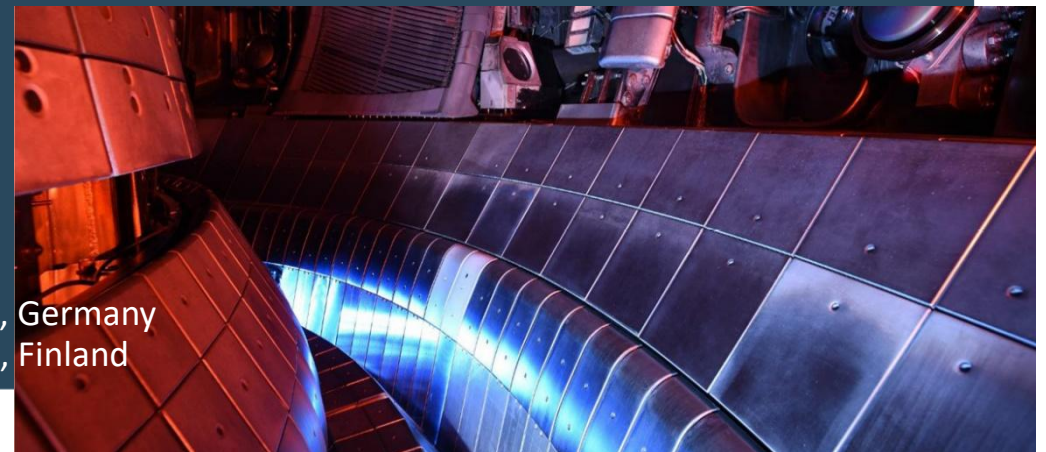




Quantitative assessment of ICRF antenna limiter tiles performance under sustained fast ion heat loads on ASDEX Upgrade

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

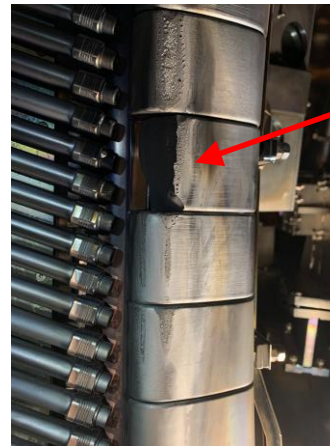
Background and motivation

Safe mitigation of particle exhaust in fusion devices crucial for reactor integrity

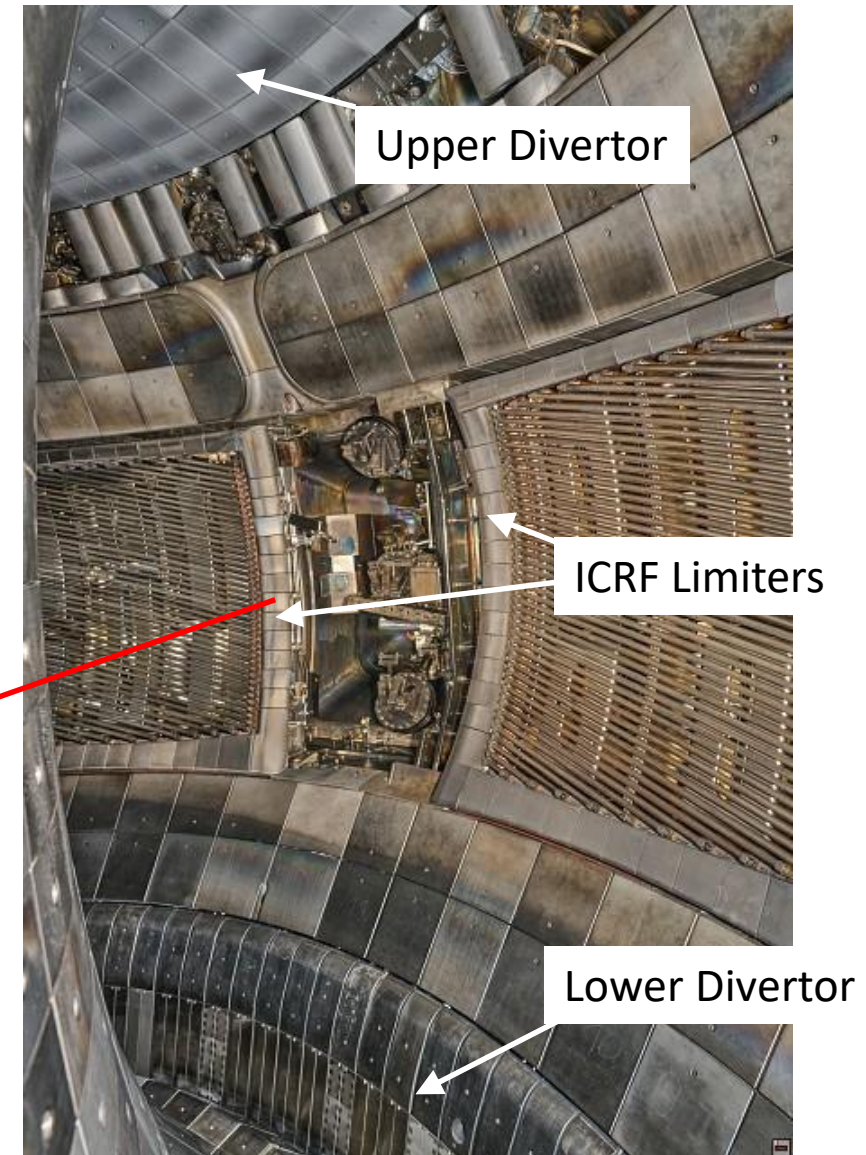
Divertors generally optimized with <1 mm accuracy (shadowing alignment, placement, shaping, etc.) to mitigate dominant (thermal) heat loads.

Limiters and outboard wall in general do not receive as much attention, in particular for fast ion heat load mitigation

Present devices can reach operational space that leads to macroscopic limiter material failure*

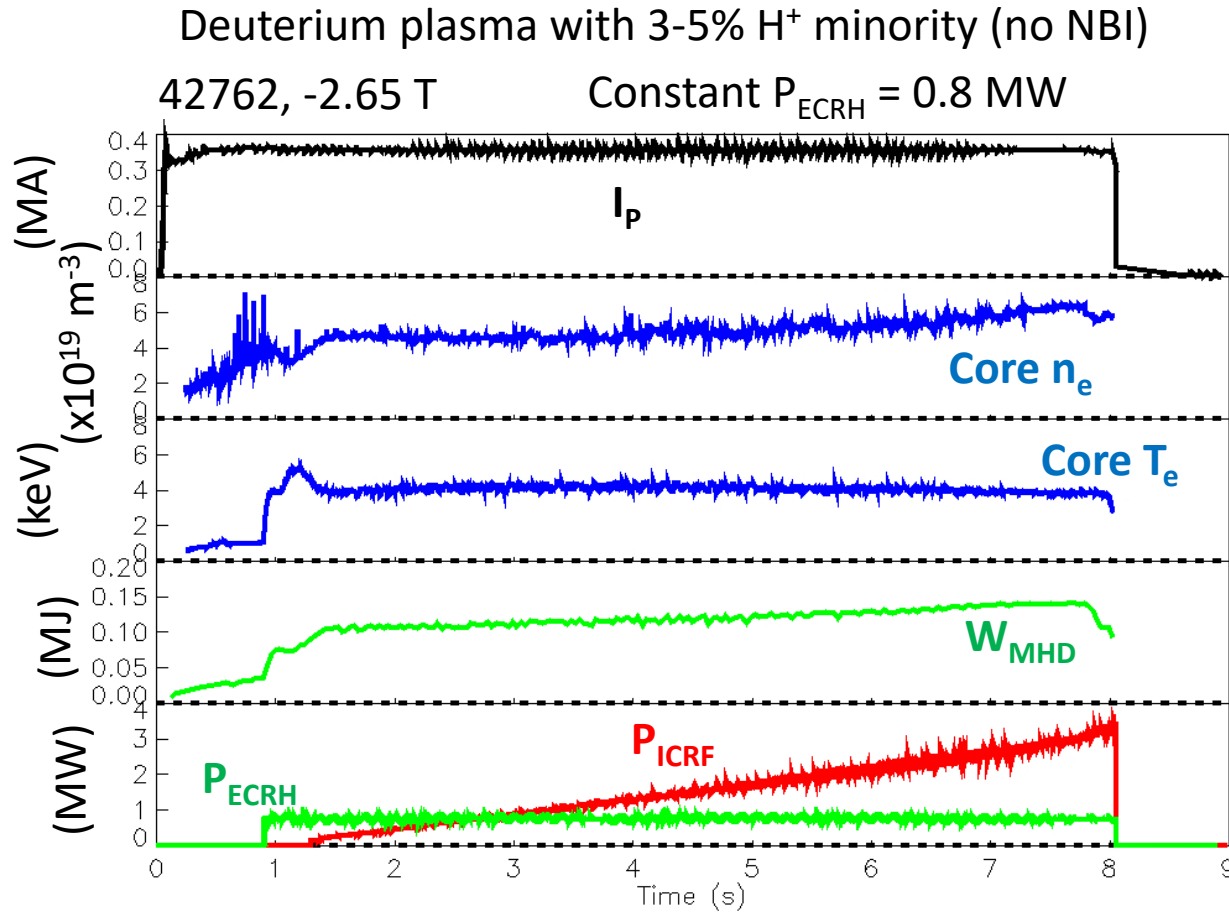


ASDEX Upgrade Outboard Sectors 10-12

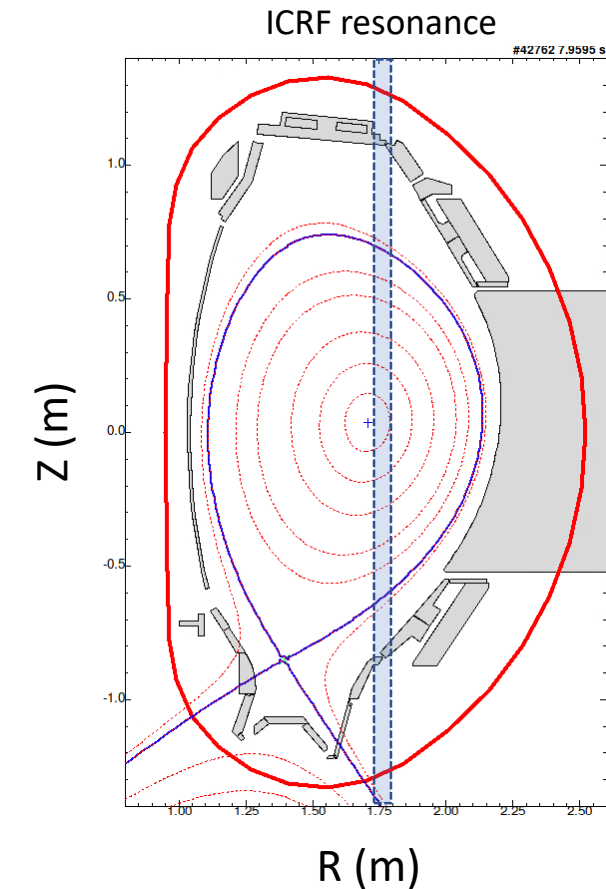


*V. Smolik et al., Thermal and structural analysis of W-7X first wall graphite tiles under direct NBI loads, Fusion Engineering and Design 218 (2025) 115178

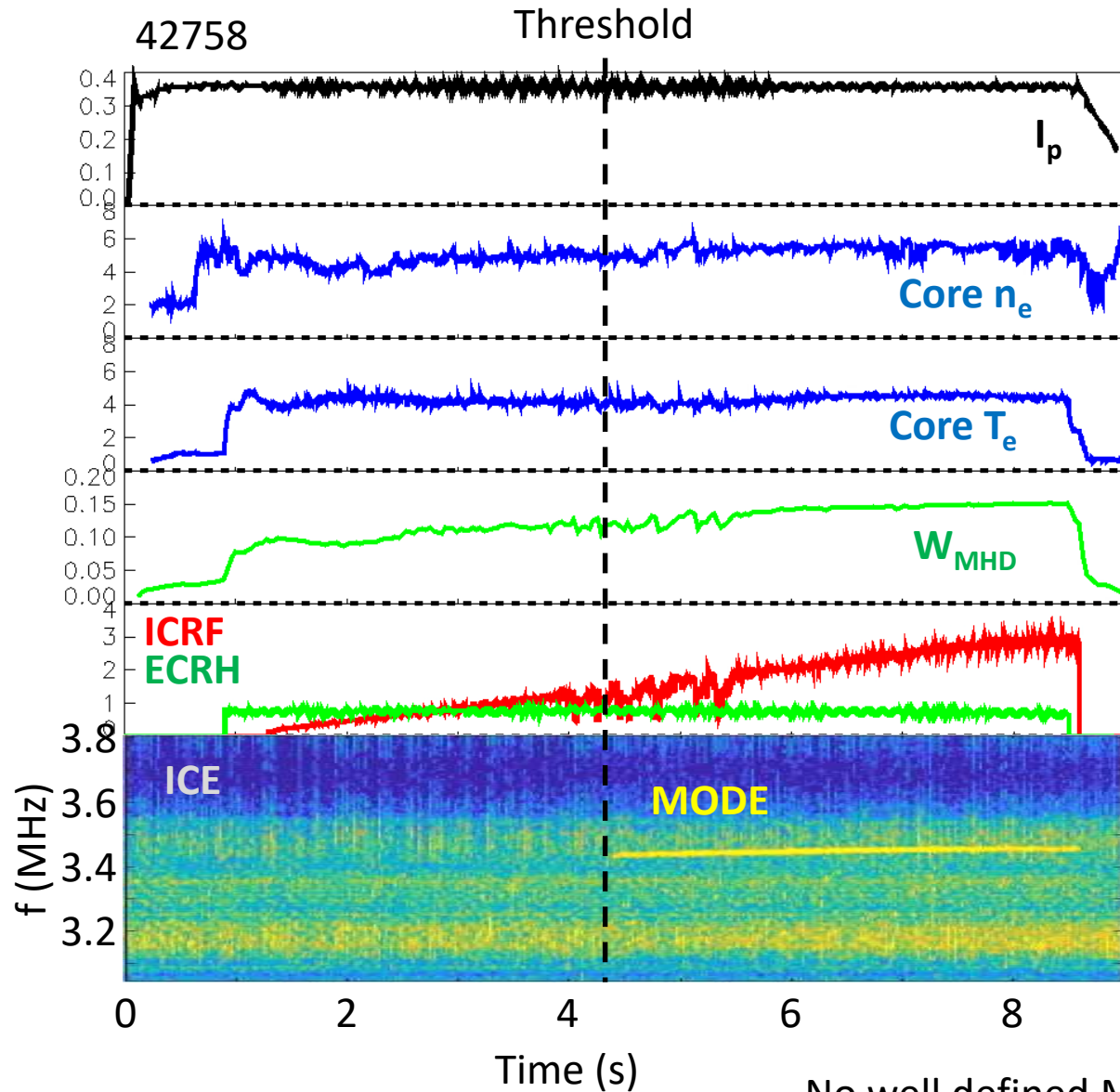
Background: study of high frequency (>1 MHz) modes driven by ICRF-accelerated H^+



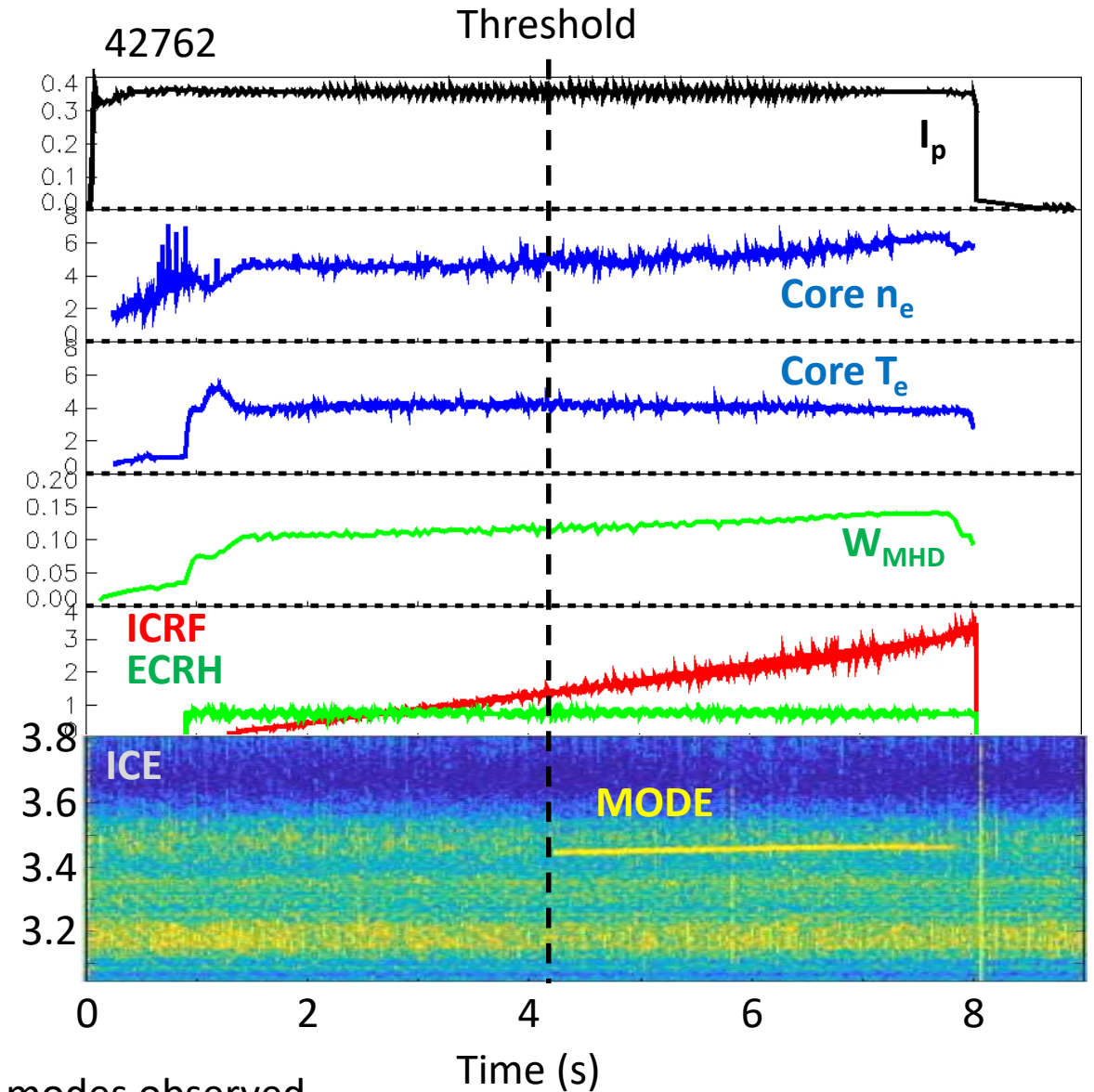
ASDEX Upgrade poloidal cross section



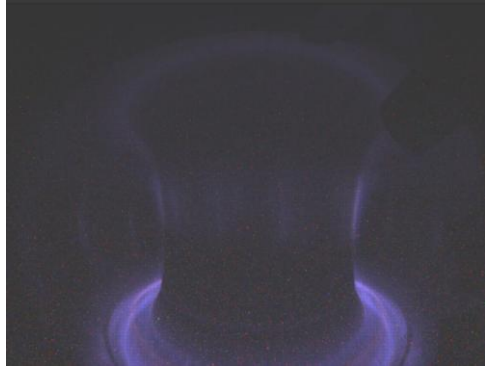
Background: study of high frequency (>1 MHz) modes driven by ICRF-accelerated H^+



