Design of a 170 GHz Waveguide-Based ENOCH Notch Filter for Burning Plasma Diagnostic Protection

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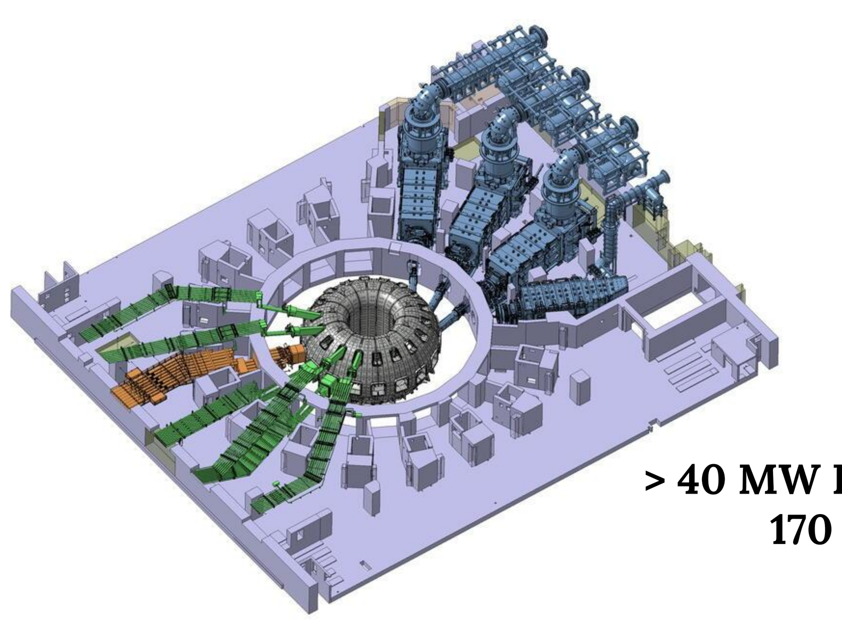
MOTIVATION & BACKGROUND

Intense stray radiation from high-power 170 GHz gyrotrons used for Electron Cyclotron Heating (ECH) in magnetic confinement fusion devices [1][2] poses a severe risk to sensitive microwave diagnostic receivers. To protect these critical front-end systems in next-generation burning plasma experiments [3][4], this paper presents **ENOCH** (Electromagnetic Notch Protection of Electron Cyclotron Heating), a novel 170 GHz waveguide-based notch filter. Engineered within a standard WR-06 waveguide geometry, the proposed eight-cavity resonant structure provides robust power protection without sacrificing diagnostic performance. Full-wave electromagnetic simulations demonstrate an exceptional rejection depth exceeding 90 dB at the 170 GHz interference frequency alongside a remarkably low insertion loss across the primary 134–166 GHz diagnostic passband. Furthermore, a coupled electromagnetic-thermal analysis confirms the filter's structural resilience under 100 W of continuous-wave input power. Compact, manufacturable, and easily integrated, the ENOCH design fulfills the stringent operational criteria required for reliable diagnostic survival in high-power, harsh environments typical of ITER- and ARC-class tokamaks.



> 40 MW ECH Power 170 GHz

TECHNICAL GAPS AND SOLUTION

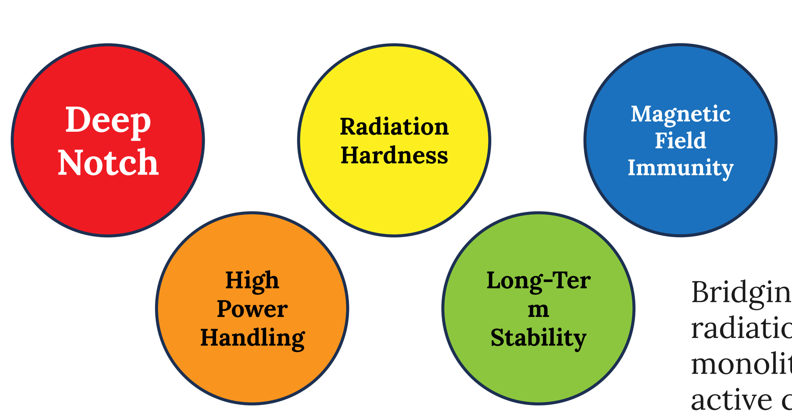
Gap # 1: State-of-the-art notch filters demonstrate excellent narrowband rejection but are not designed for ARC-like hostile environment.

