3 GHz RF for RFMTF

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Special thanks to: Luigi Faillace (INFN-LNF), Elisa Del Core (INFN-LASA)

Outline

- Introduction and motivation
- Cavity eigenmode simulation in HFSS
- Cavity + coupler design and numerical results
- Preliminary thermal simulation in COMSOL
- Preliminary mechanical drawings
- Conclusion and perspectives

Introduction and motivation

- The RF cavities for the cooling channel of the MuCol project require a medium/high electric field (nominally 28-30 MV/m) in high magnetic fields (13-15 T).

- The presence of the magnetic field increases RF breakdown rate at lower gradients in NC RF structures.

- This call for a deep understanding of the breakdown phenomena in RF cavities under the influence of the magnetic field.

- **Necessity to have a test-bench to study the problem taking into account different variables, such as magnetic field level, different cavity materials and surface treatments.**

RF breakdown tests for muon ionization cooling

- Several test configurations had been developed in the past years to study the problem.

Results from tests performed on different cavities and field configurations.

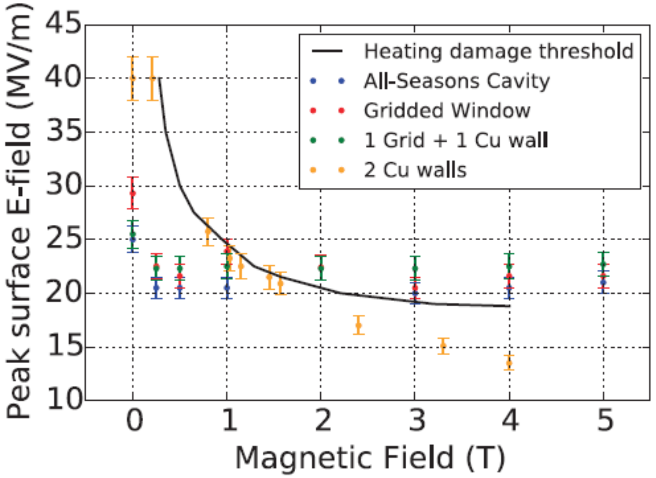
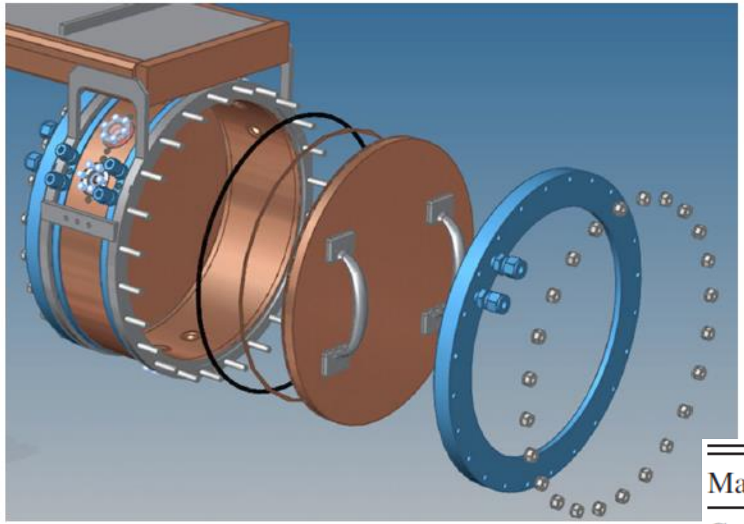


Figure 3: Peak surface electric field vs. external, applied *B*-field for cavity configurations described above. The black line indicates the threshold for surface fracture from beamlet heating, as discussed in [4].

[D. Bowring et al., IPAC2015, doi:10.18429/JACoW-IPAC2015-MOAD2]



Material	*B*-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07

[D. Bowring et al., Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration, PRAB 23, 072001 (2020)]

S-band cavity RF test stand proposal

- Reduction in costs of the magnets due to reduced bore diameter (from 704 MHz to 3 GHz may result in a reduction of cost of the order of 2 M€ over 5 M€)
- Breakdown behaviour quite close (for example with respect to 12 GHz cavities).
- Reduction in cost necessary for cavity realization (smaller size of the 3 GHz cavity).
- Cost of the klystron may be considered affordable (500-600 k€) with delivery time of about 2 years after the order finalization.
- The test stand may be installed at INFN-LASA: availability of a modern infrastructure with the space and the possibility to test both SC magnets and RF cavities (bunker structure, liquid helium liquefier, electrical power available) may allow to start experimental activities in late 2025.
- Other installation sites will also be taken into account.

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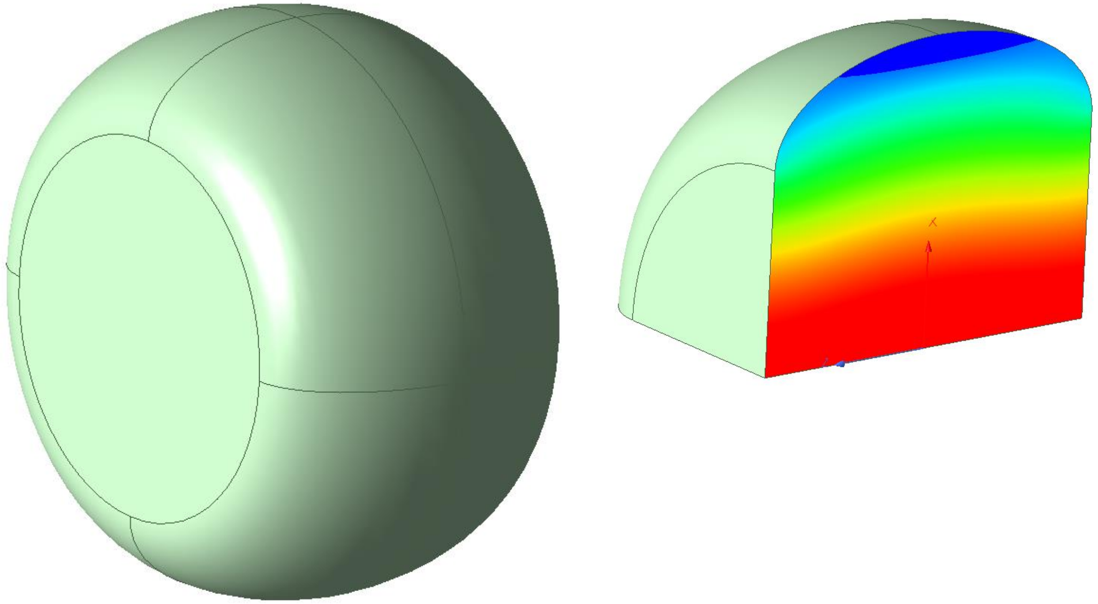
Design parameters

For the cavity design, we fixed the following parameters and geometrical specifications:

- Nominal on-axis E-field $\mathbf{E_{nom}} \approx \mathbf{30\ [MV/m]}$.
- Unloaded quality factor $\mathbf{Q_0} \geq \mathbf{20k}$.
- **Flat and removable cavity end-plates** for possibility of internal inspection after each measurement run.
- Possibility to use diagnostics during the tests.

Cavity HFSS design

- First step: cavity eigenmode simulation in HFSS.
- The elliptical profile has been chosen in order to increase the Q_0.
- First cavity design study at f_0 = 2.998 GHz (EU standard).



The simulated model consists of a vacuum volume with finite conductivity (copper) boundary condition

Parameter	Unit	Value	Description
f_0	[GHz]	2.998	Operational frequency
Q_0	-	20714	Unloaded quality factor
V_{nom}	[MV]	1.7	Nominal on-axis voltage
E_{nom}	[MV/m]	34	Nominal on-axis E-field
E_{peak}	[MV/m]	~ 34.44	Peak electric field on cavity walls
r_{SH}	[MΩ]	9.66	Shunt impedance
r_{SH}/Q_0	[Ω]	466.4	Geom. shunt impedance
P_{diss}	[kW]	~ 294	Peak power dissipated on cav. walls
t_p	[μs]	5	Pulse width
f_r	[Hz]	100	Rep. frequency
P_{avg}	[W]	150	Avg power dissipated on cav. walls

