HOM-free deflecting cavity

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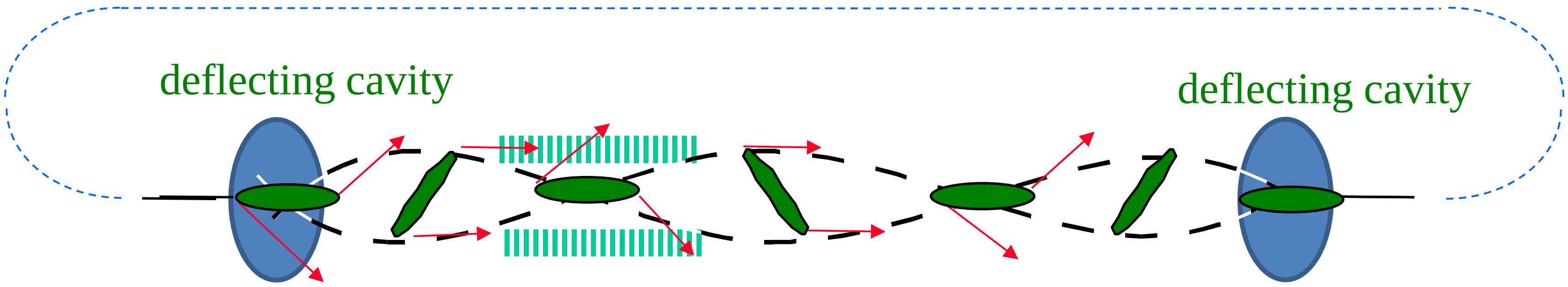
V. Yakovlev and A. Zholenz

ICFA Workshop on High Order Modes in Superconducting Cavities, 14 July 2014

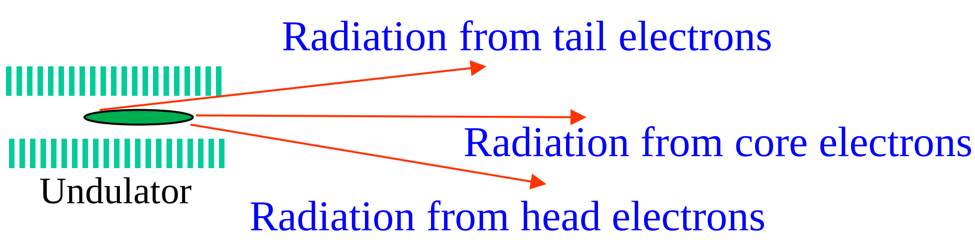
Deflecting Cavity for APS SPX upgrade

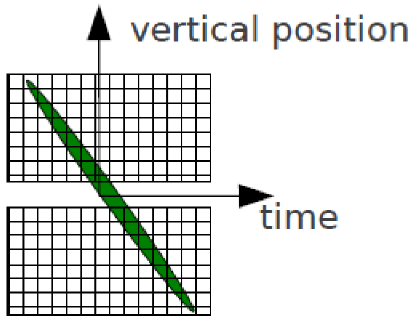
Obtaining short x-ray pulse from a "long" electron bunch



First deflecting cavity produces strong time dependent vertical kick

Second deflecting cavity exactly cancels the kick

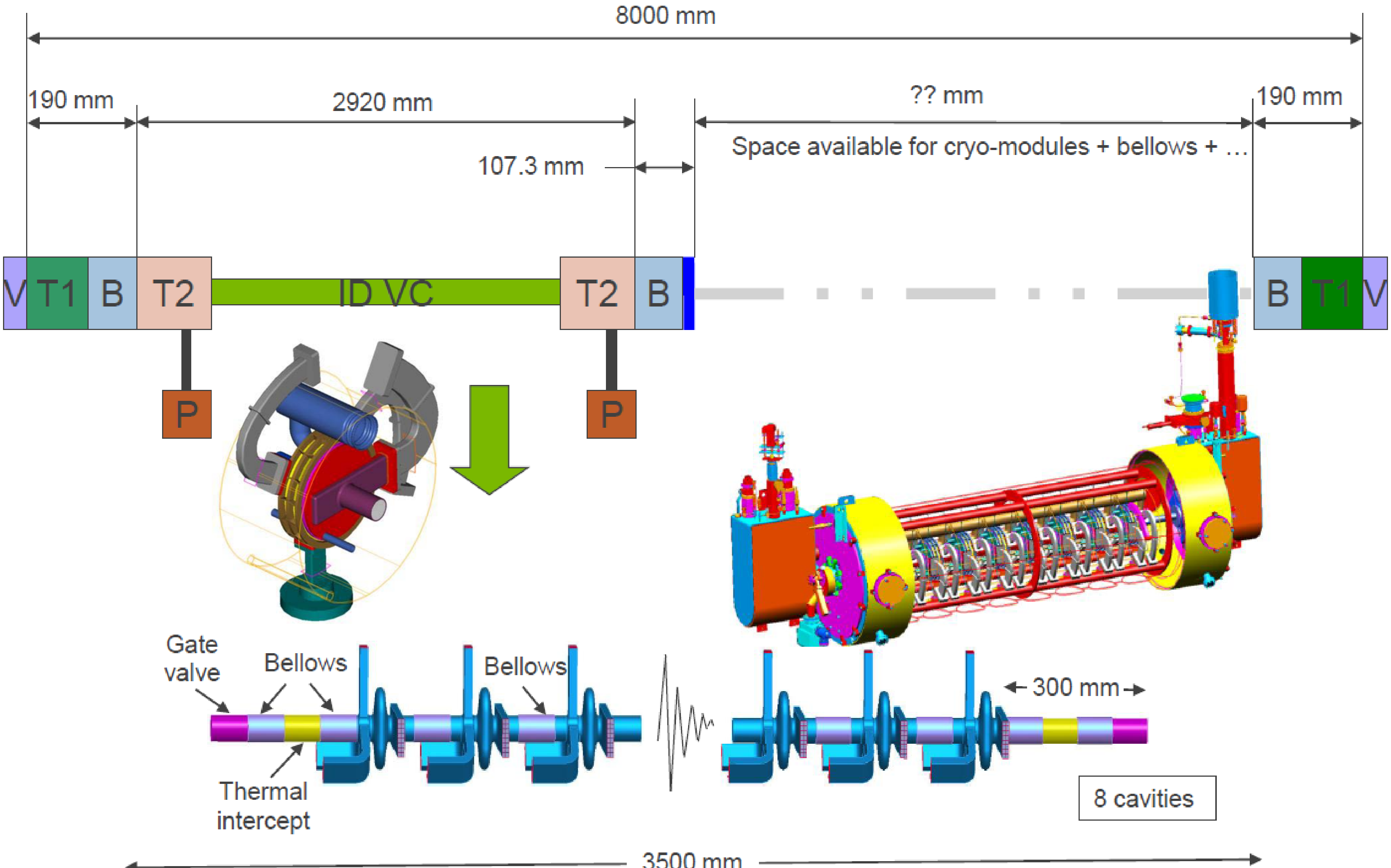




Collimator selects short x-ray pulse

Zholents, Heimann, Zolotorev, Byrd, NIM A 425, 385 (1999).

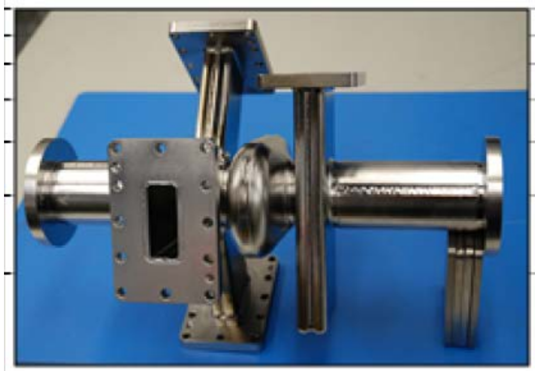
Deflecting Cavity Cryomodule Insertion

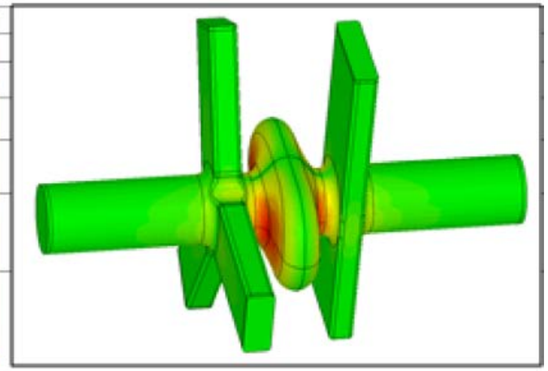


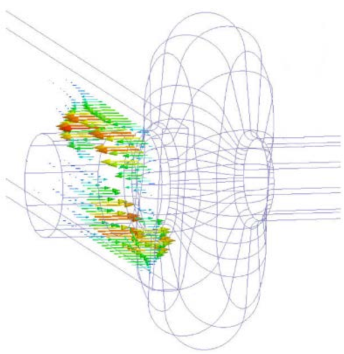
Courtesy: L. Morrison

Too many HOM modes, alignment issues, too big and expensive.

Proposed Mark-II deflecting cavity for APC upgrade







Limitations of the TM_{110} mode deflecting cavity

- **Presence of LOM**
- **Large radial dimensions and therefore dense spectrum of HOMs**
- **Complicate system of WGs for HOM damping**
- **High surface magnetic field**
- **Potentially high coherent losses**

$$Vx := \int_0^{Zend} \left[(EX(z) - HY(z)) \cdot \exp\left[i \cdot (\kappa \cdot z - \phi) \right] \right] dz$$

$$Vy := \int_0^{Zend} \left[(EY(z) + HX(z)) \cdot \exp\left[i \cdot (\kappa \cdot z - \phi) \right] \right] dz$$

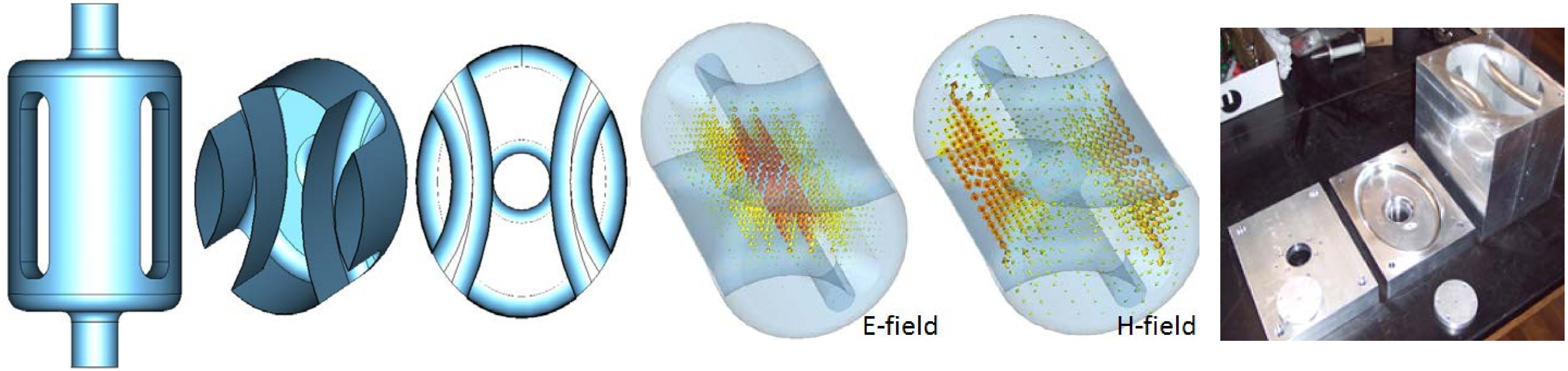
Direct integration of fields component
(Lorentz force equation)

$$\Delta \vec{V}_{\perp} = i \frac{v}{\omega} \vec{\nabla}_{\perp} (\Delta V_{II})$$

Panofsky-Wenzel (PW) theorem

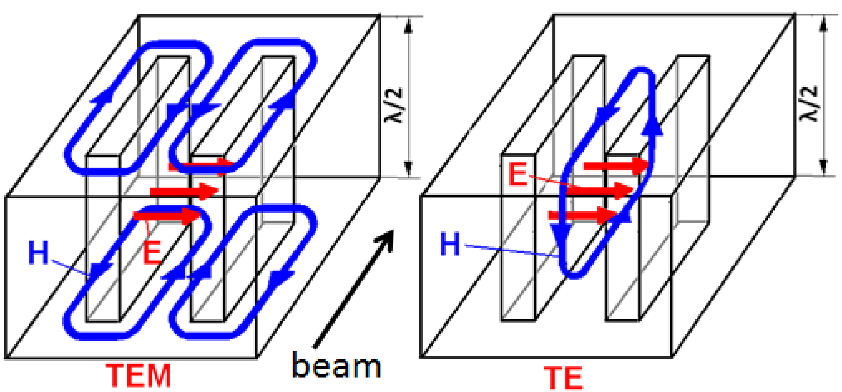
- **It is possible to use TE mode for the deflection?**
- **Single cavity replacing four?**

Parallel - bar ellipsoidal cavity (J. Delayen, ODU)

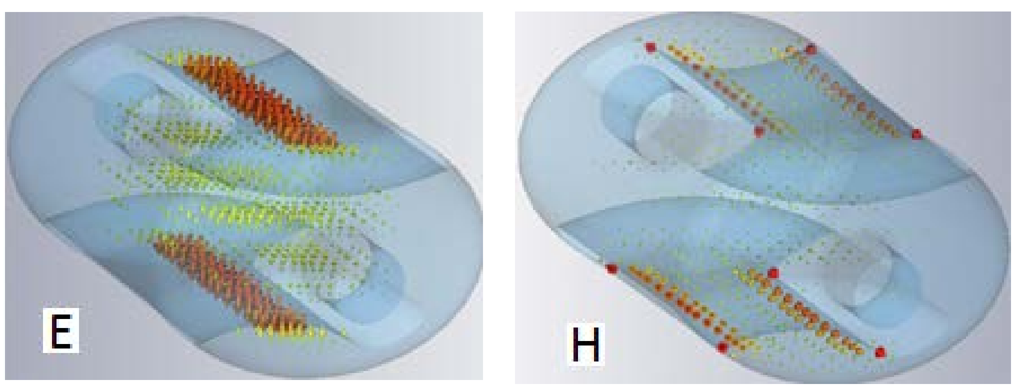


A compact cavity for the beam splitter of the Project X. V. Yakovlev. 03/01/2011

- The operating mode is not TEM as the authors claim: magnetic field does not wind around the bars, but lies in the plane parallel to the bars;
- Real operation mode is analog of TE_{111} in a pillbox cavity.
- TEM mode topologically identical to the TEM mode in the rectangular parallel-bar cavity (magnetic field winds around the bars) has higher frequency, ~1000 MHz, because of shorter effective length of the bars:

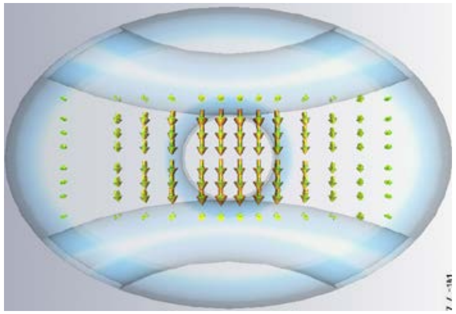


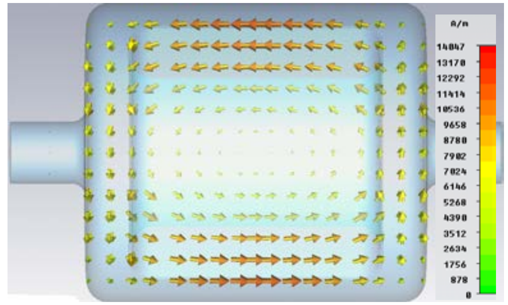
Field distributing for TME and TE modes in a rectangular parallel-bar cavity

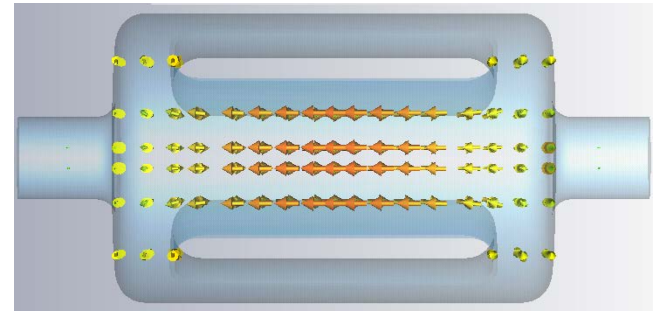


TEM-like mode in the elliptical PBC, f=1030 MHz

ORIGINAL ODU VERSION



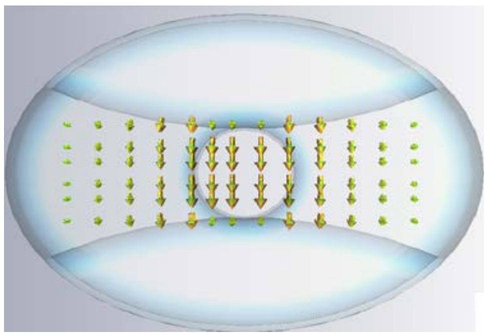


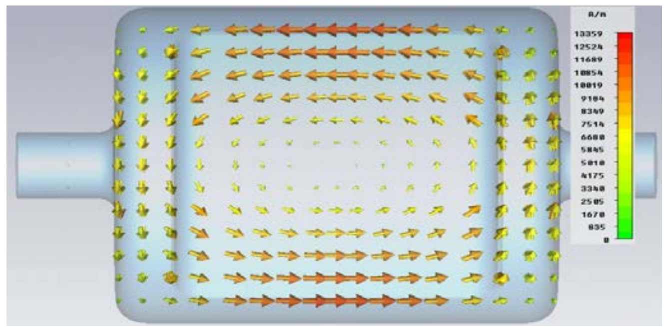


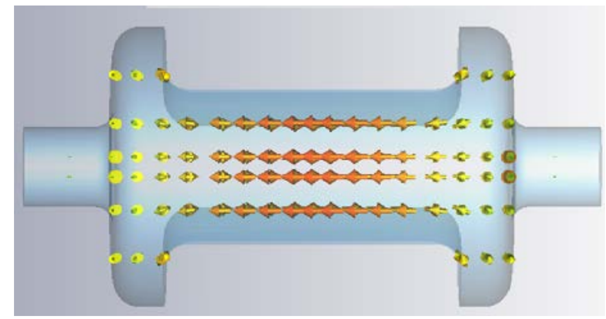
E-Field

FERMILAB VERSION OF ODU CAVITY

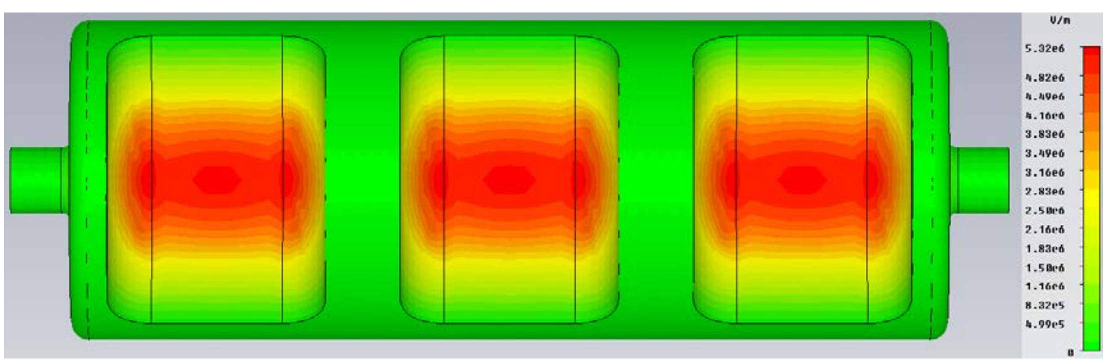
H-Field

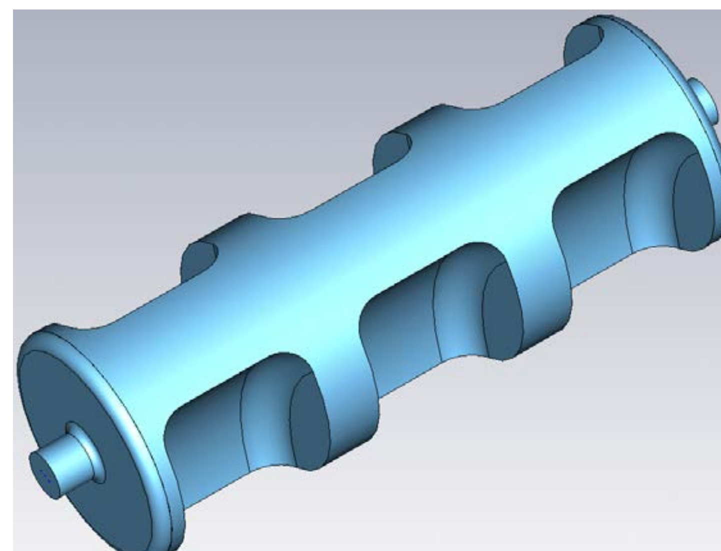






Further development of the TE cavity:
FNAL Squashed TE_{113} deflecting cavity
for Project X.





Deflecting cavity type choice.

RF Dipole Cavity properties [1-3]:

- No Low Order Modes. Operating mode frequency is in the lowest pass-band.
- High order modes well separated from operating mode.
- Mechanical stability of the cavity.
- Balanced peak surface electric and magnetic fields.
- High R/Q. As a result low surface RF power losses.
- One cavity can provide design kick.
- One cavity design easy HOM damping. No trapped modes between cavities.
- No inter-cavity alignment.
- Only one cavity frequency tuner needed.

1. V. Yakovlev , I. Gonin, M. Hassan, D. Johnson, T. Khabiboulline, A. Klebaner, and N. Solyak, "A compact cavity for the beam splitter of the Project X," Project X Technical Meeting, March 1, 2011, ProjectX Document 826, http://projectx-docdb.fnal.gov/cgi-bin/DocumentDatabase/.
2. J. R. Delayen, "Ridged Waveguide & Modified Parallel Bar," 5th LHC Crab Cavity Workshop, CERN, November 14-15, 2011, http://indico.cern.ch/contribu tionDisplay.py?sessionId=0&contribId=3&confId=149614
3. S.U. De Silva, J.R. Delayen, in Proc. SRF2011, Chicago IL USA, MOPO027 (2011).

Mini-Review of the APS-U SPX Alternative Deflecting Cavity Design. January 31, 2013

SPX Deflecting Cavity Requirements

- 2 MV deflecting kick
- Operating frequency 2815 MHz
- CW operation, superconducting structure
- Acceptable loss factor requirement
- HOM damping for the coupled-bunch instability 200 mA*
  - R_s x f_n < 0.44 MΩ-GHz (longitudinal), where $R_s = V^2/2P_l$
  - R_t < 1.3 MΩ/m (horizontal dipole), where $R_t = V_t^2/2P_l$, $V_t = V/k_r\, r_0$
  - R_t < 3.9 MΩ/m (vertical dipole)

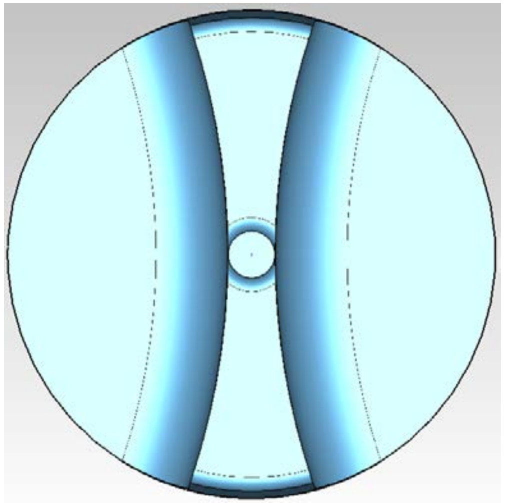
f_n is the LOM /HOM frequency, k_r is the wave number, P_l is the total loss, and r_0 is the radial offset of the voltage integration

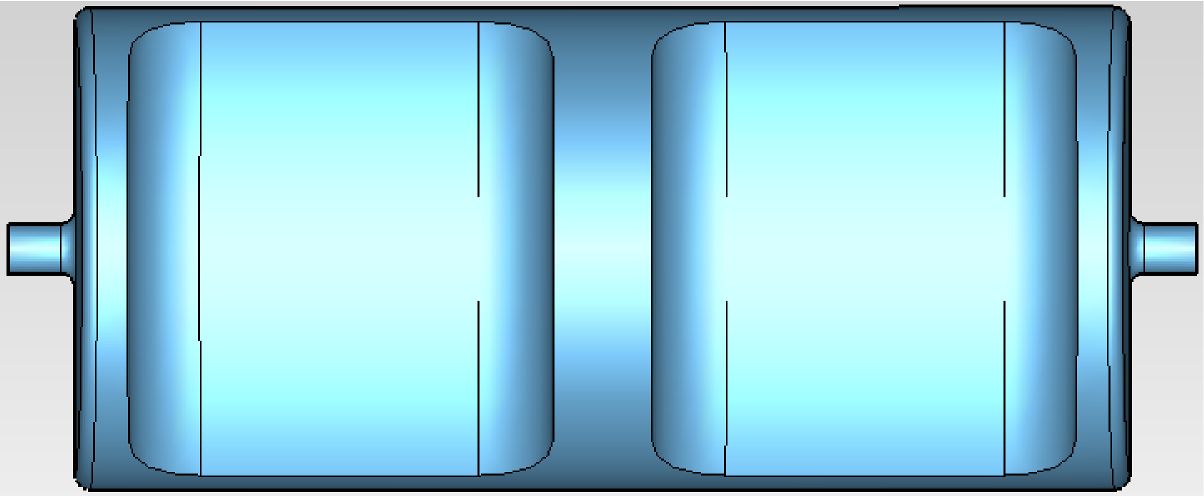
- Aperture in vertical plane minimum >10 mm
- Aperture in horizontal plane minimum >30 mm

* Advanced Photon Source Upgrade. Project Preliminary Design Report. Chapter 4-244

Mini-Review of the APS-U SPX Alternative Deflecting Cavity Design. January 31, 2013

1408MHz 2cells cavity

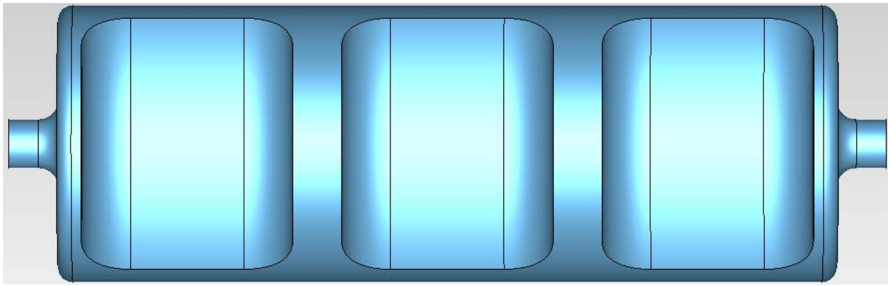




V, MV	R/Q,Ω	Es,MV/m	Hs,mT
4	1415	48	83

2816MHz 3cells cavity

V, MV	R/Q,Ω	Es,MV/m	Hs,mT
2	609	35	79



Initial couplers estimation

Power coupler estimation on operating mode										
Overhead	c, m/s	r, m	F, Hz	Ut, V	Uz, V	R/Q, Ω	I, A	P, W	Q	dF, Hz
1	3.00E+08	2.0E-04	1.41E+09	4.00E+06	2.36E+04	1415	0.20	4718	1.2E+06	1175
2								9437		
1	3.00E+08	2.0E-04	2.82E+09	2.00E+06	2.36E+04	609	0.20	4718	7.0E+05	4046
2								9437		

$$U_z = \frac{2\pi f}{c} r U_t \qquad P = U_z I$$

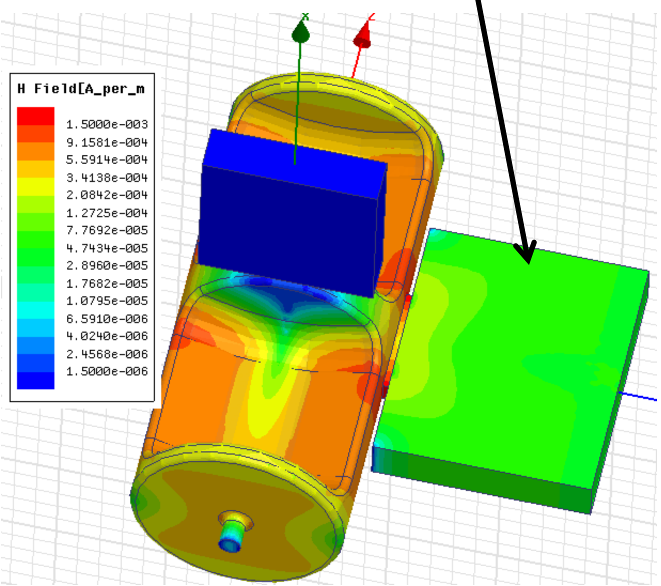
$$Q = \frac{U_t^2}{2R/Q * P} \qquad W = \frac{U_t^2}{2R/Q\omega}$$

$$P = \frac{U_z^2}{2R_z}; R_z = \frac{U_z}{2I}$$

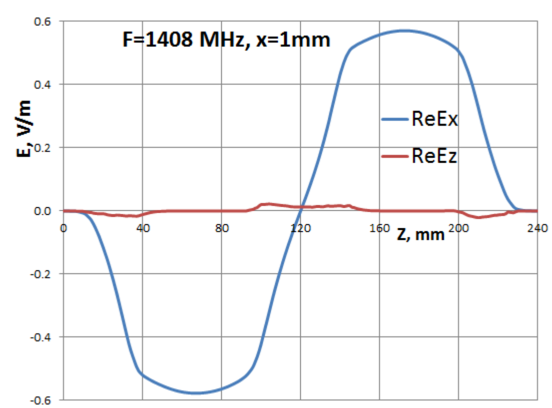
200 μm beam offset generates 5 kW power per cavity

