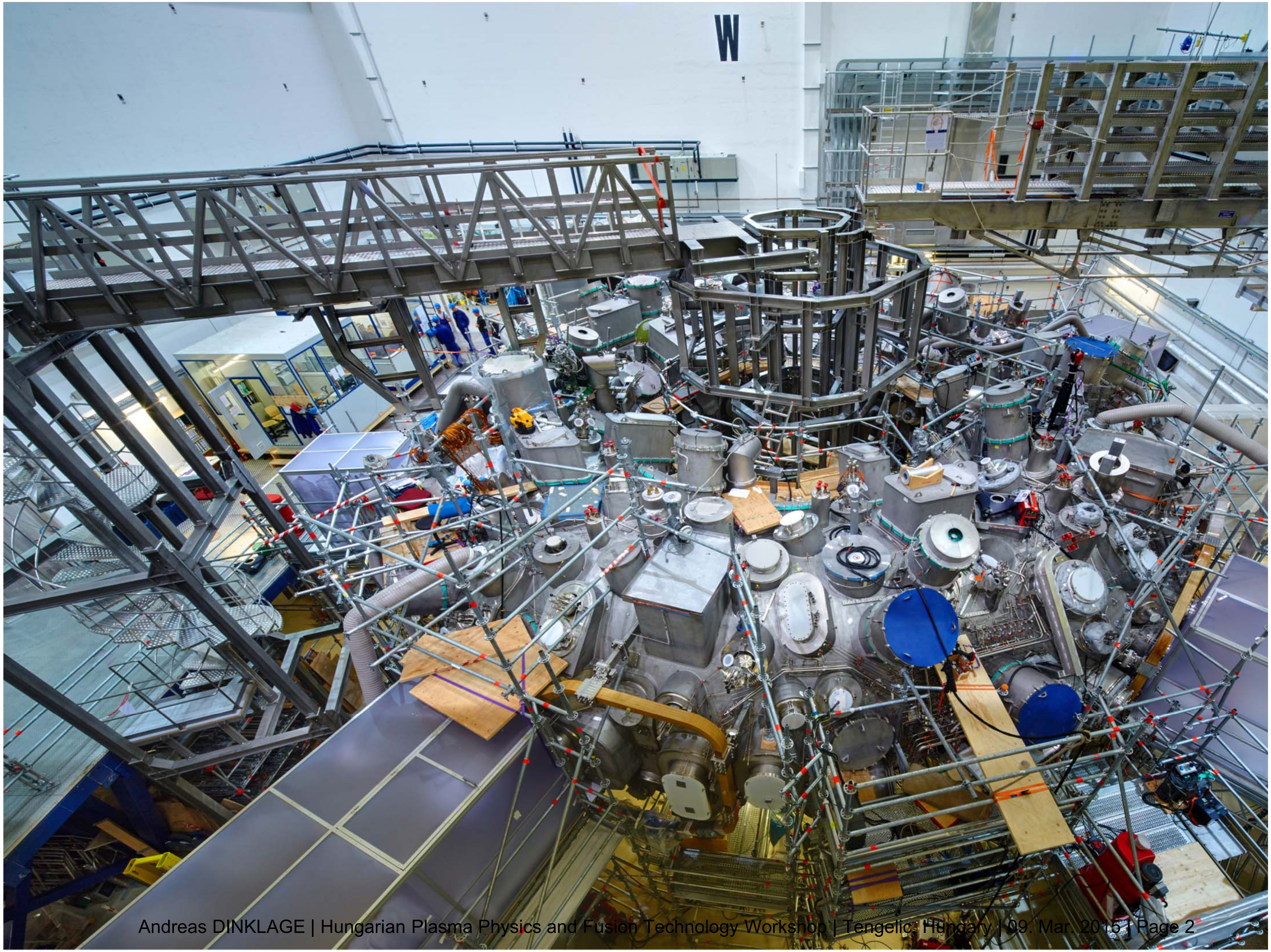
EUROfusion

Wendelstein 7-X in the European Roadmap to Fusion Electricity

Enrique Ascasíbar for the W7-X Team

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053.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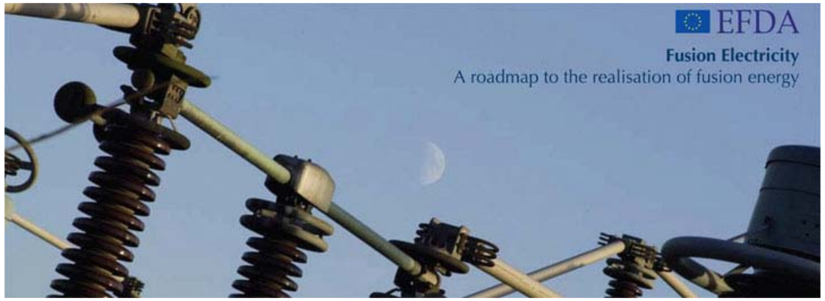
Outline



EFDA

Fusion Electricity

A roadmap to the realisation of fusion energy

1. Introduction and Motivation:Stellarators in the EU Roadmap
2. Operational Phases of W7-X: OP1.1, OP1.2
3. Aspects of SSO
4. Summary

