Superconducting Deflecting Cavities for Short Pulse X-Ray Generation at the Advanced Photon Source

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Outline

- Scientific Case
- Concept
- Rf Deflecting
- SC Cavity Design
- Summary

Scientific case for ps x-rays

APS Strategic Planning Workshop (Aug 2004): Time Domain Science Using X-Ray Techniques

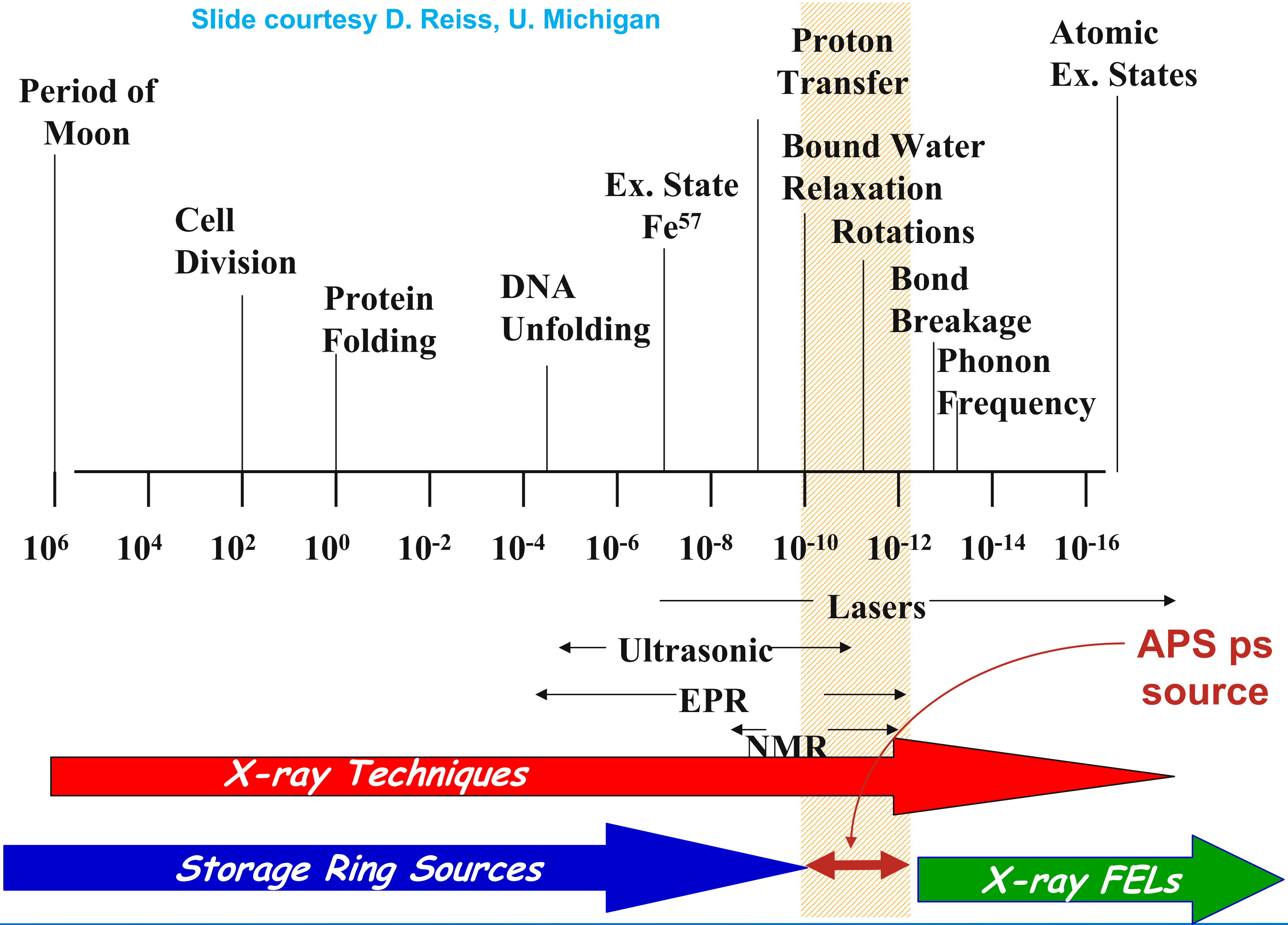
"…by far, the most exciting element of the workshop was exploring the possibility of shorter timescales at the APS, i.e., the generation of 1 ps x-ray pulses whilst retaining high-flux. This important time domain from 1 ps to 100 ps will provide a unique bridge for hard x-ray science between capabilities at current storage rings and future x-ray FELs."

Atomic and molecular dynamics, coherent/collective processes:

- Atomic and molecular physics
- Condensed matter physics
- Biophysics/macromolecular crystallography
- Chemistry

APS User's Meeting: Workshop on Generation and Use of Short X-ray Pulses at APS (May 2005)

Slide courtesy D. Reiss, U. Michigan



Period of Moon

Cell Division

Protein Folding

DNA Unfolding

Ex. State Fe^{57}

Proton Transfer

Bound Water Relaxation

Rotations

Bond Breakage

Phonon Frequency

Atomic Ex. States

10^{6} 10^{4} 10^{2} 10^{0} 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16}

Lasers

Ultrasonic

EPR

NMR

APS ps source

X-ray Techniques

Storage Ring Sources

X-ray FELs

Feasibility Study Group

ASD

Borland, Chae, Emery, Guo, Harkay, Horan, Kim, Kustom, Nassiri, Sajaev, Waldschmidt, White, Yang

ATLAS

Fuerst, Kelly, Shepard

Acknowledgement:

Zholents (LBL), Dolgashev (SLAC), Rimmer (JLAB)

Kenji Hosoyama (KEK), Derun Li and J. Shi (LBNL)

X-ray FELs & storage ring ps sources are complementary

XFELs can provide

- fs pulses
- Ultrahigh peak power
- Ultrahigh brightness
- Lower avg. repetition rate

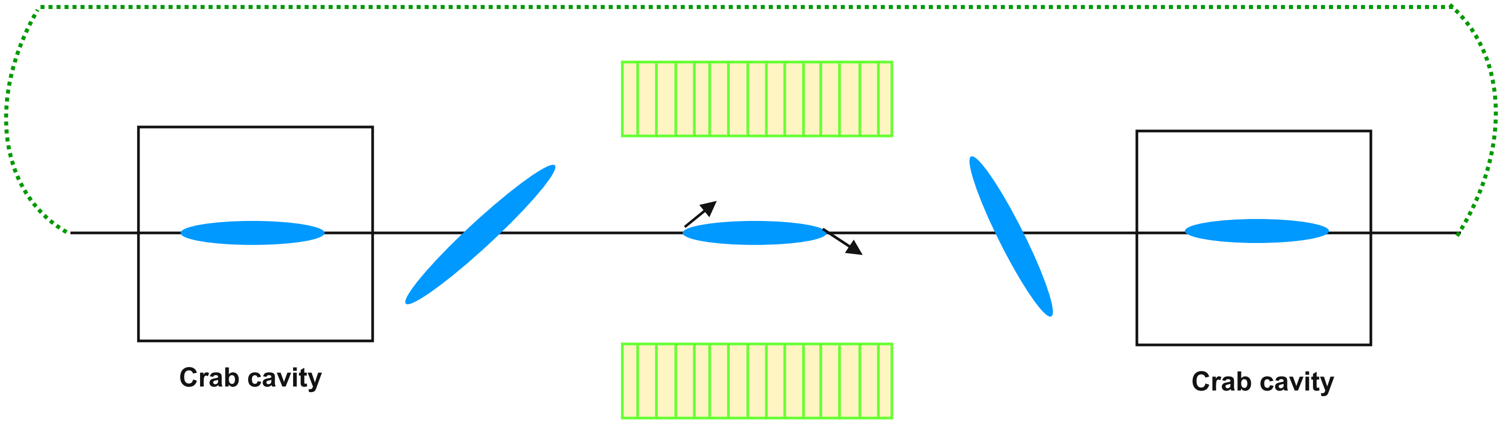
Storage rings can provide

- ~1 ps pulses
- Energy tunability
- Spectral stability
- Flux comparable to 100 ps
- High repetition rate

