FSD Planning Meeting

2024 Updates and 2025 Objectives

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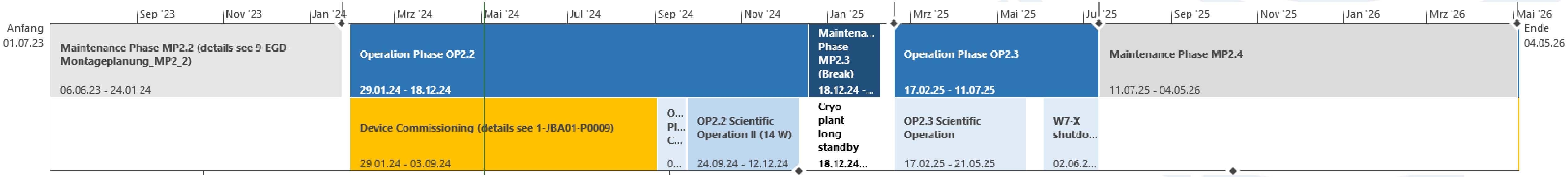
EUROfusion Facilities Review

- W7-X results have already confirmed the role of the stellarator as a **serious alternative for the reactor core of a future fusion power plant**.
- W7-X provides a springboard towards the development of a next step stellarator:
  - TJ-II: diagnostic & code validation
- **W7-X is an indispensable facility** for the further development of the stellarator concept towards a fusion power plant.
- W7-X also has the potential to support technology development for burning plasma facilities based on long-pulse tokamaks
  - URAGAN-2M: Plasma start-up, wall conditioning
  - FULGOR (KIT): development of heating systems

Recommendation: *EUROfusion should actively promote the timely launching of design and construction of a next step stellarator, leveraging where possible collaboration with international partners, with the goal of providing the scientific/technical basis for a stellarator DEMO.*

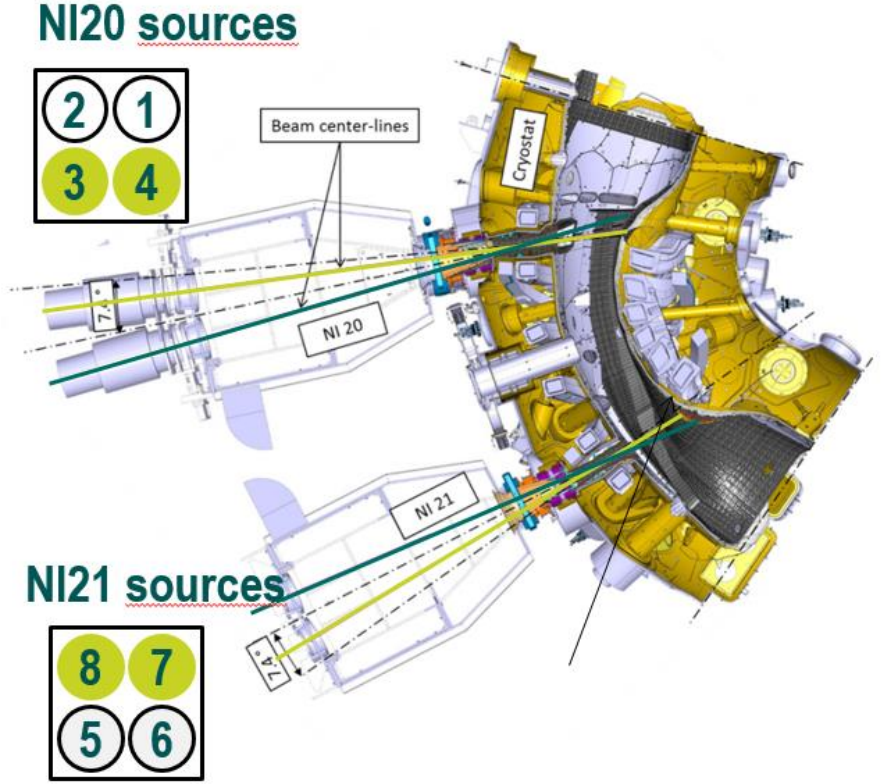
Status of Wendelstein 7-X

- Technical commissioning on (revised) schedule:
  - Vacuum conditions of plasma vessel and cryostat ready for operation.
  - Cool-down of SC coils finished
  - Major components (pellet injector, ICRH antenna, NBI/ECH extensions) on track.
  - 2 transformers for NPC-1 coils will be delivered end of June.
- Plasma commissioning starts 3 Sep 2024, shortened to three weeks
- Plasma scientific operation OP2.2 – 24 Sep 2024 until 12 Dec 2024
- Plasma scientific operation OP2.3 – 17 Feb 2025 until 21 May 2025
- Program Workshop took place on 24-24 Apr 2024
- Call for participation issued on June 1st 2024



Enhancements to heating systems

- NBI 55 kV **H injection** with all 4 sources S3, S4, S7, S8
  - injected power approx. 2-2.2 MW
  - pulse length: max. 5 sec integral
- NBI 42 kV **^{4}He injection** with 4 sources S3, S4, S7, S8
  - injected power approx. 1.2 MW (tbc)
  - pulse length 5 sec (tbc)
- ICRH (with FZJ, ERM/KMS)
  - Power > 800 kW
  - pulse length up to 10 s
  - Scenarios:
    - H minority in He plasmas
    - ^{3}He minority heating in ^{4}He or H
    - 3-ion-heating with ^{3}He, H, ^{4}He
    - Plasma start-up (also at 1.7 T)
    - ICRF wall conditioning



ECRH upgrades

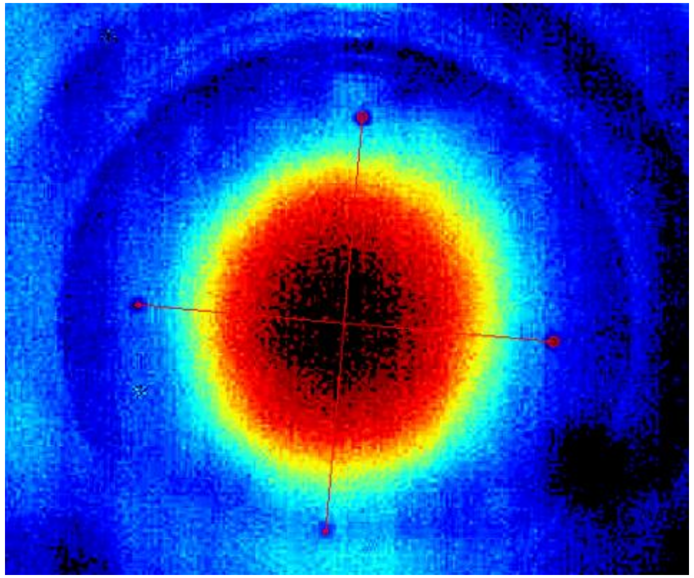
- repaired prototype 1.5MW gyrotron under commissioning
- good progress in gyrotron conditioning

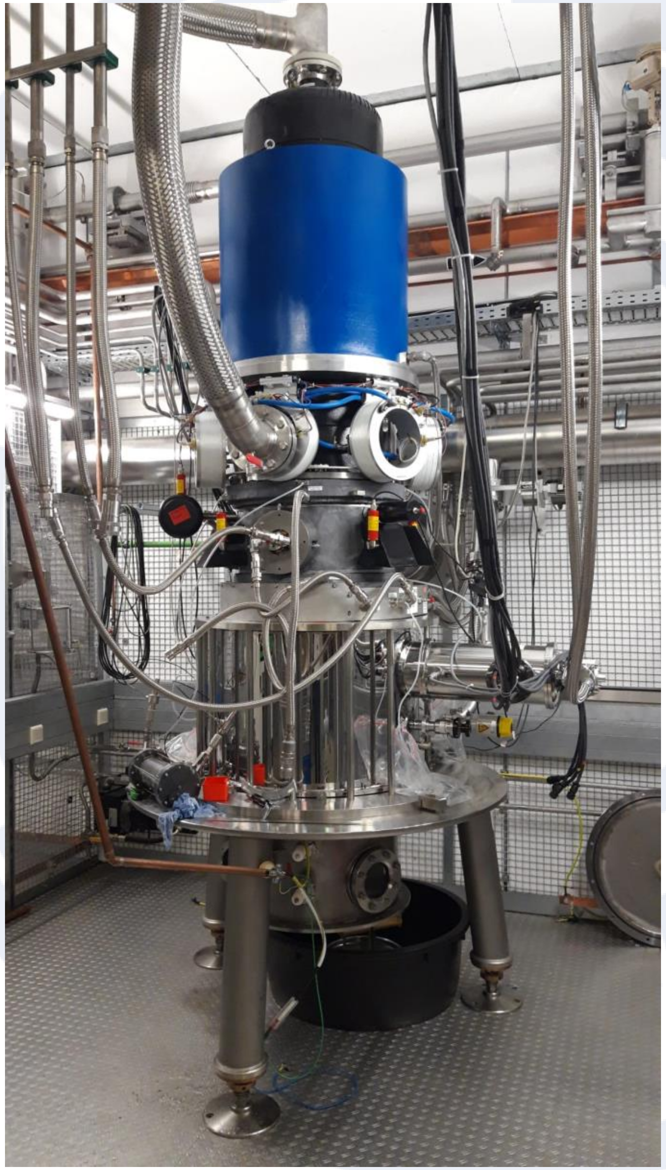
⇨ Gaussian beam shape demonstrated and centered to diamond window

