Development of RF Accelerating Structure for the Damping Ring of the SuperKEKB Injector

Simulation Aspects

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High Energy Accelerator Research Organization (KEK)

Advanced 3D EM and Particle Simulation Technology
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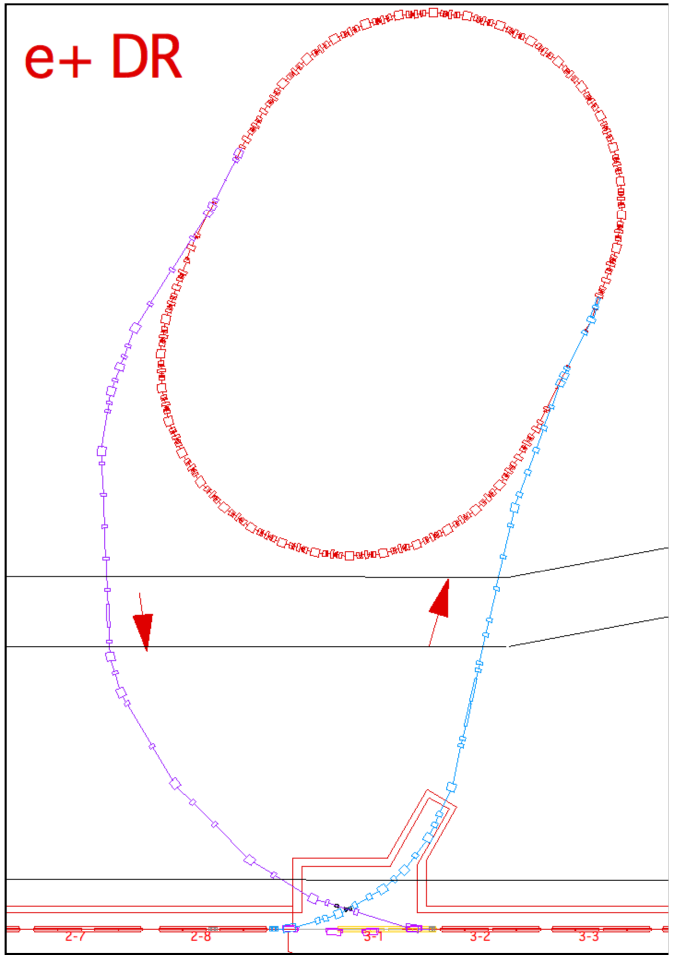
Simulation to Design the RF Accelerating Cavity in the RF Section of the Damping Ring (DR)

for SuperKEKB e+ Main Ring (MR)

Design Parameters (as of April 9th, 2010)		
Circumference	135.5	m
Beam Energy	1.0	GeV
Number of Bunch Trains	2	
Number of Bunches/Train	2	
Maximum Stored Beam Current	70.8	mA
Momentum Compaction Factor	0.00356	
Equilibrium Emittance	14.4	nm
Bunch Length	5.0	mm
Vc	0.5	MV
RF Frequency	508.887	MHz
Synchrotron Tune	0.008	
Horizontal Damping Time	12	ms
Etc.		



(N.Iida)

Basic Conditions in Designing the RF Section

- Accel.-Mode Frequency: $f_a = 508.887$[MHz] (= $f_{\mathrm{KEKB-MR}}$)

- Based on the KEKB-MR / ARES Cavity System
  - But without **S-cav** and **C-cav** (see the next page)

- Connection between
  - ϕ40 beam duct (to the regular duct of the DR) and
  - ϕ150 beam duct (on the cavity)

    → *Tapers* near the cavity

Accelerator Resonantly-coupled with Energy Storage

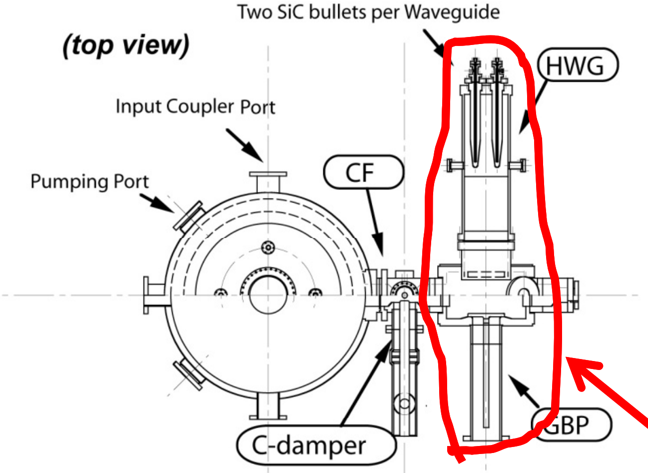
3-cavity system stabilized with the $\pi/2$-mode operation

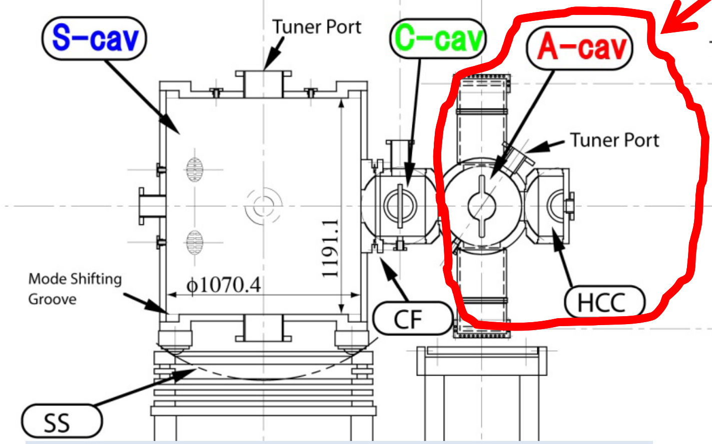
For (Super)KEKB/MR

consists of

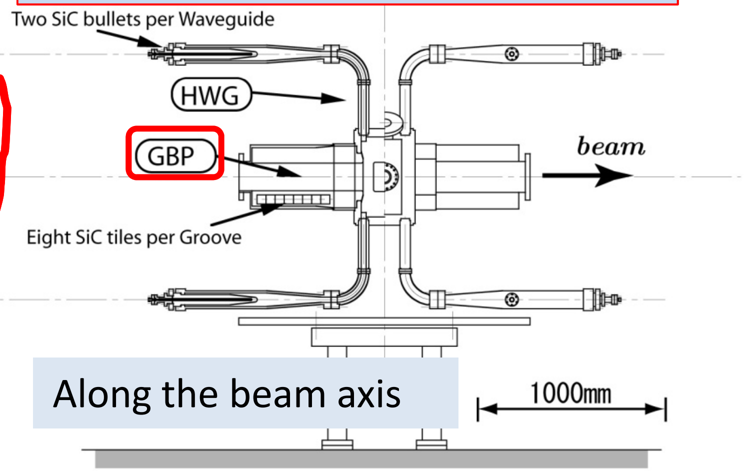
- HOM-damped accelerating cavity (**A-cav**),
- Energy-storage cavity with TE_{013} (**S-cav**),
- Coupling cavity (**C-cav**) with a parasitic-mode damper.

We use only this for the DR.





Perpendicular to the beam axis



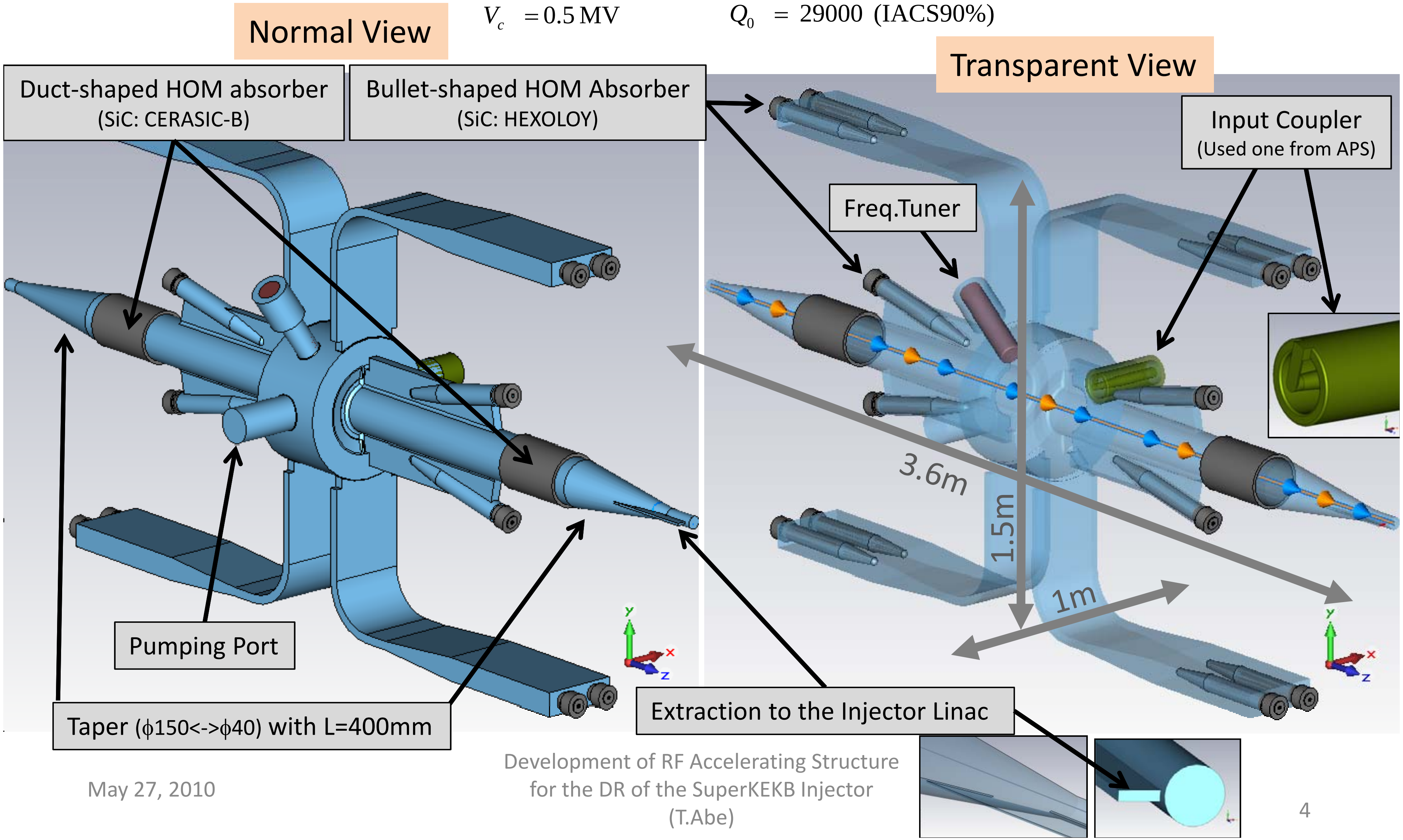
Along the beam axis

RF-Related Design of the DR/RF Section

As of April 9th, 2010

$f_a = 508.887\ \mathrm{MHz}$ $R_a/Q_0 = 150\ \Omega$

$V_c = 0.5\ \mathrm{MV}$ $Q_0 = 29000\ (\mathrm{IACS90\%})$



Main Simulation Items in Designing the DR/RF Section

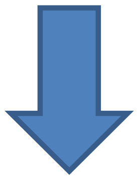
1. **Precise Determination of the Cavity Diameter**
   - To have f_a = 508.887MHz
   - Δf_a = ~100kHz (40kHz/mm by the Freq.Tuner with max. stroke length: 50mm)
   - Perform eigenmode analyses!
2. **Optimization of the New HOM Damper**
   - In the Grooved Beam-Pipe (GBP) with a winged chamber
   - Where to set the bullet-shaped SiC HOM absorbers
   - Perform FD analyses to check S-parameters!
3. **Q_0 for the HOM Absorbers in the New HOM Damper**
   - The accelerating mode may heat the HOM absorbers near the cavity.
   - Perform eigenmode analyses with the HOM absorbers!
4. **Longitudinal HOM Impedance for Coupled Bunch Instabilities (CBIs)**
   - Longer-range wakepotentials for higher-Q trapped modes!

1. Precise Determination of the Cavity Diameter

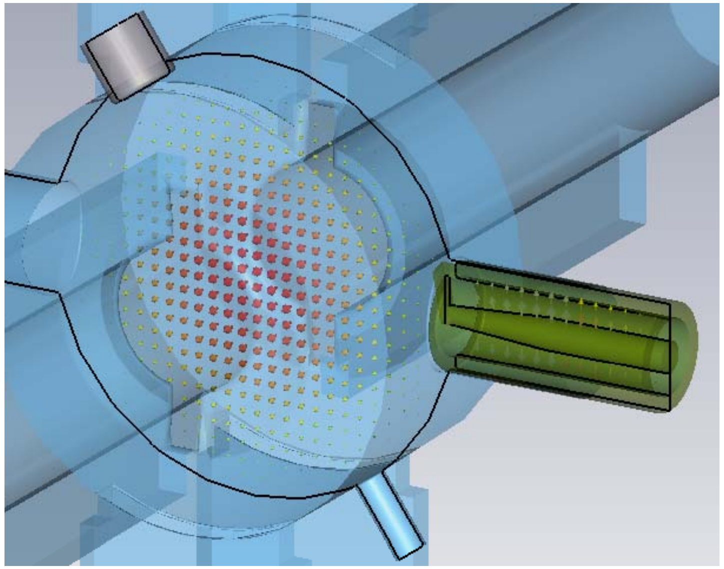
■*Eigenmode Analyses using CST MICROWAVE STUDIO (MWS)*
■*PC Workstation (DELL PRECISION T7400)*
- ➢*With 2 x Quad-Core XEON X5472 (3.0GHz) & 64GB RAM*

●Accelerating Mode
- ➢TM_{010} (508.887[MHz])
- ➢Can travel in the input coupler.

●The input coupler has a non-negligible volume.



Slater's Tuning Curve Method
is used for precise calculation.

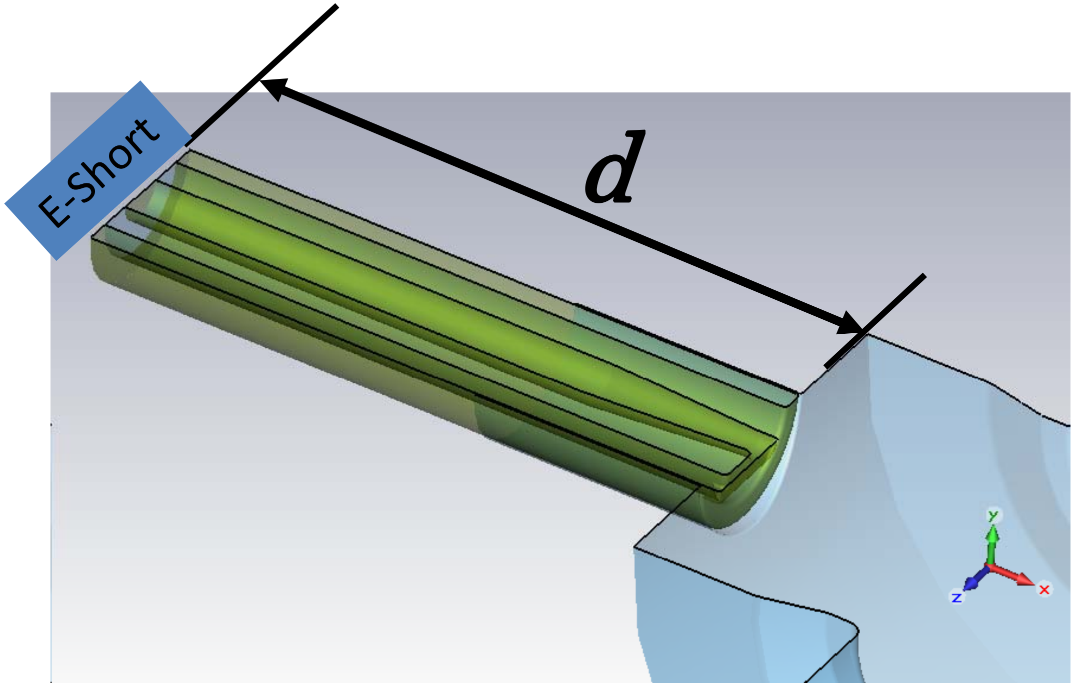


An example of the results of eigenmode analyses for the accelerating mode

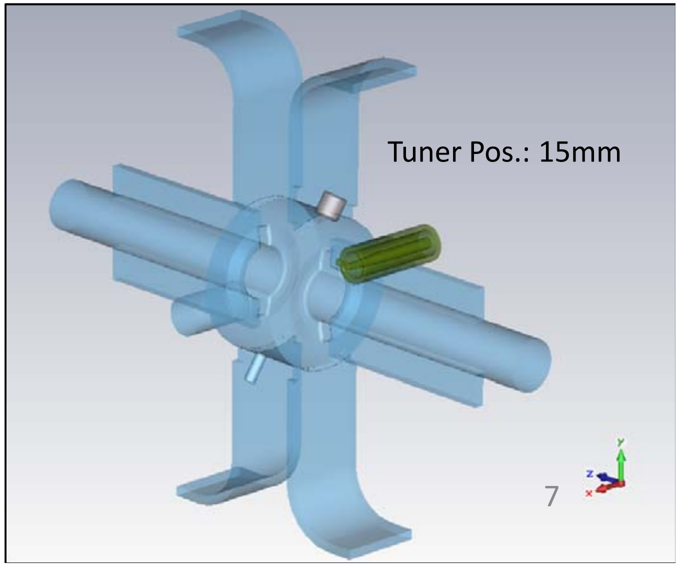
Slater's Tuning Curve Method

$$d - d_0 = \frac{\lambda}{2\pi}\tan^{-1}\frac{1/Q_{ext}}{f/f_a - f_a/f} + \frac{n}{2}\lambda$$

λ : Guide wavelength
fa: Accel.-mode frequency
n: Integer
Red: floating in fitting