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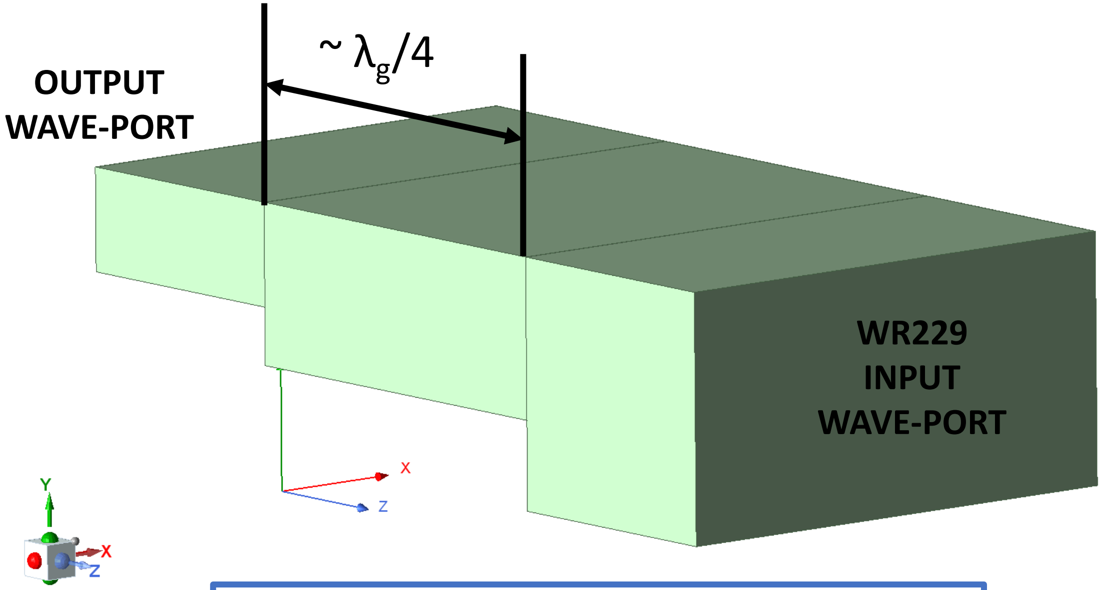
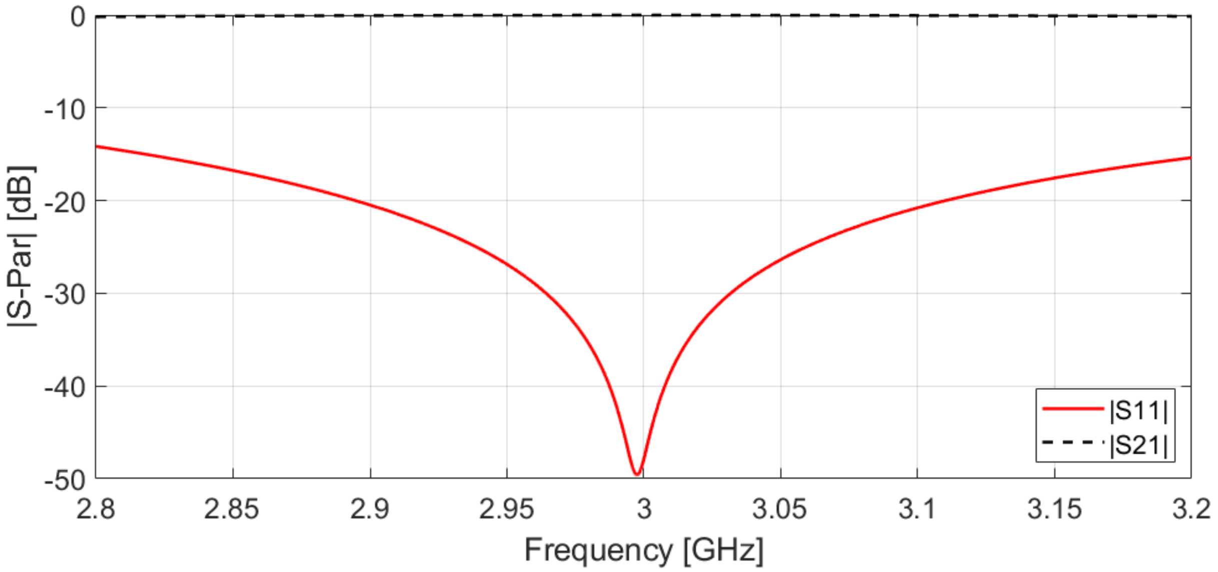
Coupler design

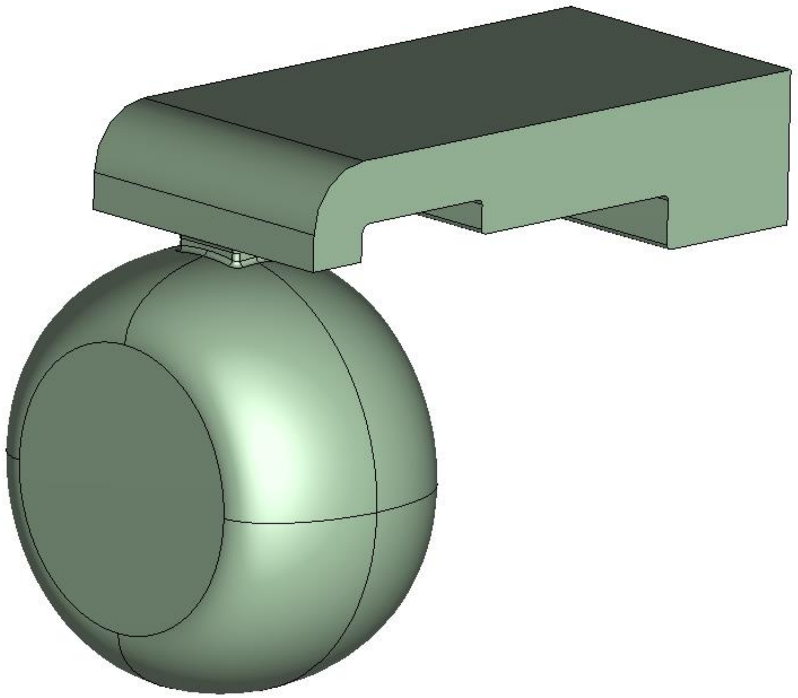
- Second step: waveguide coupler design (WR229 input).
- Composed by three parts with different short-side dimensions, to save space in the coupling slot area.
- $\lambda_g/4$ central section is employed in order to improve the matching between first and last sections.

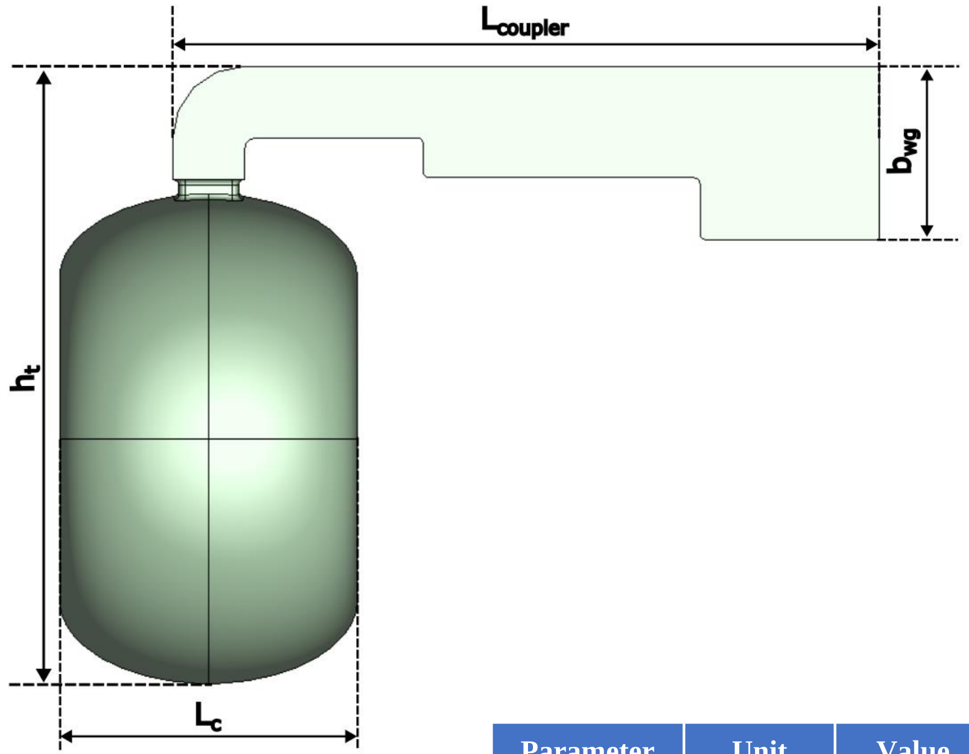


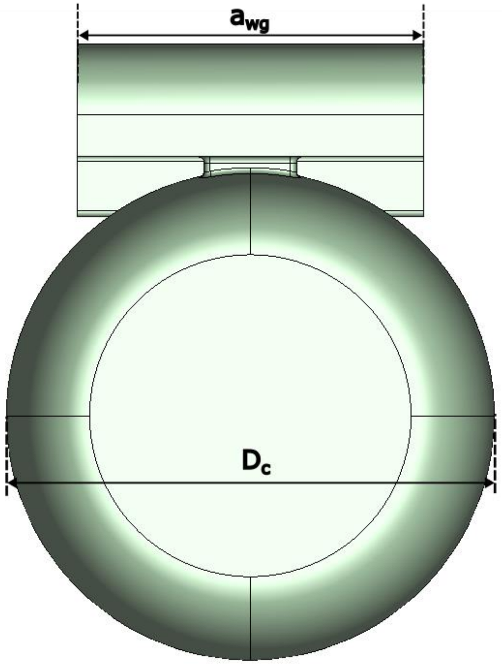
Coupler vacuum model + copper b. c.

