EUROfusion

FSD Planning Meeting – 2023 Updates and 2024 Objectives

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Wendelstein 7-X

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Why does DEMO come so late?

- Long-lead challenges on the roadmap
  - Develop feasible tritium-breeding technologies (testing on ITER)
  - Develop neutron-tolerant materials (testing on IFMIF-DONES)
    - Is this enough to obtain license for building/operating DEMO

Are there additional risks?

- Tokamak is a pulsed device and is prone to disruptions and instabilities (can we mitigate this risk?)
- Stellarator is intrinsically continuous and doesn't have disruptions
  - But stellarator is one generation behind tokamak
  - Given excellent results of W7-X we should continue exploring Stellarator Fusion Power Plant

https://www.filo.kit.edu/downloads/Forum%20FUSION%20Dtl/Event_3FFD_050623/Praesentationen/EUROfusion.pdf

Take home message

- European Fusion Roadmap is event-driven and is based on a thorough status and gap analysis of magnetic fusion research
- Elements defining the long time to fusion electricity are
  - Development, testing and validation of materials
  - Development and testing of tritium breeding technologies
- Can we move faster?
  - Decoupling DEMO from ITER
  - By joining venture capitalists' speed with holistic view of public research (incl. working on long-lead items)?
  - Start of DEMO in about 20-25 years from now is possible (provided we have budget)!
  - Risk mitigation by continued focus on Stellarator FPP

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Objectives for the AWP 2024

- High-performance, long-pulse, metallic wall operation
- Physics basis for next step device (optimization: turbulence, fast ions, neoclassics)
- Demonstration of feasible integrated discharge scenarios

WPW7X-2024.O1	Conduct and support the 2024 W7-X campaign
WPW7X-2024.O2	Exploit the 2022/23 campaigns of W7-X
WPW7X-2024.O3	Pursue the development of scenarios for the 2024 campaign
WPW7X-2024.O4	Preparation of components, diagnostics, metallic wall and support actions for the campaigns on W7-X
WPW7X-2024.O5	Successive completion of the HELIAS physics basis and support of ITER and other EUROfusion activities

2023

Summary 2023 campaign

- Overall good progress attained and milestones achieved
- Technical difficulties in components
- WPW7X contributors to the W7-X Team in 2023-24: exploitation resources involved/leading W7-X Topical Groups (resources for analysis and modelling assigned and coordinated w/ TSVV)
- Shortcomings in exploitation resources: analysis is bottleneck at present
- Shortcomings in component preparation (ECRH developments, tests)

- Lesson: previous, consciously taken risks and aftermath from CORONA partly

→ pace of exploitation affected

- W7-X is underpowered and divertor developments require close monitoring to make the metallic divertor available early after FP9

WP Milestones 2023

Sequential WP-M ID	Related WBS ID	WP Milestone Title	Due Date [mm/yyyy]	Related GA D/M No.	Criticality of Relation to the GA D/M (high/low)
WPW7X-2023.M.1.	W7X-2	Campaign Conducted (WPW7X Campaign Team)	03/2023 (last program conducted)	W7X.M.03; W7X.D.05	Both high
WPW7X-2023.M.2	W7X-2	2022/23 campaigns exploited (WPW7X Team)	12/2023 (list of submitted and planned publications along campaign deliverables)	W7X.D05	high
WPW7X-2023.M.3	W7X-2	2024 campaign prepared (WPW7X Team)	**12/2023 (participants selected)** **to be shifted to 07/2024 (because campaign begins in fall 24)**	W7X.D06	high

- WP Milestones attainable (SMART)
- Comprehensiveness w.r.t. stellarator assessment in Mission 8 bears large potential for improvements

2024

Wendelstein 7-X – planning 2024

Towards OP 2.2

tentative, but consolidated schedule:

