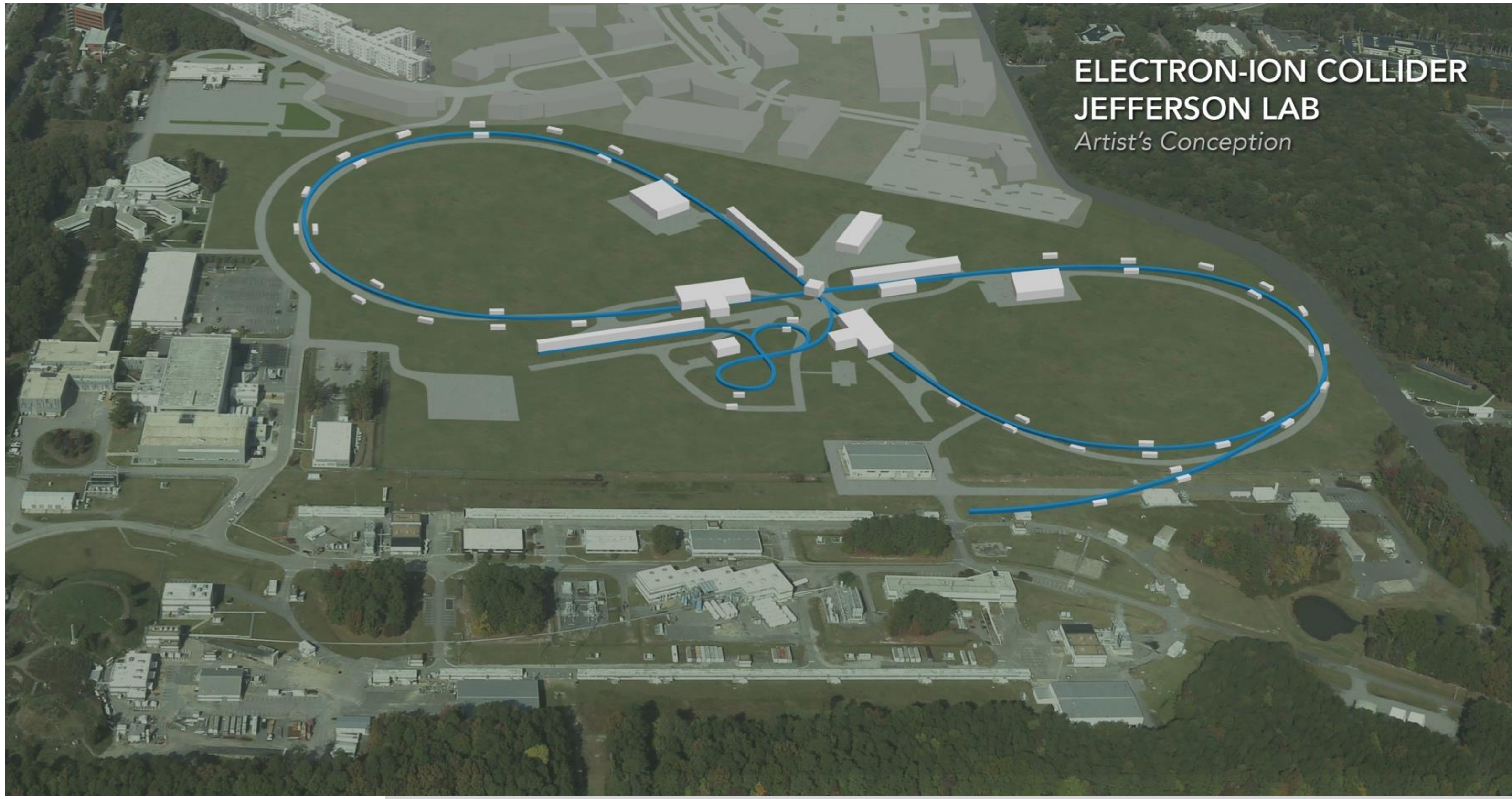
RF System Challenges in Circular Colliders

Bob Rimmer

Jlab

(with thanks to many colleagues worldwide for examples and materials)



Tuesday January 22nd, 2019, HKUST

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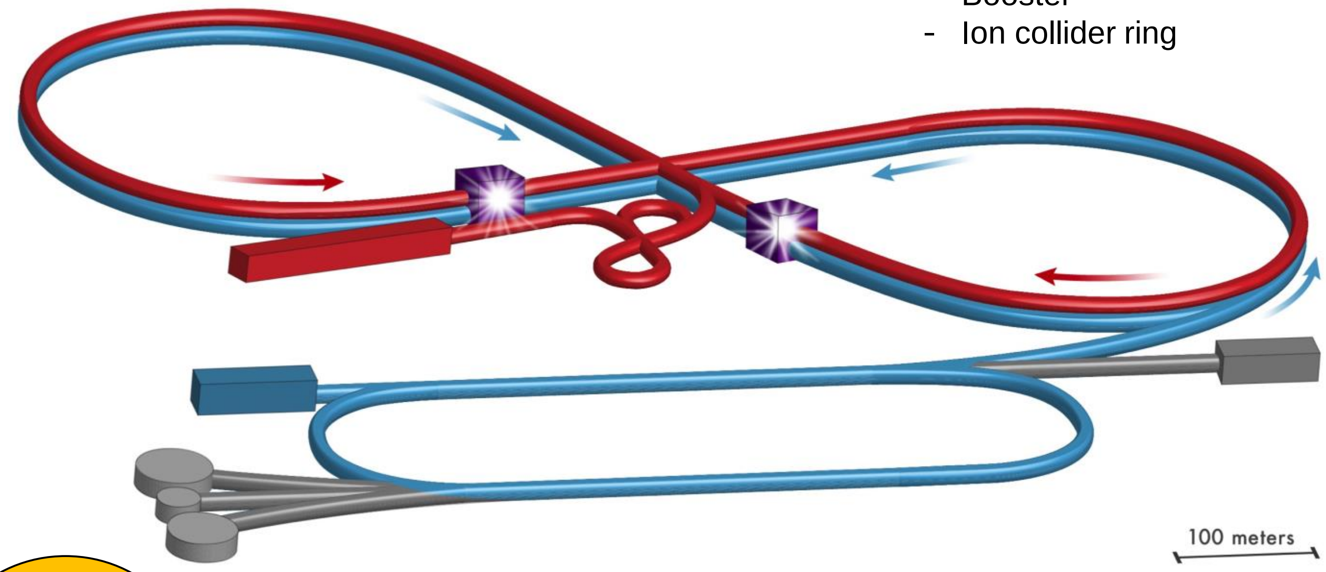
Outline: Collider challenges (using examples from JLEIC and other machines)

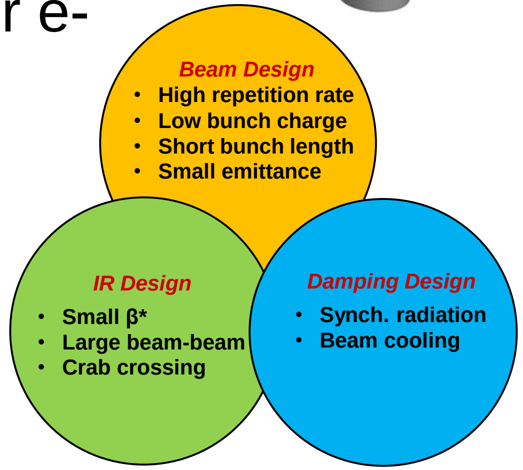
- High energy
  - Many cavities/cells
  - High synchrotron radiation power (e+e-)
- High currents, many bunches
  - High beam power
  - Detuning
  - Instabilities
  - High power couplers/windows
  - HOM damping/power
  - Coupled-bunch modes, BBU, feedback
- Gaps
  - Ion clearing or abort gaps
  - Transients
  - Complex beam spectrum
- Interaction regions
  - Impedance/heating
  - Crab crossing
- Conclusions

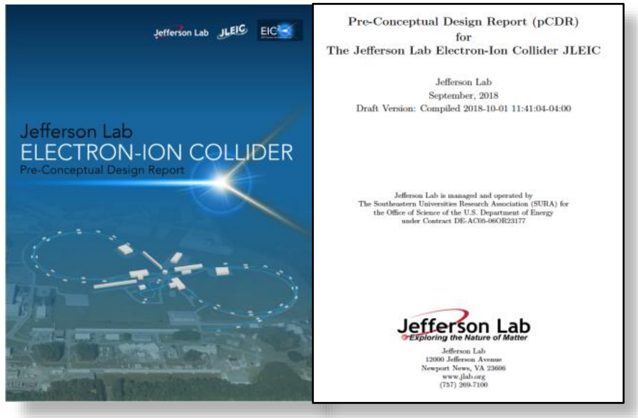
Introduction to JLEIC

- **JL**ab **el**ectron **i**on **c**ollider
- Figure 8 to preserve polarization
- High currents (3A e-, 750 mA p+)
- Many bunches
- Modest charge per bunch
- e-cooling for ions
- Synchrotron damping for e-
- Injection, top-off from CEBAF for e-
- New ion injection complex

- Electron complex
  - CEBAF as a full energy injector
  - Electron collider ring
- Ion complex
  - Ion source
  - SRF linac
  - Booster
  - Ion collider ring







Pre-Conceptual Design Report (pCDR)
for
The Jefferson Lab Electron-Ion Collider JLEIC

Jefferson Lab
September, 2018
Draft Version: Compiled 2018-10-01 11:41:04-04:00

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Exploring the Nature of Matter

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High energy requirements

- Many cavities/cells
  - Multi-cell cavities may be desirable if possible
- High synchrotron radiation power (e+e-)
  - May push coupler limits
  - Coupler power may limit the number of cells per cavity (typically 1-5 cells)
  - Practical limit of affordable power?

- Reliable operation
  - Moderate gradients, try to avoid field emission
  - Safety factor on power coupler
  - Strong cooling/thermal management

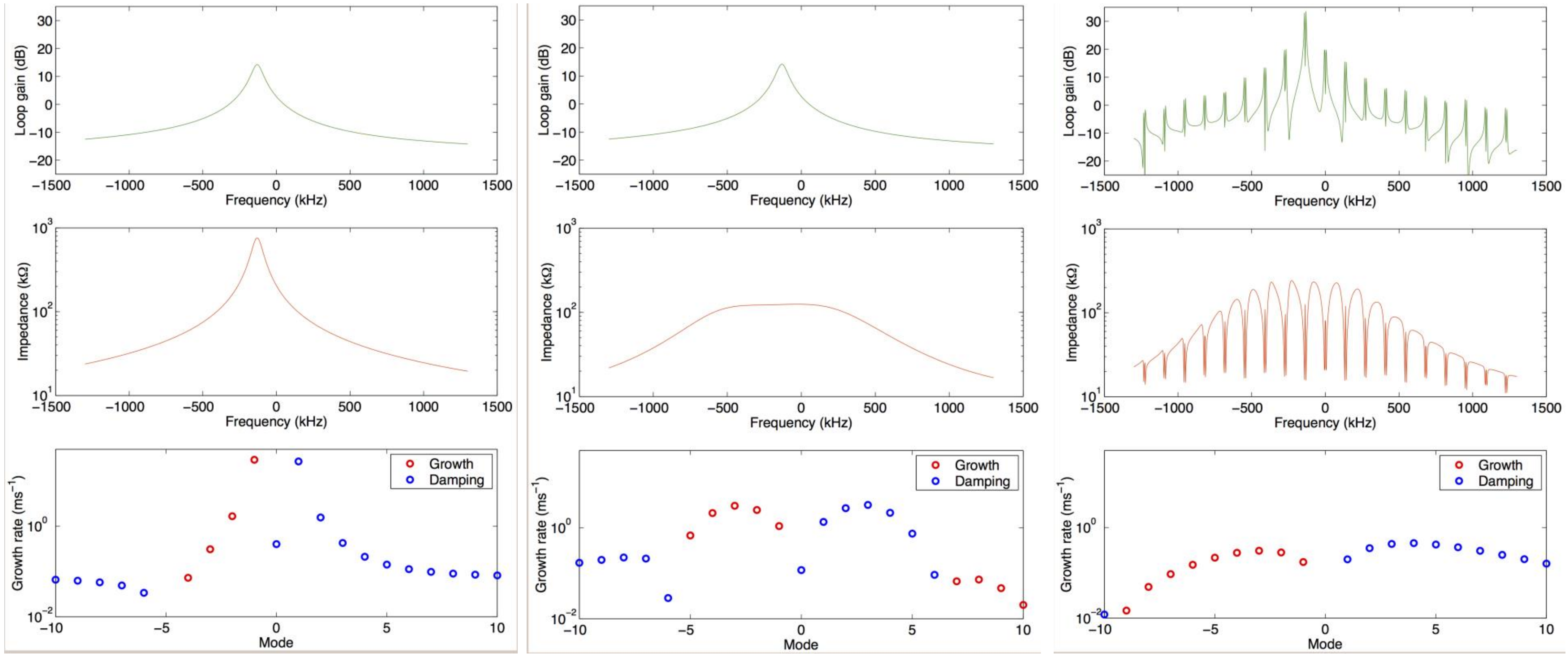
High currents, many bunches

- High beam power
  - Ampere level currents
  - 10’s to 100’s of MW beam power
  - Achieved through moderate current per bunch, many bunches
  - Requires synchrotron radiation absorbers, chamber cooling (e+e-)
  - Need collimation to protect the detector, active beam abort to protect the machine (gaps)
- Detuning
  - Heavy beam loading may require detuning over multiple revolution harmonics
- Instabilities
  - Longitudinal and transverse HOMs, detuned fundamental
  - Many possible CB modes, broad-band bunch by bunch feedback systems needed
- High power couplers/windows
  - MW class windows have been designed (not so many vendors left)
  - Typically de-rated ~50% for storage ring use (PEP-II, KEK-B, ~500 kW)
- HOM damping/power
  - HOM power can be many kW per cell
  - Cell shape should be optimized to reduce BBU, minimize power
  - High-power broad-band absorbers needed

Effect of detuning and RF feedback

PEP-II type digital LLRF system had additional loops for comb filter, klystron equalization and ripple, low mode LFB, gap loop, saturation loop, etc.

