High Current SC Cavity

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Outline

- Development of High current SC cavity worldwide
- How to design a high current SC cavity
- HOM of the High current of SC cavity

What is high current SC cavity?

Definition:

- High current SC cavity:

  Current larger than 100mA. It is developed in many labs now, like Jlab, BNL, KEK, Cornell. They are designed for ERL FEL.

- Low current SC cavity:

  Most of the SC cavities used now are in this type. Most of them the current is around 1mA or less.

*This definition is for beta=1 cavity

What is the difference between high current SC cavity with low current SC cavity

Cavity type	High current	Low current
Coupler Power	Very high without ERL	lower
Instability	BBU	BBU (not very important compare to high current)
Gradient (MV/m)	~10-~20	~10-~40
Application	Ultra high power FELs High flux and brightness ERL light source High luminosity electron hadron colliders Electron cooling of Hadron colliders Compton X-ray sources THz sources	Linear accelerator, storage ring, collider, ‥ ‥
HOM power	Very large	lower
Beam tube	larger	smaller

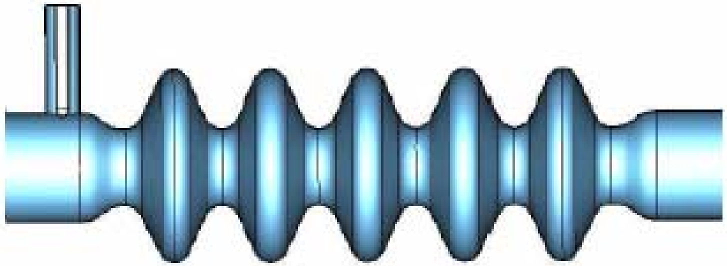
Development of high current SC cavity

Lab	Jlab	Cornell (Injector)	BNL	KEK	AMAC&MITBates Lab
Frequency(MHz)	748.5/1497	1300	703.75	1300	2850
Current(mA)	1000/100	100	>100	100	10-100
Number of cell	5	2	5	9	
R/Q(Ω)	525	218	404	897	76.433
E_p/E_{acc}	2.50	1.94	2.0	3.0	2.52
B_p/E_{acc} or Hp/Eacc	4.27 mT/(MV/m)	42.8 Oe/(MV/m)	5.8 mT/(MV/m)	42.5 Oe/(MV/m)	4.97 mT/(MV/m)
Geo. Factor	276		225	289	
K_{cc}(%)	3.26	0.7	3	3.8	
E_{acc}(MV/m)	16.7(20max)			20	15
HOM power(W)	20000	26	500-2300	100-200	
BBU threshold (A)	>1		>2	>0.6	
Power coupler (kW)		75(max)		20 CW	
HOM damper	Wave guide & ceramic material		External ferrite	Ferrite or SiC absorber	Ferrite

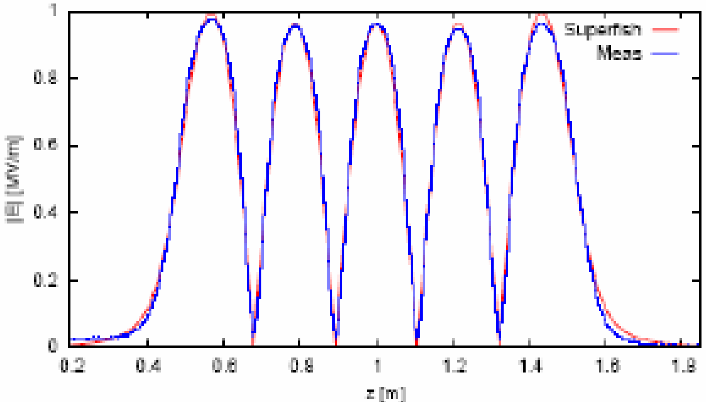
BNL

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 $[\Omega]$
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



Jlab

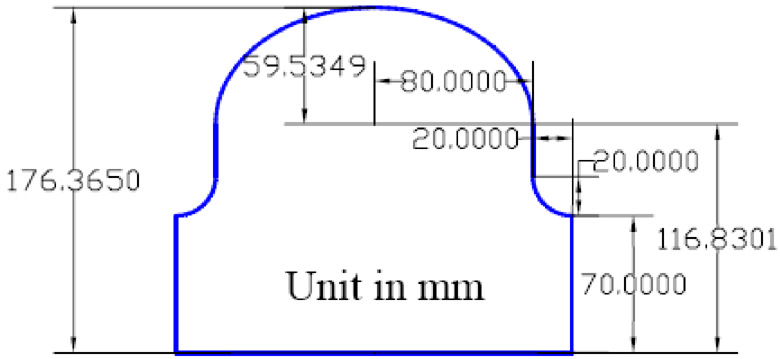


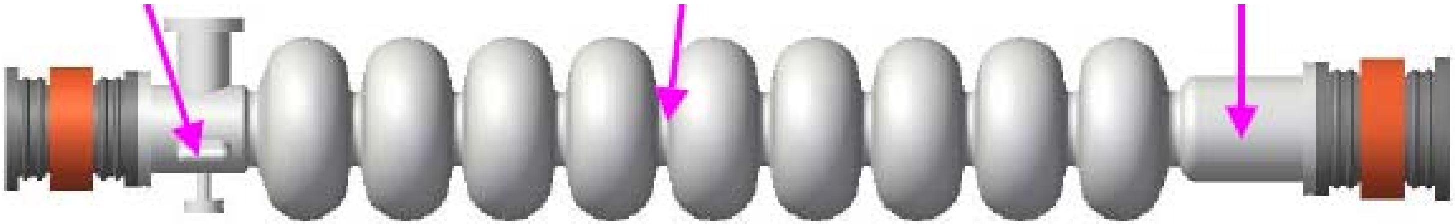
Figure 1: Center cell shape for the 748.5 MHz HC cavity.

Table 1: 5-cell, HC 748.5MHz cavity design parameters.

