The EIC, A High-Intensity Collider: A Good RF Challenge to Have (there may even be solutions)

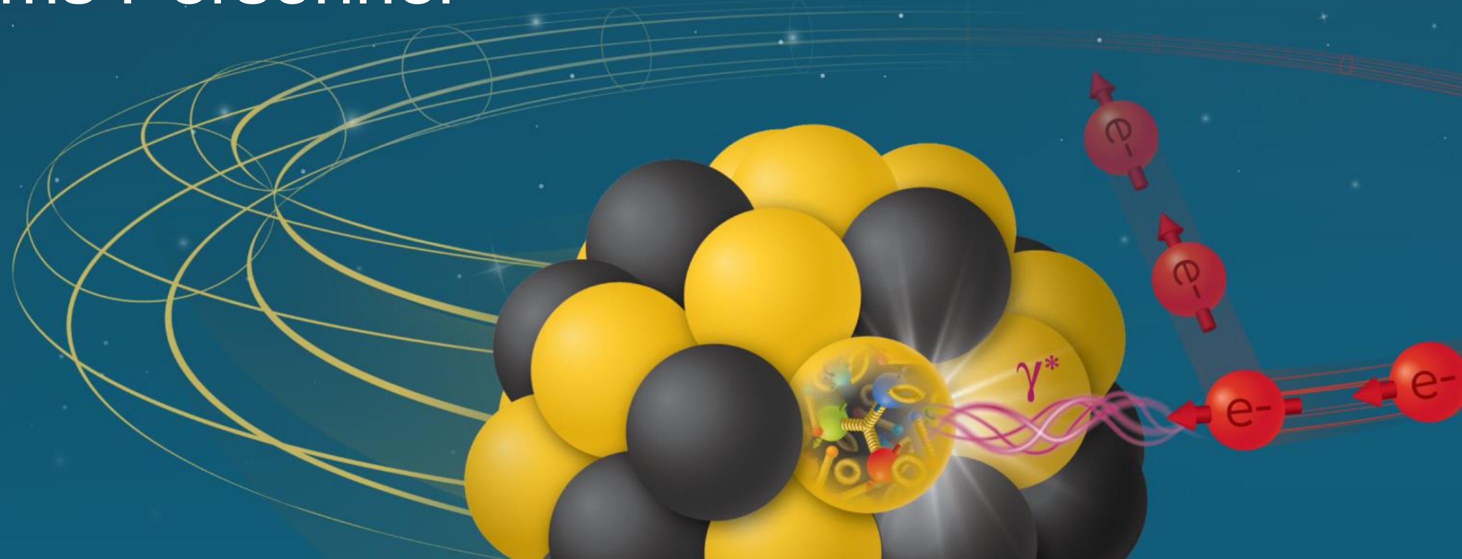
Zachary Conway

On behalf of all EIC RF Systems Personnel
& Many Others

FRIB Seminar

21 February 2025

Electron-Ion Collider



Outline

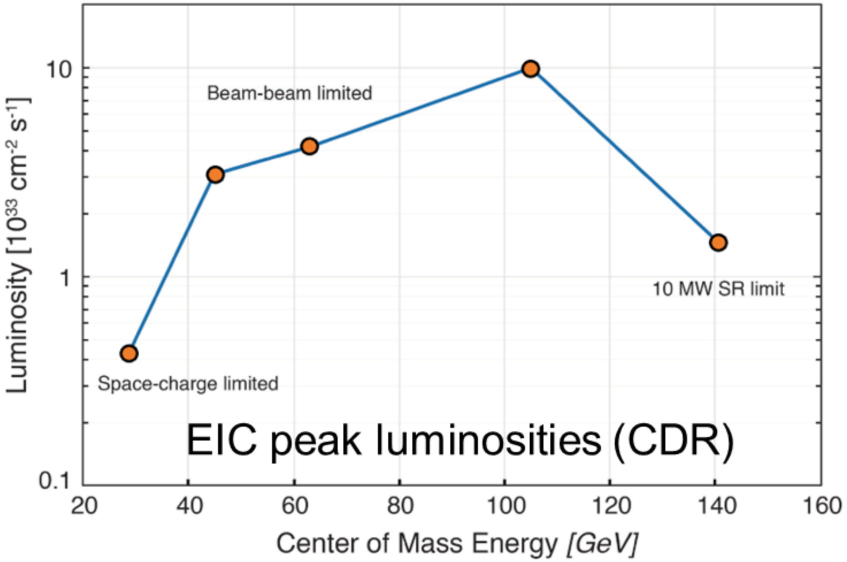
- **What is the DOE EIC Project trying to build? When?**
- **Comparisons to other high intensity colliders/synchrotrons.**
- **ESR 591 MHz 1-cell cavity SRF system.**
- **A brief overview of other EIC challenges.**

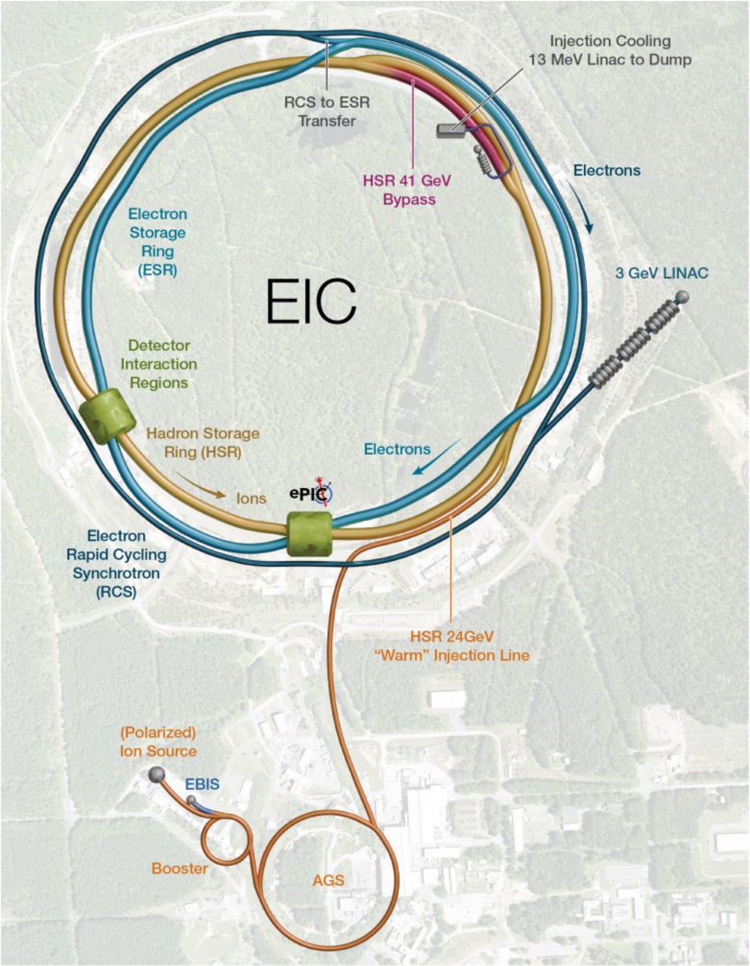
What is the Electron Ion Collider?

EIC required >70% polarization for light ions and electrons, availability of ion beams from deuterons to the heaviest stable nuclei, variable center of mass energies ~20 to 100 GeV (upgradable to 140 GeV for e-p), high collision luminosity $10^{(33 \text{ or } 34)}$ cm^{-2} s^{-1}, and possibly more than on interaction region.

$$E_{COM} \approx 2\sqrt{E_e E_h}$$

EIC Figure of Merit
~Luminosity x Polarization^2



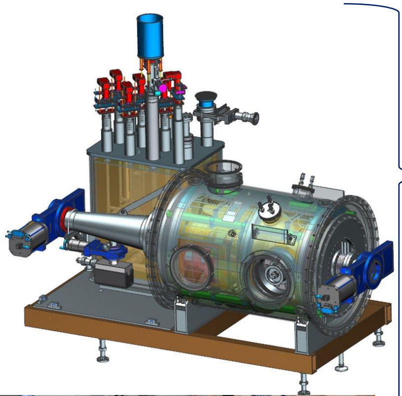


EIC Assumptions

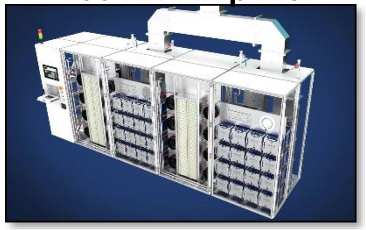
- Reuse RHIC infrastructure and hadron source, assume cryoplant and select other facilities are well-maintained:
  - Polarized (>70%) protons and He ions to be accelerated through the BNL Alternating Gradient Synchrotron with high efficiency.
  - Ion species available: protons through Uranium.
- Experimental community expectations:
  - Arbitrary bunch-by-bunch spin patterns.
  - Minimum electron beam energy at collisions: 5 GeV.
  - Maximum electron energy of 18 GeV is available on day one.
  - Proton beam energies range from 41 to 275 GeV (110 GeV/u, ions)
- Leading EIC RF Technical Challenges:
  - High electron bunch intensities: e = 28 nC/2.5 A, 1160 bunches out of 1260.
  - Increase # of ion bunches to 1160 (110 in RHIC) with up to $6.9x10^{10}$ particles per bunch (1 A max).
  - High-Power SRF Cavities: 800 kW 2.0 K.
  - SRF Crab Cavities for a 25 mrad crossing angle.
  - Low-noise precise RF field control: coupled issue for LLRF, HPRF & RF cavity systems.
    - Transient Beam Loading

EIC RF Systems

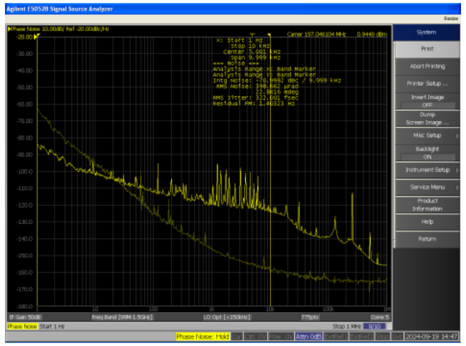
The Project is pre-CD2 and in the design phase. Many systems are still developing.



400 kW Amplifier

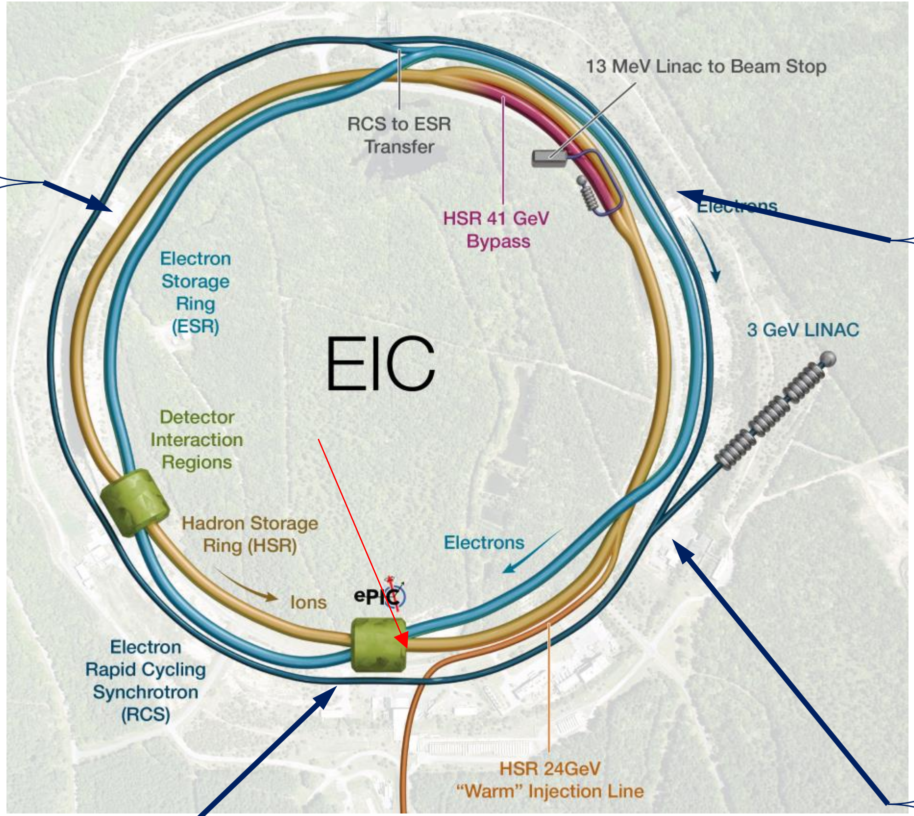


EIC LLRF DAC Clock for Crab Cavities



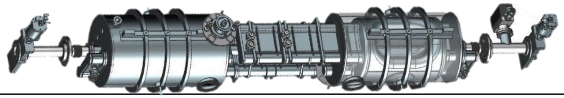
Electron Storage Ring & Hadron Storage Ring
591 MHz 800 kW 2 K
1-Cell Cavity Cryomodules
ESR = 17 CMs, IR10
HSR = 5 CMs, IR10

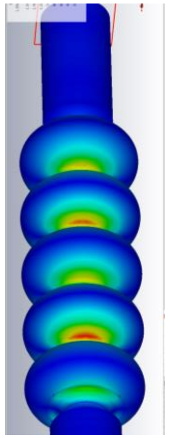
Rapid Cycling Synchrotron
591 MHz Five-Cell Acceleration Cavity Cryomodule
3 CMs, IR10

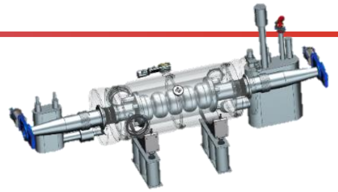


IR06
197 MHz & 394 MHz Crab Cavity Cryomodules

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

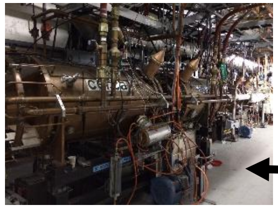




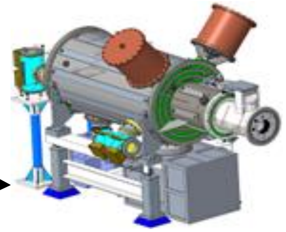


Hadron Cooling, IR02 – 9 CM 591 MHz acceleration cavities & **4 CM** 1773 MHz 3rd Harmonic Cavities

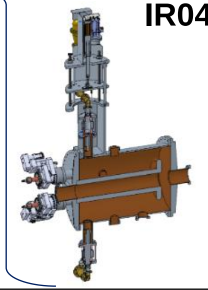
Electron Cooler, IR02 - 197 QWR, 591 SC Cavities (Not shown)
3 CMs, ERL Injector, IR02



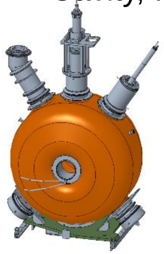
RHIC – 28 MHz acceleration cavity **IR04**



Hadron Storage Ring 24.6 MHz Accelerating Cavity, IR04



HSR – 49.2 MHz and 98.5 MHz bunch splitter cavities **IR04**



HSR - 197 MHz bunch compression cavity **IR04**

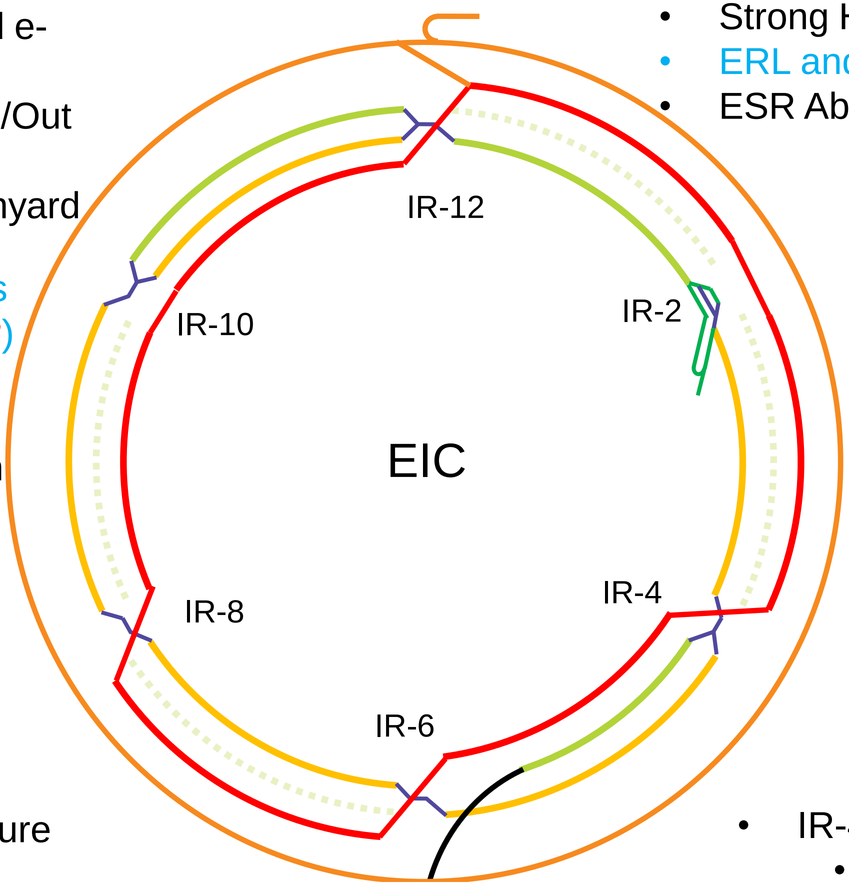
Emergent Scope Not Listed (Electron Injection Systems, Pre-Cooling, Stochastic Cooling, RF dampers/correctors, etc)

RF System Highlights

IR-12
- 400 MeV Polarized e- Injector (IR-4)
- RCS/ESR Swap In/Out Transfer (IR-4)
- 41/100 GeV Switchyard

IR-10
- Ring SRF Systems (ESR, HSR, RCS?)
- 41/100 GeV Switchyard
- HSR Abort System

IR-2
- Strong Hadron Cooling / Injection Cooling
- ERL and ERL Injector SRF systems
- ESR Abort System?



