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Coupler, LOM and HOM Damping of Crab/Deflecting Cavity

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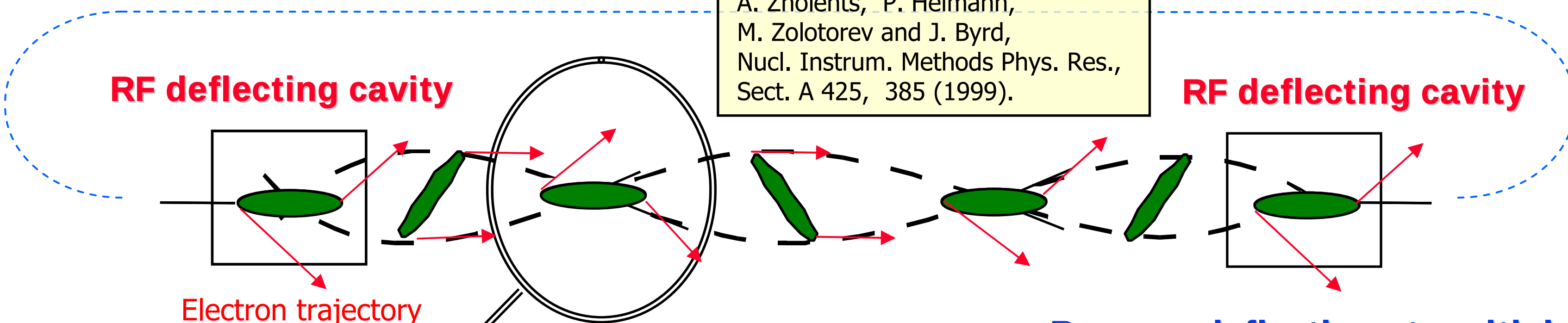
Introduction

- Deflecting RF cavity R&D at LBNL in collaboration with Tsinghua University (China), ANL and JLab
  - Using deflecting RF cavities to generate longitudinal and transverse correlation within an electron bunch
    - Berkeley LUX project
      - Multi-cell structure (one pass)
    - Possible upgrade of the ALS at LBNL
      - Single or multi-cell structure in storage ring
      - Polarization, LOM and HOM damping studies
      - Prototype cavity at Tsinghua University
    - SXP project at the APS, ANL
      - Similar requirement as for the ALS
      - Squashed SC single cell cavity (2.8 GHz)
    - Emittance exchange experiment at ANL
      - Polarization, but no damping (1.3 GHz NC cavity)
  - Design study results, techniques, fabrication and measurement experience directly applicable to crabbing cavities for LHC upgrade and ILC

X-ray Pulse Compression via Vertical Chirp

A. Zholents, P. Heimann, M. Zolotorev and J. Byrd, Nucl. Instrum. Methods Phys. Res., Sect. A 425, 385 (1999).

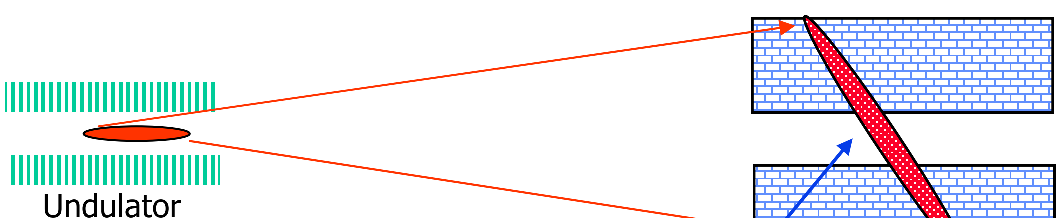


Cavity frequency is harmonic h of RF frequency

Remove deflection at multiple of betatron wavelength / 2

Extract short x-ray pulse via collimation or compress x-rays using asymmetric-cut crystal

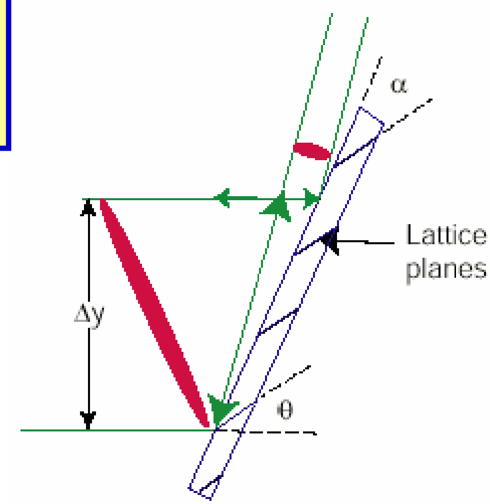
Radiation from tail electrons



Radiation from head electrons

Vertical collimator

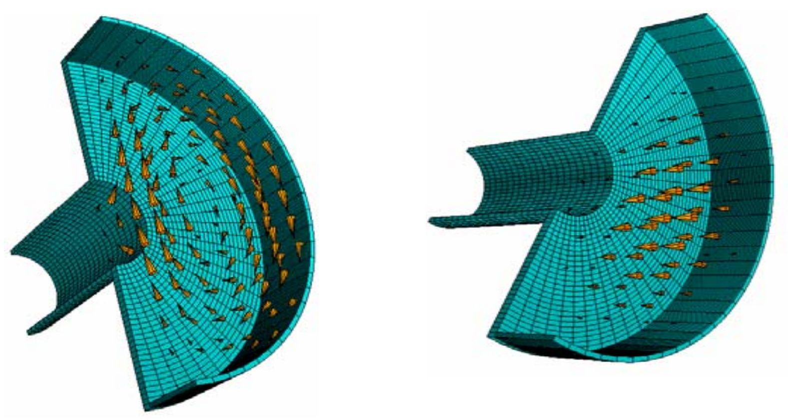
Input x-ray pulse >> diffraction limited size and natural beamsize



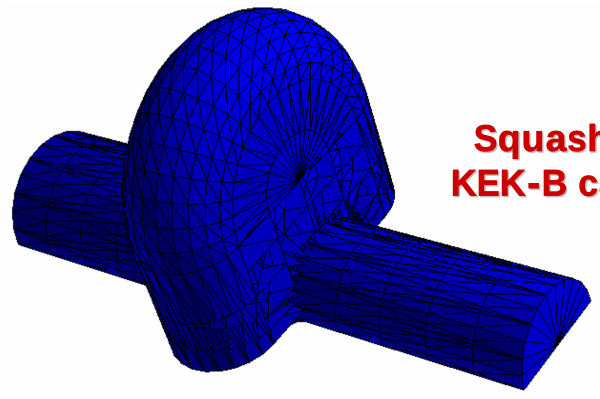
X-ray compression in asymmetric-cut crystals

Deflecting/Crabbing Mode

- Deflecting mode is not the fundamental mode
- Mode structure:
  - Single cell cavity: Lower Order Mode (LOM) and HOMs
  - Multi-cell cavity: Coupled LOM and HOM modes
- Two degenerate dipole modes for a cylindrical symmetric cavity
  - Separate the unwanted dipole mode by varying cavity shape [squashed]
  - Damp the unwanted dipole mode to an acceptable Q value



Single cell pillbox cavity with beam pipe



Squashed KEK-B cavity

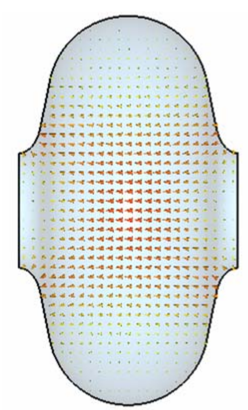
Base on KEK-B crab cavity, Cornell and Fermilab SC multi-cell deflecting RF cavities for Kaon Separation and ILC

Accelerating versus Dipole Cavity

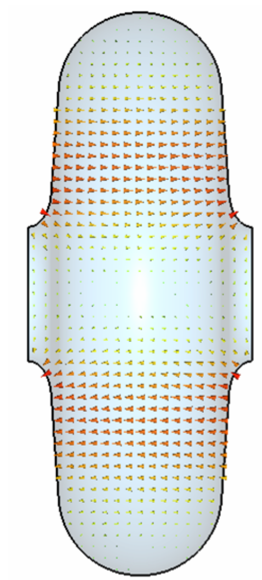
For the same resonant frequency at π- mode:

- accelerating cavity (TM_{010})
- deflecting/crabbing cavity (TM_{110} + TE_{111}):

both modes contribute to the transverse kick



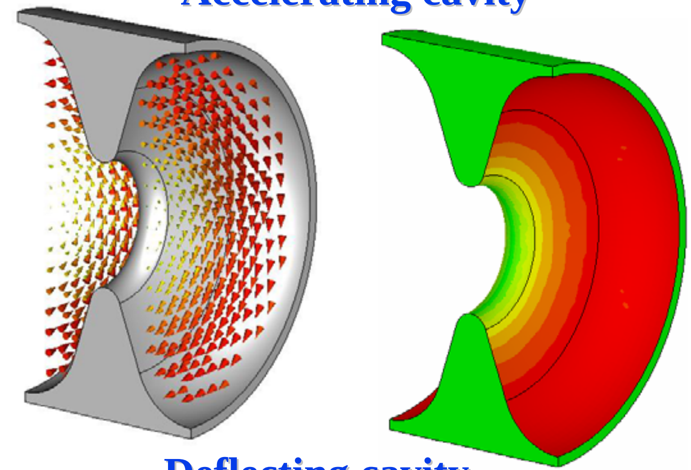
Accelerating cavity



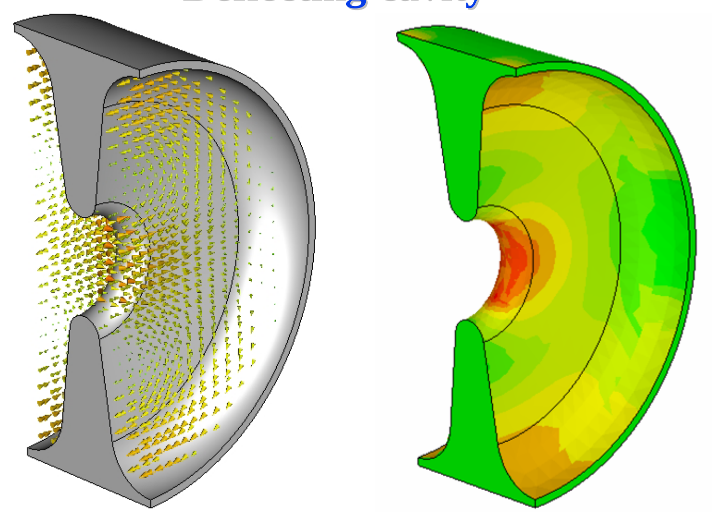
Deflecting cavity

Scaling of physical dimensions

Accelerating cavity



Deflecting cavity



Field distribution, maximum Magnetic field at different regions

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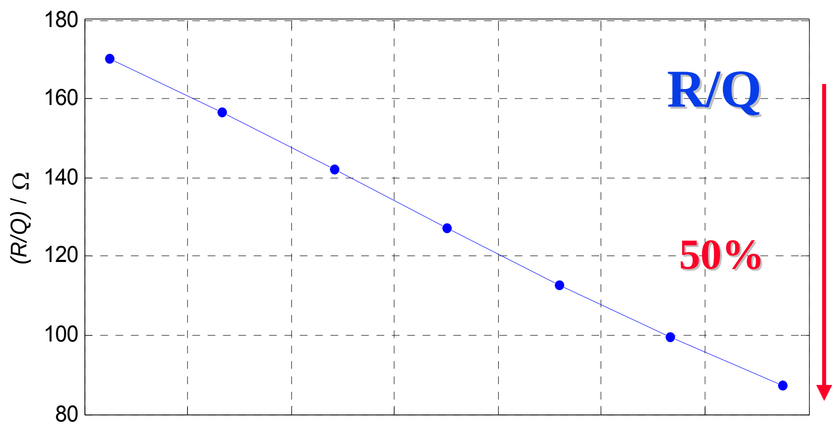
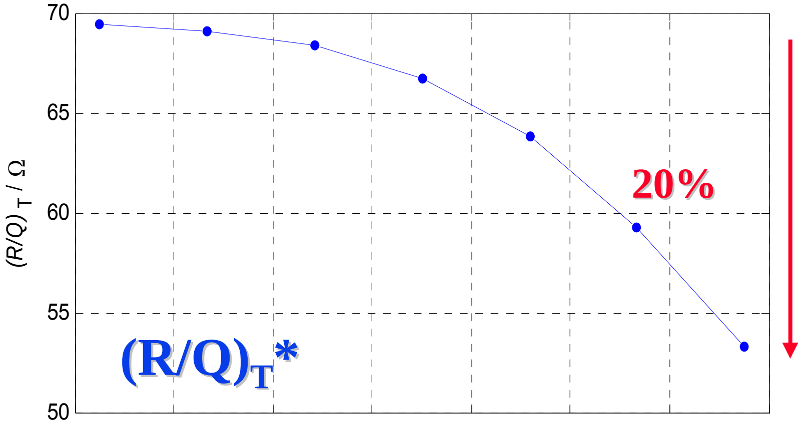
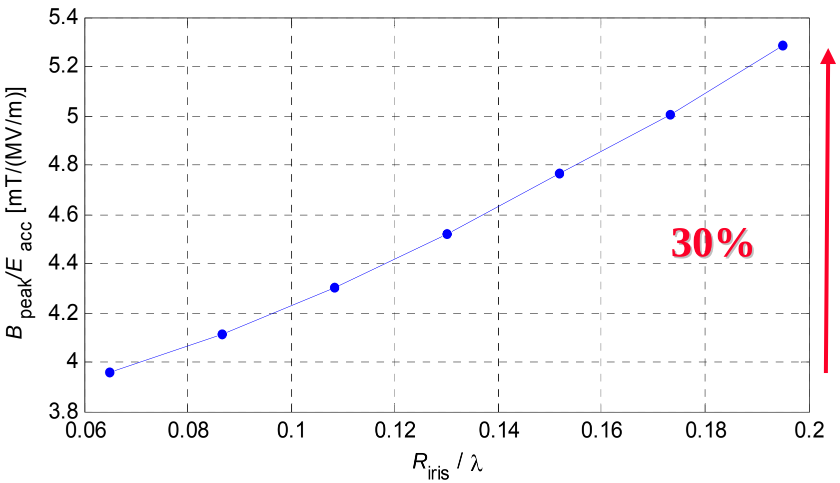
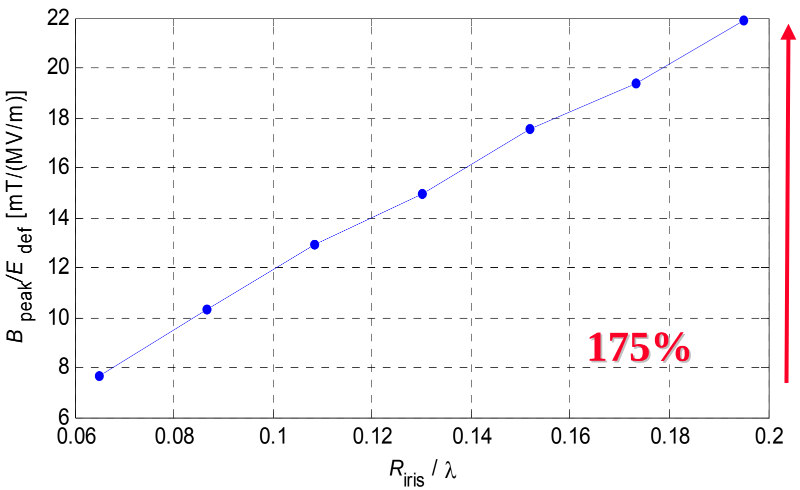
Optimization of the deflecting/crabbing cavity: Iris variation on R/Q and B_{peak}





B_{peak}[mT]/Gradient [MV/m]





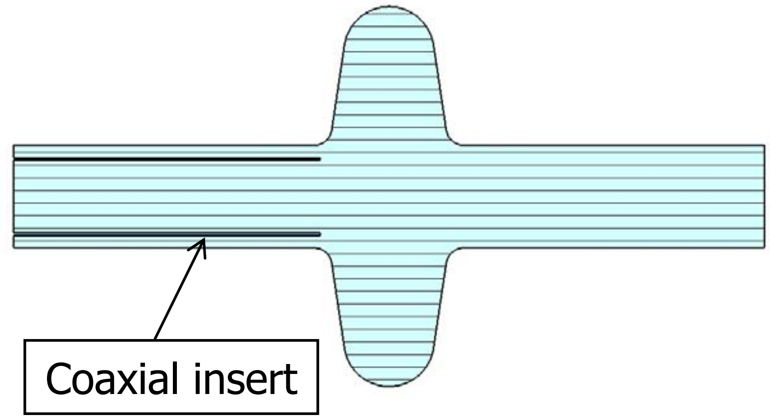
Accelerating Cavity | **Deflecting/crabbing Cavity**