"Beam loading compensation for Super B-factories", Dmitry Teytelman, PAC05



Cavity detuned for beam loading | Direct loop on | Comb loop on

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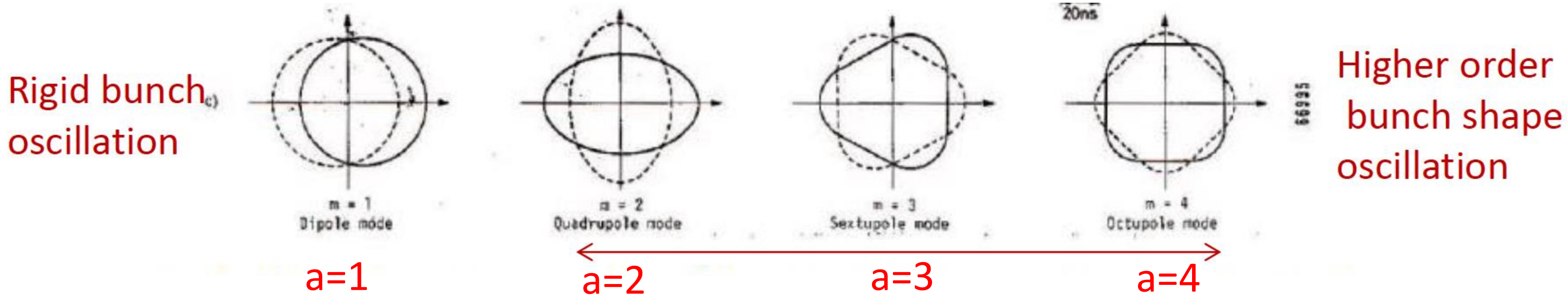
Coupled Bunch Instabilities

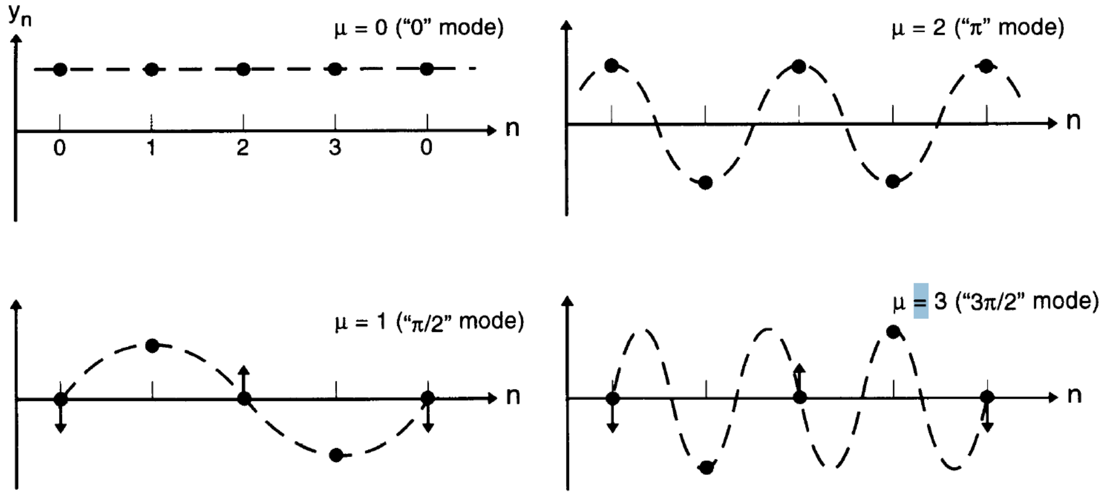
This instability happens when single bunch coherent motion gets coupled among bunches when there is long range wakefield.

Rui Li,

- Single bunch modes in longitudinal phase space



- Coupled Bunch Modes



PEP-II actual bunch rate ≤ 476/2 = 238 MHz,
119 MHz BW needed (kickers built)
Transverse FB electronics DC-238 MHz
W. Barry, PAC95
LFB cavity 952-1190 MHz
(1071 MHz center frequency, 238 MHz BW)
P. McIntosh PAC03

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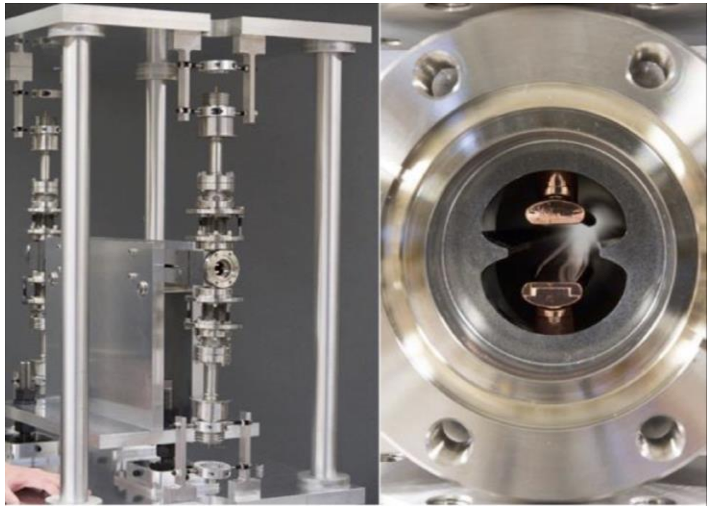
Impedance and feedback

- Broadband damping of cavity HOMs is essential
- Many other ring components need to be considered
- PEP-II feedback systems allowed running above threshold. Similar systems are now commercially available
- System will be coupled to main RF for low modes
- Reliable high-power kickers are needed



APS type transverse kicker

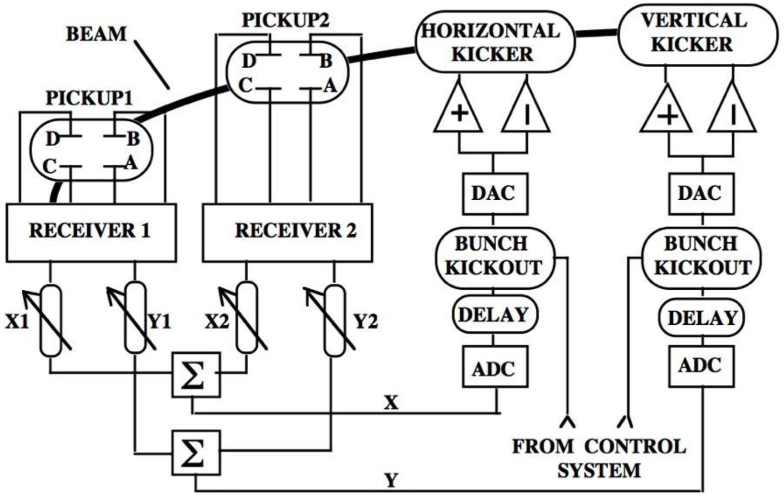
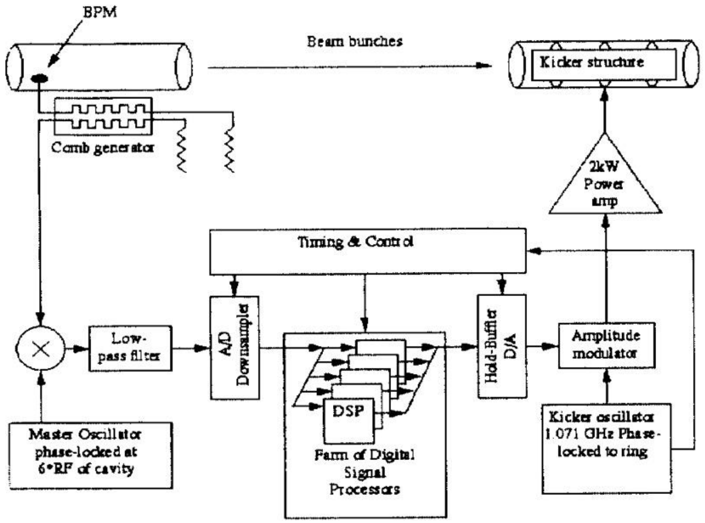
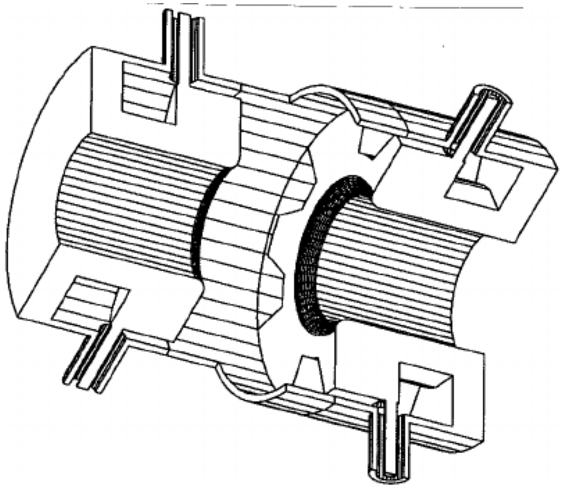


Figure 1: Transverse feedback system concept.



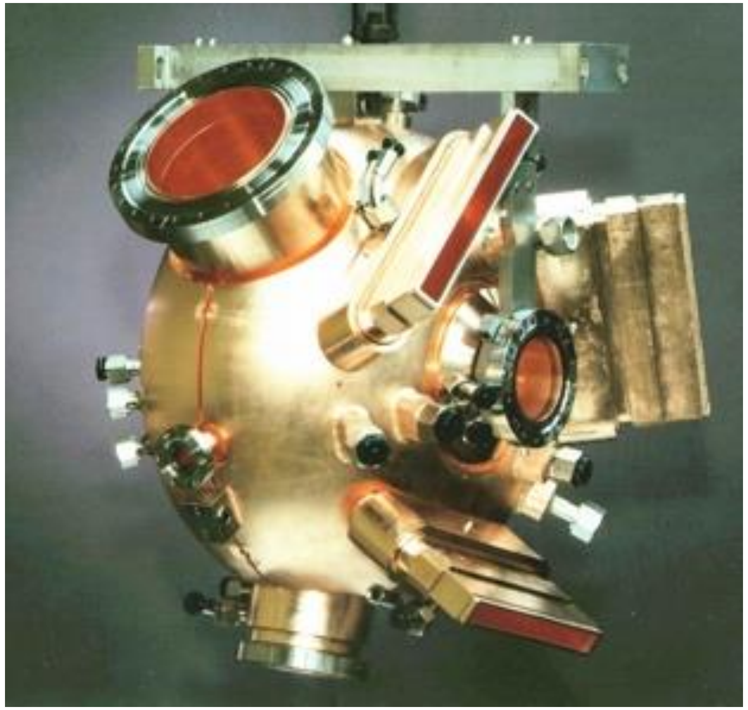
PEP-II Longitudinal Feedback system concept



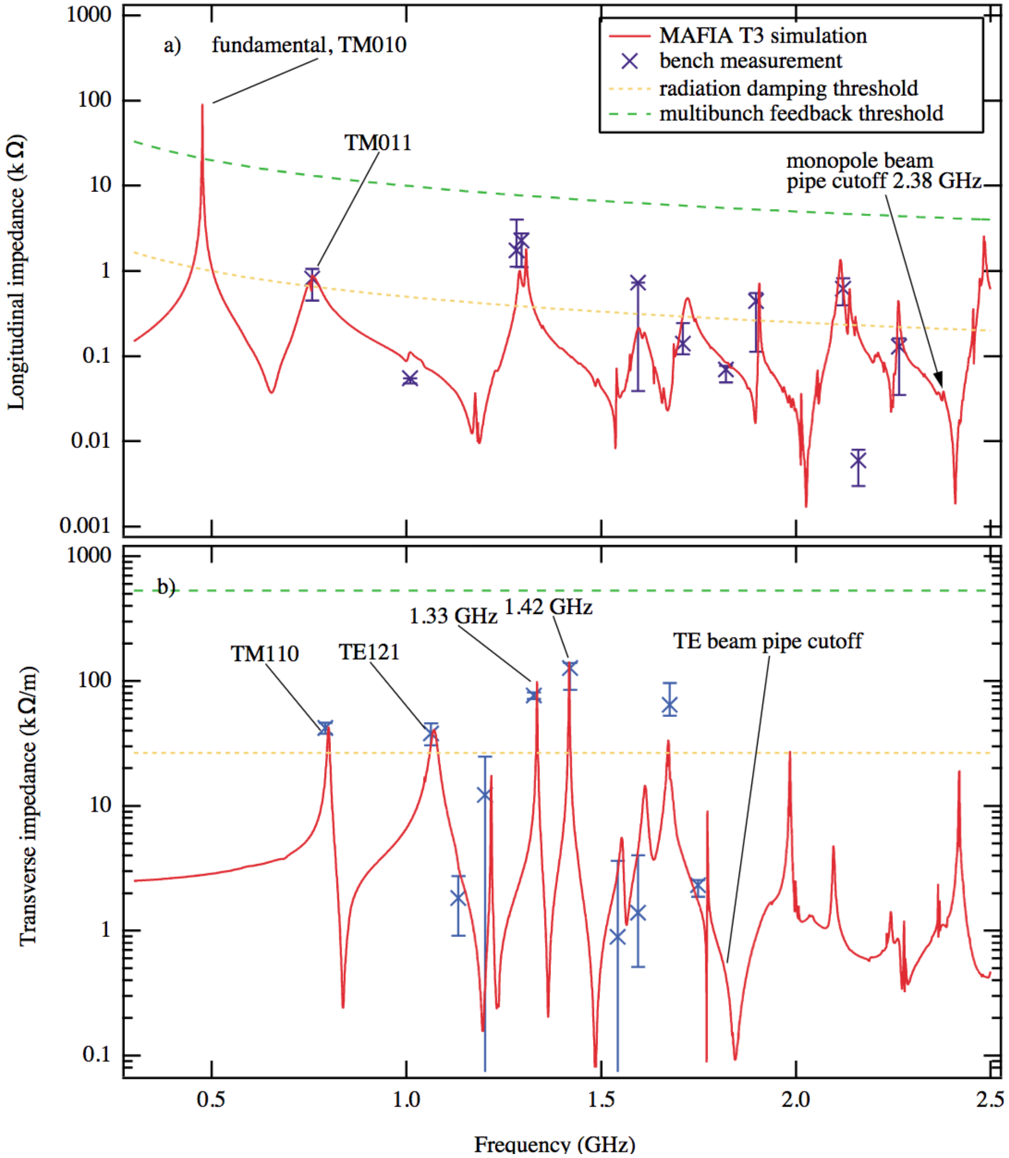
DAPHNE type kicker

Narrowband Impedance Estimation: JLEIC e-Ring

- RF cavity in e-Ring (PEP-II cavities)



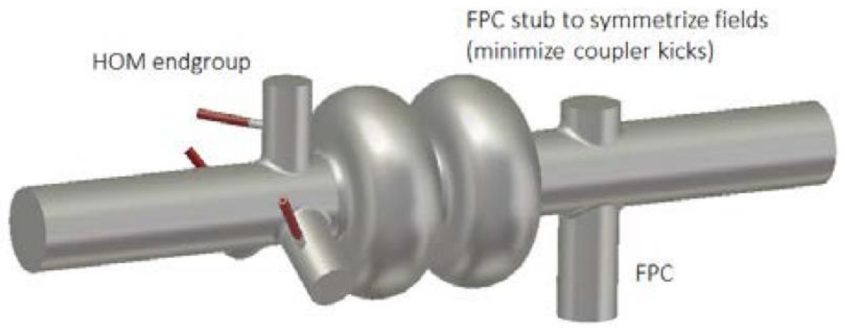
PEP II cavity
476 MHz, single cell,
1 MV gap with 150 kW,
strong HOM damping,
>400 kW RF to beam



