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ASCOT:
racetrack for tokamak particles

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on behalf of

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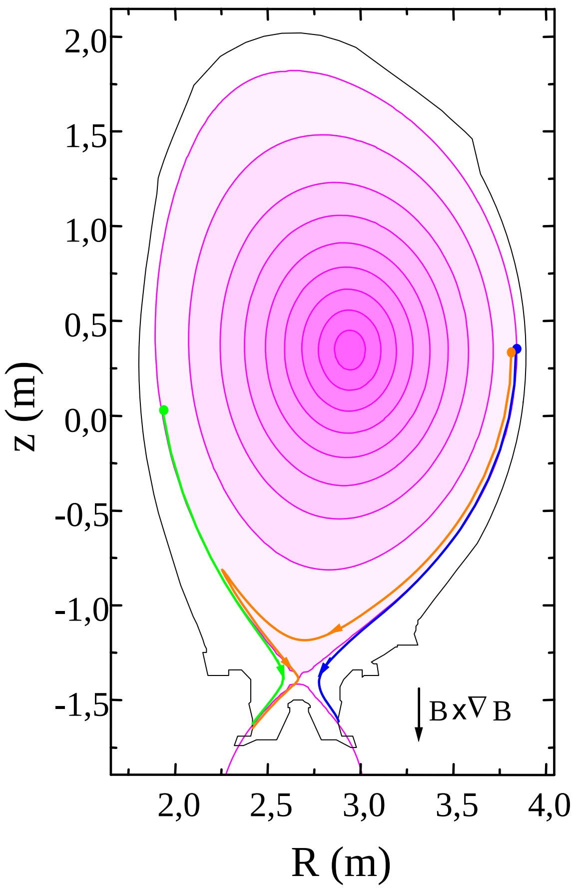
The ASCOT code

Accelerated **S**imulation of **C**harged Particle **O**rbits in **T**ori



Developed in collaboration with VTT since 1991, ASCOT has been applied to numerous problems from studies of relativistic reverse runaway electrons and LH/IC heating & current drive to orbit loss and divertor load studies and simulations of CX diagnostics.

Figure: escaping deuteron orbits at the edge region of JET (#50401, 1.6s).

The main features of ASCOT:

- **Guiding-center orbits** of test particles are solved by integrating the equation of motion over time steps in **5-dimensional phase space** across entire poloidal cross section, including the wall structures.
- Effects of particle **collisions** and **RF waves** are modelled with **Monte Carlo operators** derived from the respective Fokker-Planck terms
- $\mathbf{E_r}$ given either in analytical form or extracted from experimental database.
- **Binary collisions** can be used if momentum conservation is essential
- The magnetic and plasma backgrounds are directly extracted from the **experimental databases** (e.g. ASDEX Upgrade, JET, DIII-D, Wendelstein 7-X)
- **Relativistic treatment** of test particles can be used to facilitate electron studies
- **Parallelized** using the MPI (Message Passing Interface) standard
- Ideal for EGEE grid computation

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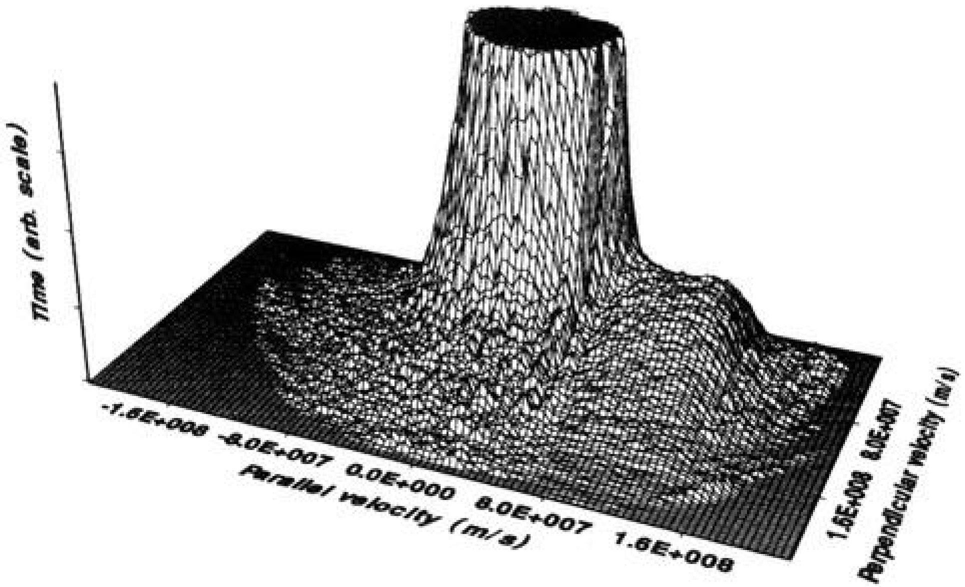
The ASCOT code …cont'd



The effect of the LH wave on the velocity distribution of 20 relativistically treated test electrons at $\rho = 0.40$ m in a JET-sized tokamak with $R_0 = 3.0$ m, $a = 1.2$ m, $B_0 = 3.45$ T, elongation $\kappa = 1.6$, plasma current $I_\phi = 4.8$ MA, $n_{e,i} = 2 \times 10^{19}$ m^{-3}, and $T_{e,i} = 5$ keV. The LH wave parameters used are $f_{LH} = 3.7 \times 10^9$ s^{-1}, $k_{LH} = 220$ m^{-1}, and the region of parallel velocity in which the wave affects particles is $\pm 4.5 \times 10^7$ m/s around the phase velocity.

