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Multiphysics Analysis of a High Power RF Window using COMSOL

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Session: Multiphysics Simulation 1

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Introduction

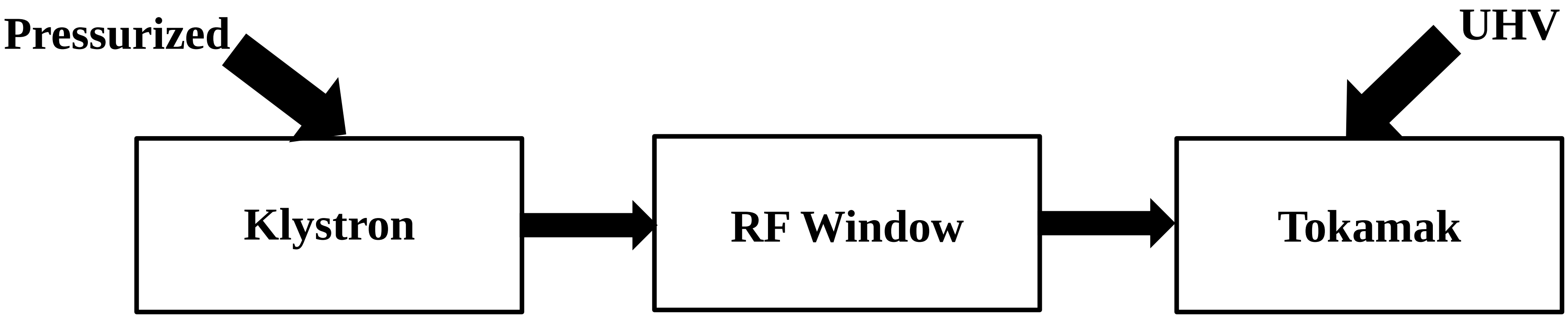


Figure 1. Basic Block Diagram of the complete system

- Nuclear Fusion experiments performed in machines called ‘tokamak’
- Antenna system radiating power into tokamaks are placed in Ultra High Vacuum (UHV) environment of the tokamak.
- Pressurized transmission line system feeding the antenna.
- RF vacuum window is used to mechanically isolate the differential pressure (~3-4 bars) and provide a high return loss and a low insertion loss.

Design

Table 1 Important design parameters for pill box type RF window

Parameters	Values
Frequency	3.7 GHz
Input Power	125 kW
Insertion loss	< 0.1 dB
Return loss	> 35 dB

Table 2 Properties of various ceramics used for the RF window design

Properties	Al_2O_3
Dielectric Constant @ 3.7 GHz	9.7
Loss Tangent @ 3.7 GHz	3×10^{-4}
Specific Heat Capacity at constant pressure (J/kgK)	800
Thermal Conductivity (W/mK)	30
Young's Modulus (GPa)	370

