NBI energetic particle confinement and orbit characterization for Divertor Tokamak Test plasma scenarios

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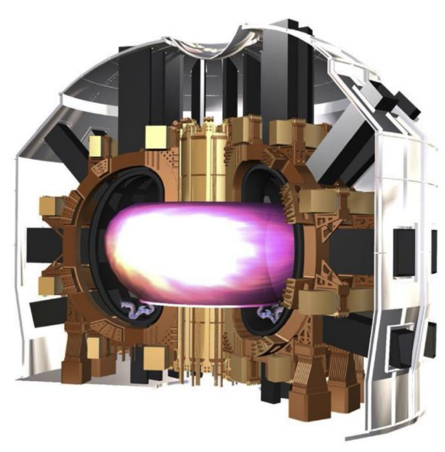
MOTIVATION and GOAL

In a superconductive tokamak, as the Divertor Tokamak Test (**DTT**) equipped with a **high-energy beam (510 keV)**, a good Energetic Particle (EP) confinement is crucial to improve plasma performances and to avoid EP losses to the machine first wall.

In this contribution we characterize the **beam-plasma interaction** and the **confinement** of beam-generated **Energetic Particles (EPs)**, in axisymmetric magnetic field for different planned **DTT plasma scenarios**, exploiting NBI energy and power modulation.

DIVERTOR TOKAMAK TEST (DTT)



- Superconductive device **under construction** in Frascati (IT) [1,2]
- Proposed for the optimization of ITER operation and DEMO design

DTT Neutral Beam Injection (NBI) [3]

- One of the highest injection energy before ITER (**E_{NBI} ≤ 510 keV, P_{NBI} ≤ 10 MW**)
- Negative ion source, tangential and co-current injection
- Capability of injection **energy modulation** (510-250 keV), accompanied by a **linear decrease of power** (10-4.1 MW)

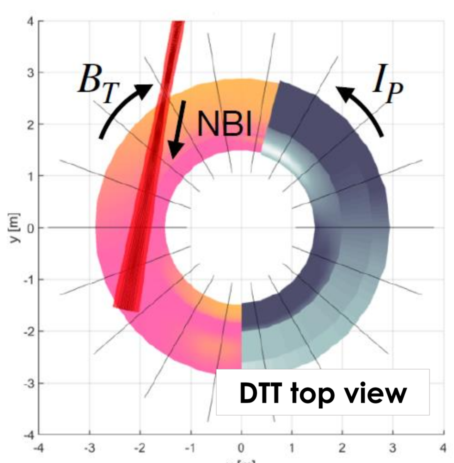


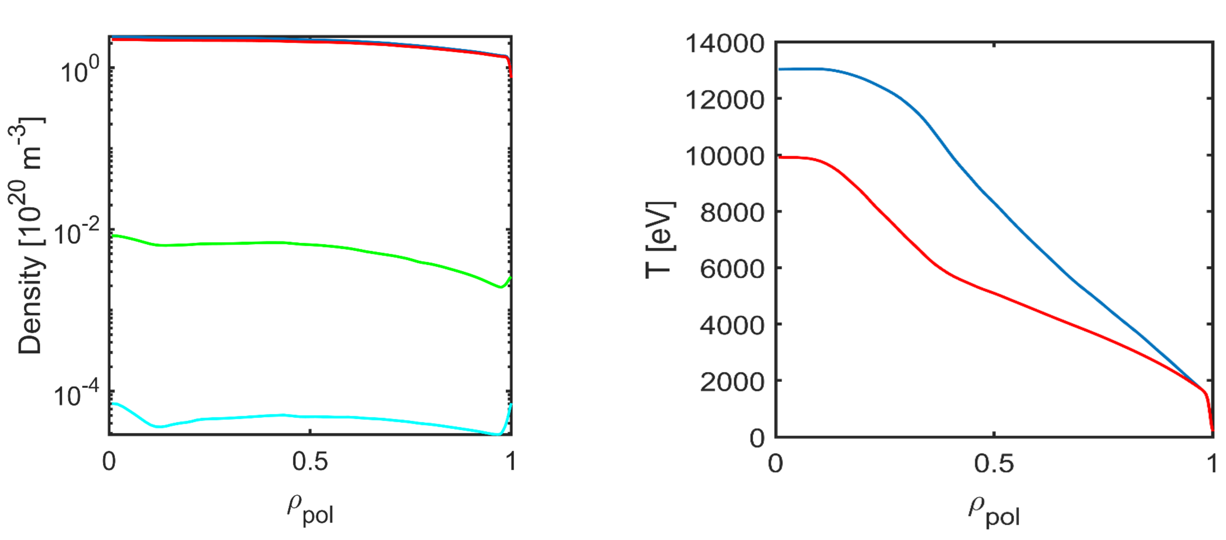
Figure from [4]