Note: Femtoslicing not practical at APS (calc per A. Zholents)

Energy modulation $\Delta E=7\sigma_e$ requires:
~10 mJ laser pulse at λ_L=400 nm and τ=50 fs
giving ~ 100 fs x-ray pulse with ~ 10^5 photons per pulse
BUT: looks difficult at a high rep. rate

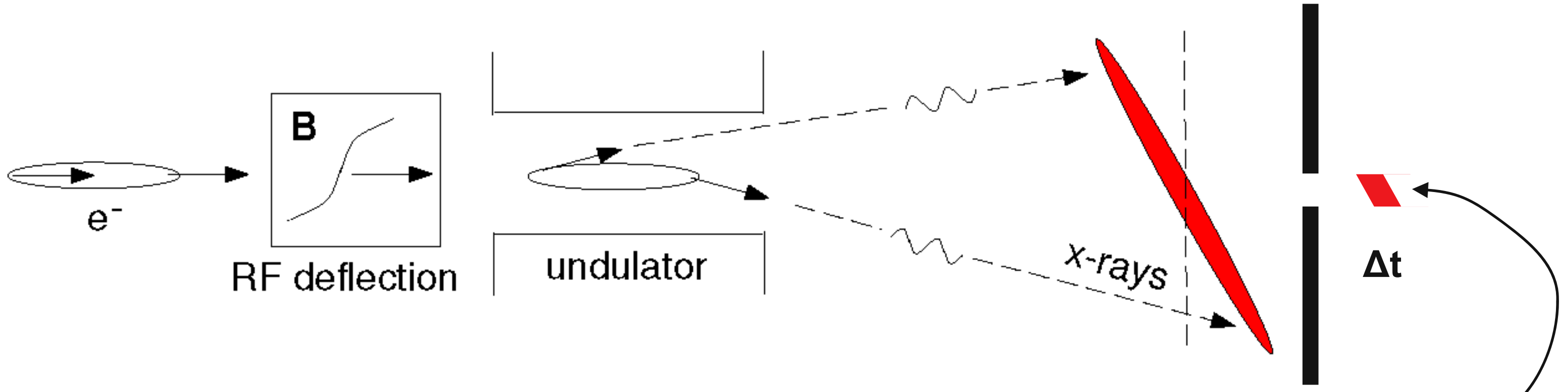
Concept†



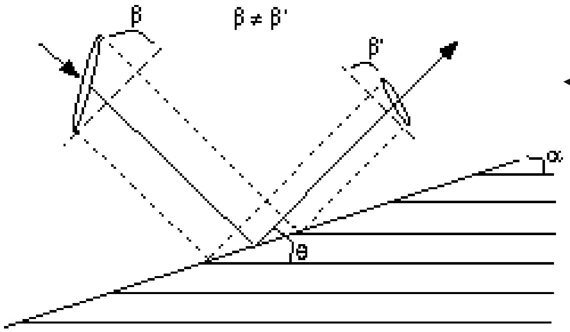
- Using magnetic field of a TM110 horizontal dipole mode
- Horizontal magnetic field creates a correlation between the longitudinal profile of the electrons within the bunch and their vertical angles, resulting in a “chirped” beam
- Electron (& photon) vertical momentum correlated with longitudinal position as bunch evolves through lattice
- Second crab cavity at nπ betatron phase cancels kick; rest of storage ring nominally unaffected

† A. Zholents, et., al. NIM A425 (1999)

Generation of ps-pulses



Slitting alone



or add compression using asymmetric cut crystal; throughput ~ 2-15x better

Compressed pulse length (linear rf):

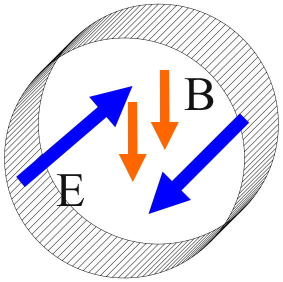
$$\sigma_{t,xray} = \frac{E}{2\pi h f_0 V}\sqrt{\sigma_{y',e}^2 + \sigma_{y',rad}^2}$$

For APS: h=8, 6 MV deflect. voltage, $\sigma_{y',e}$ = 2.2 μrad, and $\sigma_{y',rad}$ = 5 μrad; the calc'd compressed x-ray pulse length is ~0.36 ps rms.

Crabbing and parasitic modes (KEKB)†

TM110

500MHz

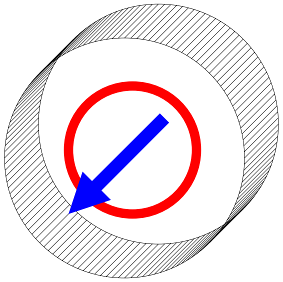


Crab Mode (h):
Bϕ, Ez off axis

Unwanted modes →

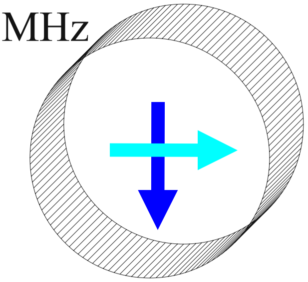
TM010

324MHz



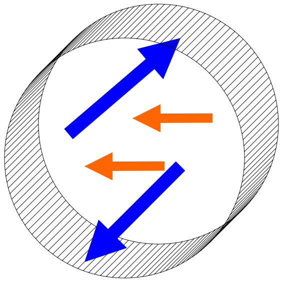
TE111

720MHz



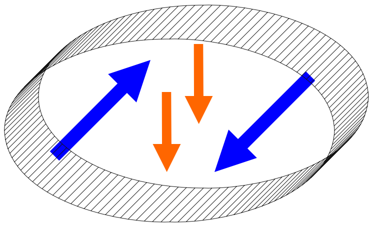
TM110

500MHz →



TM110 - like Mode

500MHz



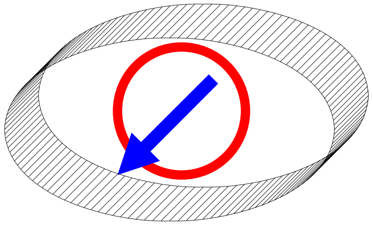
Crab Mode

Unwanted modes →

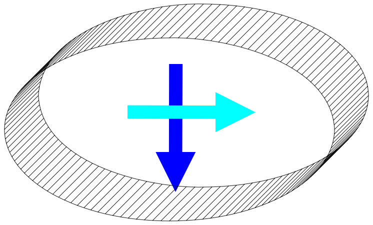
The squashed cell shape cavity scheme was studied extensively at Cornell in 1991 and 1992 for CESR-B under KEK-Cornell collaboration.