Wendelstein 7-X, the Engineers' View

mass: 725 t

R = 5.6 m

a = 0.5 m

$V_{plasma} = 30\ m^3$

$B \leq 3\ T$

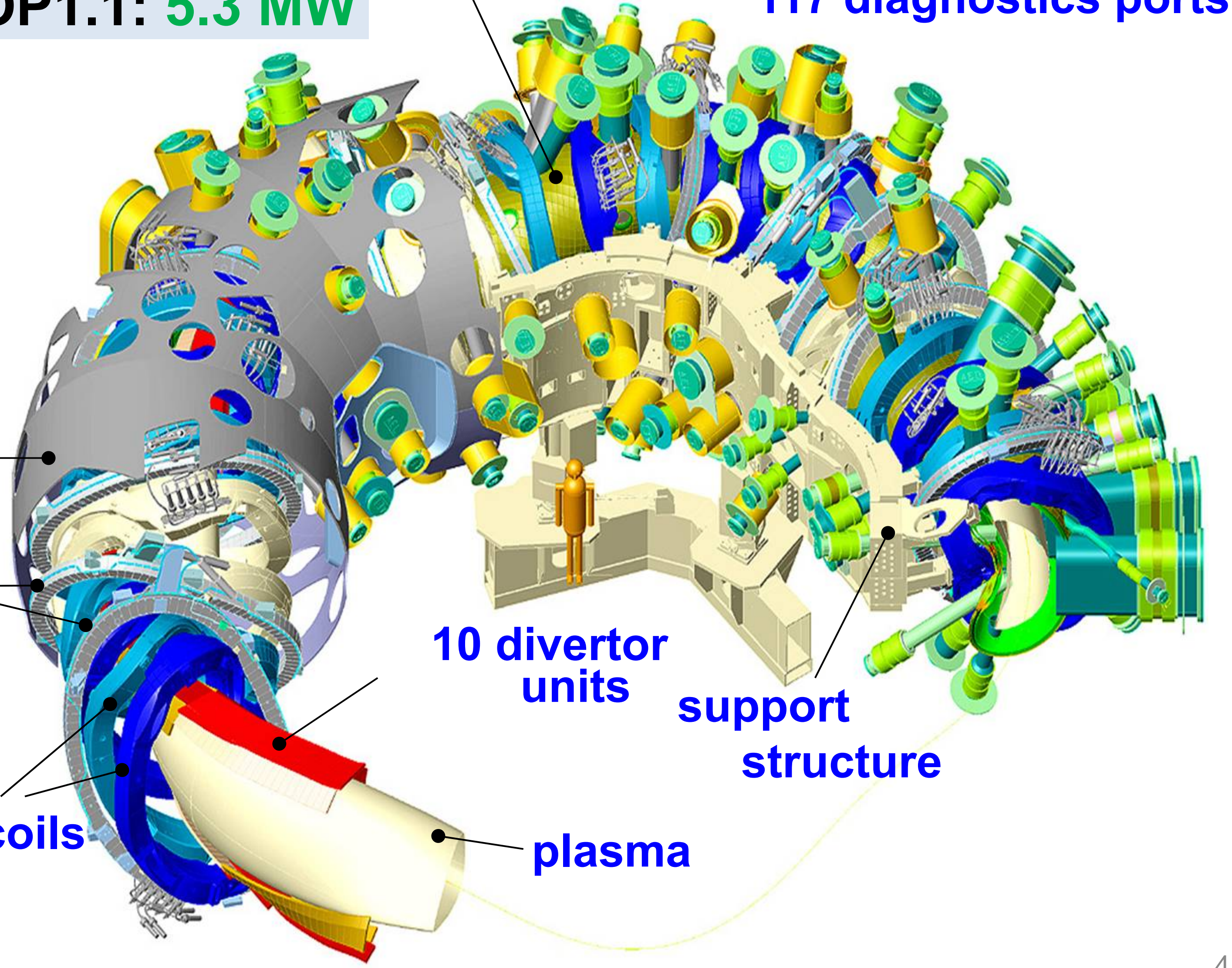
$\iota = 5/6\ -\ 5/4$

ECRH heating

OP1.1: 5.3 MW

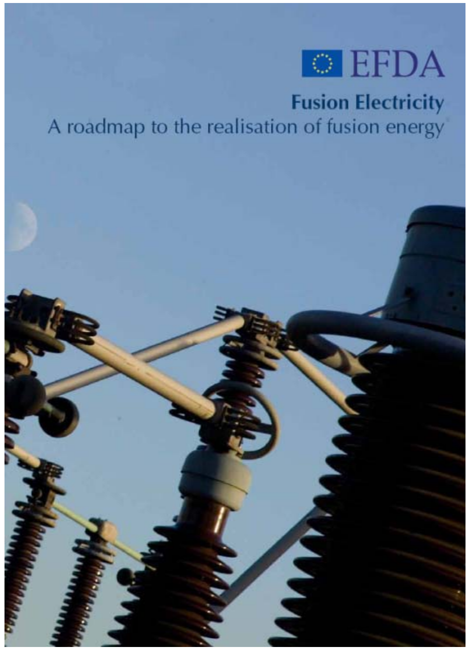
254 ports

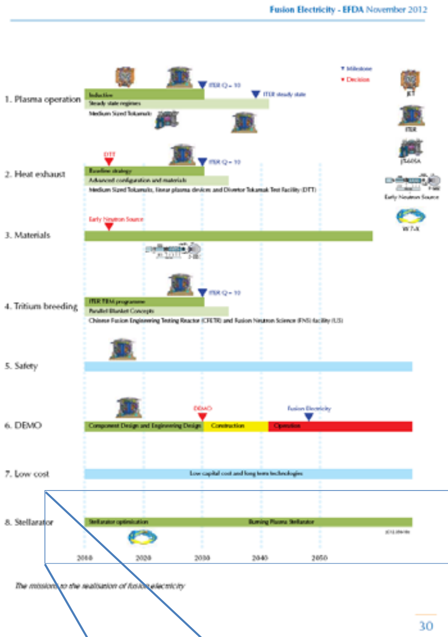
117 diagnostics ports

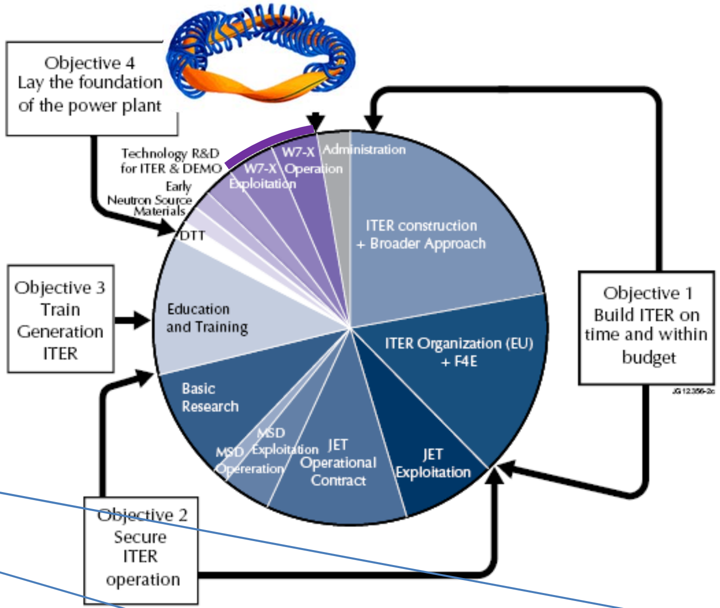


Europe and W7-X / W7-X and Europe

http://www.efda.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf?5c1bd2







EU Roadmap: Eight Missions:

Mission 8

Bring the HELIAS line to maturity

Long-term alternative to tokamaks: mitigate risks and enhance synergies:

Wendelstein 7-X is an integral part of the European fusion development strategy.

Why stellarators[1]?

Stellarators:

the main alternative magnetic confinement concept to the tokamak.

external coils generate rotational transform: 3D-confinement without plasma current

+ intrinsically steady-state
+ no current disruptions
+ no current driven instabilities
+ no need significant current drive
+ no runaway electrons
+ operation above Greenwald-limit feasible
+ lower α-particle pressure (for given P_{fus})

- 3D engineering
- 3D core impurity transport
- 3D plasma/fast ion confinement

  high neoclassical losses
- 3D MCF: one generation behind
  - divertor concept to be verified
  - operation scenarios to be developed

Stellarator Optimization[2]: mitigate 3D losses
to pave the way to a Fusion Power Plant

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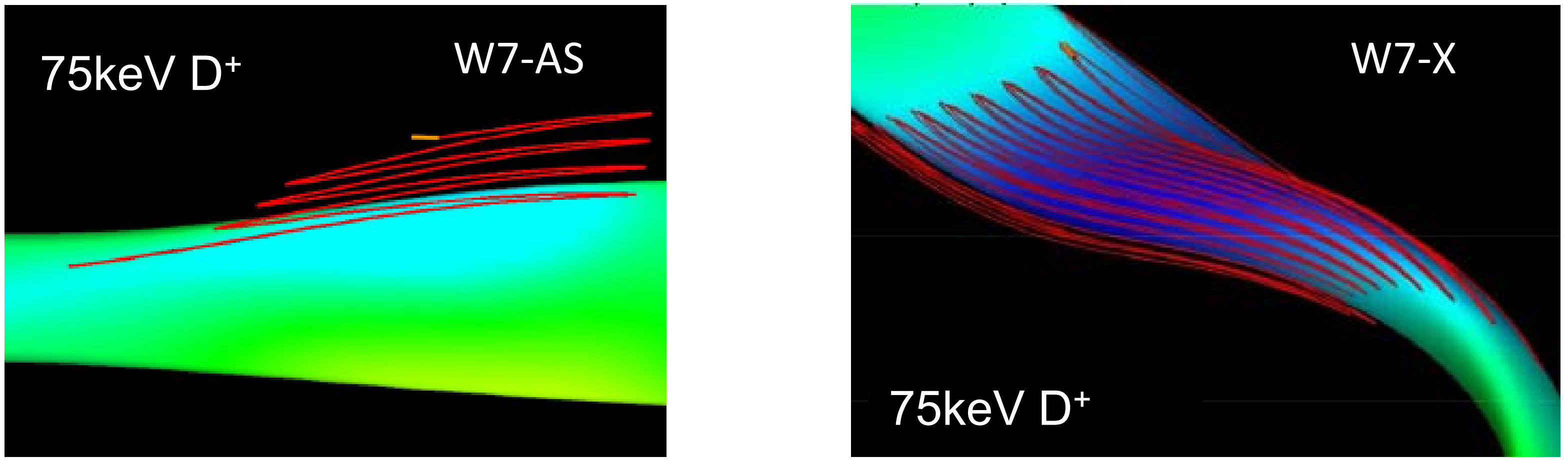
*[1] Helander, Rep. Prog. Phys. **77**, 0877001 (2014), [2] Nührenberg, Zille, Phys. Lett. **A 114**, 129 (1986)*

Why Wendelstein 7-X?