DTT PLASMA SCENARIOS

Three different DTT plasma scenarios in Single Null configuration are considered in this analysis. More details are given in [5]. E1 is the target reference scenario of DTT. Early phase A1 and C1 scenarios do not foresee NBI, but do present plasma conditions (I_p, B_{tor}, <n_e>, <T_e>, plasma shape) which can be proposed in later operation phases with NBI.

Scenario	I_p [MA]	B_{tor} [T]	ECHR power [MW]	ICRH power [MW]	NBI power [MW]
E1	5.5	5.85	32	8	10
C1	4.0	5.85	16	4	-
A1	2.0	3.00	8	-	-

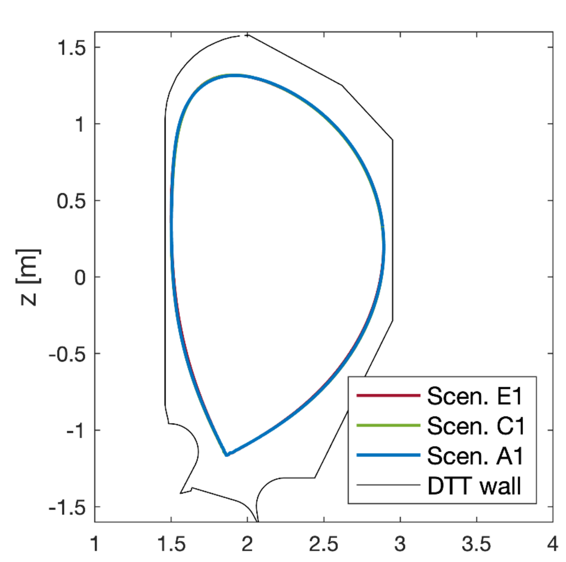
Scenario	<n_e> [10^{20} m^{-3}]	<T_e> [keV]	<n_i> [10^{20} m^{-3}]	<T_i> [keV]	E_c [keV]
E1	1.92	5.95	1.83	4.11	110.19
C1	1.39	5.91	1.34	4.36	109.74
A1	0.61	4.13	0.46	2.23	77.11



Kinetic profiles for E1 scenario [5] used in this work

NUMERICAL MODELLING

To explore beam energetic particle behaviour, the orbit-following Monte Carlo **ASCOT** code [6] is used. ASCOT solves the time evolution of particle distribution function. In this contribution ASCOT is run as a stand-alone code, and the beam ionization is calculated by the ASCOT-suite Monte Carlo code **BBNBI** [7].