TM010 - like Mode

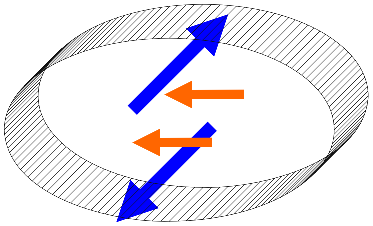
413.3MHz



650.5 MHz / 677.6MHz

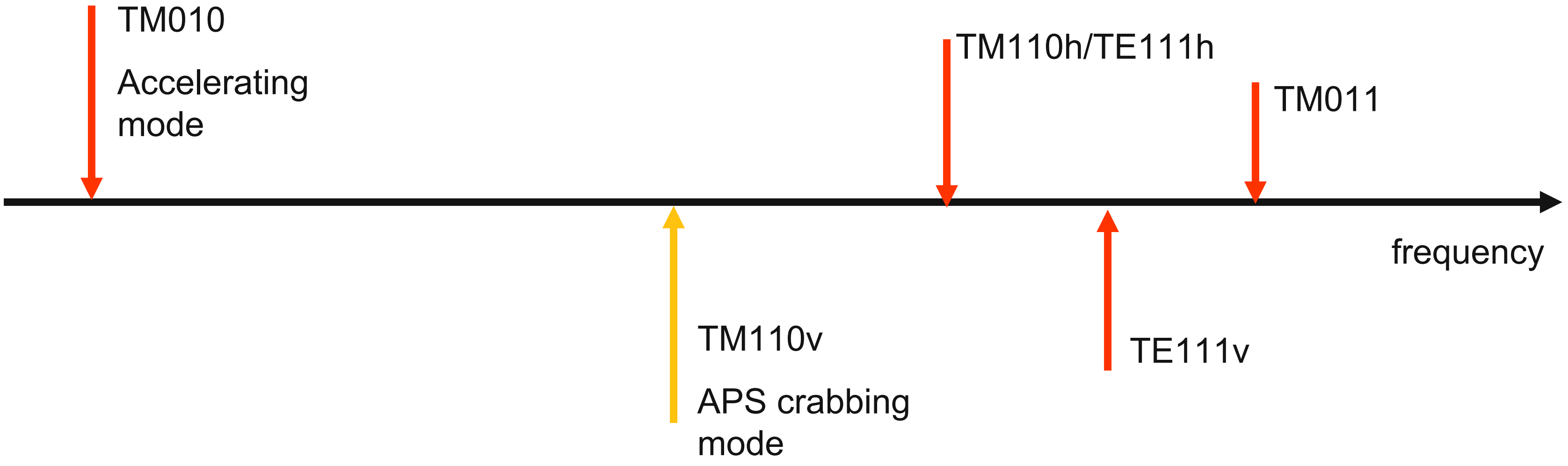


700MHz



† Courtesy K. Hosoyama, KEK, APS ps workshop (2005)

Parasitic modes (cont)



- Vertical crabbing mode (APS): horiz axis “squashed”
- Maximize mode separation for optimized damping
- HOMs above beam pipe cutoff, propogate out
- Lower-order mode (TM010) may strongly couple to beam; freq. below cutoff, adopt KEKB coaxial line strategy (for SC)
- Multiple cells produce multiplicity of parasitic modes (issue for SC)
- Orbit displacement causes beam loading in crabbing mode; adopt KEKB criterion of $\Delta y = \pm 1$ mm (for orbit distortions ± 0.1 mm)
- Generator power increased to compensate; de-Q to decrease sensitivity

Instability thresholds from parasitic mode excitation (per Y-C. Chae)

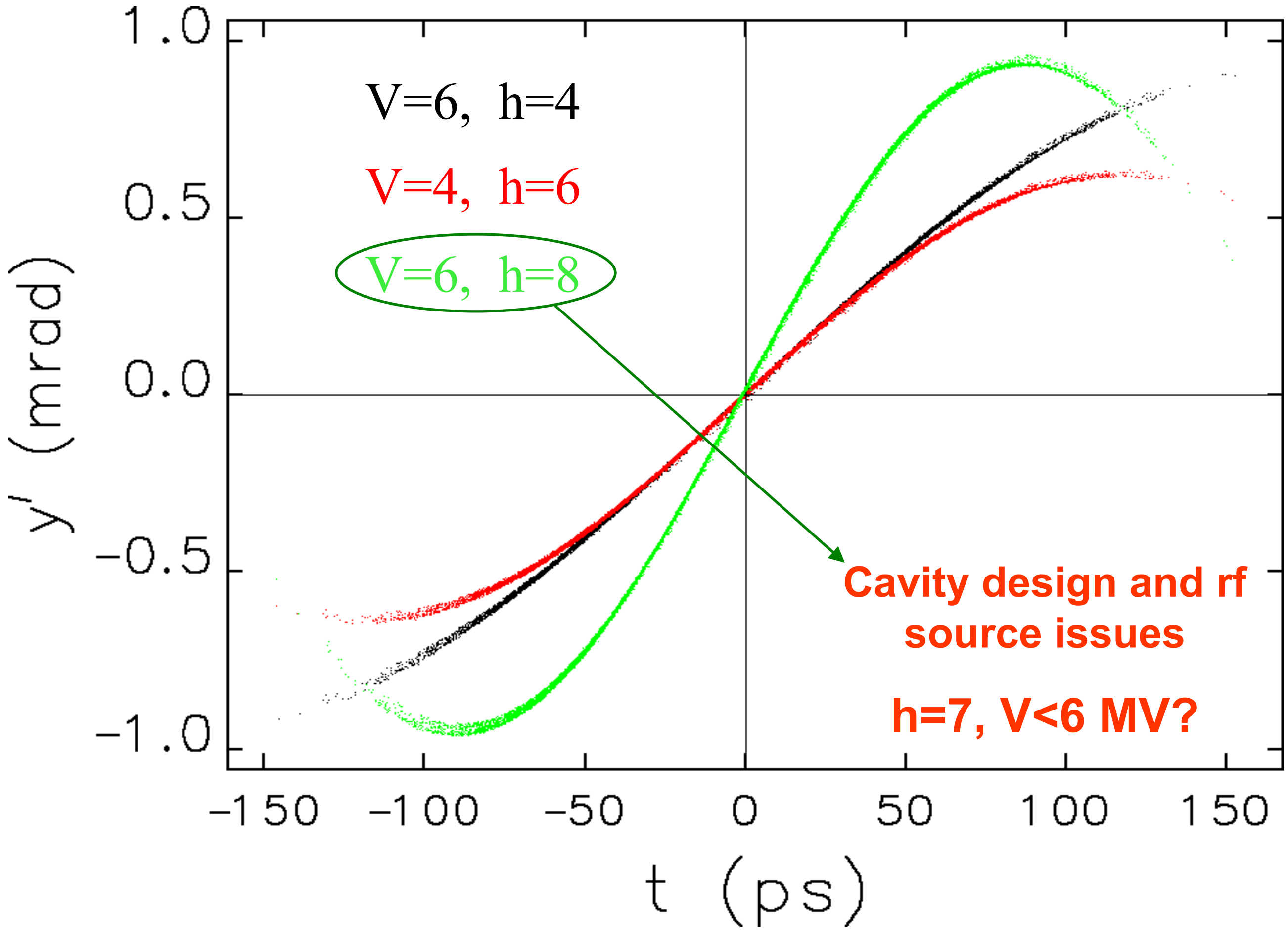
APS parameters assumed: I = 100 mA, E = 7 GeV,
α=2.8e-4, $\omega_s/2\pi$=2 kHz, ν_s=0.0073, β_x = 20 m

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

Parameters/constraints: what hV is required?



Cavity design and rf source issues

h=7, V<6 MV?