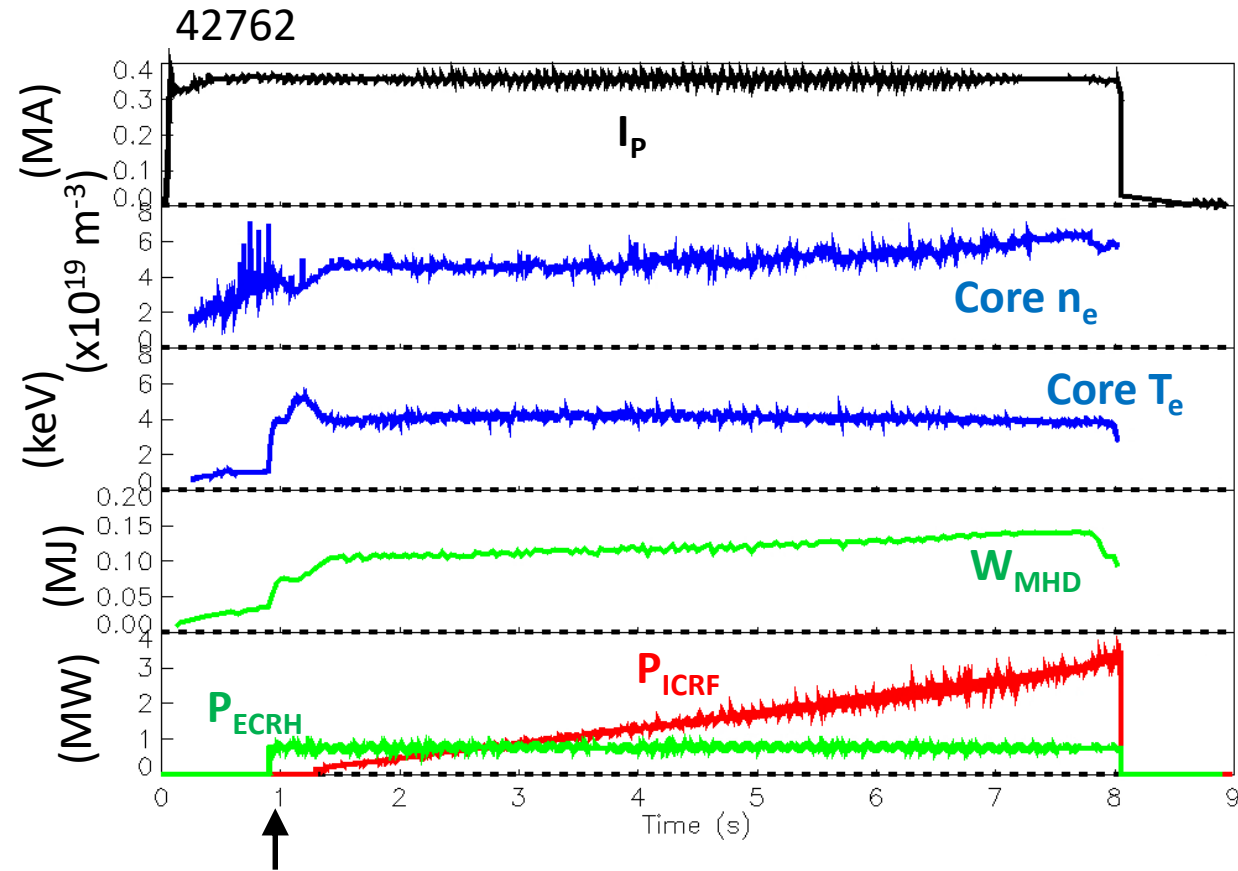
No well defined MHD modes observed



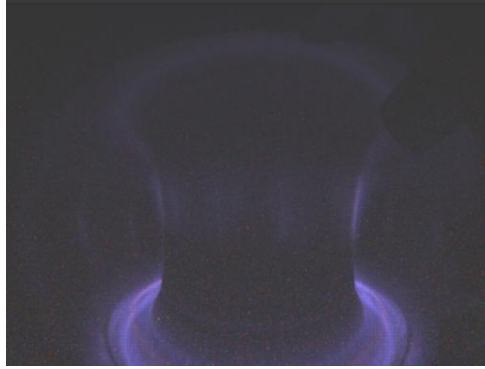
Background: study of high frequency (>1 MHz) modes driven by ICRF-accelerated H^+



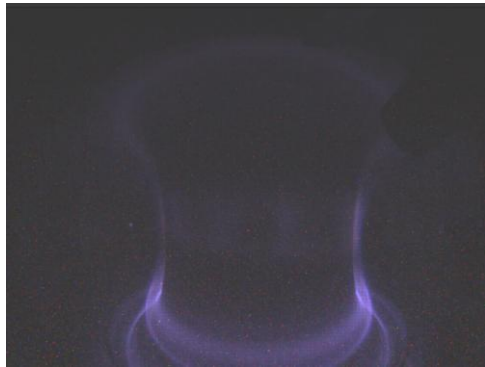
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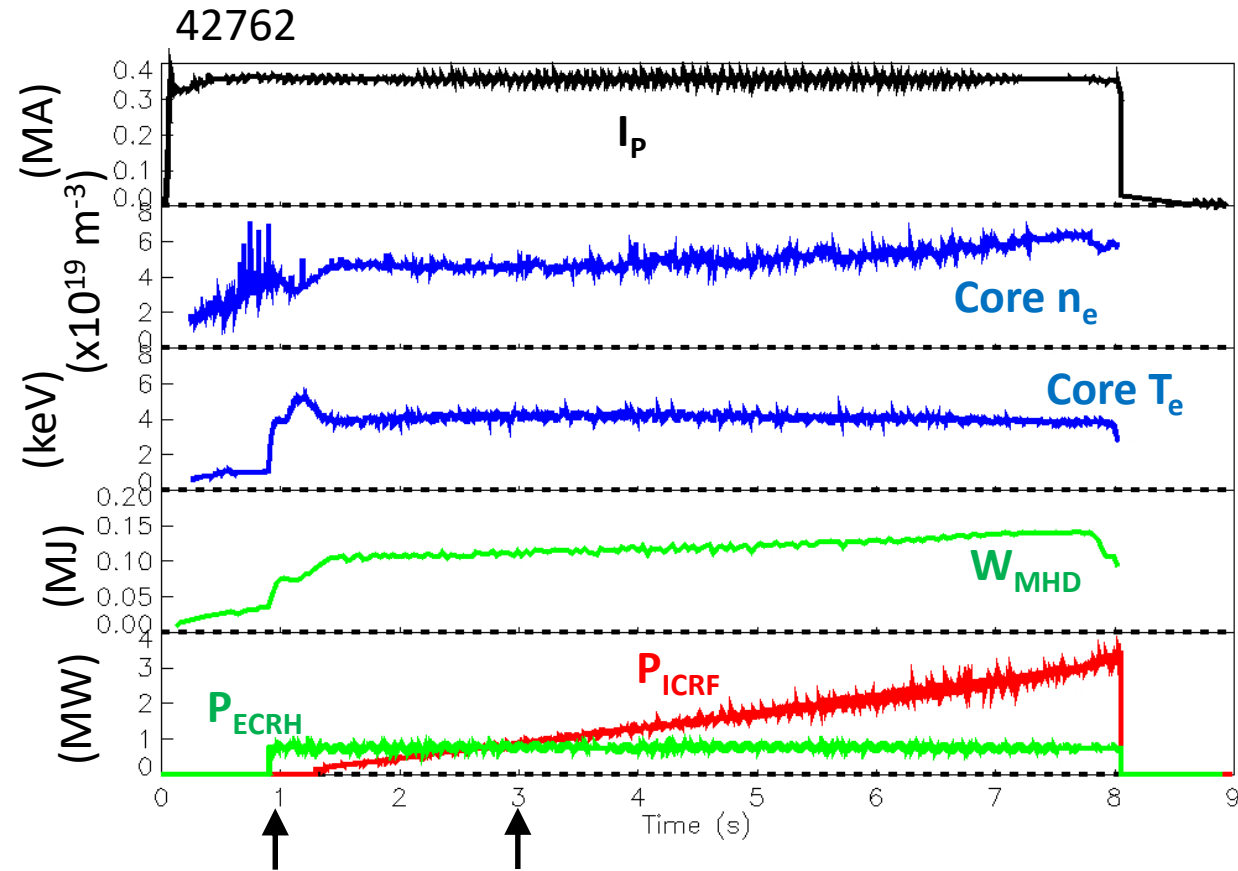
Background: study of high frequency (>1 MHz) modes driven by ICRF-accelerated H^+



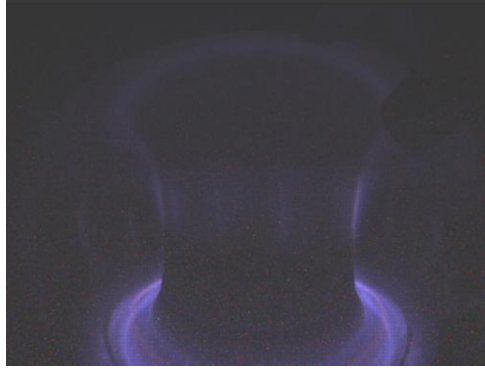
Time = 1.0 s



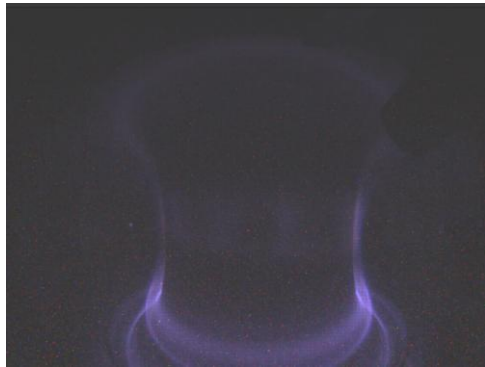
Time = 3.0 s



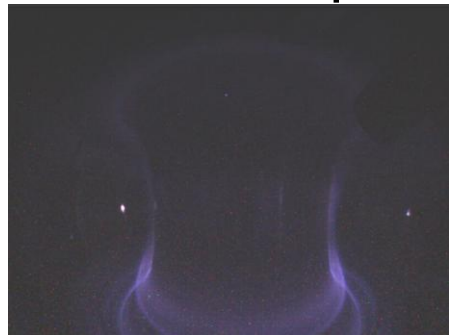
Background: study of high frequency (>1 MHz) modes driven by ICRF-accelerated H^+



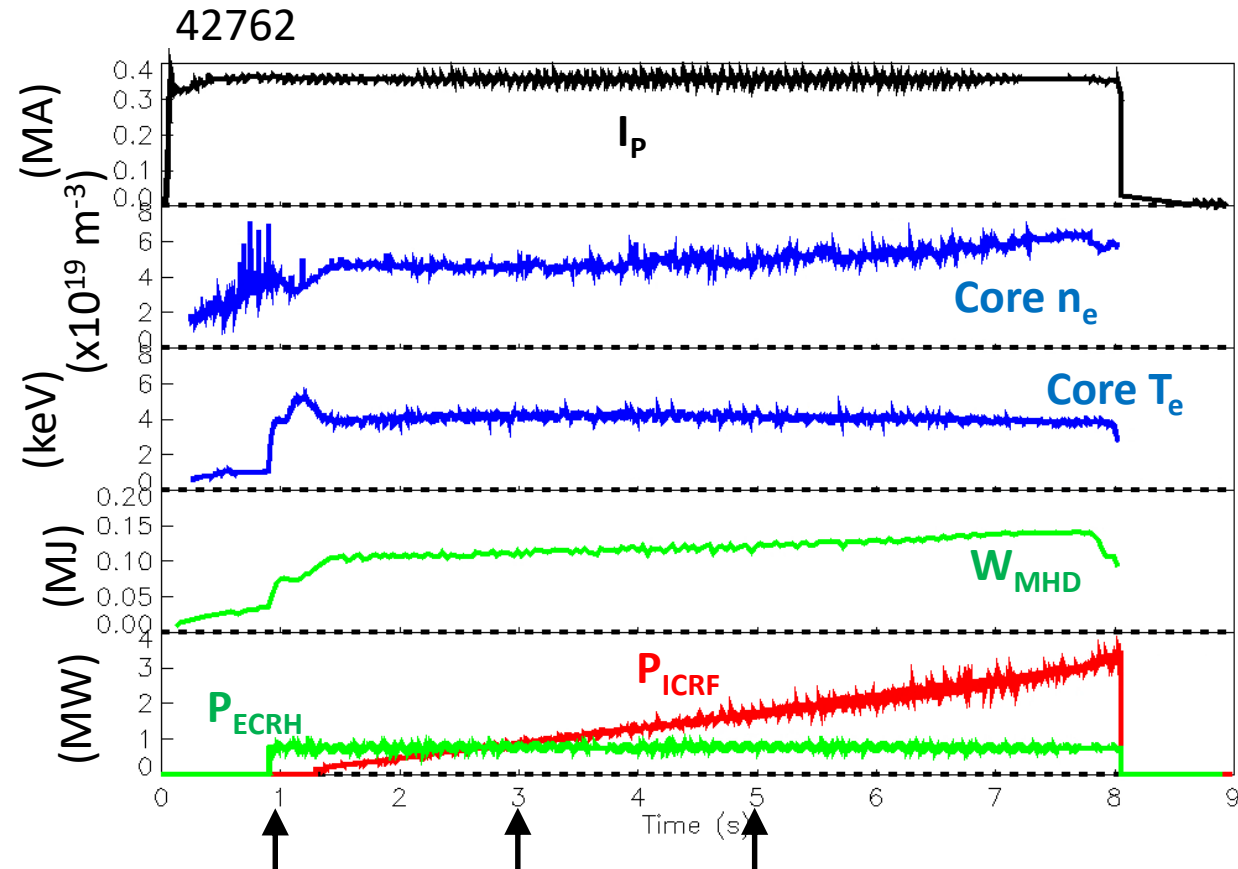
Time = 1.0 s



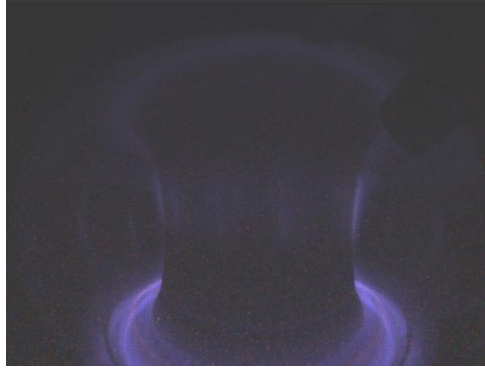
Time = 3.0 s



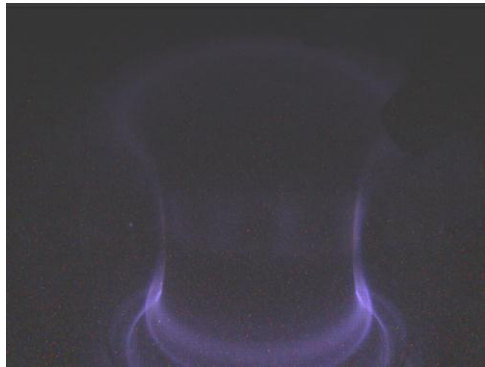
Time = 5.0 s



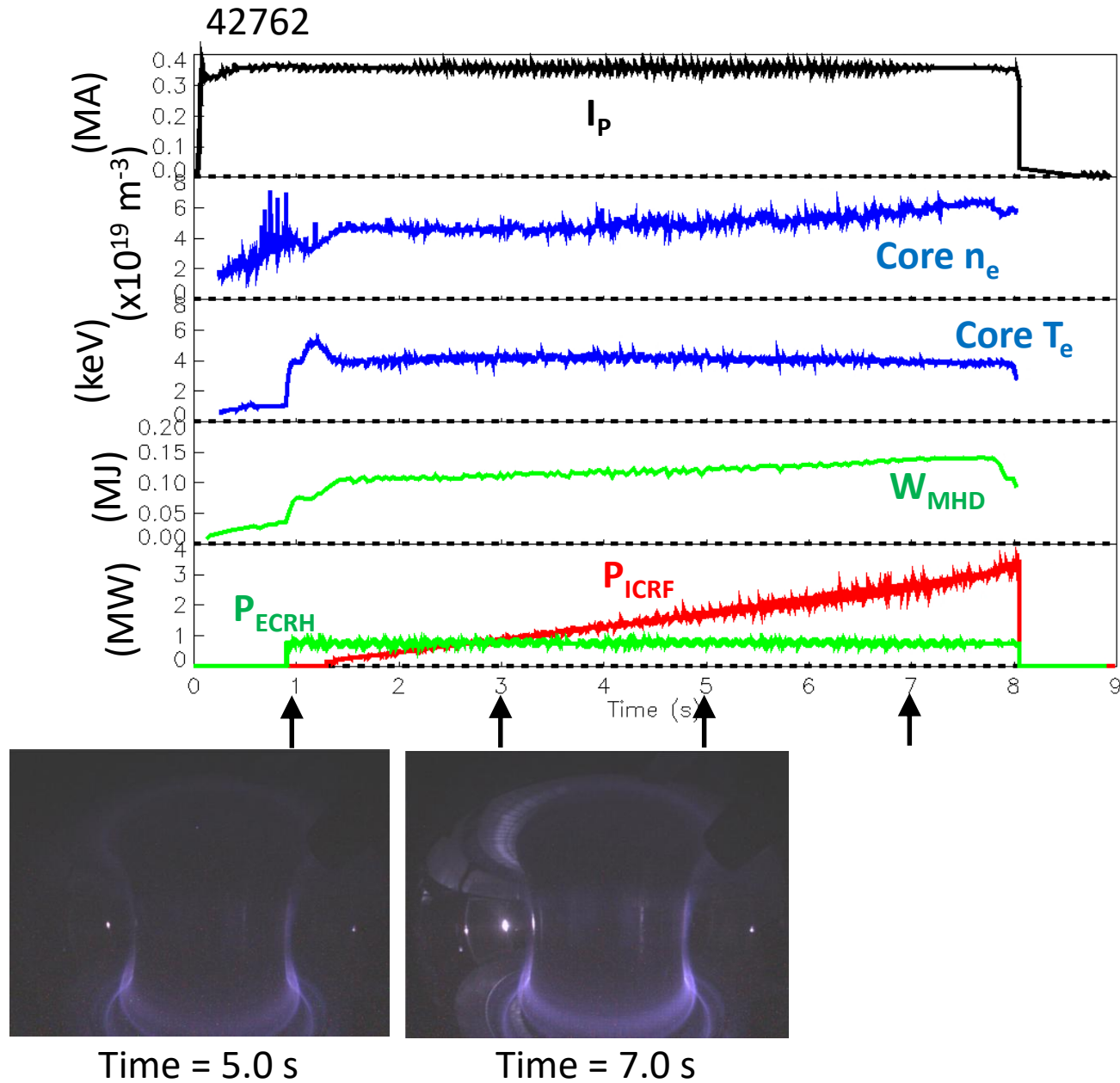
Background: study of high frequency (>1 MHz) modes driven by ICRF-accelerated H^+



