FUTURE
CIRCULAR
COLLIDER

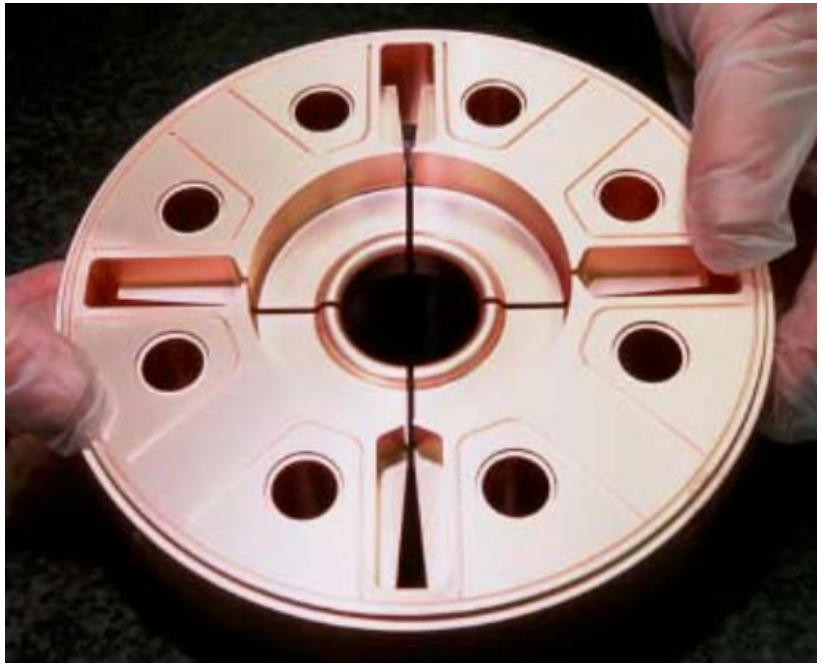
SWELL

Slotted **W**aveguide **ELL**iptical (SWELL) cavity development.

I. Syratchev, F. Peauger, I. Karpov, O. Brunner.
CERN

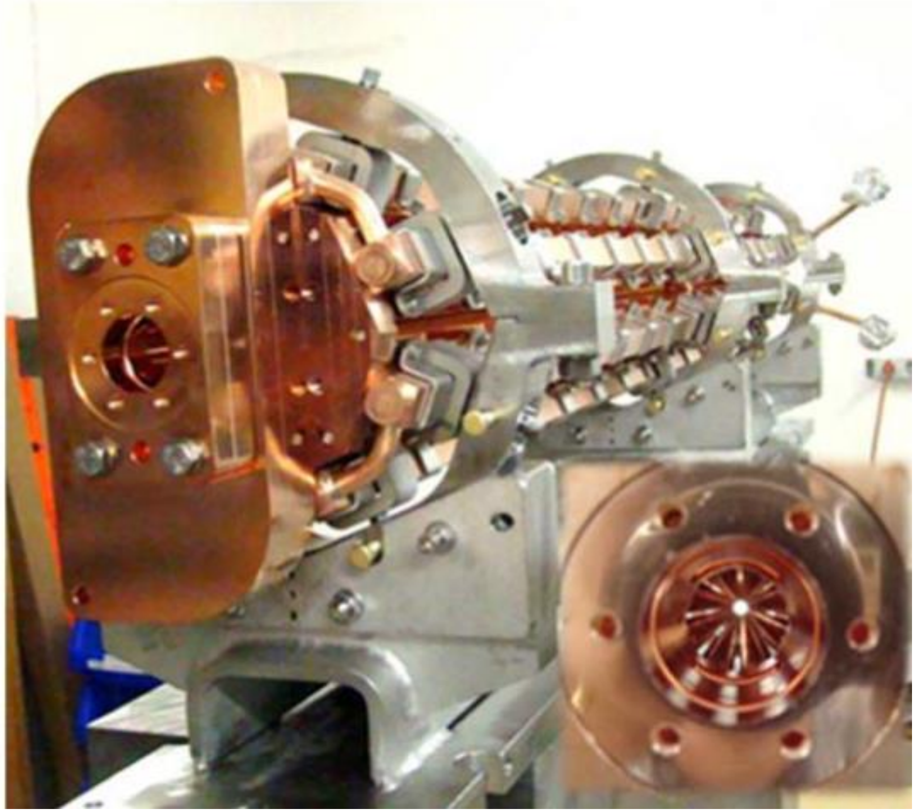
Accelerating structures with slotted irises at CERN (CLIC).

Slotted Irises Constant Aperture (SICA)
3GHz accelerating structure used in CTF3



E. Jensen, 'CTF3 drive beam accelerating structures', Proceedings of LINAC2002, Gyeongju, Korea.

CLIC 12 GHz Power Extraction and Transport Structure (PETS). Built of 8 octants.



I. Syratchev et al., "High RF Power Production for CLIC", Proceedings of the 2007 Particle Accelerator Conference, Albuquerque, pp. 2194-2196

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 012001 (2010)

Novel superconducting rf structure for ampere-class beam current for multi-GeV energy recovery linacs

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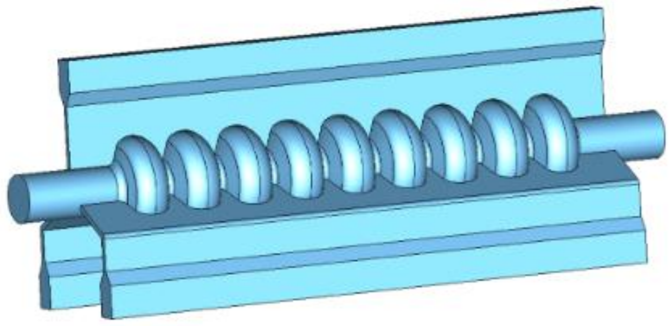


FIG. 9. (Color) Nine-cell slotted cavity model used in MWS simulation. The waveguide was bent parallel to the boundary for simulation.

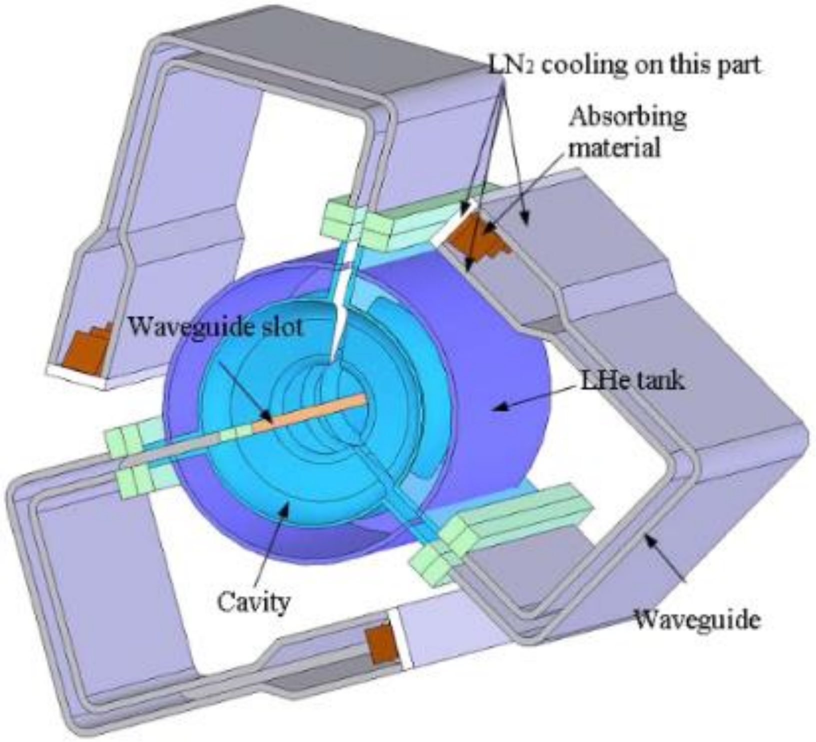


FIG. 11. (Color) Slotted cavity with waveguide attachments.

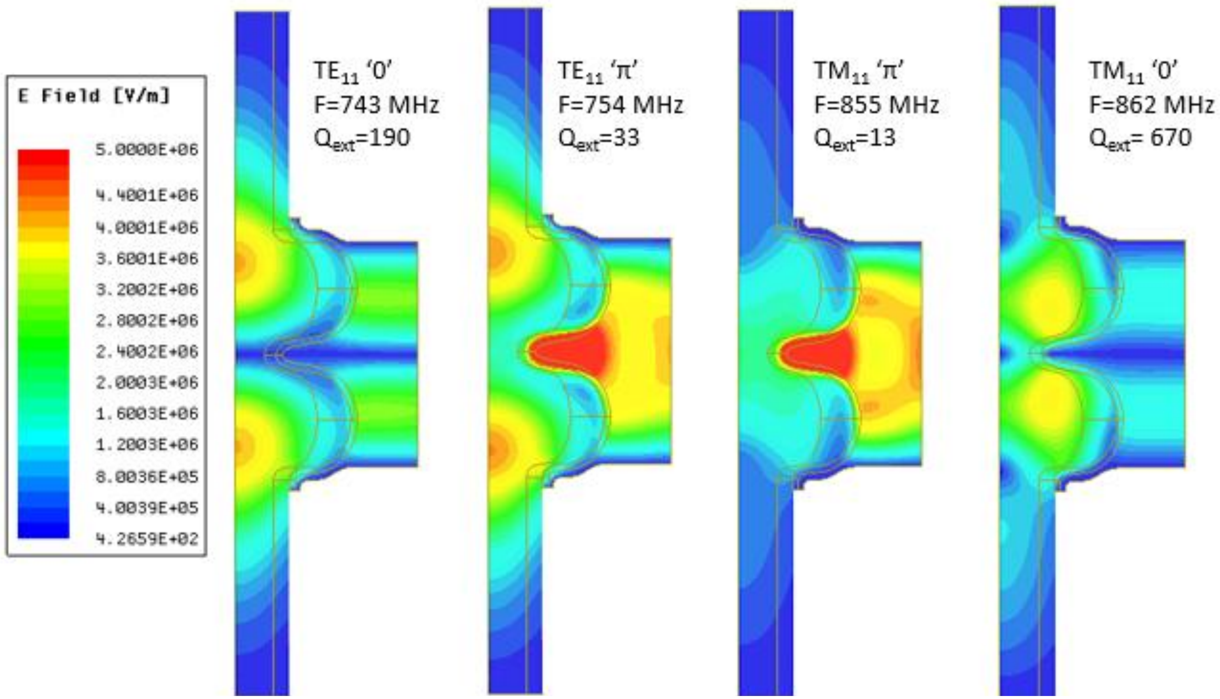
TABLE II. Q_e of the accelerating π mode at the waveguide ports for different waveguide lengths.

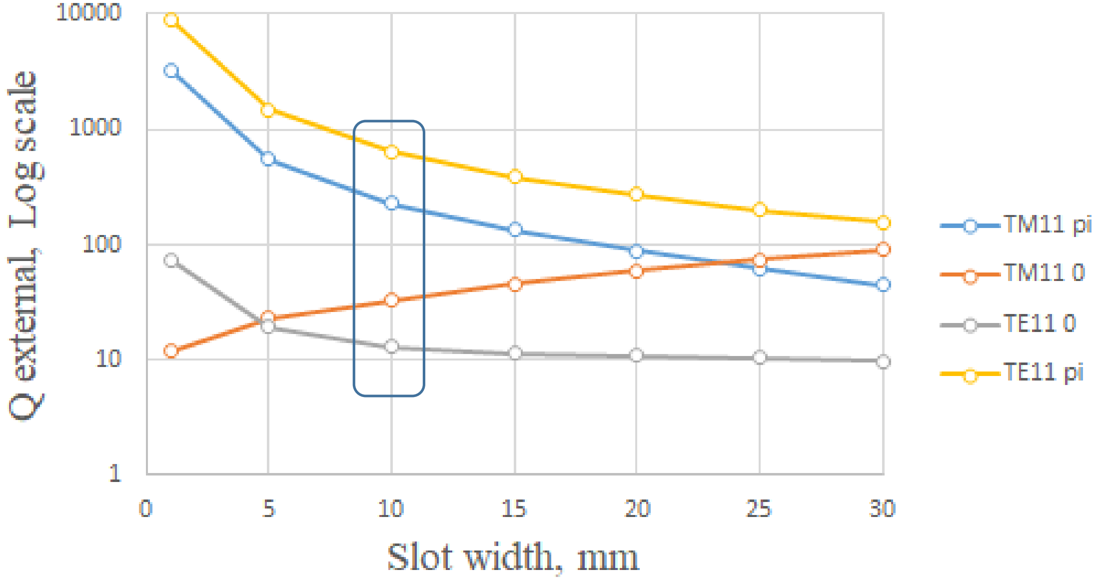
Q_e of the accelerating π mode at the waveguide ports	Waveguide length (mm, from equator)
3.79×10^6	14
6.58×10^7	19
7.91×10^8	24
1.12×10^{11}	29
1.31×10^{11}	34
7.25×10^{11}	54

Attenuation ~ 1000 dB/m!?