Can get the same compression as long as h*V is constant

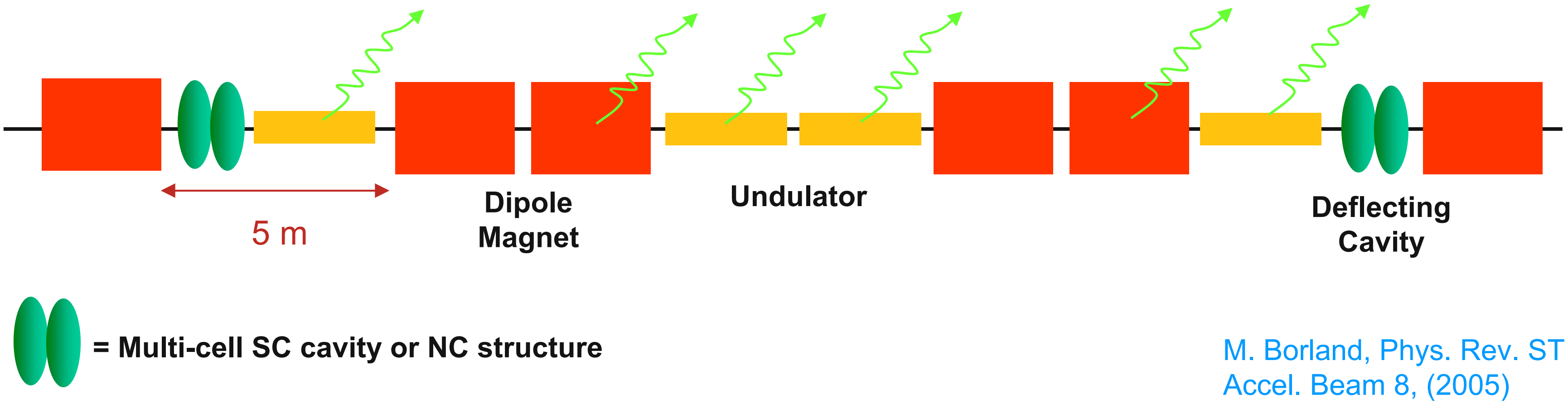
Higher V and lower h: more linear chirp and less need for slits

Higher h and lower V: smaller maximum deflection and less lifetime impact

Higher h and maximum V: shortest pulse, acceptable lifetime

Coutesy M. Borland, APS ps Workshop, May 2005

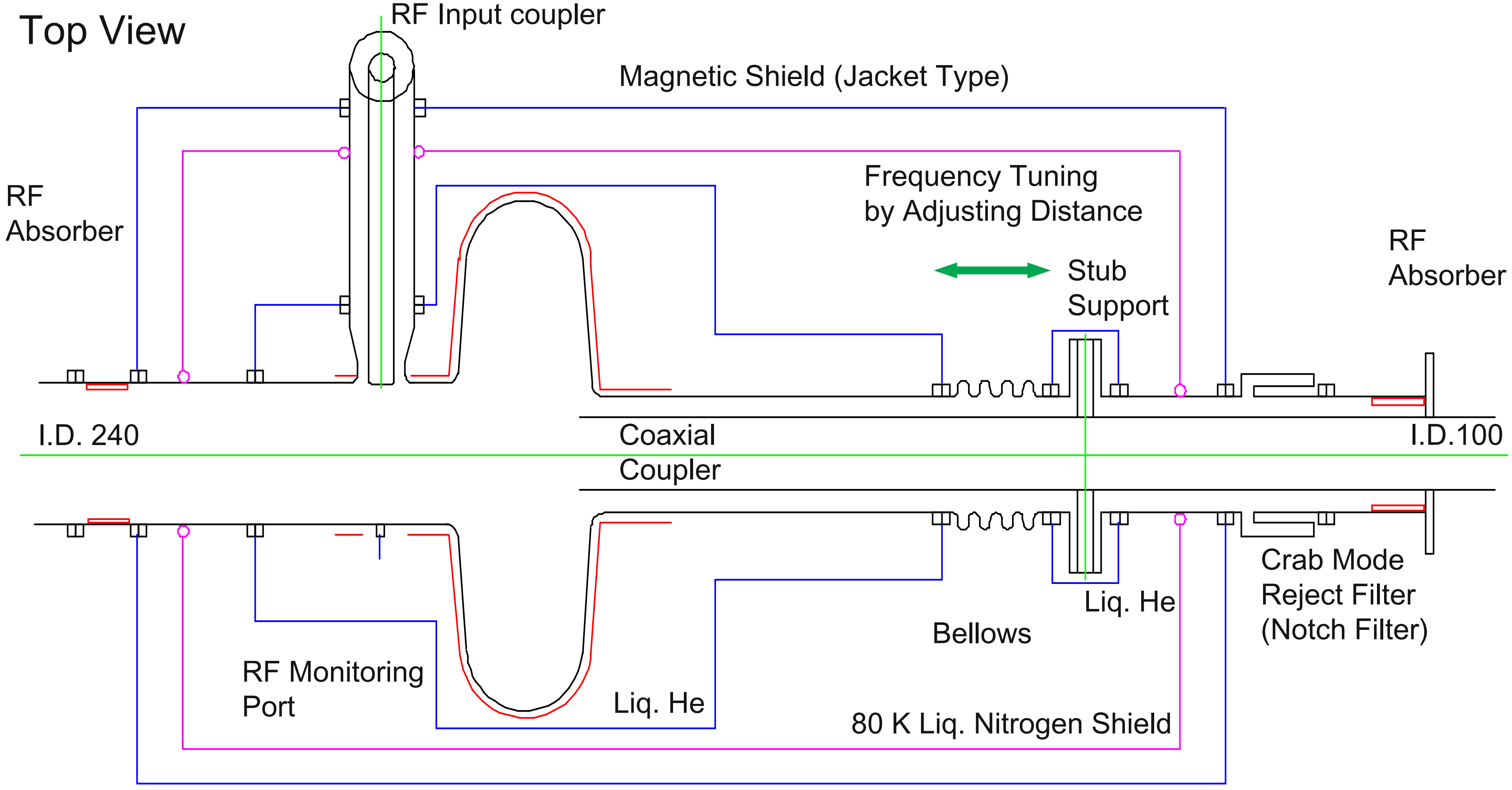
Space constraints at APS



M. Borland, Phys. Rev. ST Accel. Beam 8, (2005)

- Nominal 2-sector implementation shown: 4 IDs and 2 BMs
- Nominal insertion length available for rf cavities: 2.5 m