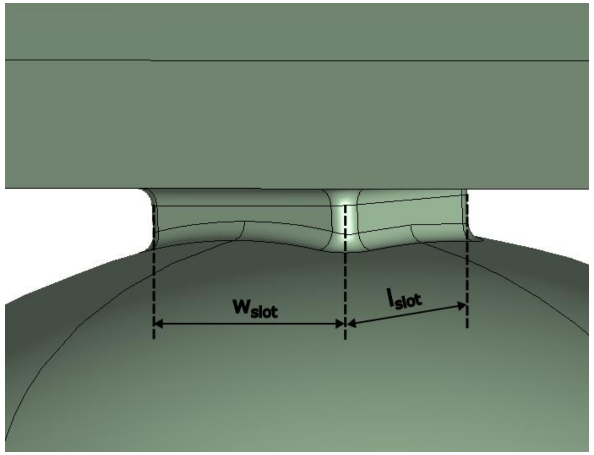


Full structure – geometry







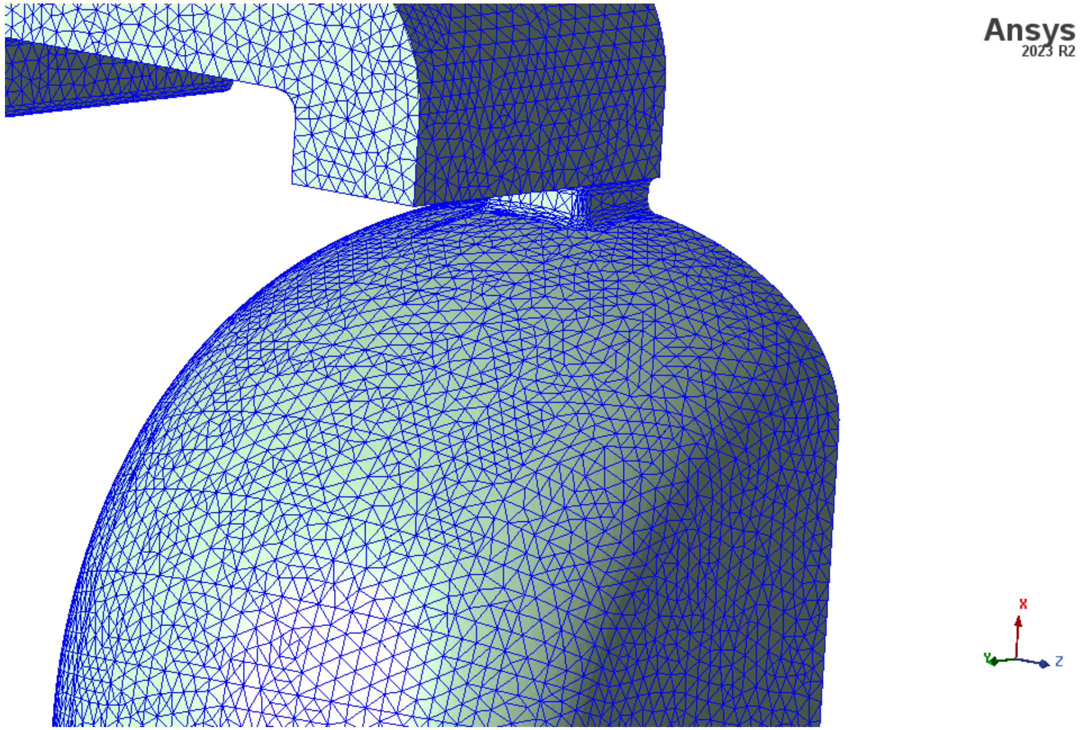


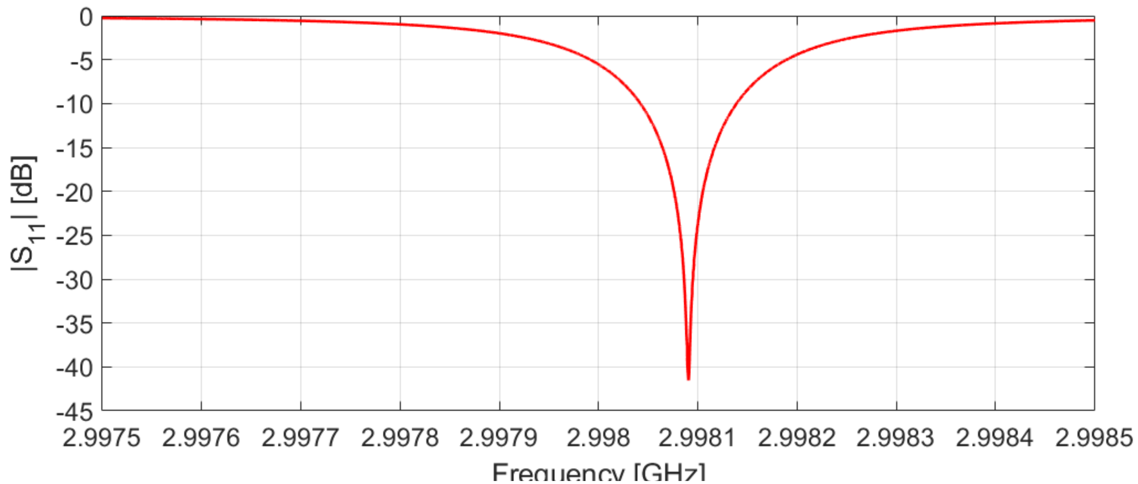
Cavity and coupler have been connected through the employment of a slot (magnetic coupling) with dimensions 15.5 × 10 [mm^2].

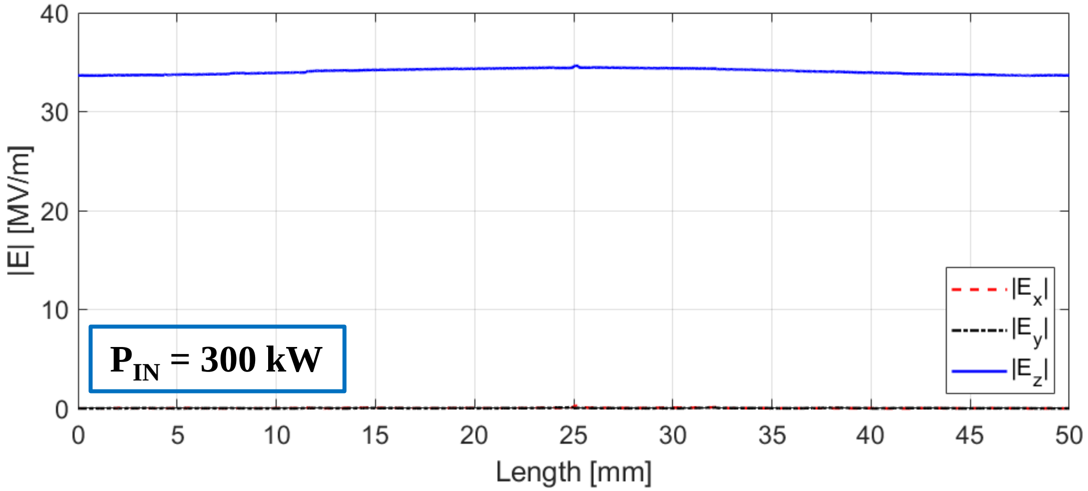
Parameter	Unit	Value	Description
D_c	[mm]	82.108	Cavity diameter
L_c	[mm]	50	Cavity length (βλ/2)
a_{wg}	[mm]	58.166	Input waveguide width
b_{wg}	[mm]	29.083	Input waveguide height
$L_{coupler}$	[mm]	118.5	Coupler length
w_{slot}	[mm]	15.5	Coupling slot width
l_{slot}	[mm]	10	Coupling slot height
h_t	[mm]	103.554	Total structure height

Full structure – HFSS results

- The structure has been designed and optimized by employing Ansys HFSS.
- Crytical coupling at the working frequency.
- On-axis electric field **Ez ~ 34 [MV/m]** has been achieved by setting an input power **P_{IN} = 300 kW.**

