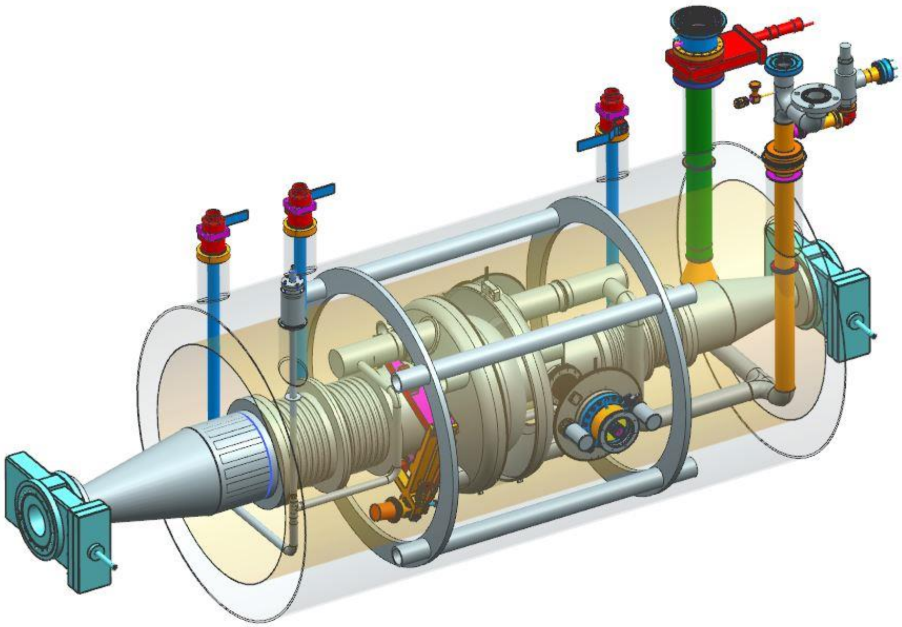
SRF

SRF Challenges and R&D for the EIC



Bob Rimmer

For the EIC RF design team

FCC week, 11.20

EIC RF Design Team and Contributors

- BNL EIC RF Leadership
  - K. Smith
  - A. Zaltsman
- BNL EIC RF Team
  - G. Bassi
  - M. Blaskiewicz
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  - S. De Silva (ODU)
  - J. Delayen (ODU)
  - H. Park
- JLAB EIC RF Support
  - J. Matalevich
  - M. Wiseman

- LLRF System Simulations
  - T. Mastoridis (Cal Poly)
  - J. Fox (Stanford University)
  - C. Rivetta (SLAC)
- Crab Cavity HOM Damping Simulations
  - Z. Li (SLAC)

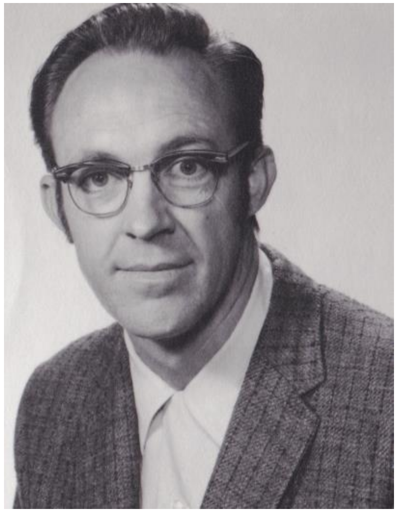
The Future Circular Collider Innovation Study (FCCIS) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant No 951754.

Outline

- Dedication
- Overview of EIC
- SRF systems overview
  - ESR
  - HSR
  - Crabbing
  - RCS
  - Strong Hadron Cooling
- LLRF
- Critical component R&D
- RF power
- Alternative materials
- Conclusions

Dedication: to Glen Lambertson, 1926-2020

Glen Lambertson, whose Berkeley Lab career in accelerator science and technology spanned more than half a century, passed away August 30 in Oakland, CA at the age of 94.



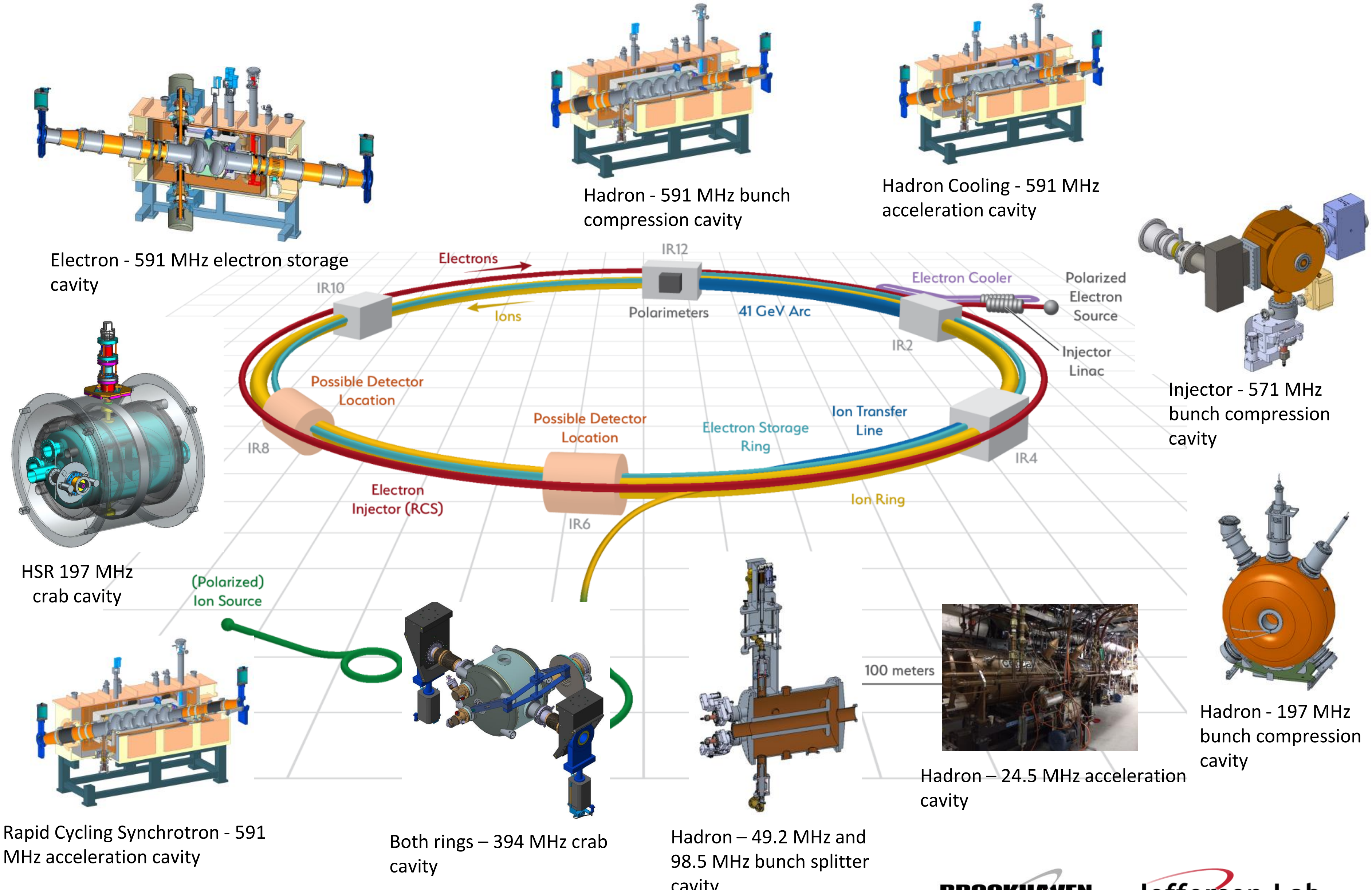
Raised in Colorado in a farmhouse without electricity, Lambertson would become known for seminal contributions to some of the most advanced and nuanced aspects of particle accelerators, making possible the infrastructure of discovery.