Stellarator Optimization[1]: mitigate 3D losses

HELIcal Axis Advanced Stellarator (Neoclassical Optimization)

taming locally trapped particles by proper shaping of mod B



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- **proof the concept of stellarator optimization to be a viable path to FPPs**
- **fundamentally new scientific field: lmfp-3D plasma physics**

⇒ 3D impurity transport
⇒ 3D turbulence
⇒ improved confinement modes
⇒ fast particles & Alfvénic instabilities
⇒ high-β operation at low $\nu_i \sim \nu_e$
⇒ new (island) divertor & SOL physics

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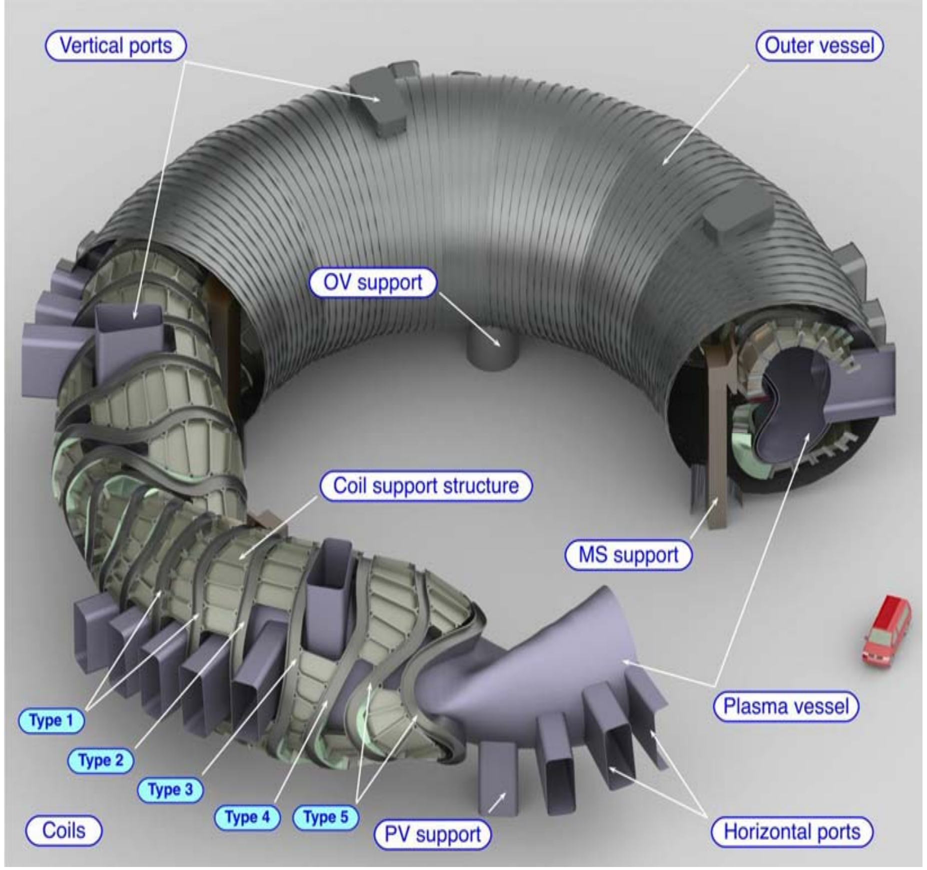
[1] Nührenberg, Zille, *Phys. Lett.* ***A 114***, 129 (1986)

And what is needed for a HELIAS-FPP?

Engineering Study HELIAS 5-B



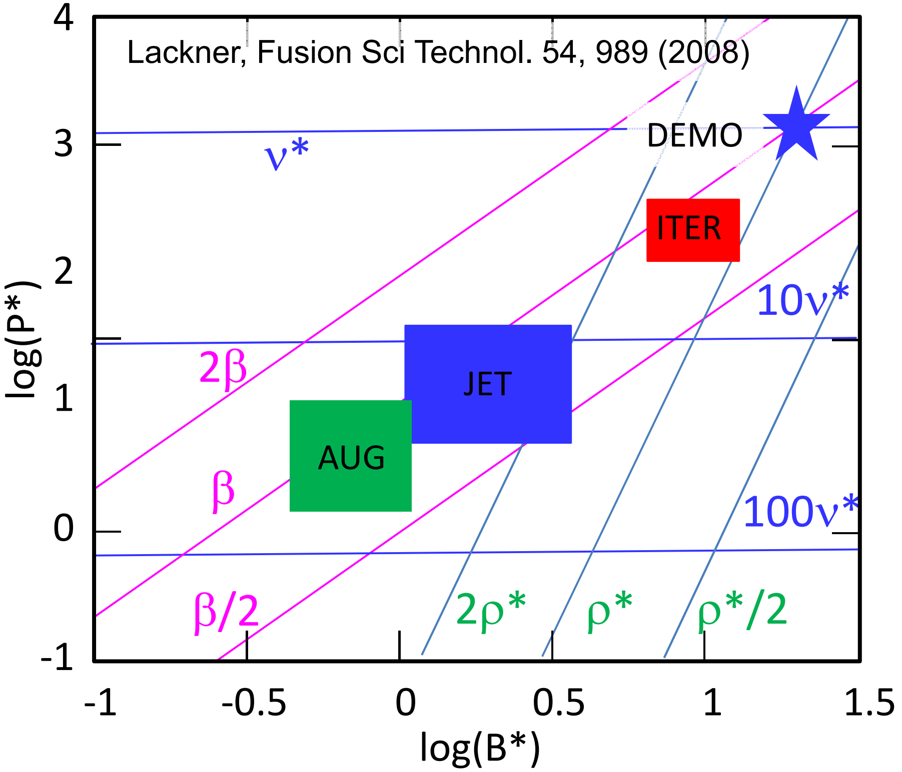
electro-mechanical feasibility of HELIAS fusion-power plants

Schauer et al., Fusion Eng. Design 88, 1619 (2013)

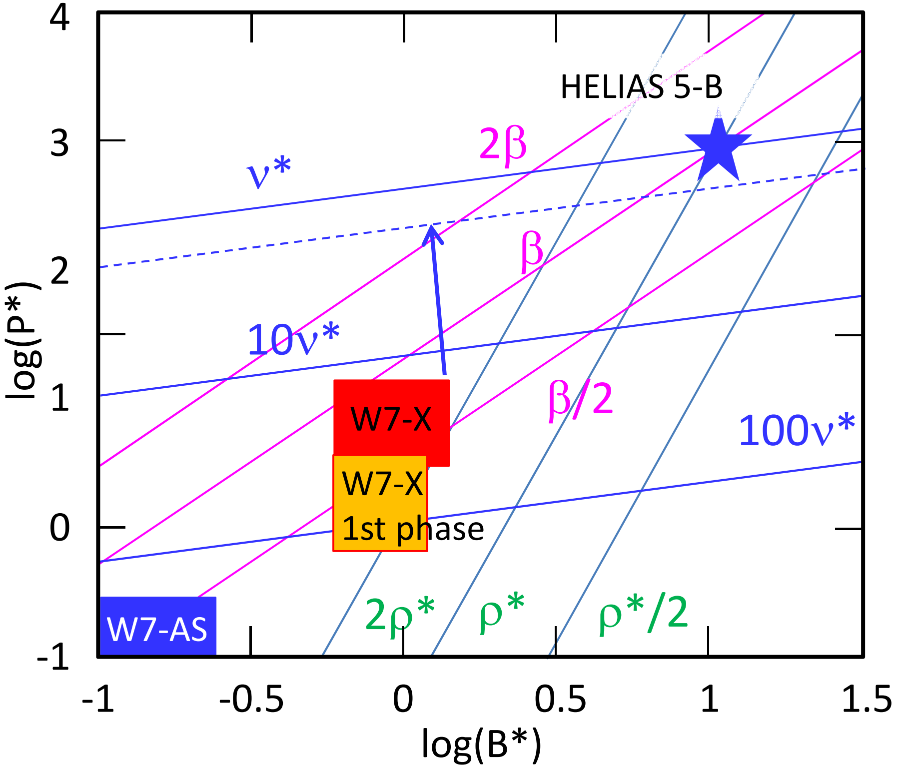
And what is needed for a HELIAS-FPP?

Gaps in dimensionless *β*, *ρ**, *ν** parameters

ITER-like shaped tokamaks


Lackner, Fusion Sci Technol. 54, 989 (2008)

Wendelstein-line



From Wendelstein 7-X there is still a large gap to the HELIAS reactor but W7-X is large enough to assess reactor physics aspects.

High-level objectives and implications

Mission 8: bring HELIAS to maturity

⇒ exploit W7-X to prepare a decision on the next-step HELIAS device: HELIAS-FPP? or HELIAS-BPX?

