ESR and HSR Store Beam Parameters

- Example: CDR Table 3.3 - Highest luminosity operation

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

Species			proton	electron						
Energy [GeV]			275	10						5
CM energy [GeV]			104.9						28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9					
No. of bunches	290		1160							
Beam current [A]	0.69	0.227	1	2.5	1					
RM		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
RM		2.0	11.3/1.0	20/1.3	30/				10	20/3.5
β^*, h/v [cm]]		5.7	80/7.2	45/5.6	63/				7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5						198/27	
K_x			11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/		187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB paramet		00	12/12	72/100	12					/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge		ig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6					1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass facto			0.94							
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

- 2.8E11 per bunch injected in 290 bunches.
- 1:2:4 bunch split at store energy

- 17.2E10 per bunch injected
- 1 or 2 bunches at 1Hz rep rate
- 28 nC per bunch
- From RCS RF

- 1260 buckets
- 1us beam abort gap (e- and hadron rings)

- 290 bunches injected
- Store pattern formation: 1 -> 2 -> 4 split

- 3x typical RHIC P current

- 9.125 MW @ 3.65 MeV per turn
- Note: 18 GeV radiates 38 MeV per turn. Thus, only 0.23A

- 0.7 eV*s (95%)
- Requires high voltage for short bunch length

- 0.7cm – 0.9cm equilibrium

- 30cm rms typical at RHIC

- Equilibrium dE/E leads to short bunches

- Hadron Crab RF, SHC ERL RF

- Electron Crab RF

EIC SRF Cavity Types and Parameters

Scope Overview – SRF Cavity Design Parameters

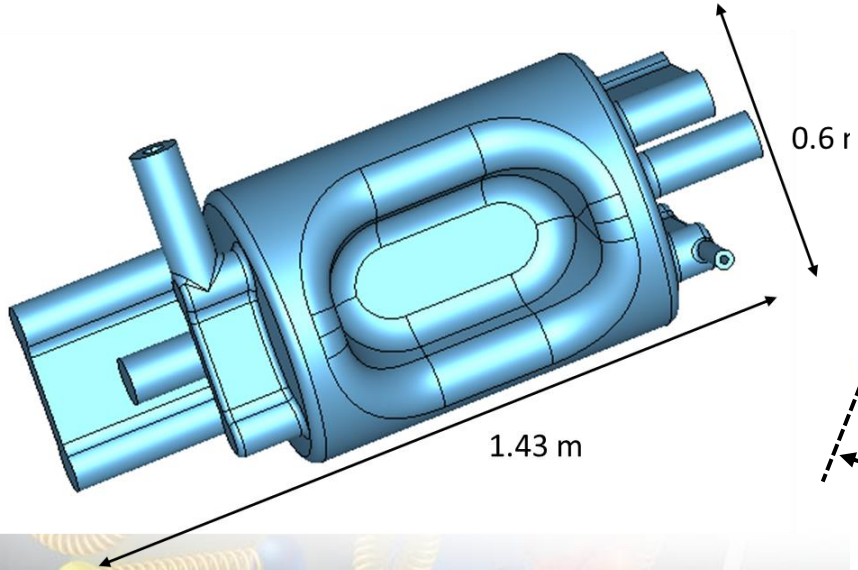
Parameter	591 MHz 1-Cell	591 MHz 5-Cell	1773 MHz 5-Cell	197 MHz Crab RFD	394 MHz Crab RFD
Application	ESR	ERL, RCS, HSR	ERL	HSR	HSR, ESR
Frequency [MHz]	591	591	1773	197	394
Number of Cavities	17	10, 3, 1	3	8	6
Number of Cavities per CM	1	1	1	2	1
Number of CMs	17	14	3	4	6
Operating Temperature [K]	2	2	2	2	2
FPCs per Cavity	2	2, 1, 1	2	1	1
Power per Coupler [kW]	400	50, 75, 75	20	70	70
RF Source Type	SSA	SSA	SSA	SSA	SSA
Beam Current [A]	2.5	0.1, 0.005, 1.0	0.1	1.0	1.0, 2.5
HOM Power per Cavity [kW]	40	0.3, 0, 3	TBD	4-6	TBD (> HSR)
V_{cav} [MV]	4.0	22.0	7.3	11.5 (V_T)	3.5 (V_T)
E_{acc} [MV/m]	15.8	17.4	17.4		
E_{pk} [MV/m]	33.6	39.4	39.4	43.4	35.6
B_{pk} [mT]	76.8	76.7	76.7	78.4	74.3
Operating Temperature [K]	2	2	2	2	2

