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ICRH SYSTEM FOR THE HL-3 TOKAMAK

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ABSTRACT

- 6 MW ion cyclotron range of frequencies (ICRF) power is under construction at SouthWestern Institute of Physics (SWIP), available in HL-3 at Sep. 2026.
- Radio Frequency (RF) range 25–50MHz with pulses up to 5s.
- Main ion heating schemes in D plasma: H minority & 2[nd] D, f=33MHz at B_0=2.2T; In D-T plasma: He-3 minority + 2[nd] T with f=25MHz at B_0=2.5T.
- RF generator consists of 4x1.5MW transmitters.
- The transmission line：520m long, incorporates 3dB hybrid couplers.
- Matching unit: 1/4λ stub tuner, 1/2λ phase shifter +pre-matching stub.
- Two 2-strap antennas with parallel wavenumber $k_{//}$ ~ 6.5 m^{-1}.

Milestones of the HL-3 tokamak

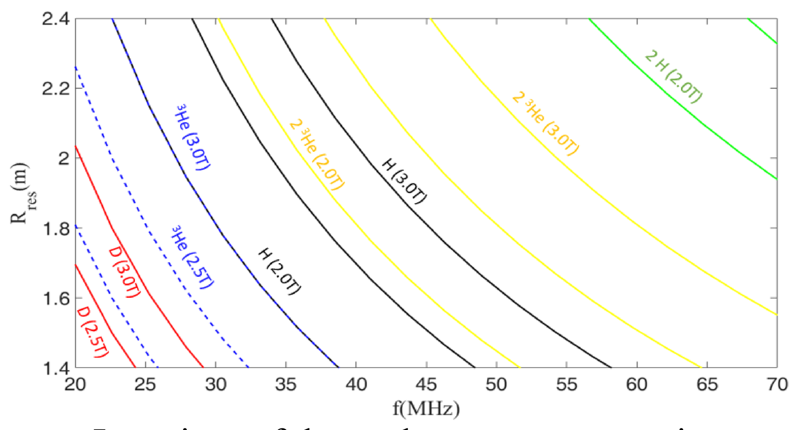
- Built in 2020 at SWIP
- Achieved 1MA plasma current in 2022
- Achieved 1MA H mode in 2023
- Achieved 1.5MA H mode in 2024
- Achieved 13.8keV T_e and 10keV T_i in 2025
- Current auxiliary heating power: 19.5MW
- Auxiliary heating power in Sep. 2026: 41MW

Auxiliary heating power in HL-3

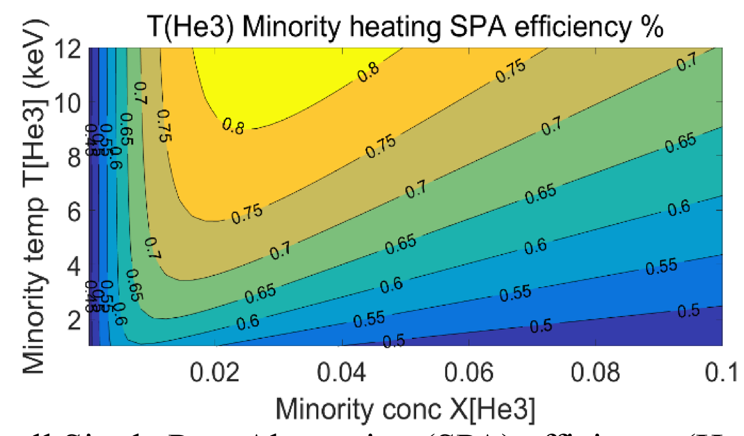
	19.5MW now	41MW in 09/2026
NBI	12MW, 2 beams, 5MW+7MW	20MW, 3 beams 6MW+7MW+7MW
ECRH	5MW 105GHz+0.5MW 68GHz	4MW 140(175) GHz+2MW 140G+5MW 105GHz
LHCD	2MW 3.7GHz	4MW 3.7GHz
ICRH	0	6MW, 25-50MHz