	Protons	Electrons
Circumference	3833.89 m	3833.98 m
Hi-Lumi Energy	275 GeV	10 GeV
Bunch Intensity	6.9×10^{10}	17.2×10^{10}
# Bunches	1160	1160
Bunch Length	6 cm	7.7 mm
Beam Current	1 A	2.5 A
$\Delta p/p$	6.8×10^{-4}	5.8×10^{-4}
Luminosity	10^{34} cm^{-2} s^{-1}	

IR-8
- Reserve space to accommodate a future second detector.
- Not on project.
- Talk of another Crab Cavity installation here.

IR-6
- Experimental detector location
- VERY, VERY different from RHIC
- New and Complex SC Magnets
- Crab SRF systems on both sides

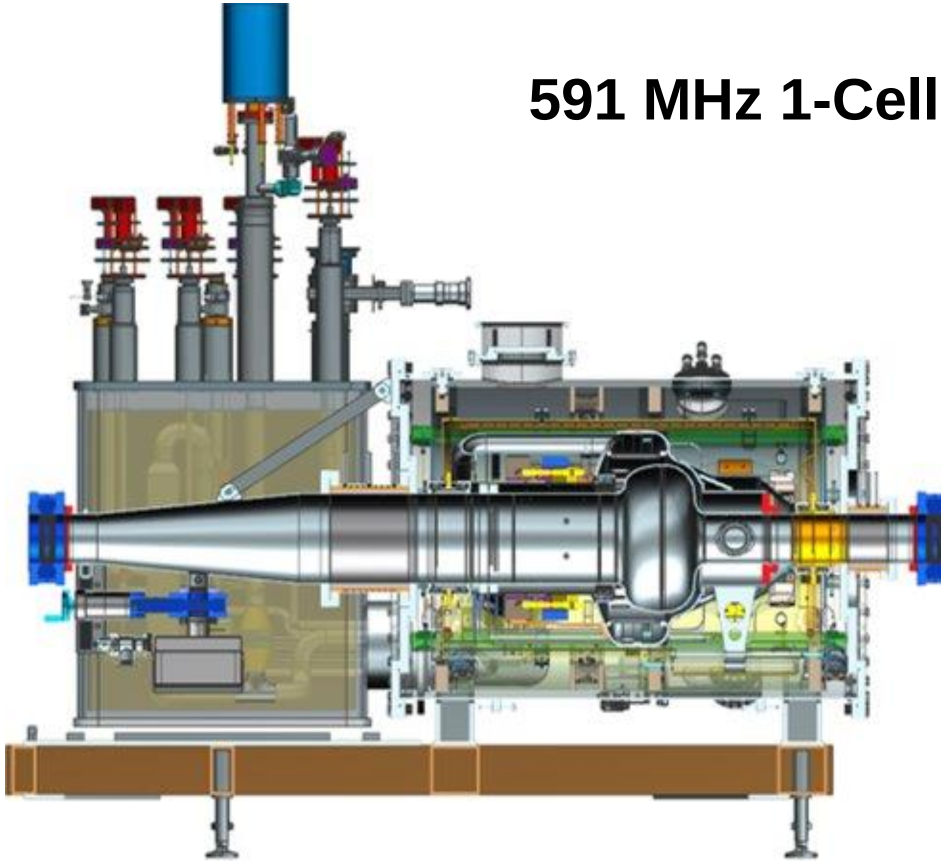
- IR-4
  - New HSR injection point
  - HSR and RCS NCRF systems (SRF)
  - pC & JET Polarimeters?

EIC RF Challenges

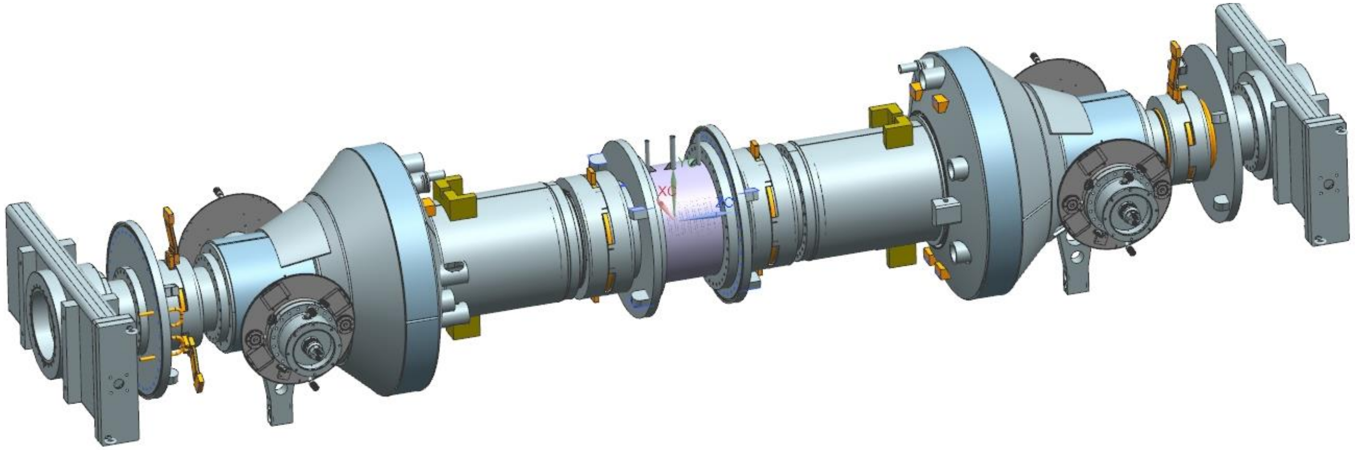
SRF Cavity Voltage & RF Parameters

RF Parameter	18 GeV	10 GeV	5 GeV
dE per turn (MeV)	36.95	3.52	0.95
# of 1-Cell Cavities	17	17	17
Voltage Per Cavity (MV)	3.62	1.27	0.57
Synchronous Phase (Degrees)	143	170	173.1
Total Voltage (MV)	61.5	20.3	7.9
Installed Voltage (MV)	68		
E_{peak} (MV/m)	39.2	13.8	6.2
B_{peak} (mT)	74.2	26.1	11.7
R/Q (Ω)	78	78	78
Cavity Dynamic Load (W)	9.0	1.5	0.3
Cavity Power (kW)	651	728	224

ESR 591 MHz Fundamental RF System



591 MHz 1-Cell Cavity Cryomodule



Overview of Challenges

- How to coupler high power RF to the beam?
  - Keep Nb superconducting
  - Require feasible 2.0 K cryogenic plant(s).

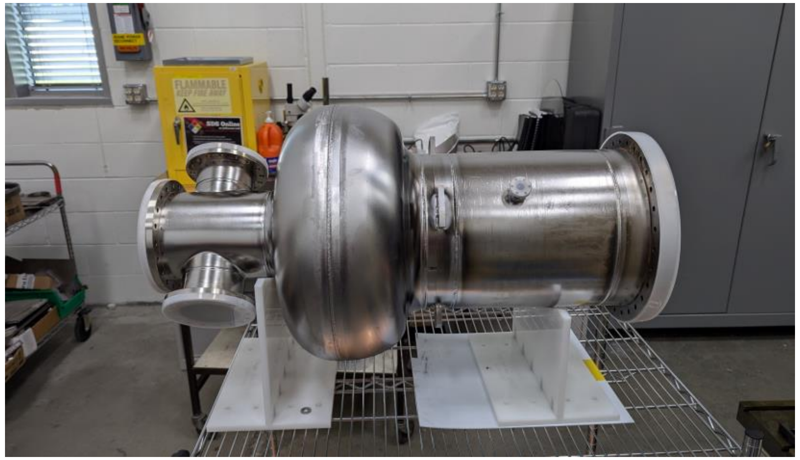
- How to damp the beam wakefield?
  - Don’t rock the boat nor the following boats. (boat = bunches)

- How to control the RF fields to the required accuracy and precision?
  - Transient beam loading.
  - Crab driven transverse instabilities.

2 Fundamental RF System Challenges R&D

- ESR Main RF System
  - Fit into RHIC IR10
  - Superconducting Radio-Frequency Systems
  - Provide 68 MV of voltage and 10 MW of 591 MHz power, not simultaneously
    - 4 MV per SRF cavity cell.
    - Peak surface fields of ~40 MV/m and ~80 mT.
    - Loaded Q = $2x10^5$
    - Requires strict voltage management (aka don't contaminate your SRF!!!)
- HSR/ESR Crab Cavities
  - Fit close to detector in IR6.
    - Superconducting Radio-Frequency Systems
  - 25 mrad
    - High voltage
  - Some of the most challenging crab parameters a person could think up.

591 MHz 1-cell Cavity Prototype



197 MHz Crab Cavity Prototype

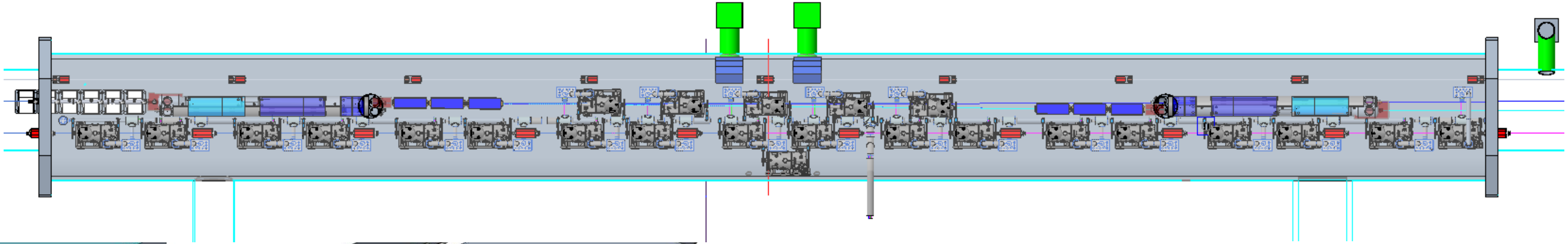
High Current Electron Storage Rings

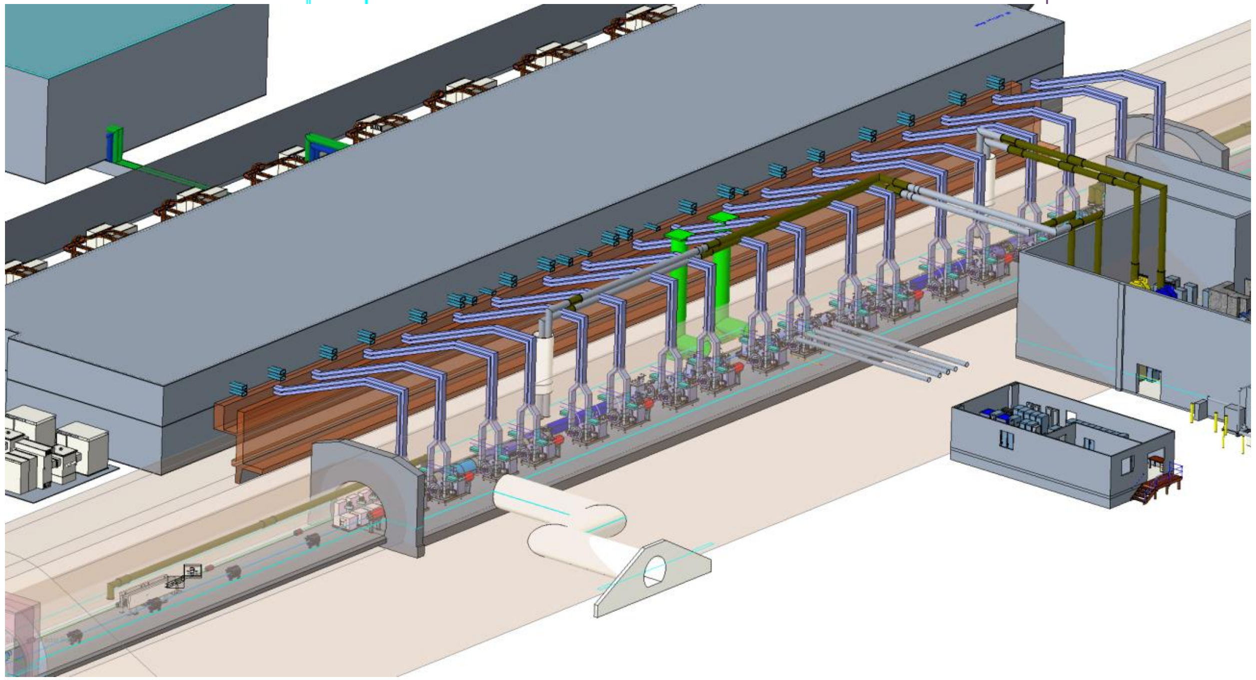
Ring	PEP-II LER	KEKB LER	SuperKEKB LER	EIC ESR	FCC-ee
Energy (GeV)	3.1	3.5	3.6	5-18	45-200
Design Beam Current (A)	2.14	2.6	3.6	2.5 (5-10 GeV)	1.28 (45 GeV)
Achieved Beam Current (A)	3.2 (2008)	2.0	1.3 (2022)	TBD	TBD
Bunch Charge (nC)	14	13	6	28	32
Circumference (m)	2,199	3,016	3,016	3,833	91,000
Cavity Type	Warm	Warm	SRF	SRF	SRF