More recent features of ASCOT:

- ITPA/ITM recommendations → Interface to experimental data using **MDSPlus** (AUG). Simulation results stored to a local MDSPlus server starting summer 2006.
- Realistic **3D magnetic field**:
  $B_\varphi = B_0\{(I_1 - I_2)/(I_1 + I_2)\}[B_1(R,z)\cos(N\varphi/2) + B_2(R,z)\cos(N\varphi)]$.
- 2D wall geometry
- Re-start option
- **NBI ion birth profiles** interfaced to FAFNER (AUG) and PENCIL (JET) codes
- **Analytical models** for NB ion and fusion alpha birth profiles
- 2D SOL background from EDGE2D or SOLPS
- **CX-reactions** modelled in SOL
- A numerical model for **NPA**
- Simulation of **thermal ions** facilitated by the calculation of a self-consistent ambipolar radial electric field.
- Runs on **several platforms**:
  - CSC (IBMSC and a linux cluster)
  - JAC at JET
  - any platform with a FORTRAN compiler, 2GB memory (and MPI).

Simulation of Bulk Plasma

ASCOT was originally developed for simulating minority particles:

- run-away electrons
- fast ions
- impurity particles

Simulation of bulk ion population was later facilitated by introducing

self-consistent radial electric field, E_r

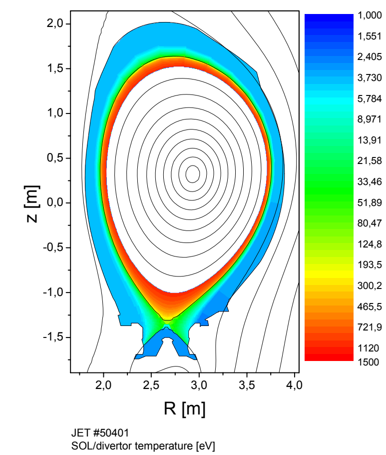
evaluated from the polarization equation

$\partial \mathbf{E_r} / \partial \mathbf{t} = -j_r$, where j_r is the calculated radial flux of test ions (excluding their polarization drift).

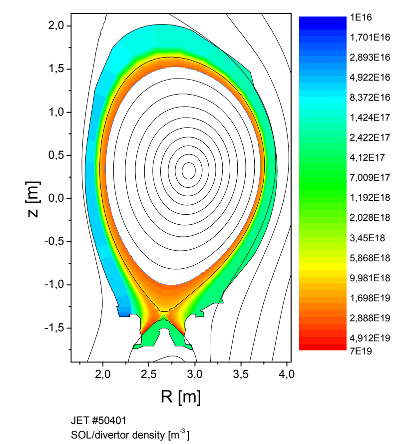
Simulation of thermal plasma allows studies such as

- steady-state particle and heat load to the first wall and divertor
- NC radial electric field across the edge transport barrier

The simulated E_r is the effective radial electric field needed to maintain a steady state density profile and thus, if turbulence plays a role in the generation of E_r the measured values may be different.



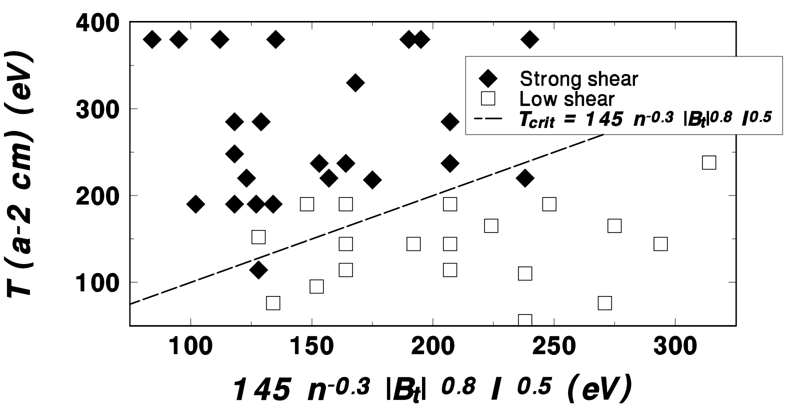
JET #50401
SOL/divertor temperature [eV]



JET #50401
SOL/divertor density [m^{-3}]

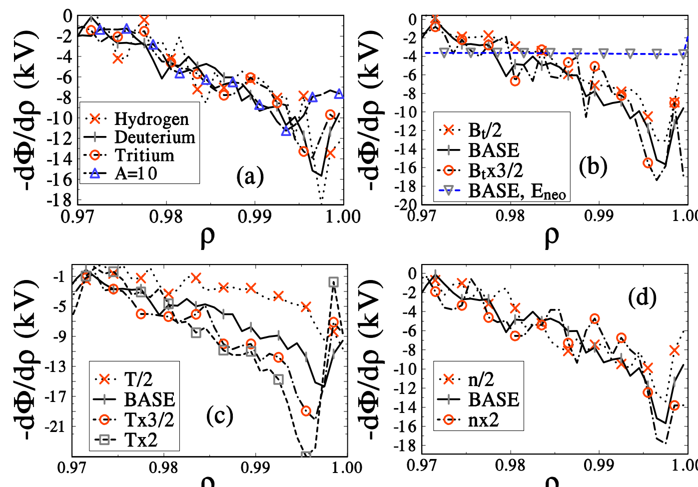
E_r shear and L-H transition

NC radial current balance in a divertor tokamak (AUG, JET) gives shearing rate $(dE_r/dt)/B_T$ high enough for strong turbulence suppression (BDT criterium) at parameter values corresponding to L-H transition.