	2023																																	
cw	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
	W7-X shutdown						maintenance phase MP 2.2																											

exploitation of OP 2.2 campaign
with a focus on the formulated main TF scientific objectives

re-start of topical groups

WS on OP 2.1 exploitation

OP 2.2:

	2024																				
cw	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	device commissioning																				

start scientific planning

call for proposals

program WS

- the detailed schedule will be fixed soon

	2024																								
cw	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
	SO-I				standby						SO-II														
	sci. prep										proposal-based scientific operation														

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK | OLAF GRULKE | 09.05.2023

OVERVIEW WENDELSTEIN 7-X 45

2024 campaign: going forward along the scientific objectives and align exploitation plan

#	Title	Deliverable description	2023 shots	Level of attain ment
01	Achieving high-performance plasmas	High-performance in the order of seconds with Ti > 1.5 keV and better confinement than ISS04.	420	?50%
02	Impurity avoidance	Avoidance and understanding of impurity accumulation.	45	?
03	Density control	Assessment and demonstration of density profile control.	51	~50%
04	Heating	Demonstration of effective heating employing upgraded heating and current drive capabilities (ECRH, NBI, ICRH) in particular ion heating.	6	?50%
05	Physics basis	Creation of an exhaustive operational map of plasma performance in the W7-X configuration space including operation limits.	119	?15%
06	Fast ion generation	Validation of fast ion loss simulation tools and fast ion detection.	18	?
07	Safe operation heating	Demonstration of safe operation with upgraded heating systems	14	?75%
08	Low-field startup	Demonstration of reliable startup scenarios at reduced magnetic field.	72	50%
09	B scaling	Development of the capability to extrapolate the B-field dependency to high-field reactor operation.	72	5%

10	Safe operation: PFCs	Demonstration of safe divertor operation scenarios to avoid overloaded plasma-facing components. -> NEXT TRL	68	100%
11	Error field correction	Determination of trim and/or control coil currents required to correct error fields.	0	?
12	Divertor actuator qualification	Demonstration of effective pumping, high divertor compression and qualification of fueling actuators.	532	~50%
13	Long pulse	Demonstration of long-pulse operation (1GJ energy turnaround). -> NEXT TRL	125	100%
14	Long-pulse detachment	Demonstration of scenarios with long, stationary divertor detachment. -> NEXT TRL	475	100%
15	Characterization of detachment conditions.	Characterization of detachment conditions.	552	33%
16	Fast detachment	Achieving rapid transition to detachment.	0	0%
17	Tungsten PFCs	Definition of the operation limits associated with plasma-facing components containing tungsten materials.	50	25%
18	Tungsten retention	Characterization of the scrape-off layer retention for tungsten impurities.	0	0%
19	Erosion	Determination of erosion effects due to seeding impurities.	0	0%
20	Low- and high-Z transport	Characterization of the enrichment or accumulation for low-Z and high-Z impurities and develop strategies for avoidance.	259	25%
21	Wall conditioning	Development and refinement of procedures to condition the walls for enabling plasmas with high density gradients as needed for high-performance operation.	ERG	?
22	Reference discharge	Conduction of regular performance documentation with a standardized discharge with well-defined diagnostic coverage throughout the campaigns.	?	?