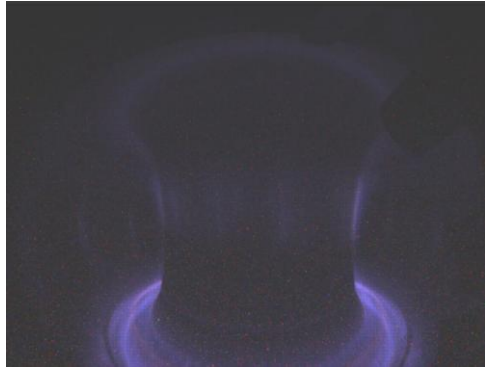
Time = 1.0 s



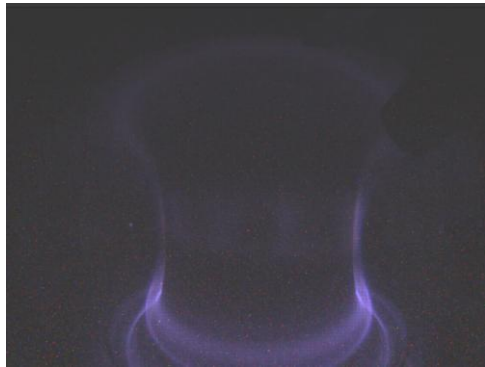
Time = 3.0 s



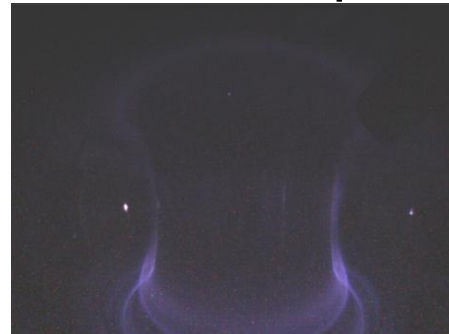
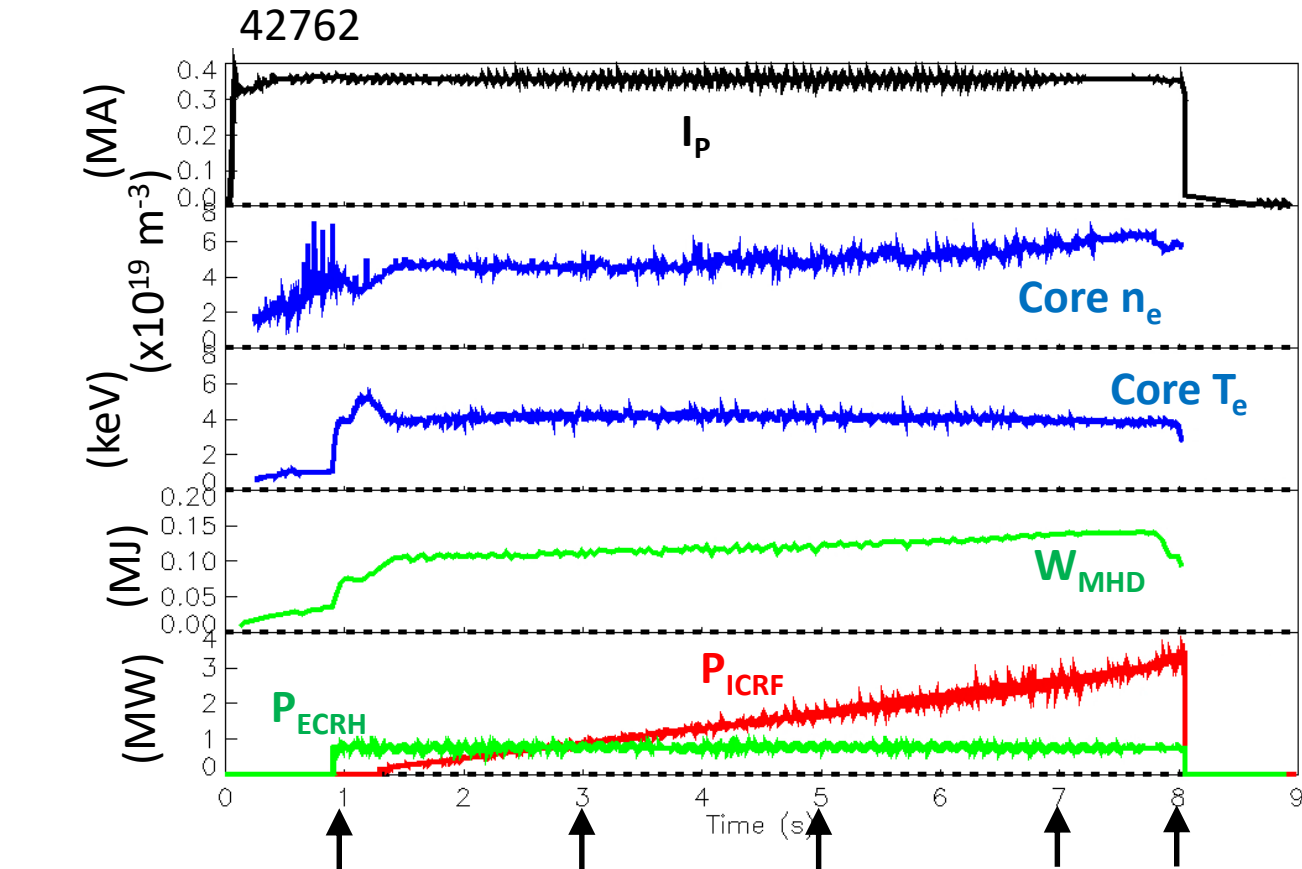
Background: study of high frequency (>1 MHz) modes driven by ICRF-accelerated H^+



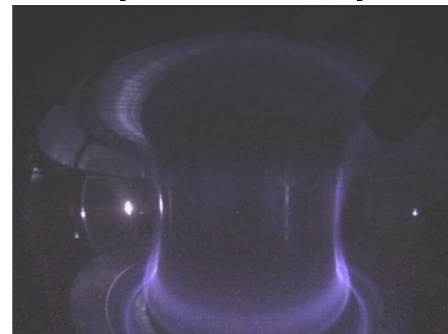
Time = 1.0 s



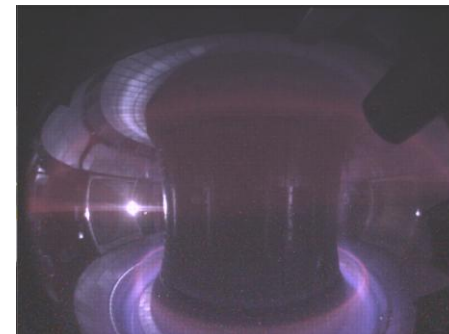
Time = 3.0 s



Time = 5.0 s

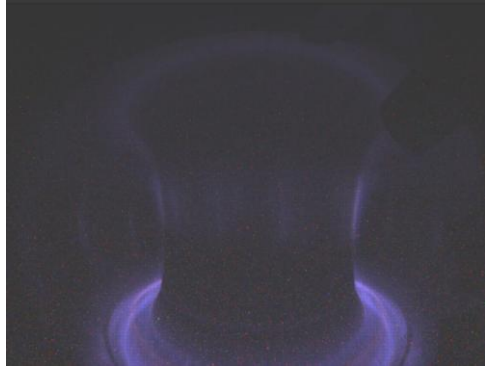


Time = 7.0 s

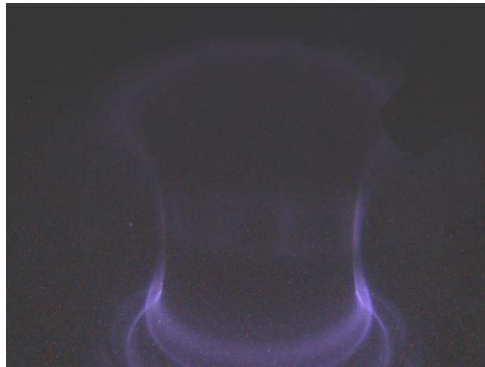


Time = 8.0 s

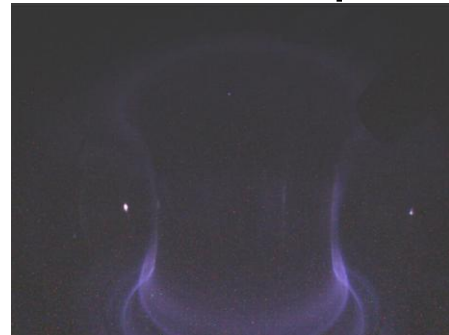
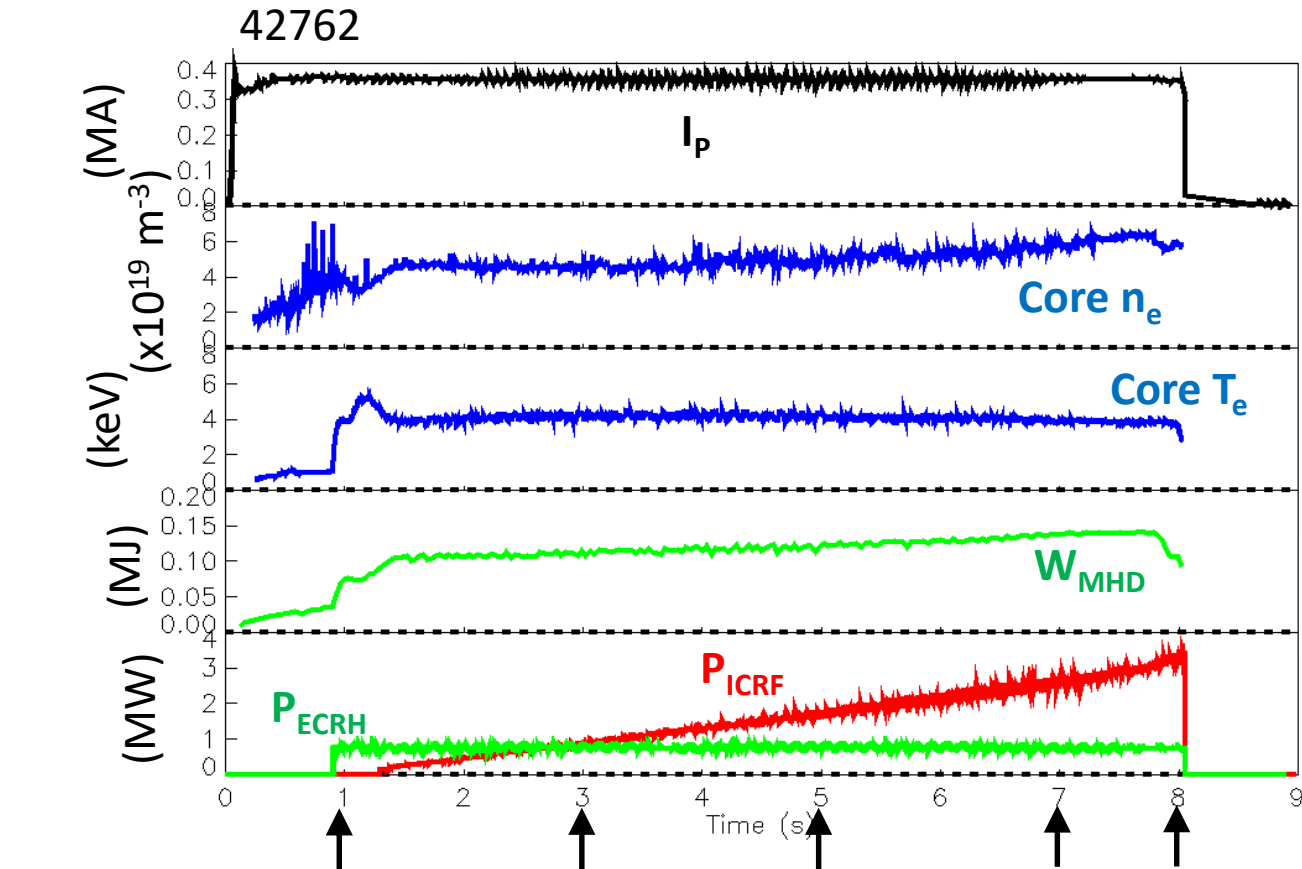
Background: study of high frequency (>1 MHz) modes driven by ICRF-accelerated H^+



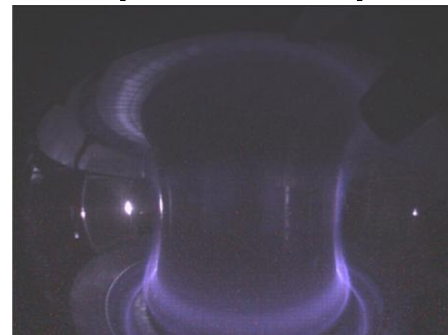
Time = 1.0 s



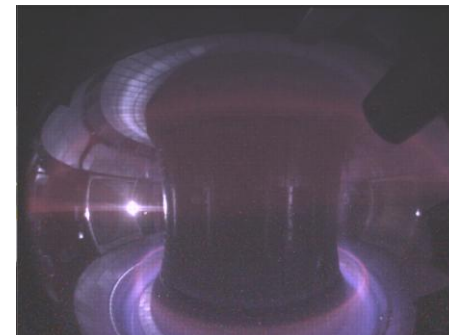
Time = 3.0 s



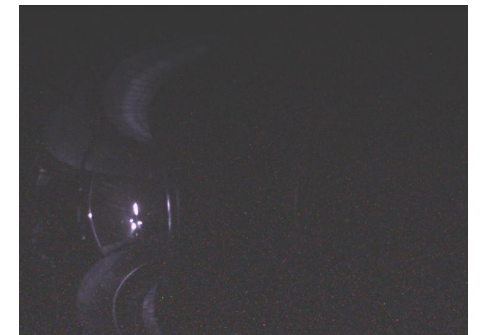
Time = 5.0 s



Time = 7.0 s



Time = 8.0 s



Time = 8.26 s

Background: study of high frequency (>1 MHz) modes driven by ICRF-accelerated H^+

Significant debris in lower divertor prevented subsequent plasma operation

42762



Time = 8.26 s



Time = 8.53 s

Debris removal required unplanned vessel opening

ASCOT modeling of heat loads induced by lost fast ions

ASCOT modeling key features*

Well integrated with ASDEX Upgrade: equilibria, profiles, wall geometry

Charged particle tracking: guiding center (GC) and full orbit (FO) capable.

Code switches from GC to FO when within 1 gyro radius from outer wall.

Code can run pure FO at expense of speed.

Equilibrium can include toroidal field ripple and non-periodic perturbations.

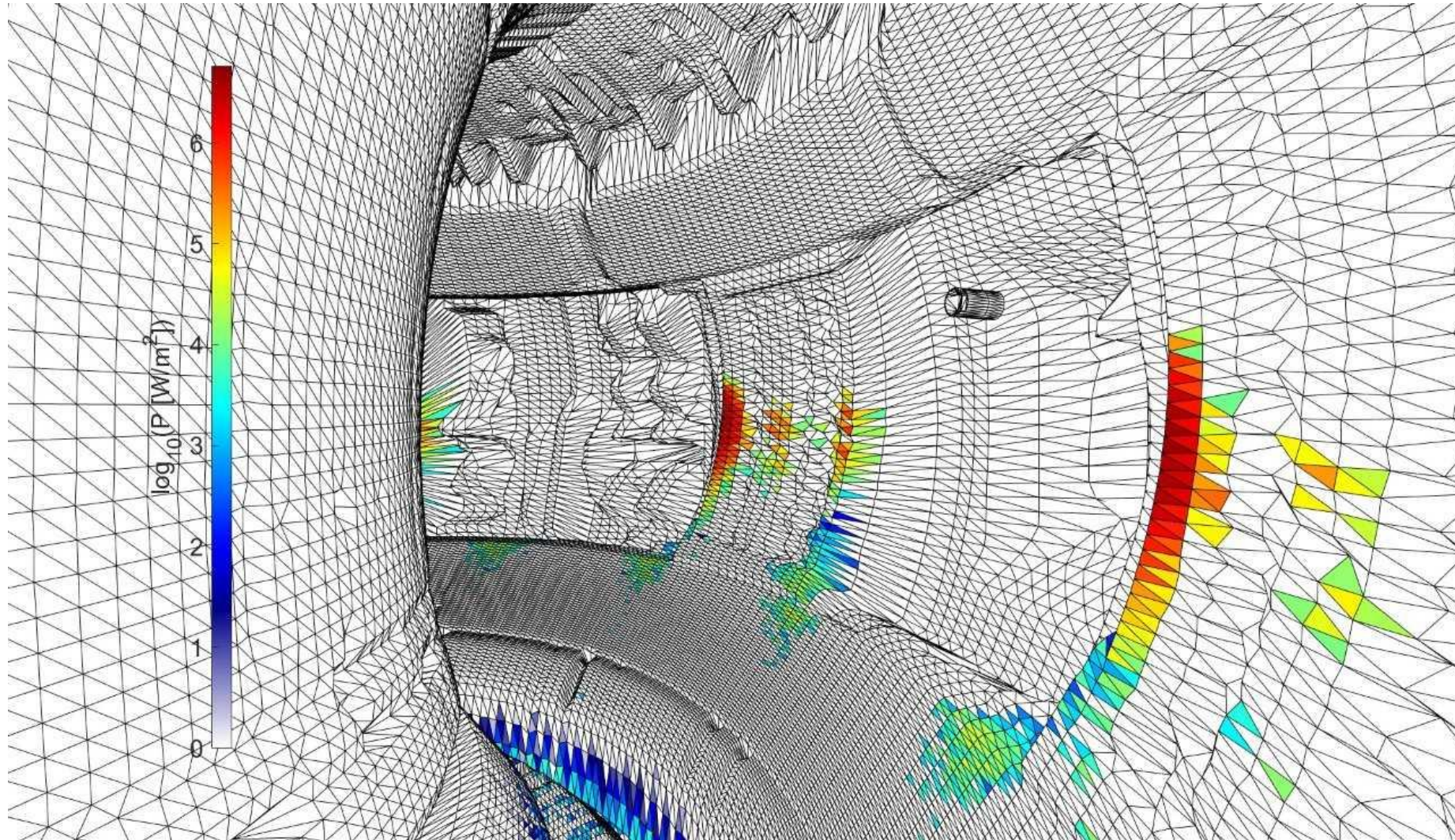
Equilibrium can include plasma MHD perturbations.