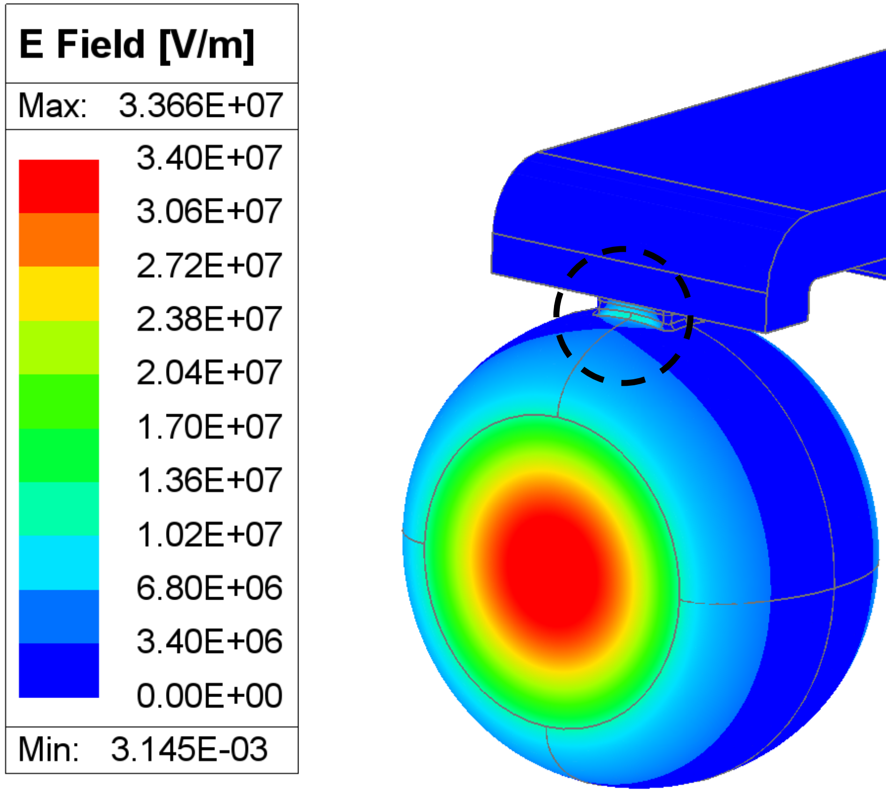


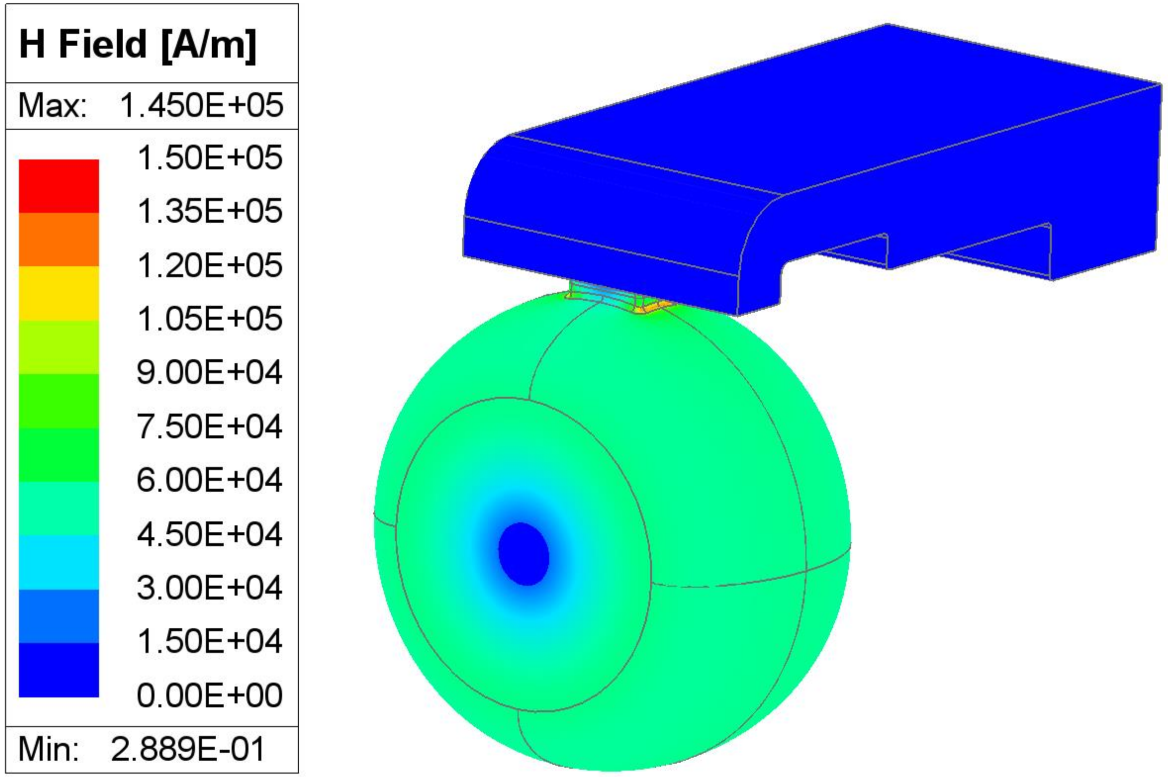




Full structure – peak fields

- Peak E-field is located on front and back end plates.
- Peak H-field is located along cavity side-walls, as usual for the TM010 mode.



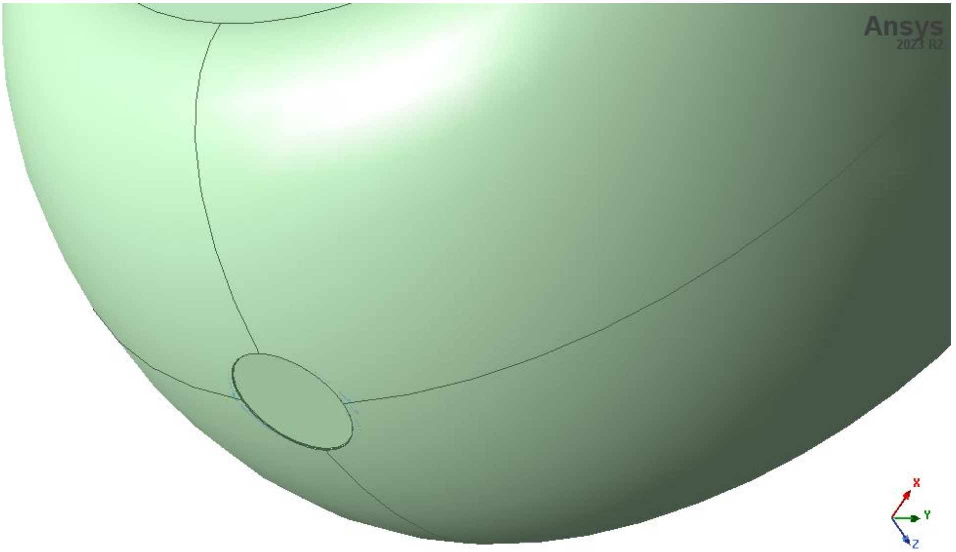


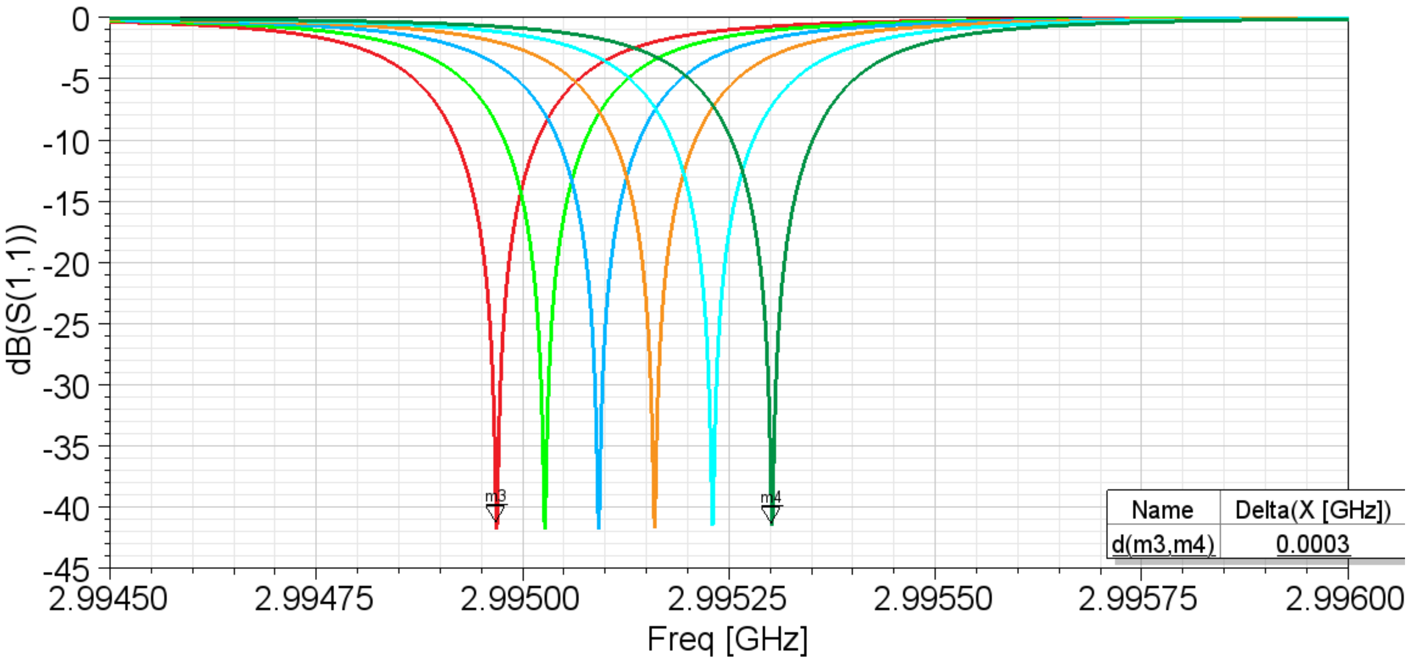
- Field in the coupler area is roughly 1/3 of the peak E-field.
- This should help localize breakdown events on cavity end-plates.

$\Delta T_{ph} \sim 11$ °C

Tuner effect

- The effect of a cylindrical tuner with diameter d = 10 mm has been investigated.
- The tuner, placed at the cavity bottom, has been inserted of a length equal to 0.5 mm.





A penetration of 0.5 mm corresponds to a Δf = + 0.3 MHz.

