First draft of DTT Research Plan Chapter 7: Fast Particle Physics

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Chapter 5: MHD, disruptions and control
Chapter 7: Fast particle physics
Chapter 8: Theory and simulation for preparation of experiments

Summary

Chapter 7: Fast Particle Physics (FPP)

Table of Content:

Rationale of Chapter 7.

- This chapter discusses the role that DTT can play in studying the energetic particle physics in the frame of "core-edge integration" while considering different plasma shapes at ITER and DEMO relevant plasma parameters.
- The peculiar role of energetic particles as mediators of cross scale couplings in reactor relevant burning plasmas is briefly introduced.
- Brief summary of test particle approach (NNBI and test particle transport: prompt and ripple losses of energetic particles).
- Self-consistent simulations for Energetic Particle (short review on past and recent activity performed and future envisaged work).
- Diagnostics: DTT as a testbed for energetic particle diagnostics (relevant to future reactors or in relation to turbulence and instabilities).
- A Table of the useful available/required numerical tools.

Section 7.1 Introduction

- One of the main focuses of the DTT research mission is studying "core-edge integration" with different plasma shapes at ITER and DEMO relevant parameters. In these conditions, DTT is expected to generate energetic ions through various methods like NNBI (Negative Neutral Beam Injection) and ICRH (Ion Cyclotron Resonance Heating). These energetic ions are anticipated to interact with Alfvén waves, including Toroidal Alfvén Eigenmodes (TAEs) and Energetic Particle Modes (EPMs), among others.
- Because of the weak Kadomtsev (see Ch. 1, 8):
  - these supra-thermal ions are characterized by typical dimensionless orbit widths (characteristic Larmor radius or magnetic drift orbit size normalized to the machine size) similar to those expected in burning fusion plasmas => generally smaller than in present day devices;
  - the ratio of ion speed to the Alfvén speed in DTT is similar to that expected in ITER/DEMO (the strength of Energetic Particle (EP) drive of Alfvénic fluctuations via wave-EP resonant interactions is preserved);
  - integrated physics behaviors of DTT plasmas similar to those expected in ITER.
- Alfvénic fluctuation spectrum resonantly excited by EPs is expected to be characterized by toroidal mode numbers n~O(10) (similarly to ITER plasmas).

7.2 NNBI and test particle transport

A brief review on the activities related to prompt losses and ripple induced losses is first presented:

- prompt losses and ripple induced losses for a beam at 510 keV and injection angle with respect to the first wall of 40° were estimated to be, respectively, ~0.01% and ~0.07%
- main losses are due to a ripple-resonant mechanism for particles with pitch $\lambda=v_{\parallel}/v=$ 0.6 and 0.65; such a behavior is consistent with the theory of ripple-precession resonance
- Resonant losses are distributed in the toroidal angle while they are instead more localized in the poloidal angle θ: detailed study of power load on the separatrix surface.

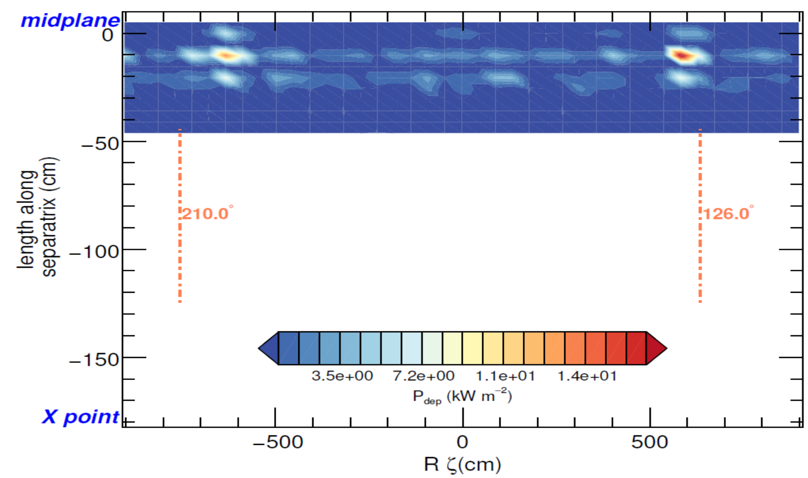


Fig.2 Map of the power load (in kW/m²) calculated with a 40 × 10 binning. In panel (b) the two vertical, dashed lines mark the injection and exit angles, ζ_{inj} = 126° and ζ_{out} = 210°.