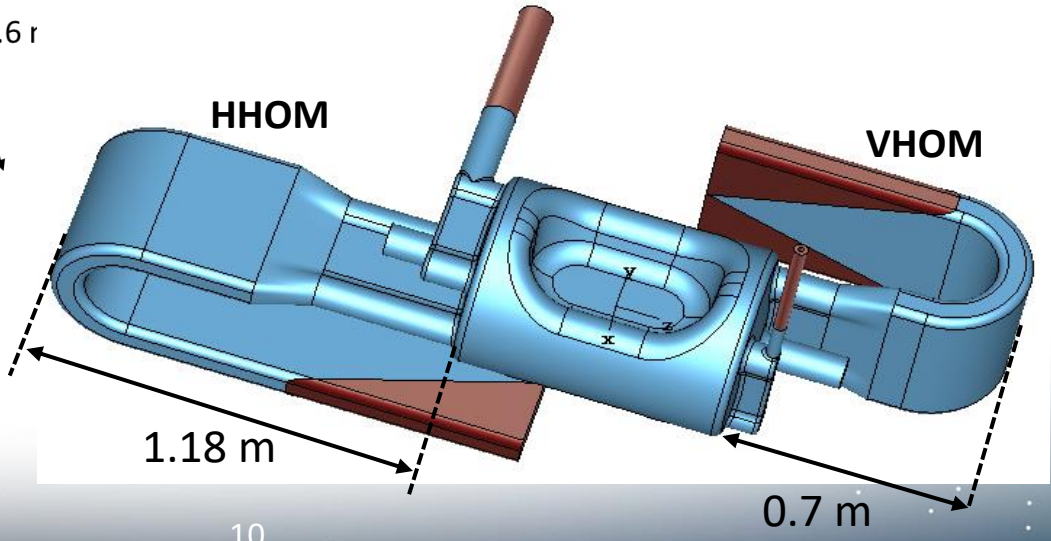
Current EIC SRF Design Overview

EIC Crab Cavity Systems – HSR & ESR

	V_t [MV]		No. of cavities (per IP, per side)	
System	**HSR**	**ESR**	**HSR**	**ESR**
197 MHz	33.83	–	4	–
394 MHz	4.75	2.90	2	1

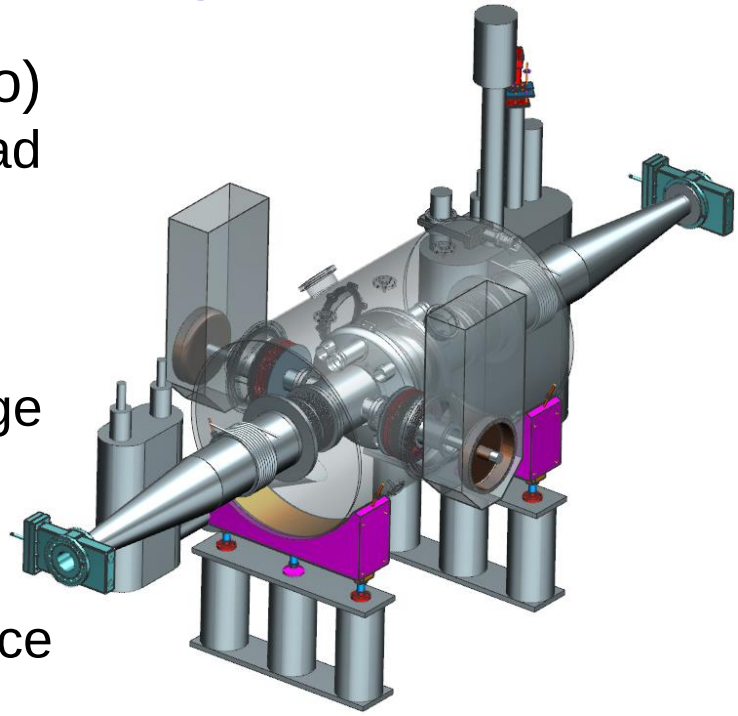
- HSR will have two 197 MHz Crab cryomodules and one 394 MHz Crab cryomodule on each side of the IP.
- ESR requires only one 394 MHz cavity on each side of the IP.
- Refer to extensive information in Crab Cavity workshop presentations by J. Preble, B. Xiao, S. DeSilva and W. Xu.

