

ELMs in High Recycling ITER Plasmas

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▶ **To cite this version:**

Guido T. A. Huijsmans. ELMs in High Recycling ITER Plasmas. 46th European Physical Society Conference on Plasma Physics (EPS 2019), Jul 2019, Milan, Italy. cea-02555095

HAL Id: cea-02555095
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Submitted on 27 Apr 2020

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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)

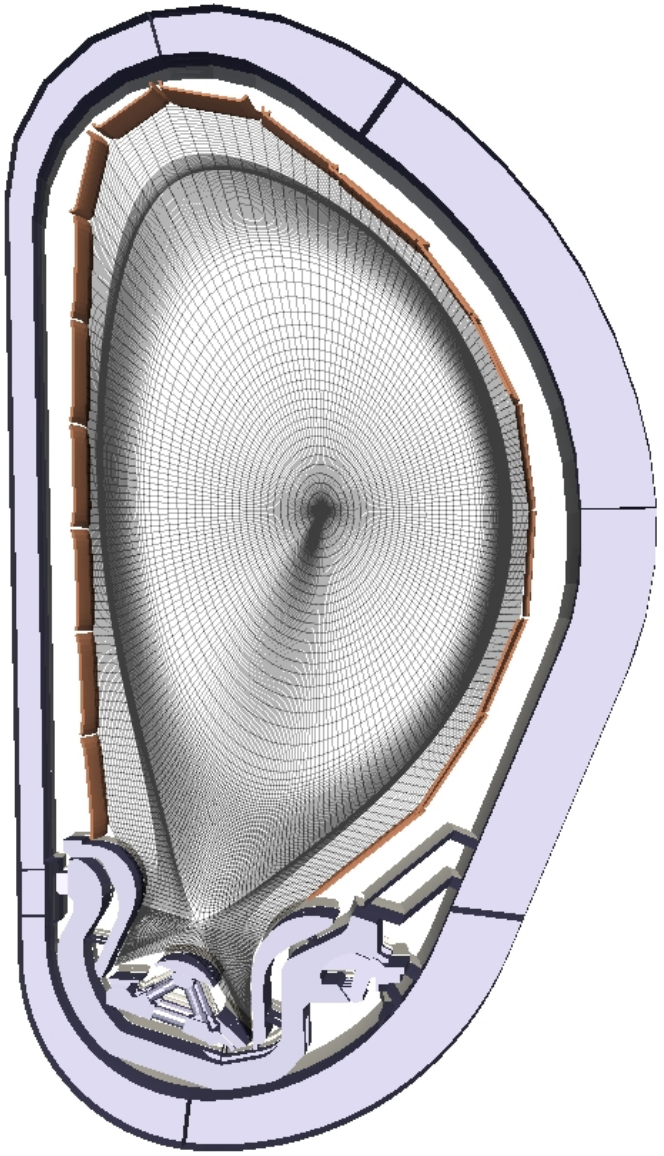
- JOREK code solves the (extended) MHD equations in 3D general tokamak geometry
  - –Closed and open field lines, plasma wall interaction, conducting structures
  - –Main applications: ELMs and disruptions
- developed with the EU fusion program
  - –14 Fusion Labs + Universities, ~25 persons
  - –GIT 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

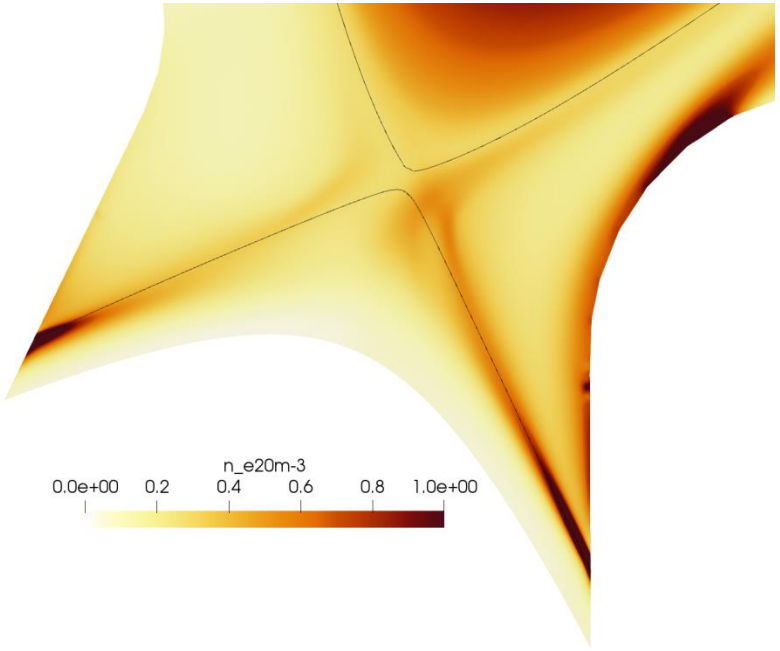
- Grid aligned on equilibrium flux surface, extending to realistic ITER wall (2D)

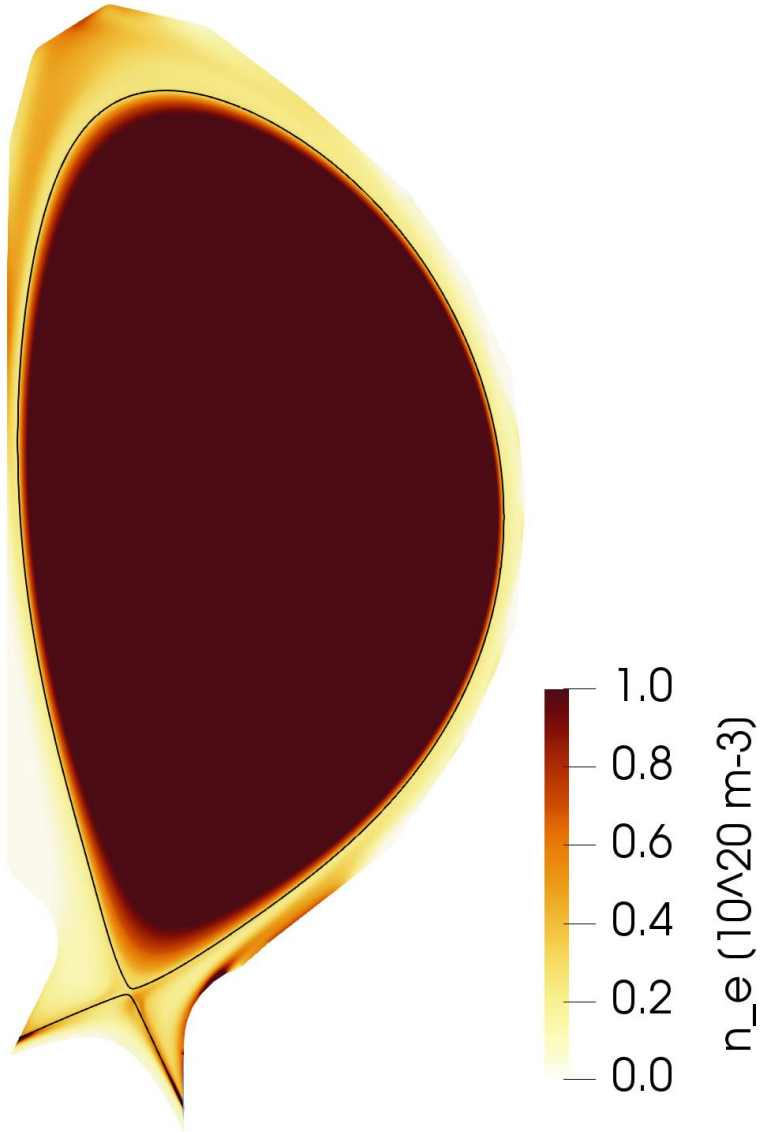
- MHD + Neutral fluid model
  - diffusive neutral model
  - Sheath boundary conditions
    - Mach one
    - Sheath transmission factor
  - Reflection of ions into neutrals



Initial Conditions ITER scenario

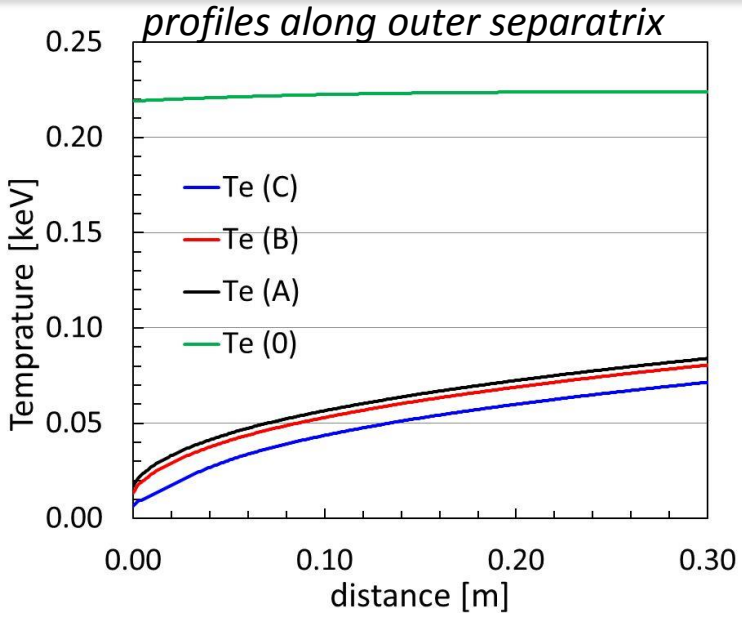
- Initial quasi-stationary state with high recycling ITER divertor
  - –15MA/5.3T Q=10 scenario (IMAS #131025)
  - – $W_{thermal}$ = 410 MJ
  - – heating power 110 MW