Future work:

- in addition to equilibrium magnetic fields, also consider perturbed e.m. fields (e.g., TAEs, EPMs)
- consider resonance structures in several DTT scenarios
- consider the effects of Resonant Magnetic Perturbation (RMP) coils (see AUG experiments)

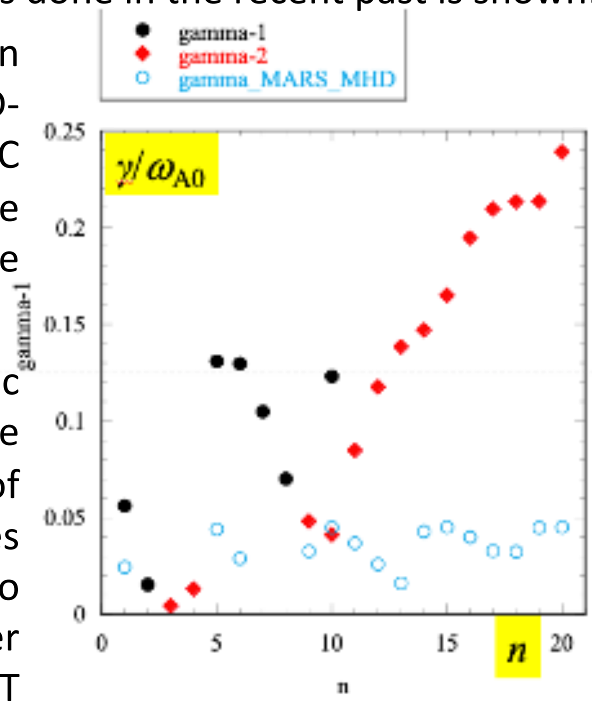
7.3 Simulation activity for Energetic Particle Physics - 1

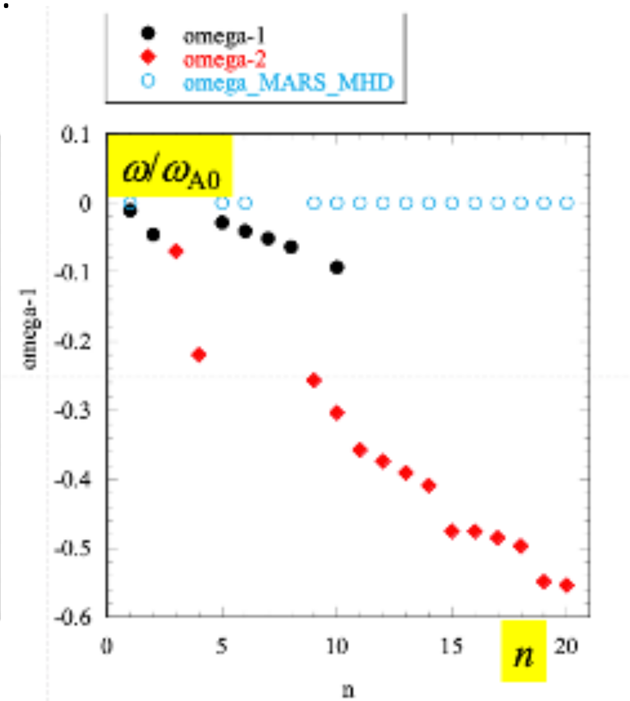
As a general comment on fast particle physics in DTT:

- preserving the super-Alfvénicity of the neutral beam will be necessary to mimic the energetic particle physics of ITER;
- this would require, roughly, that $\omega_{t,EP}/\omega_A \sim v_{th,EP}/v_A$, lies within the TAE and EAE gaps;
- the present choice of 510 keV NNBI is marginally super-Alfvénic, and interesting operation for DTT from this point of view will require full exploitation of the machine performances (full plasma current and core plasma density, e.g., at fixed Greenwald fraction, and full magnetic field to maintain constant ρ_*, the dimensionless orbits).

In this Section first a review of the activities done in the recent past is shown:

- Studies of Energetic Particle driven Alfvénic modes using the hybrid MHD-Gyrokinetic codes HMGC and HYMAGYC have been performed showing the evidence of excitation of Alfvénic type modes (considering model equilibria)
- Linear simulations for ITER-like Energetic Particle pressure profiles have shown the presence of a broad spectrum of oscillations, with linearly unstable modes for toroidal mode numbers at least up to *n*=20 (the max. toroidal mode number checked...) (considering realistic DTT equilibria)





7.3 Simulation activity for Energetic Particle Physics- 2

- To properly simulate EP physics in DTT, it is essential to have realistic scenarios with on-axis q values that are not unrealistically low;
- and it would be desirable to have equilibria optimized with respect to medium to high-n ballooning modes stability.