Can do ICRF when combined with RFOF module (+TORIC SSFPQL wave E-field input).

Anomalous microturbulence transport effects can be included.

**S. Sipilä et al Nuclear Fusion 61 (2021) 086026*

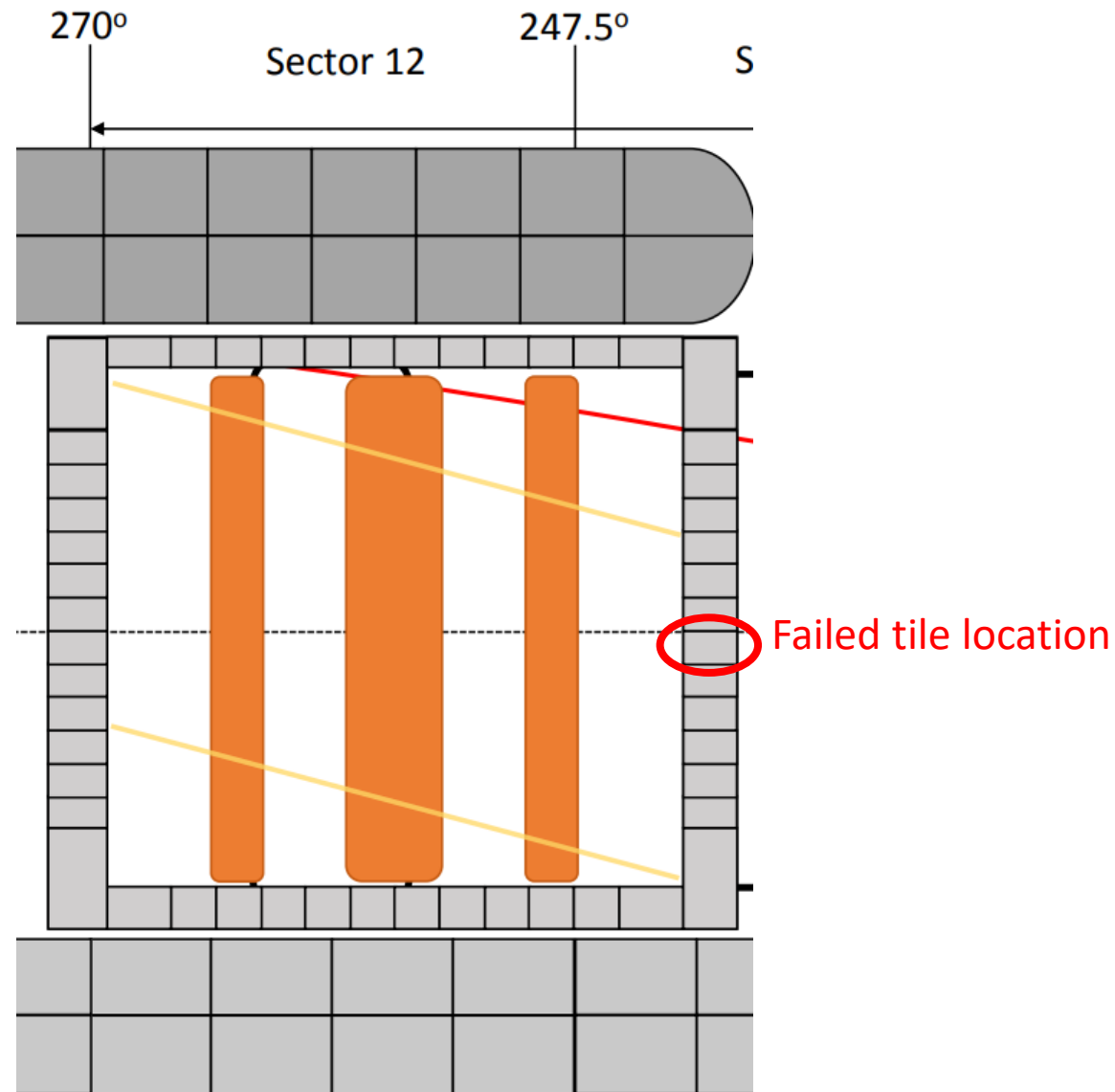
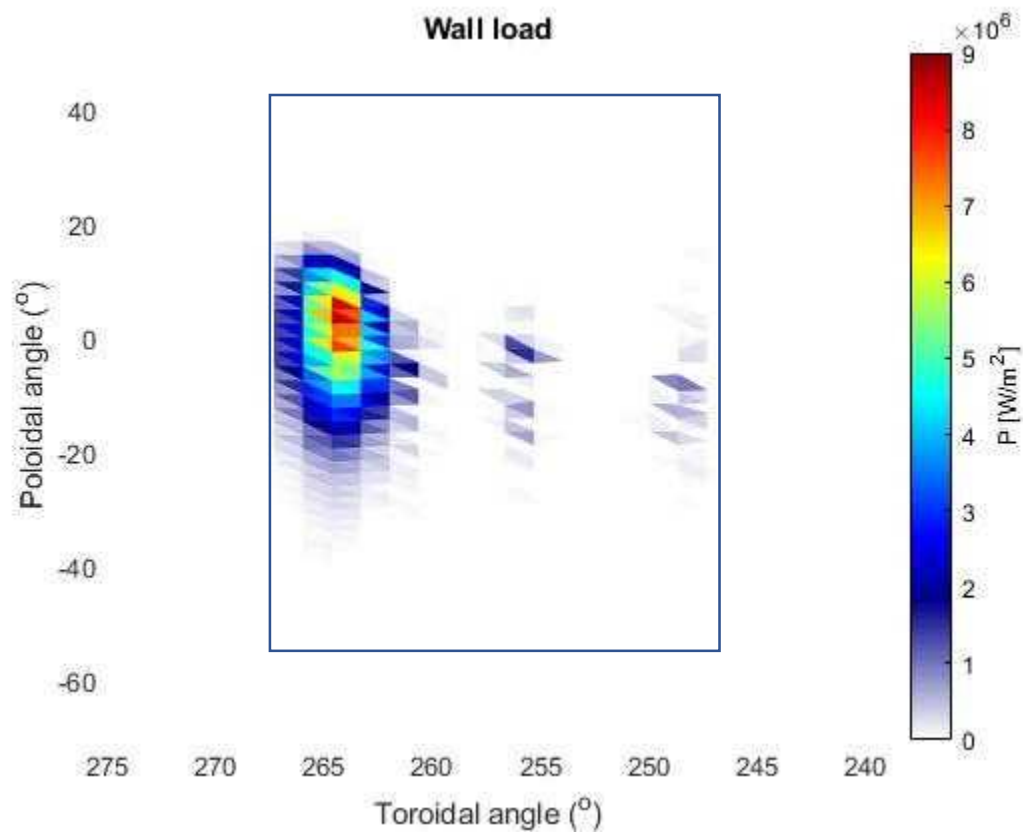
Original ASCOT* wall mesh formed in 2011: coarse with large mesh triangles



*See poster presentation by S. Sipilä at this conference

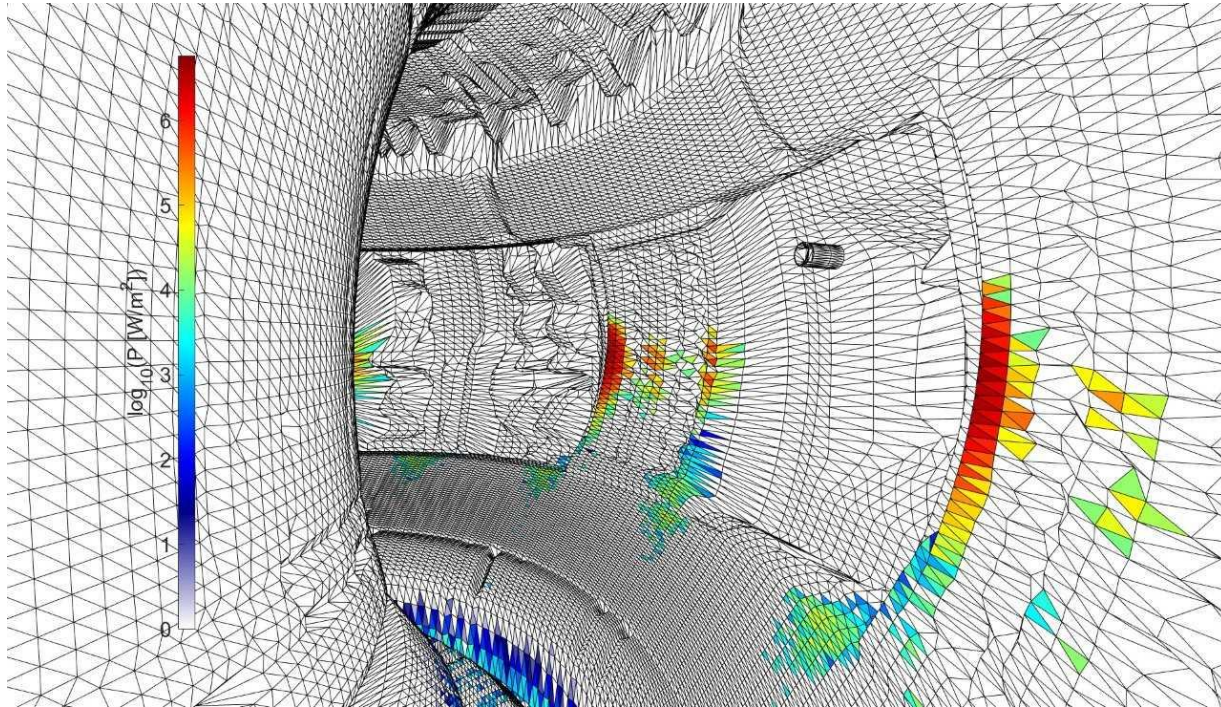
Initial ASCOT results do not match experimental picture

42762, $t = 6.95$ s, Sector 12 Antenna

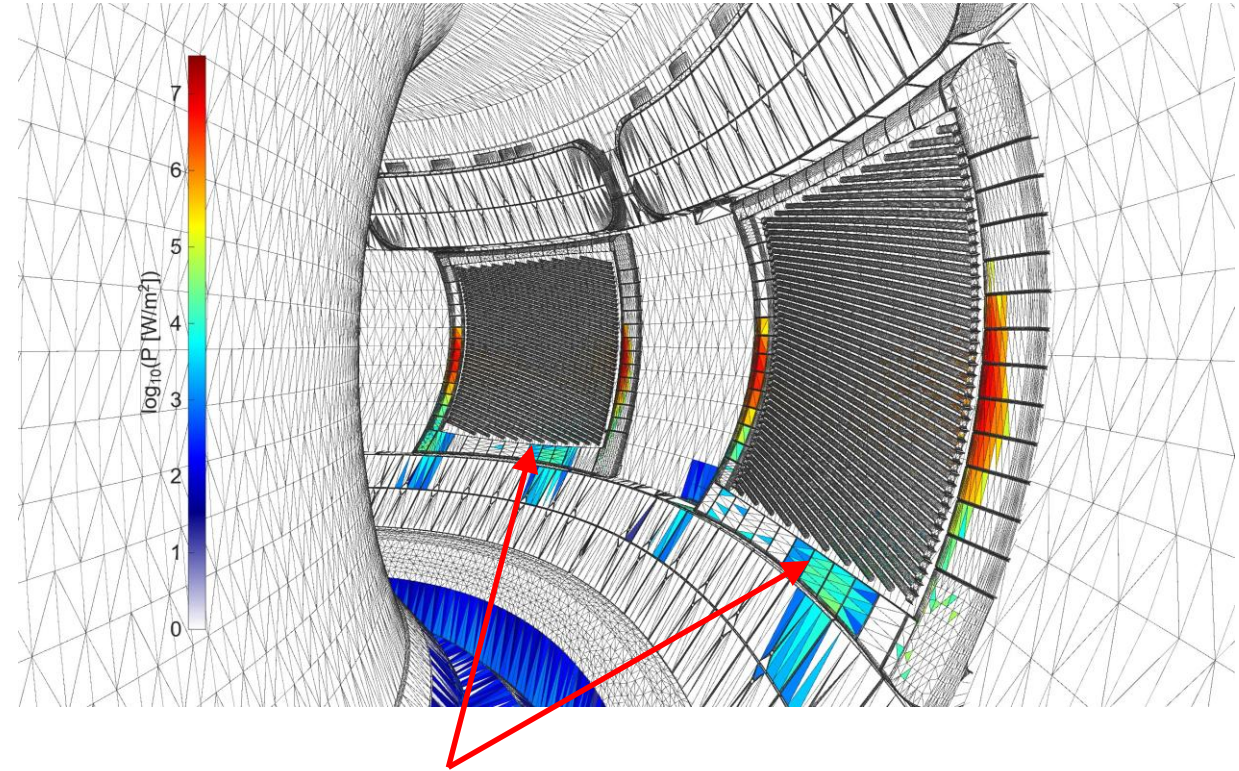


Improved ASCOT mesh in 2026

Original ASCOT mesh from 2011



Improved ASCOT mesh in 2026

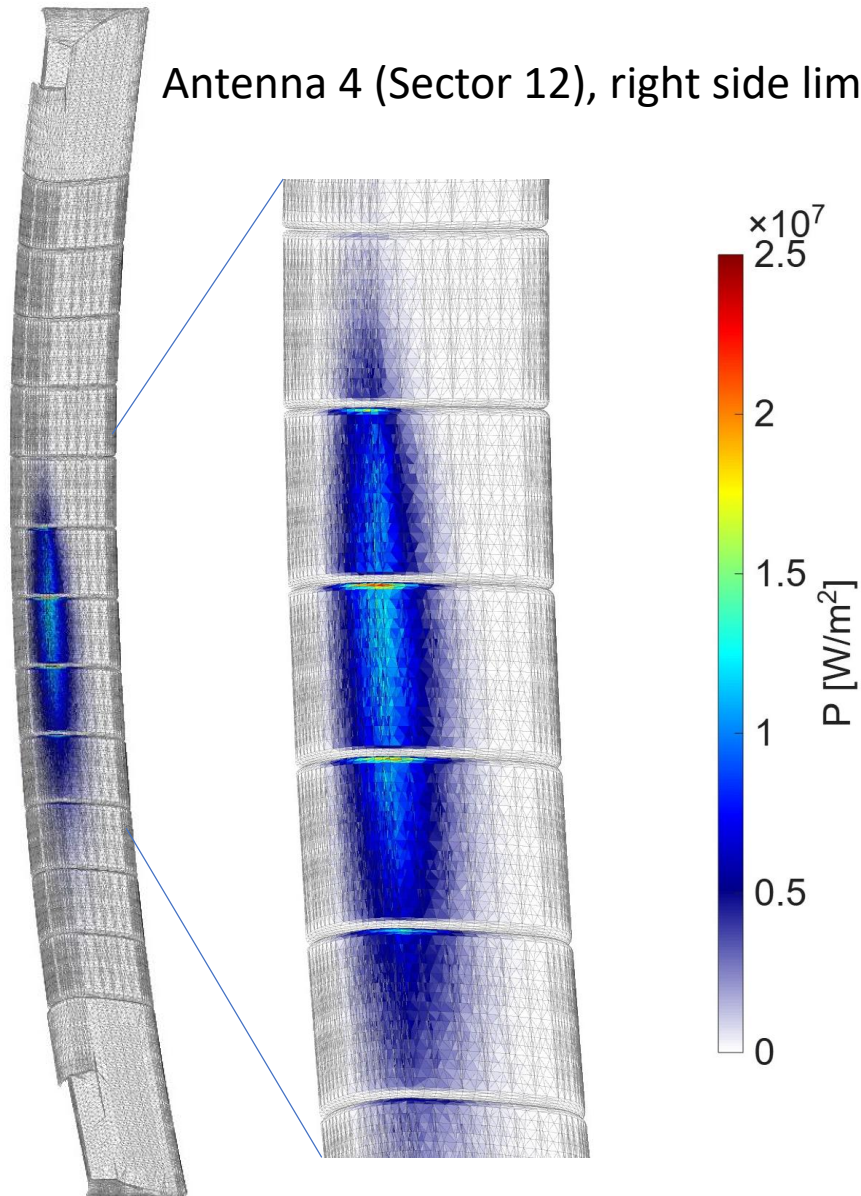


Highly detailed ICRF limiters including Faraday screen

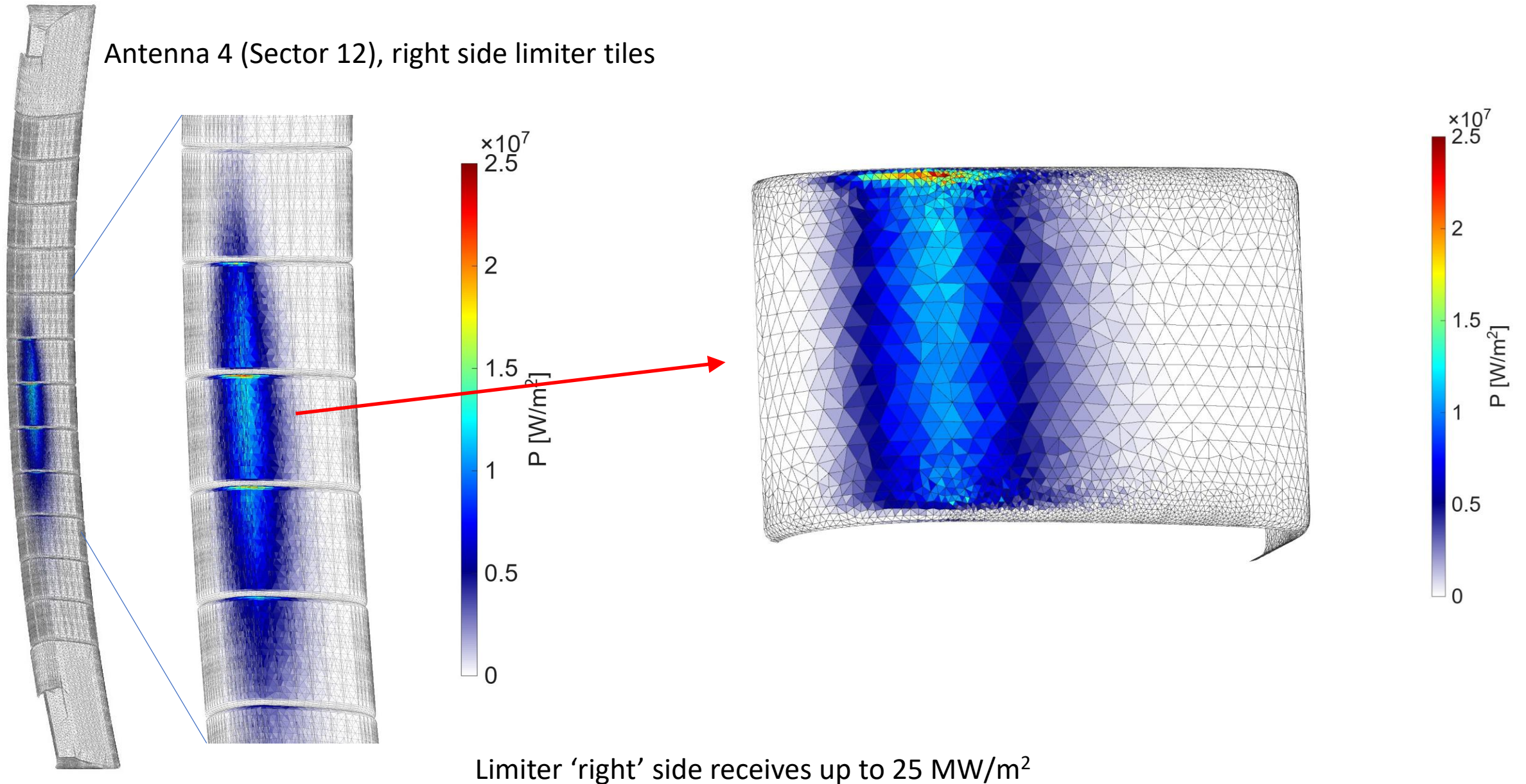
Engineering CAD drawings used for ICRF and passive limiter structures and upper + lower RMP protection tiles

