EUROfusion

PSD Planning Meeting

AWP 2025 WP W7-X

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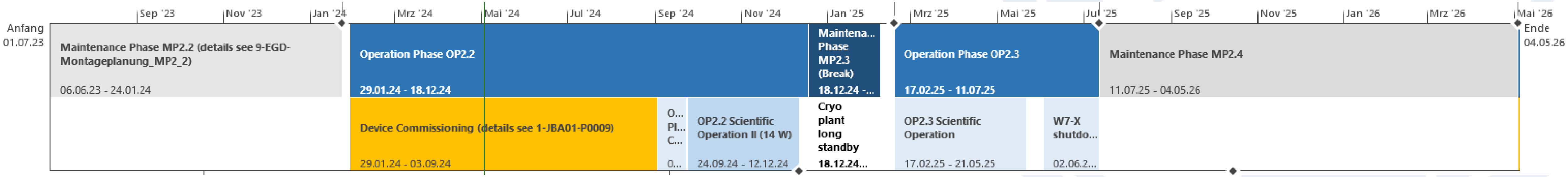
Status of Wendelstein 7-X

- Technical commissioning completed sucesfully ✓
- Plasma commissioning started 3 Sep 2024 ✓
- Plasma scientific operation OP2.2 – 01 Oct 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 ✓
- Campaign participation in OP2.2 assigned ✓
- Campaign participation in OP2.3 preliminary assigned. Announcement Nov 2024.



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 (together with WP PWIE)	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.

ECRH upgrades

- 1.5 MW successfully installed and commissioned for OP2.2

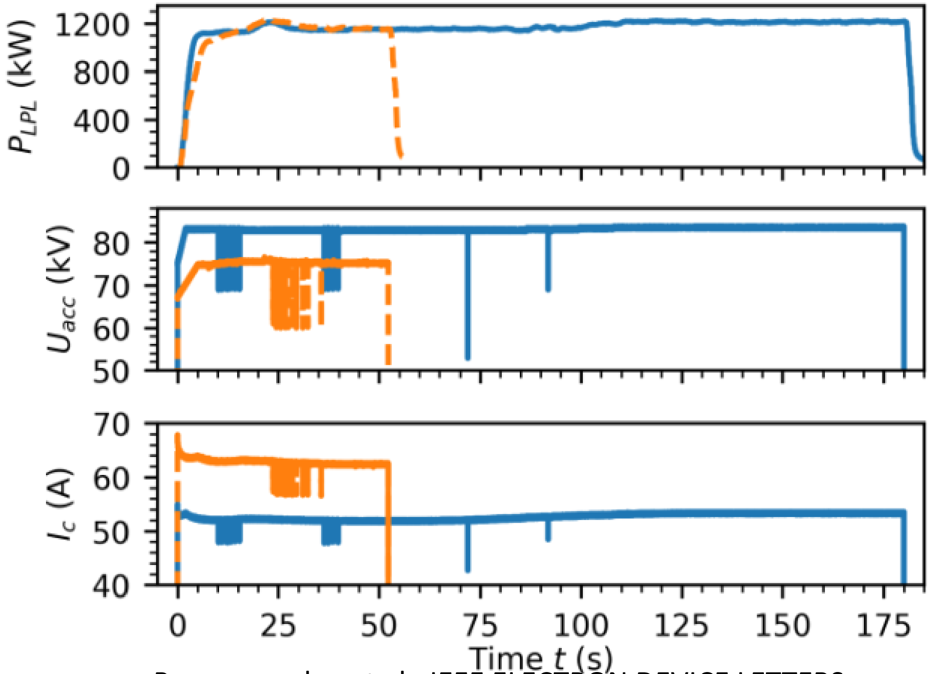
⇨ The 1-ms short-pulse tests confirmed the nominal output power of 1.5 MW

⇨At 1.3 MW pulse lengths of 3 minutes achieved

⇨At 1.2 MW pulse length of 580 s demonstrated

⇨Thales will build 3 further 1.5 MW

- Contract to develop 2 MW gyrotron awarded to Kyoto Engineering



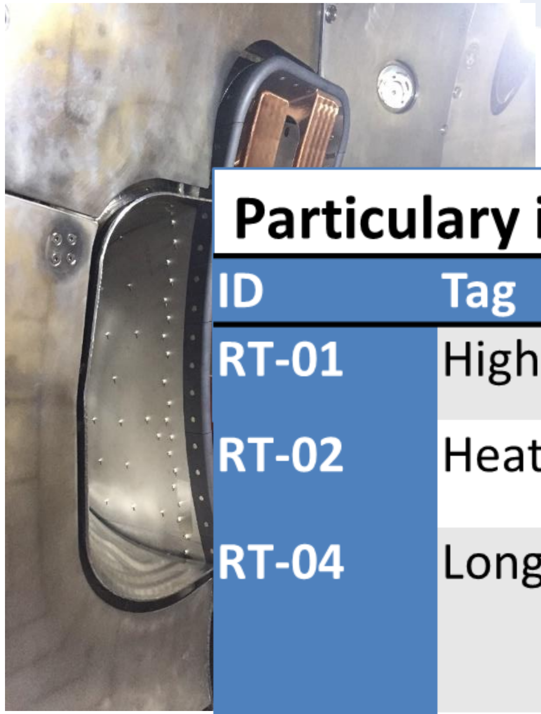
Ponomarenko, et al., IEEE ELECTRON DEVICE LETTERS, accepted