⇨ 1ms pulse length at 1.5MW demonstrated

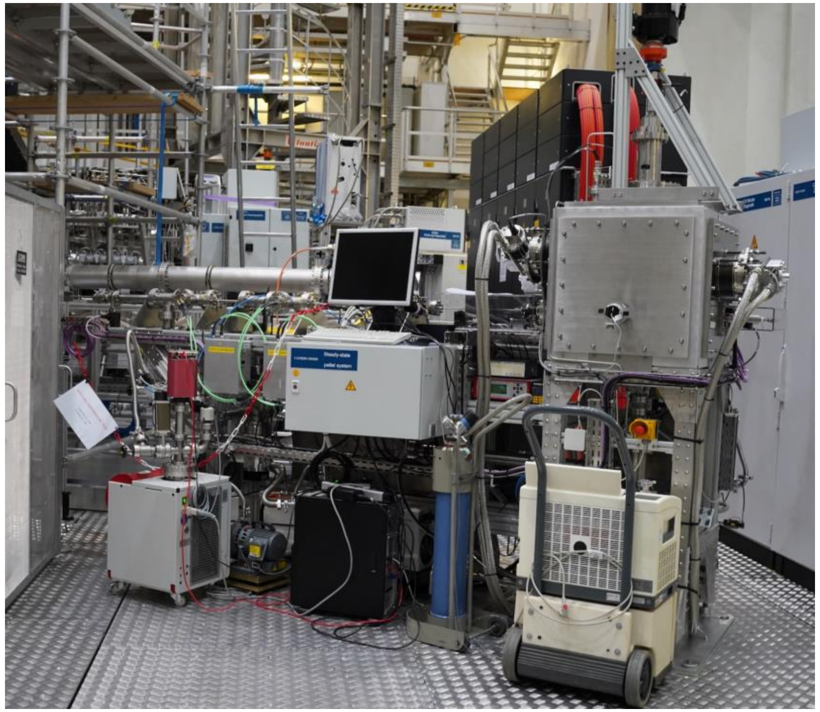
⇨ acceptance tests ongoing (1.5 s of 1MW)

⇨ afterwards, tailoring of operation to 1.5MW steady-state

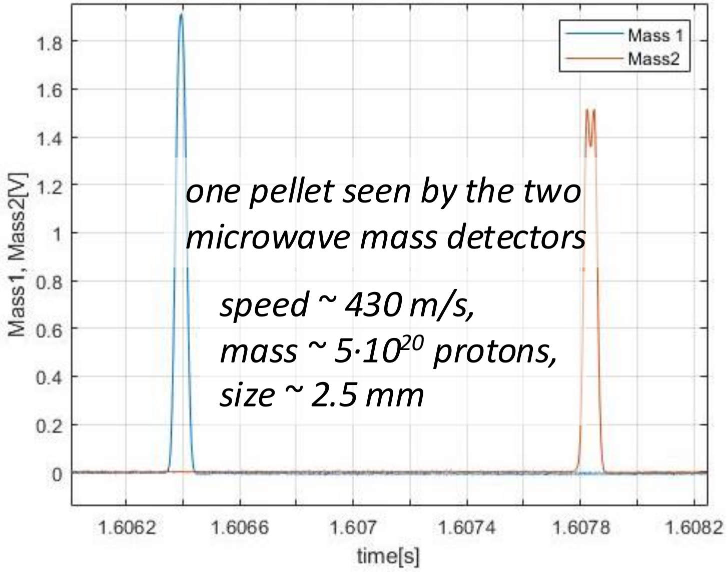


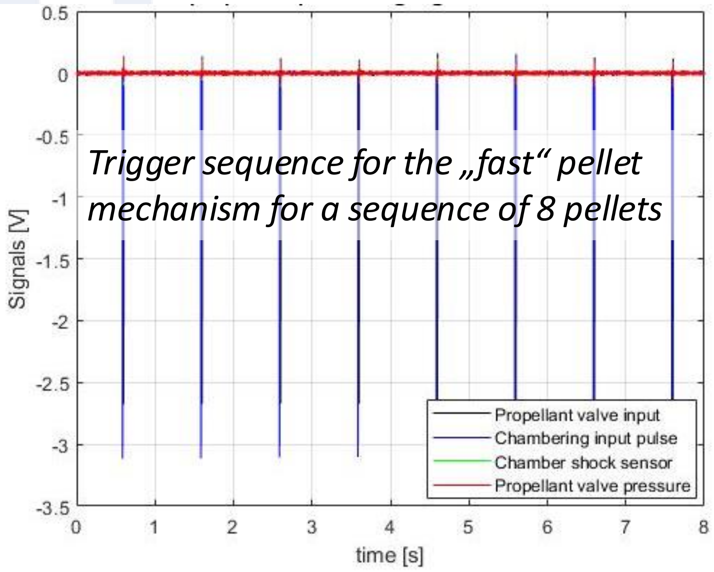


Steady-state pellet injector goes into operation OP2.2



pellet material	H_2 or D_2
pellet size	2mm – 3mm (adjustable)
pellet speed	250 – 1000 m/s
repetition frequency	single on demand, continuous up to 10 Hz
injection duration	up to 30min tested
injection modes	feed-forward, density feedback control foreseen beyond OP 2.3





Statistics of proposals for OP2.2 & OP2.3

- We continue operating W7-X in one team approach
- 371 WP W7X related proposals submitted for OP2.2 & OP2.3 (of which 115 prio-I proposals)
- 15 proposals from WP PWIE (4 prio-1)
- Three task forces:
  - Core Scenario Development
  - Edge Scenario Development
  - W7-X Optimization

Deliverables and milestones 2024/2025

EUROfusion Grant Agreement Deliverables:

- W7X.D.07: Report on the modelling of plasma heating schemes, plasmas with **fast-ions and transport regimes for long steady-state high-beta operation (energy limit 2 GJ)**
- W7X.D.08: Report on conducted Scenario & campaign preparation OP 2.3 (focus: **turbulent and neoclassical transport, high-power steady-state operation**)
- W7X.D.09: Assessment report on scenarios with **optimized transport** and **high-beta operation** ~~(energy limit 6 GJ)~~

Grant Agreement Milestones:

- W7X.M.04: **High-beta HELIAS operation at low collisionalities** achieved
- W7X.M.05: Operation with **high-power and long-pulse** completed and ~~6 GJ energy turn-around achieved~~ (pulse lengths up to 600 s**, long-pulse detachment**)

Research topics for experimental campaigns 2024/2025

ID	Tag	Description
RT-01	High performance conditions	Exploration of reduced turbulence/ high-performance scenarios in view of stationary plasma conditions with temperature-, density and impurity-profile control.
RT-02	Heating scenarios	Exploration of heating scenarios using upgraded heating capabilities (ECRH, NBI, ICRH).
RT-03	High beta scenario development	Development of high plasma beta scenario by low field operation.
RT-04	Long-pulse operation and wall conditioning	Development of integrated scenarios for long-pulse operation with PFC heat-load control, efficient particle exhaust and impurity screening; Development of wall conditioning procedures.
RT-05	Detachment	Development of long and stationary divertor detachment scenarios with and without impurity seeding.

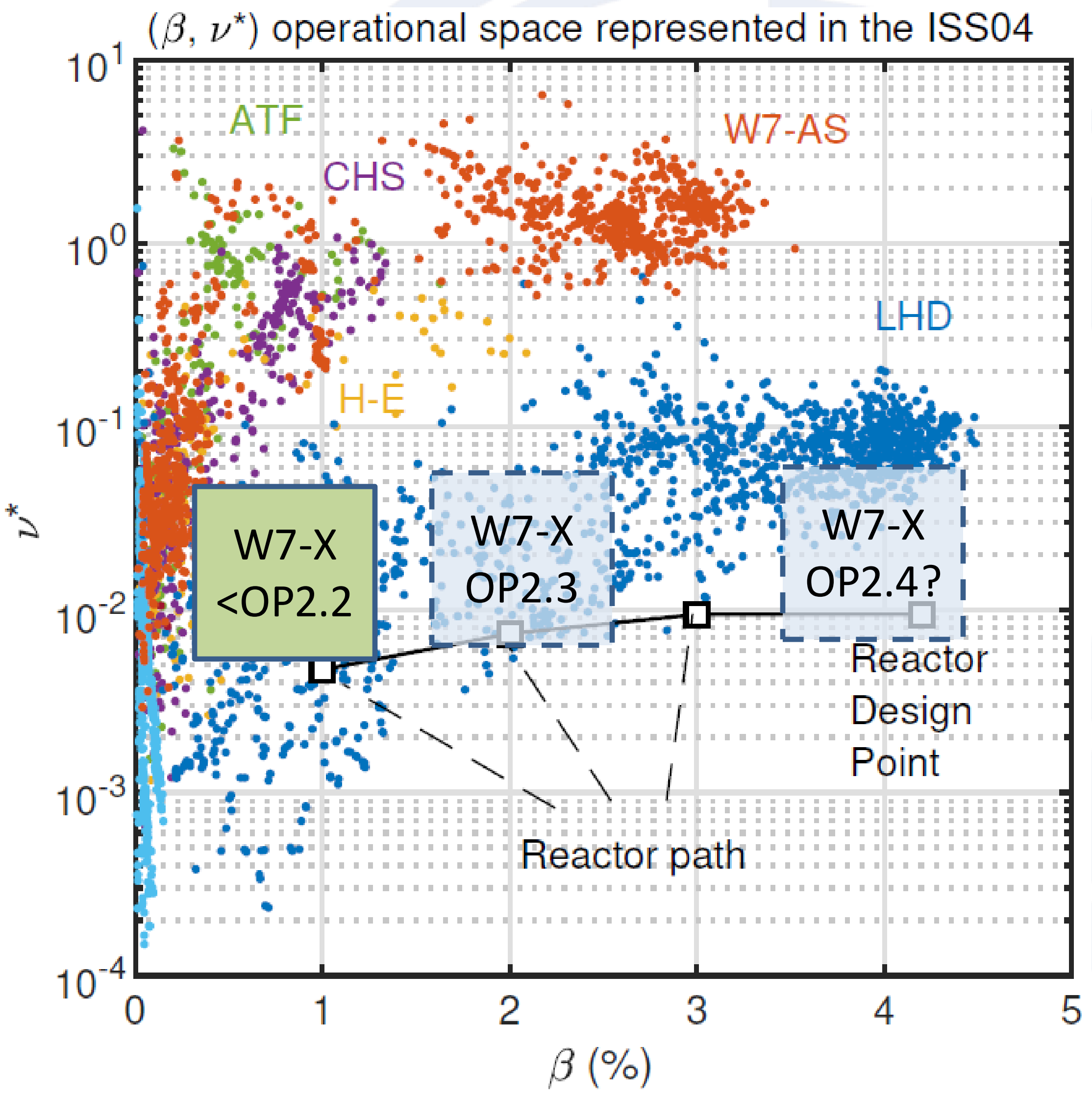
Research topics for experimental campaigns 2024/2025