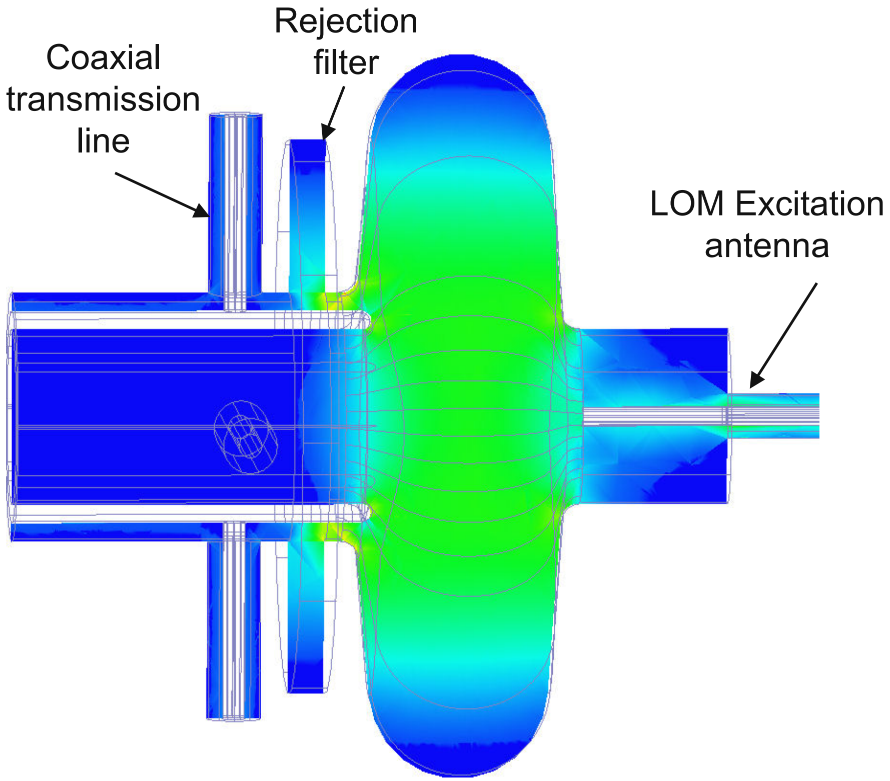
KEK Cavity Schematic



Courtesy KEK

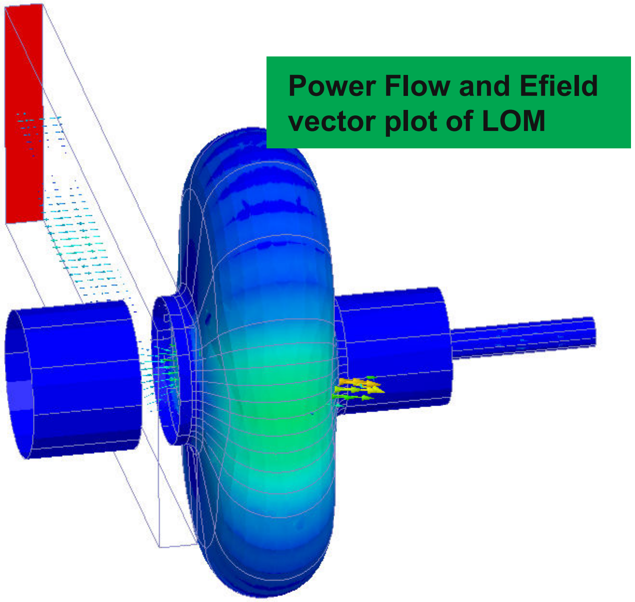
Conceptual KEK-Type Cavity at the APS (2.8 GHz)

- Ridge waveguide and/or coaxial transmission lines transport LOM / HOM to loads outside of cryomodule
- KEK-type coaxial beam pipe damper reduced the quality factor of LOM from 5.0e9 to 1.1e3. Stability condition for LOM achieved when Q < 12,900 for 100 mA beam current.
- Coaxial design rejected due to difficulty in aligning and manufacturing superconducting transmission line at 2.8 GHz.

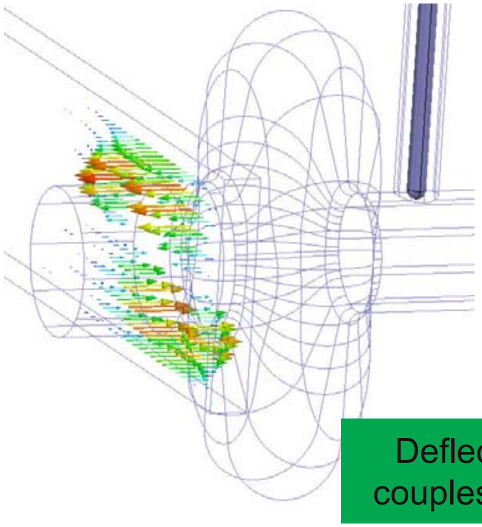


Alternate Design with Waveguide LOM Dampers

- Waveguide damper is placed near cavity to intercept leakage fields of the LOM
- LOM couples to waveguide and is strongly damped Qext= 500.
- Other monopole modes also couple to TE10 waveguide mode and are strongly damped.



Power Flow and Efield vector plot of LOM

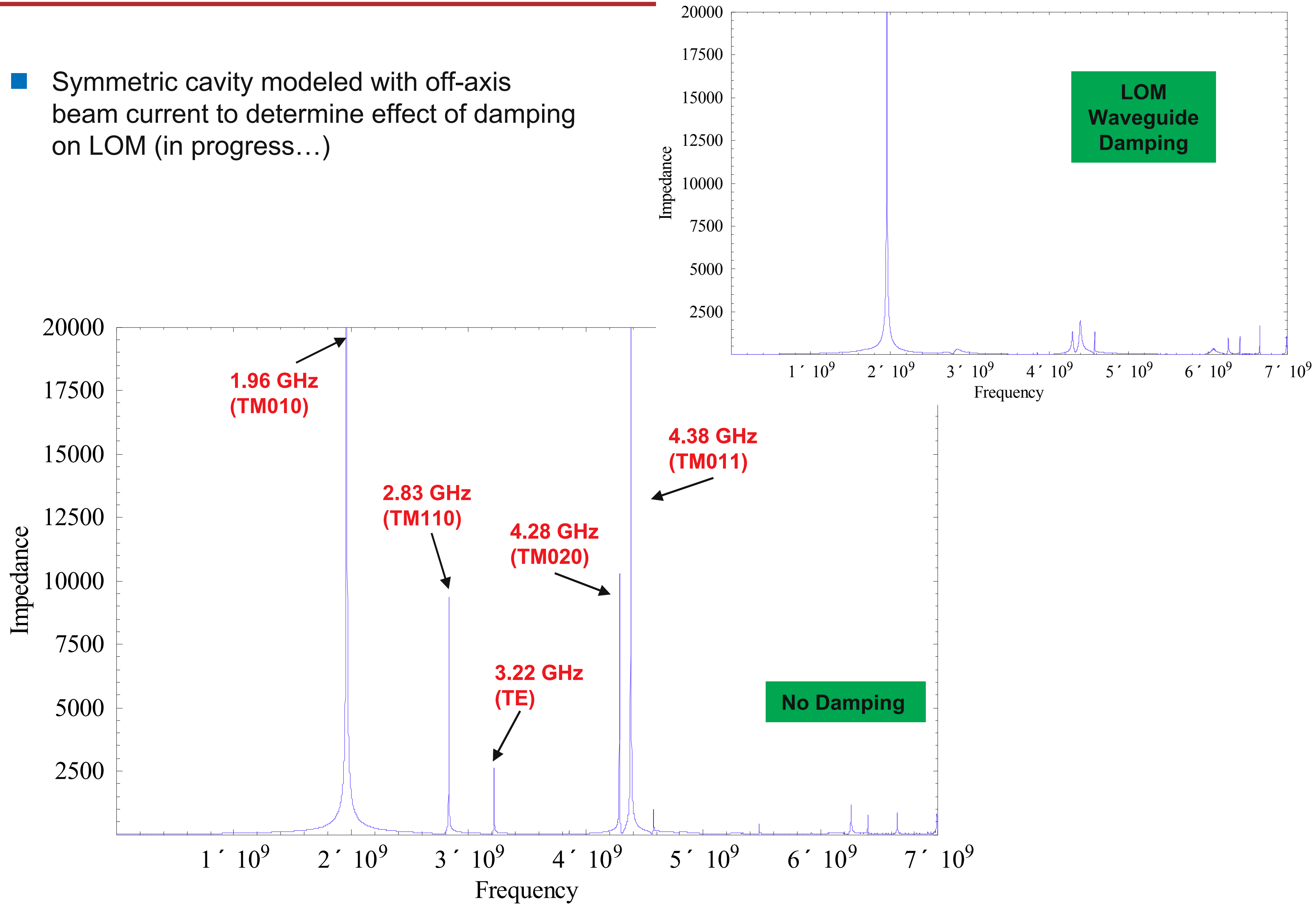


Deflecting dipole mode couples as TE_{20} wg mode

- "Degenerate" deflecting mode couples to TE_{10} waveguide mode and is strongly damped.
- Desired deflecting mode couples as TE_{20} mode and is rejected by > 30 dB in current configuration.