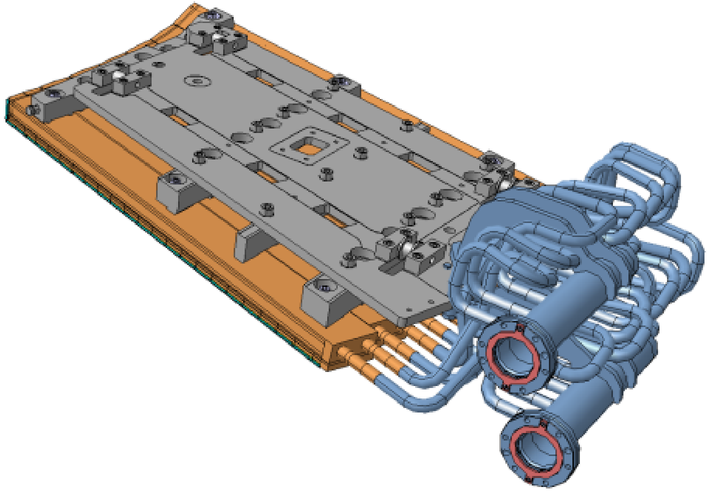
23	TSVV database	Documentation of relevant plasma profiles for detailed transport analysis and modelling (incl. turbulence).	387	?
24	Turbulence actuators	Assessment of heating and fueling actuators and magnetic configuration on turbulent transport.	664	?
25	Impurity transport	Documentation of core impurity profiles and detailed impurity transport analysis and modelling.	130	?
26	Optimization NC transport	Confirmation of neoclassical transport optimization at increased ion temperatures.	19	~0%
27	Optimization plasma currents	Confirmation of reduced equilibrium currents at higher betas and different magnetic configurations.	1	~0%?
28	MHD modes	Documentation of stability limits and fast-particle driven MHD modes.	298	~25%?
29	SOL transport	Provision of an experimental data base for understanding the transport mechanisms in the island divertor SOL.	1295	?
30	Edge code validation	Validation of edge transport codes.	469	?
31	SOL characterization	Studies of SOL width and target heat flux scaling.	140	?
32	SOL interpretation	Characterization of asymmetries of plasma conditions and radiation, mapping of diagnostic results in 3D island divertor.	390	?
33	Optimization: MHD	Documentation of high-beta profiles for detailed transport analyses and modelling with emphasis on magnetic fluctuation measurements.	0	0%
34	High-beta studies	Documentation of high-beta profiles for detailed transport analyses and modelling with emphasis on magnetic fluctuation measurements.	111	~5%
35	Field stochastization	Assessment of the effect of field stochastization on SOL transport and operational limits due to heat-flux redistribution at high plasm beta.	83	~5%

36	EF heating components	Support of the operation and exploitation of heating systems and their commissioning with plasma and the commissioning and operation of support facilities (manipulators, endoscopes) developed in EUROfusion enhancement projects. -> NEXT TRL	113	100% cont.
37	EF diagnostics/ support	Support of the operation and exploitation of diagnostics and means for safe operation (incl. software) (developed in EUROfusion enhancement projects). -> NEXT SUPPORT ACTION	35	100% cont.
38	Wall conditioning	Documentation of core impurity profiles and detailed impurity transport analysis and modelling. -> NEXT TRL	33	100% cont.
39	Modelling for safe operation and documentation	Conduction of modelling in support of overload avoidance (e.g. fast ion overloads) and for the completion of the HELIAS physics basis (interpretative modelling during the campaign). -> NEXT SUPPORT ACTION	--	100% cont.

Tungsten divertor

- two branches of development:
    1. prototype technological development: W surface on water-cooled heat sink, scalable to full divertor module
       ➪ dedicated technology program, development within EUROfusion WPDIV-W7X

    2. modeling-driven divertor surface geometry (heat loads, exhaust), validation of numerical tools
       ➪ program accompanying operation campaign, already included in OP 2.1



- technology development progressing, pursuing different heat sink and W bonding technologies

