WP STEL in FP10: Stellarator Pathway to First-of-a-Kind Reactor

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Present structure of WP STEL (in preparation of FP10)

Exploitation of W7-X*	Key Physics Gaps+	ITER, Enhancements	Stellarator DEMO+
Campaign participation incl. missions in 2026 and 2027	Continue work of expert group (reduced scope)	Diagnostic systems for ITER	Coil design for advanced configurations
Preparation of the campaign in 2026 and 2027	Address high priority key physics gaps	Heating systems (ECRH, NBI, ICRH)	Neutronic calculations and tools for neutronic analysis
Exploitation of W7-X aligned with Grand Deliverables	HELIAS physics basis	Large diagnostic projects: MATEO, sFILD	Development of 3D blanket structures

Goal: Re-orient WPSTEL towards development of FOAK Stellarator Plant

EUROfusion FPP report: at least one more step required before stellarator FOAK

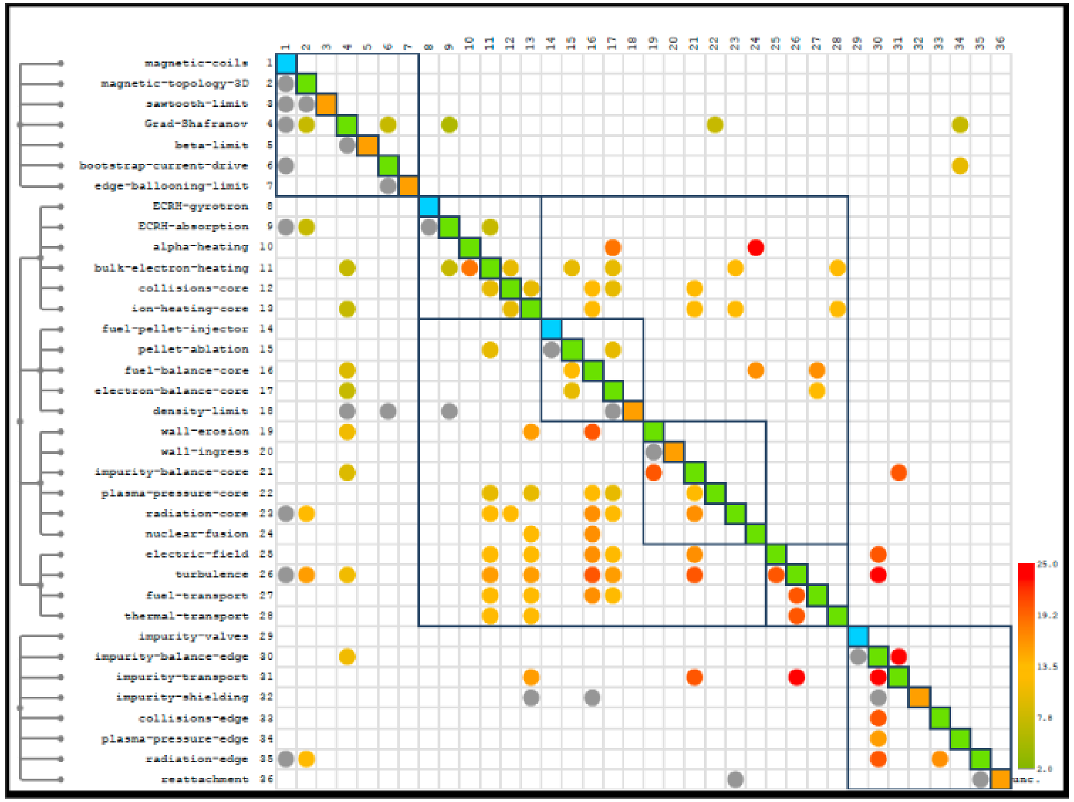


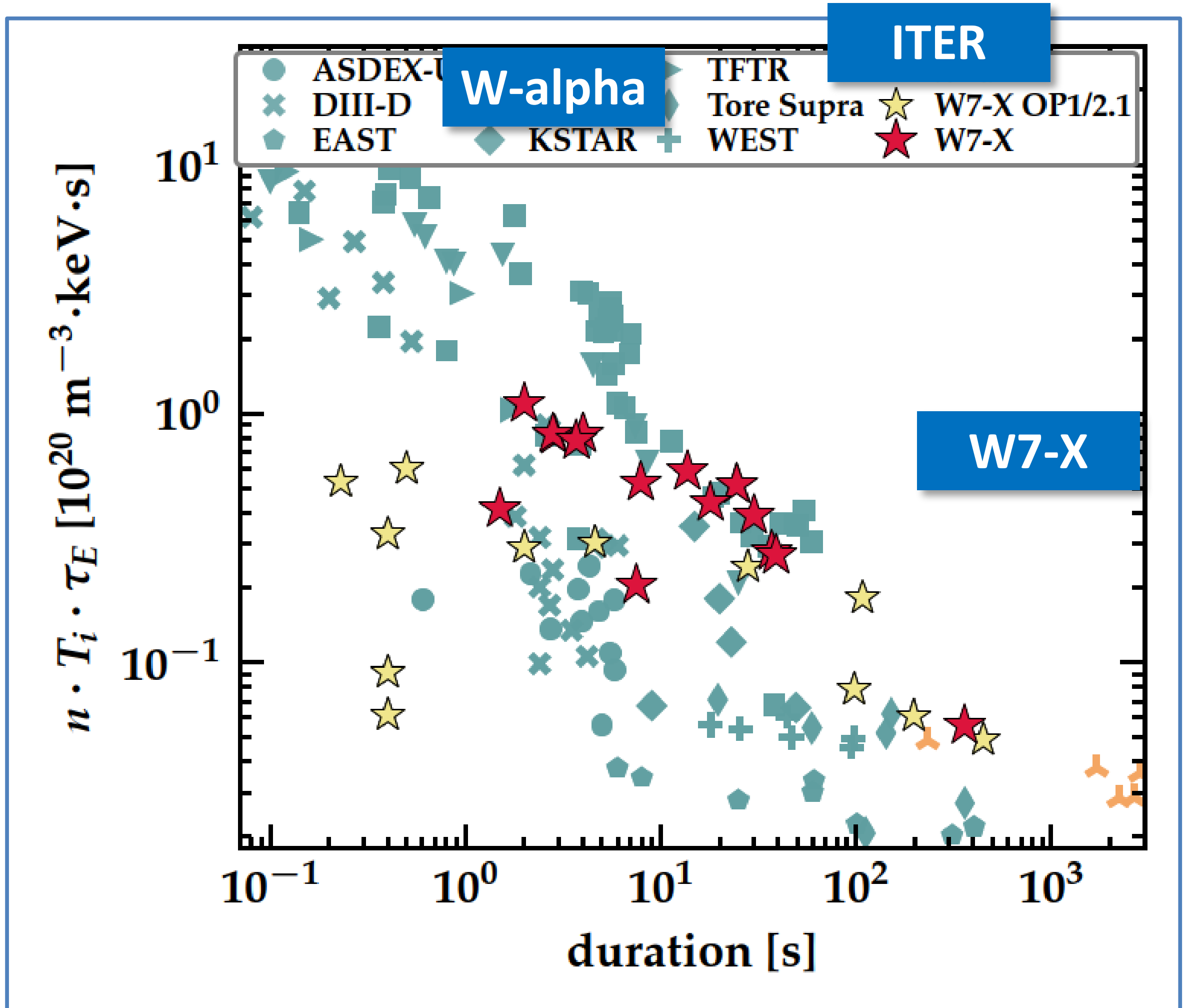
Figure 5 Physics Uncertainty for Stellarators: from W7X to Helias.

- The fundamental differences in physics, control strategies, and technology between a stellarator and a tokamak FoAK require dedicated, stellarator-specific development programmes.
- At least one intermediate experimental device is required between W7-X and a stellarator FoAK to resolve critical physics uncertainties under reactor-relevant conditions, in particular:
  - alpha particle confinement and fast-ion physics at reactor-relevant parameters
  - plasma operation at high magnetic fields
  - all-metal plasma-facing components under high fluxes
- Two major intermediate-step projects are currently being pursued by EUROfusion beneficiaries towards a stellarator FoAK:
  - Wendelstein Alpha (IPP-Proxima, start of operation FP11)
  - WISER (CIEMAT, Spain) – planned to start 2036+

Timeline of new experiments

- Wendelstein-α will be experiment built jointly between Proxima and IPP.
- IPP plans to use the exploitation model for W-α similar to W7-X (operated by IPP with strong participation from European labs).
- W-α will help to reach SRLs of up to 6-7 towards FOAK in a few areas, and generally raise SRLs/TRLs in many aspects.
- WISER-5, proposed by CIEMAT, is of W-7X dimensions, non-nuclear with QI confinement concept with improved turbulence confinement.

