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Coupler, LOM and HOM Damping of Crab/Deflecting Cavity

Derun Li
Center for Beam Physics

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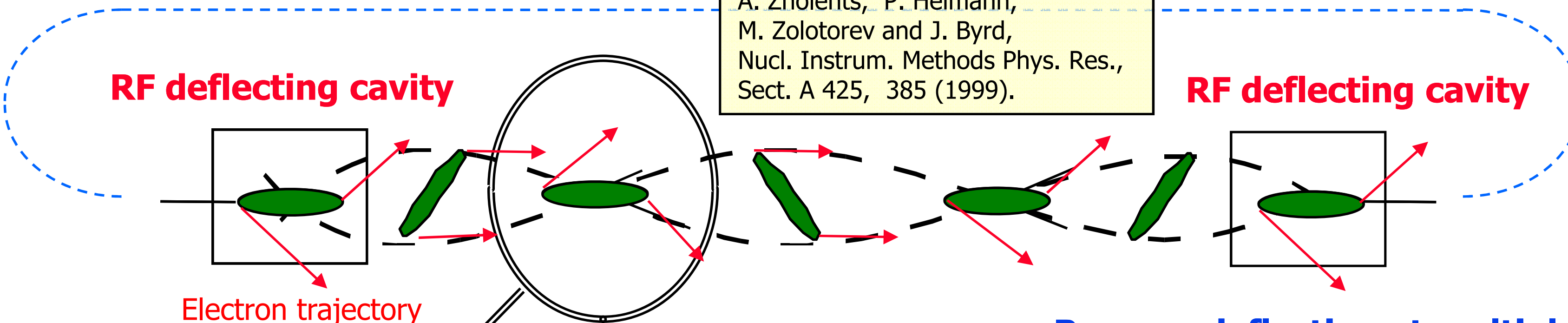
Introduction

- **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

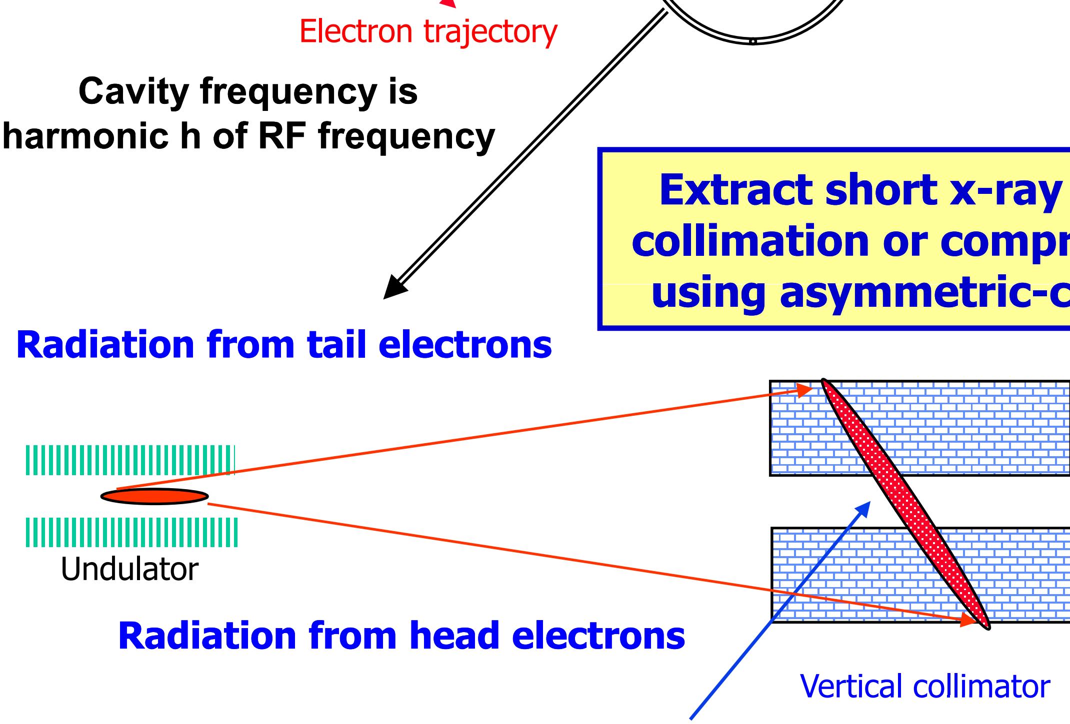
A. Zholents, P. Heimann,
M. Zolotorev and J. Byrd,
Nucl. Instrum. Methods Phys. Res.,
Sect. A 425, 385 (1999).

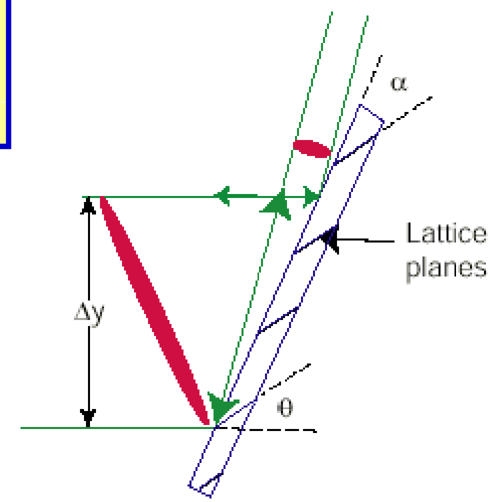


Cavity frequency is harmonic h of RF frequency

Remove deflection at multiple of betatron wavelength/2

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



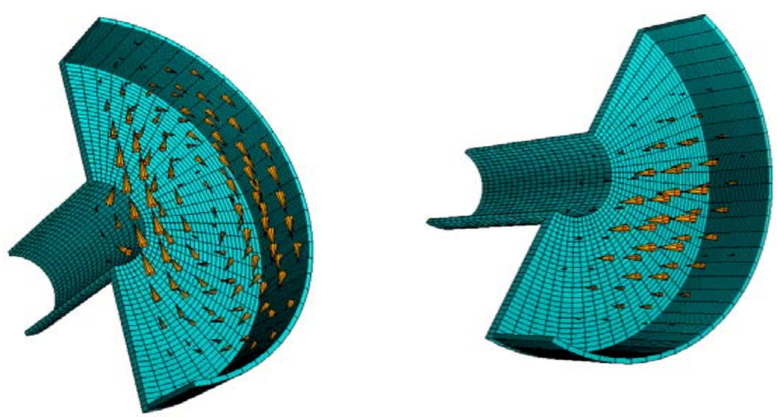


Input x-ray pulse >> diffraction limited size and natural beamsize

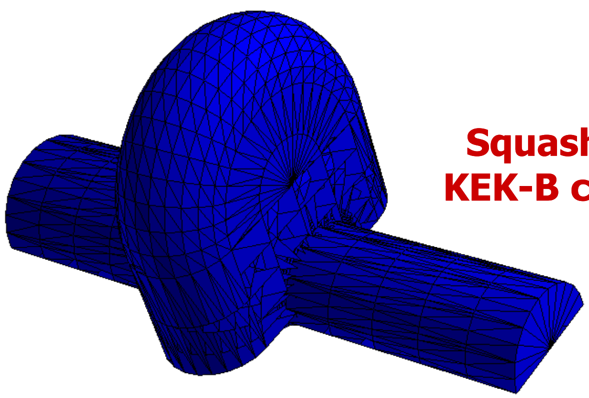
X-ray compression in asymmetric-cut crystals

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

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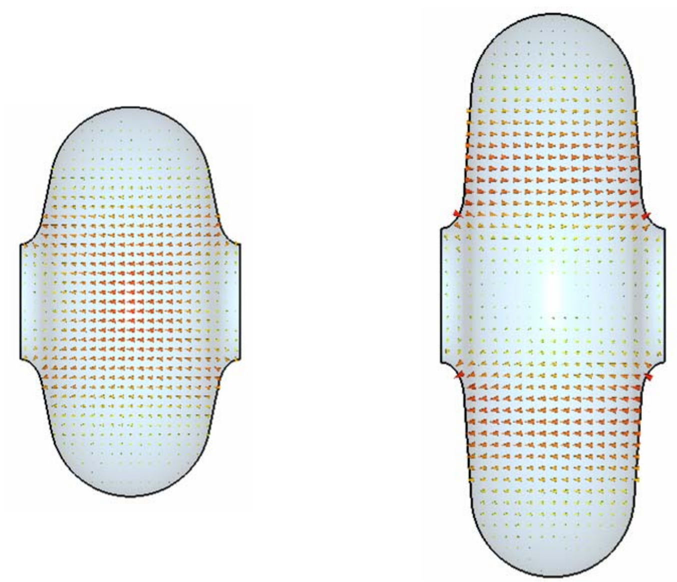
Accelerating versus Dipole Cavity

