The High-Current ERL Cavity

Who needs this? Electron cooling and ERL eRHIC!

2006 Electron-Ion Collider Workshop

July 2006

Presented on behalf of the many people who contribute
to the electron cooling R&D effort by
Ilan Ben-Zvi, C-AD

The objectives and challenges

- Accelerate a high current in an ERL avoiding Beam-Breakup
- Disposing safely high power of HOMs
- Reduce wake impedance to preserve beam density
- Reduce cryogenic losses
- Be capable of a good gradient
- Reduce sensitivity to acoustics

- Need single-mode cavity
- Need good conduit for the HOM power
- Need large apertures
- Need low frequency
- Optimum cavity shape

Loss factor

a is the cavity iris radius,
d is the cell length
σ is the beam bunch length
Nc is the number of cells

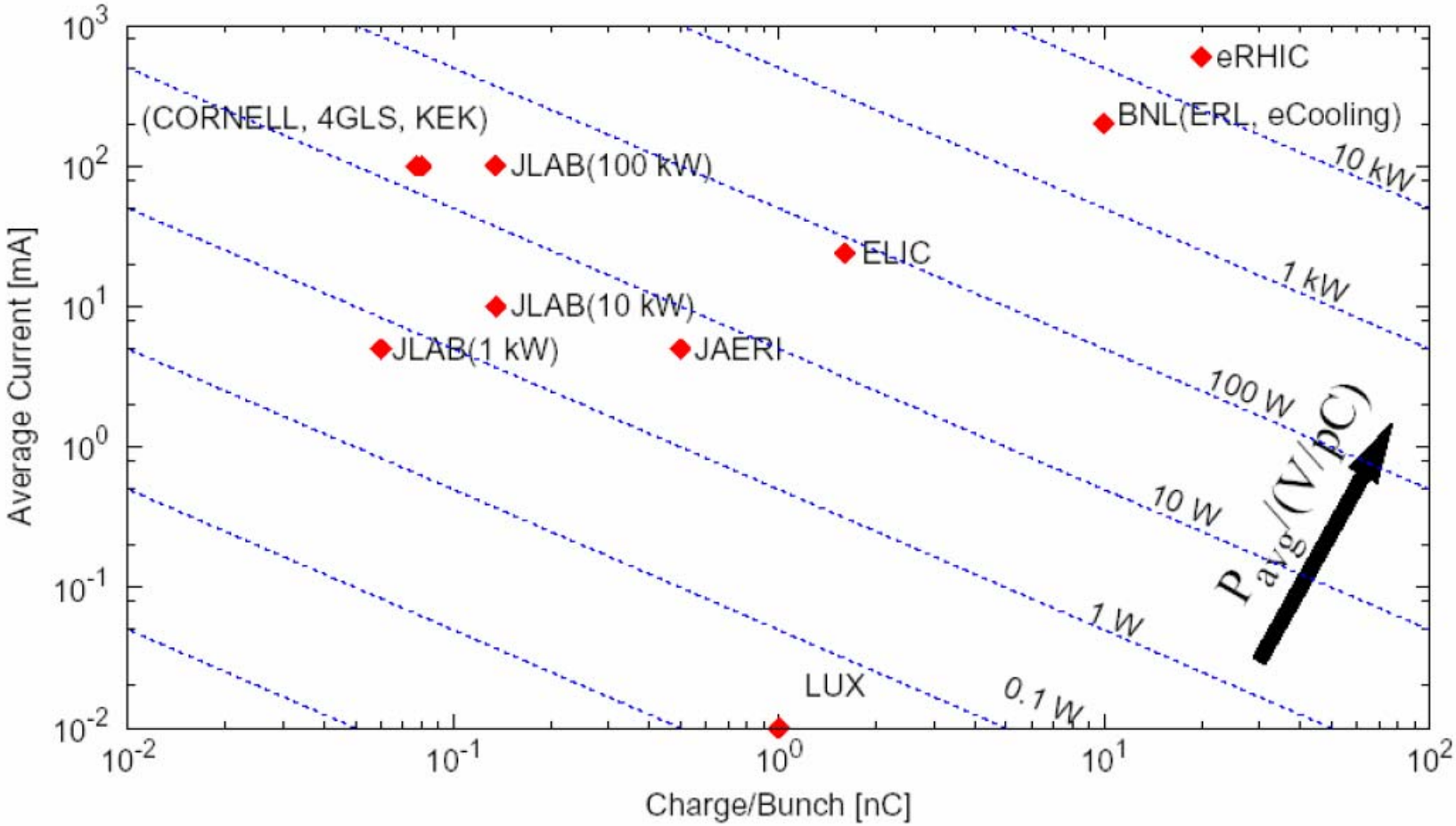
$$k_l = \frac{\Gamma(.25) Z_0 c}{4\pi^{2.5} a} \sqrt{\frac{d}{\sigma}} \sqrt{N_c}$$

$$P_{HOM} = k_l I q$$

Given $6x10^{10}$ electrons per bunch, σ=1.4 mm / 2.7 mm, bunch repetition frequency 28.2 MHz and ERL mode.

Cavity (single)	TESLA 1.3 GHz	BNL 0.7 GHz
K_l (V/pC)	7.8	1.2
Power (kW)	39.6	6.6
Energy spread	$30x10^{-4}$	$5x10^{-4}$

Existing & Future ERLs



*** Avg. Power Normalized to 1 V/pC

RHIC

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New, active high-current linac SRF structure developments

- BNL
  - Construction of 5-cell, 703.75 MHz cavity, SRF electron gun, and construction 0.5A, 20 MeV ERL (design 80 MeV).
- Cornell
  - Construction of a 2-cell, 1300 MHz injector cavities, DC electron gun, cold HOM damping of TESLA type cavities and design of 100 mA, 100 MeV ERL.
- JLab
  - Design (construction in 2007) of a 5-cell cavity, DC gun with SRF booster under construction, design of 100 mA, 120 MeV ERL.
- KEK
  - Development of radial damping scheme for TESLA type ERL cavity, design of a 100 mA, 200 MeV ERL.

The BNL approach
Aimed at ~1 ampere

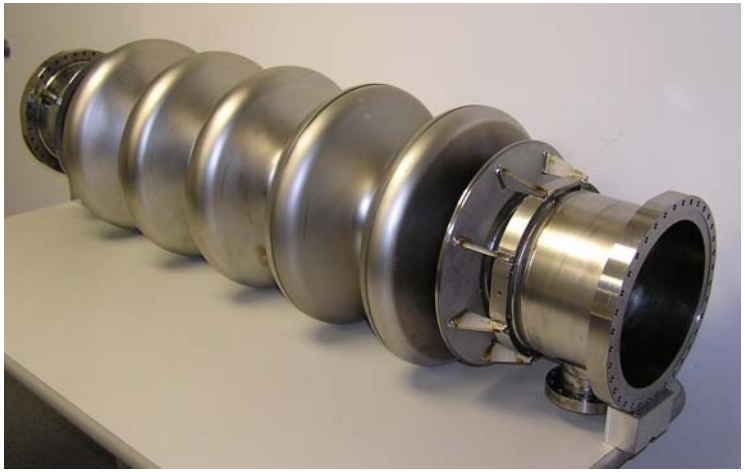
- Low frequency: 703.75 MHz
- Cavity manufactured by AES
- Large beam pipe: 24 cm diameter
- HOM loads: Cornell ferrites at room temperature (made by Accel)
- Cold loads: an alternate for multi-cavity cryomodules