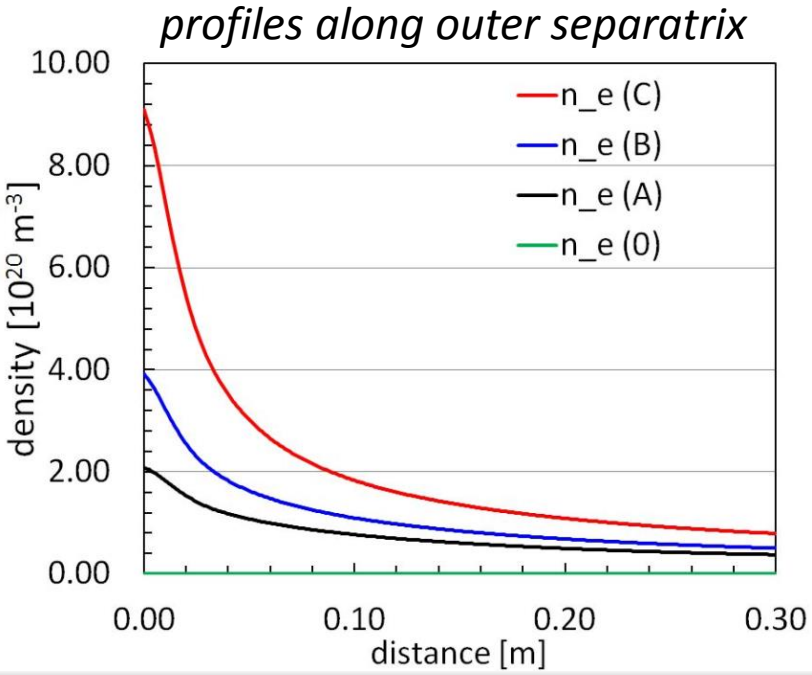


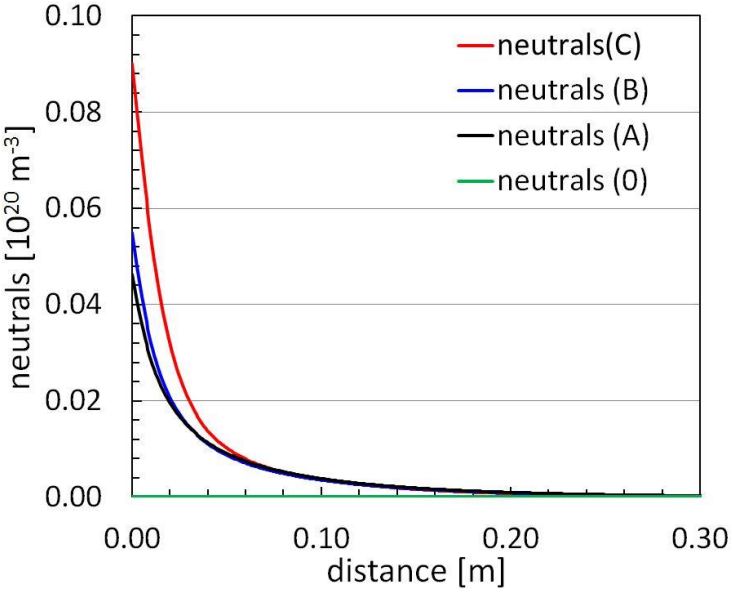


Initial Conditions: Divertor

- High recycling ITER divertor
  - neutral gas injection
  - Neon background impurity ($5x10^{-3}$)
  - T_{div} ~ 6eV, Q_{max}~ 6 MW/m^2