⇒ steady-state, lmfp, high-β, (low ν^*, ρ^*) plasmas and demonstration of favourable 3D confinement/operation

⇒ high-level priorities : address key issues in 3D confinement
  - ➢ safe operation schemes and effects of optimization
  - ➢ density control, impurities, fast particles, island divertor/edge

⇒ implement actions along high-level priorities
  - ➢ theory driven exploitation and predictive capabilities
  - ➢ delivery of key components and their operation
  - ➢ preparation of experimental schemes and FPP physics basis

specific actions to comply with WP14-18: prepare SSO

+ develop in OP1 feasible island divertor scenarios in a robust environment to mitigate later technical risks with water-cooled in-vessel components (OP2)
  - increase density
  - explore magnetic configurations compliant with reliable divertor operation

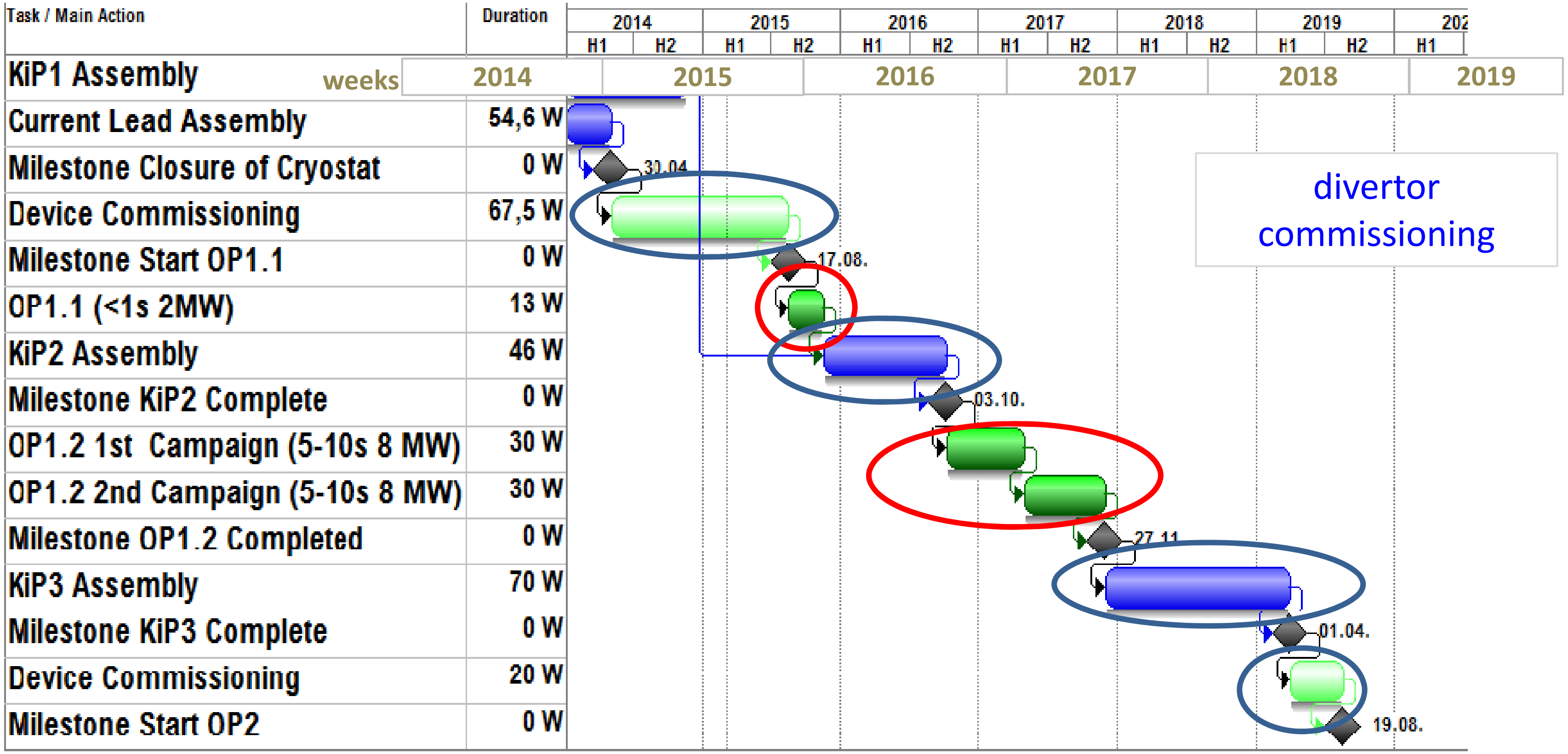
+ assess aspects of stellarator optimization, develop interpretative and predictive capabilities

Timeline OP1.1, OP1.2, OP2

Device commissioning
(cryostat, fields, vacuum)

Test divertor
installation

HHF divertor
installation



Task / Main Action	Duration
KiP1 Assembly	
Current Lead Assembly	54,6 W
Milestone Closure of Cryostat	0 W
Device Commissioning	67,5 W
Milestone Start OP1.1	0 W
OP1.1 (<1s 2MW)	13 W
KiP2 Assembly	46 W
Milestone KiP2 Complete	0 W
OP1.2 1st Campaign (5-10s 8 MW)	30 W
OP1.2 2nd Campaign (5-10s 8 MW)	30 W
Milestone OP1.2 Completed	0 W
KiP3 Assembly	70 W
Milestone KiP3 Complete	0 W
Device Commissioning	20 W
Milestone Start OP2	0 W

1st plasma
C limiter; pulsed op.
OP 1.1

C uncooled divertor plasmas
pulsed operation
OP 1.2

water-cooled HHF div.
steady-state plasmas
OP 2

W7-X: first OPs in figures

OP 1.1 **2015** 13 wks	**uncooled carbon limiter** He, (H) **pulse** limit: $E_{max} < 2MJ$ $\tau_{Pulse} \lesssim 1$ s	**P_{ECRH} ~ 2 MW** (…5MW) gas puff surveillance diag. magnetics basic *n*, *T*, imp. diagnostics	$T_e^{NC} < 3.5$ keV $T_i^{NC} < 0.9$ keV $n < 2 \times 10^{19}\ \mathrm{m}^{-3}$ $\beta_{ISS04} < 0.6\%$ **$\beta_{NC} < 1.6\%$**
OP 1.2(a) **2016** 29 wks	**uncooled test-divertor (C)** H, (D) **pulse** limit: $E_{max} < 80$ MJ $\tau_{Pulse} \lesssim$ 10s … min	P_{ECRH} ~ 8 MW P_{NBI}^{H} ~ 7 MW +profiles MHD (*n*,*T*, E_r,…) +impurity diagnostics	$T_e^{NC} < 3.5$ keV $T_i^{NC} < 3$ keV $n < 1.6 \times 10^{20}\ \mathrm{m}^{-3}$ $\beta_{ISS04} < 1.2\%$ **$\beta_{NC} < 3\%$**
OP 1.2(b) **2017** 29 wks	**test scraper elements**	+ P_{ICRH} ~ 1.6 MW **$P_{tot} \lesssim 10$ MW** + blower gun pellet inj. + diagn. upgrades	
OP 2 **>2019**	**actively cooled divertor (CFC)** **steady-state capable** D, H technical limit: 30 min/10MW $P_{target}/A < 10\ \mathrm{MW/m}^2$	P_{ECRH} ~ 10 MW P_{NBI}^{H} ~ 7 MW or P_{NBI}^{D} ~ 10 MW P_{ICRH} ~ 4 MW **$P_{tot} \lesssim 20$ MW** + quasi cw pellet injection + steady-state upgrades	$T_e^{NC} < 4.5$ keV $T_i^{NC} < 4$ keV $n < 2.4 \times 10^{20}\ \mathrm{m}^{-3}$ $\beta_{ISS04} < 2$ % **$\beta_{NC} < 5$ %**

Minimum goals of OP1.1

uncooled carbon limiter, He, (H), E_{max} < 2MJ

OP1.1 priorities: first plasma operation and integral commissioning

1. Integral commissioning of all systems needed for successful plasma operation
2. Existence of closed flux surfaces all the way to the limiter (at B=2.5 T)
3. Measurement and adequate reduction of B_{11} field errors
4. Reliable ECRH plasma startup scenario in He
5. Basic ECRH interlocks and safe operation scenarios
6. Basic impurity content monitoring
7. Central T_e>1 keV at $n_e>5*10^{18}$ m^{-3} in at least 10 discharges in He

Plus some more physics:

