Chapter 6

PHYSICS OF HEATING, CURRENT DRIVE & FUELLING

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Tasks the ≠ energy and/or particle sources contribute to

- 4 topics: ECRH, ICRH, NBI, fuelling
- Same structure for various subtopics:
  - System description and ITER/DEMO relevance
  - Heating and current drive source and system-specific tasks
  - System commissioning, required diagnostics and dedicated modelling
  - Discussion points
    - Work still to be done for Chapter 6
    - Longer term topics
- Summary of discussion points

Tasks the ≠ energy and/or particle sources contribute to

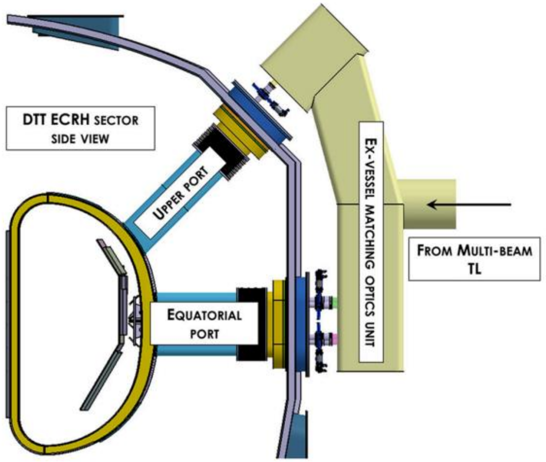
Table 0.1. Functional requirements of the heating and fuelling systems. For each system and task a categorization is given: *** essential, ** useful, *usable, - not applicable. (1) Indirect ion heating via collisions at high plasma density. (2) Combined use of heating systems and pellet should be considered since operations with pellet will require at least a minimum amount of additio heating

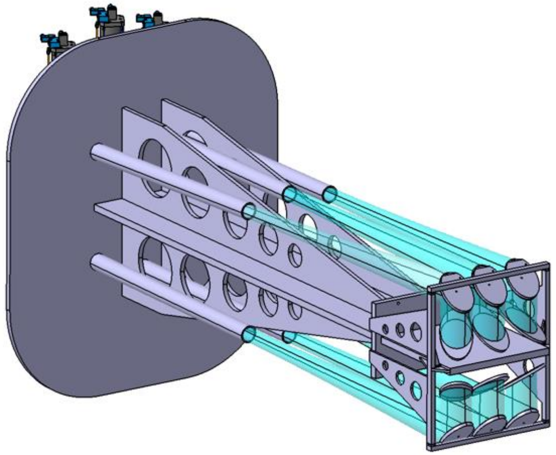
Task in DTT	ECRH	ICRH	NNBI	Pellet
Preionization, Breakdown and Start-up	**/***	*/**	-	-
Plasma current ramp-up and ramp down	**	**	*	-
H-mode access and exit	**	**	**	**
Electron heating	***	**	**	-
Ion heating	*(1)	***	**	-
Current drive	***	*	**	-
Core MHD control (NTM, ST)	***	*/**	-	-
Fast particle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

ECRH (Electron cyclotron resonance heating)

- Primary heating system in DTT: 70% of total additional power in final configuration
- Easy coupling to plasma, high localization and flexible injection system
- suitable for assisted start-up, heating, MHD control, in 1^{st} and 2^{nd} harmonics at full (~5.8T) and half (~2.9T) toroidal field

ECRH: System description and ITER/DEMO relevance





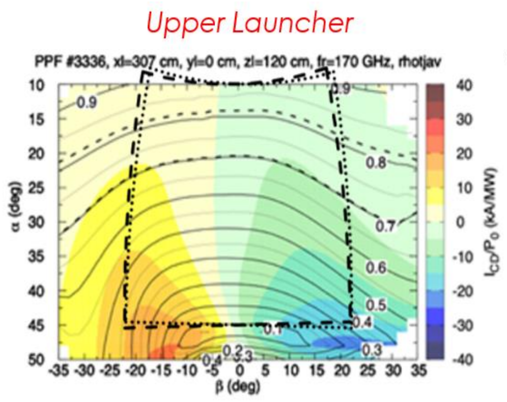
System

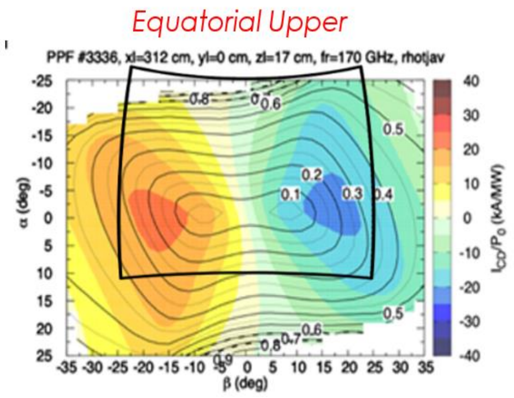
- 32 gyrotron sources at 170 GHz of 1 MW each
- 4 sectors equipped with ECRH launchers, upper for MHD control, equatorial for heating and current drive
- Full radial coverage and wide steering flexibility (e.g. more than one absorption region in plasma)
- 5 kHz modulation