ERL 5-cell cavity design for high currents
R. Calaga, proceedings SRF'05

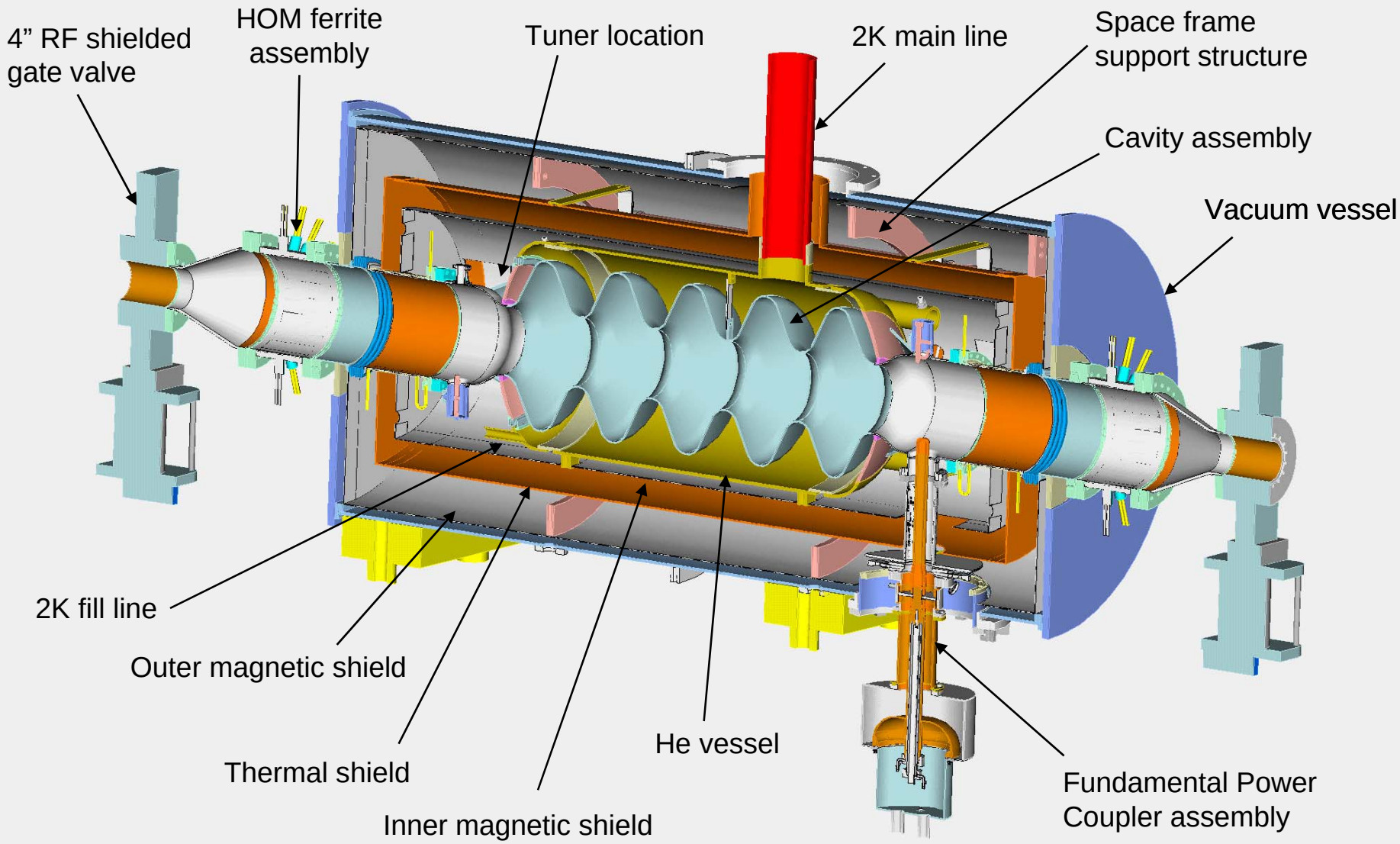
Design and Fabrication of the RHIC Electron-Cooling Experiment
High Beta Cavity and Cryomodule
D. Holmes, proceedings SRF'05

All HOM's couple strongly into the beam pipe, creating a unique "single mode" cavity!

Also record low loss factor for any linac, reducing the HOM load.



Cryomodule Design



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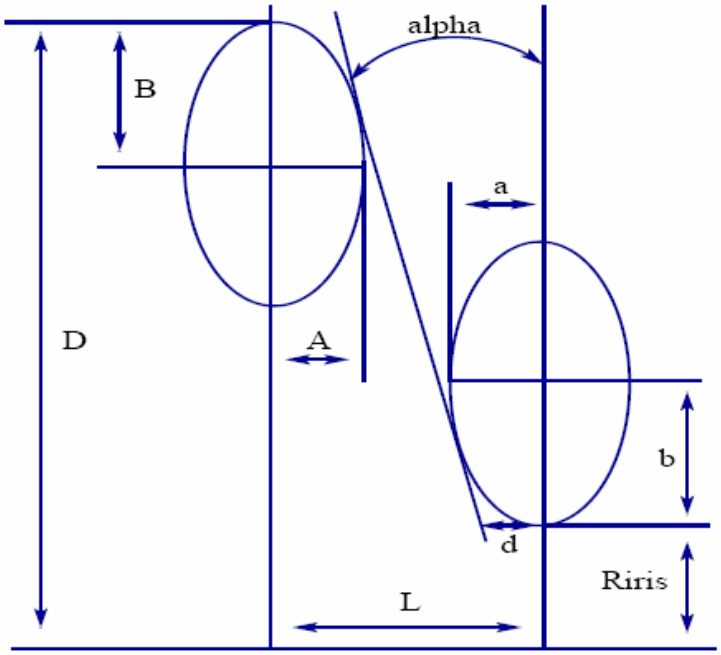
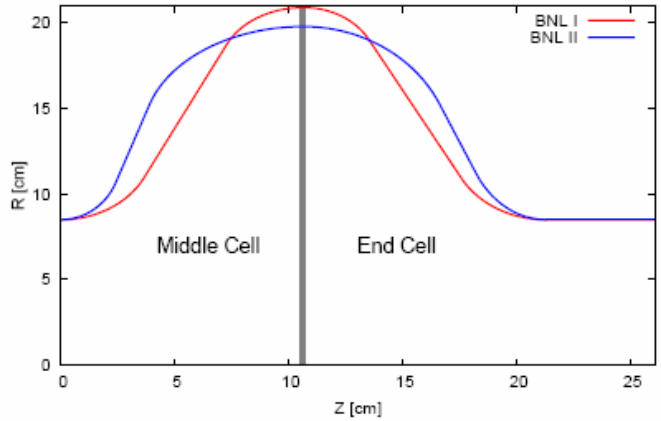
Jefferson Lab

Advanced Energy Systems, Inc.

Cavity Design Criteria





Iris Radius, R_{iris}	8.5 [cm]
Wall Angle, α	25 [deg]
Equatorial Ellipse, $R = \frac{B}{A}$	1.0
Iris Ellipse, $r = \frac{b}{a}$	1.1
Cav. wall to iris plane, d	2.5 [cm]
Half Cell Length, $L = \frac{\lambda\beta}{4}$	10.65 [cm]
$H = D - (R_{iris} + b + B)$	4.195 [cm]
Cavity Beta, $\beta = \frac{v}{c}$	1.0

- Freq: 703.75 MHz
  - 25th harmonic of RHIC
  - Lower Loss Factor ($k_{||}$, $k_{\perp}$)
  - CW power sources
  - Chemical treatment
- Five Cells
  - Fewer trapped modes
  - Field sensitivity factor: $\frac{N^2}{k_{cc}}$