ICRF heating schemes in HL-3

- Main ion heating schemes in D plasma: H minority & 2[nd] D, f=33MHz at 2.2T

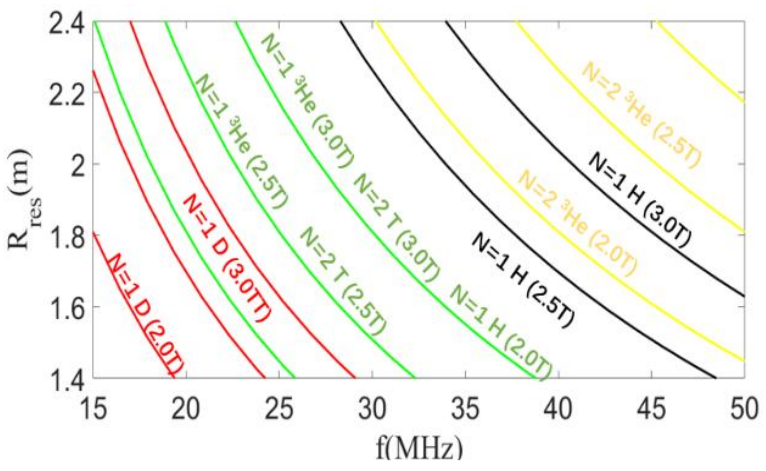


Locations of the cyclotron resonances in D plasma

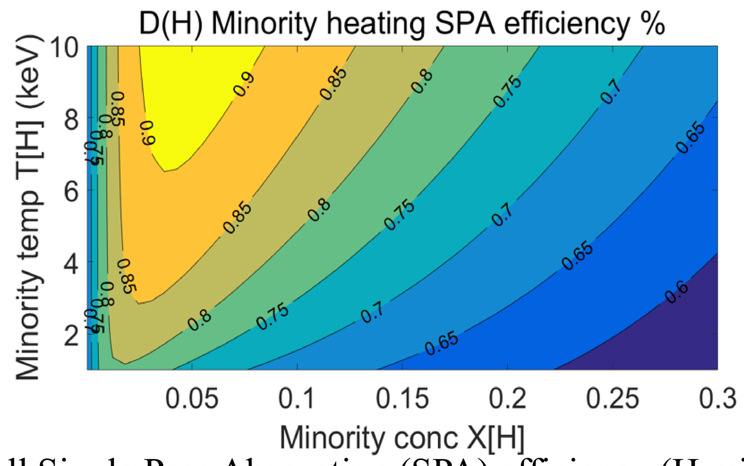


Overall Single Pass Absorption (SPA) efficiency (He-3 minority +2[nd] harmonic of T) for D-T-He-3 plasma

- Main ion heating schemes in D-T plasma: 2[nd] T & ^{3}He minority f=25MHz at 2.5T



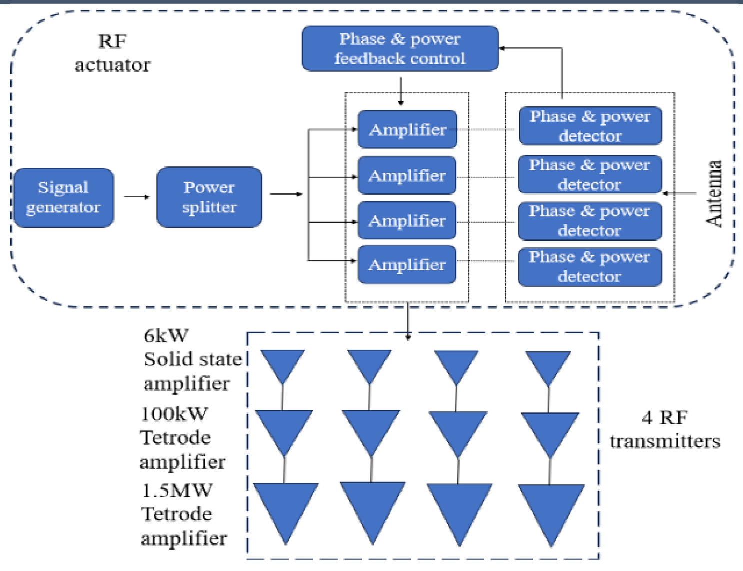
Locations of the cyclotron resonances in D-T plasma