$R/Q=V_{acc}^2/(\omega U)$	525 Ω	Geo. Factor	276 Ω
E_{peak}/E_{acc}	2.50	k_{cc} cell-to-cell	3.26 %
B_{peak}/E_{acc}	4.27 mT /(MV/m)	$k_{//}$ for σ_z=1mm	5.6 V/pC
		$k_{\perp}$ for σ_z=1mm	2.95 V/pC/m

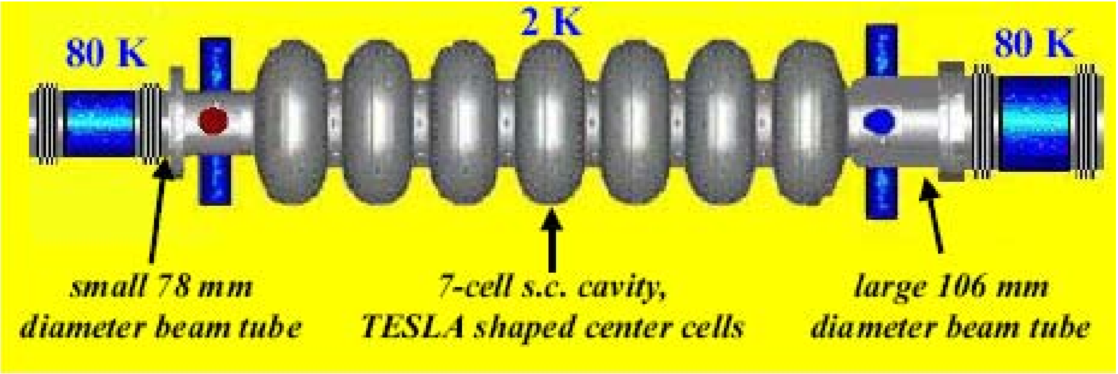
Figure 2: Copper five-cell model of the high-current cavity with waveguide end groups.

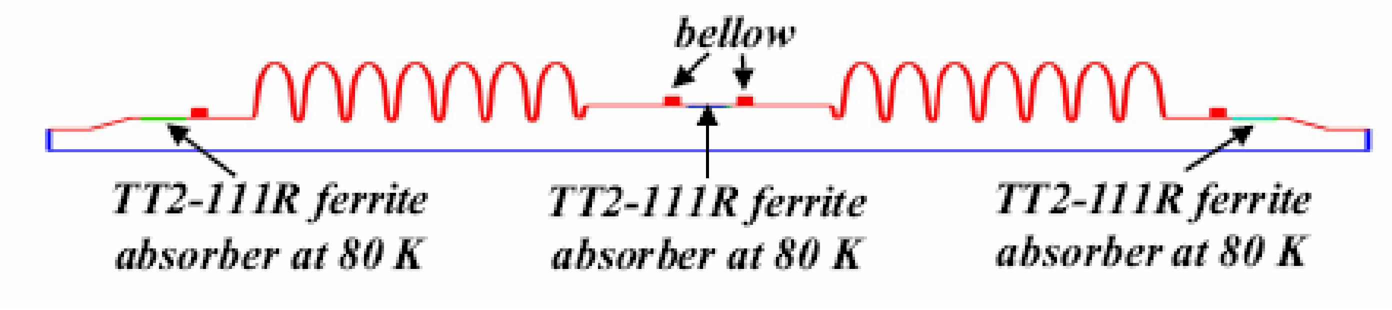
KEK



Frequency	1300 MHz	Coupling	3.8 %
Rsh/Q	897 Ω	Qo x Rs	289 Ω
Ep/Eacc	3.0	Hp/Eacc	42.5 Oe/(MV/m)

Cornell 7cell high current SC cavity





What principle should be followed to design a good high current SC cavity?

Principle:

- Frequency
  ~700-~1500MHz
- Gradient:
  Lower E_{pk}/E_{acc}(<5) and H_{pk}/E_{acc}(<50Oe/(MV/m))
- R/Q(Ω)
  >90/cell
- Number of cell
  5,7,9
- Low loss factor
- Field flatness
  >97%
- Higher order mode (HOM)
  Monopole HOM: Heat load
  Dipole and Quadrupole: BBU

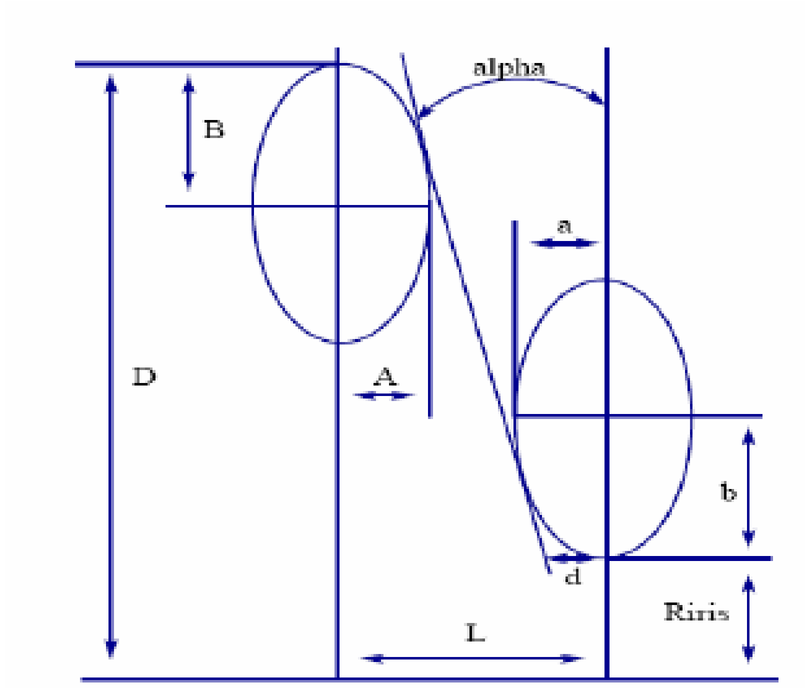
Simulation tools

Cavity Geometry	BuildCavity, Superfish
Loss factor	ABCI
HOM	MAFIA, HFSS,MWS
Beam breakup	TDBBU, MATBBU,BI
Mechanic	Ansys

1. Dong Wang, DESIGN OF A SUPERCONDUCTING LINAC CAVITY FOR HIGHCURRENT ENERGY RECOVERY LINAC OPERATION, Proceedings of the 2003 Particle Accelerator Conference
2. I. Ben-Zvi, New SRF Cavity Geometry for High-Current Applications

Cavity shape design

- Large Apertures
- Low frequency
- Good conduct for the HOM power
- Low loss facter
- High BBU threshold
- Field flatness



