DTT-RP 4TH in-person meeting

Frascati, 6-8 May 2024

Chapter 6: Physics of HEating, Current Drive and Fuelling

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INDEX

Chapter structure

- Functional requirements of the heating and fueling (Rationale)
- Sections dedicated to the four systems (ECRH, ICRH, NBI, Pellet)
  - System description and ITER/DEMO relevance
  - Heating and current drive source and system-specific tasks
  - System commissioning, required diagnostics and dedicated modelling
  - Headlines in (after) each development/implementation phase

In this presentation, also:

- Changes and improvements with respect to the first version (if any)
- Ideas on how to develop the content of the chapter for the next versions (new items, points to be developed, new simulations etc.)
- Ideas about the follow-up of the DTT-RP activity (work method, proposals of experiments on other tokamaks, code and simulation developments etc.)

Rationale

Table 6.1. Functional requirements of the heating and fuelling systems. For each system and task a categorization is given: *** essential, ** useful, *usable, - not applicable. (1) Indirect ion heating via collisions at high plasma density. (2) Combined use of heating systems and pellet should be considered since operations with pellet will require at least a minimum amount of additional heating

Task in DTT	ECRH	ICRH	NNBI	Pellet
Preionization, Breakdown and Start-up	**/***	*/**	-	-
Plasma current ramp-up and ramp down	**	**	*	-
H-mode access and exit	**	**	**	**
Electron heating	***	**	**	-
Ion heating	*(1)	***	**	-
Current drive	***	*	**	-
Core MHD control (NTM, ST)	***	*/**	-	-
Fast ions generation	-	***	***	-
Kinetic profiles control	**	**	-	**
Impurity access/accumulation control	**	**	**	**
Momentum injection and control	-	-	*	-
Transport studies	**	**	**	**
Isotopic studies	-	**	**	**
Wall cleaning	*/**	**/***	-	-
Fueling (2)	*	*	*	***
Elm pacing	*	*	*	**

- DTT mission: demonstration of a heat-exhaust system capable to withstand the power load of a fusion reactor, integrating all the main physics elements occurring in a burning plasma.
- Functional requirements of the H,CD&F systems, lines of development, commissioning steps connected with the machine operational phases
- Common approach for each of the subtopics [EC, NBI, IC, fuelling] in Chapter 6 on “sources” :
    - System description and ITER/DEMO relevance
    - Physics details & system-specific tasks
    - Commissioning, diagnostics, modelling

Headlines:

Headlines Number	Headlines contents	Priority (+, ++, +++)	ITER	DEMO
Construction Phase 2022-2029				
C.6.1	Assessment of ECRH, ICRH, NBI, matter injection performance (modelling) wrt respective high priority tasks	+++	*	*
C.6.2	Assessment of interfaces with diagnostics and control system	++	*	*
Phase 1 2029-2034				
1.6.1	ECRH, ICRH initial system commissioning, asynchronous and with plasma, including optimization of coupling	+++	*	*
1.6.2	ECRH, ICRH, Commissioning of functionalities supporting basic machine operations: wall cleaning, assisted start-up, current ramp-up and ramp-down at half and full magnetic field	+++	*	*
1.6.3	ECRH, ICRH Basic control fuctionalities: sawteeth, NTMs, impurities, density and ELM pacing at half and full magnetic field	+++	*	*
1.6.4	Access to H-mode Baseline and Hybrid	++		

Headlines Number	Headlines contents	Priority (+, ++, +++)	ITER	DEMO
Phase 2 2034-2038				
2.6.1	NBI system commissioning (asynchronous and with plasma)	+++		
2.6.2	Verification of NBI power losses (in particular duct and shine-through losses) and optimization of parameters wrt density	+++		
2.6.3	Combined use and optimization of parameters of the heating and fuelling systems for scenario access and control	+++	*	*
2.6.4	Control of kinetic and impurities profiles	++	*	*
Phase 3 2038-...				
3.6.1	H-mode operation at full power	+++		*

ECRH

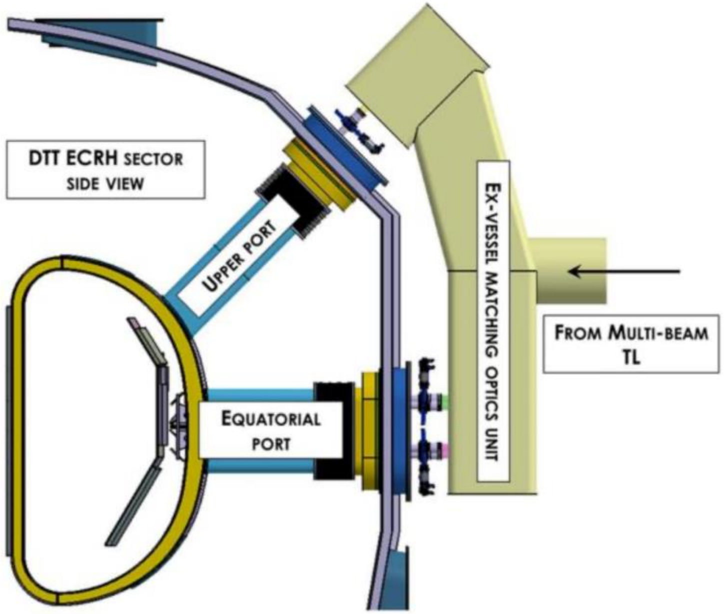


Figure 6.1. Side-view of a DTT sector housing the ECRH antennas [6.1]