CST/3D (MWS) uses perturbation method to calculate Q external. This method is based on assumption that the mode under investigation is a standalone mode. Thus, designer could draw wrong conclusion when using CST/3D for simulations of the slotted coupled cavities in the presence of external load.

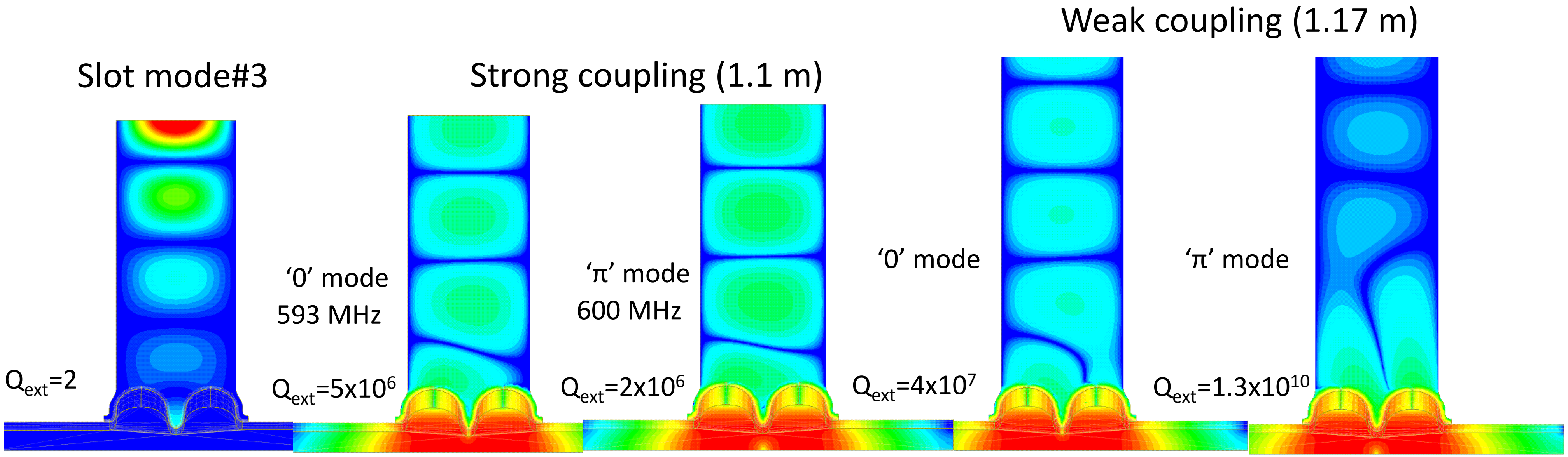
SWELL damping slot geometry configuration

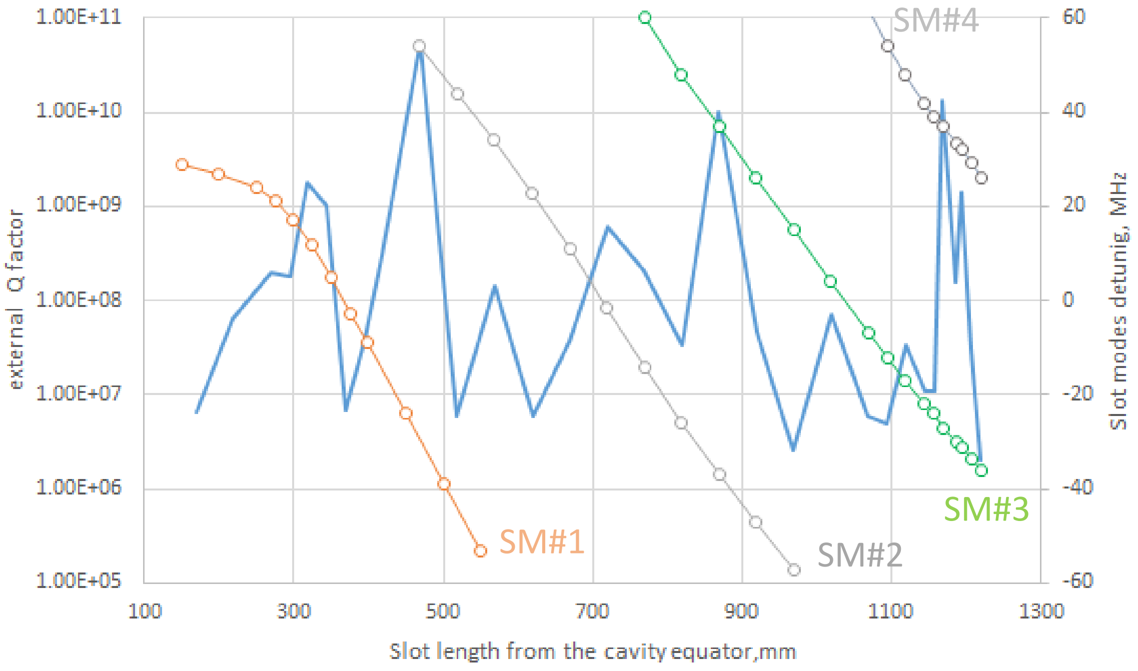




- Slot length of **430 mm** was chosen. Increasing the length does not improve HOM damping, whilst with this choice cut-of frequency of TE_{20} waveguide mode is 700 MHz – well above the operating frequency.
- **10 mm** slot width was considered as a compromise between SCRF and HOM performances.

Fundamental modes external Q factors (HFSS)

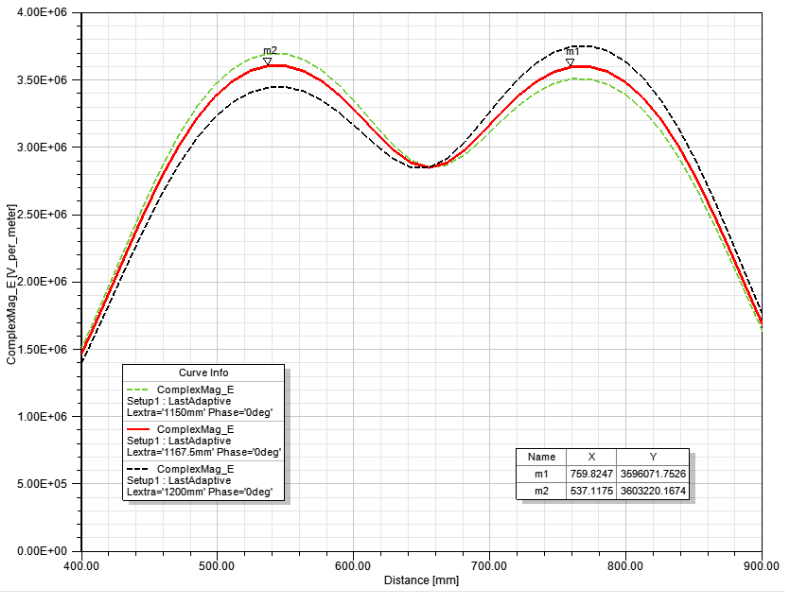




- Depending on the phase advance of the cavity modes, each of them has a preferential waveguide mode ($TE_{N,0}$) to couple with.
- In a system with modes frequencies located closely, modes will be coupled through the slot as well. Thus, coupling to the waveguides modes mixture will happen.
- Heavily damped slot modes are the legit eigen oscillations in the system with external RF power absorption (HFSS free radiation boundary).
- Slot modes can modulate accelerating modes coupling to the waveguide modes (Q external) and distort the longitudinal filed symmetry of the modes inside the cavity.

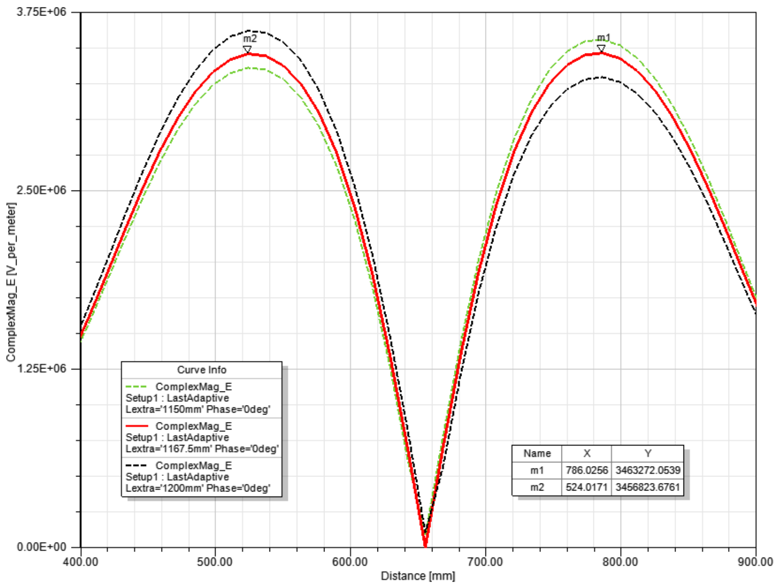
Fundamental modes external Q factors (HFSS)

Ez on axis, ‘0’ mode



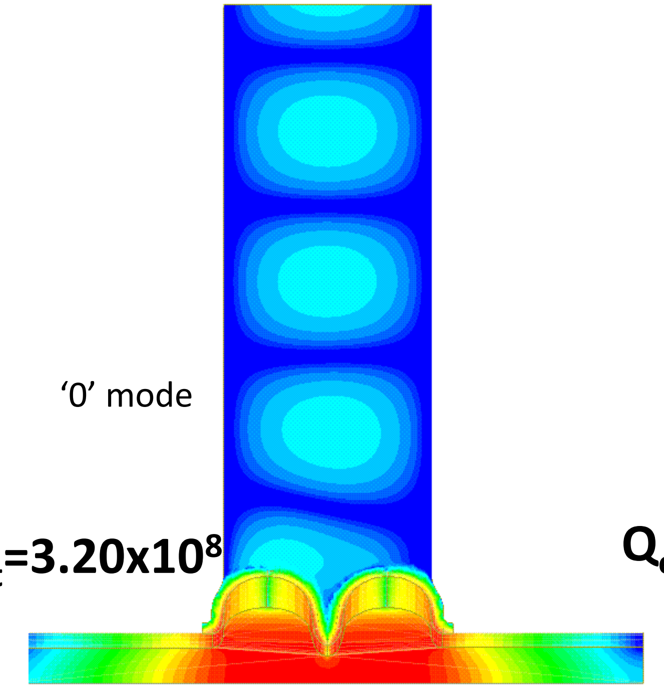
Name	X	Y
m1	759.8247	3596071.7526
m2	537.1175	3603220.1674

Ez on axis, ‘π’ mode



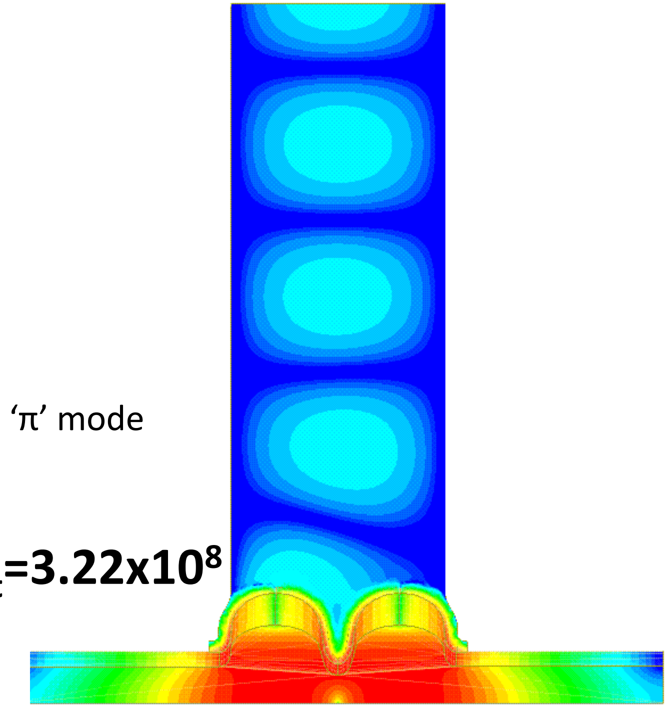
Name	X	Y
m1	786.0256	3463272.0539
m2	524.0171	3456823.6761

- With infinite length of the damping waveguide, the slot modes spectra will be dense enough, so that integrated effect of slot modes on the accelerating modes external coupling shall disappear.
- With a waveguide of the finite length, there shall be a specific length, where two nearby slot modes could compensate each other.
- At this point, the field symmetry in the cavity shall be restored (red color lines on the left plots) and external Q factors of the modes are expected to be similar:



‘0’ mode

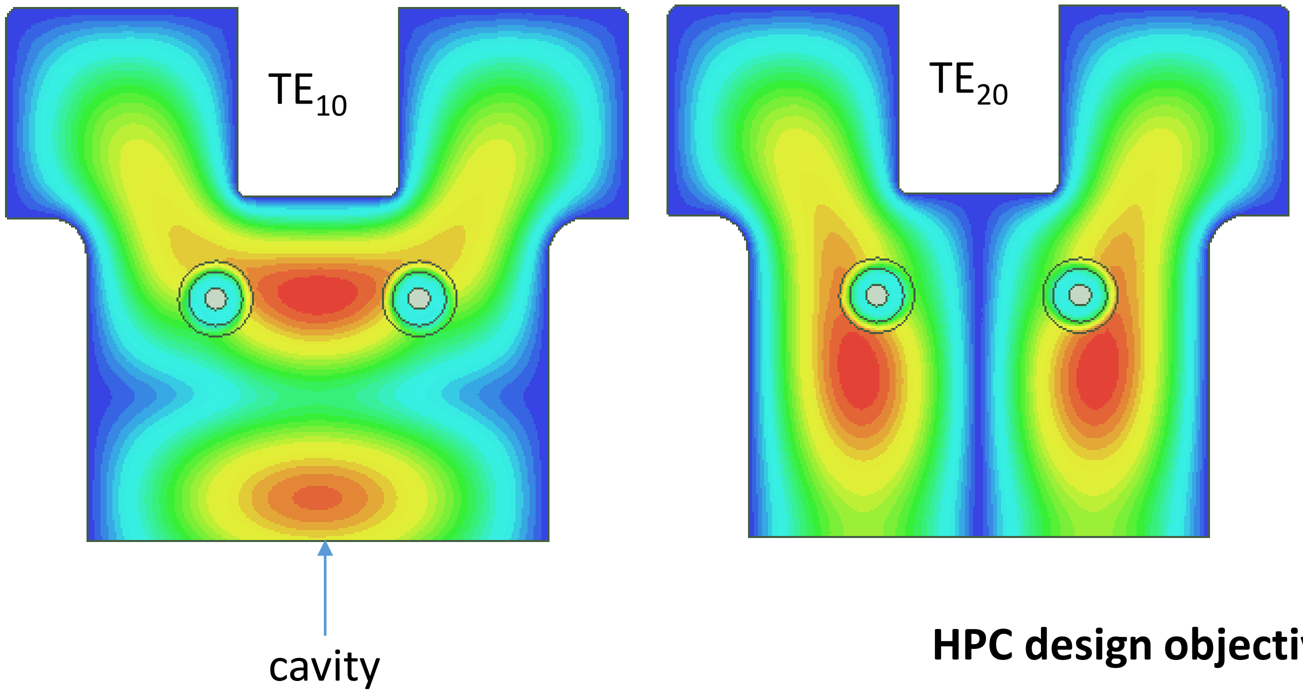
Q_{ext}=3.20x10^8

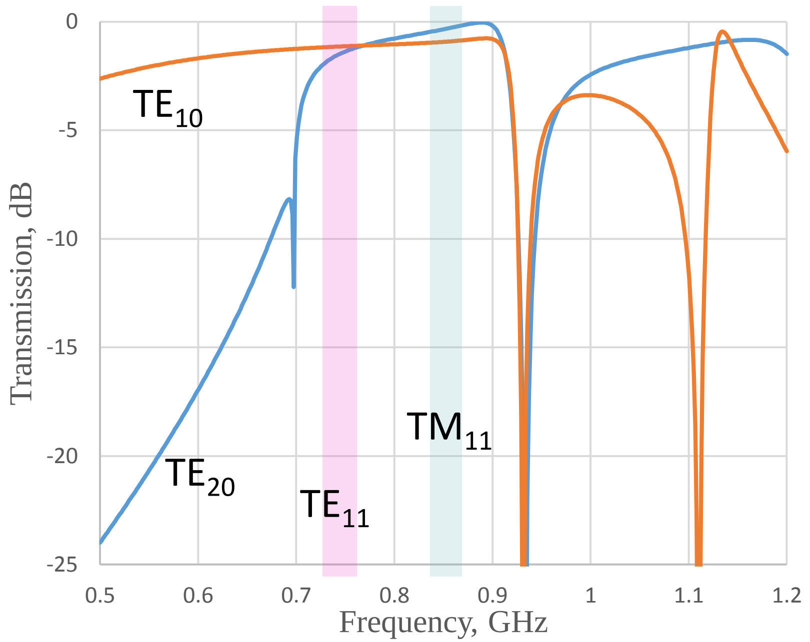


‘π’ mode

Q_{ext}=3.22x10^8

Planar HOM power coupler (HPC) with coaxial feedthrough's. Conceptual design.



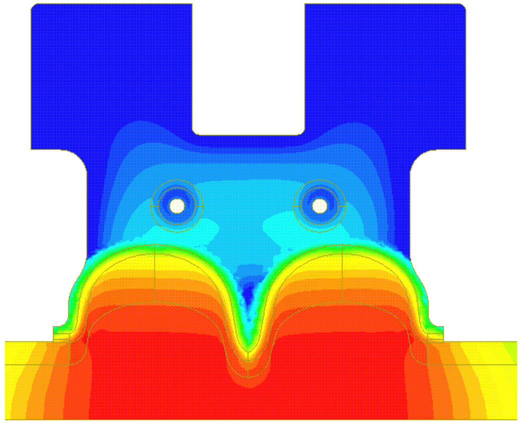


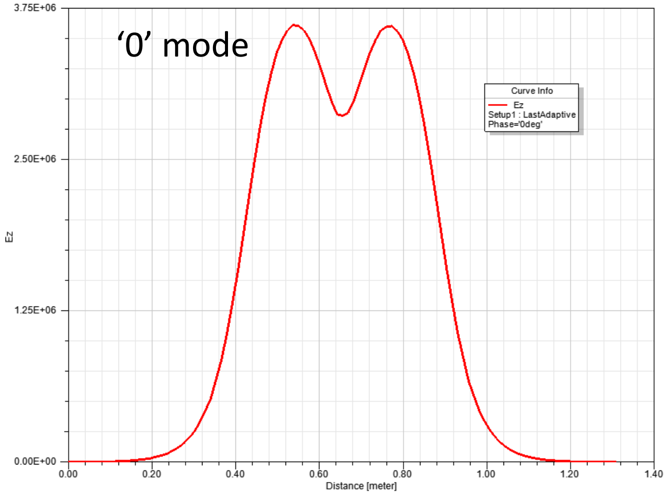
HPC design objectives

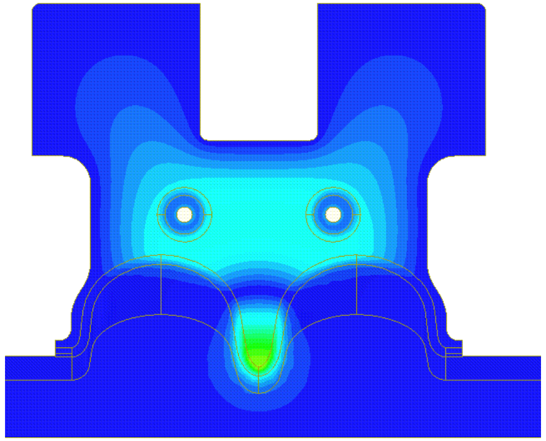
- HPC has to evacuate efficiently the RF power of HOM generated in the cavity and be able to deal with both waveguide modes.
- Sparse slot modes spectra (transverse and longitudinal) and provide their heavy damping.
- The HOM power will be collected at the HPC outputs and evacuated with coaxial cables outside the cold volume.

SWELL cavity with coaxial HPC

Q_{ext}=3.45x10^8

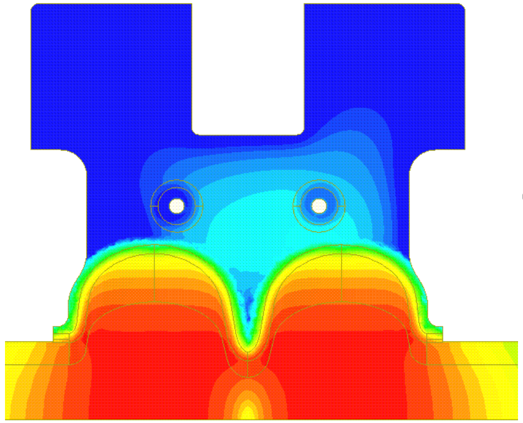


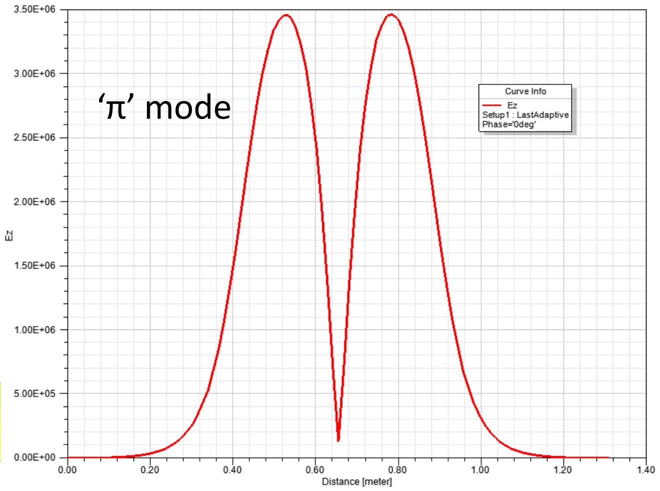




Slot mode
F= 740 MHz
Q_{ext}=6

Q_{ext}=3.41x10^8



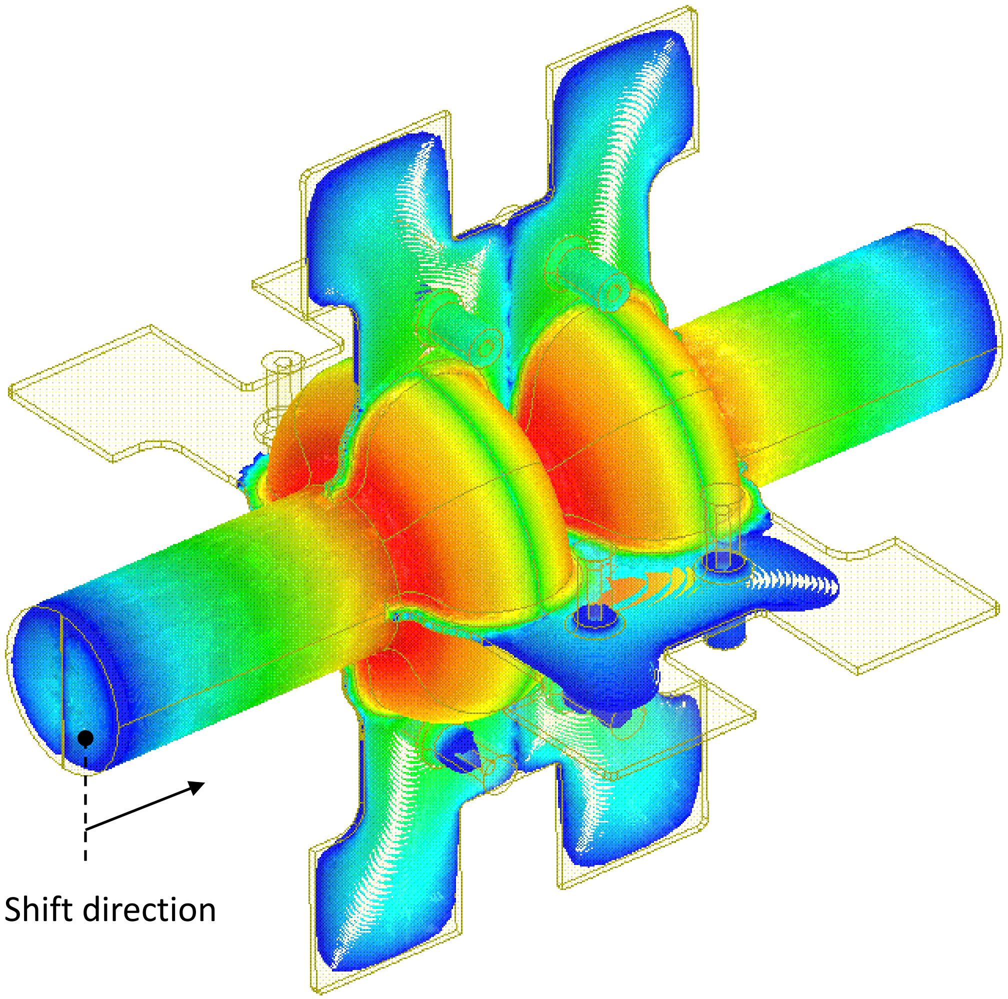


E field log scale

- Accelerating modes behavior is similar to the situation with infinitely long matched waveguide, due to the short extraction circuit length with strong detuning of the slot mode(s).
- Measured external Q factor can be accepted for the FCC_ee Z option where loaded Q factor is 2x10^4, but can be barely accepted for the low current cases like H option where loaded Q factor is 6.5x10^5 (0.2% of RF power [600 W] will be lost in HOM loads).