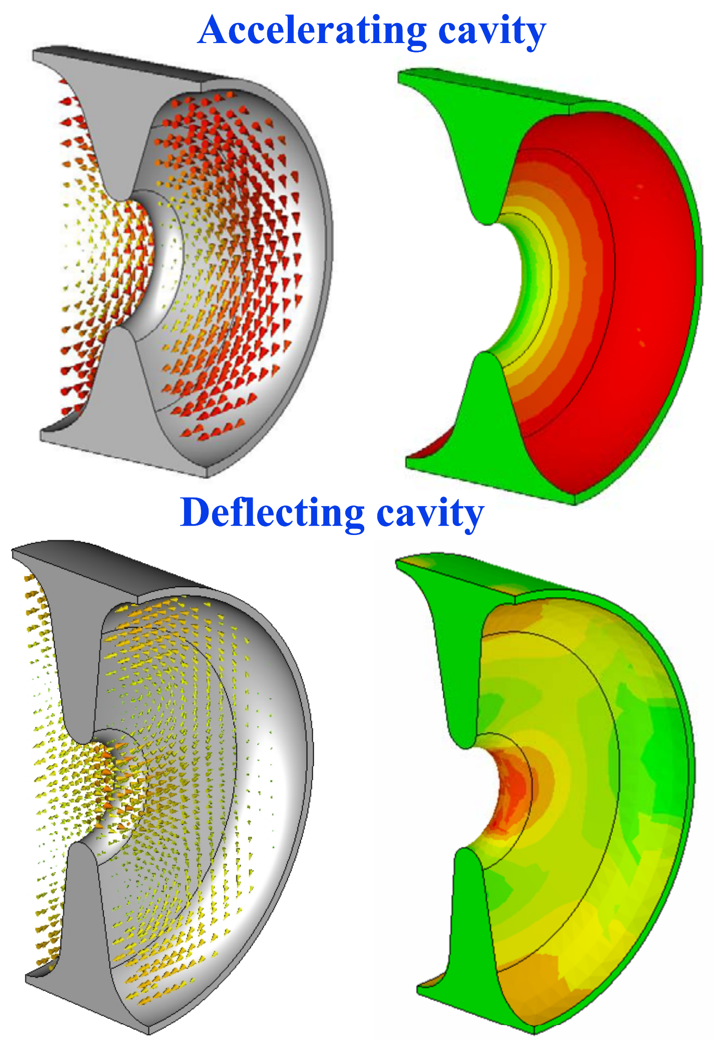
For the same resonant frequency at π- mode:
- **accelerating cavity (TM_{010})**
- **deflecting/crabbing cavity (TM_{110} + TE_{111}):**

both modes contribute to the transverse kick



Accelerating cavity Deflecting cavity

Scaling of physical dimensions



Field distribution, maximum Magnetic field at different regions

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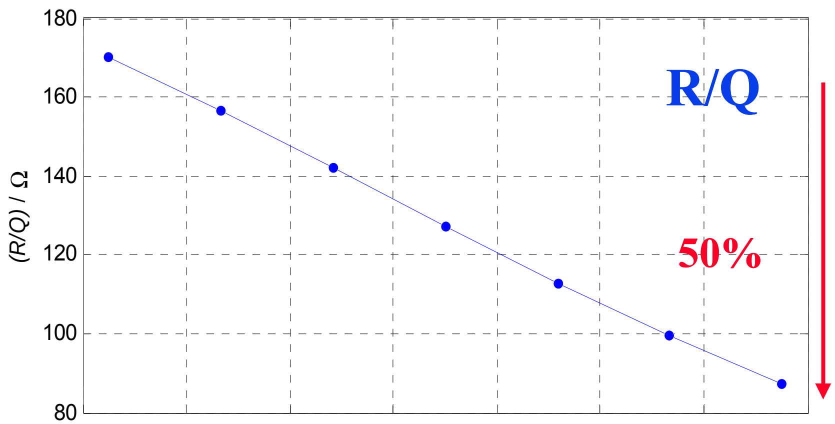
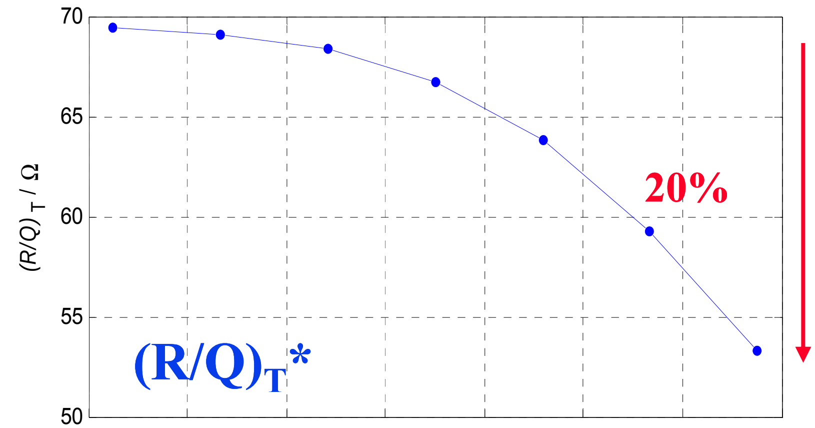
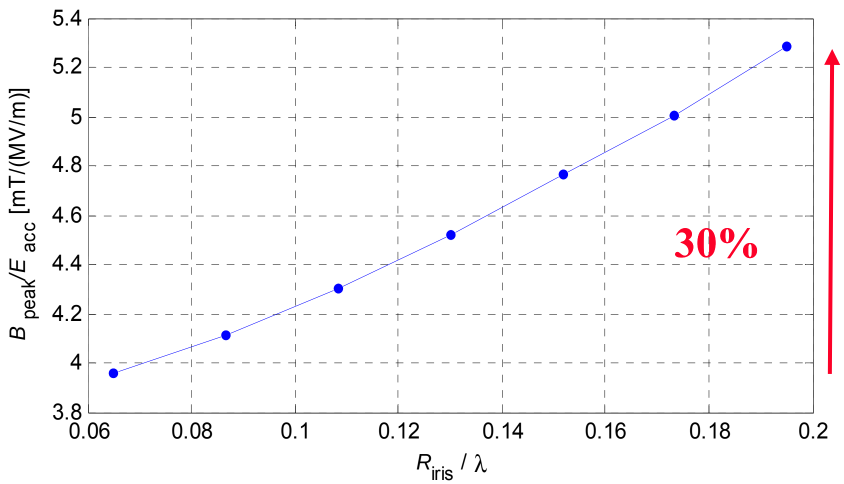
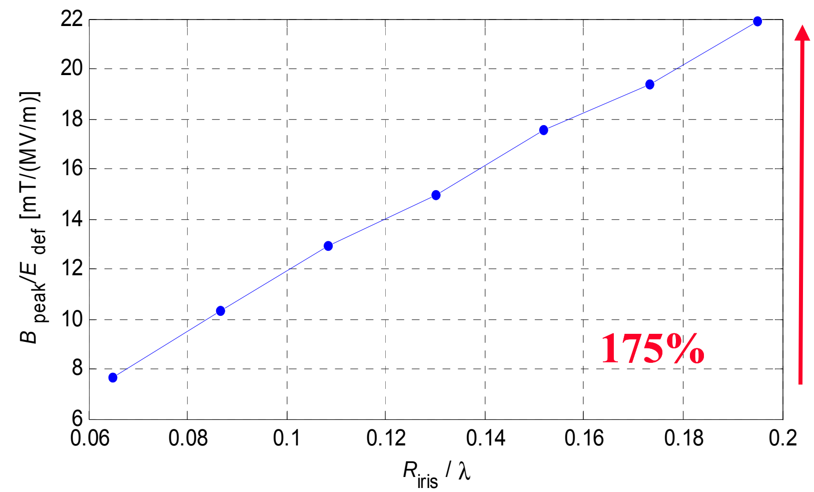
Optimization of the deflecting/crabbing cavity: Iris variation on R/Q and B_{peak}