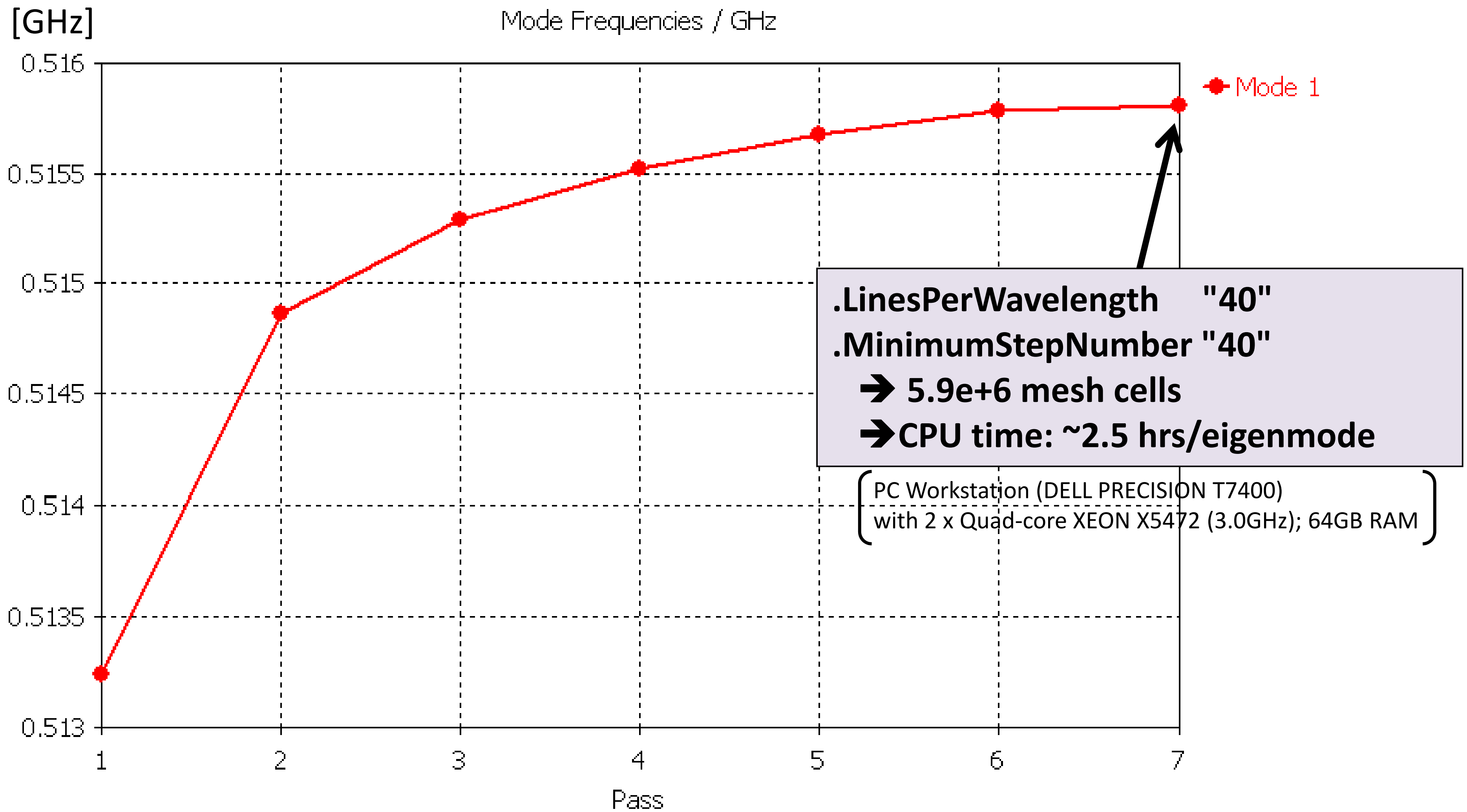


Simplified Model
for Eigenmode Analyses

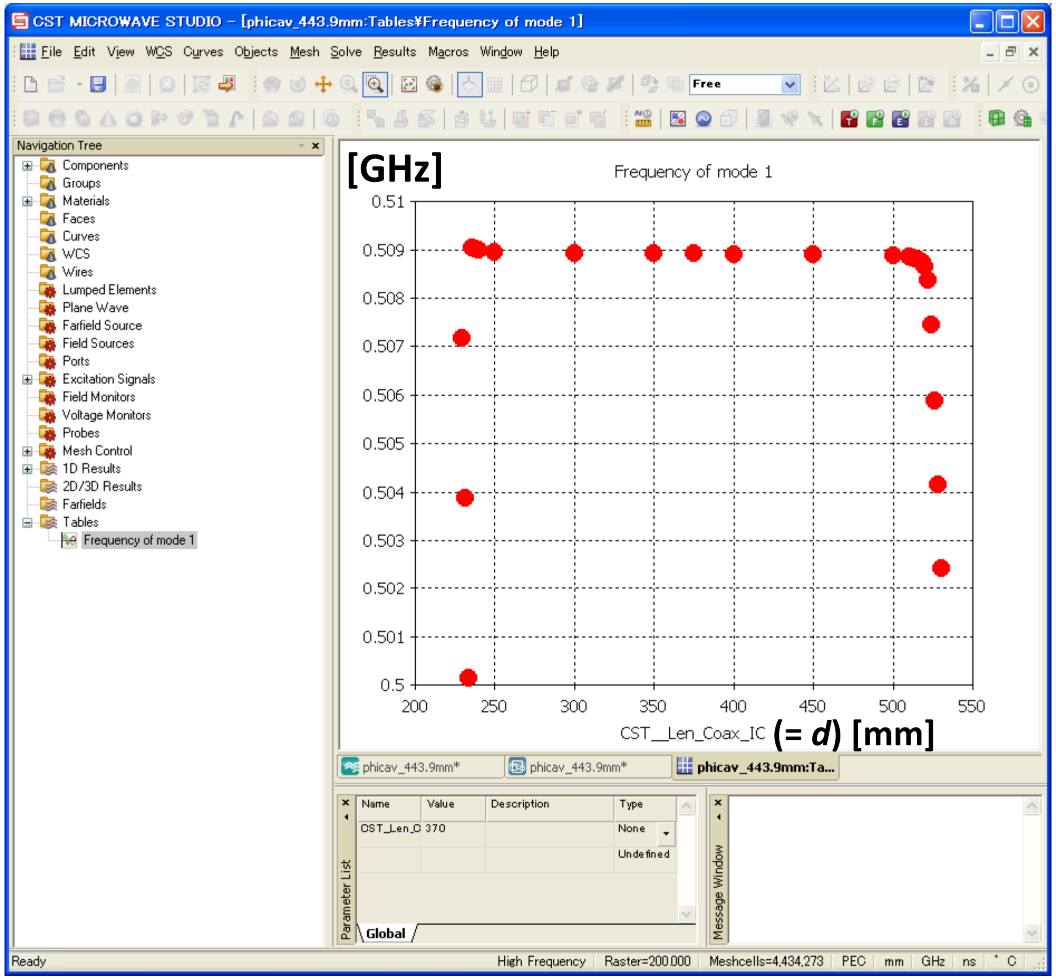


Preparation(1) for Eigenmode Analyses using MWS/JDM

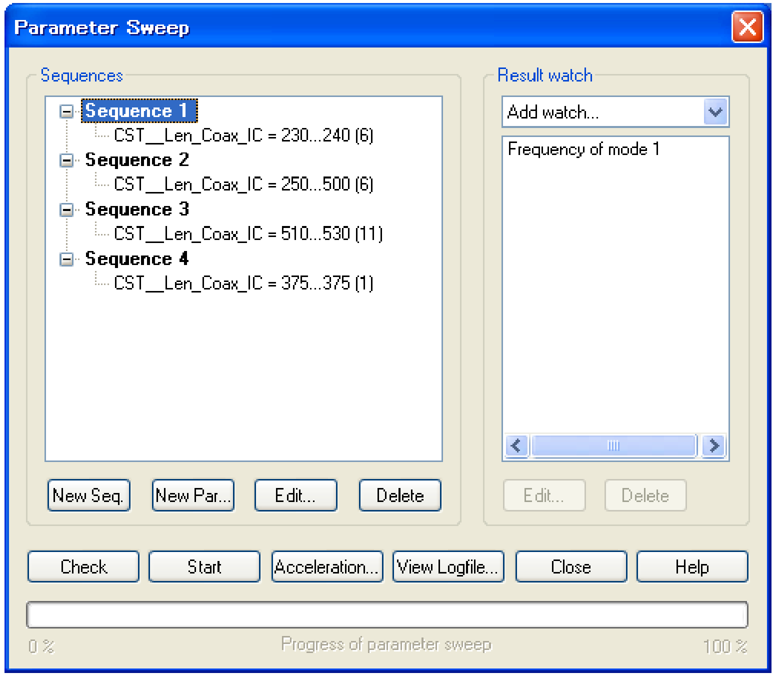
Increase the number of mesh lines so that $\underline{\Delta f_a < 100[kHz]}$

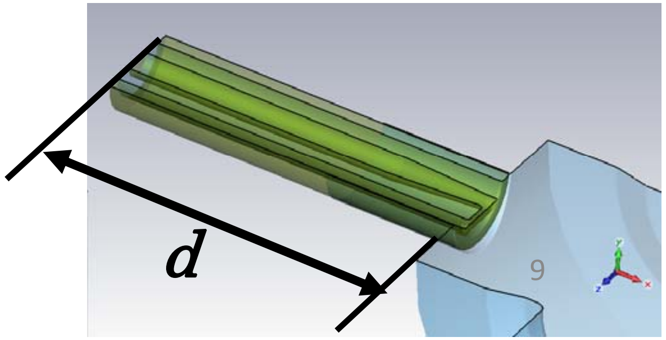


Many Eigenmode Analyses with Different Input-Coupler Length: *d* Performed by MWS Parameter Sweep



E.g.

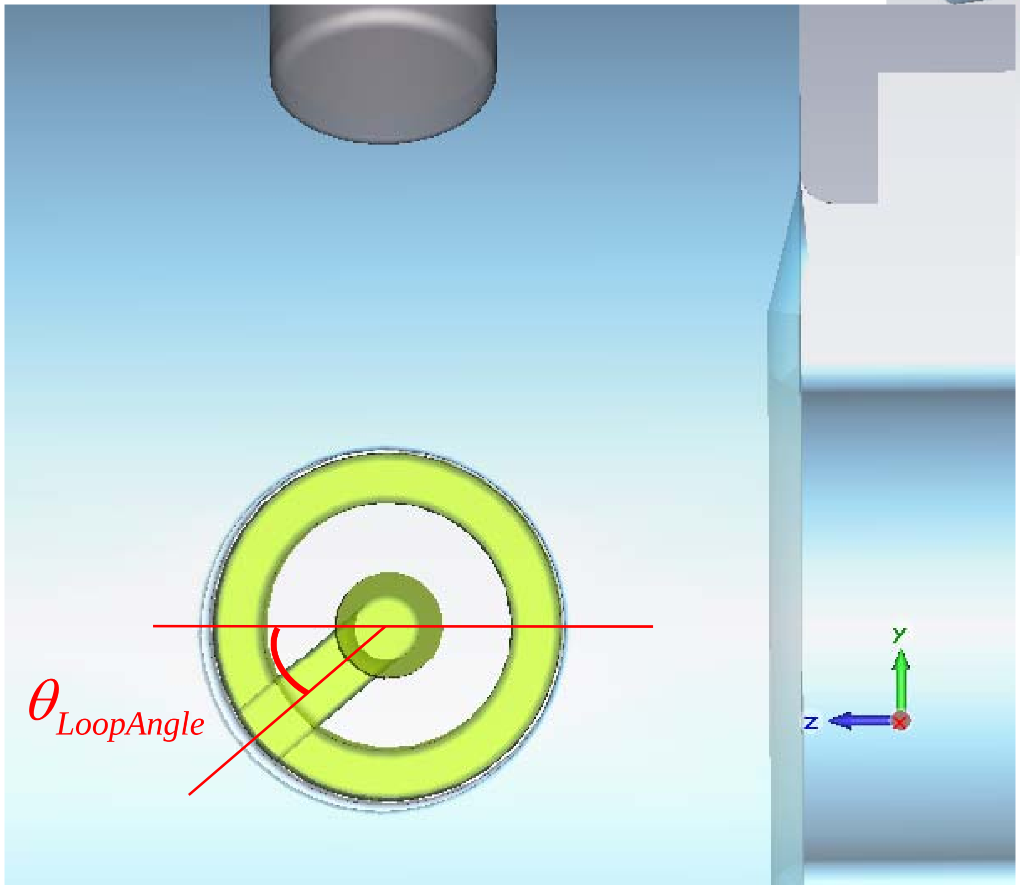


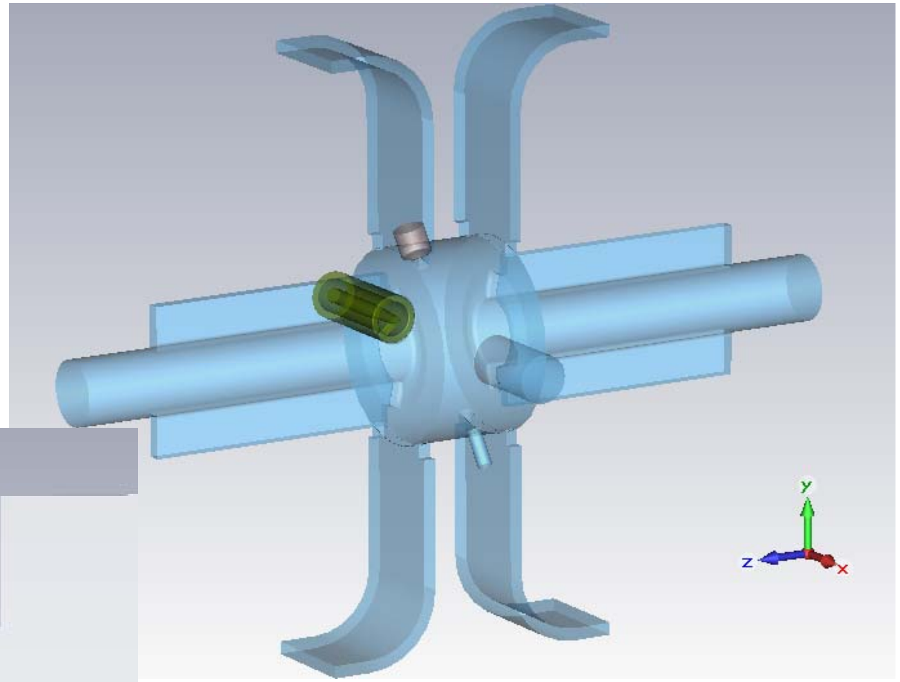


Preparation(2)

Adjust the Coupling Factor:

$$\beta = \frac{Q_0}{Q_{ext}} \quad (\Rightarrow \ \approx 1\,(\text{optimum}\,))$$



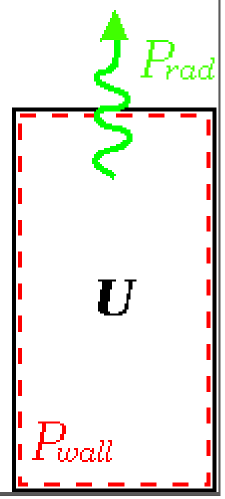


Simplified Model
for Eigenmode Analyses

$$Q_0 = \omega_a \frac{U}{P_{wall}}$$

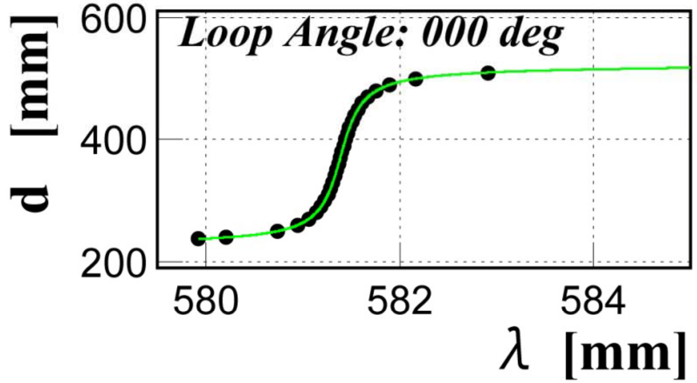
$$Q_{ext} = \omega_a \frac{U}{P_{rad}}$$

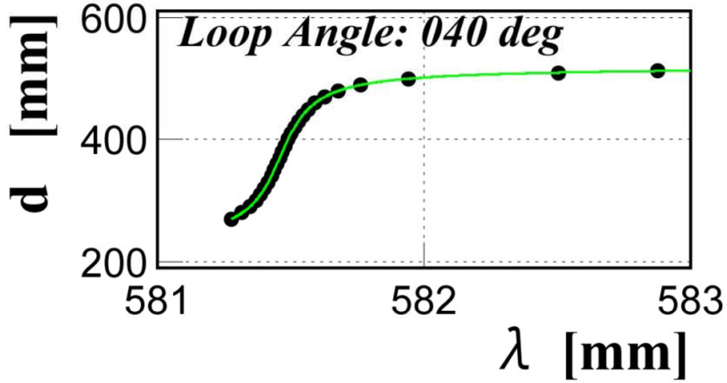
$$\beta = \frac{P_{rad}}{P_{wall}}$$

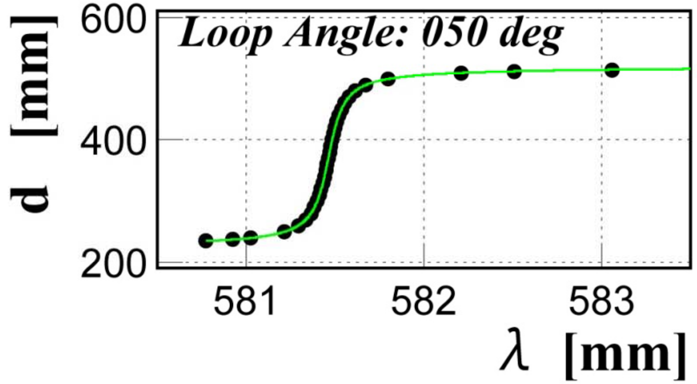


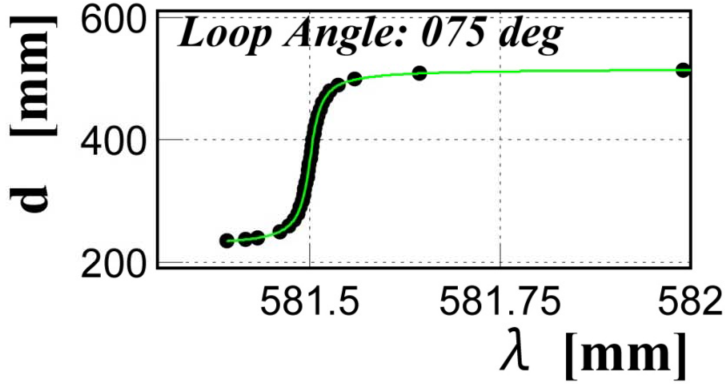
Perform Many Eigenmode Analyses
By MWS Parameter Sweep
for different Input-Coupler Lengths: *d*

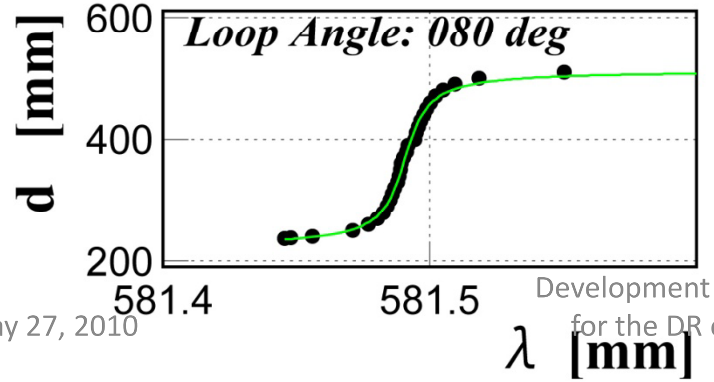
Fit the Results with the Tuning Curves
for Different Loop Angles