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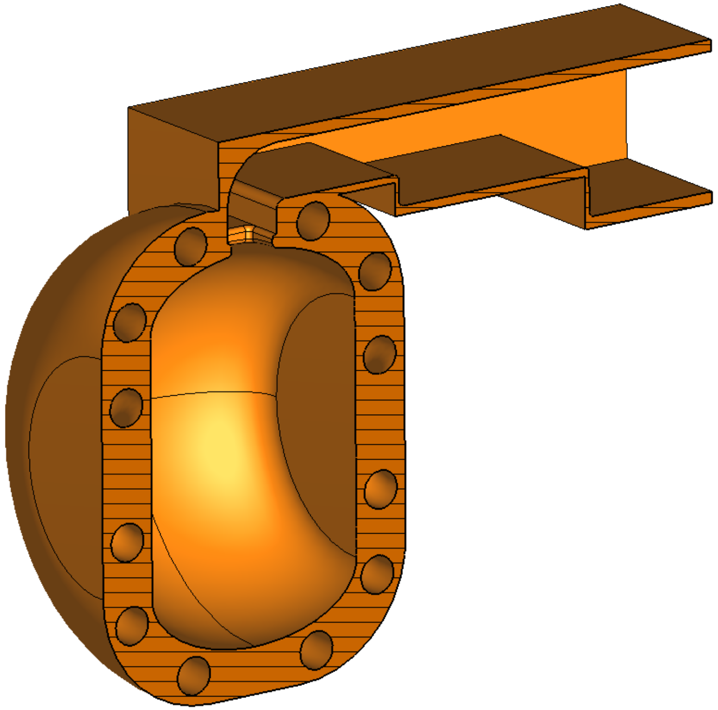
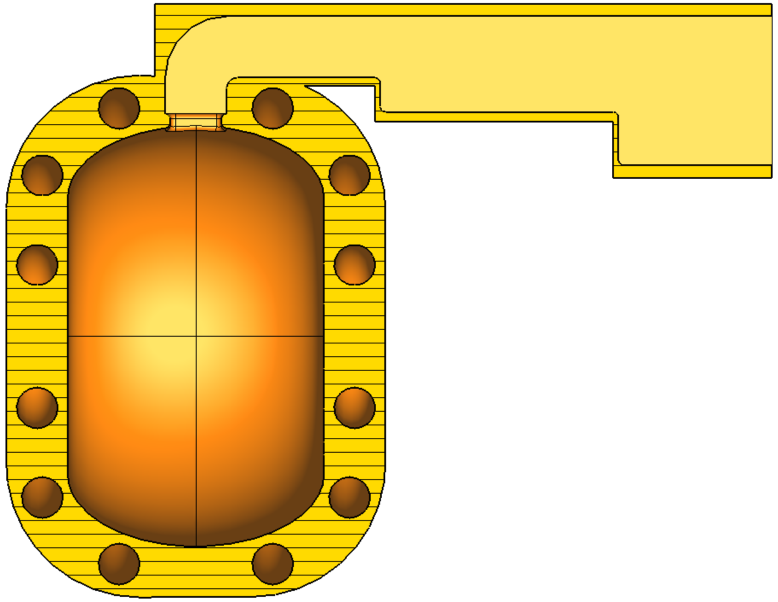
COMSOL preliminary thermal simulations

- A 3D copper model (surface thickness = 15 mm) with cooling tubes (diameter d = 8 mm) has been designed in order to perform preliminary thermal simulations.
- Water **temperature T = 30°C, water flux = 10 l/m** have been set.
- This results in a **heat transfer coefficient h = 13831**.
- This coefficient has bees set on the internal cooling tube boundaries.
- Moreover, **ambient temperature** has been set to **20°C.**
- We considered $\mathbf{P_{avg}}$ **= 150 W.**

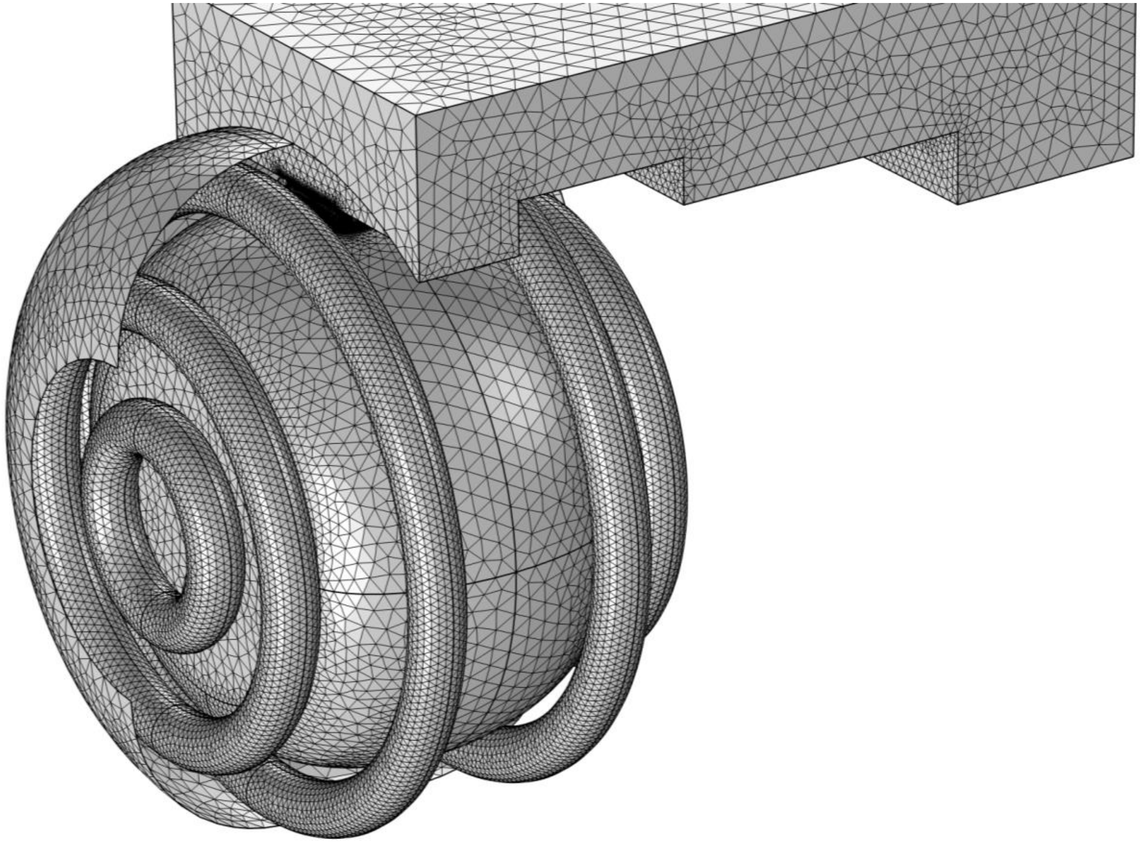


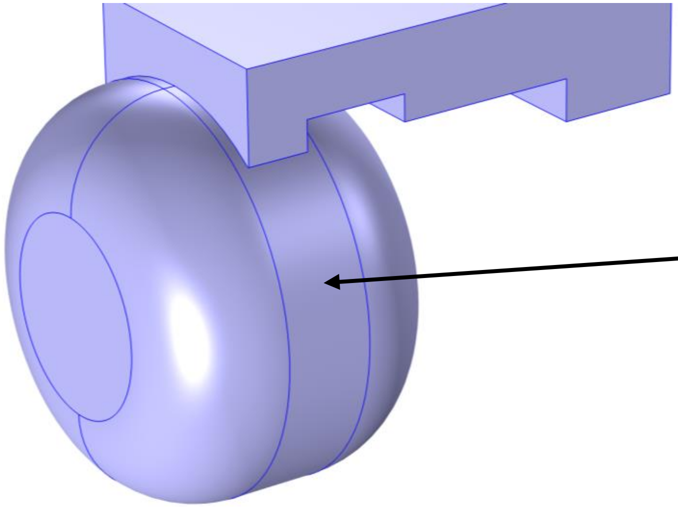


COMSOL preliminary thermal simulations

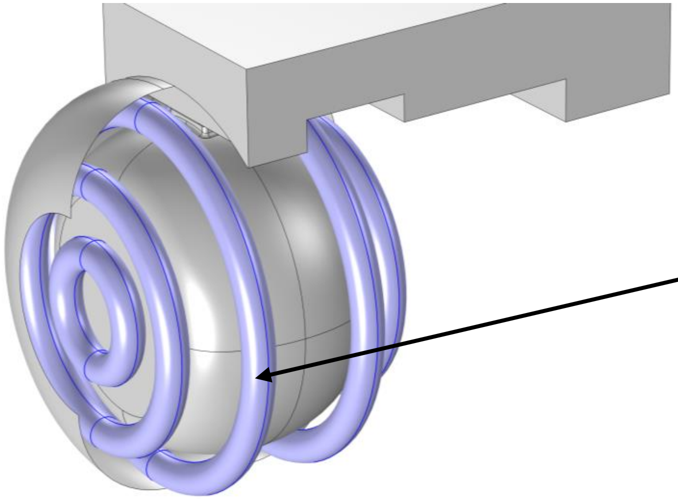
The COMSOL coupled RF-Thermal simulation is composed of two steps:

1. The structure electromagnetic solution is evaluated at the operating frequency.
2. The surface losses coming from the RF solutions are employed on copper inner walls in the heat transfer part of the model.