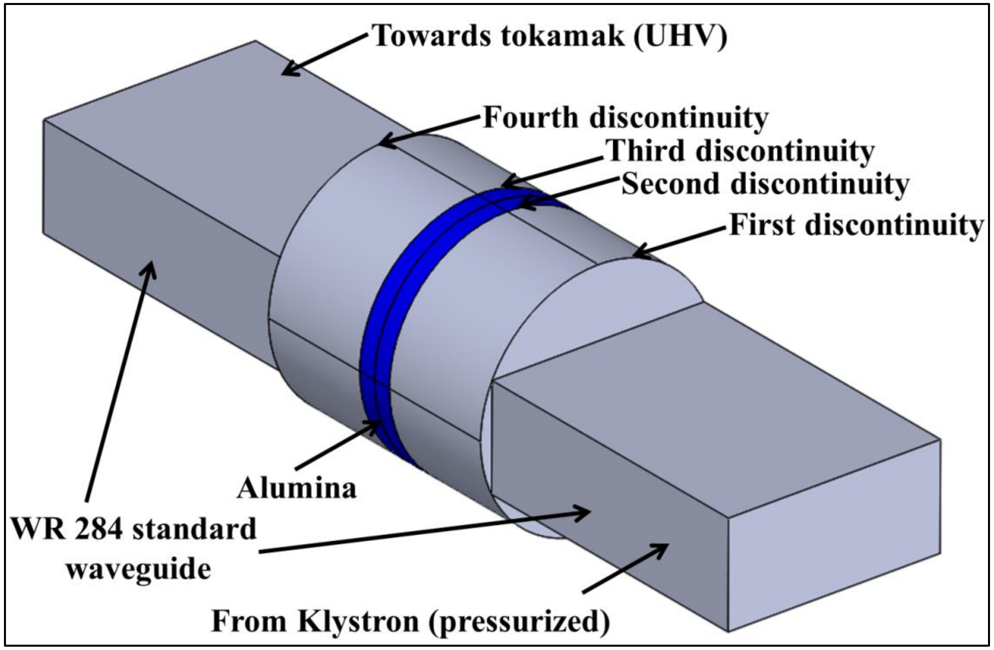


Figure 2 A 3D structure of the alumina based RF window

- Length of the circular section ~ $\lambda_g/2$ (for TE_{11} mode) ~68 mm (without alumina)
- Length of the ceramic ~ $\lambda_g/2$ (~12.5 mm)
- Ceramic placed at the centre of the circular section
- Diameter = diagonal of the rectangular waveguide

RF modelling and optimization

- Simulated in RF Module, Electromagnetic waves, frequency domain (emw) interface.
- Analysed for an input power of 125 kW at 3.7GHz.
- Impedance Boundary condition used on the inner surface to resolve the skin depth of copper.
- Multiple modes are generated due to various discontinuities, circular waveguide length is thus optimized using Parametric sweep.