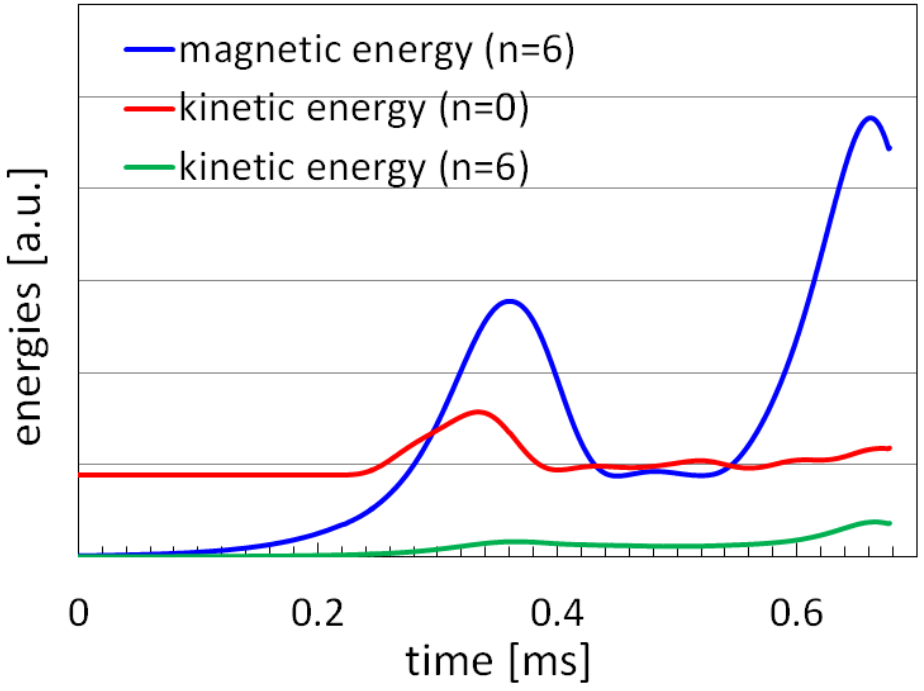


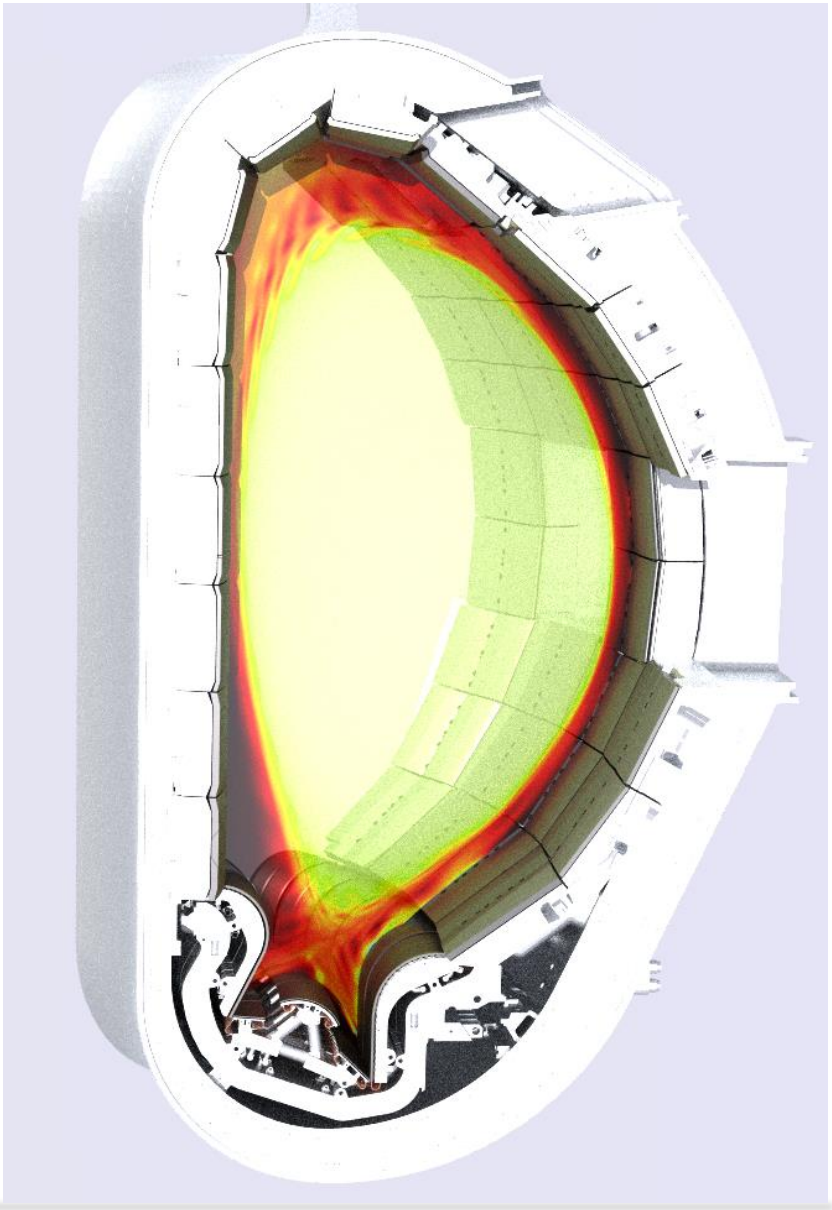




Small ELM

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

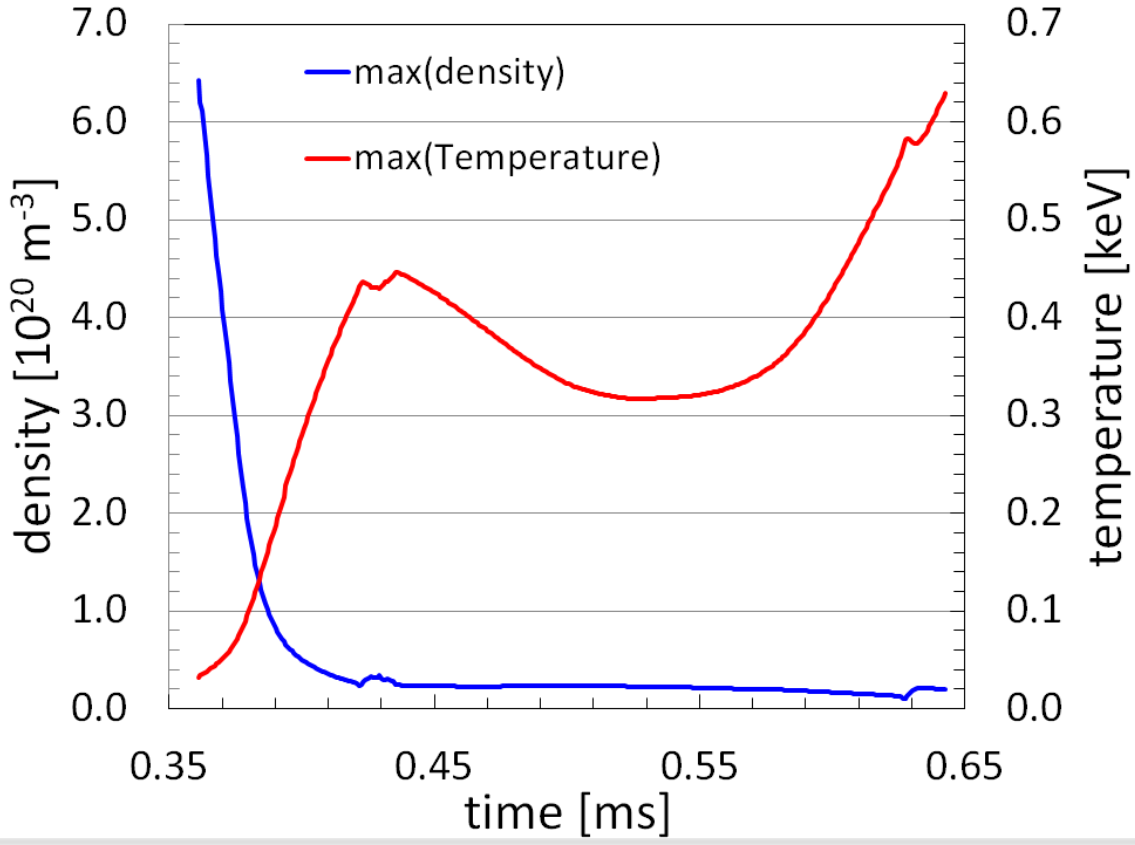




density profile at t=0.65ms

ELM “Burn through”

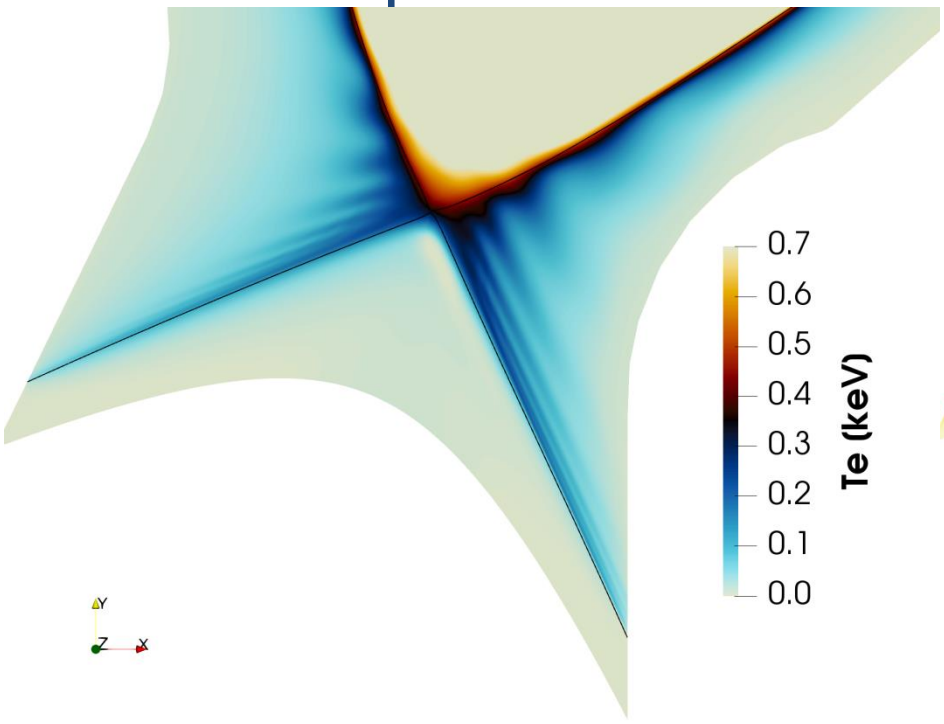
- The high density at the divertor is quickly (**within 100μs**) removed by the ELM
  - together with fast temperature rise
  - at this time very little thermal energy has been lost : **ΔW ~ 0.12 MJ**