Loss factor

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

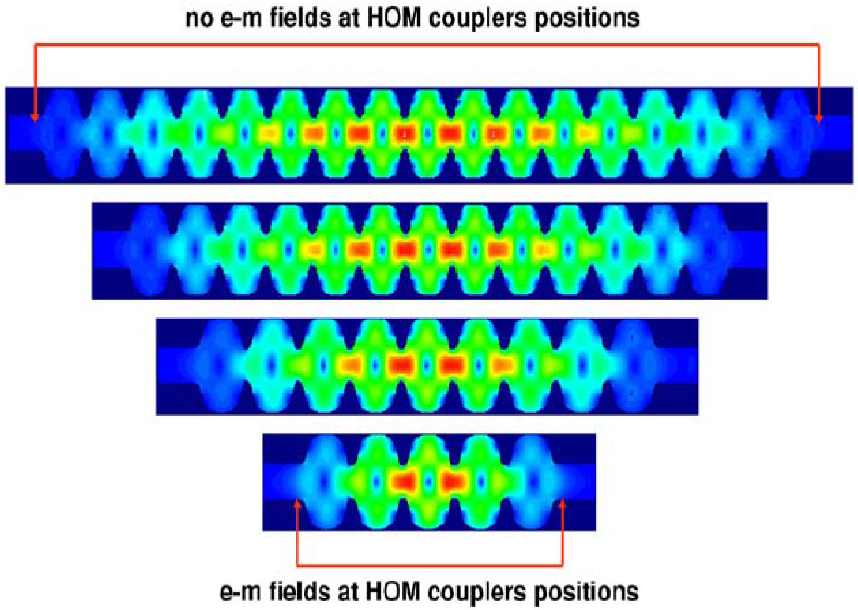
$$P_{HOM} = k_l I q$$

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

Given 6×10^{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	30×10^{-4}	5×10^{-4}

Number of cavity cells



- Multi-cell cavities with a larger number of cells would also improve linac packing factor, i.e., ratio of active length to total length
- This will reduce the cost of the ERL linac, BUT
- Strong HOM damping is essential with higher beam current which favors smaller number of cells

BBU

BBU threshold:

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

It is more convenient to calculate it by code like TDBBU or BI etc.

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

HOM damping

Monopole mode (Heat load)
–100W heat load at resonant condition

$$\left(\frac{R}{Q}\right)Q < 2500\,[\Omega]$$

Dipole mode (Beam-breakup (BBU) instabilities)
–HOM requirement for 100mA beam current

$$\left(\frac{R}{Q}\right)\frac{Q}{f} < 1.4\times10^{5}\left[\frac{\Omega}{cm^{2}GHz}\right]$$

Quadrupole mode (Quadrupole BBU instabilities)
–HOM requirement for 100mA beam current

$$\left(\frac{R}{Q}\right)\frac{Q}{f} < 4\times10^{6}\left[\frac{\Omega}{cm^{4}GHz}\right]$$

M. Liepe, CONCEPTUAL LAYOUT OF THE CAVITY STRING OF THE CORNELL ERL MAIN LINAC CRYOMODULE

Wake Impedance methods

Wake impedance real part

$$Z_R(\omega) = \frac{Z_0}{1 + [2Q(\omega - \omega_0)/\omega_0]^2}$$

Resonant frequency

Accelerator definition shunt impedance

Q of resonant mode

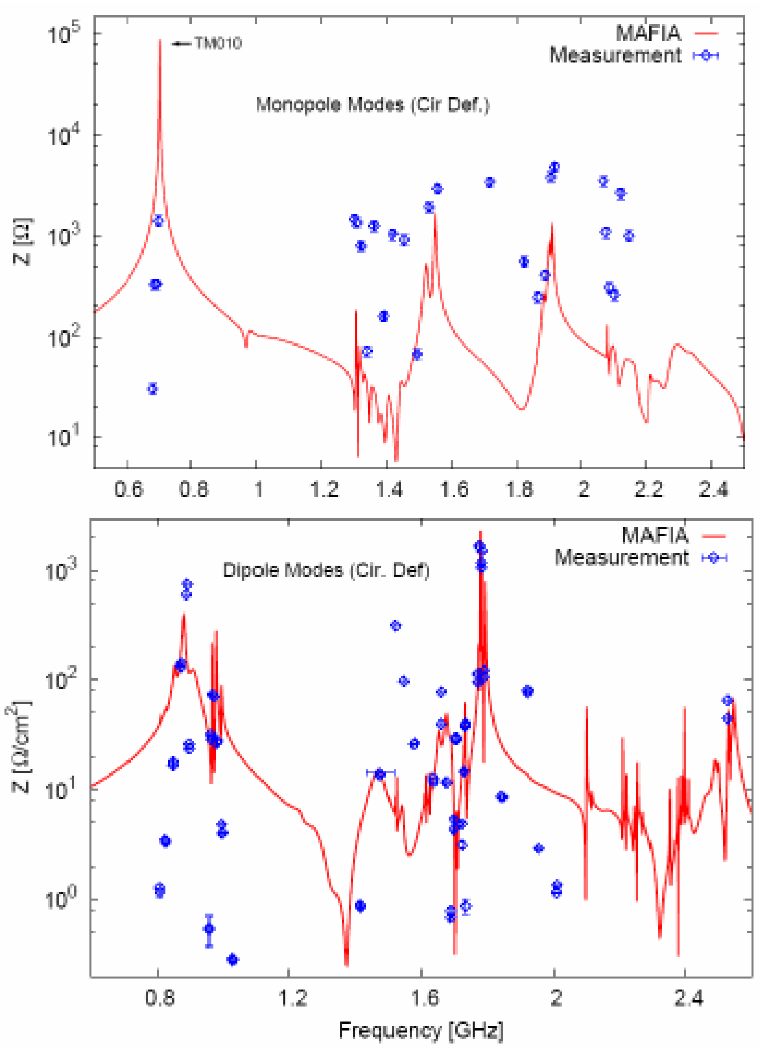
$$Z_0 = \frac{R}{2}$$

Circuit definition shunt impedance

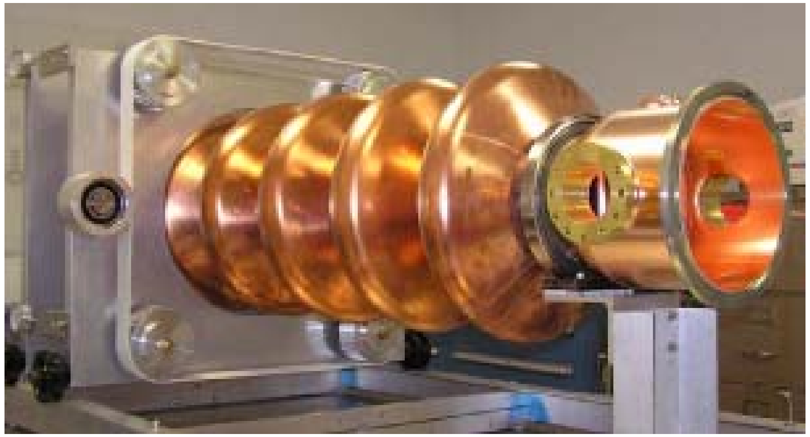
So $$Z_R(\omega_0) = \frac{R}{2} = R_C = \frac{R}{Q} Q$$