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





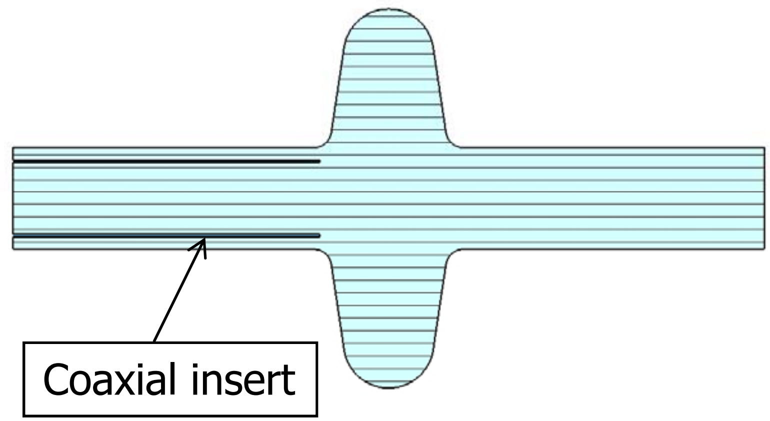
Accelerating Cavity **Deflecting/crabbing Cavity**

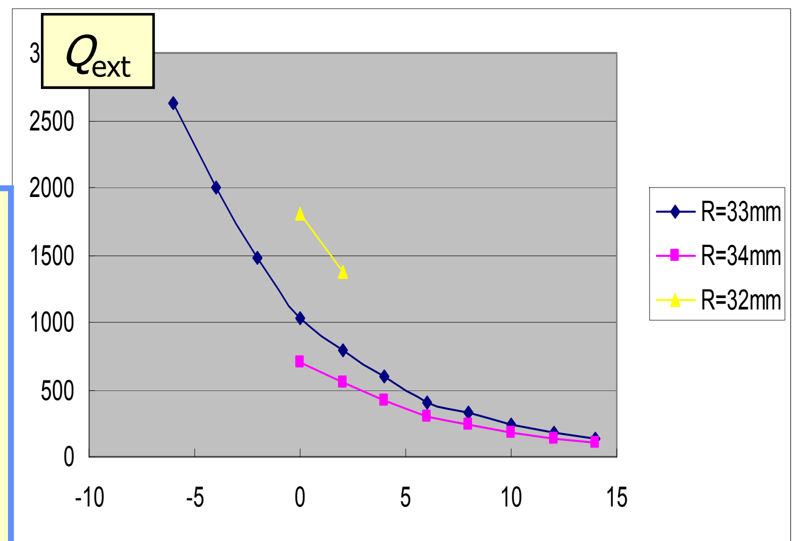
Single Cell Cavity Study

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





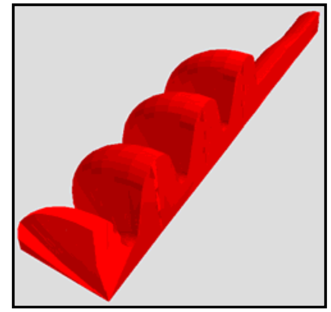
Coaxial insert length (mm)

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**

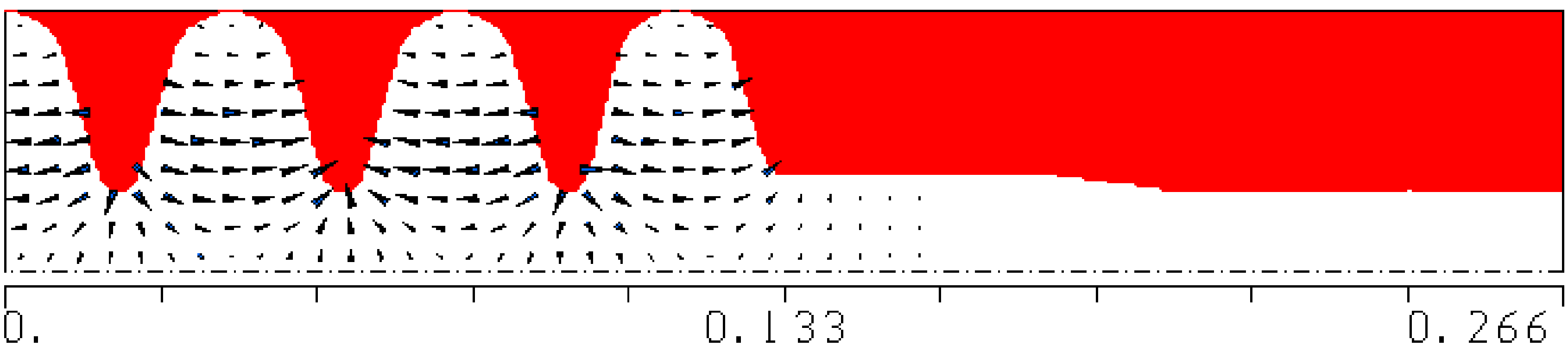
The 7-Cell Cavity Parameters

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^o	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



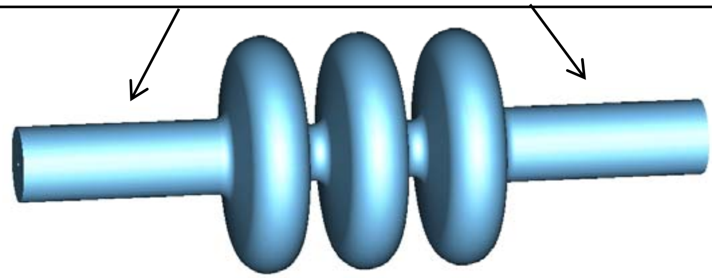
Seven 7-cell cavities required to produce 8.5 MV deflecting voltage

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**

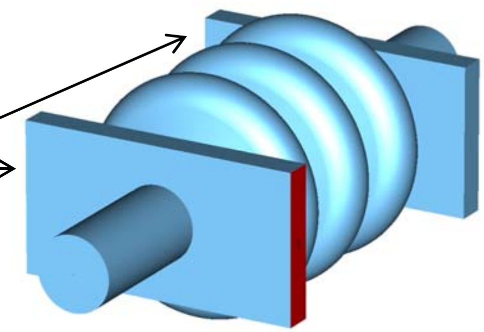
3-Cell Cavity with Damping

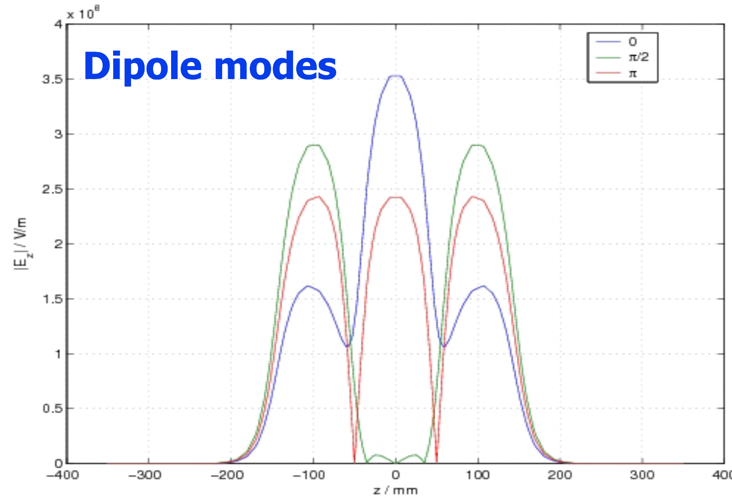
Coaxial insert (KEK design) to damp LOM, but not unwanted dipole mode (KEK squashed shape)