JLEIC ion-Ring initial design

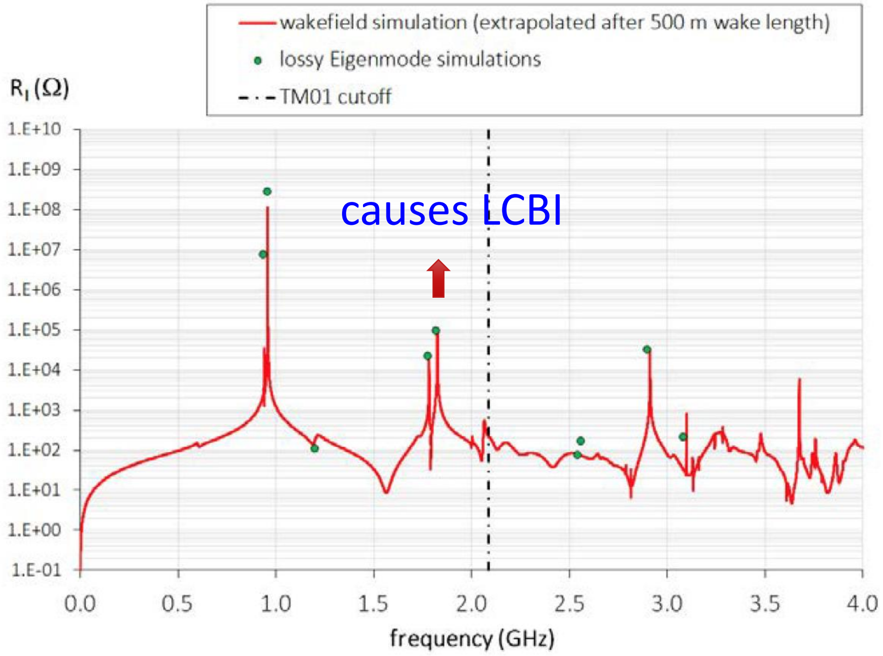
- 956 MHz 2-cell Cavity (F. Marhauser)

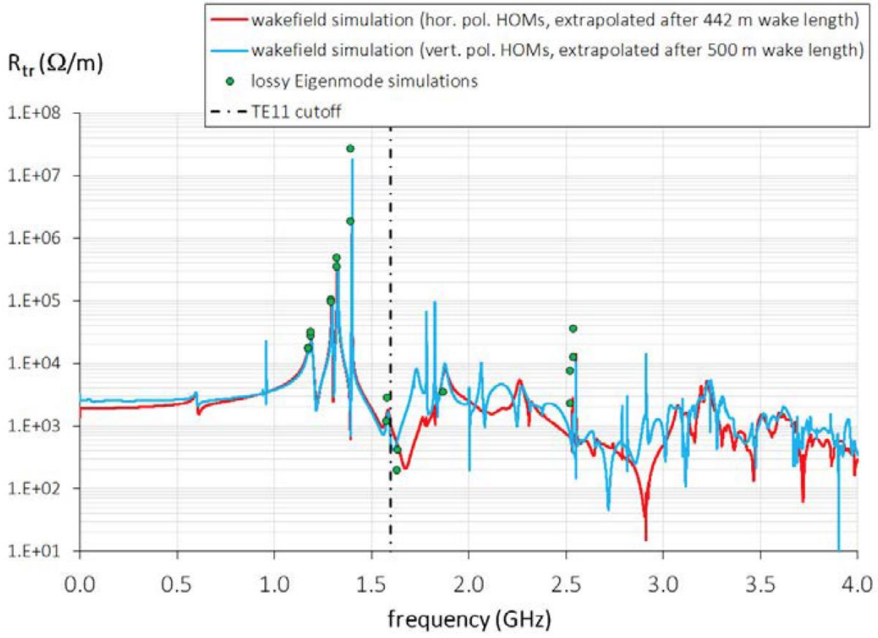
with coaxial couplers



as tradeoff between accelerating and HOM-damping efficiency

Unstable!

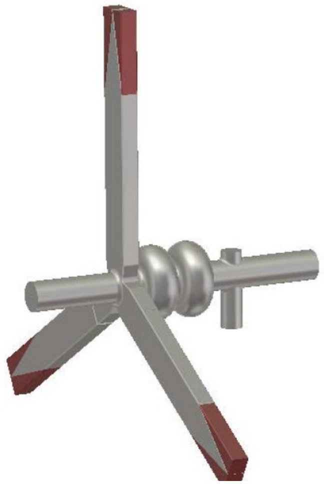




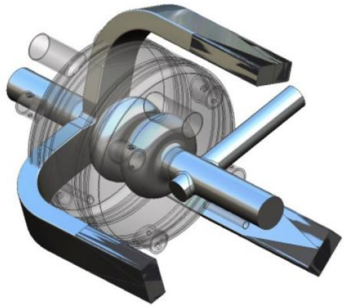
JLEIC ion-Ring new baseline

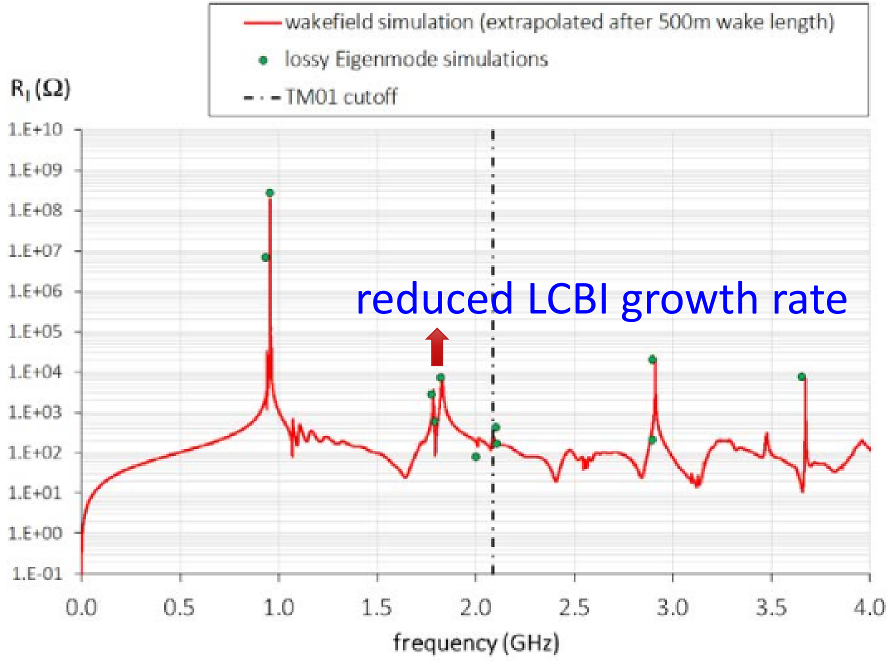
- 956 MHz 2-cell Cavity (F. Marhauser)
- Waveguide HOM dampers

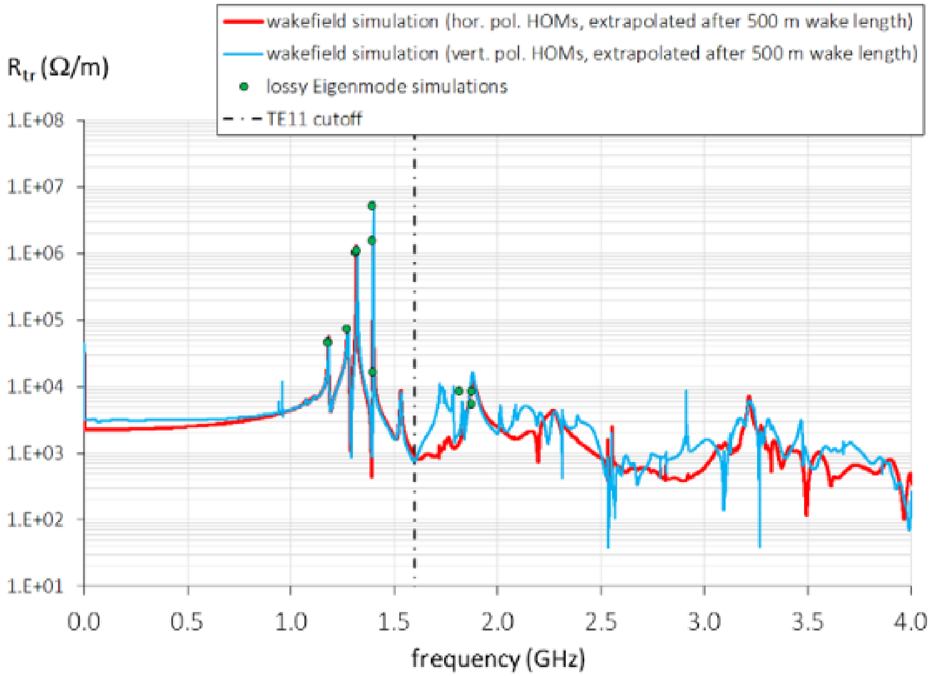
Stable!



waveguide couplers

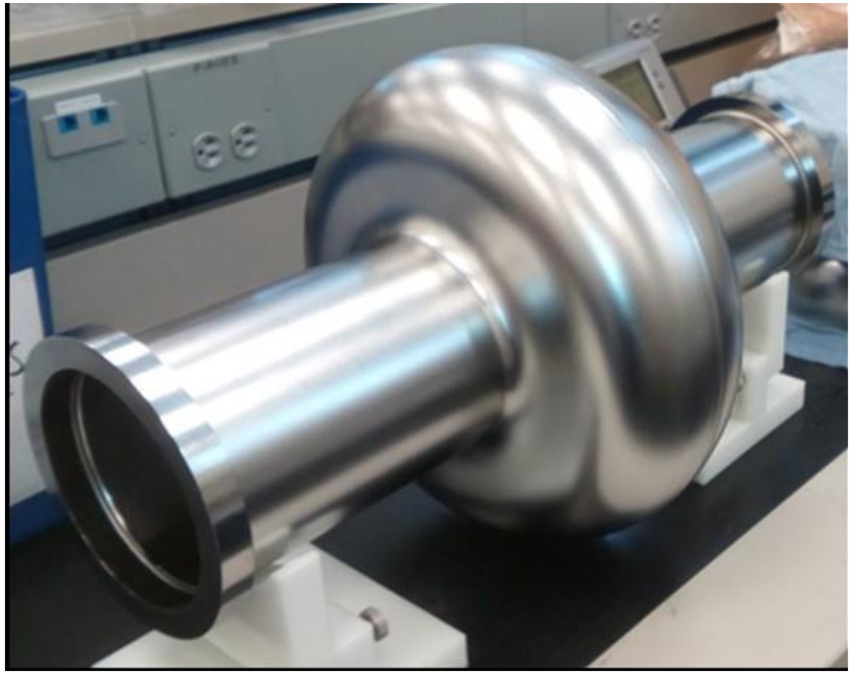


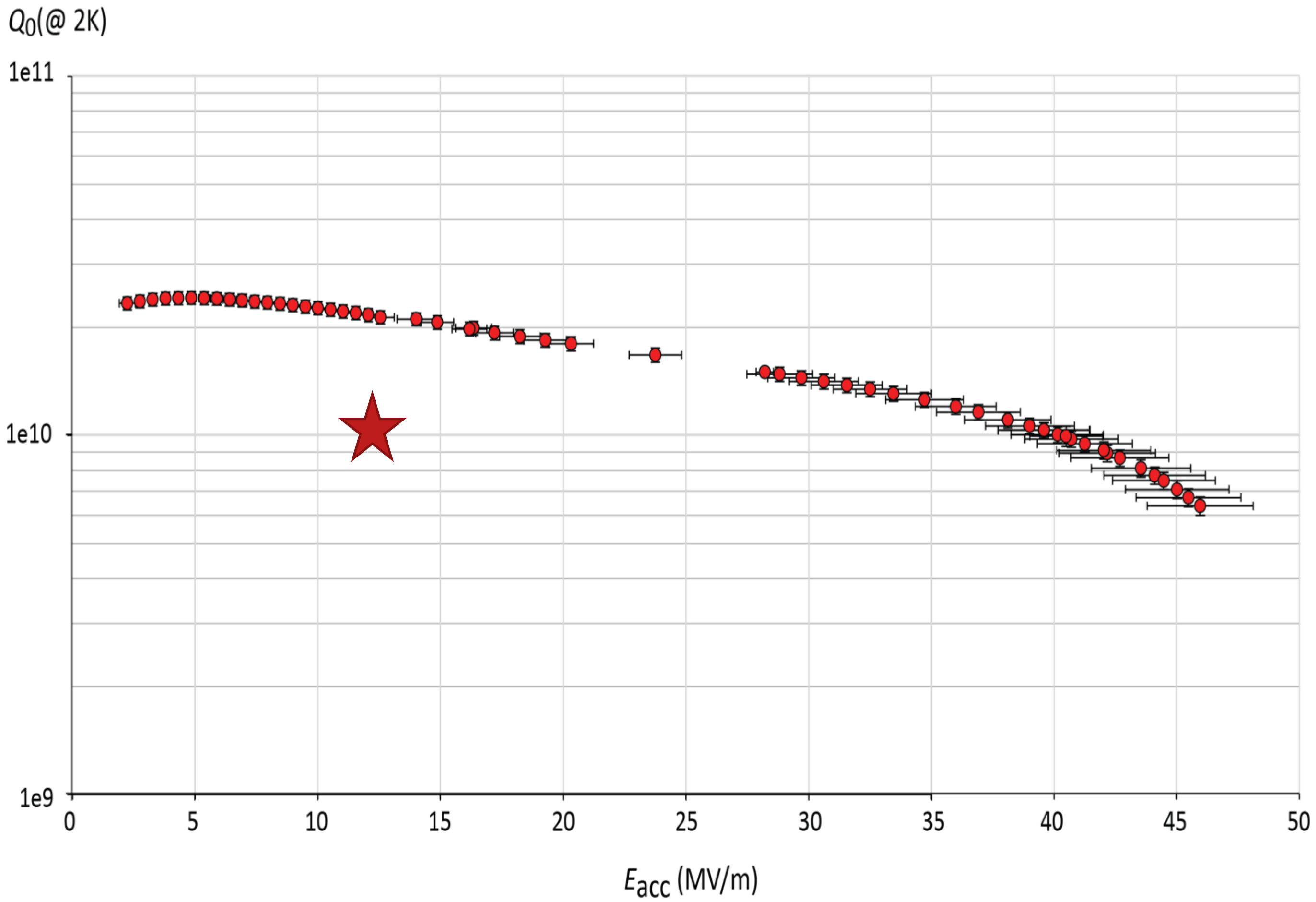




Prototype EIC cavity

- Prototype EIC high-current cavity shape, vertical test January 2019





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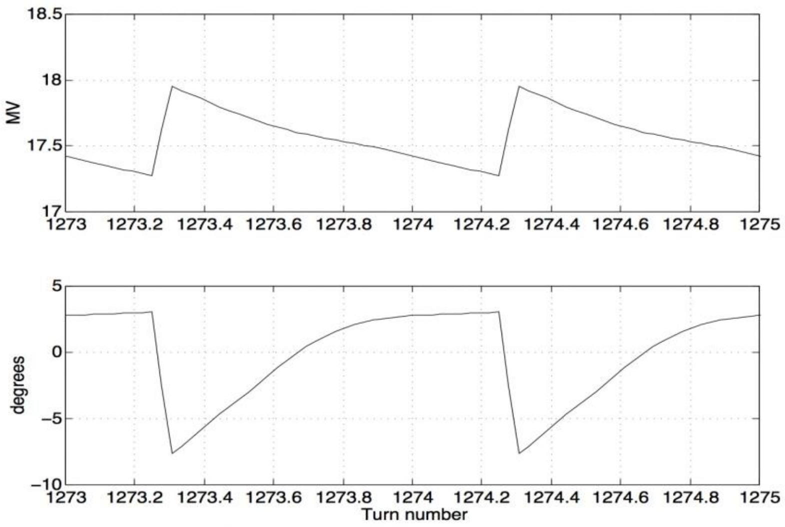
Beam Gaps