  ➪ CuCrZr heat sink diffusion-welded or additive manufacturing

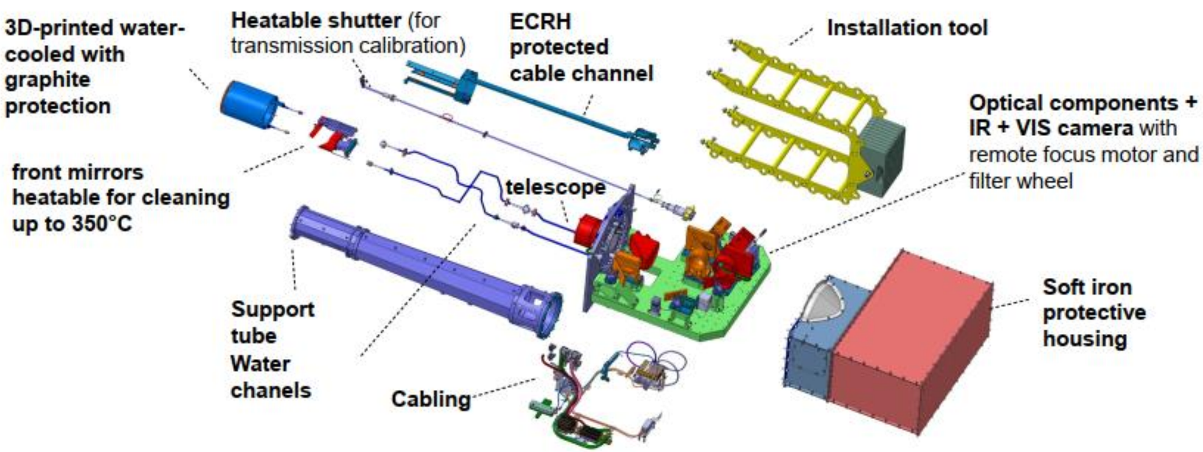
  ➪ W plasma facing surface via hot isostatic pressing or coating

- prototype development incl. testing program runs until 2026, burget of in total 4.3M€ (IPP + EUROfusion) secured

  ➪ design review process as pre-requisite for next step decisions

Safe operation

- IR divertor observation



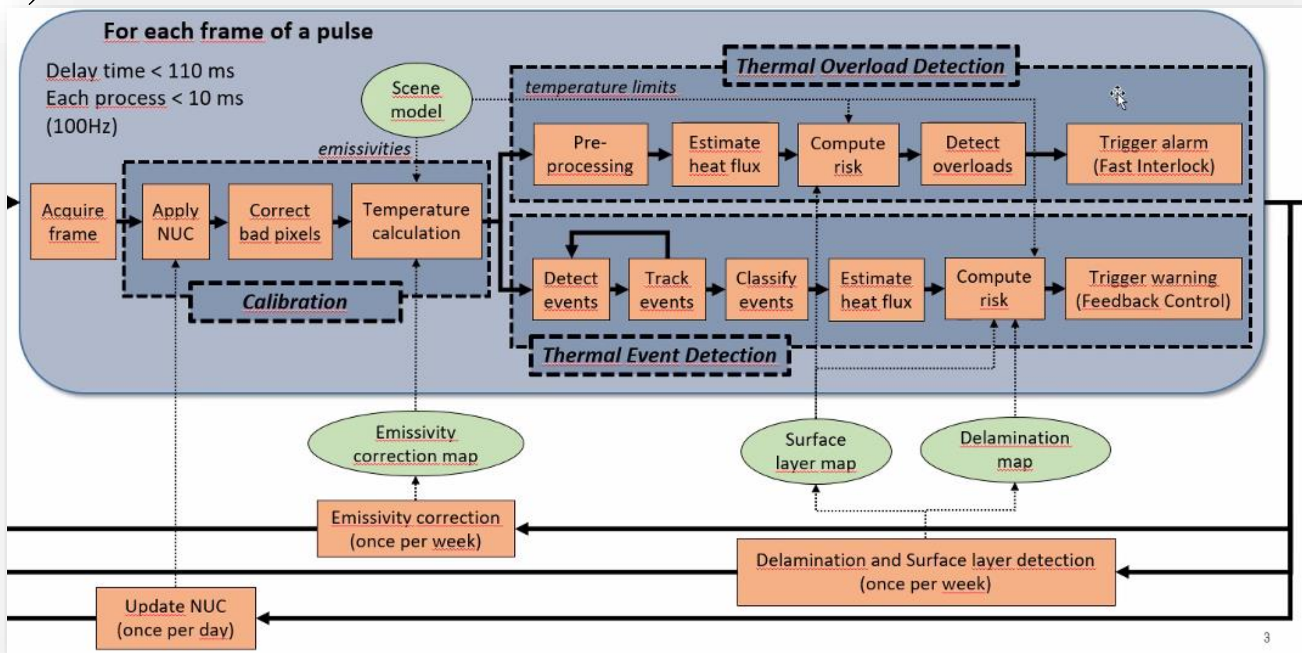
- current IR divertor observation not capable for long-pulse operation (limit: 2GJ heating energy)
  - ⇨ exchange by IR endiscope system with sufficient dynamics and spatial resolution to be included into fast interlock machine protection system
- R&D phase finished and two endoscop system successfully tested in OP 2.1, 8 endoscopes remaining
  - ⇨ total volume 3.8M€, IR optics in procurement
  - ⇨ envisaged installation mid 2025