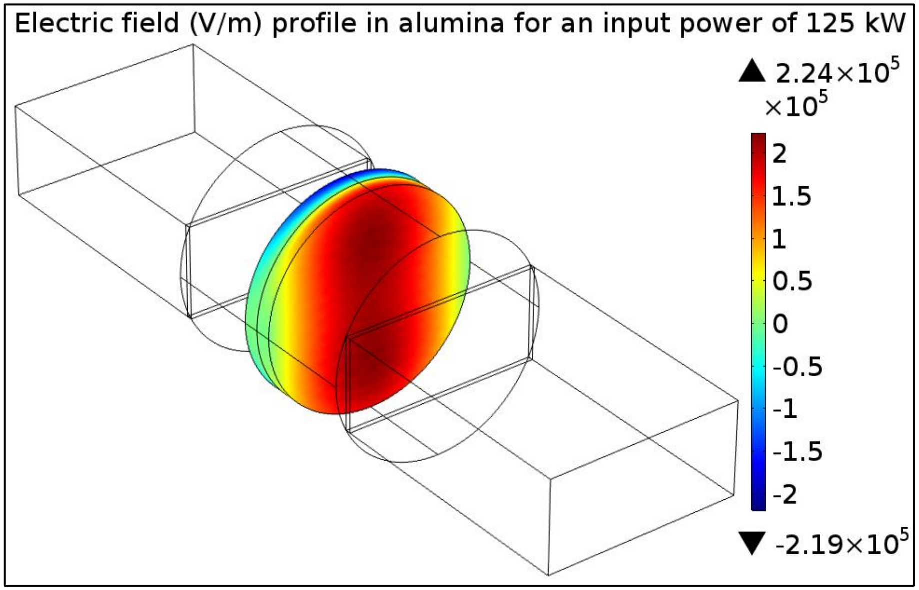


Figure 3. E-field in alumina

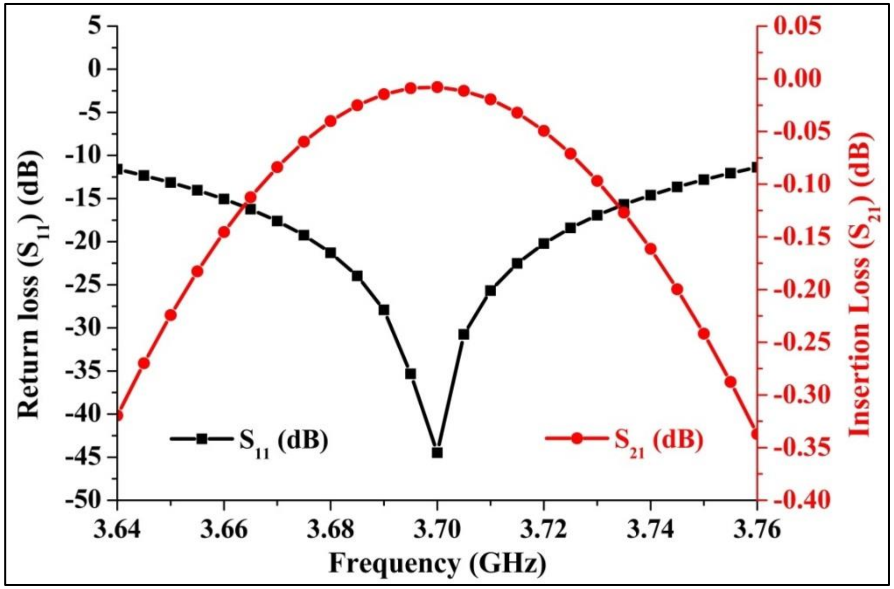


Figure 4. Frequency response of the window

- Return Loss ~40 dB
- Power absorbed by alumina ~450 W
- Surface Loss ~ 180 W
- Optimized circular waveguide length with alumina = 83.1 mm (70.6 mm + 12.5 mm)

Thermal analysis

- Heat Transfer Module, Heat Transfer in Solids (ht) interface is used.
- RF loads were coupled to the Heat Transfer in Solid (ht) interface (Electromagnetic Heat Source (emh), Boundary Electromagnetic Heat Source (bemh)).
- Analysed for an input power of 125 kW at 3.7GHz.
- Heat flux boundary condition used on the outer surface of copper to model convection cooling.