RHIC

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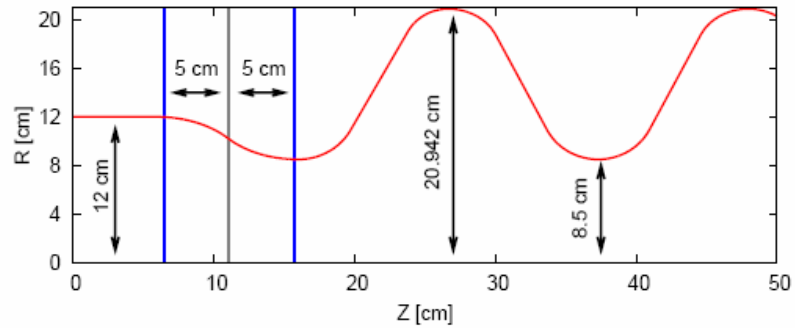
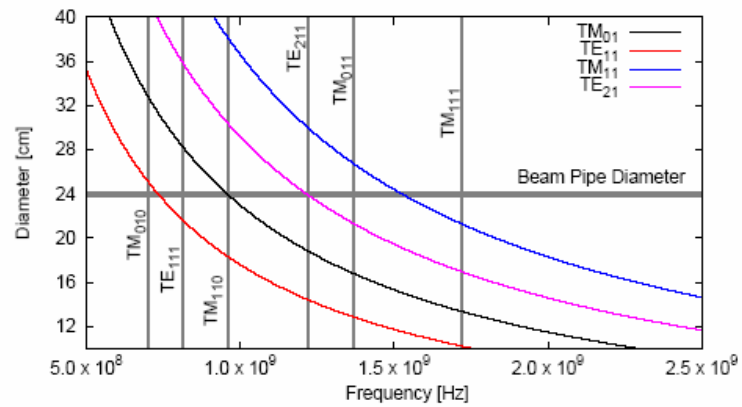
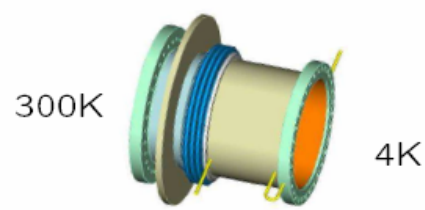
Beam Pipe Transition

- Damping HOMs
  - **Enlarged BP (KEK, BNL, CORNELL)**
  - Flutes (CORNELL)
  - Loop couplers (TESLA, CEBAF)
- Minimize fundamental leakage ($< 10\ W$).
- Minimize FPC kick
  - Enlarged BP (KEK, BNL)
  - Symm. couplers (CORNELL)
- Cold to warm transition (Counter Flow of He)

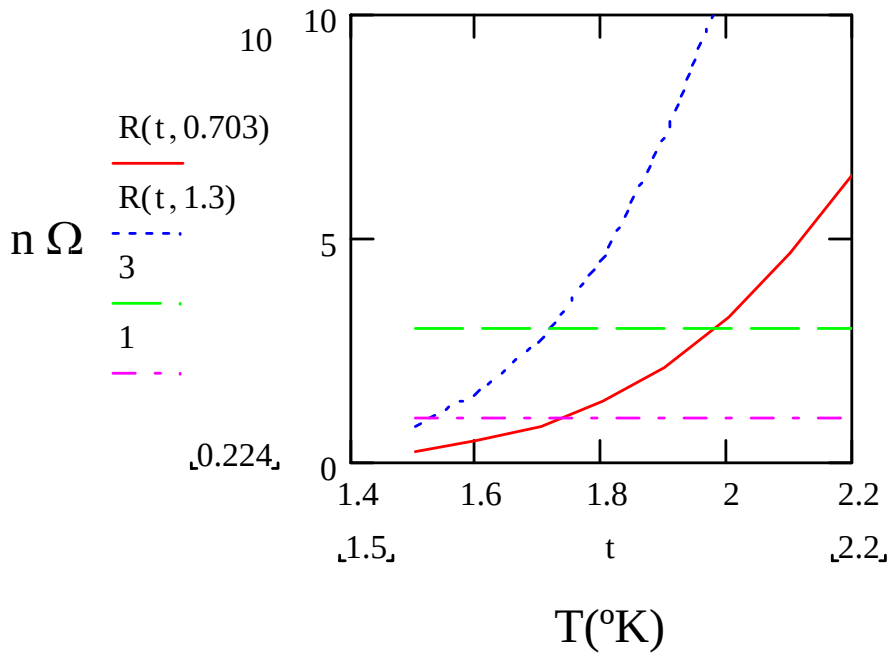






BCS and residual resistance

$$R_{BCS} = 2 \cdot 10^{-4} \frac{1}{T} \left(\frac{f(GHz)}{1.5} \right)^2 \exp\left(-\frac{17.67}{T} \right)$$



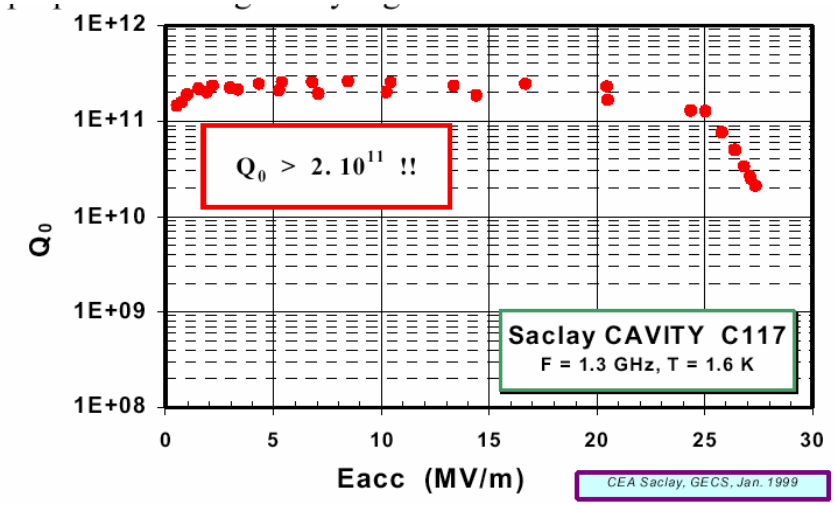
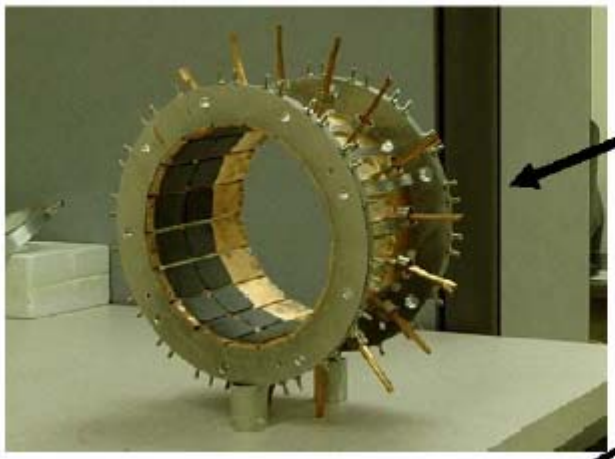


Figure 2 – Residual resistance as low as 0.5 nΩ is actually measured on large area cavities, giving an intrinsic quality factor Q_0 exceeding 2.10^{11}.

Residual resistance <1 nΩ possible

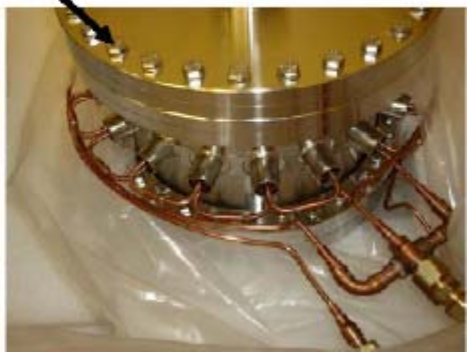
Ferrite HOM dampers



Ferrite prototype for testing

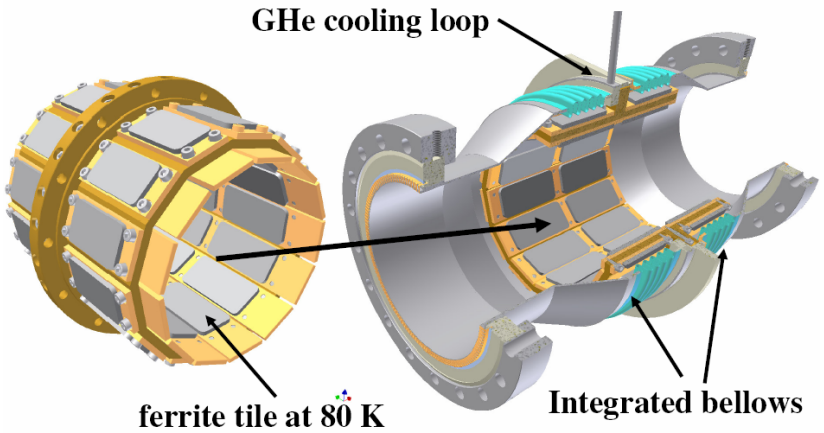
HOM Power Capacity: 5-10 kW/ferrite

Real Ferrite Absorbers
(Vendor: ACCEL)

