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ELMs in High Recycling ITER Plasmas

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ELMs in High Recycling ITER Plasmas

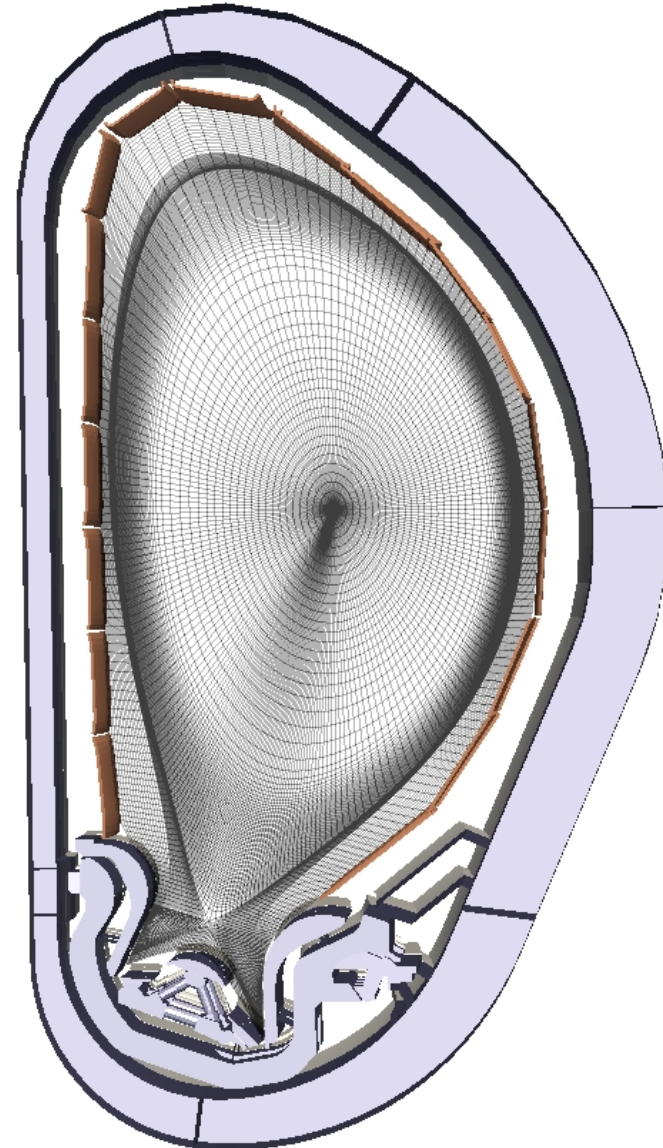
- How small are allowable ELMs in ITER?
 - related to ELM burn through of detached plasmas
- 1. **Simulations of ELMs in ITER with the non-linear MHD code JOREK**
 - using reduced MHD model with fluid neutrals
- 2. **Extension of the divertor model in JOREK**
 - implementing kinetic neutrals and impurities

Non-linear MHD code JOREK (www.jorek.eu)

- JOREK code solves the (extended) MHD equations in 3D general tokamak geometry
 - Closed and open field lines, plasma wall interaction, conducting structures
 - Main applications: ELMs and disruptions
- developed with the EU fusion program
 - 14 Fusion Labs + Universities, ~25 persons
 - GIT repository, wiki, decentralised development
- Characteristics
 - Cubic (Bezier) Finite element representation in the poloidal plane
 - Extension of cubic Hermite elements
 - Fourier series in the toroidal direction
 - Fully implicit time evolution
 - MPI/OpenMP parallelisation

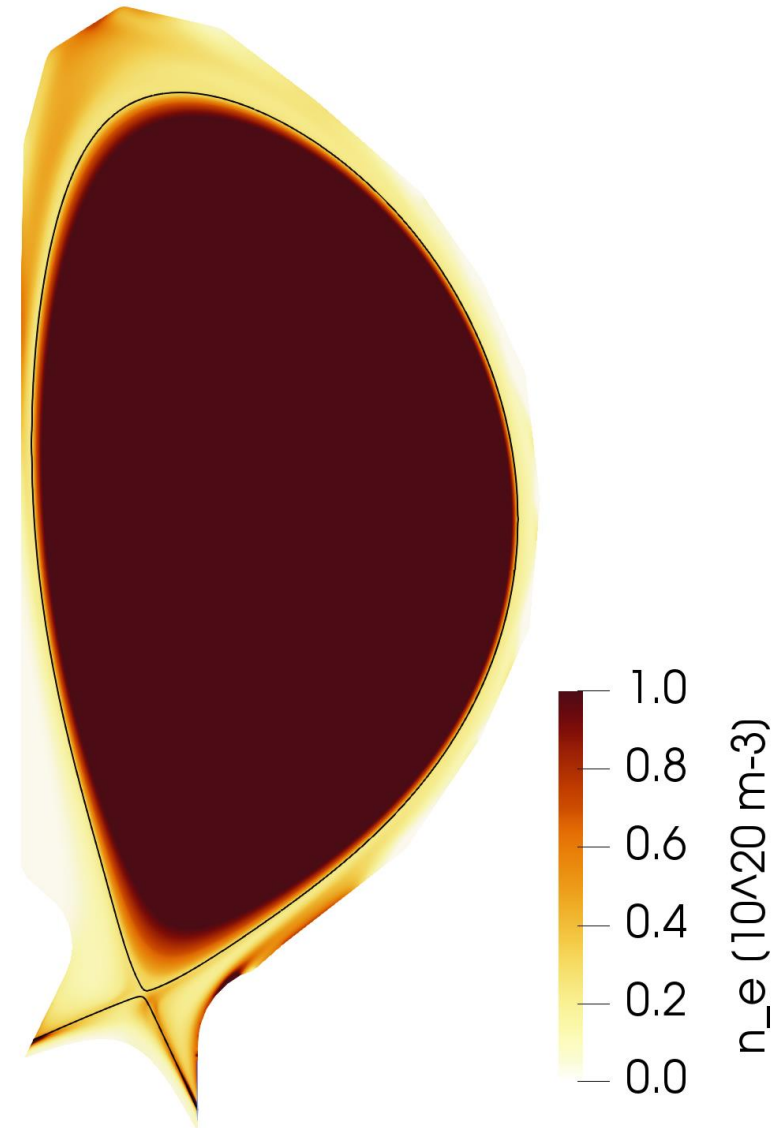
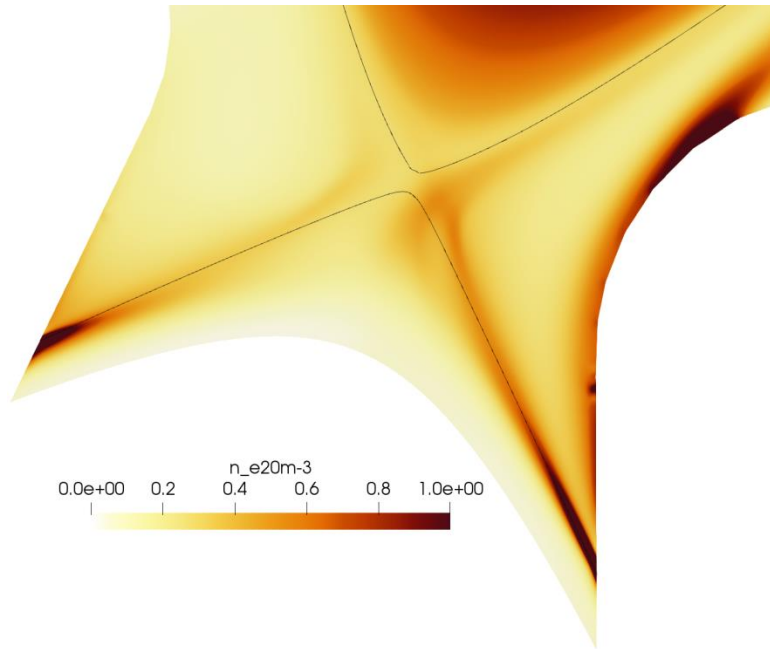
ELM Simulations in ITER

- Grid aligned on equilibrium flux surface, extending to realistic ITER wall (2D)
- MHD + Neutral fluid model
 - diffusive neutral model
 - Sheath boundary conditions
 - Mach one
 - Sheath transmission factor
 - Reflection of ions into neutrals