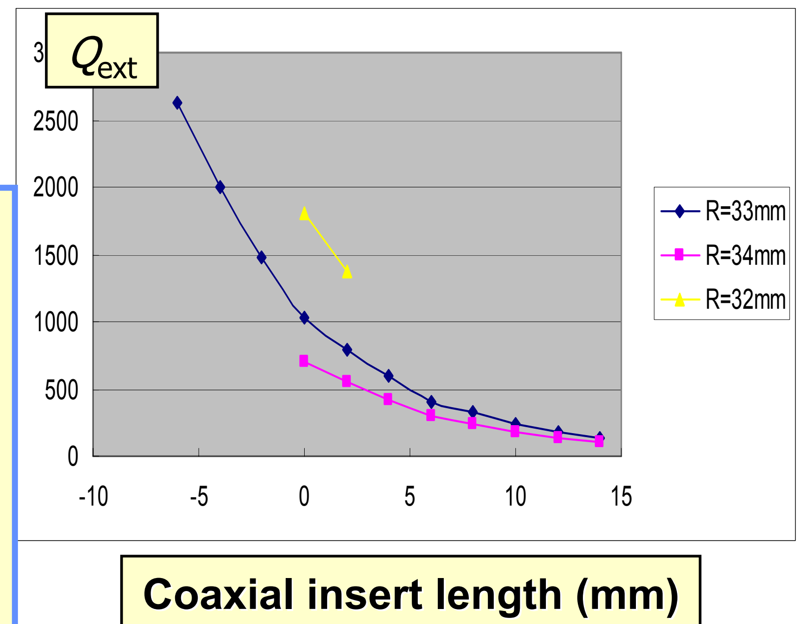
Single Cell Cavity Study

Damping of the LOM by coaxial insert is very effective (KEK design); studies were conducted for different beam pipe dimensions

- **Coaxial insert damping is very effective**
- **Unwanted dipole mode & its frequency being pushed away by geometry (squashed in one plane: KEK scheme)**

→ **Multi-cell cavity gives better packing factor**



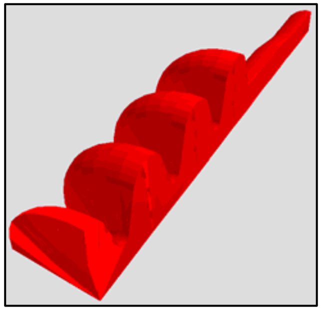


Single cell cavity study at 1.5 GHz

— Understand fundamentals
— Definitions
— Comparison with accelerating cavity
— Benchmark simulation techniques
— Damping
— Multipacting of the dipole mode (Z. Li)

Summary of the Deflecting Cavity Study for LUX

- **X-Ray pulse compression using the deflecting cavity for LUX**
  - **Studied 9-cell, 7-cell and 5-cell cavities at 1.3 and 3.9-GHz**
  - **7-cell cavity at 3.9-GHz was proposed**
    - NC and SC cavity options of the deflecting cavity
    - Impedance simulations for LOM and HOM
    - Possible damping schemes of LOM and HOM
    - Impedance requirements for LUX (2-GeV, 40-μA beam current)
      - **8.5 MV RF deflecting voltage needed at 3.9-GHz for 2-ps bunch**



- X-ray pulse compression using deflecting (crab) cavities to sub-pico-second bunches appears feasible for the 3rd generation light sources
  - Under study at Advanced Light Source (LBNL) and Advanced Photon Source (ANL)
- **Issues under study:**
  - Optics, dynamic aperture and emittance growth
  - RF amplitude and phase requirements and controls
  - X-ray pulse compression
  - **LOM and HOM-damped SC deflecting cavities**

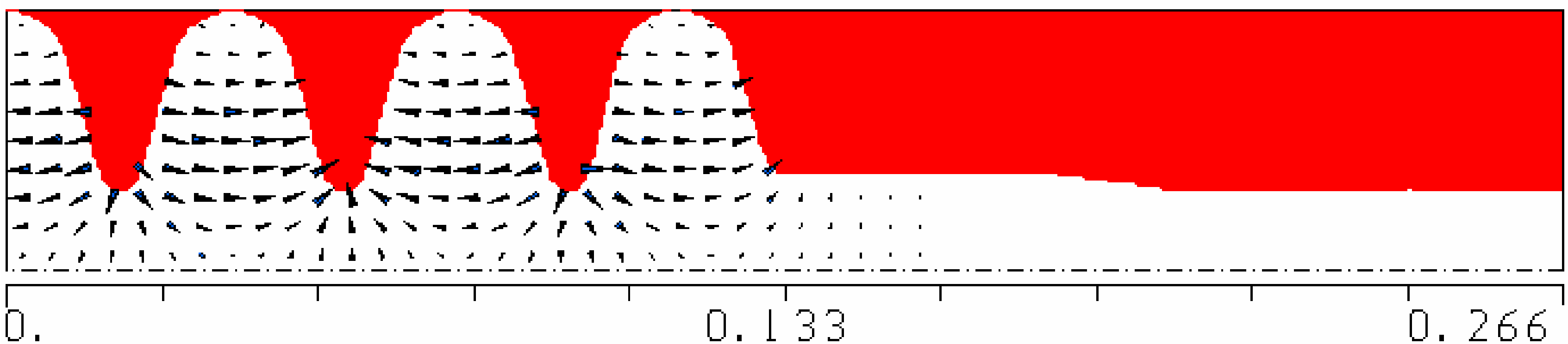
The 7-Cell Cavity Parameters

The Cavity Parameters

$(R/Q)_\perp$	350	Ω
Q_0	2×10^9	
Active length/cavity	26.92	cm
Deflecting gradient	5	MV/m
Transverse voltage/cavity	1.346	MV
Power dissipation at 2 K	2.6	Watts

Cavity frequency	3.9	GHz
Phase Advance per cell	180°	Degree
Cavity Equator Curvature	1.027	cm
Cavity Radius	4.795	cm
Cell length	3.846	cm
Iris Radius	1.500	cm
Beam pipe radius	1.500	cm
TM mode cut-off frequency	7.634	GHz
TE mode cut-off frequency	5.865	GHz

MAFIA simulations: electric field distribution of the deflecting (dipole) mode



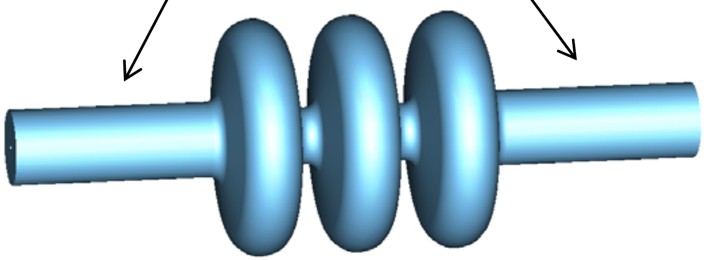
Seven 7-cell cavities required to produce 8.5 MV deflecting voltage

Deflecting Cavity for Light Sources

- **Multi-cell cavity studies for light source applications**
  - — Possible upgrade of the ALS at LBNL (1.5-GHz)
  - — SXP project of the APS at ANL (2.8-GHz)
- **Requirements**
  - — Wakefield and impedance
    - LOM damping
    - HOM damping
    - Unwanted polarization mode
  - — High beam current and high repetition rate
    - CW SC RF structure
  - — Tight available space
    - High gradient
  - — Amplitude and phase control
- **Design approaches**
  - — Cylindrical multi-cell cavity (easy fabrication)
  - — WGs to damp unwanted dipole mode
  - — WGs to damp both LOM and HOM
  - — Squashed cavity with WG damping
- **Study results applicable to LHC upgrade & ILC**

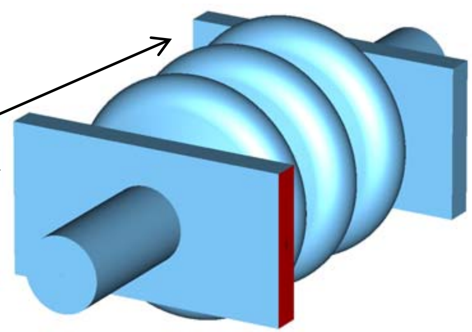
3-Cell Cavity with Damping

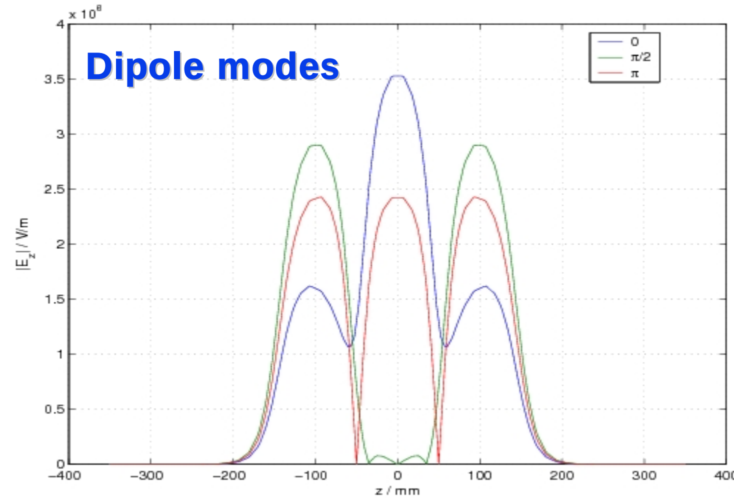
Coaxial insert (KEK design) to damp LOM, but not unwanted dipole mode (KEK squashed shape)