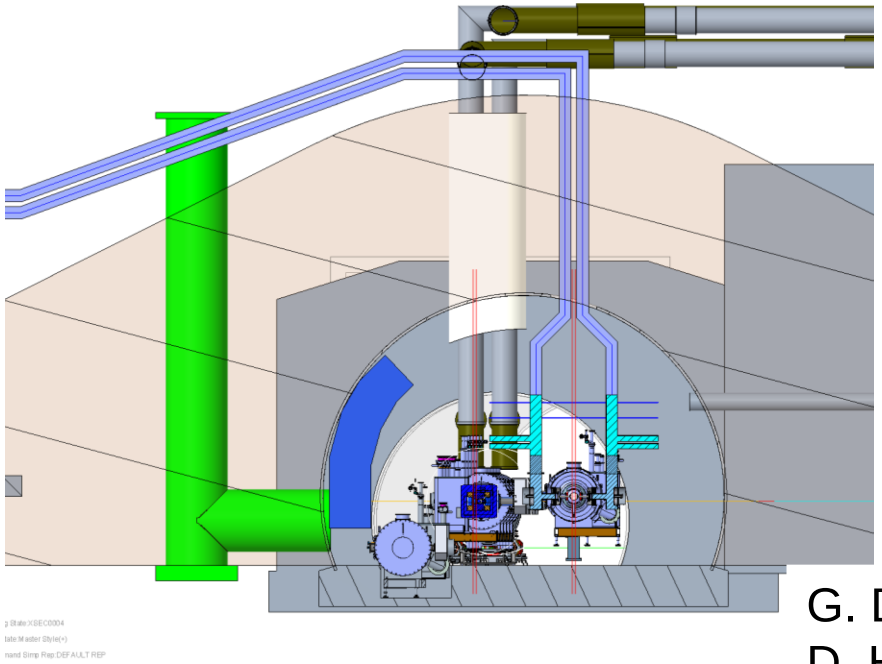
CERN LEPP 50 nC per bunch

8th June 2022, 4.65×10^{34} cm^{-2} s^{-1}

Space for Most SRF Systems – IR10







G. Dacos,
D. Holmes

591 MHz 1-Cell Cavity Cryomodule

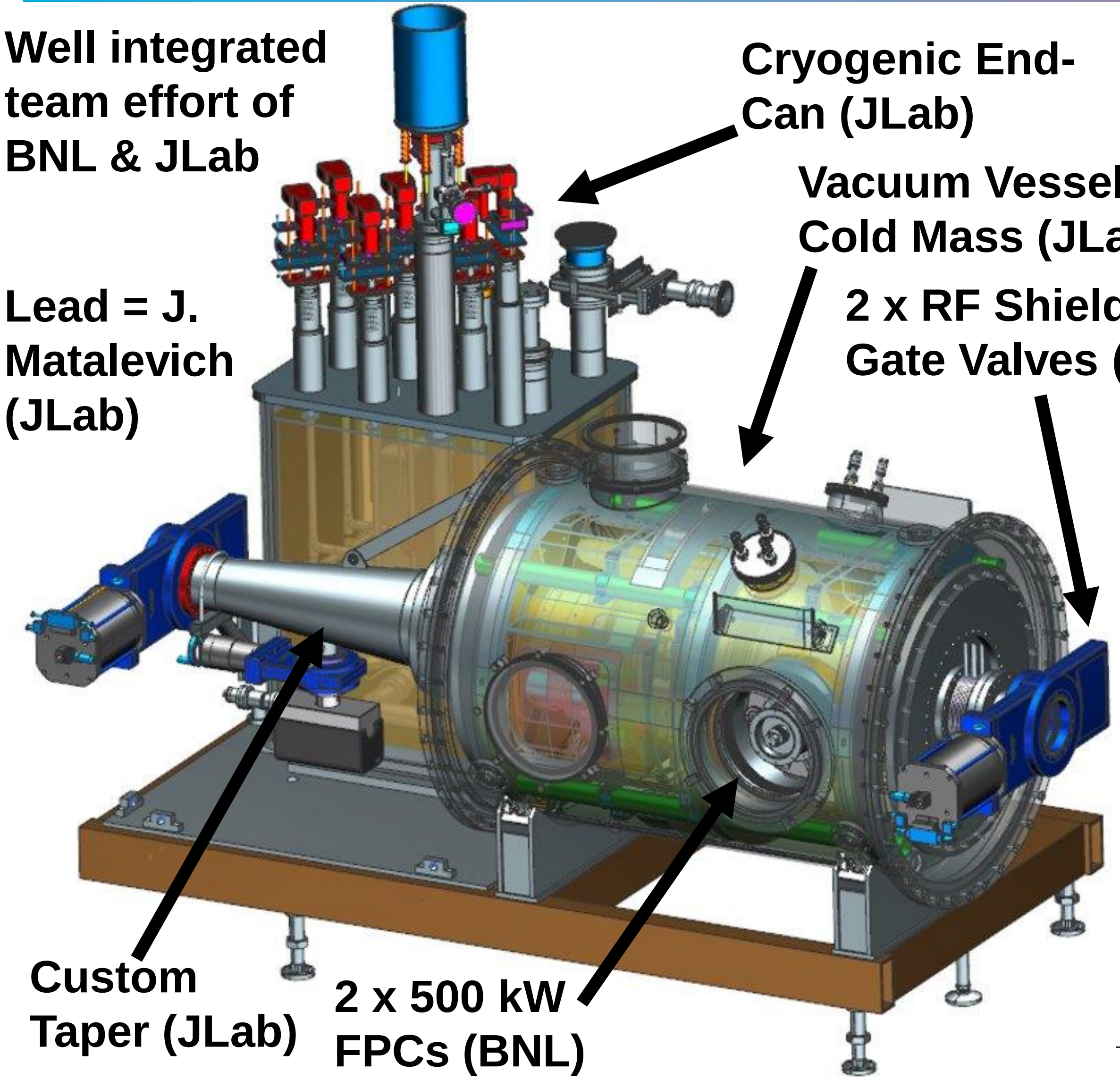
Well integrated team effort of BNL & JLab

Lead = J. Matalevich (JLab)

Cryogenic End-Can (JLab)

Vacuum Vessel + Cold Mass (JLab)

2 x RF Shielded Gate Valves (JLab)

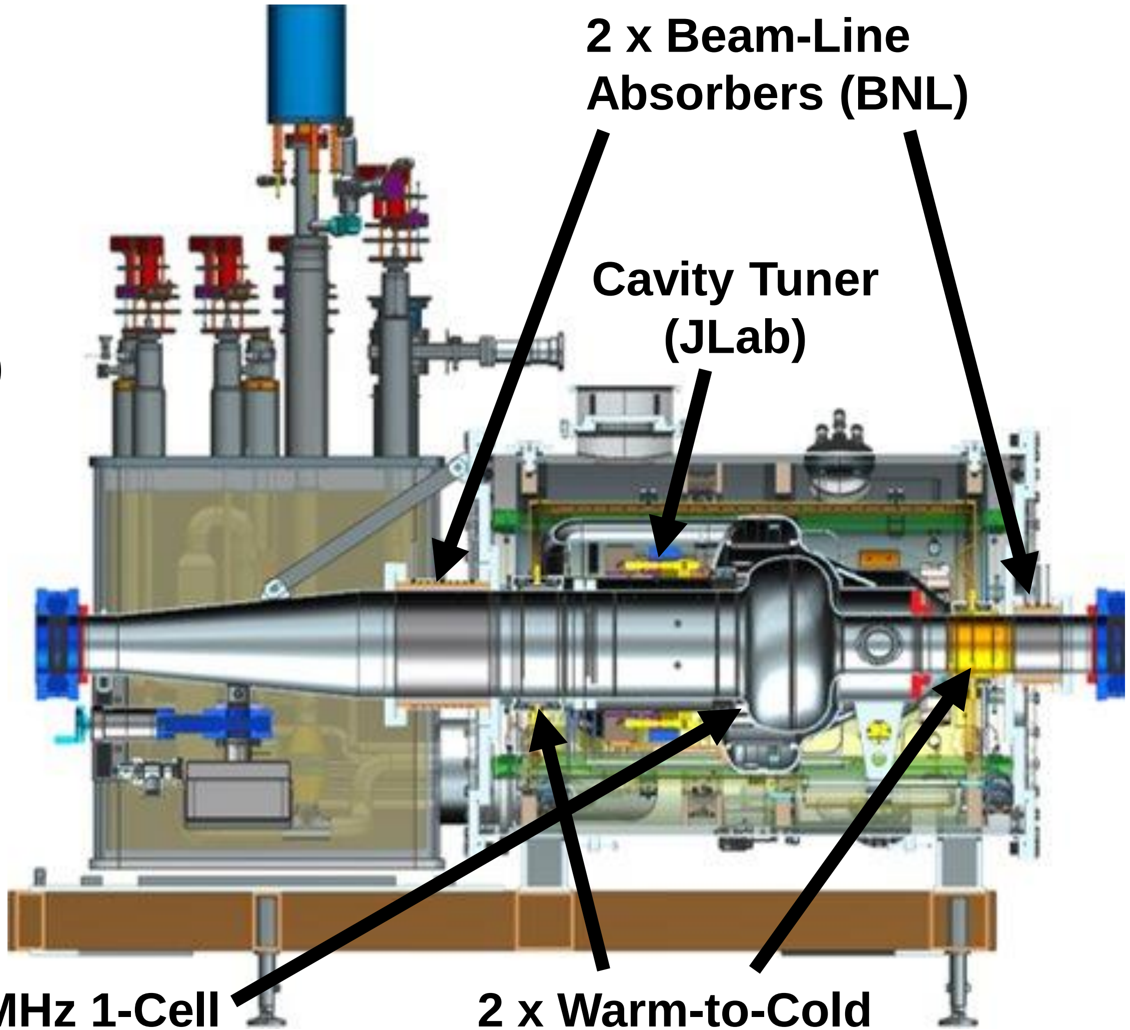


Custom Taper (JLab)

2 x 500 kW FPCs (BNL)

2 x Beam-Line Absorbers (BNL)

Cavity Tuner (JLab)



591 MHz 1-Cell Cavity (BNL & Jlab)

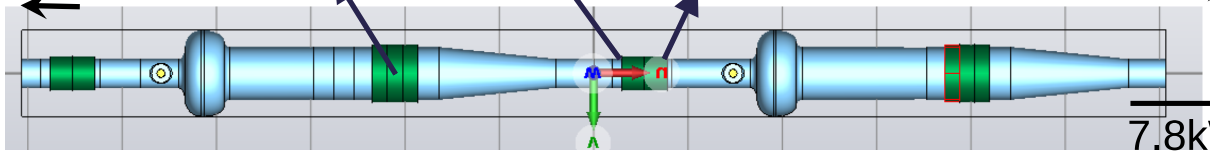
2 x Warm-to-Cold Transitions (LBNL)

J. Matalevich

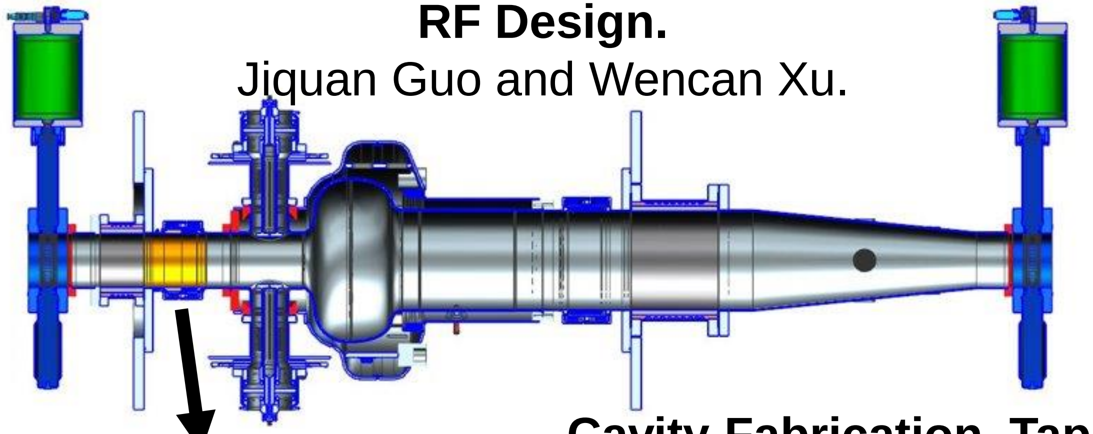
591 MHz SRF Cryomodule - Operation

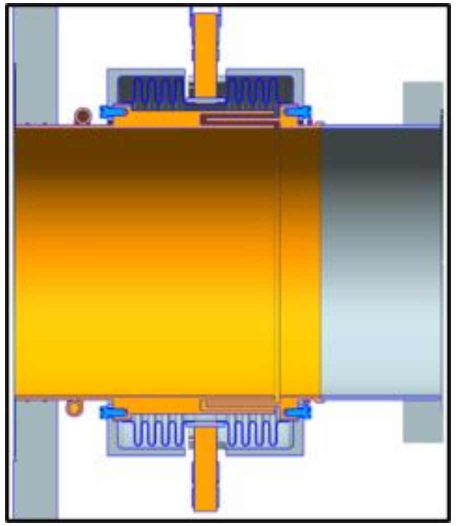
- ESR 61.5 MV, 5-18 GeV, 2.5 A, 27.6 nC/bunch, 290/580/1160 bunch fill patterns out of 7560 buckets, ~1 μs abort gap.
- ESR RF System must maintain 7.7 mm bunch length and make-up the ~9 MW synchrotron radiation losses and ~ 1 MW beam RF losses.
- 17 2.0 K SRF cryomodules capable of operating at 800 kW continuously = dual 500 kW FPCs
- World's highest power beam-line absorbers (RF dampers), ~36 kW with current requirements.

Beam Line Absorber Power Dissipation

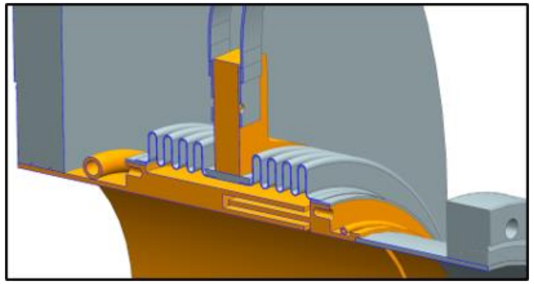


591 MHz 1-Cell Cavity String RF Design.
Jiquan Guo and Wencan Xu.





Cavity Fabrication, Taper and Gate Valves.
D. Savransky



Warm-to-Cold Transitions
A. Fuller

Fundamental Power Couplers
FPCs

Required Power Per Cavity

RF Parameter	18 GeV	10 GeV	5 GeV
dE per turn (MeV)	36.95	3.52	0.95
Beam Current (A)	0.23	2.50	2.50
Synchrotron Rad Power (MW)	8.38	8.80	2.38
HOM Power per Cavity (kW)	1.0	33.5	30.0
Total Power Loss (MW)	8.40	9.37	2.89
Power Per Cavity (kW, ÷17)	494	551	170
20% Overhead (kW)	593	661	204
10% Transmission Losses (kW)	652	728	224
Power Per Coupler (kW, ÷2)	326	364	112

SLAC-PUB-2884 (Rev.)
November 1991
(A)

HIGH ENERGY ELECTRON LINACS:
APPLICATIONS TO STORAGE RING RF SYSTEMS AND LINEAR COLLIDERS*

Perry B. Wilson
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

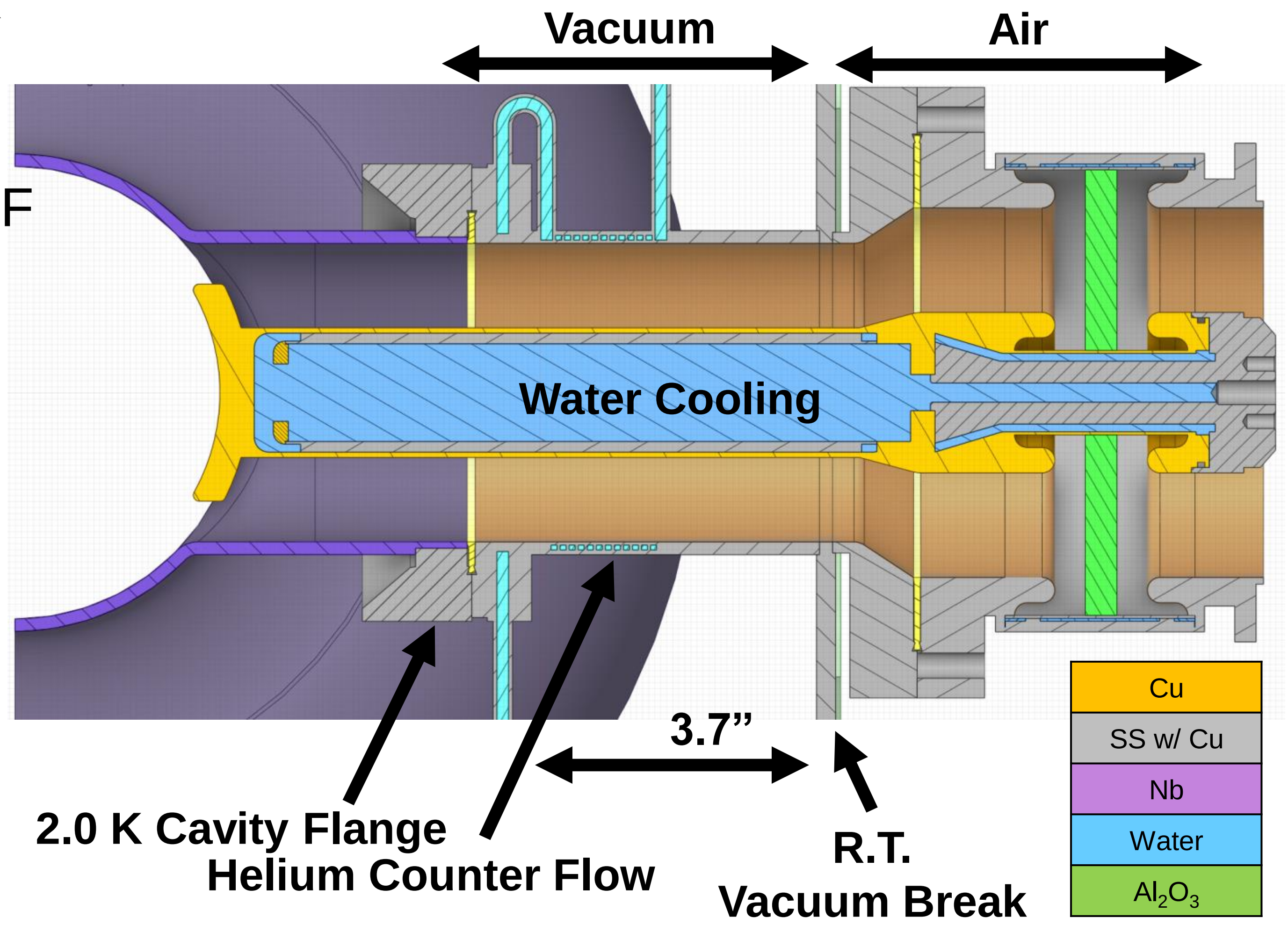
500 kW Power Couplers

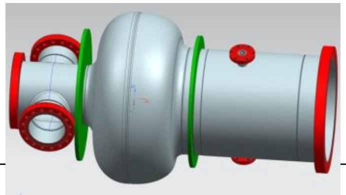
- Need to couple a 400 kW 591 MHz travelling wave from room temperature to a 2.0 K resonator in ~4.5 in (11.4 cm)?
- Need high electrical conductivity (low RF losses) and low thermal conductivity…
- Wiedemann-Franz Law (1853)