- Achieve >60 dB notch depth and fine frequency resolution in lab settings.
- Use materials (dielectrics, semiconductors, standard metals) that degrade under ITER's neutron/gamma flux, vacuum, and temperature swings [5].
- Lack radiation-hardened packaging or remote tuning for inaccessible, hot-cell operation.

Gap # 2: ARC-like requires simultaneous high-power handling and extreme long-pulse stability, which existing filters cannot provide.

- Must reject multi-megawatt gyrotron beams (e.g., 170 GHz) without arcing, passive intermodulation, or thermal runaway.
- Need frequency drift < 0.1% over 3000-second pulses, whereas lab filters drift and require frequent recalibration[6][7].
- No current filter combines high-power capability with radiation tolerance and sub-ppm thermal stability.

Statement: The gap is not incremental but fundamental; no single technology today bridges all requirements.

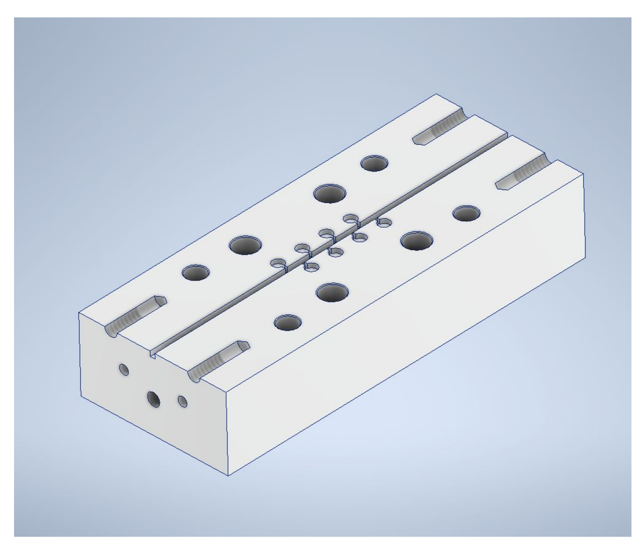


Bridging this gap demands new radiation-tolerant low-loss dielectrics, monolithic all-metal cavities, and active compensation schemes.