ID	Tag	Description
RT-06	Tungsten PFCs	Exploration of scenarios compatible with carbon free operation and tungsten PFCs.
RT-07	Documentation of physics basis	Physics basis (core, edge) and reference discharges.
RT-08	Core physics studies	Completion of the core transport and stability physics basis in the extended operational space.
RT-09	Edge physics studies	Completion of the edge and SOL physics basis in the magnetic configuration space of W7-X.

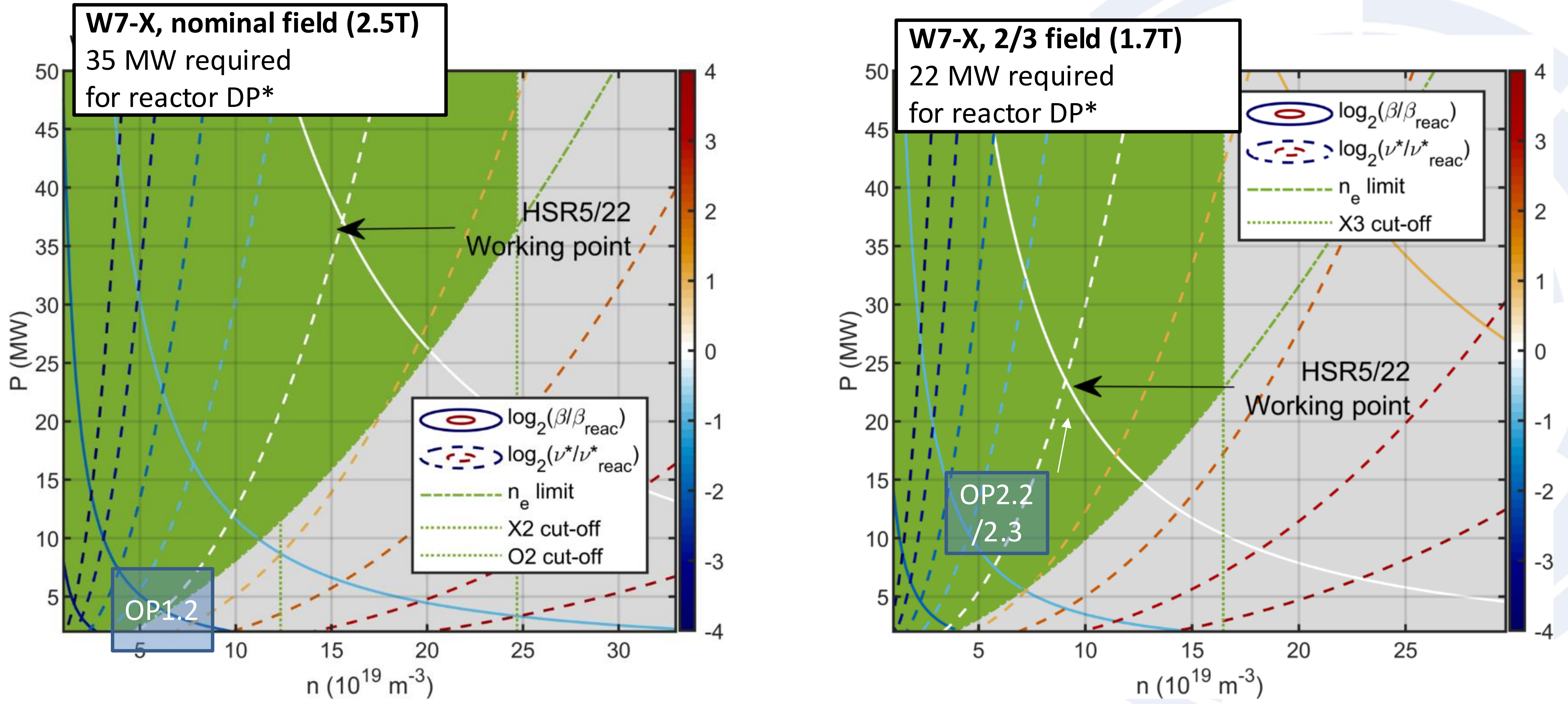
Importance of developing low-B scenarios at W7-X

The development of low-B scenarios at W7-X (namely, 1.7 T for X3-ECH heating) is programatically important beacause:

1. **Plasma start-up not based on X2-ECH will be required in a reactor.** At W7-X, the combination of ICH and NBI is being pursued.
2. **Low-B operation at W7-X allows an easier access to high-β, low-ν* operation**, potentially close to reactor design values (see next slide).
3. **Investigate B transport dependencies for reactor projections.** Notably, there is no stellarator scaling of the SOL e-folding length.



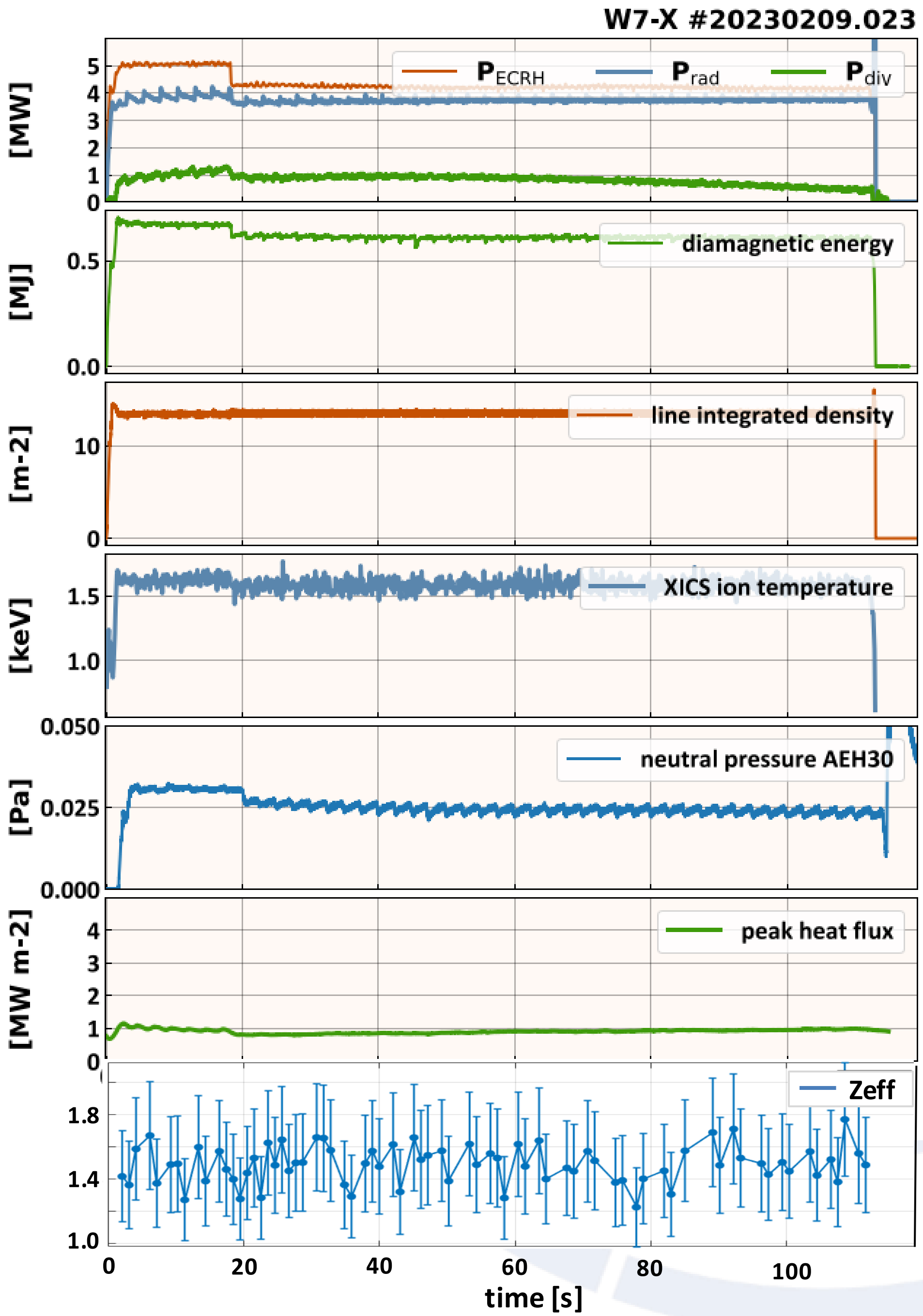
Low-B operation allows an easier access to high-β, low-ν* operation