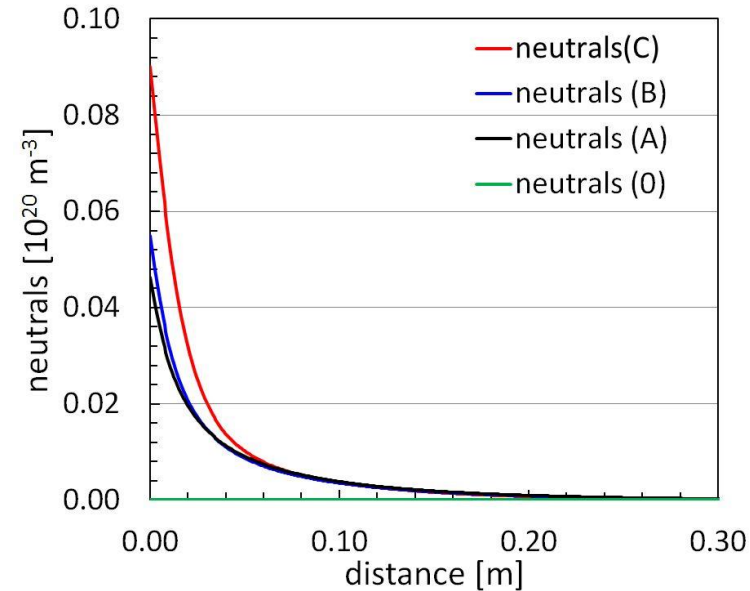
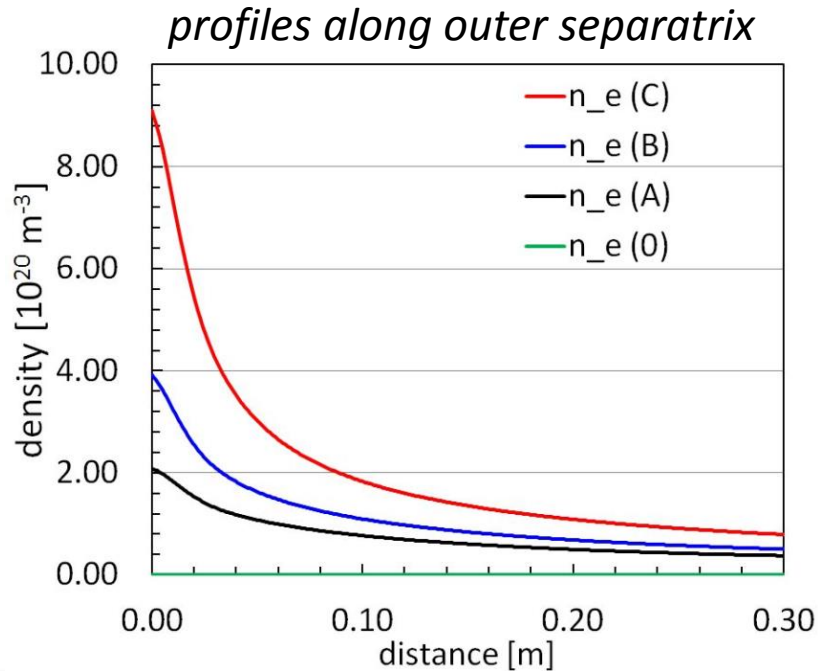
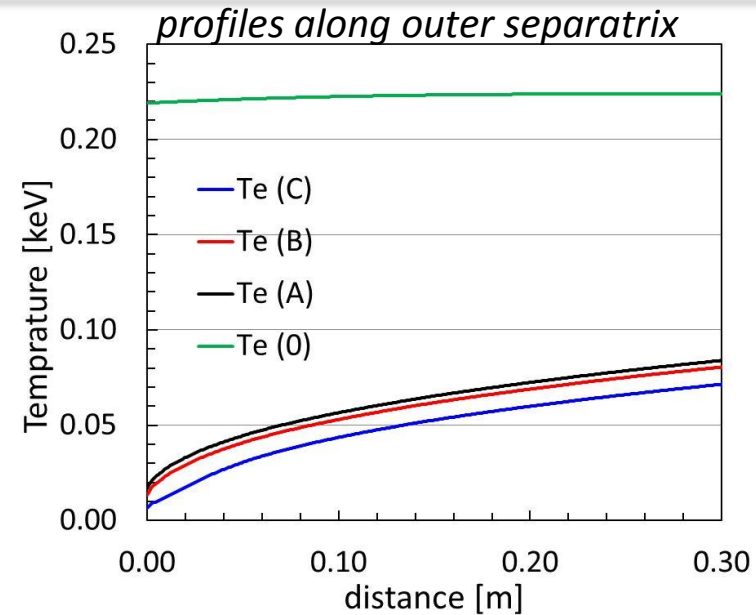
Initial Conditions ITER scenario

- Initial quasi-stationary state with high recycling ITER divertor
 - 15MA/5.3T Q=10 scenario (IMAS #131025)
 - $W_{\text{thermal}} = 410 \text{ MJ}$
 - heating power 110 MW



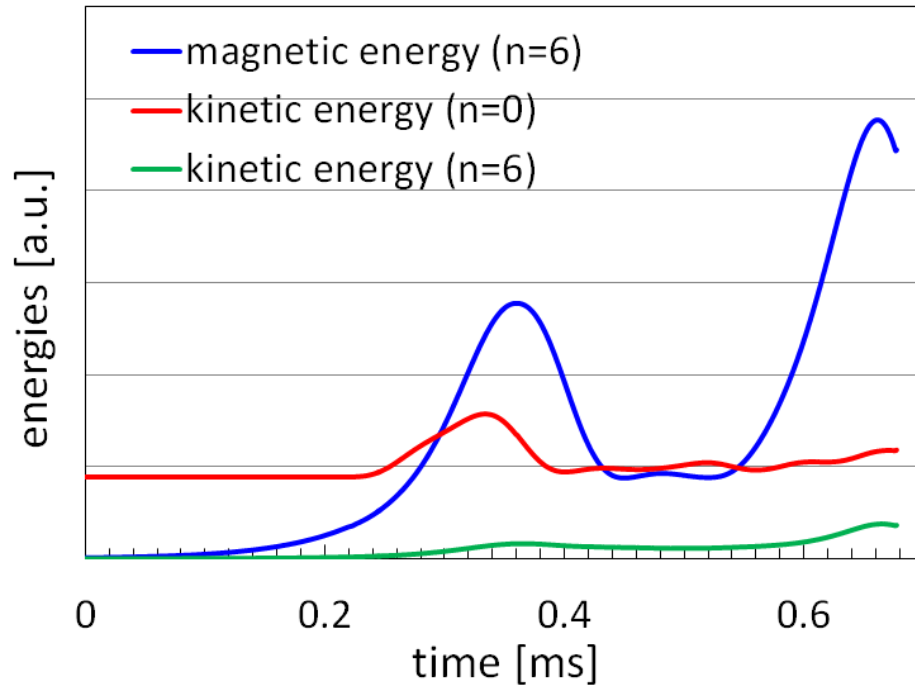
Initial Conditions: Divertor

- High recycling ITER divertor
 - neutral gas injection
 - Neon background impurity (5×10^{-3})
 - $T_{\text{div}} \sim 6 \text{ eV}$, $Q_{\text{max}} \sim 6 \text{ MW/m}^2$

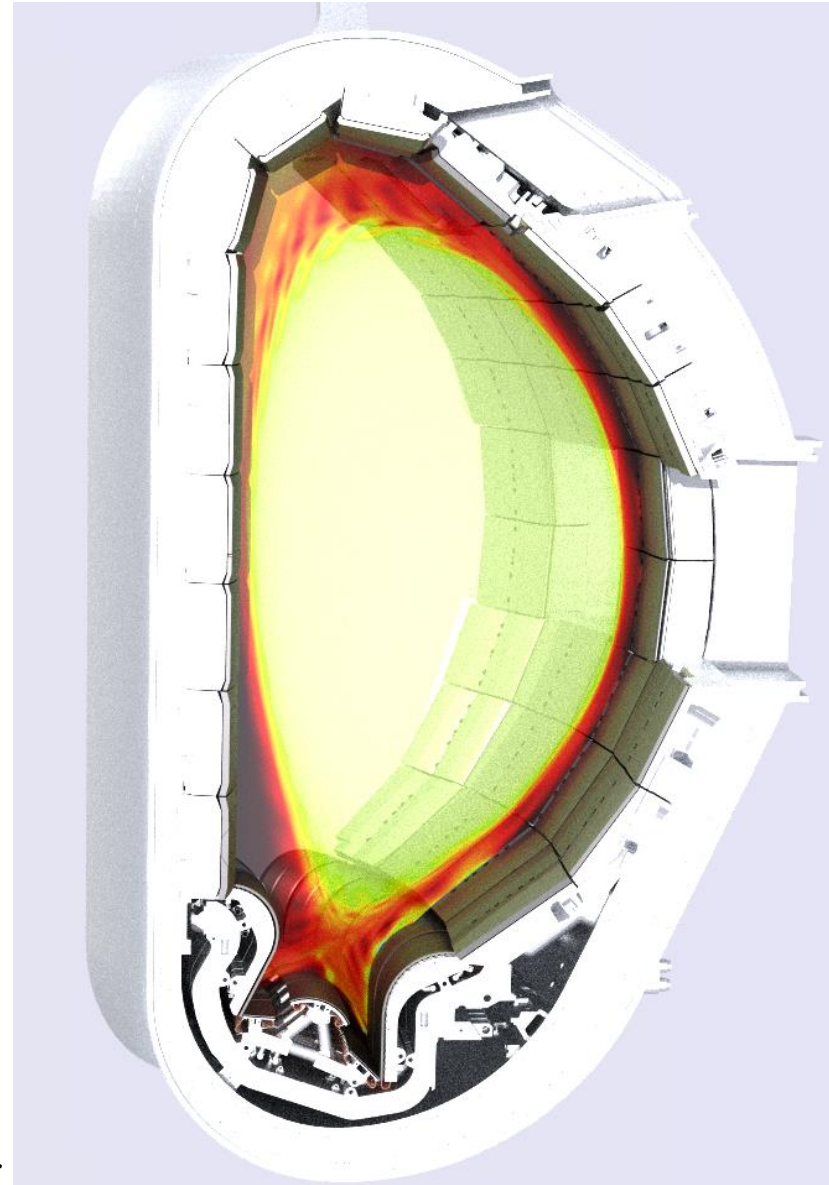


Small ELM

- $n=6$ (single harmonic)
- $\Delta W \sim 1\text{MJ}$
- Peak $dW/dt \sim 2\text{GW}$ (at 0.45 ms)