A great but humble man who was a mentor to me and many many others

His ideas live on in machines like these.

https://atap.lbl.gov/in-memoriam-glen-r-lambertson-1926-2020/

EIC RF systems



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EIC RF Systems (By The Numbers)

RF System	Sub System	Freq [MHz]	Type	Location	# Cavities
Electron Storage Ring	Fundamental	591	SRF, 1-cell	IR-10	18
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	7
	Store 2	591	SRF, 5-cell	IR-10	2
Strong Hadron Cooling	Bunch Comp.	197	NCRF, Reentrant	IR-2	1
	SRF Booster	197	NCRF, Reentrant	IR-2	6
	Linearization	591	NCRF, Reentrant	IR-2	2
	Fundamental	591	SRF, 5-cell	IR-2	8
	Third Harmonic	1773	SRF, 5-cell	IR-2	3
Crab Cavity	Hadron	197	SRF, DQW/RFD	IR-6	8 (4 CM)
	Hadron/Electron	394	SRF, DQW/RFD	IR-6	6

EIC Proton and Electron Beam Parameters

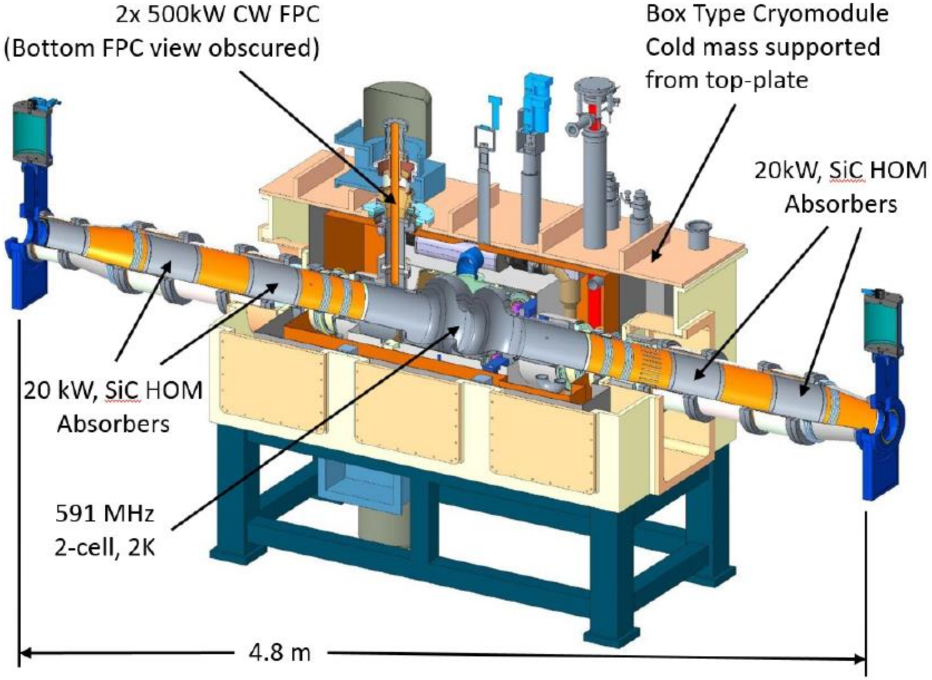
- Example: CDR Table 3.3 - Highest luminosity operation

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

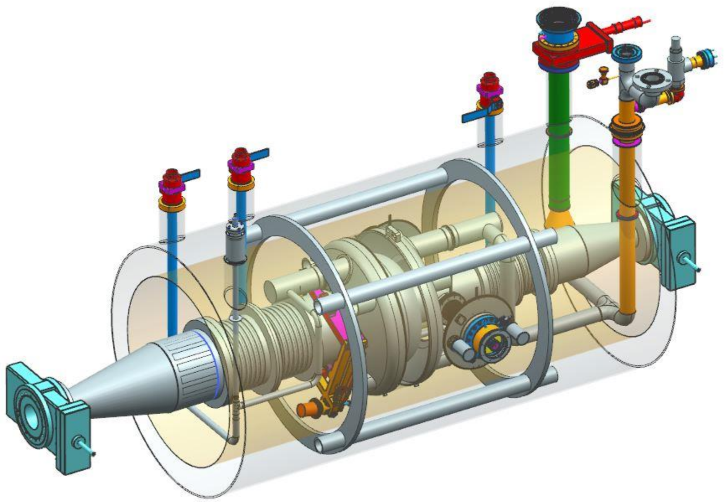
Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam 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
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	**1**	7	~1	7	~1	7.5	~1
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	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	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 factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1.54		10.00		4.48		3.68		0.44	

ESR RF system

- Up to 70 MV using new 591 MHz SRF cavities
  - maintain 1.2% Bucket height from 5-18 GeV
- Naturally short bunch length ~1cm
- 10MW maximum beam power, 2.5A maximum current
- Two fundamental power couplers per cavity, ~400kW ea.
- Beam loading effects will be significant.



CDR two cell design



Alternate single-cell design
(JLab style cryostat)

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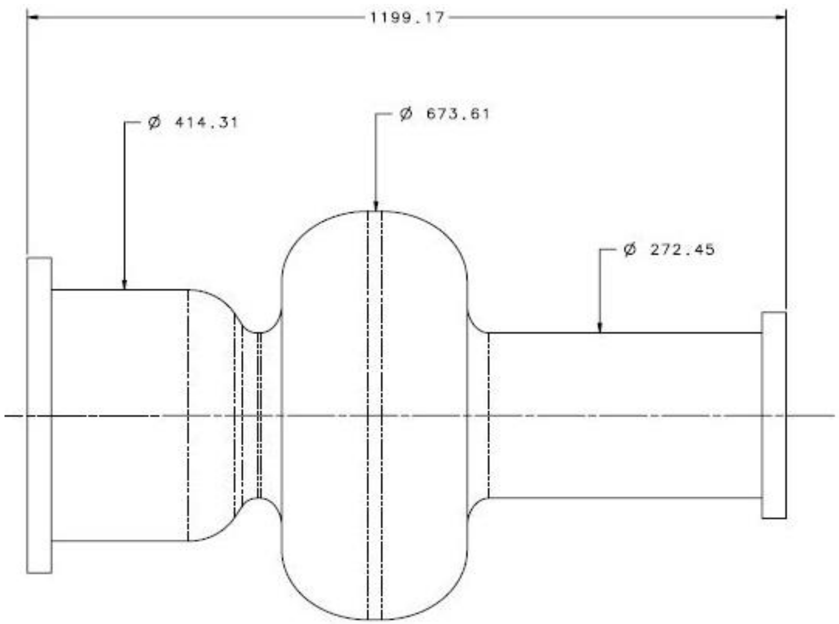
ESR frequency comparison

	394	591	788
#cells (eSR)	14	18	32
#Amplifiers (eSR)	14	18	16
impedance	least	reference	most
Est. HOM power (kW)	264	528	704
3H freq	1182	1773	2364 (1572 2^{nd}?)
Comments:	Synergy with LHC/FCC (e.g. crabs)	unique	Synergy with PERLE/FCC (e.g. crabs)
size	New cavity, cryostat, infrastructure	CDR reference design (fits in Jlab mod. cryostat)	Fits in cryostat and infrastructure
transients	least	acceptable	most
Max bunch rate (MHz)	394	197	788