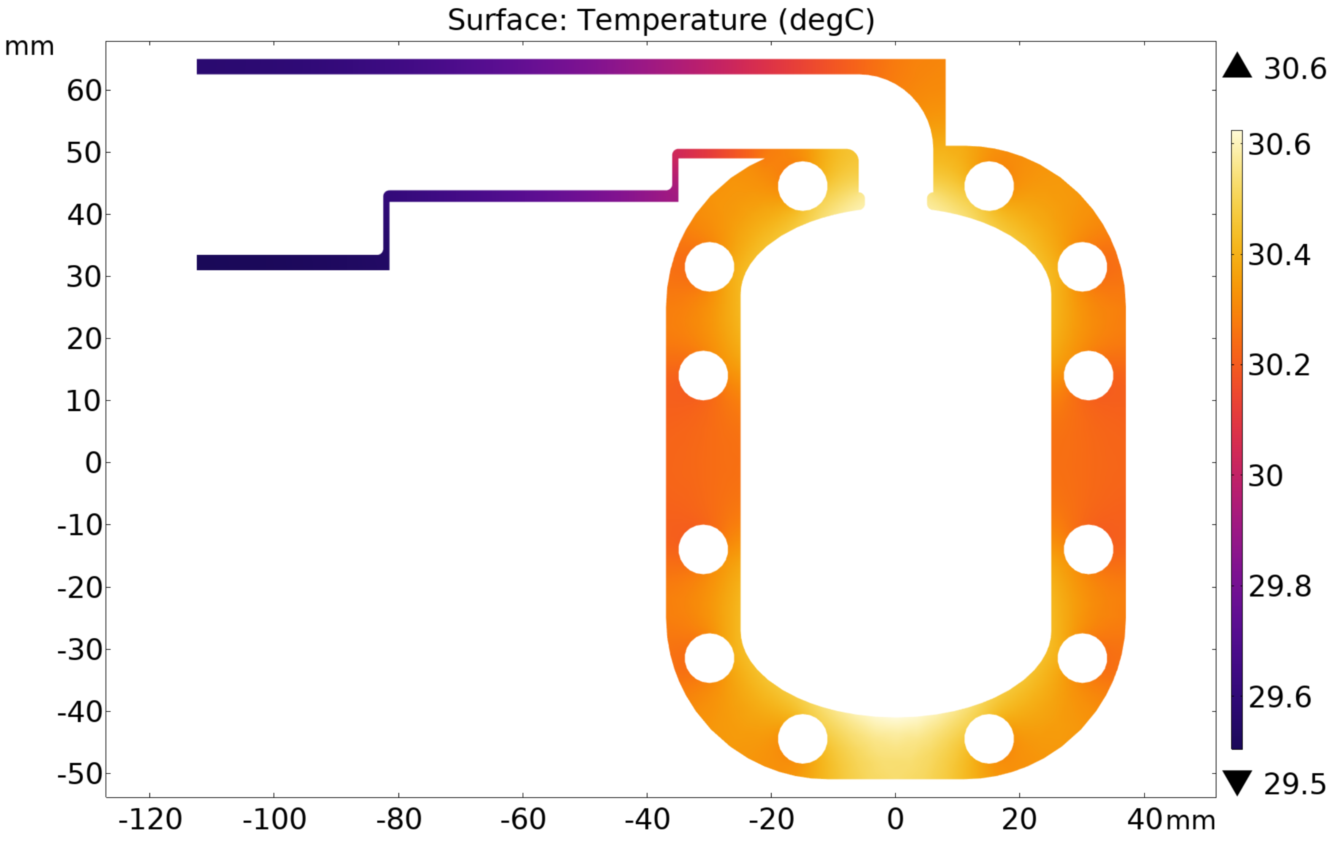


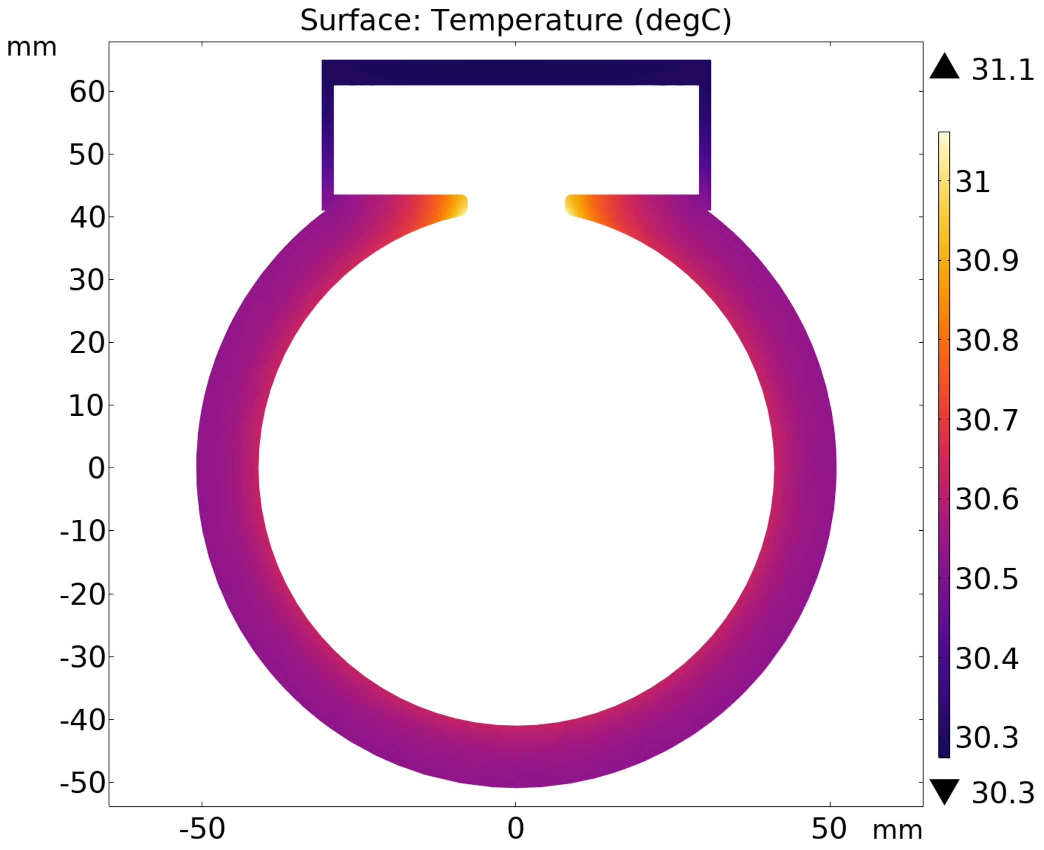
h = 10 $\left[\frac{W}{m^2 * °C}\right]$ on cavity external surfaces.



h = 13831 $\left[\frac{W}{m^2 * °C}\right]$ on tubes boundaries.