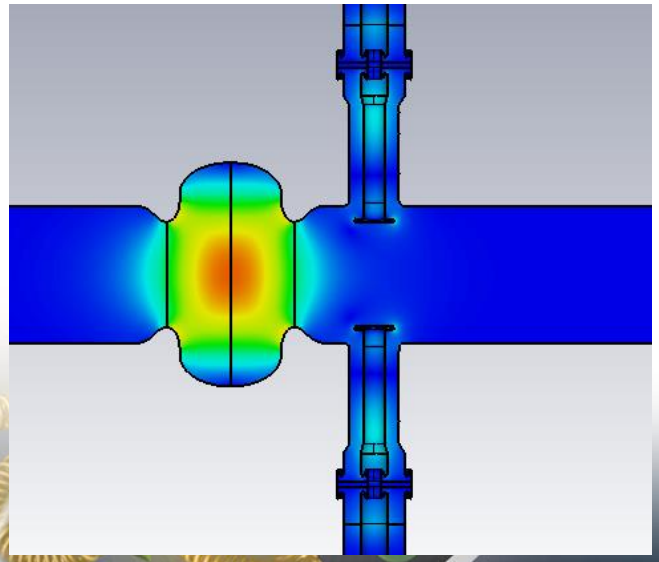


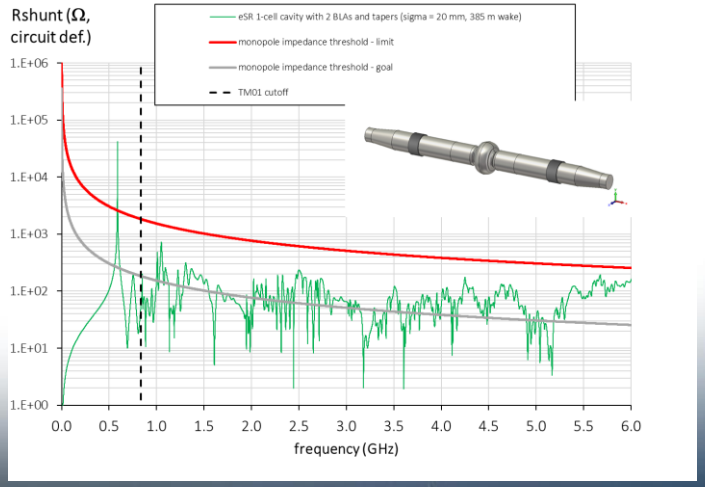


ESR 591 MHz Single Cell Cavity

- 591 MHz Single Cell Cavity for ESR (J.Guo)
  - 68MV, 17 Cav, 2.5A Beam, 10 MW SyncRad
  - Baseline symmetric cavity
    - Low R/Q, high gradient
    - 500 kW CW dual couplers
    - External SiC HOM absorbers (very large beampipe)
  - Alternative asymmetric design under optimization
    - Space saving, possible lower impedance