Present and foreseen activities:

- moderate-n simulations were performed for a realistic, up-to-date full-power DTT equilibrium;
- the study encompassed both linear and nonlinear EP-driven mode dynamics, considering a slowing-down distribution function for the EPs and an off-axis peaked EP radial density profile;
- the considered equilibrium has a plasma cross section vertically shifted w.r.t. the equatorial plan, resulting in a configuration in which the NNBI deposited EPs are peaked off-axis.
- simulations indicate the destabilization of a first mode, situated radially close to the magnetic axis in the region where the EP density radial gradient is positive;
- as this mode saturates, typically inducing a local flattening of the EP density profile, a second, weaker mode emerges in the external region of the discharge, where the EP density radial gradient is negative;
- the potential interplay between these two modes, and the associated enhanced EP radial transport if the radial regions of the discharge involved in the two modes overlap, is quite interesting and deserves further investigation.

7.3 Simulation activity for Energetic Particle Physics- 3

- Performing scans while varying the EP parameters, such as the ratio of the velocity of the EPs to the Alfvén speed ($v_{th,EP}/v_A$), the normalized Larmor radius (ρ_{EP}/a), the ratio of the EP density to the thermal ion density (n_{EP}/n_i), and radial profiles of safety factor, bulk, and energetic particle density profiles will be required to illustrate the overall stability of the EP-driven Alfvénic modes in the different proposed DTT scenarios. Note that, however, such scans can be computationally very demanding and will require access to high-performance computing (HPC) resources.
- One important impact on the EP physics and the control of plasma operation could occur because of the effect of applied Resonant Magnetic Perturbations (RMPs) on EP losses. In AUG experiments, it has been demonstrated that an edge transport layer is formed and controlled by changing RMP coil perturbation amplitude and phasing. This essentially occurs because of the overlap of EP nonlinear resonances, with the effect of either enhancing or decreasing the EP losses. The recent configuration of RMPs in DTT should have the possibility to consider in detail such effects.
- Considering a high-β scenario during the initial phases of DTT operation at a low toroidal magnetic field could provide valuable insights. Additionally, comparing DTT results with existing results from other devices like JT-60SA may offer further validation and understanding.
- Determining the typical spectrum of oscillations driven by EPs in the range of Alfvénic modes is also necessary for computing nonlinear fluxes in the phase space: this is a valuable input that can be provided by the simulation activities developed within such Research Plan section. The Phase Space Zonal Structures (PSZS) theory can provide valuable insights into the implications on transport (see Theory Chapter 8).

7.3 Simulation activity for Energetic Particle Physics- 4

Several EUROfusion initiatives related to theory and simulation efforts in the field of EP physics and burning plasma physics are of interest for the future development of this Chapter:

- CfP-FSD-AWP21-ENR-03 (ATEP: Advanced Energetic Particle Transport Models) - this initiative focuses on developing advanced models for understanding the transport of energetic particles in fusion plasmas. **The DTT reference scenario is available for benchmarking and testing, but it requires updating with more recent parameters**;
- TSVV Task 10 Physics of Burning Plasmas;
- TSVV Task 2 Physics Properties of Strongly Shaped Configurations **(in particular, Negative Triangularity (NT)) - in the activities considered in this task, DTT equilibria have been specifically considered**;
- other EUROfusion initiatives (e.g., WPs (WPTE, WPSA, WPPrIO, etc.) and International Collaborations, e.g., China, the Center for Nonlinear Plasma Science (CNPS), etc.).

7.4 The DTT as a testbed for reactor-relevant energetic particle diagnostics- 1

- The DTT is expected to have a diverse population of energetic ions in a broad energy range, from hundred keV to some MeV (**M. Nocente**):
  - NNBI 510keV for heating and current drive (deuterons from 510 keV -> ion thermal energy);
  - Diagnostic beam (?) (facilitate diagnostics systems based on CX);
  - ICRH heating (few MeV protons, deuterons, ^{3}He depending on the heating scheme).
- For the first time, the DTT will combine a mix of diagnostics based on both charge exchange and nuclear reactions:
  - fast ion loss detector (FILD) -> only system aimed at measuring unconfined fast ions;
  - fast-ion D-alpha (FIDA) system;
  - scintillator based neutral particle analyzer (NPA);
  - time of flight neutron spectrometer (TOF);
  - gamma-ray spectrometers (GRS).
- As most of the systems provide partial and/or indirect information on the fast ions, one important modelling task will be to merge the information provided by the different systems and translate it into areas of the fast ion phase space, or orbits, than can or cannot be probed by the envisaged set of systems.