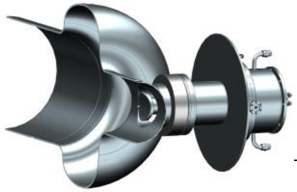
$$\frac{Thermal\ Conductivity}{Electrical\ Conductivity} = L * T, L \sim 2.4x10^{-8}\ V^2K^{-2}$$

- If we do nothing kWs of extra 2K load.

Cross Section: Power Coupler Cavity Interface







E. Drachuk

Comparison of Thermal Loads – Outer Cond.

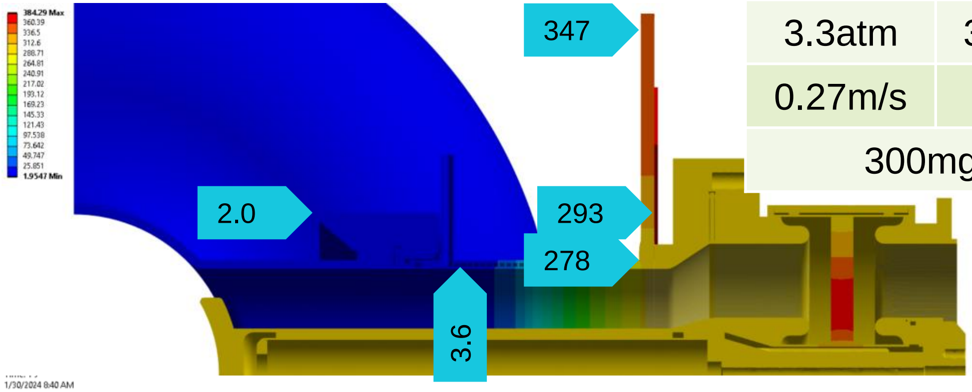
No Helium Counter Flow

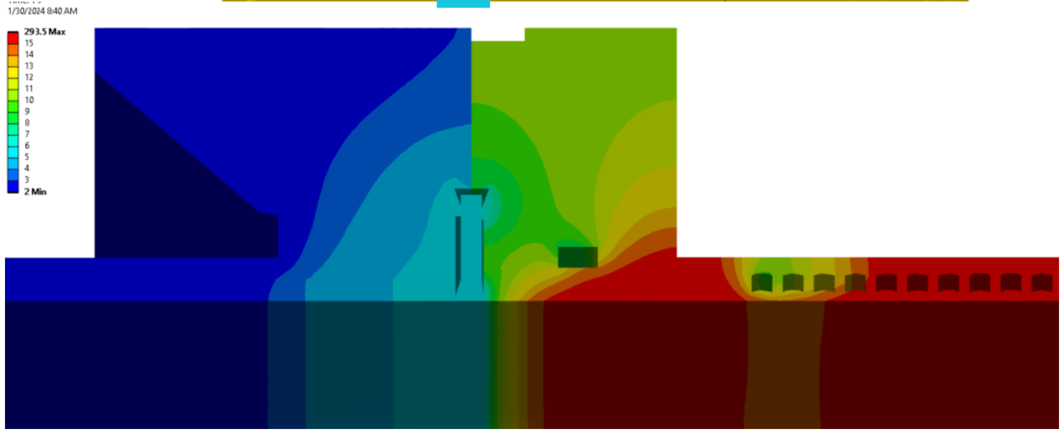
Thermal Load	Static	Dynamic
2 K	3	12
50 K @ 30 mm	11	11
Water	-20	340

With Helium Counter Flow (Small Geometry Changes)

Thermal Load	Static	Dynamic
2 K	0.2	3
50 K @ 30 mm	3	3
Water	-90	260

Inlet	Outlet
5.5K	51K
3.3atm	3.09atm
0.27m/s	8.6m/s
300mg/s	



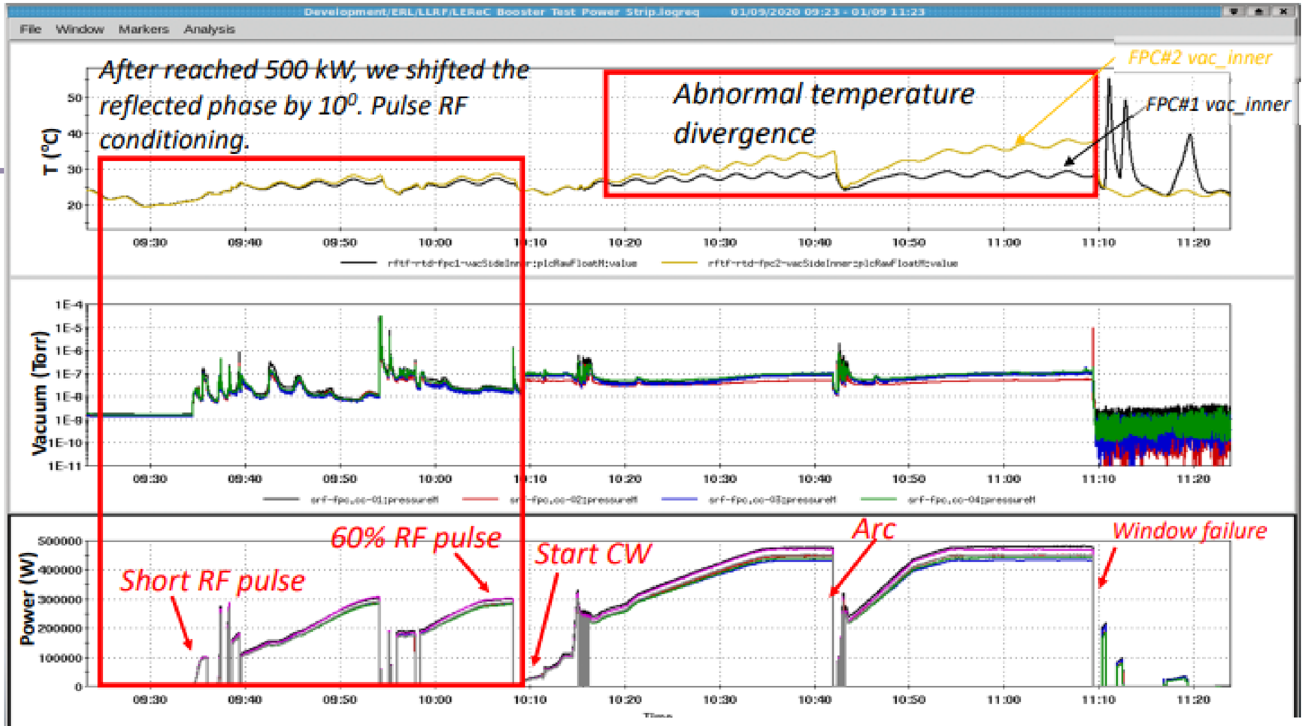


- Balancing the supercritical He flow’s change in temperature (heat capacity/time) with the static thermal load and RF dissipation gives minimum physical distance = 3.5” to keep 2K static load less than 10 W.

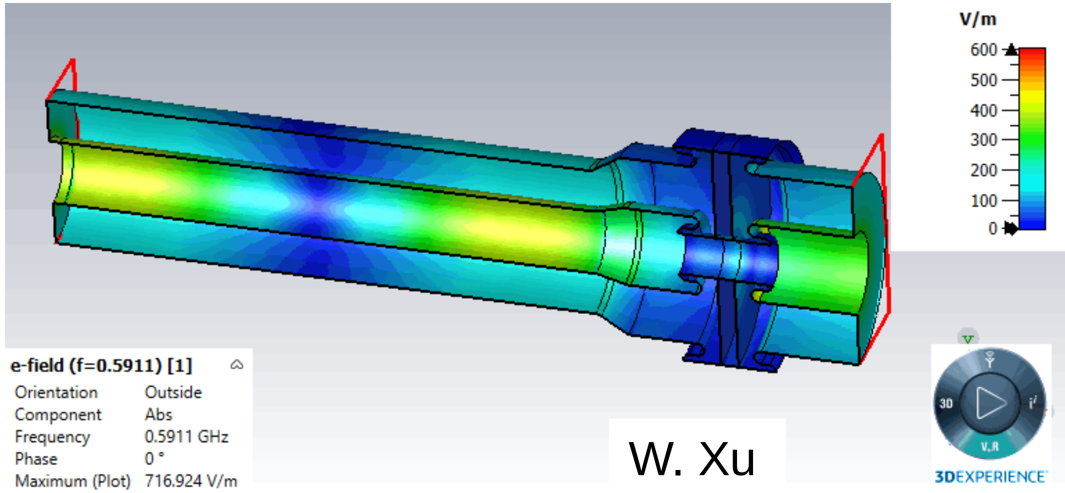
E. Drachuk

EIC FPC Operation

- EIC is building Al_2O_3 cylindrical window FPCs now.
- BeO conditioning example.
- EIC design for 500 kW, operate @400 kW continuous wave (cw)



W. Xu et al., Phys. Rev. Accel. Beams **25**, 061001 (2022)



W. Xu

Facility	Freq (MHz)	Operating Power (Testing, kW)
LEP2	352	150 (380)
LHC	400	160 (300)
CESR	500	300 (360)
KEKB	509	400
APT	700	(850)

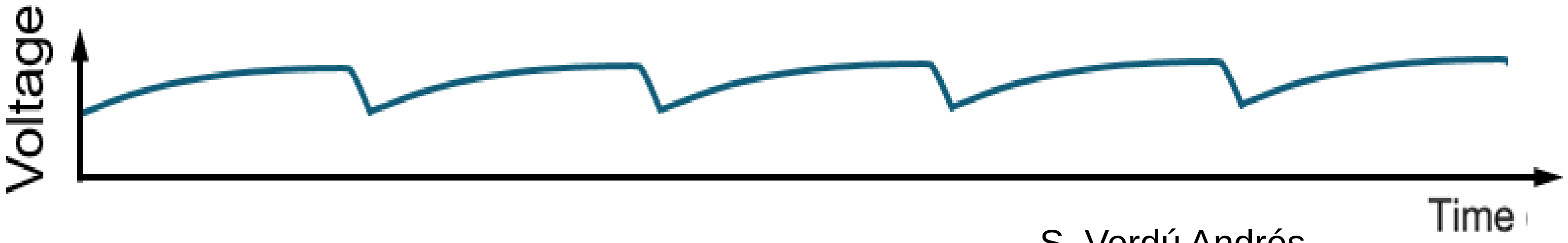
S. Belomestnykh, SRF'07

Transient Beam Loading

Transient Beam Loading

- Abort gaps in colliding bunch trains (1160 bunches out of 1260, ~100 μs gap).
  - Drive phase and amplitude transients in RF cavities.
  - Varying bunch arrival times at IPs.
  - Errors in crabbing.
- Voltage induced in RF cavity by a bunch: $V_{b0} = q\omega_o \frac{R}{Q_0}$
- Voltage seen by the bunch: $\tilde{V}_c = \tilde{V}_g + \frac{1}{2}\tilde{V}_{b0}$

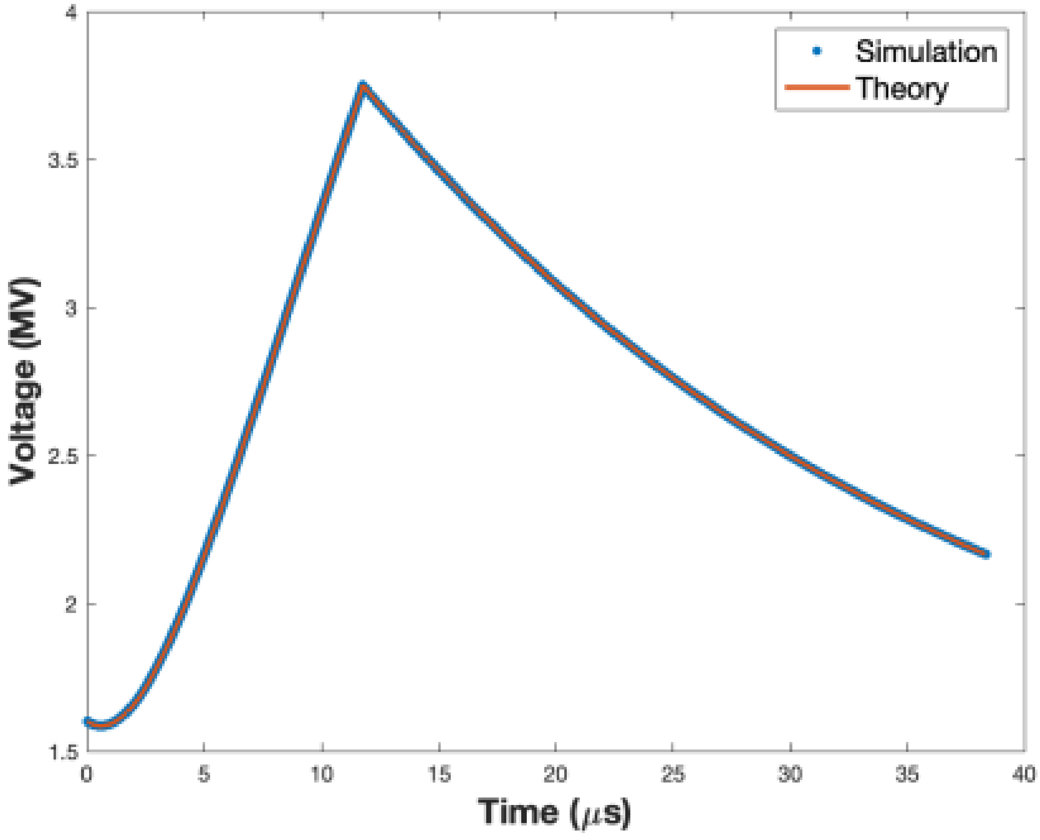
$$\tilde{V}_c = \tilde{V}_g + \frac{1}{2}\tilde{V}_{b0} + \tilde{V}_{b0}e^{-\delta}e^{i\Delta\varphi}; \qquad \lim_{n\to\infty}(\tilde{V}_c) = \tilde{V}_g + \tilde{V}_{b0}\left(\frac{1}{1-e^{-\delta}e^{i\Delta\varphi}} - \frac{1}{2}\right)$$