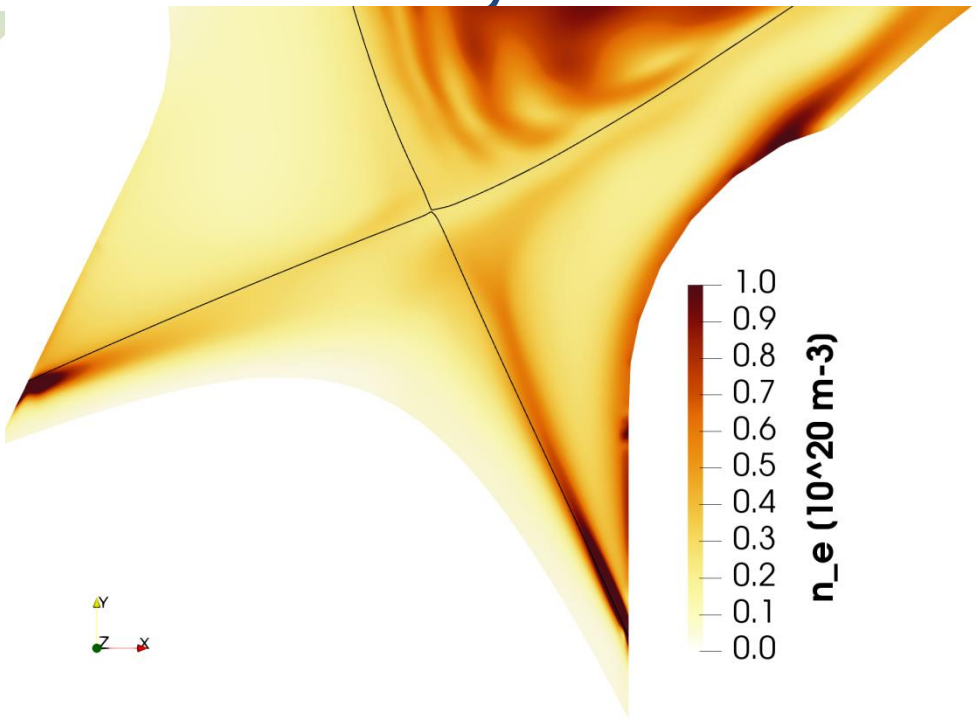
Snapshots

- t=0.35ms

Temperature

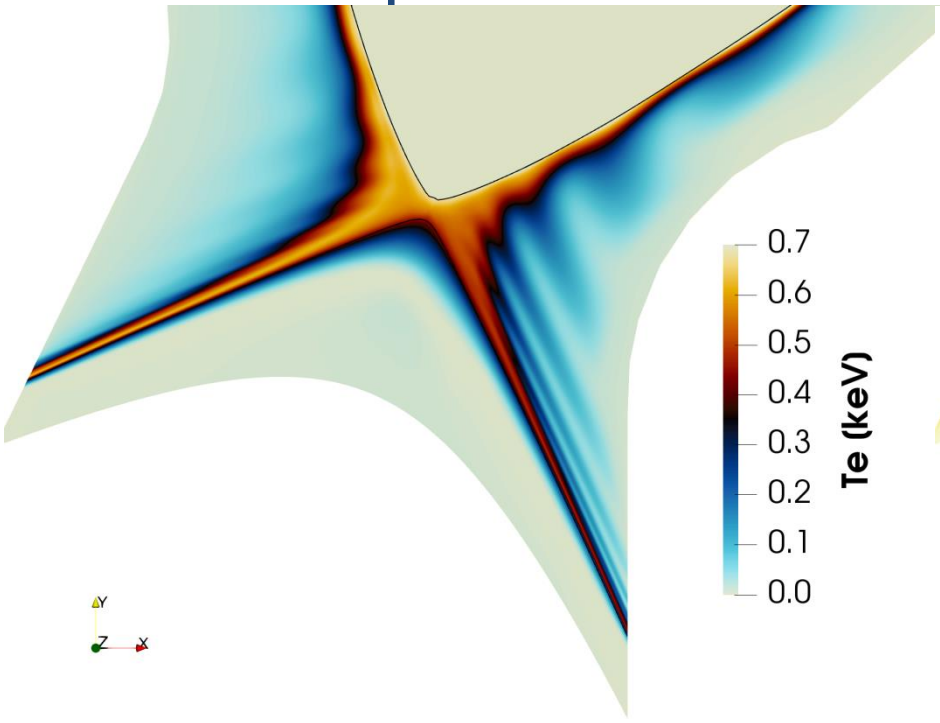


Density

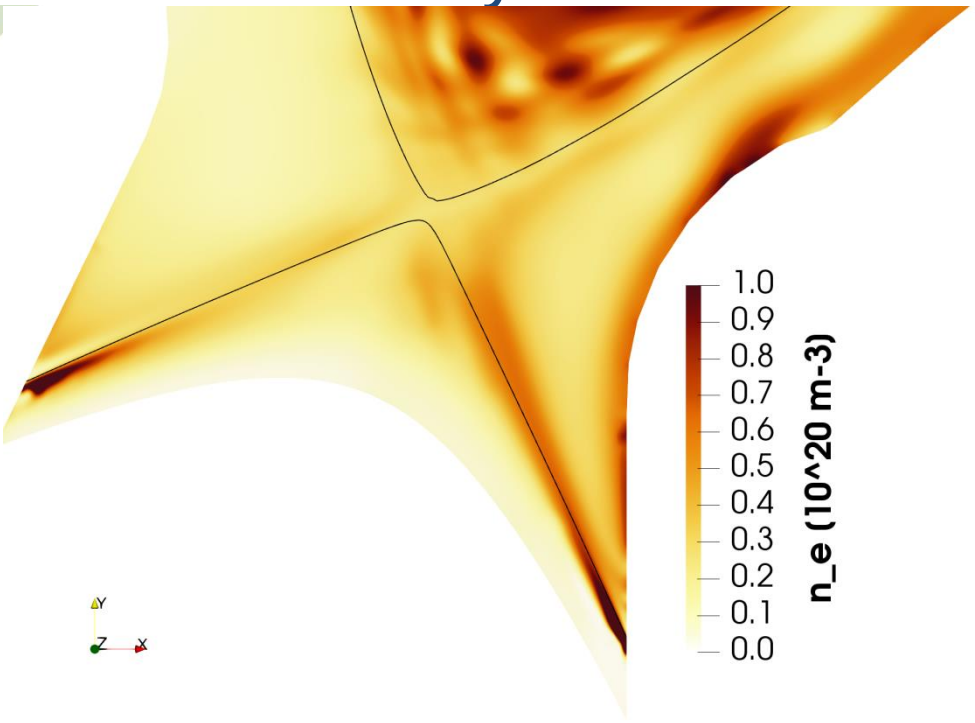


- t=0.45ms

Temperature

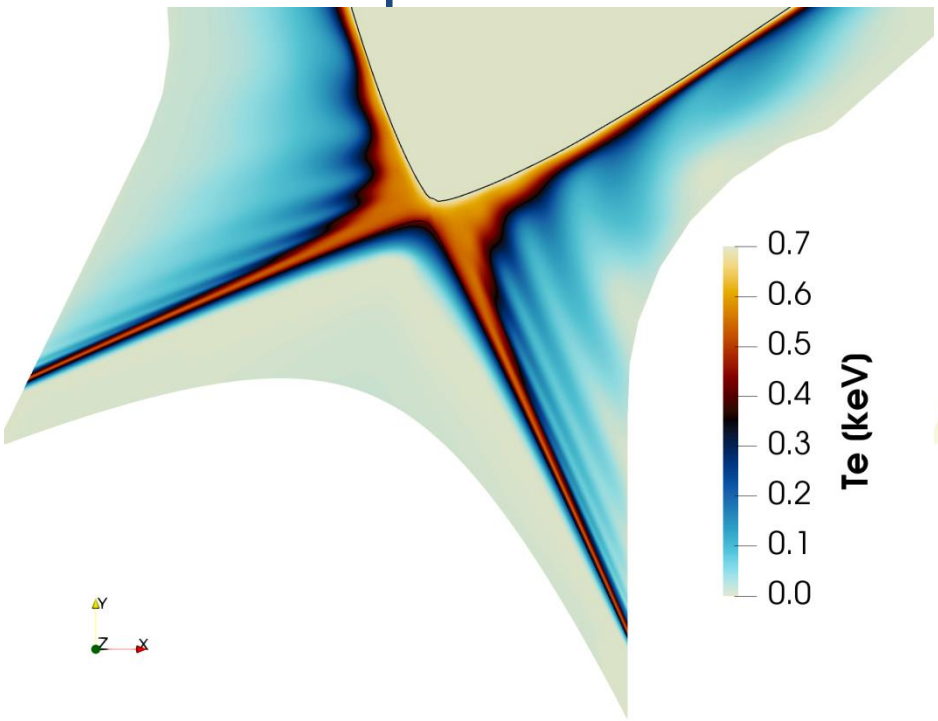


Density

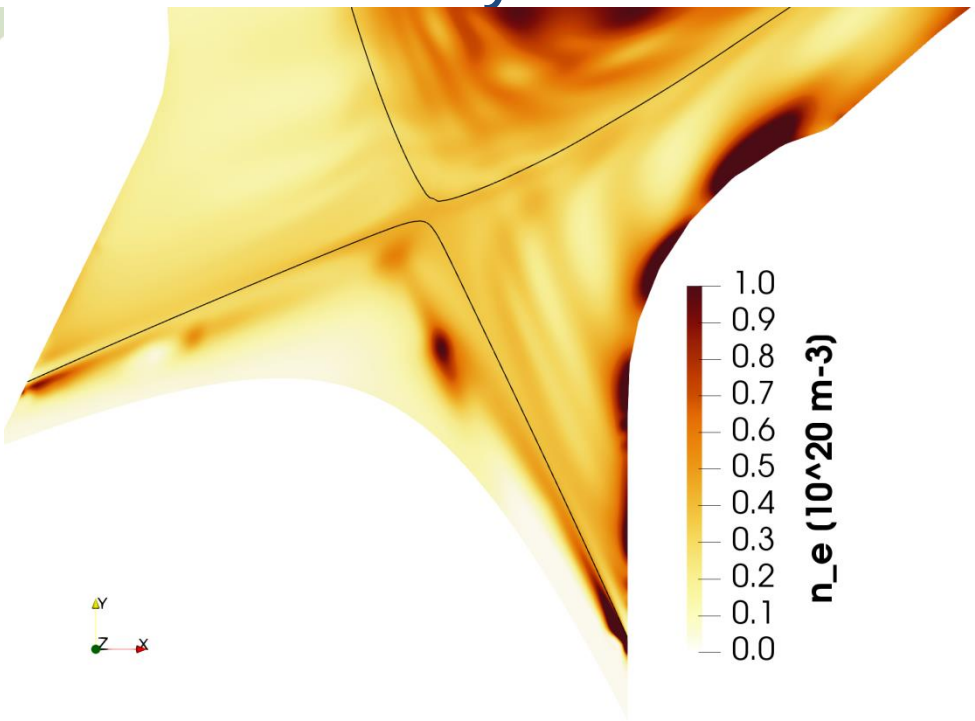


- t=0.65ms
  - a narrow channel of low density, high temperature at the main strike point