P. B. Wilson, Introduction to wakefields and wake potentials,SLAC-PUB-4547,P10

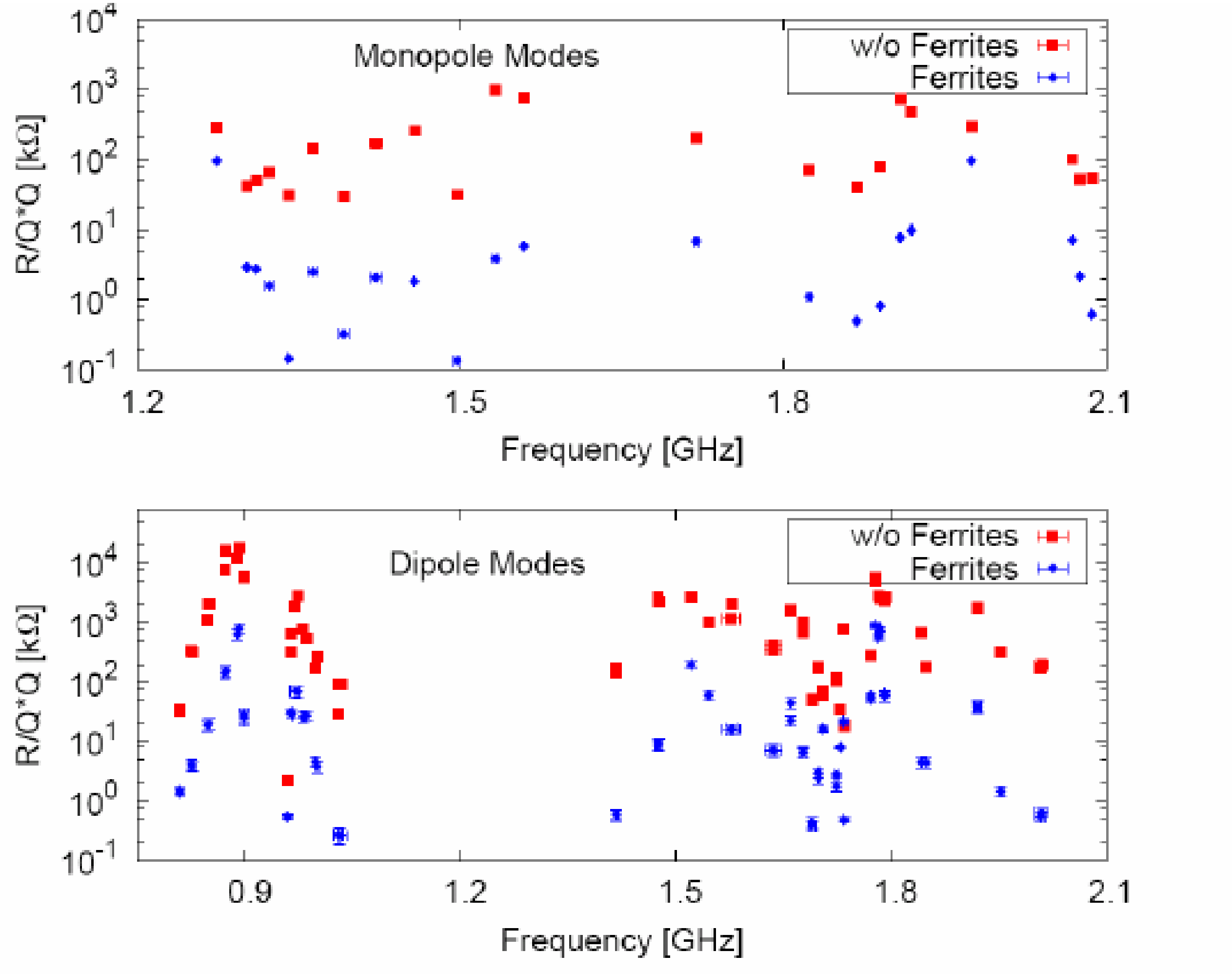
BNL

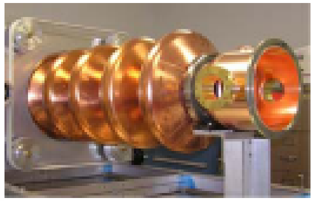


Red line: MAFIA
Blue points: Measured

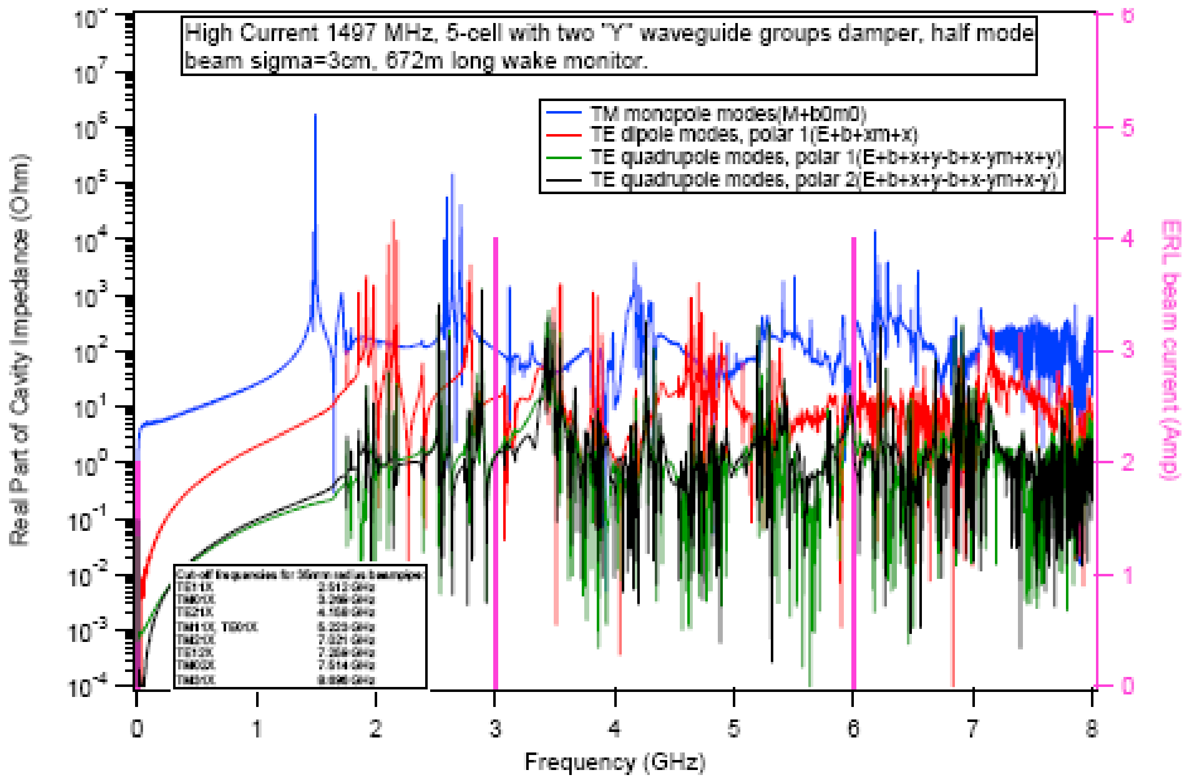


BNL HOM damping

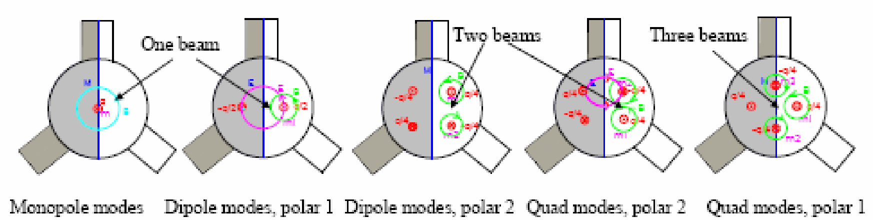




JLab HOM damping



HOM spectra calculated utilizing"multi-beam" excited wakefield schemes in MAFIA 3D,T3 solver