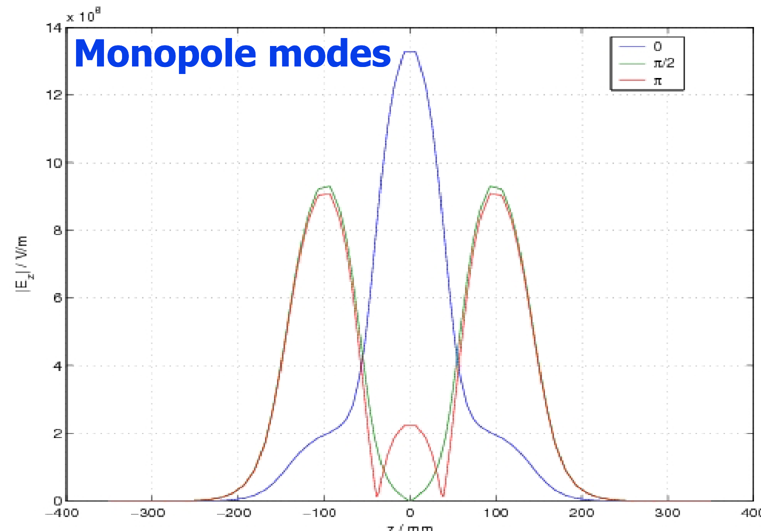


Mode	Frequency / GHz	Q_{ext}
0	1.0344	4.7E4
π/2	1.0503	1491
π	1.0508	1539

Waveguides to damp LOM, HOM and unwanted dipole mode







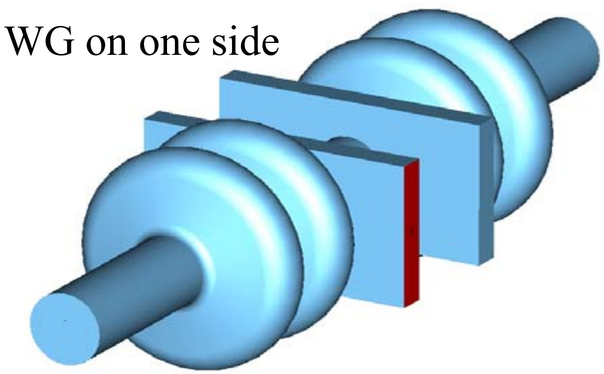
- Monopole 0 mode is trapped due to cavity symmetry
- Difficult to damp the trapped mode either by coaxial insert or waveguides

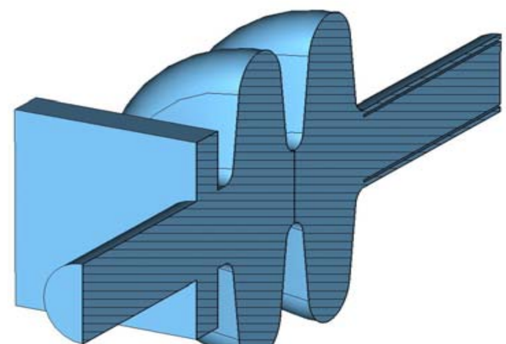
2-Cell Structure with Damping

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

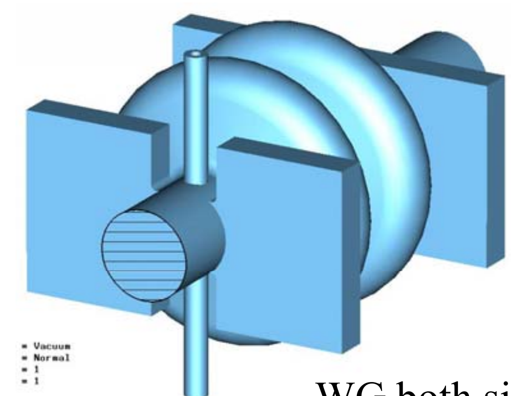
- **Strong damping on unwanted dipole mode**
- **Modest damping to LOM, 0 mode**

WG on one side





Hybrid



WG both sides

Monopole modes

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

Unwanted dipol[illegible]

Mode	Frequency / G[illegible]	Q_{ext}
π	1.5012	1059
0	1.5112	706

Monopole modes

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

[illegible]d dipole modes

[illegible]	[illegible]quency / GHz	Q_{ext}
π	1.5016	1020
0	1.5240	526

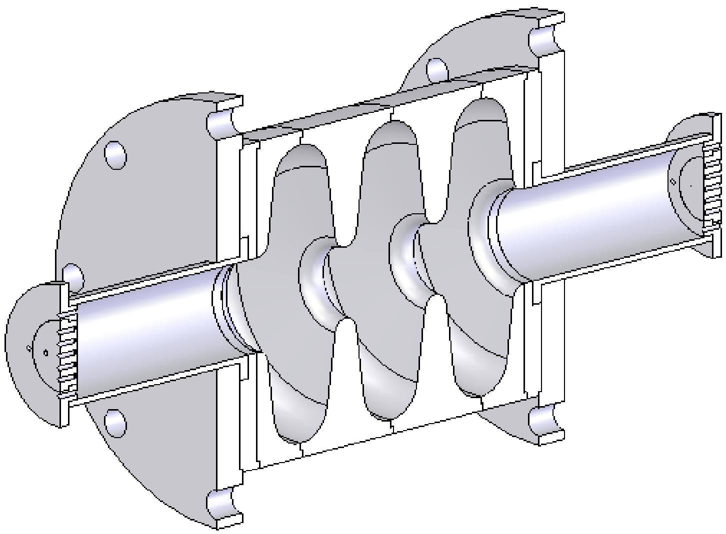
The waveguide also couples with the deflecting mode (TE_{20}), cut-off Frequency ~ 1.8-GHz → longer WG

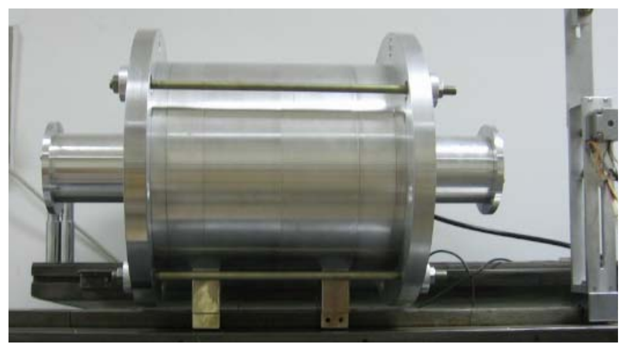
Aluminum Prototype Cavity

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

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

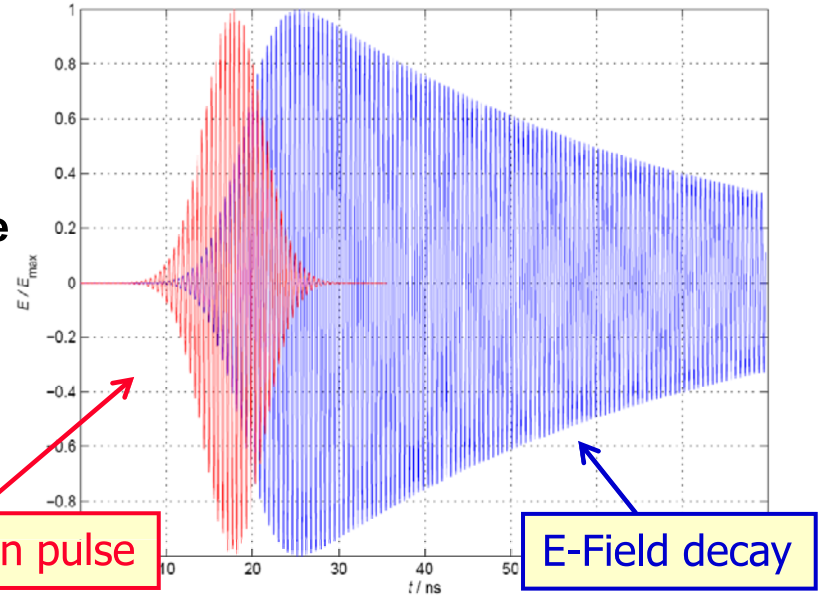
→ Very good agreement !