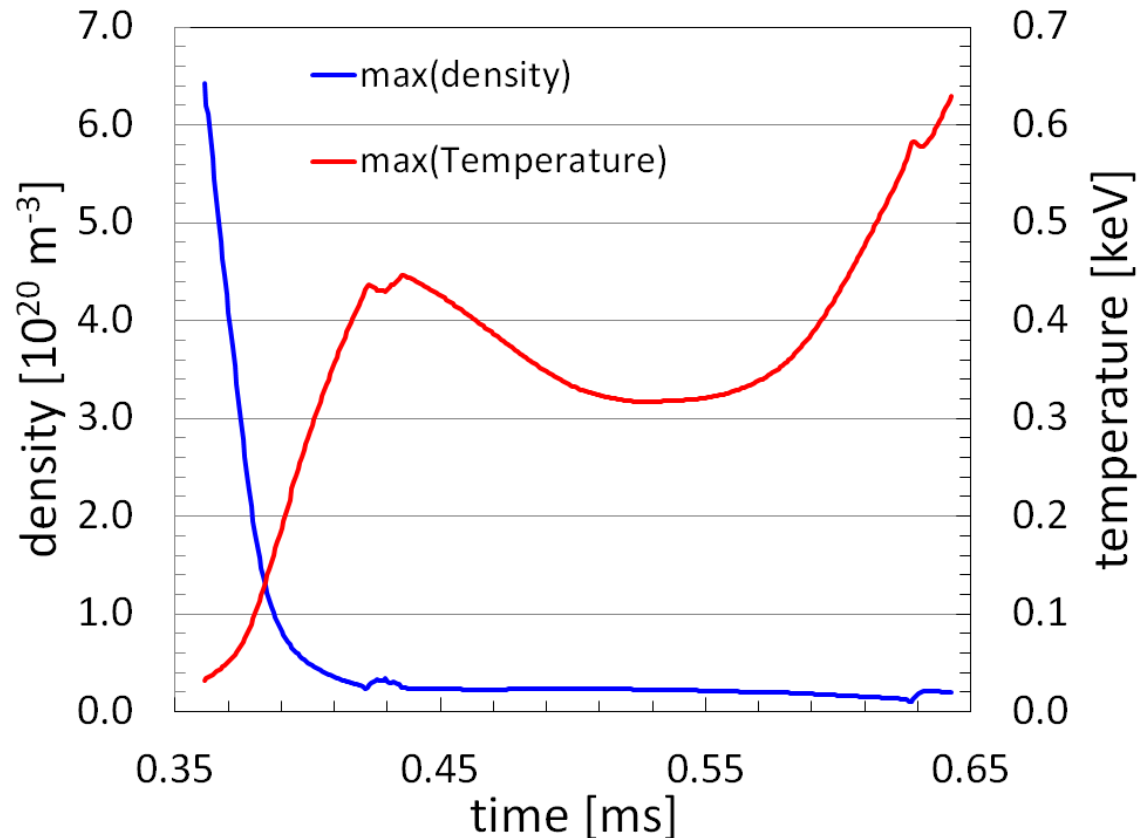


density profile at $t=0.65\text{ms}$



ELM “Burn through”

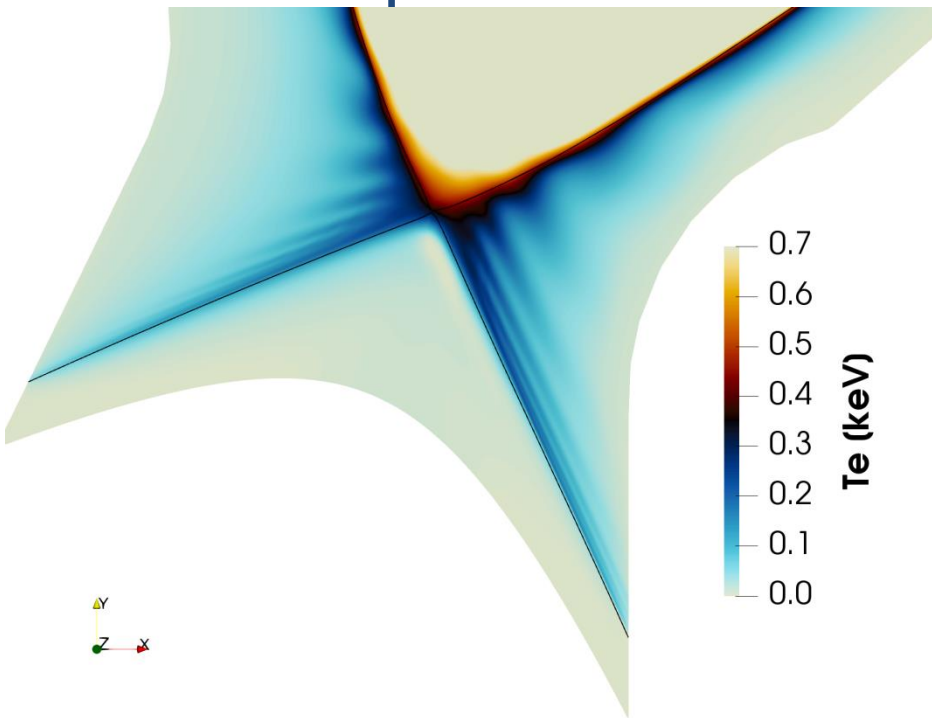
- The high density at the divertor is quickly (**within 100 μ s**) removed by the ELM
 - together with fast temperature rise
 - at this time very little thermal energy has been lost : $\Delta W \sim \mathbf{0.12 \text{ MJ}}$