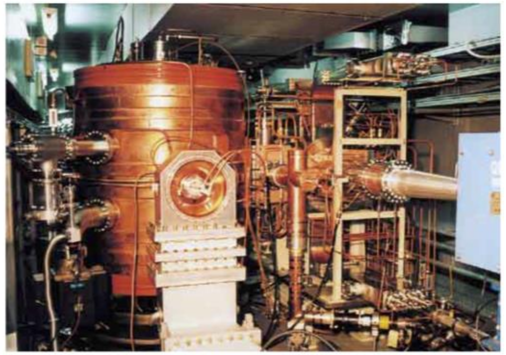
- Ion clearing or abort gaps
  - High stored beam energy requires abort gaps and special beam dump lines
  - Gap length is determined by kicker rise time
  - Gaps may also be needed for ion clearing or electron cloud
- Transients
  - Gaps cause transient beam loading
  - Can saturate klystron if high gain direct loop is used
    - Klystron small signal gain goes to zero, feedbacks stop working
  - Causes phase transient along the beam fill
  - Modulates arrival time of bunches at IP (and at crab cavities)
  - Introduces bunch length variation and synchrotron tune spread along the train



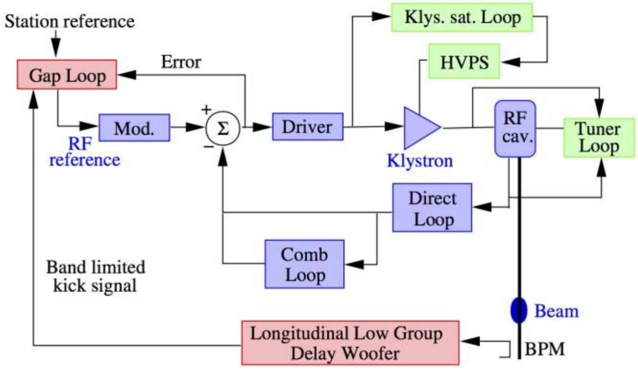
- Complex beam spectrum
  - Causes spectral lines at revolution harmonics in between RF lines
  - May induce significant power in some HOMs
  - May induce significant power in beam chamber components (bellows, IR chamber etc.)

Gap transient mitigations:

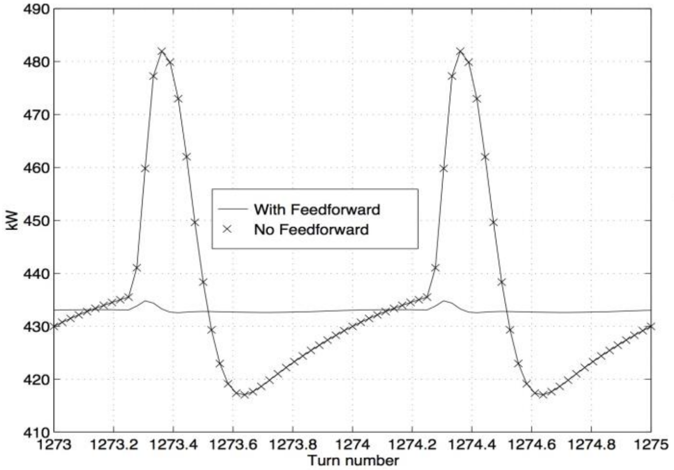
- Superconducting RF cavity has potential for higher stored energy, smaller transients
- Alternate Idea - used at KEKB - NC ARES energy storage cavity system
- Feed-forward, avoids saturating klystron due to direct feedback
- Match transients in both rings (PEP-II)
- Fill pattern shaping?



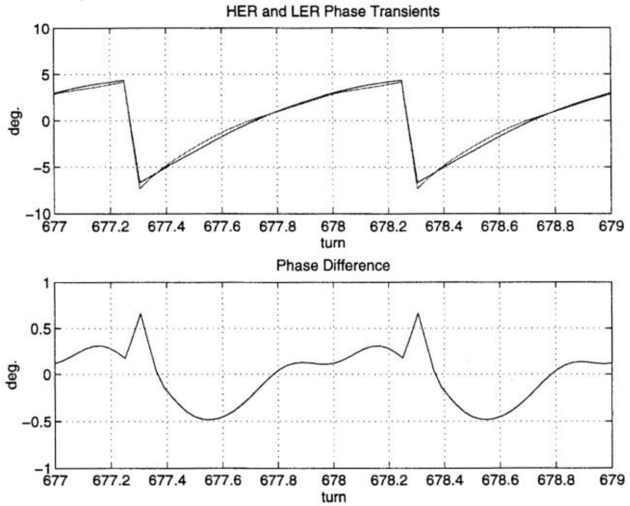
ARES cavity



System block diagram. Fast dynamics (modeled) appear in blue, slow dynamics (fixed parameters in simulation) in green, and not modeled components in red.



Forward Power Variation, with and without Feedforward.



The gap induced transients in the two rings must be matched to prevent excessive collision point variation. Here the transients from the two rings are matched to within 0.6° (0.1 σ_Z). Fine tuning of the simulation parameters is possible to reduce this further. Theoretically, the transients may be perfectly matched (assuming equal cavity coupling in the two rings)

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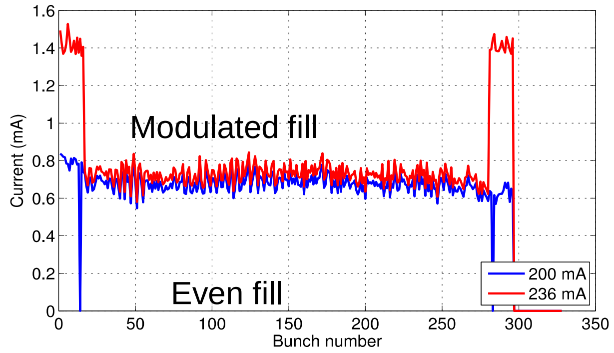
Fill pattern modulation

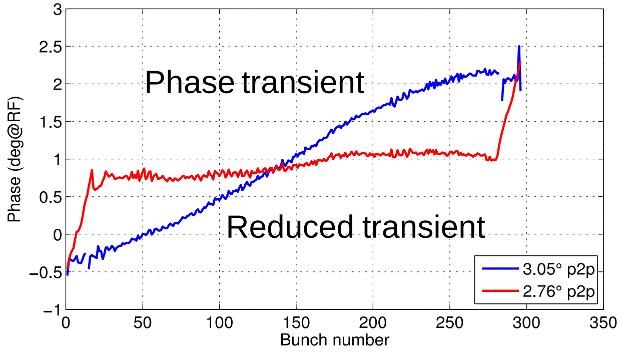
Add charge either side of the gap to reduce transient over most of the fill.

Does Fill Pattern Modulation* Work? YES!

What about ions?

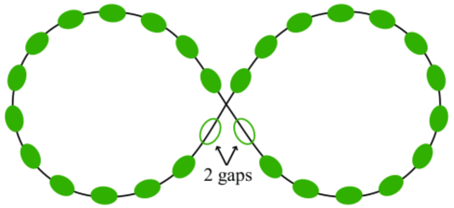
ALS data (electrons)

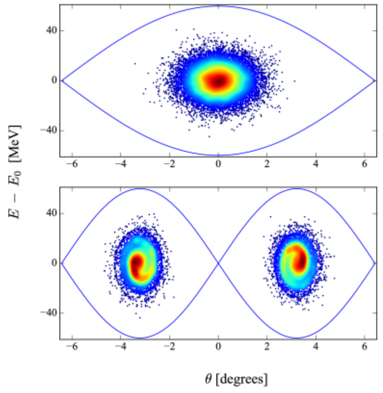




D. Teytelman, Dimtel, Inc., San Jose, CA, USA.
"Transient beam loading in FCC-ee (Z)", FCC Week 2017

Baseline: ions binary bunch splitting. Results in long gaps





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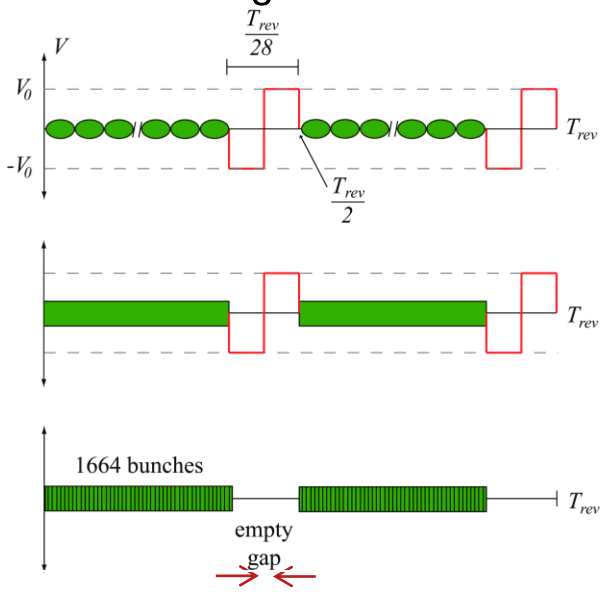
Alternative: barrier bucket re-bunching?

Injection and acceleration

Debunching and coasting

Rebunching

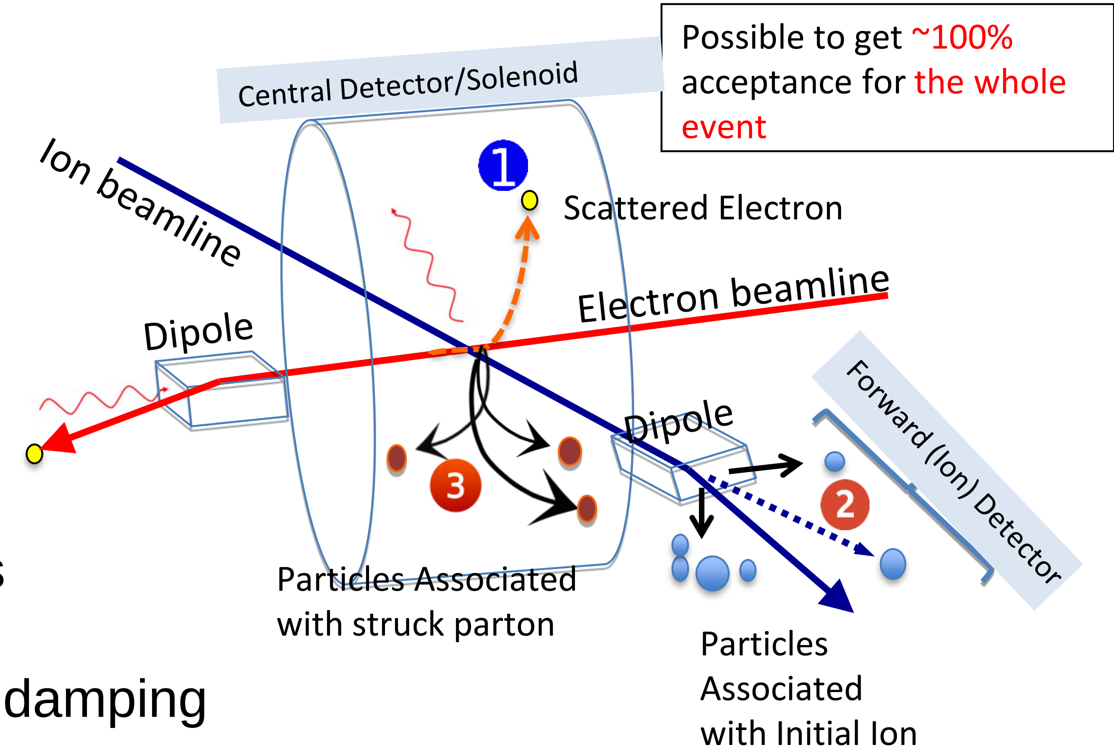


Can we shorten the gap?