Temperature

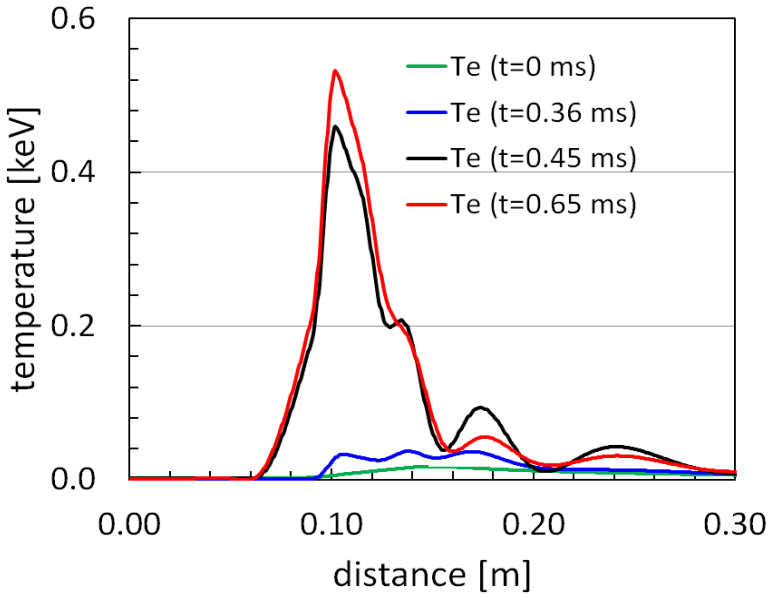


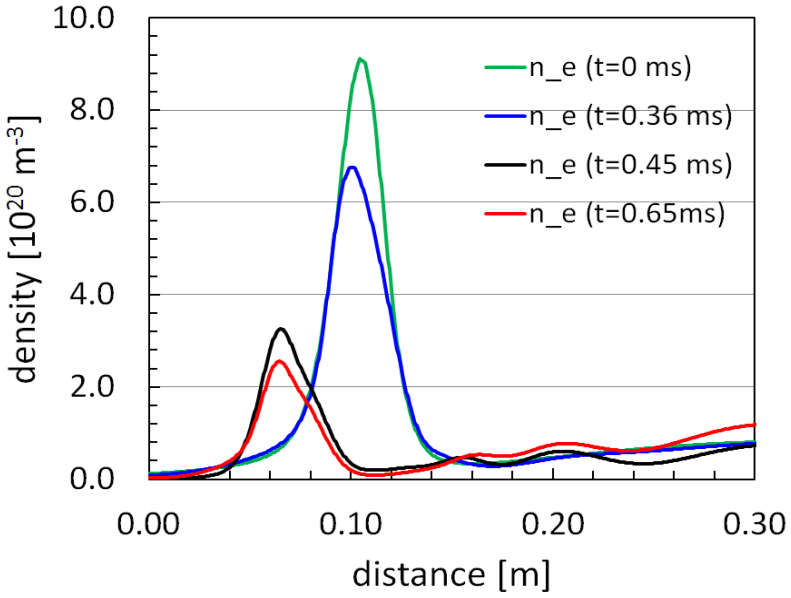
Density

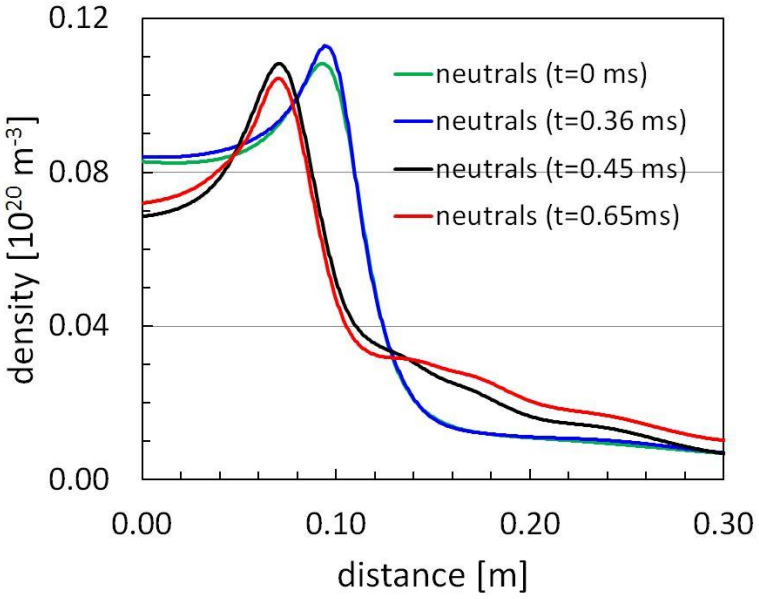


Outer Divertor Profiles

- One narrow peak in power deposition profile
  - no broadening
- High density and neutrals displaced below separatrix
- Peak heat flux ~ 1GW/m^2

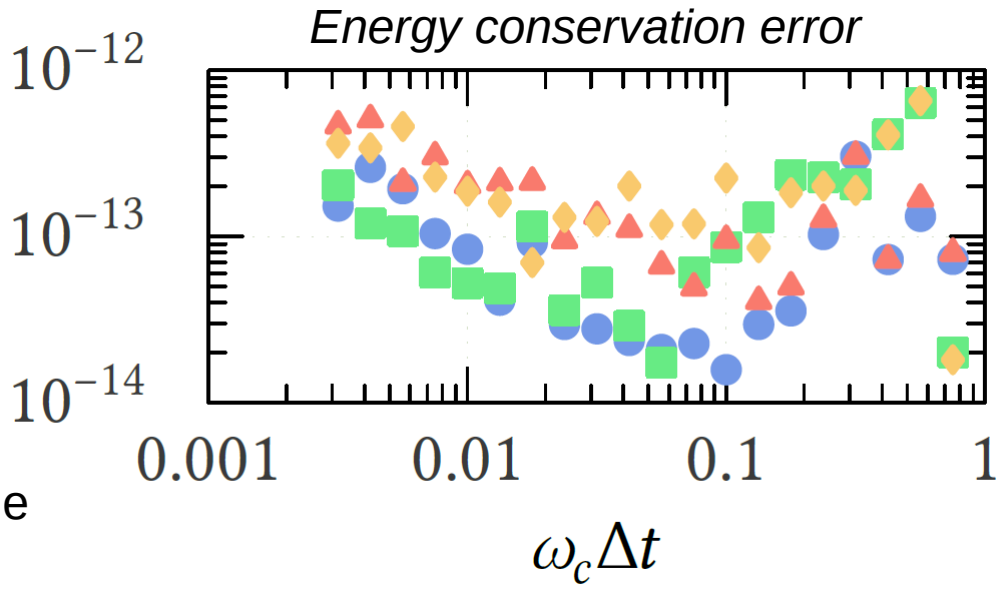






Particles in JOREK

- 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 ~Δt^2

Kinetic Neutrals

- Coupling of JOREK MHD fluid and particles
  - –Particle contributions become sources in MHD equations
    - Conservative form:

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

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

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

    - JOREK form

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

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

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

Sources, Moments

- The sources are given by:

$$S_\rho(\vec{x}) = \int m f(\vec{x},\vec{v})\, d\vec{v}$$
$$S_v(\vec{x}) = \int m\vec{v} f(\vec{x},\vec{v})\, d\vec{v}$$
$$S_E(\vec{x}) = \int \tfrac{1}{2} m v^2 f(\vec{x},\vec{v})\, d\vec{v}$$

- 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)

$$\int v^*(\vec{x}) \tilde{S}_\rho(\vec{x})\, d\vec{x} = \int v^* S_\rho(\vec{x})\, d\vec{x}$$
$$\int v^*(s,t) \sum_{ijk} p_{\rho,ijk} H_{ij}(s,t) H_{\varphi,k}(\varphi) d\vec{x} = \int v^* m f(\vec{x},\vec{v})\, d\vec{v} d\vec{x}$$
$$\int H(s,t) \sum_{ijk} p_{\rho,ijk} H_{ij}(s,t) H_{\varphi,k}(\varphi) d\vec{x} = \sum_n H(s,t)\, m w_n \delta(\vec{x} - \vec{x}_n)$$