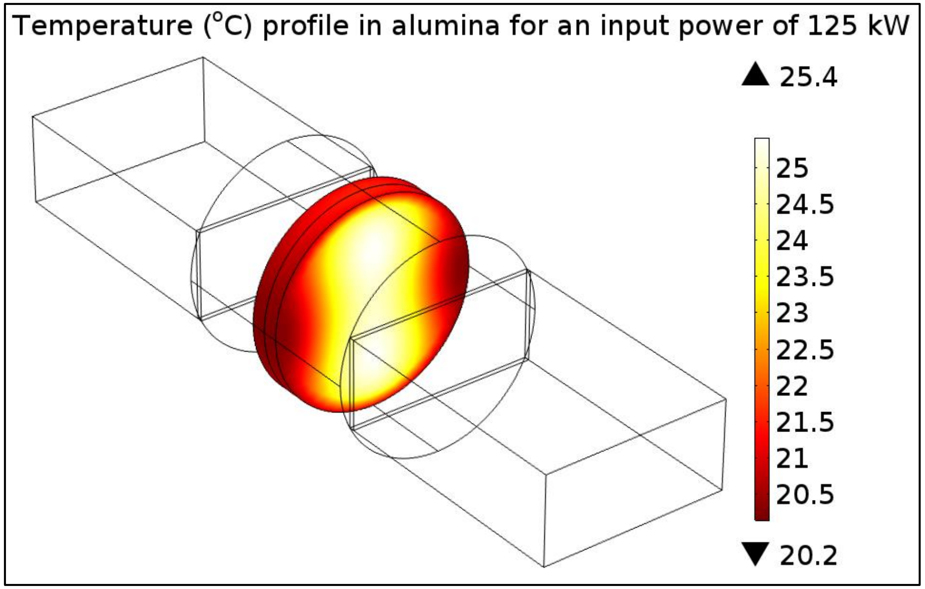


Figure 5. Temperature profile in alumina

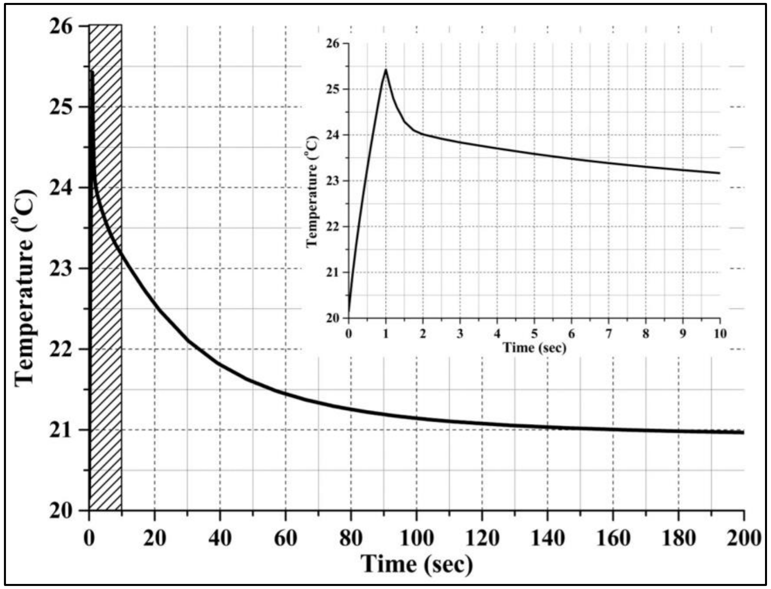


Figure 6. Convection cooling of the window

Peak Temperature = 25.4°C

Stress analysis

- Structural Mechanics module, solid mechanics (solid) interface used.
- Thermal load was coupled to the solid mechanics (solid) interface (Thermal Expansion (te)).
- Analysed for an input power of 125 kW at 3.7 GHz.
- Fixed Boundary constraint was applied to periphery of the ceramic and the waveguide ports at the input and the output.