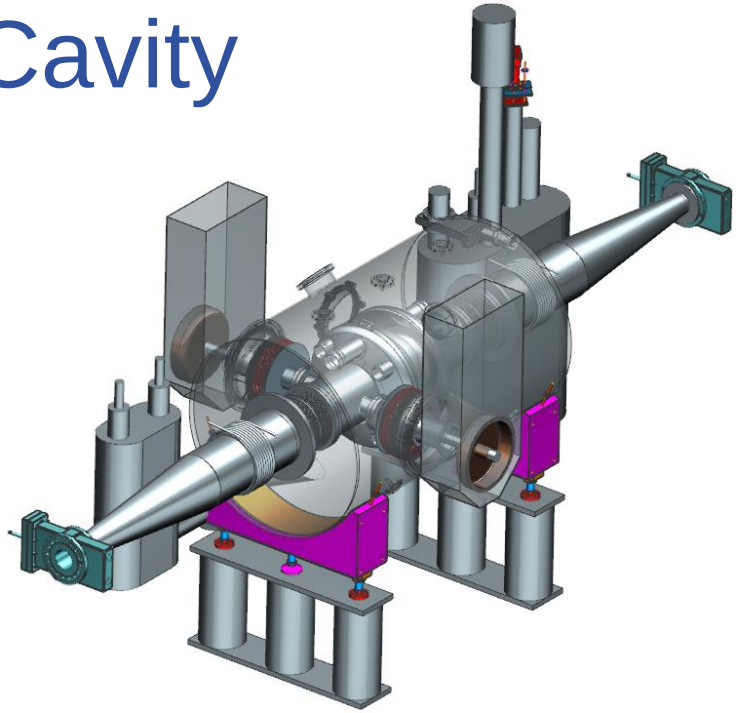




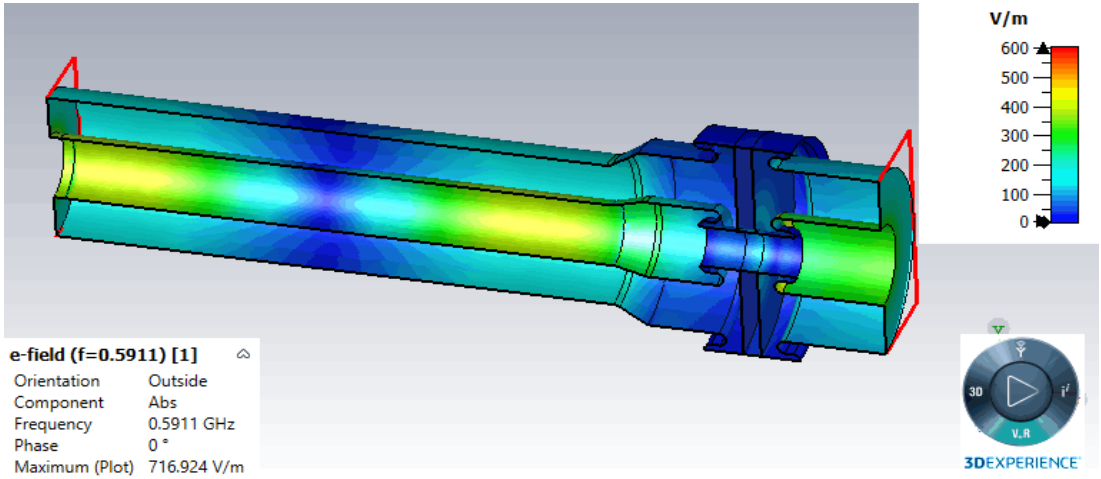


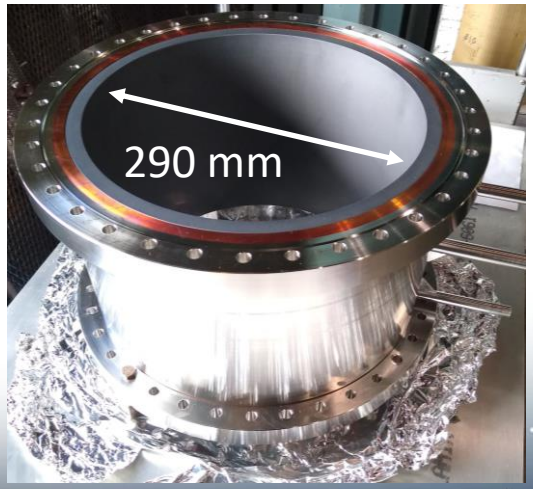
ESR 591 MHz Single Cell Cavity

- 500 kW FPC and 20 kW HOM Absorber
- Refer to workshop presentation by W. Xu.



Two 500 kW CW Fundamental Power Couplers

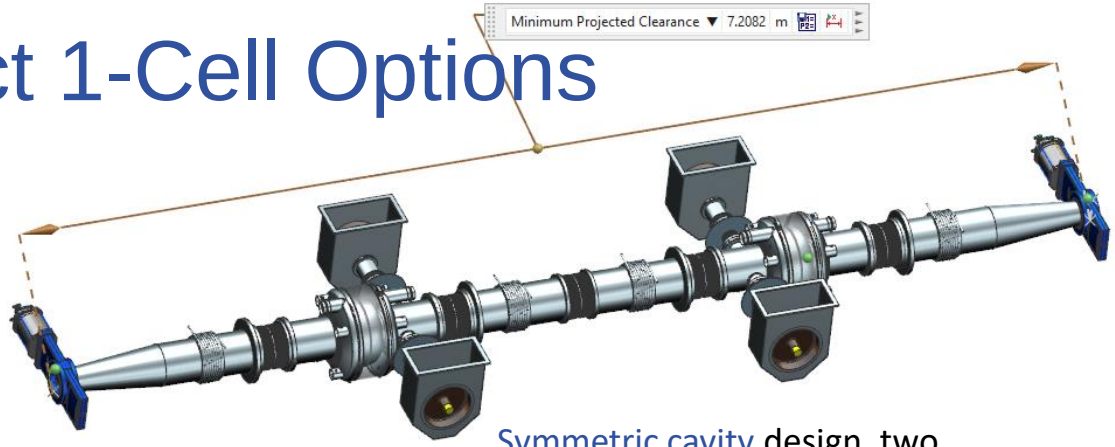




Two 20 kW SiC warm beamline HOM absorbers.