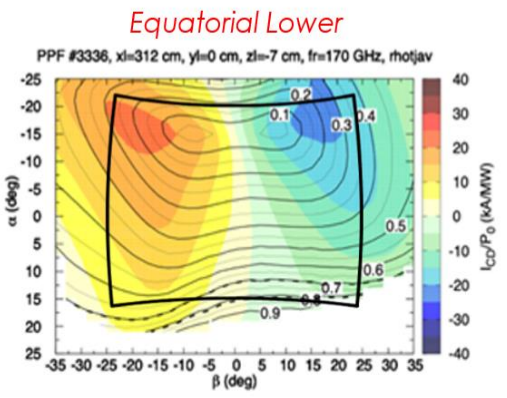
ITER/DEMO relevance

- First of a kind multi-beam, evacuated quasi-optical transmission line
- Dominant electron heating with reactor-like first wall material
- Heating at very high plasma density

ECRH: Heating and current drive source and system-specific tasks







Main applications (use cases)

- Electron Cyclotron Wall Cleaning (ECWC).
- EC assisted breakdown
- EC assisted ramp-up.
- EC heating and current drive in flat-top
- Sawteeth control
- Heating at very high plasma density
- NTM control
- Impurity control

ECRH: System commissioning, required diagnostics and dedicated modelling

Commissioning

- The gyrotron sources, including their power supplies and cryomagnets can be brought to performance using local dummy loads (asynchronous)
- Each beam routing through the transmission line up to the launching system can be commissioned by using a dummy load in the torus hall (asynchronous)
- Combined use of beams requires plasma target of suitable density
- Tasks to support basic plasma operations (preionization, breakdown, ramp-up or ramp-down, EC wall cleaning) to be developed during initial operational phase with step-by-step optimization
- Advanced tasks to be developed together with scenario development

Key diagnostics

  - Temperature (ECE in particular), density, ECE stray detectors
  - MHD activity (magnetics and soft-X)
  - Bolometry/impurities

Modelling needs

- Propagation and absorption theory and modelling tools well established
- Specific plasma-wave interaction cases (gas preionization and effect of density fluctuations on propagation) both the theory and the associated numerical tools are being developed
- Dedicated tool for real-time control involving ECRH is an essential tool to be developed or specialized for DTT

ECRH: Specific discussion points

- Quantification of power for specific tasks, in particular: NTM control, sawtooth control, impurity control
- Interaction with the machine/plasma control system for ECRH power management and sharing among potentially competing parallel tasks
- Indirect ion heating

- To be updated: a few information on density cutoff (table or ~0.5 pages)
- Cross-reference, redundancies to be solved (or may be not):
    - applications for plasma control, in particular MHD
    - EC assisted breakdown

ICRH (Ion cyclotron resonance heating)

- Flexible system: ≠ frequencies at ≠ Bo-fields allows reaching ≠ species
- Heating main task but contributing elsewhere: fast ion dynamics, MHD control, turbulence & transport studies, wall conditioning, start-up, …

System description and ITER/DEMO relevance

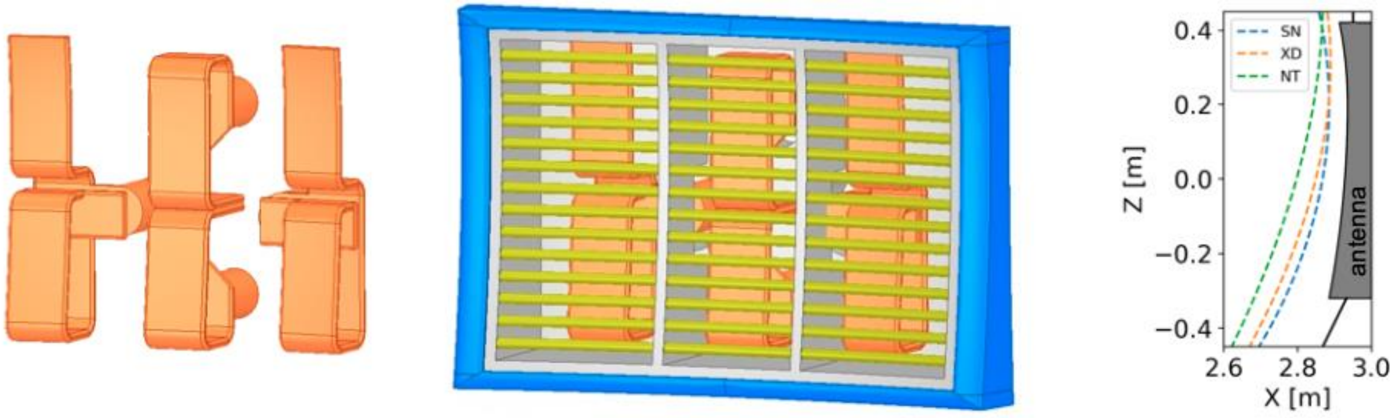


Figure 0.4. Present DTT ICRH antenna design: 3-strap structure (left), 3D view of the antenna in its antenna box with Faraday screen (middle) and qualitative side view of the front end of the antenna box with last closed flux surface for various foreseen plasma shapes (right).