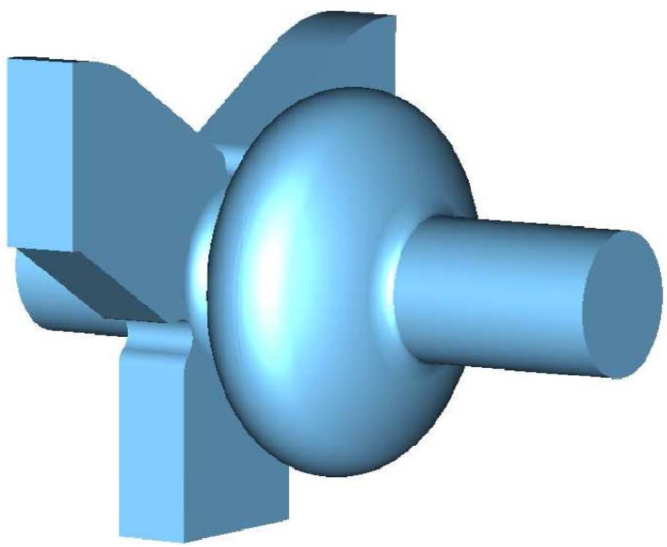
				Measurements on the Aluminum Protoype				CST Simulation	
				f / GHz	Q_0	Q_{load}	Q_{ext}	*f* / GHz	Q_{ext}
LOM	TM010	0		1.0400	10843	2030	2498	1.0400	2286
		π		1.0434	10787	1709	2031	1.0438	1686
Deflecting Mode	TM110	π	*y*	1.4962	11514	10983	--	1.4894	--
		0	*y*	1.5062	11903	12107	--	1.5013	--
Unwanted 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