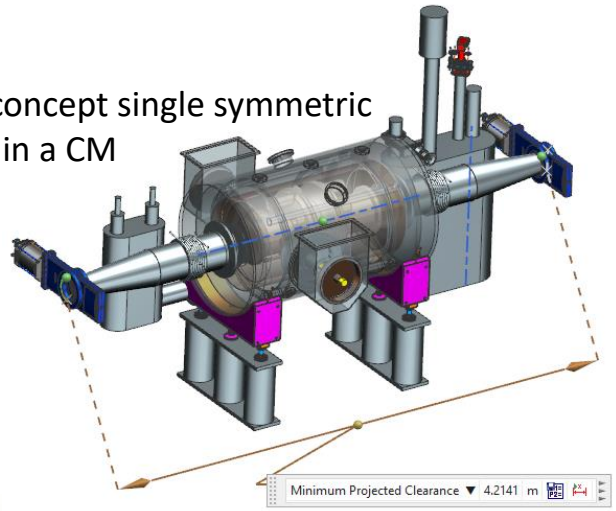
Alternative Compact 1-Cell Options

- Working on space saving options for ESR cavities
  - Minimizing longitudinal space
  - Possible transverse space saving for FPC warm-cold transition with smaller beamtube

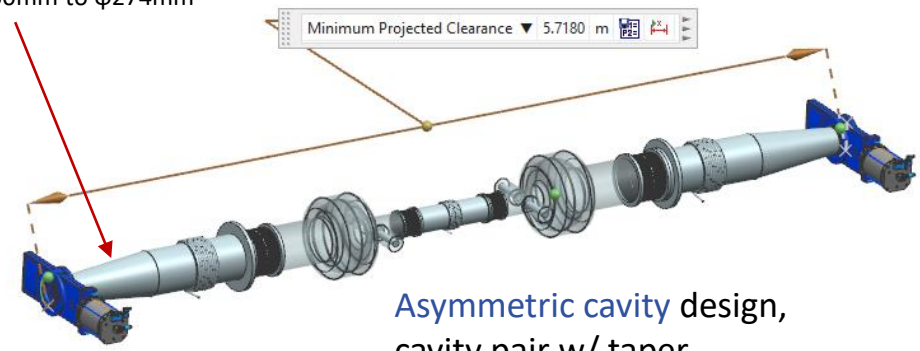


Symmetric cavity design, two cavities back to back

CD-1 concept single symmetric cavity in a CM

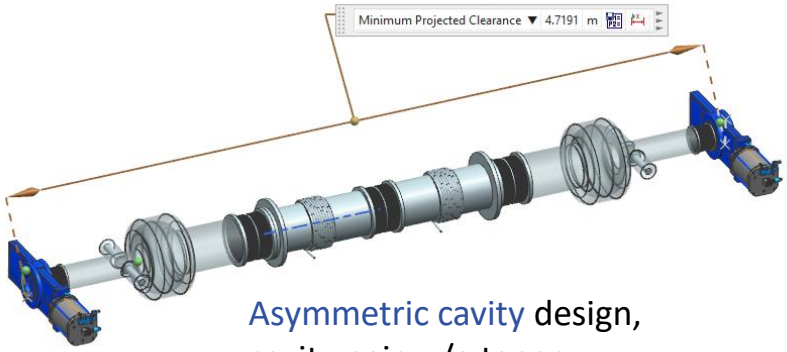


Taper from ϕ150mm to ϕ274mm



Asymmetric cavity design, cavity pair w/ taper

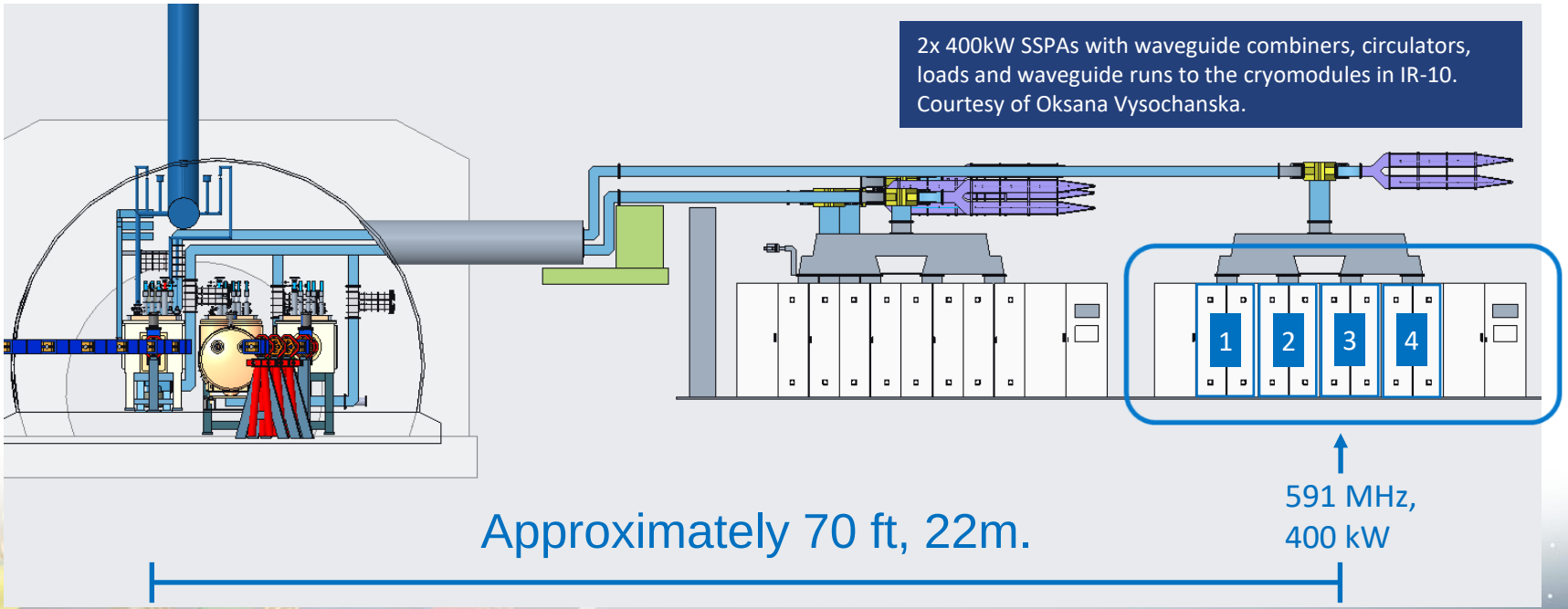
Asymmetric cavity option



Asymmetric cavity design, cavity pair w/o taper

ESR 591 MHz RF System – High Power Amplifiers

- 34 High Power RF Amplifiers