W-Alpha allows to close critical physics gaps towards FOAK

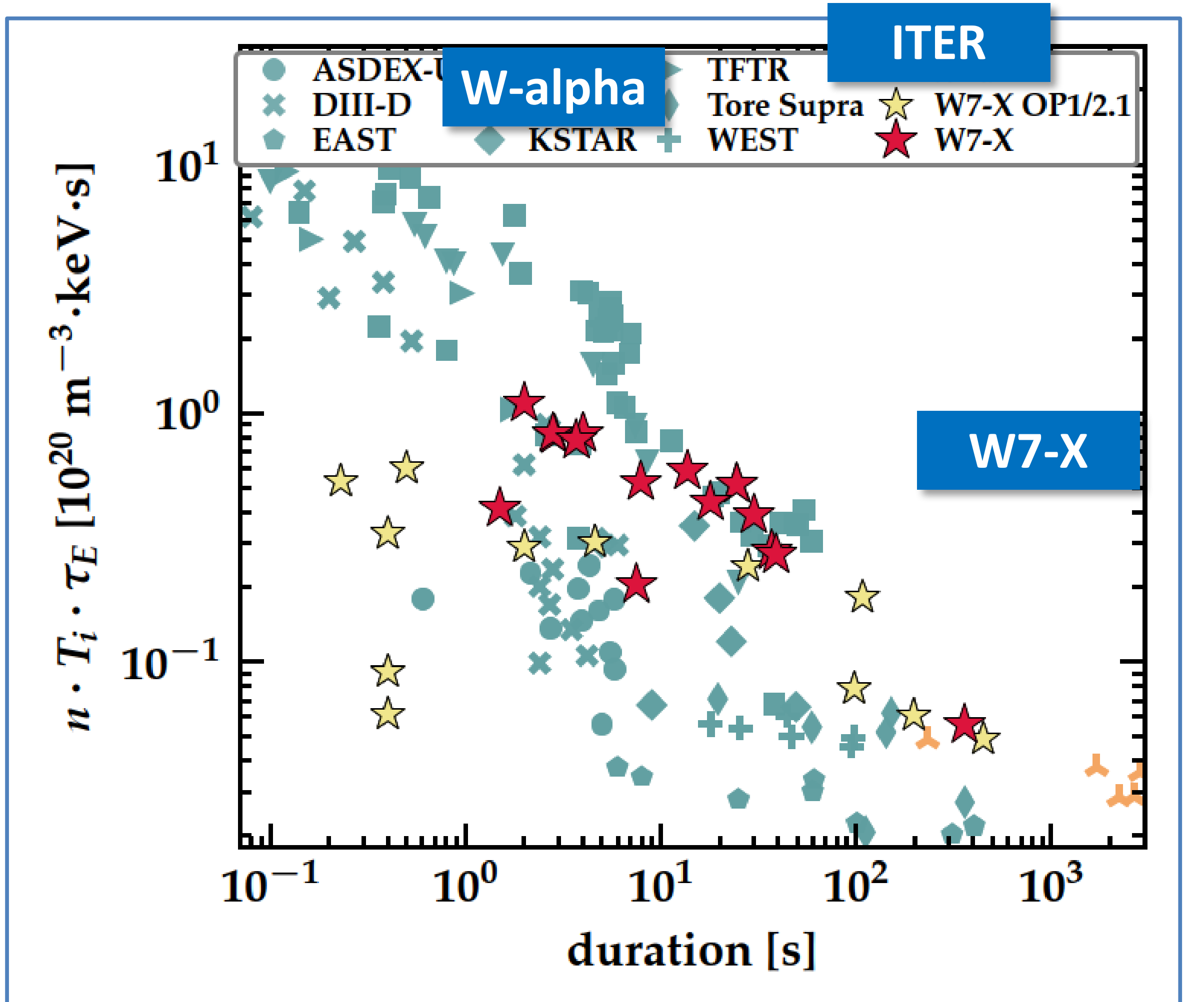


Bozhnekov et al, EPS 2025

1. Combination of reactor-relevant magnetic field (9T) and machine size allowing Qeff > 1
2. Fast-ion confinement compatible with FOAK
3. Beta operation range 1.5% to 4%