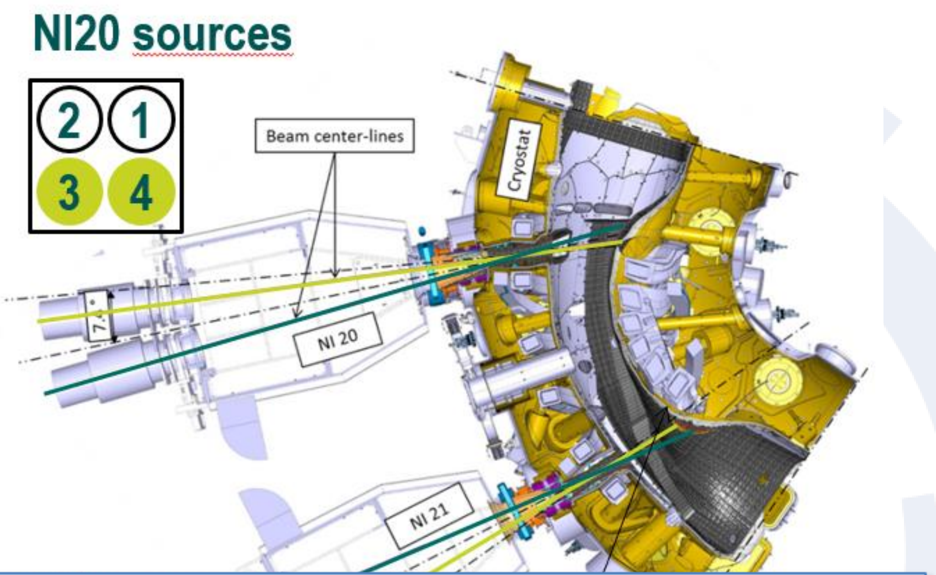
Particulary important for

ID	Tag
RT-01	High performance conditions
RT-02	Heating scenarios
RT-04	Long-pulse operation and wall conditioning
RT-05	Detachment

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
    (200 kW in comissioning)
  - 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 (at 1.7 T)
    - Antenna conditioning required





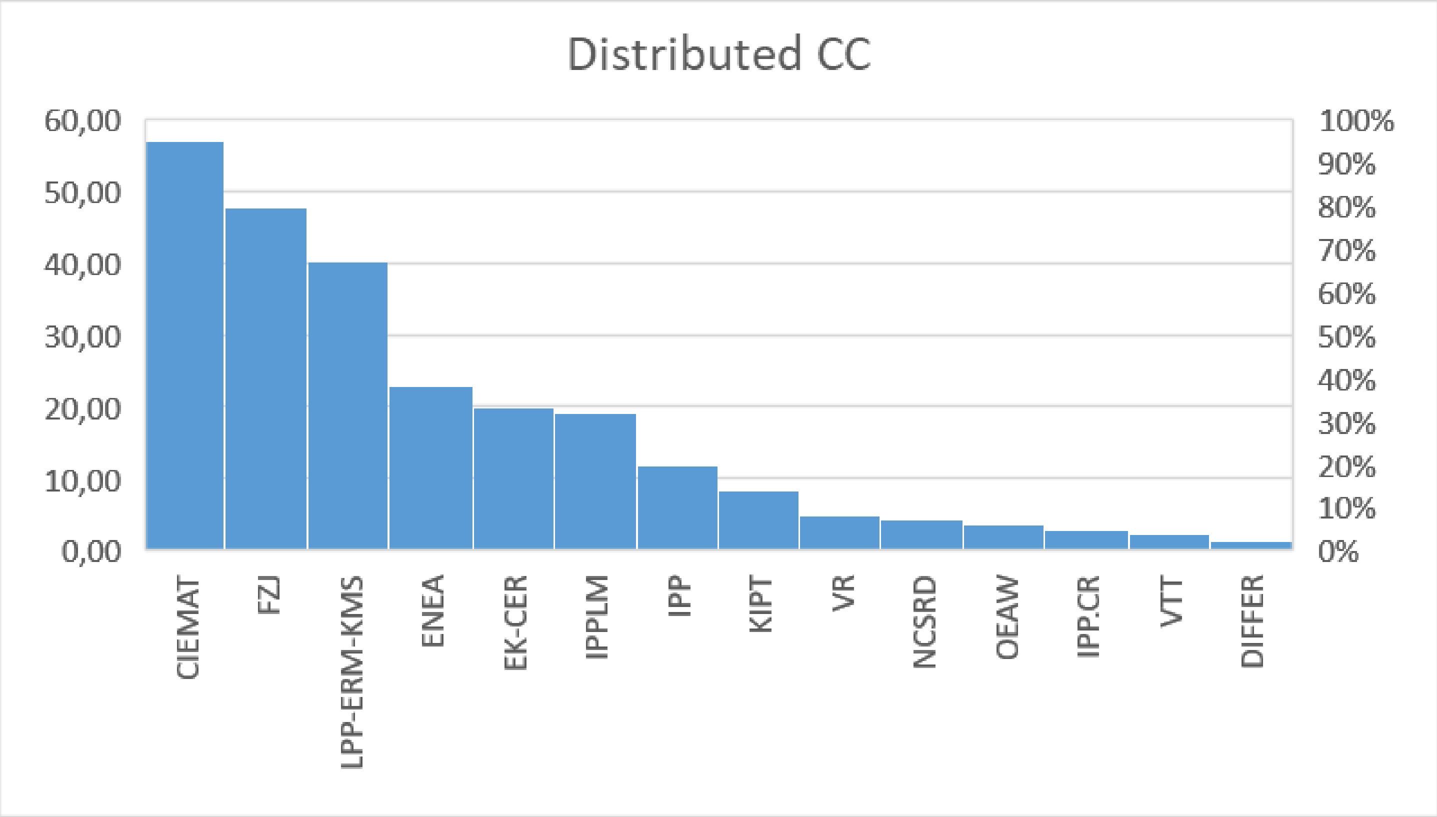
Particulary important for

ID	Tag
RT-01	High performance conditions
RT-02	Heating scenarios
RT-04	Long-pulse operation and wall conditioning
RT-08	Core physics studies