Baseline for CDR

394 MHz cavity dimensions

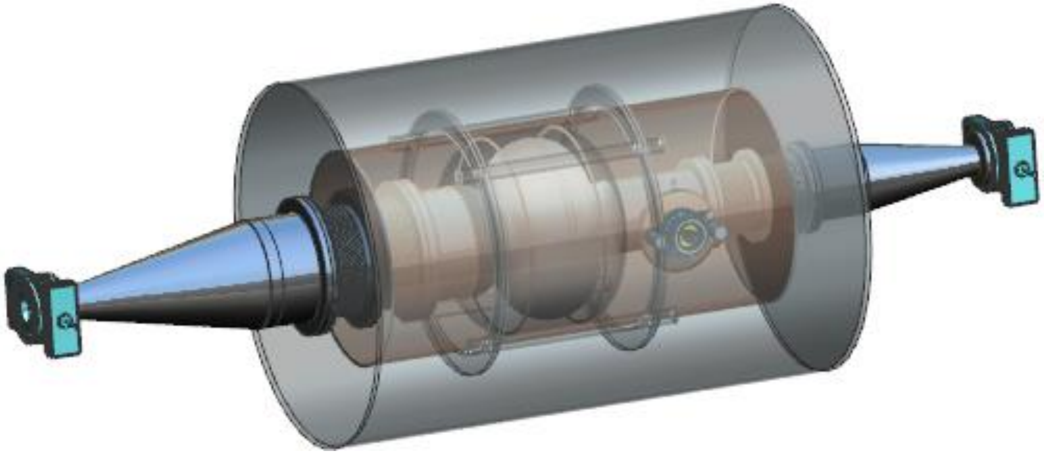


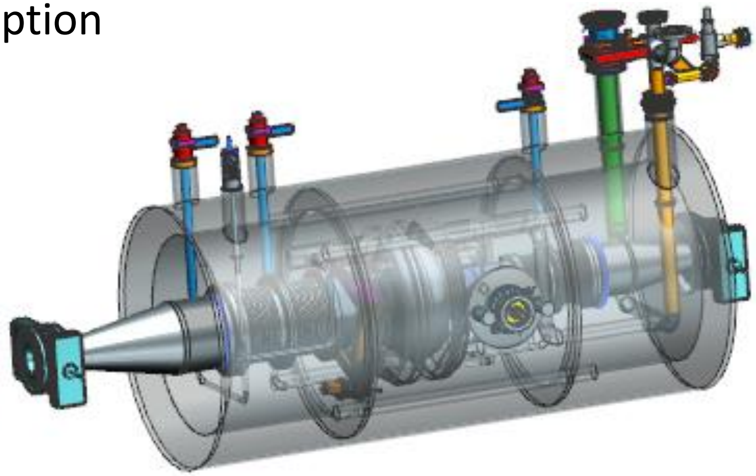
Jlab 400 MHz cavity

Feisi He thesis project
SRF2013, Paris, France

Will keep studying as a back up option

394 MHz 1-cell concept





591 MHz 1-cell concept

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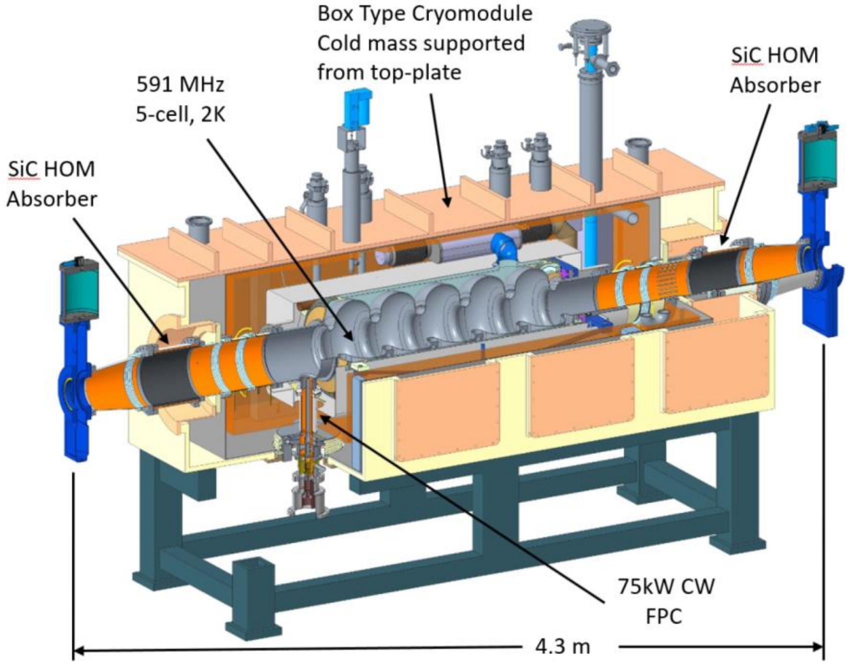
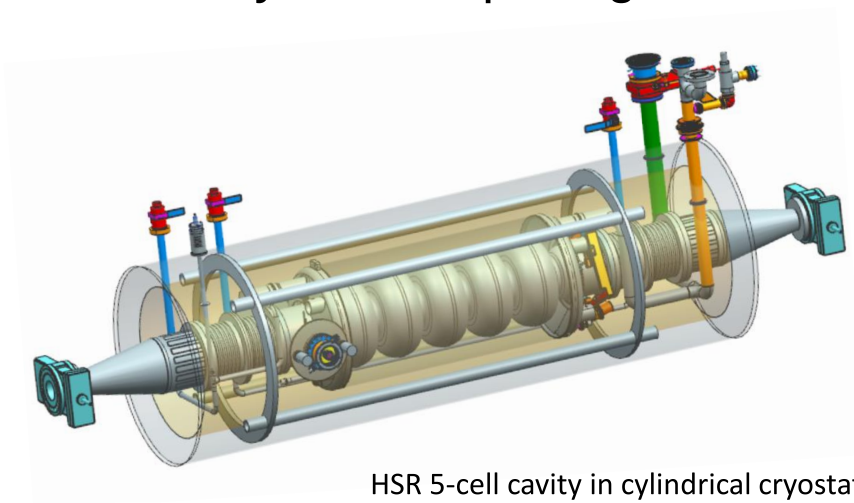
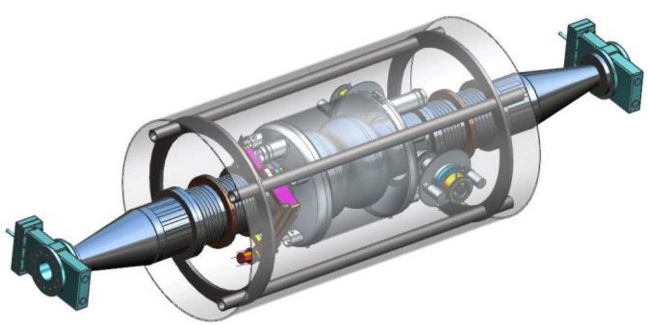
HSR RF system

- Keep existing RHIC 12 MV 12x197 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 28 MV 591 MHz SRF system
- Up to 1A beam, up to 1160 bunches



HSR RF system 5-cell cavity cryomodule design.


HSR 5-cell cavity in cylindrical cryostat.


Alternate 2-cell cavity cryomodule design.

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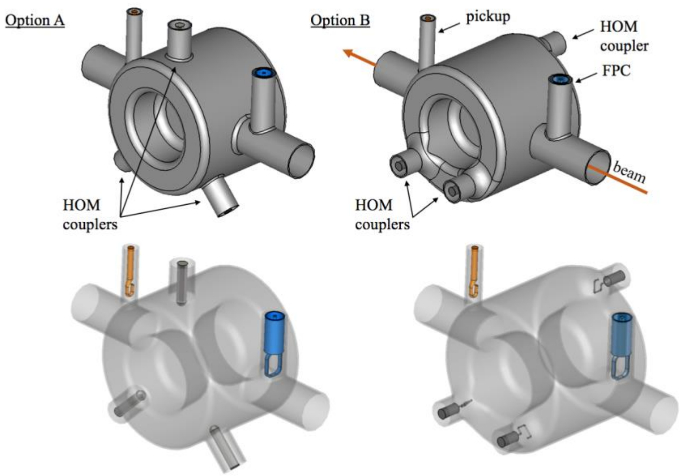
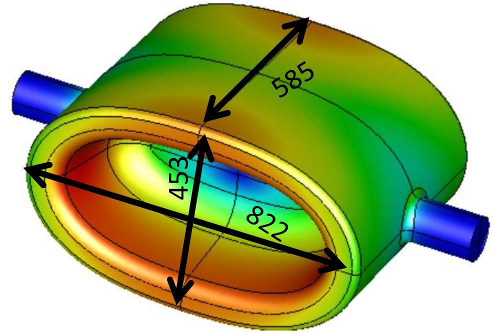
Crabbing Systems

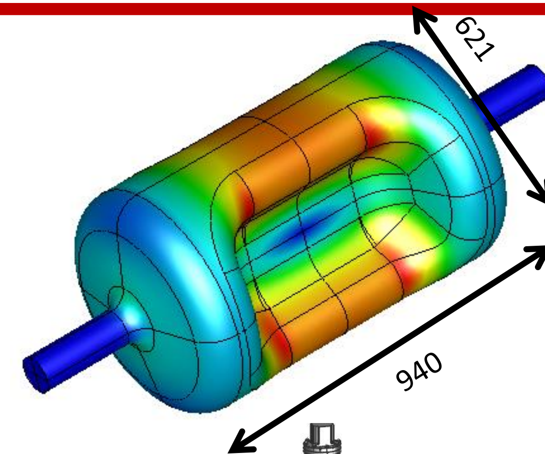
- New SRF crabbing systems for both rings
- Large voltage needed for 25 mRad crossing angle
- ESR system 394 MHz 2.9 MV each side
- HSR system 197 MHz 34 MV each side
  - Need second harmonic for linearization
- IR 6 total 8x 197 MHz cavities, 4x 394 MHz cavities
- **LHC crab cavity tests in SPS are invaluable!**
- Two candidates under consideration based on LHC experience, DQW and RFD
  - Both meet voltage requirements
  - Both can meet pressure code (even at 197 MHz)
  - Both have been fabricated at 400 MHz
  - Both need improved HOM damping for EIC