ExB flow from ASCOT simulation as a function of experimental parametrisation of T_{crit} of L-H transition for ASDEX Upgrade.

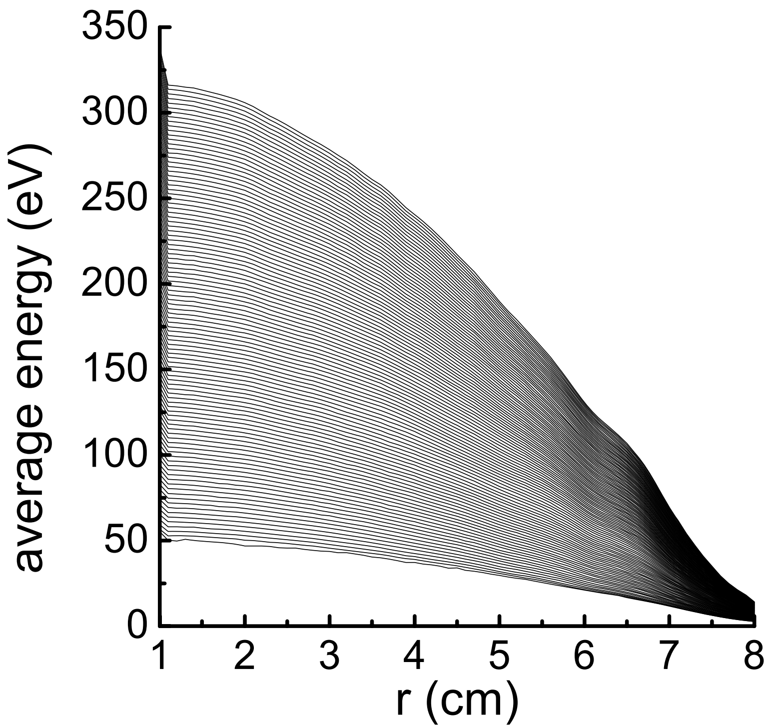
Experimental T_{crit} is shown as a straight line



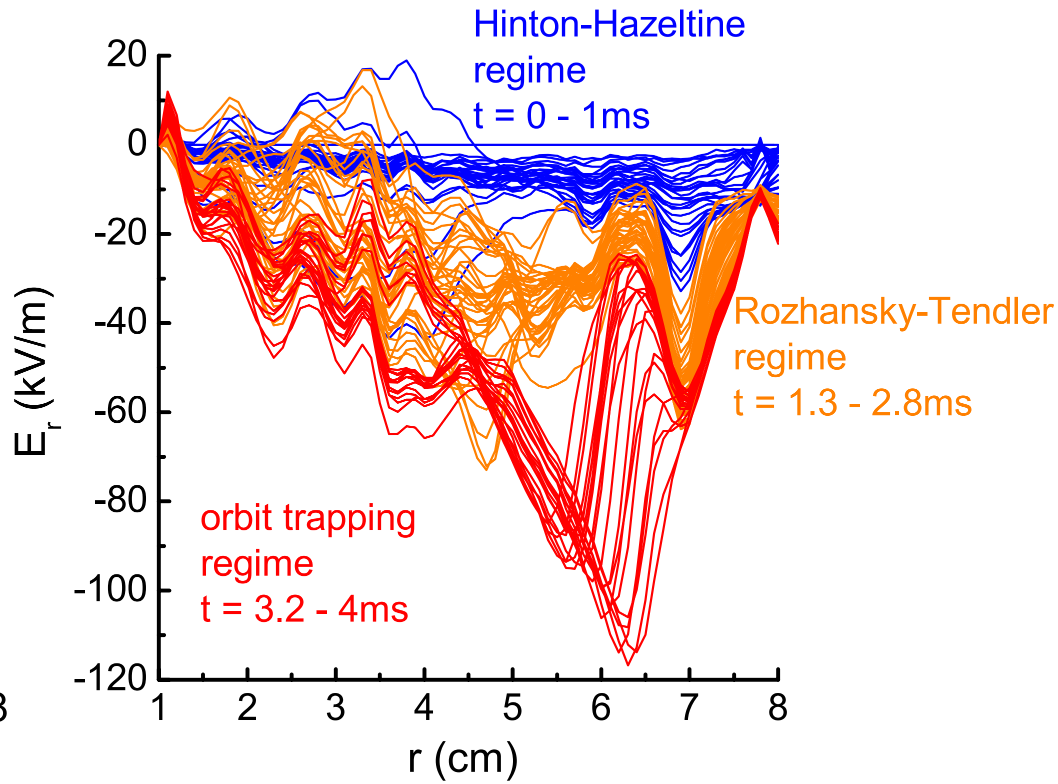
'BASE' refers to JET L-H transition conditions.