Toroidally symmetric placement, possible misalignment not included

High resolution mesh allows to resolve small scale pattern in limiter heat loads

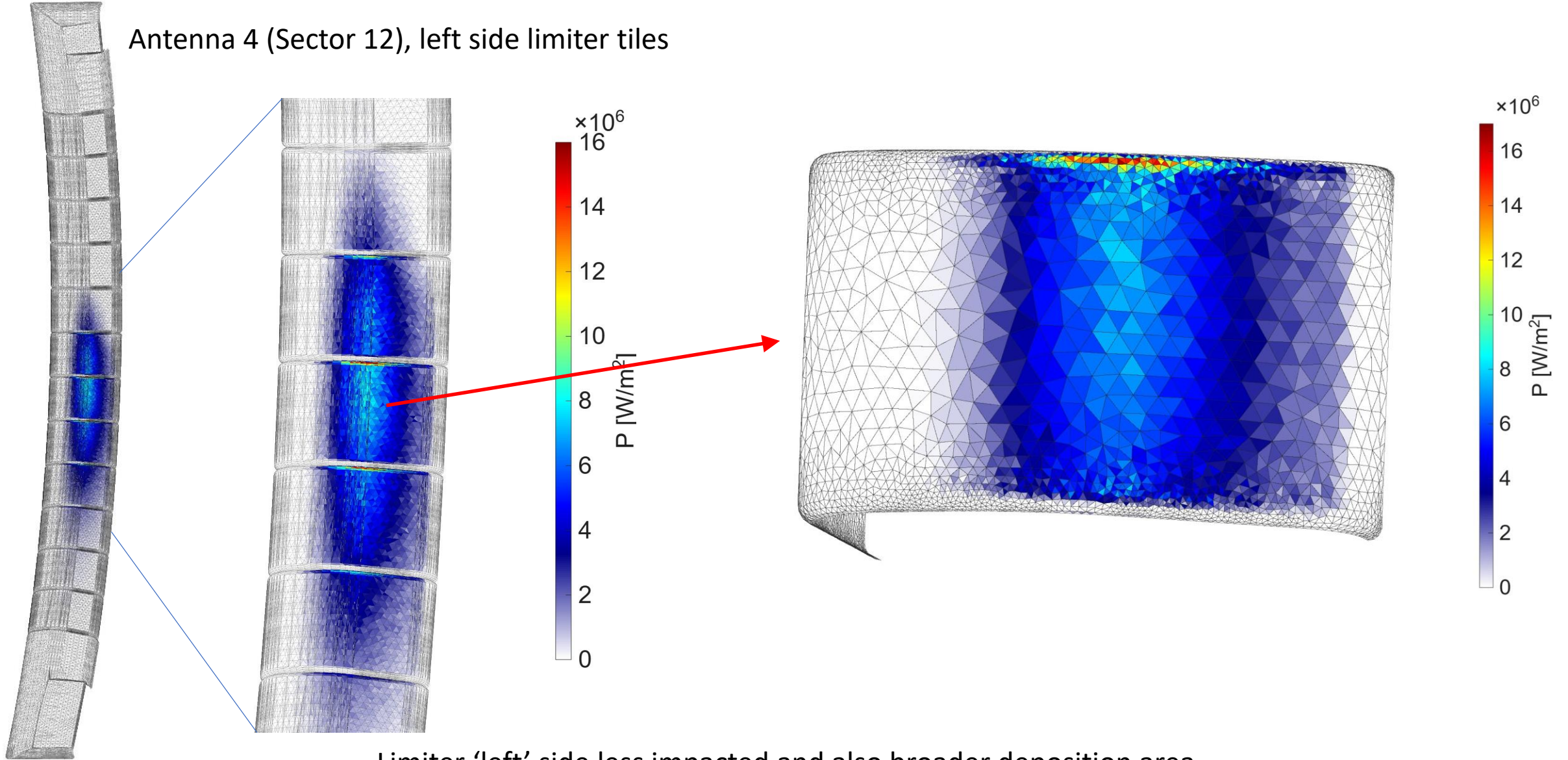


High resolution mesh allows to resolve small scale pattern in limiter heat loads



High resolution mesh allows to resolve small scale pattern in limiter heat loads

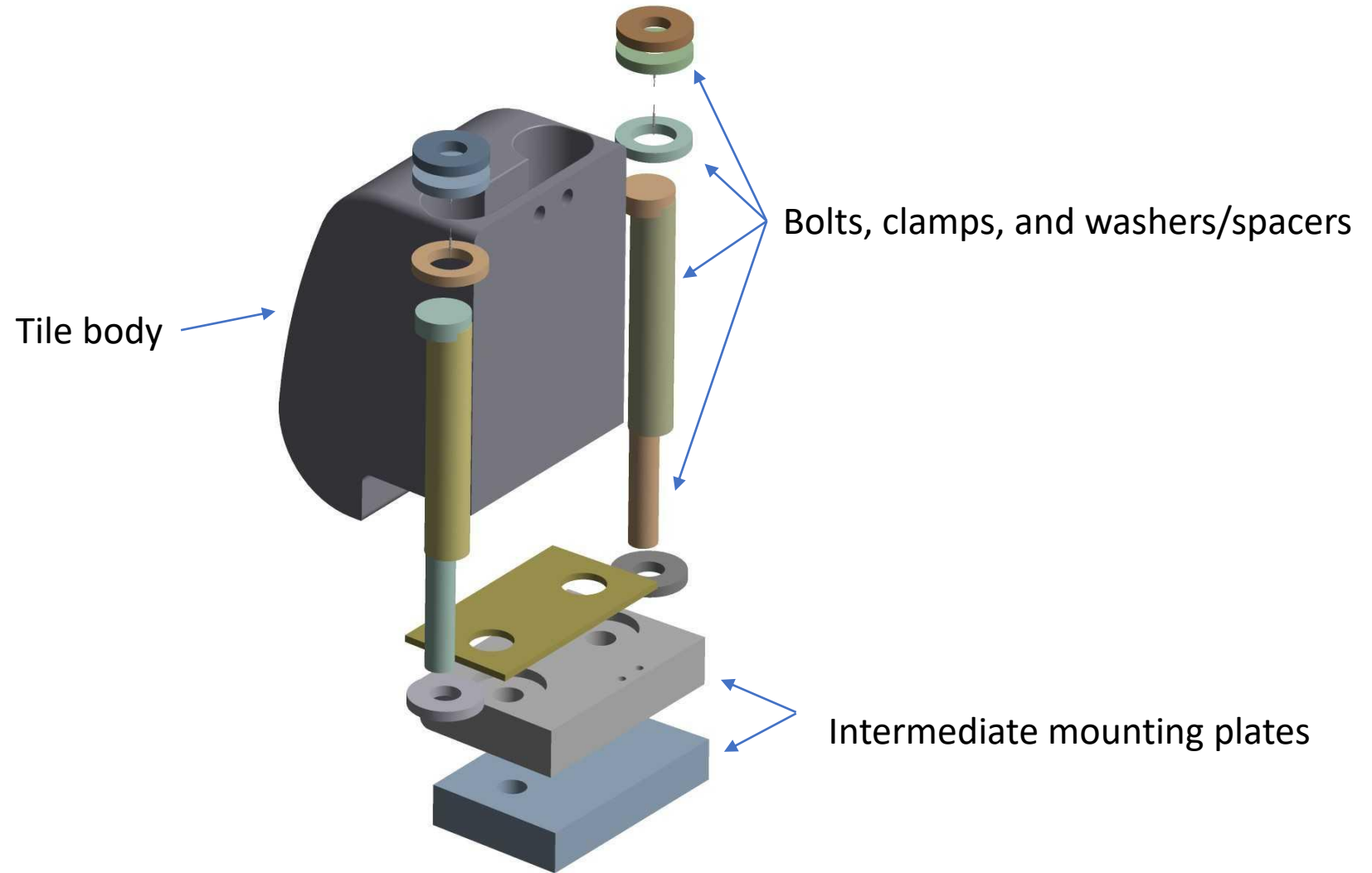
Antenna 4 (Sector 12), left side limiter tiles



Limiter 'left' side less impacted and also broader deposition area

Integration with ANSYS

Detailed tile model with realistic boundaries constructed in ANSYS

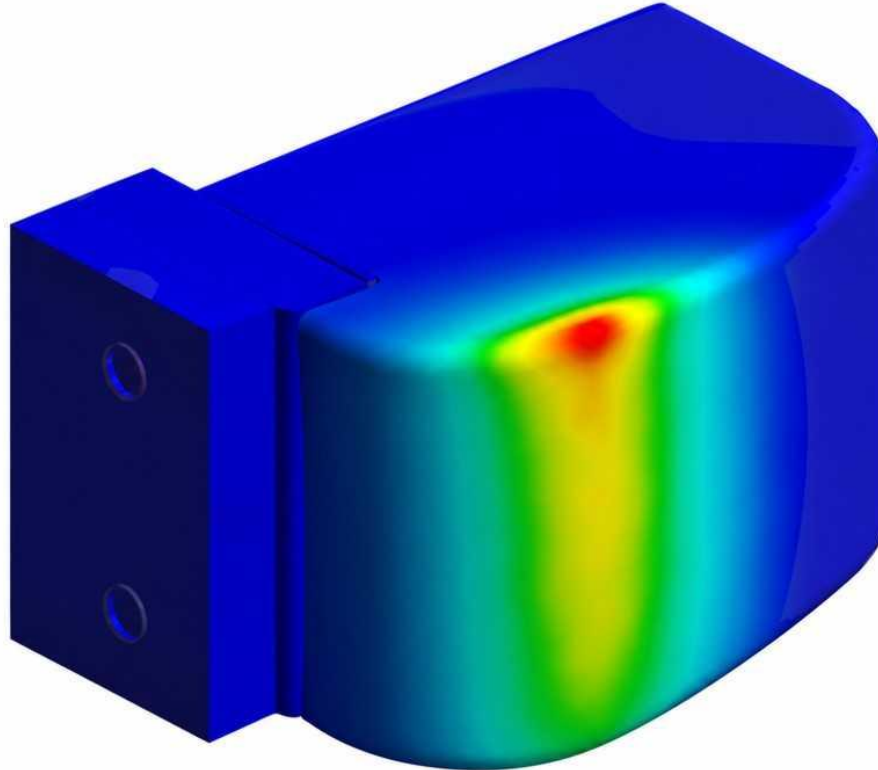
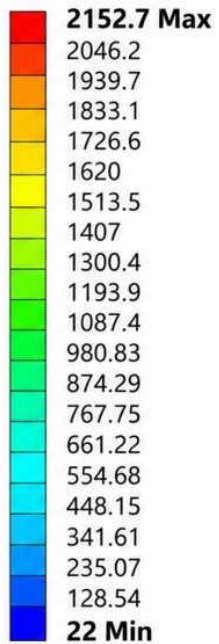


Estimated temperature reaches $>2150\text{ }^{\circ}\text{C}$, comparable to brightly glowing carbon

ANSYS modeled tile temperature response

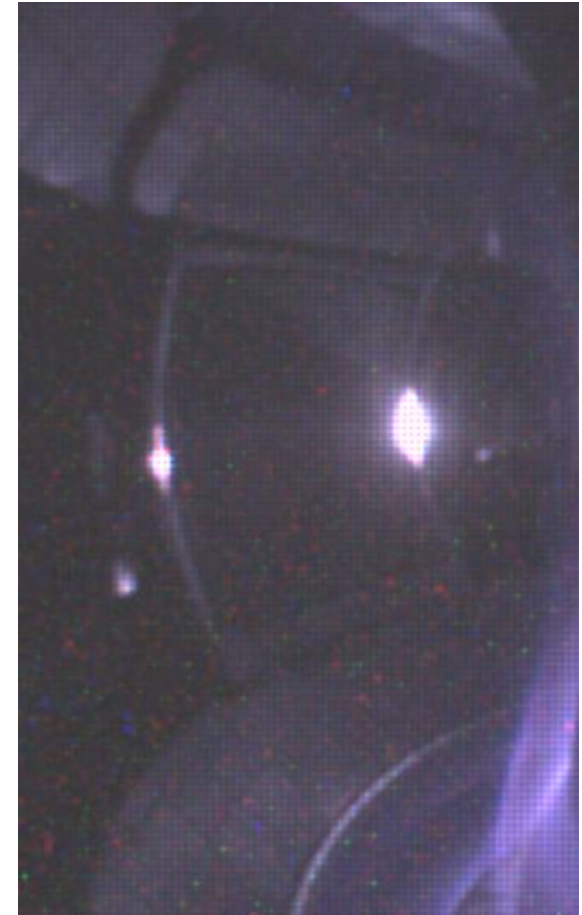
$t = 7.75\text{ s}$

Temperature ($^{\circ}\text{C}$)



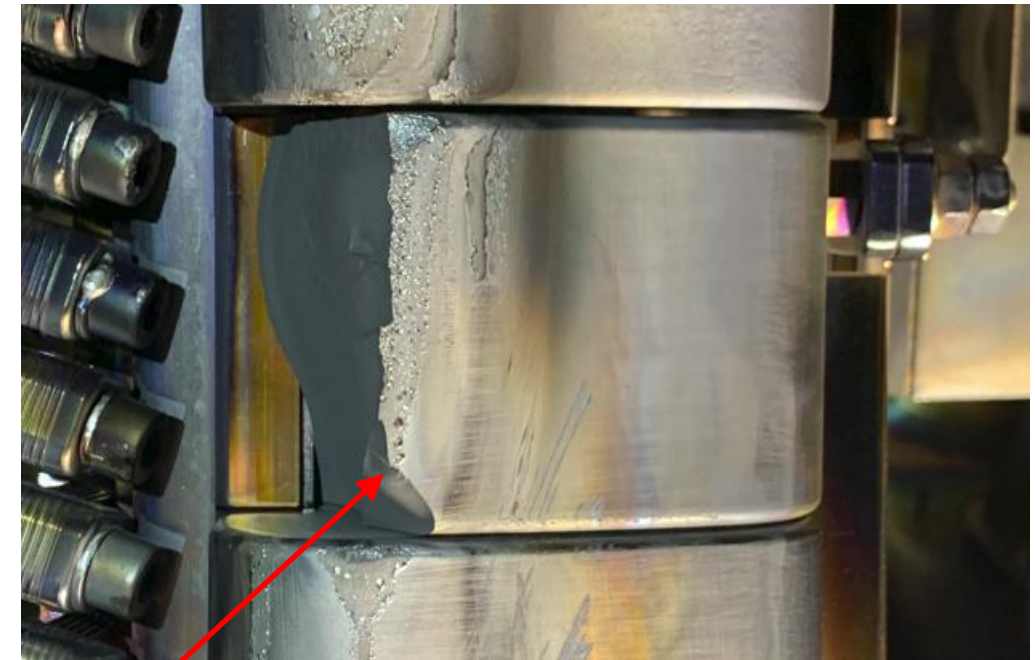
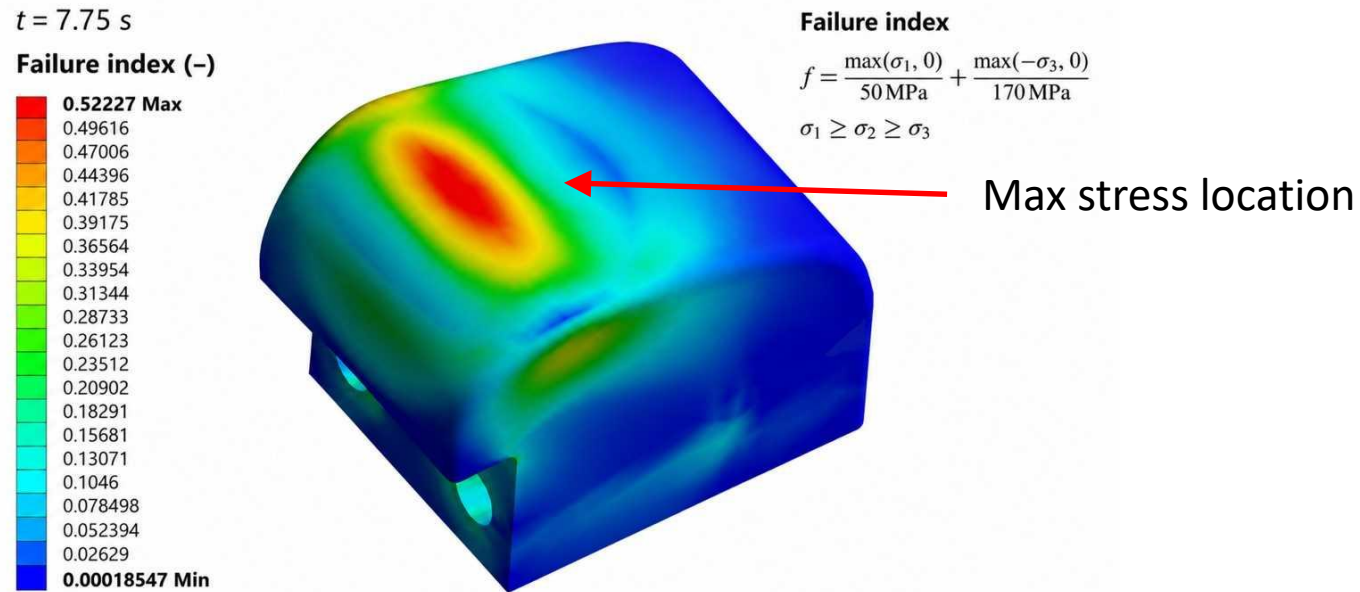
Boundary temperature = $22\text{ }^{\circ}\text{C}$