4. Integrated highly-radiative scenario in all-metal, closed divertor with reactor relevant divertor performance

W-alpha and WISER-5 fill gaps in the areas identified as critical towards FOAK



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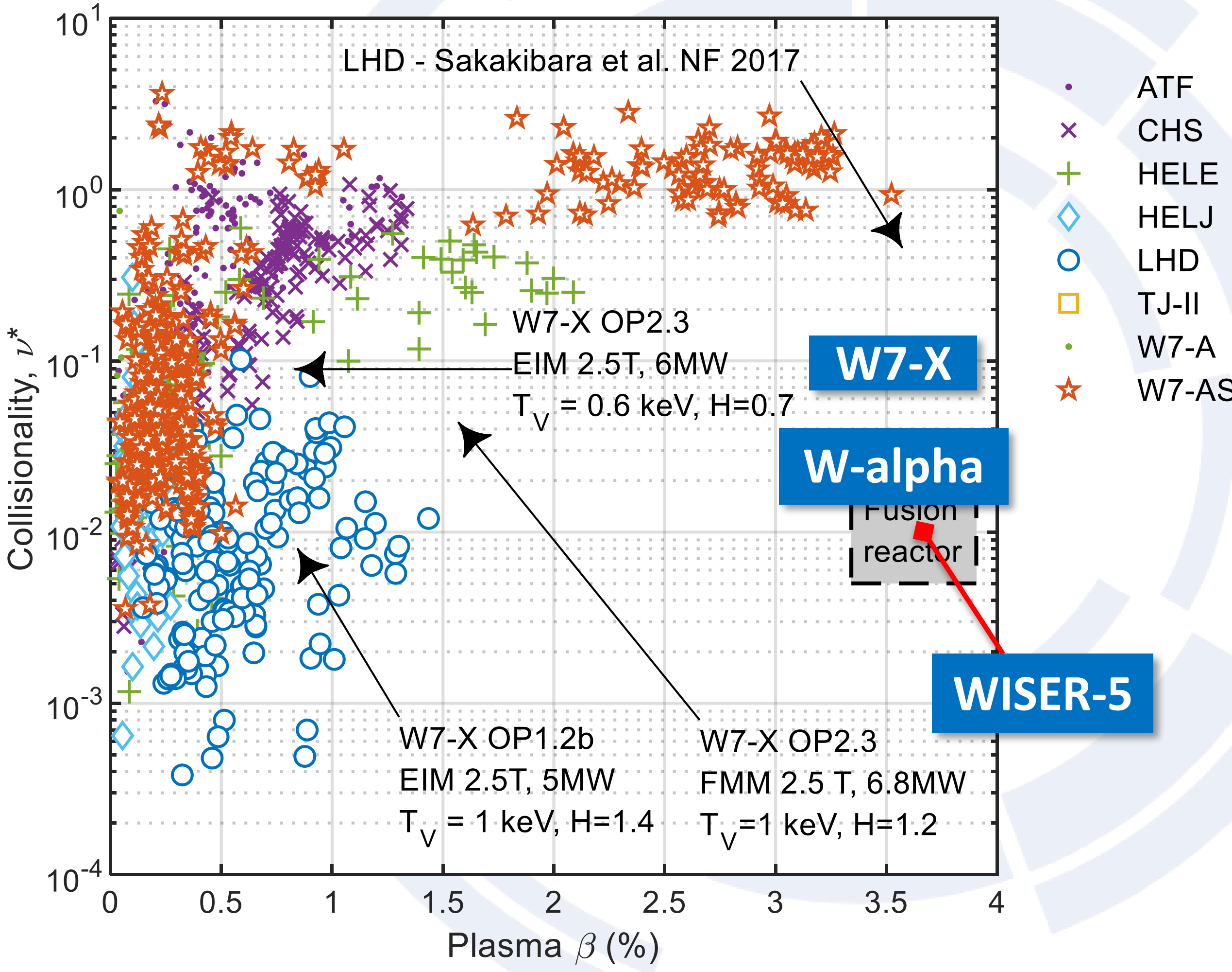


How EUROfusion Can Accelerate FOAK Stellarator

1. Manpower for open work packages
   → Plasma scenario development, e.g. turbulence modeling, divertor studies, plasma control
   → Leverages existing European expertise (IPP, CIEMAT, VTT, KIT)

2. Diagnostics development to aid exploitation in FP11
   → Fast-ions, neutrons, manipulators, microwave systems,…
   → Enables smooth integration of European beneficiaries into W-α/WISER program

3. W7-X experiments addressing to aid closing gaps towards W-α/WISER as intermediate step for FOAK
   → Core/edge transport, steady-state exhaust, detachment