7.4 The DTT as a testbed for reactor-relevant energetic particle diagnostics- 2

- Further opportunities from DTT:
  - test alpha particle diagnostics: alphas from $D+{}^{3}He$ (thermal ${}^{3}He$ and energetic D (NNBI, ICRH));
  - triton burn up component of the neutron emission (TBN) in deuterium plasmas (1 MeV tritons from the $D+D \rightarrow p+T$ reaction branch: development of a TOF system than can also measure TBN.
- **Diagnostics for Fast Ions vs. Instabilities & Turbulence (D. Testa)**: diagnostics specifically designed for measuring the interaction between fast ions and coherent (Eigenmode-like) instabilities and incoherent (broadband) fluctuations. These diagnostics are ideal to complement the more standard fast ion diagnostics (see above):
  - **High-frequency magnetic sensors, possibly 3D (HF-MAG)**: under development for DTT, 3D measurements (δB_{POL}, δB_{RAD}, δB_{TOR}) up to frequencies well into the MHz range;
  - **Beam Emission Spectroscopy (BES)**: measurement of fluctuations with moderate to long wavelengths ($k\rho_i \leq 1$) in the density profile of the background plasma;
  - **Laser Induced Fluorescence (LIF)**: this diagnostic uses selective optical tagging through resonant fluorescence to determine the multi-D velocity and spatial distribution function of the selected (fast) ion species.
  - **Experiments on the interplay between fast particles and thermal transport:** The interpretation of measurements and simulations linking the alpha-particle distribution function to the onset and suppression of ITG and TEM turbulence has first been presented in 2012, for the analyses of the sawtoothing DTE1 alpha-heating experiment at JET.

7.4 The DTT as a testbed for reactor-relevant energetic particle diagnostics- 3

- Still to be added:
  - “**Experiments on the interplay between fast particles and thermal transport**” (second contribution from M. Nocente, to be “harmonized” with Ch. 8)
  - Imaging Neutral Particle Analyzer (INPA, see X. Du et al, “Visualization of Fast Ion Phase-Space Flow Driven by Alfvén Instabilities”, PRL 127 235002, and J. Rueda-Rueda et al, “PHASE-SPACE MEASUREMENTS OF MHD-INDUCED FAST-ION TRANSPORT IN THE ASDEX UPGRADE TOKAMAK”, FEC 2023) – suggested by F. Zonca

7.5 Codes available/required

Name	Description	Availability	Owners/users
FALCON	semi-analytical tool to study various aspects of linear physics of the Energetic Particles	Available (ENEA)	M. Falessi et al.
EQUIPE	Equilibrium post processing	Available (ENEA)	M. Falessi et al.
DAEPS	Drift Alfvén Energetic Particle Stability code	Available (ENEA)	
CHEASE	high resolution equilibrium code	Available (ENEA)	G. Vlad, V. Fusco
MARS	linear MHD solver	Available (ENEA)	G. Vlad, V. Fusco
HMGC	hybrid MHD-Gyrokinetic code (visco-resistive, non-linear reduced $O(\varepsilon^3)$ MHD; $k_\perp \varrho_H$<<1 Gyrokinetic equation (guiding center limit) for Energetic Particles)	Available (ENEA)	G. Vlad, V. Fusco, S. Briguglio
HYMAGYC	hybrid MHD-Gyrokinetic code (resistive, linear full MHD in curvilinear geometry; k_perp _rho_H ~O(1) Gyrokinetic equation for Energetic Particles)	Available (ENEA)	G. Vlad, V. Fusco, S. Briguglio
Hamitonian mapping	analysis tool	Available (ENEA)	V. Fusco, S. Briguglio
JOREK	Non-linear MHD, suited for edge studies (include x-point, scrape-off layer, divertor region, resistive wall effects, two-fluid effects and neoclassical flows, kinetic particle models, and further extensions. Main physics applications are the physics and control of disruptions and edge localized modes (ELMs)	Available (RFX)	D. Bonfiglio, ...
ORBIT	single particle guiding center code	Available (RFX)	G. Spizzo, M. Gobbin.
ASCOT	"Accelerated Simulation of Charged Particle Orbits in Toroidal devices" is a Monte Carlo orbit-following code developed in collaboration with VTT Technical Research Centre of Finland since 1991	Available (RFX)	P. Vincenzi
heating codes	...	...	...
Integrated Workflow for Energetic Particle Stability (IMAS)	automated time-dependent workflow for energetic particles stability analysis within the Integrated Modelling & Analysis Suite (IMAS) (Python-based), Not available at present, but ENEA-Frascati participate actively in the ENR project which developed this tool	Available (IPP, EU)	Ph. Lauber (ENR ATEP project)

7.6 Connections with other EGs

- Phase space fluxes from DAEPS: using the Phase Space Zonal Structures (PSZS) theory and linear results allow to compute the non-linear fluxes in the phase space ↔ implications on transport (should be addressed in Ch. 8, Theory?)
- Energetic Particles and their effects on bulk plasma transport (→ EG-3 "Plasma scenarios and associated modelling") (should be addressed in Ch. 8, Theory?)
- Equilibrium and stability of MHD modes (EG-5, Ch. 5)
- Negative Triangularity...
- Energetic Particles generated by ICRH...