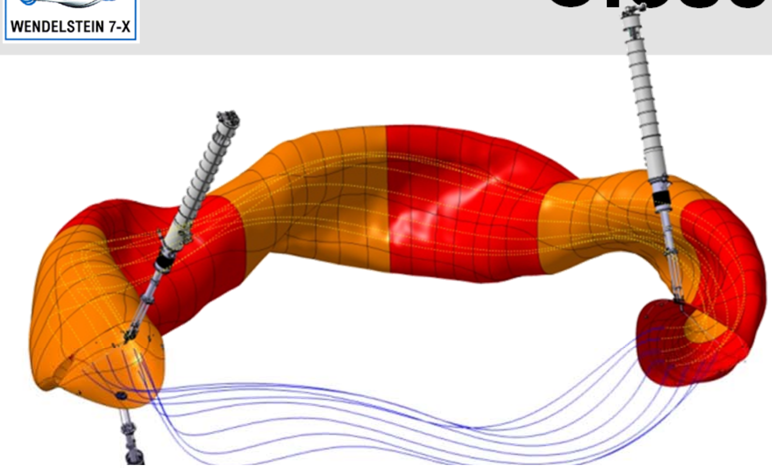
- Electron root transport studies
- Scrape-off layer studies
- First experiments with ECRH and ECCD
- First comparison He vs H (startup, pumping, confinement)

Confirmation of optimization goals of W7-X will be done in later operation phases.

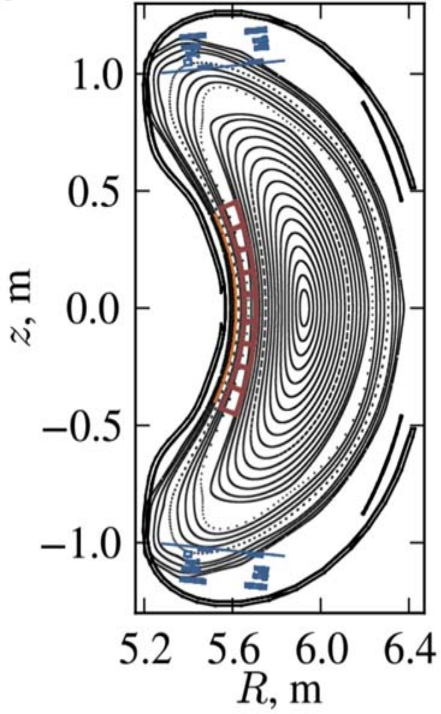
T.S. Pedersen, EPS2014 & W7-X PC Meeting,

Closed flux surfaces

OP1.1



$I_{planar}=0.23,\ \iota_0=0.75,\ \iota_a=0.81$



view into the W7-X vacuum vessel

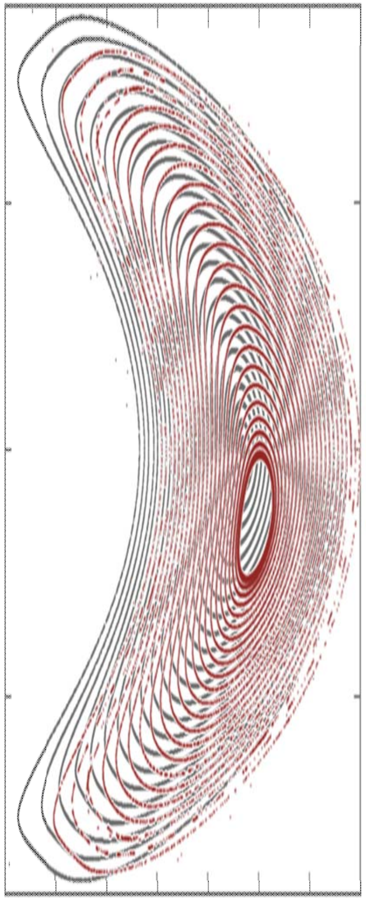
EDICAM video camera system

Field errors

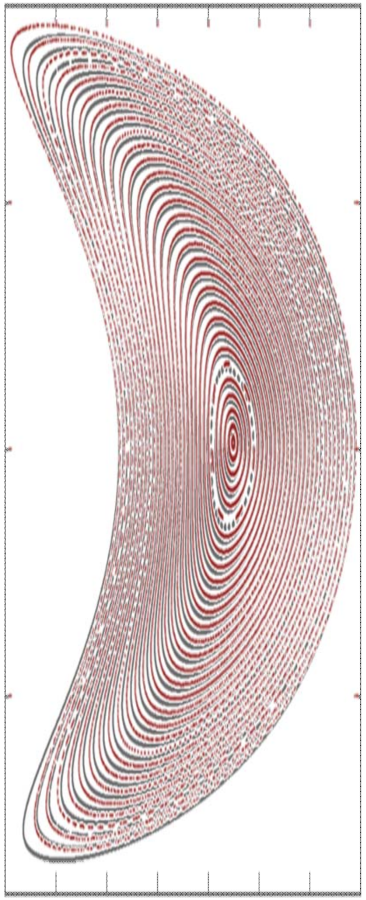
OP1.1

no magnetic field errors

$B_{11} = 10^{-4}$ T



high-iota configuration



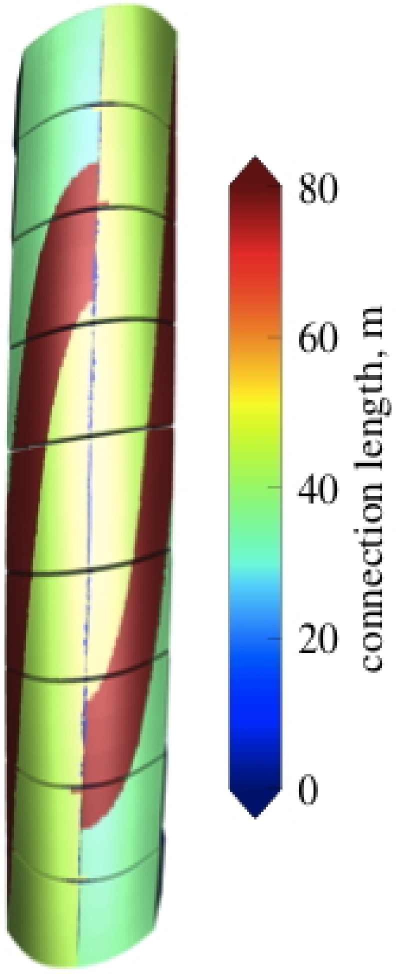
standard configuration

assessment of small field errors ⇒ development of divertor configurations

Limiter SOL physics

OP1.1

- connection length is short compared to divertor phase
- two distinct regions on limiter