Visible camera view



Time = 7.0 s

Max stresses remain factor of 1.9 below material failure level but match location

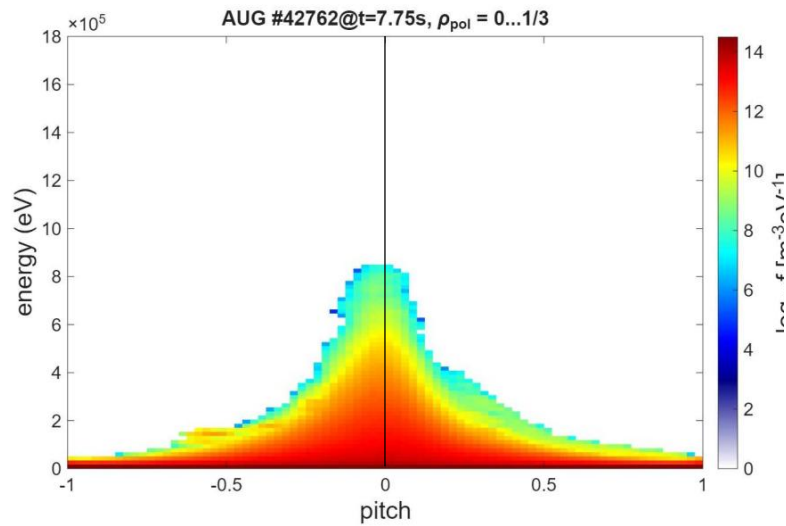


Tile break off location along same edge

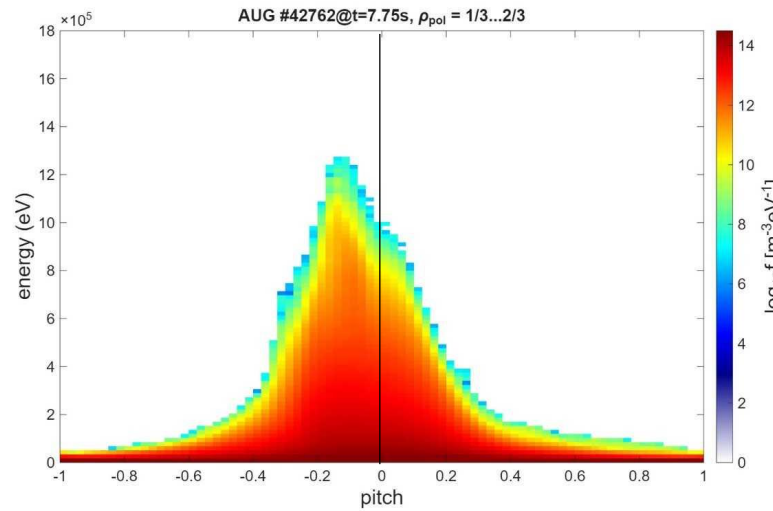
Additional fast ion loss features

Fast H⁺ ions preferentially lost with pitch ~ -0.4

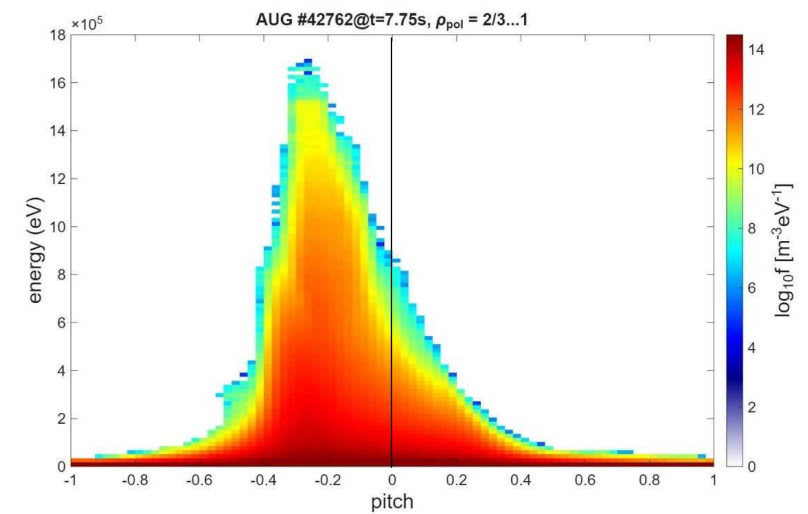
Confined H⁺ inside $0 < \rho_{\text{pol}} < 0.33$



Confined H⁺ inside $0.33 < \rho_{\text{pol}} < 0.67$



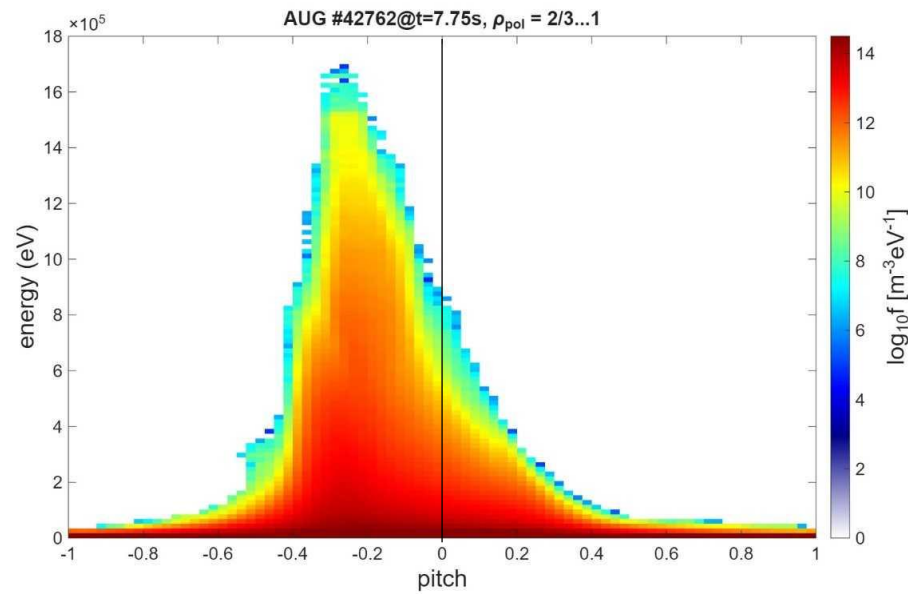
Confined H⁺ inside $0.67 < \rho_{\text{pol}} < 1.0$



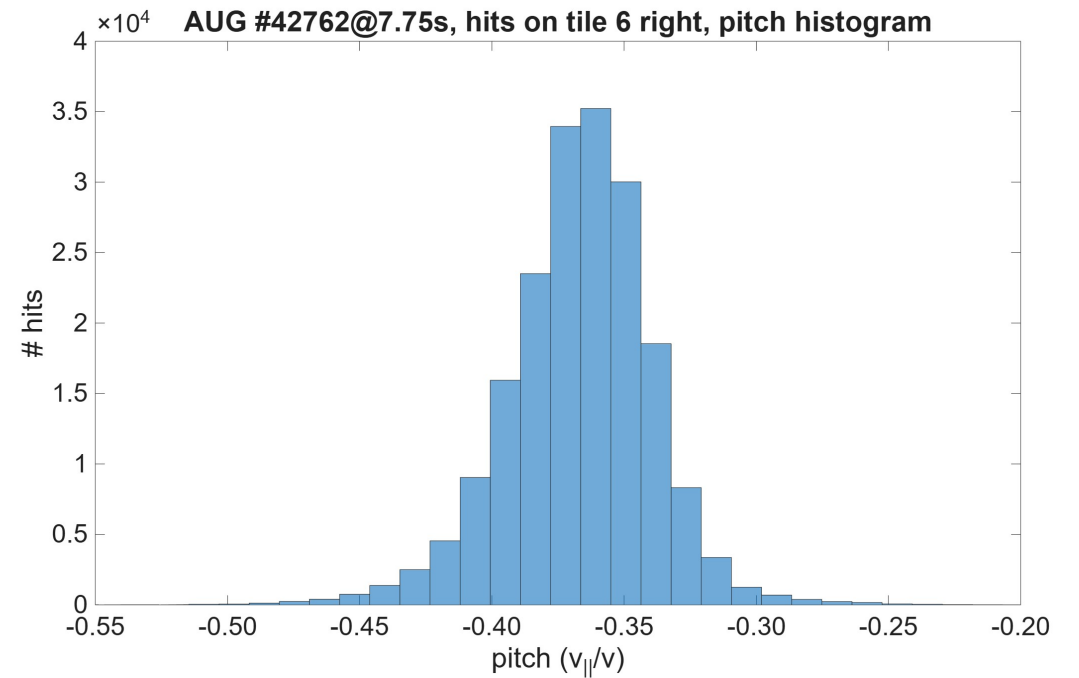
*ASCOT pitch convention ($=+0.4$ pitch for TRANSP convention)

Fast H⁺ ions preferentially lost with pitch ~ -0.4

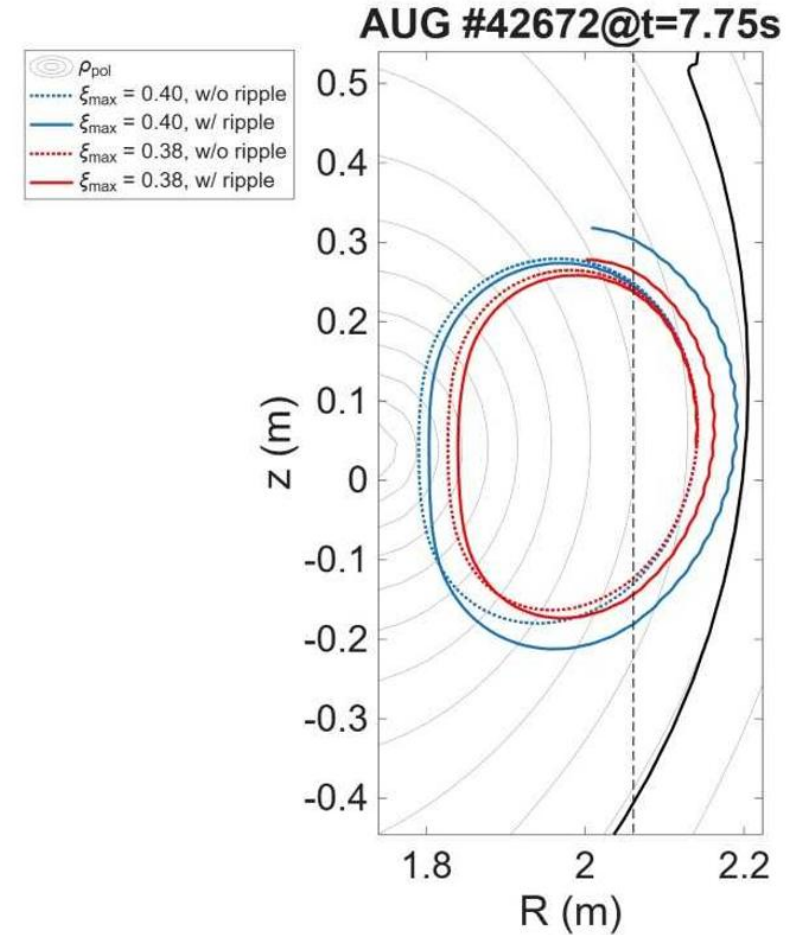
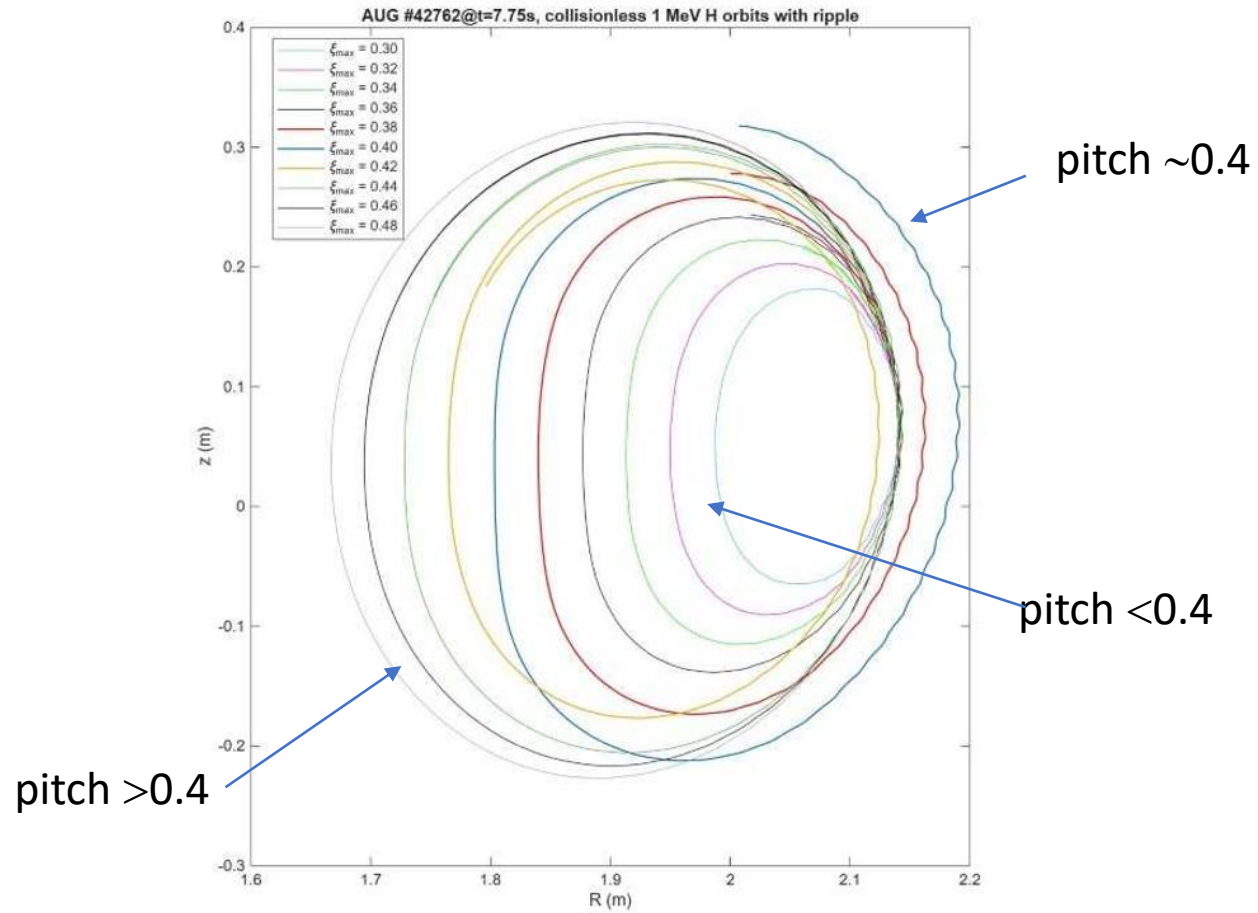
Confined H⁺ inside $0.67 < \rho_{\text{pol}} < 1.0$



Lost H⁺ striking ICRF limiter tile



Passing fast H^+ ions with co- I_p pitch ~ 0.4 more prone to be lost

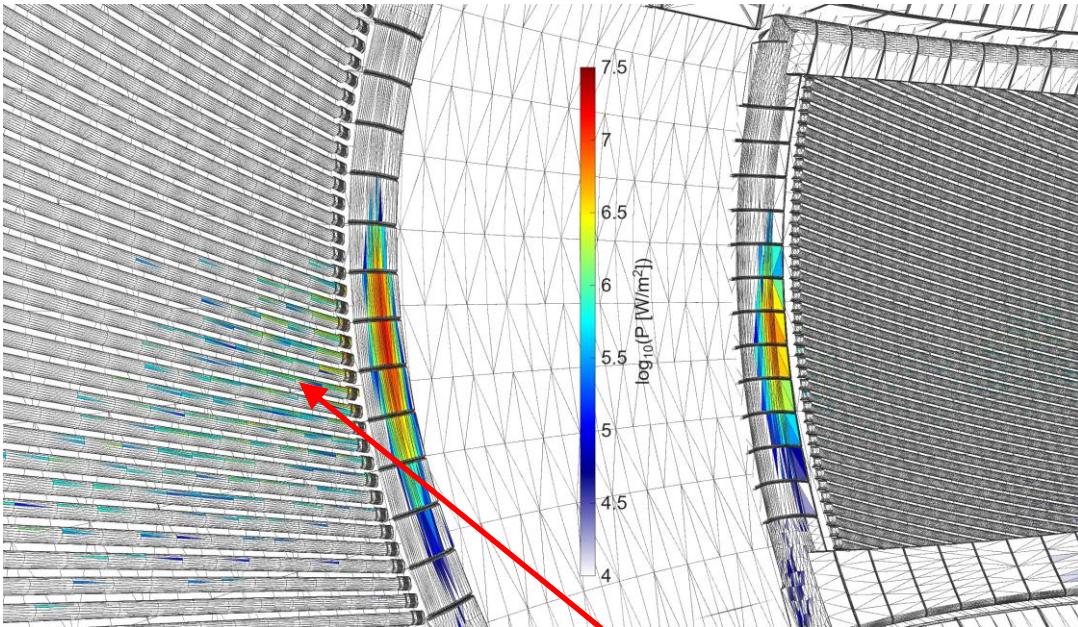


Ripple increases losses without changing overall picture

With B_t ripple included

Antenna 4 (Sector 12)