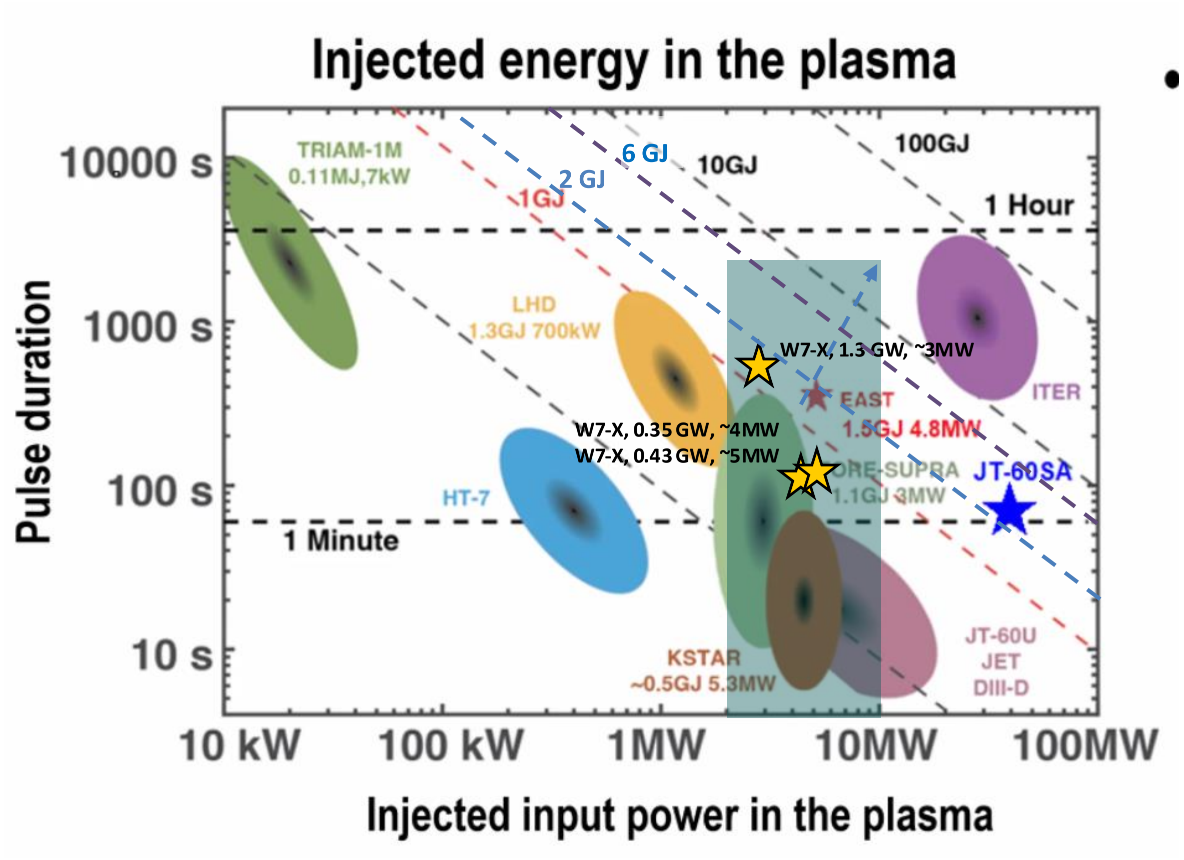
*Both extrapolations based on best observed W7-X performance

Development of long pulse

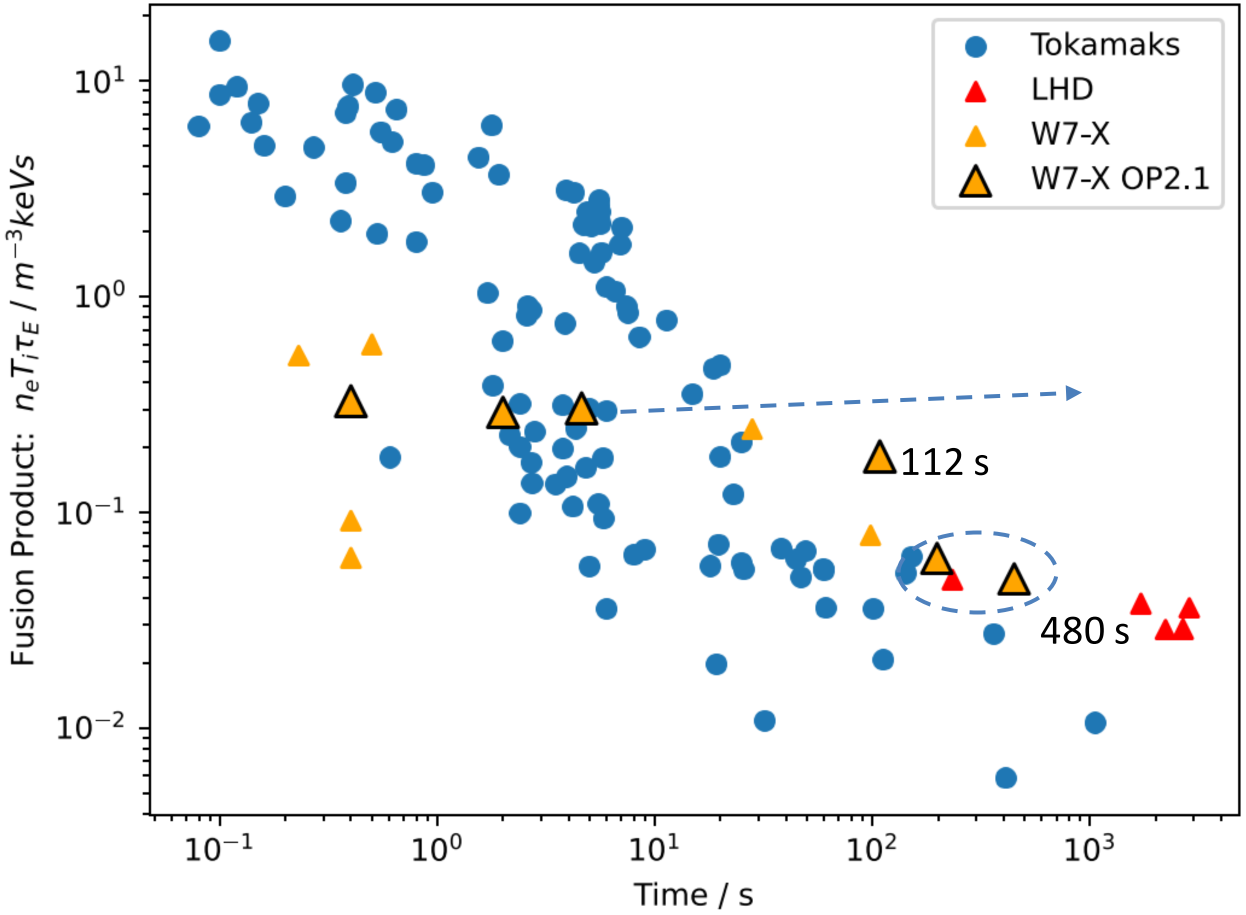
- In OP2.2/2.3 the next milestone of LPO will be reached
  - 2 GJ attached discharge (also FIS based on IR cameras will be taken into operation).
  - 2 GJ detached, if feedback on plasma radiation will be implemented.
  - Additionally scenarios with high performance plasmas will be developed to prolong their duration, e.g. with steady-state pellet injector/NBI.



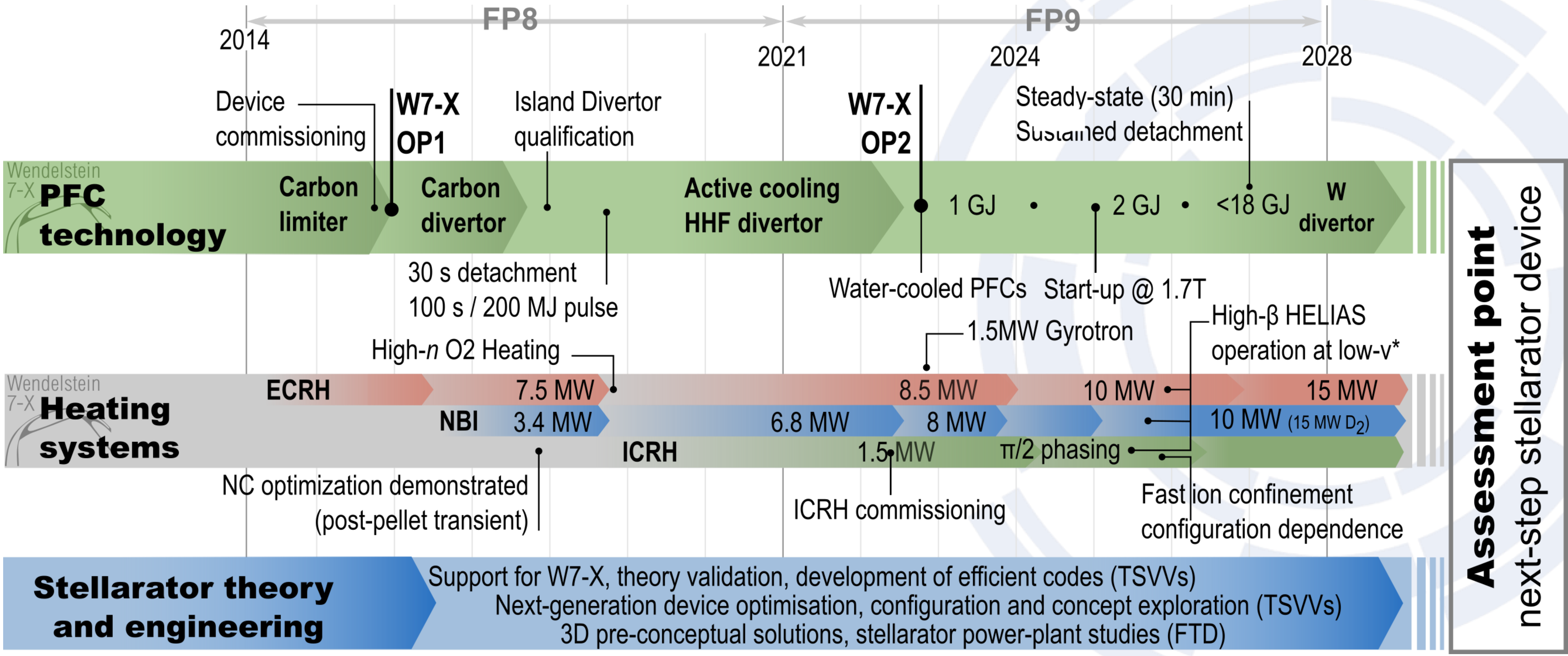
Development of long pulse operation



IAE-CICLOP database, X. Litaudon, et al., Nucl. Fus. (2024)