Moments: smoothing

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

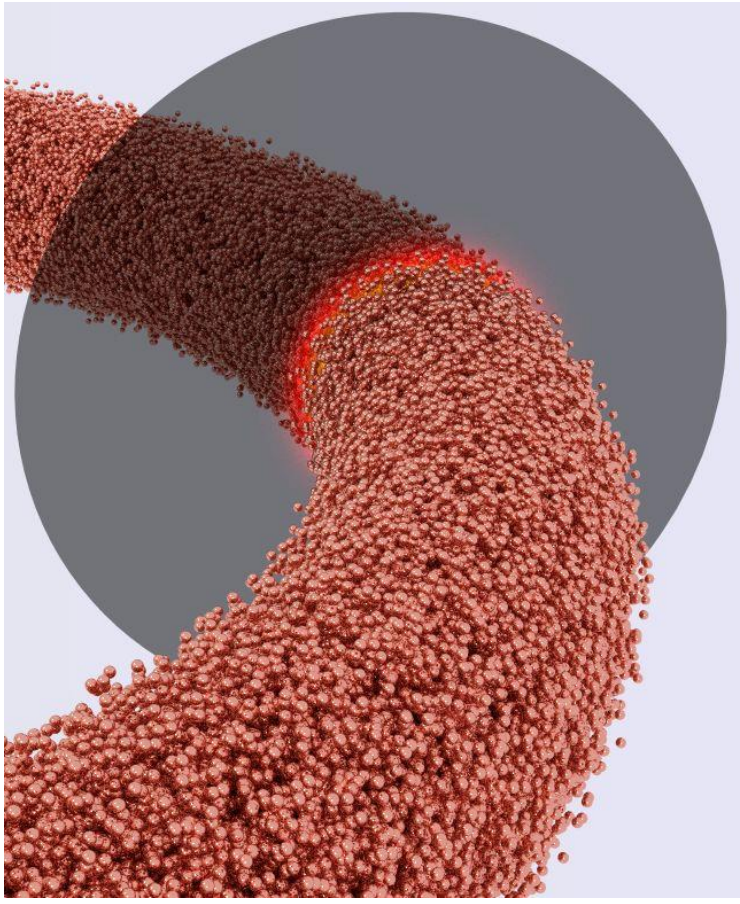
$$\int v^*(\vec{x})\left(1-\lambda\nabla^2-\varsigma\nabla^4\right)\tilde{S}_\rho(\vec{x})\,d\vec{x}=\int v^* S_\rho(\vec{x})\,d\vec{x}$$

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

  - – 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

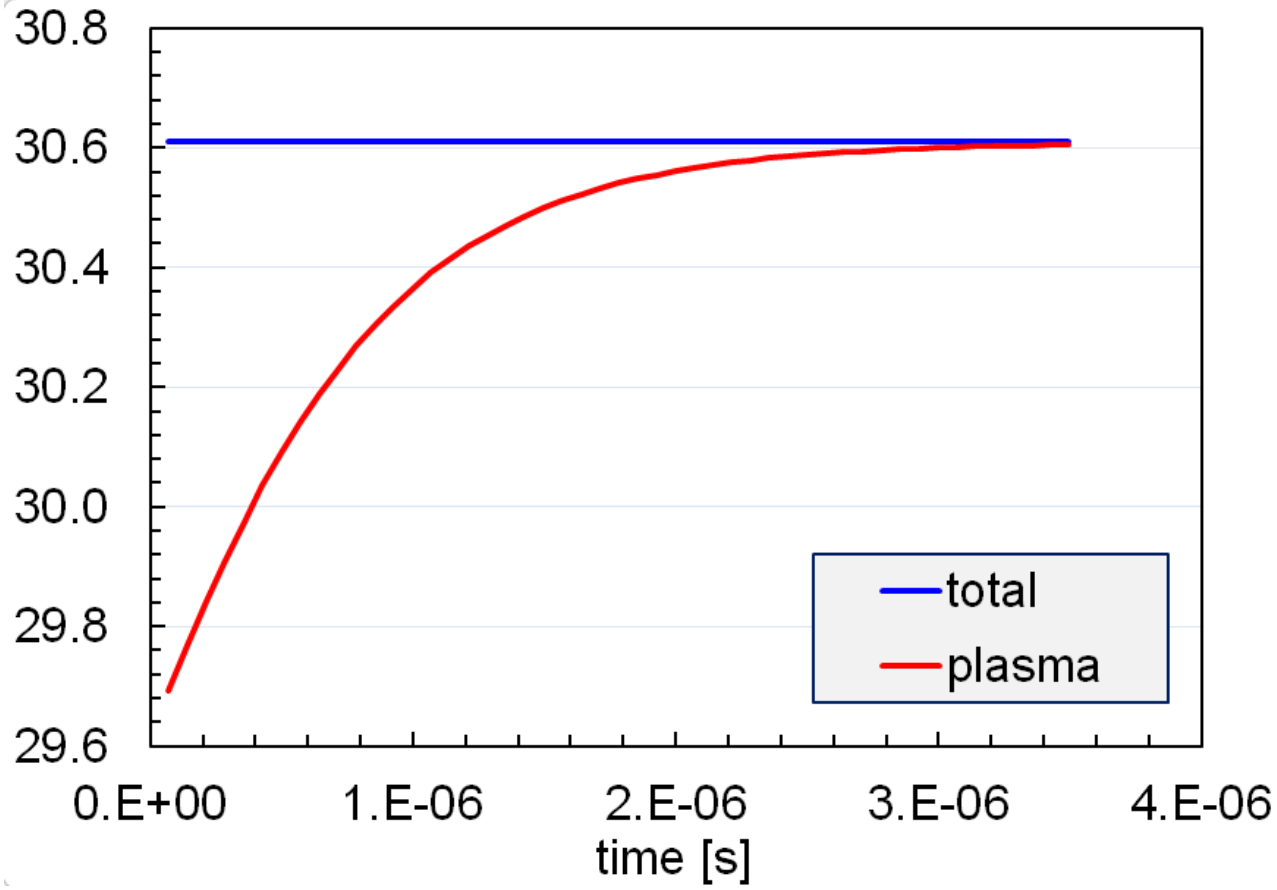
Kinetic Neutrals

- 2-way coupling of JOREK MHD fluid and particle s
  - –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 μs
      - Particle time step 10^{-9} s, jorek step 6.87×10^{-8}s

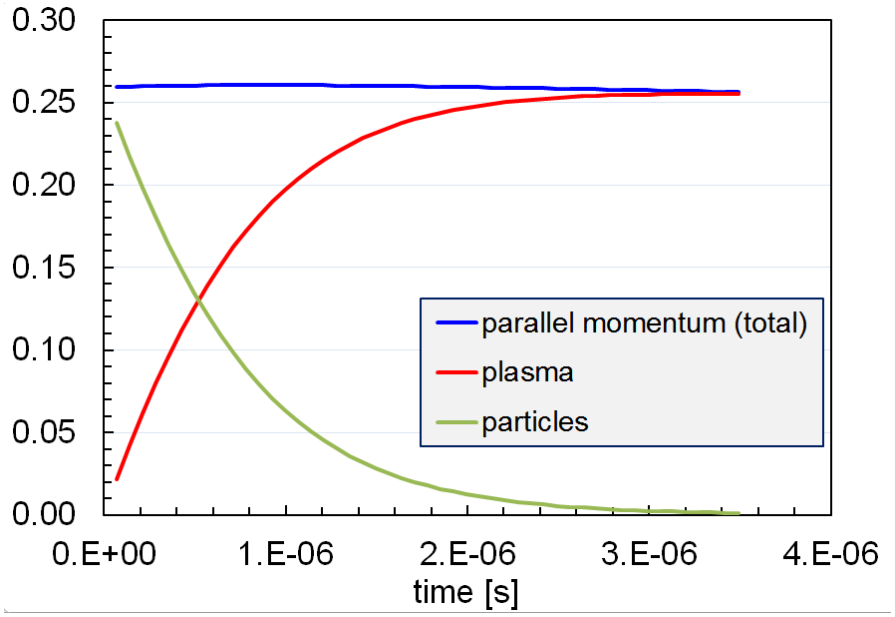


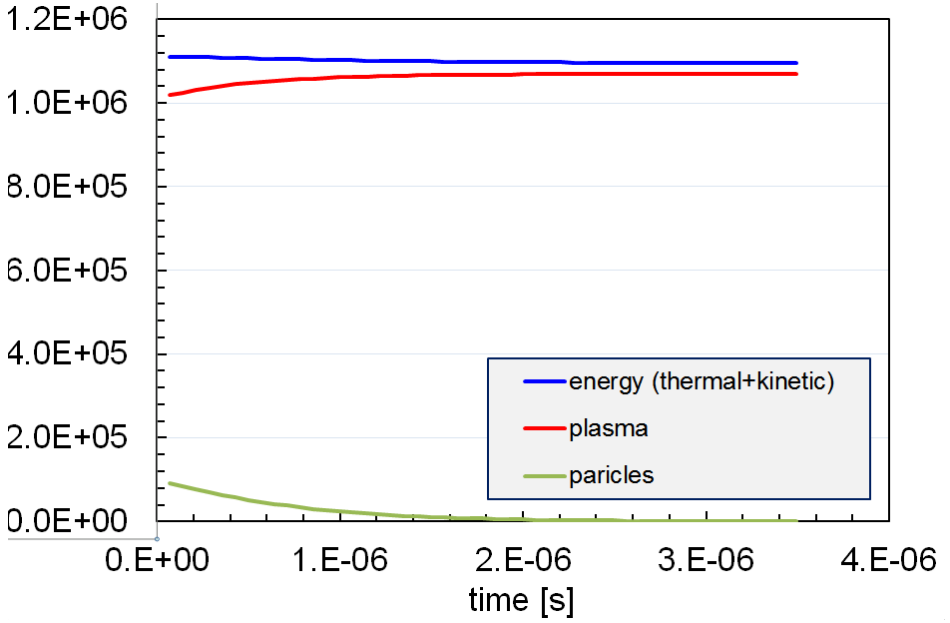
Particle Conservation

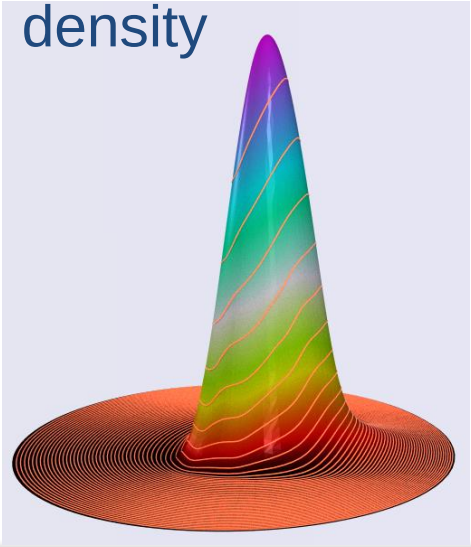
- Good particle conservation: error ~2×10^{-4}
- Good agreement with fluid neutral model