Divertor IR survelliance software

Fast interlock and feedback control

- Two distinct lines: thermal overload (fast interlock, essential for OP2.1) and themal event (feedback control) detection

Adaptation of computer vision, NN, deep learning techniques for several tasks (e.g. estimation of heat flux, Surface layer detection, strike-line charac…)



Preparatory actions for 2024 (red indicates a lack of resources)

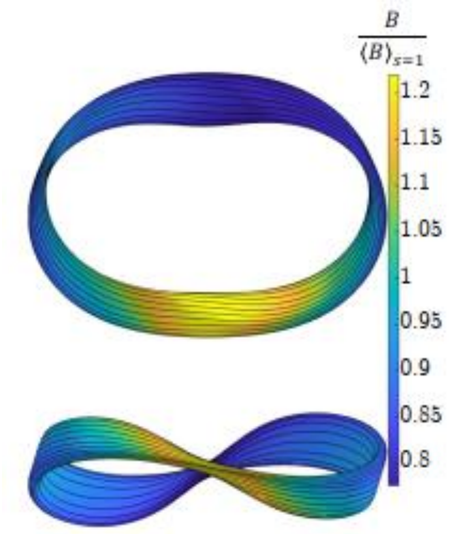
- Diagnostics and Component preparation
  - E-Band Doppler reflectometer
  - C/O monitor and PHA upgrades
  - FILD
  - Video upgrade
  - Dual Laser TS (ITER)
- Software preparation
  - Image processing
  - FPGA developments
- Preparatory modelling
  - Heating (ICRH, ECRH)
  - Fast ions
  - Scenarios
  - Scenario preparation on TJ-II (HIBP operated by KIPT)
  - Scenario preparation on U-2M

- Heating
  - Gyrotron tests
  - Gyrotron development support
  - ICRH

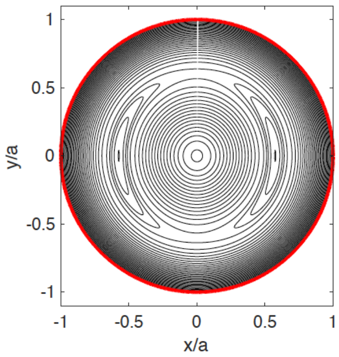
- Manipulator and endoscope developments

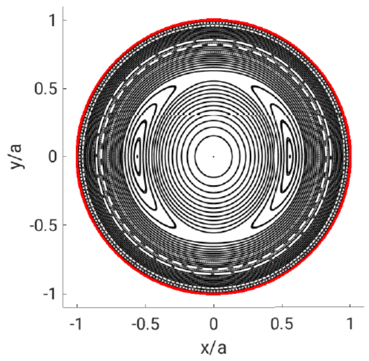
TSVV#12 : highlights and plans for 2024 - Optimization

- New methods for finding optimised stellarators.
- Novel quasi-isodynamic stellarators with few field periods, good fast-ion confinement and low bootstrap curent
- Optimised stellarators with **reduced ITG transport**.