Campaign participation

Campaign participation:

- **@ W7-X lab:**
  - **prio-I proposal**
  - **diagnostic coverage**
  - **modelling of campaign relevant deliverables**
  - **Requires mission costs**

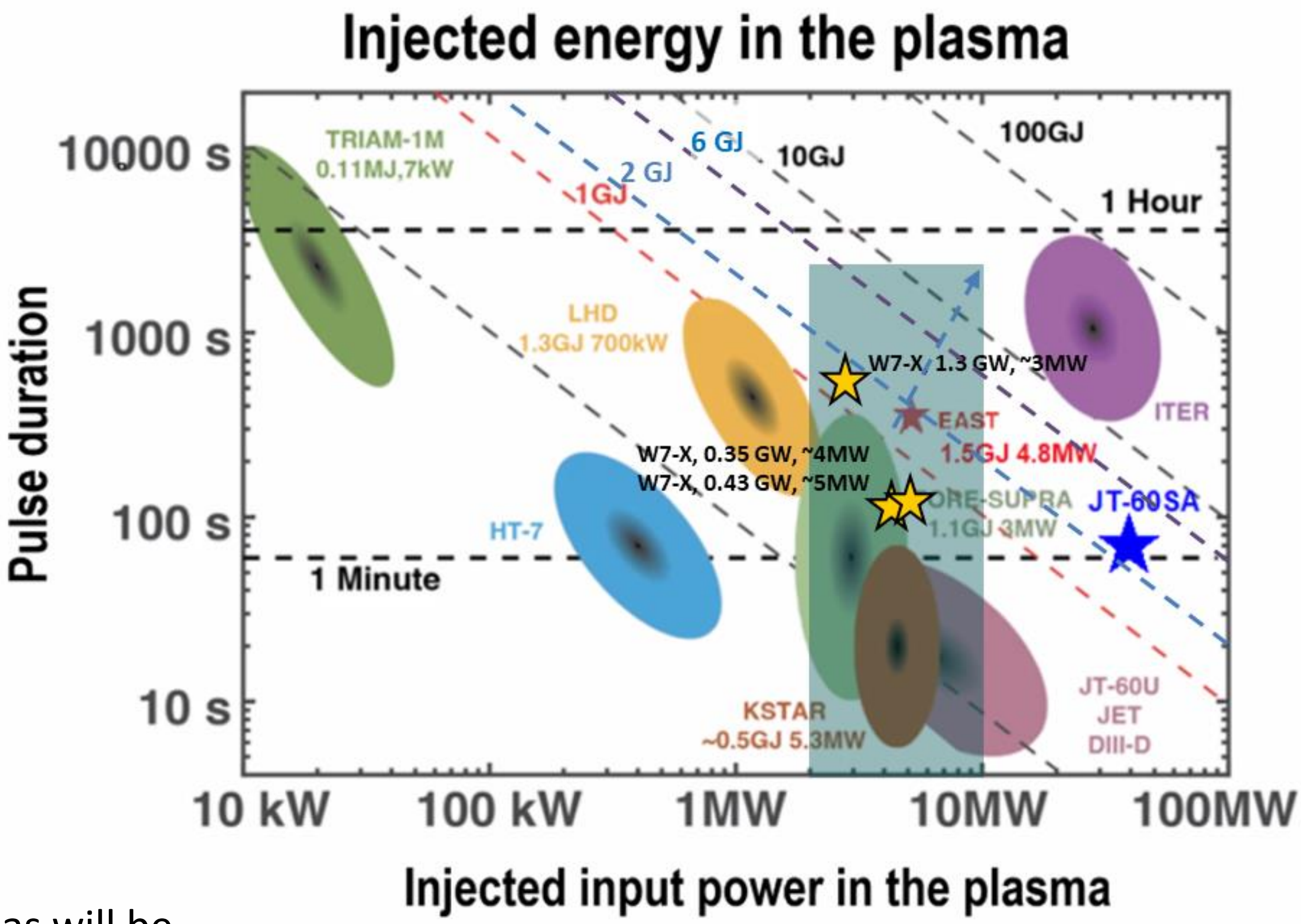


- **@ home lab:**
  - **Preparatory work for prio-I proposals**
  - **Analysis of data for prio-I proposals**
  - **Modelling for campaign relevant deliverables**

Development of long pulse

- In OP2.2/2.3 the next milestone of LPO will be reached
  - 2 GJ attached discharge:
    - test scenarios to accomodate low plasma current
    - Operate at power fluxes close to reactor design point
    - Monitor impurities in steady-state (incl. tungsten)

  - 2 GJ detached, if feedback on plasma radiation will be implemented.
    - Based on mixture of intrinsic and seeded impurities
    - Move to higher P_{SOL}
- Additionally scenarios with high performance plasmas will be developed to prolong their duration, e.g. with steady-state pellet injector/NBI.