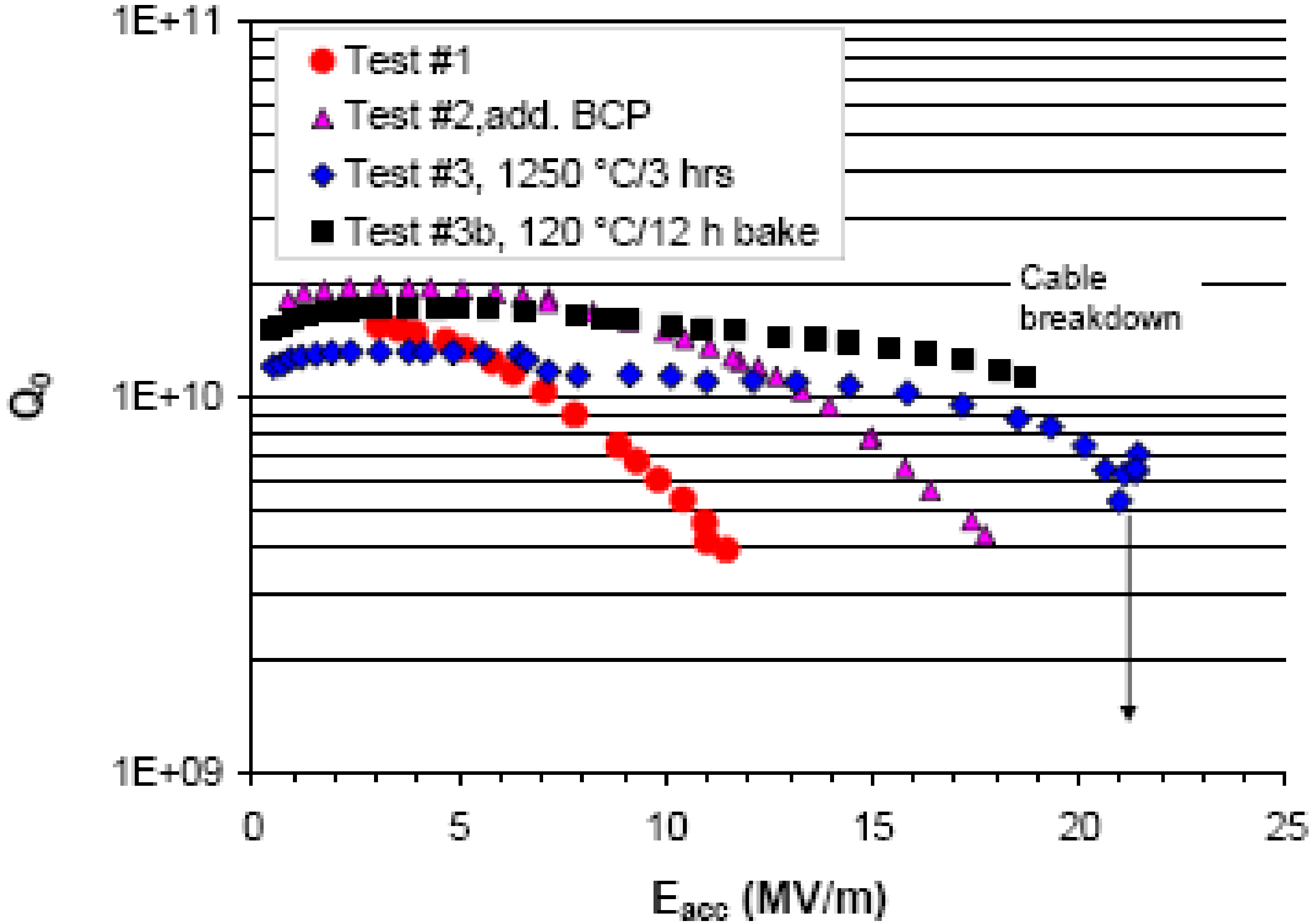


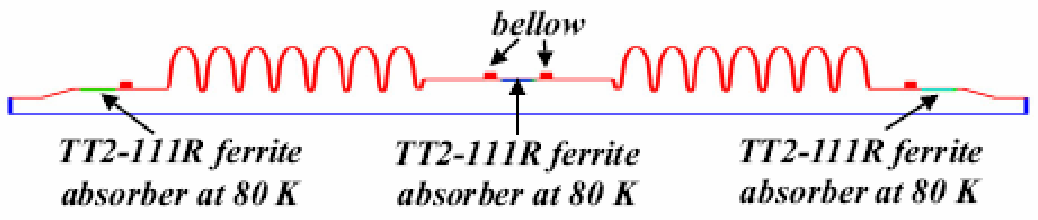
"Multi-beam" wake excitation scheme as sued in the MAFIA wakefield simulations

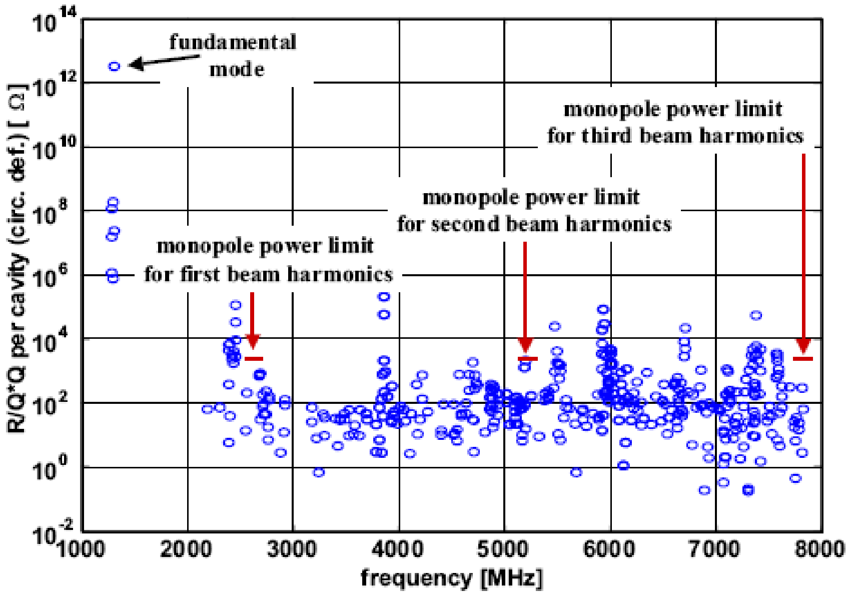
JLab prototype cavity

Cavity/ Frequency (MHz)	$1/L\sqrt{R/Q}$ (Ω)	E_p/E_{acc}	B_p/E_{acc} [mT/(MV/m)]