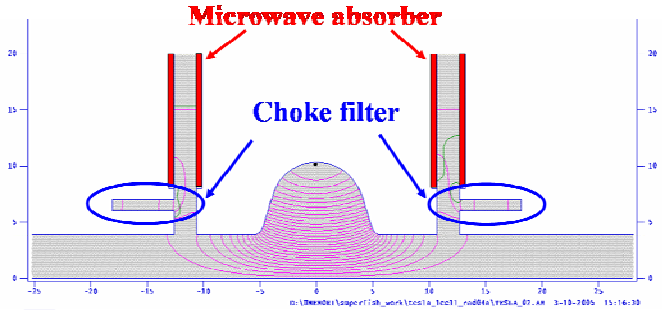


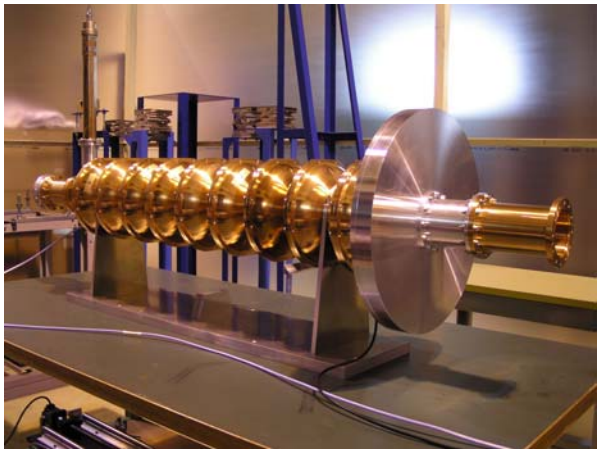
Cold ferrite loads: Once you have a “single mode” cavity, there are many options

Conceptual Layout of the Cavity String of the Cornell ERL Main Linac Cryomodule
M. Liepe, SRF’03



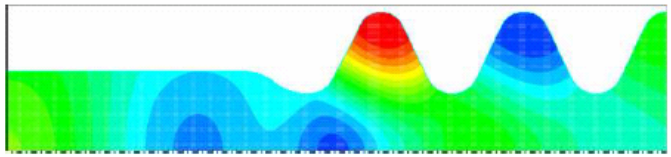
Higher-Order-Mode Damping of L-band Superconducting Cavity Using a Radial-line HOM Damper
K. Umemori, et. al., proceedings PAC’05



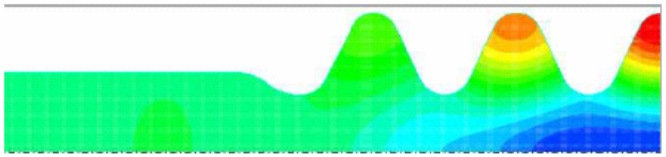


Some Dipole Modes of Interest (B_ϕ)

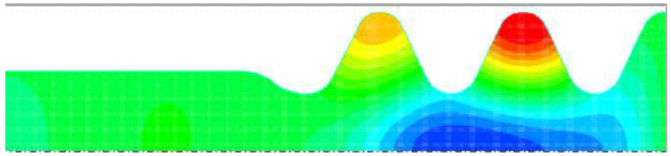
959 MHz, Q_{ext} - 8×10^3



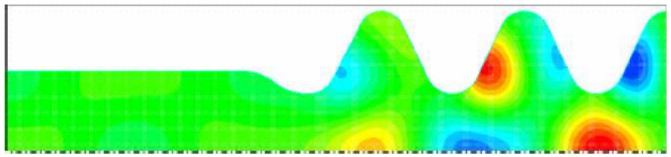
965 MHz, Q_{ext} - 1.4×10^3



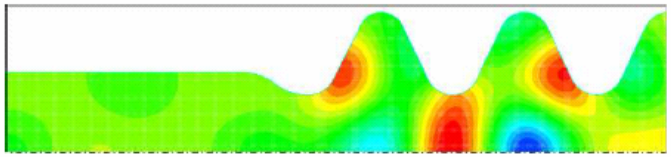
973 MHz, Q_{ext} - 3.3×10^2



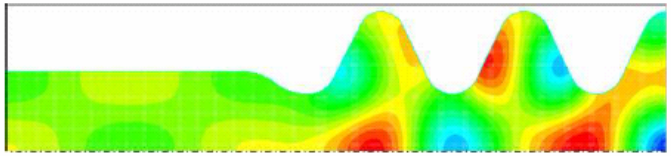
1.771 GHz, Q_{ext} - 1.2×10^4

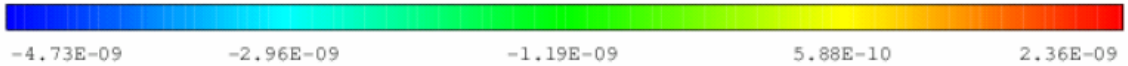


1.776 MHz, Q_{ext} - 7×10^3



1.781 MHz, Q_{ext} - 1×10^4

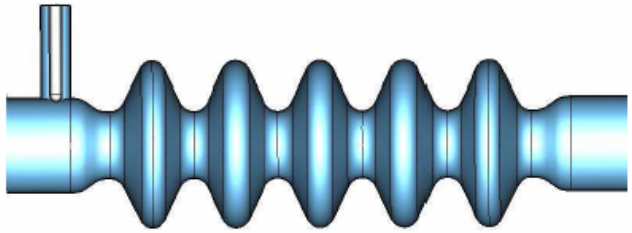




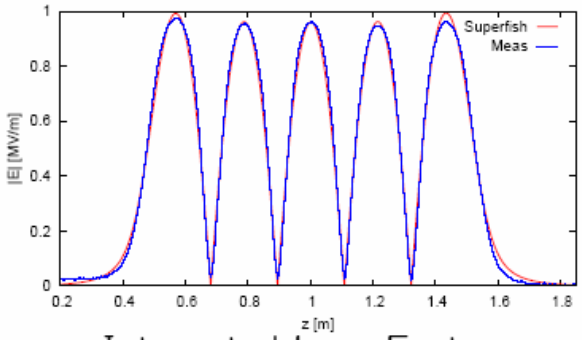
BNL Cavity

Main Parameters:

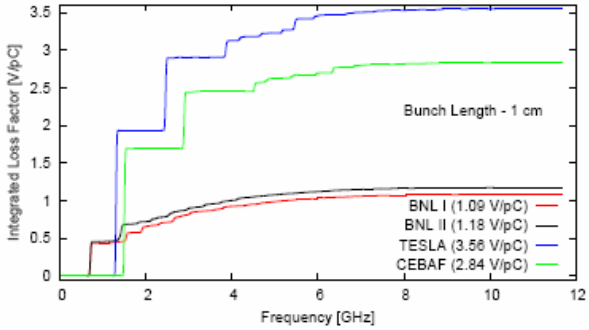
Frequency	703.75 [MHz]
RHIC Harmonic	25
Number of cells	5
Active cavity length	1.52 [m]
Iris Diameter	17 [cm]
Beam Pipe Diameter	24 [cm]
G (Ω)	225
R/Q	403.5 [Ω]
Q BCS @ 2K	4.5×10^{10}
Q_{ext}	3×10^{7}
E_p/E_a	1.97
H_p/E_a	5.78 $[mT/MV/m]$
cell to cell coupling	3%
Sensitivity Factor ($\frac{N^2}{\beta}$)	833
Field Flatness	96.5 %
Lorentz Detuning Coeff	1.2 $[Hz/(MV/m)^2]$
Lowest Mech. Resonance	96 [Hz]
$k_{\|}$ $(\sigma_z - 1cm)$	1.1 [V/pC]
$k_{\perp}$ $(\sigma_z - 1cm)$	3.1 [V/pC/m]
HOM Power (10-20 nC)	0.5-2.3 [kW]