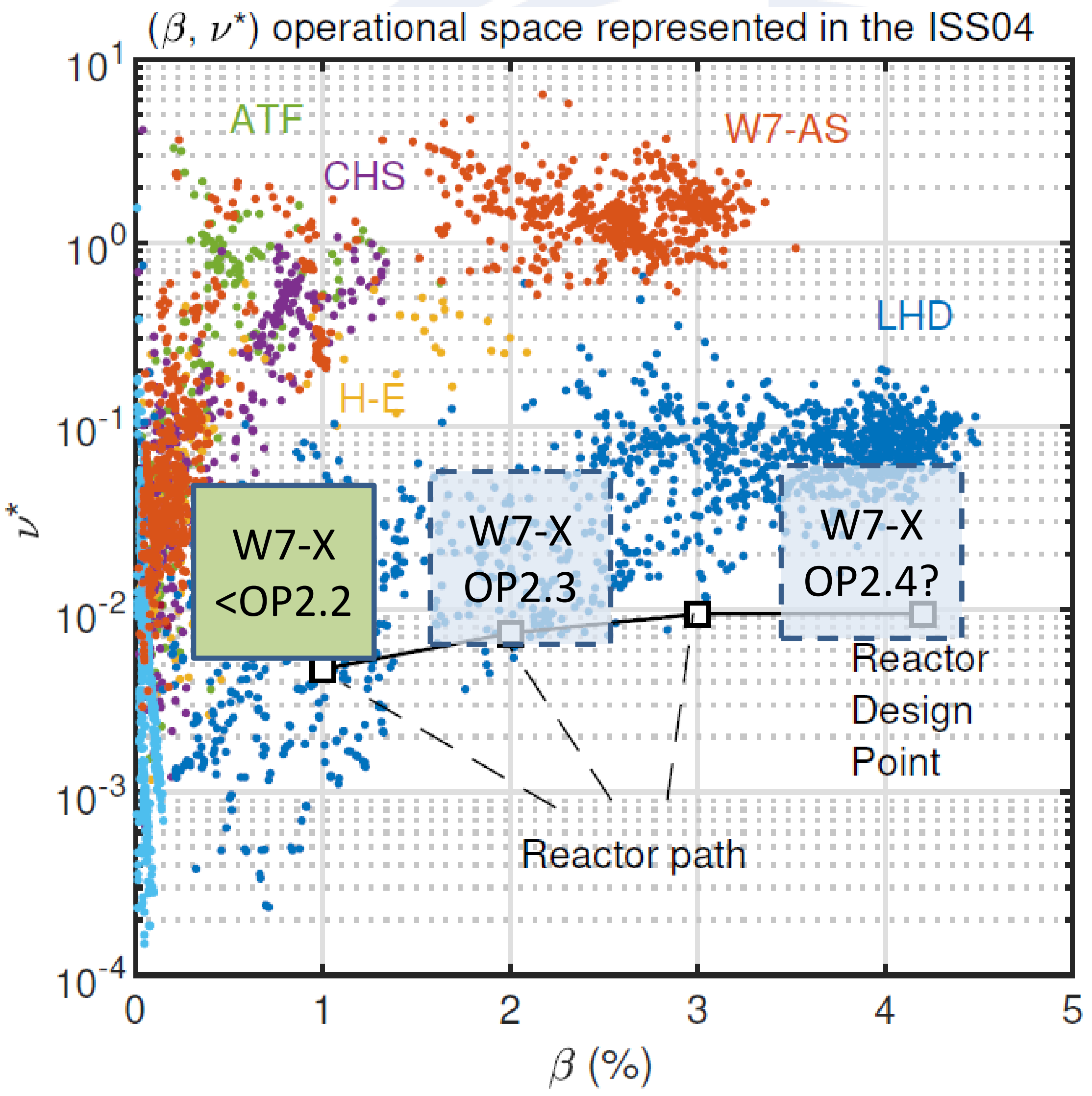


time [s]

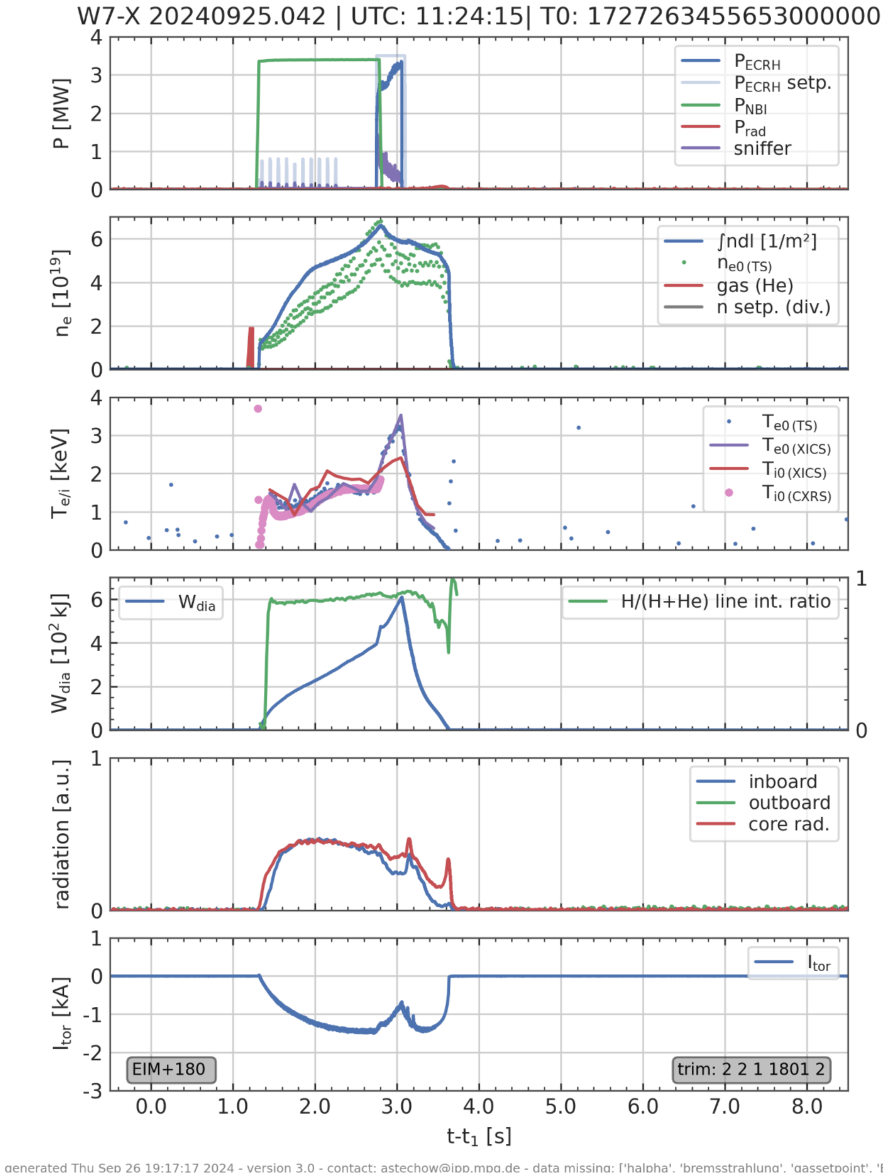
Importance of developing low-B scenarios at W7-X