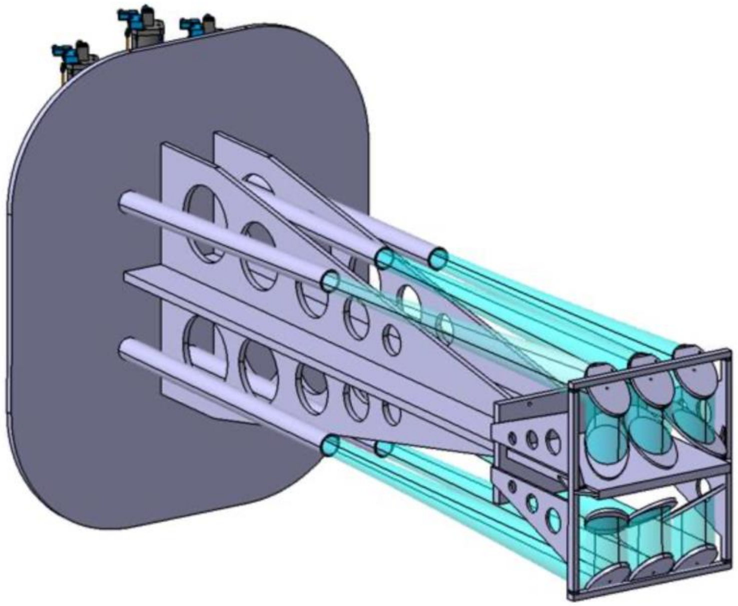
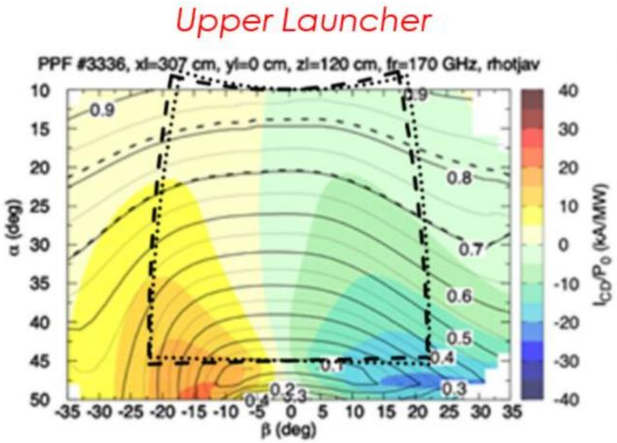
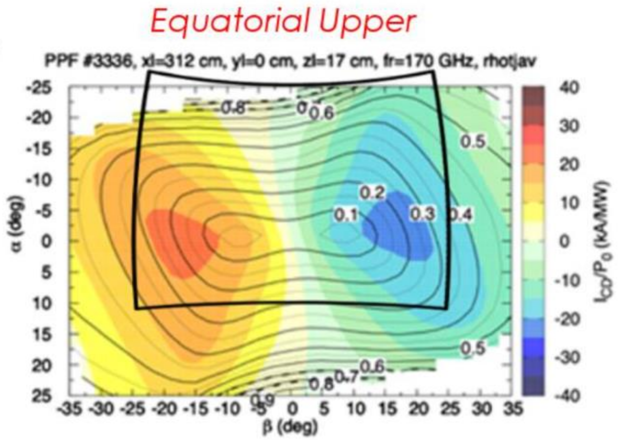
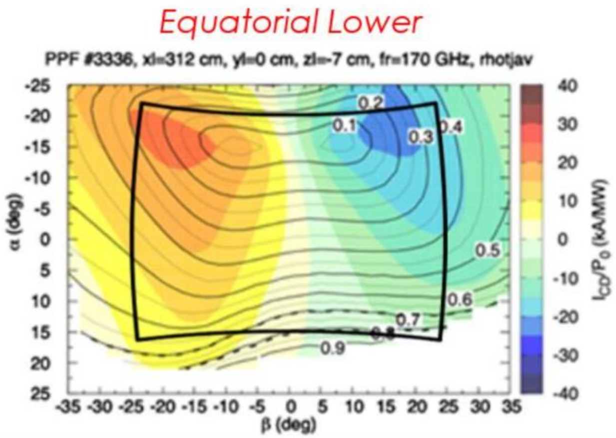


Figure 6.2. The ECRH equatorial antenna

- ECRH sector is equipped with 6 independent, plasma-facing launching mirrors located in the equatorial port and 2 in the corresponding upper port
- Each launching mirror is steerable in both poloidal and toroidal directions
- The upper launcher has favourable access to the 2/1 and 3/2 rational surfaces and is mainly dedicated to the control of the MHD activity while the equatorial launcher is dedicated to heating and current drive