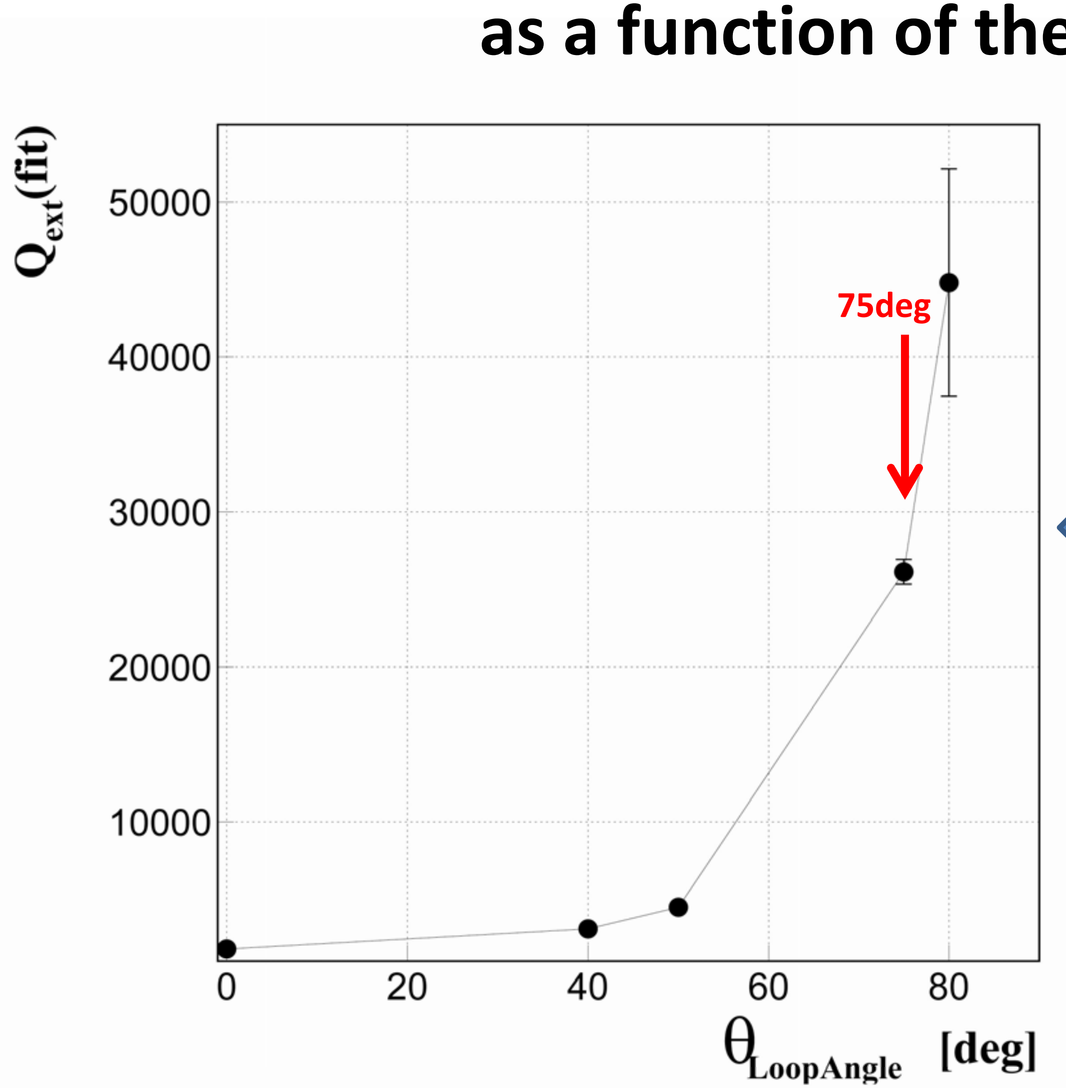




Cavity Diameter: 438mm (KEKB-MR) fixed

Fit with $d - d_0 = \frac{\lambda}{2\pi}\tan^{-1}\frac{1/Q_{ext}}{f/f_a - f_a/f} + \frac{n}{2}\lambda$

Q_{ext} from the Tuning Curves as a function of the Loop Angle

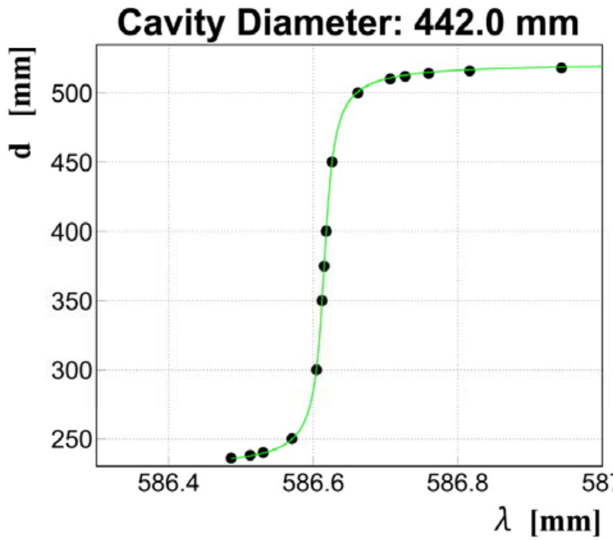


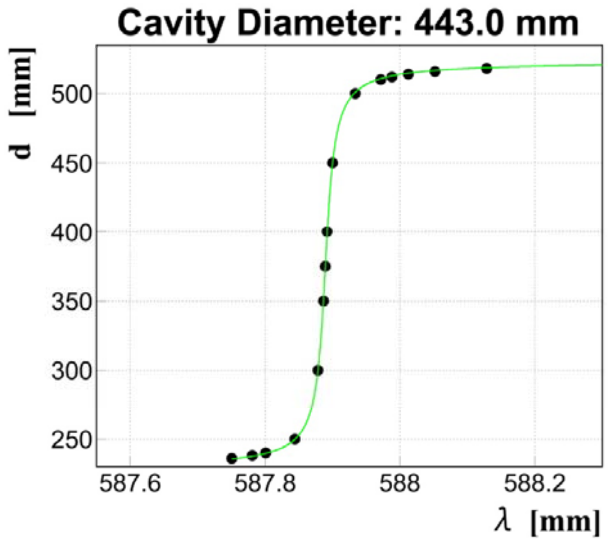
$Q_0 = 29000$ (IACS90%)

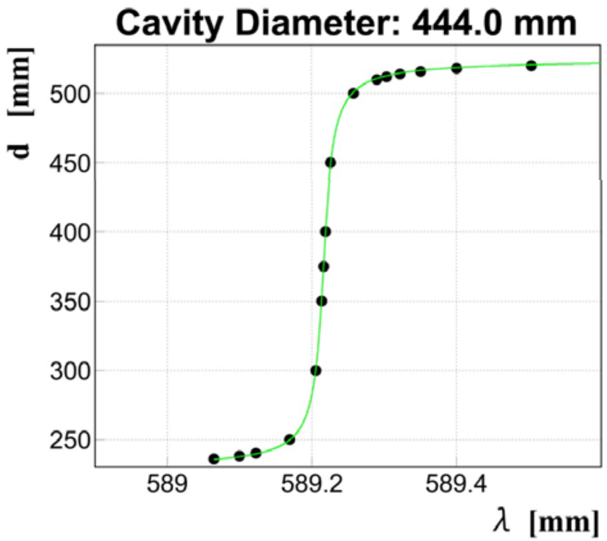
Error bars assuming $\chi^2/ndf \equiv 1$

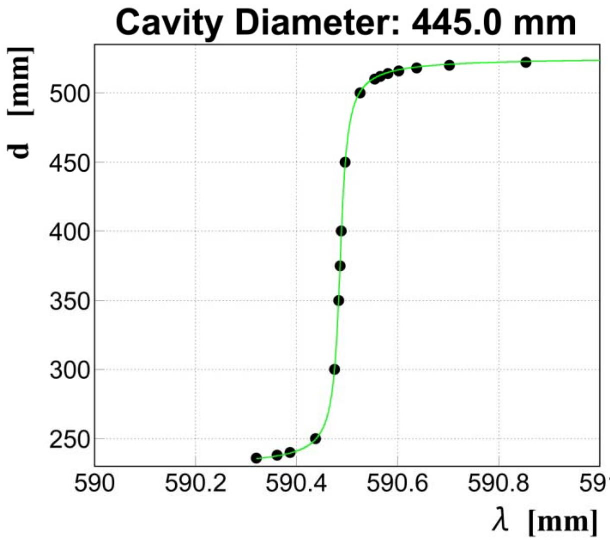
— Fit Results with the Tuning Curves for Different Cavity Diameters

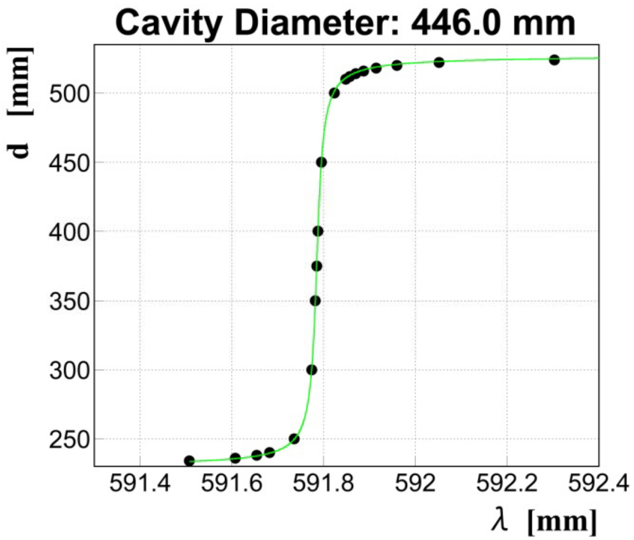
with the Loop Angle: 75deg fixed





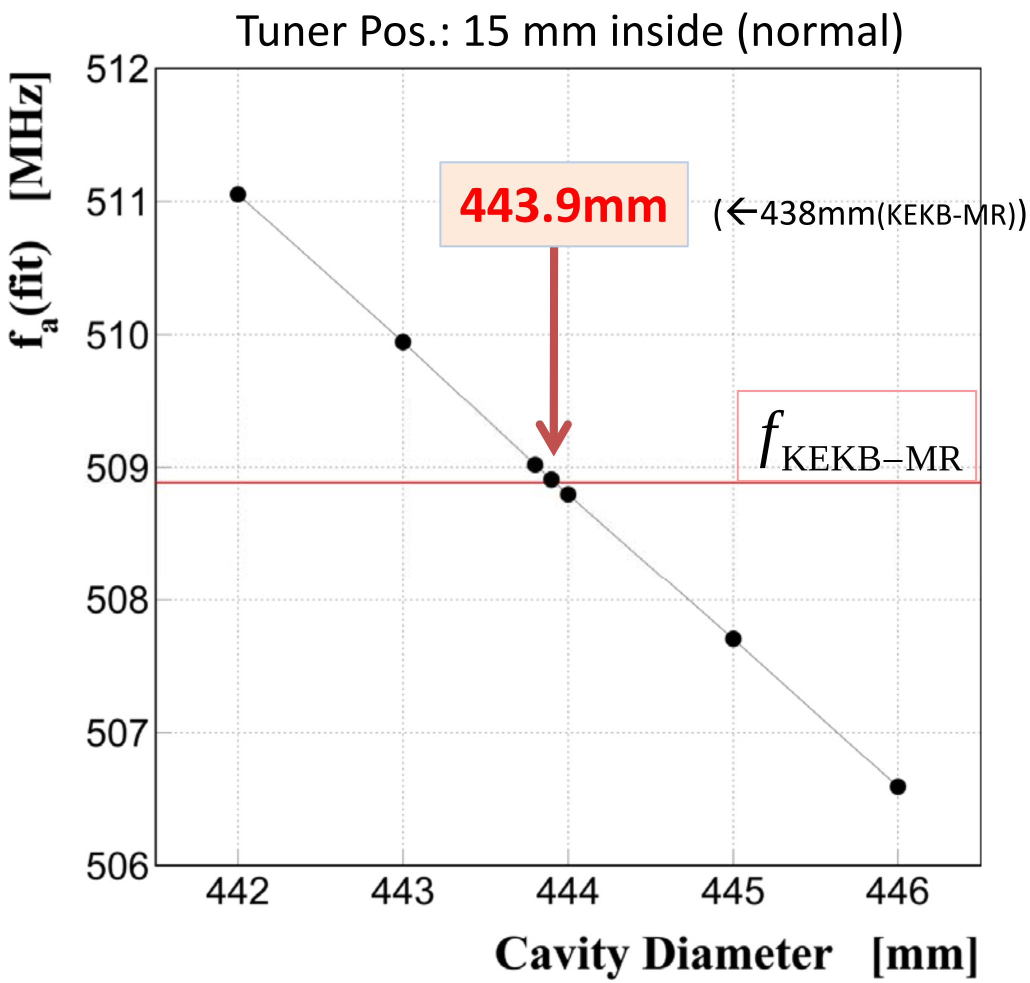


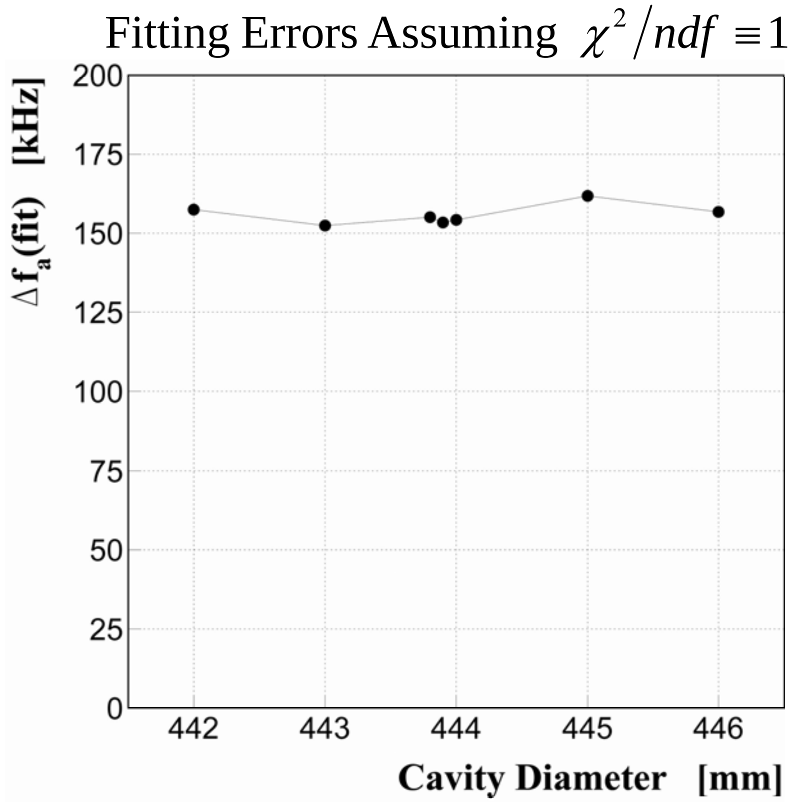




Determination of the Cavity Diameter

from Fitting with the Tuning Curves

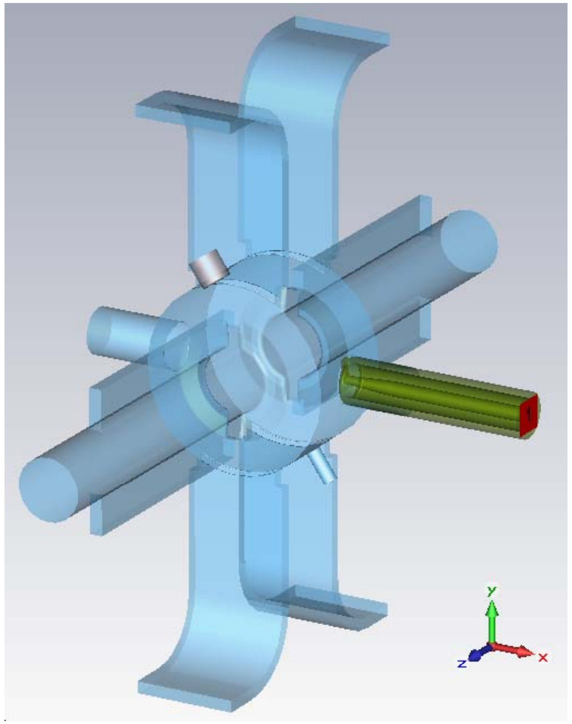




Cross-Check by MWS/FD Solver

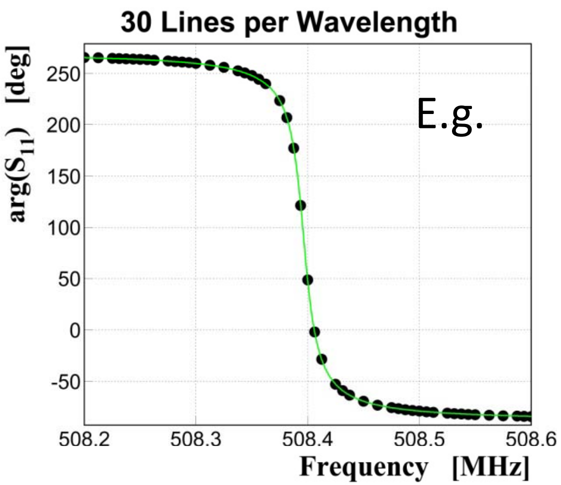
$$\arg(S_{11}) = -2\tan^{-1}\left[Q_{ext}\left(\frac{f}{f_a} - \frac{f_a}{f} \right) \right] + \theta_0$$

(Red: floating parameters in fitting)

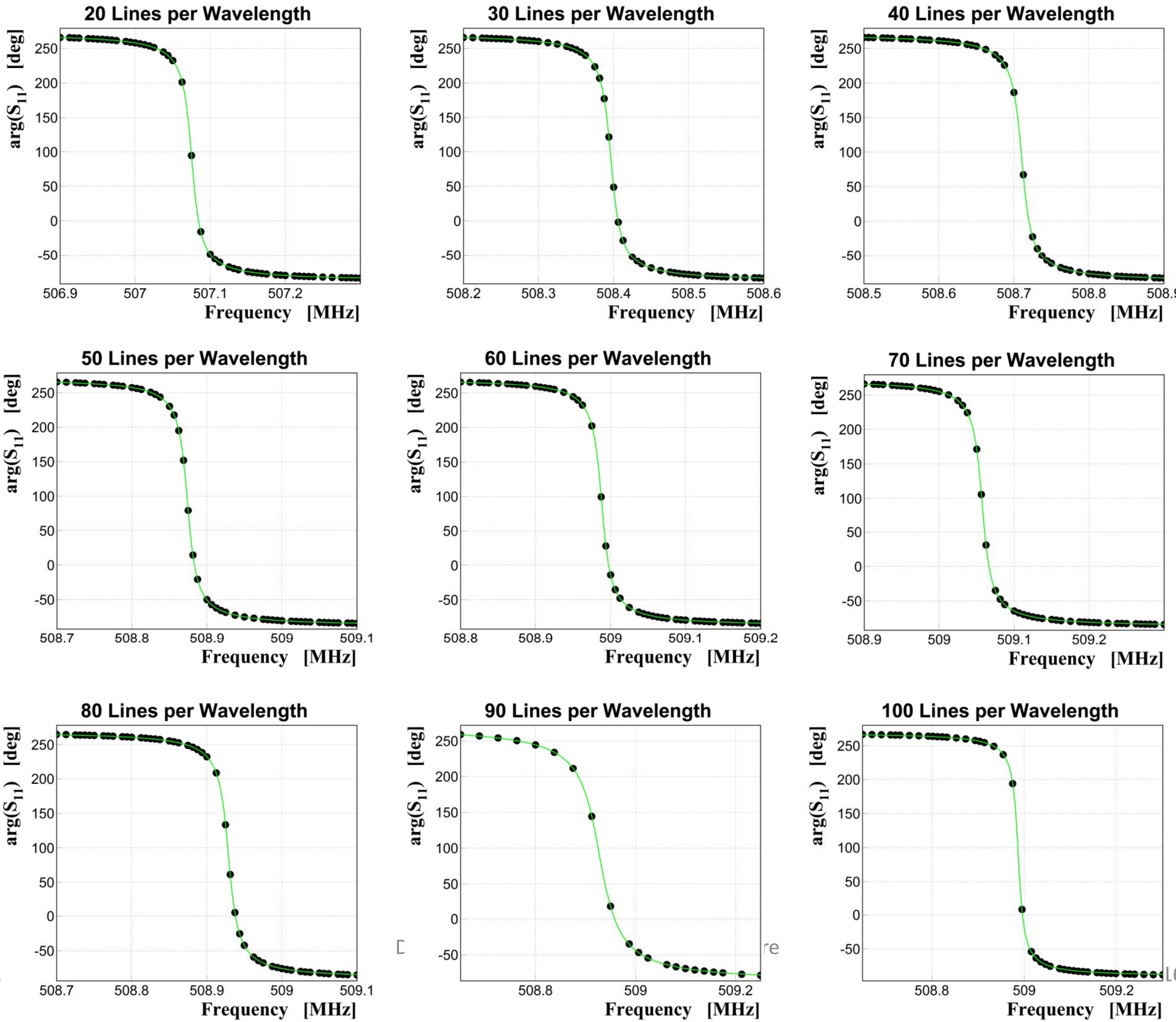


Run the MWS/FD Solver with:

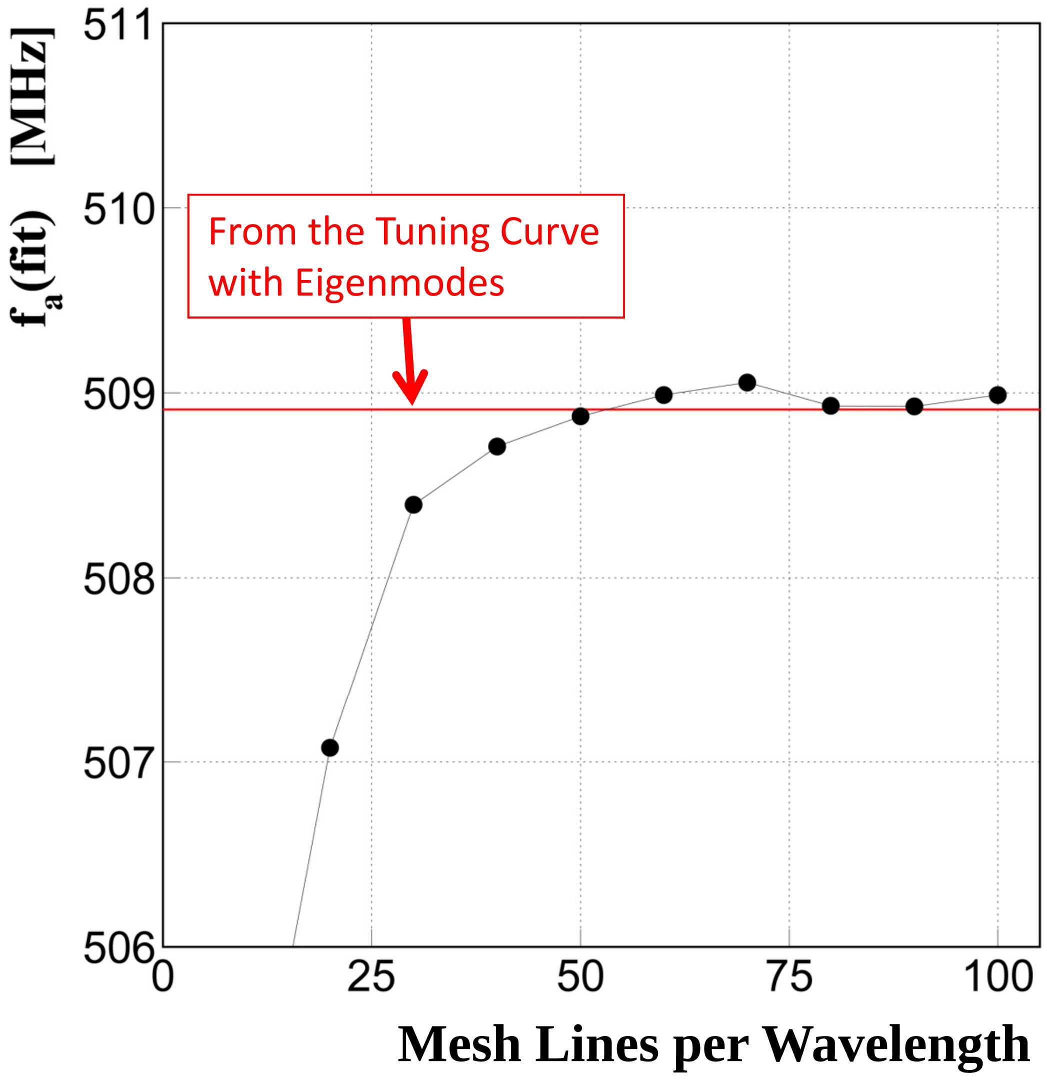
- $f =\sim f_a$
- Mesh Type: Hexahedral



Fit with the above formula

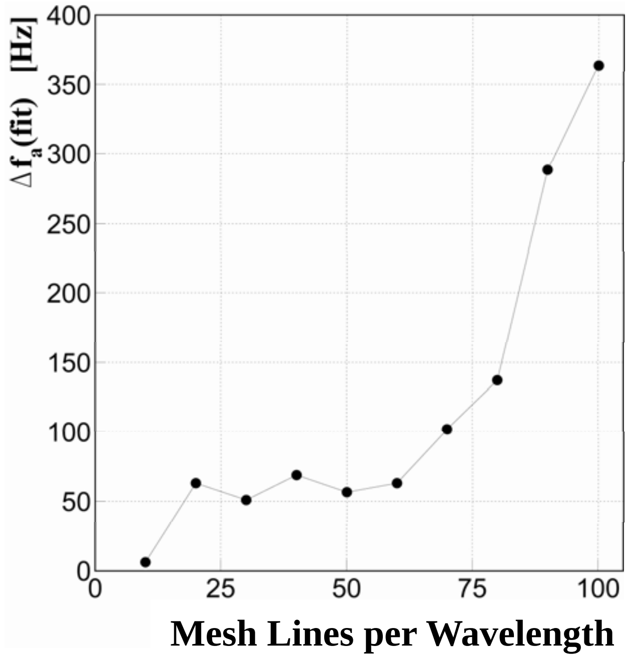

20 Lines per Wavelength
30 Lines per Wavelength
40 Lines per Wavelength
50 Lines per Wavelength
60 Lines per Wavelength
70 Lines per Wavelength
80 Lines per Wavelength
90 Lines per Wavelength
100 Lines per Wavelength
arg(S11) [deg]
Frequency [MHz]

Resonance Frequency from arg(S_{11}) in FD

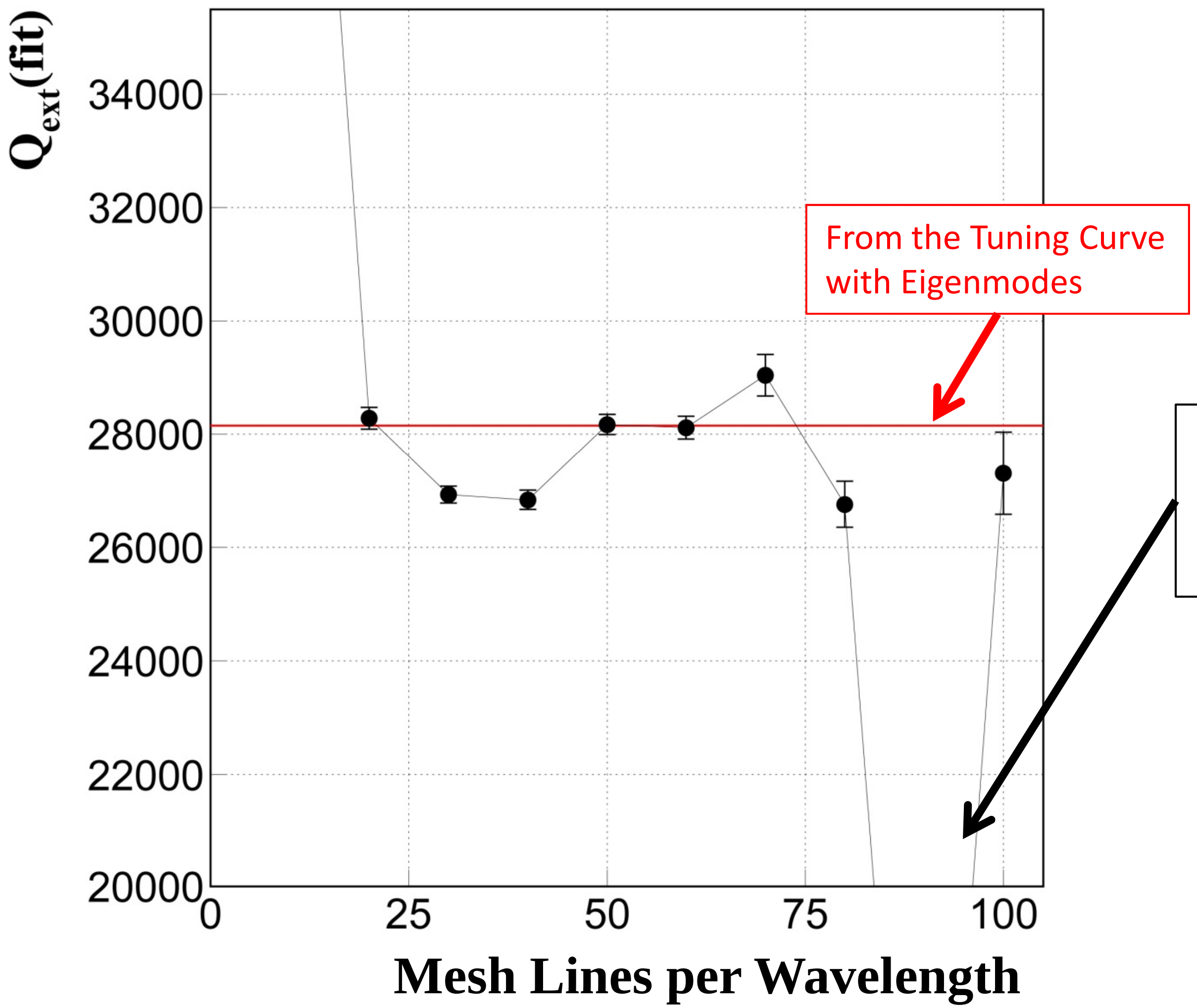


Good Agreement with Δf_a=~100kHz Accuracy

Fitting Errors Assuming $\chi^2/ndf \equiv 1$



Q_{ext} from arg(S_{11}) in FD



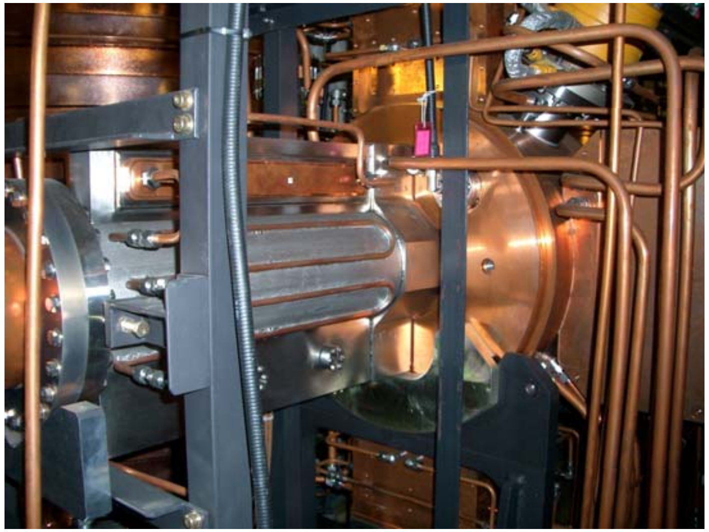
(?) Something is wrong with
.LinesPerWavelength “90"
.MinimumStepNumber “90“.

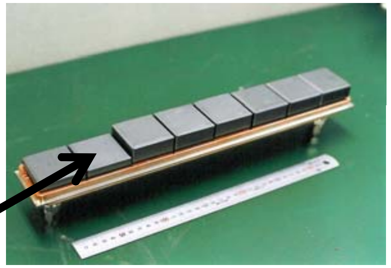
2. Optimization of the New HOM Damper

Current in MR

Grooved Beam Pipe with SiC Tiles Installed

Absorbs Horizontally-Polarized Dipole Mode (TM_{11})

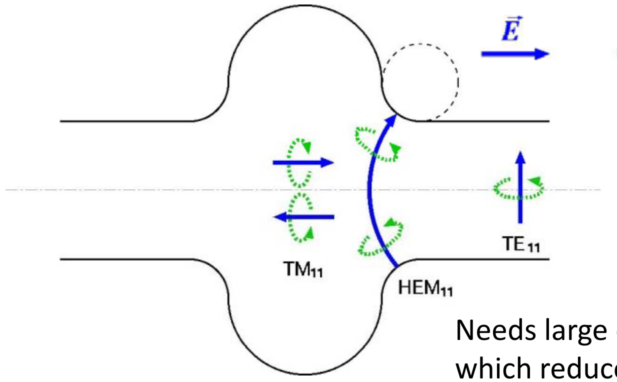




SiC *Indirectly* water-cooled

Cutoff Freq. of TE_{11} in a Regular ϕ150 Duct

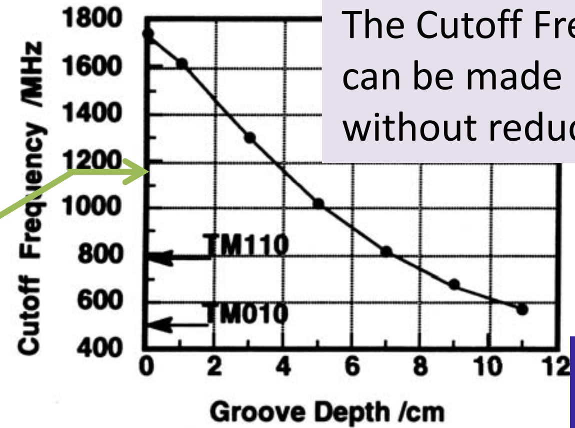
In the case of SC cavities

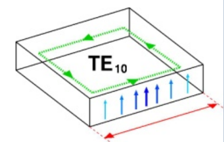


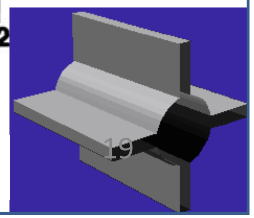
Needs large ducts, which reduce Rsh.

In the case of ARES (NC)

The Cutoff Freq. of TM_{11} can be made lower without reducing Rsh.







(by T. Kageyama using MAFIA)

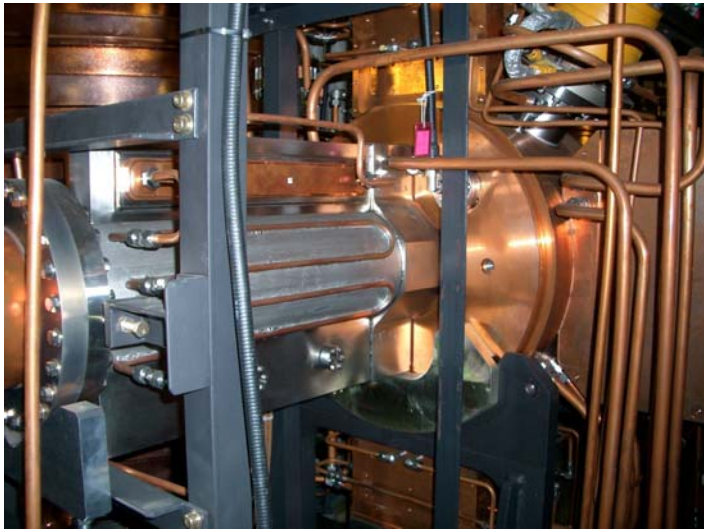
Current in MR

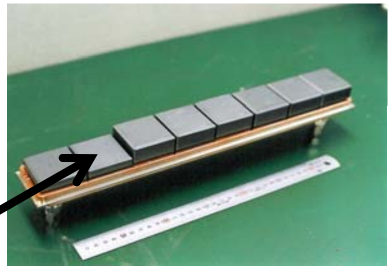
NEW *(More Power Capability)*

Grooved Beam Pipe with SiC Tiles Installed → ***Winged Chamber Loaded with SiC Bullets***

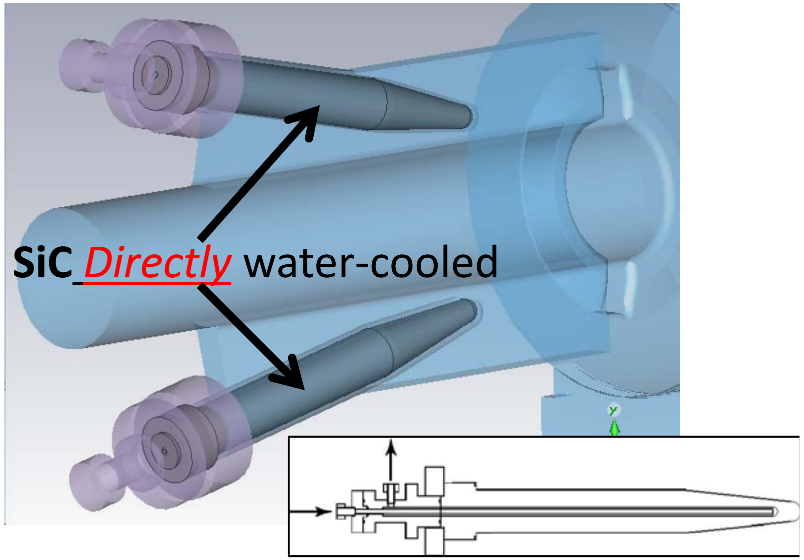
$P_{HOM}^{Capability(1.3\mathrm{GHz})} \approx 1\,\mathrm{kW}$

$P_{HOM}^{Capability(1.3\mathrm{GHz})}$ to be $5\,\mathrm{kW}$





SiC *Indirectly* water-cooled



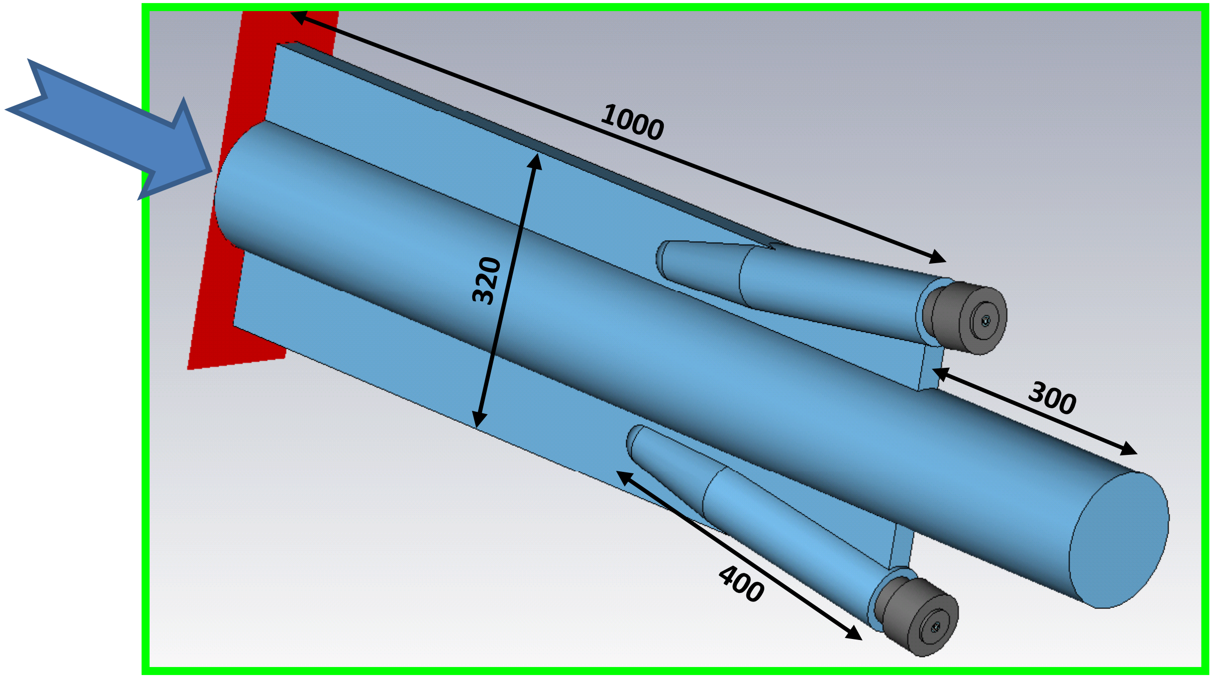
SiC *Directly* water-cooled

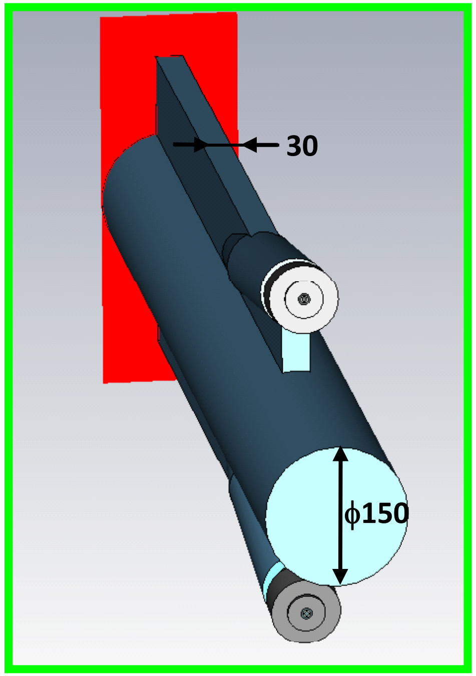
Like the HOM damper
at the Movable Mask Section of KEKB