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, also 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.

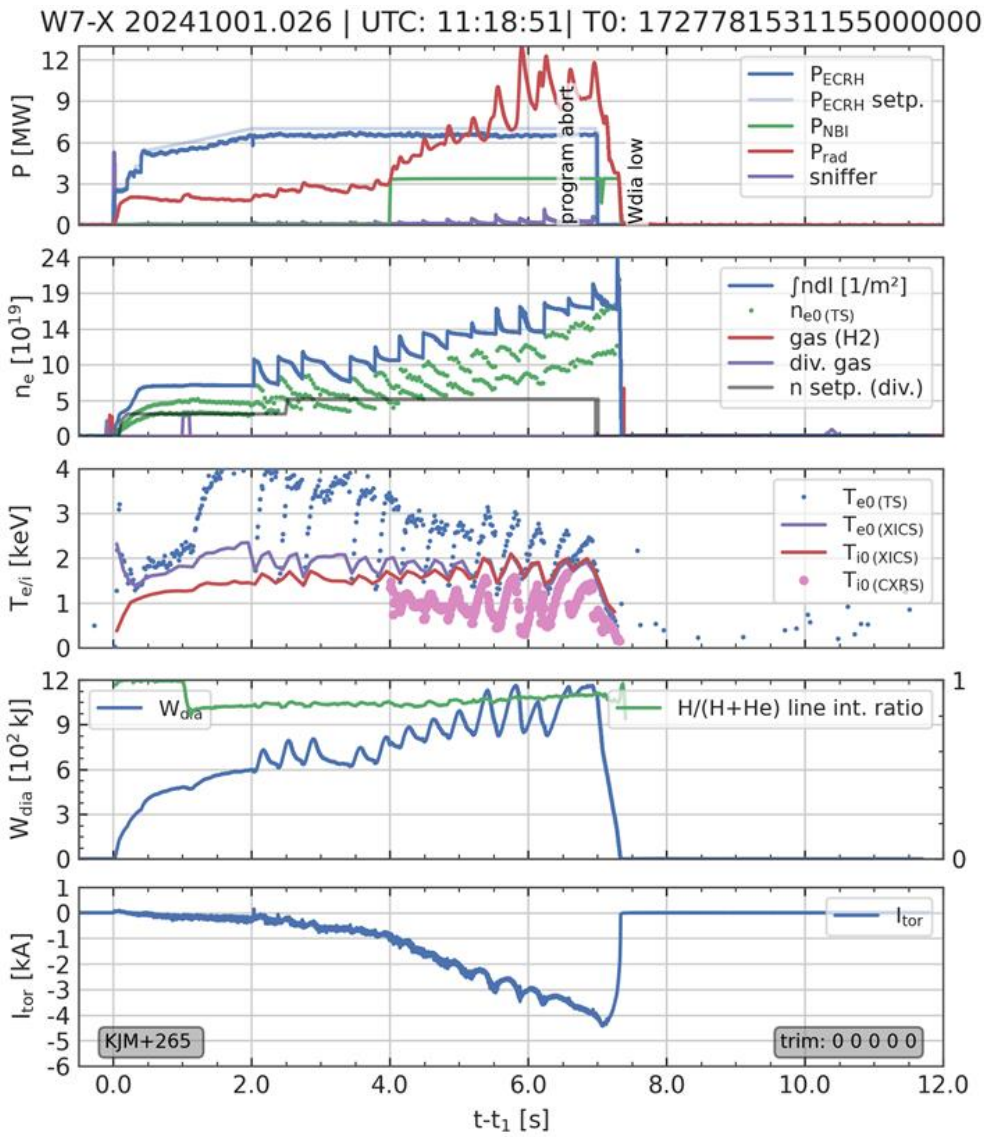


Plasma start-up at 1.8 T with ECRH & ICRH



- A full plasma start up in the core could be achieved with a combination of X2 ECRH (101GHz, 250 kW, 40ms duration) and NBI (2 sources).
- IRCH was sucesfully taken into operation. Power deposition within the SOL island and at the separatrix. Further optimization required.
- Operation at lower field provides easier route towards high beta plasma → closer to reactor design point.