Assembly/fabrication tolerance issues

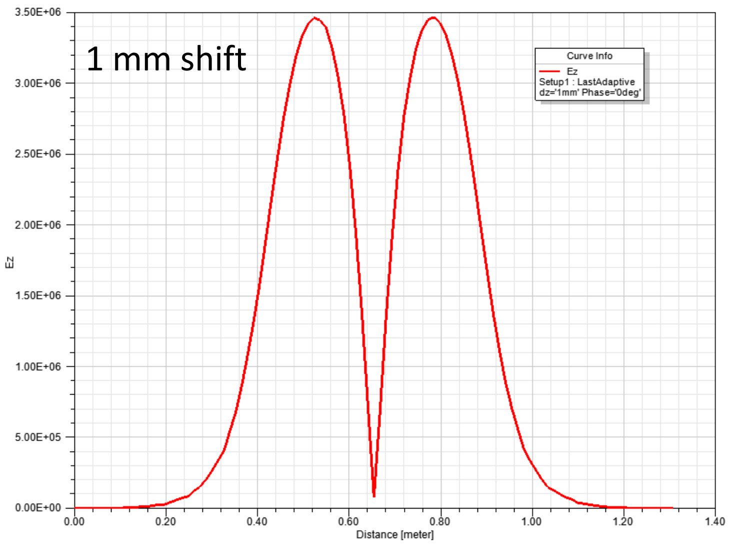
E field log scale



0.1 mm shift: Q_{ext}=2.4 x10^6
1 mm sift: Q_{ext}=2.0 x10^6

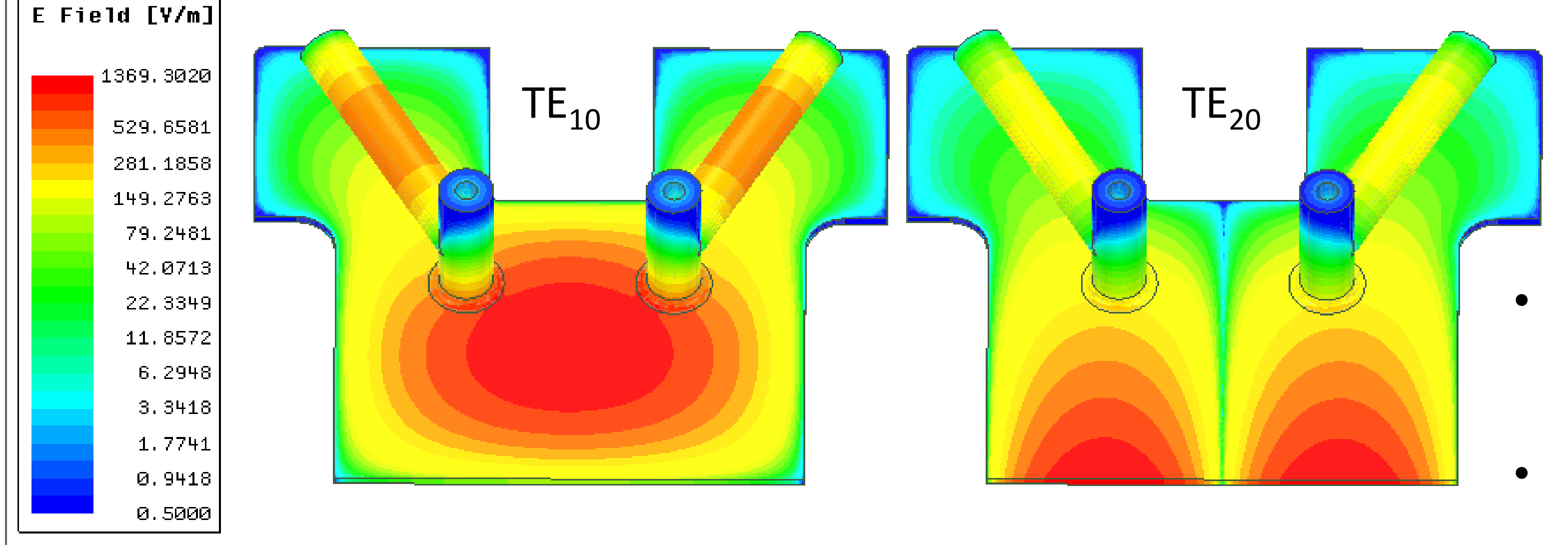
- The sheer longitudinal shift between two pairs of adjusted quadrants appeared to have the most dramatic effect on the operating mode Q factor degradation.
- With such an asymmetry, the operating mode couples strongly to TE_{20} mode in the slots oriented along the shift plane.
- With compact HPC arrangement, decay properties of TE_{20} mode vanished away and Q_{ext} degrades very rapidly. Whilst longitudinal field symmetry of the modes is not perturbed.

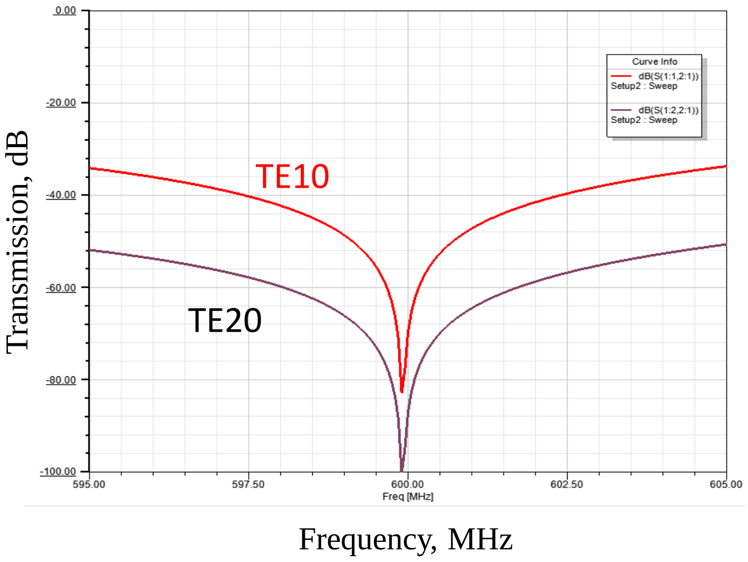
E_z on axis

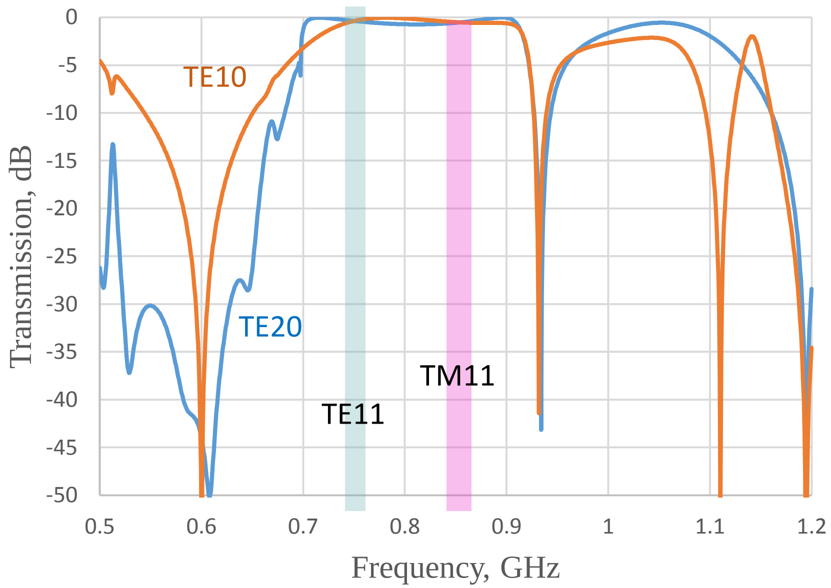


HPC RF circuit with external rejecters (HPC_R)

E plot, log scale



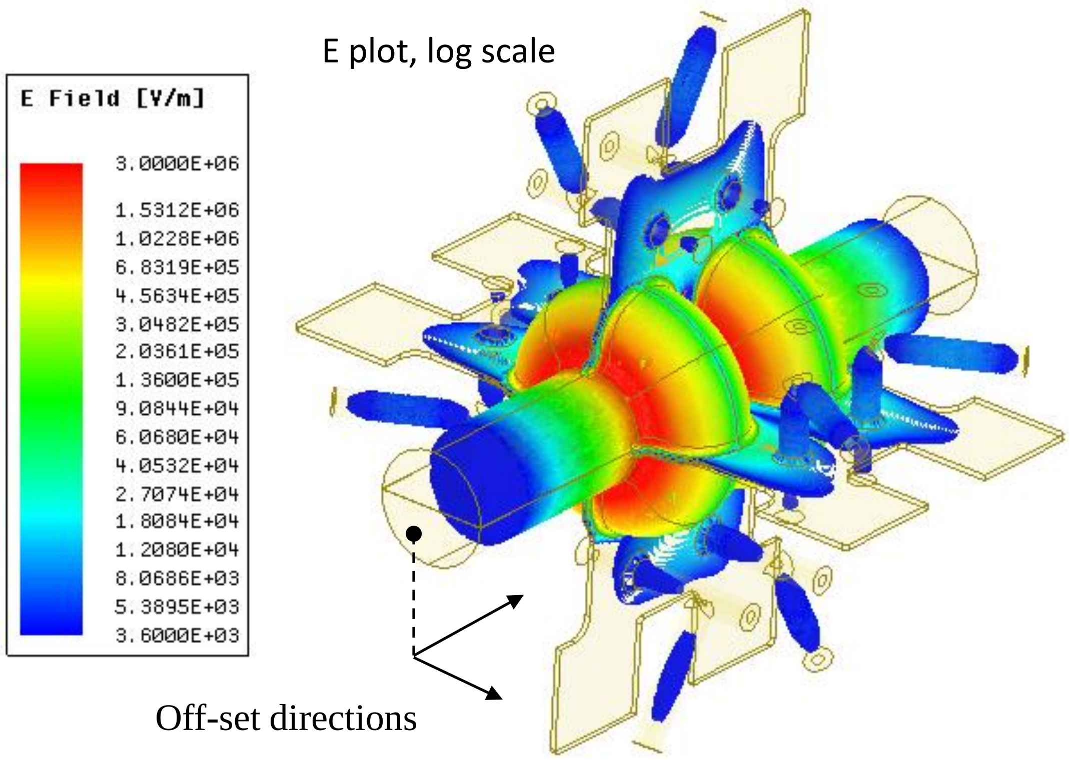


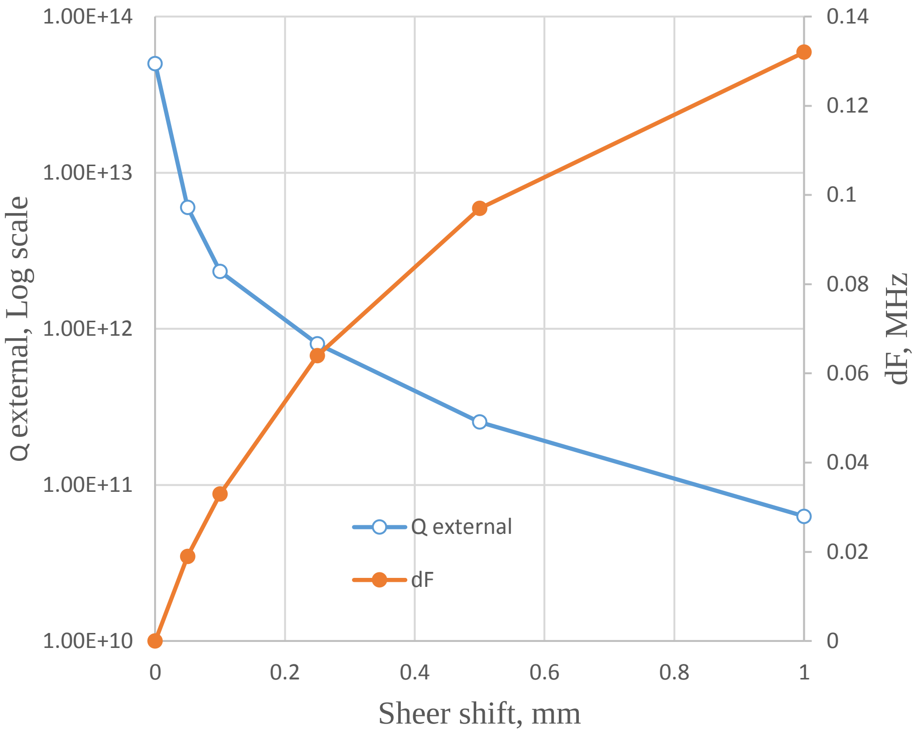


- External lambda/half coaxial rejecters can trap efficiently both waveguide modes at a designated frequency.
- These separate RF devices can be tuned individually and connected to SWELL after the cavity is fully assembled.