Reaching goals of W7-X within FP9



Gyrotron development (with KIT, NCSRD, PoliTo)

- Experimental verification of improved cavity cooling.
- Activities to support the manufacturing and testing of the 1.5 MW gyrotron, e.g. Modelling of the magnetic field configuration and the propagation of the electron beam
- Test with short pulse gyrotron of improved gyrotron components in support of 1.5 MW and 2 MW gyrotron
- Simulations of gyrotrons: Perform preliminary component design for the 2 MW gyrotron and studies on the optimization for improving further the 1.5 MW
- Optimization of the resonator - Thermal-hydraulic and thermo-mechanical analysis in support of the optimization of the resonator for improving further the gyrotron performance

W divertor: geometry development

- power exhaust analysis using simple criteria:
  1. keep maximum heat load below 10 MW/m^2 with a heating power of at least 10 MW,
  2. keep the heat load only on the divertor targets (> 95%).
  3. minimize divertor target surface
- evaluate modified geometries against particle removal requirements: ensure high neutral gas pressure
- identify potential impurity retention drawbacks
  1. maximize distance to LCFS
  2. keep ionization front away from LCFS

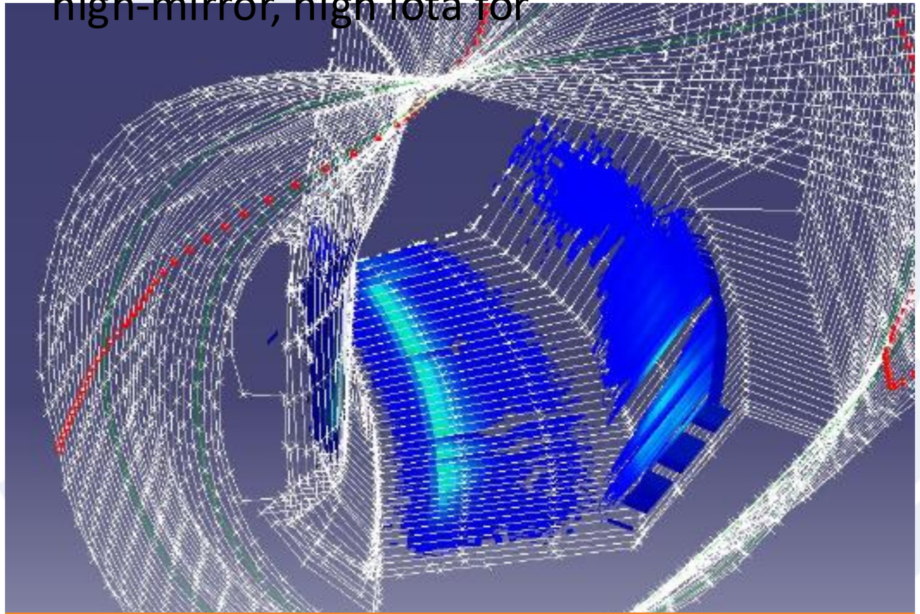
Conceptual desing review → end of 2025

- asessment is naturally based on modeling:

➢ fast: SMoLID (Simple Model for Loads in Island Divertor)
Catia + EMC3-Lite (checking >200 configurations of standard, high-mirror, high iota for different beta & I_{tor})
final check: EMC3/Eirene

➢ fast: in development
final check: EMC3/Eirene
DIVGAS

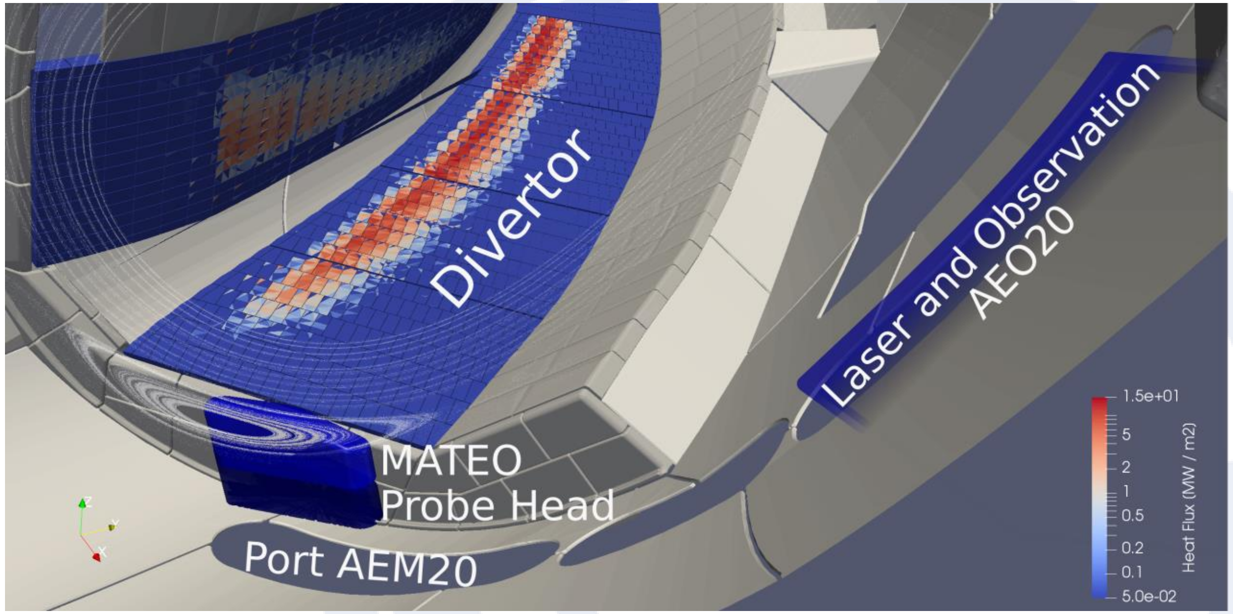
➢ final check: EMC3/Eirene
ERO2.0



Example: heat loads in the standard configuration moving the outboard baffle inward max. 8 cm to “close” the divertor when there are no loads in the current setup.

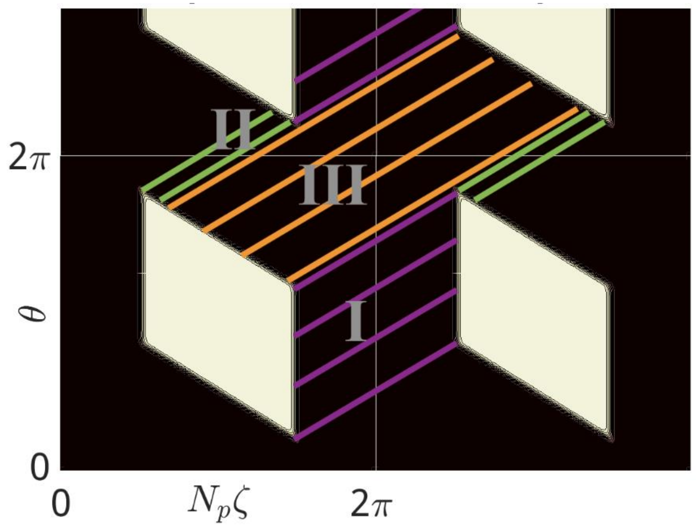
MATEO (FZJ)

- Total duration for manipulator and observation system: 1/24 – 12/27
- *Manipulator*
  - Done: CDR, prototype test, final detailed design
  - Next: DDR, order material and components, assemble, test, ship to IPP, install (spring 2026 according to W7-X schedule), commission
- *Observation*
  - In work: optical concept design running, prototype test for first mirror tilting running
  - Next: design up to commissioning as above to be planned according to resources available



TSVV#12 : highlights and plans for 2025

- **Quasi-isodynamic stellarators with few field periods, good fast-ion confinement, low bootstrap current and also with reduced turbulent transport.** Goodman et al. PRX-Energy 2024
- **Piecewise-omnigeneous fields: Finding explanation for good confinement outside the standard pictures.** Velasco et al 2024



- **MONKES: a fast (< minute/point) and accurate NC kinetic equlibrium solver for the evaluation of the bootstrap current.** Escoto, et al., NF (2023)
- **Inventing fast metrics for alpha particle losses.** Albert et al JPP (2023)
- **Global fluid turbulence simulations have been performed in the edge and scrape-off-layer of stellarators using the BOUT++ framework.** Shanahan et al. JPP 2024
- **Semi-automated divertor plate design algorithm for lower heat loads.** Davies et al. (2024)
- **A new compact quasi-axisymmetric stellarator-tokamak hybrid concept.**