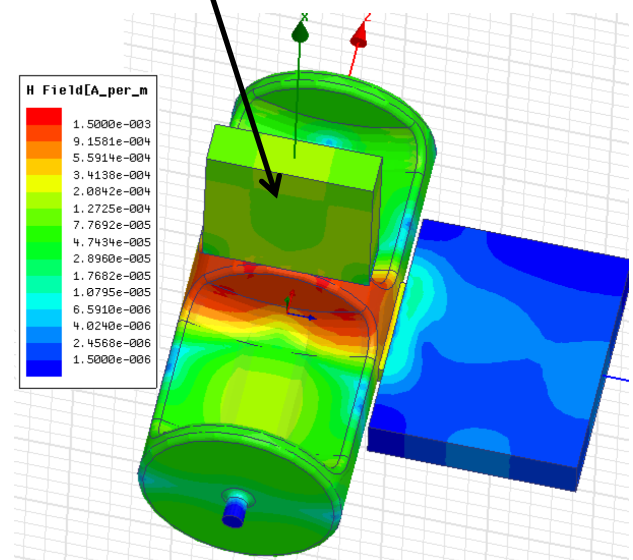
Operating mode coupler dumps lower mode (0-mode) very well

Monopole mode couplers dumps monopoles and can have coaxial port if max power < 100 W

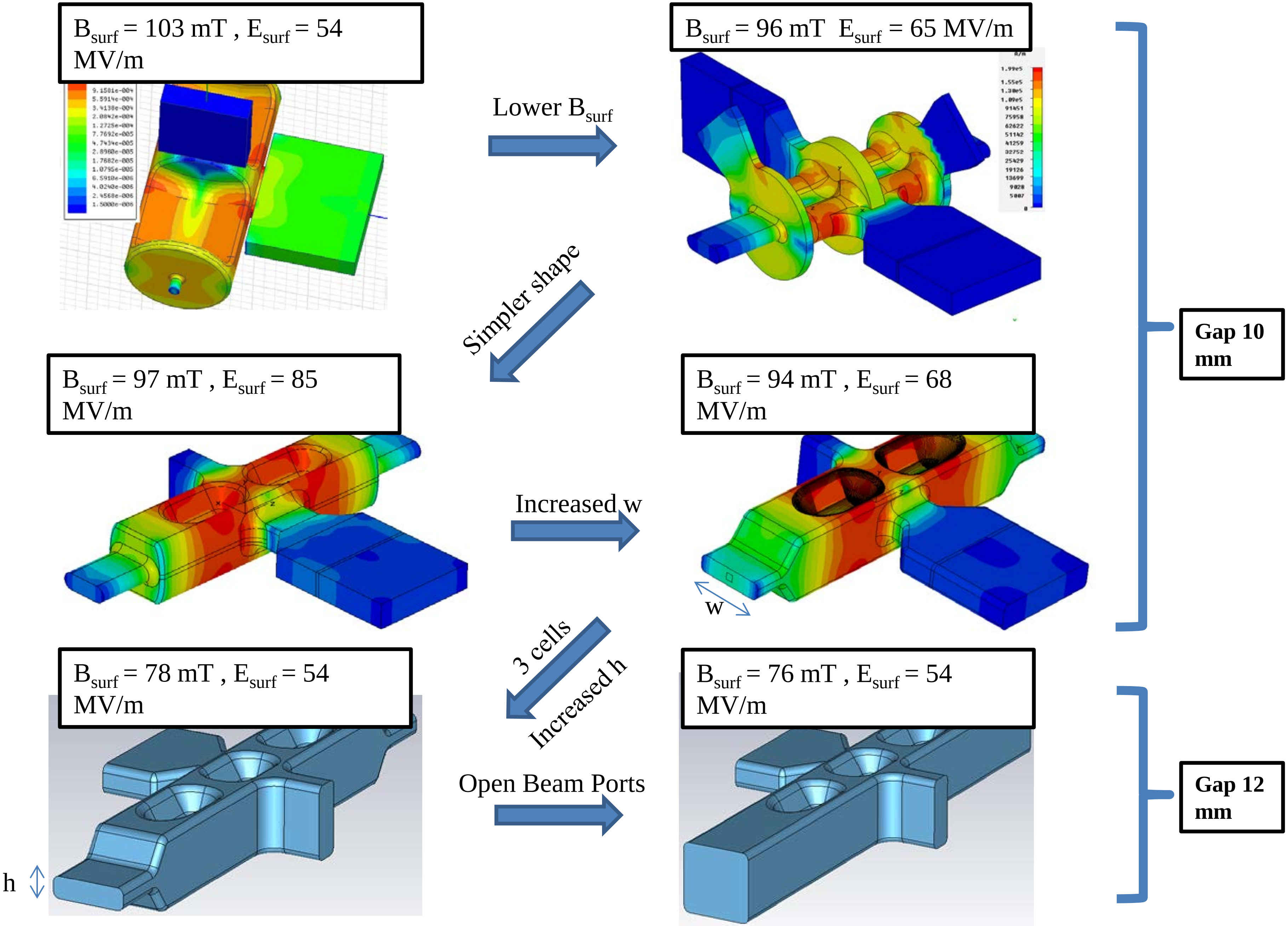


Frequency	R/Qx	Ql
1.30E+09	4.37	1.85E+03
1.41E+09	**1404.71**	3.22E+05
2.45E+09	66	700



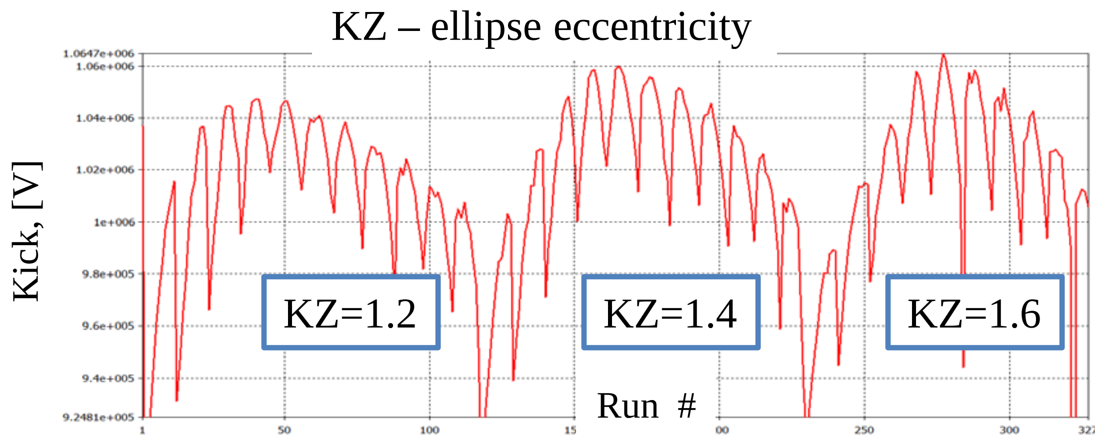


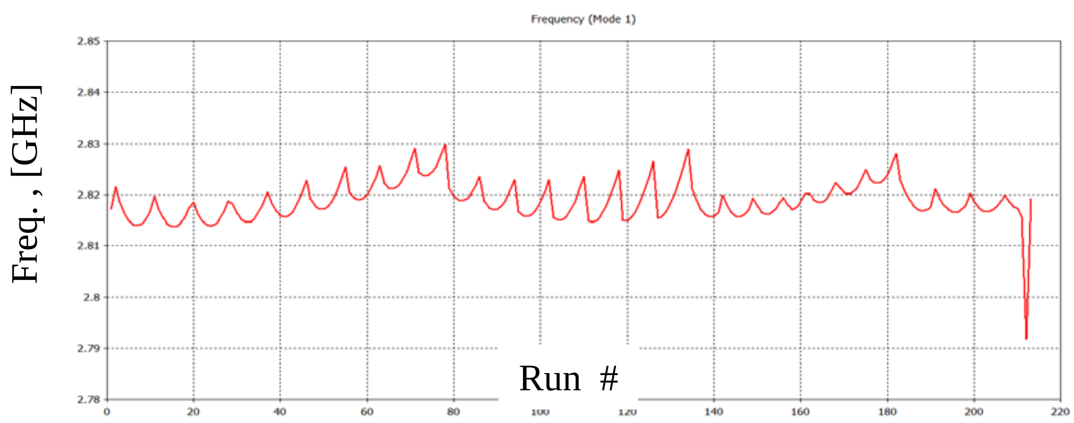
Evolution of the Deflector Cavity Design (2 MV Vertical Kick & Q_L ~ 5e5)



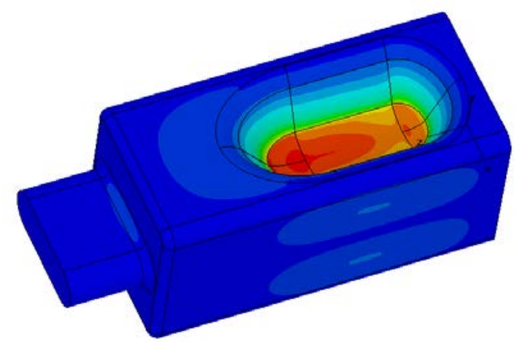
Surface EM-fields optimization

- Model is fully parameterized
- The frequency derivation was calculated for each parameter in order to preserve the operating mode frequency on the stage of geometry creation.
- Multiple parameters sweep run
- General ellipsoid is used for the hollow surface