* J.Byrd et. al.,Phys.Rev. ST Accel. Beams 5, 092001 (2002)

Interaction regions

- Impedance/heating
  - IR chamber has complex geometry and may have high loss factor and trapped modes
  - Masks and collimators may make the problem worse
  - May drive BBU instabilities
  - May couple unacceptable power from the beam
  - Should minimize impedance by design
    - Avoid trapped/re-entrant volumes
    - Smooth tapers
    - Damp residual modes with absorbing material
  - Manage remaining heat with active cooling
- Crab crossing
  - Avoid parasitic crossings for closely spaced bunches
  - Avoid e+ or e- bends close to IP
  - Need crab cavities with high voltage and good HOM damping
  - Tight alignment tolerance to minimize beam loading
  - May experience (or need to follow) gap transients



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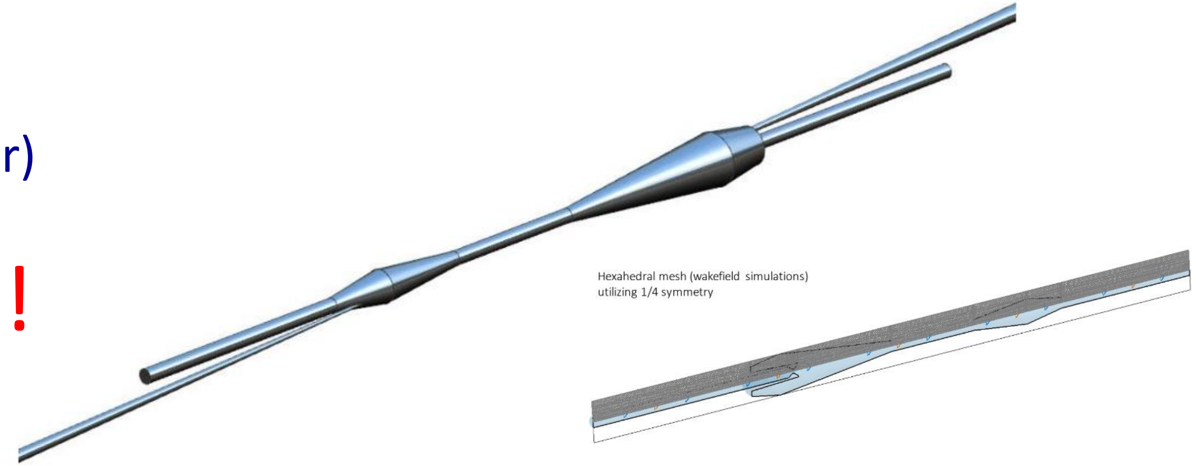
Narrowband Impedance: IR Chamber first look

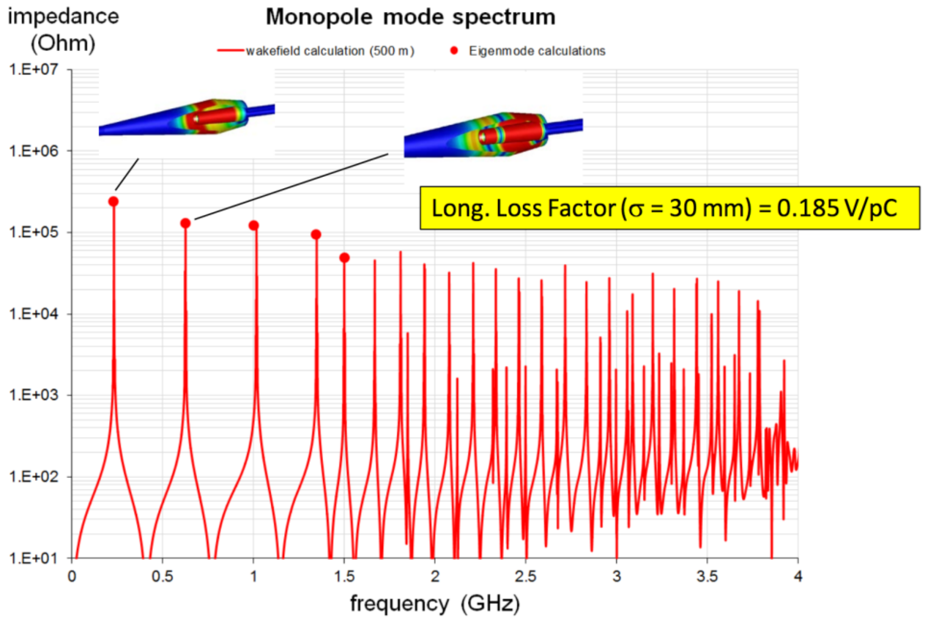
JLEIC IR Chamber CAD Model (Marhauser)



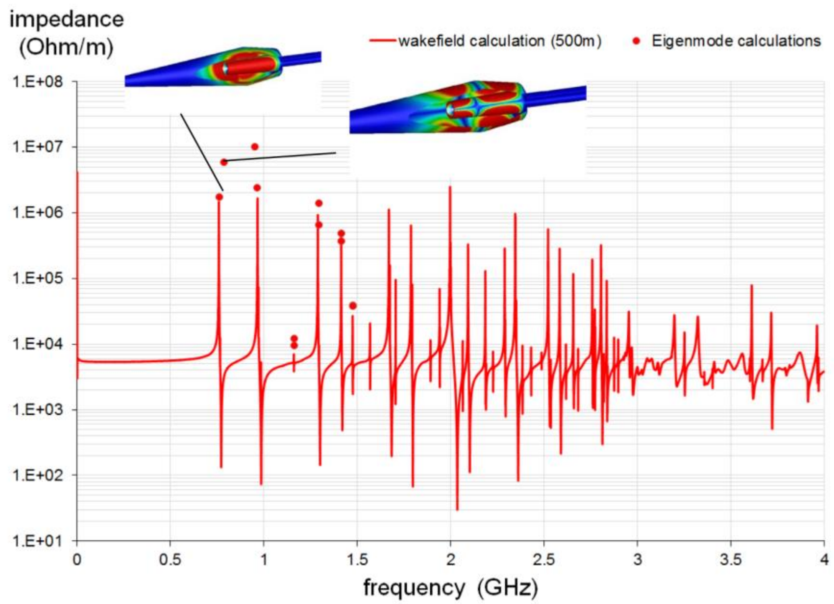
Many trapped modes!

Needs optimization

Monopole Modes



Dipole Modes



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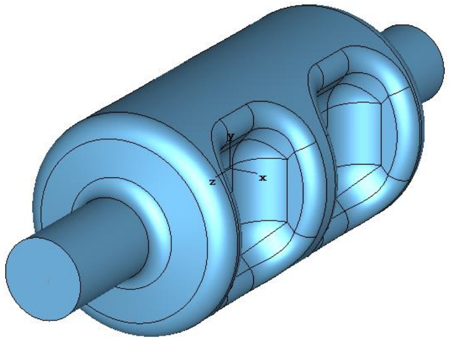
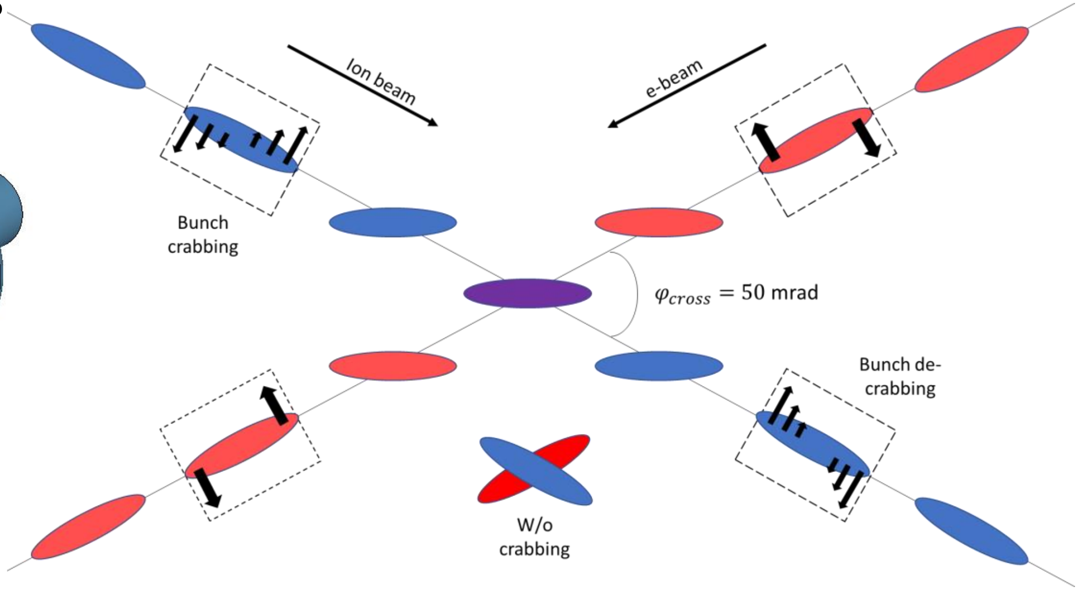
Crab Crossing

- Electron and ion beams have to cross at an angle in an EIC
  - Create space for independent electron and ion IR magnets
  - Avoid parasitic collisions of shortly-spaces bunches
  - Improves detections
  - Improves detector background
- Without compensation, geometric luminosity loss is about a factor of 12 and there is potential for dynamic instabilities
- Crabbing restores effective head-on collisions
- Local compensation scheme
  - Set of crab cavities upstream and downstream of IP
- Deflective crabbing
  - Demonstrated at KEK-B
  - Tested with ions at CERN SPS
  - JLEIC Prototype being developed by ODU





Conclusions

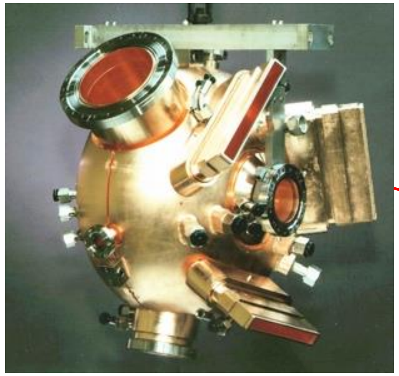
- High current and high energy colliders provide many RF system challenges
- Techniques from light sources and “Factories” can be adapted and updated
- New SRF cavity designs can advance the state of the art
- RF power costs are significant
- Gap transients are challenging and not completely solved
- Crab crossing brings its own challenges
    - SPS test with protons very encouraging!
- These problems are common to all new circular colliders

Thank you for your attention

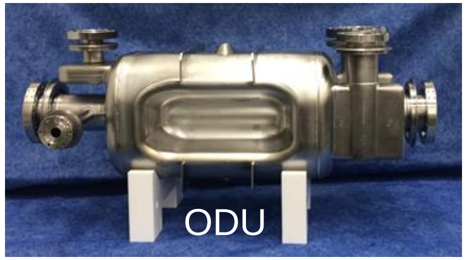
Back-up

JLEIC

- Define RF system requirements
- Support the pre-CDR
- Cooler ERL injector, and harmonic kicker
- New Ion ring cavities
- New e-ring cavities (?)
- Cavity prototyping
- Fast feedback
- Impedance (incl. IR)
- CEBAF as injector

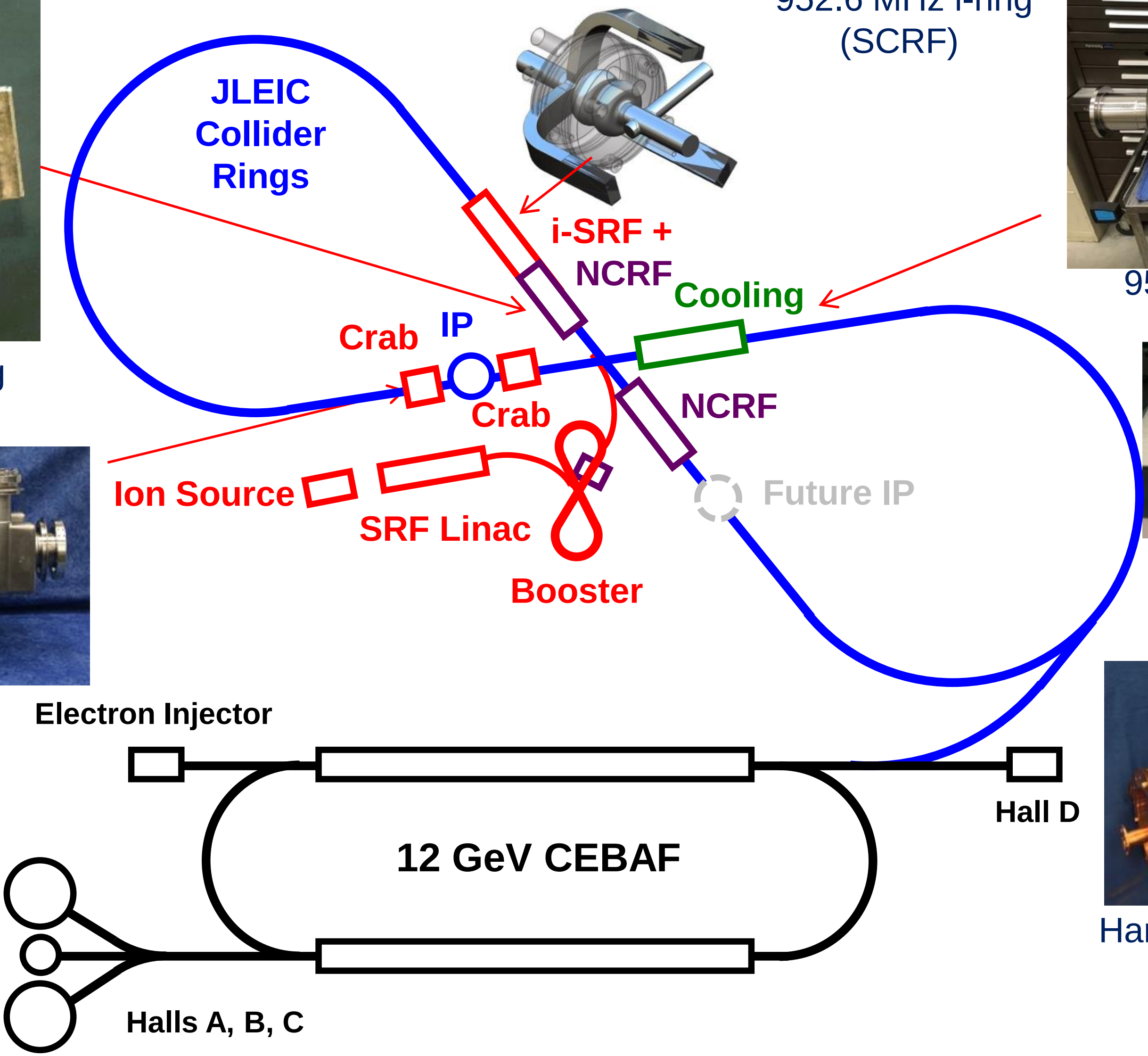


476.3 MHz e-ring (NCRF PEP-II)



952.6 MHz crab (SCRF)

952.6 MHz i-ring (SCRF)



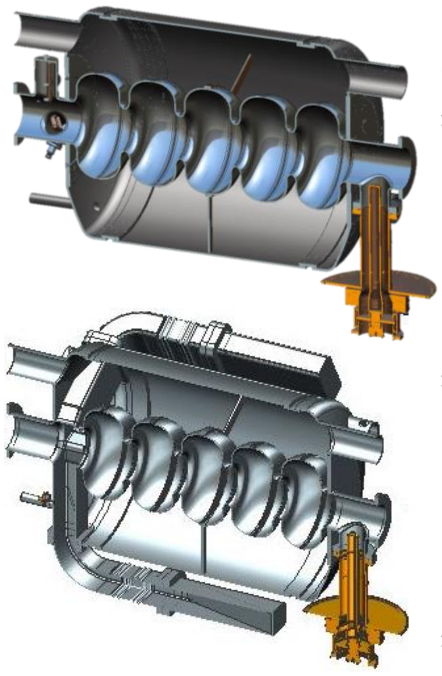
952.6 MHz cooler ERL (SCRF)