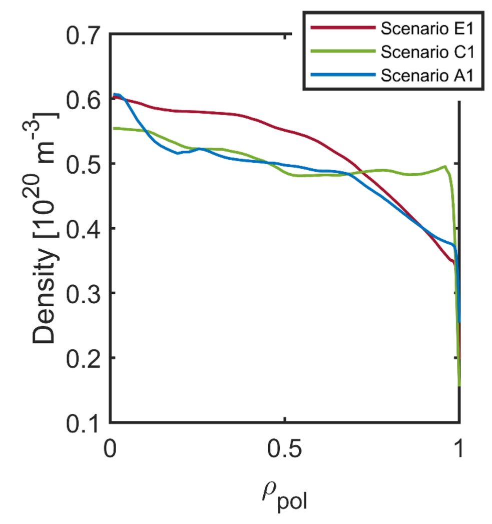


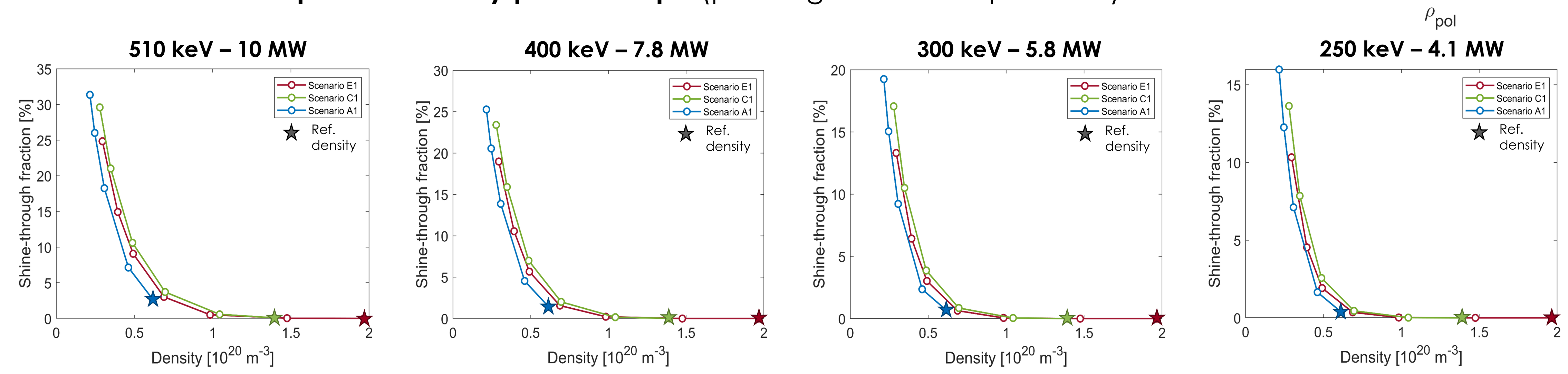
Last Closed Flux Surfaces

SHINE-THROUGH (ST) ANALYSIS

Shine-Through (ST) losses, i.e. neutral particles which cross the plasma without being ionized ending up to the machine first wall, are one of the main concern of high energy NBIs. ST losses have been studied for the **three plasma scenarios** at four representative **NBI energies** (and power), with a **scan in plasma density**. Here the main results:

- decreasing the NBI energy or increasing the plasma density, the ST fraction decreases, as expected from beam mean free path dependence $\boldsymbol{\lambda \propto \frac{E_{NBI}}{n}}$
- At a given energy and density, ST losses are similar for the three scenarios with differences due to **plasma density profile shape** (peaking factor and pedestal)