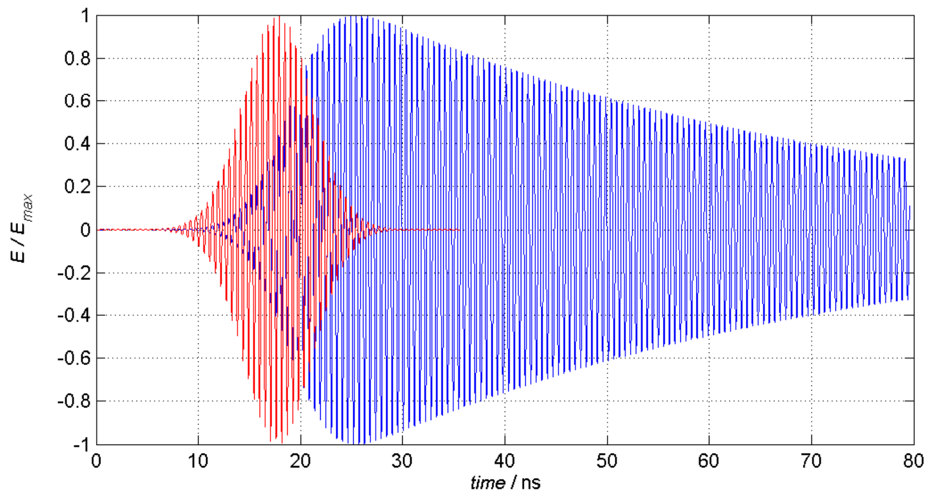


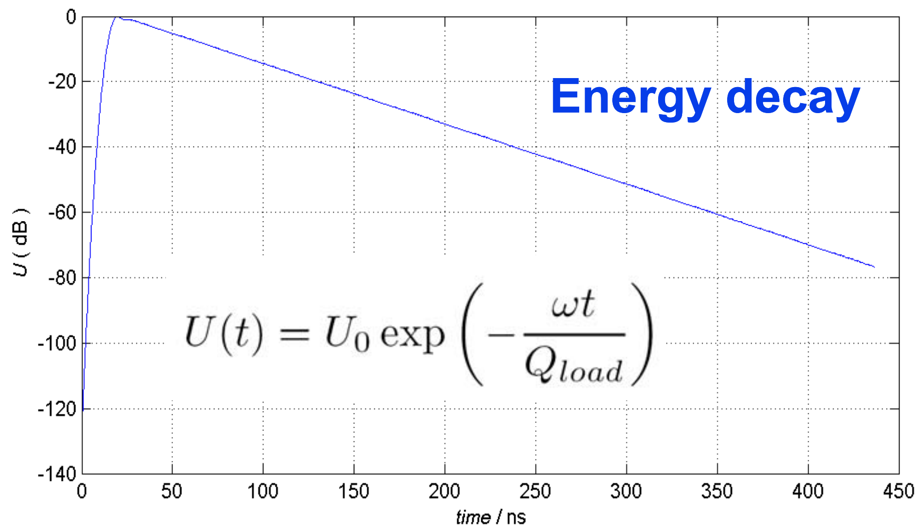
MWS model of J-Lab HOM damped SC cavity

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

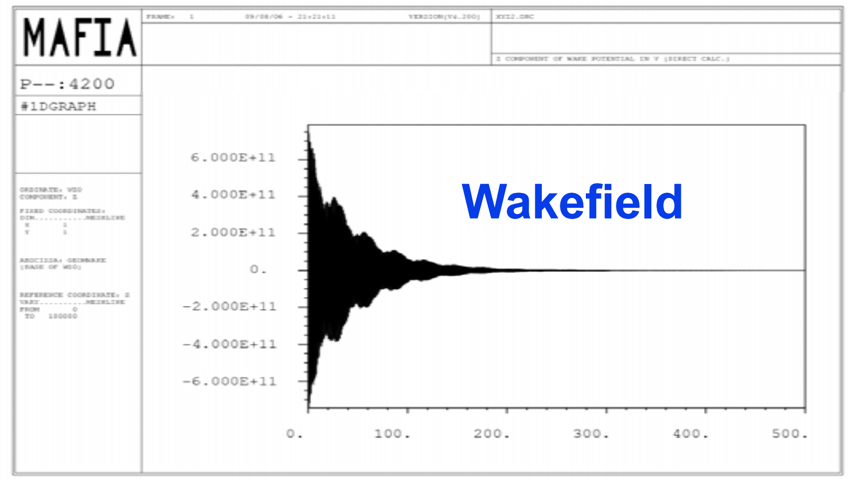
Wakefield and Impedance

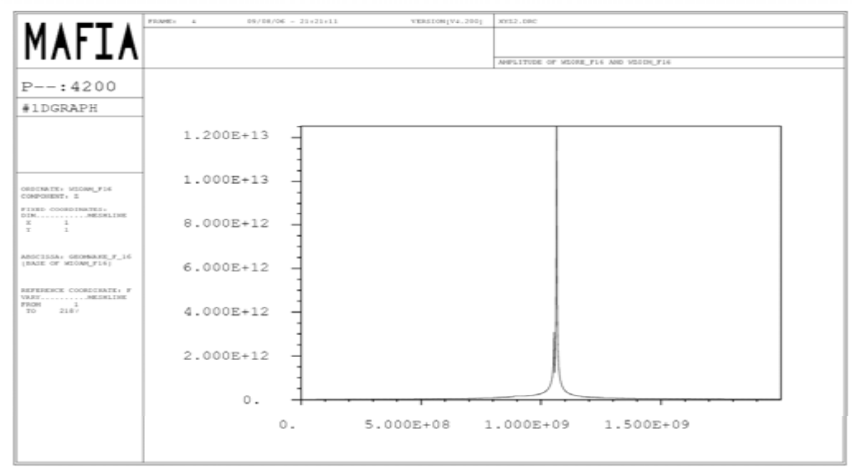
- External Q simulations





- Impedance simulations





Impedance

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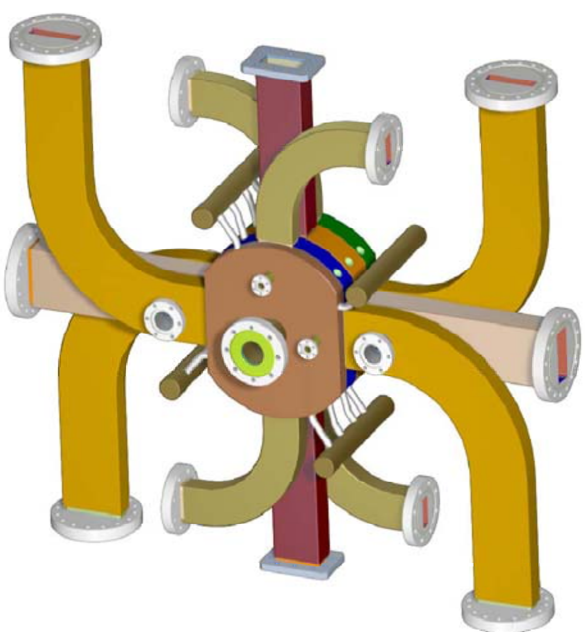
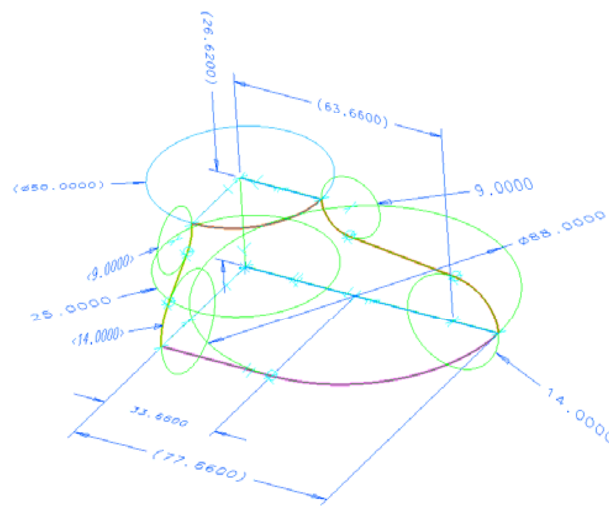
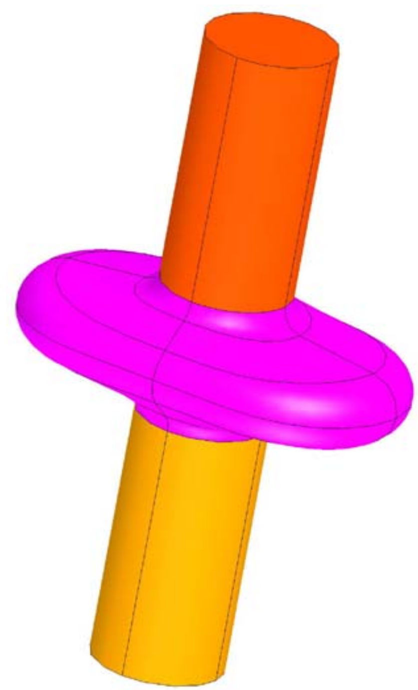
Deflecting Cavity Study for APS

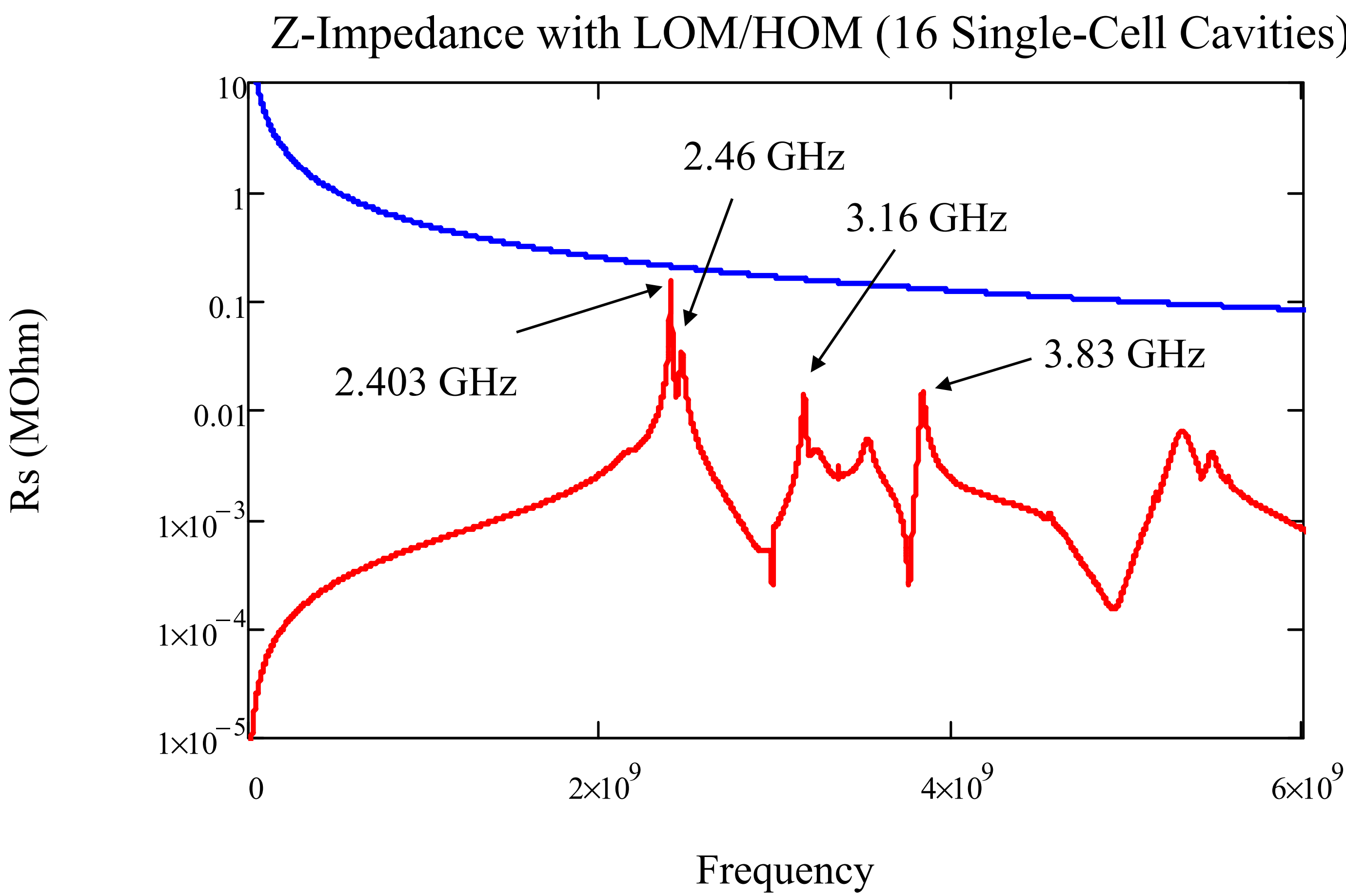
- **Collaboration with Tsinghua University, ANL, JLab and SLAC**
  - — **Normal conducting multi-cell deflecting cavity with LOM and HOM damping (Ali's talk)**
  - — **Single cell SC deflecting cavity (Haipeng's talk)**