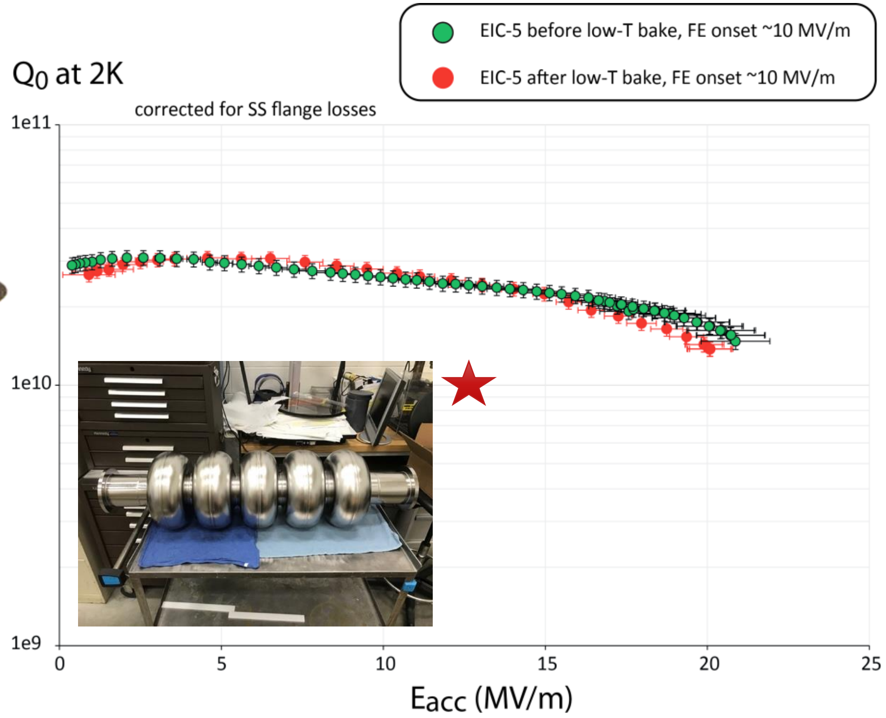
952.6 MHz booster (SCRF)

Harmonic Fast kicker for cooling ring

Cooler ERL 5-cell cavity

- Evaluated coax and WG end groups
- Estimated HOM power for various fill patterns including gaps
- Worst case ~6 kW so prefer WG
- 5-cell bare prototype tested





f_{RF} (MHz)	952.636			
Cooling bunch rate (MHz)	119.075	238.15	476.3	952.6
Gun laser rate (MHz)	10.825	21.65	43.3	86.6
bunch train repetition rate (MHz)	0.349	0.698	1.397	1.397
CCR circumference (m)	213.955			
ERL path length (m)	2573.32 ((8184-5.5)λ)			
Laser bucket pattern	7 on, 1 off, 7 on, 1 off, 7 on, 1 off, 6 on, 1 off	14 on, 2 off, 13 on, 2 off	27 on, 4 off	54 on, 8 off
Charge per bunch (nC)	3.2			
Average ERL injection current (mA)	30	60	120	241
HOM power per cavity (kW)	0.33	0.76	2.0	5.9
HOM power per cavity scaled to CCR current 1.5A (kW)	6.7	3.9	2.6	1.9

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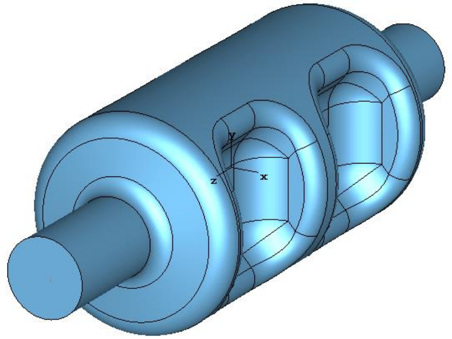
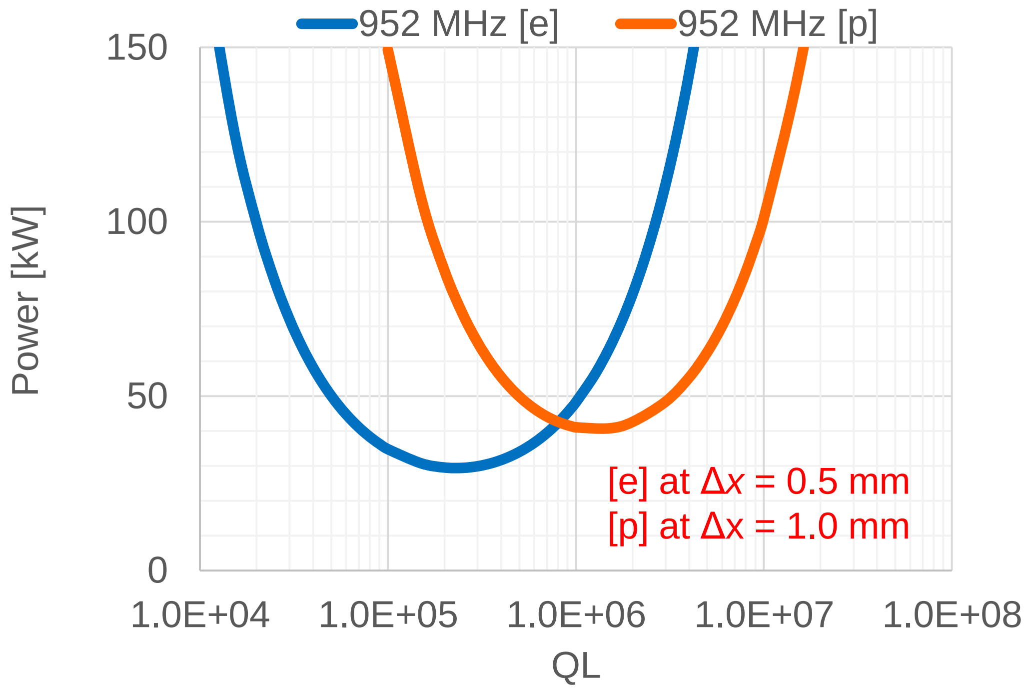
Crab Cavity – RFD 2-cell cavity (HyeKyoung Park)

- After design survey, the prototype is converging to 952.6 MHz 2-cell RFD cavity.
- 10 GeV electron beam and 200 GeV proton beam.
- Input power coupling through beam pipe provides the QL range.

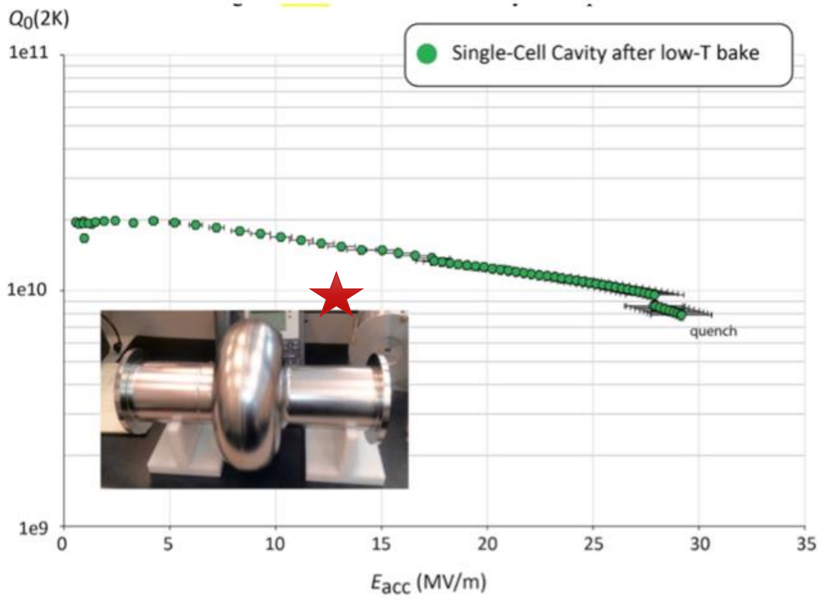


	protons	*electrons*	*Units*
Frequency	*952.6*	*952.6*	*MHz*
Required total kick	*37.34*	*2.8*	*MV*
V_t per cavity/side	*2.7*	*1.4*	*MV*
Number of cavities	*14*	*2*	*-*
Peak electric field	*48.6*	*25.2*	*MV/m*
Peak magnetic field	*99.9*	*51.8*	*mT*
Surface resistance	*95.0*	*95.0*	*nΩ*
Shunt impedance	*0.26*	*0.26*	*MΩ*
Dissipated power/cav	*27.8*	*7.5*	*W*



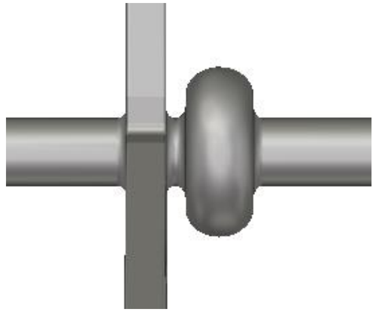
Input RF power

i-ring: new 952.6 MHz SRF Cavities

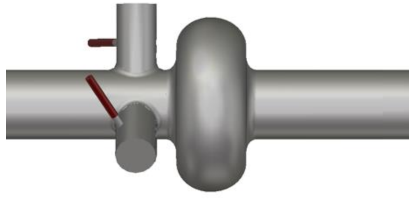


New 952.6MHz High-current cavity shape

- 4 different HOM damping schemes evaluated
- Focus on 3 waveguide damper design for ion ring
- Possibly on-cell damper for e-ring
- 1-cell prototype tested

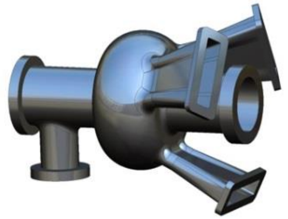


1) 3WG.

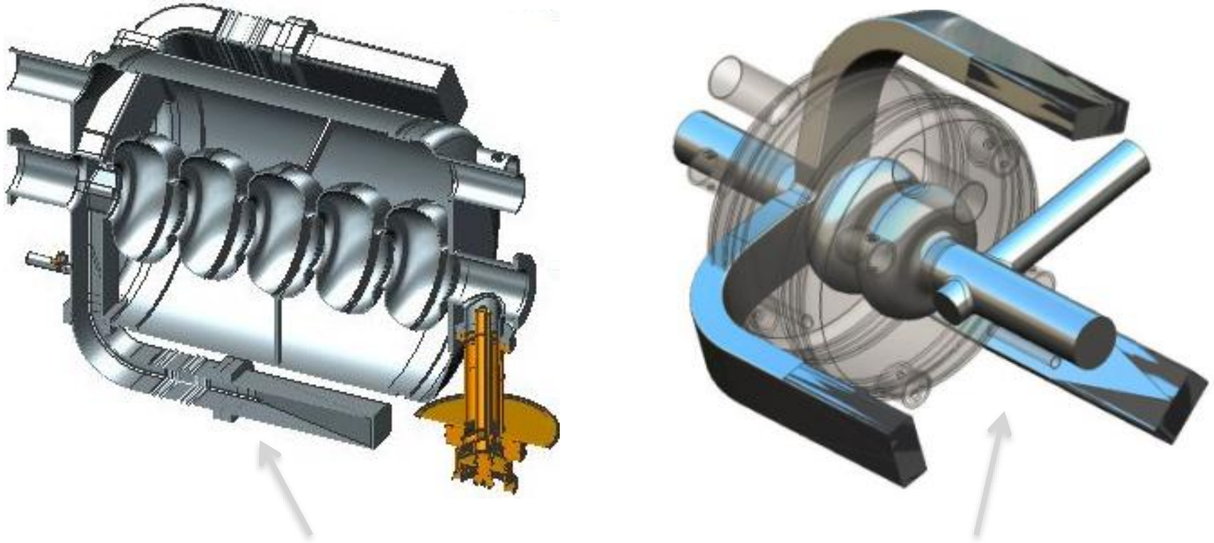


2) 3 coax dampers.