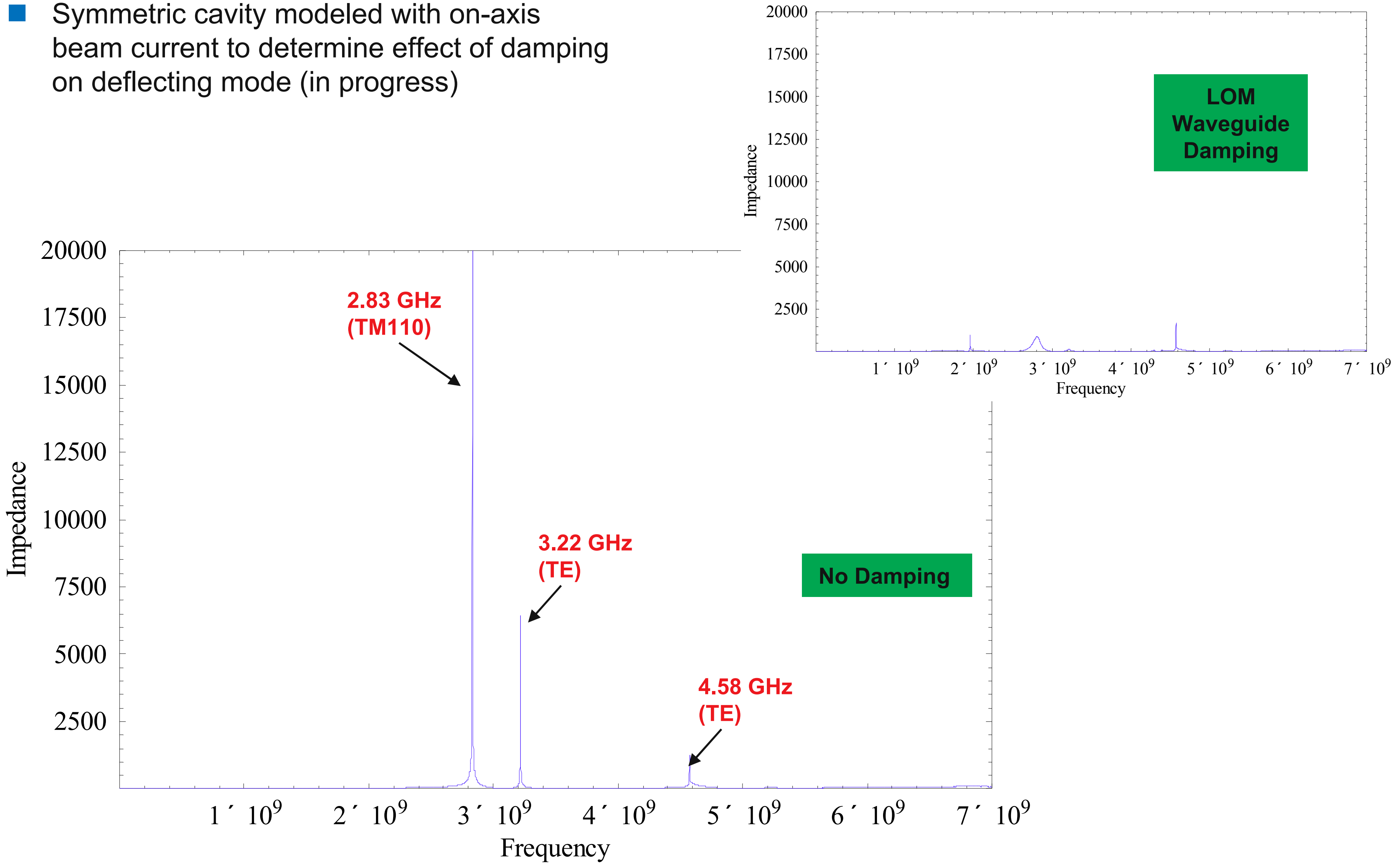
Longitudinal Impedance (off-axis) with and without Damping

- Symmetric cavity modeled with off-axis beam current to determine effect of damping on LOM (in progress…)



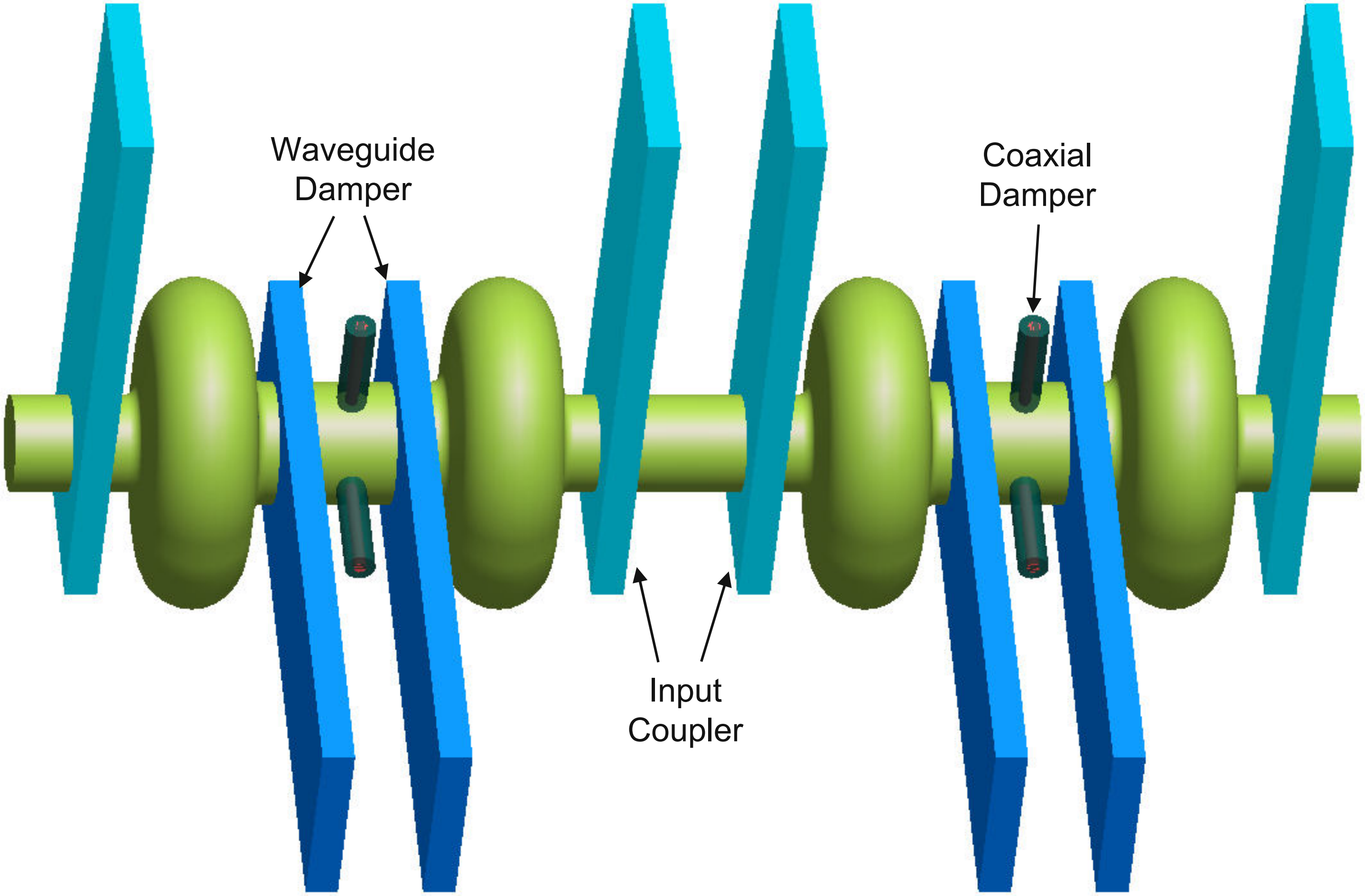
Transverse Impedance (on-axis) with and without Damping

- Symmetric cavity modeled with on-axis beam current to determine effect of damping on deflecting mode (in progress)