Development of the content for the next versions

ECRH

- Modelling
  - Specification/quantification of the ECRH parameters (requests) needed for each of the basic task/functionality such preionization, breakdown, assisted ramp-up or ramp-down
  - Specification/quantification of the ECRH parameters (requests) needed for
    - more advanced tasks (ST, TM control, ECRH&CD at high density, impurity control),
    - scenarios access and control including possible synergies with other heating systems,
    - definition of the priorities for each operation scenario/discharge phase
- Experiment preparation:
  - Development of the control schemes for the various tasks, interfaces with the relevant diagnostics/control signals, interface with the aster plasma control
  - Beam tracing/power deposition in real time
- Theory
  - Pre-ionization
  - Density fluctuations

ICRH

Antenna design

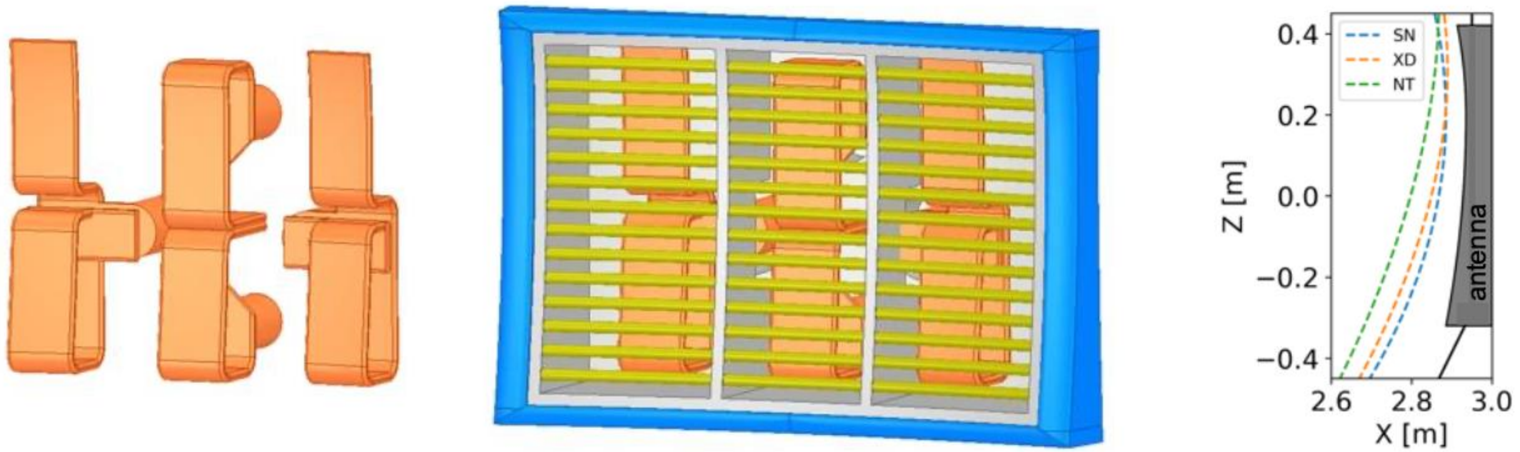
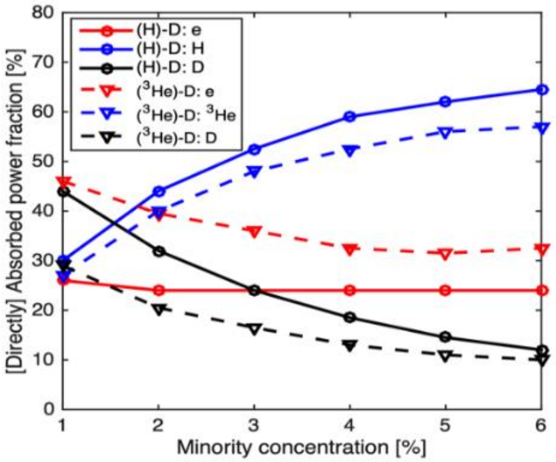


Figure 0.4. Present DTT ICRH antenna design: 3-strap structure (left), 3D view of the antenna in its antenna box with Faraday screen (middle) and qualitative side view of the front end of the antenna box with last closed flux surface for various foreseen plasma shapes (right).

- 3-strap antenna with lateral folded straps and an end-fed centre-grounded central strap
- Optimized coupling is ensured through a (largely external) matching circuit with 3dB hybrid couplers and impedance transformers
- Poloidal antenna "curvature" not optimized for any specific scenario

Heating efficiency: minority (H or ^{3}He)



Heating efficiency: 3-ion scheme (^{3}He in H+D)

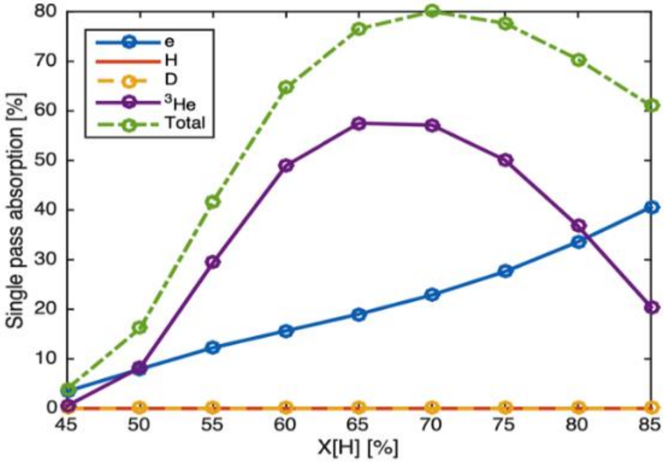


Figure 0.5. Example of the directly absorbed power fraction as a function of the H or 3He minority concentration in a D plasma for the standard minority heating scheme with minority concentrations of a few percent (left) and single transit absorption for the 3-ion scheme involving 0.1% of 3He as the trace ion in a H+D plasma (right).