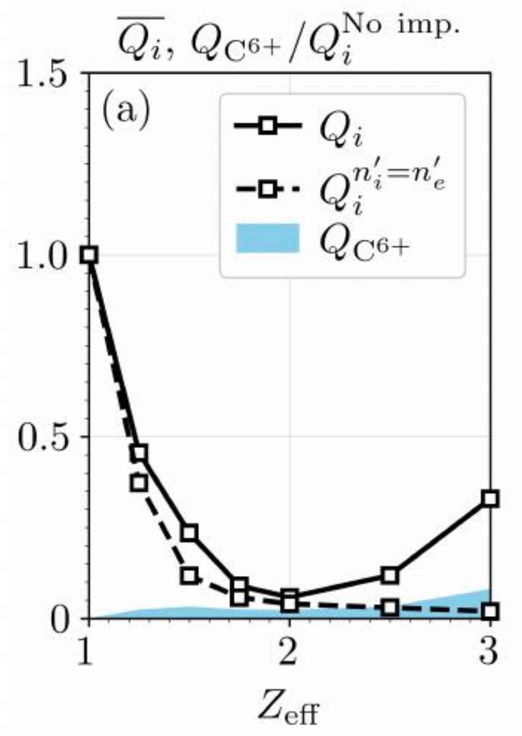
Henneberg, Plunk, PRR (2024)
Schuett, Henneberg (2024)

- **Divertor optimisation (to aid development of W divertor at W7-X).**
- **Free-boundary version of GVEC.**
- **Comparison of stellarators of different topological classes.**

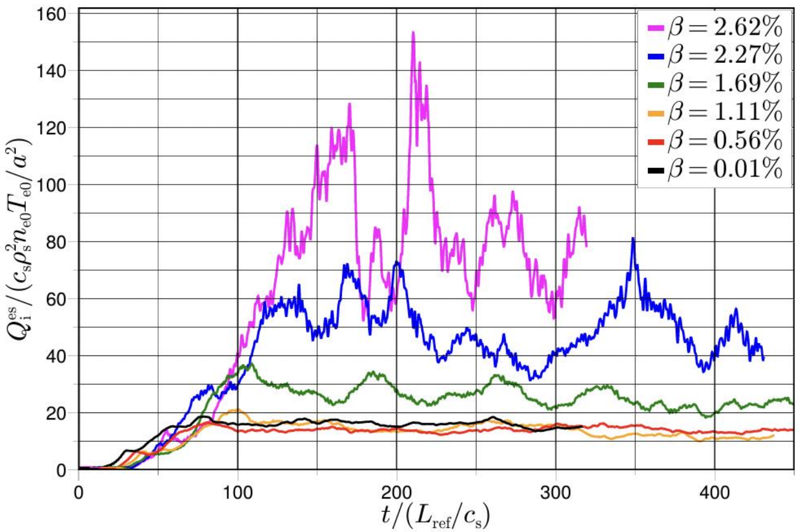
2025

TSVV#13 : highlights and plans for 2025

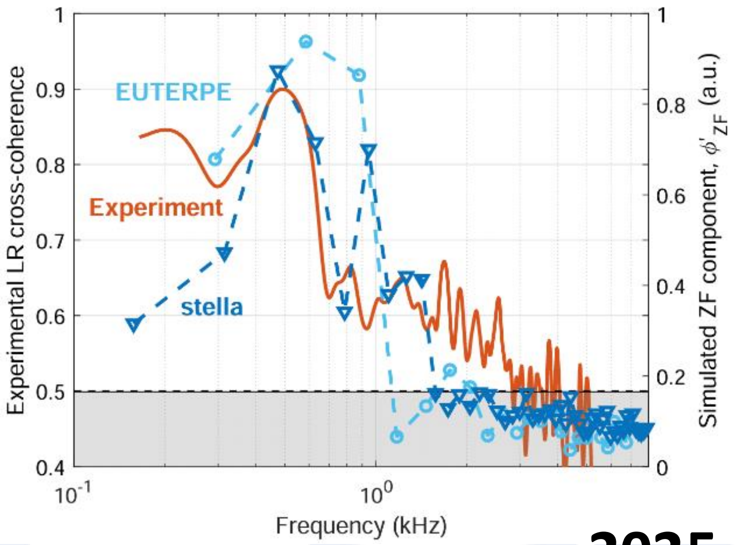
- **The effect of impurities on turbulence** has comprehensively been characterized for W7-X and other config. (LHD and ITER).
- Under certain conditions and Z_{eff} a minimum ion heat flux is found [García-Regaña in progress´24].



- **Electromagnetic simulations** show strong **increase of turbulent heat losses at moderate** β, attributed to linearly subdominant KBMs [Mulholland PRL´23]



- The TSVV13 has supported **the first detection of Zonal Flow (ZF) activity in W7-X** with **stella** and **EUTERPE** simulations [Carralero in progress´24].



2025

- **Support OP2.2 and OP2.3 W7-X campaigns**, with emphasis on validation of particle transport of both main and impurity ions, ZFs, electromagnetic effects.
- Immersion in the study of **turbulence in 3D-perturbed tokamaks**.

Stellarator Database – implementation of the HELIAS physics basis (Mission 8)

- Physics basis for next-step devices
- Documentation of W7-X discharges
- International collaboration to involve other devices
- Objectives
  - Scaling of energy confinement
  - Effect of magnetic configuration on transport
  - Validation of transport models (TSVV)
  - Operation limits
  - Documentation of long-pulse operation (IEA collab.)
  - 3D PWI
  - …
- Technical implementation to be pursued
- Integration with tokamak databanks

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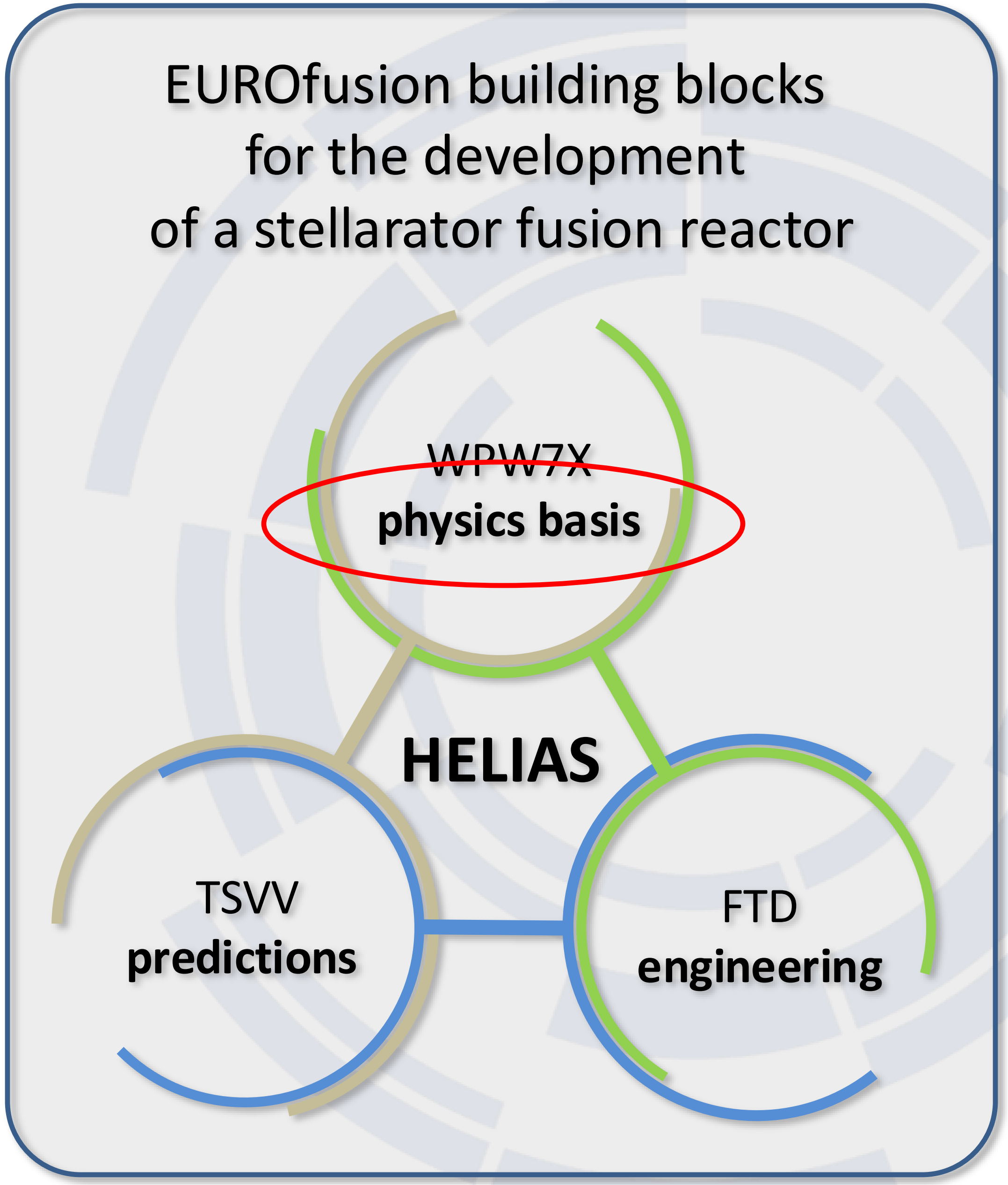