Partial Configuration with Waveguide Dampers

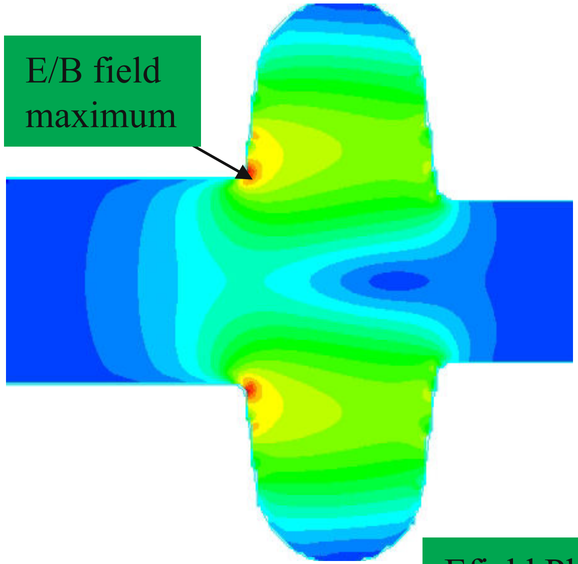
- At least ten single-cell cavities with dampers and input couplers will be required.
- Additional space will be required for ion pump/valves/bellow assembly installed on both ends.



Symmetric vs Squashed Cavity Shape

- Squashed cavity has disadvantages
  - Mechanical issues at KEK
  - Probably harder to fabricate – therefore harder to maintain surface quality
  - Tuning can not be easily performed by deforming cavity wall due to ribs (but may be performed in large beam pipe?)

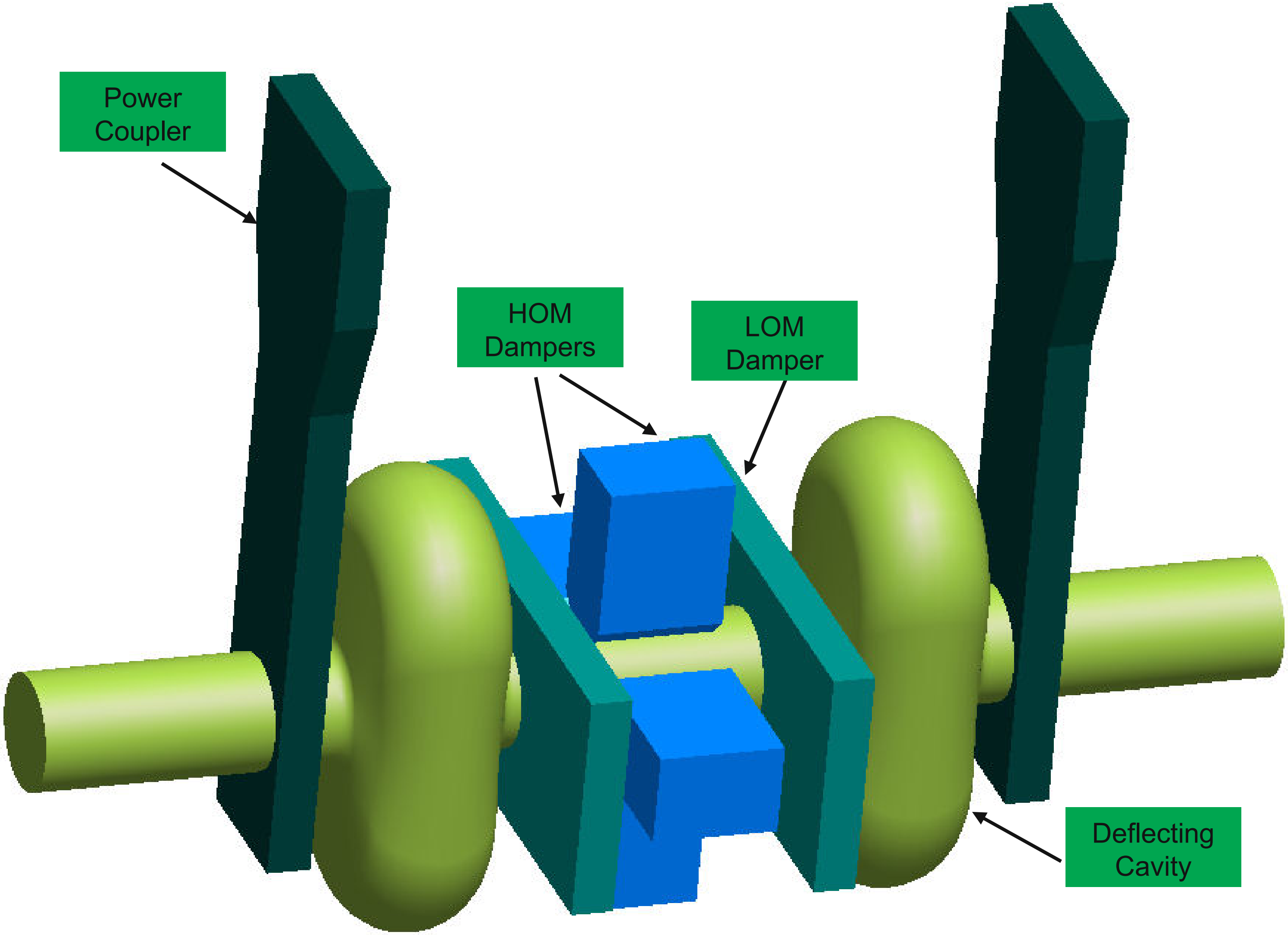
	Symmetric	Squashed
Frequency	2.815 GHz	2.815 GHz
No. Cavities	10	10
Beam radius	2.4/1.9 cm	2.4/1.9 cm
R_T / Q	47.2 Ω/m	46.8 Ω/m
Deflecting Voltage	6 MV	6 MV
Deflecting Gradient	11.3 MV/m	11.3 MV/m
Esp	44.6 MV/m	41.5 MV/m
Bsp	146 mT	111 mT
Esp / Vkick	74.3 MV/m/MV	69.2 MV/m/MV
RF loss at 2K	7.6 * 10	7.7 * 10