3) enlarged beam pipes



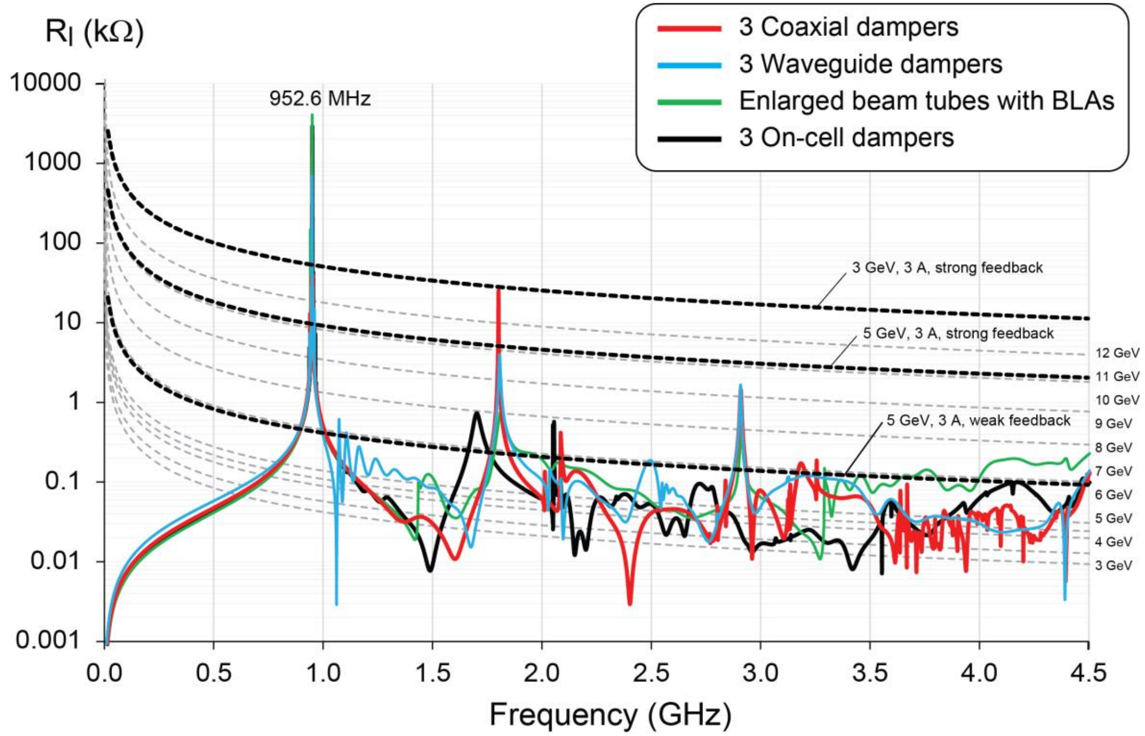
4) on-cell dampers

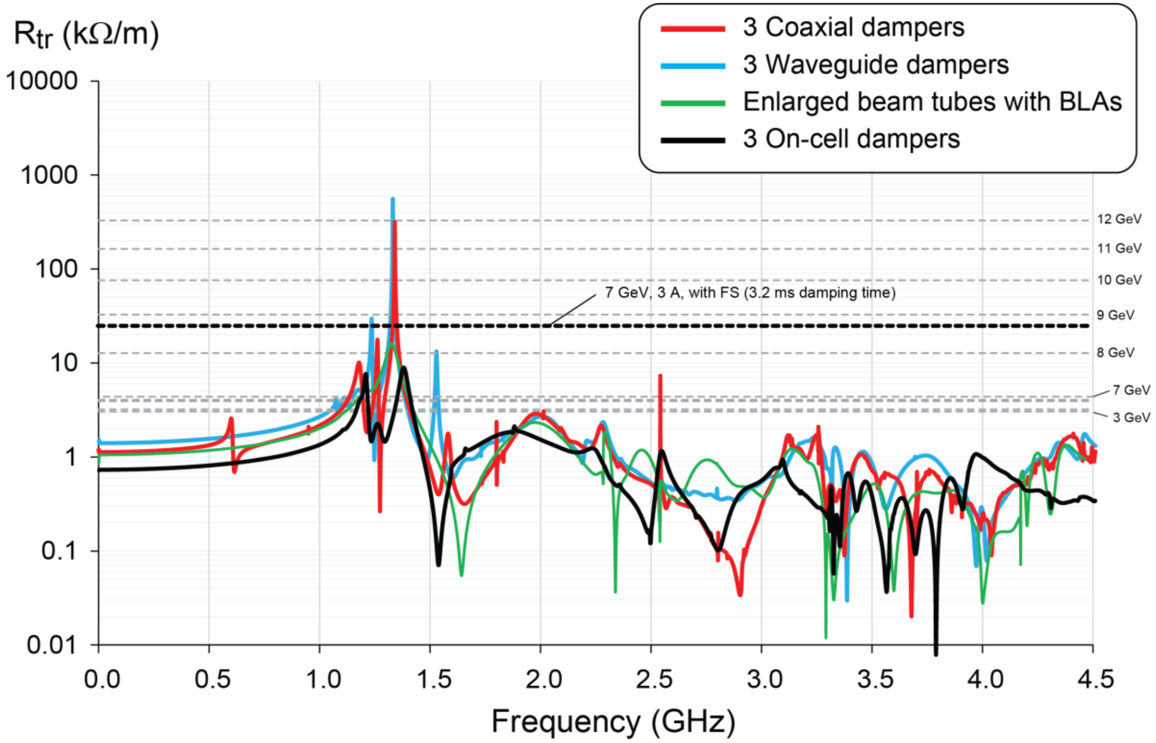


Cooler needs **5-cells** in the ERL, 1 or 2 -cells in the injector.
Ion ring might use **2-cells.**

Collider Ring Impedance Thresholds

- Broadband damping of HOMs with on-cell dampers better than with any other design including enlarged tubes to un-trap low frequency modes
- PEP-II type feedback systems allow running above threshold.
- Beam tube absorbers might still be needed outside of cryomodules for high frequency power

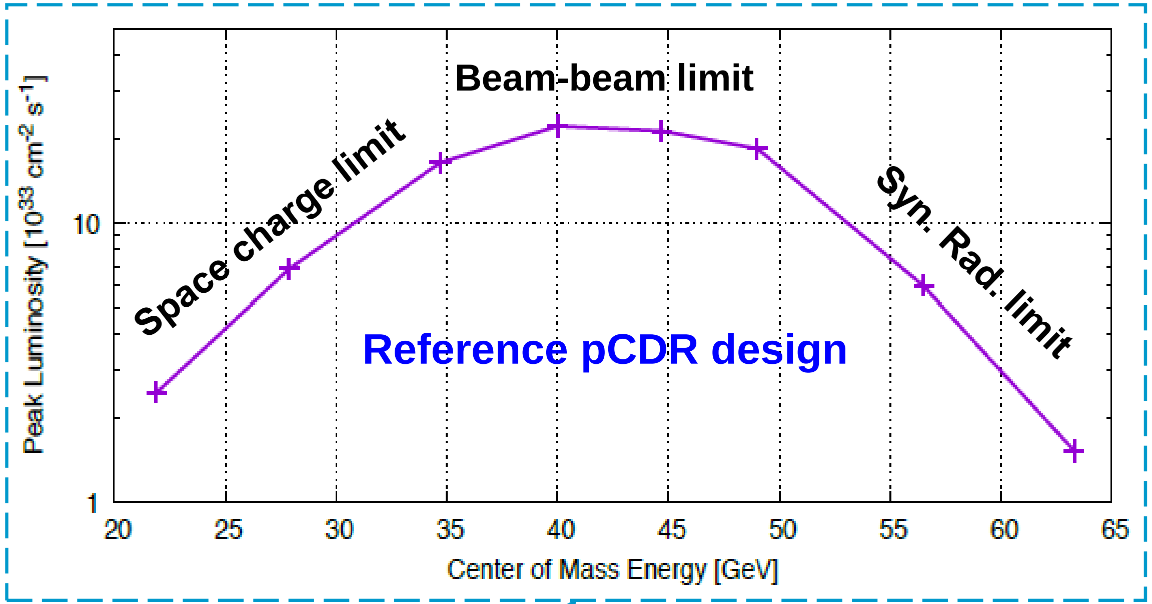


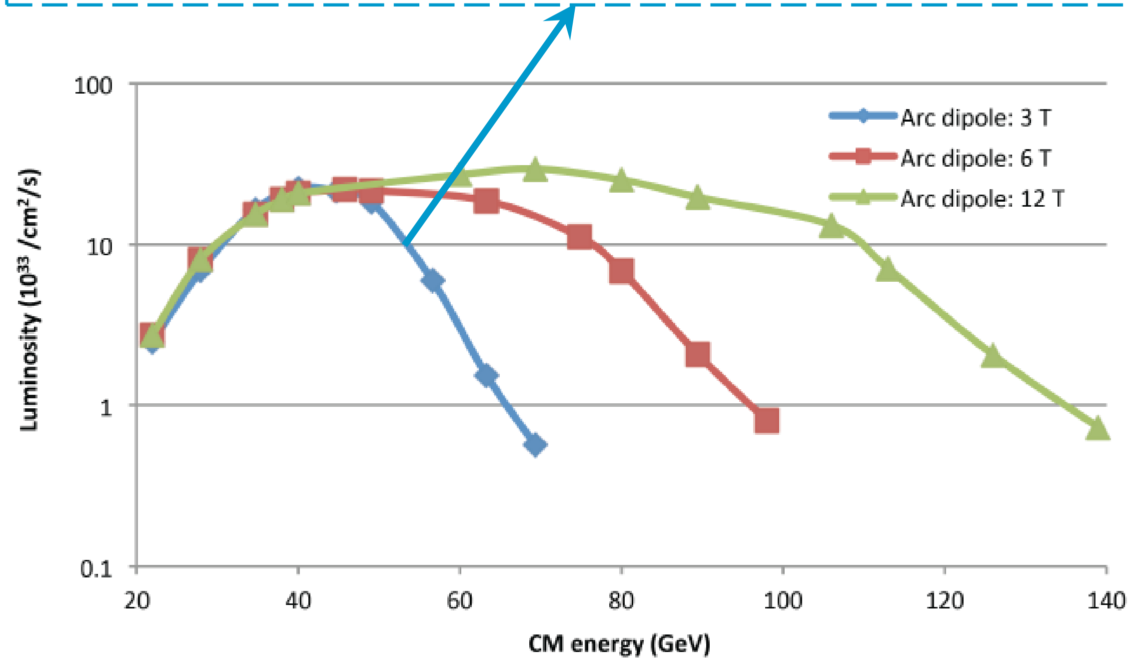


F. Marhauser, "Next Generation HOM-damping", Special Issue on Superconducting RF for Accelerators, to be published

JLEIC e-p Parameters and Luminosity Performance

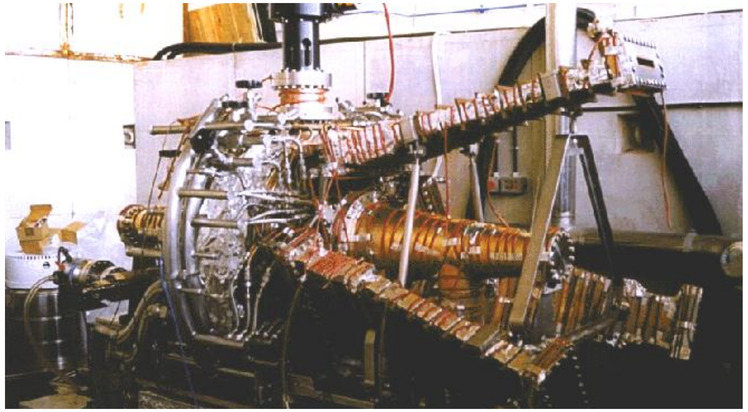
CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476	
Particles per bunch	10^{10}	**0.98**	3.7	**0.98**	3.7	**0.98**	0.93
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	**80**	**80**	**80**	**80**	**80**	**75**
Bunch length, RMS	cm	1	1	1	1	1	1
Norm. emitt., horiz./vert.	μm	**0.3**	**24**	**0.5/ 0.1**	**54/ 10.8**	**0.9/ 0.18**	**432/ 86.4**
Horiz, & verti. β*	cm	8/8	13.5/ 13.5	6/1.2	5.1/1	10.5/2.1	4/0.8
Vert. beam-beam param.		0.015	0.09	0.015	0.068	0.002	0.009
Laslett tune-shift		0.06		0.055		0.03	
Detector space, up/down	m	3.6/7	2.96/2.2	3.6/7	2.96/2.2	3.6/7	2.96/2.2
Hourglass(HG) reduction		1		0.87		0.86	
Lumi./IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	**2.5**		**21.4**		**1.7**	