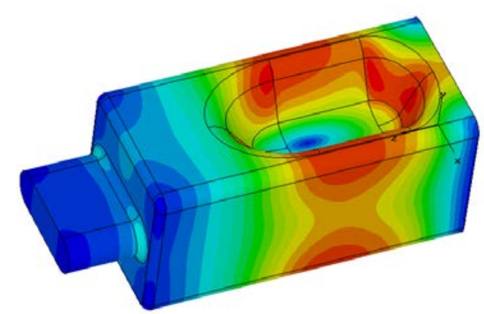




Surface E-field

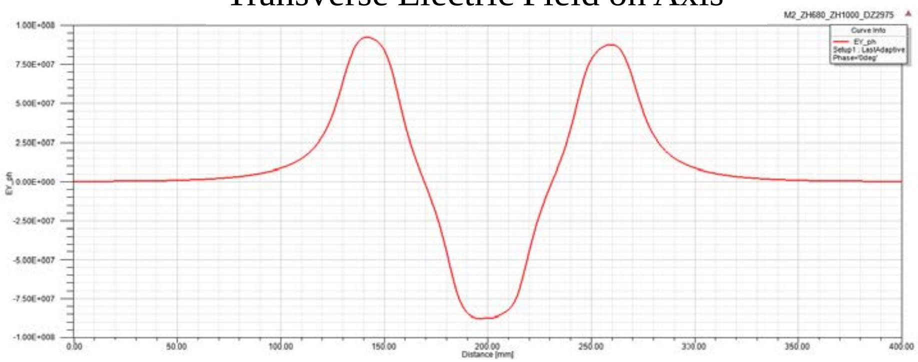


Surface H-field

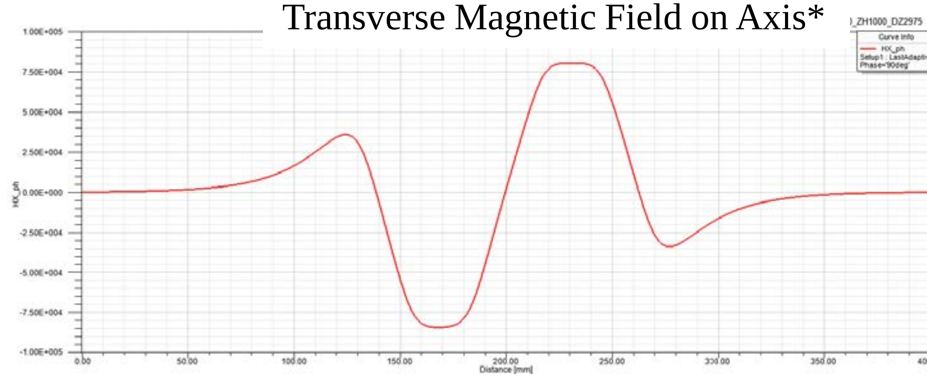


Kick fields at operating Mode, F = 2815 MHz

Transverse Electric Field on Axis*

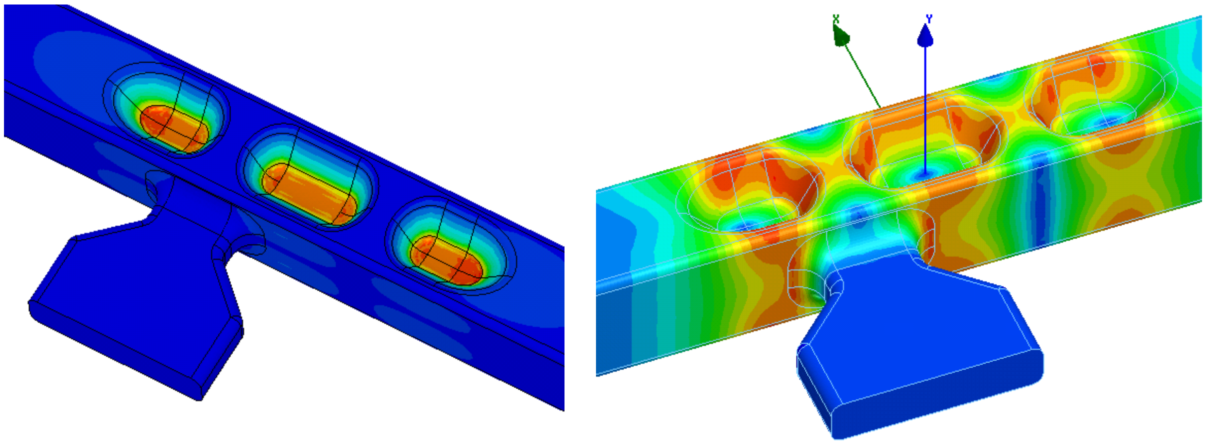


Transverse Magnetic Field on Axis*



* Normalized to 1J stored energy

Surface Electric (left) and Magnetic (right) Fields

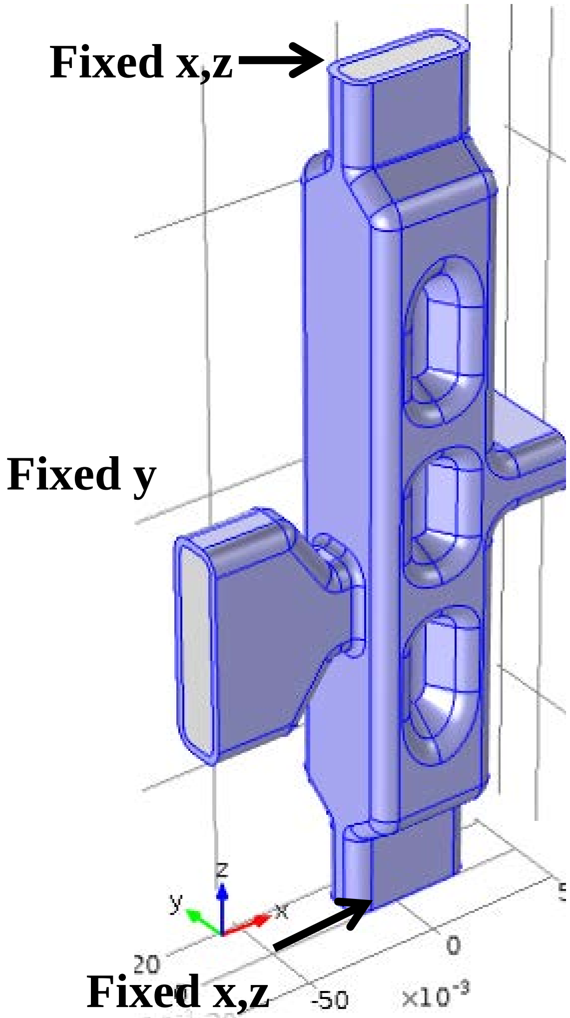


Freq	2815 MHz
V_{kick}	2 MV
E_{max}	55 MV/m
B_{max}	76 mT
$(R/Q)_Y$	520 Ω
G	130

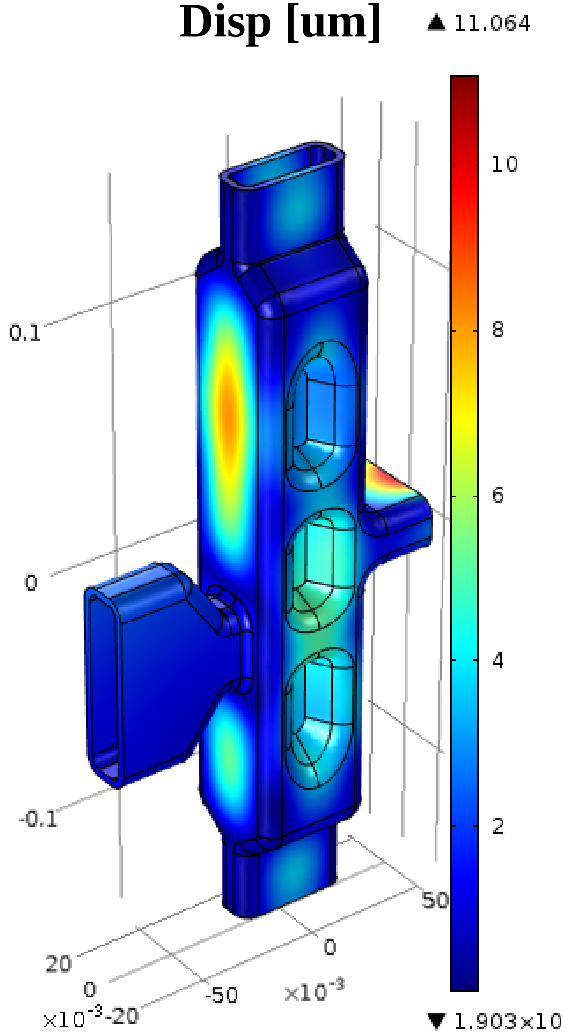
- The WG is shifted by ~ 30 mm in Z-direction in order to make Q_{ext} ~ 5E5

df/dp simulations with fixed ends

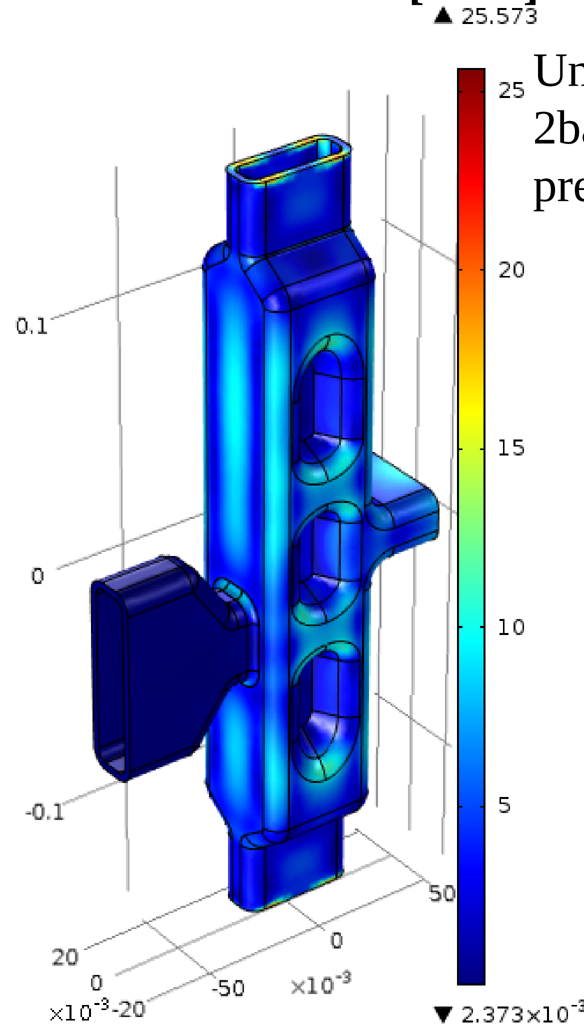
3mm Shell Thickness



Disp [um]



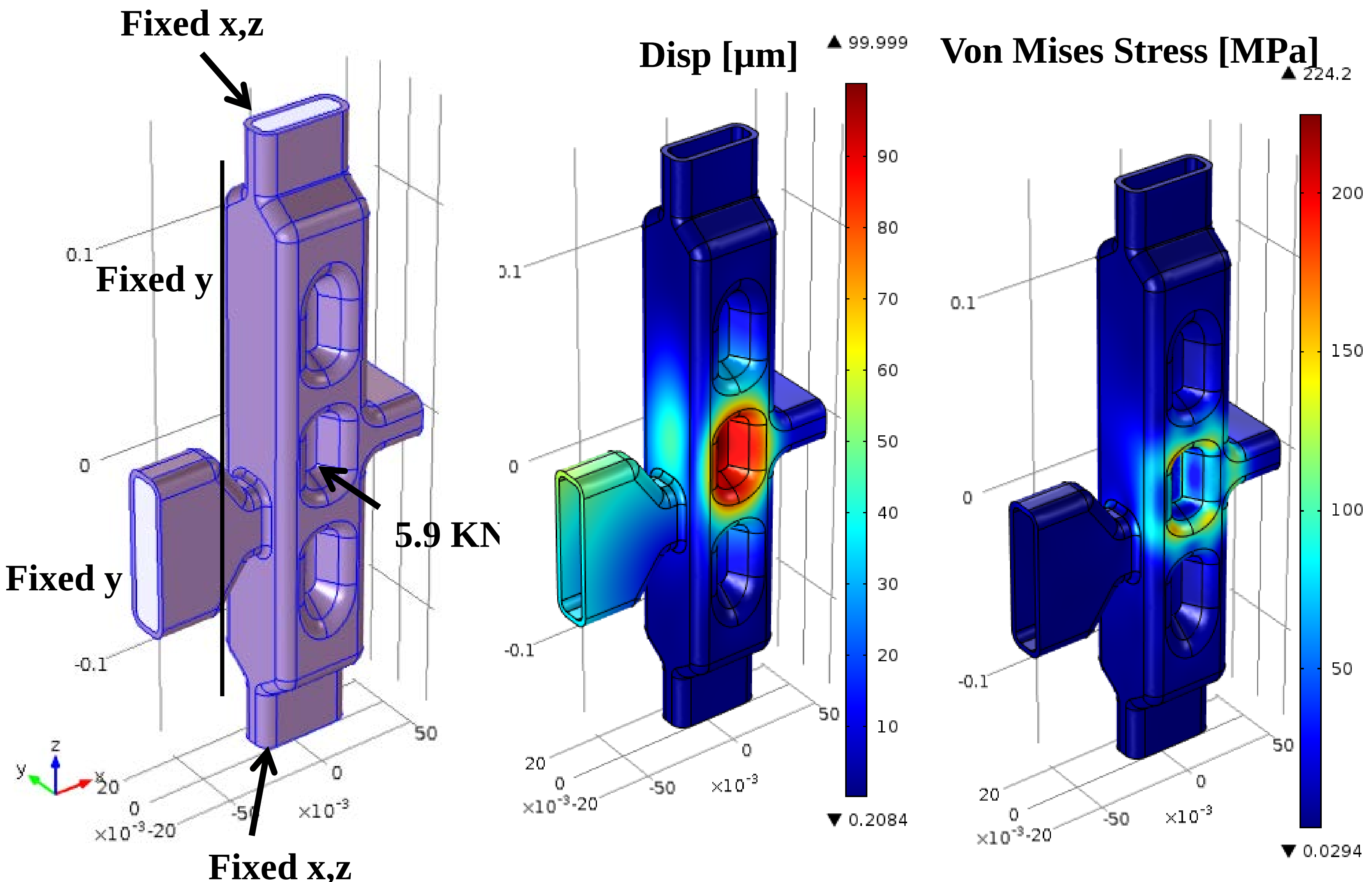
Von Mises Stress [MPa]



Under 2bar pressure

df/dp= -72.5 Hz/mbar

Frequency tuning simulations, fixed ends

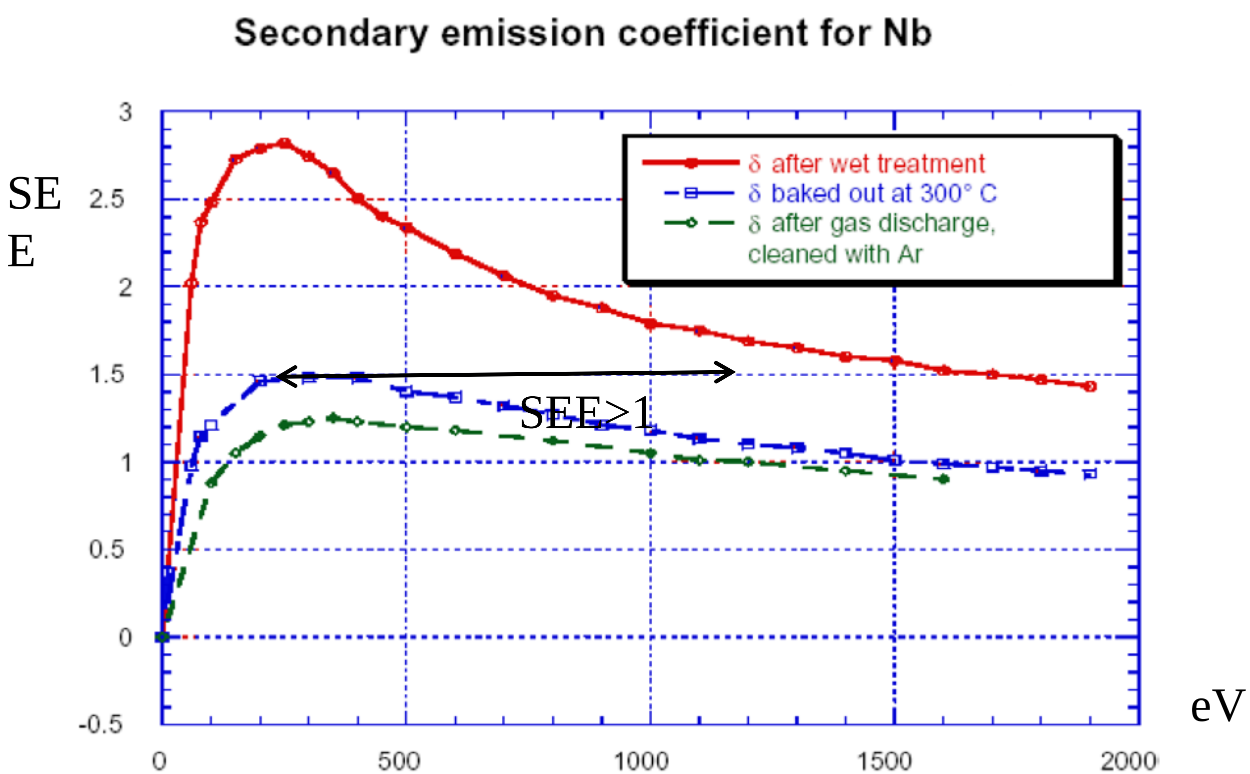


df/dl= -28.46 KHz/µm

Multipactor Simulations with CST Studio

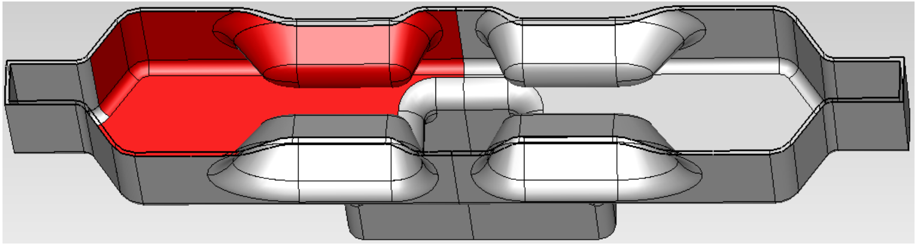
CST Studio SEE Library for Niobium has 3 options :