- H minority and D majority central heating are available adopting 60MHz and Bo~4T. Off-axis – and hence less optimal - heating can be achieved if operating at half field.

Development of the content for the next versions

ICRH

- Antenna-plasma coupling studies accounting for the actual shapes foreseen in DT
- Earmarked work ICRH:
  - Wall conditioning (0-phasing),
  - Ramp-up and ramp-down (modest density and temperature)
  - Main phase: High density and temperature operation
    - as fast particle source (Do we couple this to MHD studies?)
    - core high-Z impurity chaser
    - plasma-wall interaction studies would be useful experimentally and via modelling
  - ICRH scenario's & their potential (or absence of it) based on list of tasks:
    - H minority in D (only partly done);
    - He3 minority in D (only partly done);
    - 3-ion options using He3 (likely H-D mix)
  - Options for synergy studies NBI-ICR

- Coupling with the transport studies Paola/Clemente does so that we get an integrated approach. Fate/role fast particle populations.

- Implementation under IMAS? [already ongoing for WE+FP part]

NBI (Changes and improvements with respect to the first version)

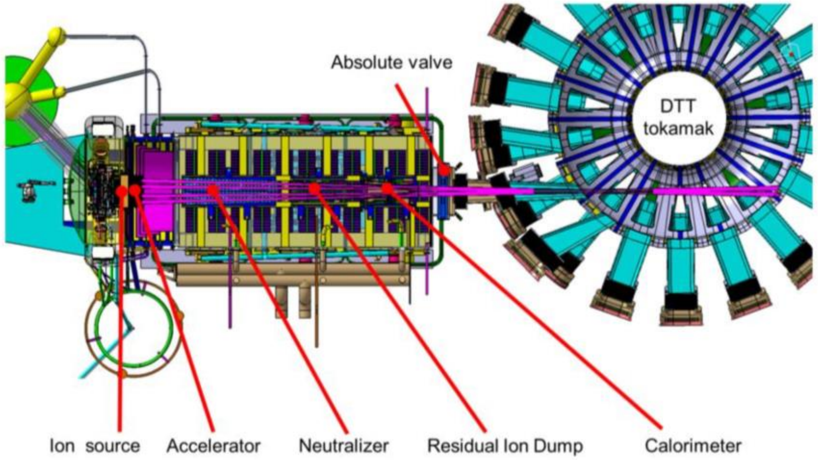
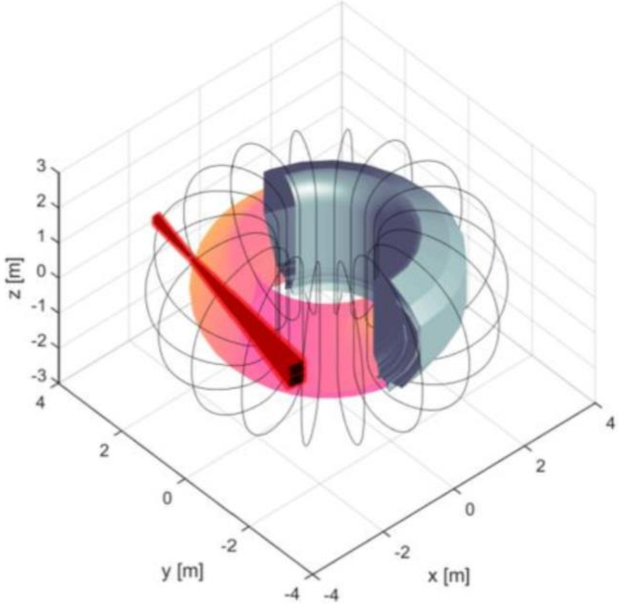


Figure 6.7. DTT neutral beam sketch. Adapted from [6.15] and [6.16].



Impact of NBI shine-through and beam-plasma interaction on the Divertor Tokamak Test facility

C. De Piccoli[1,2], P. Vincenzi[1,3], F. Veronese[1], P. Agostinetti[1,3], I. Casiraghi[4,5], A. Castaldo[6], P. Mantica[5], A. Murari[1,3], T. Bolzonella[1]

Scenario	I_p [MA]	Vacuum B_t [T]	ECRH power [MW]	ICRH power [MW]	NBI power [MW]	Plasma composition	Zeff
A	2.0	3.00	8	-	-	D, nitrogen (N), W	2.5
C	4.0	5.85	16	4	-	D, neon (Ne), W	1.4
E	**5.5**	**5.85**	**32**	**9.5**	**10**	**D, argon (Ar), W**	**1.8**

Table 1. Main parameters of the analyzed DTT plasmas. In bold the DTT target reference scenario "E".