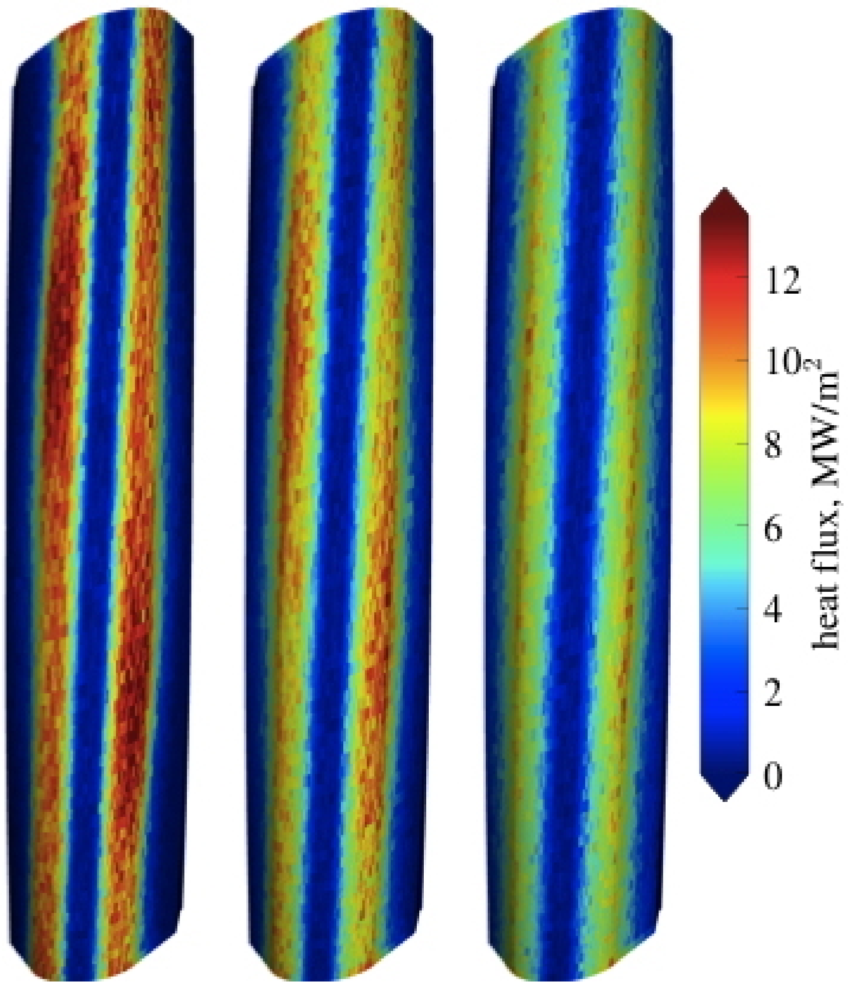


Langmuir probes

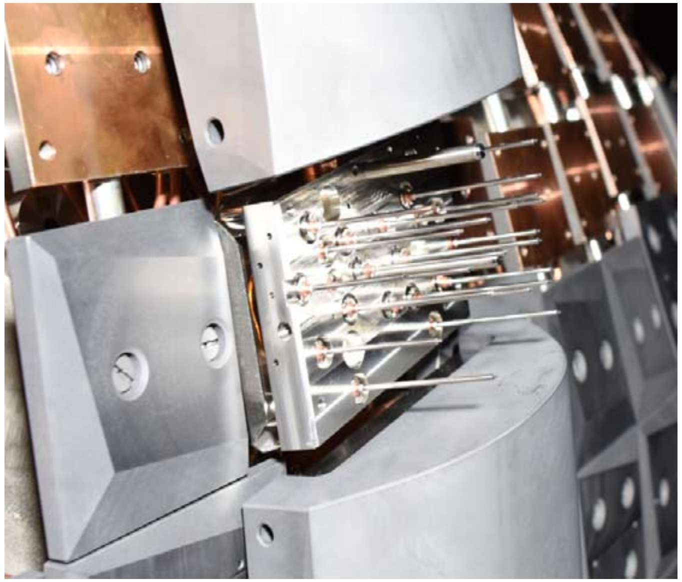
Langmuir probes

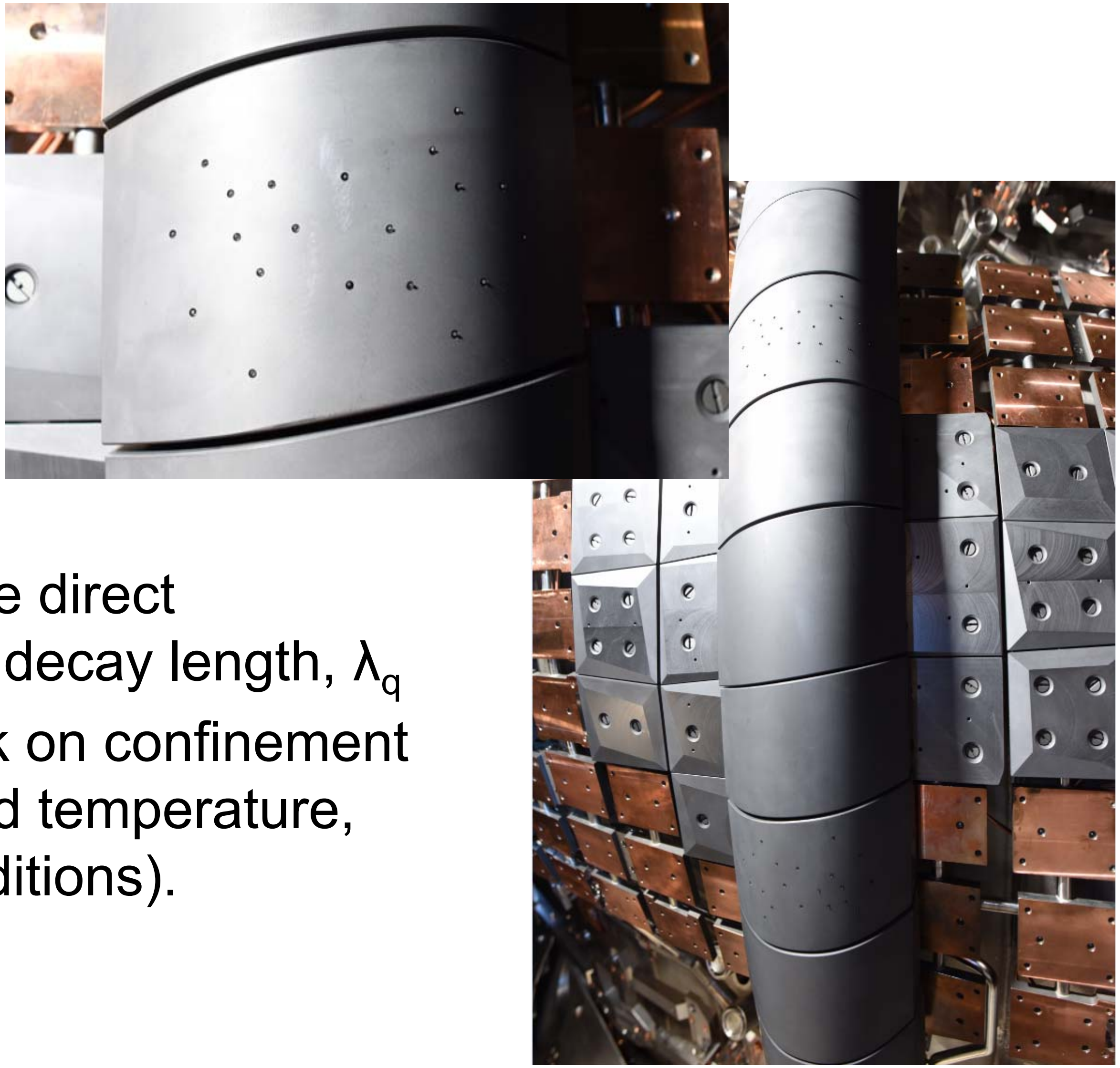
Cross field diffusion rate visibly affects heat load patterns