SWELL cavity with HPC_R

Simultaneous longitudinal and transverse
1 mm sheer shift of 2 blocks pairs:



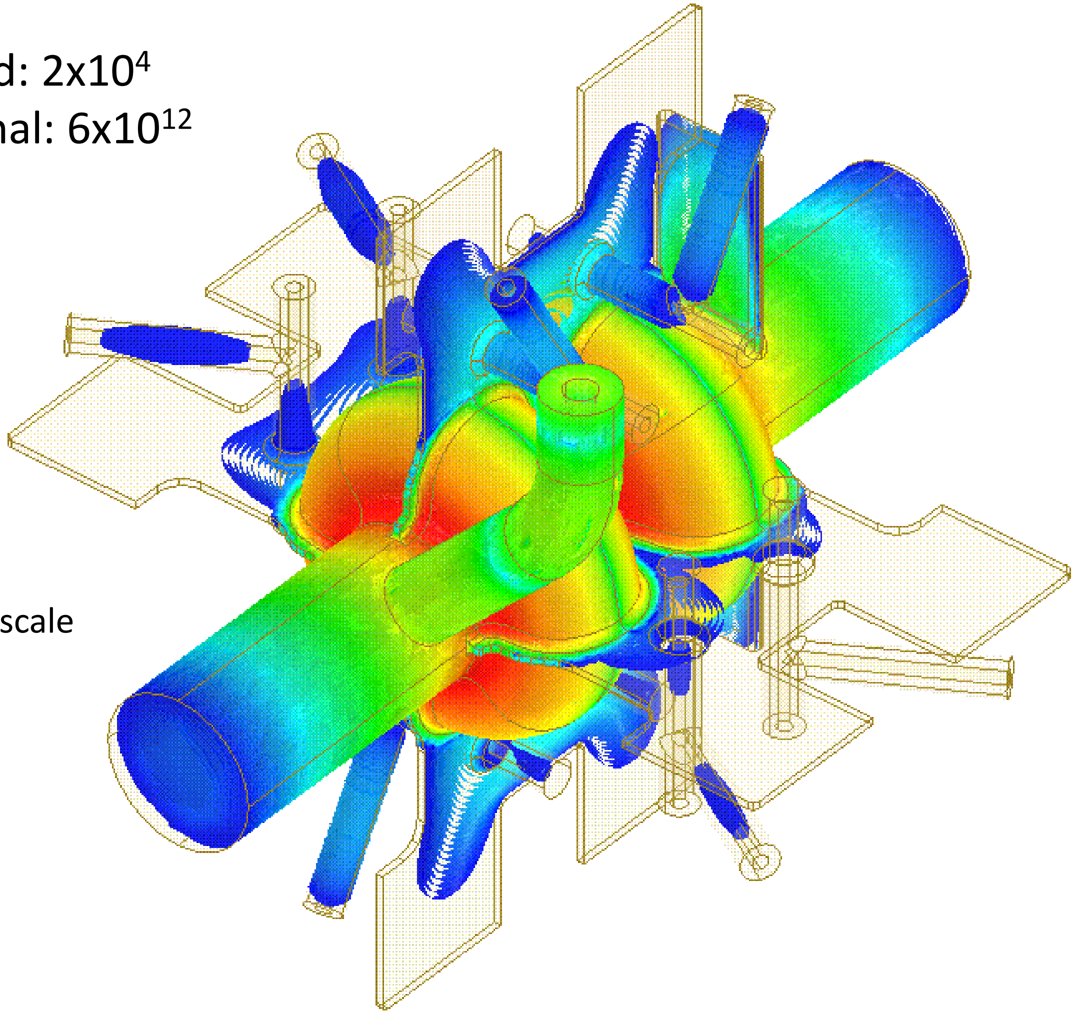


- With new HPC configuration, external Q factor is remarkably stable and stays well above 10^{10} in the shifts range (both planes together) up to 1 mm. Thus, SWELL + HPC_R shall be compatible with all types of FCC_ee machines.
- In application to the beam acceleration, the actual required tolerances on the shift values will be defined later in the beam dynamic simulation.

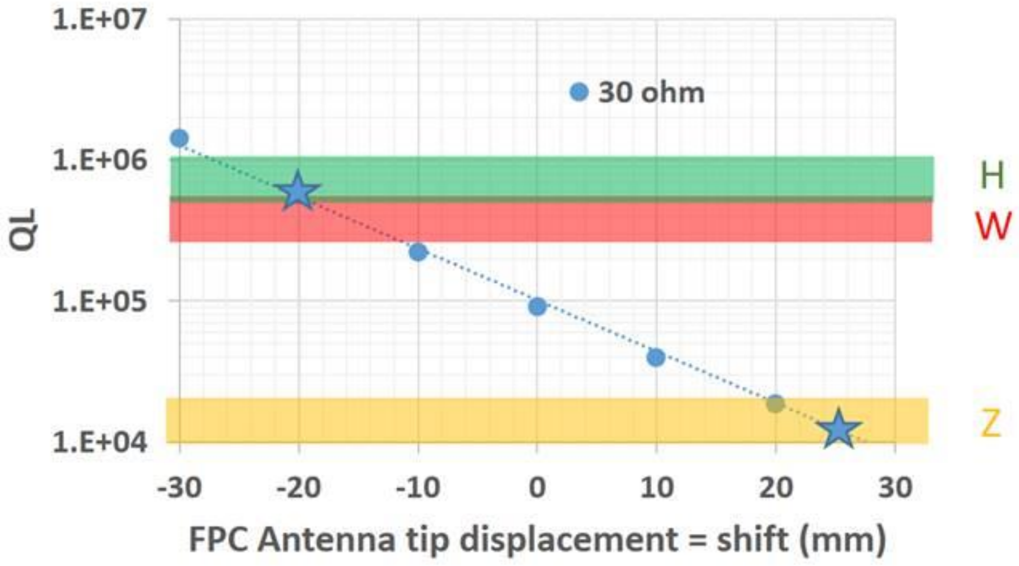
SWELL with FPC and 1.1 GHz WG dampers

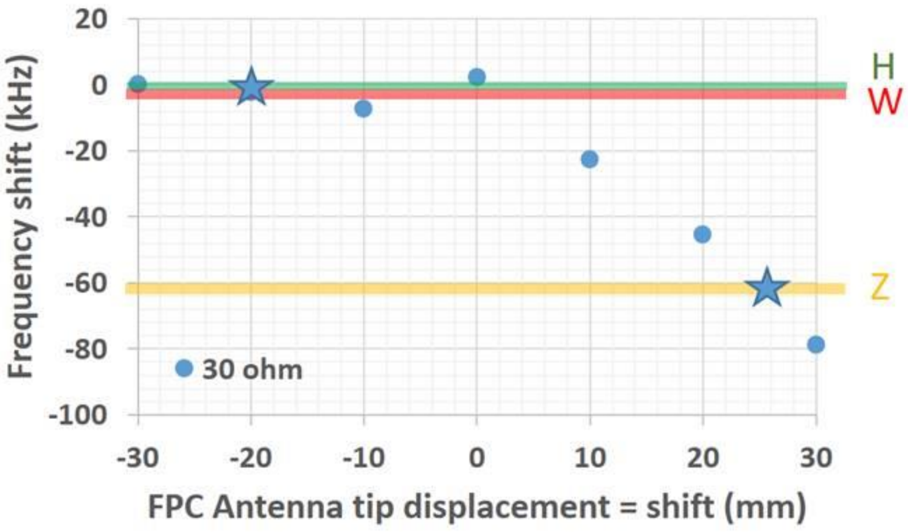
Q loaded: $2x10^4$

Q external: $6x10^{12}$



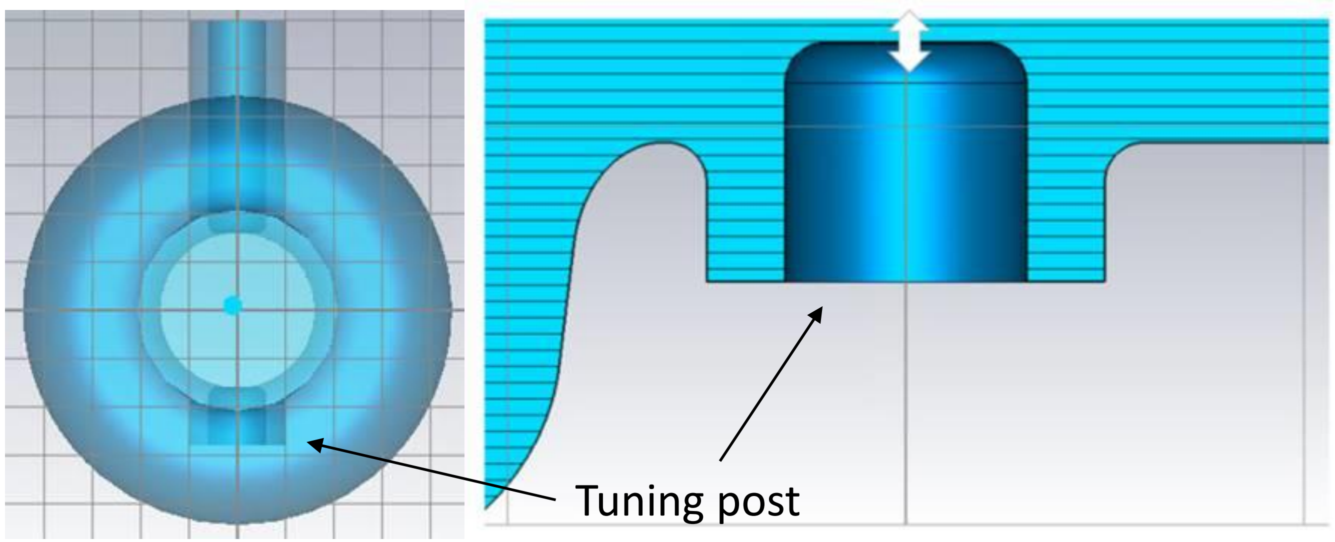
E plot, log scale

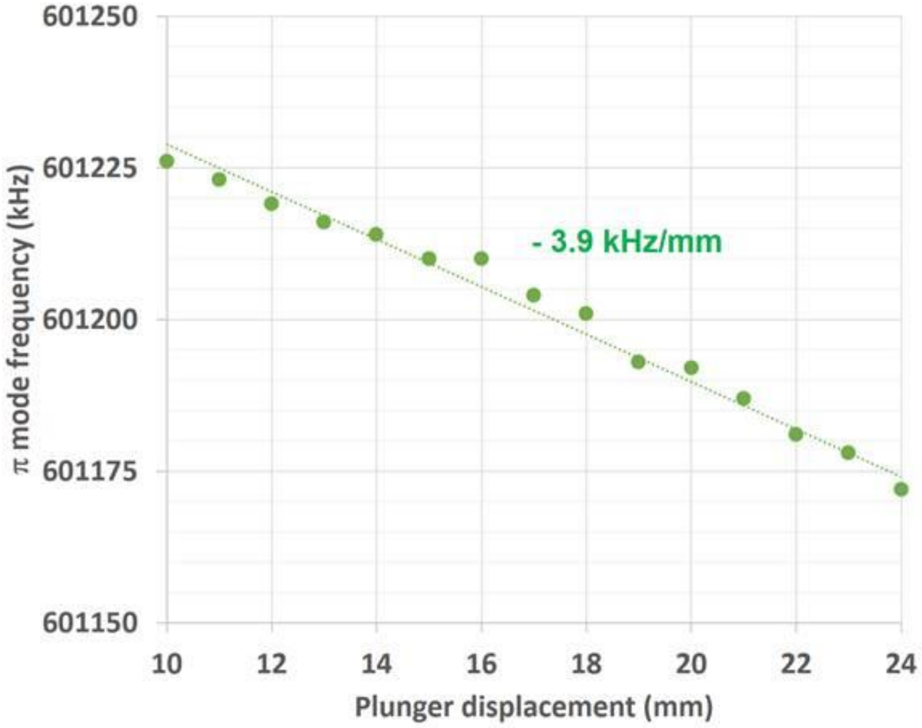




- FPC is represented by the **30 Ohms** coaxial feedthrough with an outer diameter of 100mm. Total linear stroke of the inner conductor tip position of 45mm allows to cover the range of the loaded Q factors from $2x10^4$ up to $6.5x10^5$ and provides necessary frequency detuning.
- As a last modification of the damping circuit we introduced two orthogonal waveguides with cut-off frequency of 0.95 GHz. The objective of these waveguides is to damp the longitudinal trapped modes at the beam pipe cut-off frequency around 1.1 GHz