*J. Heikkinen et al. PRL **84** (2000) 487*

Global E_r calculations for FT-2



Linearly increasing temperature



Different phases in the E_r evolution

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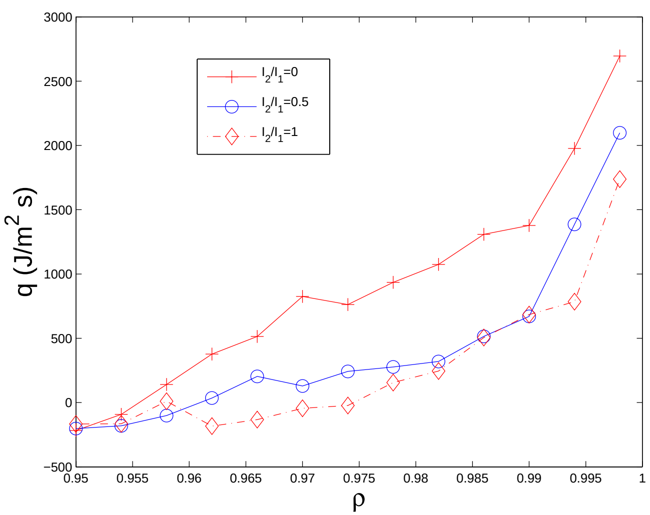
Ripple and ELM Mitigation

- Mitigation of Type I ELMs is a necessity for ITER
- ELMs are localized to the LFS where transport is enhanced by ripple
- Across the H-mode pedestal anomalous transport is suppressed

  → Maybe ripple can be used to tailor ELM behaviour?



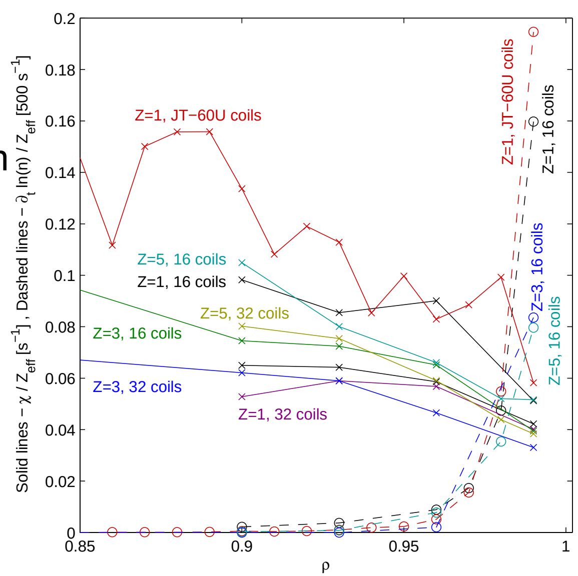
Heat flux from full simulation for different ripple values

Heat diffusion can be evaluated from

•variance growth of δ-peak in radius
→*pulse-spreading technique*

or

• from the energy-weighted radial motion of the particle ensemble



Thermal conductivity using pulse-spreading technique for different ripple values

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Divertor load studies for JET & ITER

Main results:

Many factors affect the divertor loads and their distribution on the targets, e.g.:

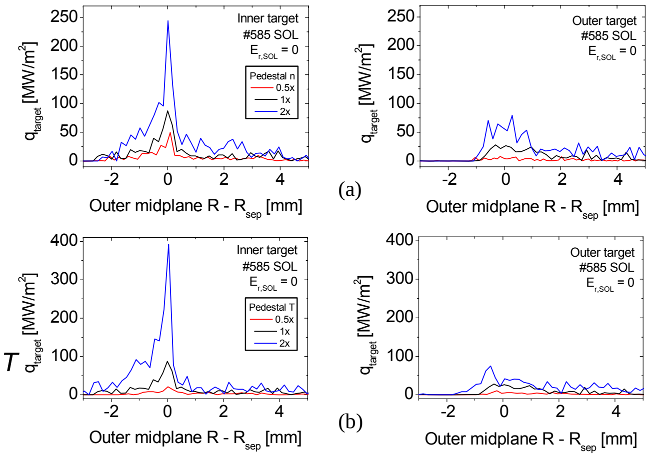
- edge collisionality
- scrape-off layer (SOL) collisionality
- divertor collisionality
- SOL radial electric field

Orbit losses from the edge cannot alone explain the experimentally observed load distributions.

Effect of pedestal height:

(a) *n* pedestal
(b) *T* pedestal

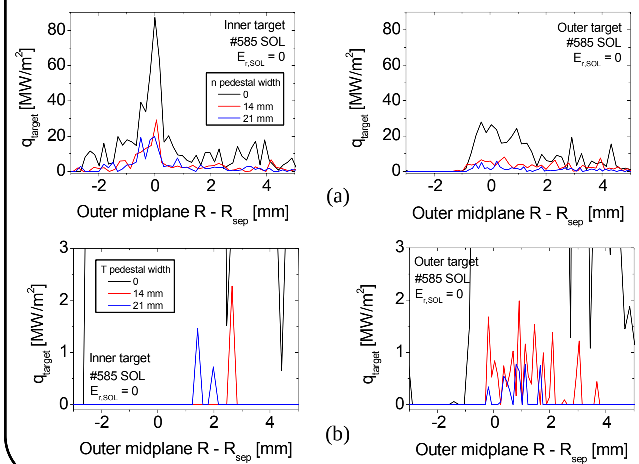
As expected, the loads scale linearly with *n* pedestal height, but the *T* pedestal has a much stronger effect through SOL & divertor collisionality.



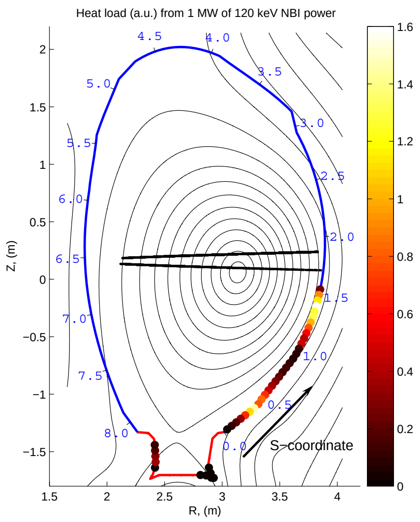
Effect of pedestal width:

(a) *n* pedestal
(b) *T* pedestal

The energy of the escaping ions (b) has a dramatic effect on target loads!