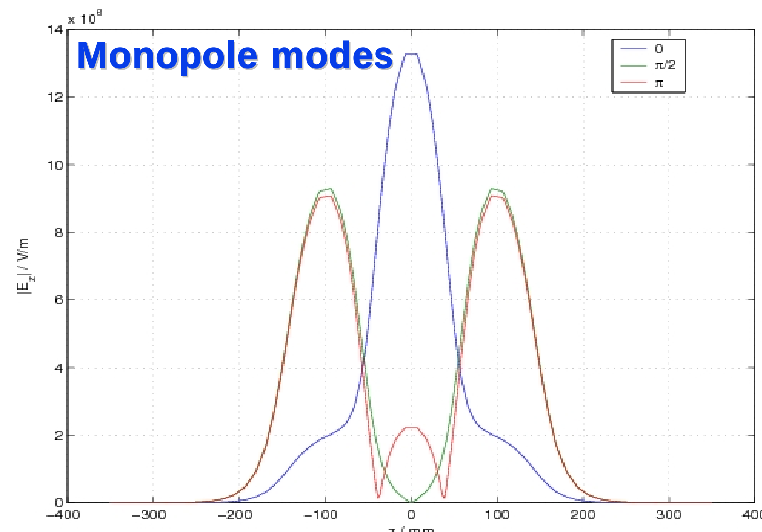


Mode	Frequency / GHz	Q_{ext}
0	1.0344	4.7E4
π /2	1.0503	1491
π	1.0508	1539

Waveguides to damp LOM, HOM and unwanted dipole mode







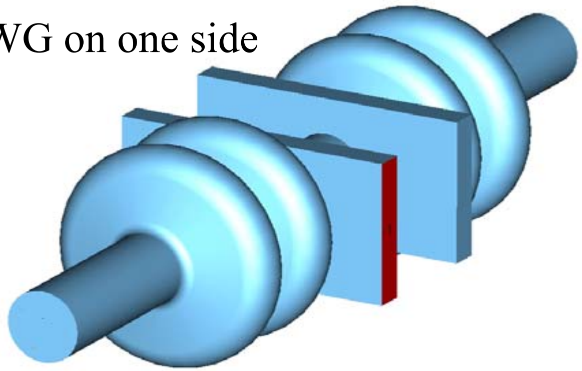
- Monopole 0 mode is trapped due to cavity symmetry
- Difficult to damp the trapped mode either by coaxial insert or waveguides

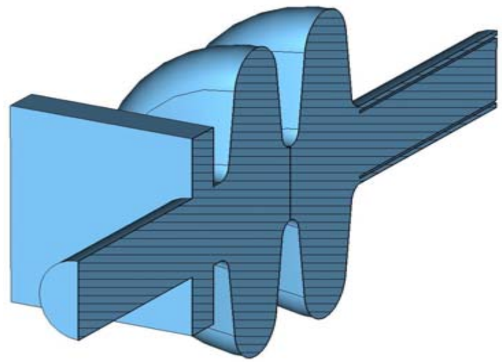
2-Cell Structure with Damping

Waveguide near beam iris to damp unwanted dipole mode (TM) directly

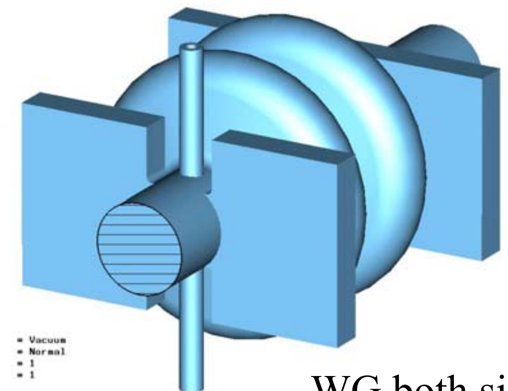
- Strong damping on unwanted dipole mode
- Modest damping to LOM, 0 mode

WG on one side





Hybrid



WG both sides

Monopole modes

Mode	Frequency / GHz	Q_{ext}
0	1.0505	7330
π	1.0554	

Unwanted dipo

Mode	Frequency / GHz	Q_{ext}
π	1.5012	1059
0	1.5112	706

Monopole modes

Mode	Frequency / GHz	Q_{ext}
0	1.0633	1694
	1.0711	1762

d dipole modes

Mode	Frequency / GHz	Q_{ext}
π	1.5016	1020
0	1.5240	526

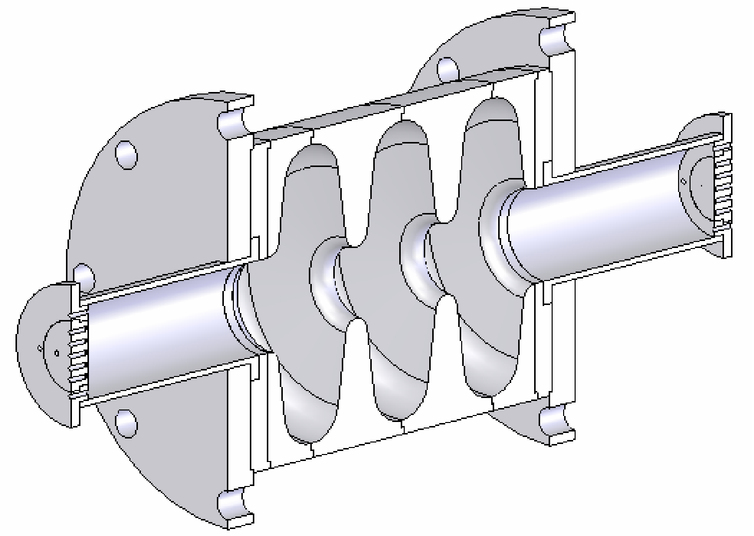
The waveguide also couples with the deflecting mode (TE_{20}), cut-off Frequency ~ 1.8-GHz → longer WG

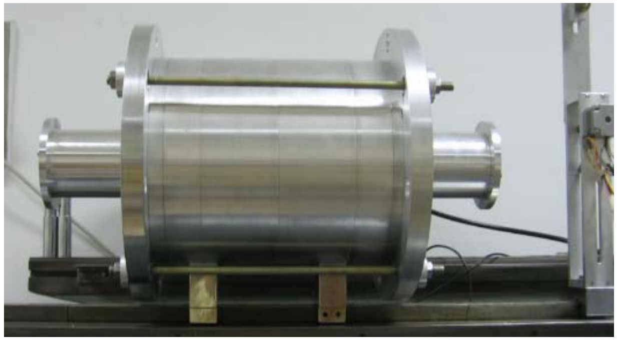
Aluminum Prototype Cavity

A 3-cell aluminum prototype cavity was built at Tsinghua University to benchmark simulation results and study LOM and HOM damping.

The cavity can be assembled to one-cell, two-cell and three-cell cavities, respectively.

— Good agreements have been achieved between CST Microwave Studio simulations and measurements





Simulations and Measurements

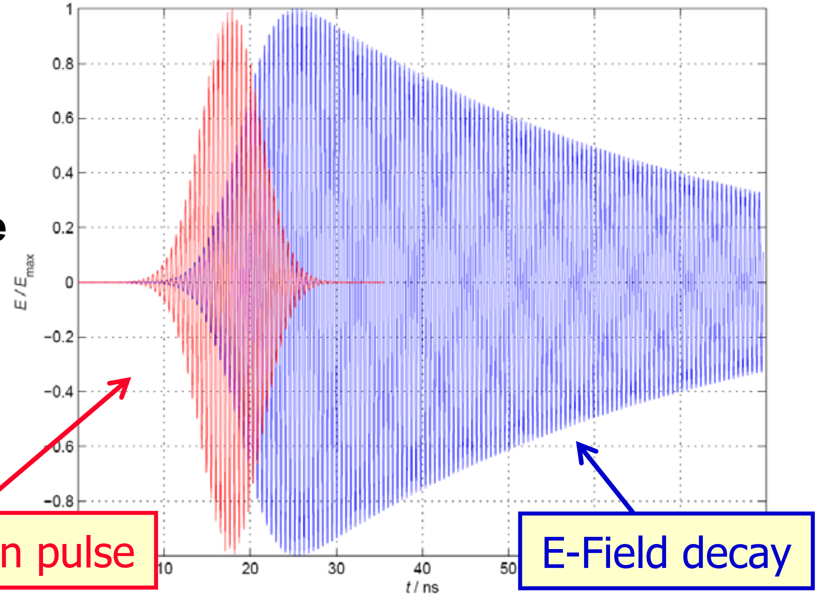
Low power microwave measurements on the Al 2-cell prototype cavity with WG damping at Tsinghua University: external *Q*
→ Very good agreement !