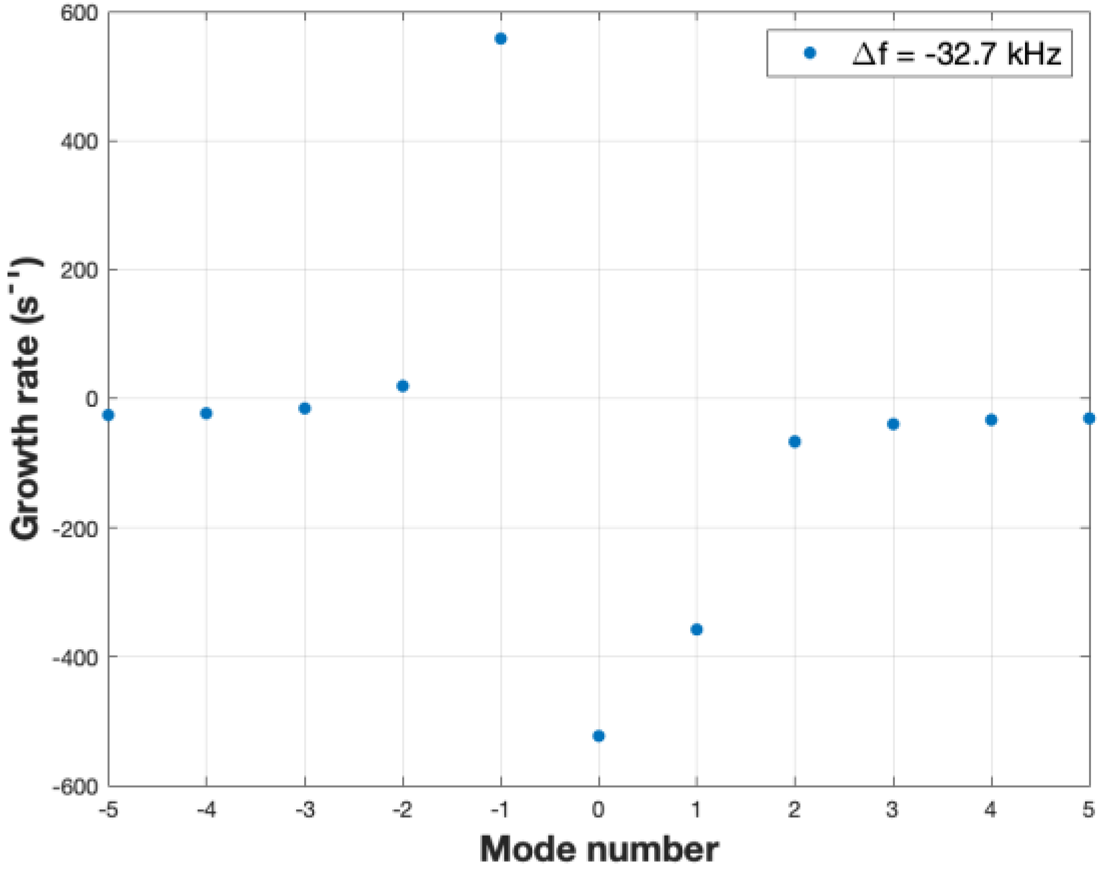


S. Verdú Andrés

ESR 591 MHz 1-Cell No Feedback – Beam Loading

10 GeV, 580 Bunches





T. Mastoridis

Alternating Gradient Focusing

- Swenson, Alternating Phase Focused Linacs, Particle Accel **7, 61-67**(1976)
  - Bunches which are accelerated at the peak of the RF voltage get maximum acceleration, but little longitudinal and transverse focusing.
  - Bunches which are accelerated when the RF voltage crosses 0 get little acceleration (deceleration) but lots of transverse focusing and longitudinal defocusing.
  - Good (1953), Mullet (1953, unpublished), Fainberg (1956), Bousard (1970)
  - Increase acceptance for low-charge state heavy ions = Argonne 2004, Ostroumov, Shepard, Kolomiets, Masunov (MEPhI).
- Can be applied to synchrotrons too.
  - KEKB, 2010

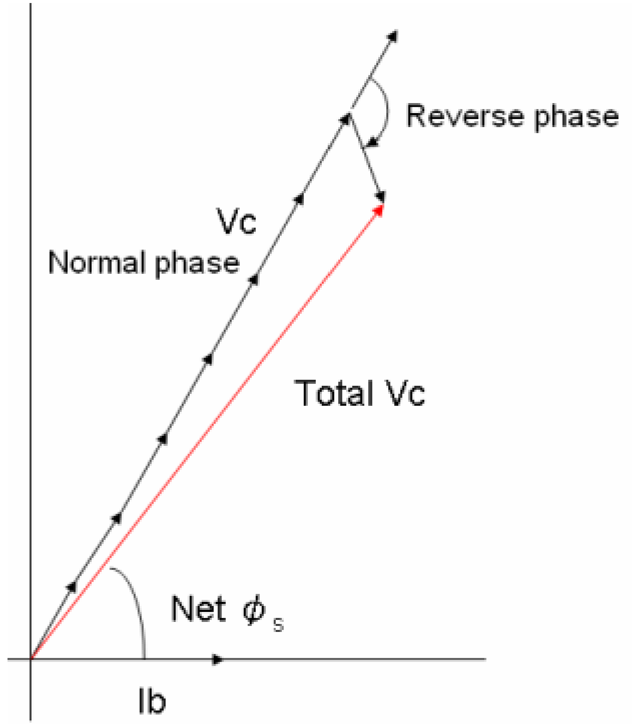
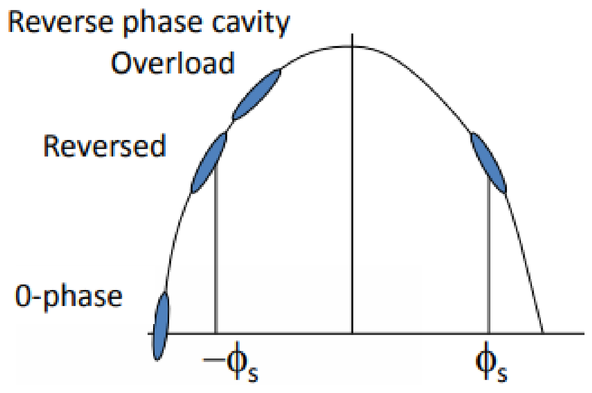


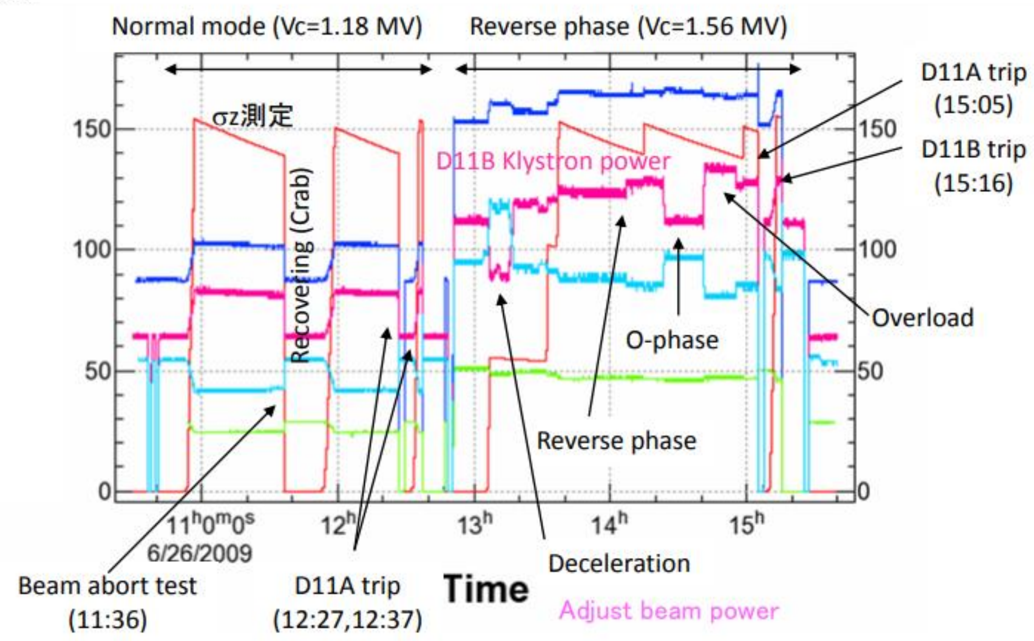
Figure 2: Phasor representation of the cavity voltage. The synchronous beam phase of one cavity is reversed. Each cavity has the large RF voltage, while the total voltage is kept as low as the required value.

Y. Morita et al., IPAC'10

Reverse Phasing

- Introduced by KEKB
  - Reverse synchronous phases of several storage ring RF cavities.
  - Total voltage is kept as low as the designed value.
- Merits
  - Each RF cavity run with high voltage over broad range of beam energies/currents.
    - No need to vary external or loaded quality factors.
  - Each RF cavity provides equal beam power.
- Tested up to ~1.2 A at KEK for 5 days, but not used in operation.
- Things to consider:
  - Higher voltage.
    - RF cavity trips.
    - Contamination.



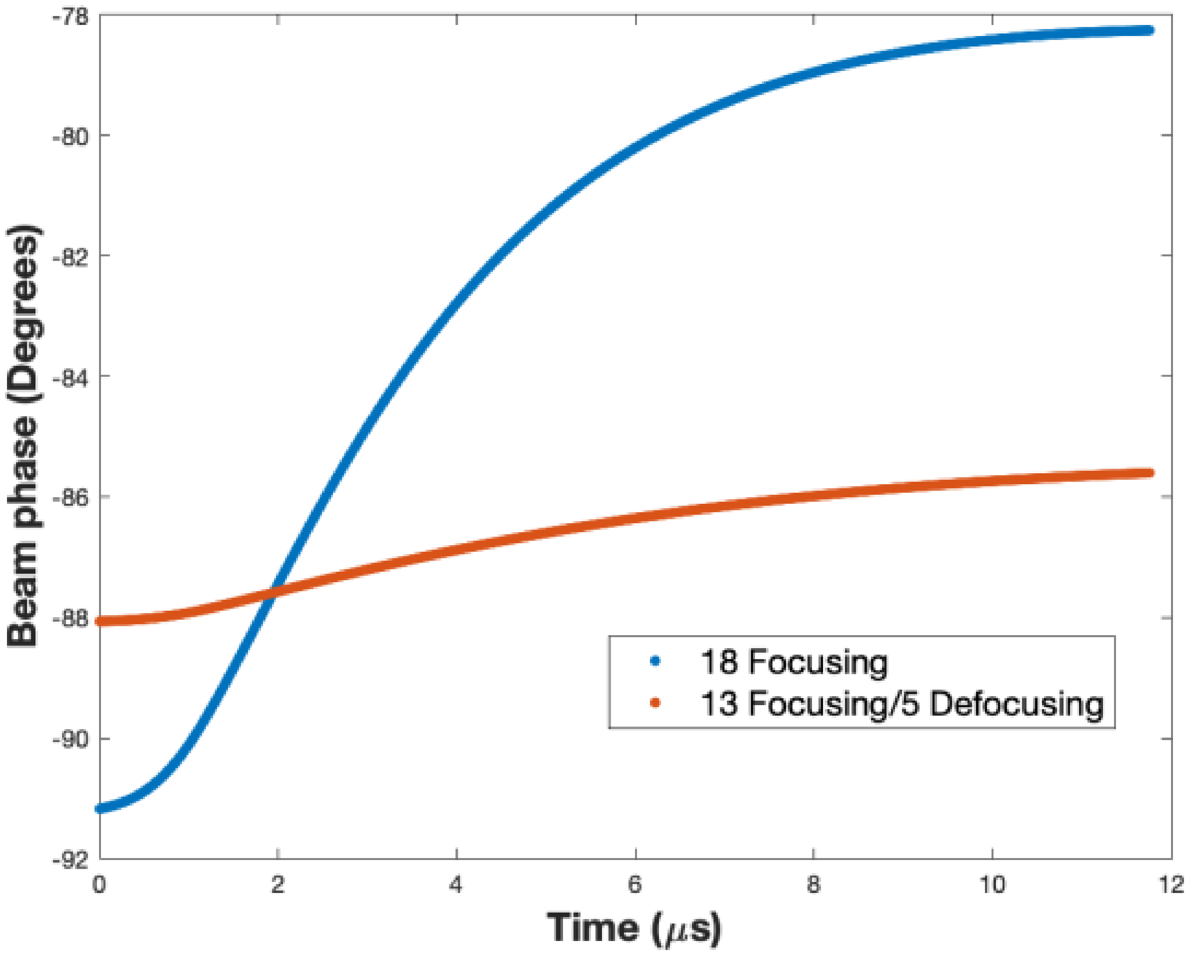


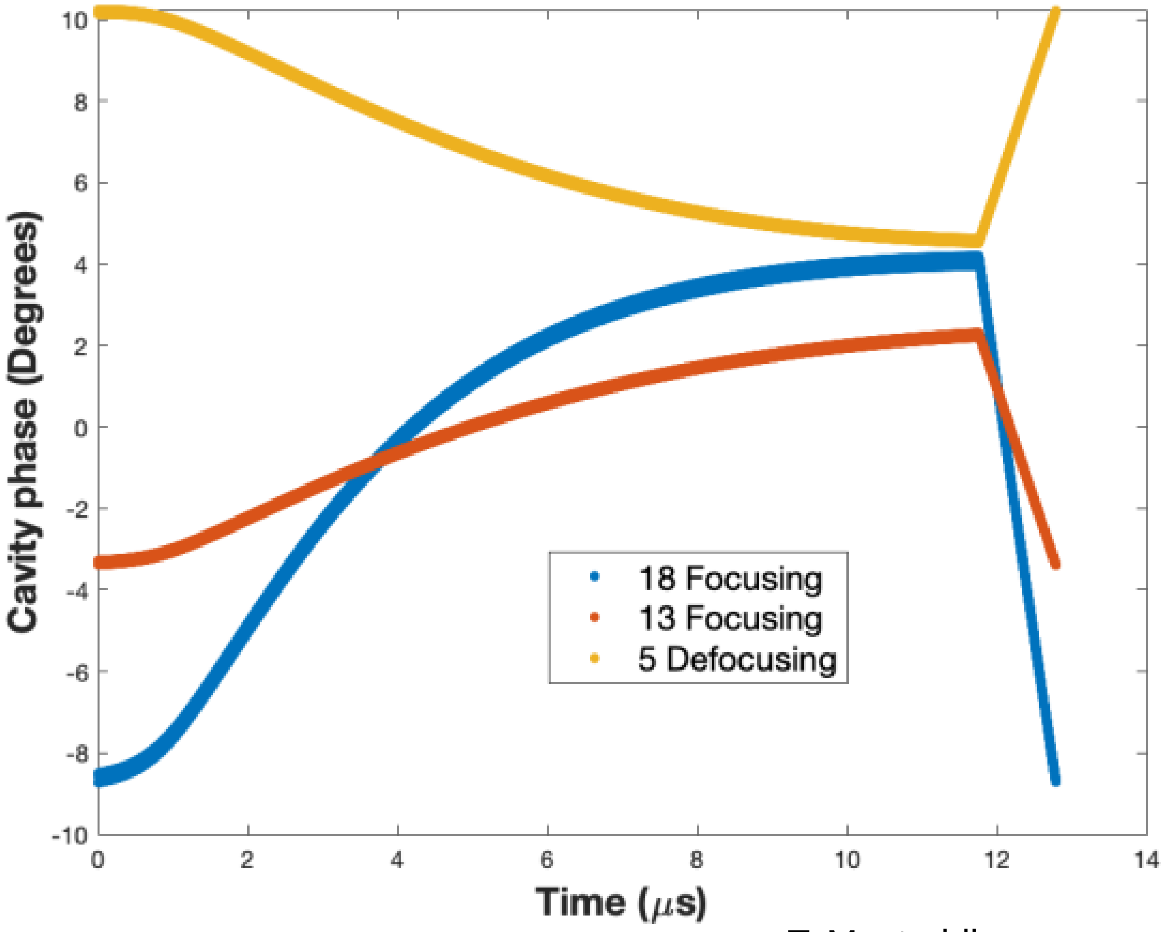
Y. Morita et al., IPAC'10

EIC Reverse Phase Operation

RF Parameter	Focusing	Focusing/Defocusing
Electron Energy	10 GeV	10 GeV
Particles Per Bunch	3.4×10^{11}	3.4×10^{11}
# Bunches	580	580
RF Frequency	591 MHz	591 MHz
Harmonic Number	7560	7560
# Cavities	18	13/5
Energy Loss Per Turn	3.88 MeV	3.88 MeV
Total Voltage	28.9 MV	28.9 MV
Voltage per Cavity	1.6 MV	3.7 MV
Cavity R/Q	74	74
Loaded Quality Factor	6.68e4	2.4e5
Δf	-32.7 kHz	-14.5/+14.5 kHz