Fast ions and ripple: NBI

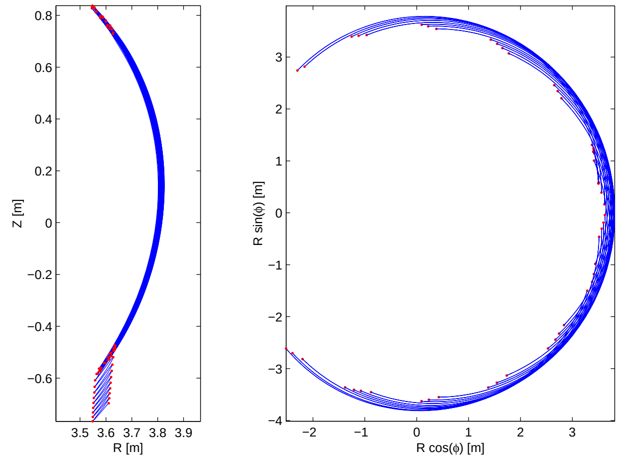


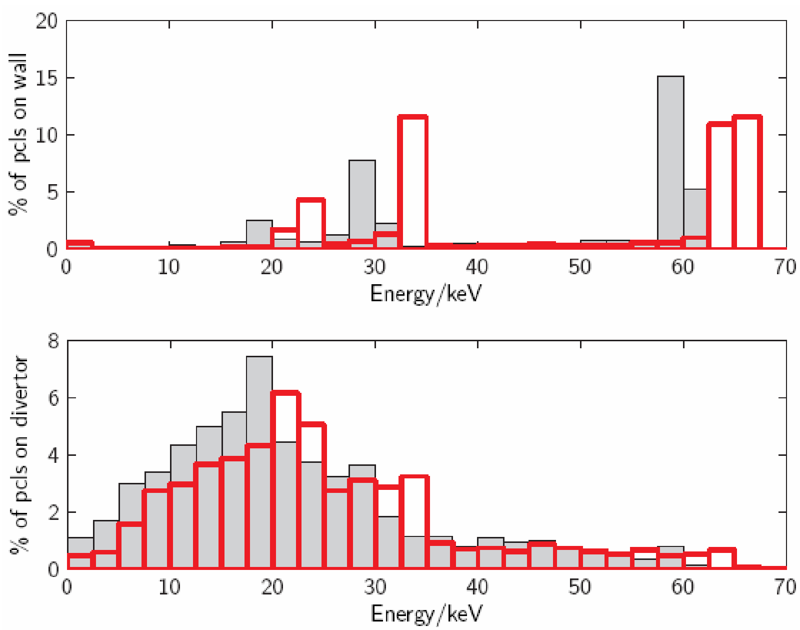
Finite number of toroidal coils →

- magnetic ripple →
  - increased diffusion & direct orbit losses

Presence of fast ions (neutral beams, ICRH, fusion reactions) →

- unacceptable local fluxes to plasma-facing components?





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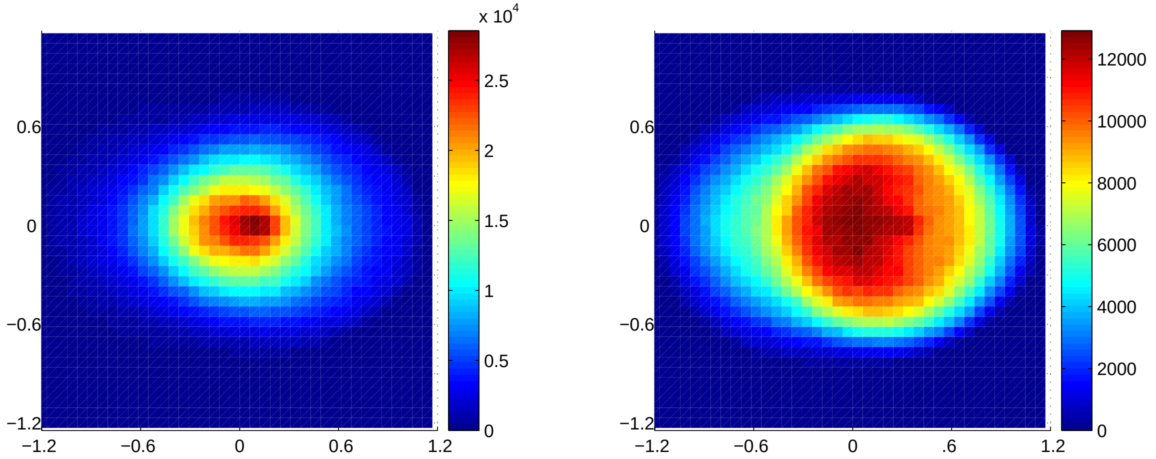
Fast ions: fusion alphas