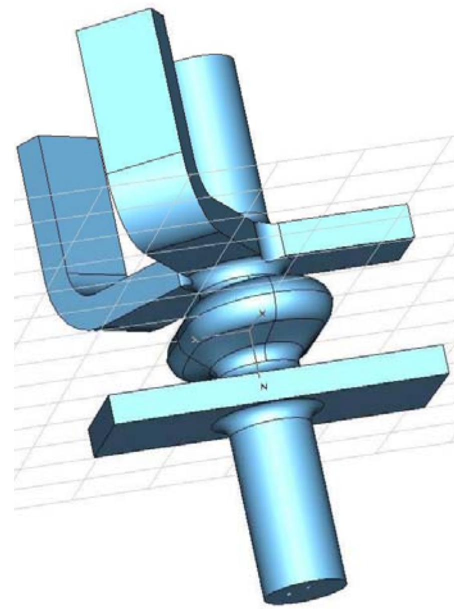




Preliminary Damping Studies



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



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

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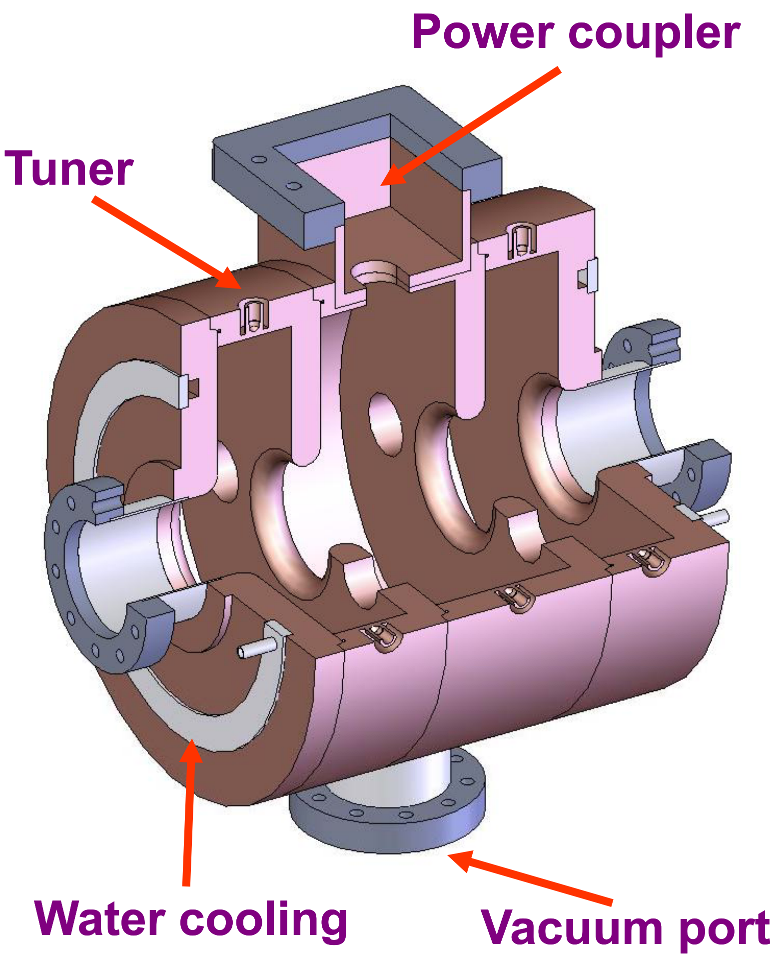
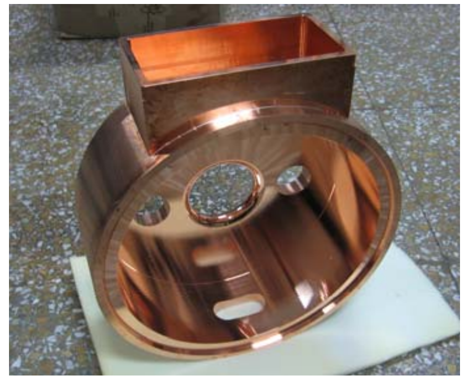
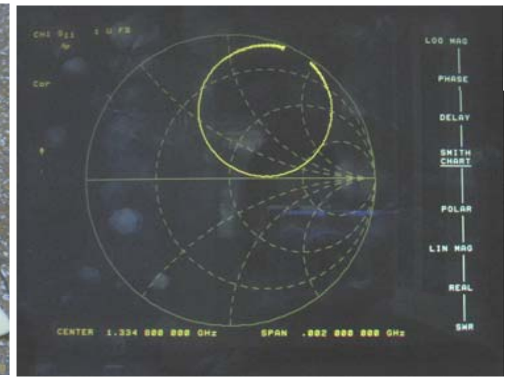
D-Cavity for Emittance Exchange Experiment at ANL

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







Mode Separation w/o Coupler

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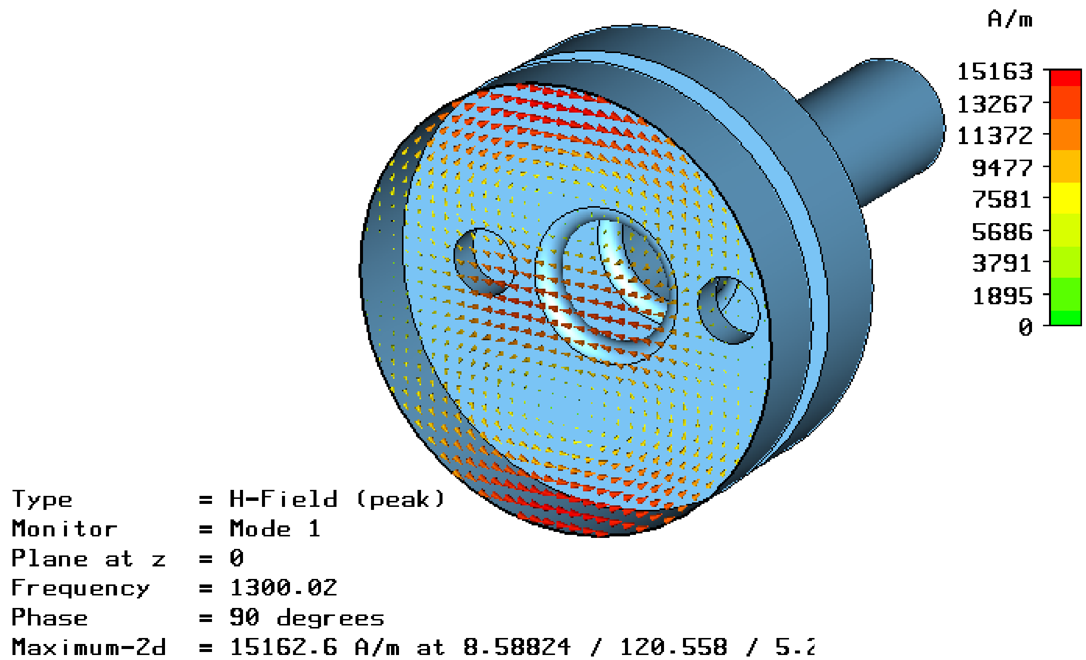
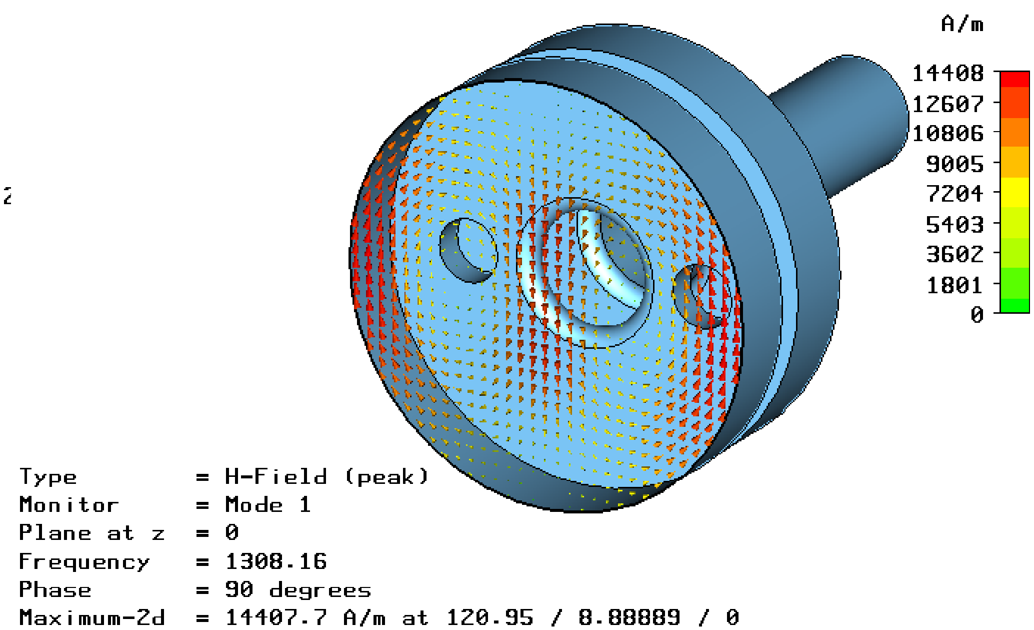


Power coupler is at critical coupling, the design was conducted by time domain simulations:
Coupling measurement and simulation agree within 20%