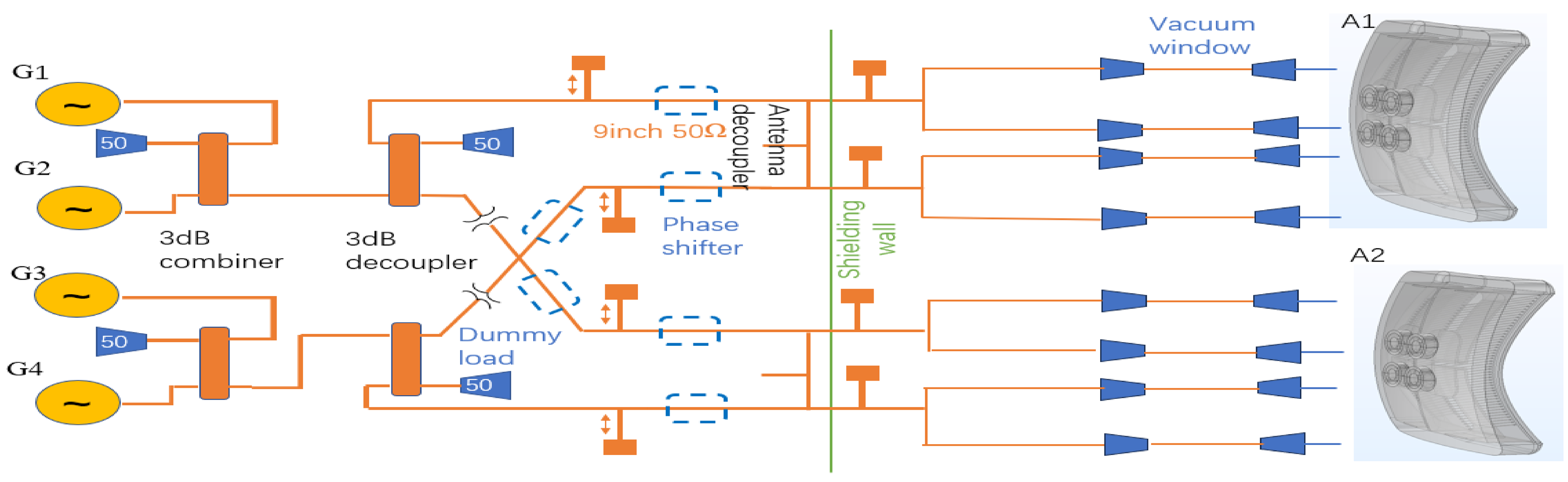
Overall Single Pass Absorption (SPA) efficiency (H minority +2[nd] harmonic of D) for D-H plasma