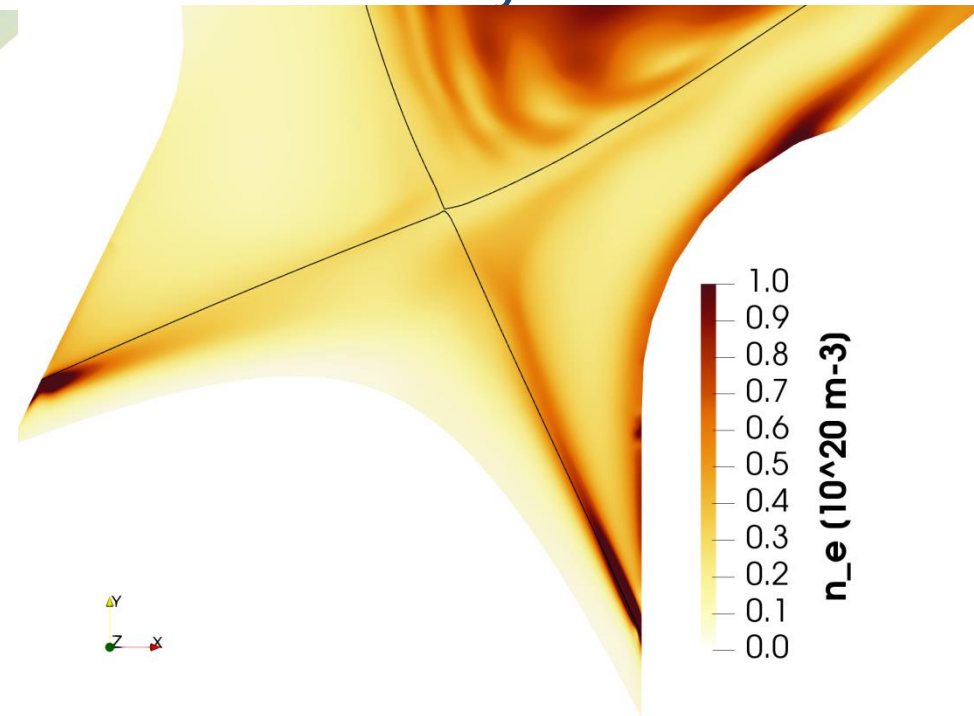
Snapshots

- $t=0.35\text{ms}$

Temperature

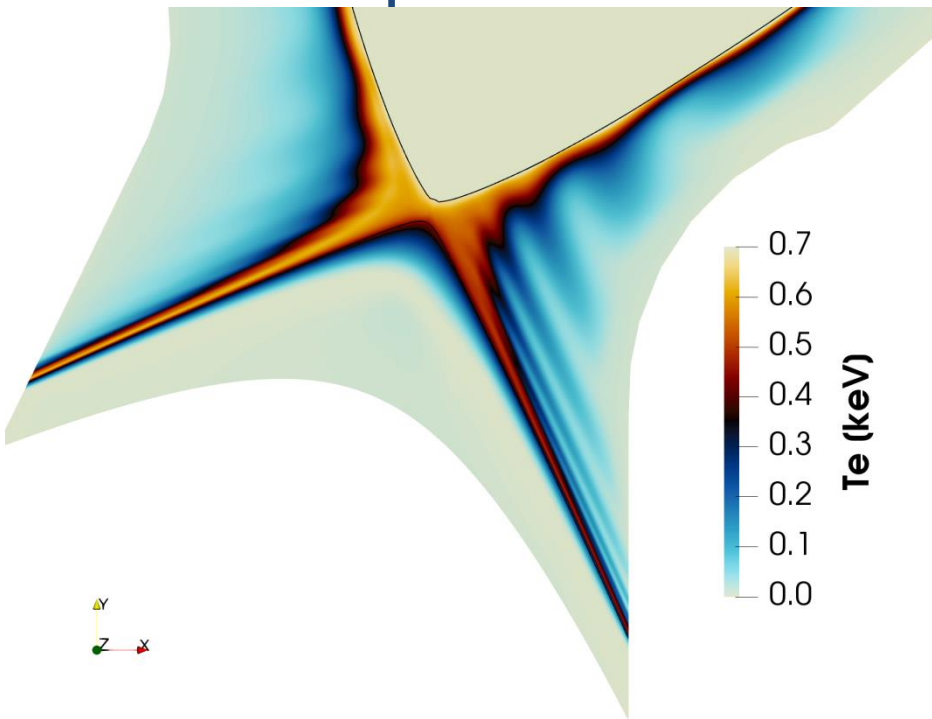


Density

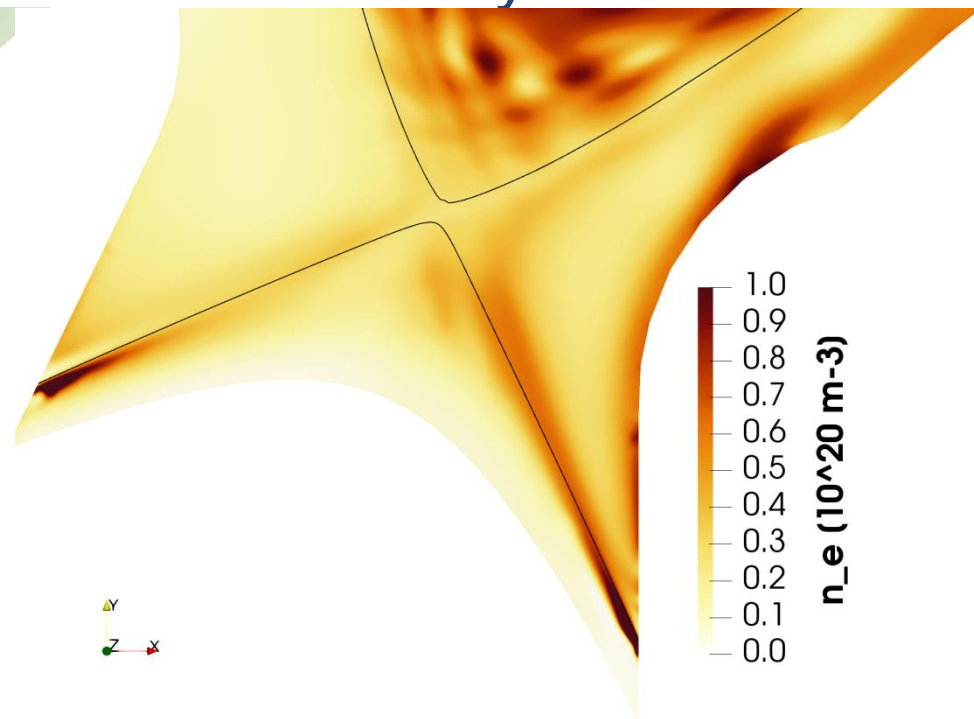


- $t=0.45\text{ms}$

Temperature



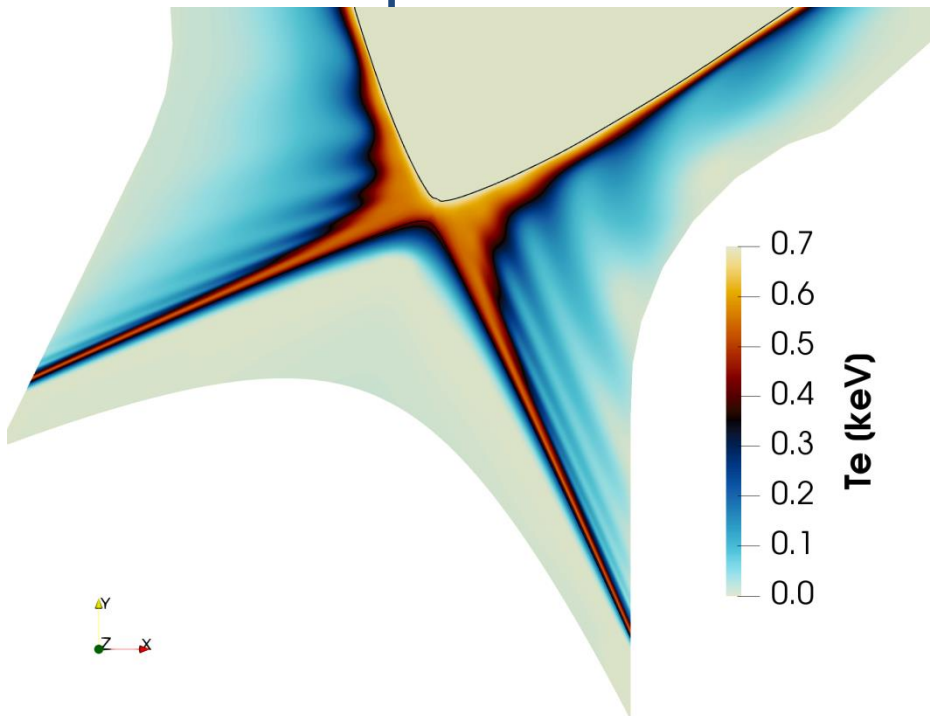
Density



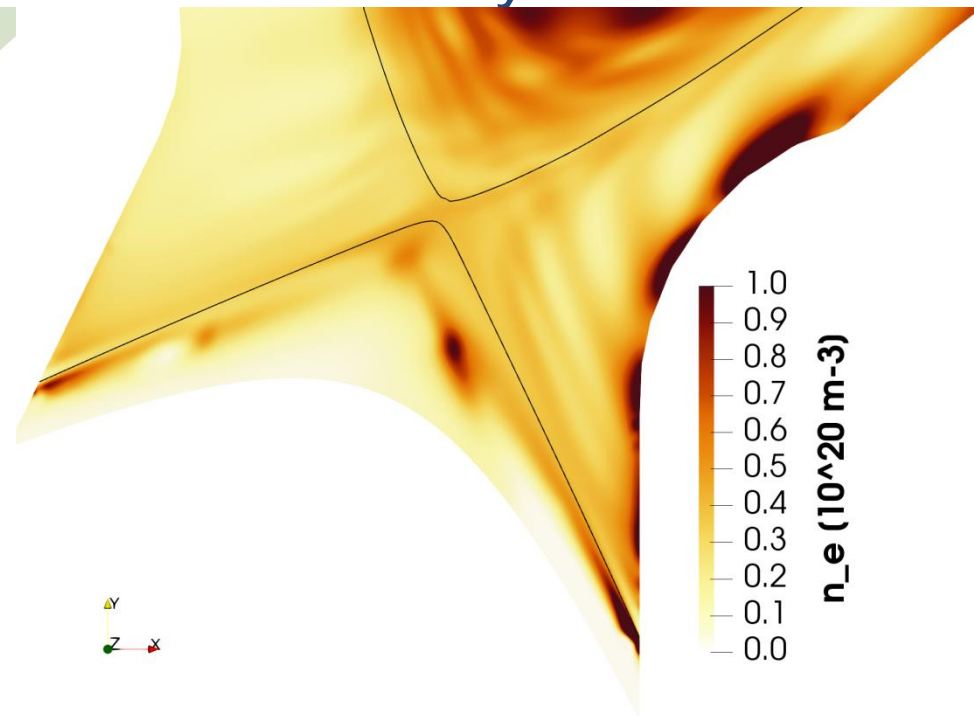
- $t=0.65\text{ms}$

- a narrow channel of low density, high temperature at the main strike point

Temperature

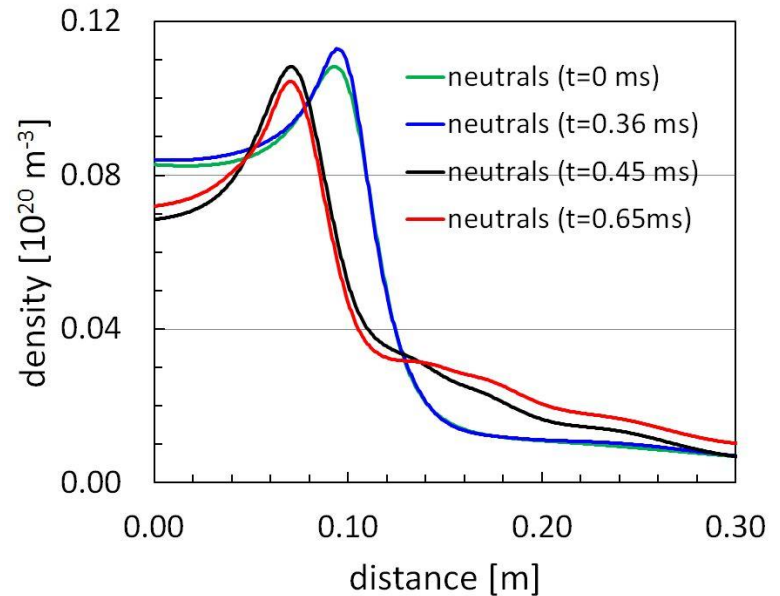
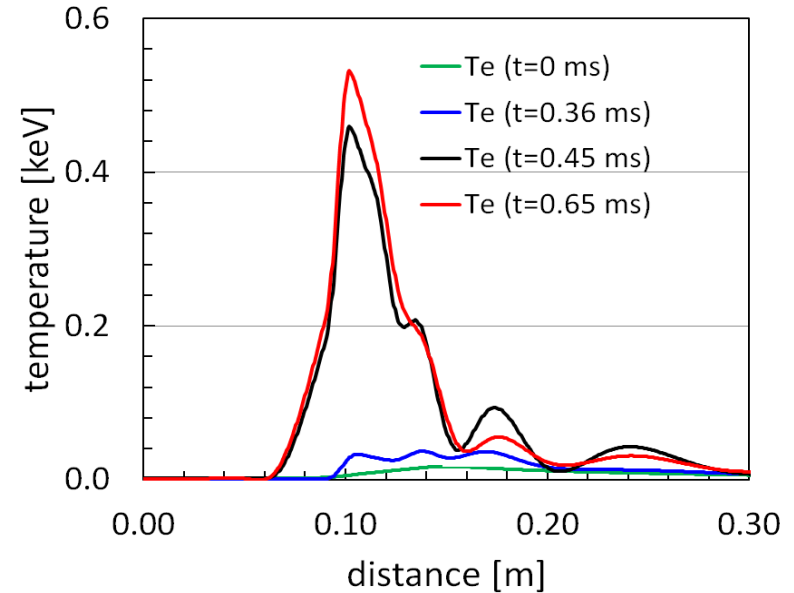
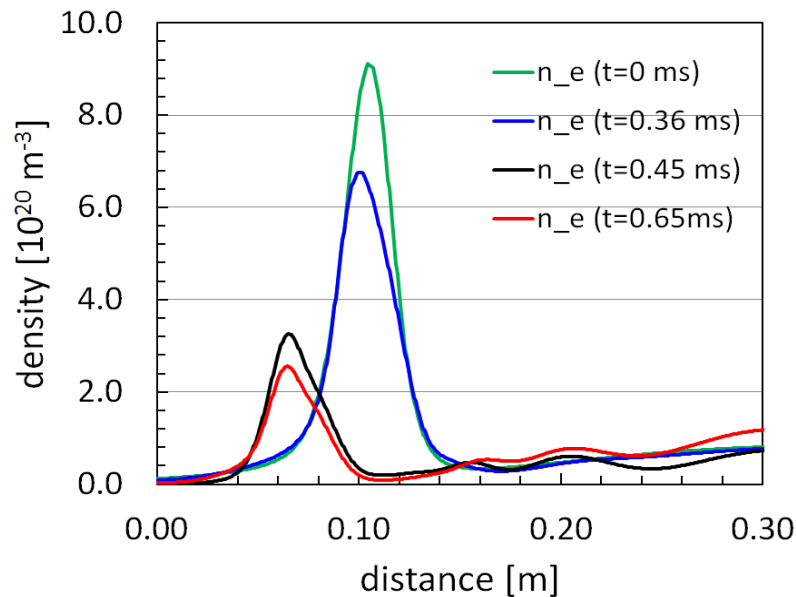


Density



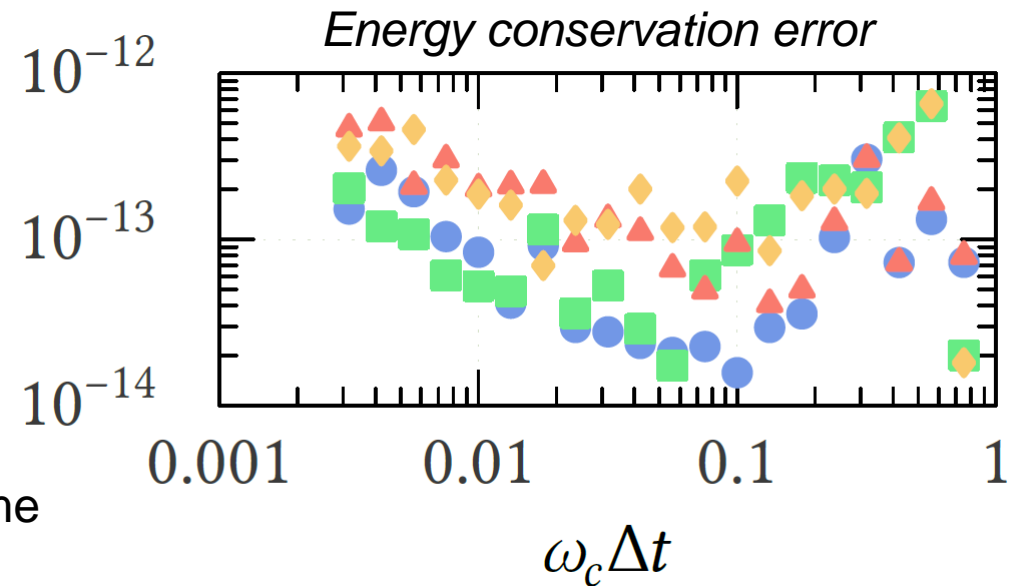
Outer Divertor Profiles

- One narrow peak in power deposition profile
 - no broadening
- High density and neutrals displaced below separatrix
- Peak heat flux $\sim 1\text{GW/m}^2$



Particles in JOREK

- Particles are followed in the time evolving magnetic and electric field of the MHD fluid
 - full orbit using well-known Boris method (with correction toroidal geometry)
 - particles are followed in real space (R,Z,φ) and finite element space (s,t,φ)
 - charge states are evolving in time (ionisation, recombination, CX)
 - Particle-background collisions with binary collision model
 - sputtering model for impurity and neutral sources



Energy conservation independent of time step Δt , momentum conservation $\sim \Delta t^2$

Kinetic Neutrals

- Coupling of JOREK MHD fluid and particles
 - Particle contributions become sources in MHD equations

- Conservative form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_\rho$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) + \nabla \cdot \bar{\bar{P}} - \vec{J} \times \vec{B} = \vec{S}_v$$