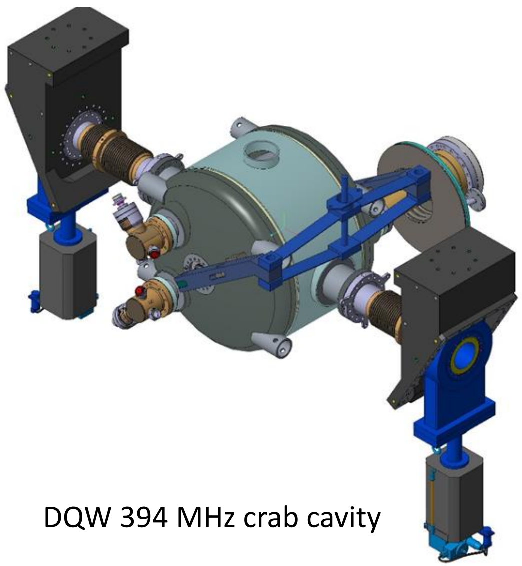
Crabbing Systems



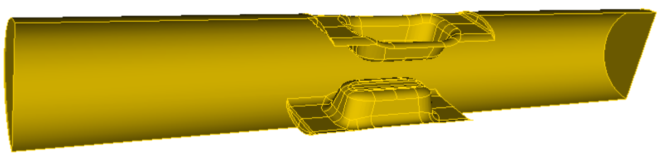


DQW 197 MHz crab cavity



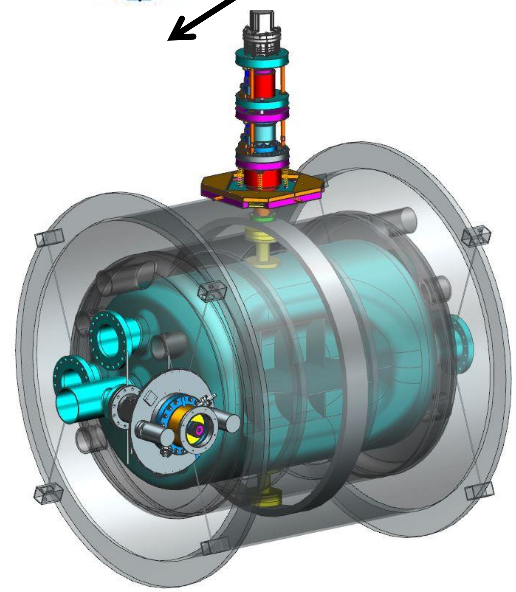


DQW 394 MHz crab cavity



“WOW” crab cavity

Courtesy: Zhenghai. Li



RFD 197 MHz crab cavity

Courtesy: Qiong Wu, Silvia Verdú-Andrés, Doug Holmes, Binping Xiao

Courtesy: Suba Da Silva, HyeKyoung Park, Jean Delayen, ODU, Jim Henry Jlab.

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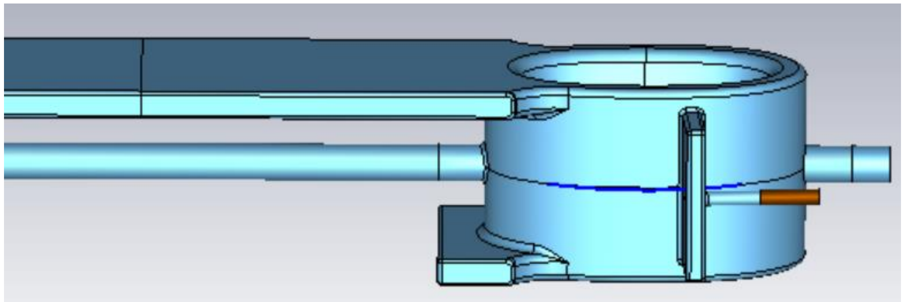
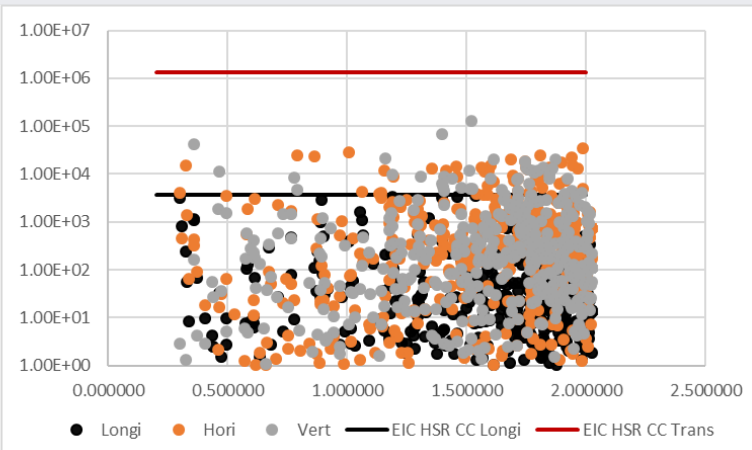
Crabbing RF systems HOM damping

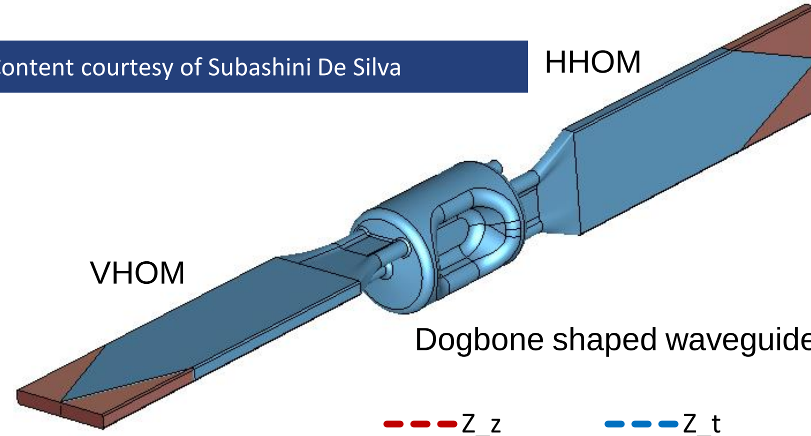
Content courtesy of Binping Xiao

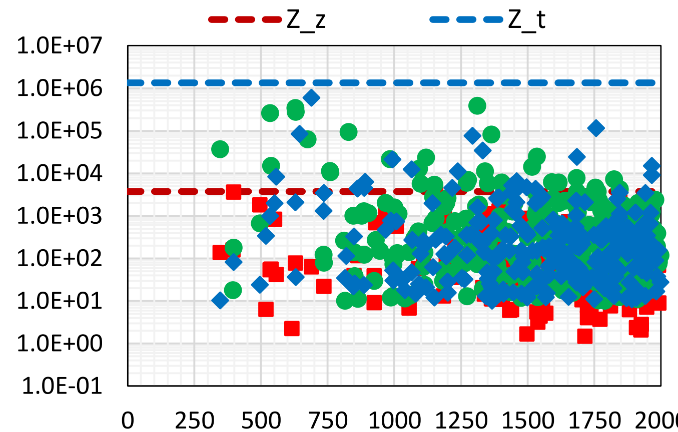




- 290 bunches 0.74A, and 1160 bunches 1A, are considered, with 6cm bunch length.
- HOM power is <3.41kW, with more than 80% from longitudinal modes.