1-cell/1497	104.1	2.19	4.09
1-cell with WG/1497	101.4	2.63	4.30
5-cell/1497	45.8	2.5	4.27
1-cell/750	50.9	2.24	4.18

JLab 5cell prototype large grain Nb cavity







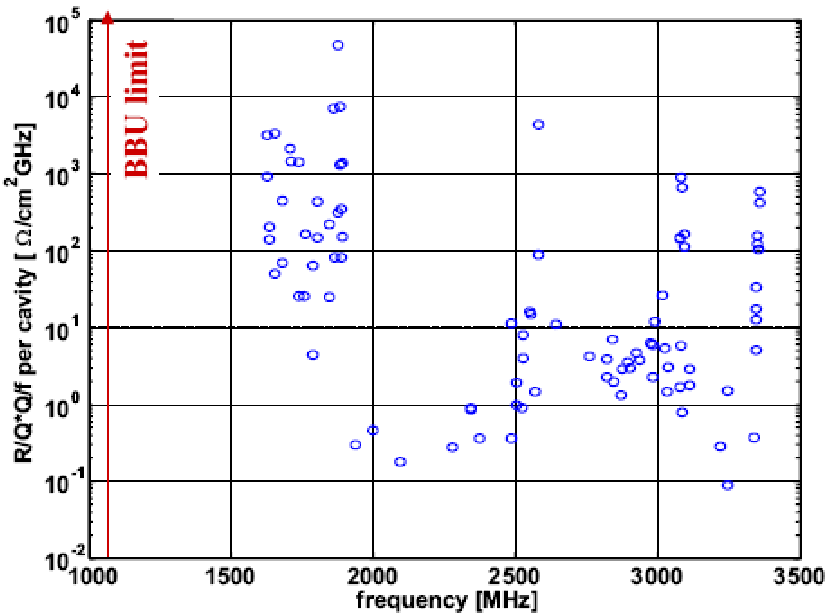
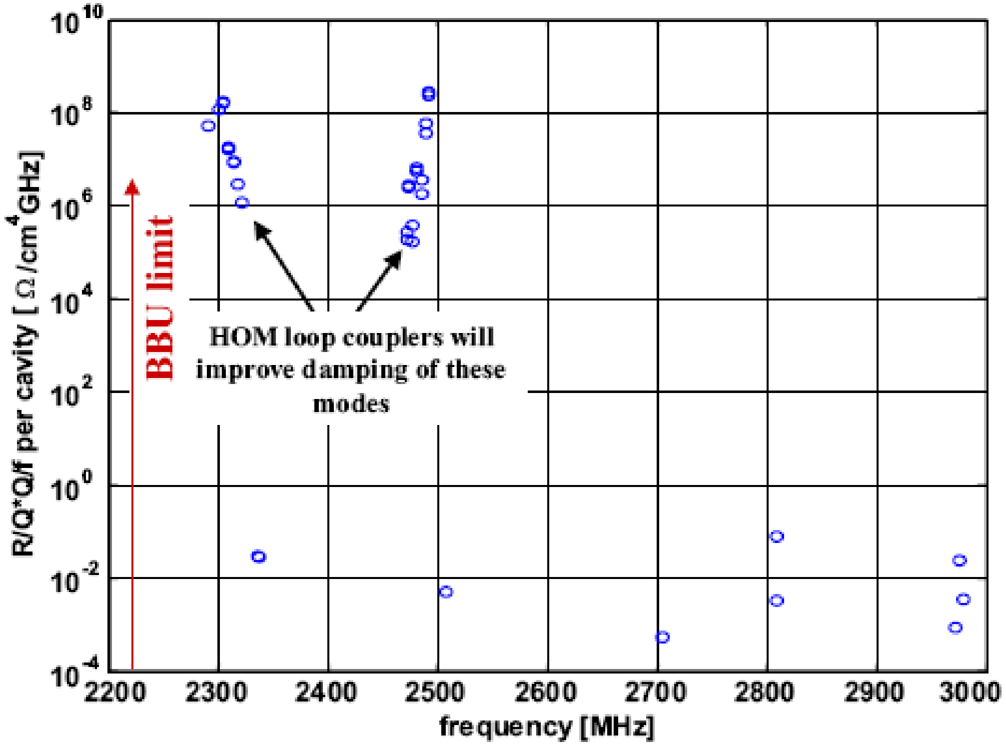