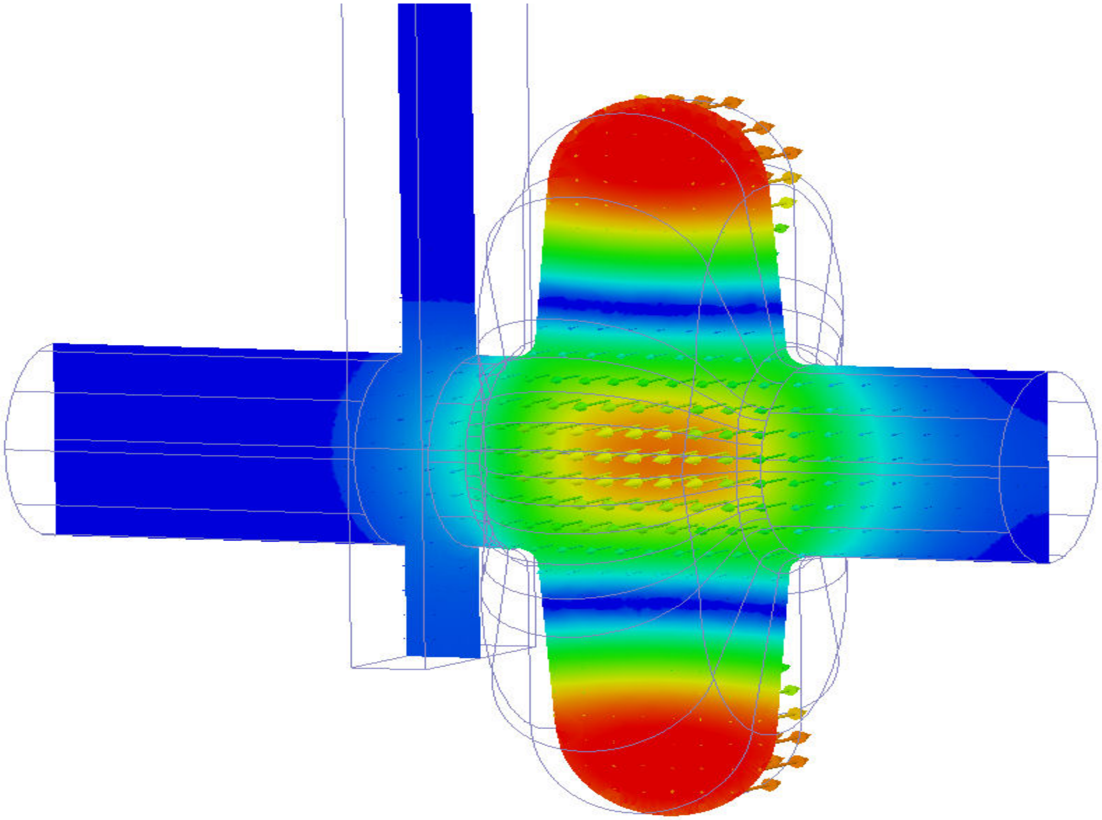
Efield Plot of Symmetric Cavity

- Symmetric cavity has disadvantages
  - Higher peak surface fields
  - More cavities possibly needed

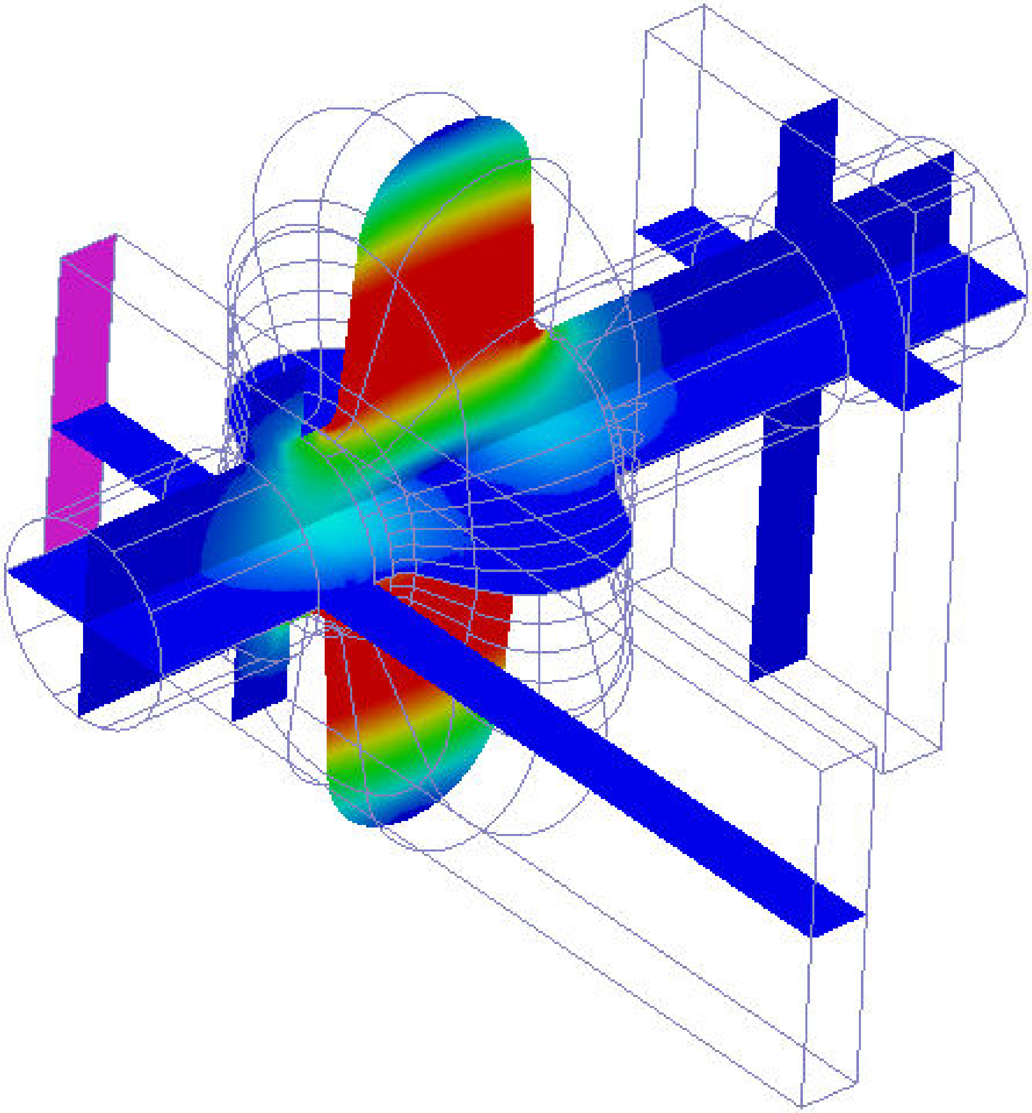
Squashed-Cell Cavities with Dampers



Deflecting Magnetic Field



Asymmetric LOM Damper



Longitudinal Mode Power Loss

Freq	Mode	Qext	Min Power* (100mA)	Min Power * (300mA)
2.247	TM010	6,500	1250	11250
3.784	TM020	36,000	66	594
4.622	TE(h)/TM	19,000	307	2763
5.425	TE(v)/TM011	67,500	28	252
5.705	TM011/TE	44,600	67	603

* Assumes a 23 bunch pattern with 16nC (100mA), or 48 nC (300mA)

$$\mathrm{PwrOutPeak} = \frac{w^2\ \mathrm{RoverQ}\ q^2}{4.0\ \mathrm{Qext}};$$

Partial List of Issues

- Cryomodule design criteria
  - Impact on component layout and design
  - Additional length requirements
- State of the art peak E and H surface gradient limitations
- Squashed vs. rotationally symmetric deflecting cavity
- Thermal and stress analysis requirements
- Copper / niobium cavity prototypes
- Vertical cryostat testing capabilities
- Cavity processing capabilities at Argonne

Summary of RF Design Considerations

- Goal ≤1 ps in crab insertion
- No impact of crab cavities on performance outside insertion
- Parasitic modes must be damped ~ 103-104 (Chae)
- Deflecting voltage V= 6 MV for lifetime issues; Harmonic number h = 8 (2.8 GHz) due to rf non-linearities and available 100 kW rf sources
- Available insertion length for cavities nominally 2.5 m
- Effects of errors: emittance growth or orbit kicks (M. Borland)
  - Intercavity phase error < 0.04 for <y'>/σy' < 10%
  - Intercavity voltage difference < 0.5%
- Superconducting RF option
  - May offer a greater degree of compatibility with normal SR operation
  - Compatible with future development of higher rep rate pump probe lasers

R&D Plan

- Feasibility study completed
- SC rf technology chosen

- Finalize RF system design, refine simulations
- Observe assembly and testing of KEKB crab cavities in 2005, 2006
- Model impedance effects (parasitic modes, head-tail)
- Conduct proof of principle tests (beam dynamics, x-ray optics)
  - Chirp beam using synchrobetatron coupling (transient) (W. Guo)
  - Install warm model of SC rf cavity (passive), parasitic mode damping (K. Harkay, A. Nassiri) (AIP)

Summary

- We believe x-ray pulse lengths ≤ 1 ps achievable at APS
- SC RF chosen as baseline after study of technology options
- Recent simulation results on LOM and HOM damping are encouraging
- Input coupler design is underway
- Beam impedance calculation may have appreciable effect on final design
- Proof of principle R&D is underway: beam/photon dynamics