1. 300°C Bakeout (SEE_{max} ~ 1.5) (blue)
2. Wet treatment (SEE_{max} ~ 2.8) (red)
3. Ar Discharge cleaned (SEE_{max} ~ 1.2) (green)

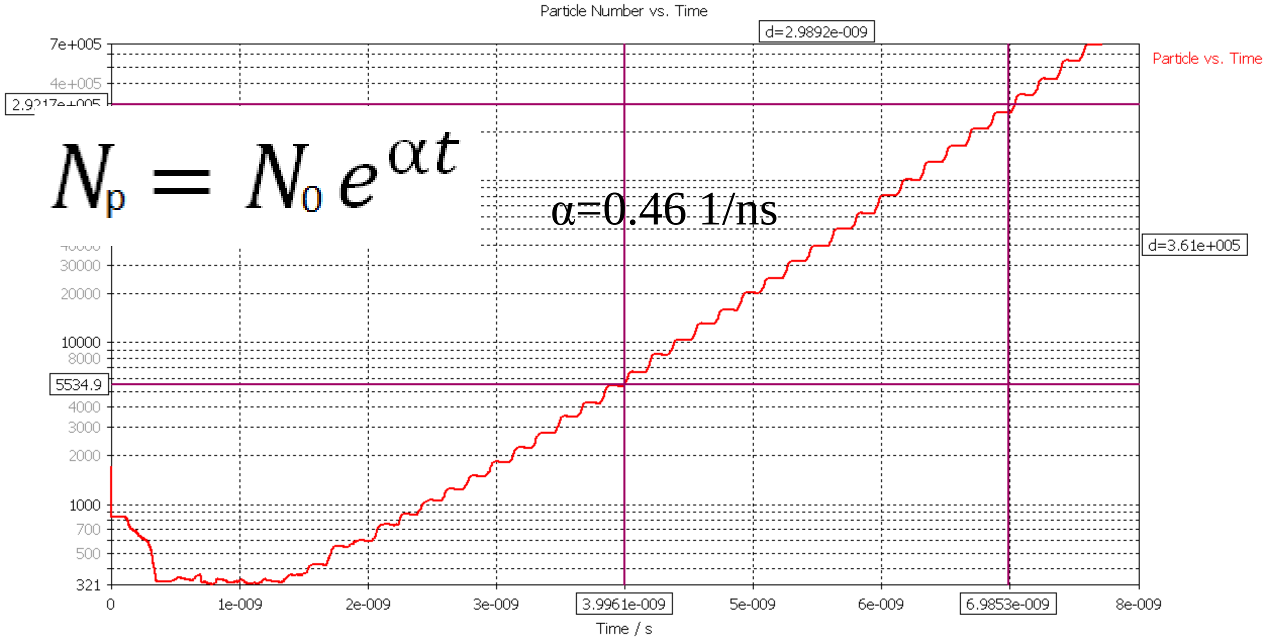


Multipactor Simulations with CST Studio

- RED faces are setup as particle source for MP simulations (right picture)
- 3 SEE are taken into account



Growth rate α is the criteria of MP

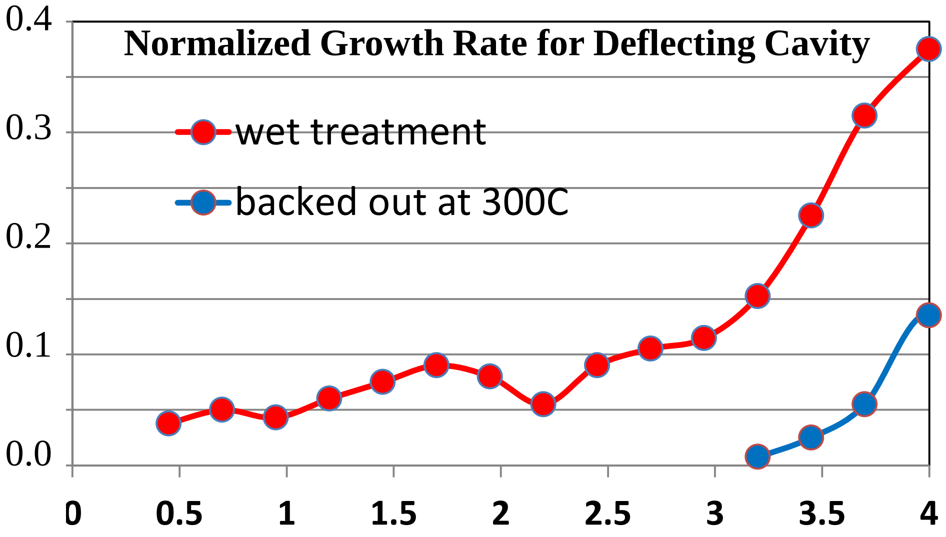


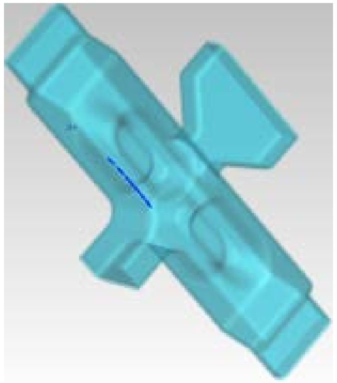
$$N_p = N_0 e^{\alpha t}$$

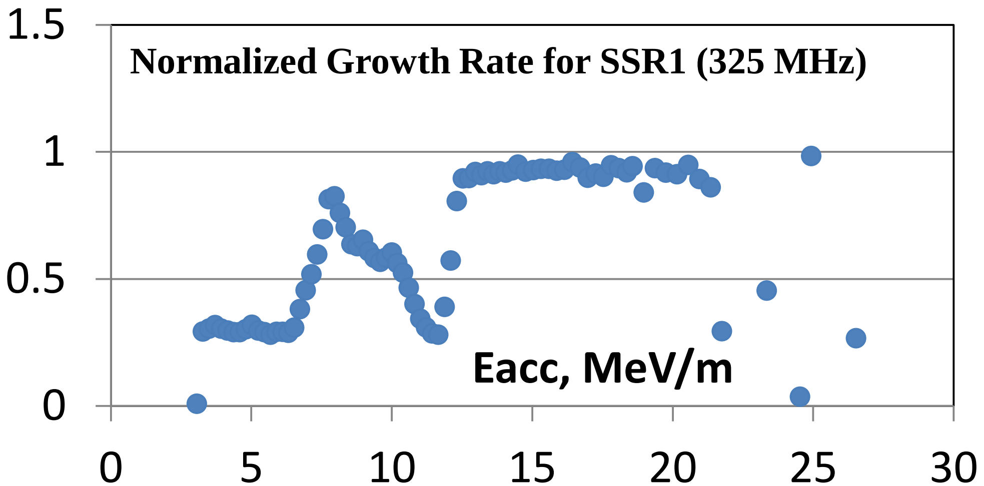
α=0.46 1/ns

CST calculate the particle number N_p vs. time according to the SEE function, starting from initial N_0 particle distributed on the defined particle source faces. This plot shows the N_p vs. time for **V_{kick}=3.5MV** and red SEE function on previous slide (wet treatment)

Multipactor Simulations with CST Studio

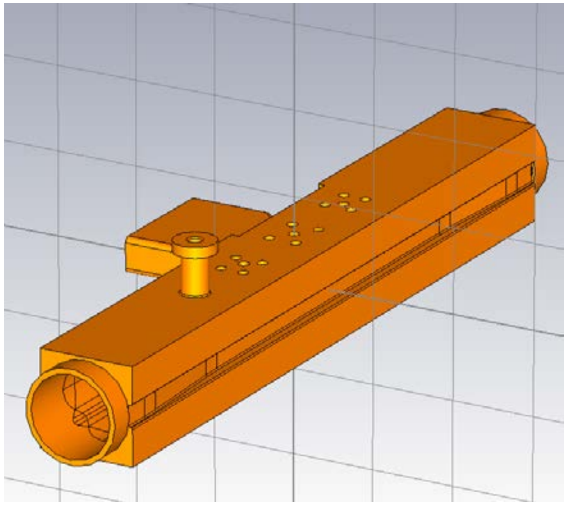


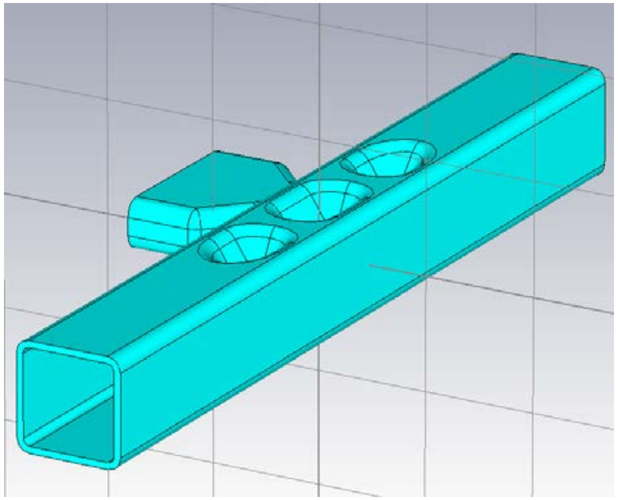




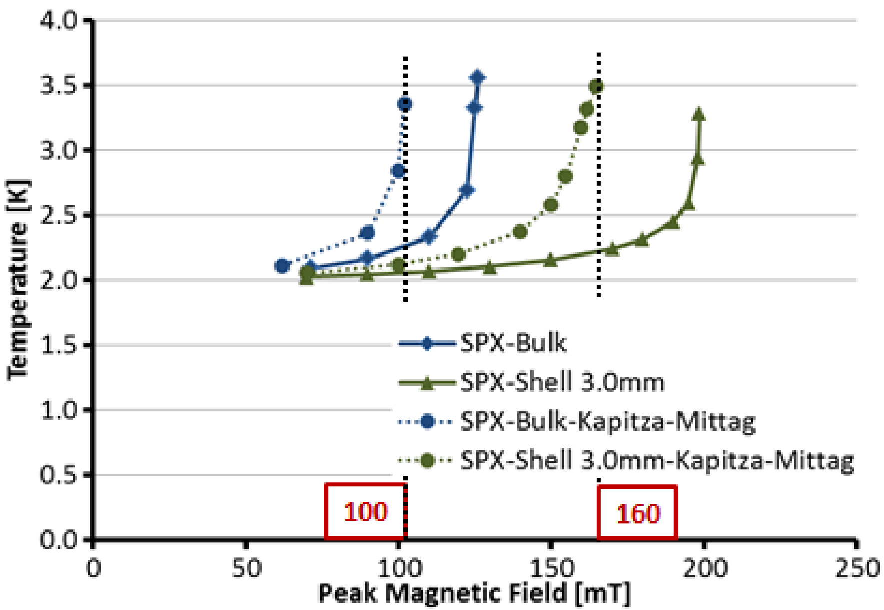
- Normalized Growth Rate in SSR1 cavity are ~ 6 times higher than in Deflecting cavity.
- MP in SSR1 cavities is successfully processed.
  It gives a confidence that it will be processed as well for Deflecting cavity .

Thermal Breakdown Analysis of SPX Cavity





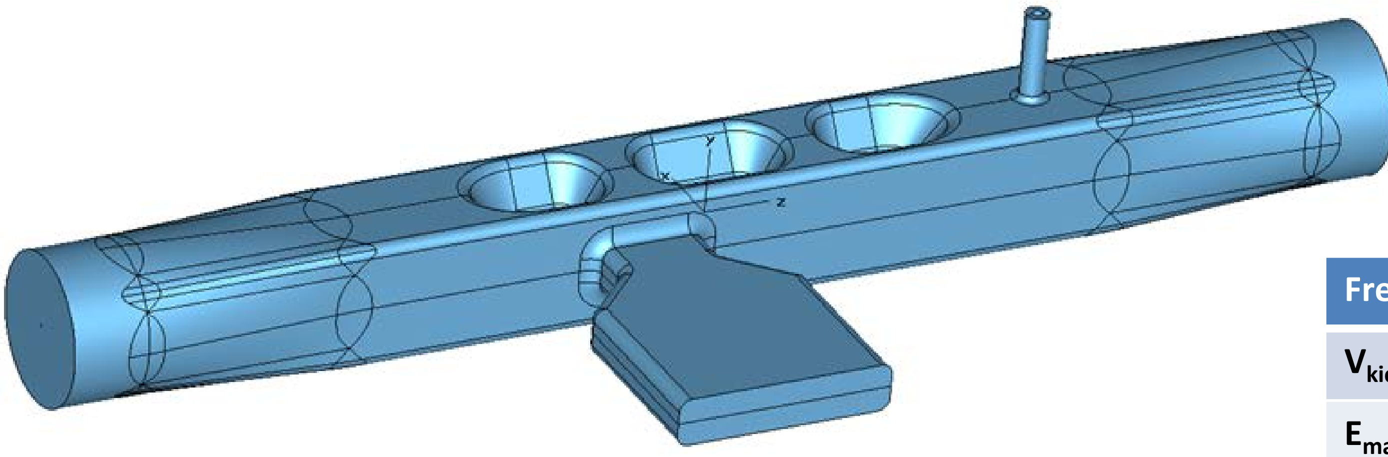
$$Rs_f = \frac{2e^{-4}}{T}\left(\frac{f}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$



- Kapitza resistance effect might have uncertainty of ±10 mT
- SPX cavity is projected to have a quench field of 90 mT for the bulk geometry, while it is 150 mT for the Shell geometry