Y. Suetsugu et al., "Development of Winged HOM Damper for Movable Mask in KEKB", Proc. PAC2003.

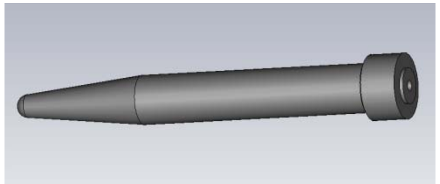
Search for the Best Position and Attitude of the SiC Bullet

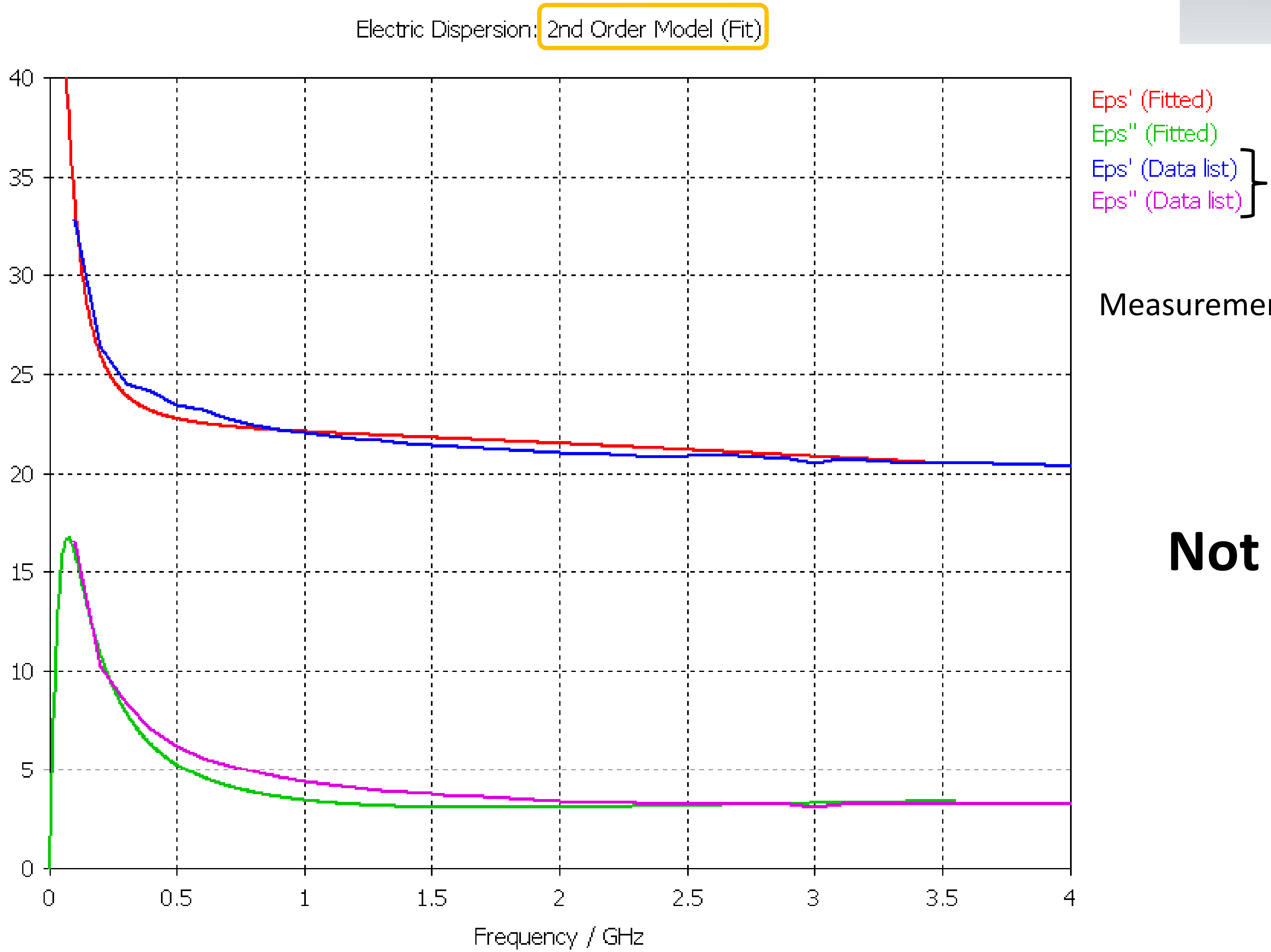
Looking at |S_{11}|
by FD Analyses using MWS
(Tetrahedral mesh)





Permittivity of HEXOLOY for SiC Bullets

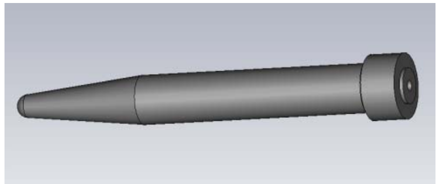


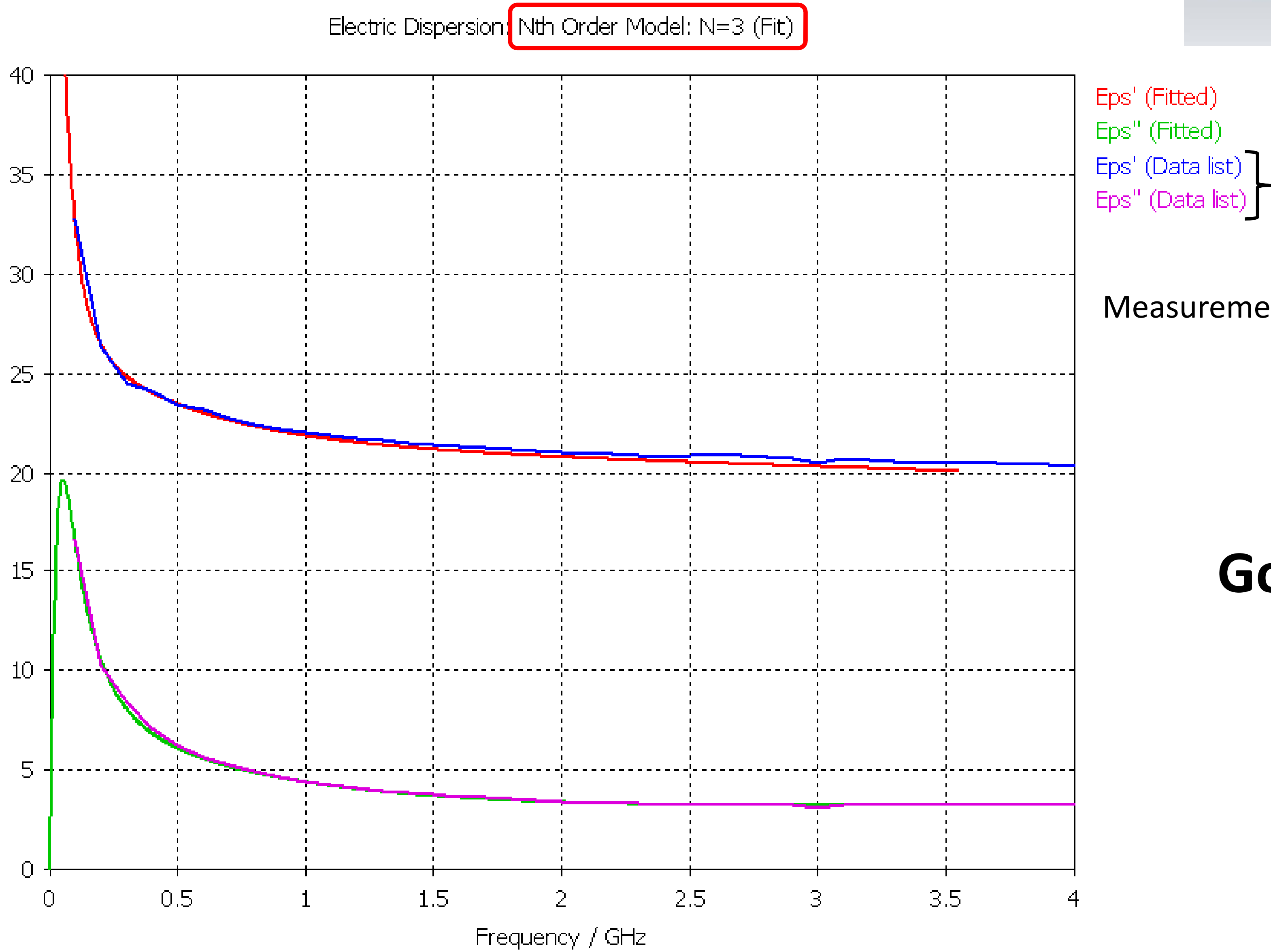


Measurements by Y. Takeuchi

Not Good!

Permittivity of HEXOLOY for SiC Bullets

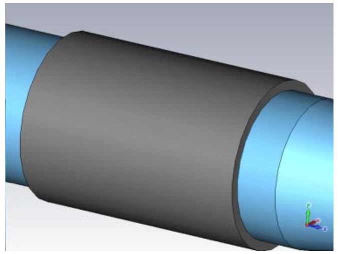


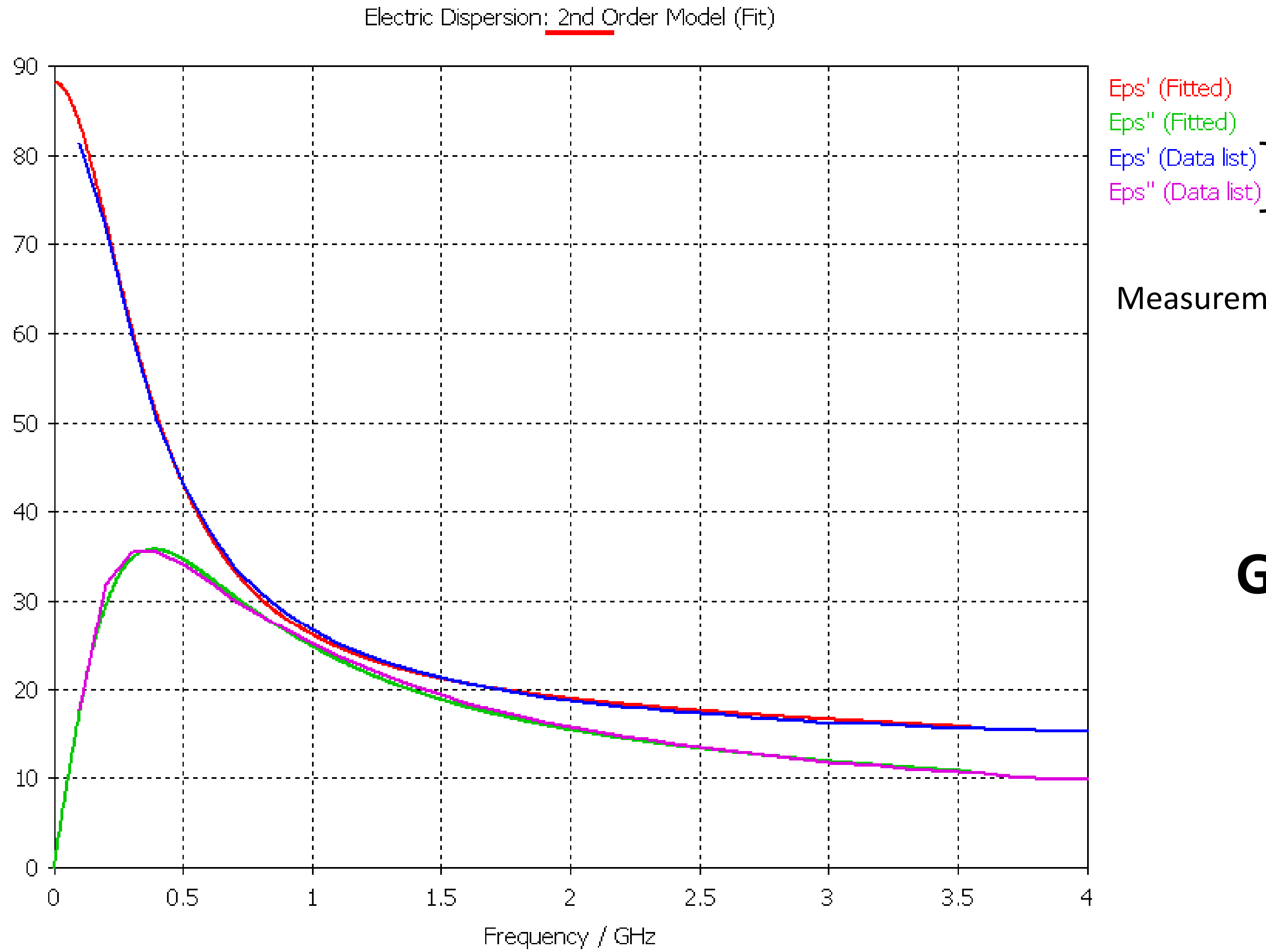


Measurements by Y. Takeuchi

Good!

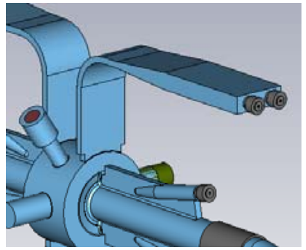
Permittivity of CERASIC-B for SiC Ducts





Measurements by Y. Takeuchi

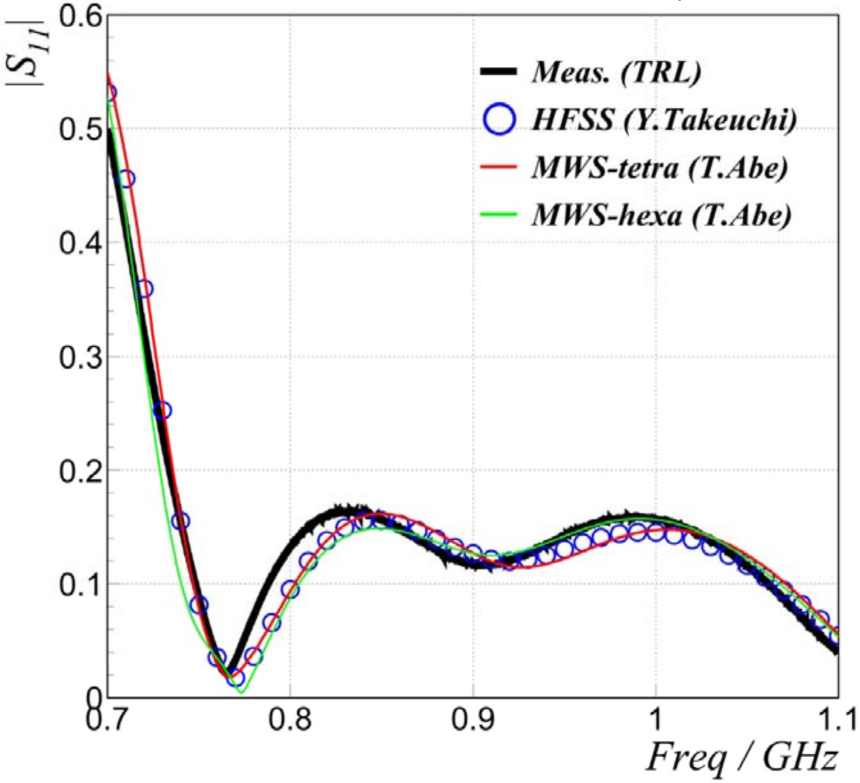
Good !

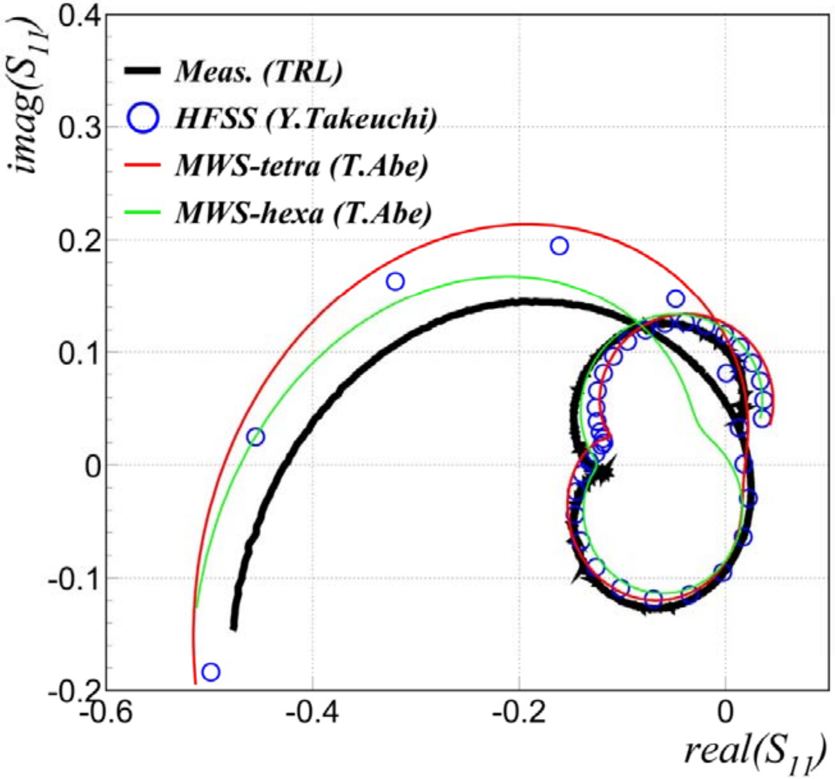


Check if S_{11} by MWS can reproduce the data.