$$\frac{\partial}{\partial t} \left(\frac{1}{2} \rho v^2 + \frac{3}{2} \rho T \right) + \nabla \cdot \left(\frac{1}{2} \rho v^2 \vec{v} + \frac{3}{2} \rho T \vec{v} + \vec{v} \cdot \bar{\bar{P}} \right) = S_E$$

- JOREK form

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_\rho$$

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho (\nabla \cdot \vec{v}) \vec{v} + \nabla \cdot \bar{\bar{P}} = \vec{S}_v - \vec{v} S_\rho$$

$$\frac{\partial \left(\frac{3}{2} \rho T \right)}{\partial t} + \vec{v} \cdot \nabla \left(\frac{3}{2} \rho T \right) + \frac{5}{2} \rho T (\nabla \cdot \vec{v}) = S_E - v S_v + \frac{1}{2} v^2 S_\rho$$

Sources, Moments

- The sources are given by:
$$S_\rho(\vec{x}) = \int mf(\vec{x}, \vec{v}) d\vec{v}$$
$$S_v(\vec{x}) = \int m\vec{v}f(\vec{x}, \vec{v}) d\vec{v}$$
$$S_E(\vec{x}) = \int \frac{1}{2}mv^2 f(\vec{x}, \vec{v}) d\vec{v}$$

- Express sources in JOREK finite element representation to obtain a continuous function from a list of discrete particles

$$\tilde{S}_\rho(\vec{x}) = \sum_{ijk} p_{\rho,ijk} H_{ij}(s, t) H_{\varphi,k}(\varphi)$$

- Projection using weak form (system of equations to be solved)

$$\int v^*(\vec{x}) \tilde{S}_\rho(\vec{x}) d\vec{x} = \int v^* S_\rho(\vec{x}) d\vec{x}$$

$$\int v^*(s, t) \sum_{ijk} p_{\rho,ijk} H_{ij}(s, t) H_{\varphi,k}(\varphi) d\vec{x} = \int v^* mf(\vec{x}, \vec{v}) d\vec{v} d\vec{x}$$

$$\int H(s, t) \sum_{ijk} p_{\rho,ijk} H_{ij}(s, t) H_{\varphi,k}(\varphi) d\vec{x} = \sum_n H(s, t) mw_n \delta(\vec{x} - \vec{x}_n)$$

Moments: smoothing

- Some smoothing is required
 - depending on number of particles
- Modified projection equation:

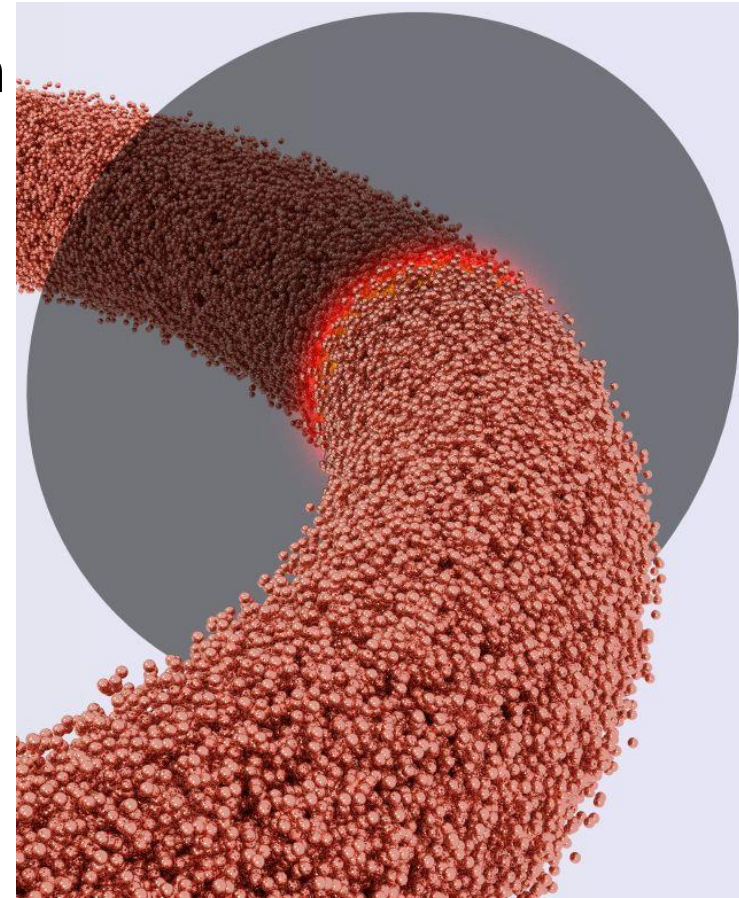
$$\int v^*(\vec{x})(1 - \lambda \nabla^2 - \zeta \nabla^4) \tilde{S}_\rho(\vec{x}) d\vec{x} = \int v^* S_\rho(\vec{x}) d\vec{x}$$

$$\int (v^* \tilde{S}_\rho + \lambda \nabla v \cdot \nabla \tilde{S}_\rho + \zeta \nabla^2 v^* \nabla^2 \tilde{S}_\rho) d\vec{x} = \int v^* S_\rho(\vec{x}) d\vec{x}$$

- LHS matrix is calculated and factorised once (using MUMPS)
- **RHS is collected at every particle step**
 - Important for conservation properties
- Projection (i.e. MUMPS solve) at every JOREK fluid time step

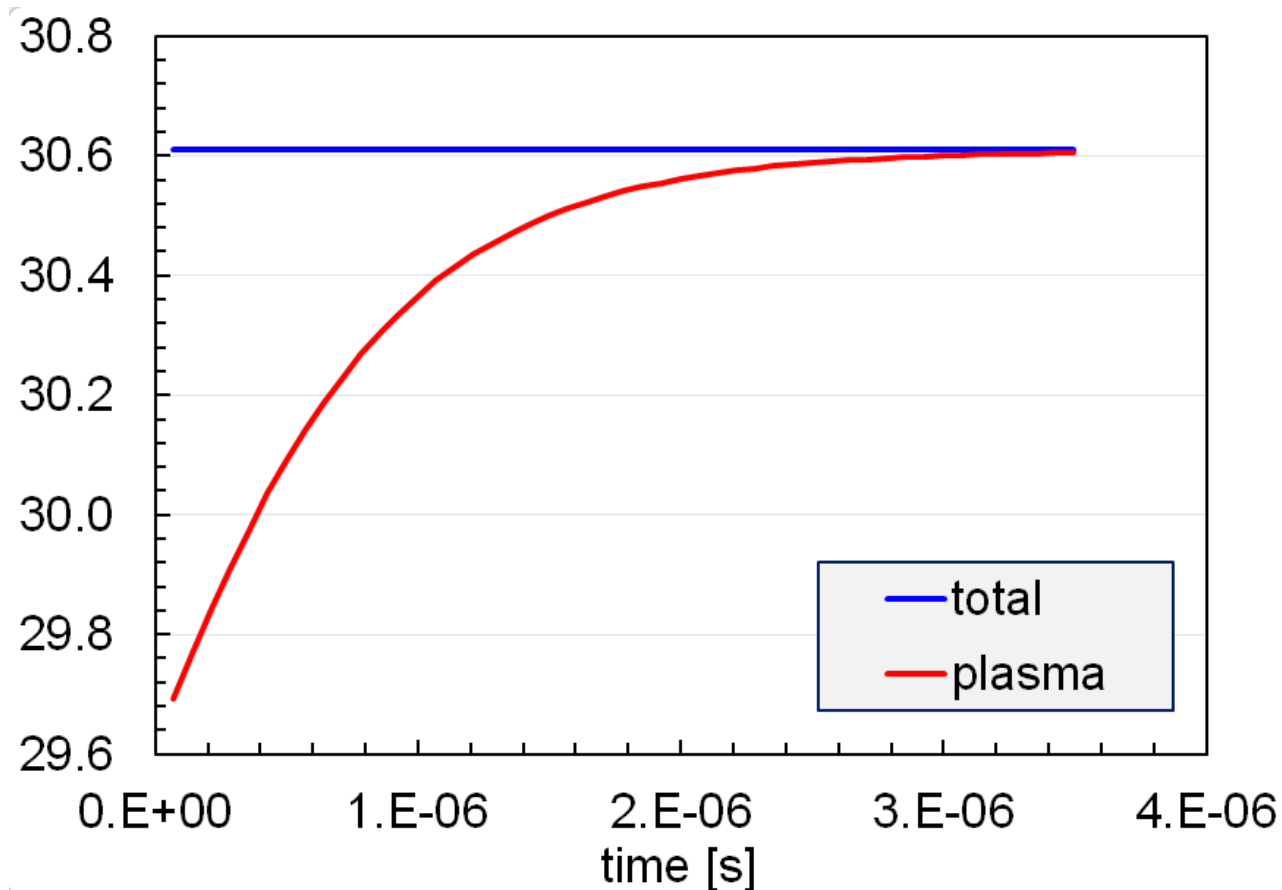
Kinetic Neutrals

- 2-way coupling of JOREK MHD fluid and particles
 - Kinetic neutrals have been implemented and verified
 - Ionisation, charge exchange, radiation
 - Fluid ions arriving at the divertor/wall are reflected as neutral particles
- Test case:
 - Initial particle beam with parallel velocity
 - 100000 neutral particles (10^{20})
 - Ionising within $3.5 \mu\text{s}$
 - Particle time step 10^{-9} s, jorek step 6.87×10^{-8} s

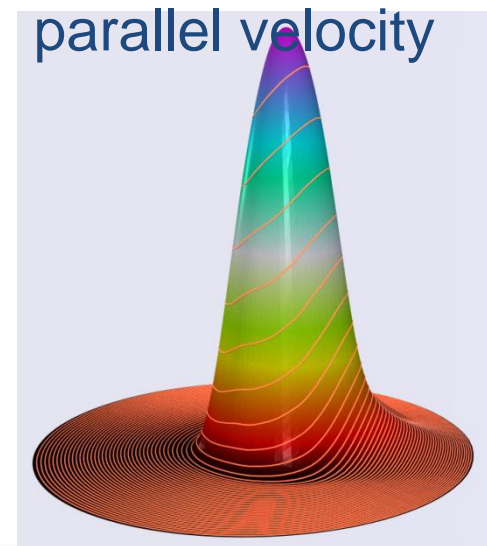
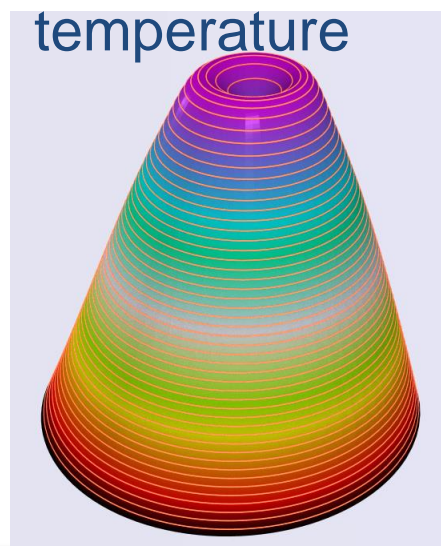
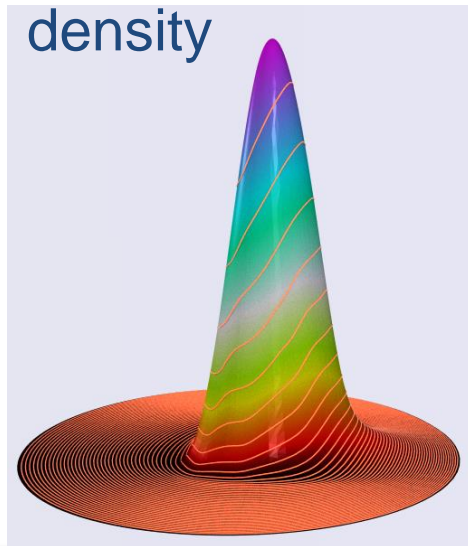
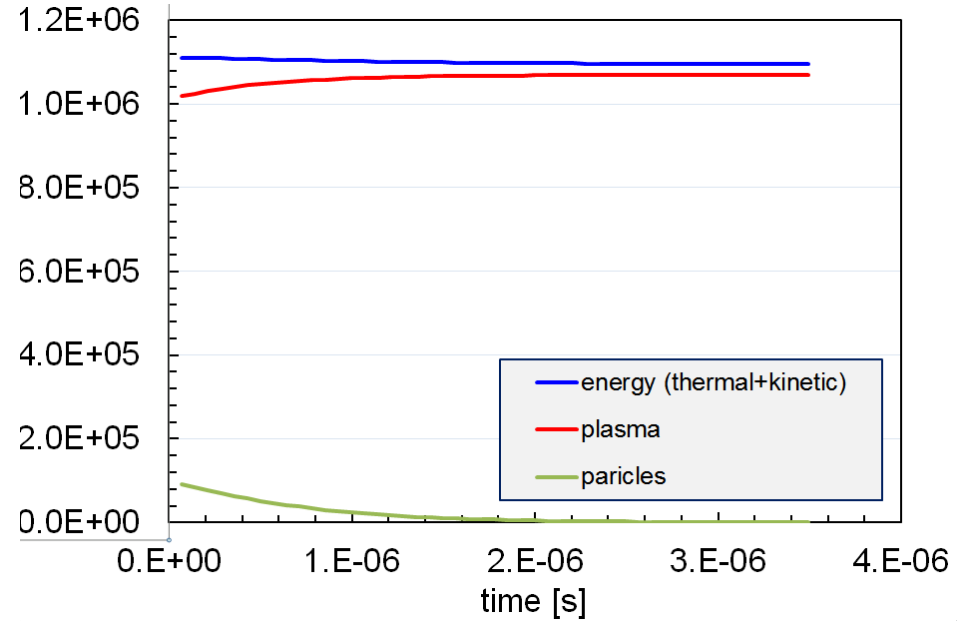
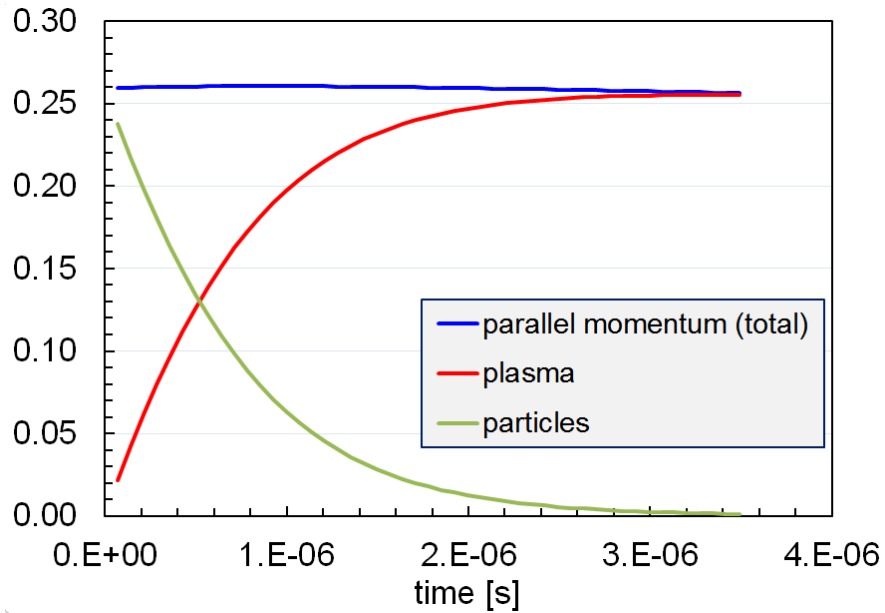