  - 13 MW total installed power for ~9 MW sync rad power, HOM power, other parasitic ring losses. Systems designed for 10 MW sync rad.
  - 350kW – 400kW solid state amplifiers (4x cabinets of 90kW – 100kW ea. + DC power + controls)
  - Solid state has become competitive on cost, power density, space.
  - Additional advantages w.r.t. safety (low voltage), modularity, commonality, future proofing.



591 MHz 5-cell Cavity, Single Cavity Cryomodule

- A common 591 MHz 5-Cell single cavity cryomodule is the CD-1 concept for RCS, HSR and the SHC ERL.

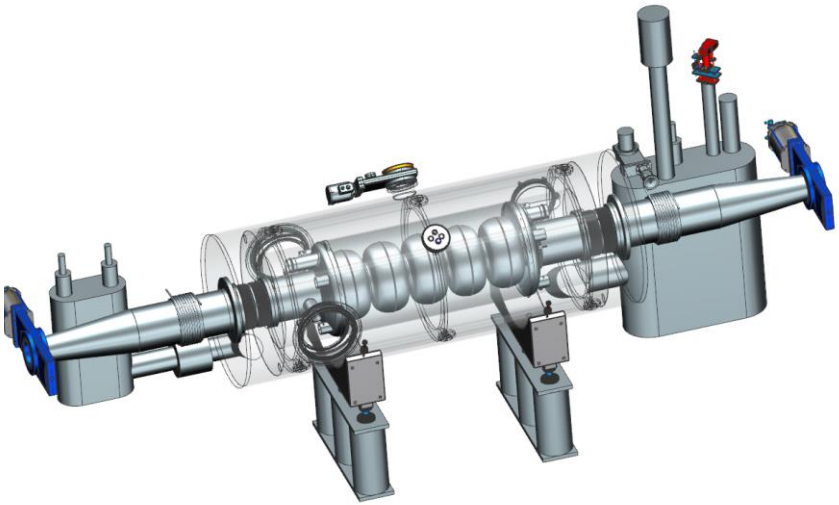
→

- ERL 591 MHz Cryomodule (Qty: 10)
- RCS 591 MHz Cryomodule (Qty: 3)
- HSR 591 MHz Cryomodule (Qty: 1)