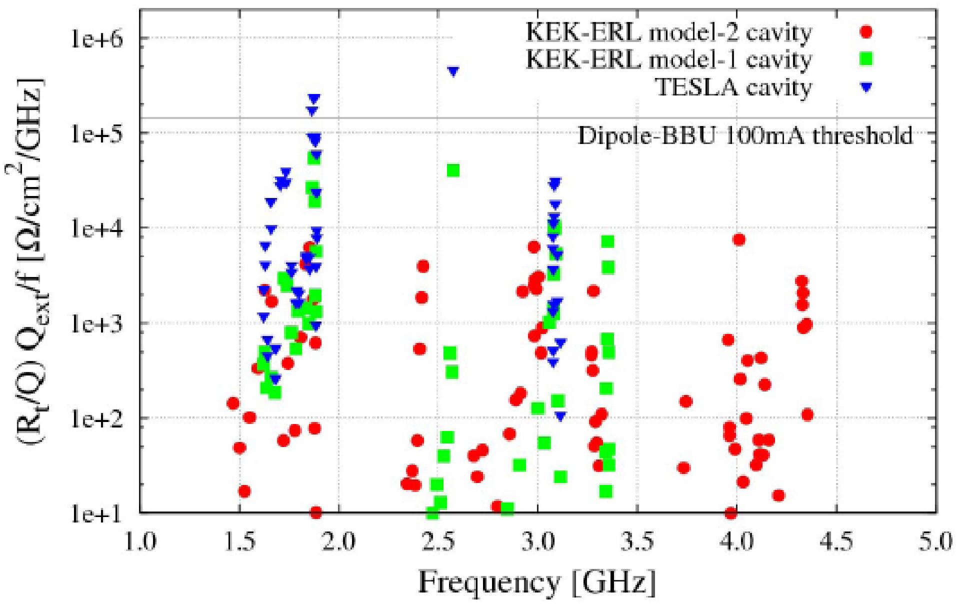
Figure 1:Calculated damping of TM monopole modes by the three ferrite HOM ring-absorbers in the cavity string. The damping is represented by the mode impedances $Z = (R/Q) \cdot Q_{ferrite}$, with $Q_{ferrite}$ being the mode quality factor caused by the losses in the ferrites.

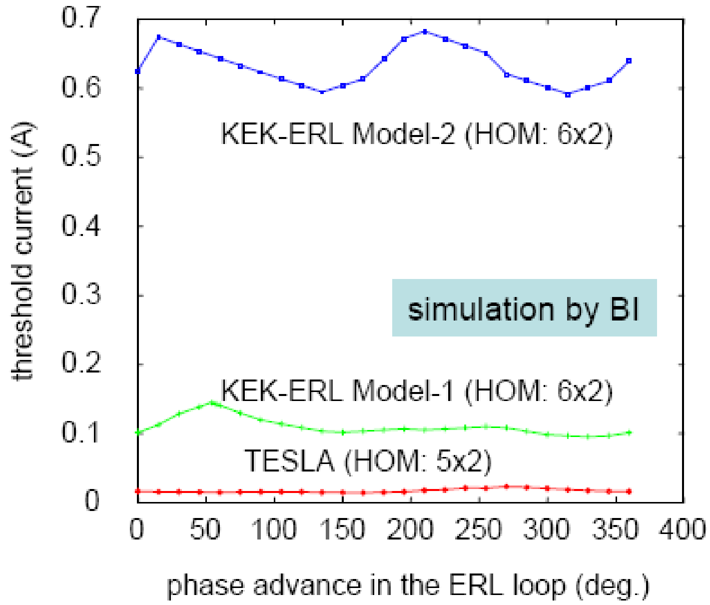
Figure 2: Calculated damping of dipole modes by the three ferrite HOM ring-absorbers in the cavity string. The damping is represented by the BBU factor $(R/Q) \cdot Q_{ferrite}/f$, with $Q_{ferrite}$ being the mode quality factor caused by the losses in the ferrites.



Calculated damping of quadrupole modes by the three ferrite HOM ring-absorbers in the cavity string. The damping is represented by the BBU factor $(R/Q) \cdot Q_{ferrite}/f$, with $Q_{ferrite}$ being the mode quality factor caused by the losses in the ferrites.

KEK

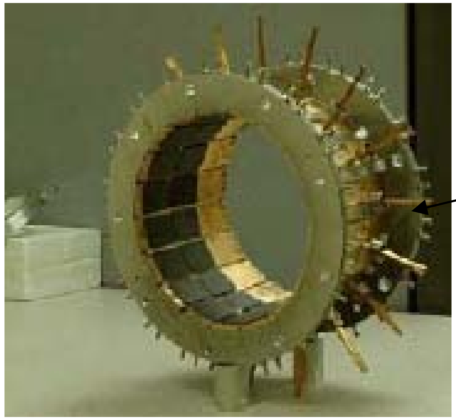




E_{inj} = 10 MeV, E_{loop} = 5 GeV, E_{acc} = 20 MV/m

Ferrite HOM damper

Prototype



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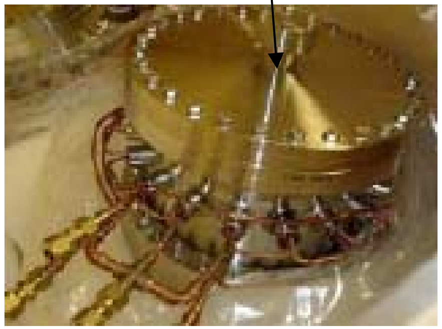
Real Ferrite absorbers