D (m^2/s) 0.5 1.0 2.0



Scrape-off layer physics with a limiter

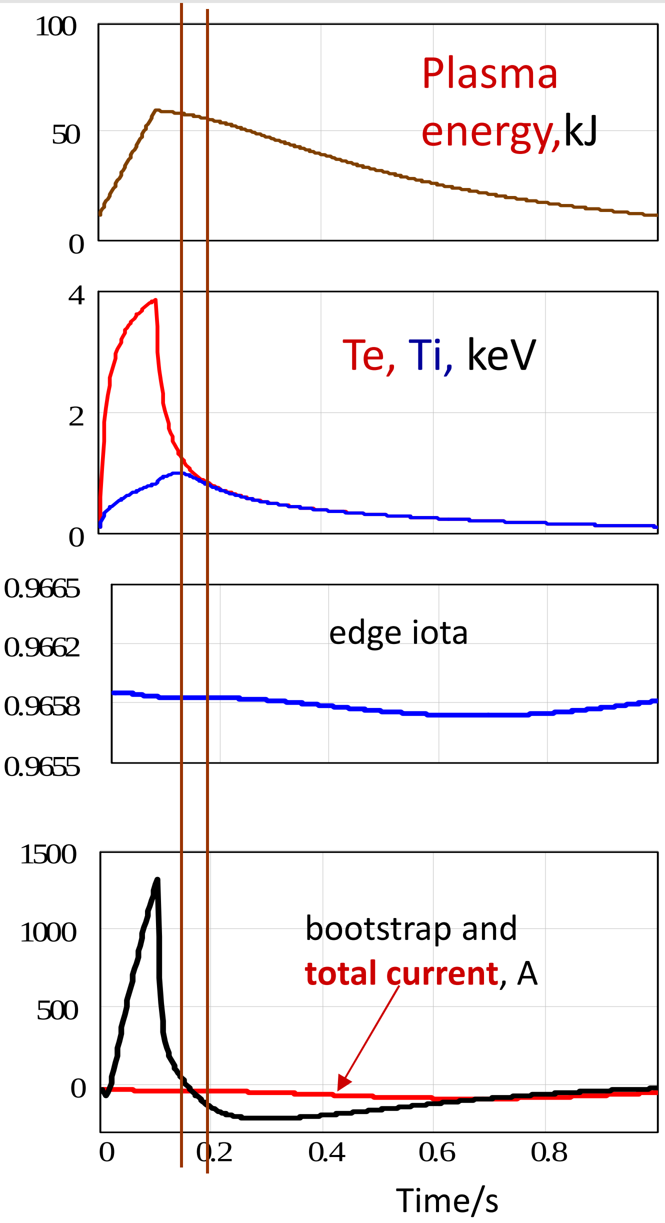


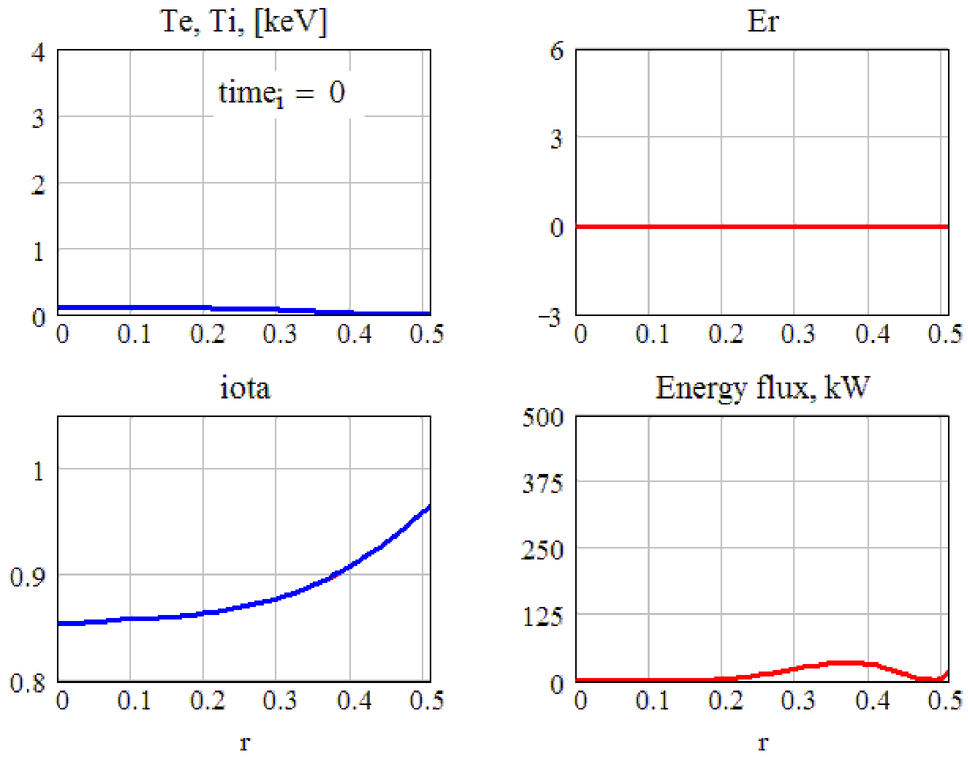


- Langmuir probes provide direct measurements ofpower decay length, λ_q
- Can be done piggy-back on confinement studies (vary density and temperature, reach quasi-steady conditions).

Predictive simulations of 1st plasmas

OP1.1





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- 500 kW ECRH; 100 ms after burn-through
- bootstrap current shielded by the plasma response
- strong electron-root feature in the core – high T_e

OP 1.2: the test-divertor unit (TDU) phase

Uncooled but robust TDU:
unique possibility to explore aggressively the configuration space

It gives flexibility to react on
new insights and technical changes

Guiding principles:

1. **increase density**

target: beyond X2-ECRH cut-off (~1.5…2 x 10^{20} m^{-3})
divertor operation, towards high-nTτ/high-β@low-ν^* …

2. **employ configurational flexibility**

optimization (small Shafranov shift, good NC confinement, small bootstrap, MHD stability…)

→ **arrange physics topics along these lines**

1) **Prepare high-density, high-power steady-state operation**
2) **Prove and assess elements of stellarator optimization**

Guiding Principle 1: increase the density

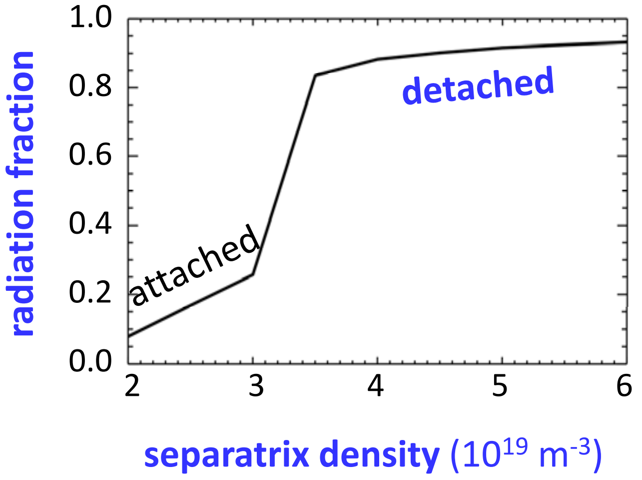
OP1.2

towards safe divertor operation

towards high-$nT\tau_E$, high n & high T → high τ_E, high-β

EMC3/EIRENE simulations

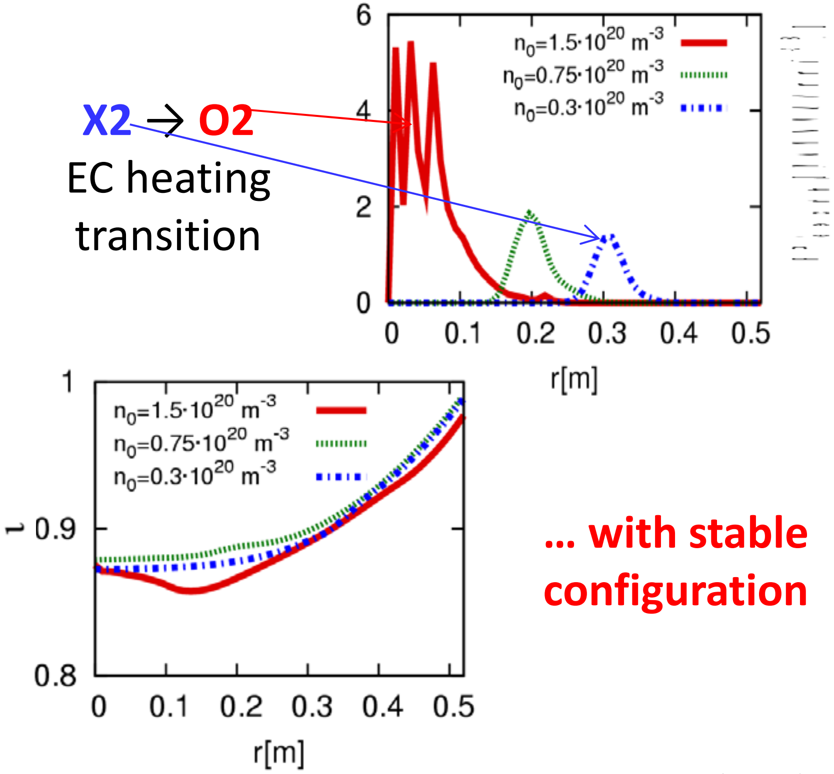
detachment in stellarator divertor plasmas



with high radiation fractions
(control: L_c, x-point location, n_{us})

Y. Feng

plasma scenario development



… with stable configuration

Geiger et al., PPCF (2015)

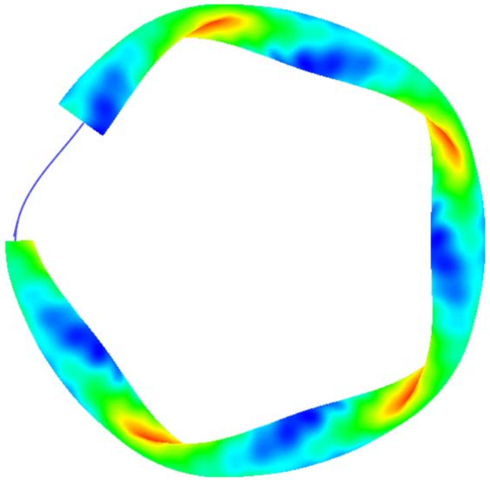
Guiding Principle 2: exploit configuration space