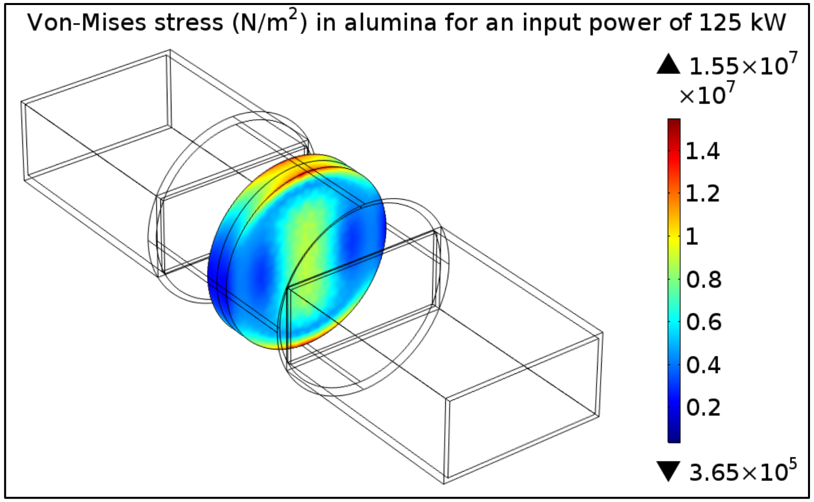


Figure 7. Stress generated in alumina

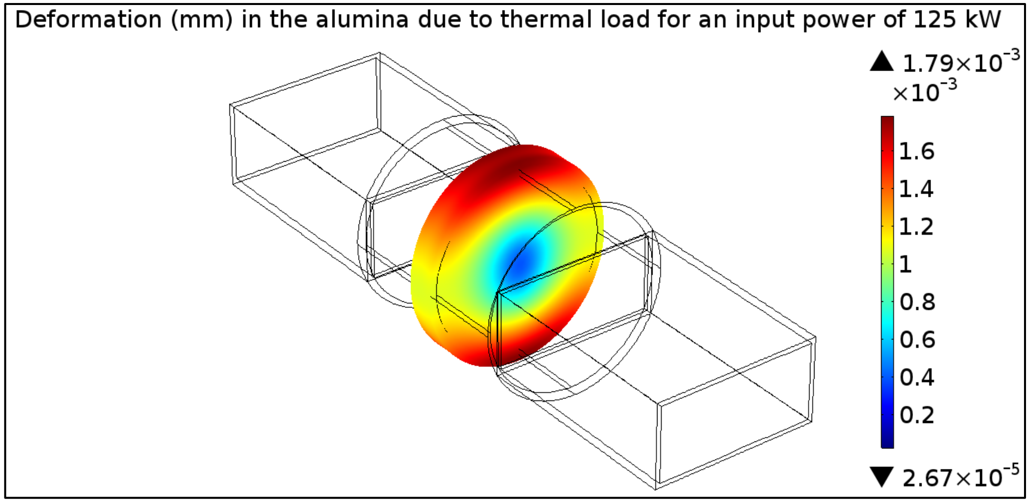
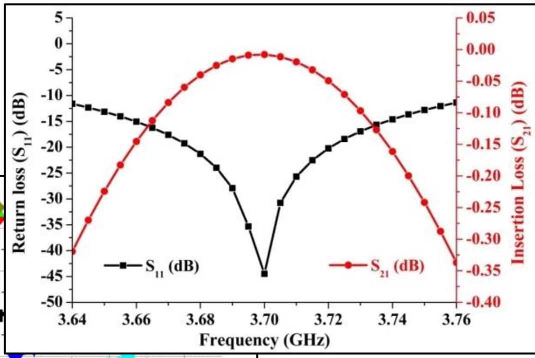


Figure 8. Deformation in alumina

Max. Deformation = 1.8 μm

VNA characterisation of the developed window

- The RF window was developed using vacuum brazing technique.
- The window was characterised for its S-parameters using a Vector Network Analyser (VNA).