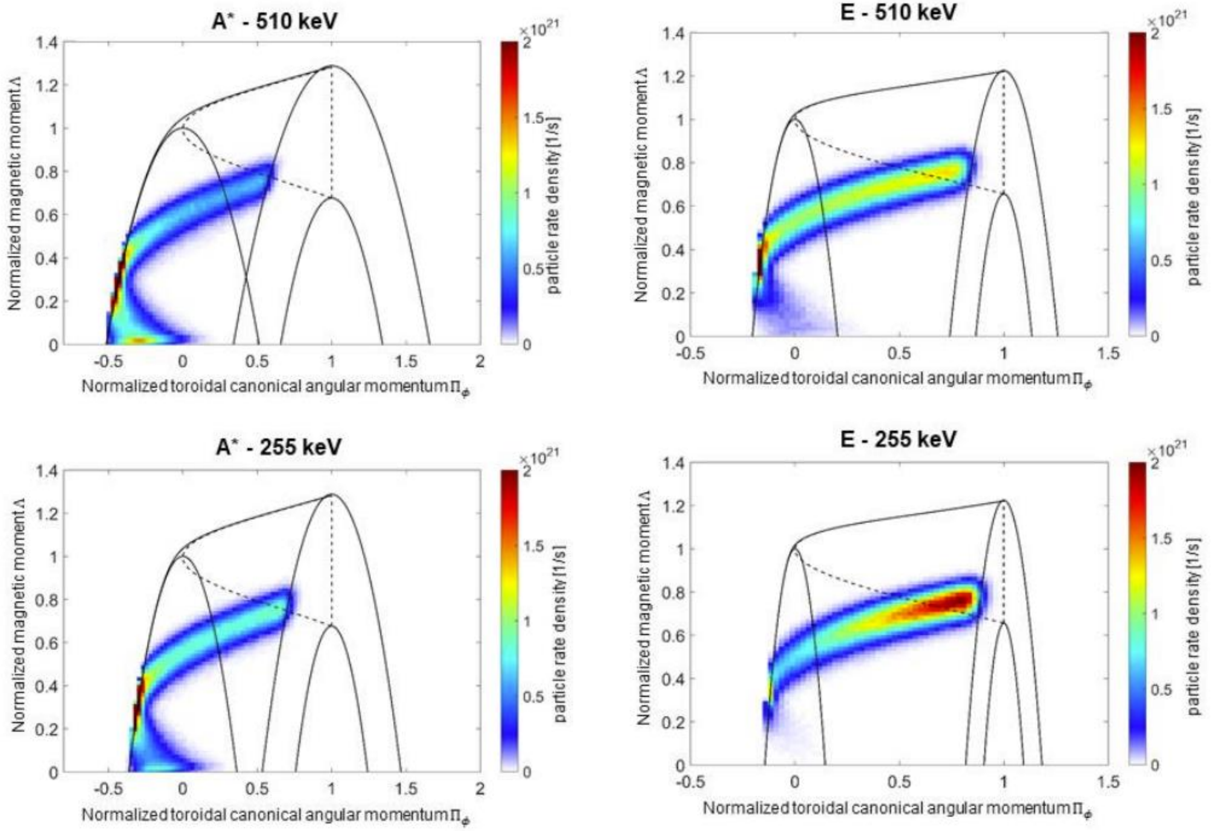
E_{NBI}		255 keV			510 keV		
Scenario		A*	C*	E	A*	C*	E
Confined orbits [%]	Co-passing	92.80	84.94	74.24	92.93	90.36	84.26
	Trapped	3.79	13.29	24.85	1.29	6.46	14.50
	Stagnation	2.25	1.09	0.25	5.00	2.78	0.79
	Total	98.84	99.33	99.34	99.22	99.60	99.55
Lost orbits [%] (prompt losses)	Co-passing	0.39	0.11	0.04	0.41	0.11	0.03
	Trapped	0.77	0.57	0.62	0.37	0.29	0.42
	Total	1.16	0.68	0.66	0.78	0.40	0.45

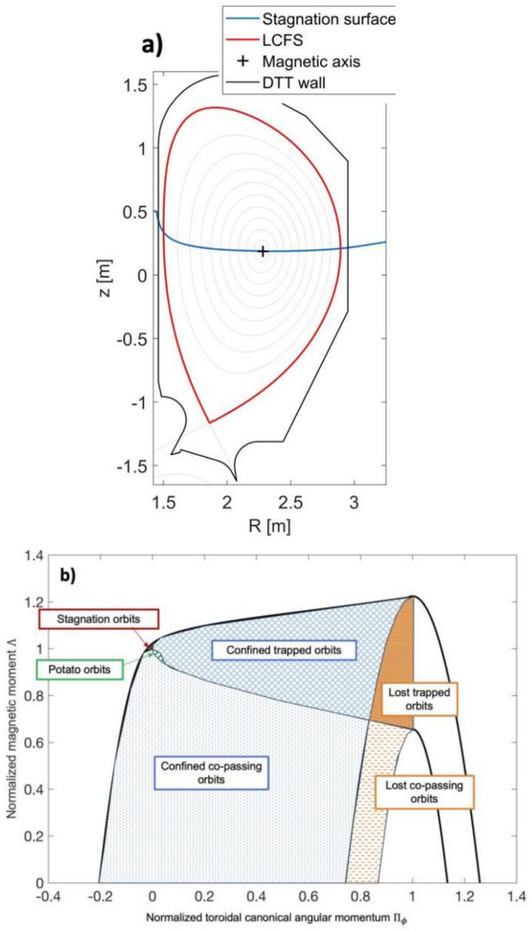
Table 7 Fraction of newly-born fast ion orbit types for DTT scenarios A, C*, E.*