Field Flatness



Integrated Loss Factor



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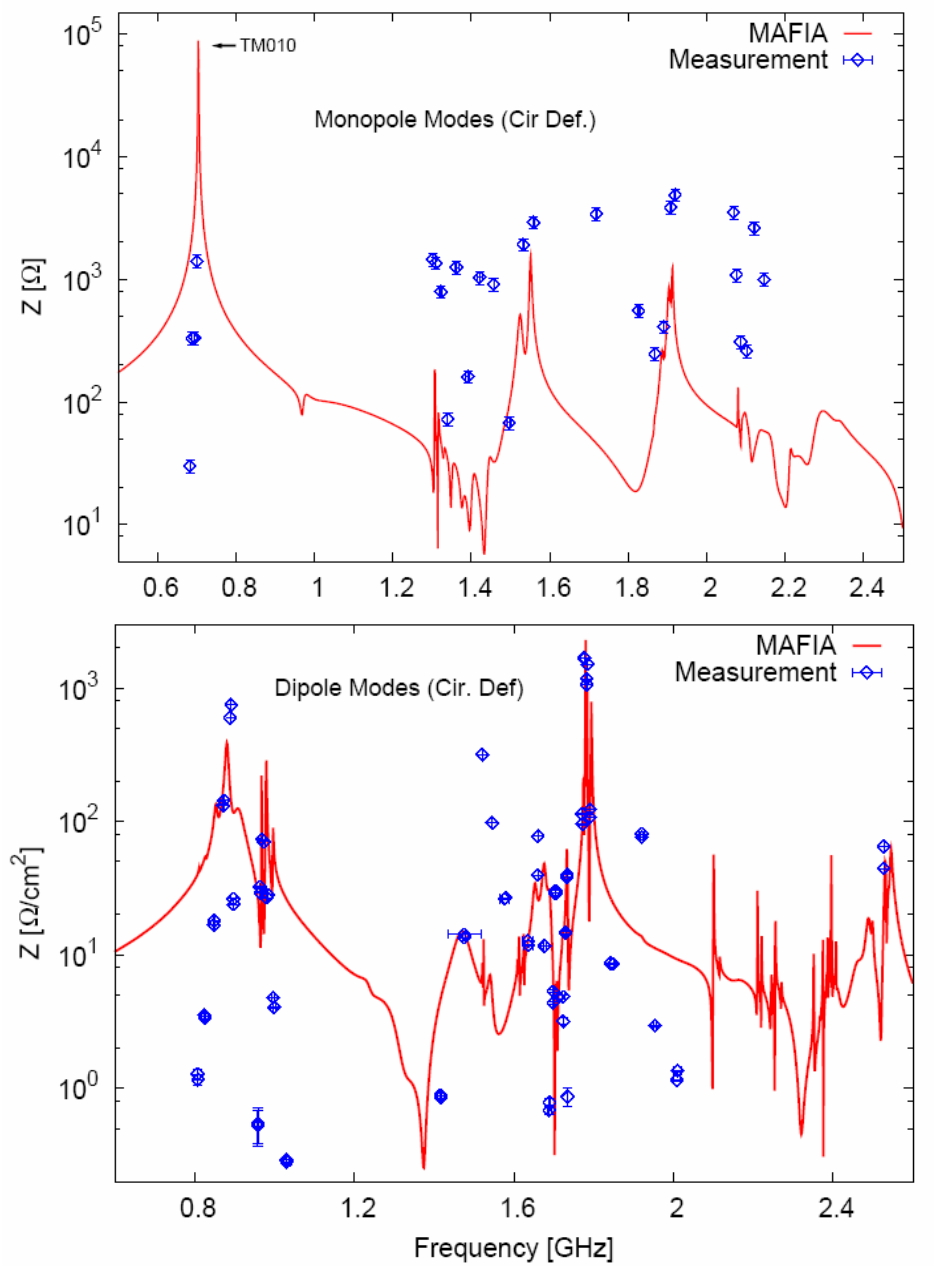
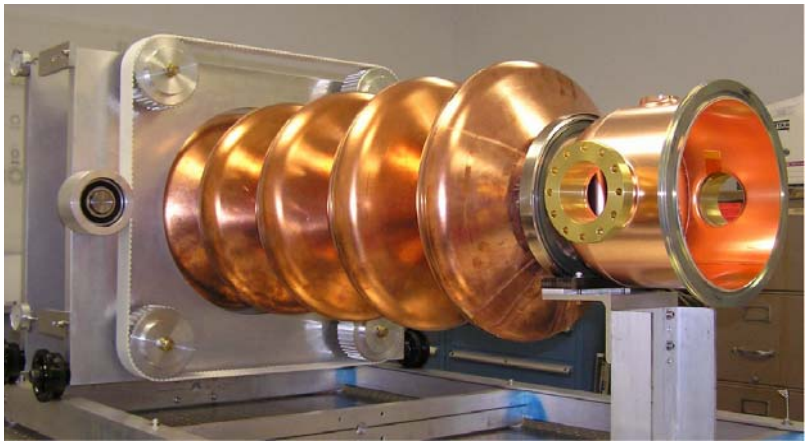
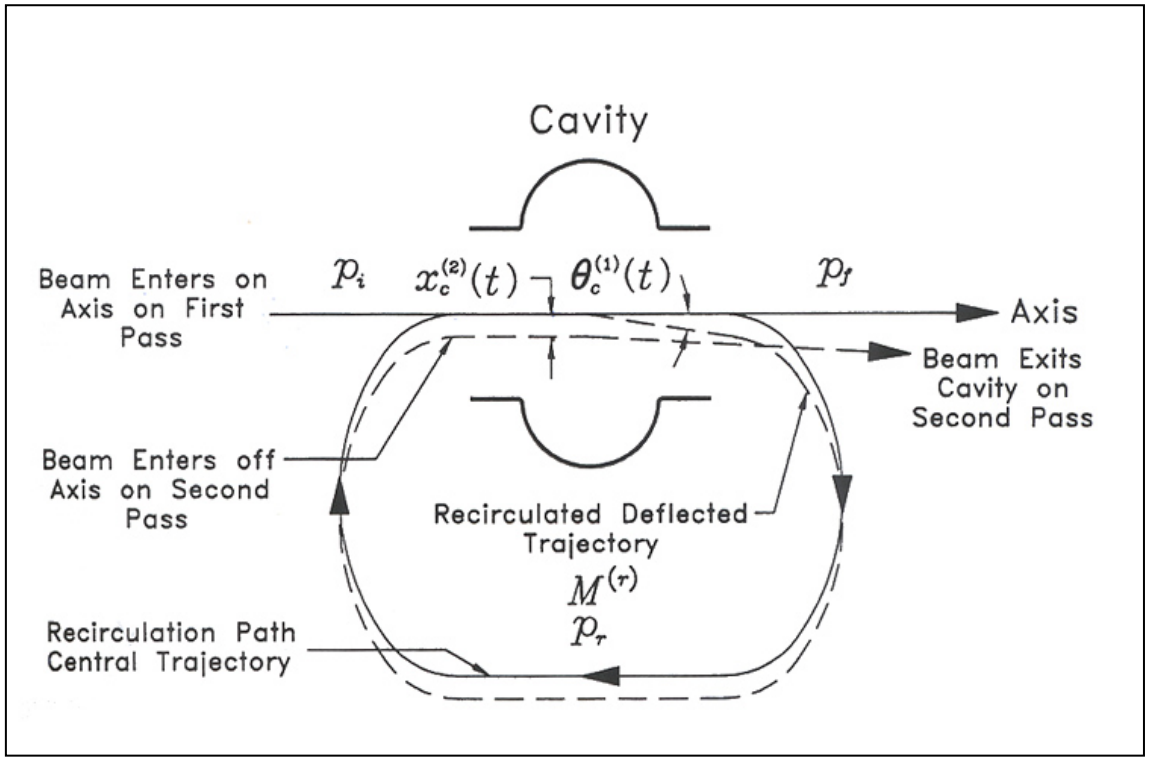
BNL 5-cell impedance – lower than any other cavity



Red line - MAFIA
Blue points - measured



Beam breakup



BBU analysis

Definitive work:

G.H. Hoffstaetter and I.V. Bazarov, “Beam-breakup instability theory for energy recovery linacs”, Phys. Rev. ST AB **7**, 054401 (2004).