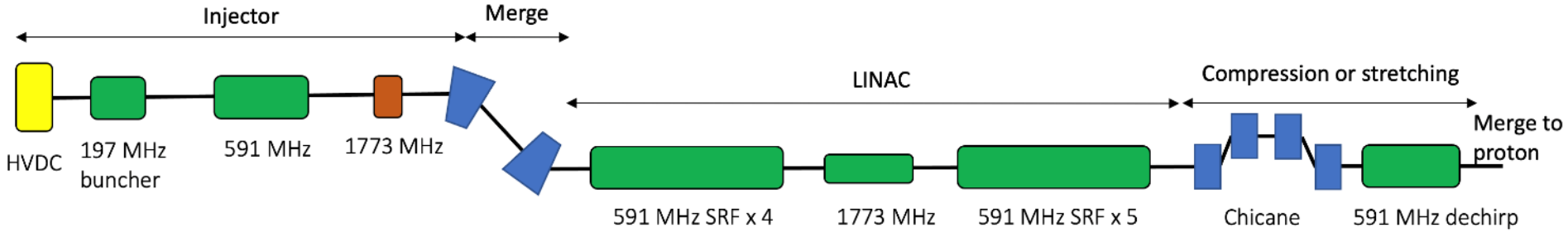
- High Voltage & Strong HOM damping

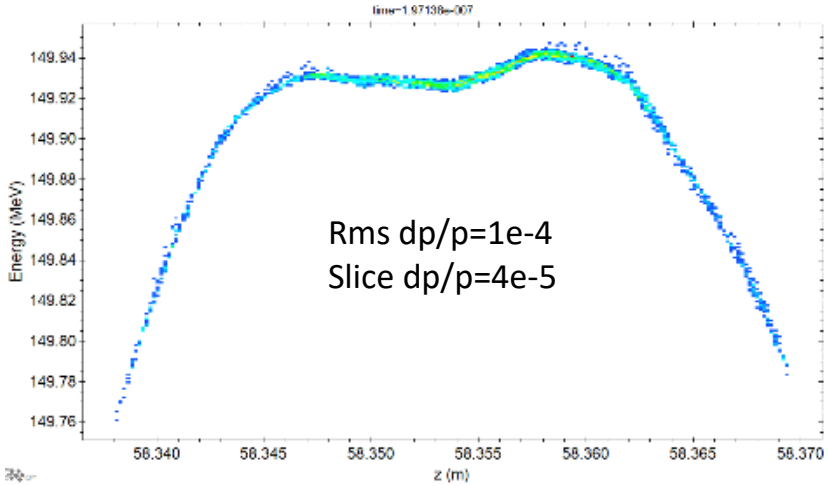
- ERL: 180 MV 591 MHz Fundamental RF
  - 100 mA beam, 98.5 MHz bunch frequency, short bunches
  - Requires strong HOM damping with modest HOM power
- HSR: 20 MV 591 MHz Storage System
  - Up to 1A beam, up to 1160 bunches
  - Requires strong HOM damping with up to 3 kW HOM power
- RCS: 60 MV 591 MHz Acceleration System
  - Up to two 28nC bunches accelerated
  - Requires strong HOM damping but very low HOM power

ERL has the most cavities:
- Strong HOM damping, but modest HOM power
- Tight space constraints
- Evaluating other options (see alternatives slide 17)