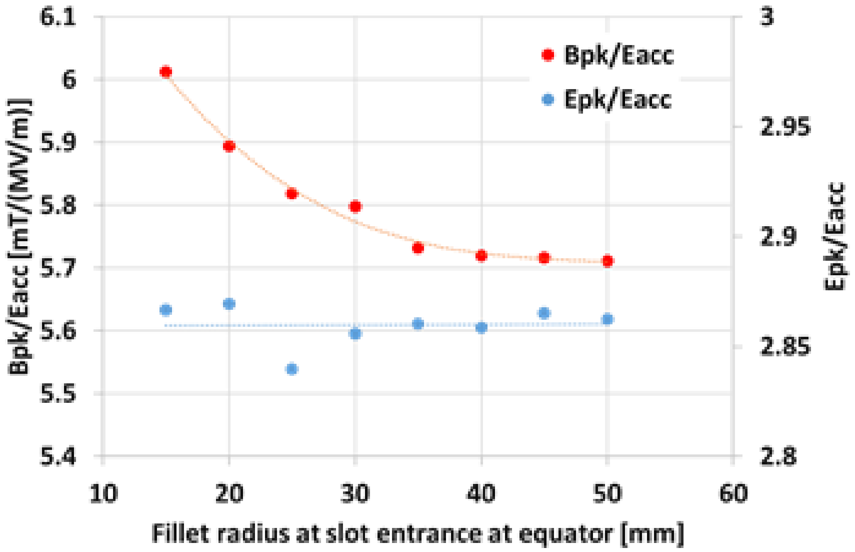
Possible SWELL cavity frequency tuning strategy



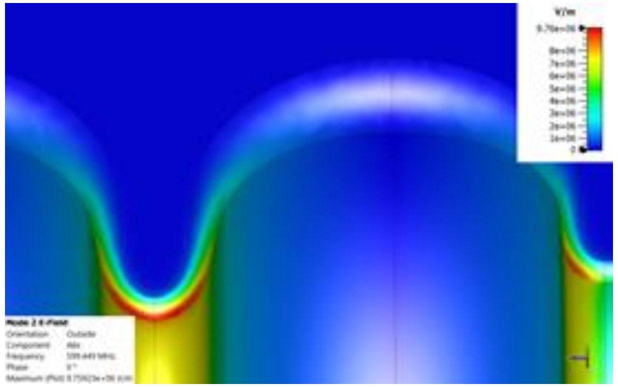


- The tuning post is located on the opposite side of the FPC. Changing the length of the post, frequency tuning range can be achieved within +/- 50KHz (25 mm total stroke).
- To avoid the needs for the mechanical movement during operation, the pool of such tuners with different length can be stocked and the necessary one to be installed and fixed during the final cavity assembly in warm environment.

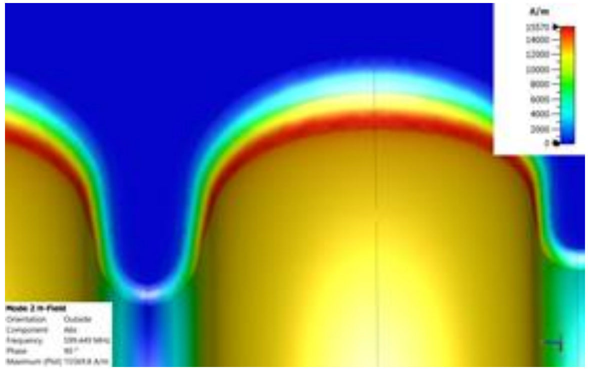
SWELL extrapolated SCRF performance



E field



H field



Slot edge fillet radius is gradually increased from 12 mm at the iris tip, up to 35 mm at the cavity equator. Compared to symmetrical cavity, E field enhancement factor is 1.34 and for H field is 1.28.

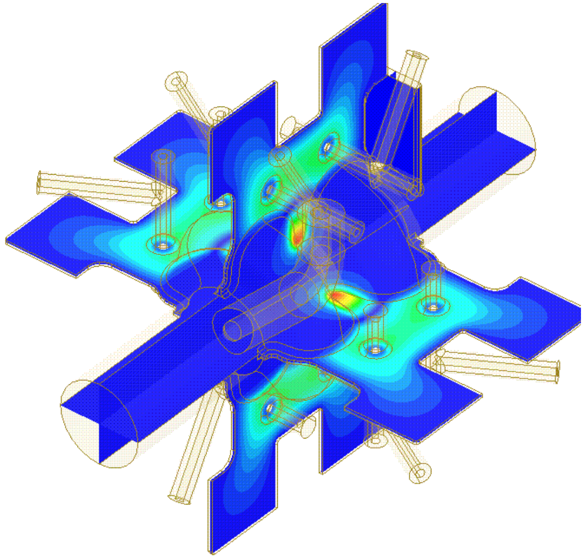
Data for extrapolation is based on measured performance of the 100 MHz seamless Nb/Cu QWR.

A. Miyazaki and W. Venturini Delsolaro., 'Two different origins of the Q-slope problem in superconducting niobium film cavities for a heavy ion accelerator at CERN', PRAB 22, 073101 (2019)

	Z	W	H	ttbar2
Frequency [MHz]	600			
r/Q [W] (circuit definition)	96.7			
Transit Time Factor	0.579			
G [W]	272.2			
Lacc [m]	0.5			
Epk/Eacc	2.86			
Bpk/Eacc [mT/(MV/m)]	5.72			
Accelerating voltage [MV]	1.2	3	8	10
Accelerating gradient Eacc [MV/m]	2.4	6	16	20
Max. surface electric field Epk [MV/m]	6.9	17.2	45.8	57.2
Max. surface magnetic field Bpk [mT]	13.7	34.3	91.5	114.4
Operating temperature [K]	4.5	4.5 or 2	2	2
Stored energy [J]	2	12.3	87.8	137.2

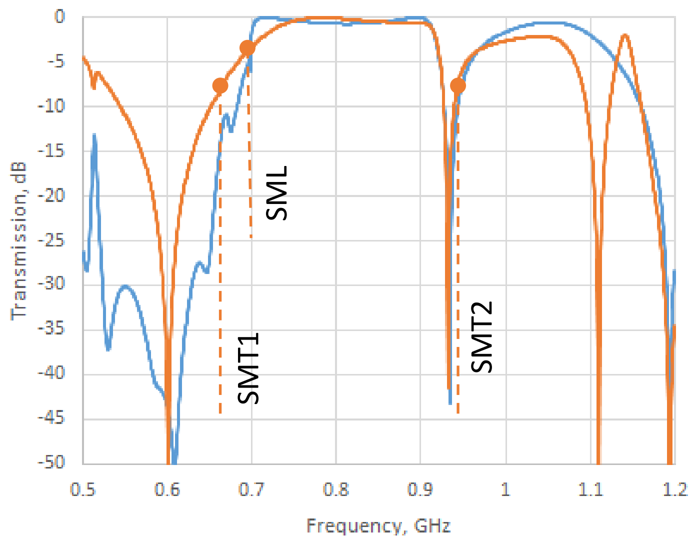
Slot modes in SWELL

Monopole slot mode (SML)



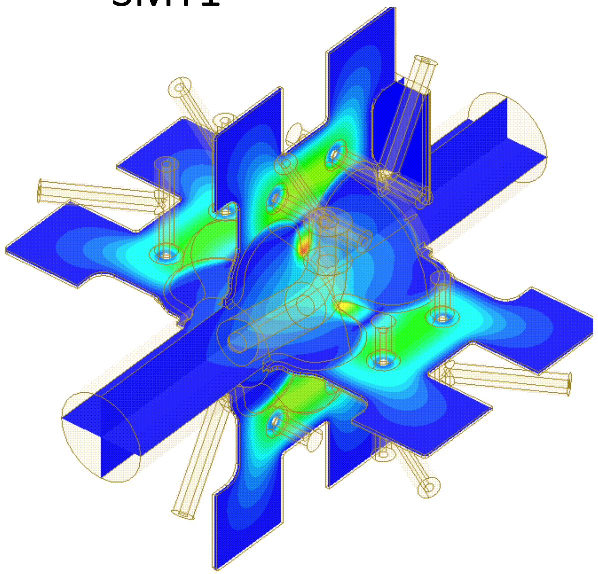
F=697 MHz; Q_{ext}=36; R/Q=1.5x10^{-4} Ohms

- The drawback of HPC_R is that RF length associated with slot modes is increased due to external rejecters, thus modes frequencies were moved down in frequency.
- The monopole mode responsible for the modulation of accelerating modes coupling to the slots is still far apart (+100 MHz).
- The dipole slot modes are more of a challenge, as they moved closer to the HPC_R frequency stop bands. Still their impedances are lower than the ones of the damped dipole HOM.