4. Laboratory tests on European facilities
   → Component qualification advancing TRLs for W-Alpha/WISER systems

Proposed structure of WP STEL in FP10 towards stellarator FoaK

Four complementary pillars targeting stellarator FoAK readiness

Exploitation of W7-X

- W7-X remains main work horse for stellarator community.
- Support from TJ-II, Uragan-2M
- Preparation, participation, evaluation of campaigns 1 campaign/year
- Exploitation of W7-X aligned to GDs and evaluated based on SSRLs

Reactor Scenarios

- Define stellarator FoAK requirements
- Address physics gaps
- Develop scenarios for intermediate devices validating FoAK assumptions
- Scenario control
- (Prepare) physics models validation: closed divertor, tungsten wall, turbulence optimization, fast ions

Systems & diagnostics

Develop systems and diagnostics required to close the gaps towards FoaK:

- W7-X
- Wendelstein-Alpha
- ITER, if aligned with stellarator

For instance:

- Heating systems
- Neutron diagnostis
- microwave diags.
- maniupulators

Reactor Technology

Intensify developement on

- remote maintenance,
- closed island divertor technology
- Neutronics
- 3D blanket
- Integration of the system components
- Modular coils

Pillar 1: Exploitation of W7-X

- W7-X remains main work horse for stellarator community.
- Operated as in FP9: one-team approach, one campaign per year with one longer maintenance break between the campaign.
- Physics topics developed to close physics gaps towards FOAK. Progress measured with SSRLs
- Machine operation support at the level of 40%, which represents actual EUROfusion participation in the exploitation of the device.
- New diagnostic systems: neutrons, observation system MATEO,..
- Support from TJ-II (Spain), Uragan-2M (Ukraine)
- IPP formulated TWG on Strategy 2030+ for W7-X. Not clear yet, if all metal device

Pillar 2:

Strategic Objective

- Further evaluate key physics gaps towards FoaK
  - Re-evaluate the gaps and propose measures to close the gaps
- Develop conceptual framework for stellarator First-of-a-Kind (FoaK) reactor that establishes:
  - Order-of-magnitude parameters (size, power, cost envelope)
  - Critical physics requirements and validation gaps
  - Technology development roadmap to reactor readiness
  - Role of intermediate devices (W-alpha, WISER) as FoAK stepping stones
  - Scope: Conceptual only – no detailed engineering design (left to private sector)

Key Research Questions to Answer

- What magnetic configuration achieves FoAK physics goals (confinement, stability, alpha confinement)
- Develop FoAK scenarios with intermediate steps at predeceasing devices

Pillar 3: Develop Systems & Diagnostics Required to Close Gaps Towards FoAK

Platforms:

- W7-X (technology validation)
- Wendelstein-Alpha (integrated FoAK testbed), also WISER if already at the stage for detailed diagnostic development.
- Support of ITER (if stellarator-aligned systems)

Priority Developments:

- Heating systems (ICRF antennas) to further push capabilites of W7-X
- Neutron diagnostics (steady-state production measurement)
- Microwave diagnostics (ECE radiometry, reflectometry, correlation reflectometry)
- Manipulator systems (remote handling for 3D stellarator maintenance)?