RF SOURCE AND TRANSMISSION LINE

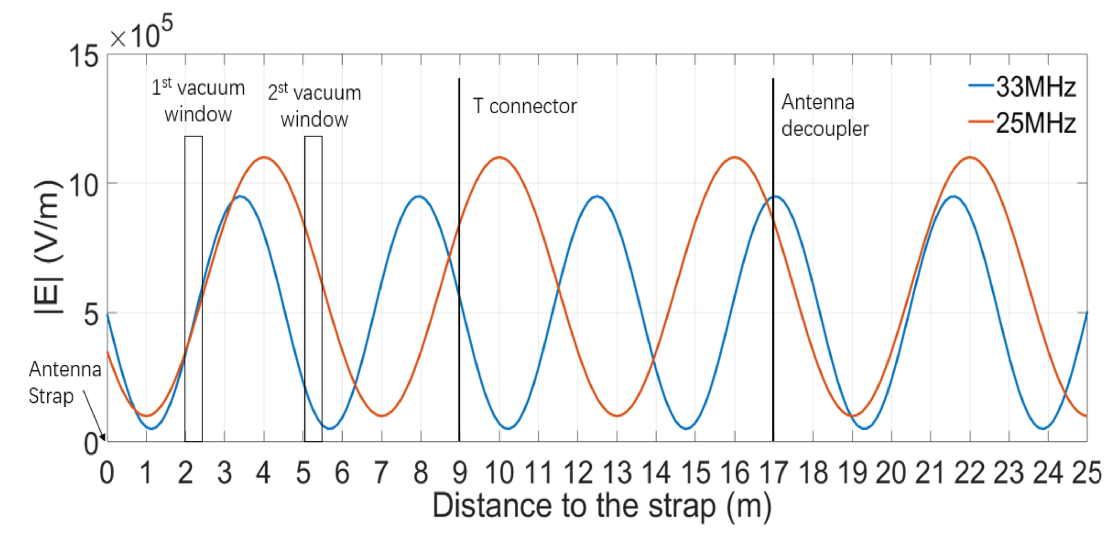
- RF generator: 4x1.5MW tetrode amplifiers
- 3dB combiner & decoupler are used
- 4 transmission lines, in total 520m long. Each splits into 2 feeder lines via a T-connector.
- Matching unit composed by a phase shifter + single stub tuner + pre-matching stub
- Antenna decoupler to diminish multi-coupling
- T-connector, antenna decoupler close to voltage maximum
- Double vacuum window in each feeder line