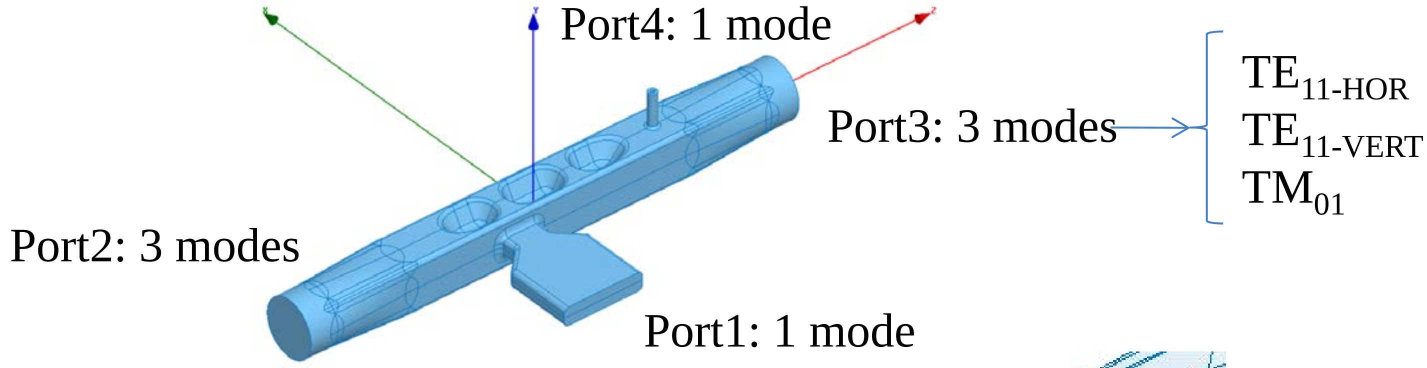
Latest changes:

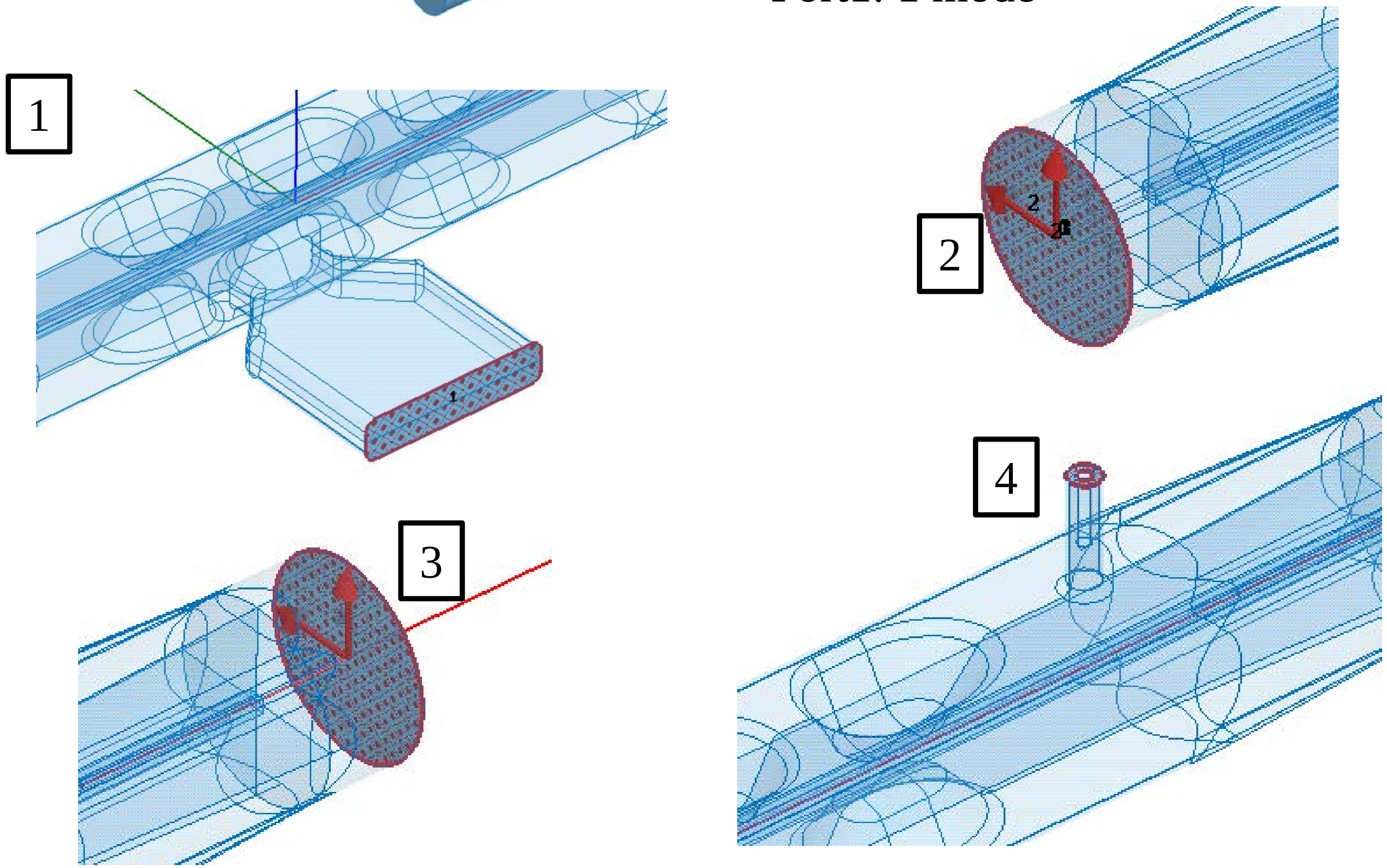
- HOM port removed
- Optimized square to round transition



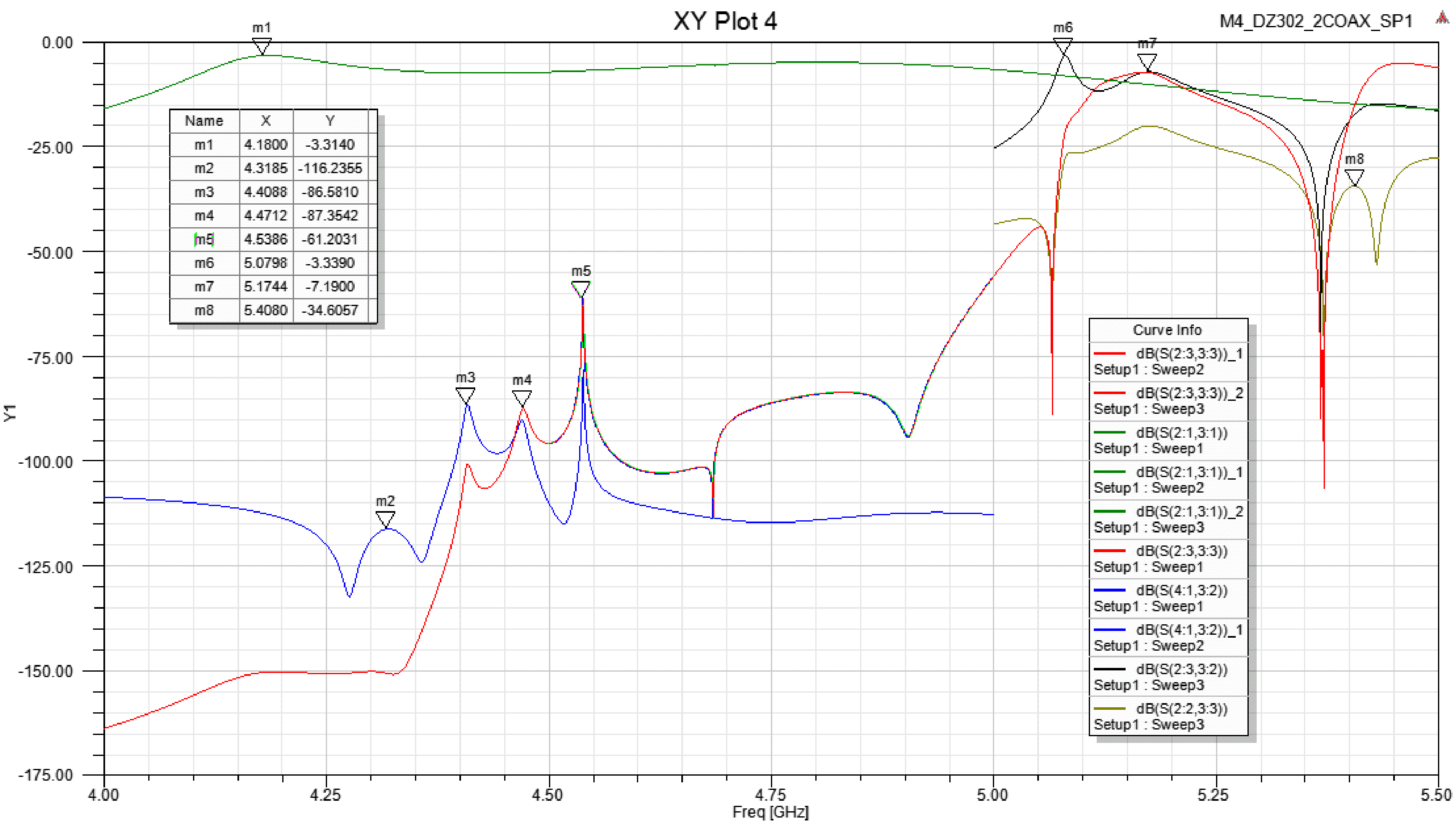
Freq	2815 MHz
V_{kick}	2 MV
E_{max}	54 MV/m
B_{max}	75 mT
$(R/Q)_Y$	521 Ω
G	130
Q_{ext}	5.3E5
P_{out}	7.2 kW

3-cell Deflector Cavity Driven Modal Simulations





Driven Modal Simulations: S-parameters Results



The resonances are happened on modes transformation, one has to check all s-parameters curves !

3-cell Deflector Cavity EigenMode analysis

Frequency [MHz]	$(R/Q)_x$	$(R/Q)_y$	$(R/Q)_z$	Modal K_{loss} [V/pC]	Q_{ext}	Q_{WG}	Q_{P1}	Q_{P2}
2476	0.001	0.034	-	-	2400	2400	-	-
2675	1.7e-4	4.95	-	-	6800	6800	-	-
2815	1e-5	521	-	-	5.1E5	5.1E5	-	-
4170	1.4e-4	7.3	-	-	32	160	125	74
4303	-	-	0.64	3.7E-3	55	-	160	85
4408	-	-	19.5	0.12	530	-	2500	680
4471	-	-	18.7	0.11	400	-	960	680
4538	-	-	0.17	1E-3	4900	-	14300	7750
5080*	-	-	60 - 80	0.3 -0.4	390	-	490	1900
5115*	-	-	10 - 20	0.05 – 0.1	100	-	4500	110
5165*	-	-	2 - 8	0.01 - 0.04	65	-	90	270
5410*	-	-	2 - 6	0.01 – 0.03	80	-	160	160
				$\sum K_m = 0.62 - 0.81$				

* R/Q is roughly estimated because the TM_{01} mode is above cut off and have fields in a beam pipe

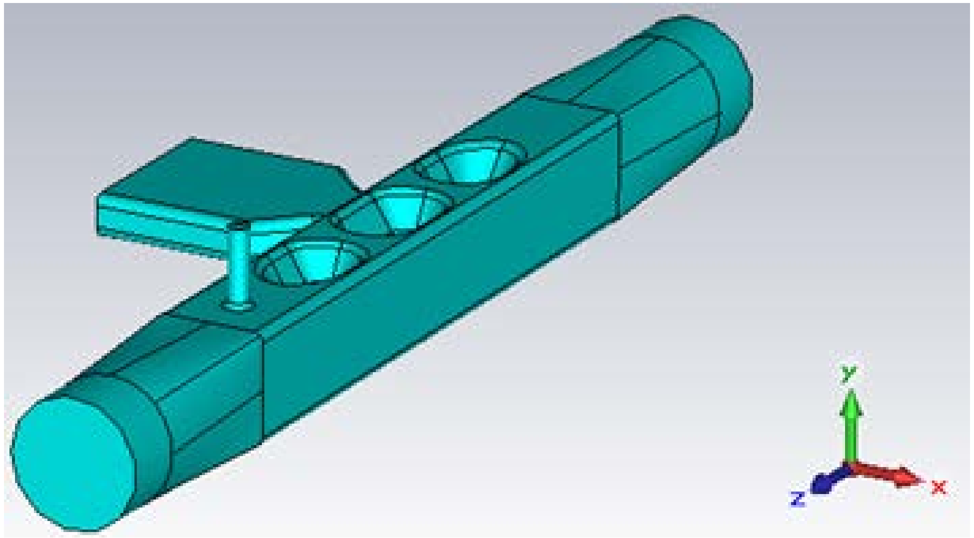
$$R/Q = \frac{U^2}{2\omega W}$$

Modal loss factor: $(K_{loss})_m = \frac{1}{2}(R/Q)_m * \omega_m * (A_{damp})_m$

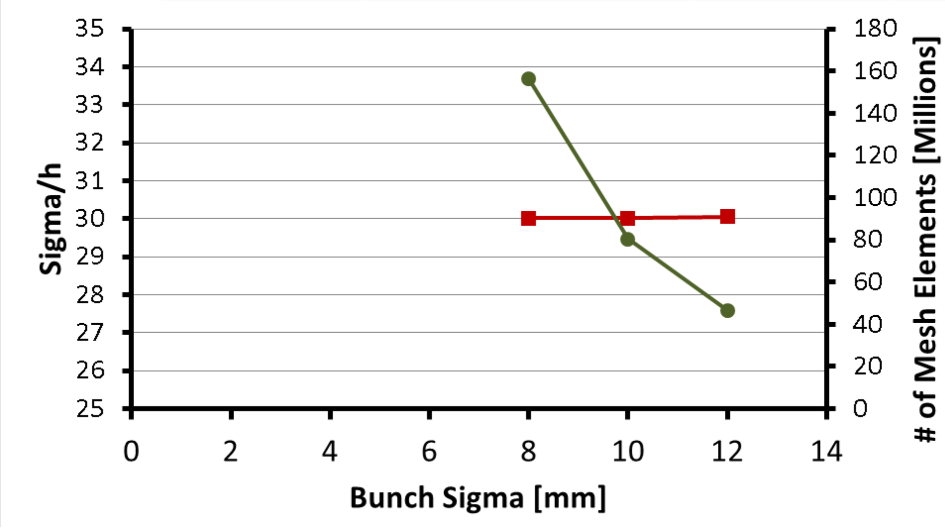
Damping factor: $(A_{damp})_m = e^{-k_m{}^2\sigma^2}, \quad k_m = \omega_m / c$