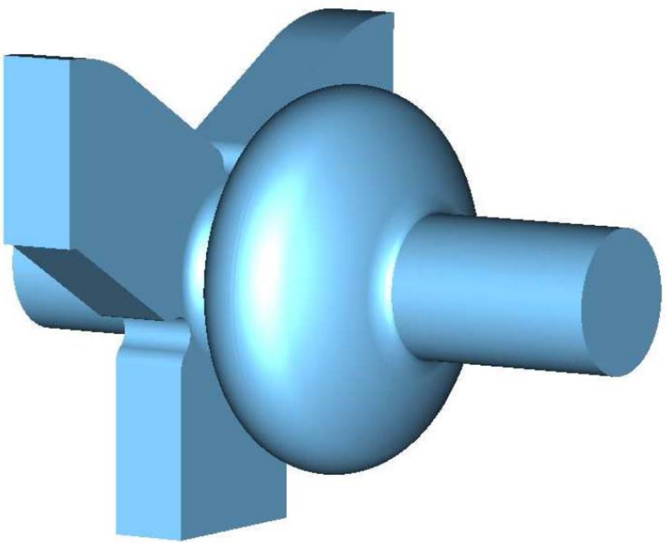
				Measurements on the Aluminum Protoype				CST Simulation	
				f / GHz	Q_0	Q_{load}	Q_{ext}	f / GHz	Q_{ext}
LOM	TM010	0		1.0400	10843	2030	2498	1.0400	2286
		π		1.0434	10787	1709	2031	1.0438	1686
Deflecting Mode	TM110	π	y	1.4962	11514	10983	--	1.4894	--
		0	y	1.5062	11903	12107	--	1.5013	--
Unwanted Dipole	TM110	π	x	1.4962	11233	673	716	1.4917	686
		0	x	1.5062	11547	844	911	1.5025	930
HOM	TE111	0	y	1.8607	7898	159	163	1.8539	174
		0	x	1.8607	7757	202	207	1.8465	196
		π	y	1.9369	6045	252	263	1.9278	260
		π	x	1.9369	6103	356	378	1.9243	338

Q_{ext} calculations in Time Domain

Method has also been benchmarked against measurements for a HOM damped cold test cavity at J-Lab

- MWS or MAFIA simulations in time domain
- Waveguide boundary conditions at ports
- Excite cavity from one RF (HOM) port or inside the cavity
- Record and observe field (energy) decay as a function of time inside the cavity
- External *Q* is computed from decay time



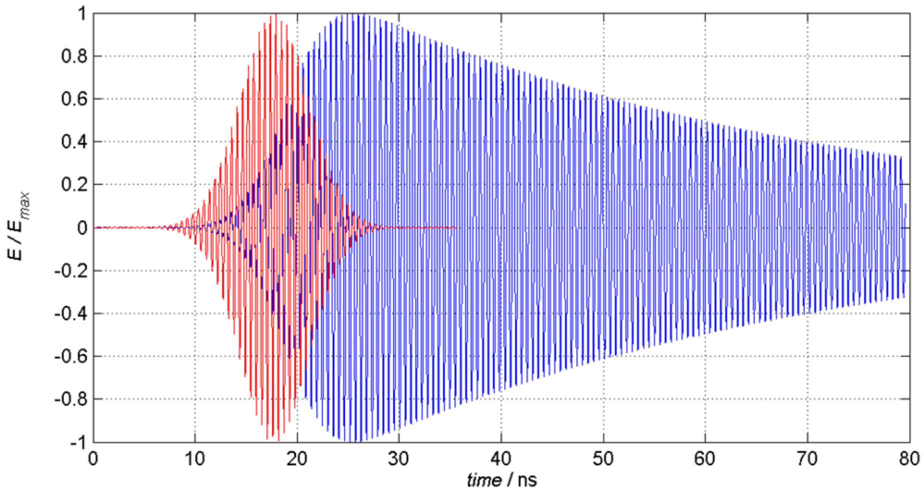


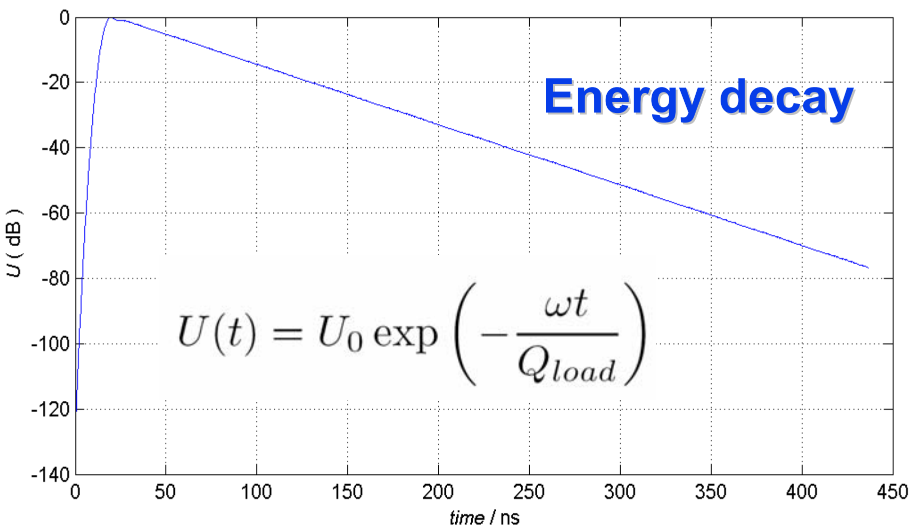
MWS model of J-Lab HOM damped SC cavity

MS Calculated		Measured	
f/GHz	Q_{load}	f/GHz	Q_{load}
1.84727	276	1.848006	317
1.84764	264	1.848252	227
2.03046	719	2.029628	996
2.03055	746	2.030226	667
2.43190	2750	2.426183	2878

