Current quench heat loads on an ITER tungsten first wall using the refactored TOKES code

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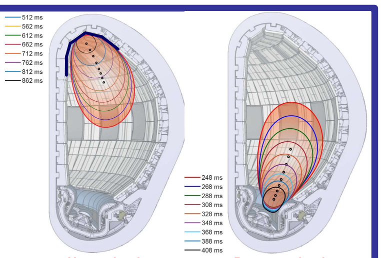
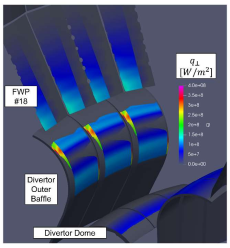
Introduction

- Disruption current quench (CQ) heat loads on ITER first wall (FW) → very high stored magnetic energies at high I_p [1]
  - Stored magnetic energies at the current quench (CQ), $E_{mag} \lesssim 700$ MJ, τ_{CQ} ~ few 100 ms
  - elimination of Beryllium (Be) in favour of a full tungsten (W) FW as part of the ITER re-baseline proposal → improving resilience to transient melting compared with Be [2]





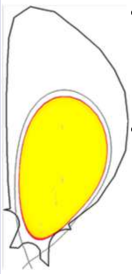
Example map of $q_\perp$ calculated in SMITER for a 15MA Downward VDE [7], also [4]

- Upward VDE CQ transient impact already studied for W FW with original TOKES [3]:
  - With vapour shielding (VS) damage threshold for W: ~10 MA, highly conservative simulations: lack of melt motion and equilibrium temporal evolution
- Downward VDE CQ simulations with MEMOS-U [4]: significant melting on the baffle region of the W outer divertor vertical target
- **This work:** repeat upward VDE CQ on FW, perform downward VDE CQ simulations on divertor damage with/without increasing impact angles on the baffle
  - Use refactored TOKES code on the ITER SDCC cluster
  - Study the impact of VS on heat fluxes and melting on the FW and divertor

Refactored TOKES code

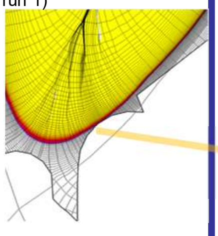
- 2D magneto-hydrodynamic code [5], refactored to open-source Lazarus IDE [6]:
  - simulates dynamics of deuterium-tritium (DT) plasma in ITER core and in SOL
  - uses rectangular curvilinear coordinate system aligned with magnetic field
  - calculates heat flux to the tokamak walls and heat transport inside the solid walls
  - takes into account the wall melting and vaporization
  - after vaporization start, it simulates the dynamics of vaporized W in the vacuum vessel, its ionization and W-D-T plasma dynamics, including photonic radiation

TOKES code and input



Initial position of the downward shifted core for TOKES simulations

- Repeated first wall upward VDE CQ simulations:
  - 15 MA DINA DS simulation (IMAS shot #100187, run 1) → equilibrium @562 ms [7]
  - $\lambda_{q,omp}$ ~3.5 cm (halo heat flux channel width), E_{mag} = 670 MJ, τ_{CQ} = 250 ms
- Divertor downward VDE CQ simulations:
  - IMAS shot #100200, run 1, equilibrium @248 ms
  - $\lambda_{q,omp}$ ~3.7 cm, E_{mag} = 670 MJ, τ_{CQ} ~250 ms
  - extrapolate to lower I_p: $E_{mag} \sim I_p^2$ and $\tau_{CQ} \sim I_p^{1/2}$
  - increasing impact angles on the baffle [8] → simulated by artificially increasing 2.5x the poloidal angle at small part of the baffle