System

- 3-strap system with lateral folded straps; end-fed, centre-grounded, central strap
- straps poloidally curved but not specifically tailored to a specific configuration
- radially movable to enhance coupling
- matching system with 3dB hybrid couplers and impedance transformers: catch changes in (plasma) load
- active cooling
- up to 9MW by end DTT (innovative design being examined; possibly adopted for later set of straps)
- frequency range 60-90MHz

ITER/DEMO relevance

- DTT explores wide range of plasma parameters and configurations – flexible systems required
- ICRH coupling studies and study of means for improvement under challenging conditions

Heating and current drive source and system-specific tasks

- ICRH contributes birth-to-burial of shot, and beyond
- Start-up (initiation plasma)
- Ramp-up (low density & temperature)
- Main phase
  - Heating
    - ≠ f/Bo allow targeting ≠ species
    - Minority (e.g. 3-ion), majority, beam, e
    - Full field and half-field options
    - Synergies ≠ heating systems
  - MHD control (e.g. pacing)
  - ≠ studies (e.g. localized heat source for transport)
- Real time control landing high performance shots
- Between shots: all conditioning
- Side-by-side experiments and modelling required

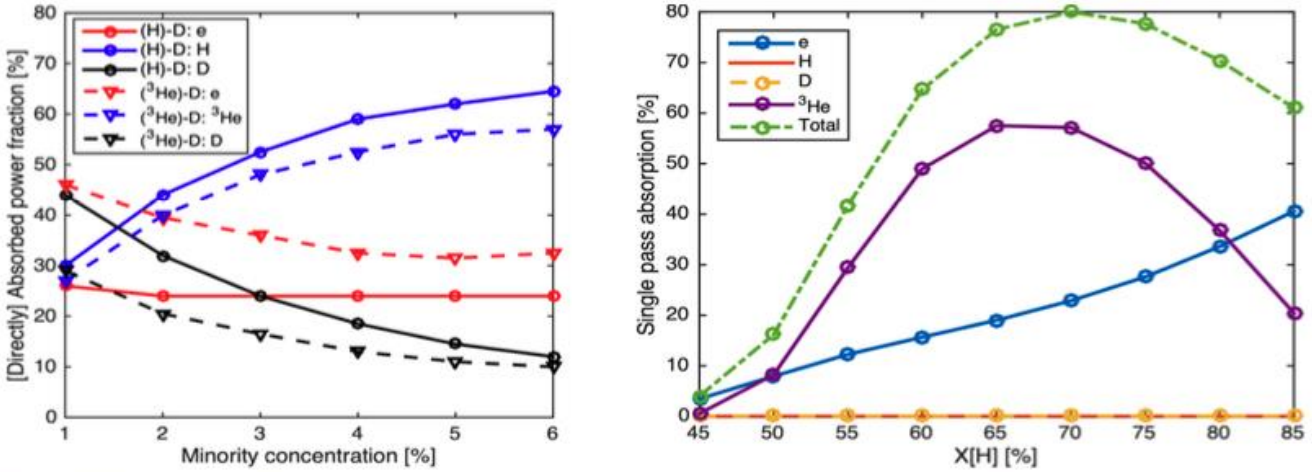


Figure 0.5. Example of the directly absorbed power fraction as a function of the H or 3He minority concentration in a D plasma for the standard minority heating scheme with minority concentrations of a few percent (left) and single transit absorption for the 3-ion scheme involving 0.1% of 3He as the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