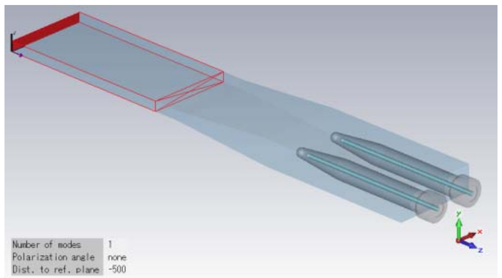
For the WaveGuide-Type HOM Damper

(Measurements by Y. Takeuchi in 2008.07)





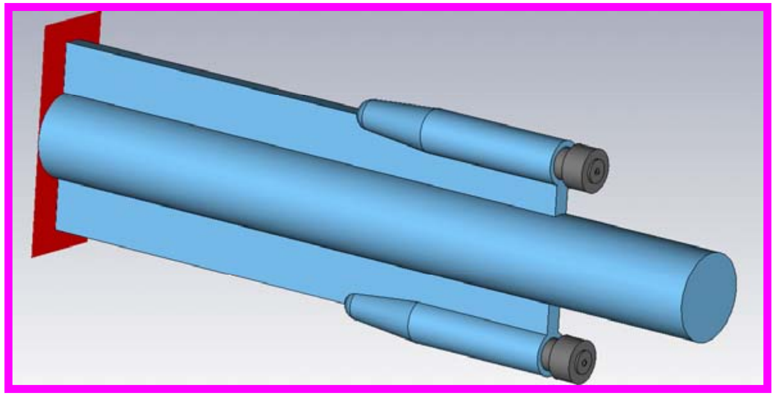
Meas. Setup by Y. Takeuchi



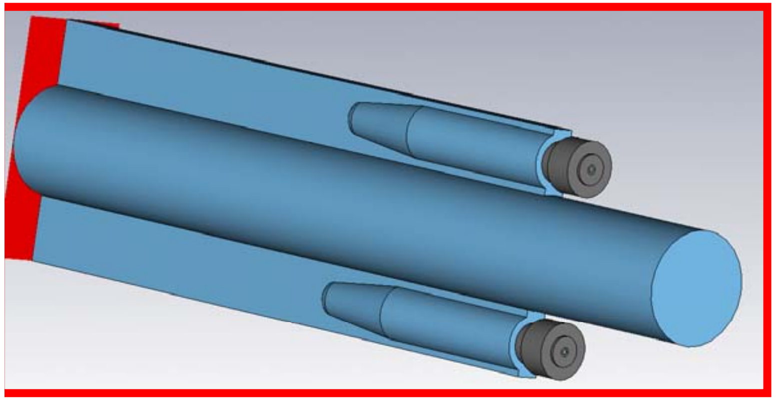
→ **OK!**

Positions to be Considered

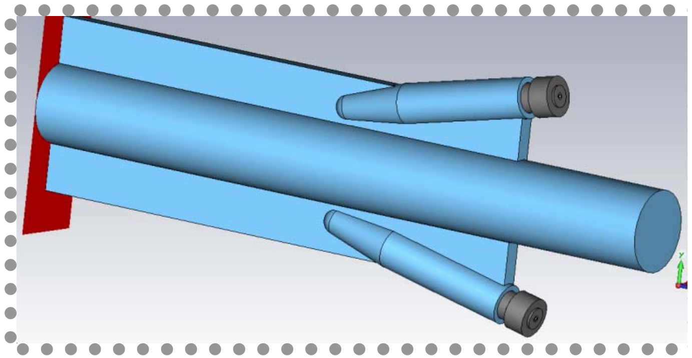
ParaH



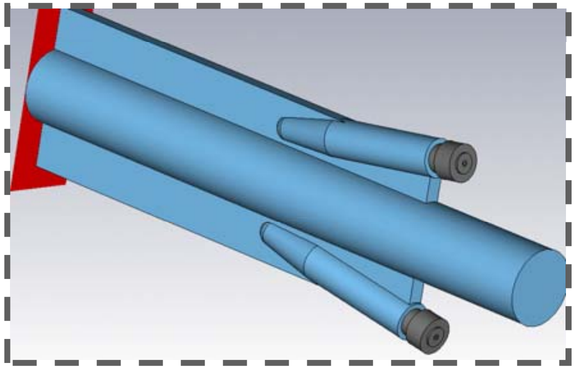
ParaL



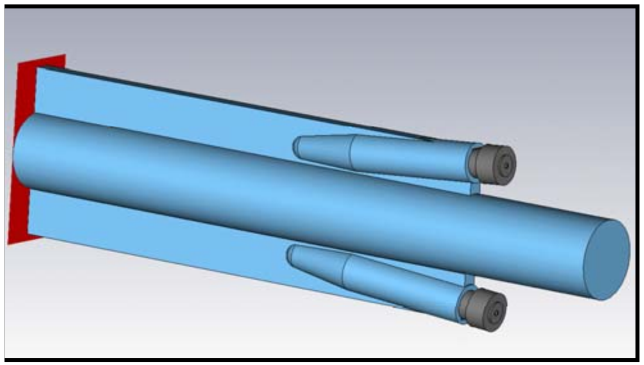
(←Just for reference)



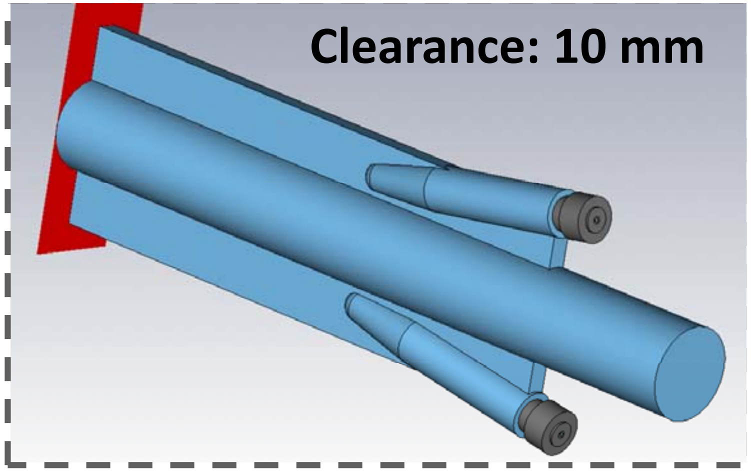
Slope3

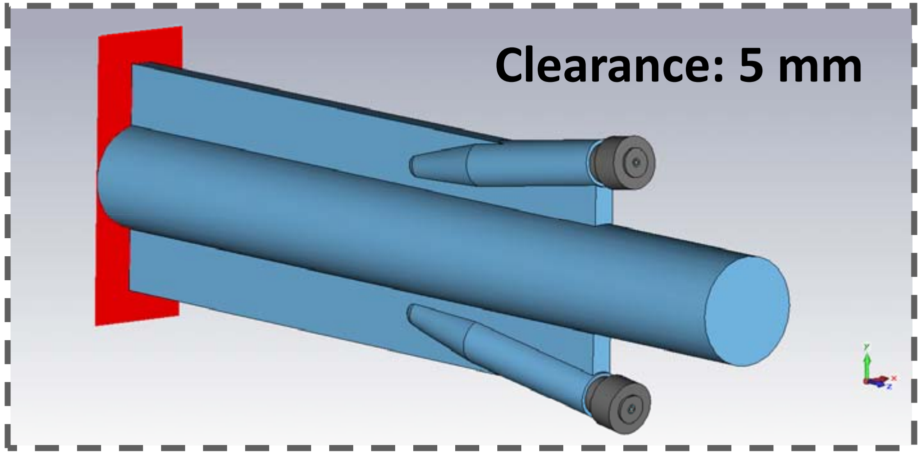


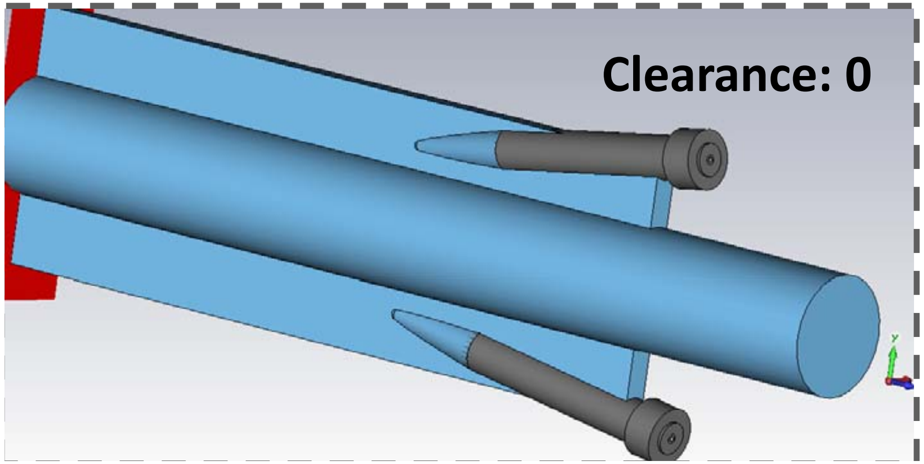
Slope2



Slope1 (←Just for reference)



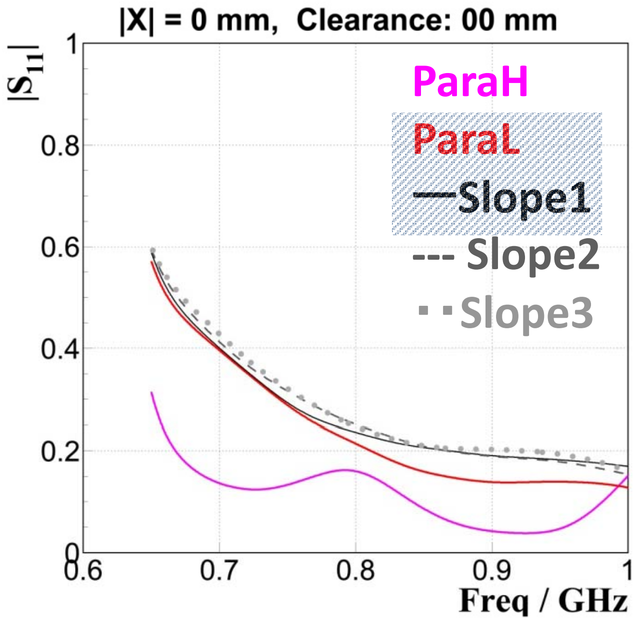




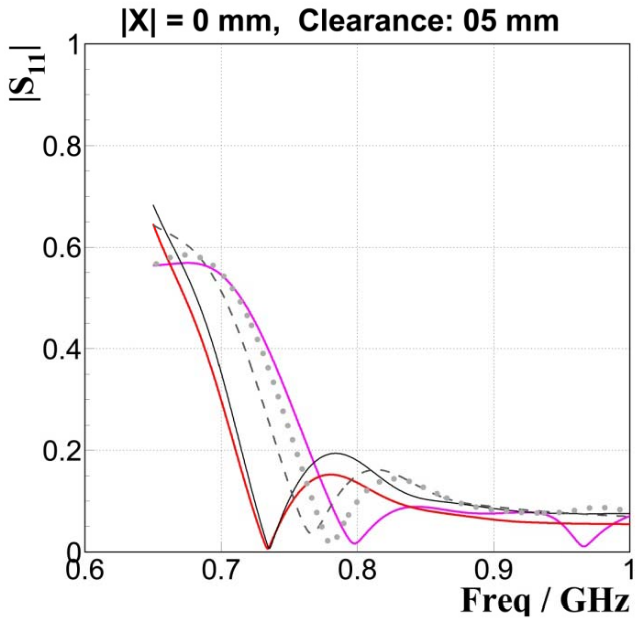
(←Just for reference)

Computation Results

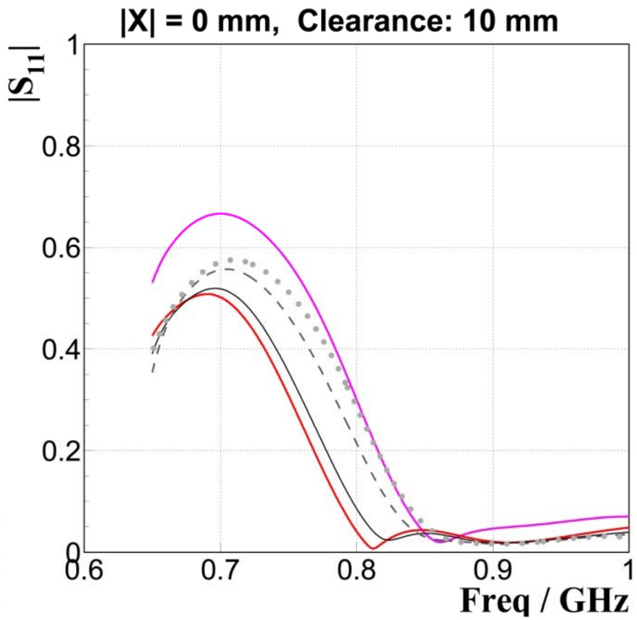
Clearance: 0mm



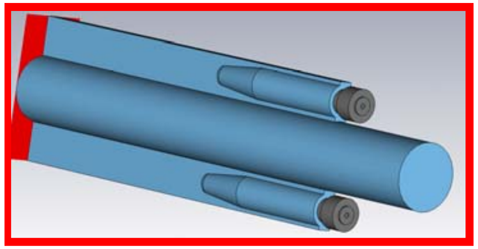
Clearance: 5mm



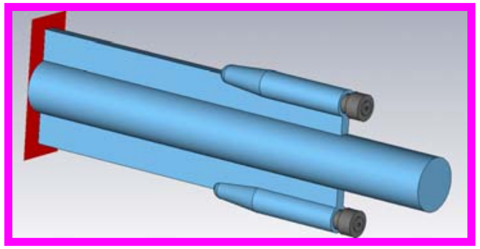
Clearance: 10mm



ParaL

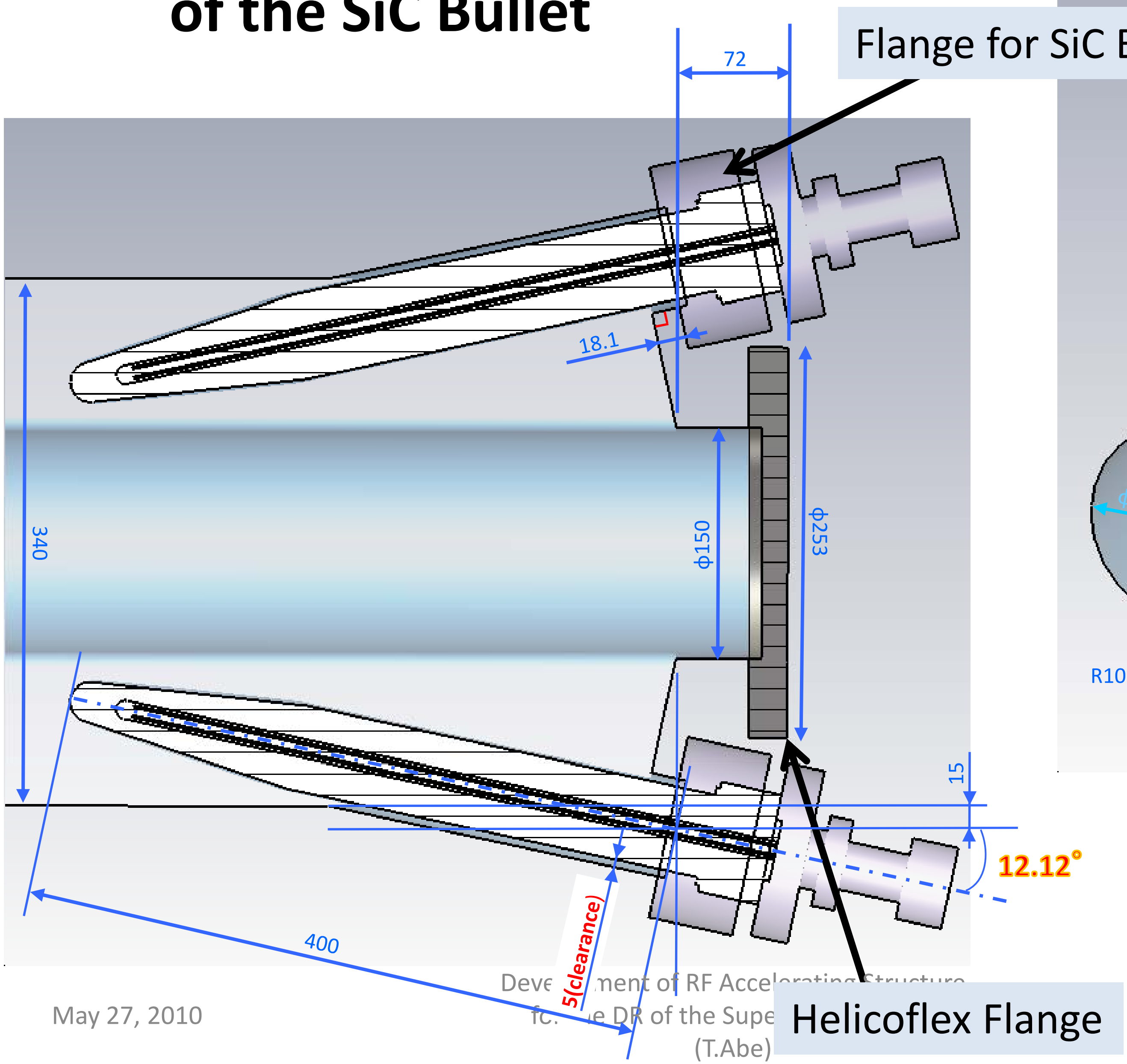


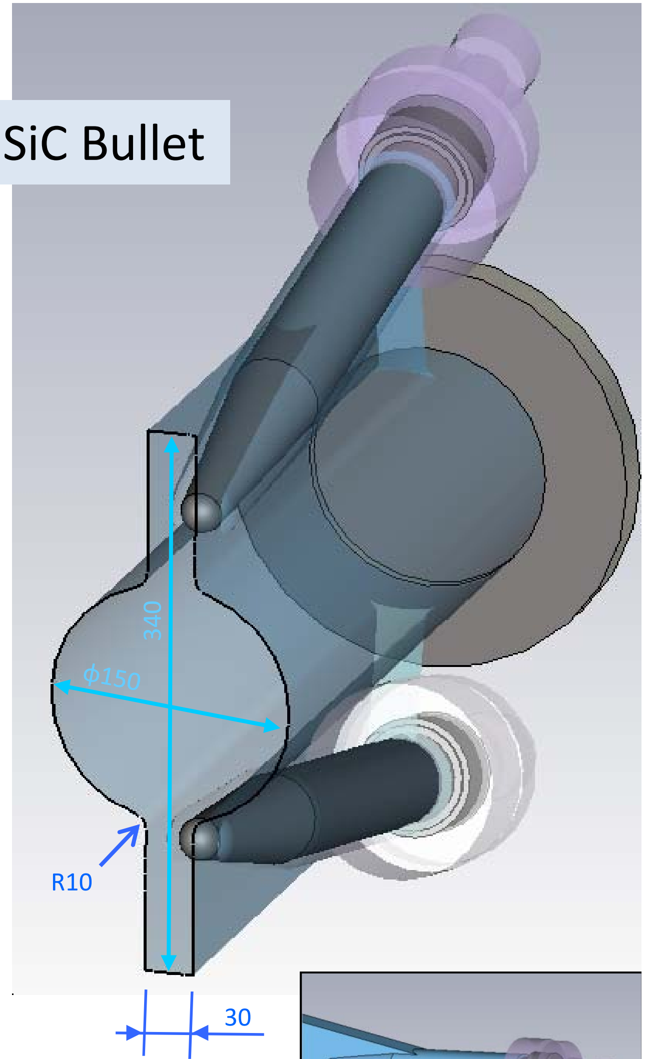
ParaH

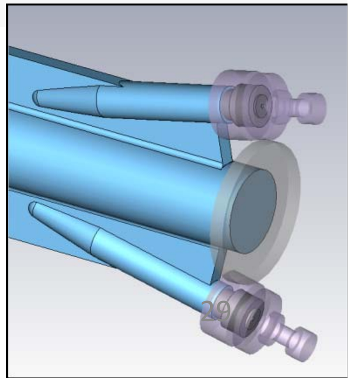


- ParaL:best, ParaH:worst
- Steeper slope worse
- Smaller clearance better

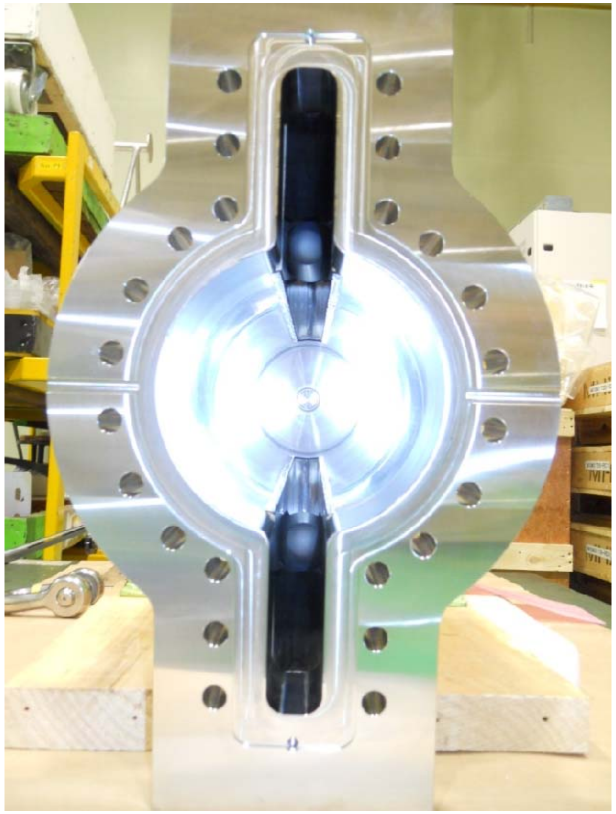
Final Position and Attitude of the SiC Bullet