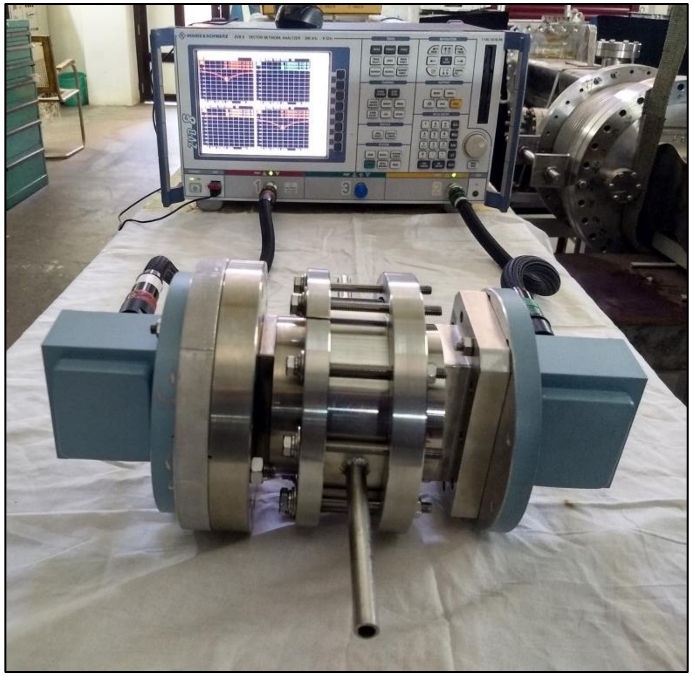


Figure 9. VNA characterisation of the window

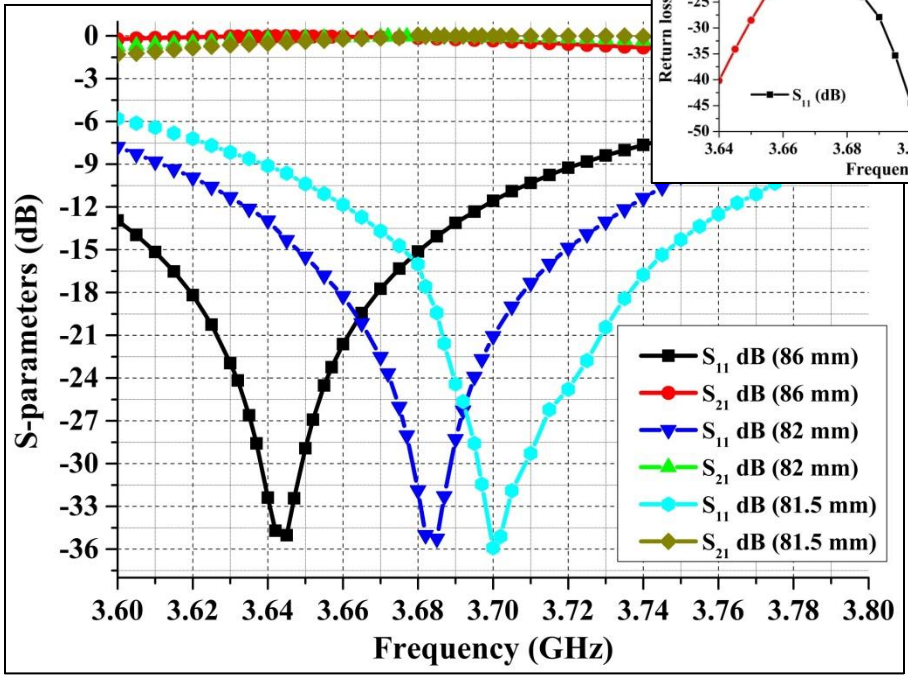


Figure 10. Frequency response of the fabricated window

- Minima of S_{11} is obtained at 81.5 mm of the circular waveguide length which is in good agreement to the COMSOL simulated value (83.2 mm).
- Measured return loss ~ 36 dB (simulated ~44 dB)
- Variation is due to the deviation in the alumina properties and fabrication tolerance errors.

High power testing of the developed window

- High power testing at 125 kW for 1 s , 3.7 GHz was done using klystrons.
- IR camera was used to measure the temperature at the periphery of the alumina