Particle Conservation

- Good particle conservation: error $\sim 2 \times 10^{-4}$
- Good agreement with fluid neutral model

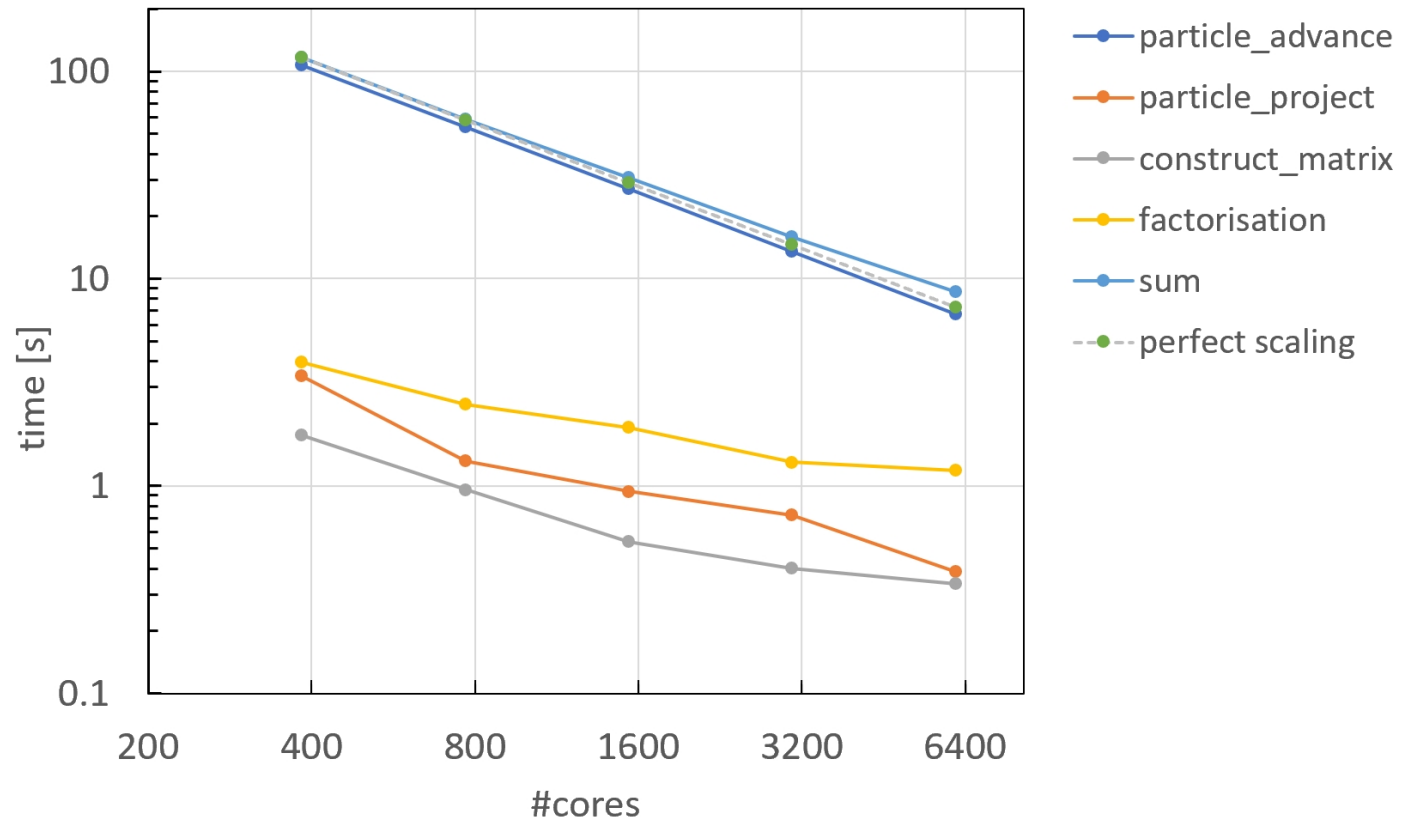


Momentum, Energy conservation



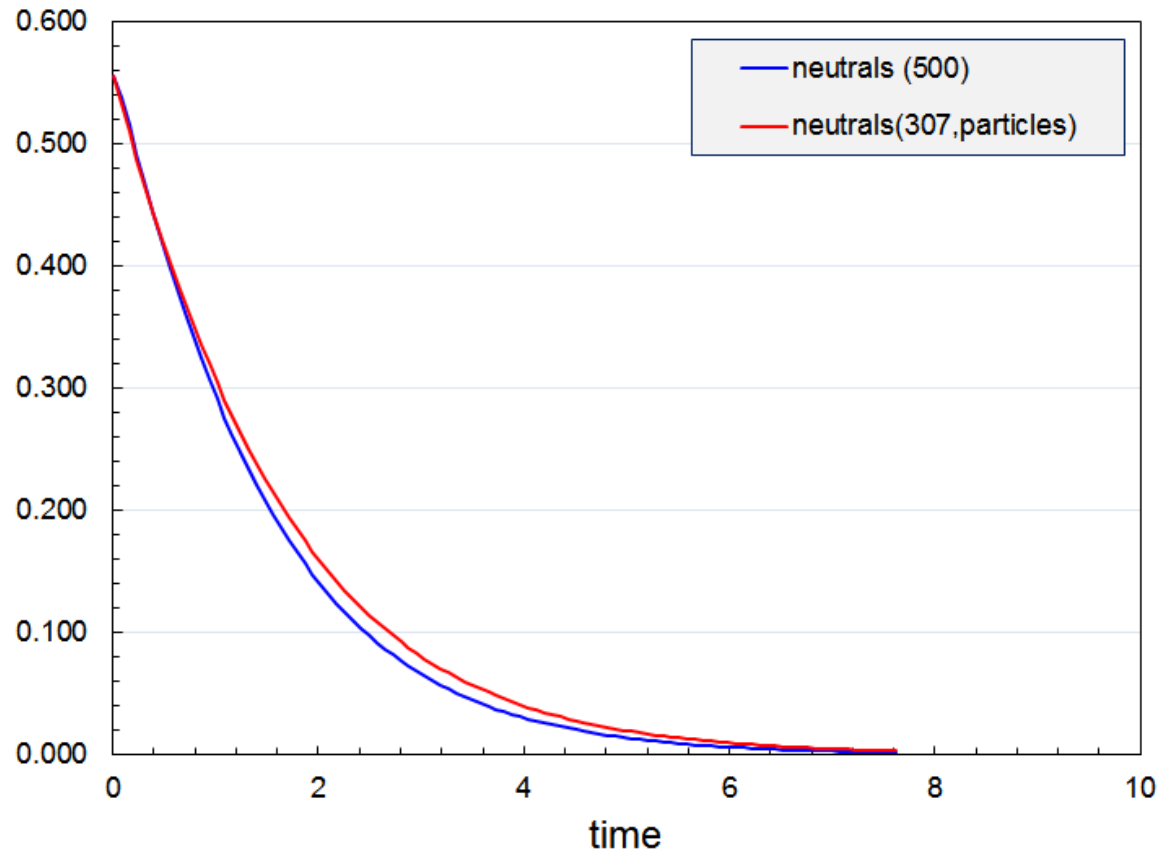
Parallelisation Scaling

- Good parallel scaling as long as particles dominate total time
 - 4×10^7 particles, 1600 elements, 8 toroidal harmonics
 - Marconi, Skylake (1 mpi, 48 threads per node)
 - efficiency 84% at 6000 cores