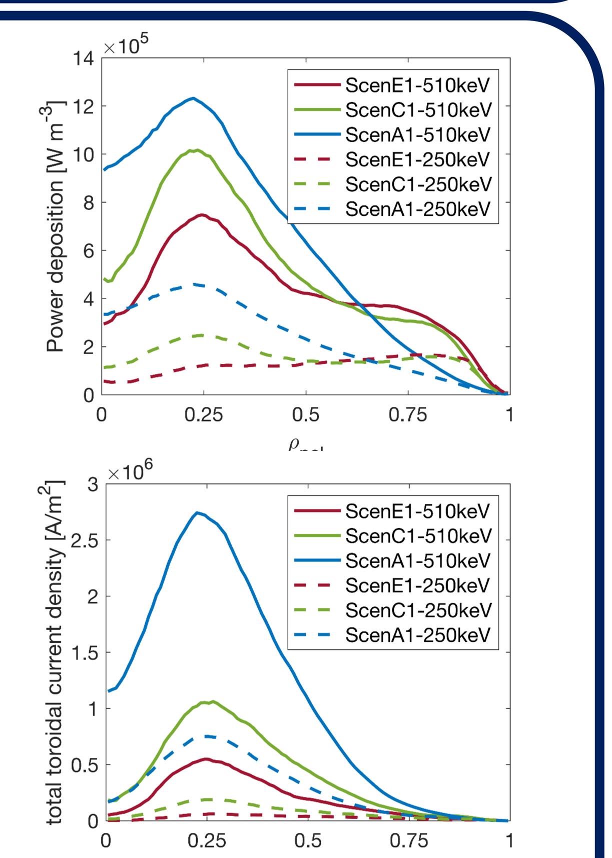




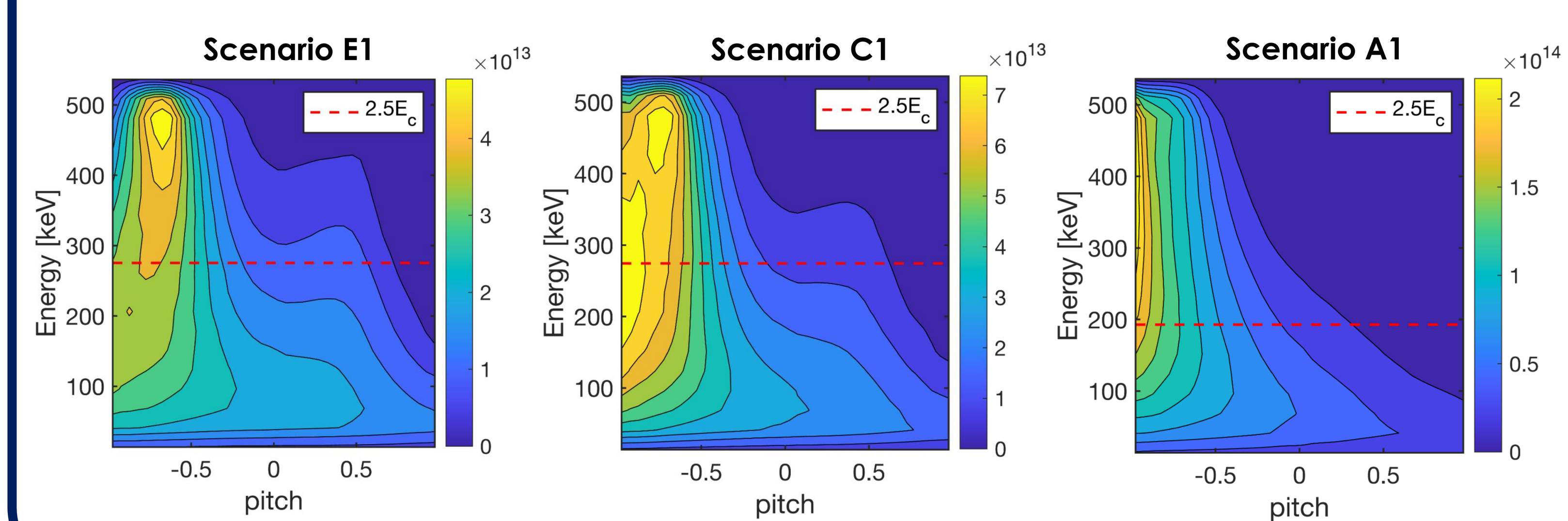
SLOWING DOWN ANALYSIS AND FAST ION DISTRIBUTION FUNCTIONS

During slowing down, NBI particles exchange energy with the plasma.
It is possible to notice that:

- The **power absorbed by plasma electrons increases with beam energy** since the ion-beam collision frequency decreases; the same happens looking at the Current Drive (CD) and the CD efficiency
- The CD efficiency depends also on the electron density: the lower the density, the higher the CD efficiency.
- A1 scenario with 510keV of injection energy presents the higher fraction of **shine-through and orbit losses**



Scenario	Energy [keV]	Absorbed power [%] (electrons – ions)	Current Drive (CD) [MA]	CD efficiency [10^{20} A/Wm^2]	ST losses [%]	Orbit losses [%]
E1	510	99.99 (58.49 - 41.51)	0.25	0.11	0.00	0.01
	250	99.91 (46.74 - 53.26)	0.050	0.05	0.00	0.09
C1	510	99.92 (56.94 - 43.06)	0.47	0.14	0.08	0.00
	250	99.98 (44.03 - 55.97)	0.10	0.075	0.00	0.02
A1	510	97.12 (60.60 - 39.40)	1.12	0.15	2.74	0.14
	250	99.57 (44.05 - 55.95)	0.33	0.10	0.36	0.07

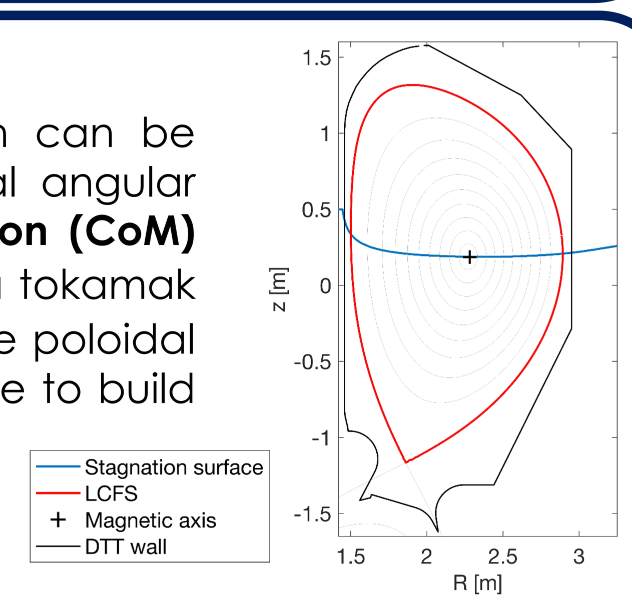


Energetic particle distribution functions for each scenario (beam energy 510 keV)