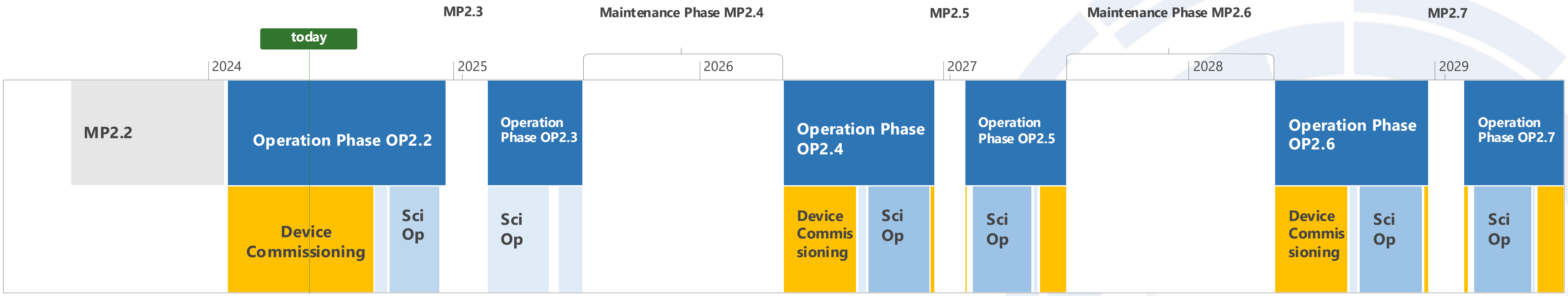
Interface with other WPs

- FTD - WPPRD implements HELIAS engineering activities
  - Support by HELIAS physics basis and experiments on W7-X
- FTD – WPHCD, WPDIV
  - Reliable high-power gyrotrons
  - W7-X metal divertor design – incl. DIVGAS calculations.
- FSD - WPTE, JT60SA, PWIE: fostering European leadership in fields of key expertise
  - metallic wall and 3D modelling
  - safe steady-state operation: surveillance and fast control (also with machine learning)
  - steady-state technology: hardening
  - fast-ions: physics and diagnostics
- International Collaborations
  - ITPA and ITER IO: specific scientific (e.g. EMC3-EIRENE) and diagnostics/technological support (e.g. LaB6 pressure gauges, stray-radiation tests, Thomson Scattering)
  - IEA TCP-SH: participation in the LHD and Heliotron-J experiments
  - DoE laboratories: collaboration on diagnostics and theory

Summary

- Wendelstein 7-X is on the path to provide input for the decision on the next step stellarator and the stellarator-based reactor design
- In 2025 the main focus of the research will be experimental campaigns OP2.2 & 2.3:
  - 2 GJ long pulse detached / attached
  - Operation at lower field → high beta / low collisionality plasmas
  - High performance operation at Ti = 3 keV
  - Transition to tungsten PFCs
  - Diagnotics: XICS, dual Thomson scattering, PHA,….
- In the next years, the development and deployment of enhancements will expand the operational space and diagnostic capabilities of the device.
  - Clear objective: approach relevant conditions and clear the way for the *helias* reactor concept..
- Important components like steady-state pellet injector, high power gyrotrons and MATEO in development.

W7-X timeline FP9 and beyond

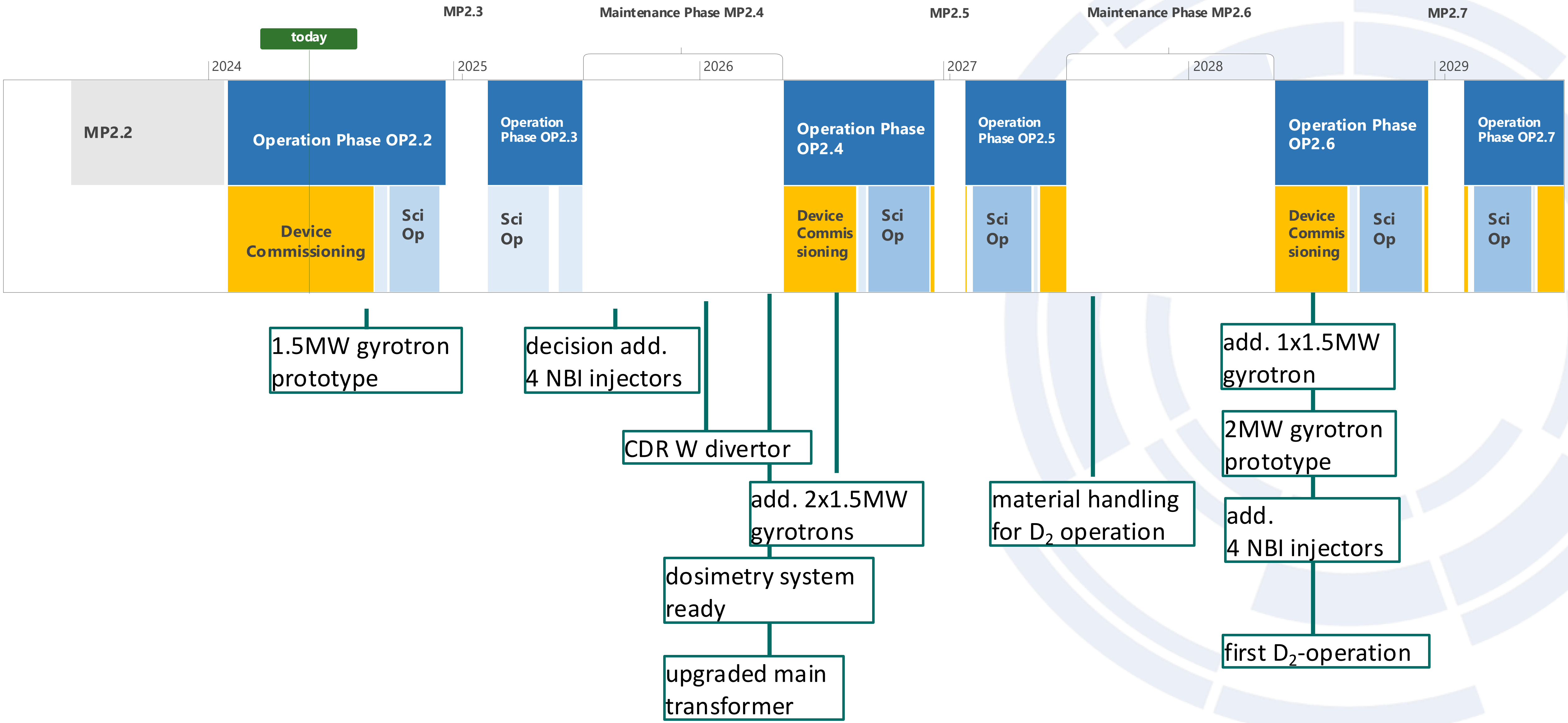


- planning foresees one operation campaign per year
- due to the time-consuming device commissioning, we will conduct two operation campaigns w/o venting in between, respectively (the cryo system remains cold)

⇨ high reliability of systems required (vacuum and cryo systems need to be in full operation for ~1 year)

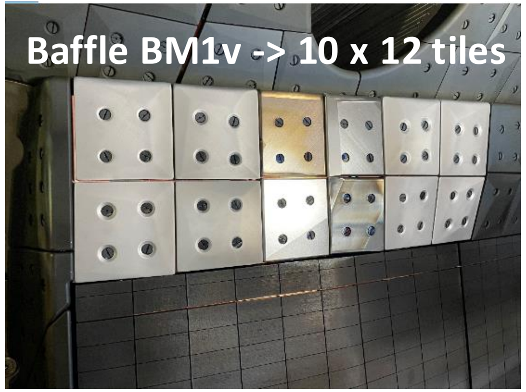
⇨ more efficient use of device for plasma operation

W7-X timeline FP9 and beyond

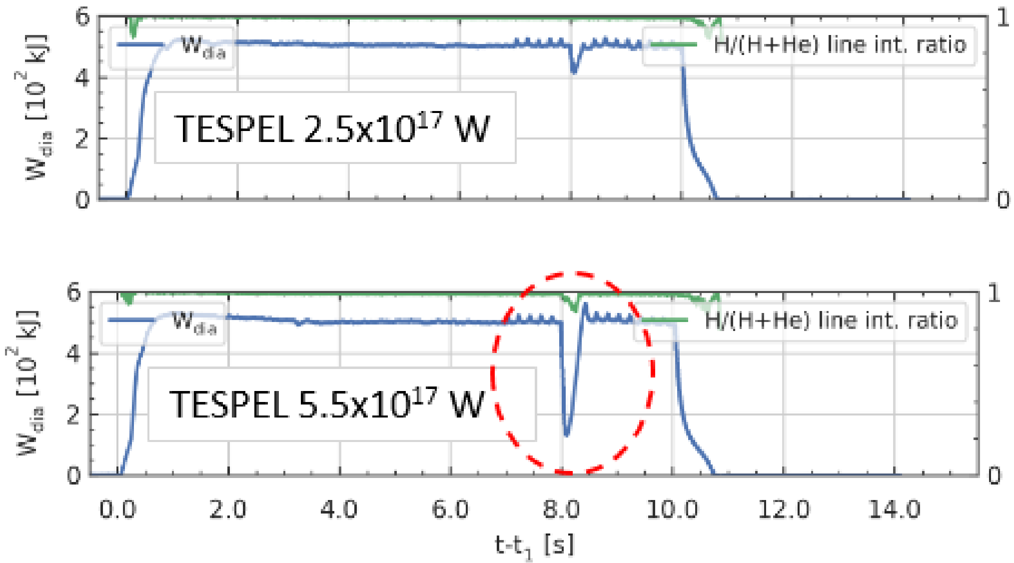


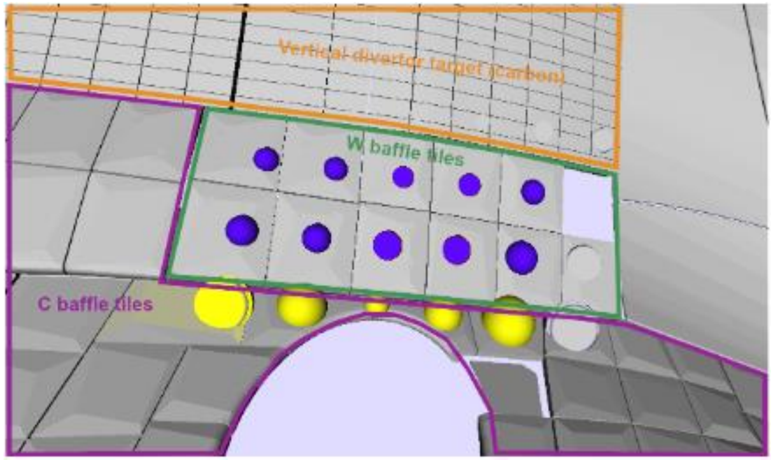
W divertor: accompanying experimental program

