MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Stellarator DEMO Physics Gaps Scenario Integration

Pavel Aleynikov, Arturo Alonso, Heinrich Laqua, Nerea Panadero, Felix Warmer

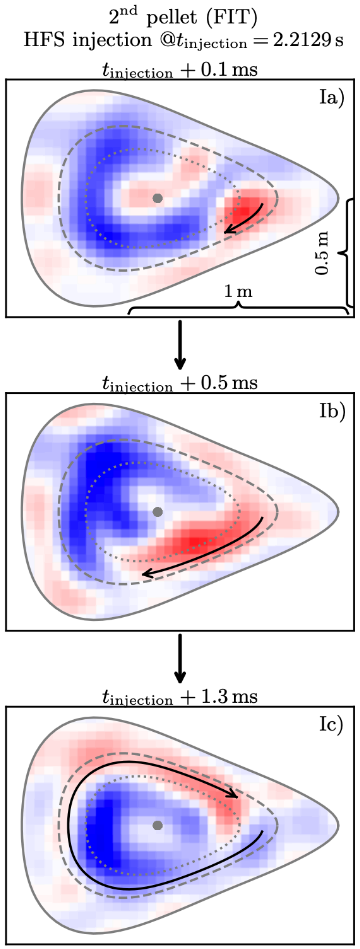
1. Plasma fuelling

- Density profile and D/T mixture ratio are maintained through continuous pellet fuelling.
- The ablation rate is reasonably well predicted and depends strongly on the local temperature.
- However, the subsequent transport of detached plasmoids remains poorly understood.

1. Develop a predictive capability for core fuelling in stellarators, incorporating both pellet ablation and the radial transport (deposition) of ablated material.

2. Improve understanding and interpretation of density profile formation in current experiments, considering mechanisms such as plasmoid drift and gyro-kinetic particle pinch.

Relevance	Density profile control is essential for high-performance. Experimental observations are not fully understood. Theory and modelling lags behind.
Urgency	Fuelling profile is an essential part of transport and confinement analysis.
Effort	Theoretical tools improvement and validation, especially for ‘detached plasmoid’ phase. Analysis of experimental data.



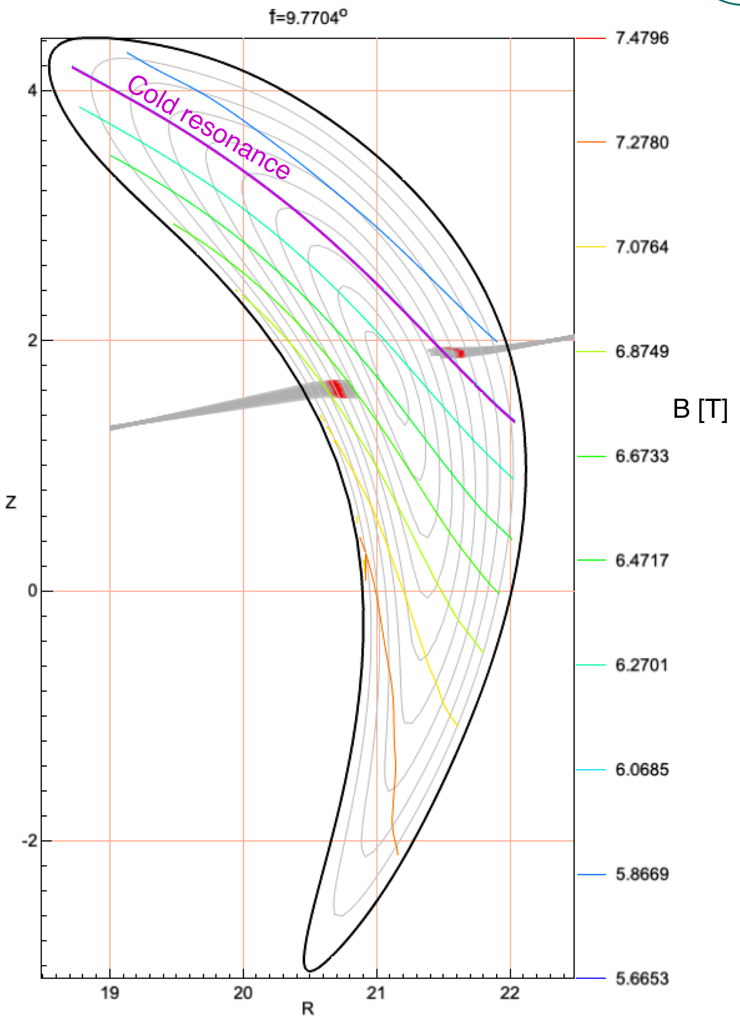
X-ray emission tomograms of the plasma poloidal plane in experimental program 20180918.047 W7-X shows detached plasmoid behaviour which is not predicted by modelling [H. Damm et. al. Submitted]

2. Auxiliary Heating

- ECRH is the primary heating method considered for DEMO.
- X2 and O2 heating schemes are routinely and successfully used in stellarators.
- However, the higher magnetic field in DEMO (5–7 T) necessitates the use of O1/X1 heating. O1 low-field-side heating at 170 GHz is considered for ITER.

1. Design ECRH scenarios for 5–7T DEMO magnetic field configurations:
   - X1 requires high-field-side (HFS) launch, which still needs stronger experimental validation
   - $v_{res} \gtrapprox 3v_{Th}$ particles are heated in HFS scenarios. “Decoupling” of supra-thermal population must be avoided to ensure effective high-power HFS heating
   - Develop strategies to compensate finite-beta effects that can distort the deposition profile
2. Improve understanding of heat and particle transport when heating at locations away from B_{max}.
3. Investigate how ECRH influences density and impurity transport (pump-out effects).