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

Deliverables and milestones for 2024/2025

W7X.D.07	D03.07	Deliverable	Report on the modelling of plasma heating schemes, plasmas with fast-ions and transport regimes for long steady-state high-beta operation (energy limit 6 GJ) - **modification requested**	31.12.2024
W7X.D.08	D03.08	Deliverable	Report on conducted Scenario & campaign preparation (focus: turbulent and neoclassical transport, high-power steady-state operation) **– on track**	31.12.2024
W7X.D.09	D03.09	Deliverable	Assessment report on scenarios with optimized transport and high-beta operation (energy limit 6 GJ) – **modification requested**	31.12.2024
W7X.D.10	D03.10	Deliverable	Verified and validated stellarator gyrokinetic codes for the calculation of turbulent transport (TSVV-13) – **on track**	31.12.2025
W7X.D.11	D03.11	Deliverable	Report on conducted scenario & campaign preparation (focus: high-power steady-state operation) – **on track**	31.12.2025
W7X.D.12	D03.12	Deliverable	Assessment report on HELIAS optimization (with data from carbon PFC operation) (energy limit 18 GJ) – **modification requested**	31.12.2025
W7X.D.13	D03.13	Deliverable	Report on conducted scenario & campaign preparation (focus: PFC upgrades) **– on track**	31.12.2025
W7X.D.14	D03.14	Deliverable	Comparative assessment of the HELIAS reactor physics basis with respect to other stellarator concepts (with International Collaborations). **– on track**	31.12.2025

Change of deliverabls and milestones

FSD	W7X	D3.9	W7X.D.09	D03.09	Deliverable	Assessment report on scenarios with optimized transport and high-beta operation (energy limit 6 GJ)	31.12.2024	48	

Should be

FSD	W7X	D3.9	W7X.D.09	D03.09	Deliverable	Assessment report on scenarios with optimized transport and high-beta operation (energy limit 2 GJ)	31.12.2024	48	on track
FSD	W7X	M20	W7X.M.06	M03.06	Milestone	Operation with High power and long-pulse Completed and 6 GJ energy turn-around achieved (pulse lengths up to 600 s, long-pulse detachment).	31.12.2025	60	Unknown

Should be

FSD	W7X	M20	W7X.M.06	M03.06	Milestone	Operation with High power and long-pulse Completed and 2 GJ energy turn-around achieved (pulse lengths up to 600 s, long-pulse detachment).	31.12.2025	60	Unknown
FSD	W7X	D3.12	W7X.D.12	D03.12	Deliverable	Assessment report on HELIAS optimization (with data from carbon PFC operation) (energy limit 18 GJ)	31.12.2025	60	Unknown

Should be

FSD	W7X	D3.12	W7X.D.12	D03.12	Deliverable	Assessment report on HELIAS optimization (with data from carbon PFC operation) ~~(energy limit 18 GJ)~~	31.12.2025	60	Unknown

PCR 2025

2025-W7X-2.3.5: Data Analysis and Modelling of OP2.3 and IC (CC 194 k€)
Accelerate closing HELIAS gaps in two fundamental areas:
- high performance and high beta
- steady-state exhaust concept

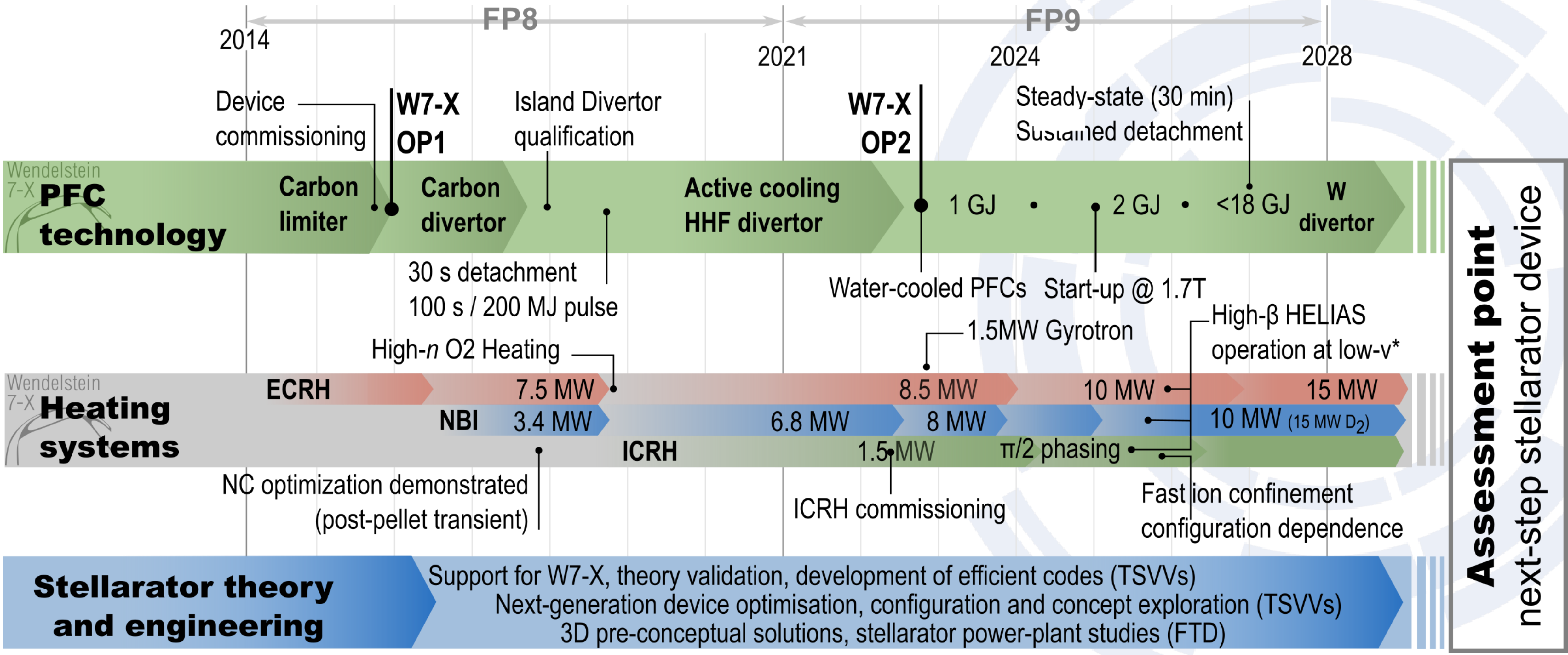
ID	Task	PM @ 50%	BEN	CC [k€]
W7X-1	Complete the HELIAS physics basis and develop high performance scenarios for W7-X - validation of physics models and codes (fast ions, turbulence characterization, enhanced confinement regimes)	24	CIEMAT	81.80
W7X-2	Increase the efforts on the analysis and modelling for OP2.2 & OP2.3:	42		112.66
	- EMC3-Eirene modelling of high β plasmas, incl. synthetic diagnostics, AI to provide quick assessments - analysis of divertor plasmas with four endoscopes	12	FZJ	56.79
	- Validation of PHA and C/O monitor experimental data for long pulses using modelling; - Development of scripts for fast data processing;	12	IPPLM	23.81
	- fast cameras data: fueling (pellets), high performance, impurity transport (TESPEL) - filaments at the plasma boundary and alkali beam: density profiles, CXRS	18	EK-CER	32.06