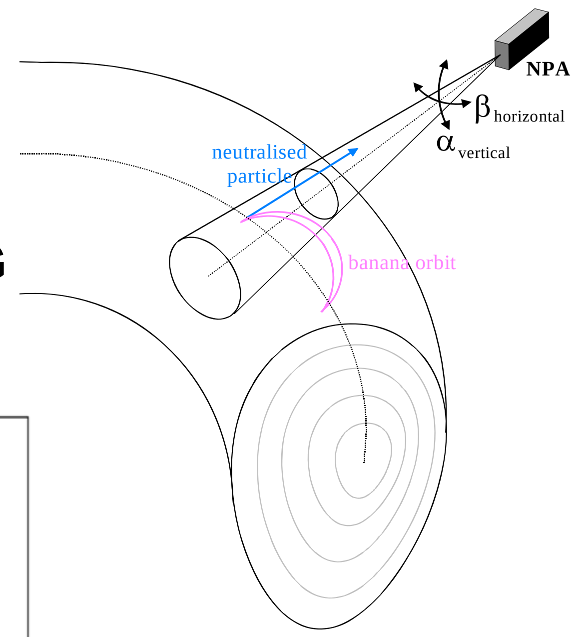
ASCOT simulations of 3.5MeV fusion alphas indicate that with plasma current manipulation (reversed central magnetic shear) a better utilization of fusion fuel can be obtained

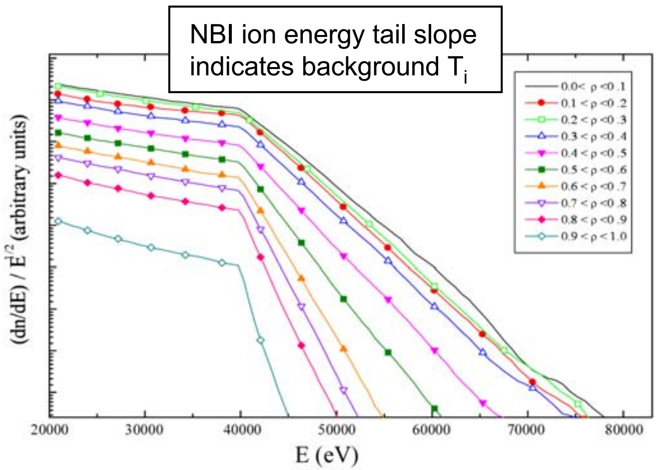
NPA Simulations

Neutral Particle Analyzer (NPA) simulation model:

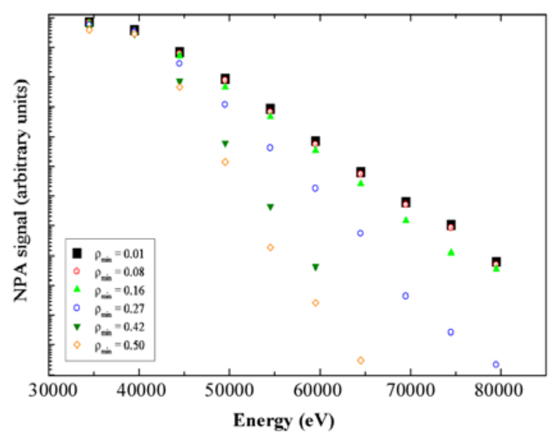
- horizontal and vertical sightline adjustment
- multiple energy channels
- realistic viewing aperture.

Currently benchmarked against dedicated shots on AUG





NBI tail distributions



Simulated NPA signal

NBI/NPA simulations → use of NPA signal for determining central T_i is feasible but sensitive to NPA viewing angle.

Edge E_r from NPA measurements

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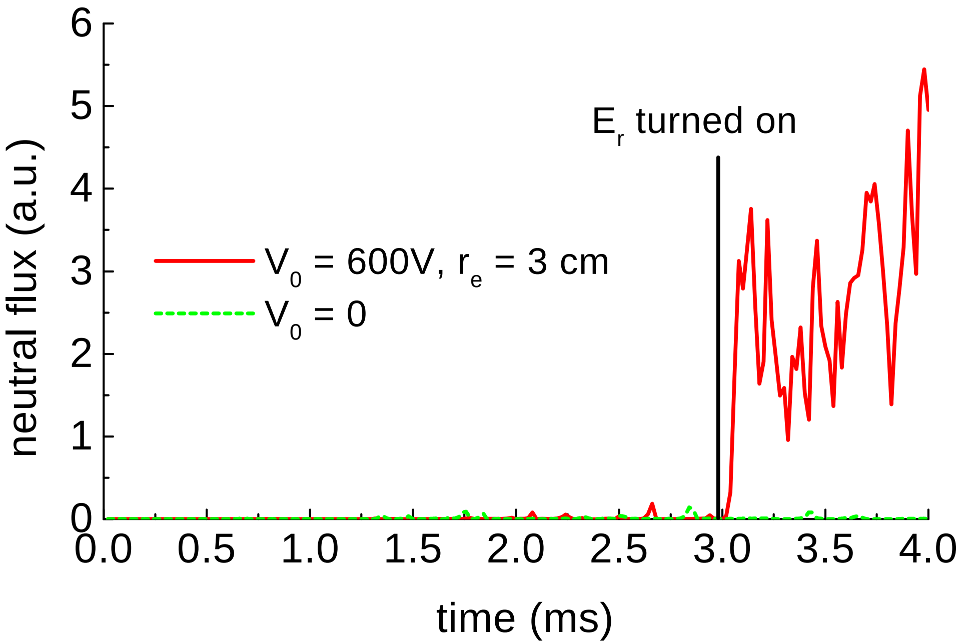
In the edge pedestal region, in the presence of a finite toroidal ripple, the NPA signal due to NBI ions is found sensitive to the radial electric field which can re-confine the ripple-blocked ions drifting out of the plasma.

- New ions throughо
- The signa about 50 onset.