Wakefield and Impedance

- External Q simulations

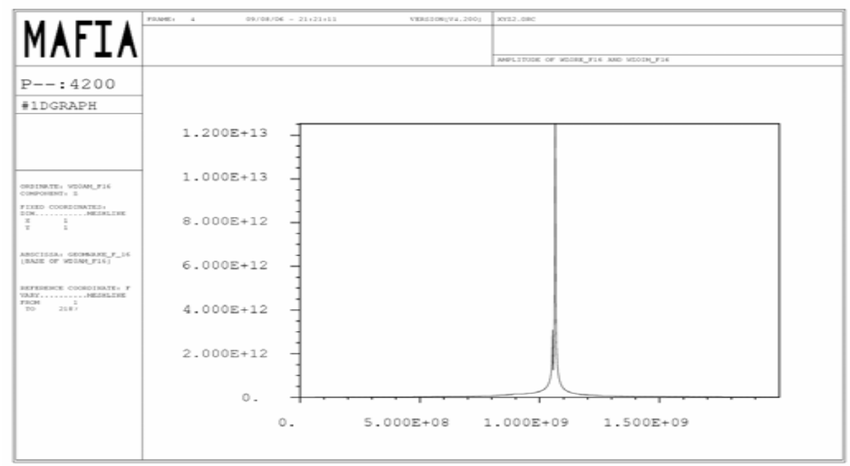




$$U(t) = U_0 \exp\left(-\frac{\omega t}{Q_{load}}\right)$$

- Impedance simulations

Wakefield



Impedance

Deflecting Cavity Study for APS

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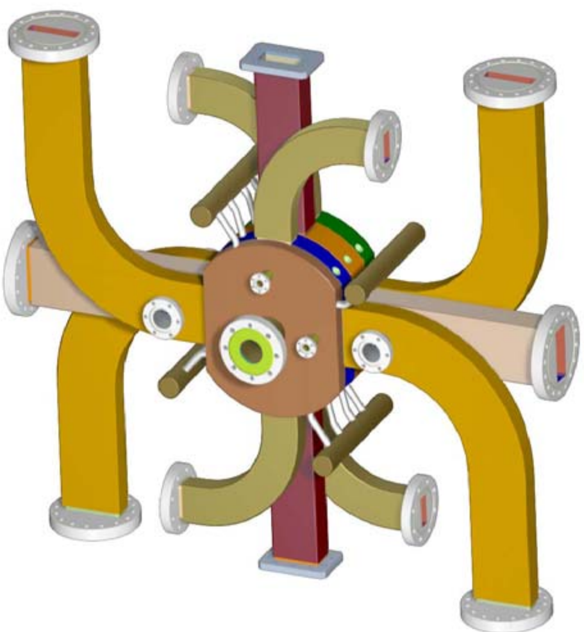
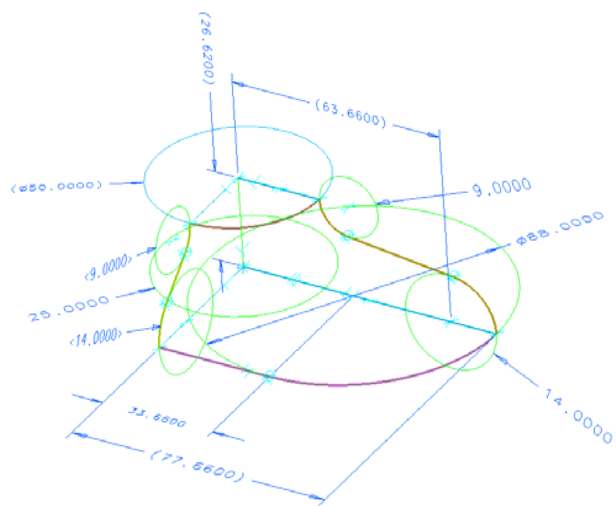
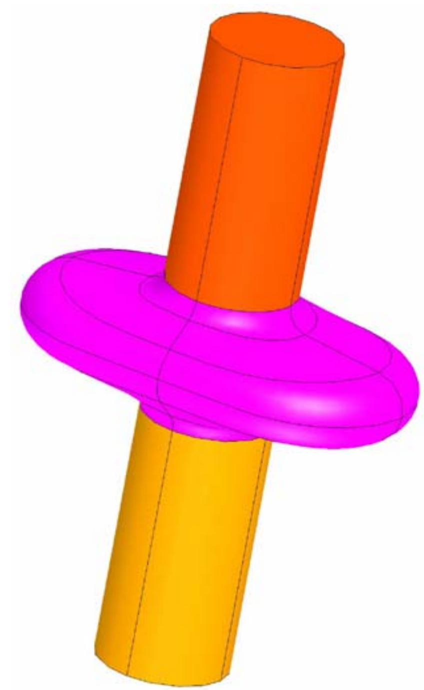
- **Collaboration with Tsinghua University, ANL, JLab and SLAC**
  - — Normal conducting multi-cell deflecting cavity with LOM and HOM damping (Ali's talk)
  - — Single cell SC deflecting cavity (Haipeng's talk)







Preliminary Damping Studies

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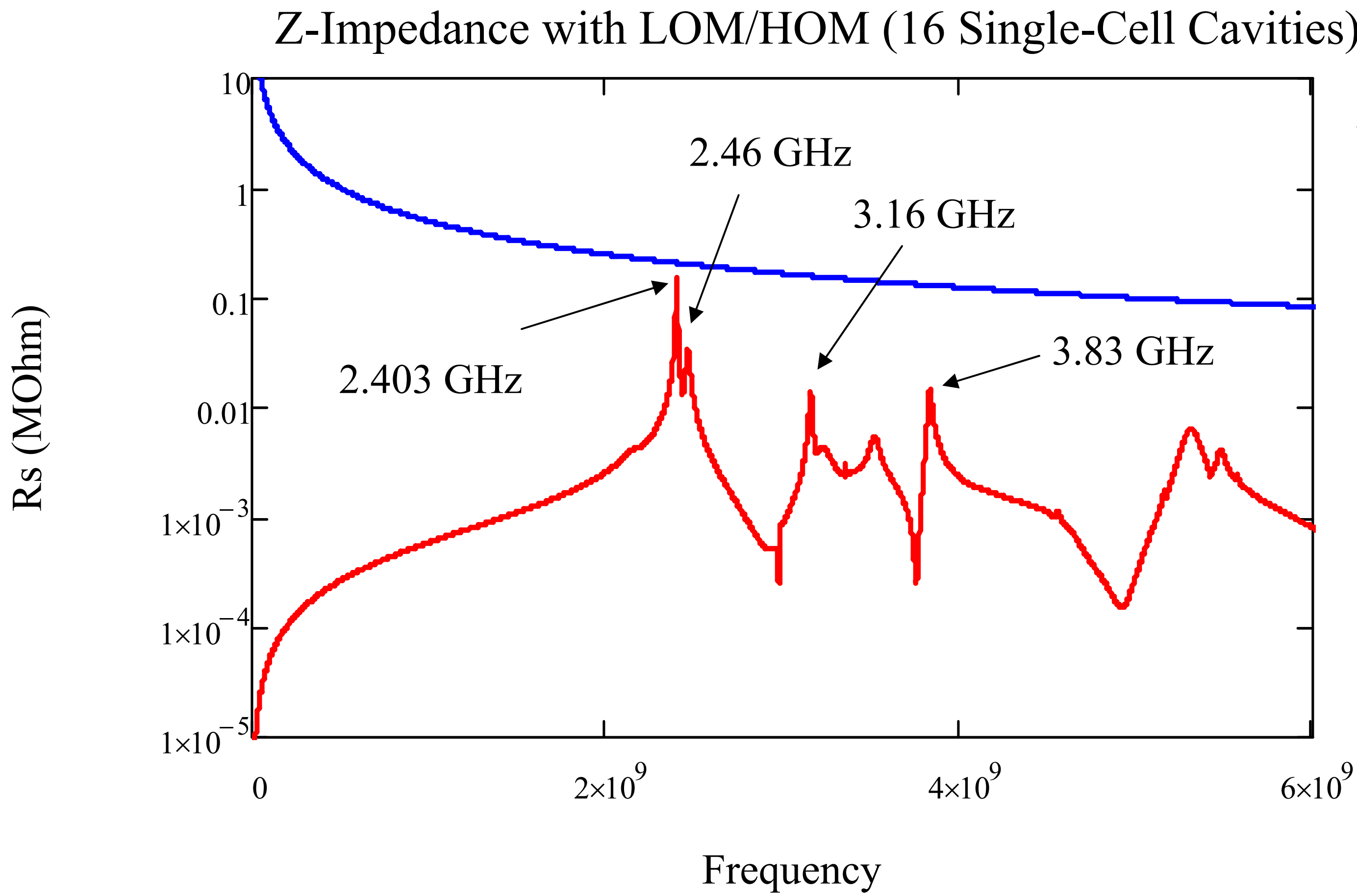
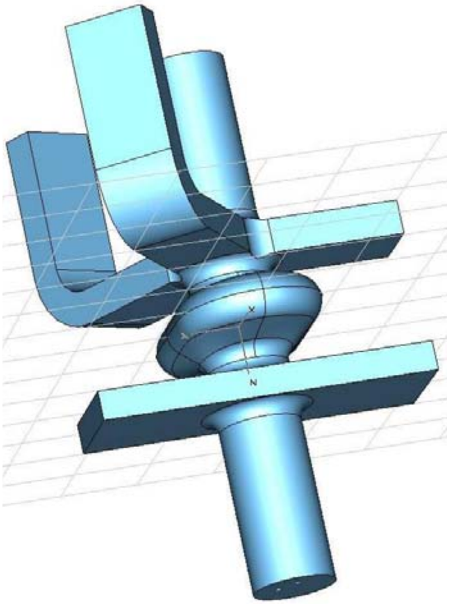


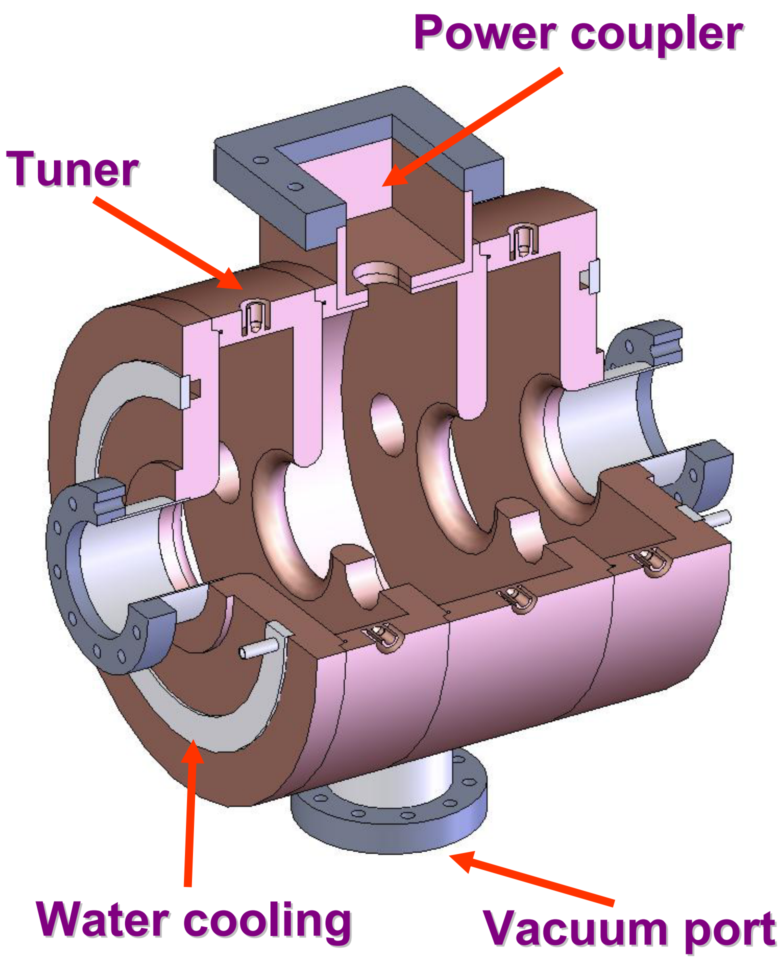
Squashed single cell cavity with Y-WG damping and power coupler