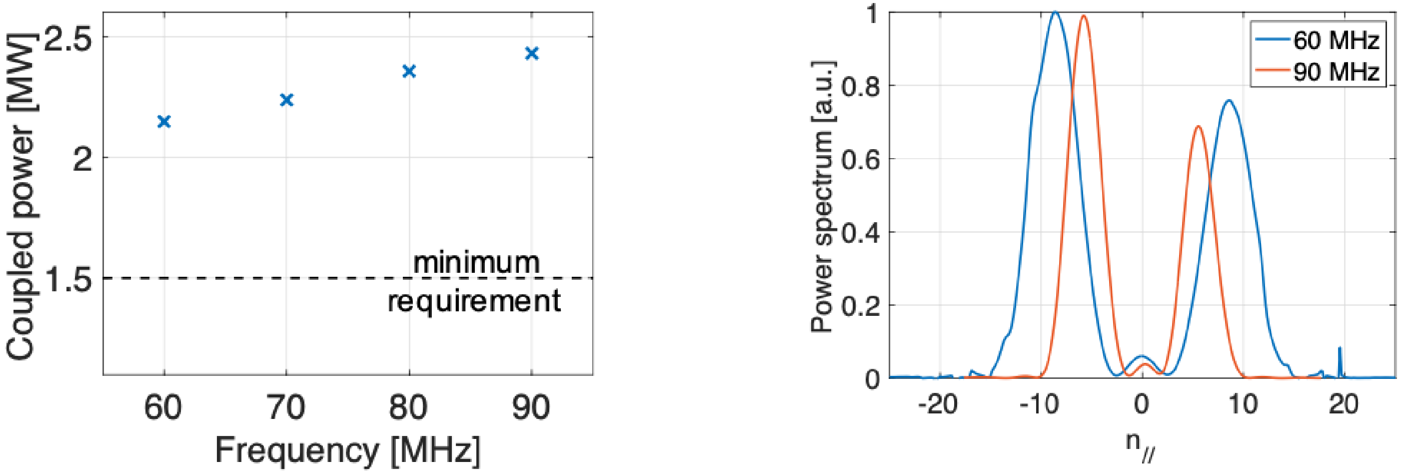


Figure 0.6. Coupled power as a function of the generator frequency for a distance of 30 mm between the antenna and the plasma (left) and corresponding antenna spectrum (right).

System commissioning, required diagnostics and dedicated modelling

Commissioning

- Done in steps: vacuum tests, then low power L-mode, gradually to high performance H-mode discharges with associated conditioning
- ≠ plasma configurations → optimization coupling required

Diagnostics required for proper steering and understanding

- Core:
  - Temperature, density, plasma composition (spectroscopy)
  - MHD activity
  - Fast particle analysis
  - Bolometry/impurities
- Edge
  - Edge density (Li beam)
  - Probes (sheaths)
  - Impurities

Modelling needs

- Wave equation modelling, ideally accounting for non-Maxwellian character ion distributions
- Fokker-Planck modelling, ideally coupled set of equations for various species
- Transport modelling
- Self-consistent time-dependent loop ideal

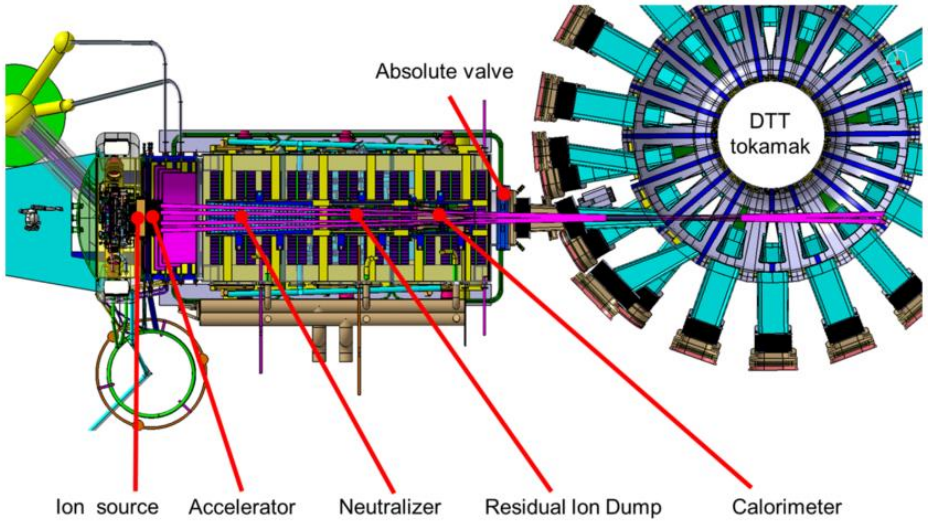
ICRH-specific discussion points

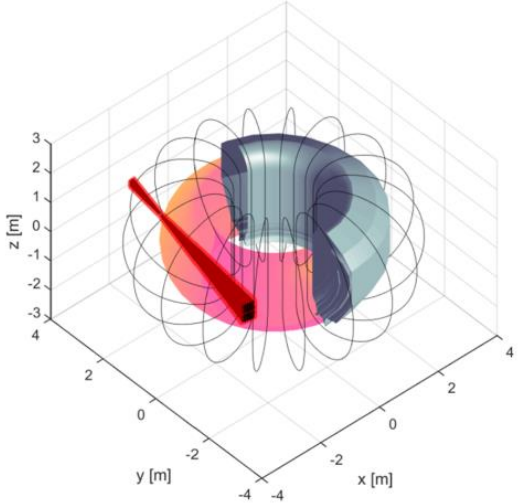
- Recent new results available that should be included in Chapter?
  - Current-drive computations missing (but first results not very promising at high densities intended)
  - Status innovative design extra antenna?
- Deeper coupling with other chapters needed (scenario's, MHD)
  - So far no deep study of various scenarios, nor of all phases discharge
  - No interaction fast particle modelling with MHD (correct?)
- How do we proceed beyond the writing of this reference book: further modelling and designing needed
  - Synergies
  - 2D wave studies accounting for ≠ configurations: in depth coupling studies