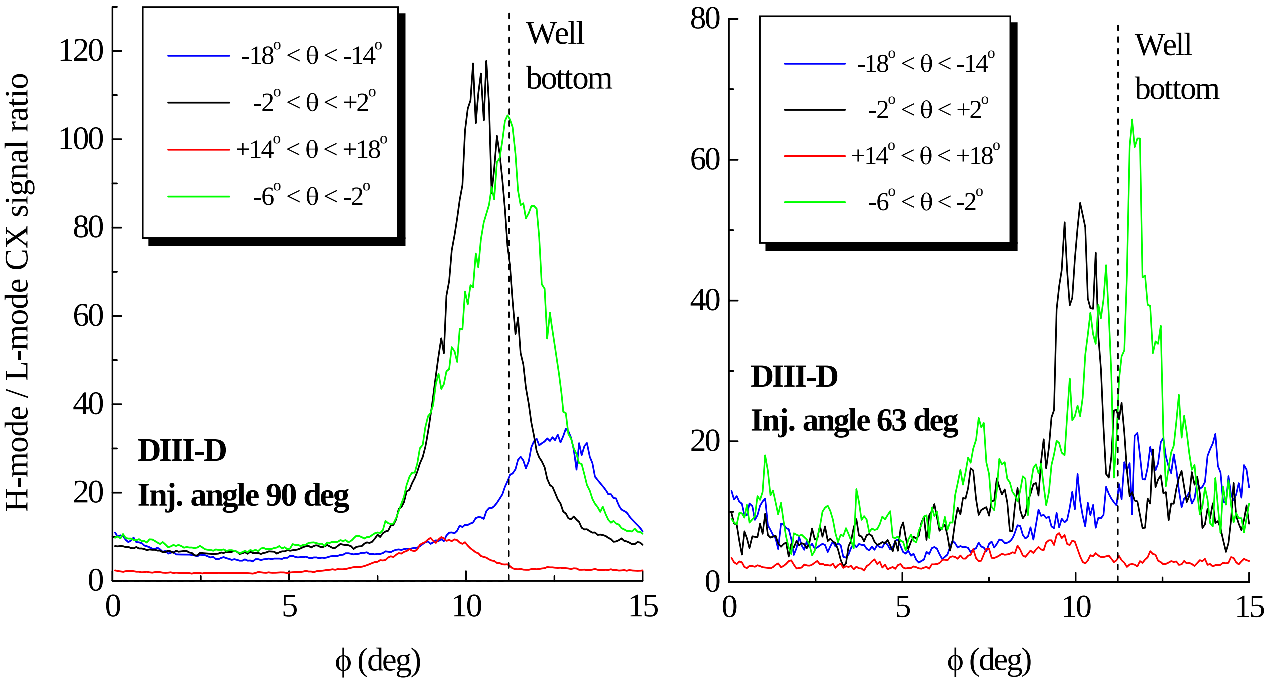
Eı

Time evolution of the neutral flux with an abrupt onset of $E_r = -d/dr\ [\ V_0 \exp(-r^2/r_e^2)\ ]$ at t =3ms.



Edge E_r … cont'd

NBI/NPA simulations → use of NPA signal for determining edge E_r is feasible but sensitive to plasma shaping and NPA viewing angle.



Rule of thumb for optimal sensitivity:

- ***view the plasma along the mid-plane***

Fine-tuning:

– Non-shaped plasmas: ***view the plasma slightly above the midplane*** (AUG # 8044)

– strong plasma shaping: ***view from below the midplane*** (DIII-D # 82093)

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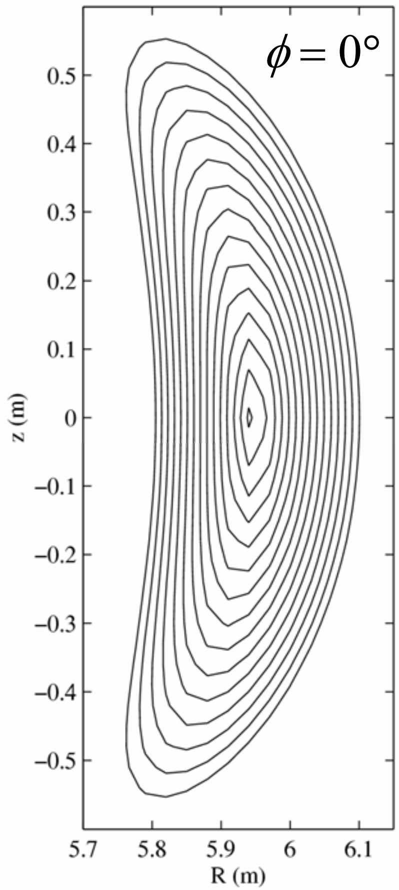
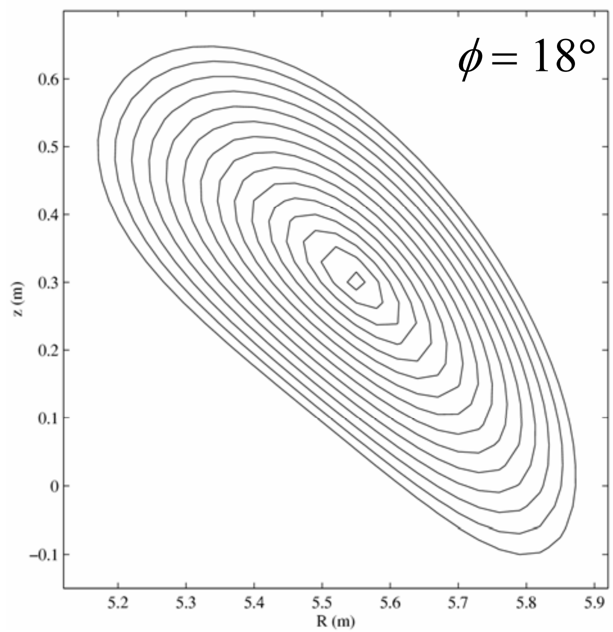
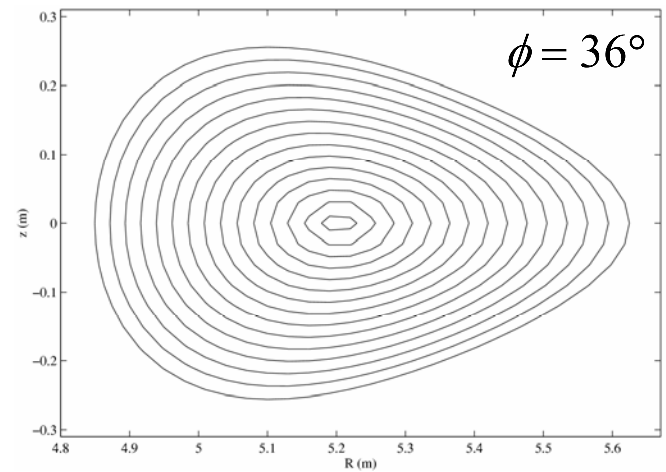
Stellarator configuration