- New equilibrium code GVEC parallelised (support from Garching ACH).
- New predictions for **beta-limits based on transport from magnetic-fieldline chaos.**
- Prediction of nonlinear saturation of tearing modes using stellarator equilibrium code SPEC.





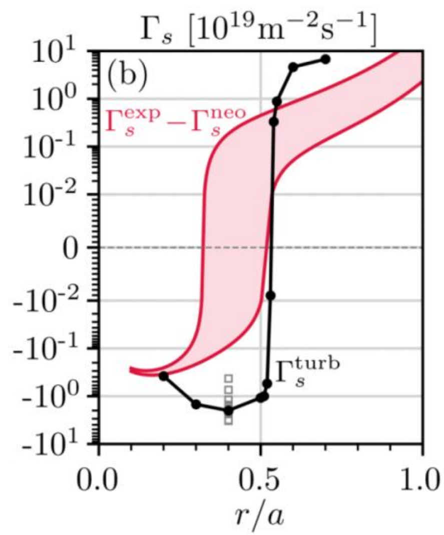
2024

- Quasi-isodynamic stellarators with reduced turbulent transport.
- Divertor optimisation.
- Free-boundary version of GVEC.

TSVV#13 : highlights and plans for 2024 - Transport

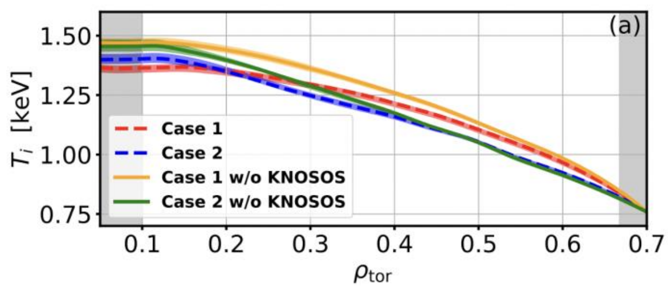
- **Turbulent particle transport** has been addressed numerically for the first time **in W7-X.**

⇒ **Turbulence prevents** neoclassical **core density depletion** [Thienpondt PRR´23].



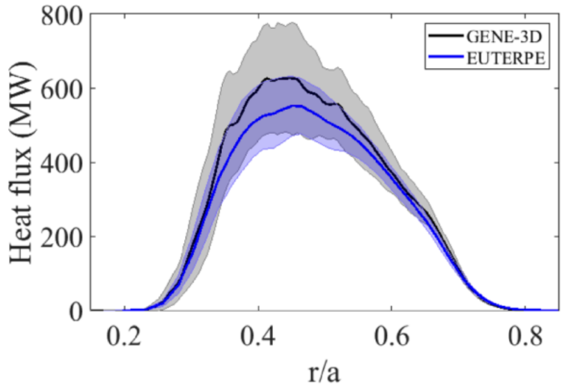
- **Transport** code **TANGO** coupled to **gyrokinetic** code **GENE3D** and **neoclassical** code **KNOSOS**

⇒ **transport simulations** including **neoclassical and turbulent physics of routine application in stellarators** [Bañón Navarro NF´23].



Cross code verification among the European gyrokinetic codes is **in constant progress**.

[Sánchez NF´23].



2024

- **Improve model completeness of gyrokinetic simulations (role of impurities, electromagnetic effects), `stella` code developments (EM version), etc.**
- **Support OP2.1 and OP2.2 campaigns.**

Thrust 4: organization, status and plans

Thrust 4 is the interface between TSVV 12 “Stellarator Optimization”, TSVV 13 “Stellarator Turbulence Simulation” and WPW7X.