PCR 2025

- Insufficient mission budget for 2025 considering that
  - campaign participation budget 334 k€
  - available mission budget for 2025: 225 k€
- In comparison 2024:
  - campaign participation budget for 2024: 240 k€
  - mission budget for OP2.2: 242 k€.
  - used mission budget outside the campaign in 2024: 42 k€.

- Proposal: Transfer unused secondment budget from 2024 (63 k€) to mission budget in 2025 to ensure both adequate campaign participation and still allow for missions outside the campaign.

Reaching goals of W7-X within FP9



HELIAS optimization

- **Feasible modular coils**
- **Low plasma currents**
  Minimization of all internal plasma currents (except the diamagnetic current)
  A. Dinklage, et al., Nature Physics volume 14, 855–860 (2018)

- **Good magnetic flux surfaces**
  Good magnetic surfaces of the vacuum magnetic field without major resonances, islands or stochastic regions. Needs also high beta. Planned OP2.3, OP2.4
  T.S. Pedersen, et al., Nature Comm. Vol. 7, 13493 (2016)

- **Stiff equilibrium configuration**
  For W7-X the equilibrium should exhibit only minor modification up to an average β of 5%. Needs high beta, planned, OP2.3, OP2.4

- **Reduced anomalous transport**
  At the moment only transiently, more work is planned for the following campaigns

HELIAS optimization

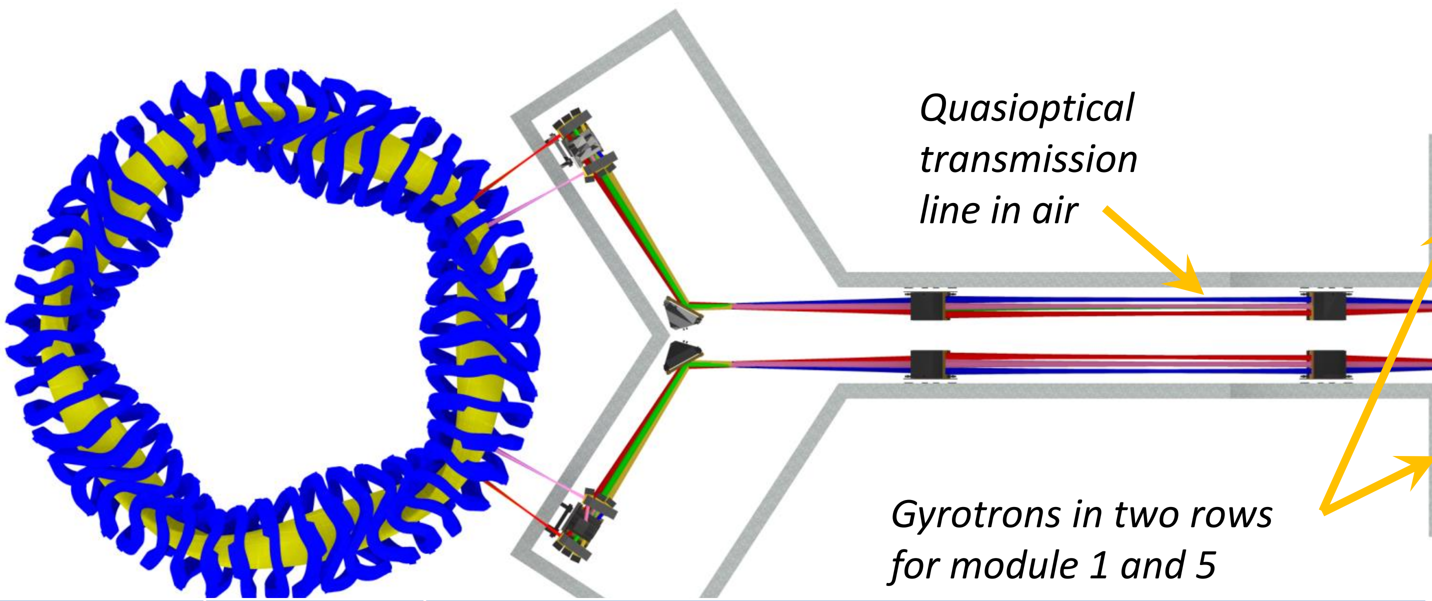
- **Small neoclassical transport**
  Sufficiently low neoclassical confinement in the 1/v regime, the effective helical ripple must not exceed 2%. C. Beidler, et al., *Nature* **596**, 221–226 (2021)