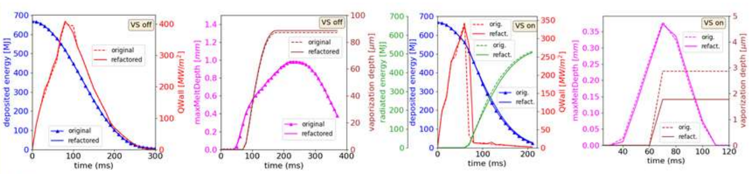


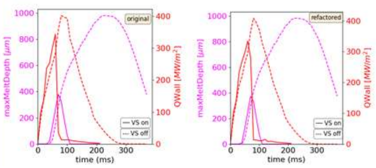
TOKES calculation grid for downward VDE CQ simulations

First wall: repeated upward VDE CQ

- Compare results: original vs refactored code, with and without vapour shielding

I_p = 15 MA: E_{mag} = 670 MJ, τ_{CQ} = 250 ms, $\lambda_{q,omp}$ ~3.3 cm





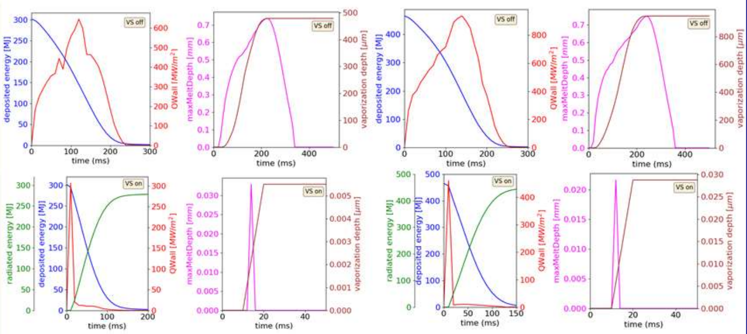
- refactored TOKES code results match the original TOKES code results in terms of accuracy
- minimum discrepancies (e.g., for erosion results) can be attributed to the stochastic nature of Monte Carlo algorithms of the TOKES code

Divertor baffle: downward VDE CQ

- W divertor, with and without vapour shielding, vary E_{mag} (= varying I_p)

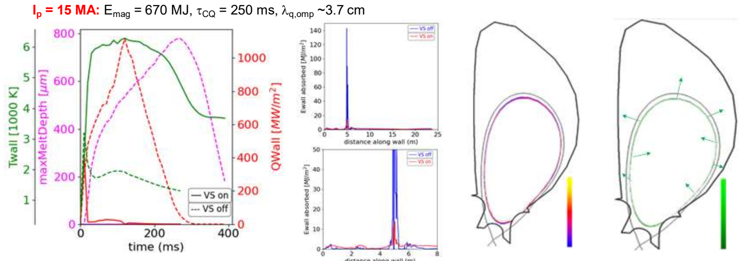
I_p = 10 MA: E_{mag} = 300 MJ, τ_{CQ} = 210 ms, $\lambda_{q,omp}$ ~3.8 cm

I_p = 12.5 MA: E_{mag} = 465 MJ, τ_{CQ} = 230 ms, $\lambda_{q,omp}$ ~3.6 cm



- Without VS melt depth saturation at 0.74 mm → with VS a reduction to 33 μm with Δt_{melt} reduced by a factor ~155
- Without VS maximum vaporization at 0.48 mm → with VS a reduction to 0.006 μm
- Without VS melt depth saturation at 0.75 mm → with VS a reduction to 22 μm with Δt_{melt} reduced by a factor ~170
- Without VS maximum vaporization at 0.95 mm → with VS a reduction to 0.03 μm

I_p = 15 MA: E_{mag} = 670 MJ, τ_{CQ} = 250 ms, $\lambda_{q,omp}$ ~3.7 cm



Plasma density in blue-red-yellow scale at t = 40 ms

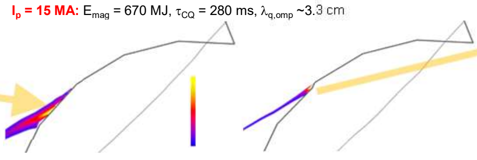
Radiation power density in green scale and fluxes at t = 40 ms