- Most of the EPs have a **negative pitch**, as expected by the injection geometry
- The **initial pitch value** depends also on density: the lower the ref. plasma scenario density, the more tangential is the ionization (i.e. |pitch| ~ 1)
- At ~ 2.5 times the critical energy (E_C), the distribution functions start to spread. This is due to the **pitch-angle scattering** that becomes more relevant in the slowing down process

ORBIT CONFINEMENT AND CHARACTERIZATION

Considering an **axisymmetric geometry** and **without collisions**, particle motion can be described by three variables, i.e. the particle energy E, the toroidal canonical angular momentum P_ϕ and the magnetic moment μ. They define the **Constant of Motion (CoM) phase space (E, $\boldsymbol{P_\phi}$, $\boldsymbol{\mu}$)** [8], where it is possible to classify EP orbits. Notice that in a tokamak with a divertor configuration, as DTT, particle orbits have the extreme values of the poloidal flux function ψ in the so-called **stagnation surface** [9], that is assumed as reference to build the boundaries of the map.



Results from CoM analysis:

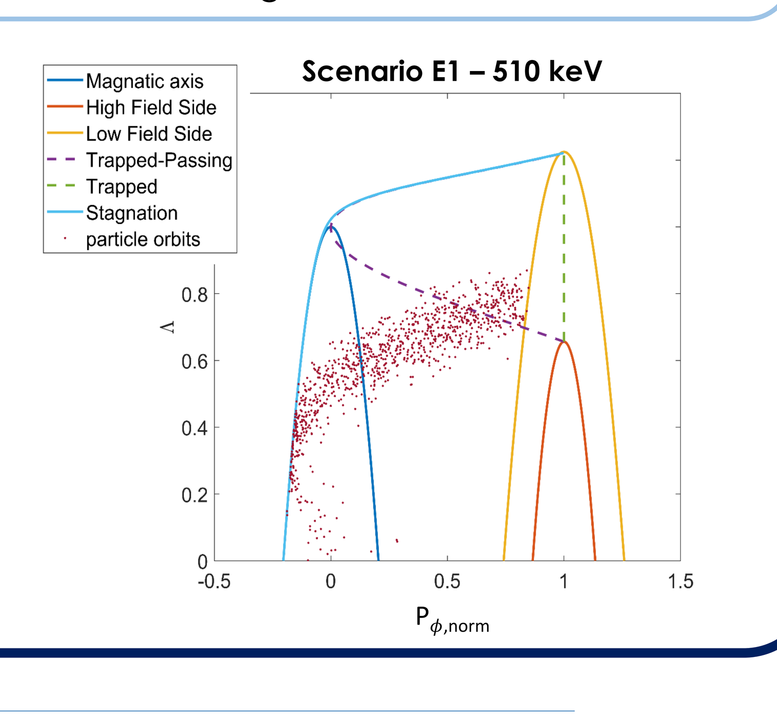
- Increasing the energy or decreasing the plasma density, the fraction of **passing particles** increases. EPs are indeed ionized closer to the plasma center where the parallel velocity becomes larger, determining a smaller fraction of **trapped particles**.
- The fractions of **lost particles** obtained from the CoM analyses are larger than that obtained by ASCOT. Indeed, CoM analyses do not take into account some aspects of the EP behaviour, e.g. particles can re-enter the plasma due to collisions. Therefore, particles that cross the LCFS are considered lost.

Scenario	E1		C1		A1	
Energy [keV]	510	250	510	250	510	250
Confined (Lost) passing [%]	84.20 (0.03)	73.76 (0.04)	89.99 (0.11)	84.41 (0.10)	92.36 (0.38)	91.94 (0.41)
Confined (Lost) trapped [%]	14.53 (0.42)	25.35 (0.69)	6.56 (0.28)	13.66 (0.57)	1.33 (0.34)	3.98 (0.82)
Total lost [%]	0.45	0.73	0.39	0.67	0.73	1.23
Stagnation [%]	0.81	0.16	3.06	1.27	5.58	2.85

Stagnation surface condition

$\boldsymbol{B} \cdot \nabla B = 0$ with $\nabla B = \partial_R B_R + \partial_z B_z$, $\boldsymbol{B} = (B_R, B_z, B_\phi)$

or the surface where each particle experience the minimum magnetic field value of its orbit.



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