[submitted to NF]

- beam ionization and beam slowing down for different DTT plasma scenarios (ASCOT)
- wide-range scan in plasma density and beam injection energy.
- shine-through losses, heat fluxes on the first wall
- consistent plasma evolution out of the scope of the study
- Pre-NBI scenarios also considered

Classification the orbits of newly-born fast ions





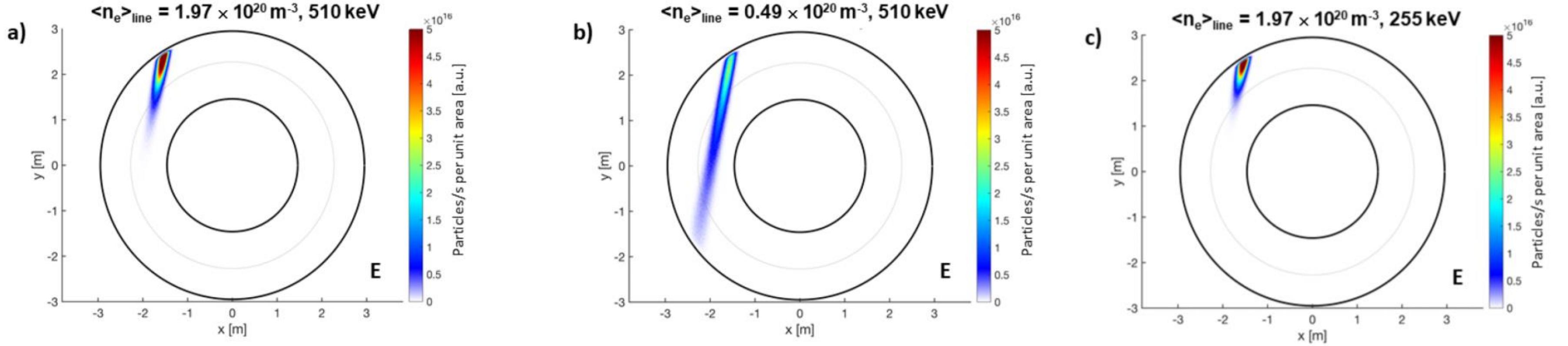


Figure 5 Top view of the beam particle ionization flux for the reference target scenario E (a), at lower plasma electron density (b) and lower injection energy (c).

- Orbits of newly-born fast ions are characterized by means of the constant of motion phase space, showing how trapped energetic particles population and prompt losses changes with plasma density and NBI energy.
- At 510 ekV ion heating, with an absorbed power ratio up to ~50% depending on plasma and beam parameters.
- An effective NBI ionization is shown for high-density DTT plasmas,
- low density plasmas may require a reduced beam energy and power due to significant shine-through losses.
- Shine-through loss differences related to plasma density profile shape and peaking

Changes and improvements with respect to the first version (if any)

Impact of NBI shine-through and beam-plasma interaction on the Divertor Tokamak Test facility

C. De Piccoli[1,2], P. Vincenzi[1,3], F. Veronese[1], P. Agostinetti[1,3], I. Casiraghi[4,5], A. Castaldo[6], P. Mantica[5], A. Murari[1,3], T. Bolzonella[1]

[submitted to Nuclear Fusion]