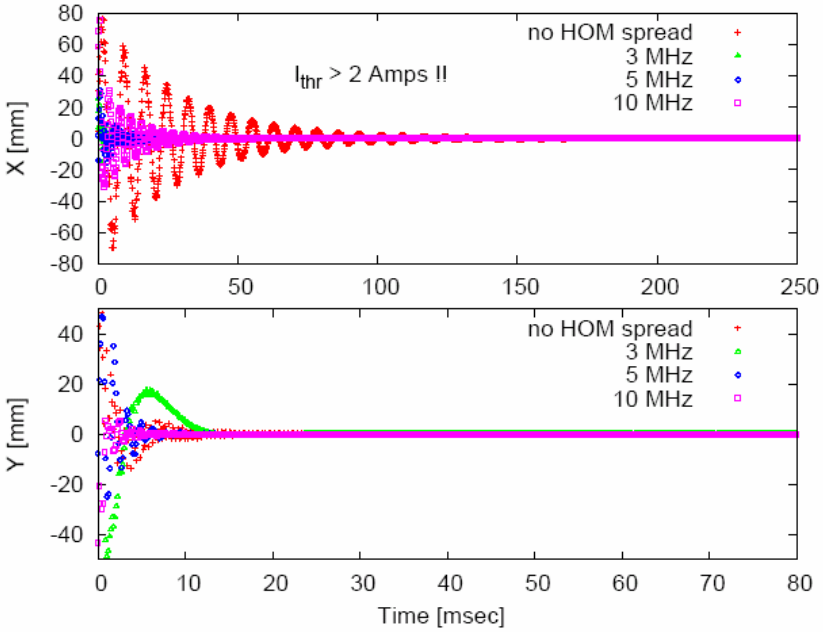
$$I_{th} = \frac{-2c^2}{e\left(R/Q\right)_m Q_m \omega_m T_{12} \sin\left(\omega_m t_r\right)}$$

Hoffstaetter and Bazarov simulations show ~200 mA threshold for a 5 GeV ERL using TESLA TDR cavities.

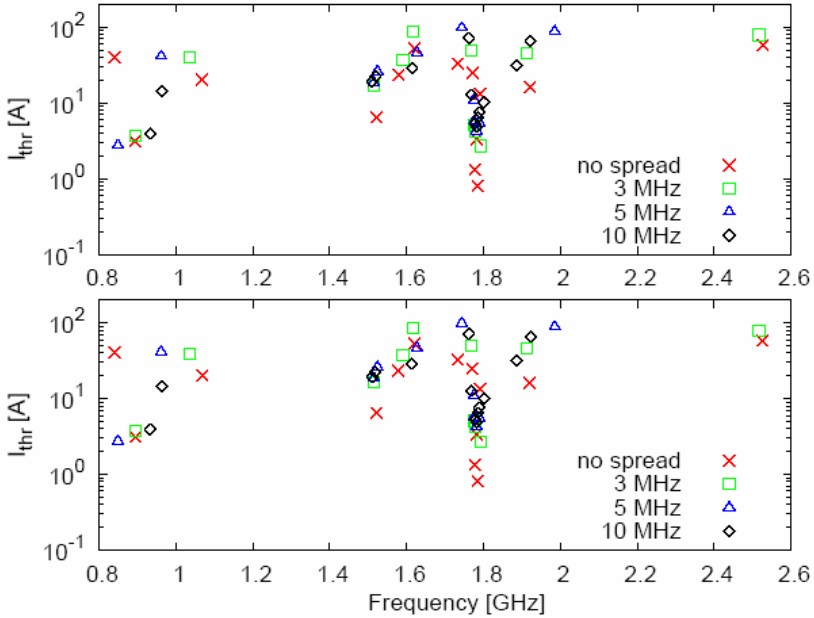
The new 700-750 MHz cavities (BNL, JLab) should have a factor of 2 by virtue of its lower frequency and another large factor, ~100, thanks to enhanced HOM damping, i.e. smaller $(R/Q)_m Q_m$