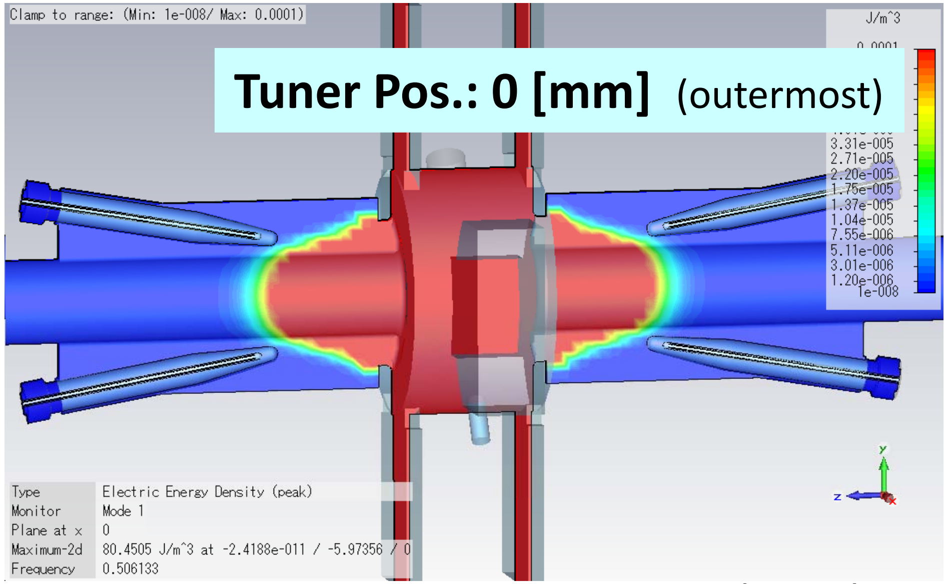


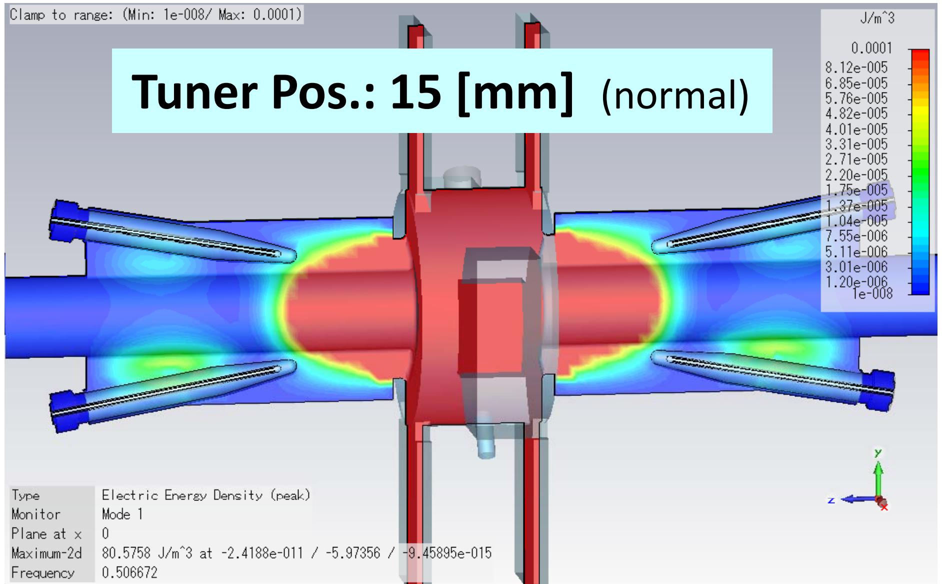
The Winged Chamber Prototype Loaded with SiC Bullets To be High-Power Tested Soon



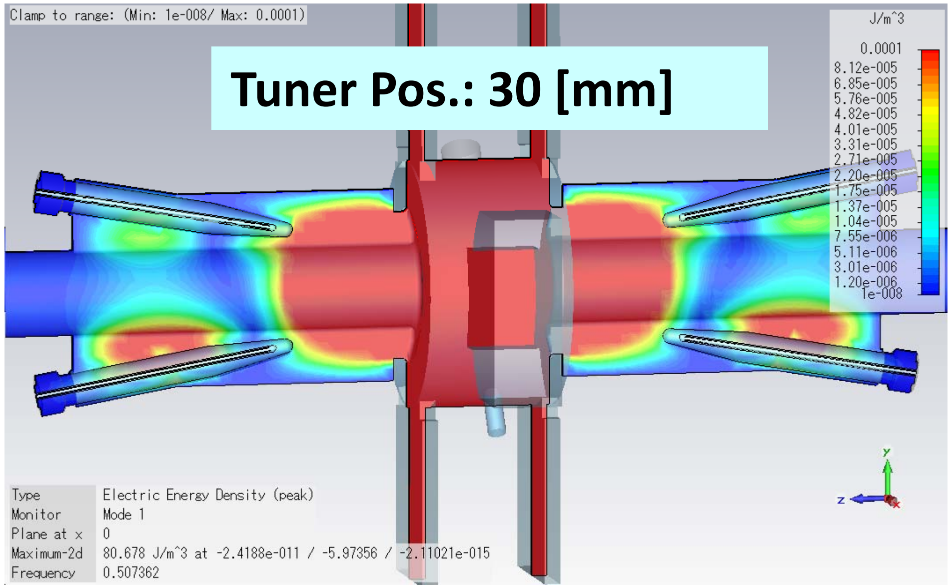
3. Q_0 for HOM Absorbers in the New HOM Damper

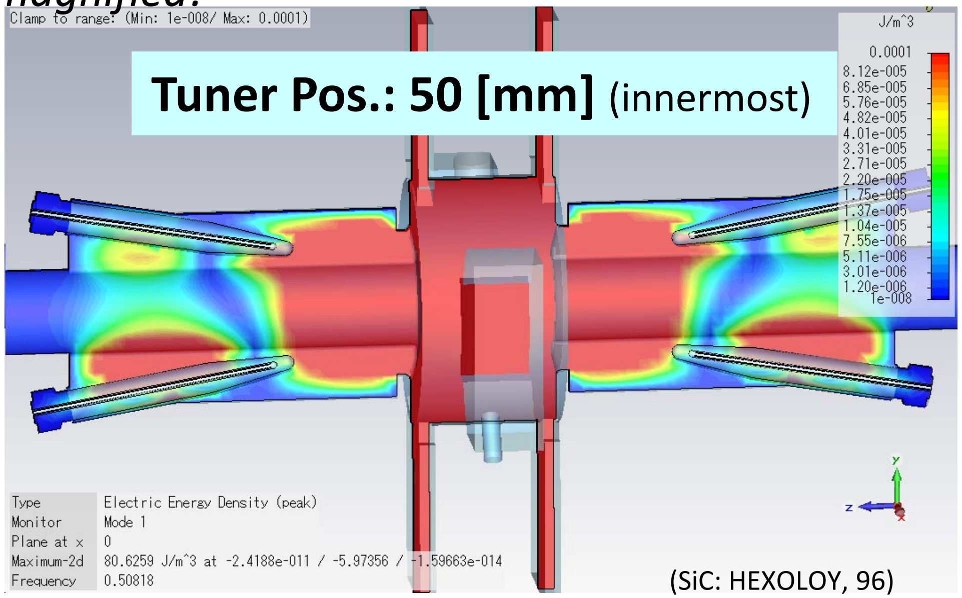
Caution! Leak of the Accelerating Mode heats the SiC Bullets in the GBP
due to the asymmetry caused by the mechanical tuner of the cavity





The tails are magnified!



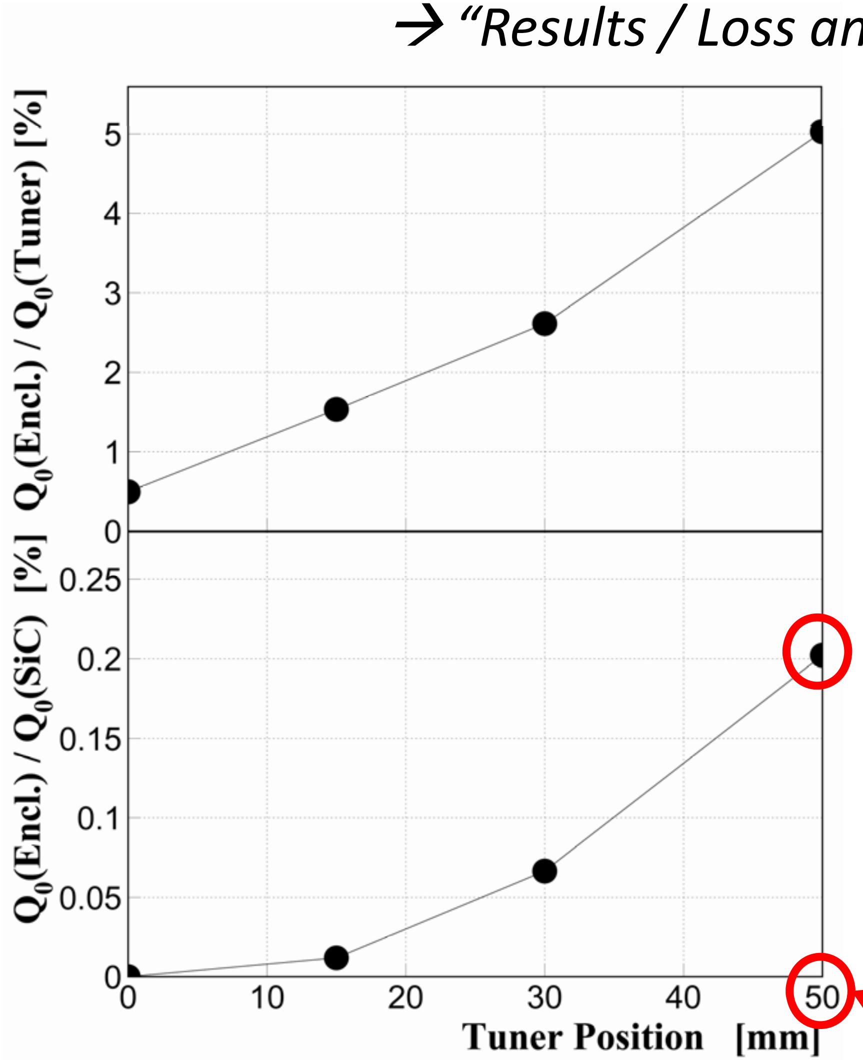


(SiC: HEXOLOY, 96)

Heating Power by the the Accelerating Mode

Estimated in Eigenmode Analyses using MWS

→ *"Results / Loss and Q Calculation" (post-process)*



$$\frac{1}{Q_0} = \frac{1}{Q_0(\text{encl.})} + \frac{1}{Q_0(\text{Tuner})} + \frac{1}{Q_0(\text{SiC})}$$

$$\left(\begin{array}{ll} Q_0 = \omega_a \dfrac{U}{P_{tot}} & Q_0(\text{Tuner}) = \omega_a \dfrac{U}{P_{Tuner}} \\ Q_0(\text{encl.}) = \omega_a \dfrac{U}{P_{encl.}} & Q_0(\text{SiC}) = \omega_a \dfrac{U}{P_{SiC}} \end{array} \right)$$

Max. Heating Power

= Q_0(encl.)/Q_0(SiC) x P_{wall}

= 0.2%/2 x 60kW(max) = **<u>60 W</u>**

<< 5kW (capability/Groove)

4. Longitudinal HOM Impedance and CBIs

Any Troublesome Trapped Modes?

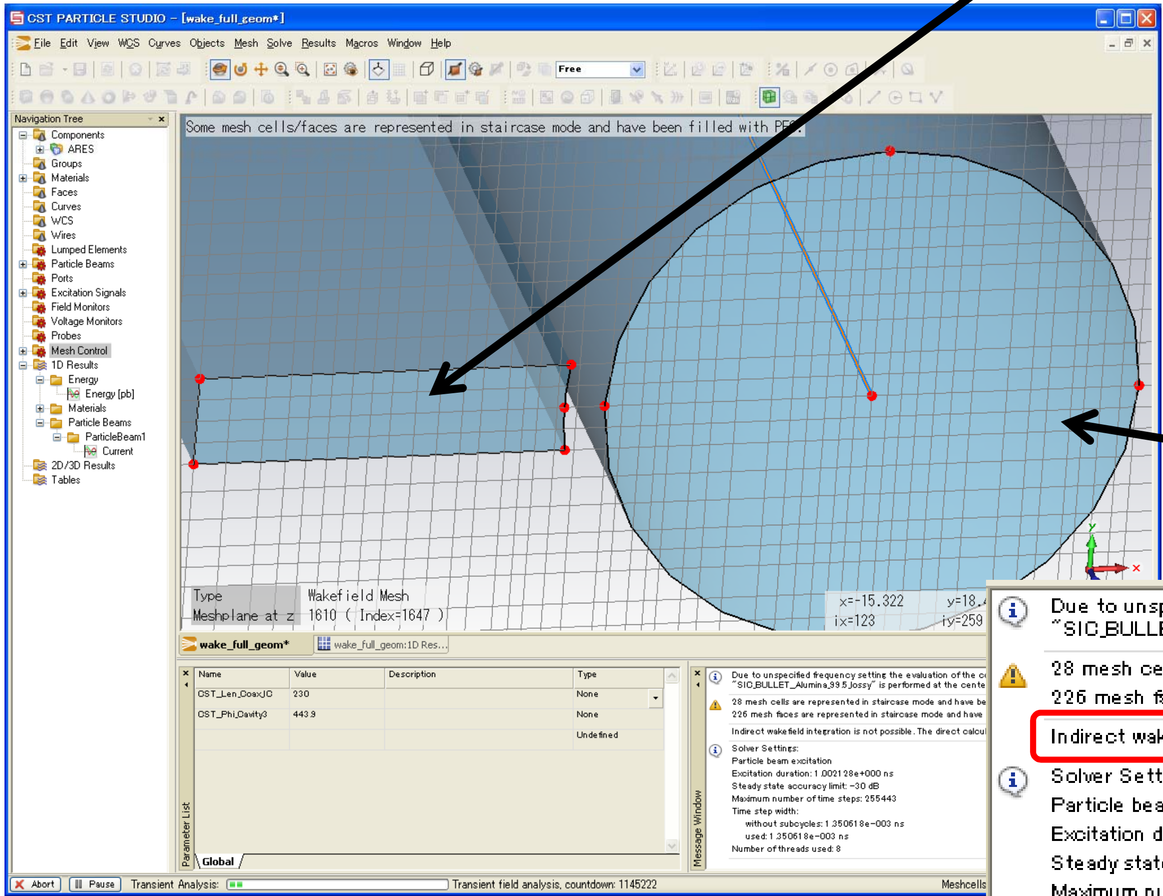
- ■Using **PARTICLE STUDIO** (PS)
- ■ParticleBeam
  - ➢.Length "50" '[mm] (→ Max. beam freq.: 3.547[GHz])
  - ➢.LinesPerSigma "True", "10"
  - ➢.WakeIntegrationType: "Indirect testbeams"
- ■Solver.FrequencyRange "0.5", "3.547" '[GHz]
- ■Mesh
  - ➢.UseRatioLimit "False"
  - ➢.SmallestMeshStep "1.0" '[mm]
- ■Without the Extraction Line
- ■Tuner Pos.: 15mm inside (normal)
- ■Loop Angle of the Input Coupler: 75[deg]
- ■Full geometry (no symmetry plane)
  - →223e6 Meshcells
- ■SolverParameter.MaximumNumberOfThreads: "8"

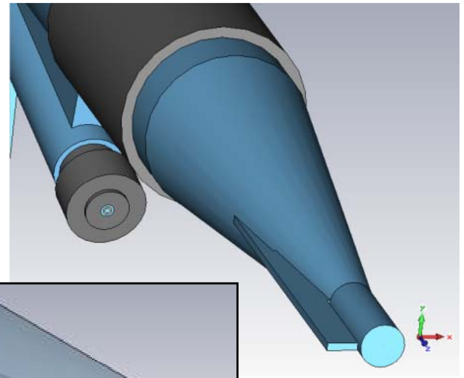
◆Peak Physical memory: 27[GB]

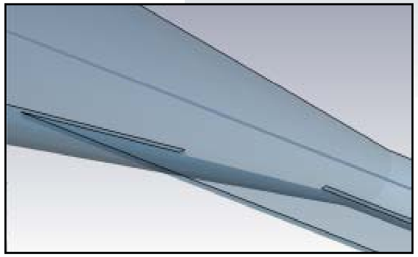
◆Elapsed time for "s_{max}=12m": 65[hrs]

(PC Workstation (DELL PRECISION T7400)
with 2 x Quad-core XEON X5472 (3.0GHz); 64GB RAM)