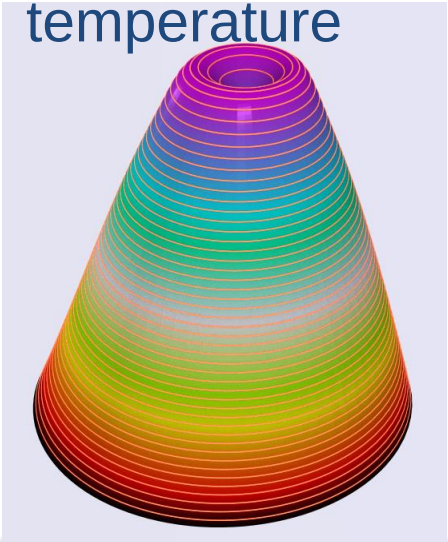


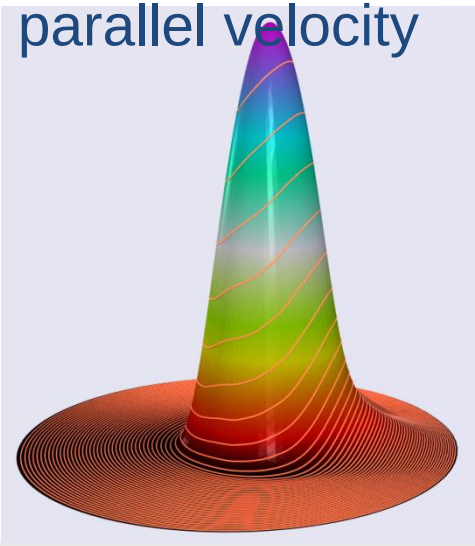
Momentum, Energy conservation





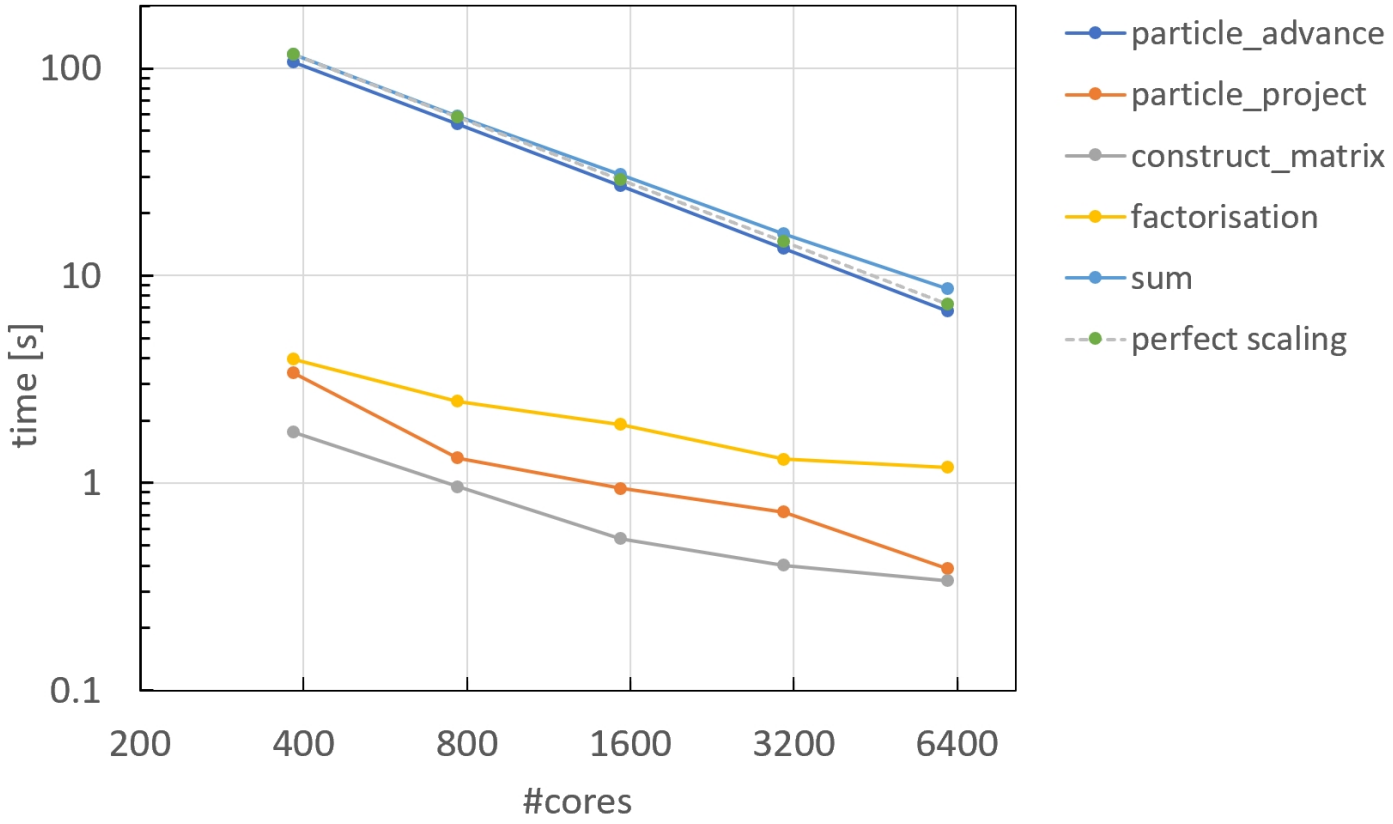






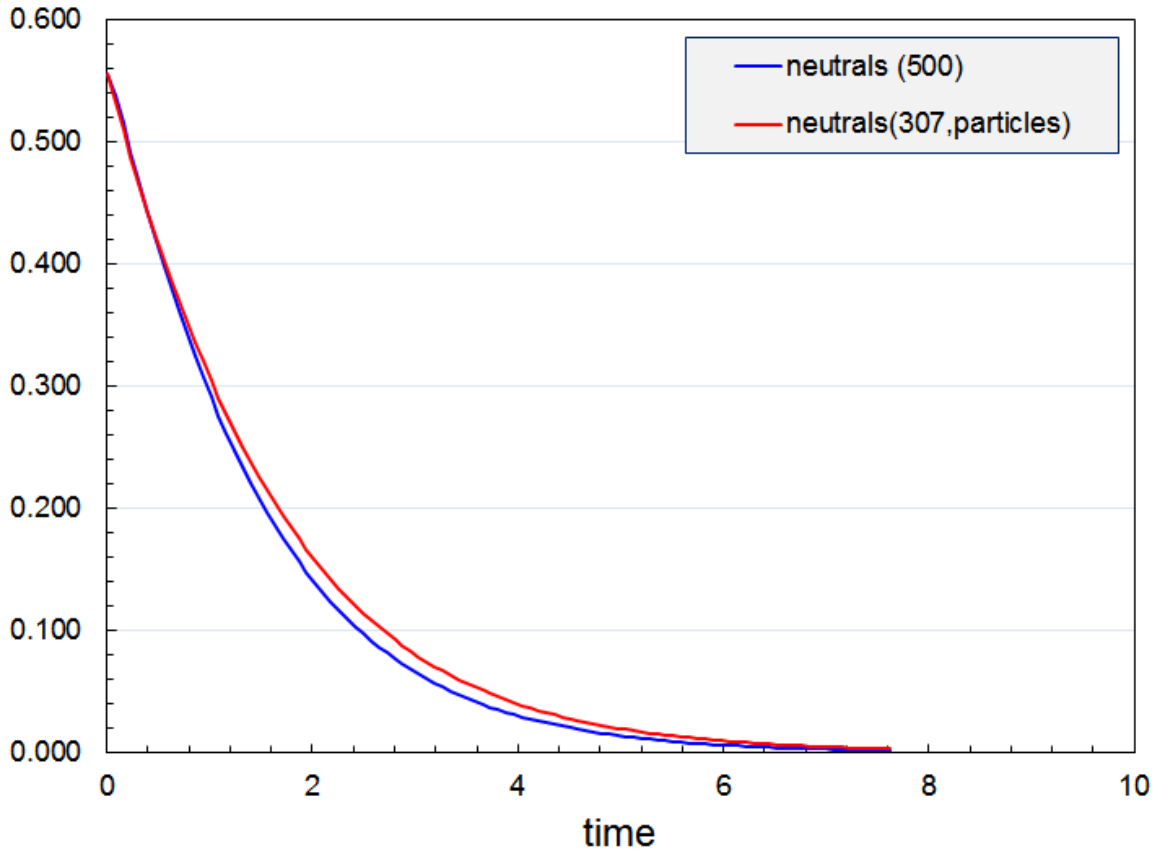
Parallelisation Scaling

- Good parallel scaling as long as particles dominate total time
  - $4x10^7$ 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}