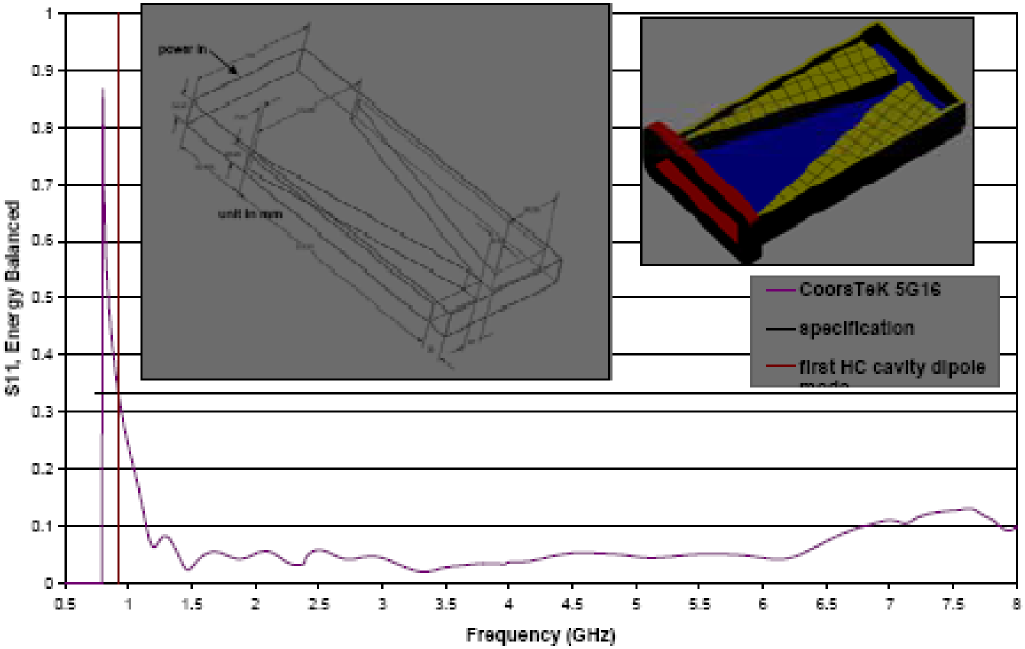


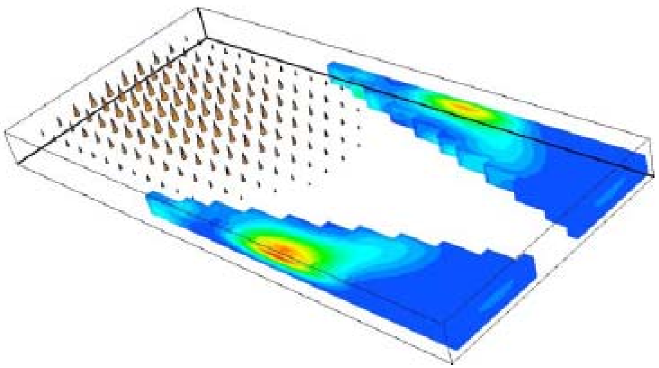
Accel

Accel

KEK

JLab damper

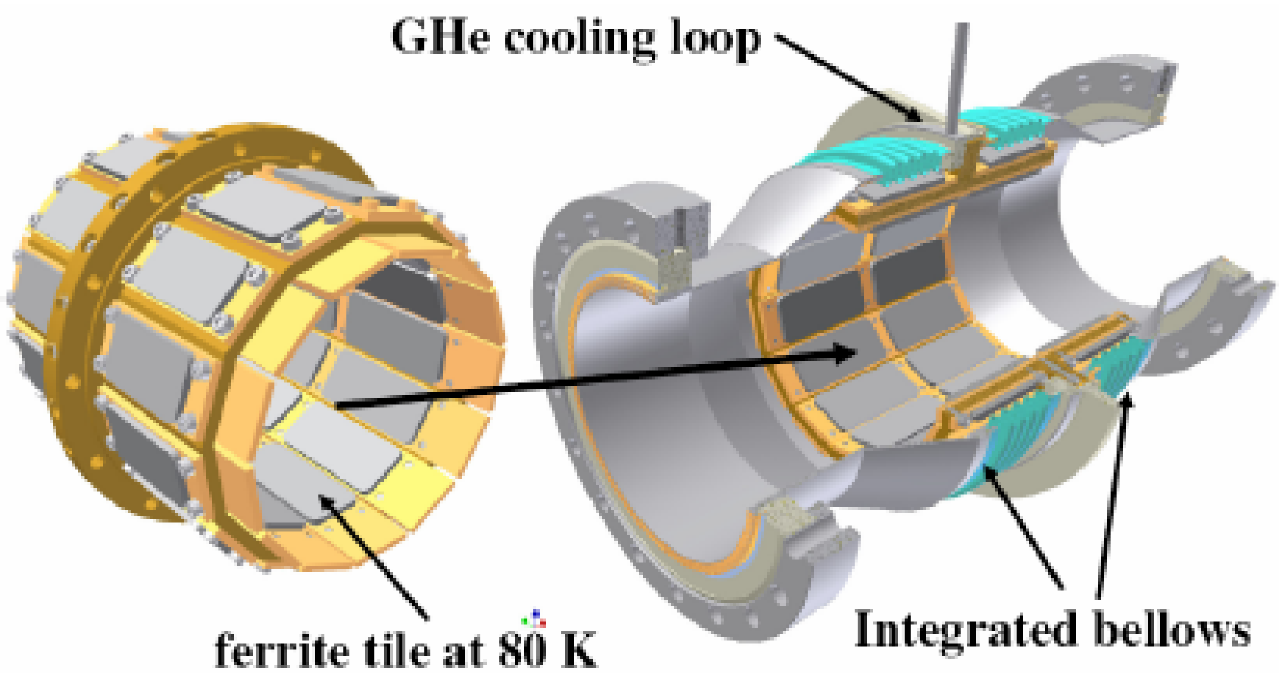




MAFIA model of broadband dielectric absorber

MWS design of the 4kW broadband HOM load

HOM damper working temperature



Summary

- Many labs have started high current development.
- But still have to do more test and improve.
- HOM damper is a challenge and important work for high currrent cavity.
- There are still many challenges for the development of high current cavity.

Thank you!

Reference

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