IPP Greifswald, 24 June 2025

Key Physics Uncertainties and Research Needs for Stellarator DEMO Development

M. Jakubowski, A. Alonso, I. Calvo

https://indico.euro-fusion.org/e/HELIAS_gaps

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

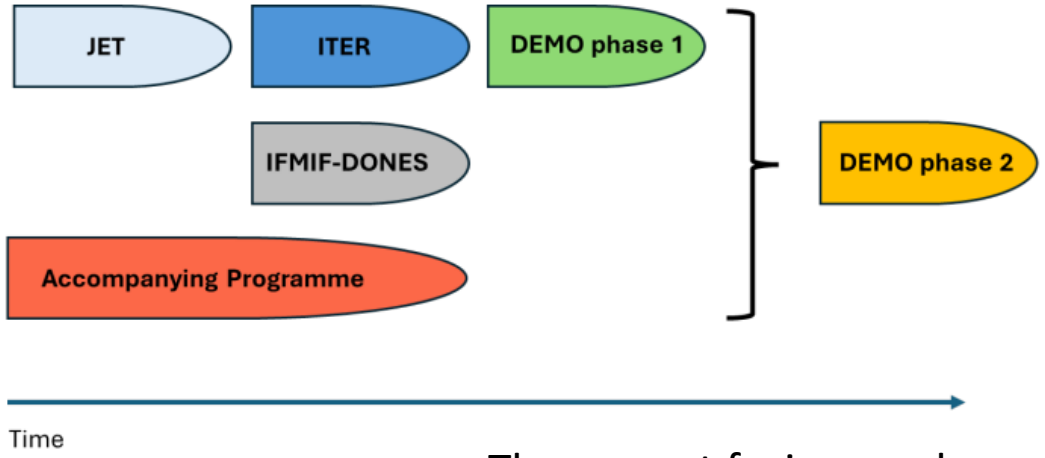
Key Physics Gaps

Purpose of this Activity

- Identify and prioritize the key physics gaps between current stellarator experiments and a future fusion reactor. Similar document for DEMO tokamak created in 2022
- Support strategic planning for European stellarator development.

Context

- Growing momentum in stellarator research both in Europe and the U.S. (parallel efforts underway in the U.S. stellarator community).
- Active discussions on the physics basis and design features of a stellarator-based fusion reactor.
- Transition from WP W7-X to WP STEL (incl. reactor studies): opportunity to define how our work can contribute to the European fusion roadmap.



The current fusion roadmap

WP W7-X becomes WP Stellarator

Exploitation of W7-X*	Key Physics Gaps+	ITER, Enhancements	Stellarator DEMO+
Campaign participation incl. missions in 2026 and 2027	Prepare a list of high priority key physics gaps	Diagnostic systems for ITER	Coil design for advanced configurations
Preparation of the campaign in 2026 and 2027	Address them if possible within WP STEL	High power gyrotrons	Neutronic calculations and tools for neutronic analysis
Exploitation of W7-X aligned with Grand Deliverables	HELIAS physics basis and stellarator database	Large diagnostic projects: MATEO, sFILD	Development of 3D blanket structures

* Engage stronger tokamak community within WP STEL
+ Engage in exchange with TSVVs, DEMO central team, but also stellarator start-ups

Objectives of this undertaking

1. Identify Critical Physics Gaps

- Assess key physics uncertainties essential for a Stellarator DEMO based on the **quasi-isodynamic** concept.

2. Ensure a Reactor-Driven Focus

- This is **not** a programmatic review of W7-X — the emphasis is on **scientific challenges and pathways forward for a stellarator reactor**.

3. Define Targeted Research Needs

- Outline what research is required to close the identified gaps, grounded in experimental and theoretical feasibility.

4. Scope Within WP STEL

- Determine which priorities can be tackled under the **Work Package STEL** framework.

5. Produce Key Deliverables

- **Summary report** (short, actionable)
- **Comprehensive paper** (in-depth, with context, justification, and references)

6. Guide Future Community Efforts

- Provide clear, strategic direction for the stellarator community to **prioritize research** and align collaborative efforts.