COMSOL preliminary thermal simulations



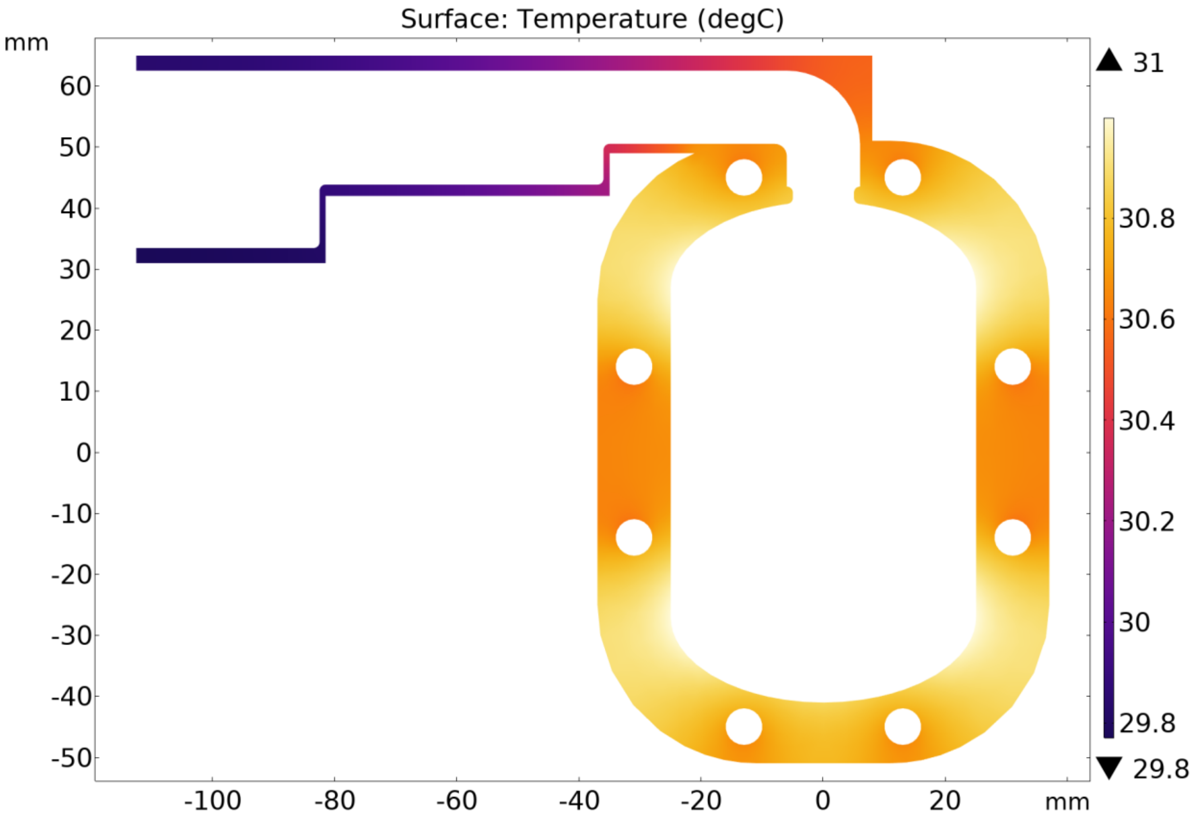


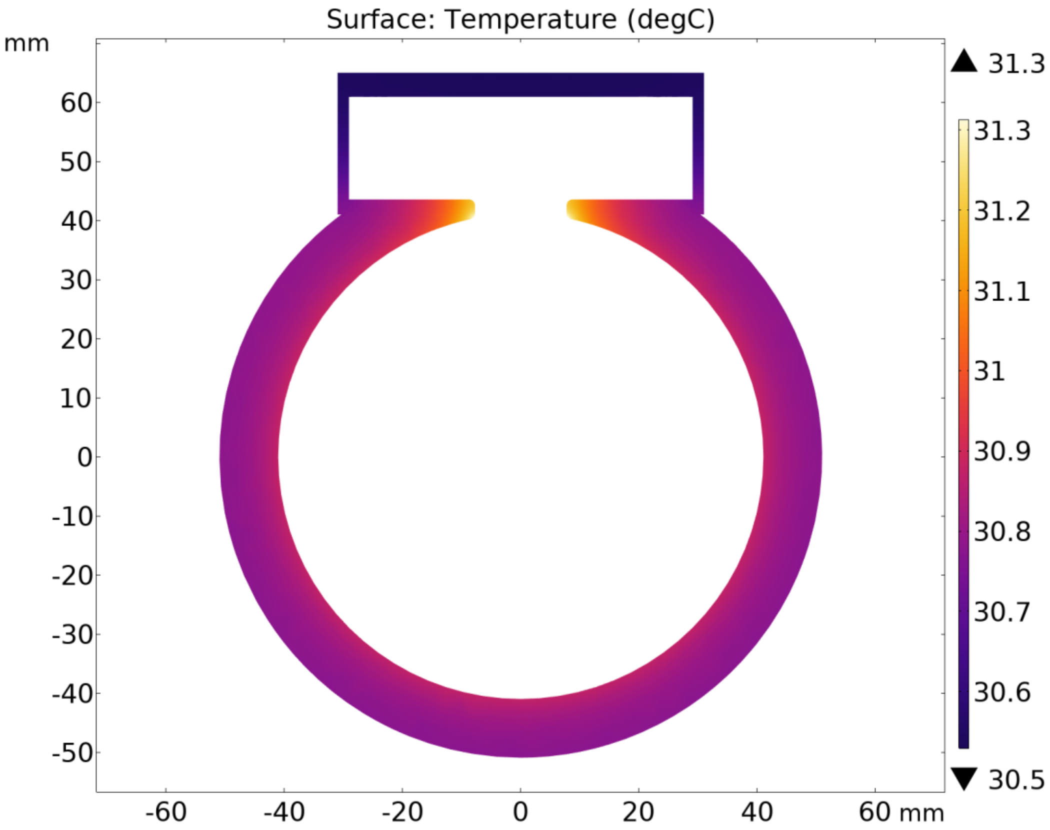
ΔT ~ 0.5 °C on cavity volume

COMSOL preliminary thermal simulations

Alternative scenario:

- Four cooling tubes of diameter d = 6 mm.
- Placement: near coupling slot and inside the removable cavity end-plates.

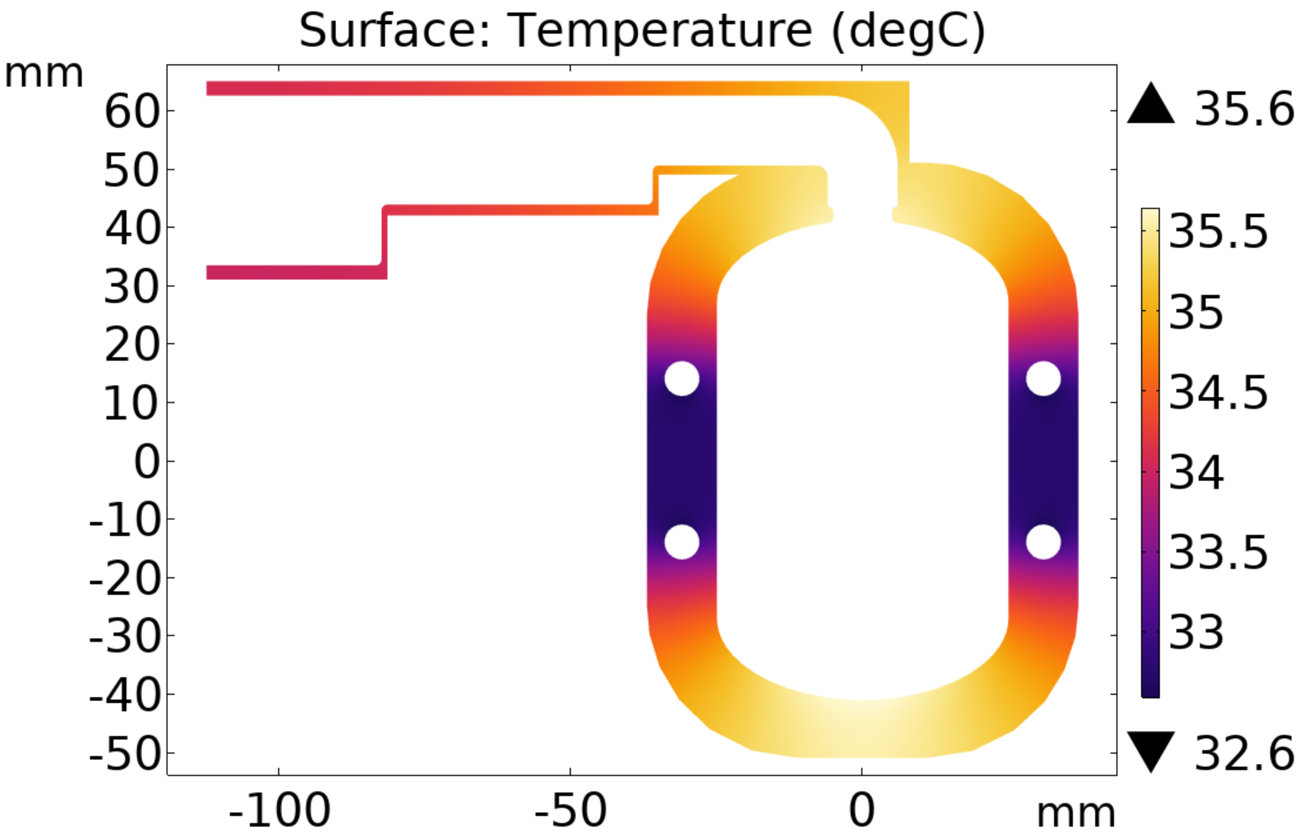


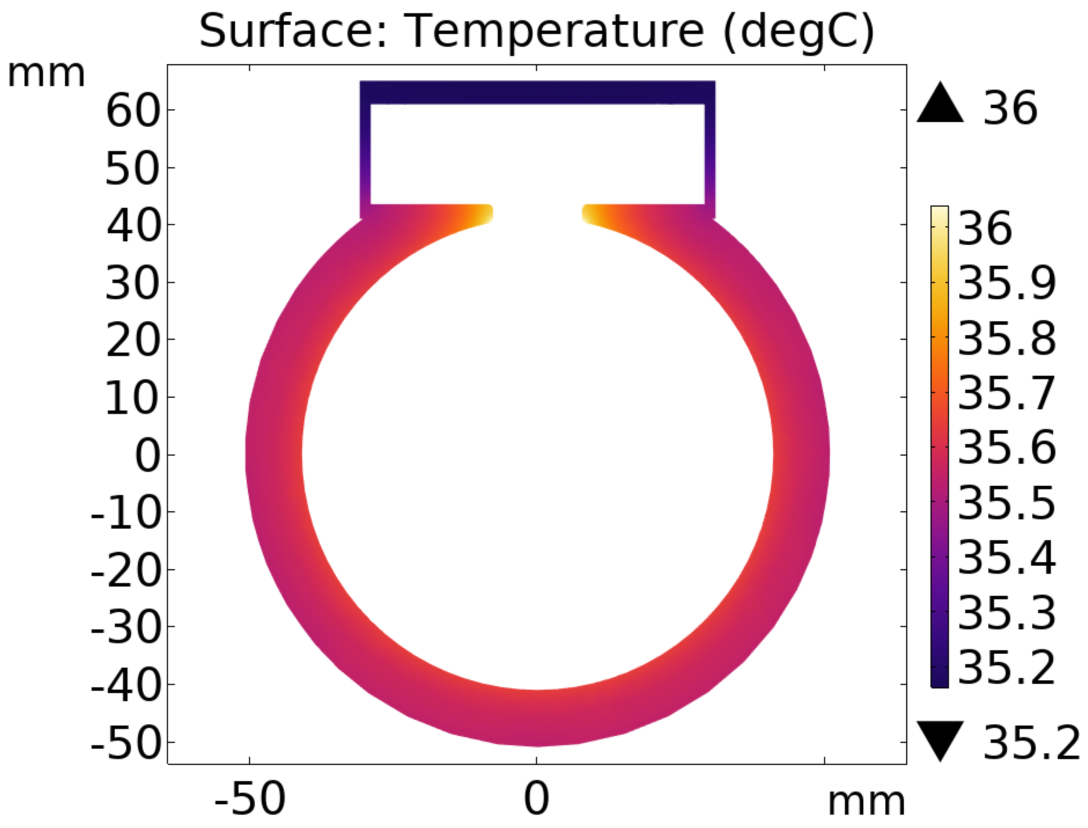


ΔT ~ 0.5 °C on cavity volume

COMSOL preliminary thermal simulations

- Two tubes positioned on cavity end plates.





