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Simulation of divertor targets shielding during transients in ITER

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P2.014

ISFNT-12
INTERNATIONAL SYMPOSIUM ON FUSION NUCLEAR TECHNOLOGY
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ABSTRACT

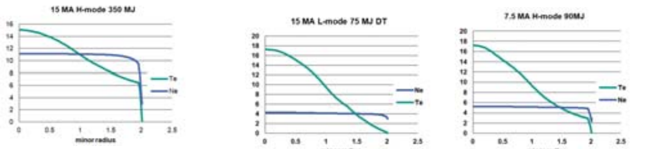
- Disruptive heat flux on ITER divertor causes severe melting and vaporization of the targets
- However, tungsten vaporized from the target creates plasma shield, which effectively protects the target
- Estimation of the shielding efficiency has been performed using the TOKES code
- The shielding effect under ITER conditions is found to be very strong:
  - maximum melt layer depth reduced 4 times,
  - melt layer width – more than 10 times
  - vaporization region shrinks 10-15 times
- A simplified analytic model, for the shielded flux to the target and for the melt depth has been developed

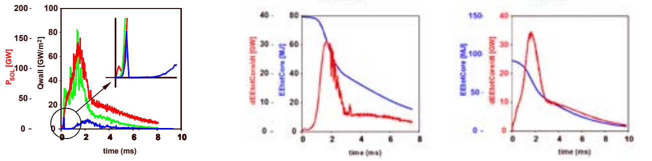
INTRODUCTION

- Operation of ITER will begin with a divertor fully armoured with tungsten.
- One of the key risks of this decision is that ITER transients will be sufficiently powerful to cause local melting of the divertor targets.
- Direct extrapolation of the transient heat flux parameters to ITER predicts severe melting and vaporization of the divertor targets causing their intolerable damage.
- However, tungsten vaporized from the target at initial stage of the transient can create plasma shield in front of the target, which effectively protects the target surface from the rest of heat flux.
- Plasma shielding effect, investigated in this paper, is a complex physical phenomenon, combining MHD convection and diffusion of the tungsten plasma shield with conversion of the transient heat flux from the core into radiation heat flux.

DISRUPTION SIMULATION WITH THE TOKES CODE :

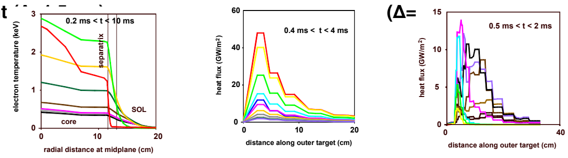
- The disruptive fluxes are simulated with the TOKES code using special model, which does not describe the details of the disruption processes
- The model determines increase of the cross-field transport in the core and in SOL by adjustment of the cross transport coefficients
- The e-folding width at the thermal quench of the simulated disruptions is of 1.5 cm in the central plane of SOL for the H-mode (DT) discharge of 350 MJ plasma energy.
- The heat and the particle transport enhancement are assumed to be due to the MHD turbulence.
- First part for plasma energy flux is determined by electron heat conduction. The characteristic rise time of this part is adjusted by the core transport coefficient.
- Long tail due to ions





footprint

SOL at midplane SOL
(Δ=



Analytic model for plasma shielding:

- Vaporized material shields the surface from the incoming flux, thus keeping the surface temperature close to the vaporization temperature.
- The target vaporization process with constant surface temperature approximately equal to T_{vap} is stable.
- This assumption allows analytic solution for the 1D equation of thermoconductivity in the solid target:

$$\frac{\partial T(x,t)}{\partial t}-\gamma^2\frac{\partial^2 T(x,t)}{\partial x^2}=0$$

with the boundary and initial conditions:

$$T(x,t)\big|_{x=0}=T_{vap}=const$$

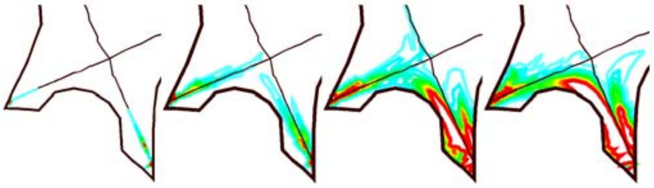
$$\int_0^\infty T(x,t)dx<\infty \qquad T(x,0)=0$$