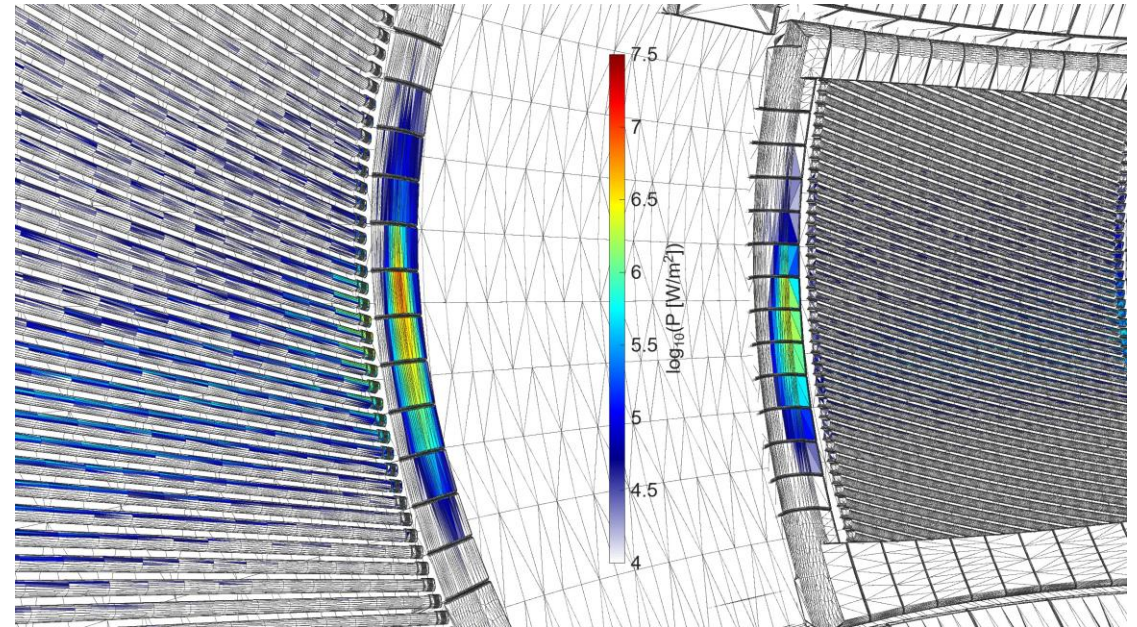
Antenna 3 (Sector 10)



Without B_t ripple

Antenna 4 (Sector 12)

Antenna 3 (Sector 10)



Faraday screen also impacted by fast ion losses

Summary and conclusion

ICRF limiter protection tile on AUG experienced macroscopic failure in plasma with significant FI contents

ASCOT suitable to examine FI induced heat loads to outer wall

Improved AUG ASCOT wall model allows to estimate heat load profiles with ~ 1 mm scale:

- Values up to 25 MW/m^2 observed

- 'Right' side limiter receives higher heat loads compared to 'left' side

- Impacted areas consistent with glowing limiter sections

Integration of ASCOT output with ANSYS allows to model thermo-mechanical stresses

- Carbon limiter tile predicted to reach $>2150^\circ\text{C}$ under estimated heat load

- Temperature consisted with brightly glowing carbon from camera views

- Maximum stresses on tile remain within factor of 1.9 safety

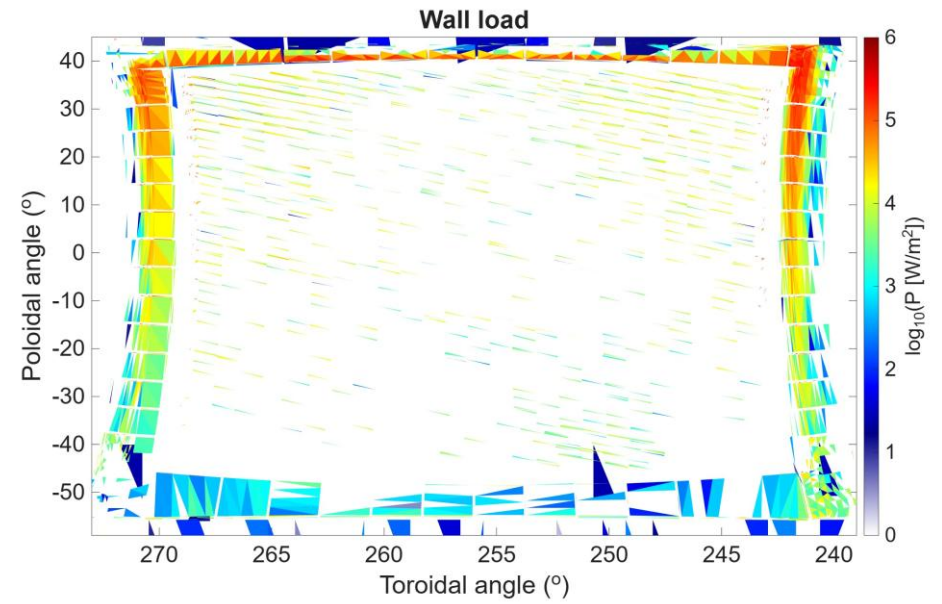
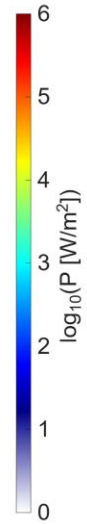
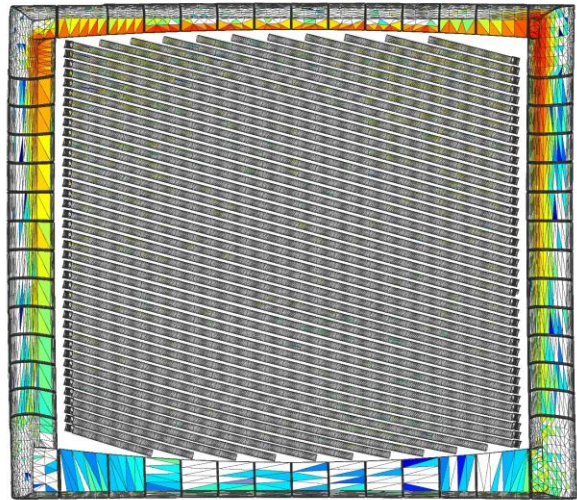
Fast ion losses enhanced by presence of toroidal field ripple

Work motivates to optimize outer wall shape and structure to mitigate heat loads from lost fast ions

Additional slides

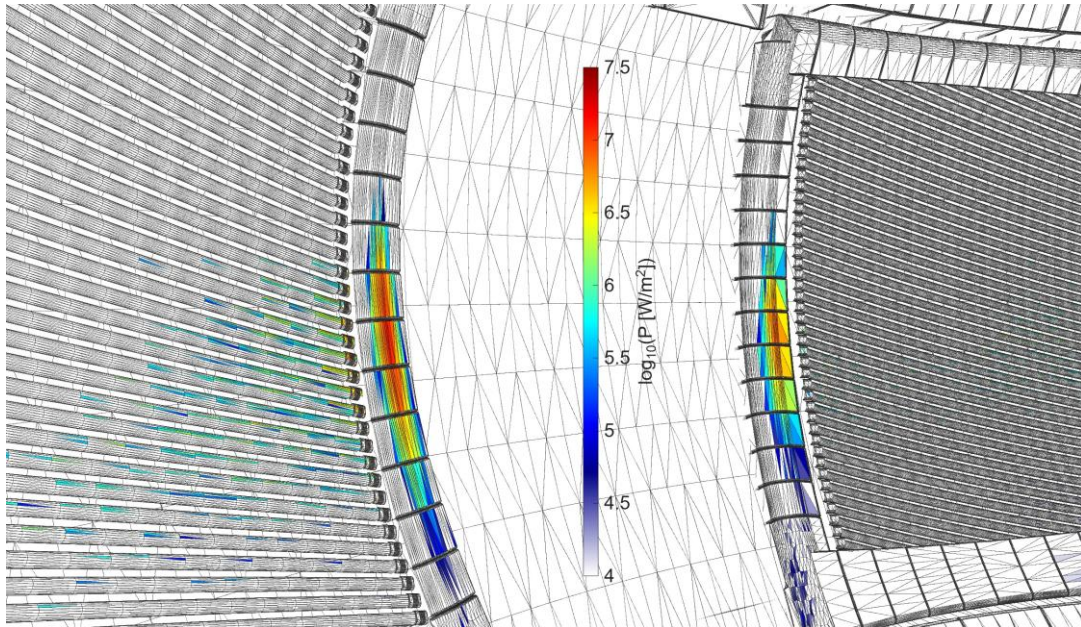
NBI only heat loads in std. H-mode

41161

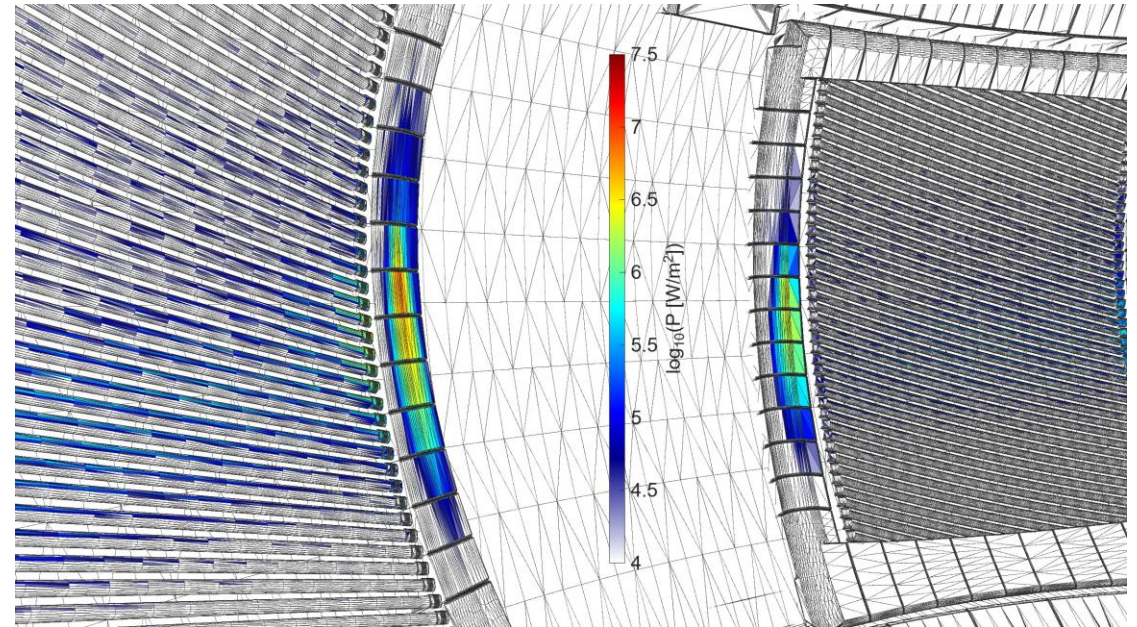


With and Without the Bt ripple results

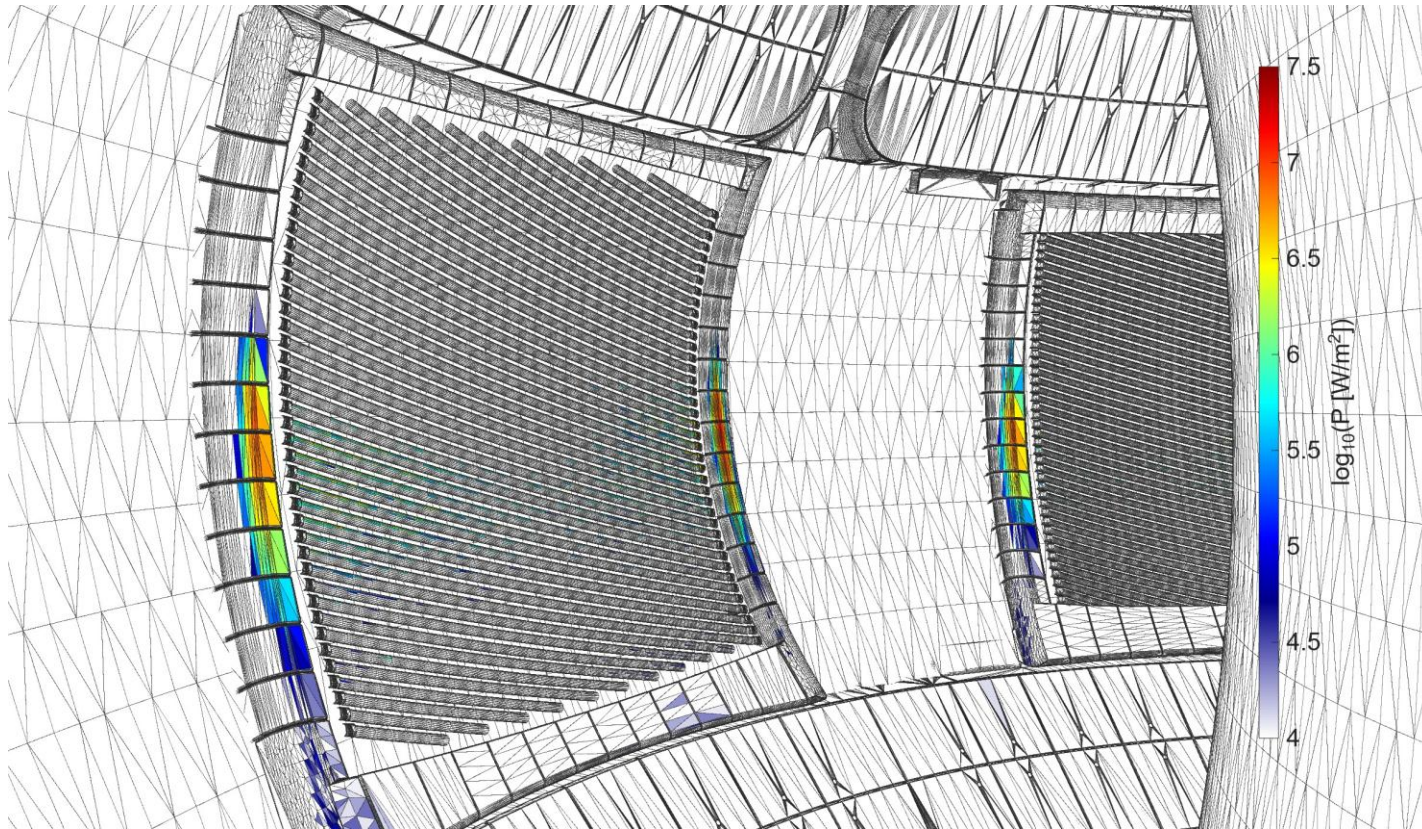
With Bt ripple included



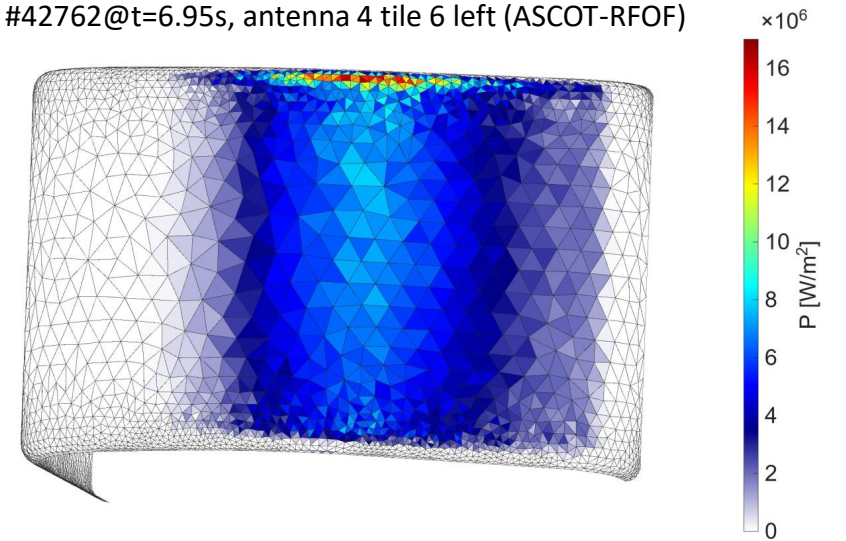
Without Bt ripple



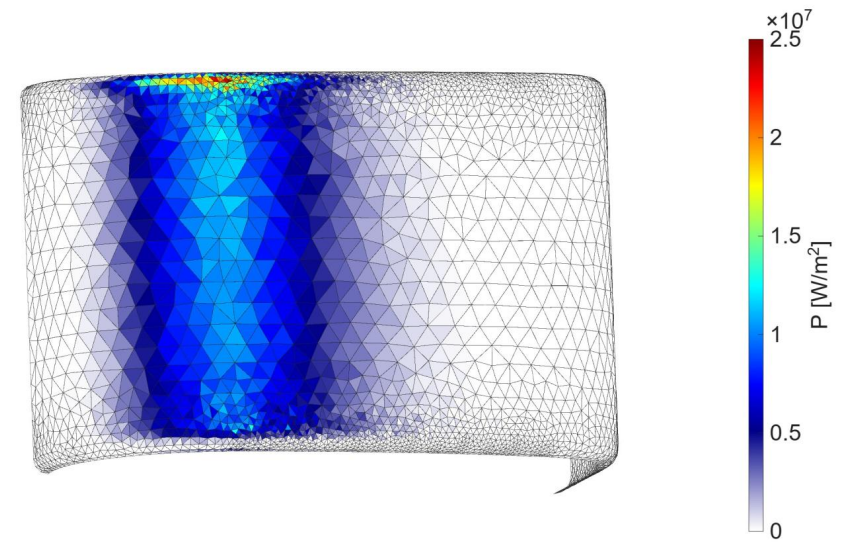
High res result, 42762, t = 7.75 s



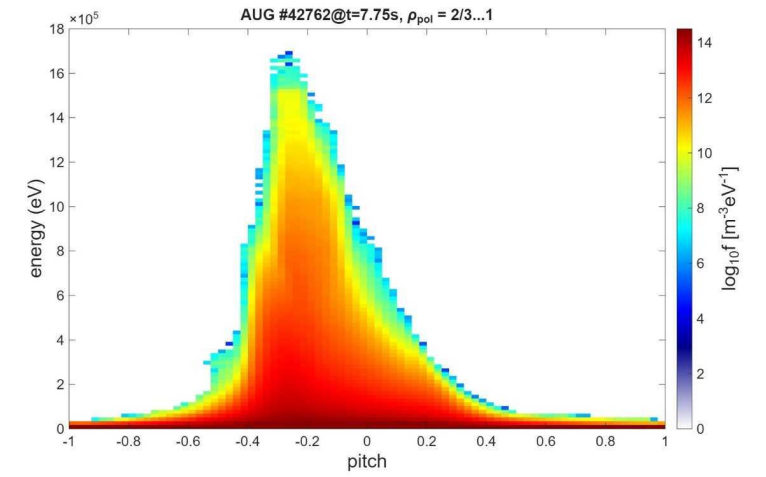
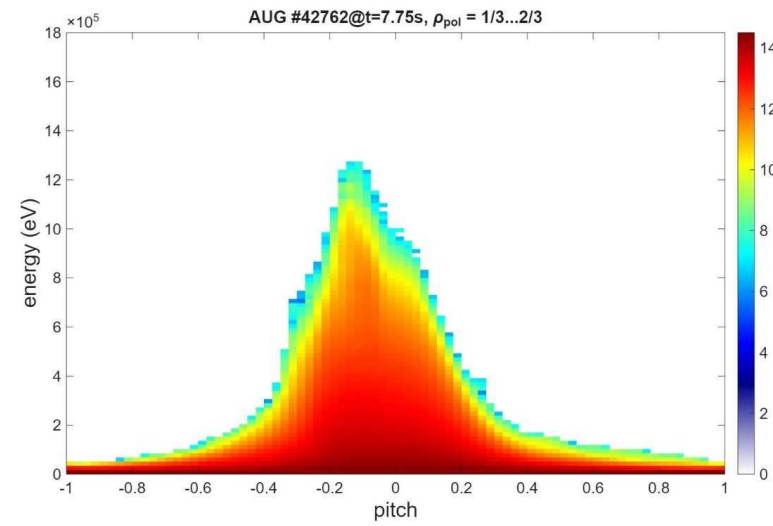
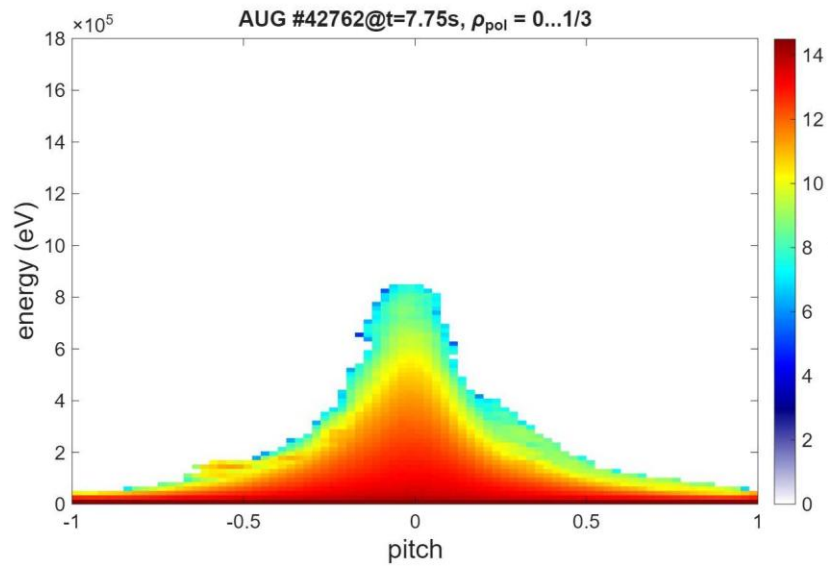
AUG #42762@t=6.95s, antenna 4 tile 6 left (ASCOT-RFOF)