- Without VS melt depth saturation at 0.8 mm and maximum vaporization at 1.2 mm
- With VS, rapid vaporization (after a few ms) of W (maximum at 1.2 mm) → formation of W plasma that spreads along the Scrape-Off Layer (SOL) → radiation of almost all E_{mag} (E_{rad} ~0.94 E_{mag}) and redistribution throughout the whole wall without large peaks
- Heat flux at the evaporation point drops drastically nearly to zero preventing further melting, with VS a drastic reduction to 30 μm with Δt_{melt} reduced by a factor ~200

Divertor baffle (chamfer): downward VDE CQ

- W divertor, with and without vapour shielding

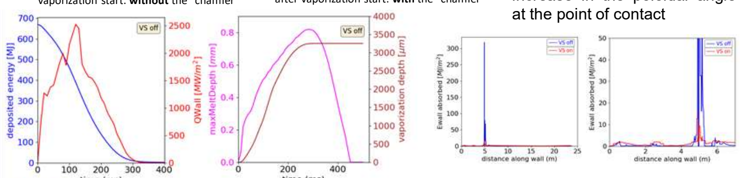
I_p = 15 MA: E_{mag} = 670 MJ, τ_{CQ} = 280 ms, $\lambda_{q,omp}$ ~3.3 cm

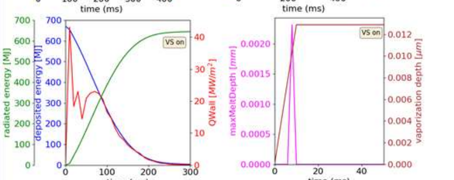


Baffle shape and W plasma density shortly after vaporization start: **without** the "chamfer"

Baffle shape and W plasma density shortly after vaporization start: **with** the "chamfer"

An increase in the toroidal angle between the magnetic field and the chamfer surface is artificially simulated by an increase in the poloidal angle at the point of contact





- Without VS melt depth saturation at 0.82 mm → with VS a drastic reduction to 2.3 μm with Δt_{melt} reduced by a factor ~215
- Without VS maximum vaporization at 3.3 mm → with VS a drastic reduction to 0.012 μm

- Expansion of the W plasma as quick as in the case without the "chamfer" → emission of E_{mag} just as effective (E_{rad} ~0.97 E_{mag}), increase of the heat flux (2.5x) at the chamfer accelerates vaporization, reducing maximum melt to 3-10 μm and keeping maximum vaporization at ~0,1-0.03 μm
- MEMOS-U [4]: melt on the chamfer region (without VS) at ~1 mm → close to TOKES at 0.82 mm, **BUT:** TOKES: 2D, VS, not following time dependent motion, MEMOS-U: 3D, no VS, following motion

Conclusions

- Refactored TOKES 2D code used to study the damage of ITER first wall and divertor during upward/downward VDE transients of various I_p/E_{mag}
- **First wall (upward VDE CQ)**: refactored TOKES results match the original TOKES results in terms of accuracy, minimum discrepancies intrinsic to the code itself
- **Divertor baffle (downward VDE CQ)**: at highest I_p/E_{mag} without vapour shielding (VS) the melt depth saturates at 0.8 mm, with VS a drastic reduction of the maximum melt depth to 30-40 μm and maximum vaporization at ~0.01 μm
- **Divertor baffle with 'chamfer' (downward VDE CQ)**: qualitatively same results as without the 'chamfer' (in line with simulated MEMOS-U melt depth at ~1 mm), incident angle increase ~2.5x → heat flux increase → acceleration of vaporization, with VS reducing maximum melt to 3-10 μm and keeping max. vaporization at ~0,1-0.03 μm
- Plasma shielding during VDE is due to the rapid propagation of vaporized W plasma to the entire halo and rather even radiation of magnetic energy over the entire wall

References

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