Areas of focus

- **Heat and particle exhaust in the island divertor**, including SOL regimes and perpendicular transport, wetted area prediction, detachment, impurity and particle compression, radiation, compatibility with high-Z materials, necessity for closed divertor geometries.
  - **Victoria Winters (IPP)**
  - Thierry Kremeyer (IPP)
  - Felix Reimold (IPP)
  - Valeria Perseo (IPP)
  - Marcin Jakubowski (EF)
- **MHD equilibrium and stability**, including beta limits and equilibrium effects on core and divertor magnetic topologies.
  - **Ksenia Aleynikova (IPP)**
  - Joachim Geiger (IPP)
  - Joaquim Loizu (EPFL)
  - Arturo Alonso (EF)
- **Core transport and confinement**, including the development of turbulent transport predictive capabilities in reactor-relevant multi-species plasmas (incl. the effects of high plasma beta, fast ion and He/impurity populations on bulk turbulence).
  - **José Manuel García-Regaña (CIEMAT)**
  - José Luis Velasco (CIEMAT)
  - Daniel Carralero (CIEMAT)
  - Andreas Dinklage (IPP)
  - Ivan Calvo (EF)

Areas of focus (continued)

- **Fast particle confinement and interaction with Alfvén waves**.
  - **José Luis Velasco (CIEMAT)**
  - Alexey Mishchenko (IPP)
  - Christoph Slaby (IPP)
  - Sergey Bozhenkov (IPP)
  - Ivan Calvo (EF)
- **Plasma-wall interaction and plasma-facing components**, including the prediction of impurity sources and separatrix concentration levels
  - **Juri Romazanov (FZJ)**
  - Sebastijan Brezinsek (FZJ)
  - Dirk Naujoks (IPP)
  - Joris Fellinger (IPP)
  - Marcin Jakubowski (EF)
- **Scenario integration**, including operation at reactor-relevant radiation levels, density limit, seeding, fuelling and heating scenarios with beta-induced magnetic field changes, plasma start-up. Also technological aspects, which are deviating from the tokamak issues should be named.
  - **Pavel Aleynikov (IPP)**
  - Nerea Panadero (CIEMAT)
  - Felix Warmer (IPP)
  - Heinrich Laqua (IPP)
  - Arturo Alonso (EF)

What’s not included

- This activity concerns the key physics gaps. The separate key technical gaps should follow.
- We have decided not to focus on pedestal/H-mode physics as it seems not required to reach the goal of attractive reactor scenarios.
- To ensure comprehensive coverage of impurity-related physics gaps while avoiding confusion during presentations, a coordinated split of responsibilities has been decided.
- Some duplication across subgroups is acceptable at this stage to avoid omissions; final consolidation will resolve overlaps.
- Tentative focus areas:
  - PWI subgroup: local W transport (e.g., prompt redeposition, erosion rates)
  - Edge physics subgroup: impurity seeding, edge transport, and radiative exhaust
  - Core/transport subgroup: impurity accumulation and core profile evolution

Prioritization of gaps

Criterion	Description
Reactor Relevance	**How critical is this gap for reactor feasibility or performance?**
Urgency	**How soon must this be addressed to inform design or next-phase work?**
Maturity of Physics Tools	**Are models, codes, or diagnostics available to study/resolve the gap?**
Experimental Access	Can the gap be addressed with current or planned facilities (e.g., W7-X)?
Impact on Other Areas	Does resolving this unlock progress in other missions or systems?
Time to Closure	How long will it take to resolve this with current resources?

Key Physics Gaps

Timeline

- **February – May 2025**: Working groups formulate and prioritize key physics gaps
- **June 24, 2025**: Community consultation meeting – gather scientific feedback
- **By end of summer 2025**: Final version of a concise, focused report
- **By end of 2025**: First draft of a comprehensive community paper
- **2026–2027**: Ongoing refinement through broader community engagement

Next steps

- **All slides will be provided on indico https://indico.euro-fusion.org/e/HELIAS_gaps**
- **Provide your input to speakers (cc me)**
- **The brief summary document will be provided by the end of summer 2025**
- **We will look what can be realized with present experimental/modelling capabilities and what needs new investments**
- **Hopefully this activity will also serve as a guidance and inspiration to the fusion community to bridge the gap towards stellarator reactor.**