Content courtesy of Subashini De Silva



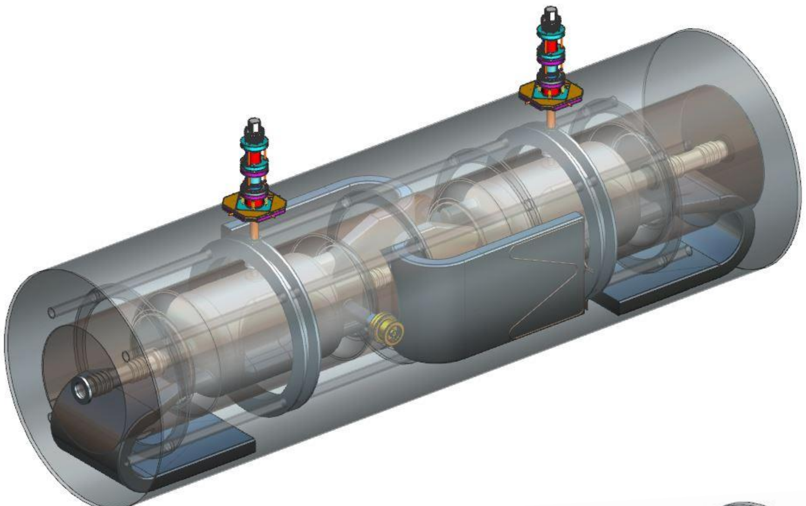


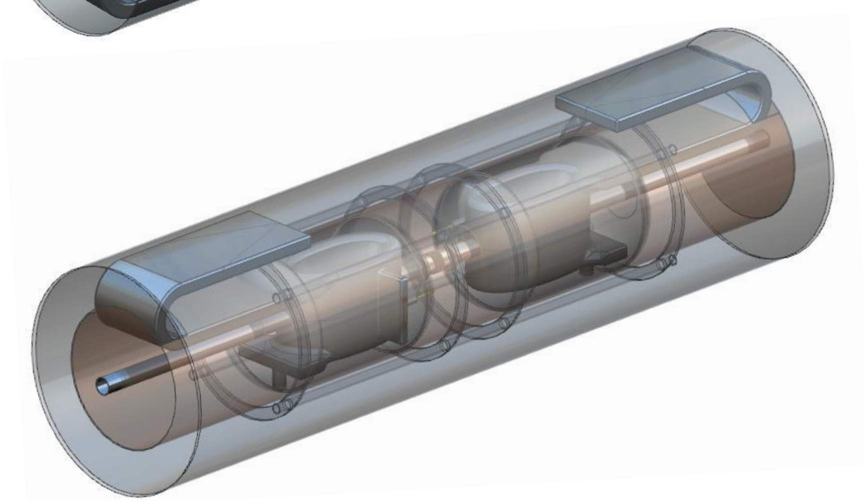
Case	Accumulated Power [kW]
1160 buckets ON 100 buckets OFF	5.5
290 buckets ON 25 buckets OFF	10
1260 buckets NO GAP	4.8

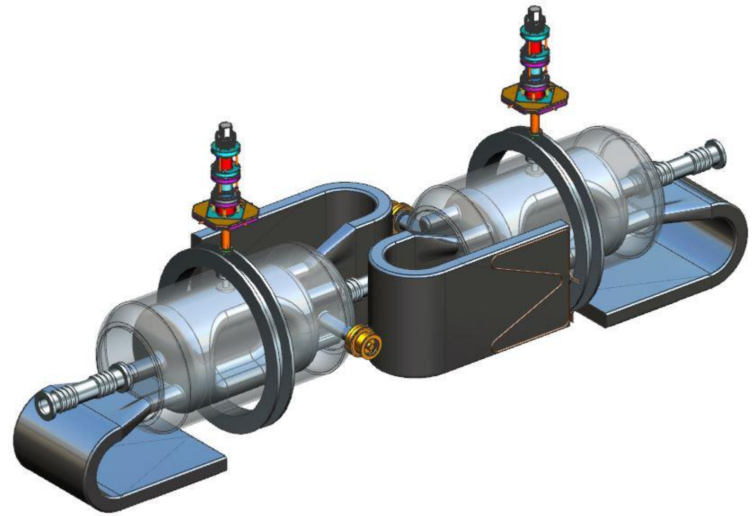
Impedance thresholds:
$Z_l = 3750\ \Omega$, $Z_t = 1.35\times10^6\ \Omega/m$

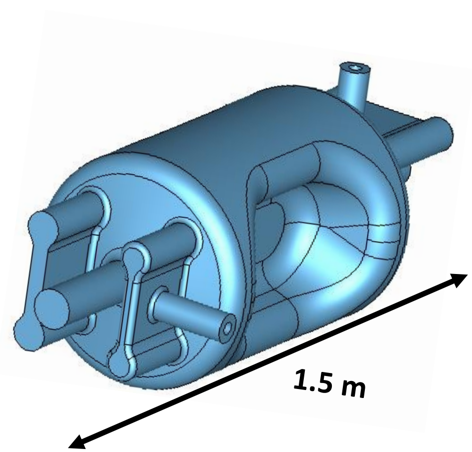
Crab cavity packaging

- Waveguides can be folded
- HOM loads in warm region outside thermal shield







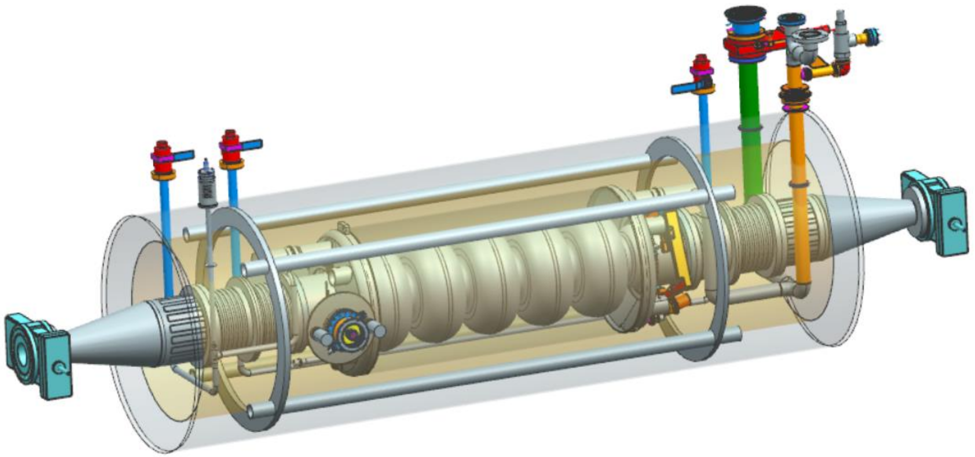


Also looking at coax transitions

Rapid Cycling Synchrotron

- 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
- Fast tuning during ramping

E_{acc}: 15.8 MV/m
P_{dyn}: 32 W
U_{sync} = 36 MeV / turn (18 GeV)
Δf_{acc} = 500 Hz from 400 MeV – 18 GeV.



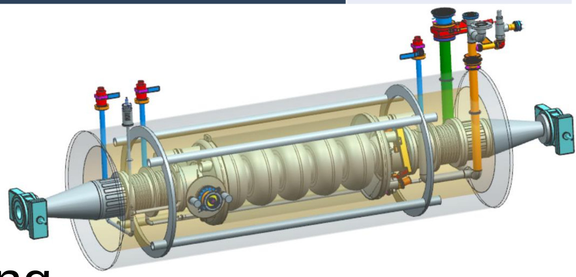
RF Power Amplifiers

3x 591 MHz, 65 kW CW, IOT
Solid State looks very promising

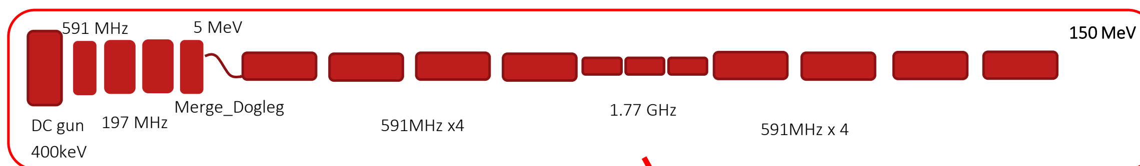
Strong Hadron Cooling (SHC)