NBI (Neutral Beam Injection)

- State-of-the-art injector design
- Flexible system to contribute to various scenarios and plasma phases

System description and ITER/DEMO relevance





System

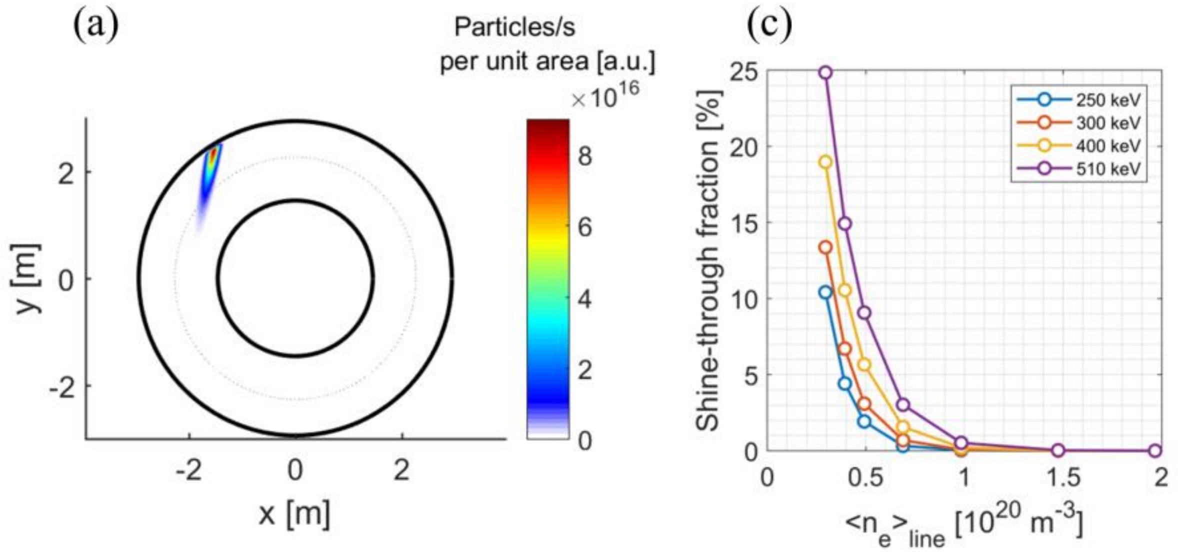
- Modular injection energy and power: up to 510 keV, 10 MW (linear decrease of E_{NBI} and P_{NBI} to ~250 keV, ~5 MW)
- Horizontal, tangential injection, co-current, H and D injection

ITER/DEMO relevance

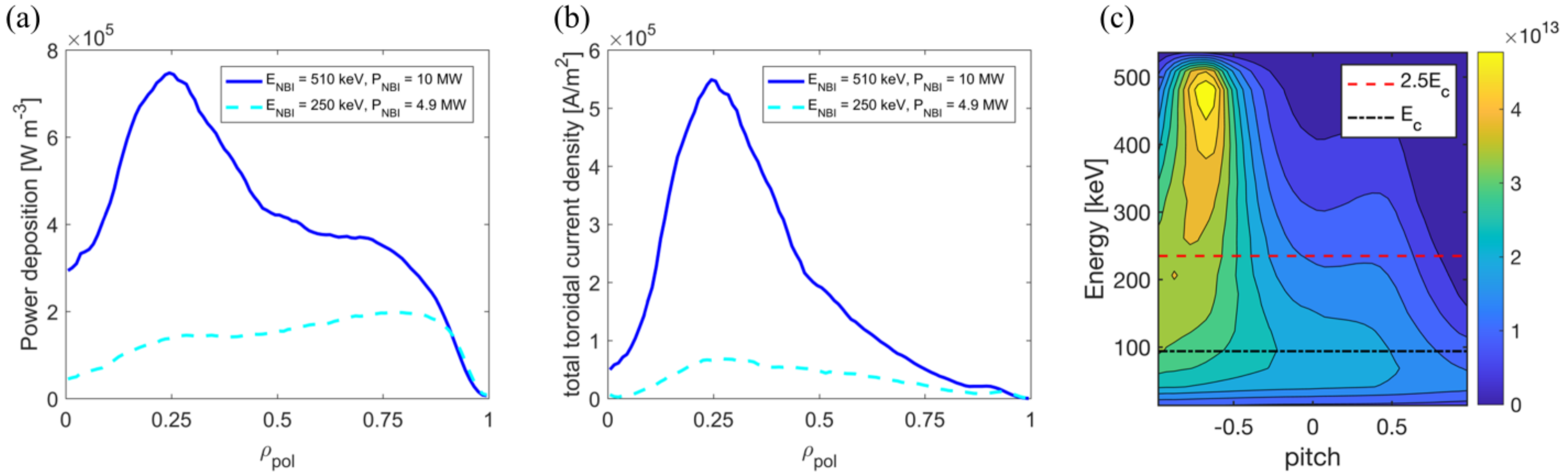
- ITER will have 2 injectors, with possible upgrade to 3
- ITER H, D NBI operations close in time with DTT NBI operation
- DTT will be equipped with the highest energy NBI after ITER, the only NNBI in a full-metal machine
- Synergy on commissioning due to several similar design solutions
- DTT B field, Ip and NBI EP energy ranges enable studies on EP physics relevant for ITER NBI EP+alphas and DEMO alphas
- NBI-ICRH synergy
- DTT significant contribution for NBI ionization cross section validation at high-energy
- Development of measurement techniques for MeV-class ions in future reactor devices