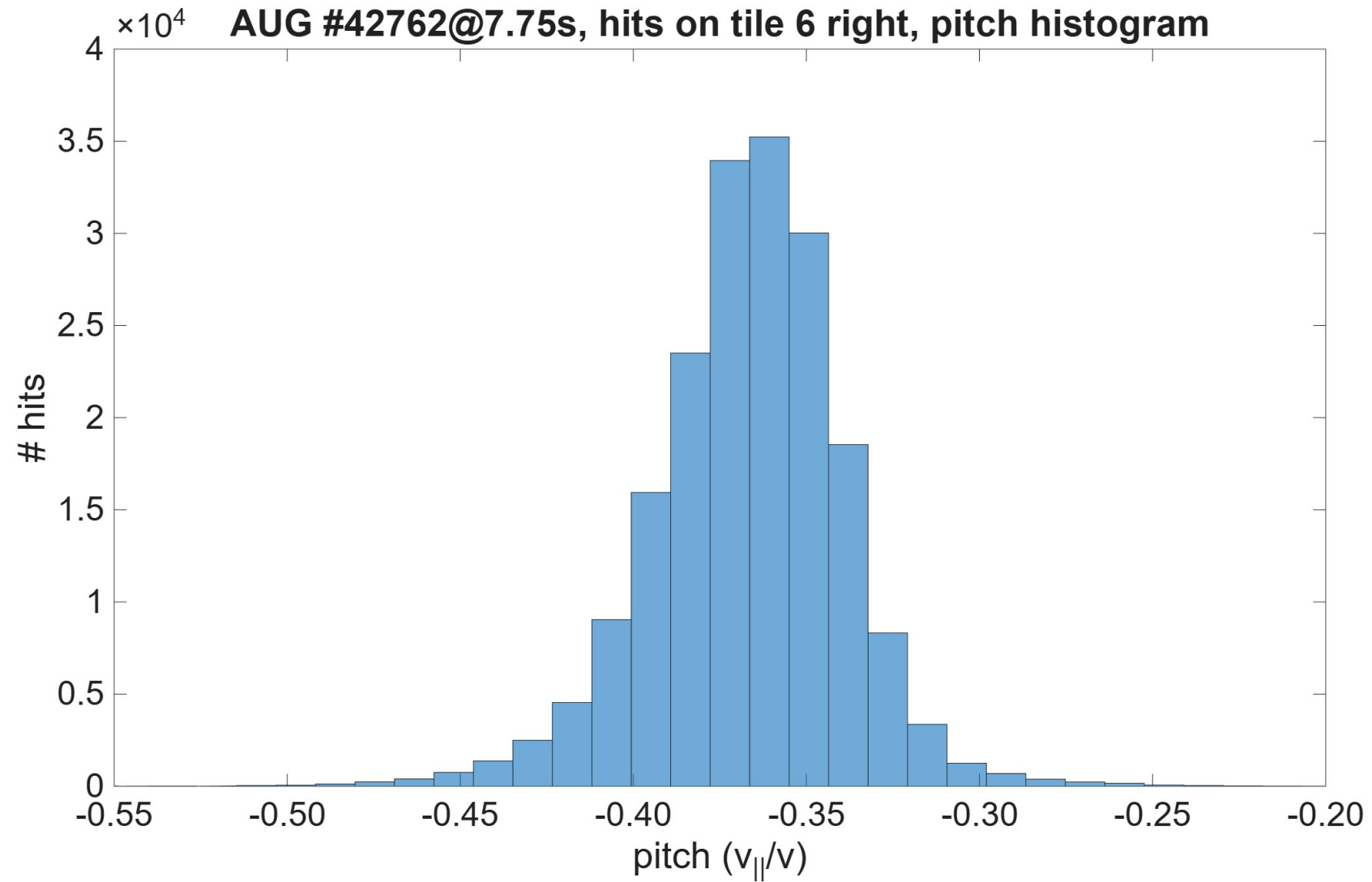
AUG #42762@t=6.95s, antenna 4 tile 6 right (ASCOT-RFOF)



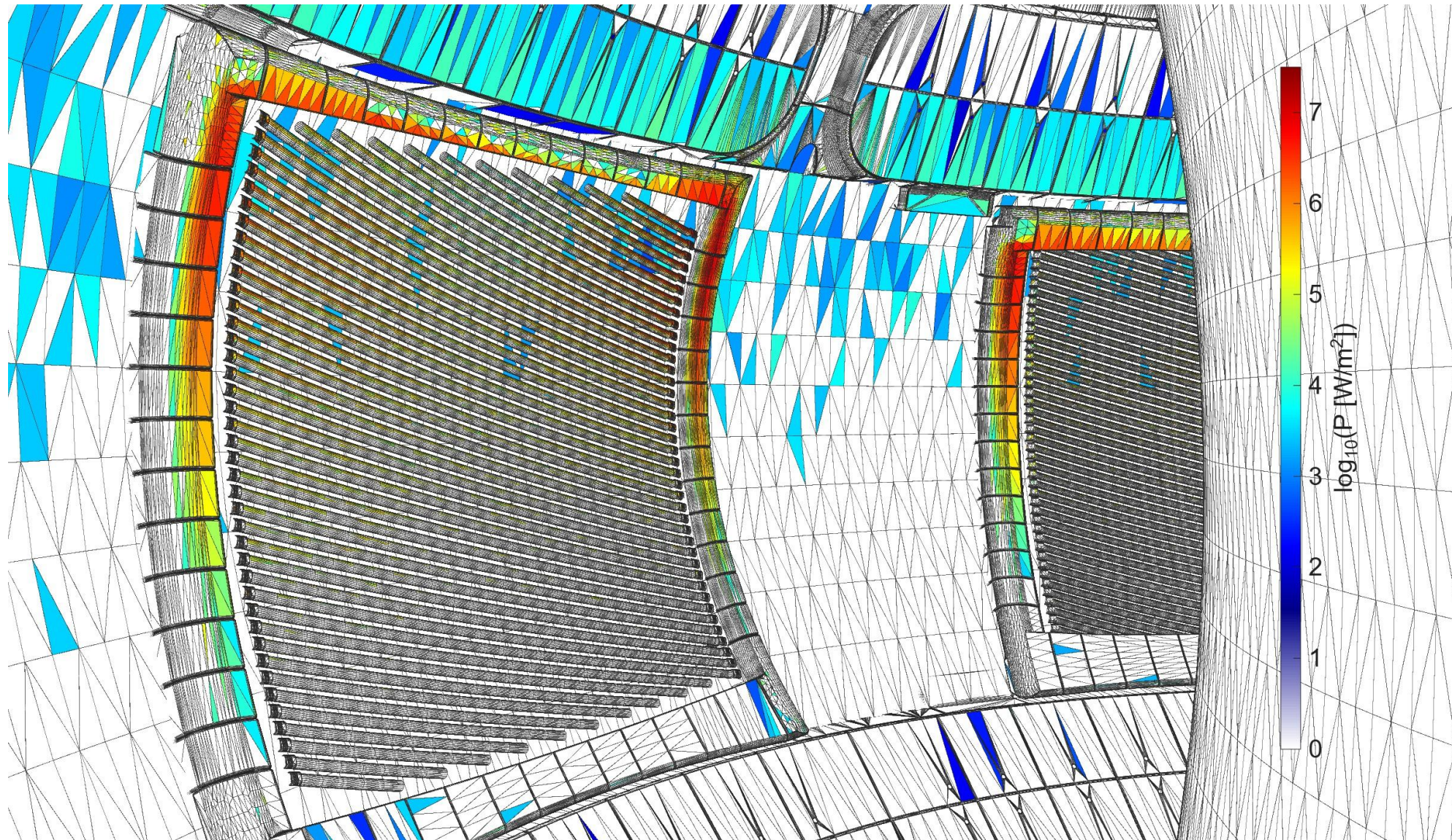
Confined fast H⁺ energy-pitch distributions

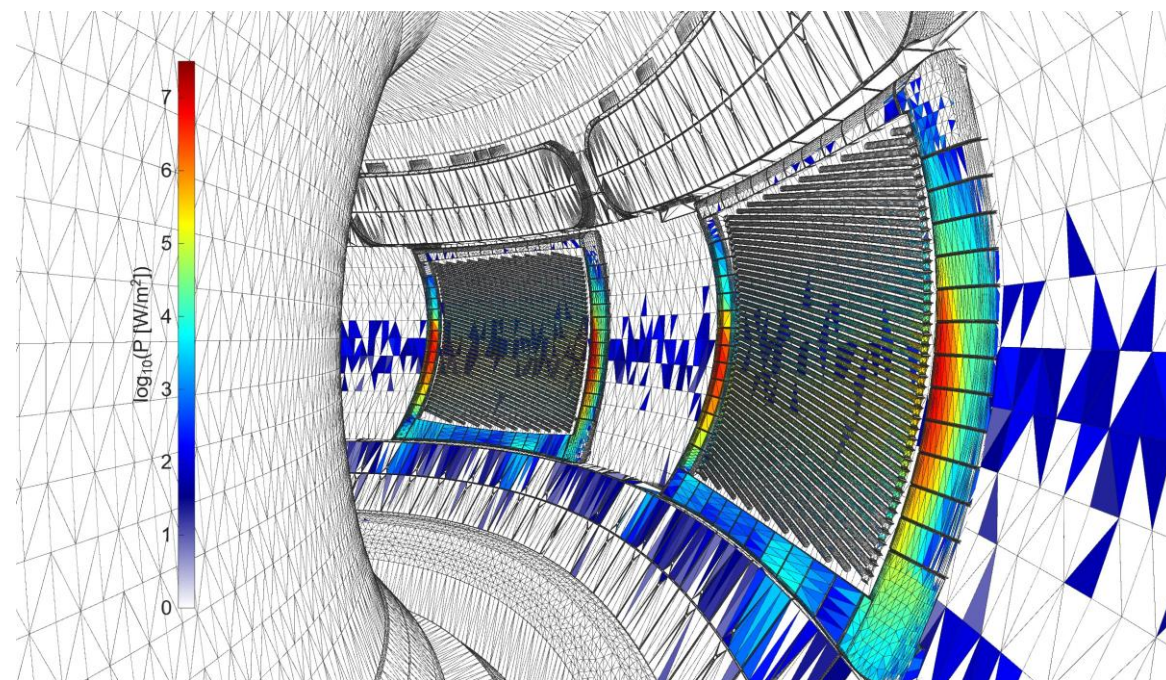
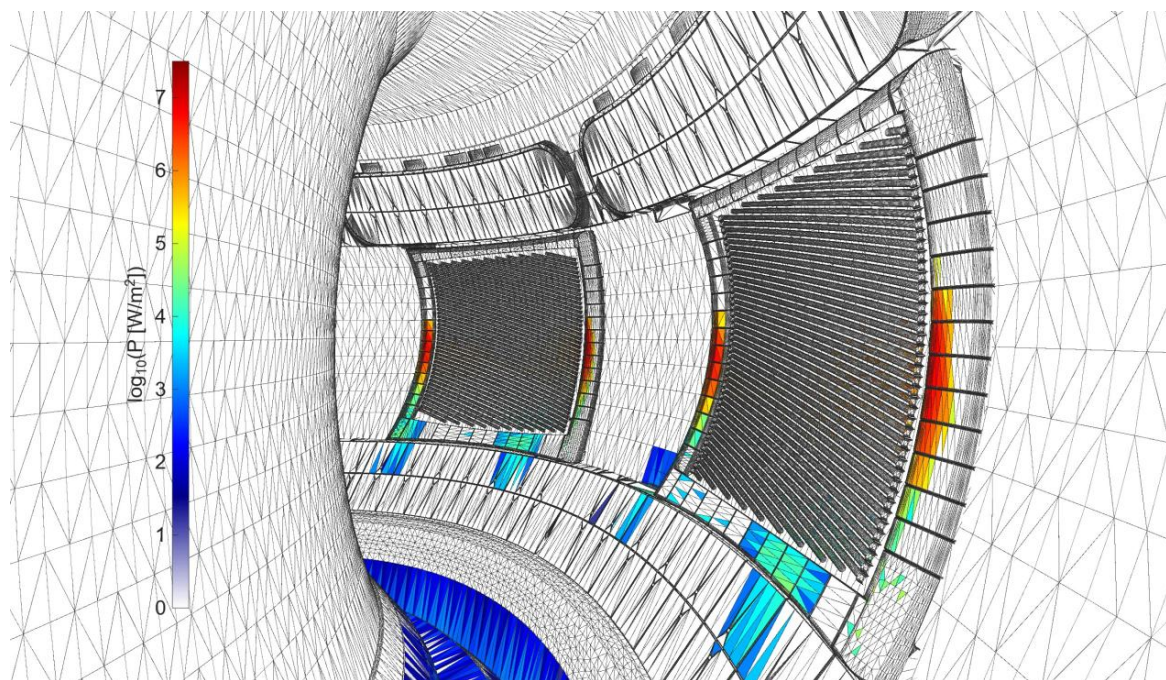


H⁺ pitch distribution of ions lost to limiter tile

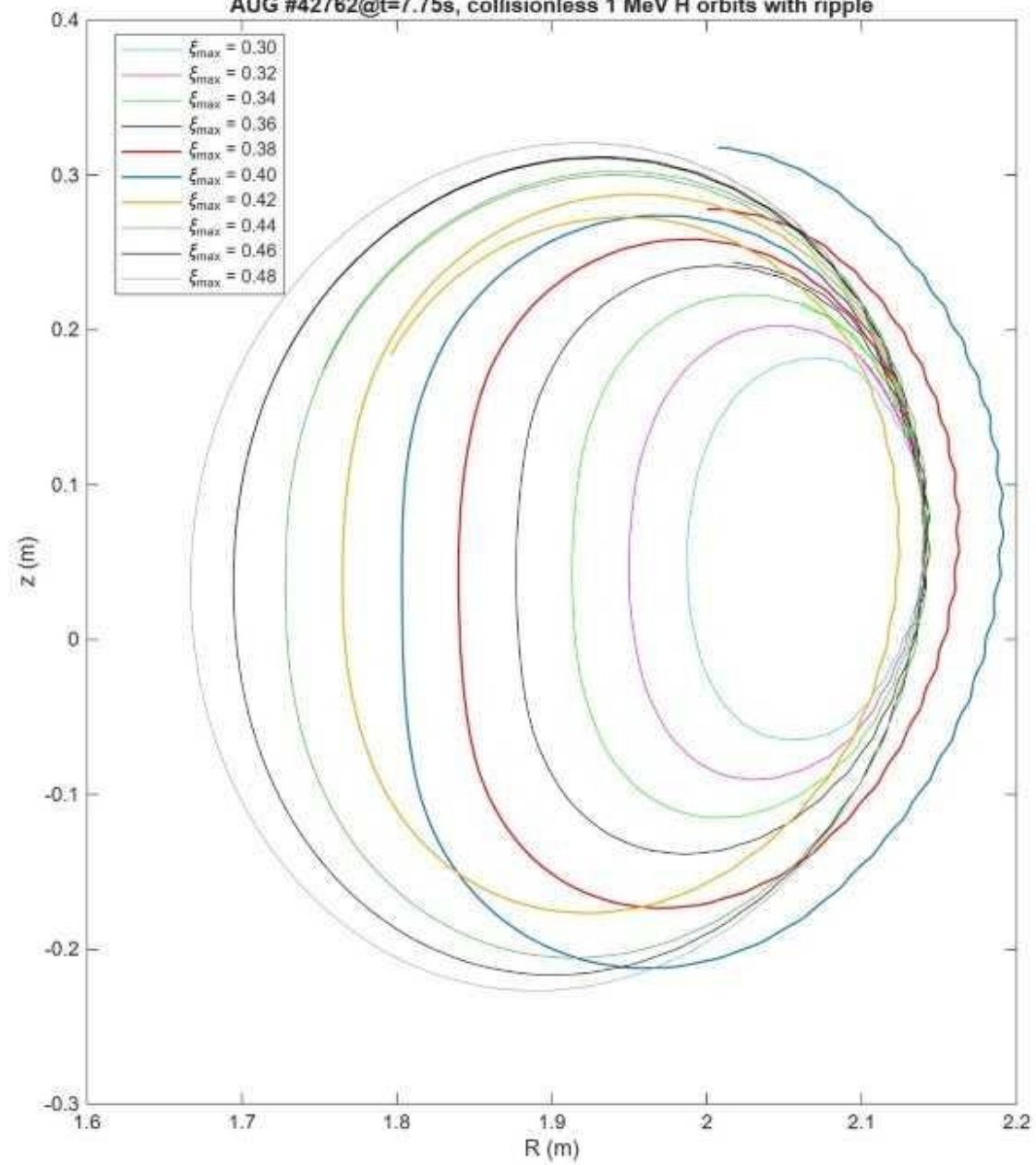


33147, $t=1.0$ s, ICRF H+ minority, -2.5 T, 0.7 MA, 5% H fraction, 2.5 MW





AUG #42762@t=7.75s, collisionless 1 MeV H orbits with ripple



AUG #42672@t=7.75s