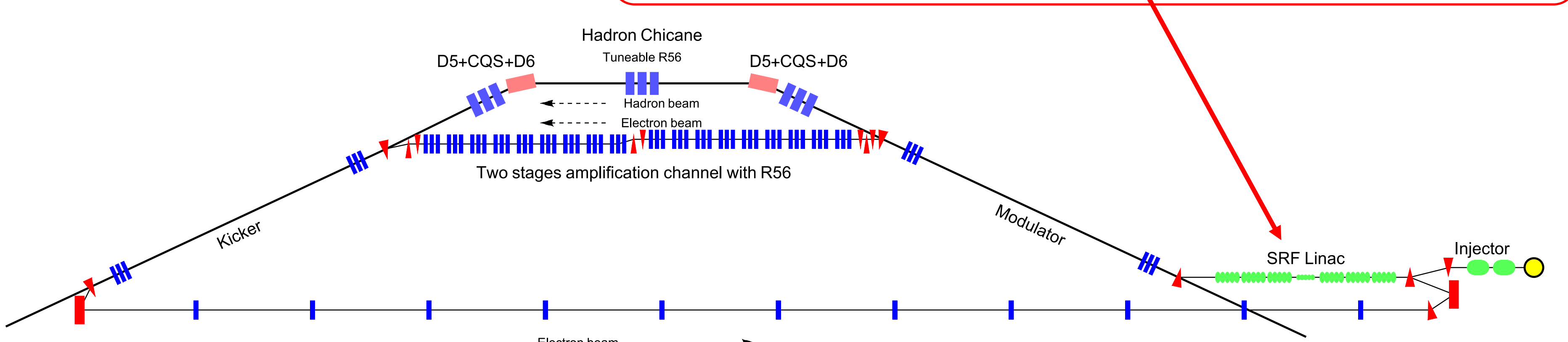
- Single Pass 150 MeV ERL (1 up, 1 down)
- 8x 591 MHz, 5-cell elliptical, 2K
- Maximum 180 MV, Eacc 15.8 MV/m
- 9x 591 MHz, 65 kW CW RF Power Amplifiers
- 100 mA single pass current
- 98.5 MHz bunch frequency
- HOM power well below the 20 kW per absorber rating.

	parameter
Bunch charge	1 nC
Peak current	30 A
RMS Bunch length	5.1 mm
RMS Normalized emittance	2.8 mm-mrad
Energy	150 MeV
RMS dp/p	5.5 e-5



Courtesy of Erdong Wang





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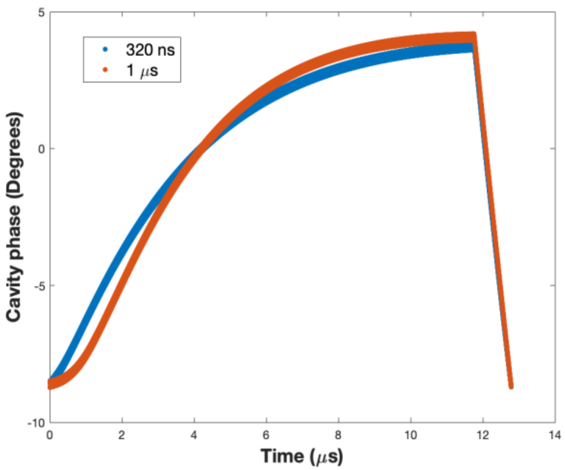
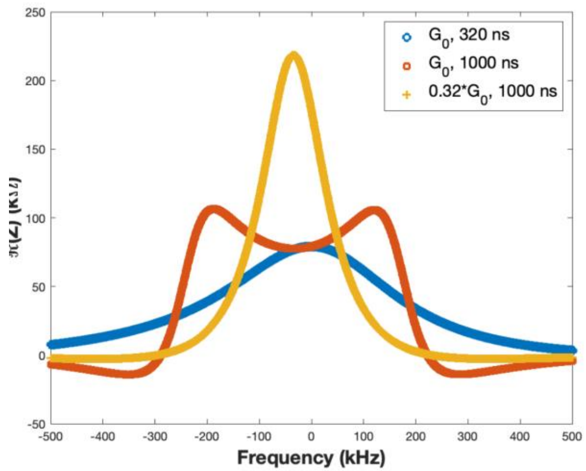
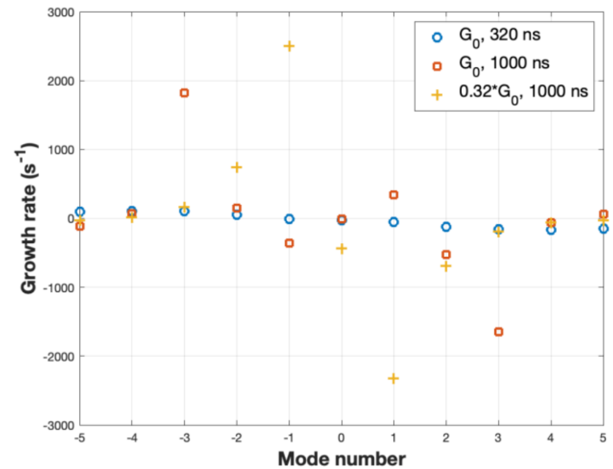
LLRF controls

- High currents, abort gaps require state of the art LLRF
- Will benefit from experiences at LHC, PEP-II, Super KEK-B etc.







- Simulations by T. Xin and G. Bassi with full RF beam physics.
- Working with collaborators to develop the LLRF control requirements.
  - T. Mastoridis (Cal Poly), C. Rivetta (SLAC), J. Fox (Stanford University)
  - Utilizing and further developing proven tools to understand transient beam loading, optimal detuning, coupled bunch thresholds, feedback architecture and power requirements.
  - Will include real-world effects (loop delay, linearity, noise, dynamic range, etc.).

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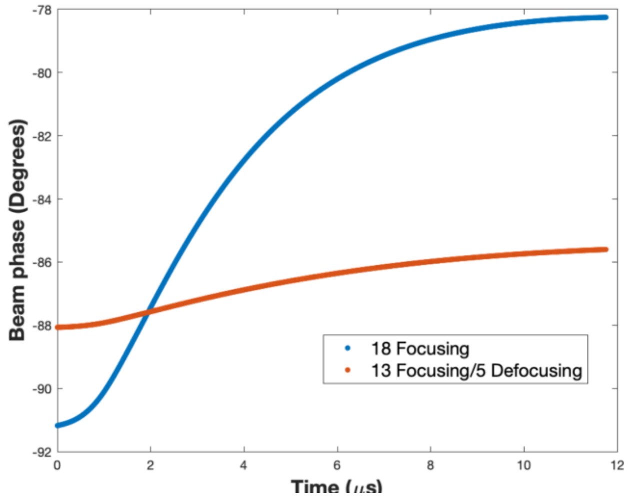
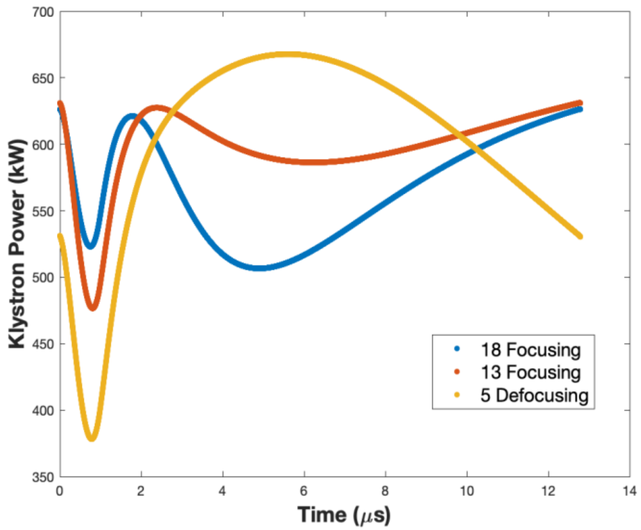
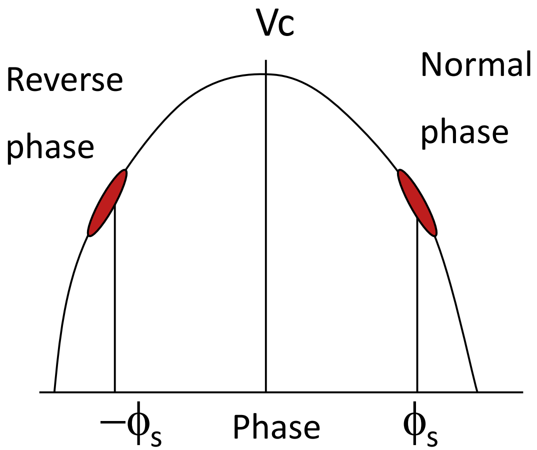
Reverse phase operation