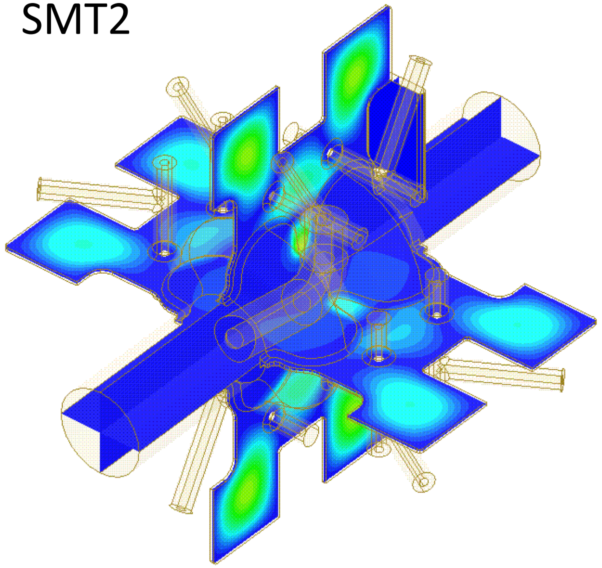
Dipole slot modes

SMT1



F=661 MHz; Q_{ext}=120; R_T/Q=8.6 Ohms

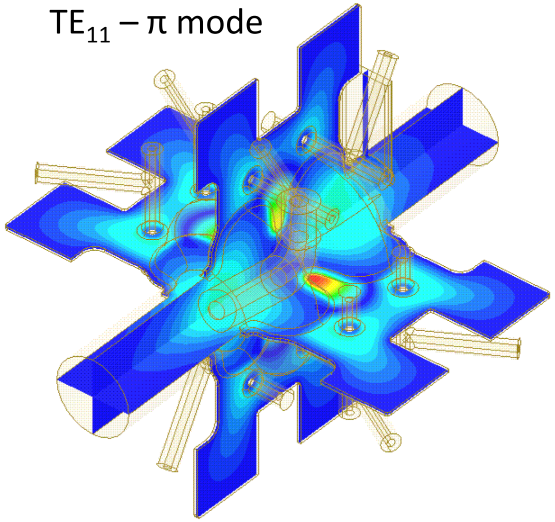
SMT2



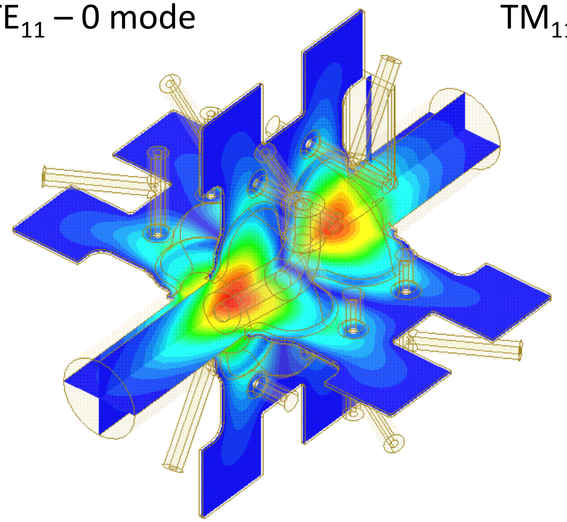
F=941 MHz; Q_{ext}=450; R_T/Q=0.8 Ohms

HOM modes in SWELL

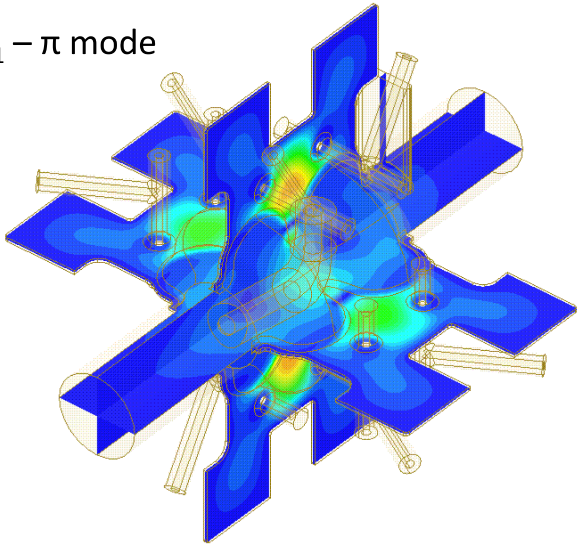
$TE_{11} - \pi$ mode



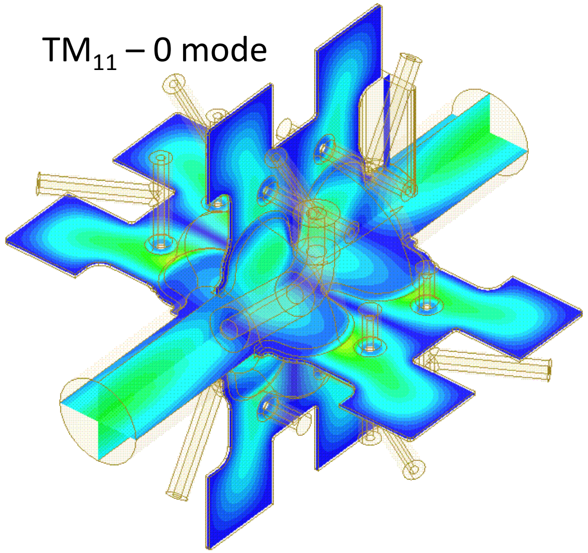
$TE_{11} - 0$ mode



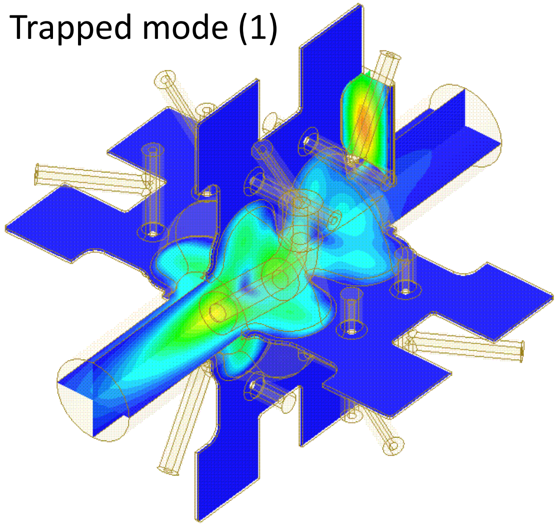
$TM_{11} - \pi$ mode



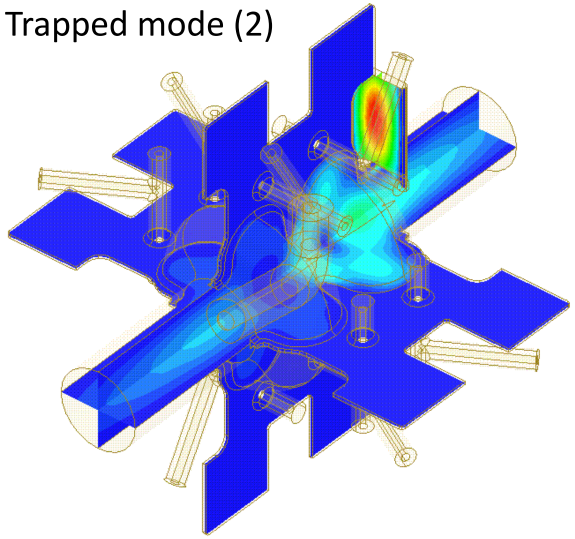
$TM_{11} - 0$ mode



Trapped mode (1)

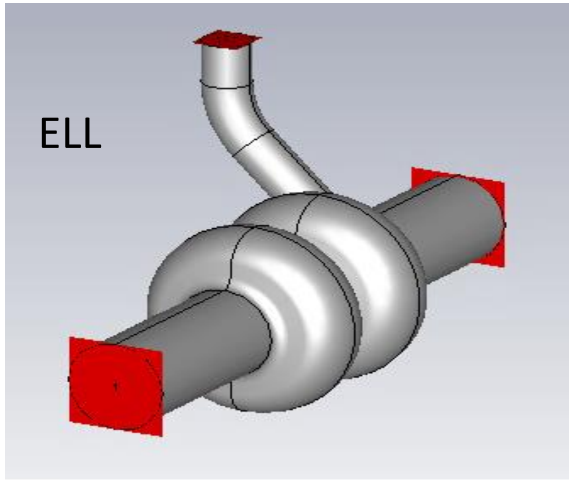


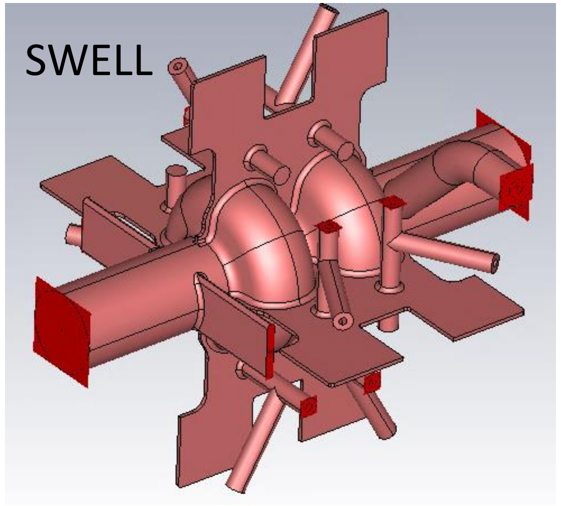
Trapped mode (2)



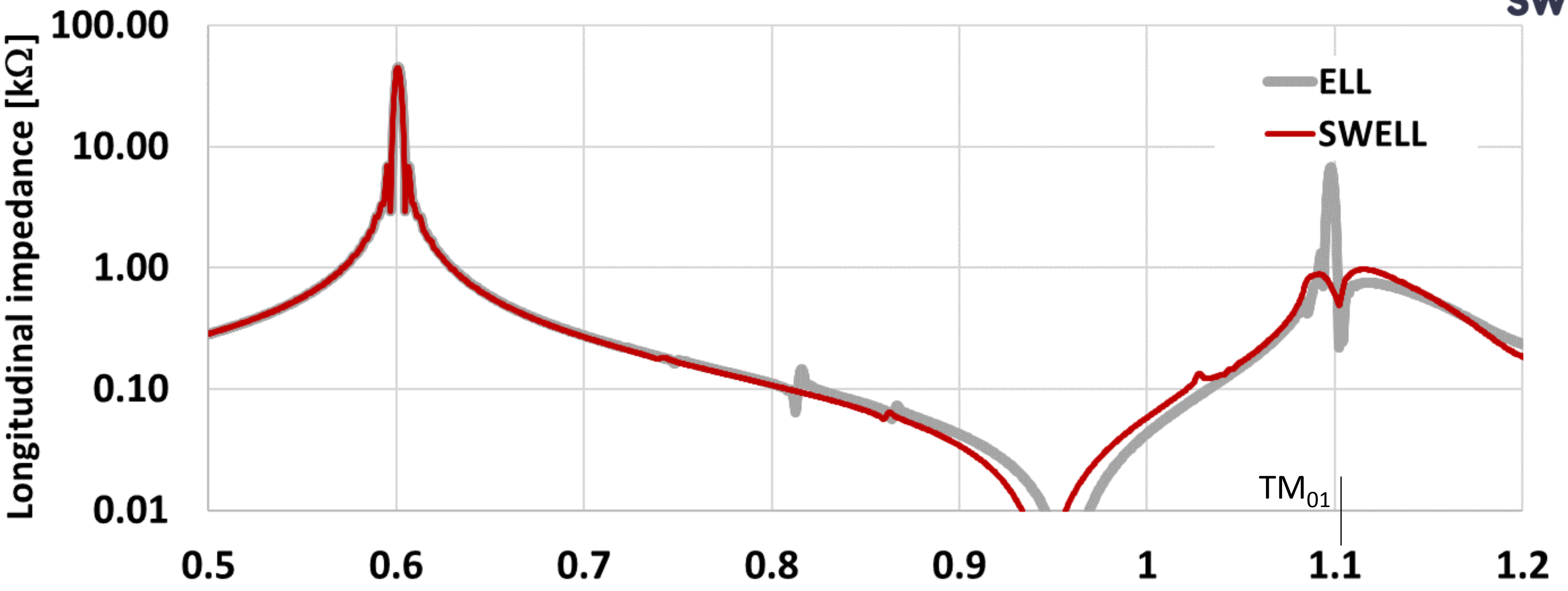
Modes	F (MHz) SWELL	R/Q longitudinal (linac ohms)	R/Q transverse (linac ohms)	Q external SWELL	F(MHz) ELL	Q external ELL
$TE_{11} - \pi$ mode	754.4	-	4.3	**61**	724.3	1.05×10^6
$TE_{11} - 0$ mode	740.7	-	15.2	**202**	752.6	5.2×10^5
$TM_{11} - \pi$ mode	811	-	38.3	**9.5**	817	8.7×10^3
$TM_{11} - 0$ mode	861.9	-	8.1	**280**	866	700
Trapped mode (1)	1085.4	4.2	-	**196**	1088	5.5×10^3
Trapped mode (2)	1097.1	20.3	-	**59**	1100	1.9×10^3