The dipole polarization is locked by introducing coupling irises

The frequency of the unwanted dipole mode was pushed up by
Δf ~ 8 MHz

No HOM damping



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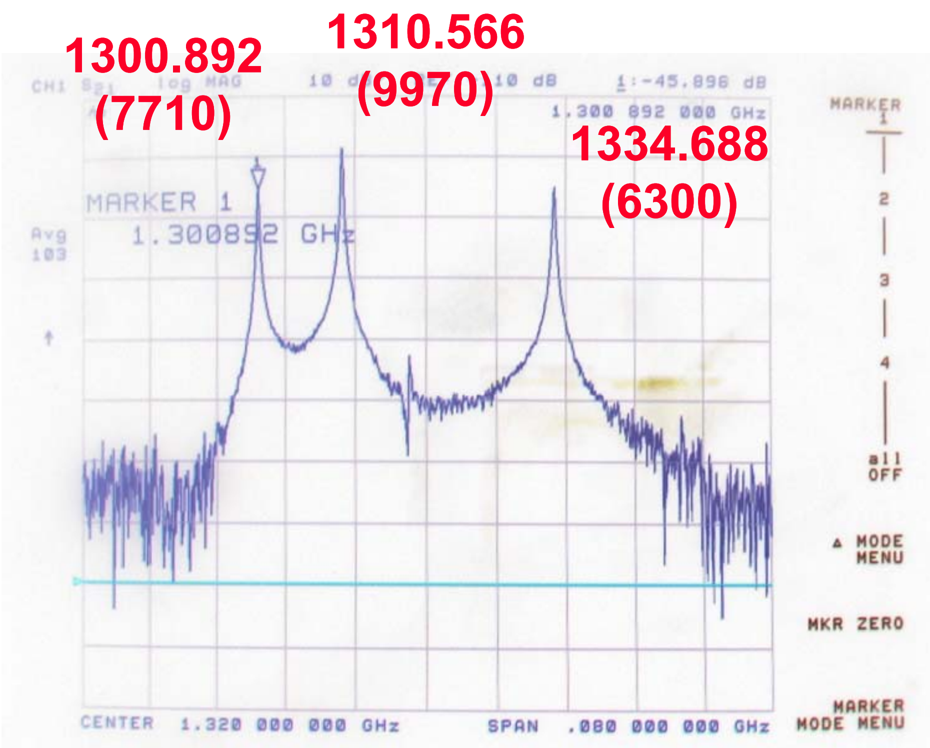
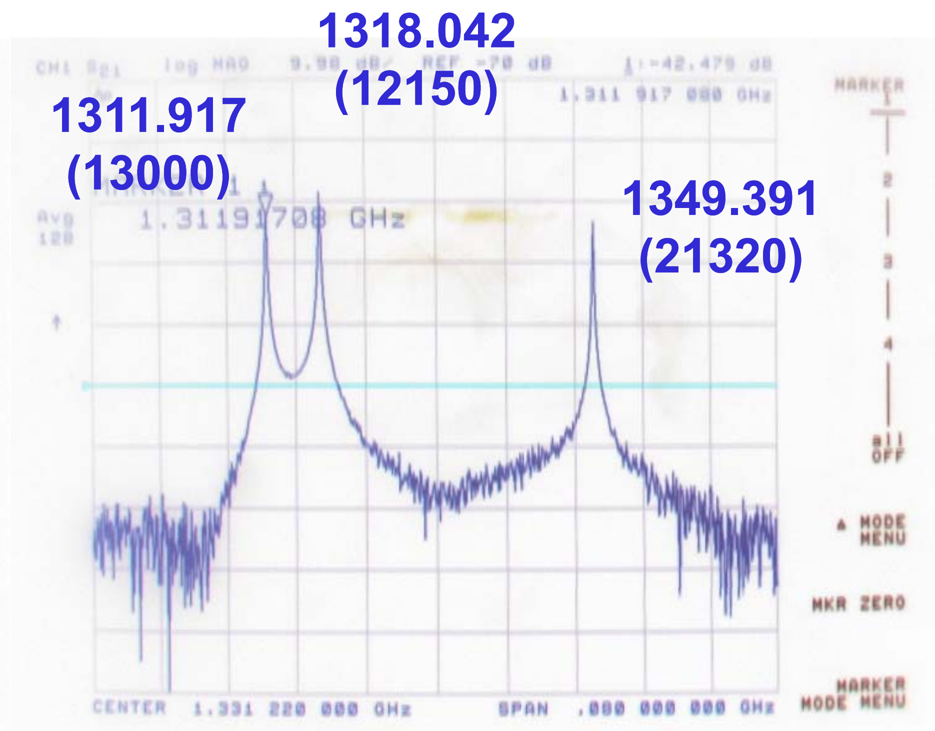
Measurements of Degenerate Modes

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



Deflecting Mode



Unwanted Dipole Mode

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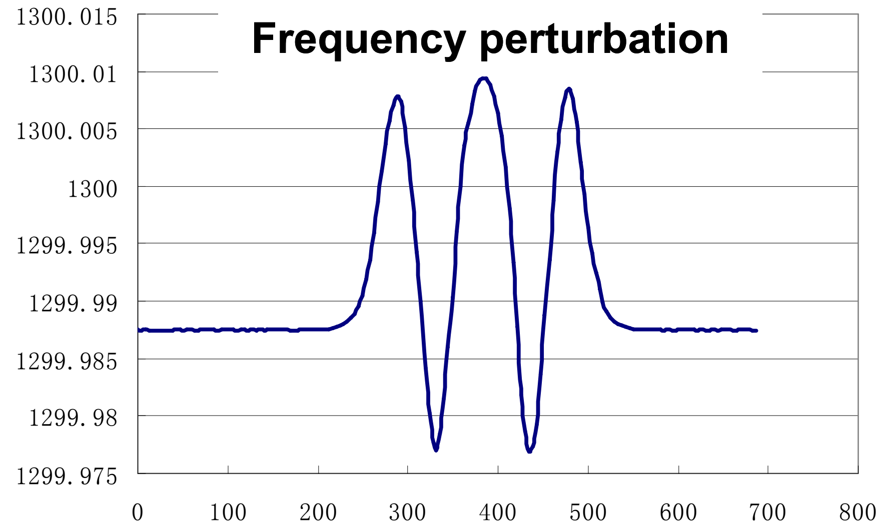
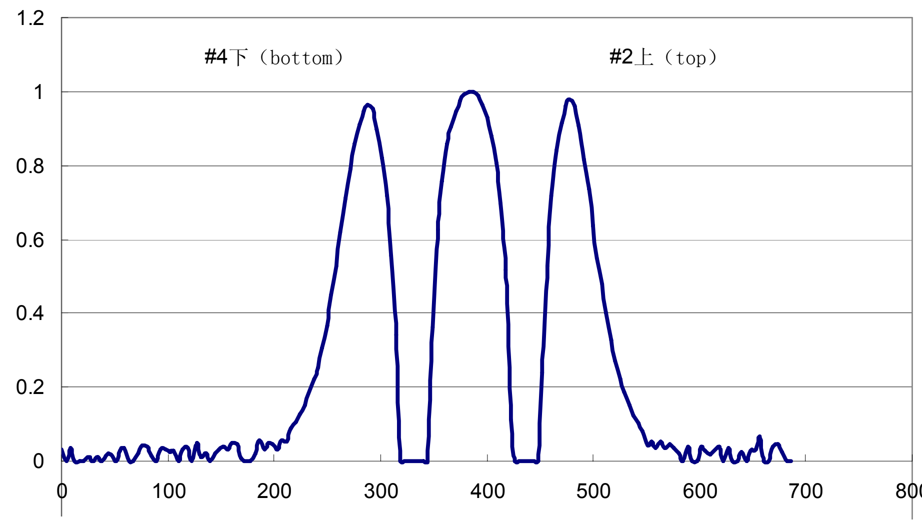
Field Measurement by Bead Pull





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

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

Ernest Orlando Lawrence
Berkeley National Laboratory

Deflecting Cavity for APS, ANL

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

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

♋ = 2.8×10^{-4}, $(\omega_s/2\pi)$ = 2 kHz, $■_s$ = 0.0073, β_x = 20 m

	Longitudinal	Transverse
Growth Rate, τ_g^{-1} (s^{-1})[1]	$\tau_g^{-1} = \frac{\alpha I_{tot}}{4\pi(E/e)\nu_s}\sum_p \omega_p \operatorname{Re} Z_z(\omega_p)$ $< \frac{\alpha I_{tot}}{2(E/e)\nu_s}\left(R_s \times f_p\right)$	$\tau_g^{-1} = \frac{\omega_0 I_{tot}}{4\pi(E/e)}\beta_\perp \sum_p \operatorname{Re} Z_t(\omega_p)$ $< \frac{\omega_0 I_{tot}}{4\pi(E/e)}\beta_\perp R_t$
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).