ESR with Feedback – Beam Loading





T. Mastoridis

Instabilities, Dampers, and Wakefields

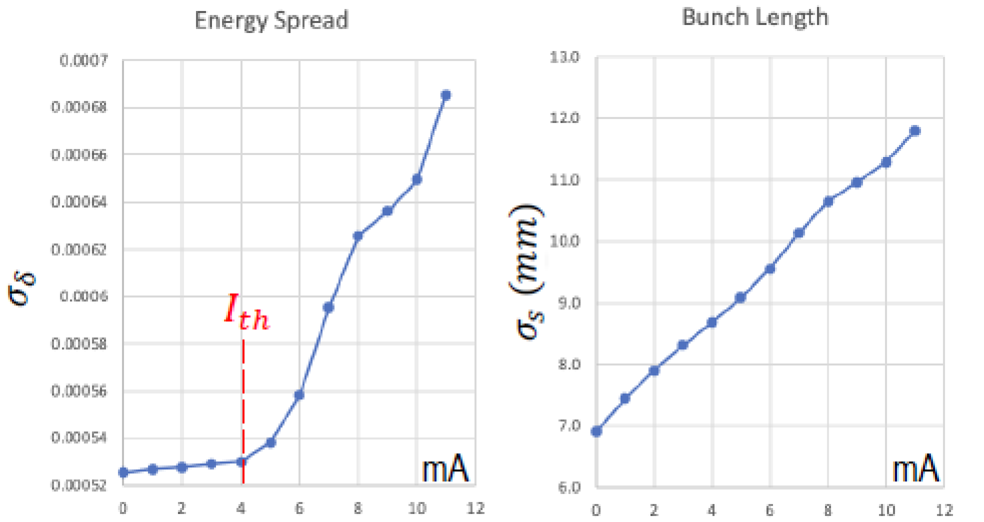
Beam Intensity Limitations

- Single Bunch
  - Short-Range Wakefields (Broad-Band Impedance)
    - Microwave Instabilities
      - Inductive and resistive components.
      - 1960’s Theory for Coasting Beams: Neil, Sessler, Keil & Schnell
      - 1975 Adapted to Bunched Beams: Boussard
      - 1973-1977 mode-coupling: Sacherer.
      - Integrated theory: Pelligrini, Wang, and Krinsky
    - Transverse Mode Coupling Instabilities
      - Resistive wall, geometric impedance
- Beam Intensity Limitations
  - Long-Range Wakefields (Narrow-Band Impedance)
    - Longitudinal/Transverse Coupled-Bunch Instabilities (HOMs of RF Cavities, Main Mode of Crab Cavities, Resistive Wall,…)
    - Ion Instabilities (vacuum, bunch patterns, collimators)
    - Electron Cloud (vacuum chamber, resistive wall surfaces, …)

Boussard Criterion

In the early stages of ring design

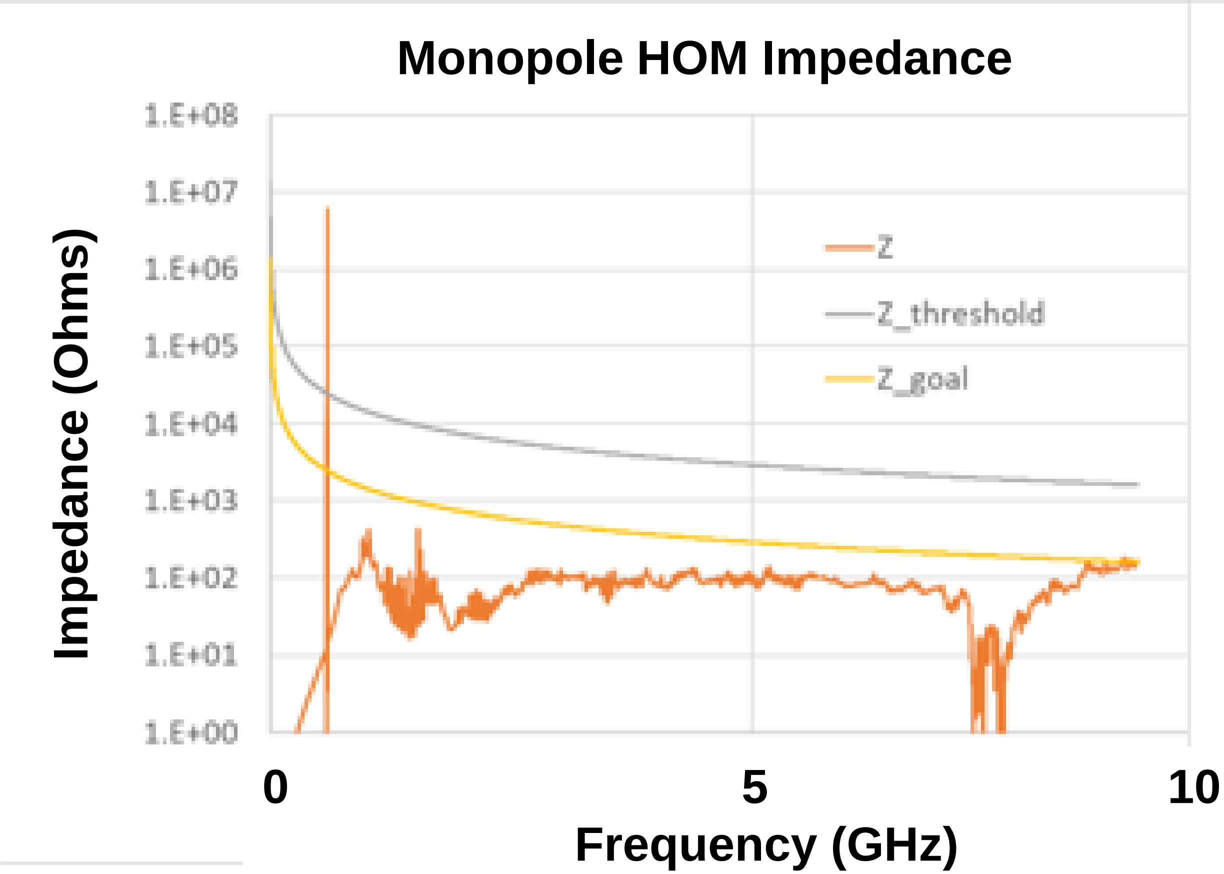
$$I_{th} = 9.4\frac{E\nu_s^2}{e\alpha(ImZ/n)_0}(\omega_0\sigma_\tau)^3$$

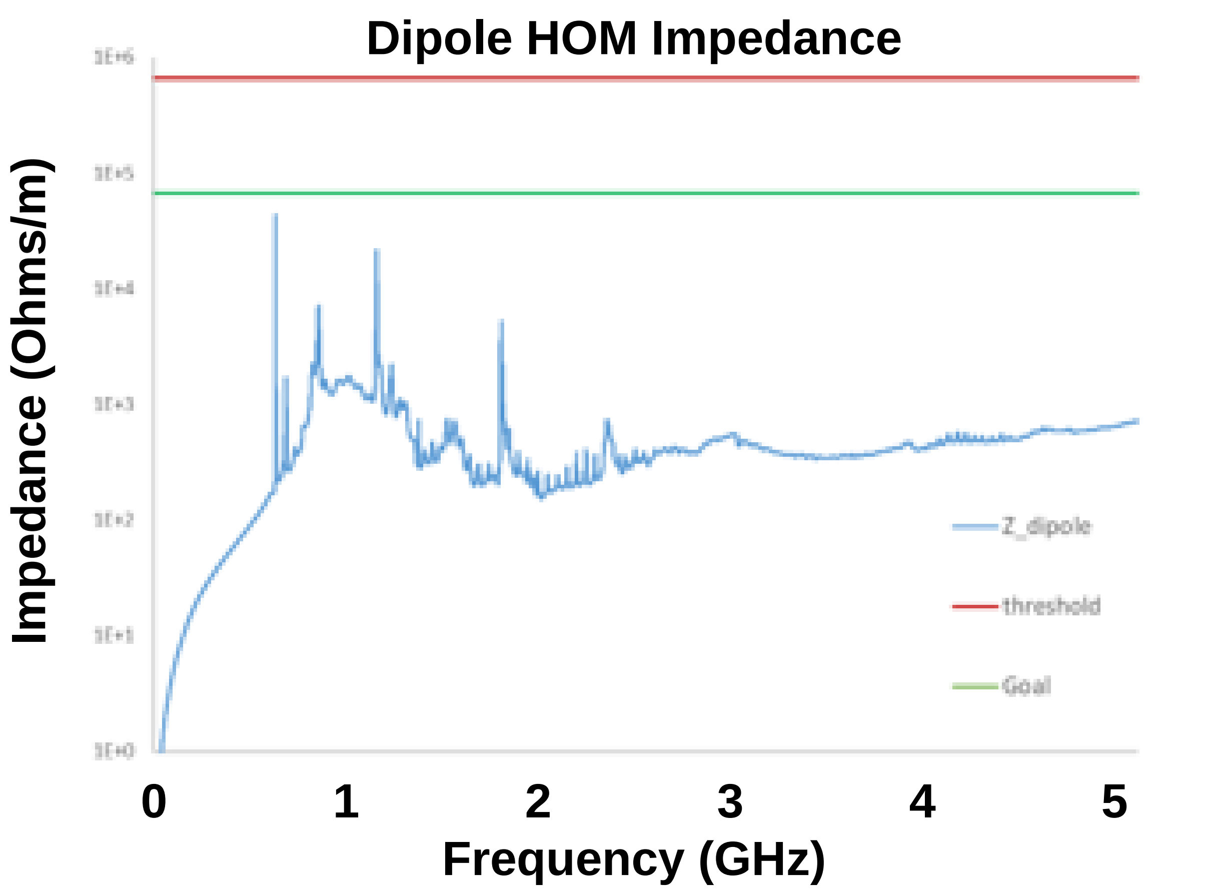


Energy spread σ_δ and bunch length σ_s as a function of single-bunch current

A. Blednykh & M. Blaskiewicz

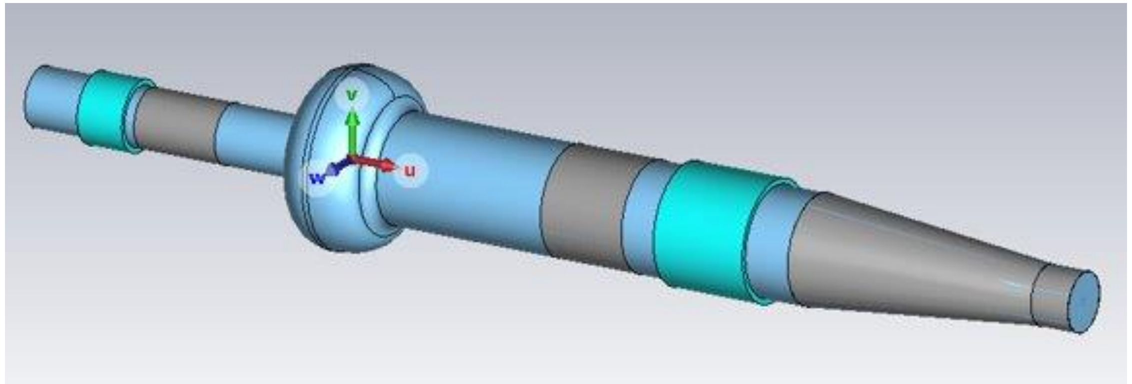
Damping Requirements





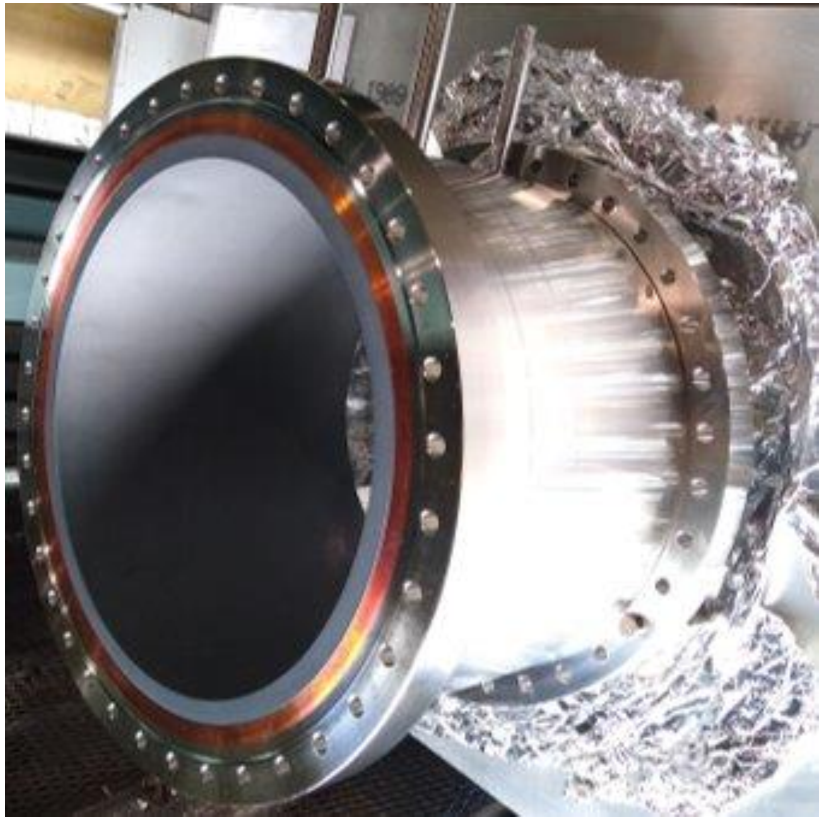
BLA – Damping HOMs & Wakefields

	LBLA	SBLA 1	SBLA 2
Radius (mm)	137	75	75
Length (mm)	240	120	240
HOM power (kW)	34.4	26.5	38.3
Power flux (W/mm^2)	0.19	0.47	0.34