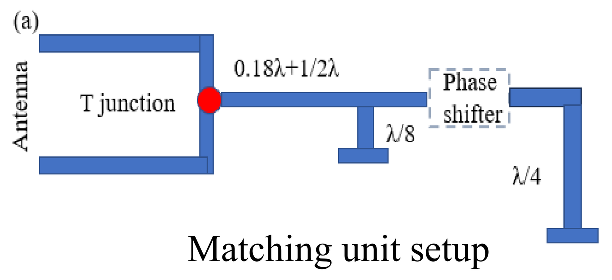
Layout of the RF source for ICRH system



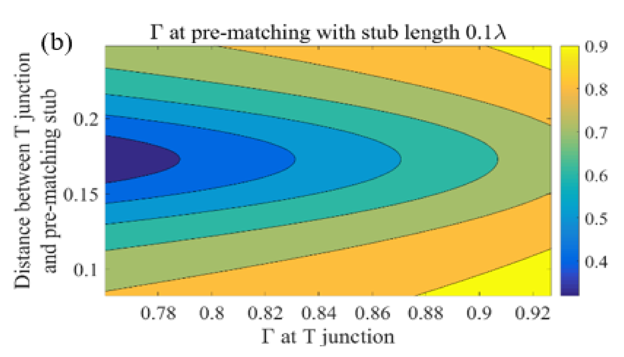
Sketch of the 6MW ICRF system for HL-3



Locations of the vacuum windows, T connector and the antenna decoupler



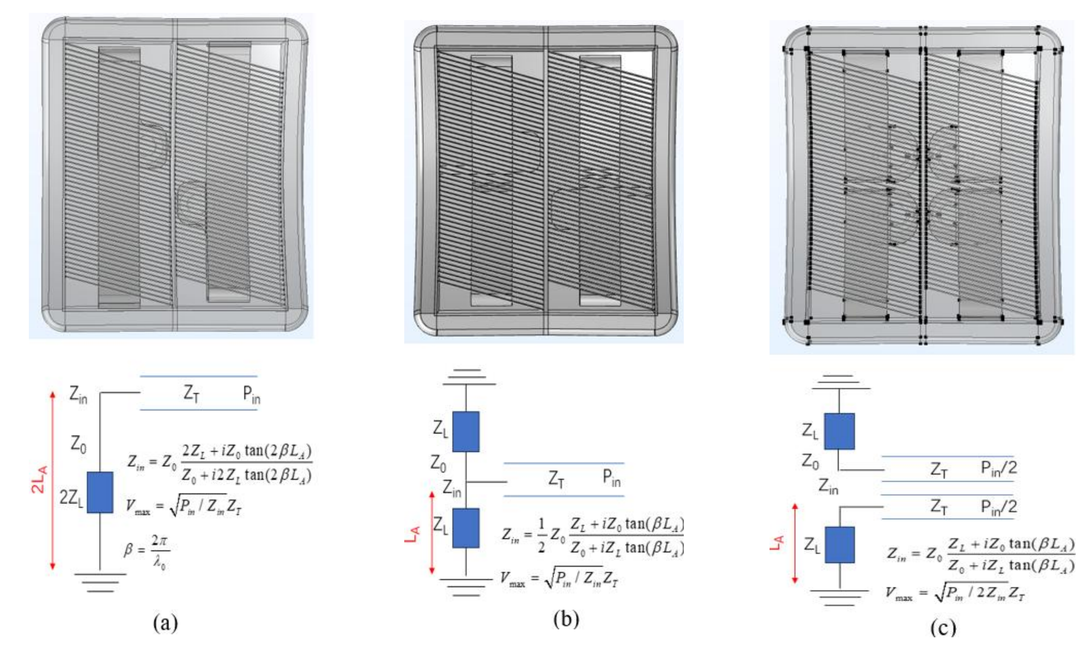
Matching unit setup



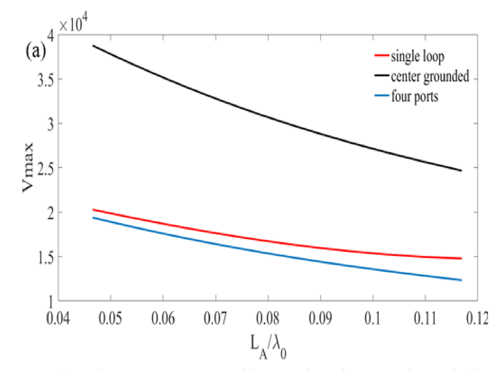
Voltage reflection coefficient (Γ) at pre-matching stub