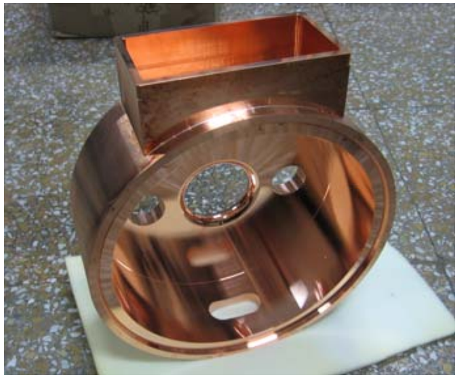


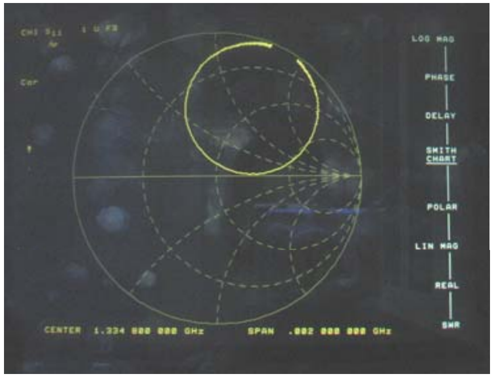
GdFidl wakefield results of the longitudinal impedance of LOM/HOM damper cavity assembly.

D-Cavity for Emittance Exchange Experiment at ANL

3-cell normal conducting cavity at 1.3 GHz: design and fabrication at Tsinghua University







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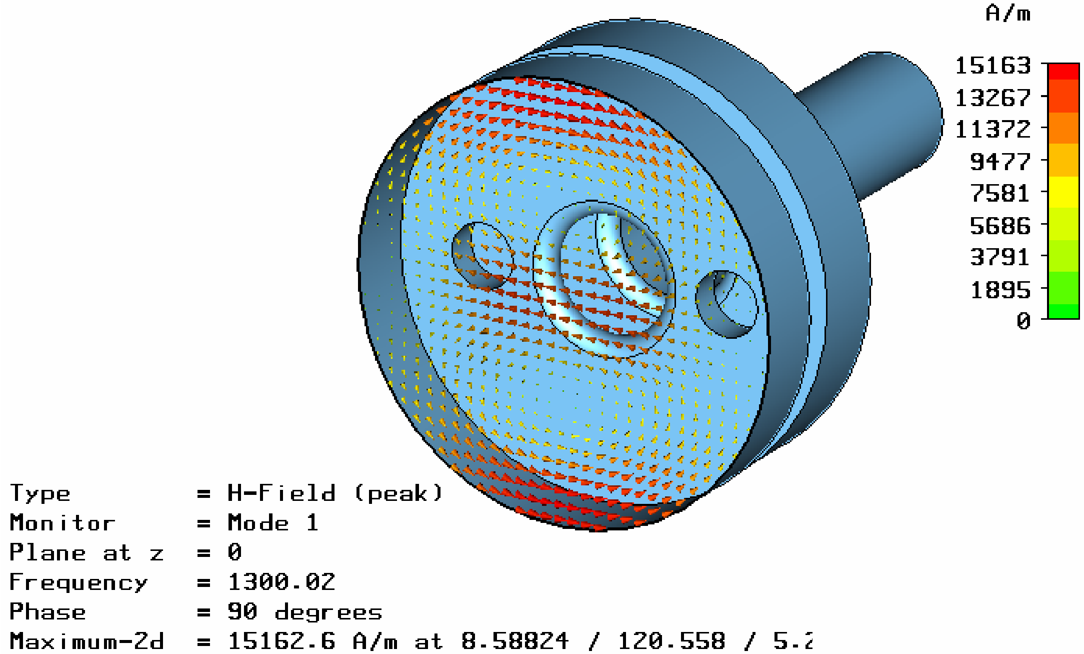
Mode Separation w/o Coupler

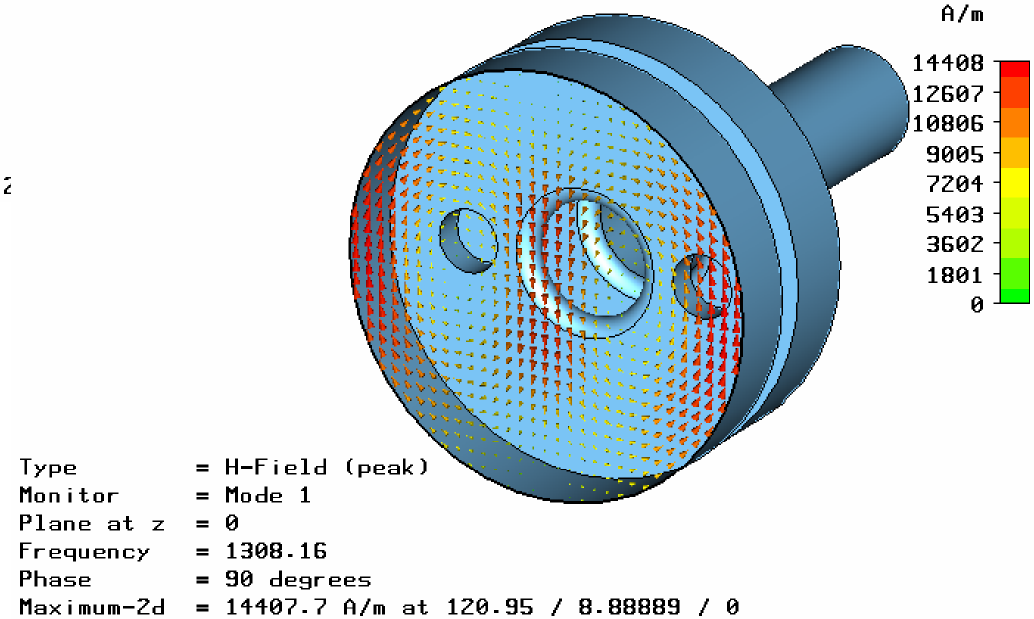


Power coupler is at critical coupling, the design was conducted by time domain simulations:
Coupling measurement and simulation agree within 20%

The dipole polarization is locked by introducing coupling irises

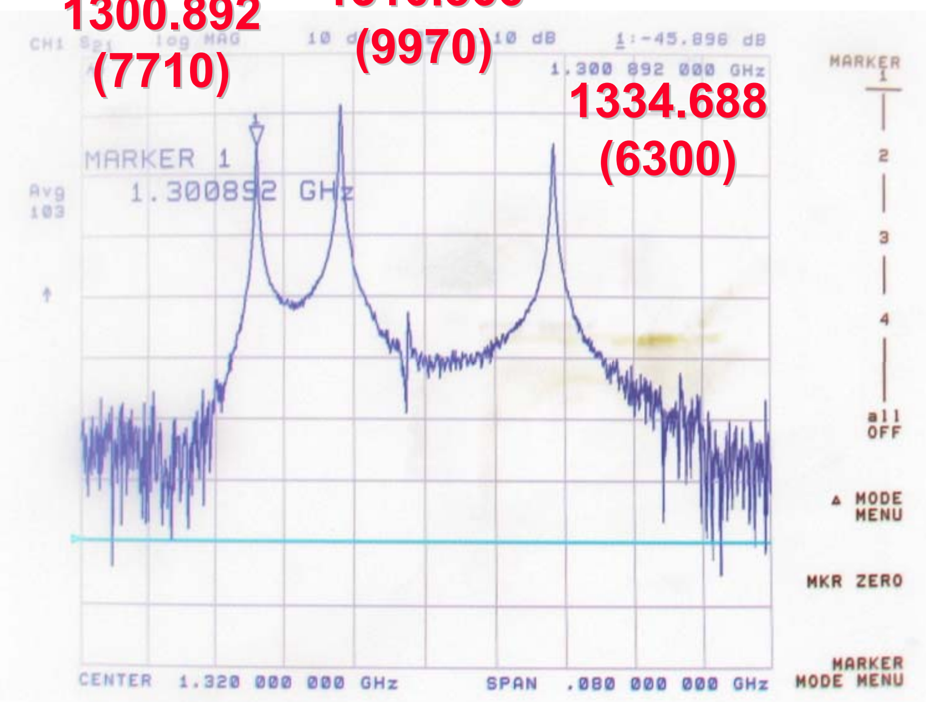
The frequency of the unwanted dipole mode was pushed up by
$\Delta f \sim 8$ MHz