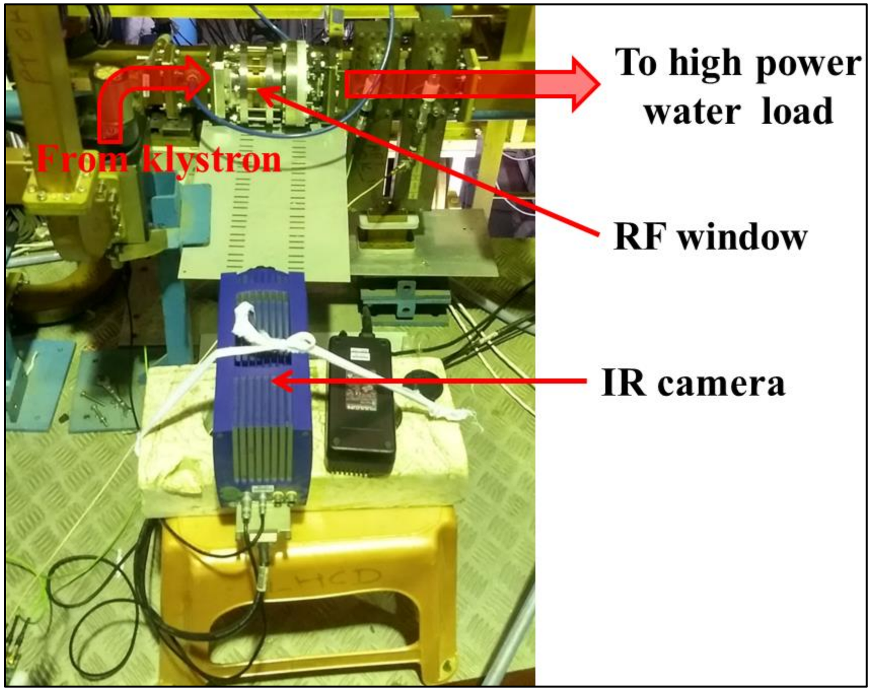


Figure 11. High power testing setup of the window

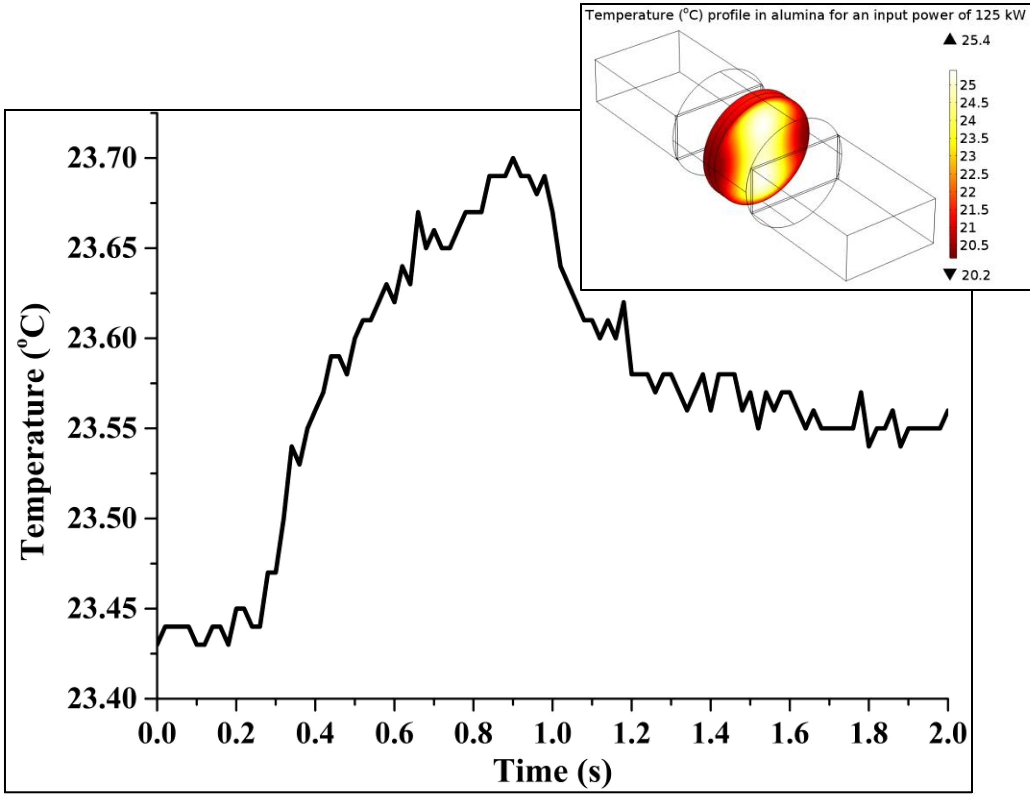


Figure 12. Temperature detected by the IR camera at the periphery, Inset: simulated temperature profile

- Peak temperature detected by the IR camera ~23.7°C at the periphery which matches with the temperature obtained by COMSOL simulations

Conclusion and Future Scope

- RF Vacuum window was designed and analysed using COMSOL Multiphysics.
- The fabricated window was tested and the measured results were found to be in good agreement with the simulation results
- Such windows are used in Nuclear fusion experiments and a window for higher power CW operations can be designed.

- Installing of cooling channels and testing the window for longer durations and higher RF power.

References

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[3] D. Pal et al., “Design and Testing of RF Window for a High Power Klystron,” Eur. J. Adv. Eng. Technol., vol. 1, no. 2, pp. 29–34, 2014.

[4] M. Neubauer *et al.*, “High-Power RF Window Design for the PEP-II B Factory,” in *Fourth European Particle Accelerator Conference (EPAC 94)*, 1994, no. June, pp. 1–3

Thank You

Additional slides