- 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

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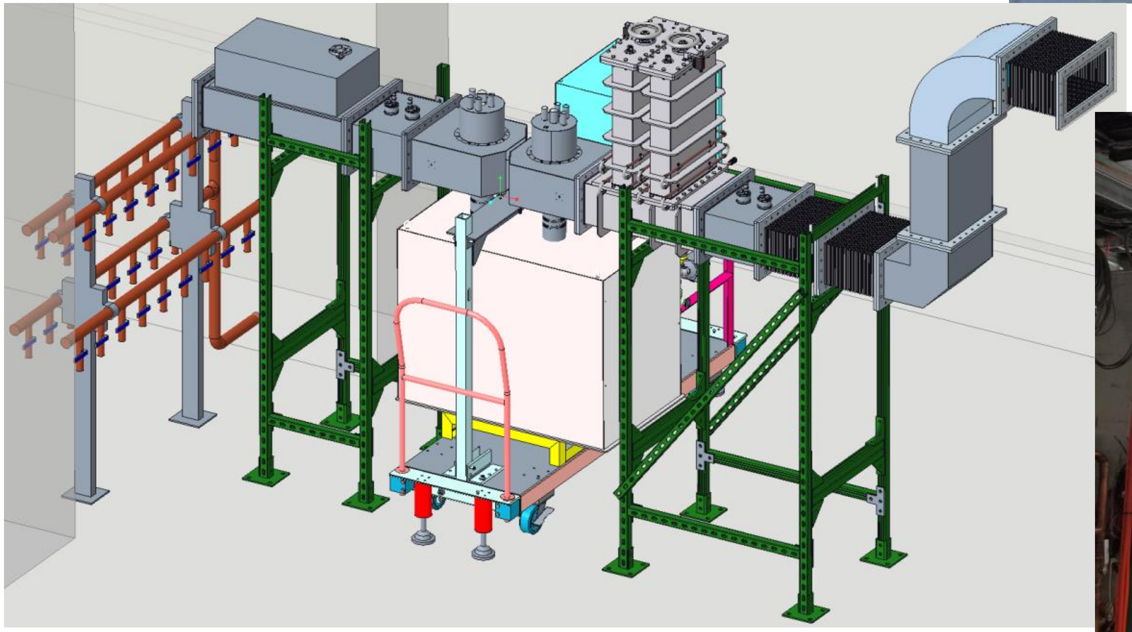
500 kW CW, Variable Qext Couplers

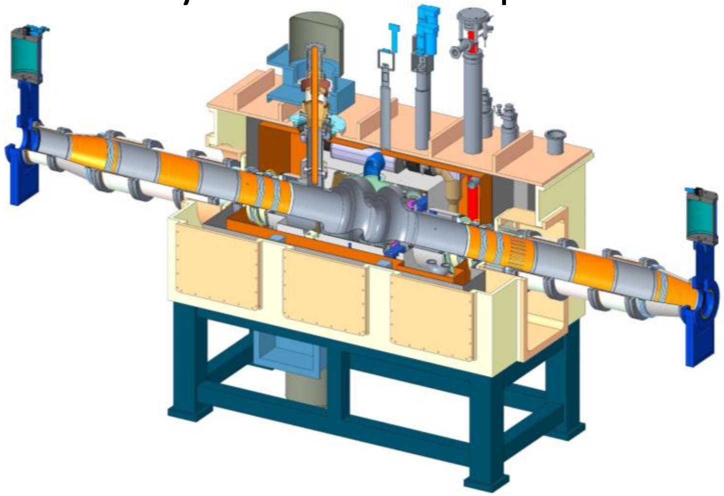
- Use existing fixed 500 kW CW coupler design.
- Vary Q_{ext} using adjustable waveguide tuner section.
- Initial funding by BNL LDRD.
- Testing delayed by Covid19.



High Power SIC HOM Absorber

- Requirement and challenge
  - High power, broadband HOM damper
  - Large size of SiC HOM damper for low frequency
- Initial LDRD program on SiC HOM absorber:
  - Low power test on a cavity to test effective damping bandwidth
  - High power test to test the power handling capability
- Results:
  - Tests were delayed due to CoVID-19.
- Inspiration
  - Instead of one solid piece HOM damper, fabrication and RF study of piece-by-piece (tile) type HOM damper
  - HOM damper suitable for various temperature environments

ESR cryomodule concept



HOM Absorbers

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RF power options

Super-power klystrons

- Limited vendors, high cost, low efficiency

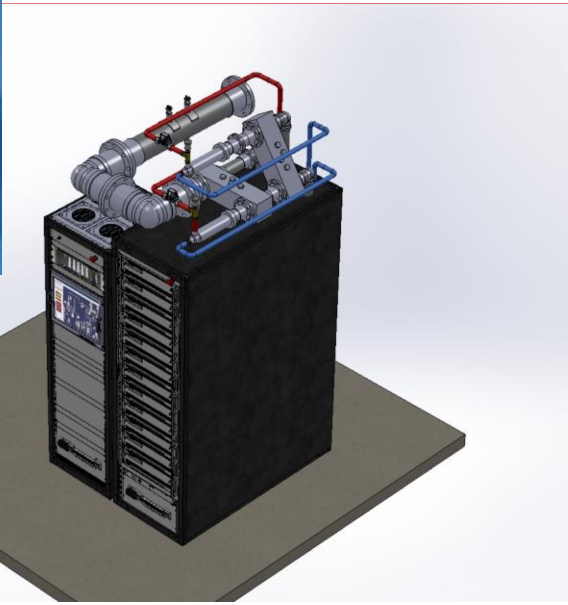
Combined IOT's

- Better efficiency, becoming obsolete

Combined SSA's

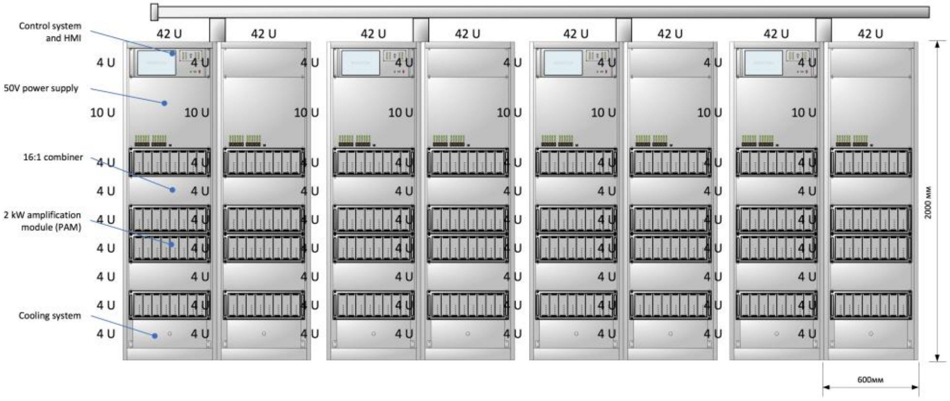
- High efficiency, redundancy, costs falling