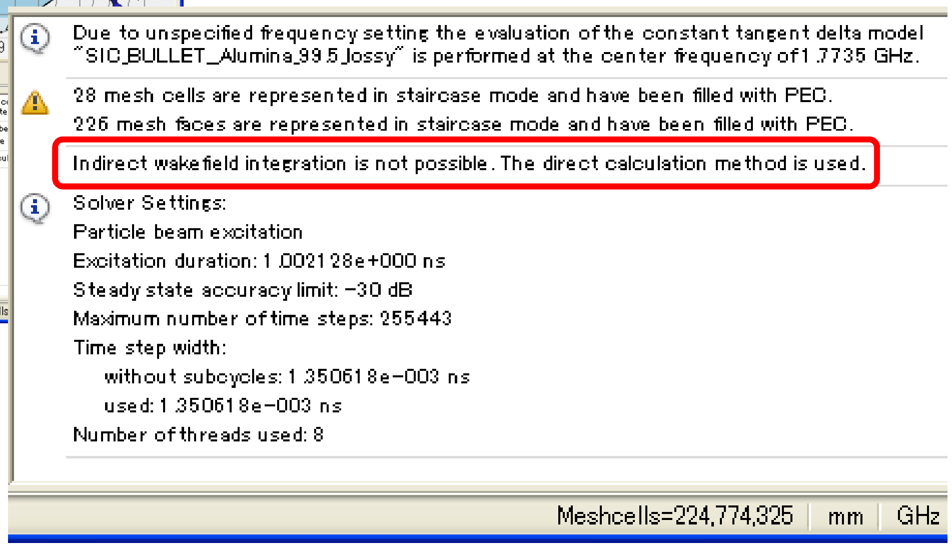
With the Extraction Line…



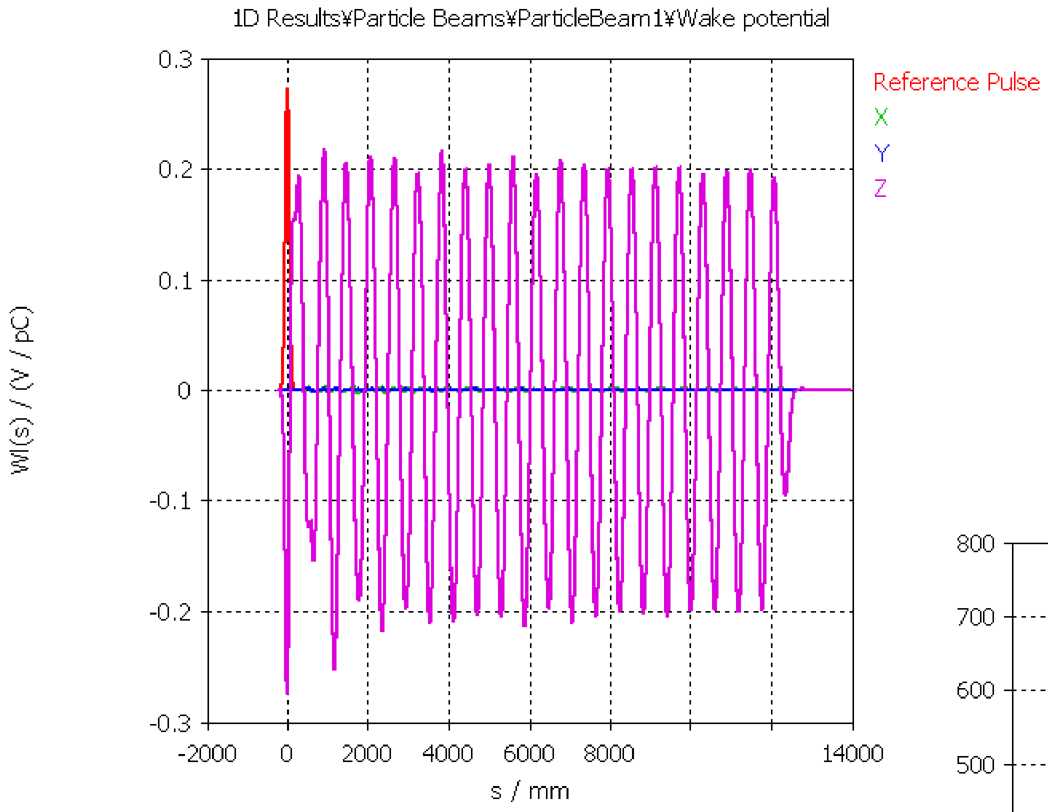




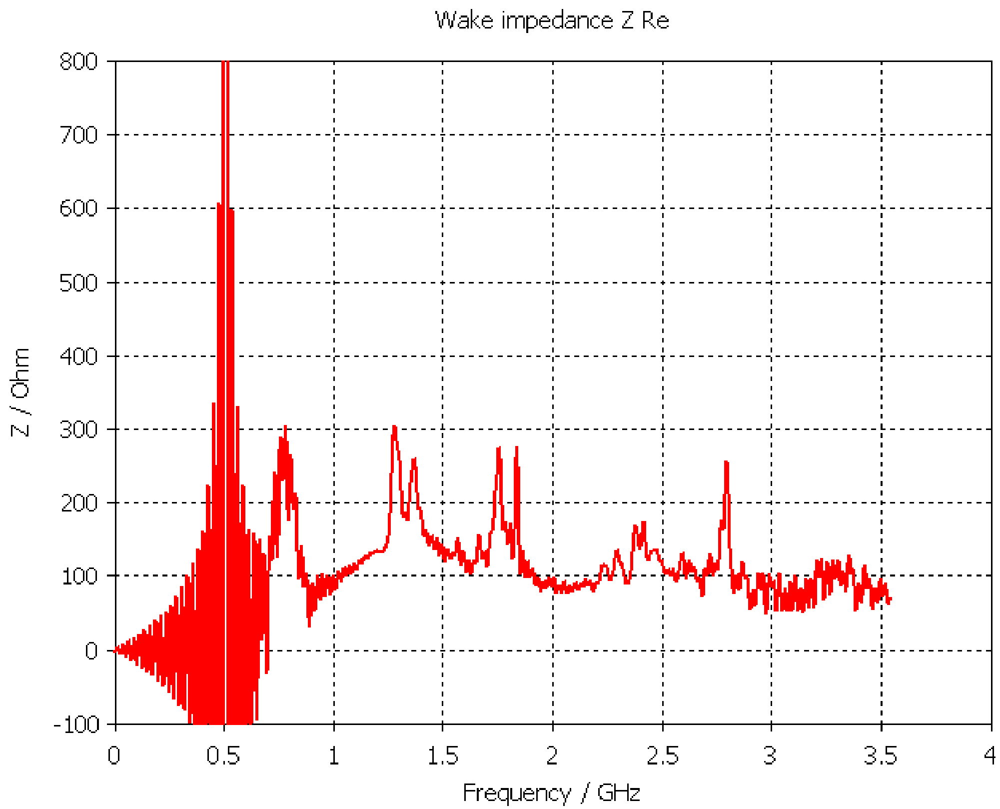
The regular beam duct of the DR



Computation Results

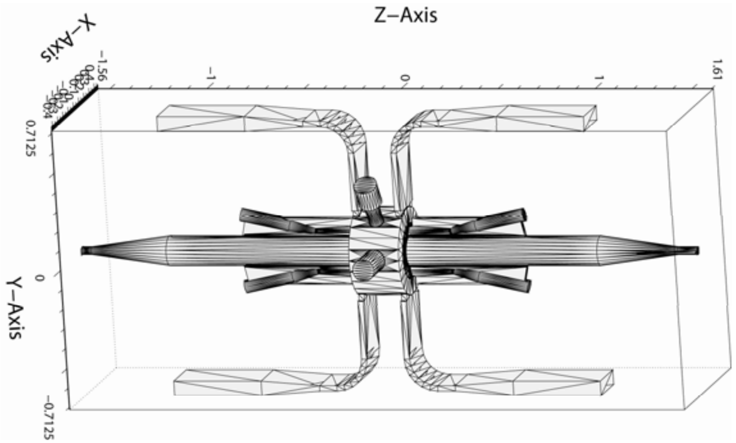


Smax = 12 [m]



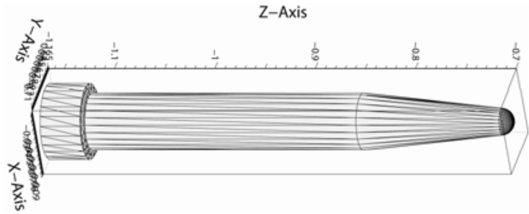
Comparison with GdfidL (www.gdfidl.de)

Geometry Conversion via STL

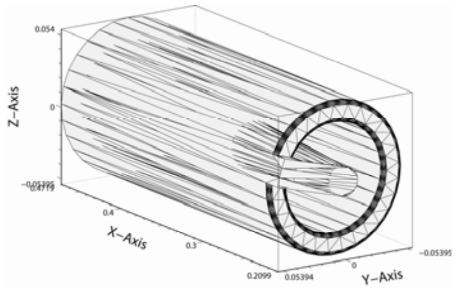


Cavity (Vacuum)

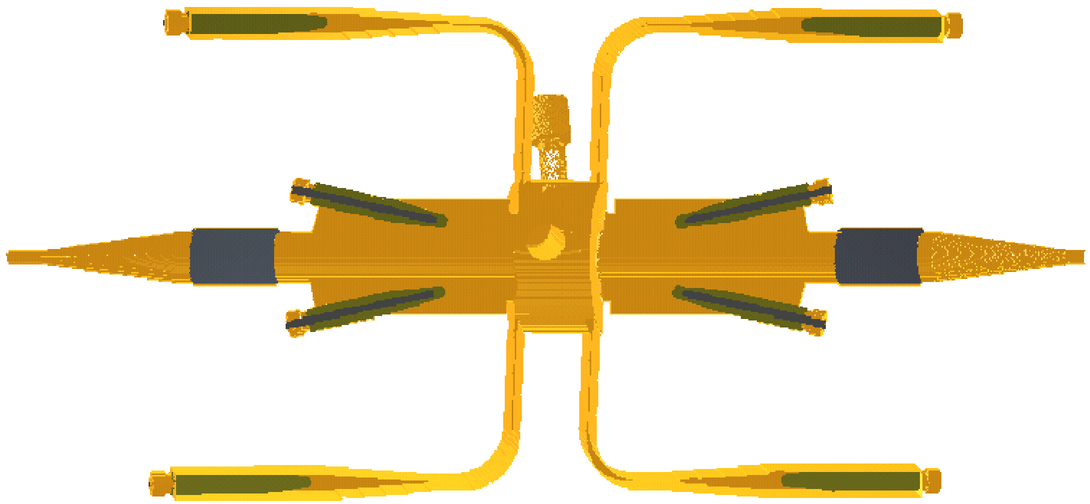
HOM Absorber (SiC)



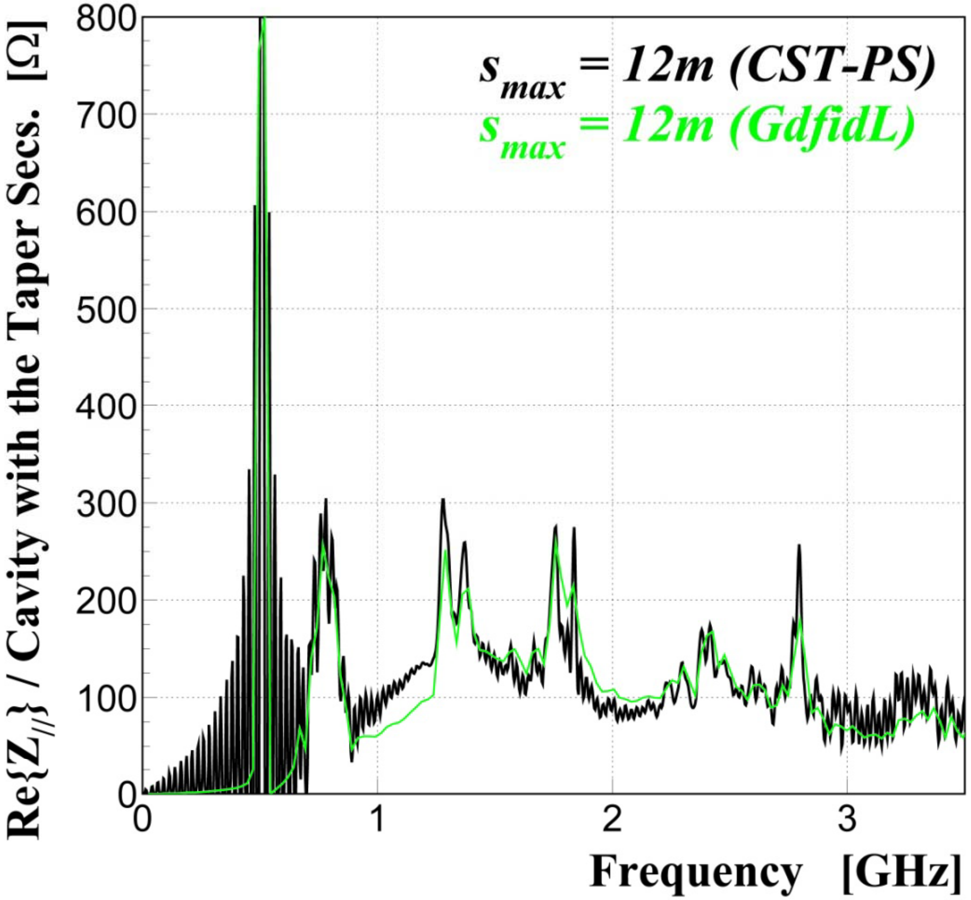
Input Coupler (PEC)



etc...

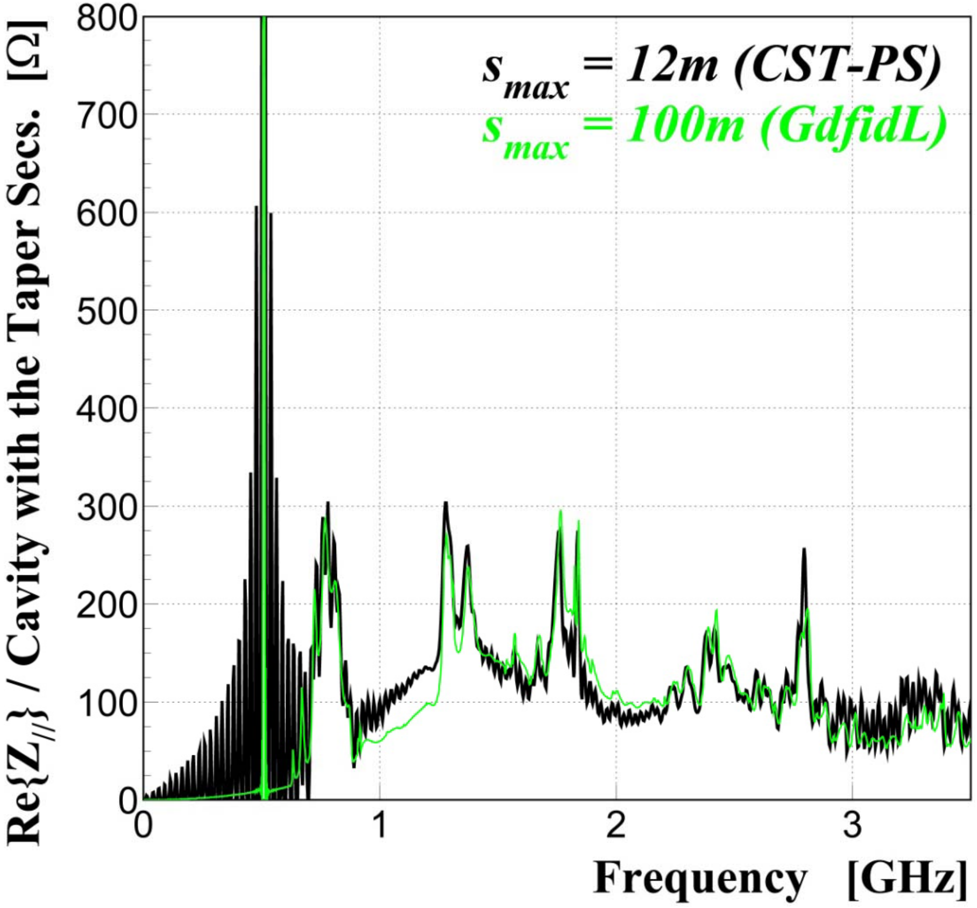


Comparison wit GdfidL



■For the same geometry
■Bunch Length: 5.0 [mm]
■Mesh Sizes: 1.0[mm] (transverse), 0.5[mm](longitudinal)
→25[GB] memory
■Using 64 cores of AMD Opteron 2348 (2.7GHz) CPUs
(PC cluster)

Comparison wit GdfidL

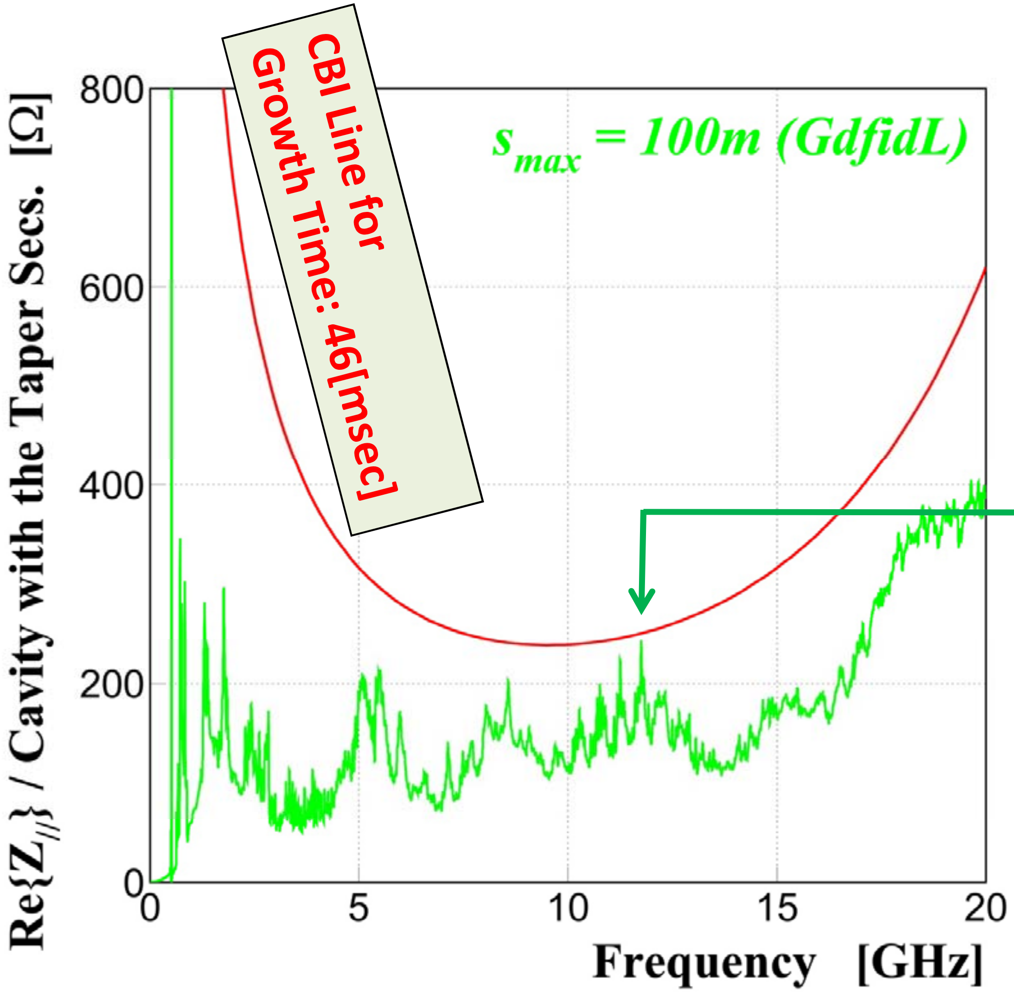


- Geometry
- Bunch Length: 5.0 [mm]
- Mesh Sizes: 1.0[mm] (transverse), 0.5[mm](longitudinal)
  →25[GB] memory
- Using 64 cores of AMD Opteron 2348 (2.7GHz) CPUs (PC cluster)
  →Elapsed time: 71[hrs] for s_{max}=100[m]

Fairly-Good Agreement for Frequencies < 3.5GHz

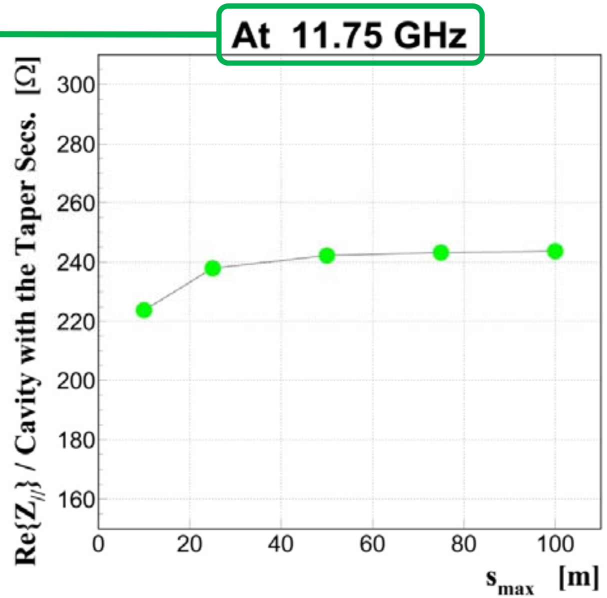
Actually Dominant Contribution to Longitudinal CBIs

(for the DR parameters as of April 9th, 2010)



- Geometry
  - With the Extraction Line
  - Tuner Pos.: 50 [mm] (innermost)
- Finer Mesh set around the Extraction Line

To compute impedance at 11.75GHz by CST-PS,
Bunch Length: 15.2mm
→ 1,818e6 Meshcells
→ 1,818/223*27GB = 220GB Memory Needed



Summary

- **RF Accelerating Structure for the DR of the SuperKEKB Injector has been designed using**
  - ➢ MICROWAVE STUDIO for
    - Determination of the Cavity Diameter
    - Optimization of the new HOM Damper
  - ➢ PARTICLE STUDIO for
    - HOM Impedance for CBIs
- **MICROWAVE STUDIO**
  - ➢ High Precision
  - ➢ User Friendly (GUI, Parameter Sweep, etc.)
- **PARTICLE STUDIO**
  - ➢ HOM Impedance in fairly good agreement with the GdfidL results (< 3.5GHz)
  - ➢ To estimate the actually dominant contribution to the CBIs at 11.75[GHz] (for the DR parameters as of April 9th, 2010)
    - More computing resource needed (PC workstation → PC cluster or GPU?)
    - Efficient usage of memory by PS desired (e.g. no mesh info. needed in PEC)