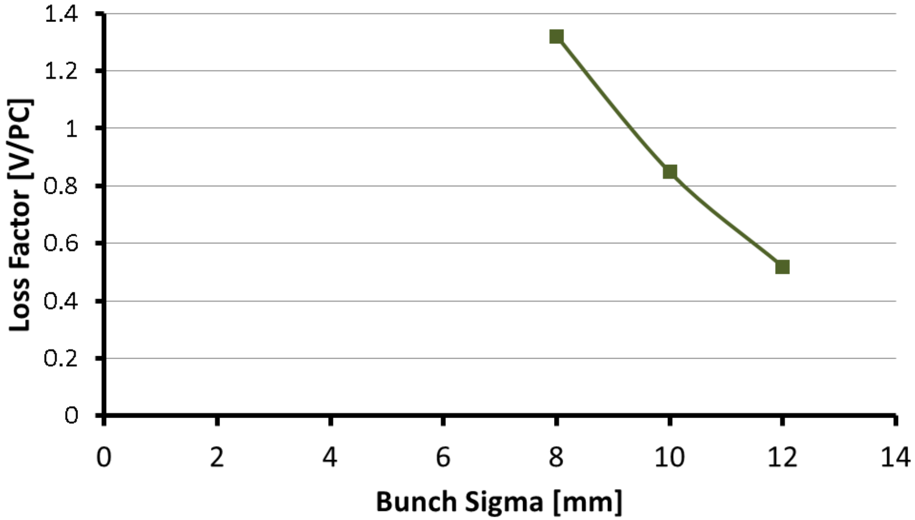
Gaussian bunch rms: σ = 10 mm

Wakefield Losses simulations in CST



Sigma [mm]	Loss Factor [V/PC]	Nz	h (Mesh Step z) [mm]	Sigma/h	# Mesh Elements [million]
12	0.519	1127	0.40	30.03	46.6
10	0.848	1351	0.33	30.02	80.3
8	1.321	1689	0.27	30.02	156.3

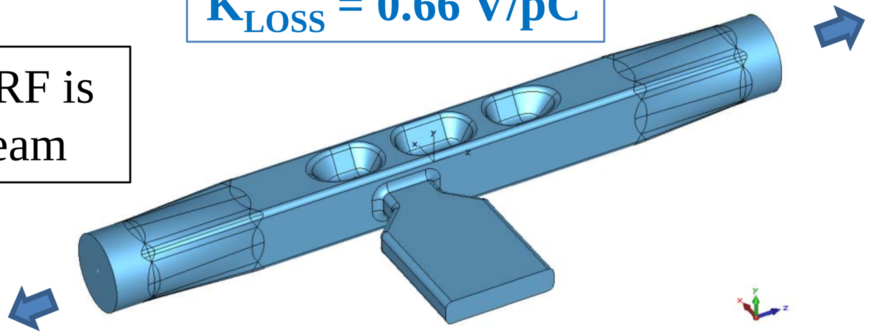




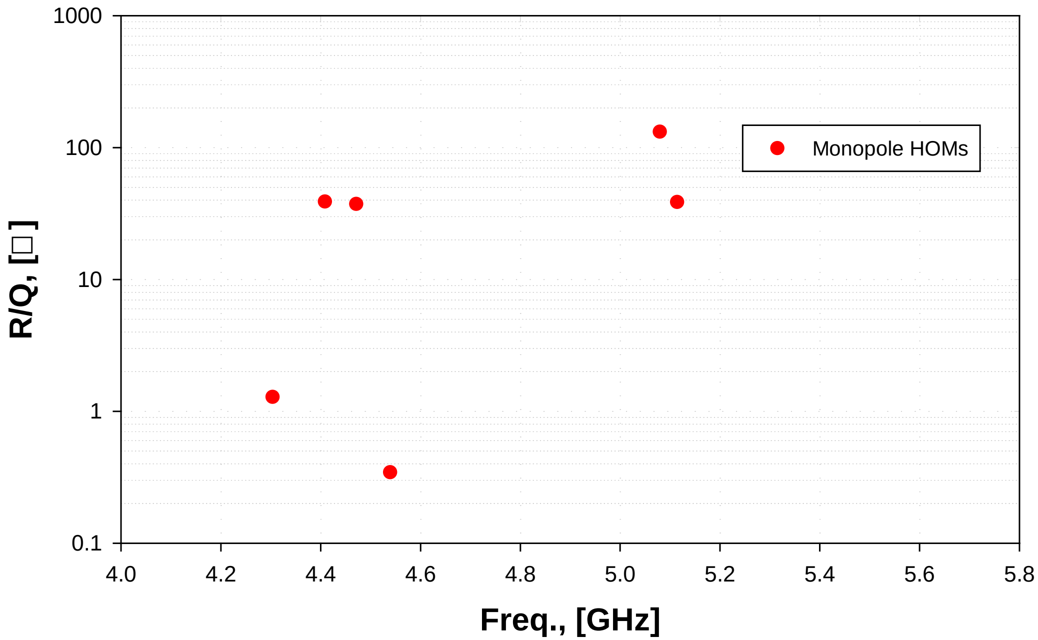
QMiR Cavity Monopole HOMs

K_{LOSS} = 0.66 V/pC

~ 50 % of HOM RF is radiated downstream



~ 50 % of HOM RF is radiated upstream



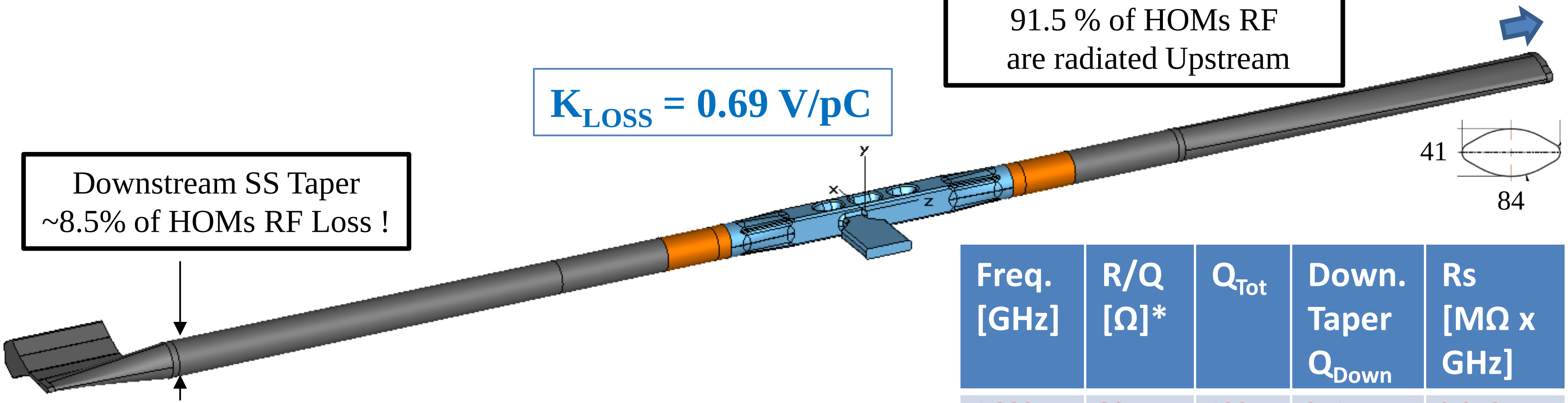
Freq., [GHz]	R/Q, [Ω]	Q	Rs, [MΩ x GHz]
4.304	1.3	55	3E-4
4.409	39	530	0.09
4.471	37	400	0.07
4.530	0.35	4900	8E-3
5.080	132	390	0.26
5.114	39	108	0.02

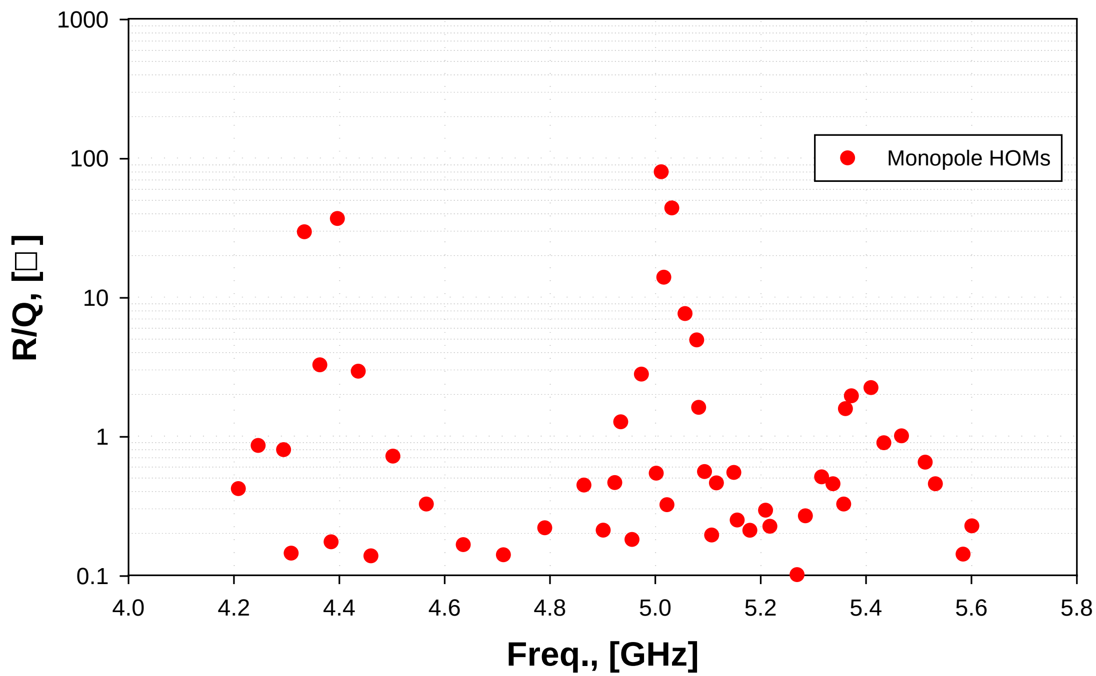
QMiR Cavity with Beam Pipe (52 mm Downstream Taper)

91.5 % of HOMs RF are radiated Upstream

K_{LOSS} = 0.69 V/pC

Downstream SS Taper ~8.5% of HOMs RF Loss !

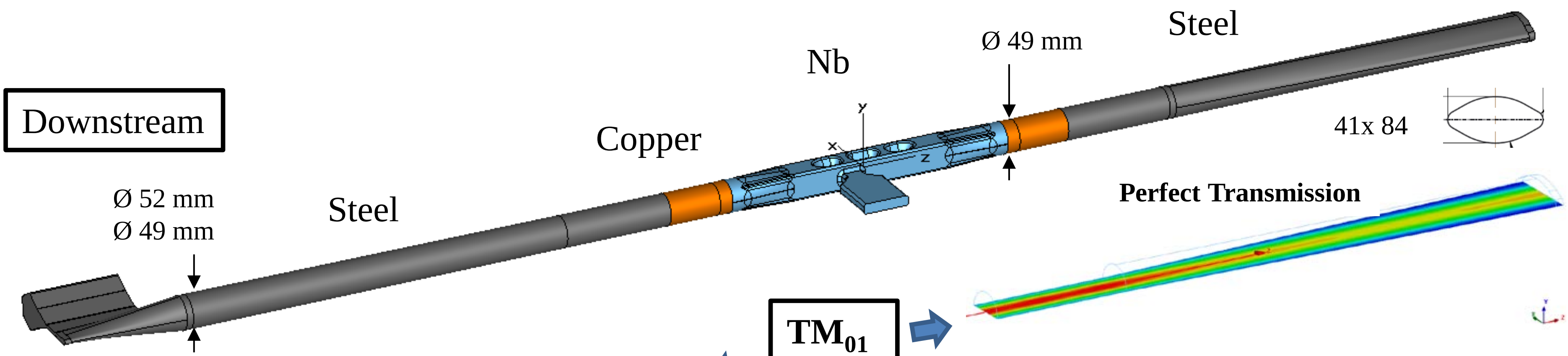




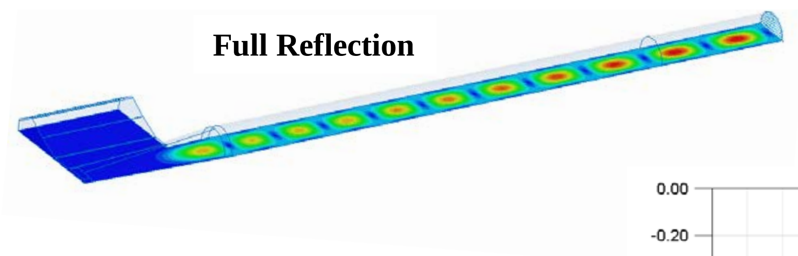
Freq. [GHz]	R/Q [Ω]*	Q_{Tot}	Down. Taper Q_{Down}	Rs [MΩ x GHz]
4.333	30	430	9e4	0.056
4.363	3.3	350	6500	5.1e-3
4.396	37	670	1e4	0.11
4.436	3.0	340	6800	4.5e-3
4.973	2.8	5000	5010	0.07
5.011	80	730	1.5e4	0.29
5.016	14	105	2.0e4	7.4e-3
5.031	44	1160	5700	0.26
5.056	7.7	120	2e5	4.6e-3
5.078	5.0	740	7500	0.019
5.082	1.6	130	1.5e4	1.1e-3
5.360	1.6	1850	8300	0.016
5.409	2.3	1350	7100	0.017
5.467	1.0	1400	8500	7.6e-3

*** Modes with R/Q > 1Ω only**

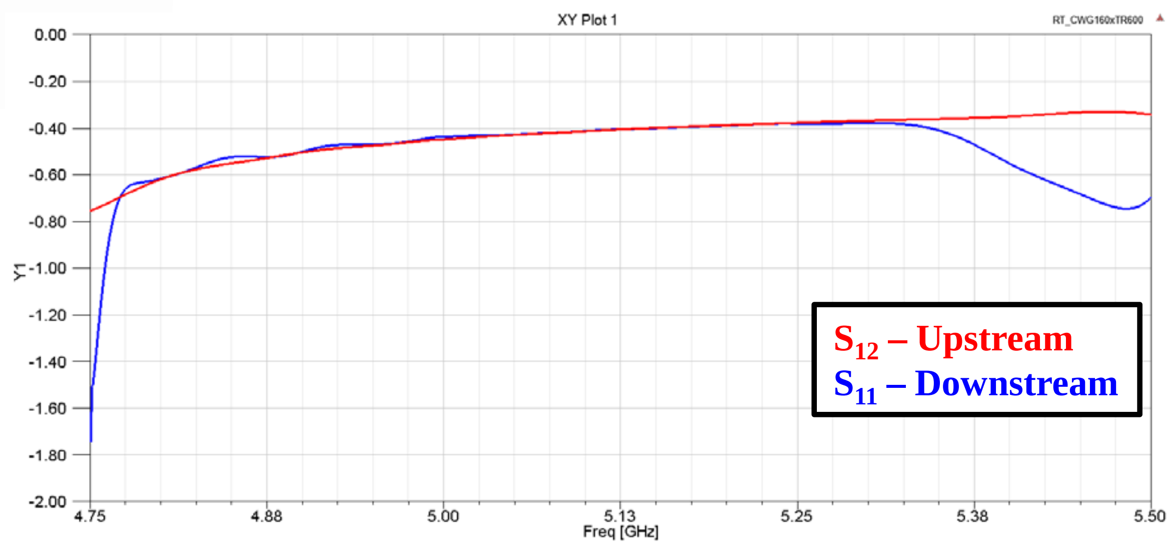
QMiR Cavity Monopole HOMs



TM_{01} Mode



Cross Section	TM_{01} Cut Off
Ø 52 mm	4.4 GHz
Ø 49 mm	4.7 GHz
Upstream	4.5 GHz



Monopole HOMs RF power is radiated to the Upstream beam pipe !