Heating and current drive source and system-specific tasks

- Heating both ions and electrons (40:60 in ref. scenario “E”)
- Current drive (0.2 MA i.e. ~ 20 kA/MW, ~ $0.1 \cdot 10^{20}$ A/Wm^2 in ref. scenario “E”)
- Small torque injection and particle flux
- Contribution in various scenarios for phases “D” and “E” (H-mode, hybrid, negative-triangularity, I-mode, no/small ELM regimes…), thanks to energy/power modulation
- Efficient NBI ionization for ref. scenario “E”



- Shine-through losses > 1% (0.5 MW/m^2 at ref. E_{NBI}, P_{NBI}) when n_e < 1e20 m^{-3}
- DTT NBI will generate mainly confined, passing particles, with trapped particles quantity depending on E_{NBI} and n_e



System commissioning, required diagnostics and dedicated modelling

Commissioning

- Initial commissioning without plasma, on calorimeter:
  - operative pressure verification, high-voltage commissioning, beam extraction, neutralization, RID
- Commissioning with the plasma:
  - Short NBI pulses, plasma density above shine-through limitations, heat loads check

Diagnostics required for proper steering and understanding

- NBI-related diagnostics for NBI/machine protection and beam operation to check:
  - NBI power supplies, beam alignment, heat load detection, leak detections
  - Shine-through & heat load detection
- NBI-related diagnostics for EP studies to measure:
  - Fast ion energy (incl. spectrum) and density, fast ion losses

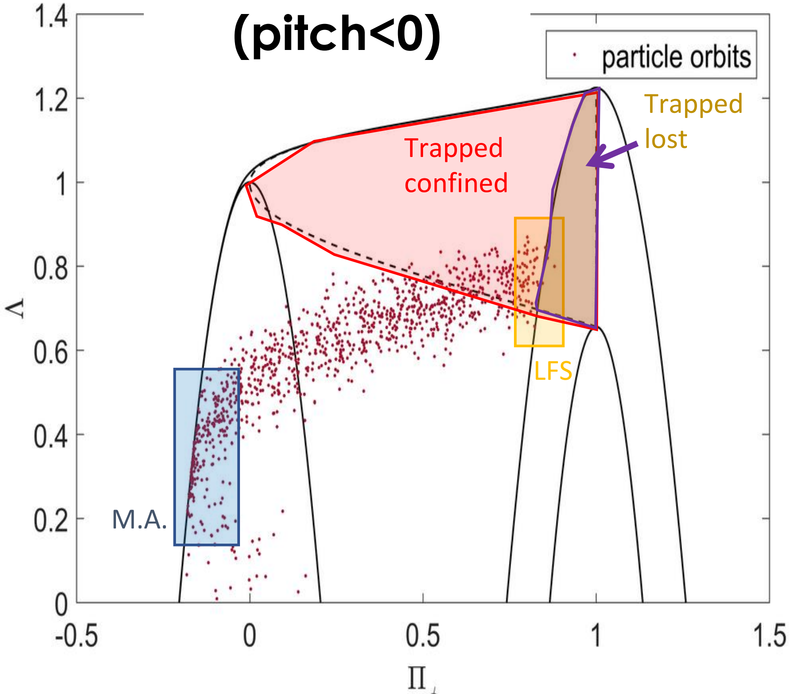
Modelling needs

- Stand-alone and integrated NBI-plasma interaction modelling
- Transport modelling
- IMAS integration
- EP workflow