Multibunch BBU

TDBBU



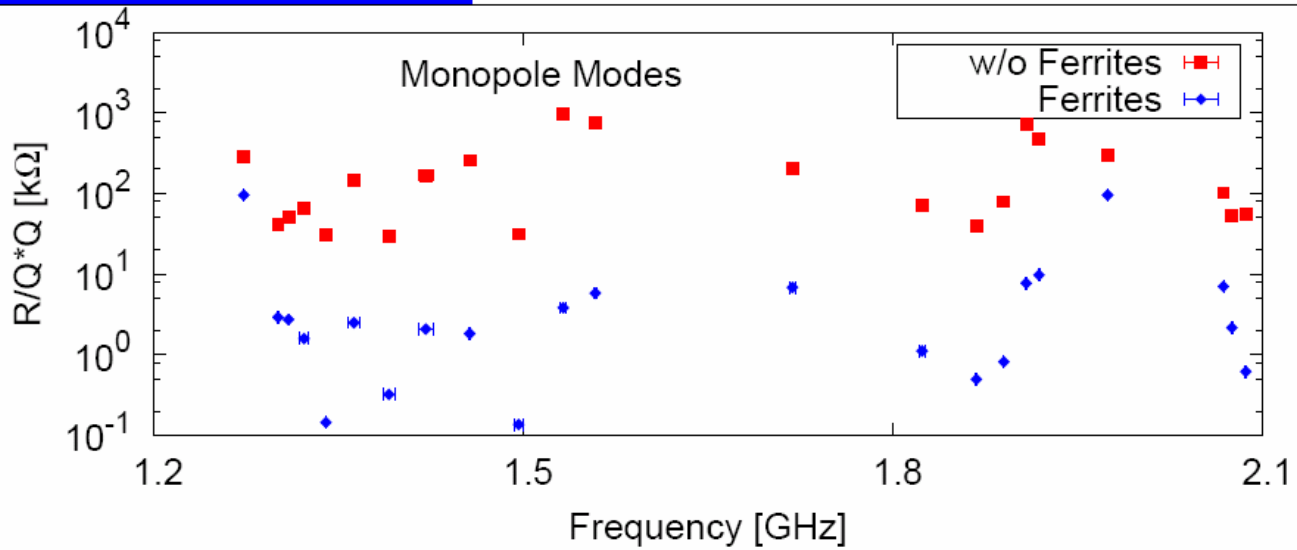
MATBBU

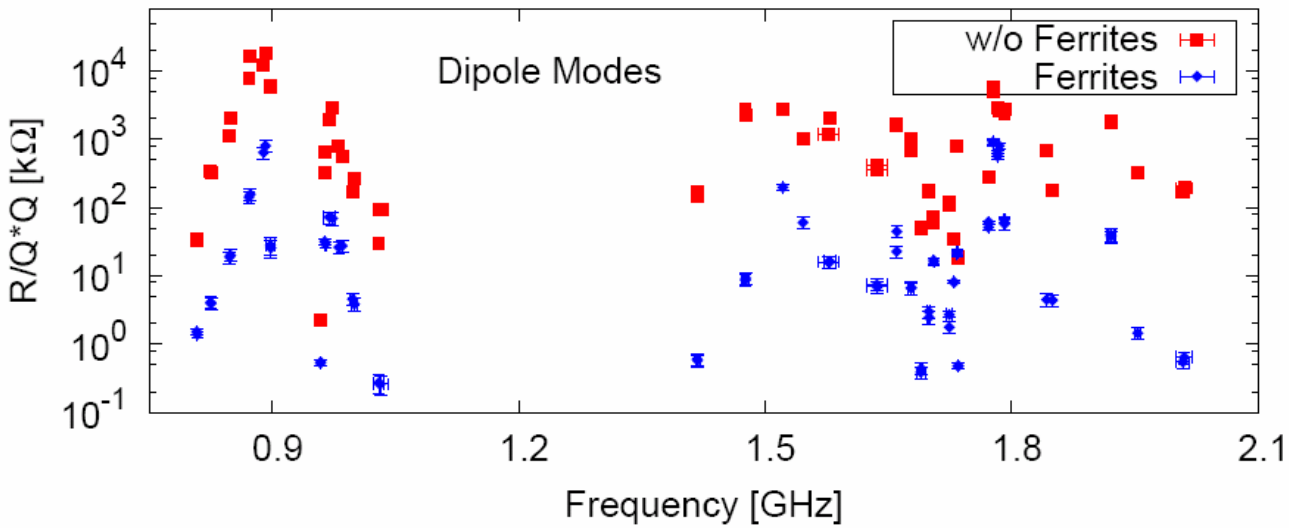


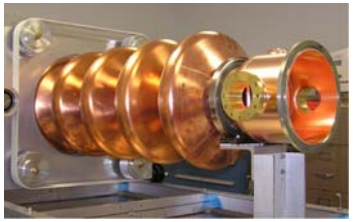
Electron Cooling Configuration (4 Cavities - 54 MeV)

Simulations for eRHIC sized machine yet to be done,
but starting with a well damped cavity is a good beginning.

Higher Order Modes



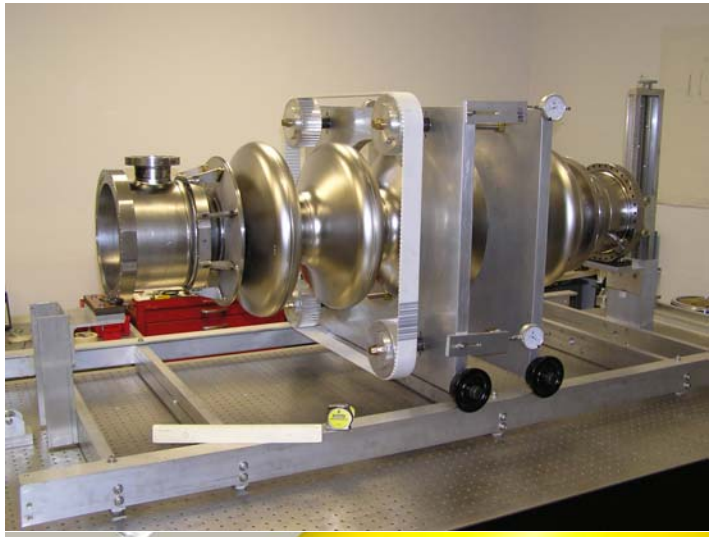


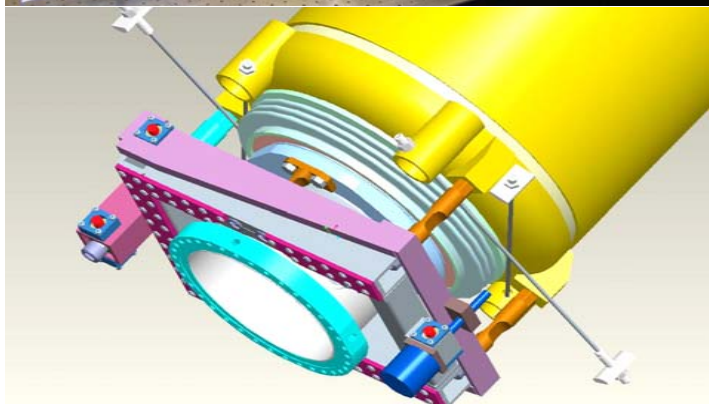


Cavity mechanical stiffness

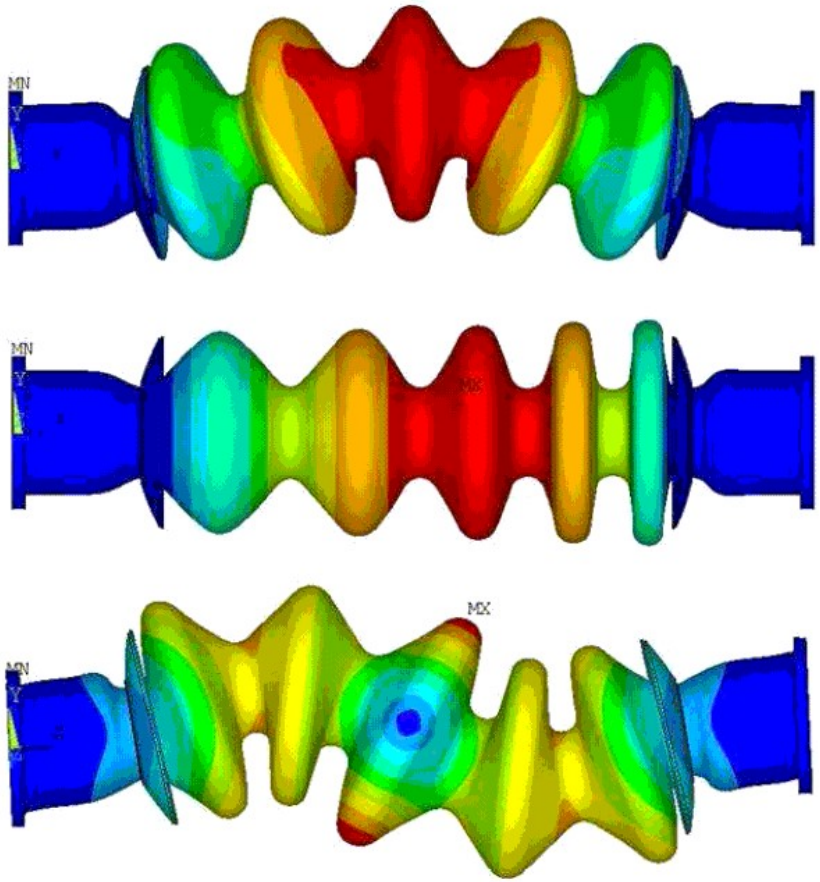
1.2 Hz/(MV/m)^2

Mechanical Resonances (D. Holmes - FEA)





Modes 1-5 (96 - 214 Hz)