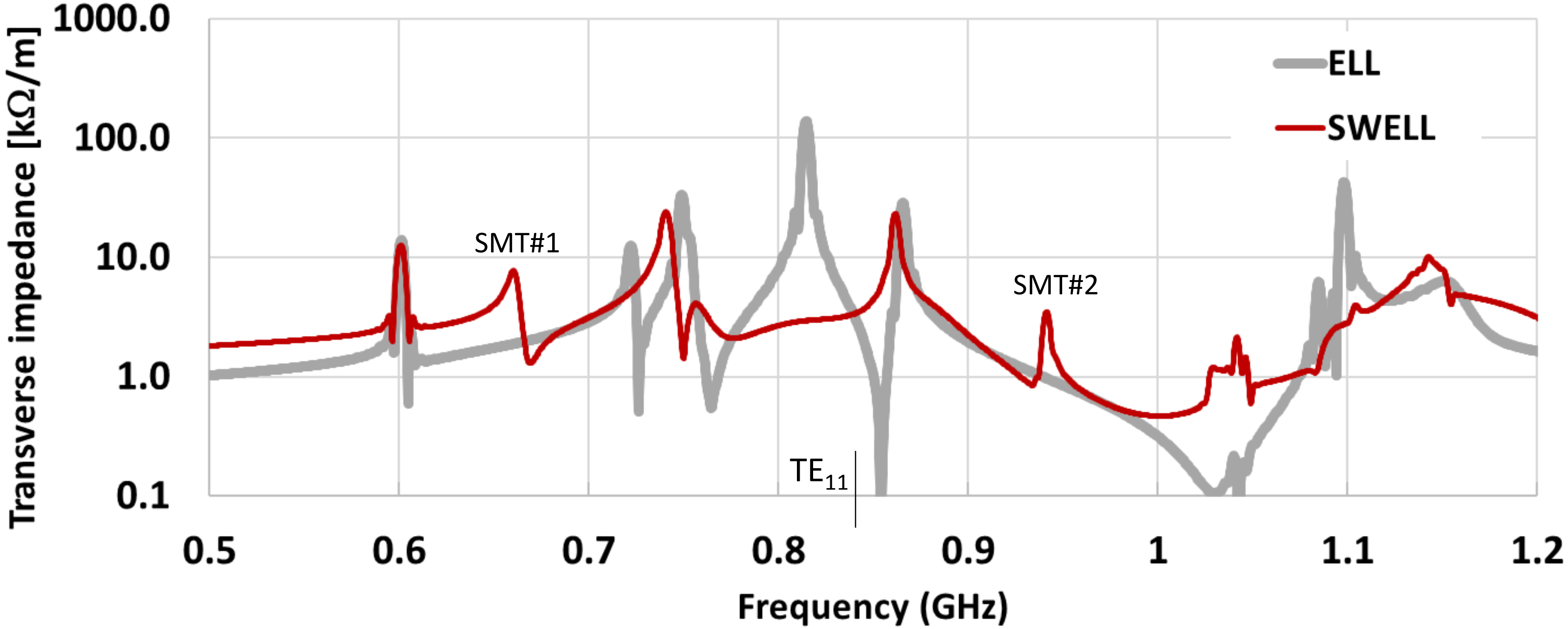
SWELL wake filed simulation in CST



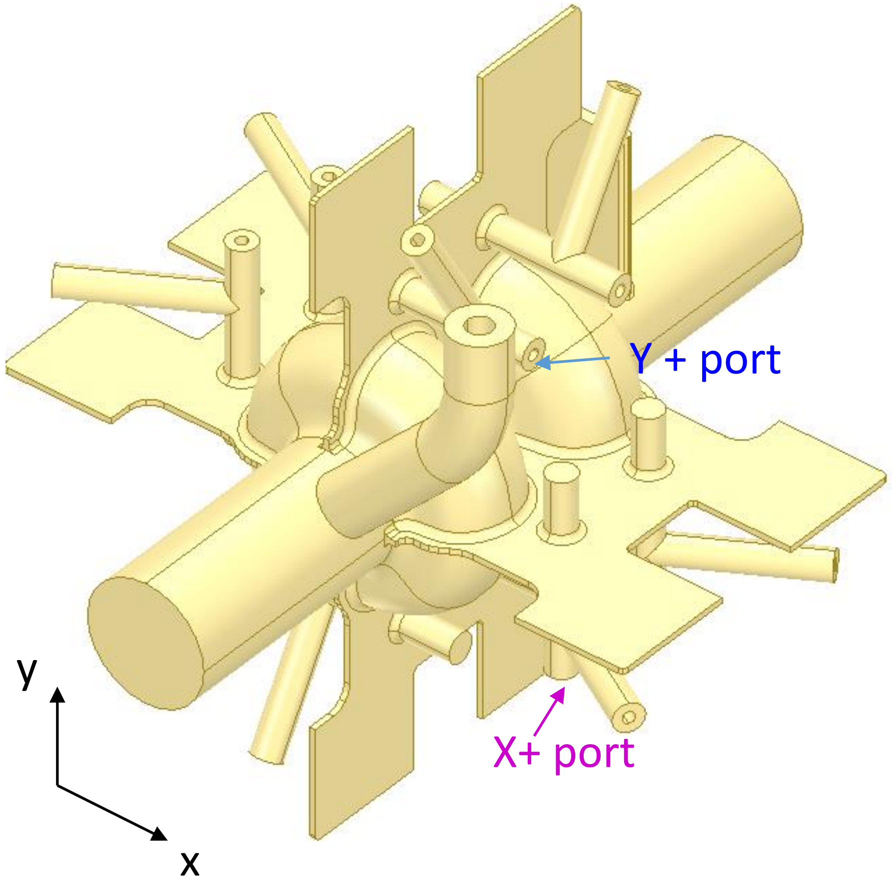


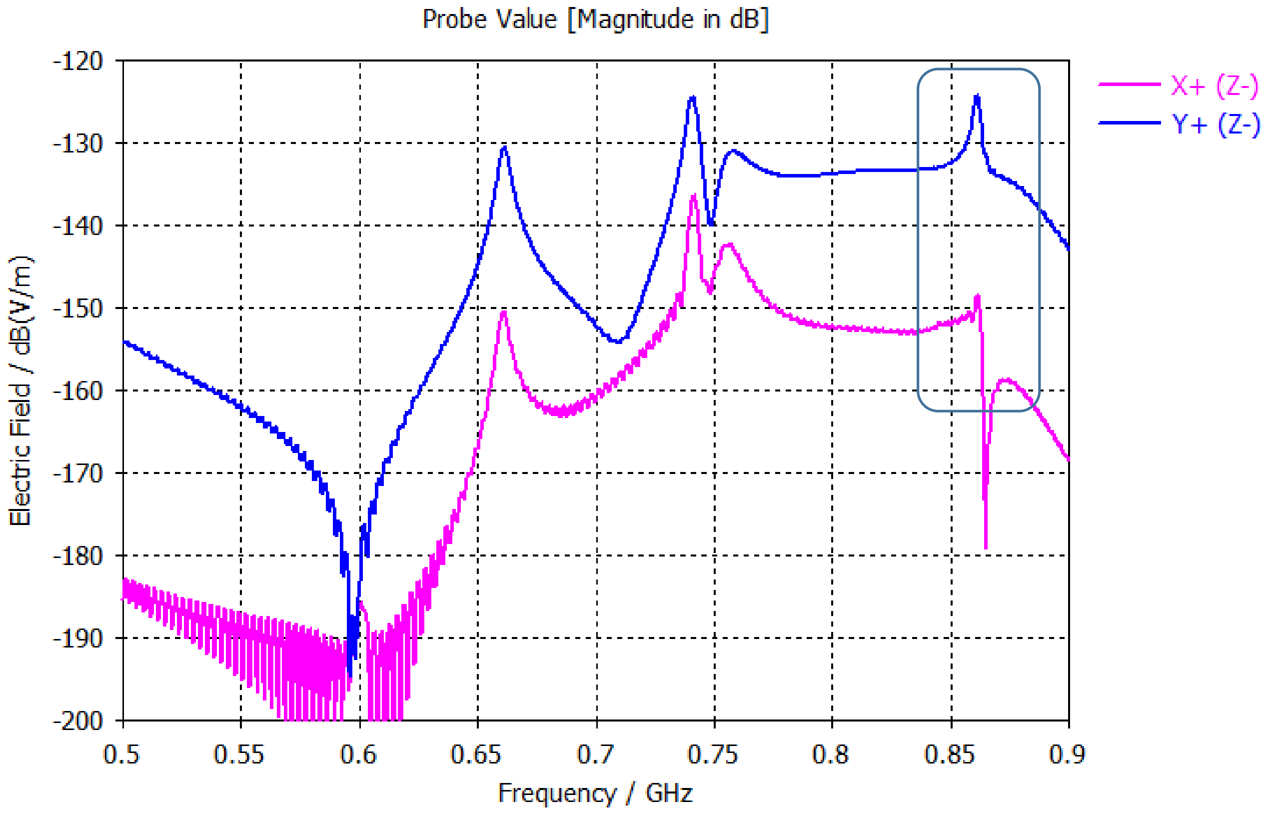
Simulated wake length is 100 m.
Frequency resolution on the impedances plots is ~ 3MHz.





SWELL as a BPM





- The efficient rejection of the fundamental modes in the SWELL cavity makes it as a good candidate to be used as a high resolution beam position monitor.
- Beam off-set in simulations was 5mm in X direction. The residual coupling between x-y HPC branches comes from the FPC field symmetry distortion. With filtered TE_{11} 'π' mode at 861 MHz and fundamental mode relative rejection at a level of >60dB, the internal beam position resolution can go down to the sub micrometer levels.

SWELL

FUTURE CIRCULAR COLLIDER	A SUPERCONDUCTING SLOTTED WAVEGUIDE ELLIPTICAL CAVITY FOR FCC-EE	FCC-2105010000-OBR 25 June 2021

Future Circular Collider

REPORT

A SUPERCONDUCTING SLOTTED WAVEGUIDE ELLIPTICAL CAVITY FOR FCC-ee

	Name	Organisation	Date
Authored by	Igor Syratchev, Franck Peauger Ivan Karpov, Olivier Brunner	CERN	29/04/21

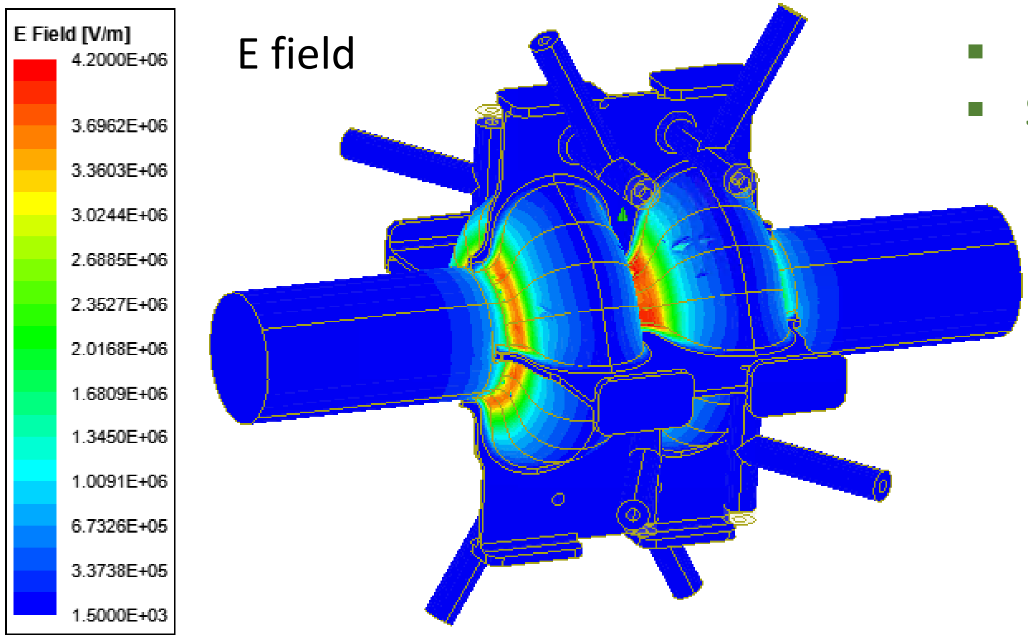
https://zenodo.org/record/5031953#.YNXjUG6xVp8

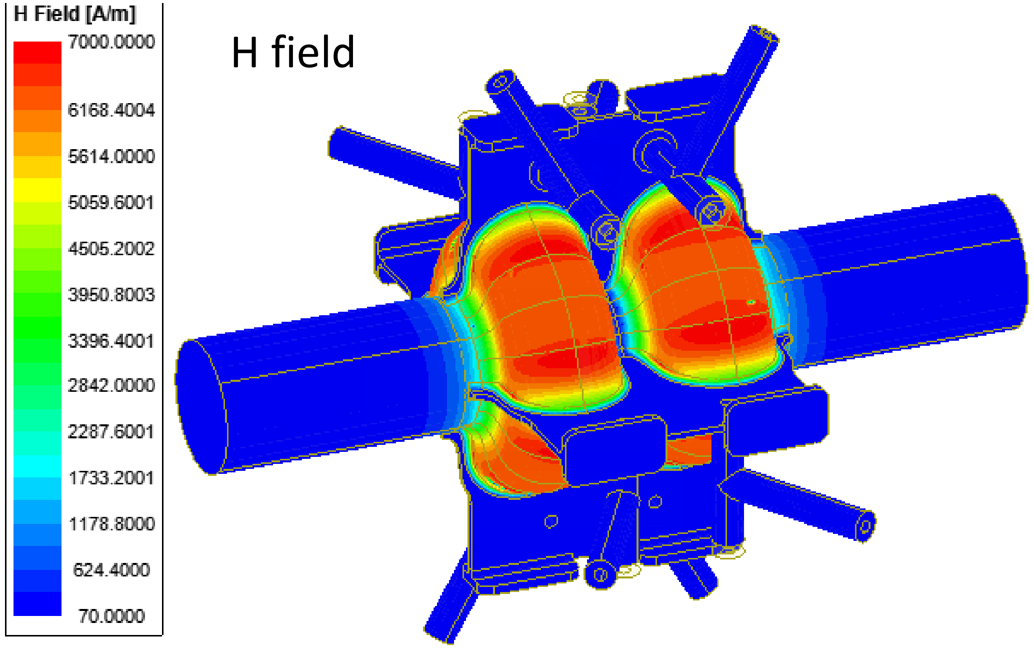
DOI is: https://doi.org/10.5281/zenodo.5031953

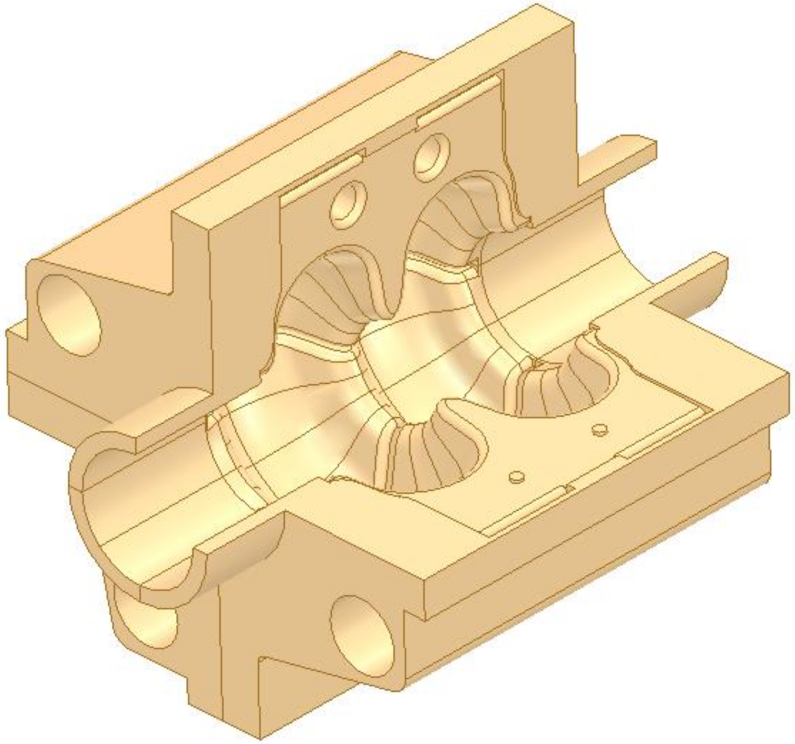
Second SWELL generation (work in progress).

- New Compact HPC
- Special cavity shape with optimized/reduced surface E/H fields

1 Joule







	Z	W	H	tt
Energy, J	2	12.3	87.8	137.2
E_{surf} max, MV/m	5.93	14.7	39.3	49.2
B_{surf} max, mT	12.5	31	82.8	103

Thanks for your attention!