No HOM damping

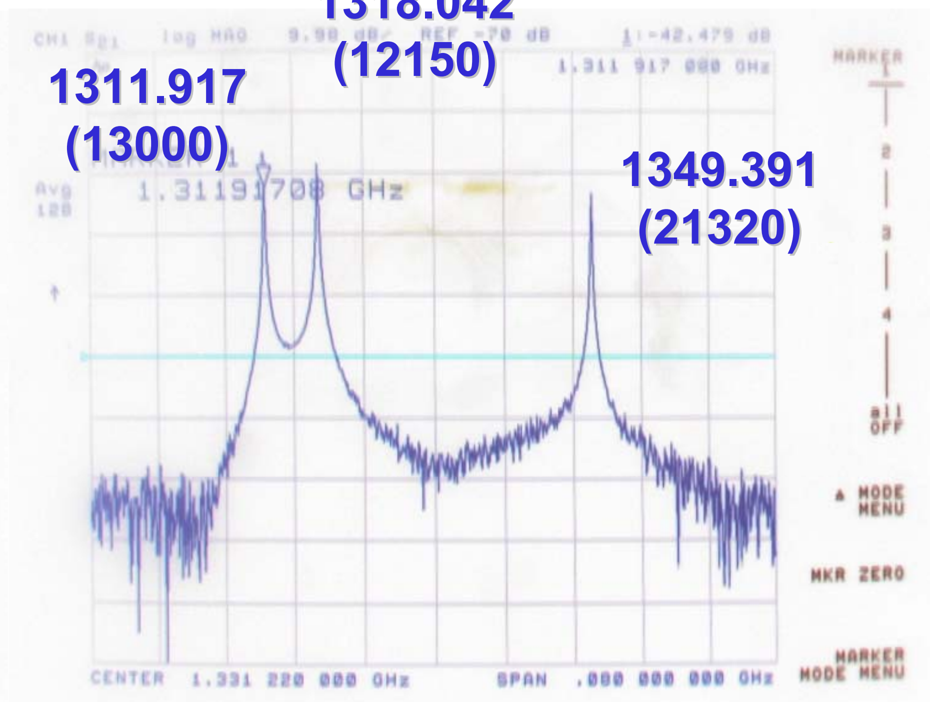


Measurements of Degenerate Modes

Low power microwave measurement after assembly of the power coupler: frequency (MHz) and Q_L

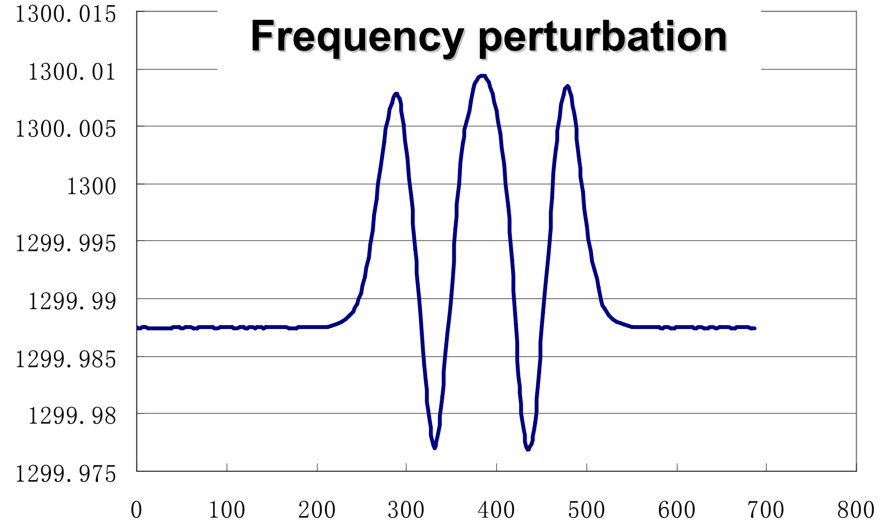


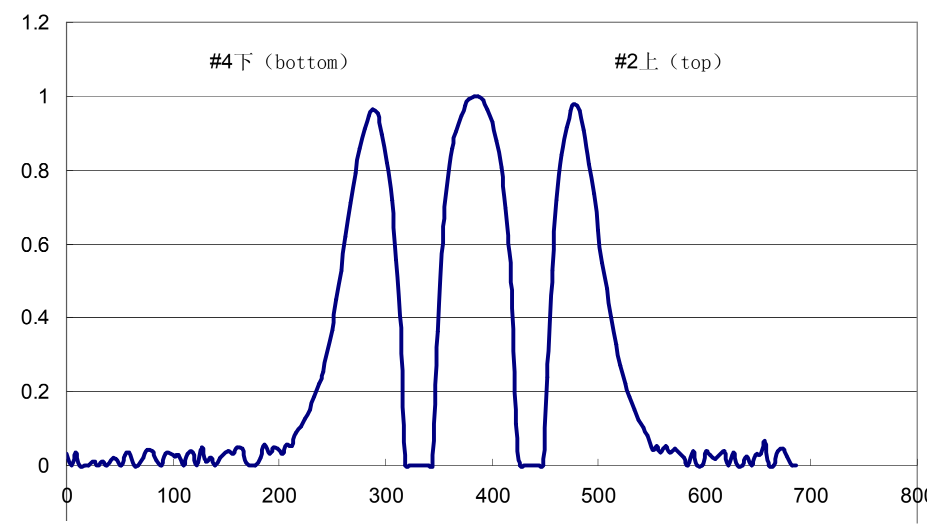
Deflecting Mode



Unwanted Dipole Mode

Field Measurement by Bead Pull





Field distribution of π mode $\propto \sqrt{\Delta f}$

Summary

- Deflecting/crabbing cavity studies
  - Multi-cell cavity for LUX or ILC
  - Single and multi-cell cavities for light sources or LHC upgrade
- Explored options for damping LOM, HOM and unwanted dipole modes by waveguides in multi-cell cavity with cylindrical symmetry
  - 3-cell cavity has trapped LOM mode and hard to damp
  - 2-cell is promising
    - Hybrid damping scheme
    - Waveguide damping scheme
    - Waveguide damping on beam pipe for LOM, HOM and unwanted dipole mode
  - Single cell works (KEK)
- SC squashed single cell cavity
  - Prototype
  - WG to damp LOM and HOM modes (ongoing)
- NC multi-cell cavity for emittance exchange experiment at ANL
- Preliminary studies indicate single or two-cell cavity designs may meet the LHC crabbing cavity requirements, but need to be further studied
- We are ready to do more studies and are willing to collaborate on the LHC-Crabbing Cavity upgrade
  - Iterations between beam dynamics and cavity studies are necessary to better define the LHC crabbing cavity scope

Deflecting Cavity for APS, ANL

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Instability Thresholds from Parasitic Mode Excitation (by Y.-C Chae)

APS parameters assumed: I = 100-mA; E = 7 GeV

α = 2.8x10^{-4}, $(\omega_s/2\pi)$ = 2 kHz, ν_s = 0.0073, β_x = 20 m

	Longitudinal	Transverse
Growth Rate, τ_g^{-1} (s^{-1})[1]	$\tau_g^{-1} = \frac{\alpha I_{tot}}{4\pi(E/e)\nu_s}\sum_p \omega_p \operatorname{Re} Z_z(\omega_p)$ $< \frac{\alpha I_{tot}}{2(E/e)\nu_s}(R_s \times f_p)$	$\tau_g^{-1} = \frac{\omega_0 I_{tot}}{4\pi(E/e)}\beta_\perp \sum_p \operatorname{Re} Z_t(\omega_p)$ $< \frac{\omega_0 I_{tot}}{4\pi(E/e)}\beta_\perp R_t$
Impedance[2] (Ω; Ω /m)	$Z_z(\omega) = \frac{R_s}{1 + jQ(\omega/\omega_r - \omega_r/\omega)}$	$Z_t(\omega) = \left(\frac{\omega_r}{\omega}\right)\frac{R_t}{1 + jQ(\omega/\omega_r - \omega_r/\omega)}$
Damping Rate, τ_d^{-1} (s^{-1})	212	106
Shunt Impedance[2]	$R_s = V^2/2P$	$R_t = (c/\omega_r)R_s/b^2$
Stability Condition: $\tau_g > \tau_d$	$R_s \times f_p < 0.8 M\Omega - GHz$	$R_t < 2.5 M\Omega / m$

[1] A. Mosnier , Proc 1999 PAC.

[2] L. Palumbo, V.G. Vaccaro , M. Zobov , LNF -94/041 (P) (1994; also CERN 95 - 06, 331 (1995).