Relevance	ECRH is essential for DEMO and is a well-established and tested heating method, except for X1
Urgency	Understanding effects on transport is urgent. Other topics can be researched parallel with DEMO design.
Effort	Experimental validation of HFS heating scenarios is required. Kinetic ECRH modeling tools must be developed for HFS heating validation.



Example TRAVIS calculation of 170 GHz ECRH for ~7T SQuID-like configuration.

3. Integrated Plasma Scenario development

- Plasma conditions and confinement evolve during the build-up of plasma pressure.
- While optimization and performance assessments are typically focused on the operating point, sub-optimal performance along the Cordey path can result in unrealistic auxiliary heating requirements.
- Option for ECCD bootstrap current compensation for strike-line control if required.

1. Develop an integrated plasma ramp-up simulation tool—a "flight simulator"—that combines core and edge transport predictions with models for heating and fuelling actuators.

2. Because confinement and power balance are tight along the Cordey path (impurity concentrations have a significant impact) accurate performance predictions during the entire ramp-up phase are critical.

Relevance	Prediction of performance alone the Cordey path is important for economical DEMO design
Urgency	R&D can be done parallel with DEMO design
Effort	Development of "flight simulator" software is needed

[F. Warmer et. al.

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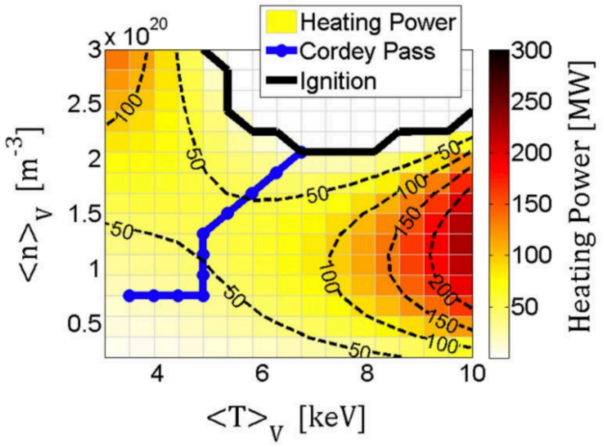


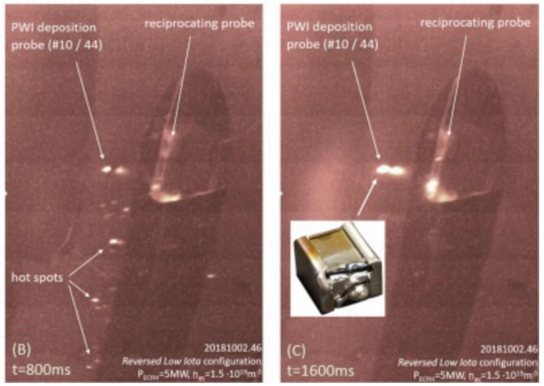
Fig. 4. POPCON analysis for an HELIAS power plant design point with $R = 22$ m, BT = 5.5 T, 10% helium ash concentration, and $f_{\mathrm{ren}} = 1.2$. Shown in color code and isocontours are the external heating power and in blue the Cordey-Pass to the ignition regime (white area).

4. Quenches and operation limits

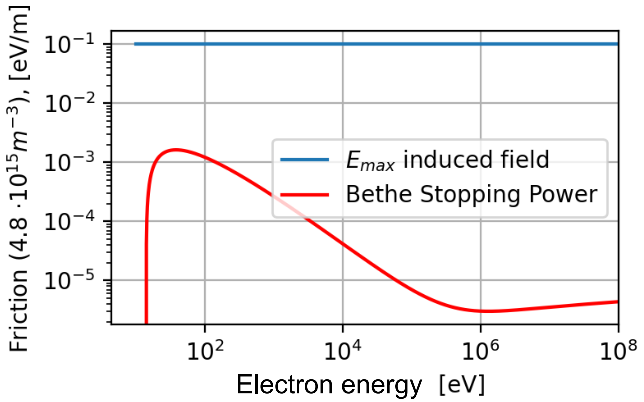
No significant plasma current quenches are expected in low-toroidal-current stellarators. However, a sudden loss of thermal energy cannot be excluded. The DEMO thermal energy-to-surface ratio is only ≈0.5 that of ITER.

1. Assess the risk of quenches triggered by component failures or unidentified foreign objects, e.g., thermal quenches. Develop a Quench Mitigation System if necessary.
2. Characterise the risk of component damage due to coil quenches.
3. Clarify the physical mechanisms that limit plasma density under DEMO conditions. Reassess the Sudo limit for DEMO operation, assuming a metallic first wall.
4. O-mode operation near the cut-off in repetitive pellet fuelling conditions

Relevance	This is a safety- and licensing-related issue
Urgency	Can be researched parallel with DEMO design
Effort	Theoretical research is still in its infancy. Greater efforts are needed to provide reliable risk assessments.



Non-thermal electrons in low density ECRH plasmas suspected to cause hot spots on PFCs with considerable heat fluxes.
[C. Killer et. al Observation of non-thermal electrons outside the SOL in the Wendelstein 7-X stellarator Nuclear Materials and Energy **33** 101274]



A toroidal electric field can be induced during coil quenches. In W7-X, the estimated induced field is sufficient to trigger runaway breakdown between discharges (low pressure).