RHIC

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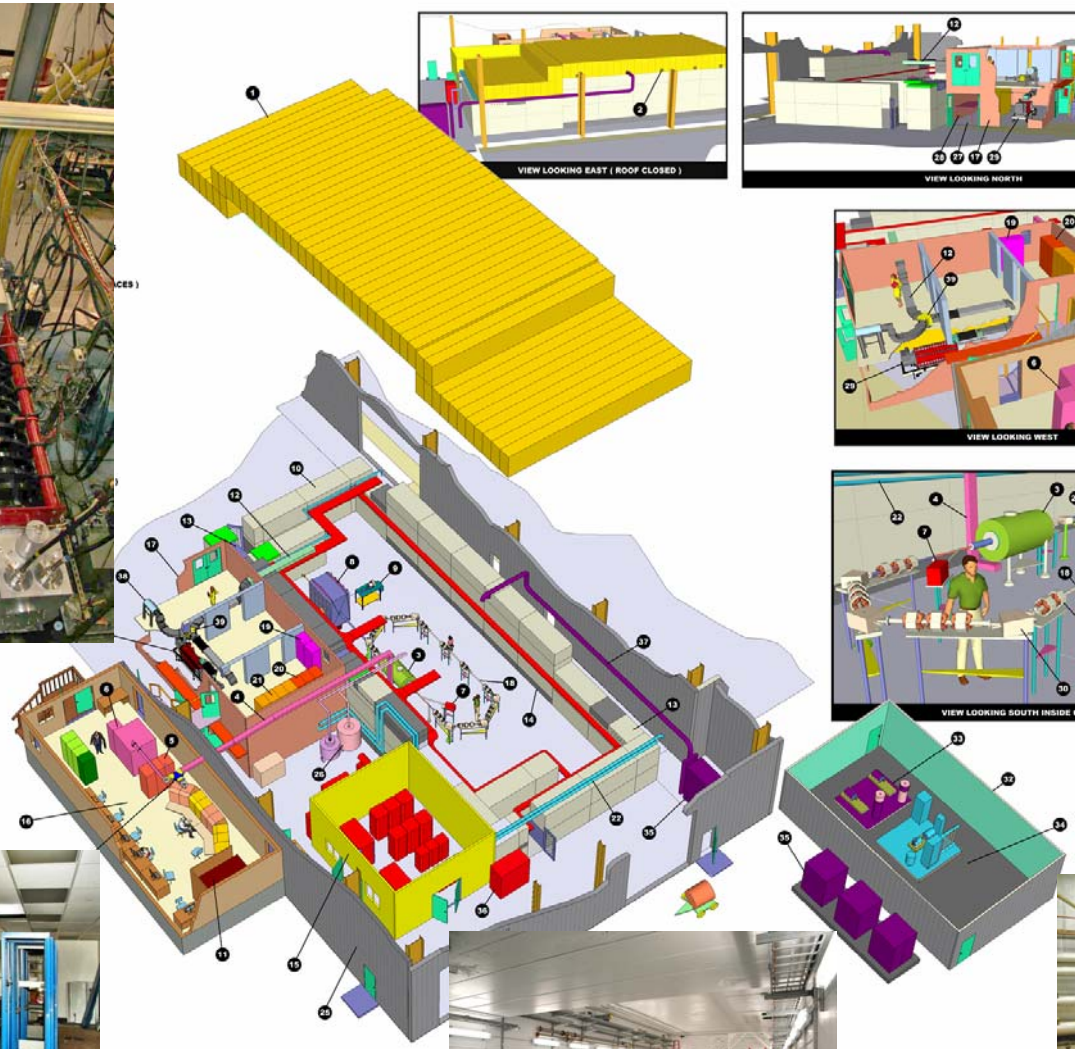
Future work: Use copper prototypes for "Super-Cryomodule" Tests

Future work: Test in ERL



RHIC

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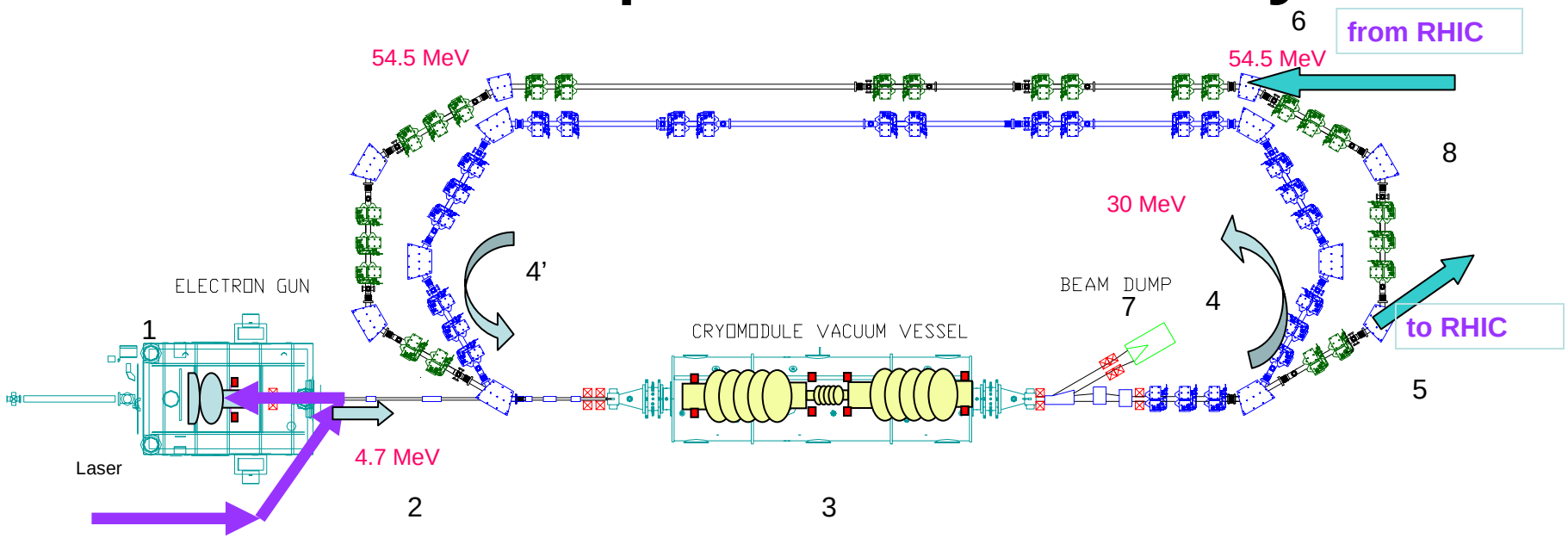
E-cooler: 2 passes ERL layout



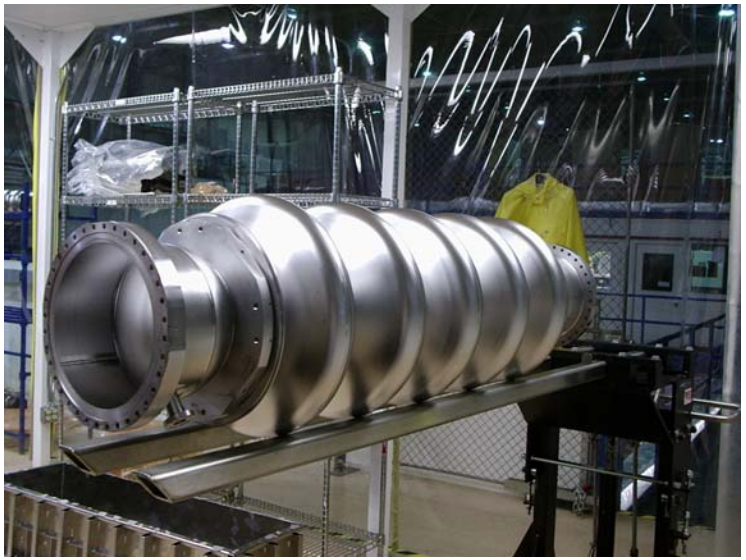
1. SRF Gun,
2. Injection merger line
3. SRF Linac two 5-cell cavities and 3rd harmonic cavity

4, 4'. 180° achromatic turns

5, 6. Transport lines to and from RHIC,

7. Ejection line and beam dump
8. Short-cut for independent run of the ERL.

The cavity at JLab



Current status

- The cavity is at JLab
- First BCP cycle was done.
- Vertical test shows a low field Q of over 10^{10}.
- Fields of up to 10 MV/m were established for a short time with same good Q
- There is a slow thermal heating which is being investigated (most likely not from cavity)
- Horizontal test at BNL about January 2007.

Thanks and acknowledgements

- The cavity was developed by a collaboration of BNL, AES and JLab.
- Thanks for people associated with the BNL project:
  - A. Burrill, R. Calaga, H. Hahn, V. Litvinenko
  - G. McIntyre, H.C. Hseuh, A. Nicoletti, C-I. Pai, D. Phillips, J. Rank, J. Scaduto, K. Smith, A. Zaltsman and many others in C-AD
  - AES: D. Holmes, M. Cole A. Favale, J. Rathke, T. Schultheiss, others
  - JLab: P. Kneisel, R. Rimmer, L. Phillips, J. Preble, J. Mammosser, E. Daly, others
  - ORNL: R. Campisi
  - DESY: J. Sekutowicz

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