ΔT ~ 3 °C on cavity volume

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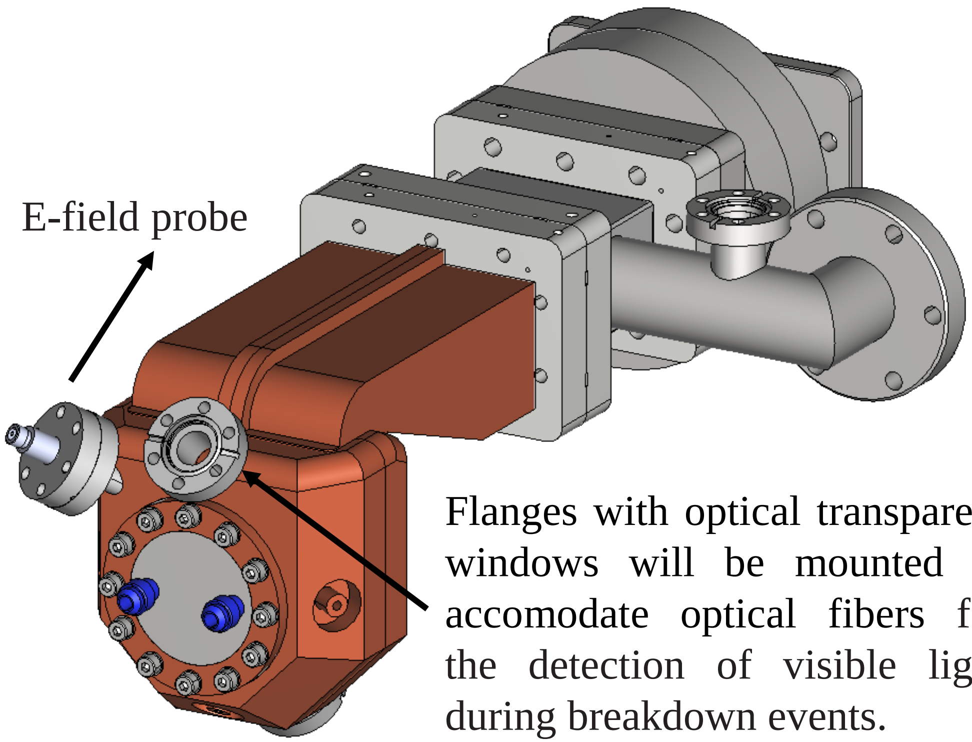
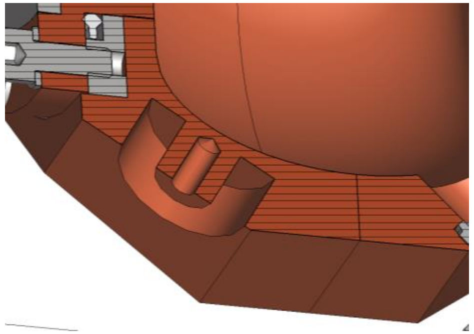
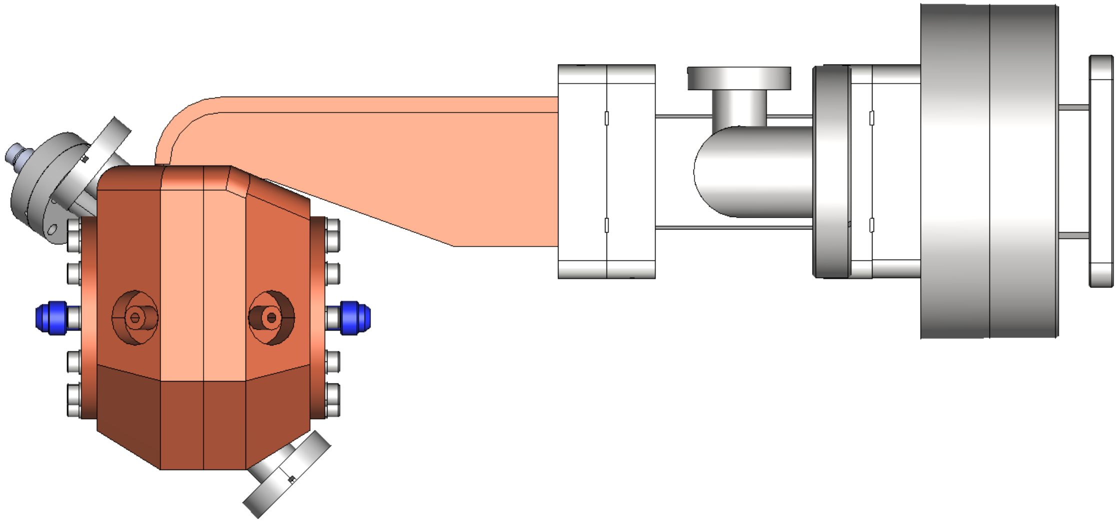
Mechanical model

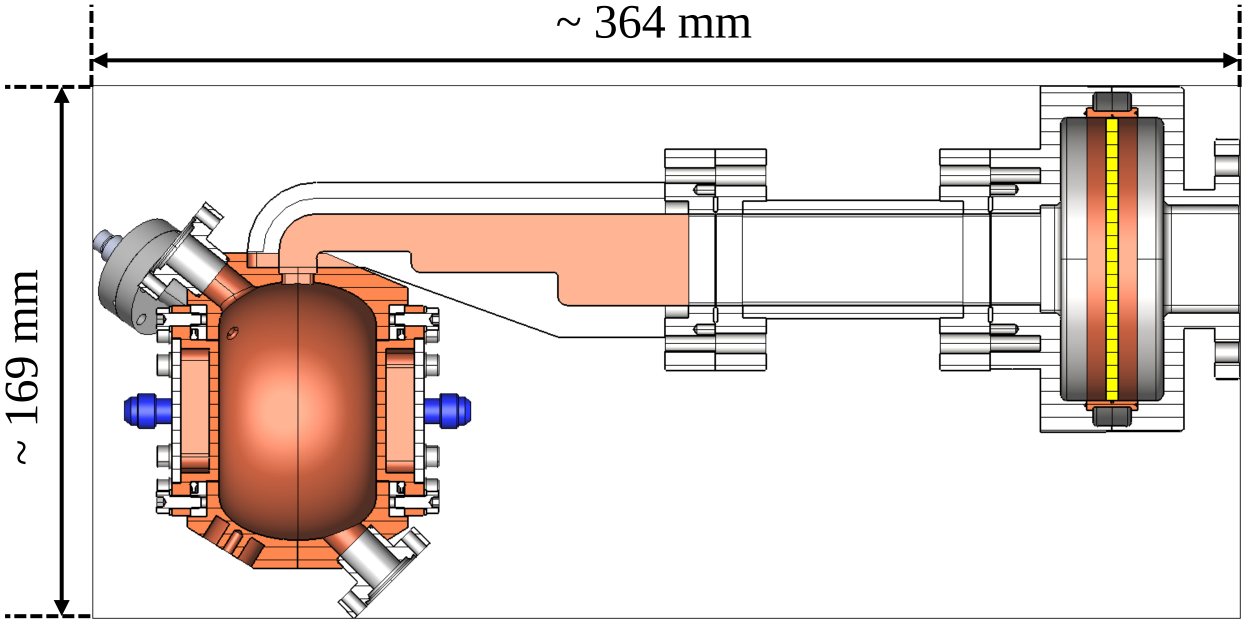


Flanges with optical transparent windows will be mounted to accomodate optical fibers for the detection of visible light during breakdown events.



Cavity is expected to be equipped with five tuners.





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Conclusion and perspectives

- HFSS simulations have been performed in order to obtain and optimize a S-band (2.998 GHz) elliptical cavity (Cu walls) for RFMTF.
- The full structure employs a waveguide coupler, magnetically coupled to the cavity through a side-wall positioned slot.
- Peak E-field has been minimized in the coupling slot area while peak H-field, in the same area, has values that allow to obtain a ΔT due to pulsed heating ~ 11 °C.
- An evaluation of tuners effect has been done by considering a cylindrical tuner with 10 mm diameter. For a penetration of 0.5 mm a Δf = + 0.3 MHz is obtained.
- Preliminary thermal simulations have been performed in COMSOL, using three different cooling tubes placement scenarios, to evaluate the temperature distribution inside the copper enclosure. The thermal gradient result equal to ~ 0.5°C for the first two cases and ~ 3°C for the third case.
- A first structure mechanical model, comprising of tuners and ancillaries for several diagnostics, is available.
- Thermal stress simulations will be performed during the next weeks to evaluate the eventual effect of temperature gradient on resonant frequency.
- The final mechanical model will expected to be ready by the end of this February.

Thank you!