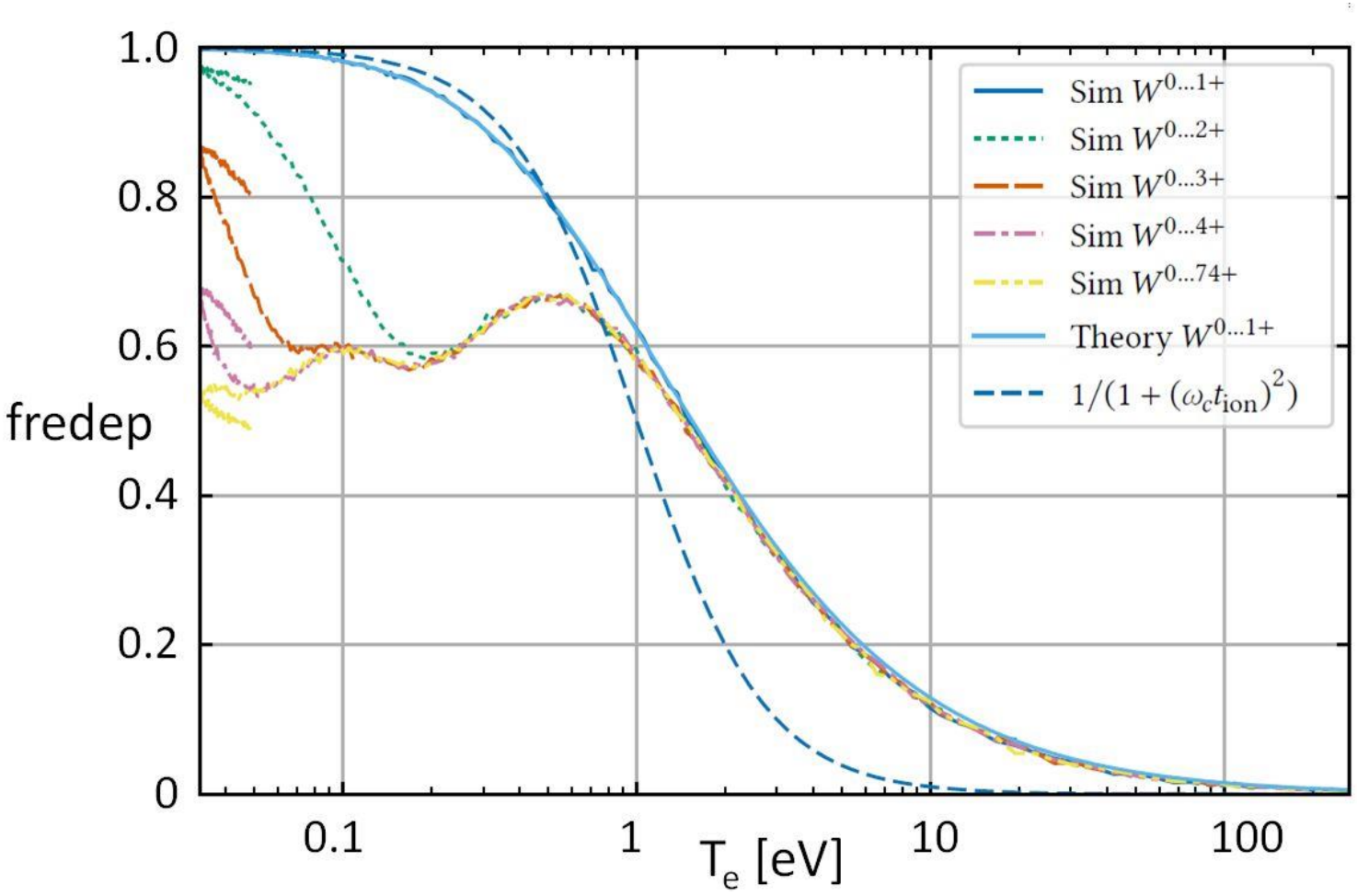


Impurities in JOREK

- **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

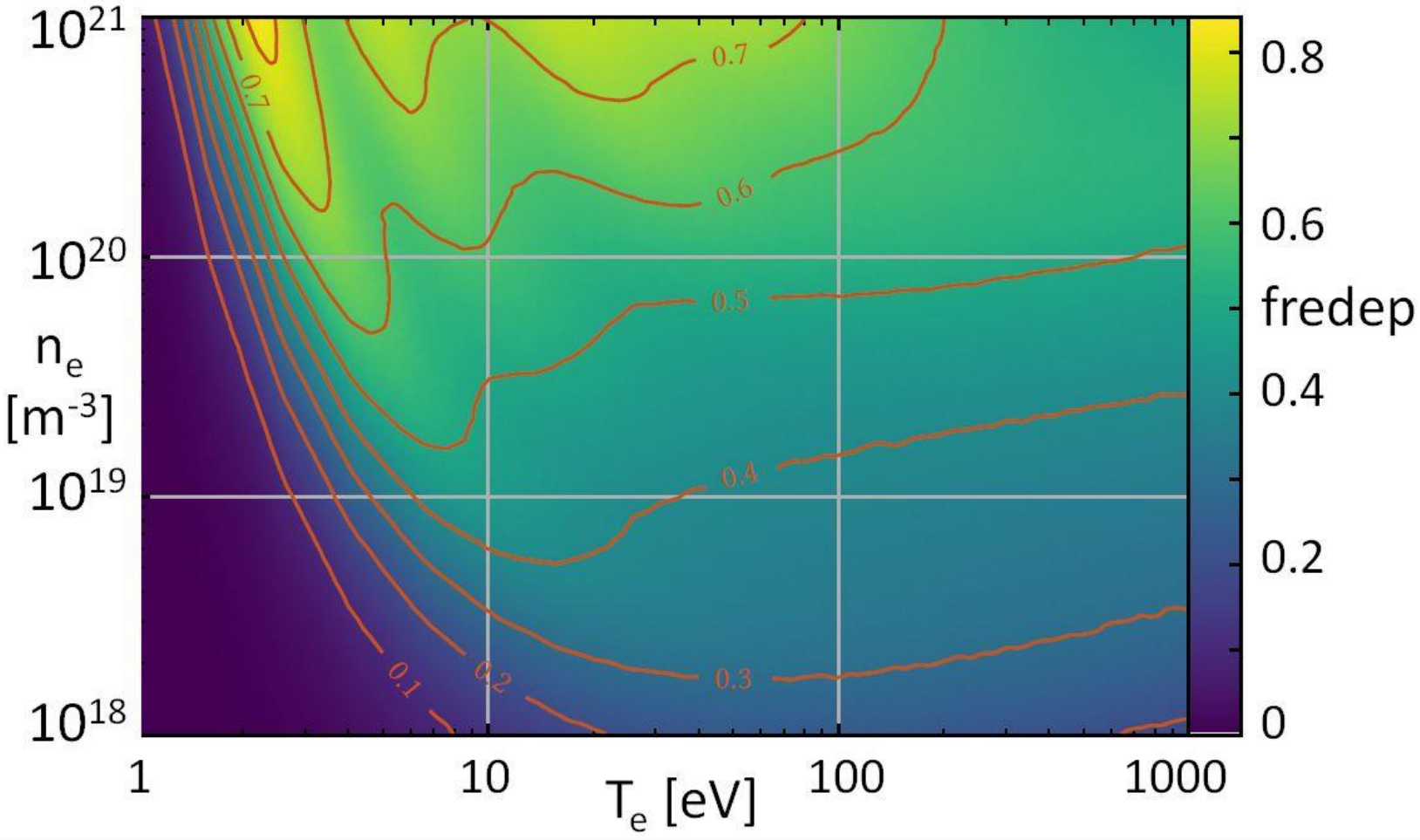
Tungsten Prompt Redeposition

- 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