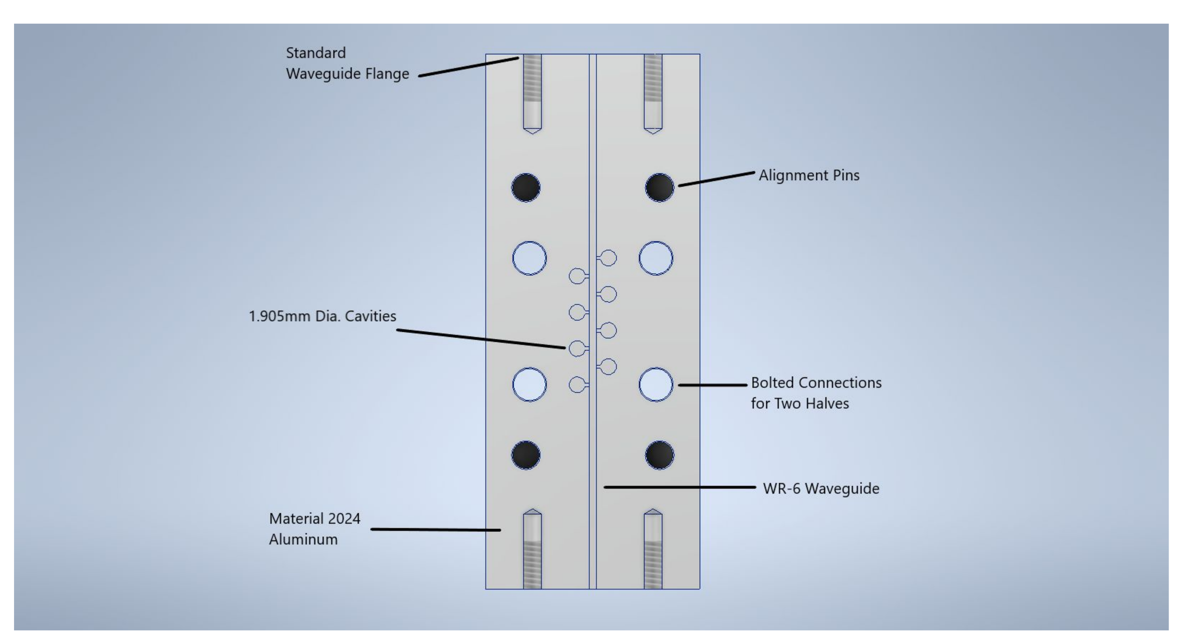
FILTER DESIGN AND KEY PARAMETERS

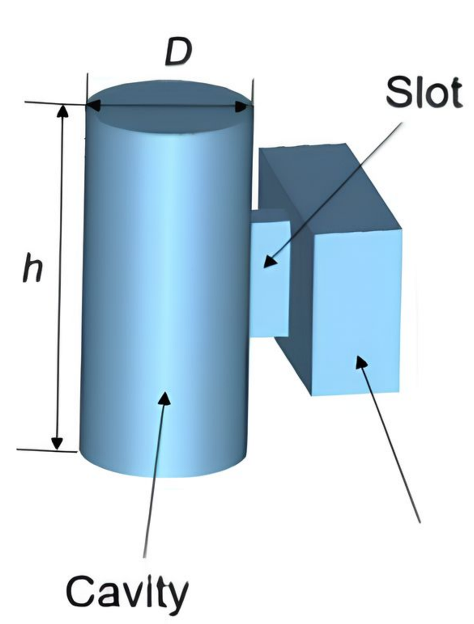
Primary design of ENOCH notch filter is focusing on the D-band millimeter-wave front-end receiver module protection against the unexpected ECH leakage up to 100 W.

Target Parameters Description	Value
Primary Notch Frequency (center)	170 GHz
Notch Bandwidth (3dB)	< 5 GHz
Notch Depth	> 60 dB
Passband Frequency	134 – 166 GHz
Passband Insertion Loss	< 1 dB
Working Temperature	< 100 degree C
Input/Output Port	WR-06
Enclosure Volume	41 cm³
Material	Aluminum/Copper



- 8 pieces of resonance cavities on both side of WR-06 waveguide.
- The axis of cylindrical cavities must remain perpendicular to the TE_{10} mode polarization orientation in a rectangular waveguide.





$$\lambda_g = \frac{\lambda}{\sqrt{1-\left(\frac{\lambda}{\lambda_c}\right)^2}}$$