J. Guo

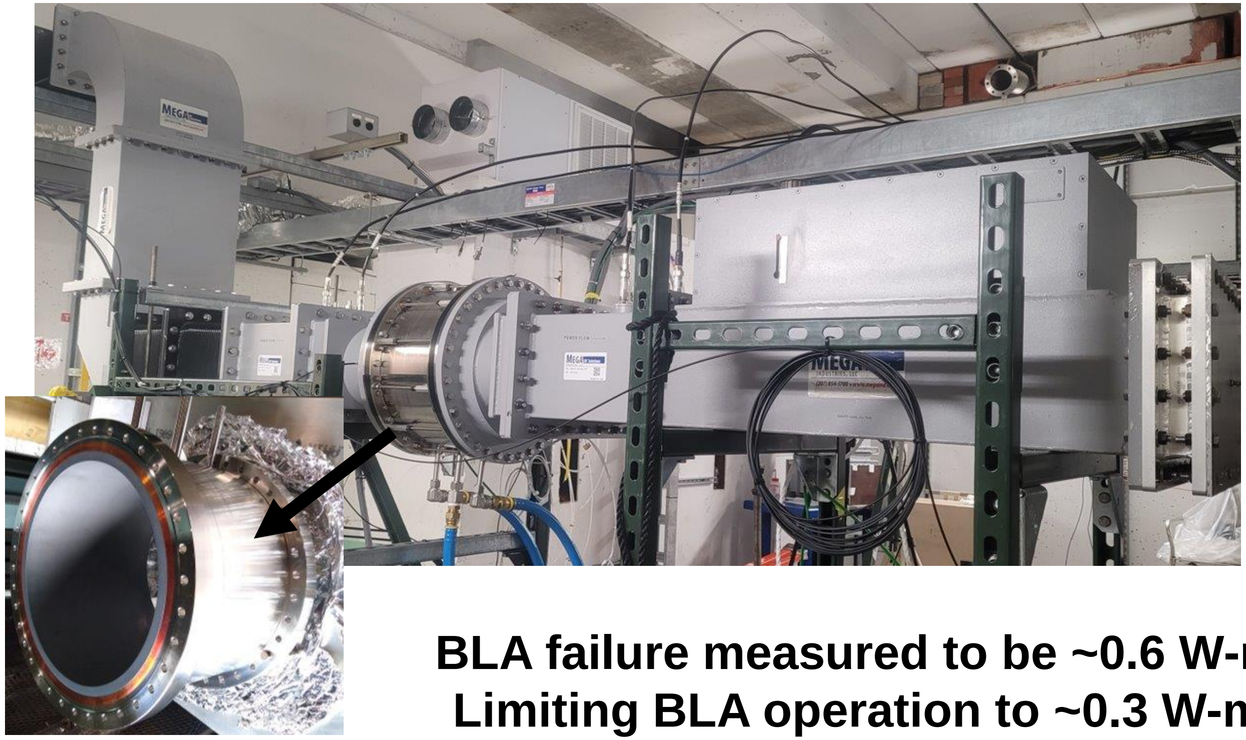
LDRD 274 mm Diameter BLA



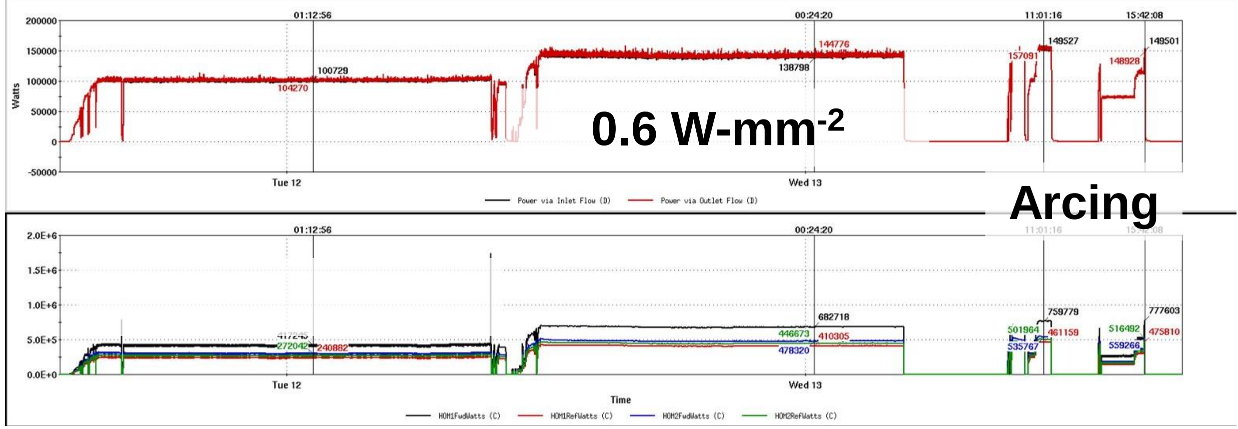
W. Xu et al, Phys. Rev. Accel. Beams **27**, 031601

Beam-Line Absorbers – Damping Wakefields

LDRD Funded Large Diameter Absorber
Close but a bit too large for the EIC.



Testing BLA to progressively higher powers



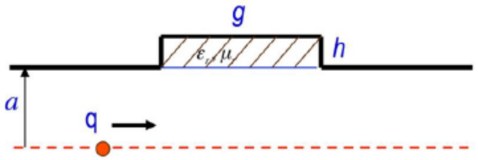
BLA Arc Damage & Cracking

BLA failure measured to be ~0.6 W-mm^{-2}
Limiting BLA operation to ~0.3 W-mm^{-2}

591 MHz 1-Cell Cryomodule – Requirements

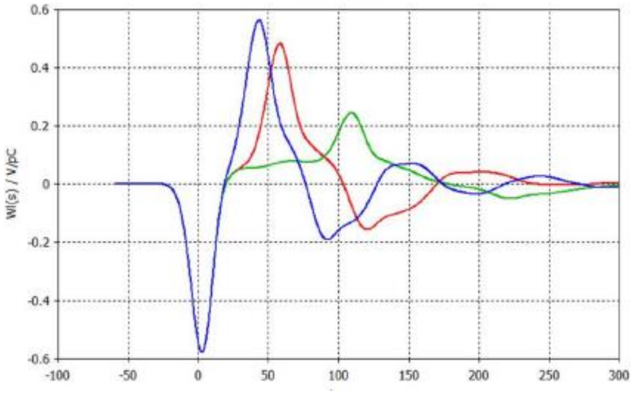
- **Issues:**
  - **Post FDR: Cryomodule does not meet ESR beam stability requirements – ϕ150 mm beam line absorber.**
    - **ϕ150 mm shielded bellows overheating.**
  - **Multipacting concerns at cell equator.**
  - **Tuner lifetime concerns due to cavity stiffness.**

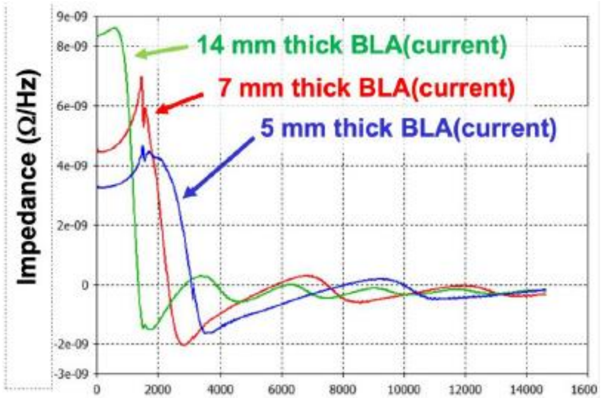
- **Delayed 591 MHz DVC testing leaves unresolved:**
  - **Multipacting concerns at cell equator.**
  - **Tuner lifetime concerns due to cavity stiffness.**



I_{th} ~ 1.8 mA

$$ImZ_{\|}(\omega) = \omega \frac{hgZ_0}{2\pi ac}\mu_r$$

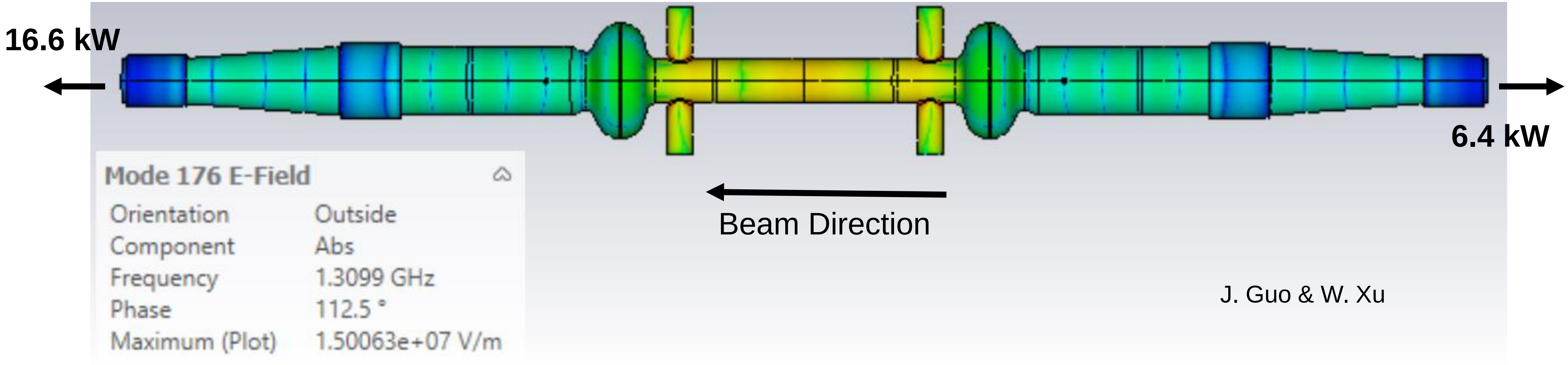




J. Guo

Future Cryomodule Damping Loads

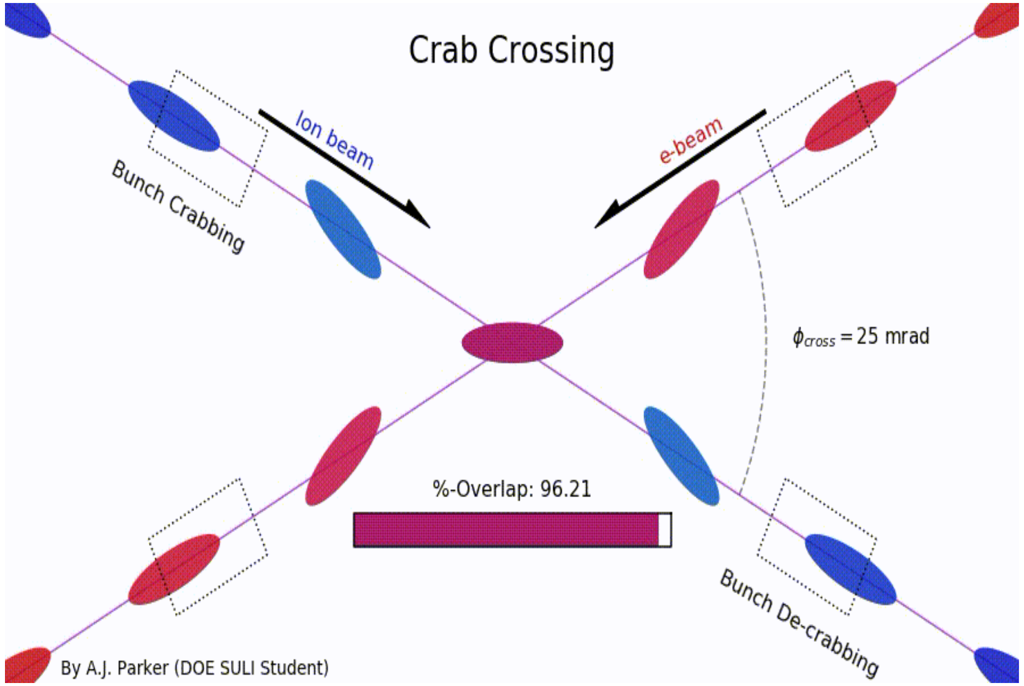
Cryomodule Broadband Losses and RF Power Emitted from Beam Ports	
Total Loss Factor (V/pC)	1.171
Loss Factor Without 591 MHz Cavity Resonance (V/pC)	1.034
Total HOM Power (2 Cavity Cryomodule) (kW)	72.4
Downstream Beam Line HOM Power (kW)	16.6
Upstream Beam Line HOM Power (kW)	6.4

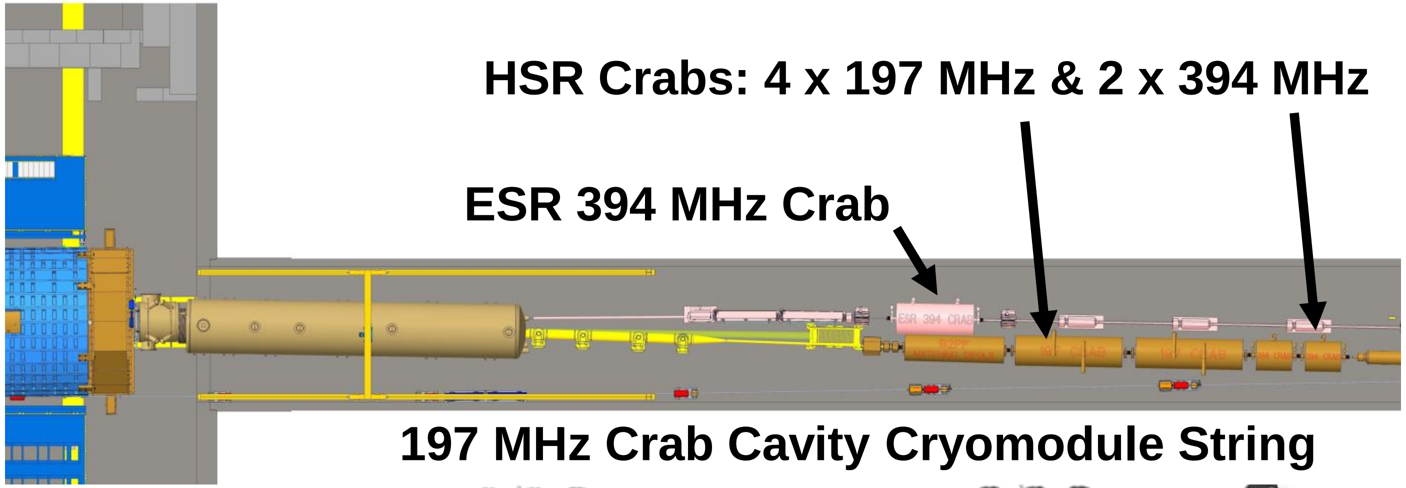


Crabbing
KEK, Hosoyama et al., APAC'98

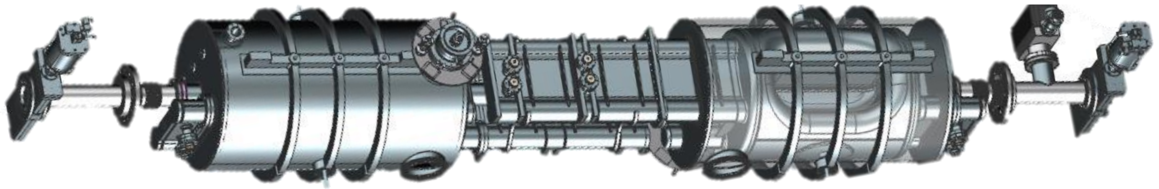
EIC RF Crab System

- Correct bunch orientation @ collision for the crossing angle.
- 4 x 197 MHz crab cavities and 4 x 394 MHz crab cavities each side of HSR IP.
- 1 x 394 MHz crab cavity each side of ESR IP.
- Bunch rotation (crabbing) via transverse deflection.





197 MHz Crab Cavity Cryomodule String



Crab Cavities

Parameter	EIC	HL-LHC	ILC
Crossing Angle (mrad)	25 (37.5)	0.59	14
Frequency (MHz)	197 & 394	400	1300/2600 /3900
Voltage (MV)	33.8 @ 197 2.9 @ 394	6.8	7.4 @ 1300
Longitudinal Space (m)	15 (HSR) 4.5 (ESR)	3.5	3.8
Transverse Space (m)	1.0 (HSR) 0.7 (ESR)	0.194	0.197

197 MHz Crab Cavity Prototype Model

Damping	EIC	HL-LHC	ILC
Longitudinal	316 kΩ (HSR) 26 kΩ-GHz (ESR)	2.4 MΩ	-
Horizontal	2.64 MΩ/m (HSR) 0.96 MΩ/m (ESR)	1.5 MΩ/m	48.8 MΩ/m (250 GeV) 195.2 MΩ/m (1 TeV)
Vertical	13.2 MΩ/m (HSR) 0.96 MΩ/m (ESR)	1.5 MΩ/m	61.7 MΩ/m (250 GeV) 246.8 MΩ/m (1 TeV)