510 keV

255 keV

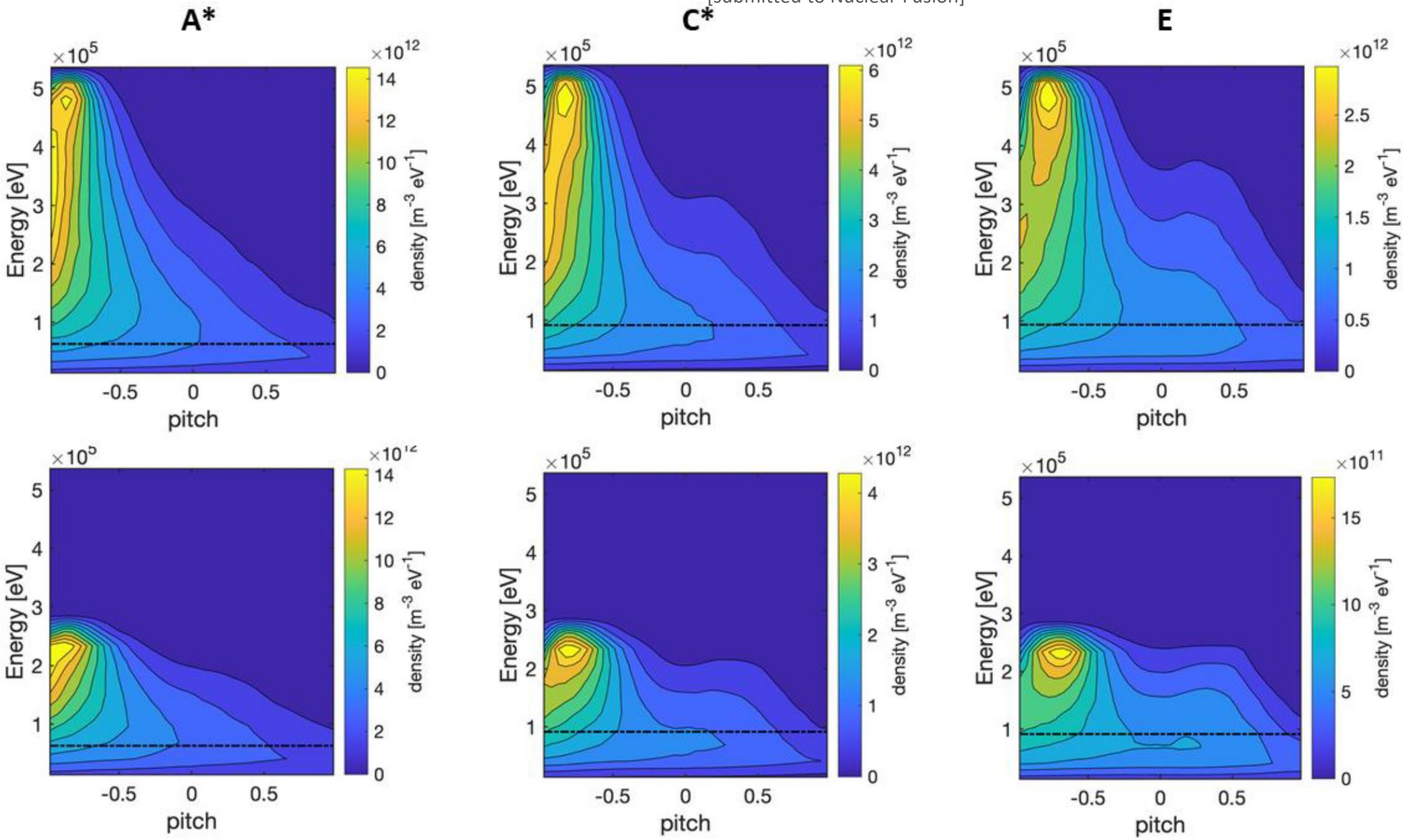


Figure 16 DTT beam EP energy-pitch distributions for A, C*, E scenarios, considering an injection energy of 510 keV (top row) and 255 keV (bottom row). The black dashed line represents the critical energy E_c.*

- The lower the plasma density, the more tangential the ionization) due to deeper beam penetration.
- Each distribution spreads towards positive pitch values when the fast ion energy decreases, due to the pitch-angle scattering effect that becomes more relevant when particle energy E approaches the critical energy Ec

Development of the content for the next versions

NBI

- NBI (Fokker-Planck) studies
  - Ideally for all configurations & key scenarios
  - NBI coupling
  - SN & alternative schemes
  - Other divertor configurations
- Studies of 3D effects (non-axisymmetric Bo-fields) and transients
- Options for synergy studies NBI-ICRH

Fuelling

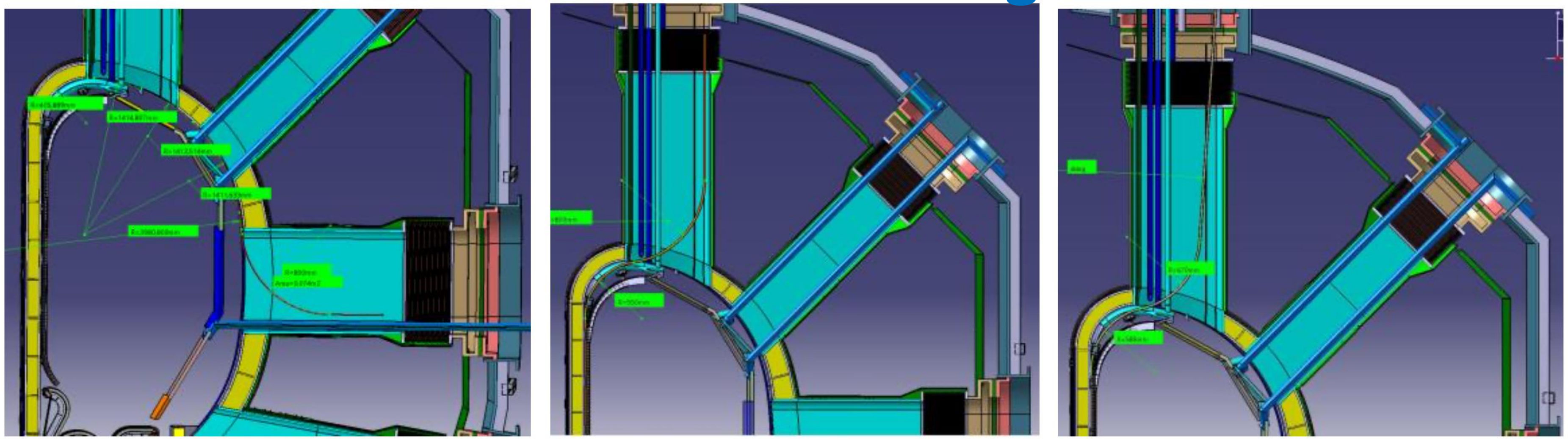
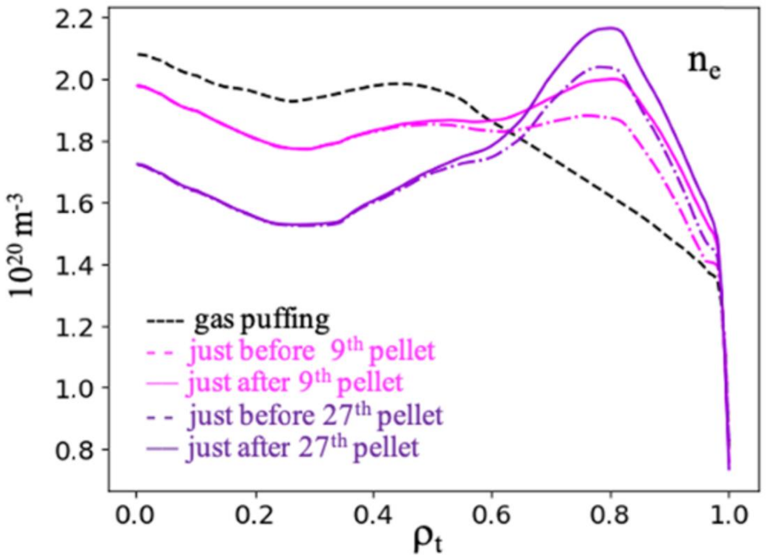