ANTENNA DESIGN

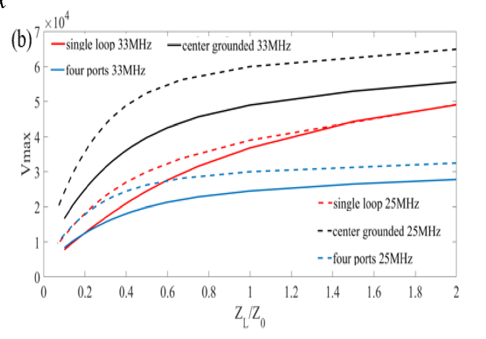
- Electrical analysis



Three antenna configurations and their electrical circuit models



V_{max} VS the normalized electrical length

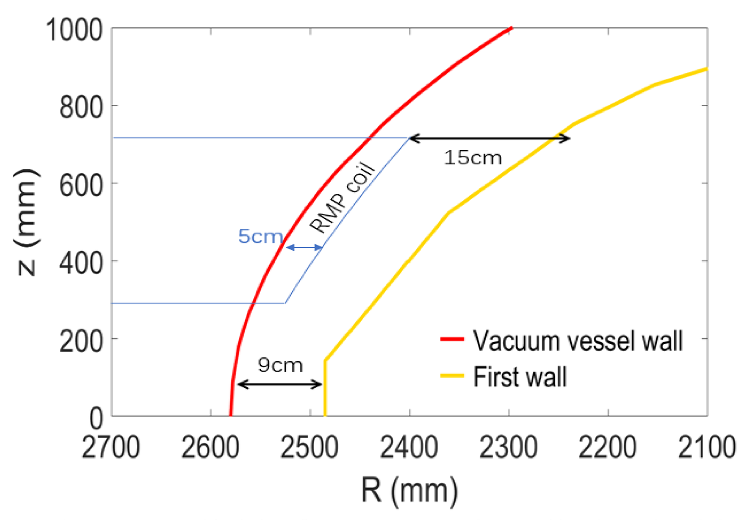


V_{max} VS normalized antenna load impedance

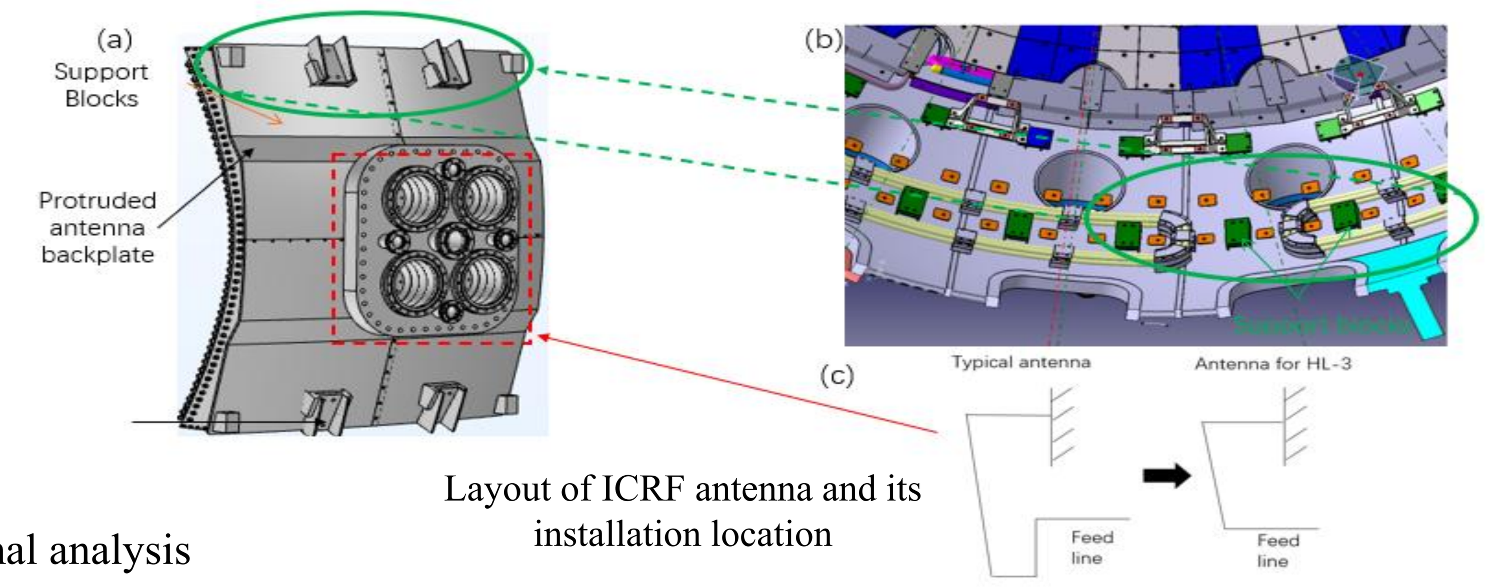
- Configuration C has a larger coupling resistance while maintaining a V_{max} at the feeder is selected

- Mechanical constraints

- Antenna needs in vessel installation, material: FS: TZM with TiC coating, others: 316L stainless steel
- Large plasma size required by high plasma current operation and high fusion power → space constraints at the front
- Resonant Magnetic Perturbation (RMP) coils → space constraints at the back
- Available radial space for antenna: 9cm at the middle plane, 15cm at top and bottom
- Design strategy: short circuit at top and bottom, remove detour structure