B. Xiao, S. De Silva, N. Huque

Crab Cavity Field Control

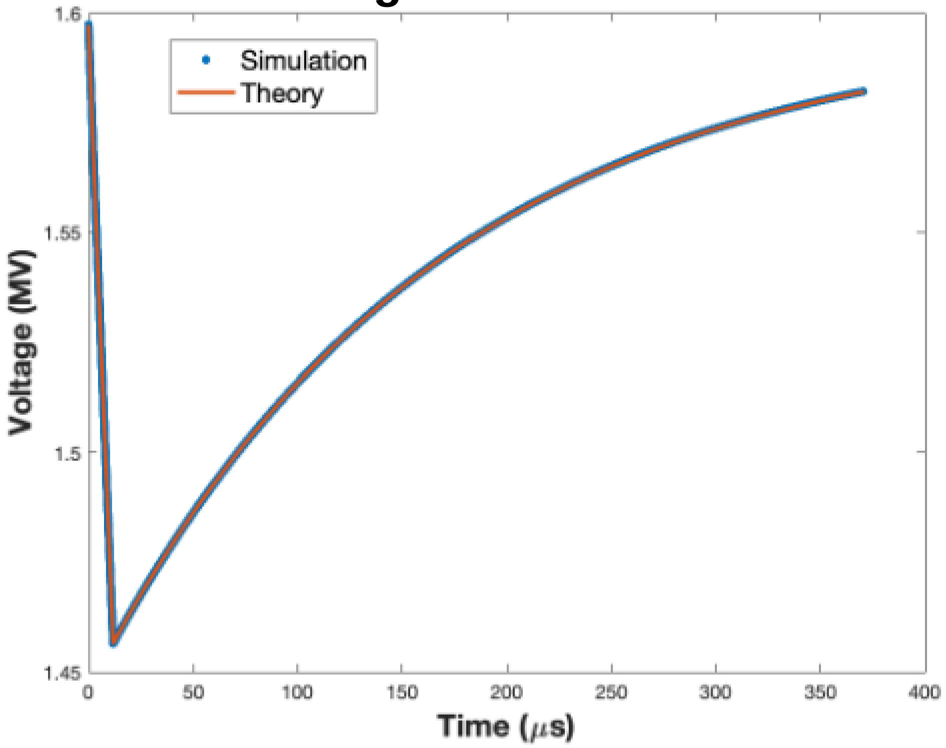
- Crab cavities have large transverse impedances and the beta functions at the cavity are large = strong transverse instabilities.
  - M. Blaskiewicz, Instabilities Driven by Fundamental Crabbing Mode, BNL-222221-2021-TECH
- High gain RF feedback needed to reduce effective cavity impedance by ~2500 (68 dB).
  - Amplify noise injected into the system by LLRF, cross talk, etc.
- One-Turn Delay Feedback (OTFB) required to further reduce transverse impedance at the betatron sidebands by an additional x10 (20 dB).
- Transient beam loading.
  - T. Mastoridis: OTFB and low-delay RF feedback can address transient with moderate peak RF.
- Crabs themselves can limit luminosity lifetime due to low level of noise injected into the fundamental crabbing mode.
  - T. Mastoridis: BNL-222748-2022-TECH

Crab Cavity Field Control

Sample Noise Thresholds

	$\sigma_{\Delta\varphi}$ (μrad)	$\sigma_{\Delta A}$ (1e-6)
HL-LHC	8.17	13.30
ESR 5 GeV	805	12700
ESR 10 GeV	860	13600
ESR 18 GeV	548	7060
HSR 41 GeV	3.09	10.1
HSR 100 GeV	2.69	9.36
HSR 275 GeV	**1.75**	**7.07**
Au 41 GeV	18.7	39.4
Au 110 GeV	5.12	17.8

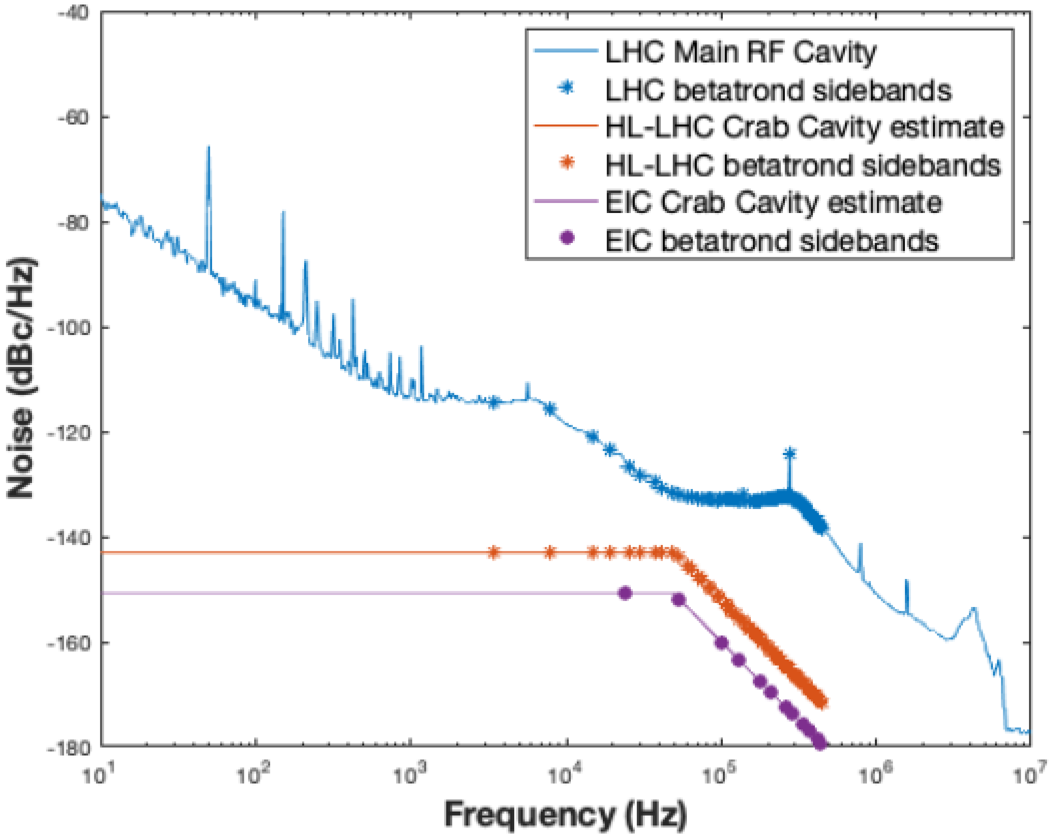
Crab Cavity Voltage Transient Single Bunch Train



Baudrenghein & Mastoridis, PRST-AB **18**, 101001 (2015)
T. Mastoridis, NAPAC'22
T. Mastoridis et al, BNL-224087

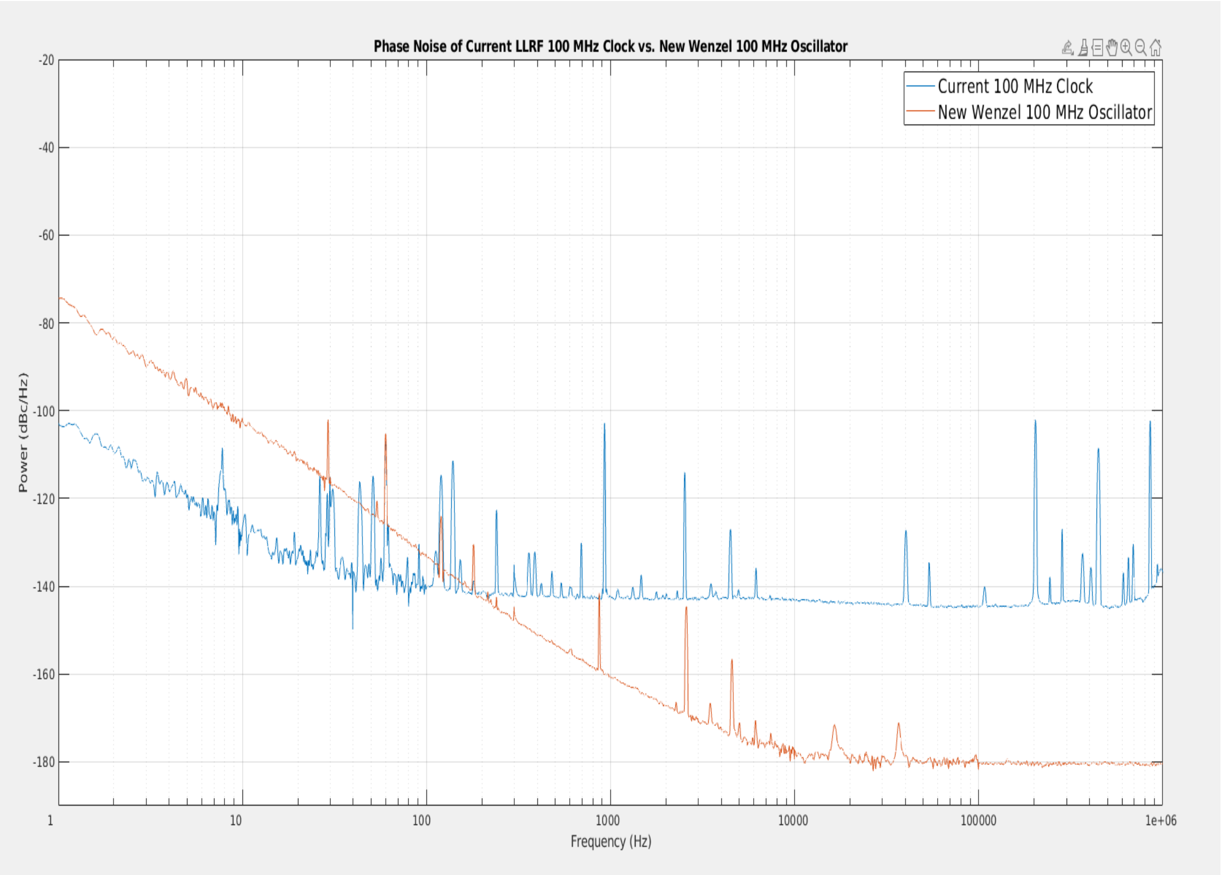
LLRF Noise

EIC 197 MHz Crab Cavity Noise Requirements



T. Mastoridis, NAPAC'22

RHIC 100 MHz Master Clock vs Eval Master Clock



F. Severino

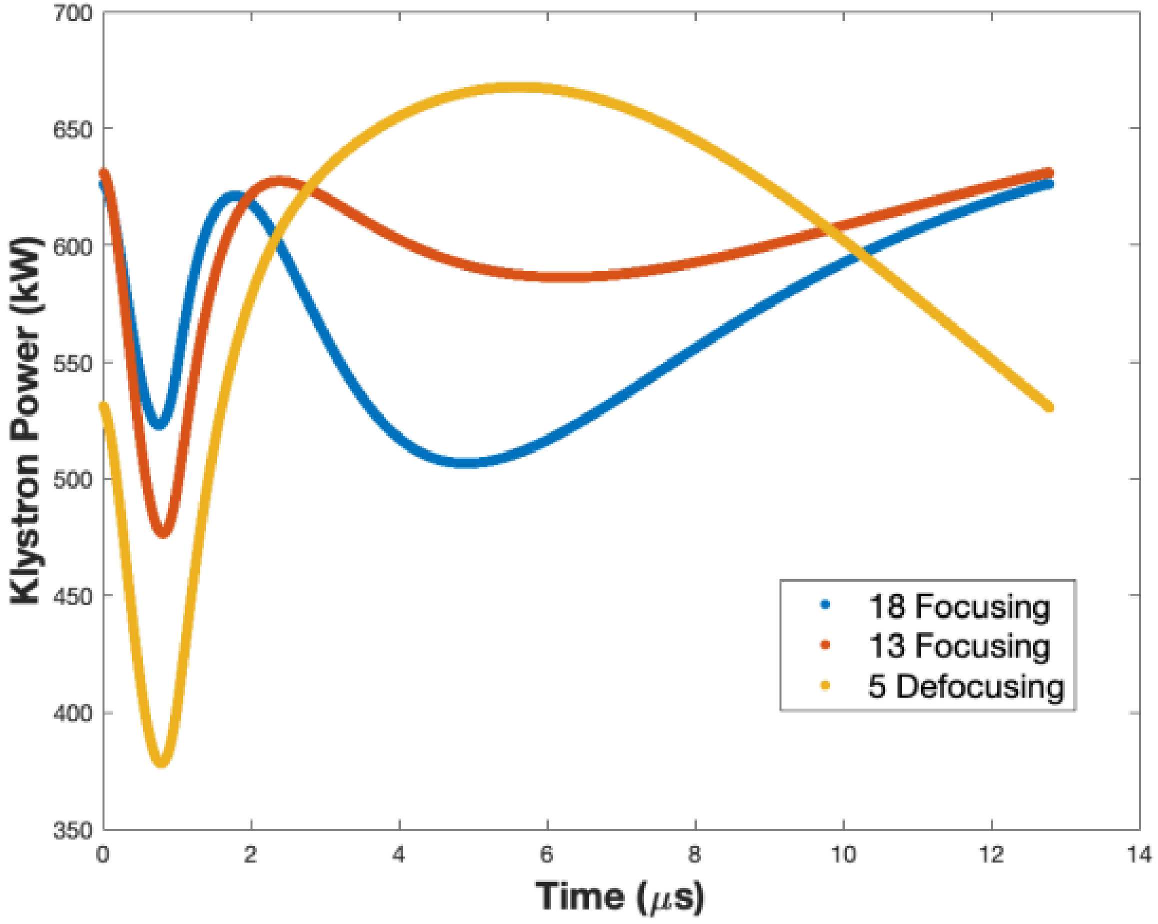
That's All Folks

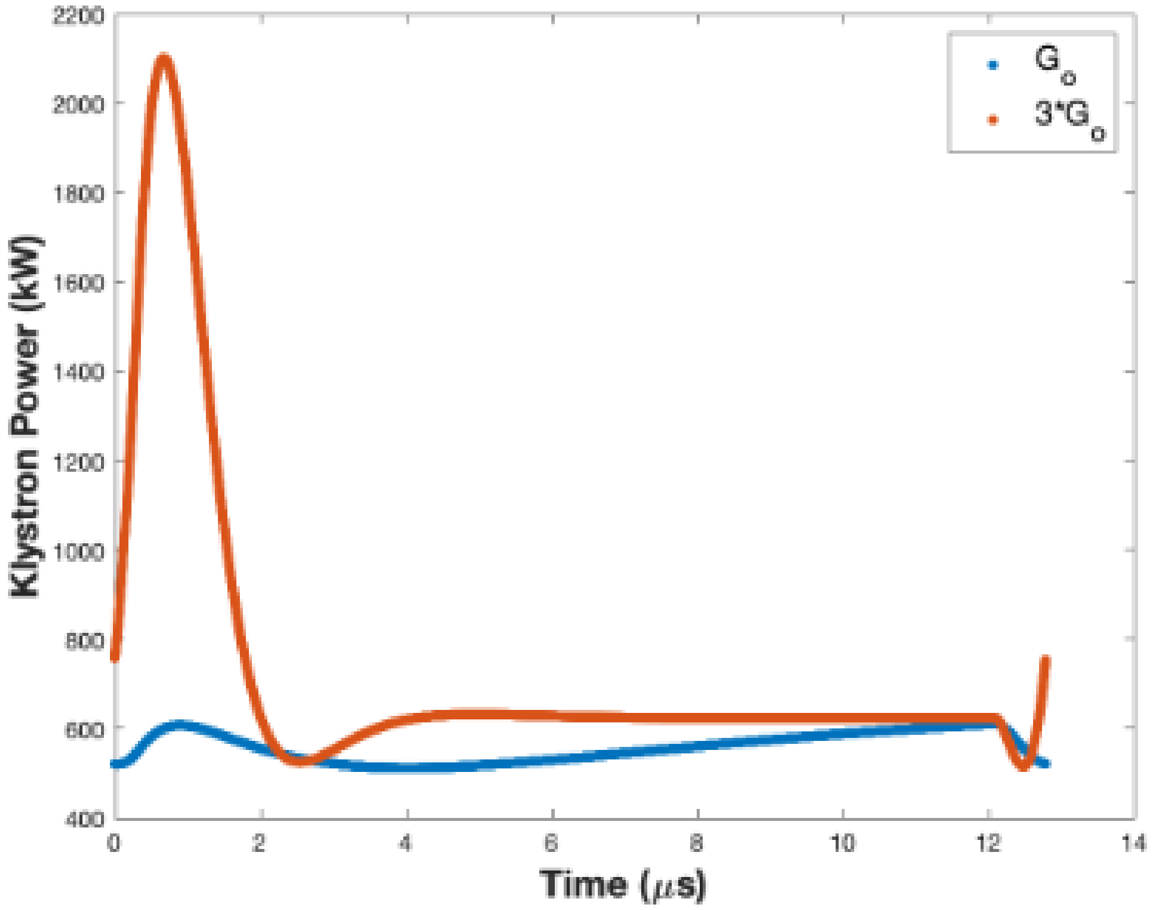
Closing Remarks

- Most of what we discussed today cannot be proven until EIC operations start.
- FPCs operating at ½ the EIC requirement and lower frequencies took a while to attain stable operation.
- Beam line absorbers: $arned if you do, $arned if you don’t.
- RF Control will push limits of amplifiers, RF delivery components, and control system.
- Crab cavities have enough challenges, we will find more.

- None of this would be possible without an excellent EIC RF Systems team enjoying strong support from JLab/BNL EIC: Accelerator Physics, Controls, Cryogenics, Facilities, Accelerator Subsystems, etc.
- The people make this work and are our most precious resource.

ESR With Feedback – RF Power





T. Mastoridis