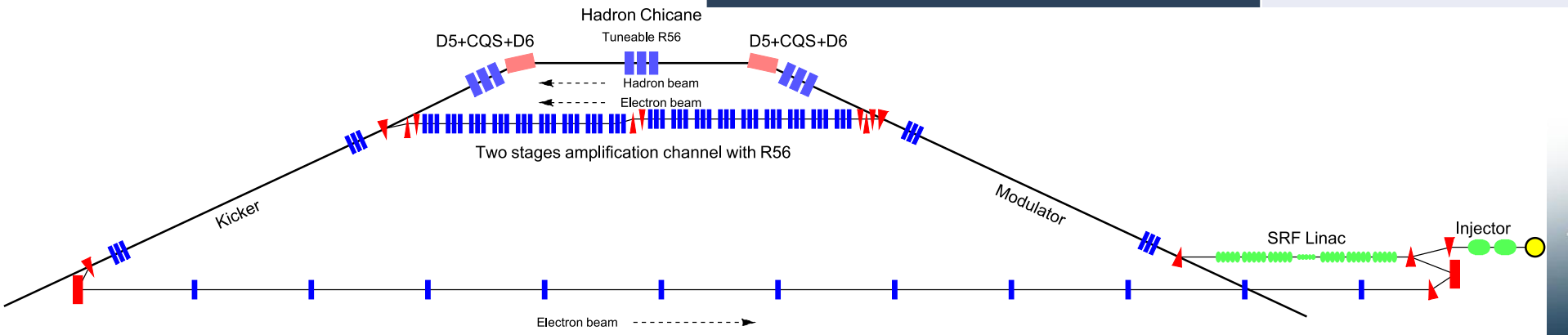


Strong Hadron Cooling (SHC) ERL RF Systems



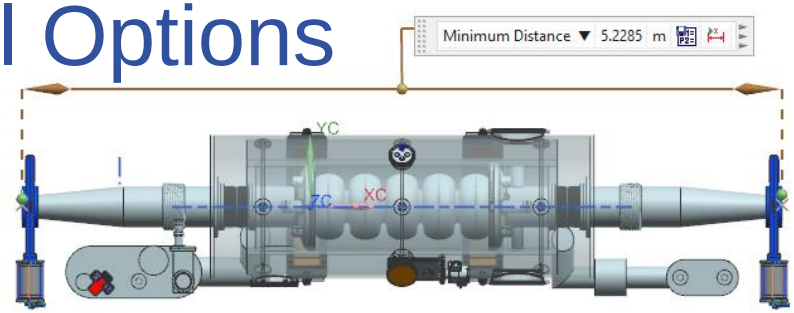


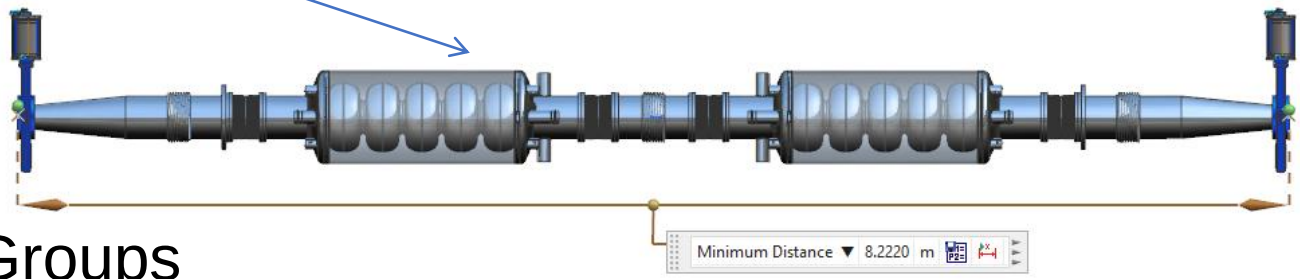
	parameter
Bunch charge	1 nC
Peak current	8.5-34 A
RMS Bunch length	14-3.4 mm
RMS Normalized emittance	3 mm-mrad
Energy	150 MeV
RMS dp/p	<1 e-4



Alternative Compact 5-Cell Options

- CD-1 Concept 5-cell
- Two per cryomodule

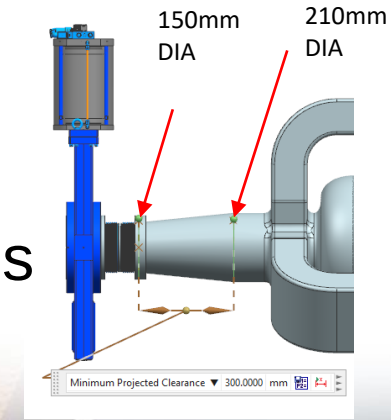




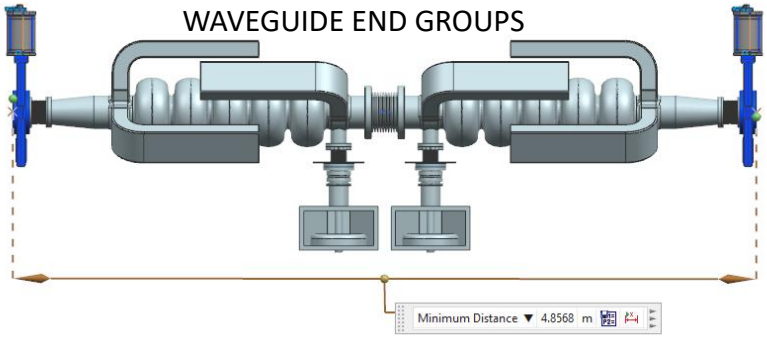
- Compact End Groups
  - Waveguide

    Jlab, HZB
  - Coaxial

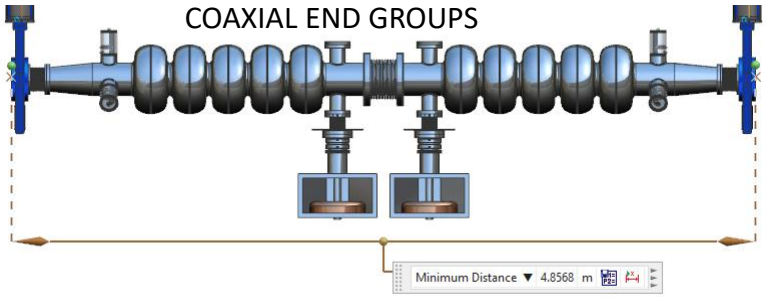
    HERA, LHC,
    TESLA, C100
- Need more analysis



WAVEGUIDE END GROUPS



COAXIAL END GROUPS



Conclusion

Conclusions

- EIC requires multiple new SRF systems (cavity, power, and control). Many opportunities for new and exciting work.

- Focused effort to retire risk determines current work. Early work based at BNL and JLab is the basis for developing the appropriate understanding and reducing risk.

- Requirements and designs are mature but not final. The beam and machine physics are still being finalized. Some requirements remain to be understood and finalized. SRF systems may need to be updated as the design is finalized.

- Need to leverage common designs where possible. The schedule and the cost of developing these systems needs to be minimized where possible.

Thank You