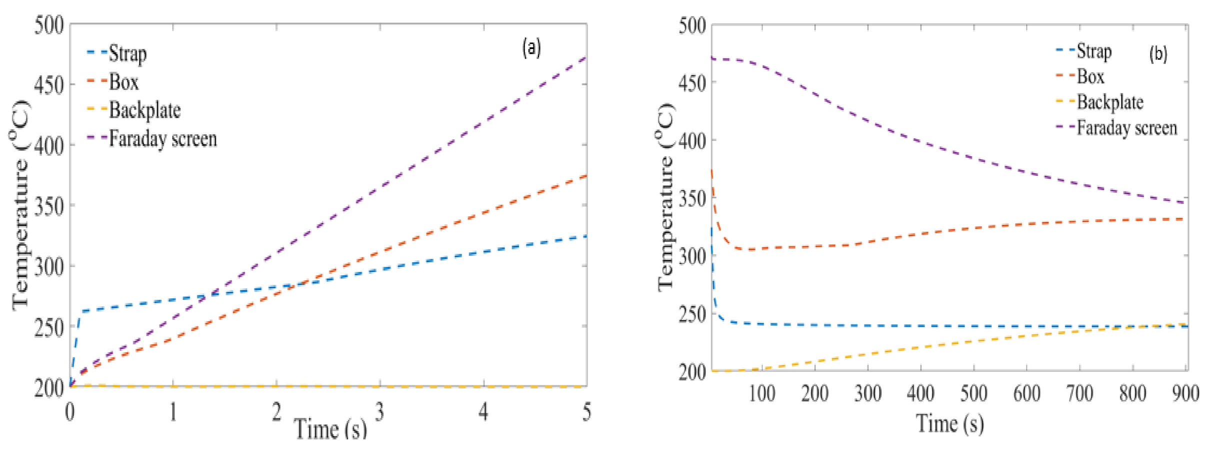


Space available for antenna installation inside the HL-3 vacuum vessel

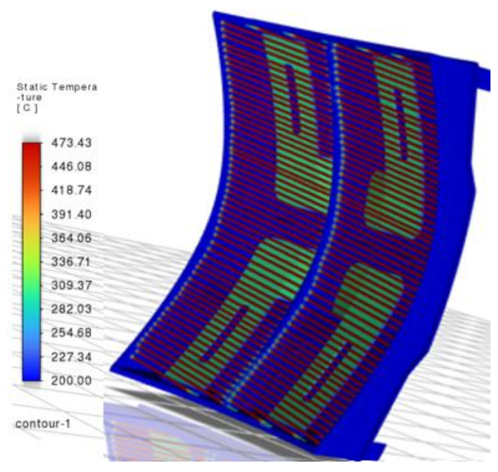


Layout of ICRF antenna and its installation location

- Thermal analysis



Antenna temperature variations during heat up and cool down



Temperature distribution at t=5s

- 200°C hot wall operation, antenna operates 5s with 3MW full power
- Heat load at FS: 0.6MW/m^2, strap: 0.3MW/m^2
- The temperature at FS, antenna box and strap are 473°C, 374°C and 324°C, far less than the melting points of the 316L stainless steel (1400°C) and TZM (2623°C)
- After 15mins pulse gap, the temperature at the FS, antenna box and strap reduce to 343°C, 331°C and 238°C

CONCLUSION

- 6MW ICRH system envisaged to be complete in Sep. 2026 at SWIP
- Frequency band: 25-50MHz with main operational frequency: 33MHz for Deuterium plasma & 25MHz for Deuterium-Tritium plasma
- 4 transmission lines with total length 520m, consists of 3dB combiner and decoupler, matching unit, antenna decoupler, T connector, double vacuum window are designed
- Two 2-strap antennas, each has 4 feed lines, designed to couple 3MW. Antenna radial depth is constrained to be 9cm at middle and 15cm at poloidal ends. The frequently used detour structure has to be removed
- It is possible to operate the antenna without water cooling. However, antenna temperature must be monitored carefully

ACKNOWLEDGEMENTS / REFERENCES

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