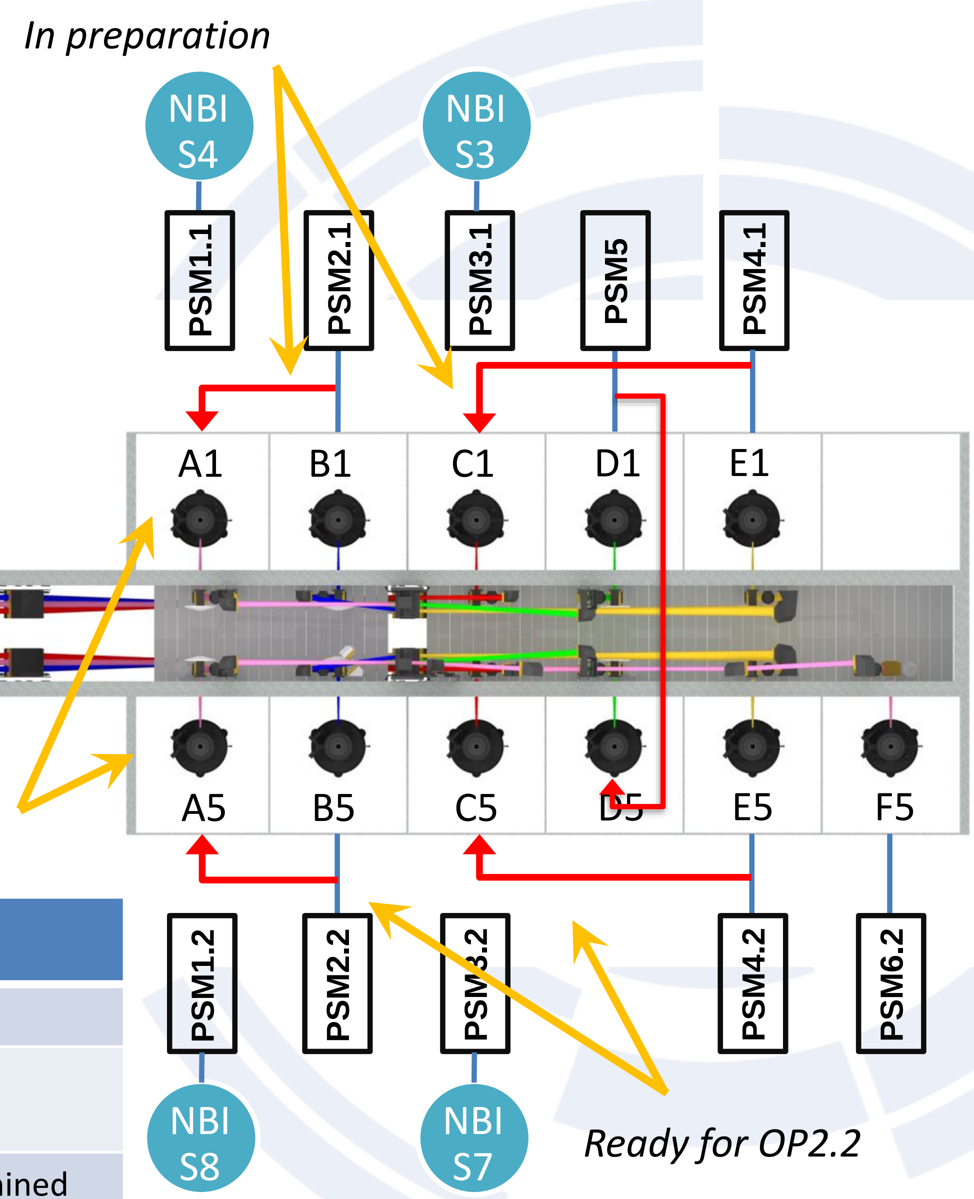
- **Good magneto-hydrodynamic (MHD) stability at high beta**
  Lack of show-stoppers: e.g. resistive interchange, balloning modes at higher β.
  W7-X might have a soft β limit that is fairly immune to major MHD events
  Y. Zhou, et al., Phys. Rev. Lett. **133**, 135102
  Some simulations show increase of turbulent heat losses at moderate β
  (KBM) Mulhollandm et al., PRL 2023.

- **Good confinement of fast particles**
  The quasi-isodynamic symmetry of W7-X solves this problem by increasing the magnetic field in transition areas between the five field periods, basically establishing a system of linked mirrors A particular characteristic of the W7-X configuration is that the collisionless fast particle confinement requires a finite β of about 2–3%

- **Island divertor compatible with magnetic equilibrium**
  with sufficient heat and particle exhaust. Requires:
  - Higher heating power, higher beta, long pulse

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