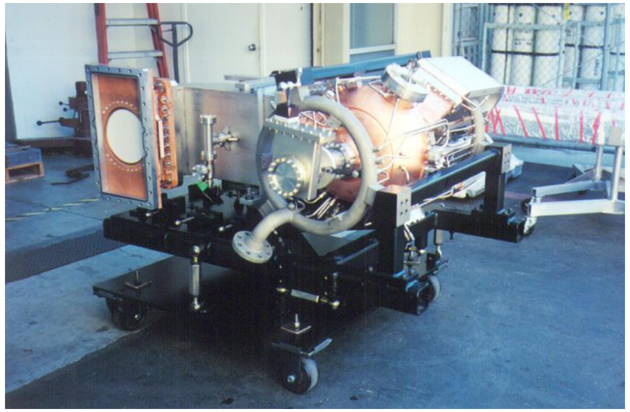


Similar high performance for electron-ion (*e-A*) collisions

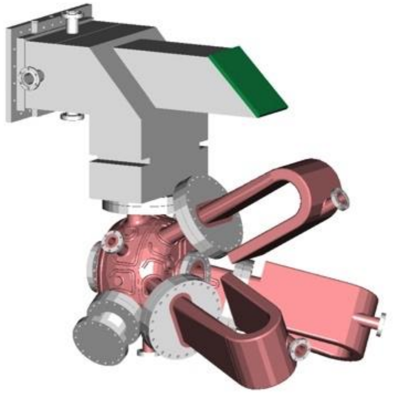
Some NCRF high current cavities



Daphne cavity, 368.26 MHz, 250 kV, 2 MΩ

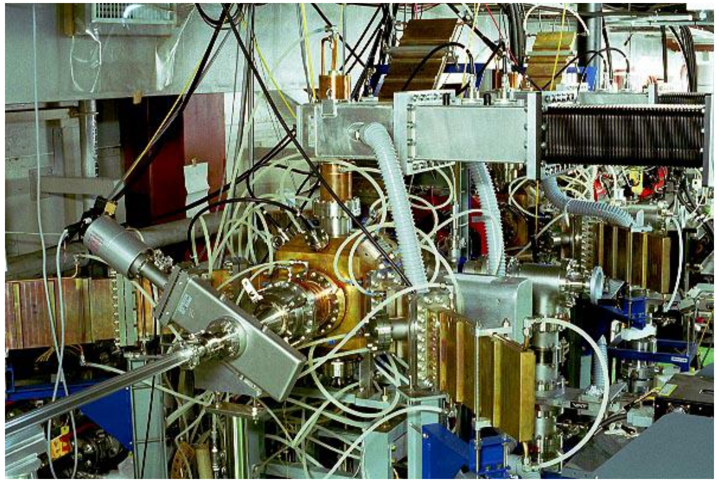


PEP-II cavity, 476 MHz, 850 kV, 3.7 MΩ

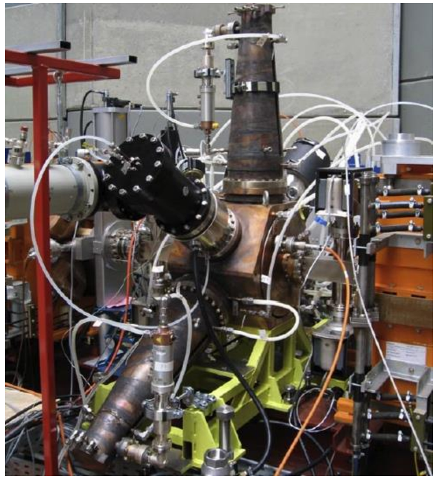


NLC DR, 714 MHz

KEK ARES cavity, 508 MHz, 500 kV, 1.75 MΩ



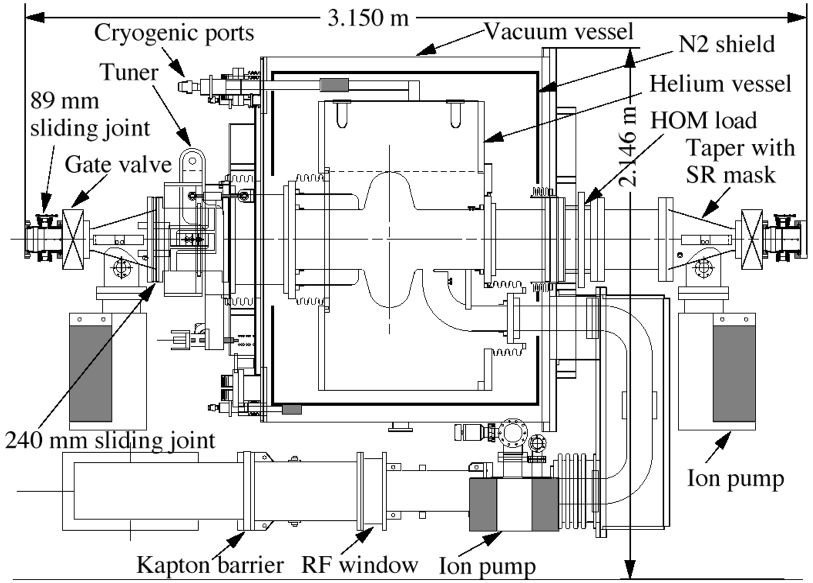
ATF cavity, 714 MHz, 250 kV, 1.8 MΩ

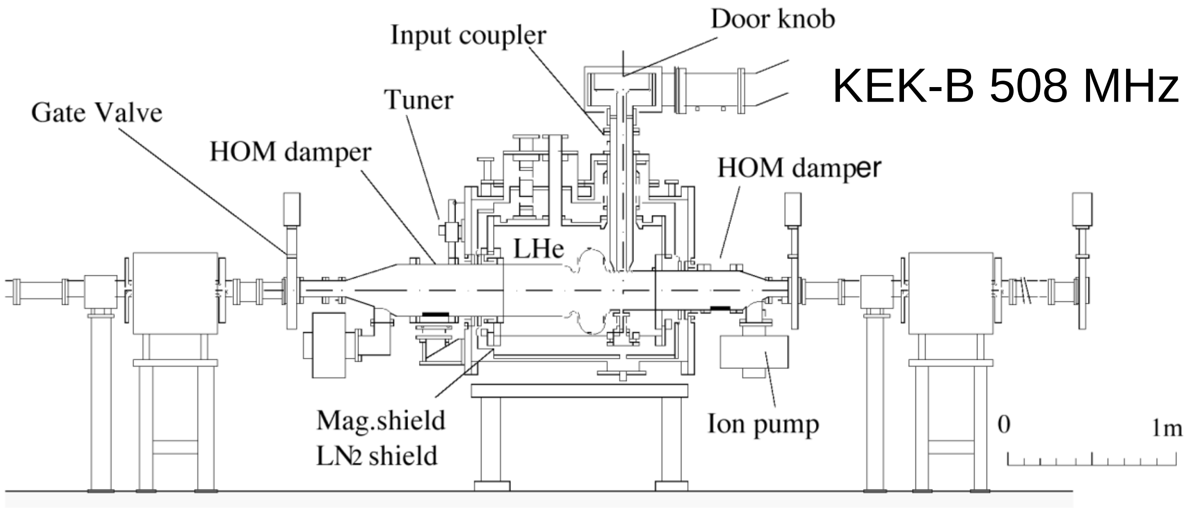


BESSY cavity,
500 MHz, 3.7 MΩ

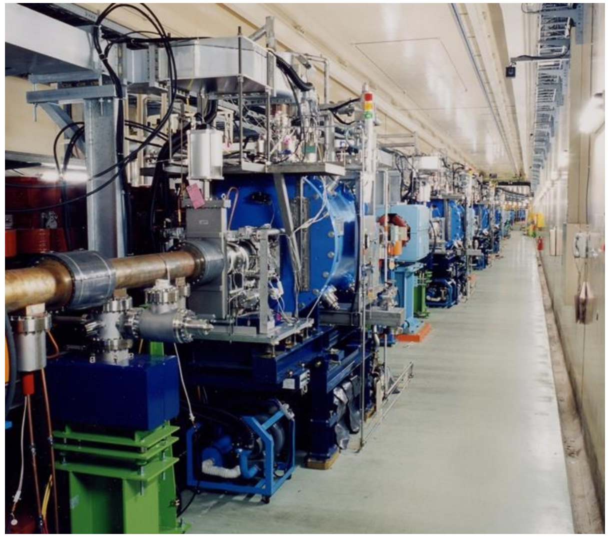
SCRF high current cavities

Cornell CESR-B type 500 MHz





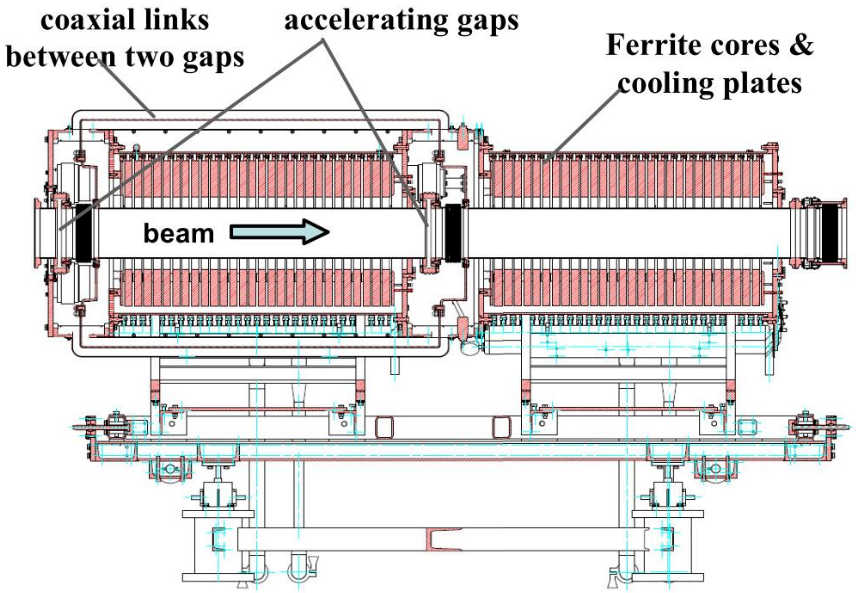
KEK-B 508 MHz



Low Frequency RF examples

Needed to capture and accelerate ions in booster and collider ring

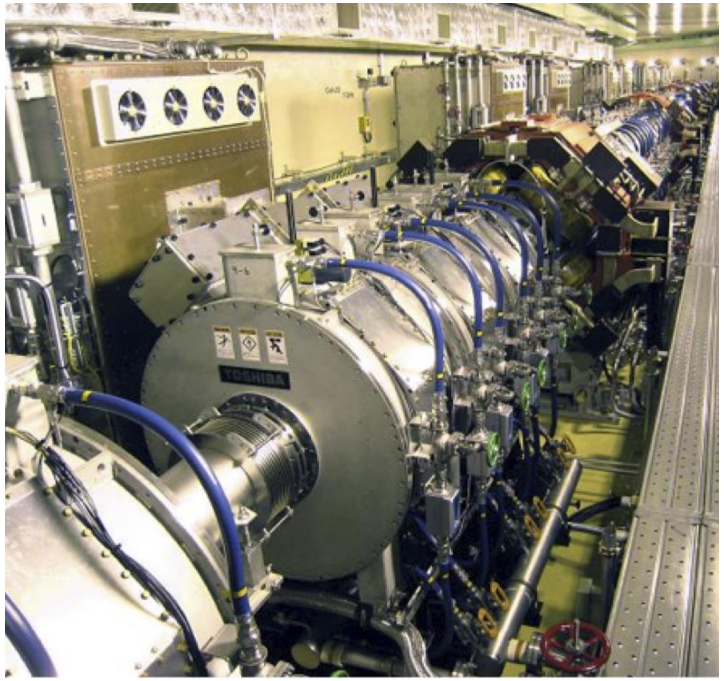
- Low frequency (~1 MHz)
- Tunable for ramping



CSNS cavity (ferrite loaded)

JPARC cavity (Metglass loaded).

Used as basis for JLEIC.

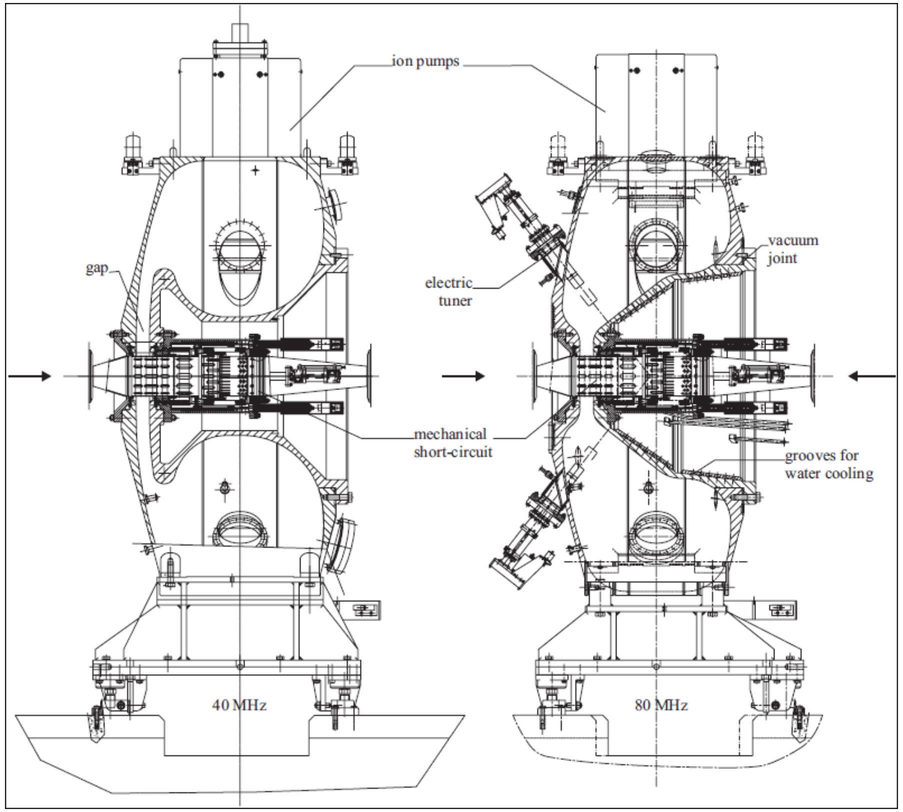


Ion Ring Bunch Formation Cavities

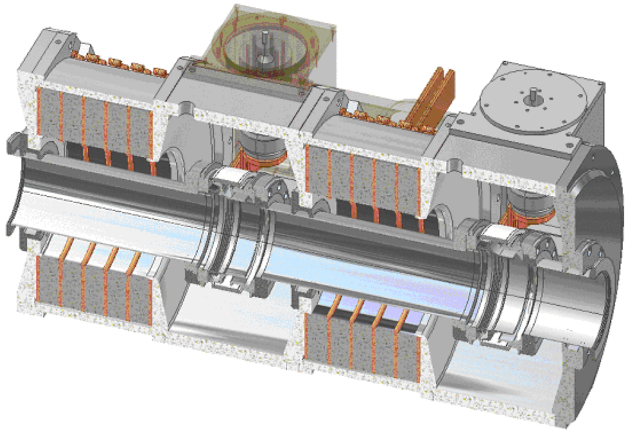
J. Guo

JLEIC ion bunch formation injects h=56 , E=2 GeV (Pb) to 8 GeV (p) long bunches into the ion ring, then perform binary RF splitting 6 times into h=3584.

Cavity function	β range	Energy (GeV)	Frequency (MHz)
Collider ring acceleration	0.957-0.999	2.0-20	7.05-7.44
Collider ring bunch splitting	0.999	20	14.87
			29.75
			59.49
			118.98
			237.96
Collider ring bunch splitting, bucket manipulation, acceleration, bunching	0.999-1.000	20-100	475.9-476.4



CERN PS 40MHz and 80MHz "button" cavities for LHC bunching
A sliding beampipe shields the cavity from HOM excitation when the cavity is not in use
May use as a reference for most of the bunch splitting cavities



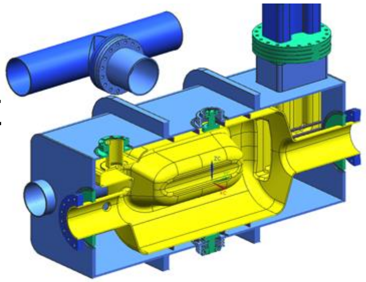
CERN PS 13.3-20MHz low Q Ferrite loaded cavity, as a reference for JLEIC ion ring 7 MHz acceleration cavities and ion booster acceleration/bunching cavities

Other crab cavity examples

"RF Dipole developed by ODU for LHC
- Compact transverse dimensions
- **NO low order mode (LOM)**
- Must have good **HOM damping**
- Multi-gap RF dipole may be very desirable

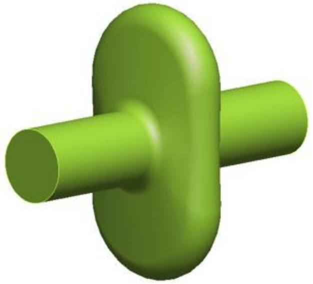
Squashed elliptical crab cavity (e.g. KEK-B, SPX)
- **Large** size for a given frequency (952 OK?)
- **Strong LOM**, must be damped
- High **LOM power** must be absorbed at room temp
- Multi-cell version impractical

ODU RFD concept

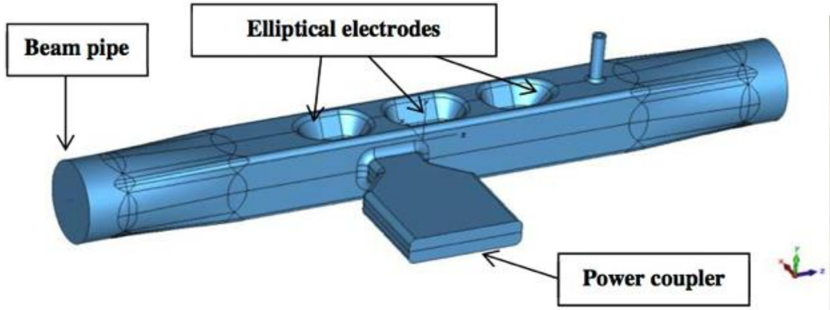


reality

Elliptical concept

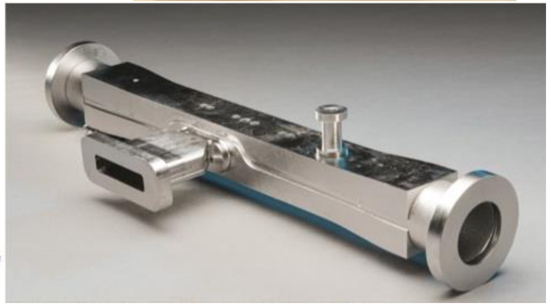


JLab waveguide damped RFD concept



A. Lunin et. Al.

ANL/FNAL multi-gap concept



Z.A. Conway et. al. IPAC14

reality