The wavelength in the cylindrical cavity

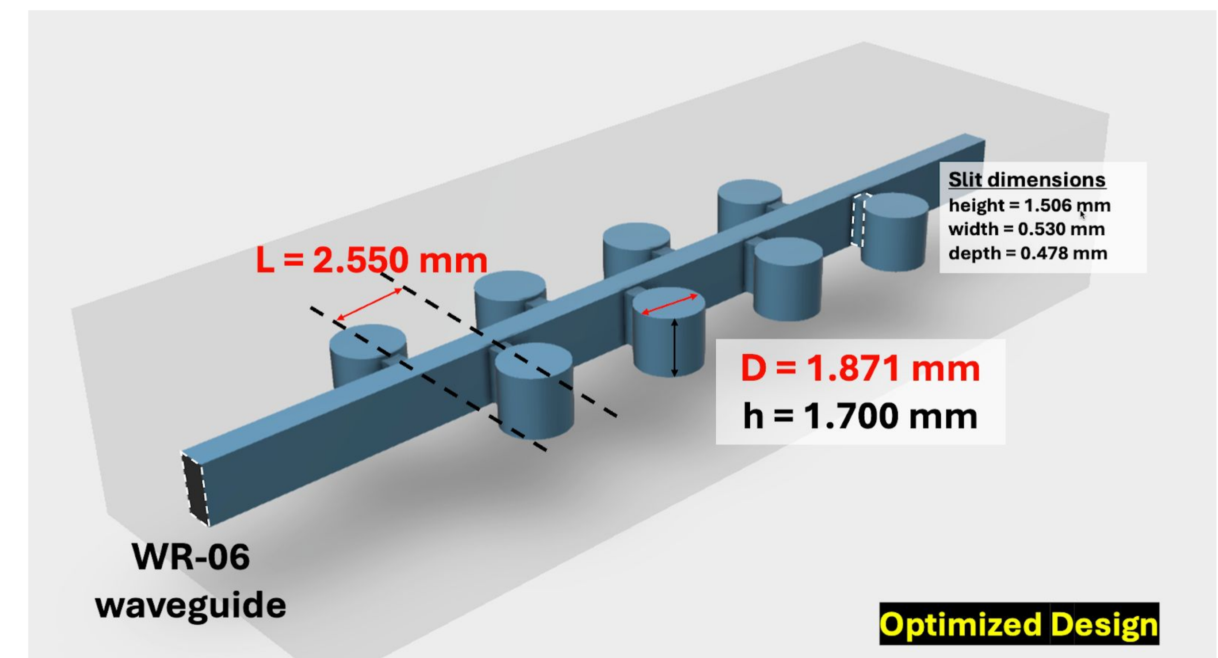
The cutoff wavelength in the cylindrical cavity Depends on D

The cavity height

$$h = p * \frac{\lambda_g}{2} \quad (p = 1, 2, 3, \ldots)$$

FILTER STRUCTURE AND OPTIMIZATION

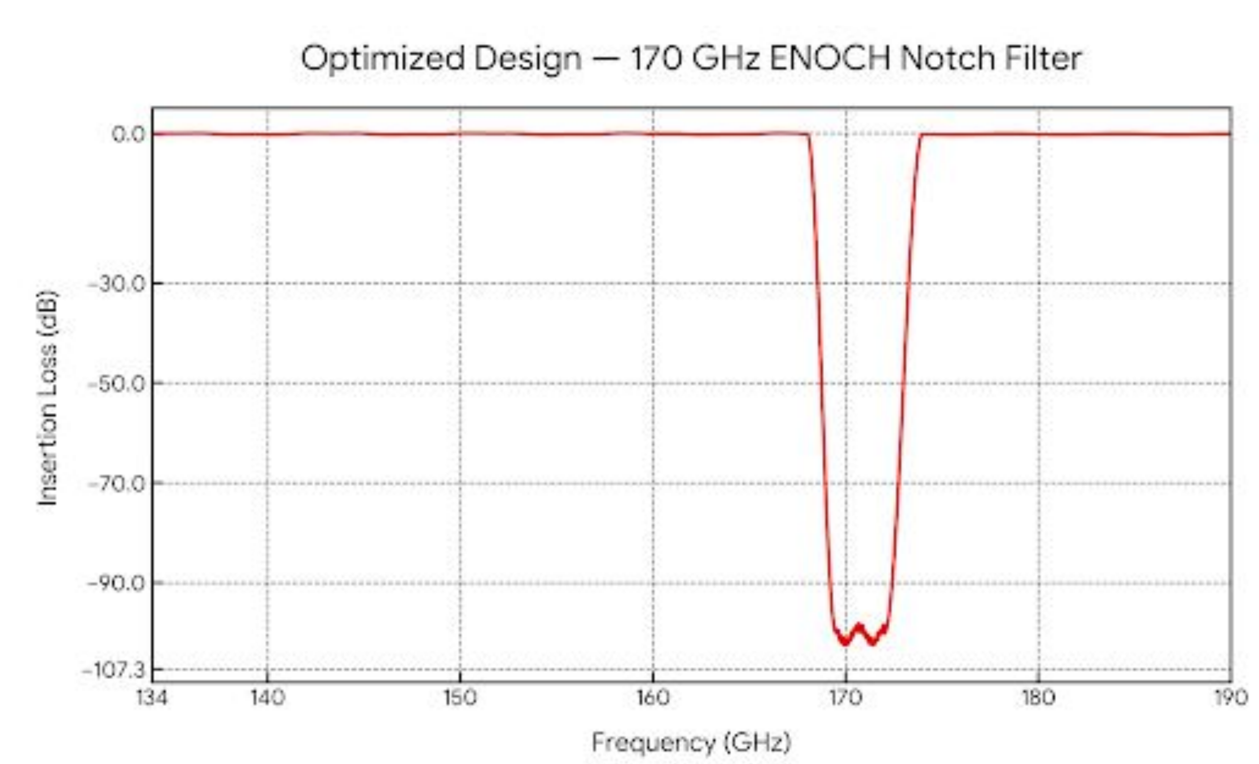
This waveguide notch filter is designed for integration at the front-end of a D-band receiver module for microwave radiometry, serving to protect the nanowatt-sensitivity receiver from ECH leakage entering through the vessel or other coupling paths. To achieve an optimal balance between performance and fabrication feasibility, an eight-cavity configuration was selected. The cavities are spaced with a gap of 1.5642 mm between adjacent channels, corresponding to 3 quarter-wavelengths within the standard WR-06 waveguide structure.