- focus on two main aspects:
  1. definition of operation limits (erosion/accumulation) and studies of scrape-off layer retention



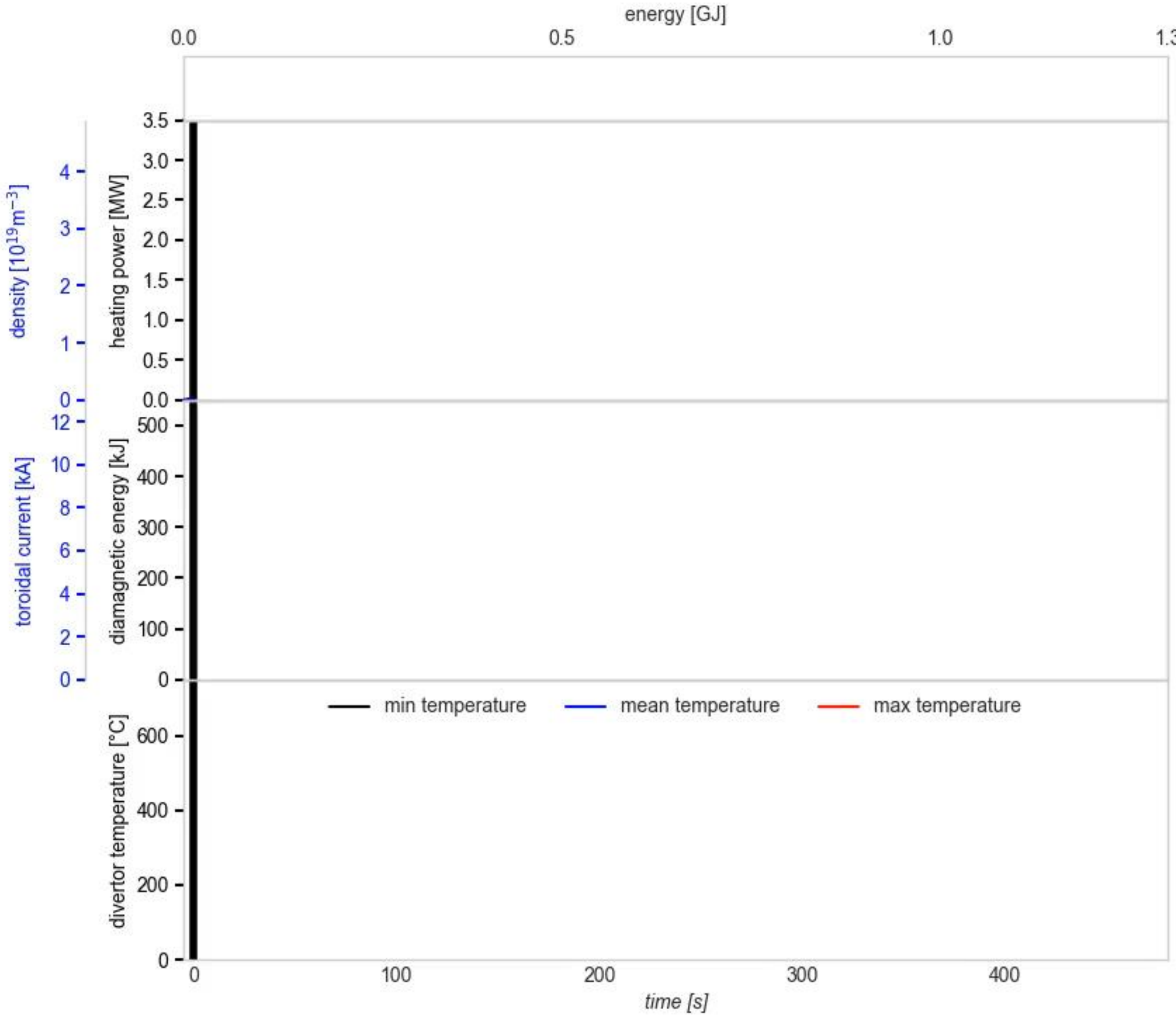
observation via divertor spectroscopy



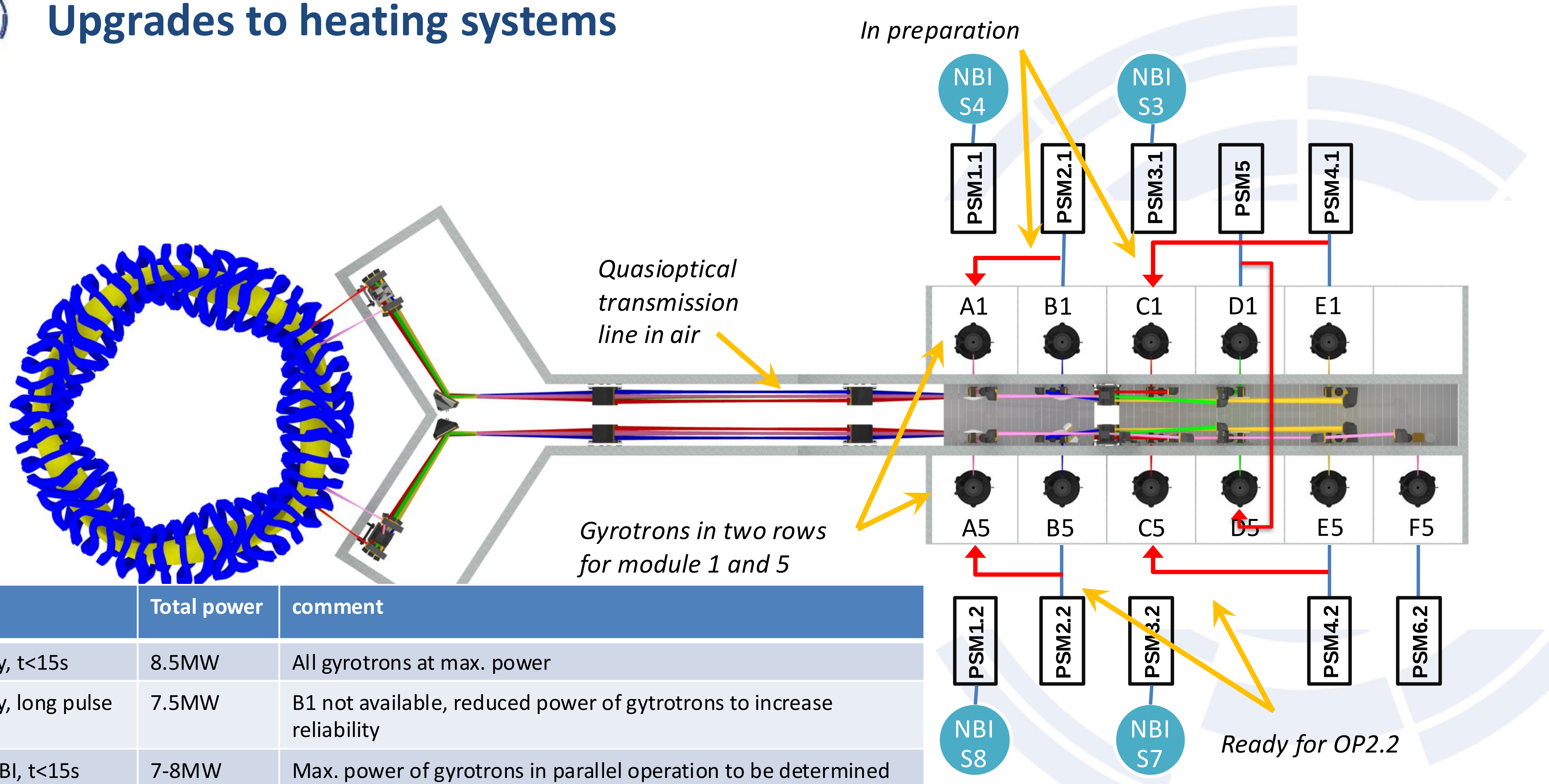


- observation of W eroded from baffle and wall tiles
- injection of W (core or edge) to assess transport of high-Z material in different transport scenarios

Record heating energy of 1.3GJ w/ attached divertor



Upgrades to heating systems



Scenario	Total power	comment
ECRH only, t<15s	8.5MW	All gyrotrons at max. power
ECRH only, long pulse	7.5MW	B1 not available, reduced power of gyrotrons to increase reliability
ECRH + NBI, t<15s	7-8MW	Max. power of gyrotrons in parallel operation to be determined
Stabilized total power	0.8*Pmax	Individual gyrotron power of 10-11 gyrotrons reduced to compensate failure of 2-3 other gyrotrons

Scenario development with increased confinement and high-β

- stabilization and prolongation of pellet-induced peaked density profile
- improved confinement NBI-ECRH scenario
- high-density ECRH scenario and studies of particle transport
- role of magnetic topology on profile evolution
- direct ion heating via NBI and ICRH
- high-β scenario development at reduced magnetic field: startup and X3 heating