Comparison model 500-307

- Start with central population of neutrals:
 - this is with an updated model for the ionisation rate in model500
 - 100.000 neutrals, total number 0.555555×10^{20}

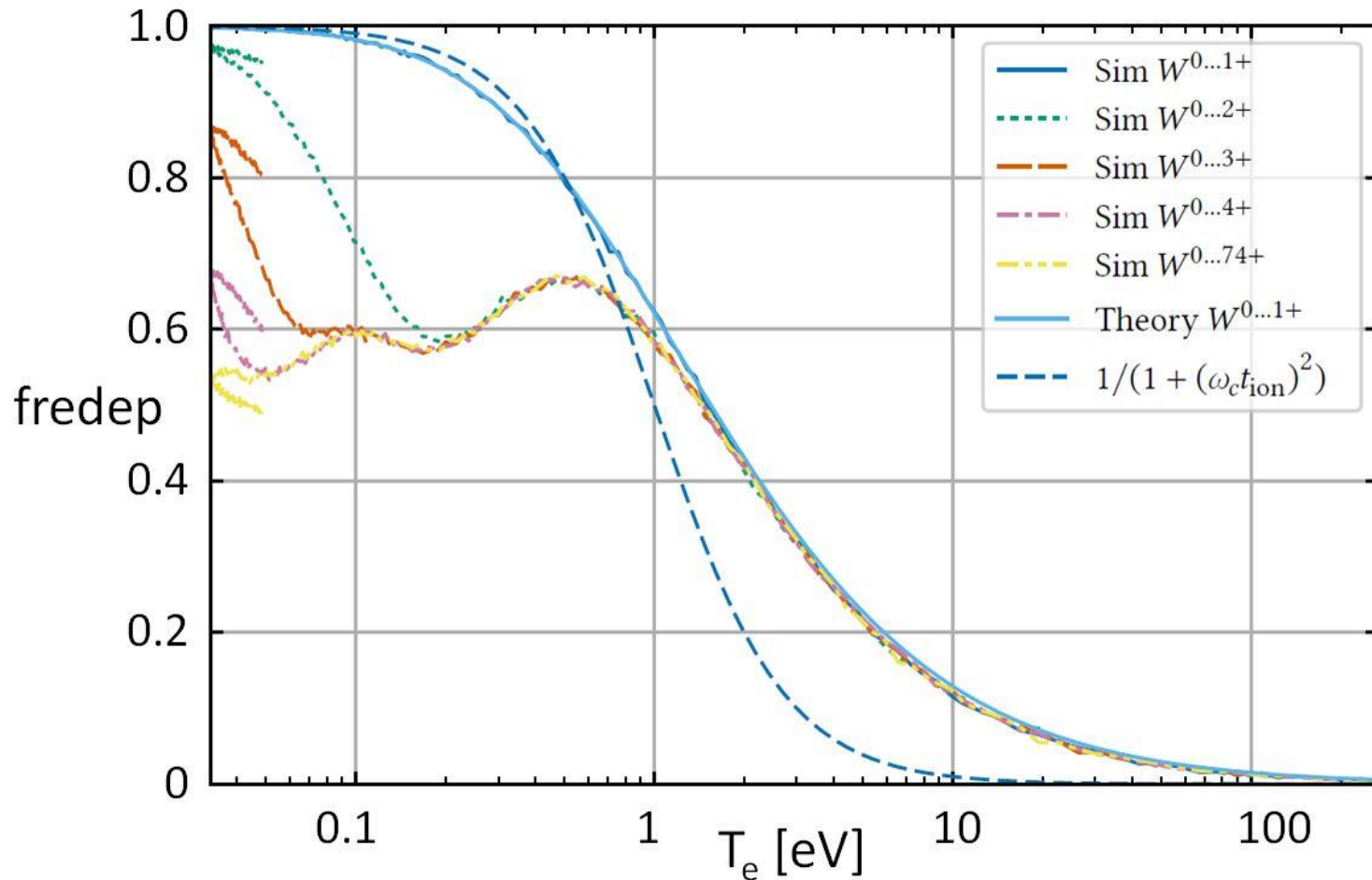


Impurities in JOREK

- **Impurities implemented as kinetic particles**
 - ionisation, recombination, radiation
 - following all charge states, multiple species
 - binary collision model
 - collisions with back ground plasma
- **Sputtering source**
 - sputtering due to plasma fluid and kinetic impurities
 - using Eckstein sputtering yields
- **Applications:**
 - Tungsten source with and without ELMs, prompt redeposition
 - Tungsten transport due to ELMs

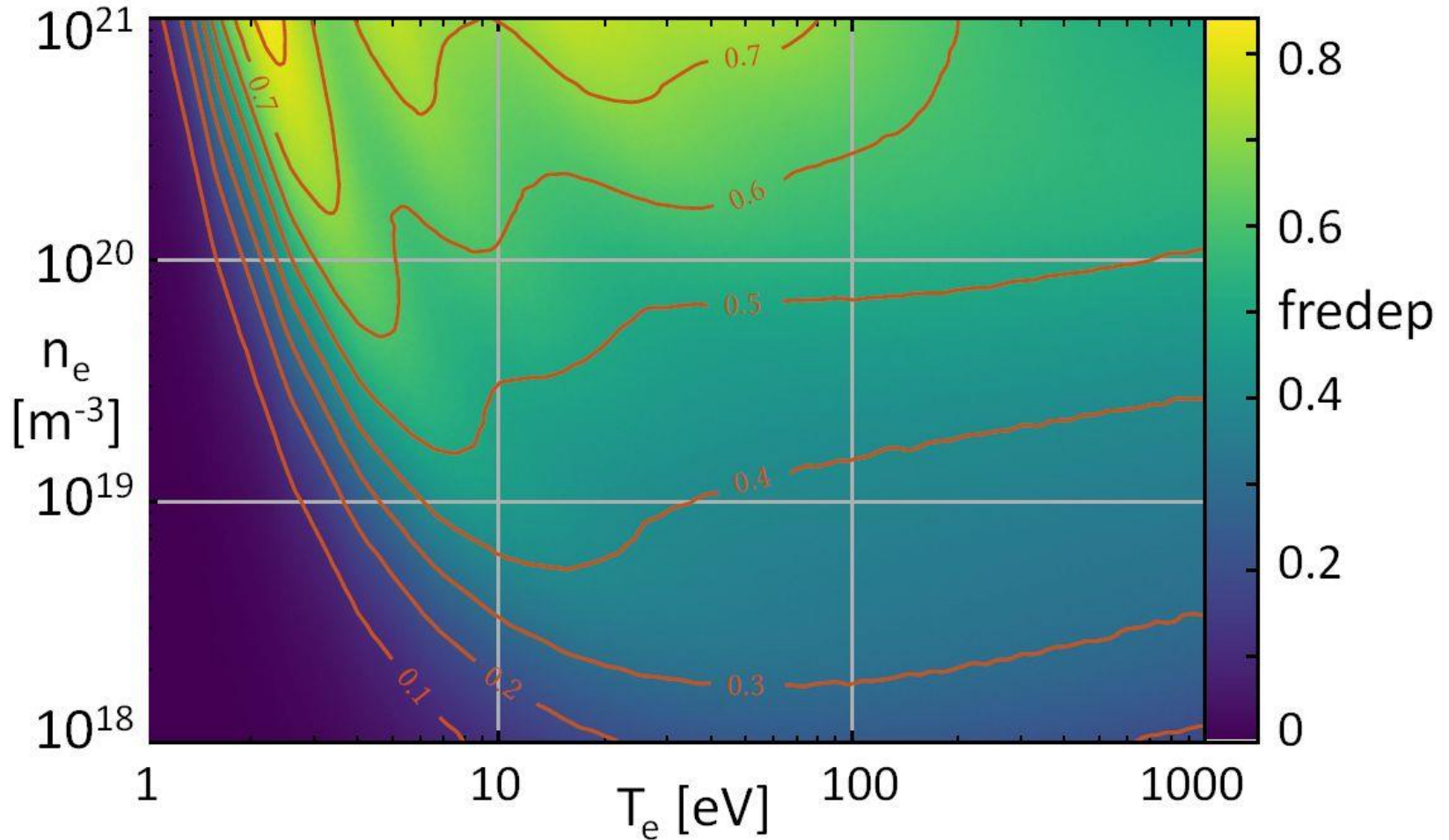
Tungsten Prompt Redeposition

- Multiple ionisations have a strong influence on prompt redeposition fraction



Tungsten Prompt Redeposition

- Density and temperature dependence
 - including multiple ionisations (0-5)



Next Step: Applications

- **Benchmarking**
- **Detachment, ELM burn-through**
- **Divertor solutions in 3D magnetic geometry (RMP)**
- **Impurity transport in ELM controlled regimes**
 - RMP, QH mode
- **Fast particles**
- **Massive Gas Injection , Shattered Pellet Injection**
- **Runaway electrons**