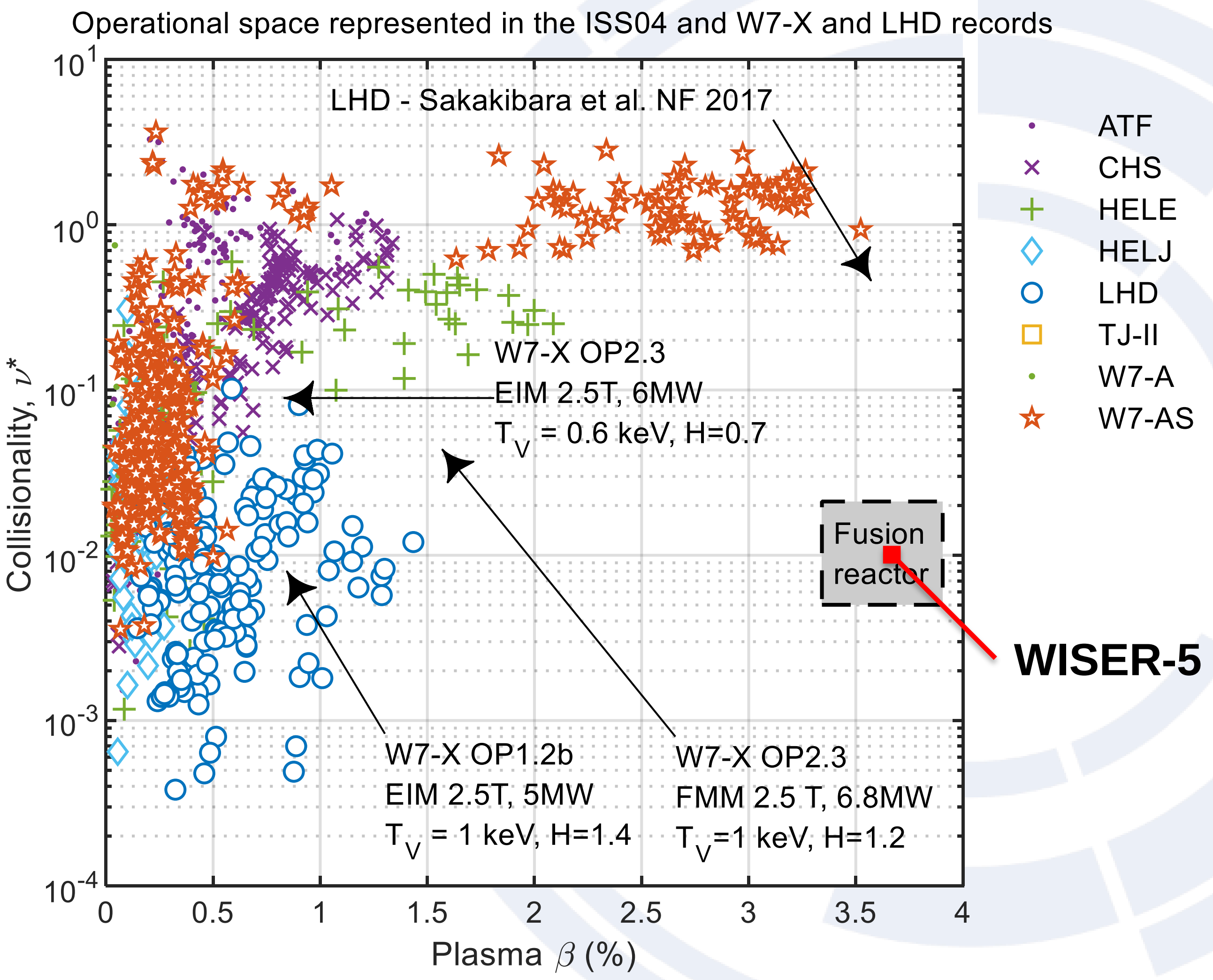
Pillar 4: Reactor Technology Development – Critical Engineering for FoAK

- **Systems Studies & Design Space**
  - Systems code for stellarator FoAK parameter space definition
  - Define feasible design points (size, cost, field strength) before detailed engineering
- **Structural Engineering**
  - Inter-coil support structure mechanical stress analysis for 3D geometry
  - Maximum achievable magnetic field depends on complex force distribution management
- **Remote Maintenance**
  - Novel remote handling strategies for stellarator 3D component access
  - Reactor architecture definition: interfaces between coils, vessel, blankets, divertors
- **Closed Island Divertor Technology**
  - Complete island divertor design with component interfaces (breeding blanket, shielding, cooling)
  - Stellarator-specific solution for particle/heat exhaust
- **First Wall & Breeding Blanket**
  - Innovative PFC solutions adapted from tokamak programs to stellarator 3D geometry
  - Integration with remote handling, auxiliary systems, tritium breeding requirements
- **Core Technologies from Original Slide**
  - Neutronics for 3D blanket structures
  - Modular coil manufacturing and assembly concepts

The end

WISER-5: Low field at reactor relevant parameters: an intermediate-step device

- Fusion reactor **conditions never achieved** in past or existing stellarator devices (figure).
- The simultaneous achievement of reactors' collisionality ν^* and β is the **most stringent test** on a reactor-candidate magnetic configuration.
- **WISER-5** is a non-nuclear device designed and engineered to operate in reactor-similar conditions in the philosophy of wind tunnels.



WISER-5

- Demonstrate the **viability of the reactor** operation point with a **reduced-scale device**.
- **Field/size** combination of possible wind tunnels is derived via rigorous scaling laws chosen to allow for **reactor-similar** operation (figure).
- **WISER-5** (*R* = 5.0 m, *B* = 1.9 T) is the wind tunnel of choice in the WISER Project.