Iterative EM optimization (Table I) walked the notch on the 170 GHz ECH line while flattening the passband.

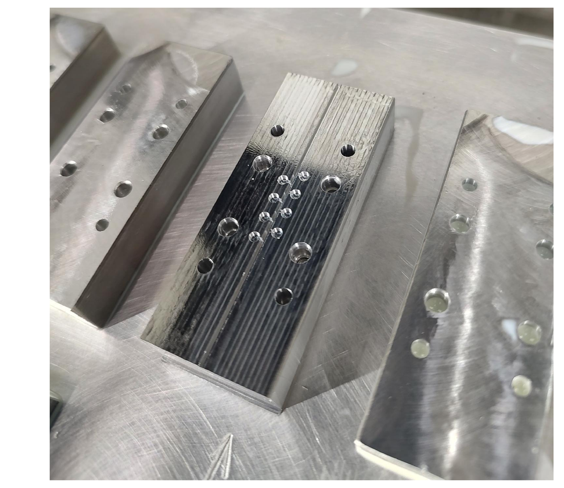
Parameter	Initial (nm)	Final (nm)
Cavity Height	1700	1700
Inter-cavity Gap	2300	2550
Slot Width	530	530
Slot Height	1506	1506
Cavity Diameter	1905	1871

TRANSMISSION RESULTS



- **3 dB bandwidth : 168-173 GHz**
- **60 dB bandwidth : 172.05 – 168.90 GHz**

FILTER FABRICATION AND QUALIFICATION



- Micro-fabrication of high-precision notch filters is essential for target frequency performance but poses significant micro-manufacturing challenges due to tight tolerances.
- These challenges were addressed with an integrated methodology combining advanced machining, specialized equipment, precise CAD/CAM, and extensive team experience.
- Proprietary in-house CAD/CAM workflows and state-of-the-art high-precision CNC equipment enabled production of functional test filters.
- End-to-end control (design → manufacturing review → CAM programming → final part) guarantees design integrity, reduces external vendor dependencies, and supports ongoing protocol advancement.
- The team's advanced micro/nano manufacturing methodology uses novel principles to achieve exceptional precision and performance.

Conclusion and Outlook

- All design targets met: 94.5 dB rejection at 170 GHz with ≤0.85 dB insertion loss across the 134–166 GHz diagnostic passband.
- Thermally safe at 100 W CW: peak inner-wall temperature 97.9 °C with air cooling only — within the <100 °C operational limit.
- Stopband biased above 170 GHz (60 dB BW: 168.90–172.05 GHz) — preserves passband headroom and absorbs gyrotron frequency drift.
- Fixed, non-tunable geometry — deep rejection comes from cascading identical cavities, not per-unit tuning: improves yield, integrability, and mechanical robustness.
- Fully CNC-machinable with existing high-precision milling — practical, low-risk fabrication path.
- Next: prototype fabrication → high-power experimental validation → architecture scaling for ITER- and ARC-class reactors with >20 MW ECH systems.

References

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