IOT



50 kW SSA module

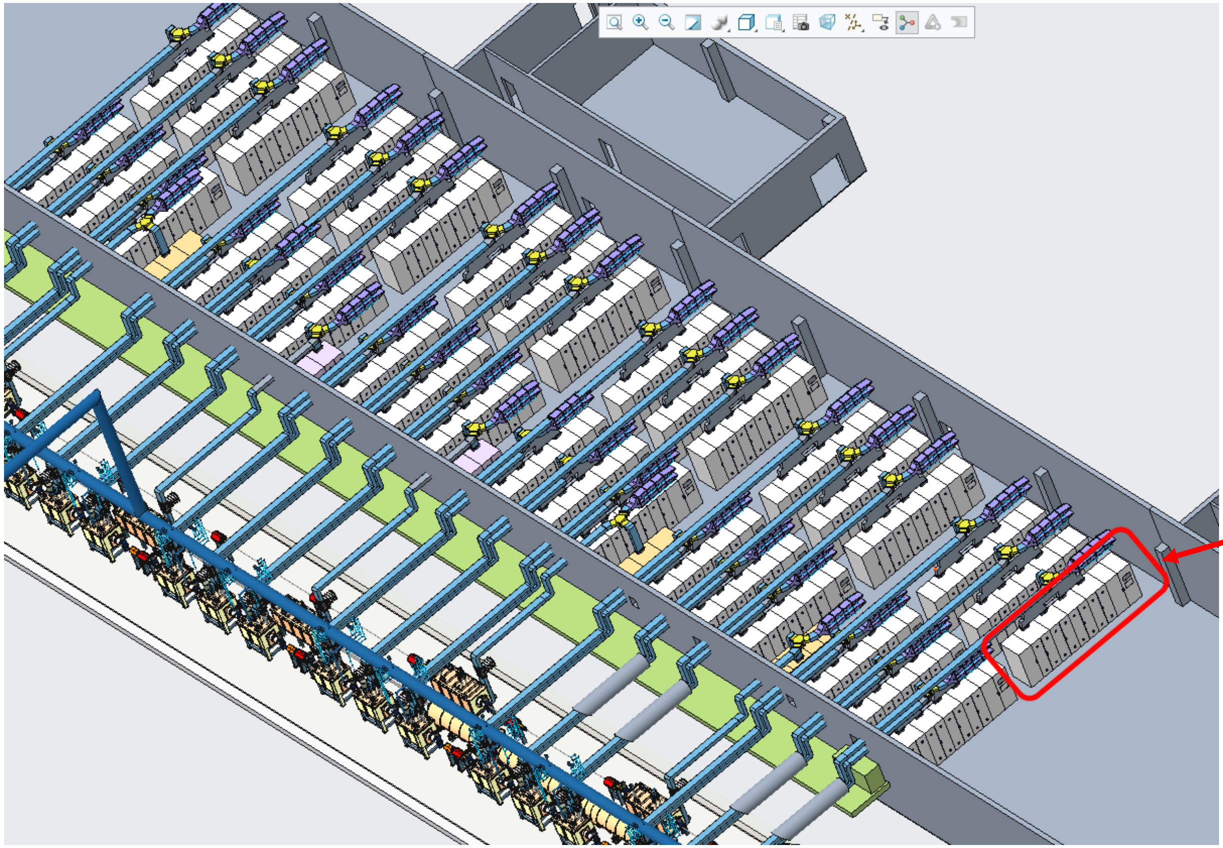
PEP-II 1.2 MW klystron and HVPS



400 kW SSA module

Scope Detail: RF1010 Building

- 2020: RF1010 Support Building with 14.4 MW* total SSA based high power RF, interface to IR-10 and IR-10 cryomodule layout.**
  - Remarkable power densities becoming realistic for solid state power across the digital TV broadcast frequencies.
  - 3D model is based on one of the vendor budgetary proposals.



* 14.4 MW is just the result of showing 36x 400 kW "units". Vendor budgetary quote in this case is based on 400kW = 4x 100kW per amplifier.

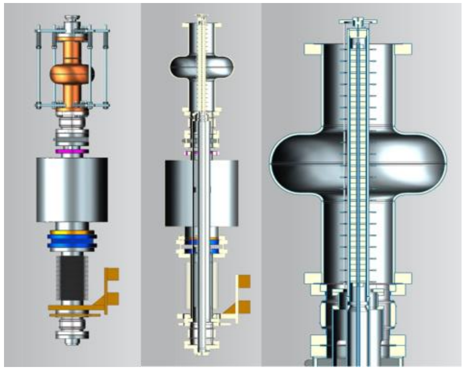
** This layout is a conceptual layout to explore the space requirements for 18x single cell 591 MHz ESR cryomodules. The 18 cryomodules fit in the available IR space. The SSA power density leads to reduced building space needs.

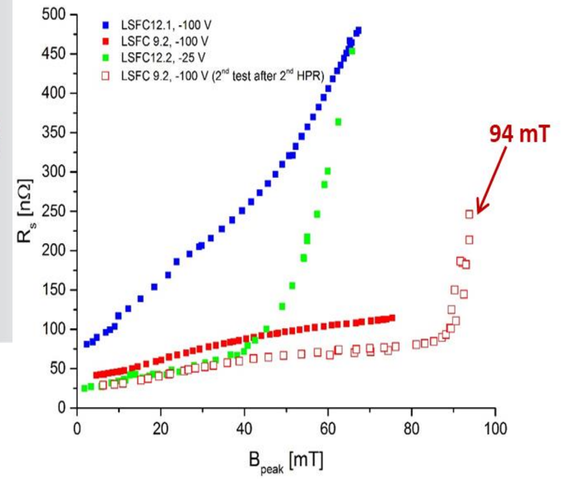
591 MHz, 400 kW modular amplifier unit.
36 = 18 * 2 shown.

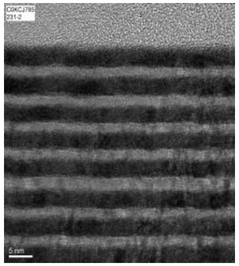
7.2m (L) x 1.4m (D) x 2.2m (H)

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 who knows?

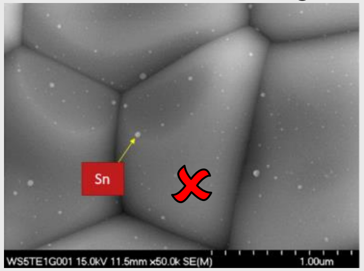


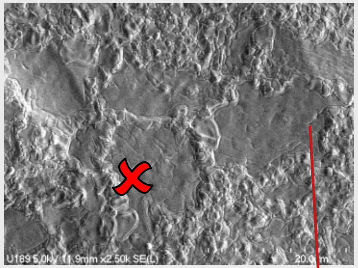




PI: Anne Marie Valente Feliciano

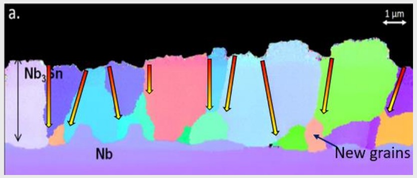
Research to understand the fundamental growth mechanism of Nb_3Sn linked with RF performance

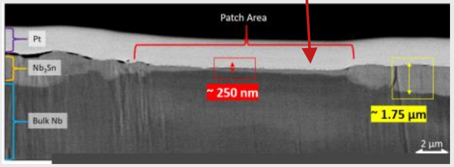


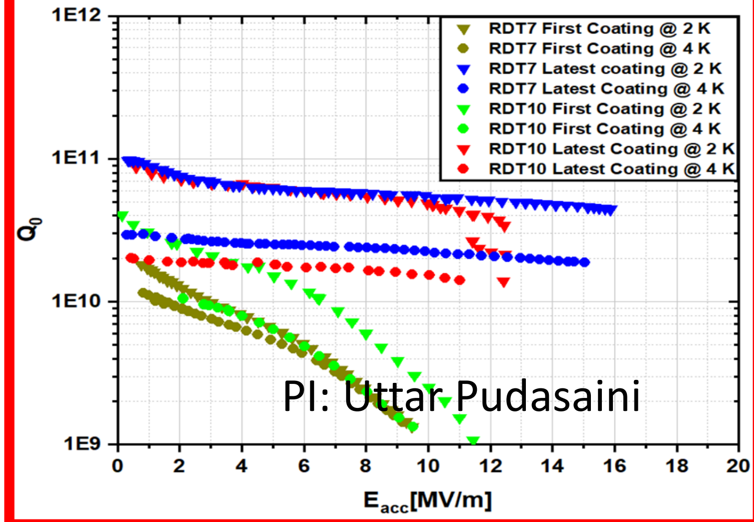


Grain-boundary diffusion primarily controls thin-film growth. Patchy regions lack grain boundaries resulting in thin regions.

Factors contributing to Q-slopes in Nb_3Sn cavities







PI: Uttar Pudasaini

BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

Conclusions

- Making good progress on EIC design
- Taking full advantage of community knowledge
  - Combined BNL and JLab RF team
  - Modern light-source practices (e.g. impedances)
  - LHC crab cavity, beam loading, FCC studies
  - T. Mastorides, J. Fox on transients and RF controls
  - PEP-II and KEK-B experience
  - Recent large scale SRF projects
- Developing the RF systems as an integrated set
- High degree of modularity in cryomodule design.
- Many challenges ahead and **much synergy with FCC**

Thank You