Qualitative picture of NBI counter current

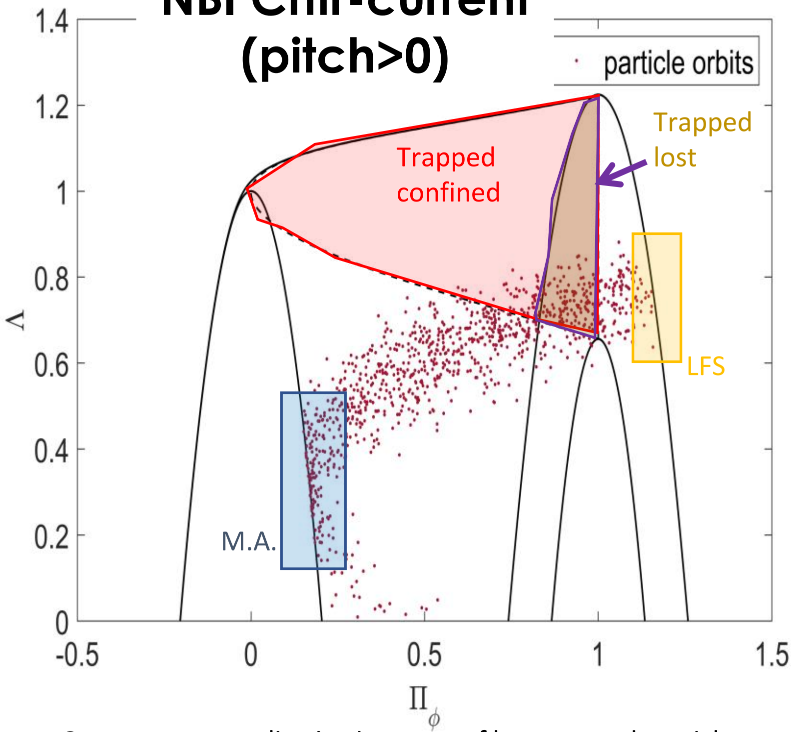
Scenario E1 – 510 keV
First orbit losses (qualitative picture, only changing EP pitch)

NBI Co-current (pitch<0)



Co-current: ~14% of trapped particles (mostly confined, only ~ 0.5% lost)

NBI Cntr-current (pitch>0)



Cntr-current: qualitative increase of lost trapped particles, decrease of confined passed particles

*Work by C. De Piccoli, RFX. Preliminary calculations for cntr-current, co-current case presented in EFTC 2023, paper being submitted.
Plots in normalized coordinates. Points corresponds to BBNBI ionization simulation, no collisions, no ICRH.

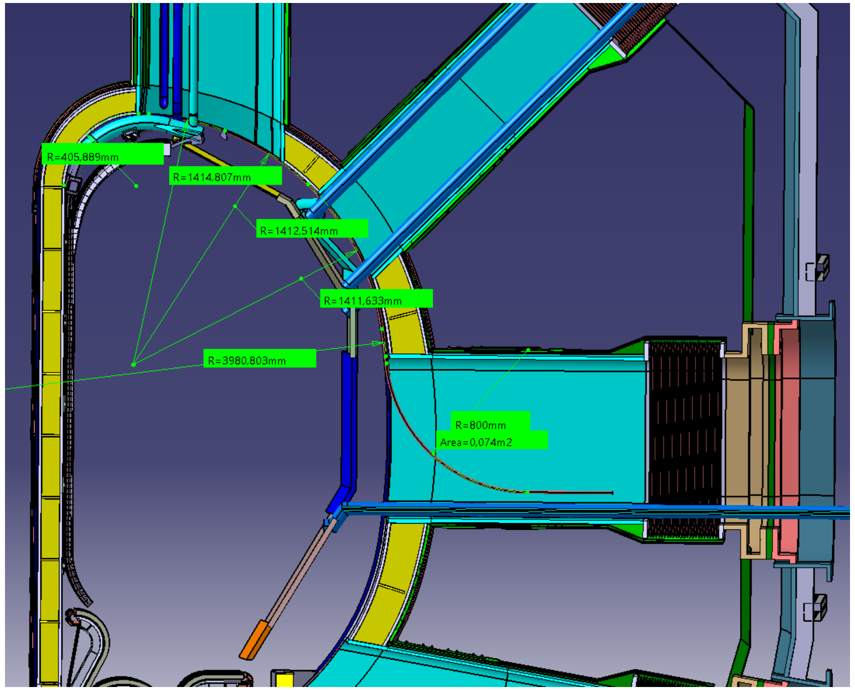
NBI-specific discussion points

- Ongoing work on (not yet finished):
  - NBI shine-through heat load calculation
  - NBI on different scenarios
  - 3D-effects on NBI-plasma interaction
  - NBI-ICRH synergy
- Similar to ICRH discussion point: deeper coupling with other chapters needed (scenario’s, MHD, fast particle)
- More “system capabilities” than “RP experiment proposal”
- NBI part in RP too long (4.5 pages): should we cut it?