The first step towards ITER magnetic configuration





ASCOT has been upgraded to handle also toroidally non-symmetric configuratons: in the case of W7X the torus is divided to 5 symmetrical segments

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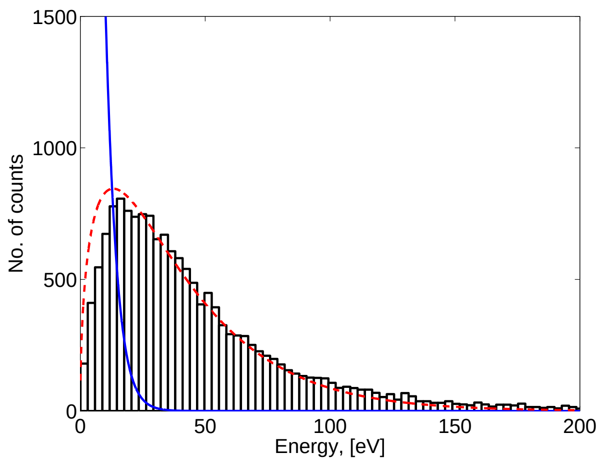
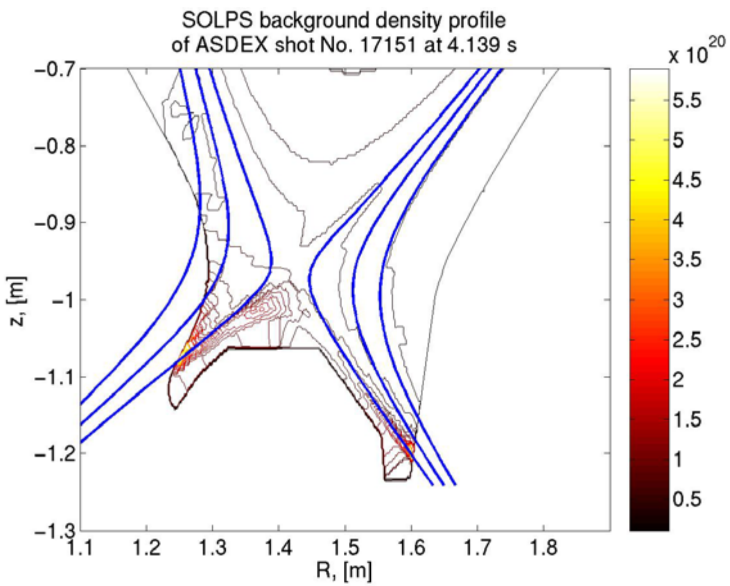
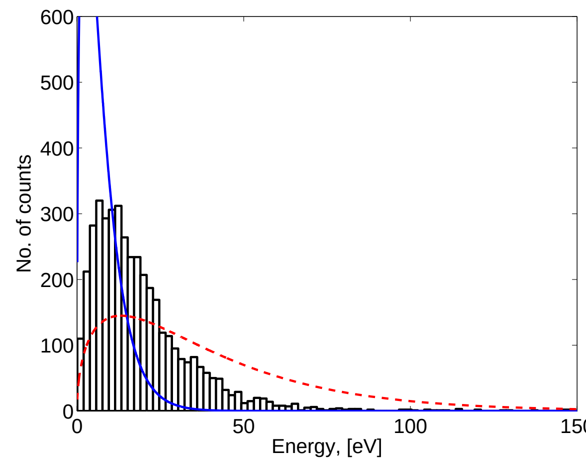
Simulations in SOL

- 2D background from SOLPS or EDGE2D imported to ASCOT (MDSPlus tree)
- Due to open field lines, special care must be taken with the Monte Carlo collisions
- Kinetic electrons from the main plasma arrive
  - at the outer divertor with practically undistorted Maxwellian distribution,
  - with significantly lower energies at the inner target



Outer target





Inner target

Looking forward…

The current/future development projects for ASCOT include:

- Tailoring the ASCOT input/output interfaces to facilitate ITM compatibility
- 3D magnetic background and 3D wall structures for ITER
- 2D electric field in the scrape-off layer (INTAS project)
- Extending the CX-reaction model and simulation of neutrals all across the poloidal plane
  - Upgrade all plasma-profiles to 2D when relevant