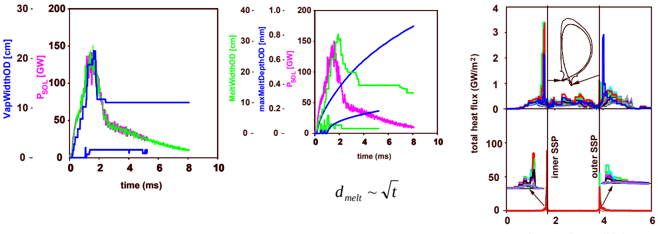
The solution is:

$$T(x,t)=T_{vap}\,\mathrm{erfc}\left(\frac{x}{2\gamma\sqrt{t}}\right) \qquad q_0(t)=-\kappa\frac{\partial T(x,t)}{\partial x}\bigg|_{x=0}=\frac{\kappa T_b}{\gamma\sqrt{\pi t}}$$

TOKES SIMULATION RESULTS

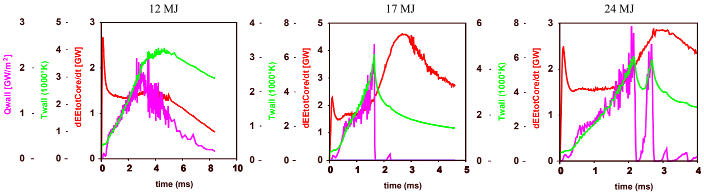
- The maximum of the disruptive heat flux is always at SSP due to electron thermoconductivity.
- In quasi-stationary regime the amount of vaporized W, supporting the shield is in equilibrium with the shield depletion by diffusion.





$$d_{melt}\sim\sqrt{t}$$

- The larger heat flux to the target the more efficient the shielding.
- Cross-diffusion of the W plasma shield protects the neighboring regions from vaporization
- Width of the vaporization stripe with shielding is very narrow:
  - ~1.5 cm at SSP with shielding
  - up to ~20 cm without shielding
- Melt pool evolution at the outer divertor: the melt depth at the SSP is ~4 times smaller with shielding.
- Total heat flux to divertor for the simulated disruption with and without shielding:
  - Unshielded incoming plasma flux has e-fold length of ~15 cm along the target
  - The heat flux with shielding has much smaller peak values, but the heat flux redistributed over stripe of ~4 m wide due to the radiation
- For lower energy release during the disruption the scenario described for the 350 MJ case is valid with some peculiarities:
  - the quasi-stationary shielding regime exists during shorter time
  - oscillations of the shielding efficiency
  - it needs longer time before the quasi-stationary regime self-organization.
  - for very small energy release the quasi-stationary regime is not reached, so the surface heat flux stops after one or several outbursts of vaporization.



CONCLUSIONS

- Simulations of plasma shield effect in ITER conditions, which can drastically reduce the disruptive heat flux at the divertor targets, has been performed using the TOKES code.
- The simulation results has shown drastic effect of the plasma shield.
- The maximum depth of the melt pool with shielding is ~4 times smaller than without and the melt pool width is even 10 times smaller.
- Existence of the plasma shield requires permanent vaporization at the SSP, where vaporization is unavoidable
- A simplified analytical model for the shielding effect, valid for heating of SSP, has been developed.
- Generally, the simulations show complex and essentially two-dimensional evolution of the plasma cloud, which needs numerical simulation for predicting the divertor targets damage.

Acknowledgements: This work was supported by the ITER Organization and carried out within the framework of the contract ITER/CT/14/4300000998. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.