QMiR Cavity Monopole HOMs

	K_{LOSS} [V/pC]	Max Rs [MΩ x GHz]	Downstream HOMs RF Loss [%]	Upstream HOMs RF Loss [%]
Single cavity	0.66	0.26	50	50
Cavity with Ø 49 mm SS Taper	0.68	0.35	7.7	92.3
Cavity with Ø 52 mm SS Taper	0.69	0.29	8.5	91.5

1. **The Upstream and Downstream tapers add 5% only to the total loss factor coefficient.**
2. **The expected RF loss due to HOMs dissipation at the downstream SS taper is less than 10% of a total loss (~150W max for the standard APS operating mode ~ 100 mA & 19nC)**
3. **The difference between the Ø49mm and Ø52mm downstream SS taper options is marginal 1% for the HOMs RF loss, but the Ø52mm aperture has less maximum shunt impedance and, thus, is preferable.**
4. **The Upstream End RF matching is crucial for keeping HOMs Q-factor low**

RF and mechanical simulations done:

- Sensitivity to manufacturing and chemistry of RF parameters
- df/dp simulations
- Fast and slow tuning simulations
- Qext of flanges
- Sensitivity of probe position
- Surface field depending on tolerances
- Power coupler coupling dependence on tolerances
- Sensitivity of kick on beam position
- Thermal breakdown analysis

Conclusions

- No HOM couplers in proposed design
- Cavity has only one high power port, used for feeding the cavity and dumping of same order modes
- The proposed simple and compact TE_{113} mode deflecting cavity satisfies to maximum EM surface fields requirements
- Dipole and monopole HOMs could be damped below the instability threshold
- The cavity is free from multipactor in the operating RF field domain
- There is no problem with microphonics
- The cavity frequency tuning is feasible
- Both loss and kick factors are acceptable for operating bunch lengths
- Cavity mechanical design is straightforward
- HOM power emitted to beam pipes could be a an issue needed to address

The end

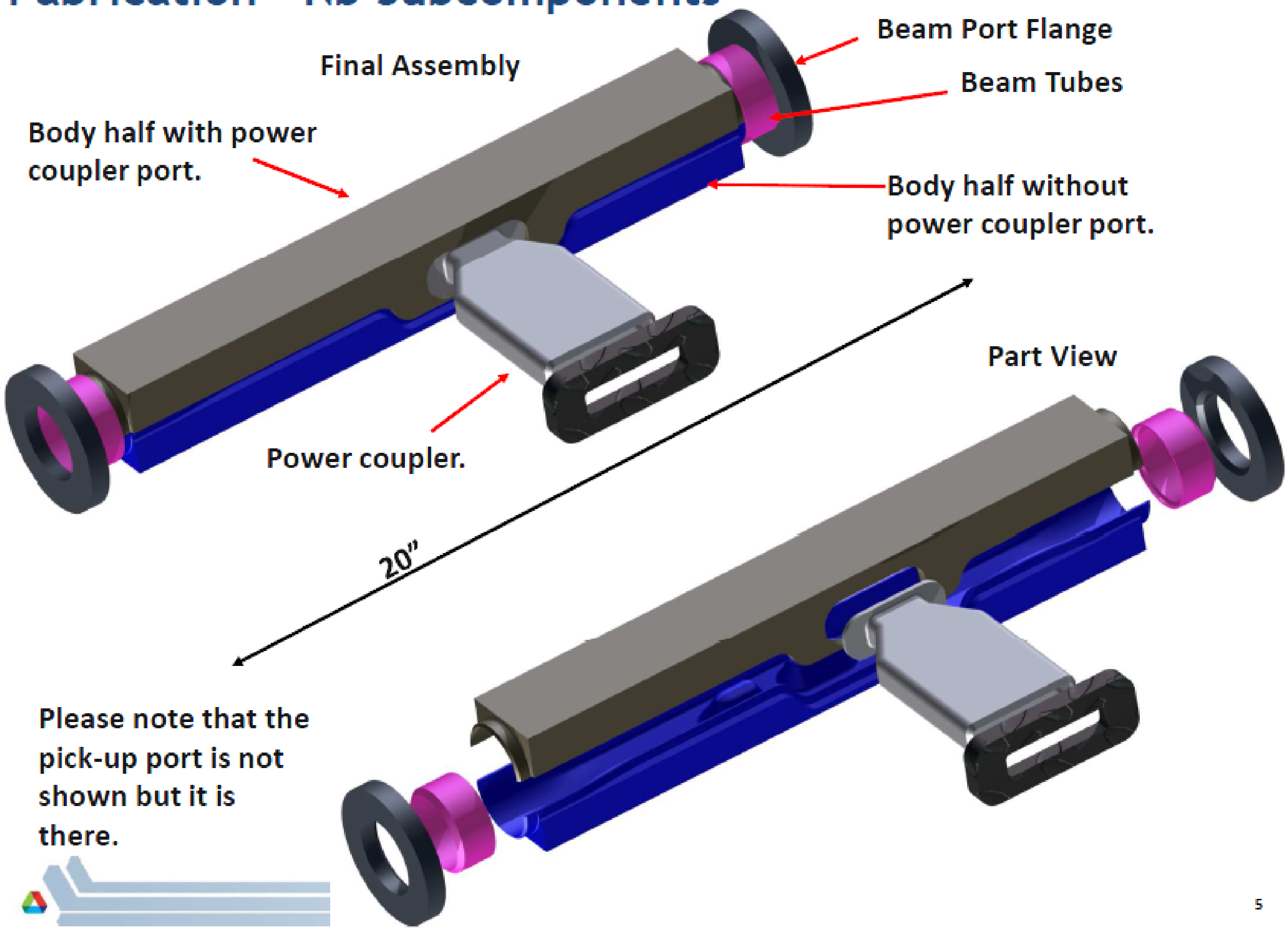
APS SPX Alternate Cavity Fabrication

Zachary Conway

on behalf of the ANL PHY LINAC development group

04/23/2013

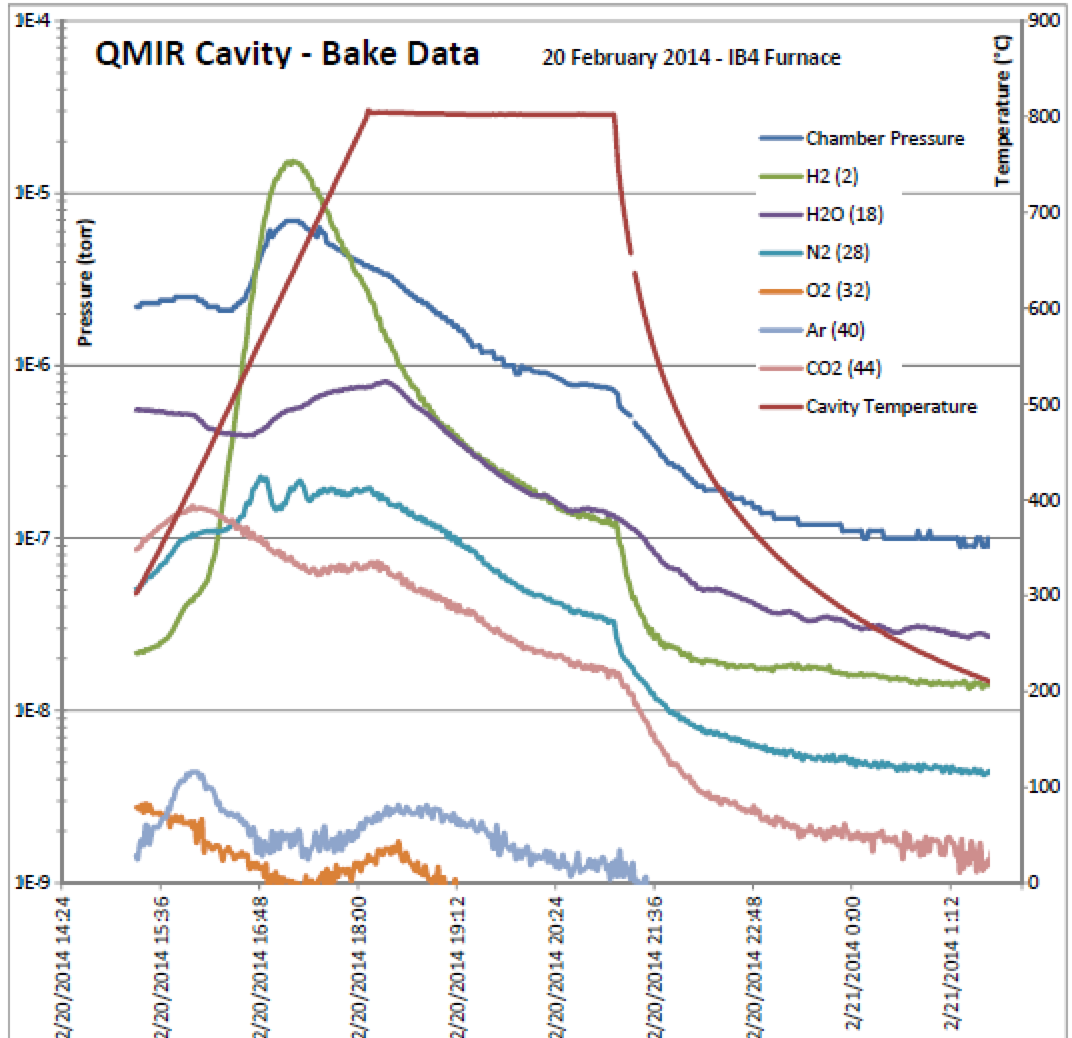
Fabrication – Nb Subcomponents



Please note that the pick-up port is not shown but it is there.

5

QMIR resonator Manufactored by ANL is placed on the Nb support frame before being introduced in the vacuum furnace at Fermilab.



Margherita Merio and Mayling Wong February 21, 2014

GHOST MODES IN IMPERFECT WAVEGUIDES

BY

E. T. JAYNES

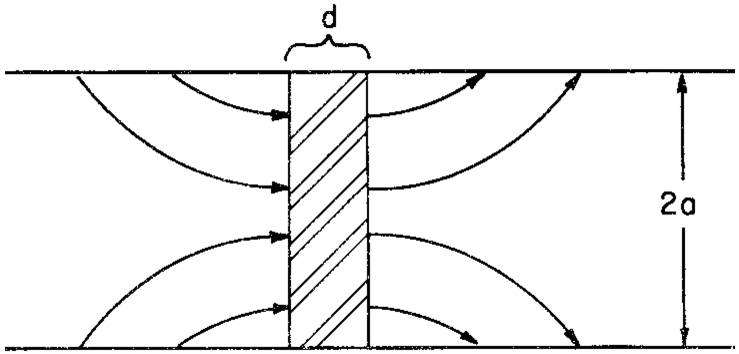
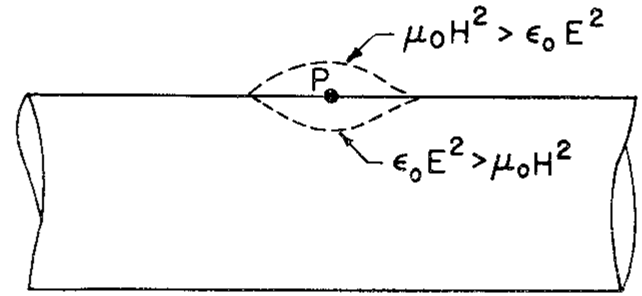
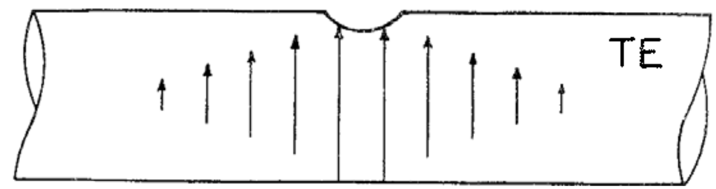
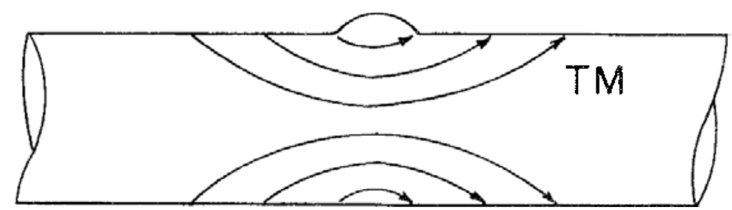


Fig. 1—TM_{01} ghost mode due to a dielectric disk.







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