Plasma Fuelling

- Gas injection
- Pellet injection (fuelling, density profile control, ELM pacing, …)

System description and ITER/DEMO relevance



System gas injection

- The main gas injection system is positioned in the midplane in port 5.
- Central fuelling and divertor fuelling
- Main gas and impurities

System pellet injection

- Pellet injection location port 3: fuelling from HFS (mandatory); ELM pacing from LFS.
- Both centrifuge and pneumatic injector are viable.
- Injection speed up to 500 m/s. Injection frequency up to 20-30 Hz (modelling required).
- Complex injection line.

ITER/DEMO relevance

- Testing complex pellet injection line and reproducibility of pellet characteristics.
- Synergy between RMP and pellet injection for ELM pacing.

Fuelling system-specific tasks

- Gas injection and density profile tailoring

- Start-up (initiation plasma)

- Main phase
    - Synergies with ≠ heating systems
    - MHD control (e.g. ELM pacing)
    - Pedestal control
    - ≠ studies (e.g. transport, impurities, …)

- Real time control of density

- Side-by-side experiments and modelling required

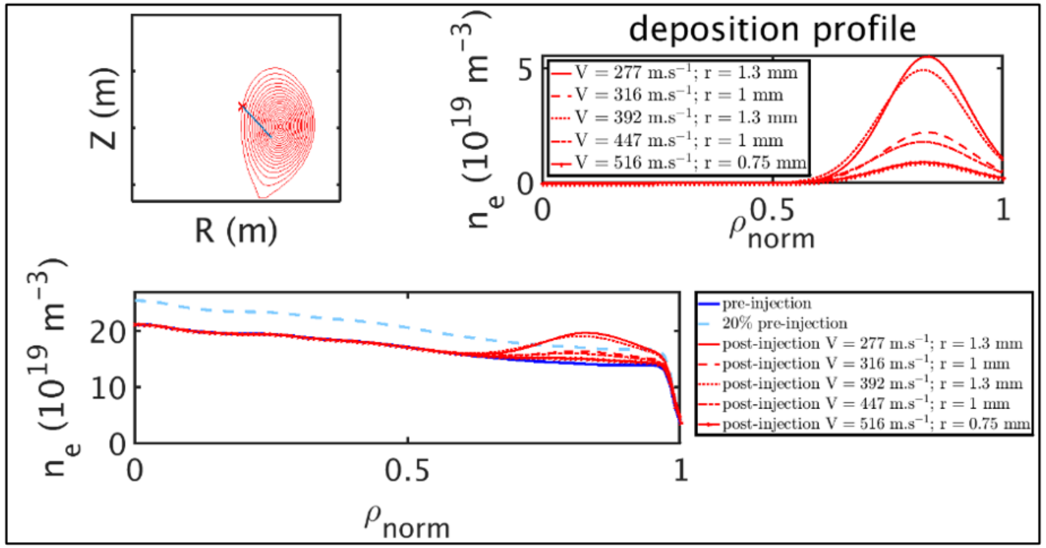


Figure 6.5.1. Considering panels from the left: injection from port 3, from port 1 vertical, from port 1 tilted.

System commissioning, required diagnostics and dedicated modelling

Commissioning for pellet injection system

- Test injection line geometry and reproducibility of pellet characteristics (as soon as possible).
- Identify the best extruding system.
- Identify the best launching system (centrifuge or pneumatic).

Diagnostics required for proper steering and understanding

- Pellet:
    - speed (optical detector) and mass (microwave cavity).
    - Pellet trajectory reconstruction (camera, PSD, …)
- Core:
    - Temperature, density, plasma composition (spectroscopy)
    - MHD activity
    - Bolometry/impurities
- Edge
    - Edge density (Li beam)
    - Impurities

Modelling needs

- ELM pacing modelling: identify pellet injection frequency, speed and size.
- Transport: modelling of core and edge density sustainment with pellets and fuelling.

Fuelling-specific discussion points

- Fuelling and ELM pacing: different requirements
    - Consider two injection lines?
    - Real-time control combining fuelling and ELM pacing is to be considered?
- Need to test as soon as possible the injection line
- Carefully check pumping requirements
    - ELM pacing pellet may be critical
- Deeper coupling with other chapters needed (scenario’s, MHD)
    - So far no deep study of various scenarios, nor of all phases discharge
    - No ELM pacing modelling was done
- How do we proceed beyond the writing of this reference book: further modelling and designing needed
    - Synergies

Global discussion

- Cross-references among chapters concerning H,CD&F, potential redundancies, probably to be evaluated case by case with careful reading

- Including D. Terranova (fuelling) as RO
- [Non-physics/engineering point:] DTT work voluntary
  - Not ideal for ensuring results will be delivered
  - No payment for missions.
  - Ways to amend this?
- “DTT community” list should be specified/updated