Figure 6.12. Panels from the left: injection from port 3, from port 1 vertical, from port 1 tilted.



Left: electron density profiles as calculated by the simulations of the DTT full power scenario E

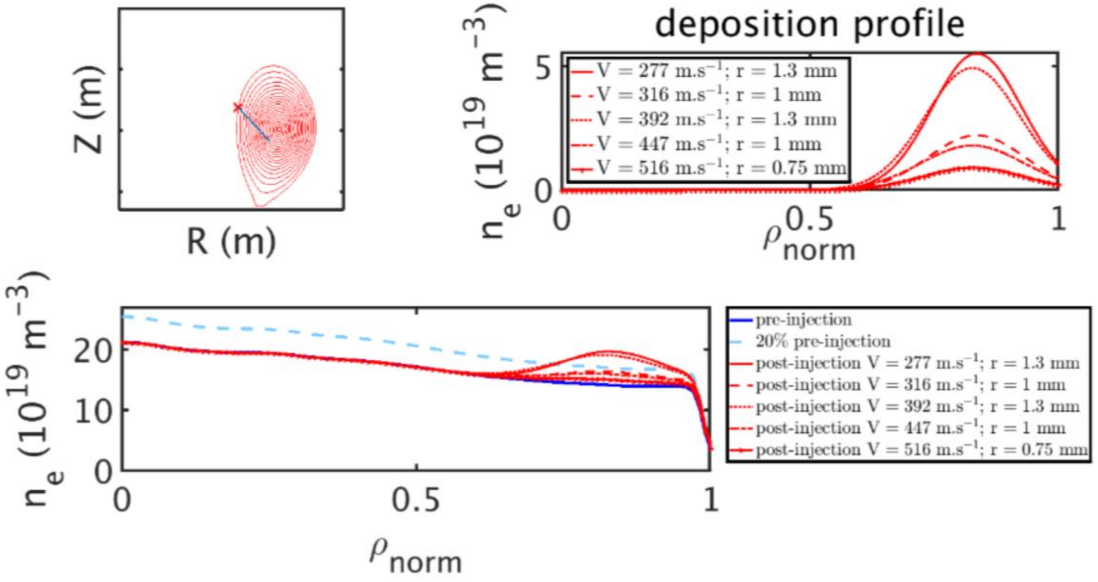


Figure 6.11. (a) Injection geometry, (b) deposition profile and (c) pre- and post-injection densities for an injection.

- Simulation of pellet injection as fuelling method predict that the pedestal density is well sustained with realistic parameters for the DTT injector (gas injection insufficient to achieve the pedestal density)
- sustainment of the core density depends strongly on the EC power deposition width (broadening needed)
- HFS injection for fueling
- Pacing either form HFS or LFS (best option to be investigated)

Development of the content for the next versions

Fuelling

A number of options are still open in the design of the mass injection system (pellet speed and injection line(s) access, acceleration system, supersonic molecular beam injection for low density operation…)

- Modelling needs:
  - Improved modelling of the pellet fueling (higher realism; optimization)
  - Modelling of impact of fueling on edge and pedestal (ELMs,…)

- Needed know-how requiring experiments:
  - Lab tests for the injection line
  - Lab tests for the extrusion/launching system
  - Evaluation SMBI for representative conditions (experiments on EAST)
  - This is needed to properly choose the system and ensure an operational pellet injector is available when needed

Follow-up of the research activity

From the experience of collecting information for the Research Plan:

- Organizational structure not clear enough: recommended overview of who does what and where are the "holes"

- What in the design has been frozen (so we work with the hardware provided …)?
- What can still be upgraded based on outcome studies

- A closer integration between the Research Plan activity (driver of the preparation to the experimental phase?) and the implementing structure would be beneficial. In this respect, Pro-bono activity does not necessarily guarantee the required output with the best timing.
- Look for funding schemes for a wider (an deeper) involvement of European researchers (EUROfusion, dedicated funding through DTT or other Italian institutions, other bilateral agreements?)

- Dedicated efforts to make use of IMAS? Request CPU time on gateway?
- DTT computation cluster?