- Monthly technical meetings of each TSVV that the Thrust 4 facilitator and Deputy TFL of WPW7X, Iván Calvo, attends.
- Papers and conference presentations are rehearsed in the W7-X Physics Meeting or in the W7-X Topical Group meetings if they are of broad interest.

- In September 2023, meeting funded by CIEMAT and the *Simons Collaboration on Hidden Symmetries and Fusion Energy* on the natural topic for synergy between TSVVs 12&13: **stellarator turbulence optimization**.
- Tentative plans for a joint in-person meeting of the teams of TSVVs 12&13 in Greifswald at the beginning of 2024.
- For all the above, no formal Thrust 4 meetings are planned in 2023.

Stellarator collaborations and INCO

- Recent edition of the **Coordinated Working Group Meeting** (Kyoto, june 5-8, 2023)
  - hosted discussions on **JAs/JEs for 2024**
  - JA/JEs involve **LHD, W7-X, TJ-II, H-J, HSX, U-2M**.
  - **Next CWGM in Hiroshima**, sep. 2024 for progess reporting (with intermediate virtual sessions).
- Physics areas of INCOs in 2024 (non-exhaustive list)
  - **ICRH plasma start-up** for low-B plasmas in W7-X, LHD, U-2M.
  - Unified **radiative density limit** in Stel./Hel. Devices (LHD, W7-X, TJ-II).
  - Experimental profile database for **turbulence code validation** (All)
  - Cross-device experimental **study of magnetic-hill** plasmas (LHD, TJ-II, HSX).
  - Definition of a set of stellarator/heliotron **reactor case studies.**
  - ...

Shortcomings and issues

- Resources
- AI: coordinated actions & computing resources (meeting called today)

Grant deliverables and milestones

GA Milestone No.	GA Milestone Title	Due Date [mm/yyyy]
W7X.M.01	1.5 MW Gyrotron infrastructure completed	12/2021
W7X.M.02	Commissioning of W7-X enhancements incl. commissioning with plasma OP2.1.	12/2022
W7X.M.03	Operation OP 2.1 with water-cooled PFCs completed	12/2023
W7X.M.04	Operation OP 2.2 completed and 1 GJ energy turn-around achieved.	12/2024
W7X.M.05	High-beta HELIAS operation at low collisionalities	12/2025
W7X.M.06	Operation OP 2.4 with High-power and long-pulse completed and 6 GJ energy turn-around achieved (pulse lengths up to 600 s, long-pulse detachment).	12/2025

GA Deliverable No.	GA Deliverable Title	Due Date [mm/yyyy]
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)	12/2024
W7X.D.08	Report on conducted Scenario & campaign preparation OP 2.3 (focus: turbulent and neoclassical transport, high-power steady-state operation)	12/2024
W7X.D.09	Assessment report on scenarios with optimized transport and high-beta operation (energy limit 6 GJ)	12/2024

M‘s and D‘s appear to be achievable.

Objectives AWP 2024

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Milestones AWP 2024

Sequential WP-M ID	WP Milestone Title
WPW7X-2023.M.3.	2024 campaign prepared (WPW7X Team)
WPW7X-2024.M.1.	Campaign conducted
WPW7X-2024.M.2.	2022/23 campaigns exploited

Supplementary Information

U-2M status

- The experimental campaign on the U-2M was stopped on 24.02.2022.
- KIPT infrastructure, buildings and equipment were destroyed and damaged.
- In the summer of 2022, the KIPT Team began work to repair the damage and continues to this day.
- A technical commission of some of the U-2M equipment is expected (If it can be done).
- Researchers participate in data processing and analysis.
- Technical assistants participate in the repair of buildings and equipment.
- The main problem of full operation of the U-2M is humans safety. The threat of missile attacks is very high. The time from start to approach to Kharkiv is less than 5 minutes.
- The second problem is the stability of the power system. An emergency shutdown (after missile strikes) could result in an emergency situation on the U-2M.
- Safe conduct of experimental companies on the U-2M is possible after the end of the war.