OP1.2

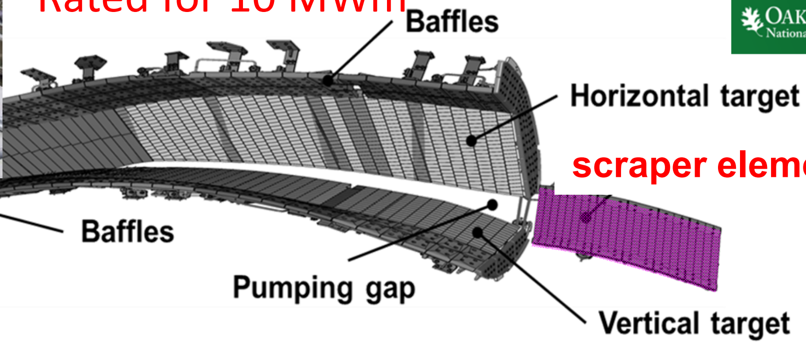
W7-X coils & protection components: systematic explorations & adjustments

Geiger et al., EPS 2014

mod B
red: high
blue: low



Rated for 10 MWm^{-2}



Lore et al., Lumsdaine et al., IEEE Trans. Plasma Science (2014)

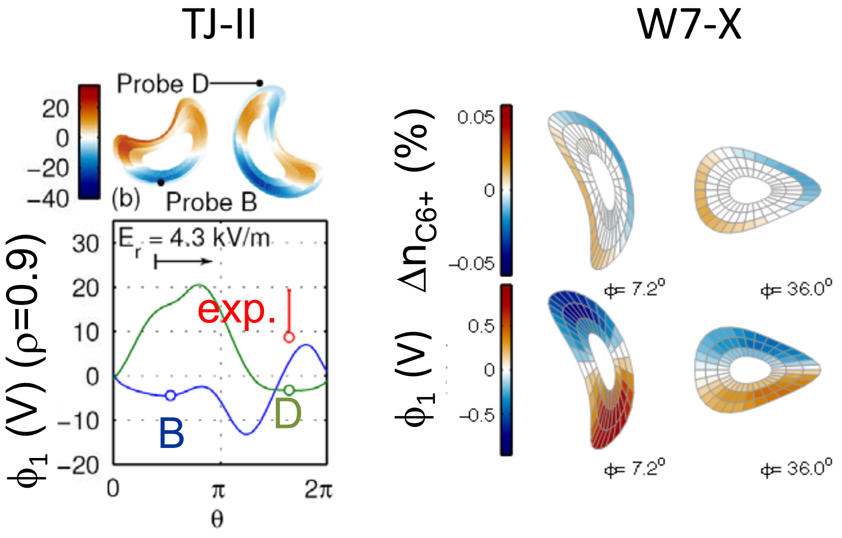
Risk of overload on the target plates:
Scraper elements: CFC monoblocks able to handle peak heat fluxes ≤ 15 MWm^{-2}:to protect overloaded areas intercepting part of the flux

Configurational flexibility: qualify scenarios & address physics topics

Prepare Operation Schemes for W7-X

OP1.2

Efficacy through targeted scenario preparation and validation of theory



Simulations of potential variations ϕ_1 experimental value (red, TJ-II) and resulting C6+ density variations (W7-X), respectively. For low-density and temperature (6x10^{19}m^{-3}, 1 keV) W7-X predictied scenarios, variations exist but have a minor effect e.g. for diagnostics interpretation (C6+).

[1] Alonso et al., EPS2014

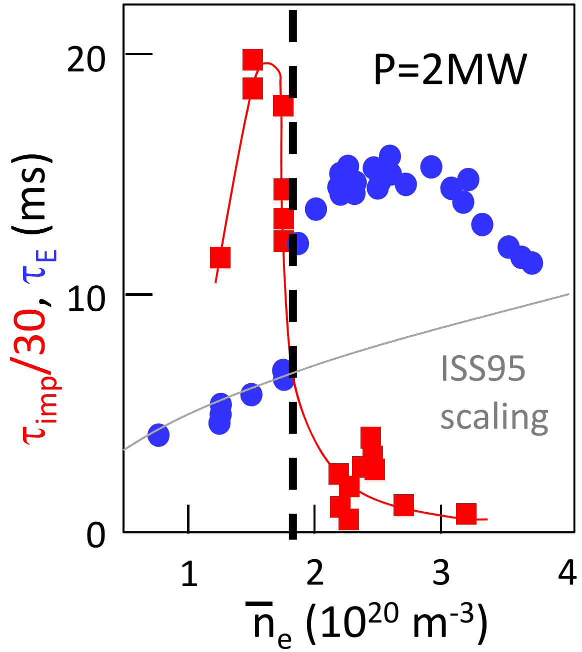
[2] Satake et al., EPS2014

- Context
  - Actions to prepare short experimental campaigns in fields of strategic impact:

    optimization and impurity transport
  - Long-term action towards a validated physics basis for a stellarator fusion power plant
- 2014 achievement
  - Experimental schemes
    - to assess in-flux-surface potential variation ϕ_1[1]
    - to investigate the interplay of neoclassical and turbulent transport
  - validation of non-local effects (ISHPDB)[2]
- 2015 Outlook & Prospects
  - Continue scheme development (impurity transport, turbulence).
  - Broaden stellarator reactor basis
  - Fuelling and density control assessments.

Impurities, improved confinement

Improved Confinement Modes:
High-Density H-mode transition in W7-AS



McCormick et al., PRL (2002)

avoidance of impurity accumulation:

employ the interplay of transport, sources (SOL), and improved operation modes

Safety Diagnostics & Control

freedom in OP1.2 to prepare high-power divertor operation …

… prepare safe steady-state operation

Heating

at moderate densities: small ECCD (some 10kA) for configuration adjustments

at high-densities: transition from X2- to O2- heating

… provide means for high-density operation / configuration control

Fuelling and Density Control

avoid core depletion by 3D transport (thermodiffusion)

… qualify fuelling schemes

… control core and separatrix density

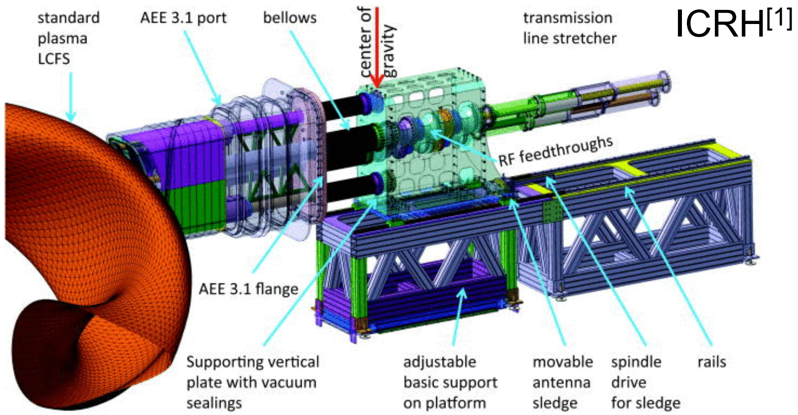
Divertor operation schemes

→ mitigation of operation risks with water-cooled PFCs (OP2)

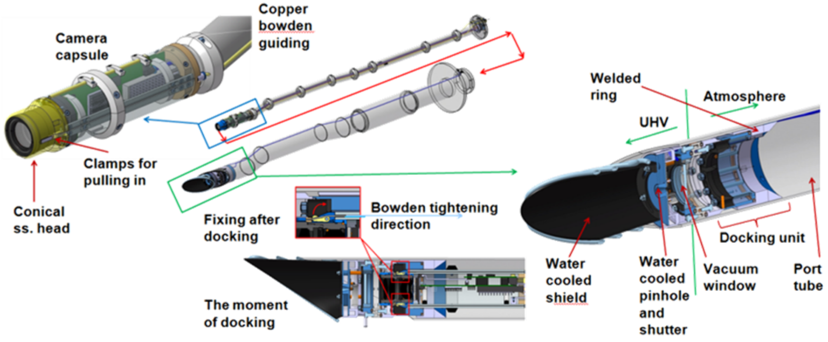
Diagnostics and Components for W7-X

Materializing European Expertise for W7-X: Hardware deliveries for OP1.1

Examples for hardware developments for W7-X


ICRH[1]

Video Surveillance[2]

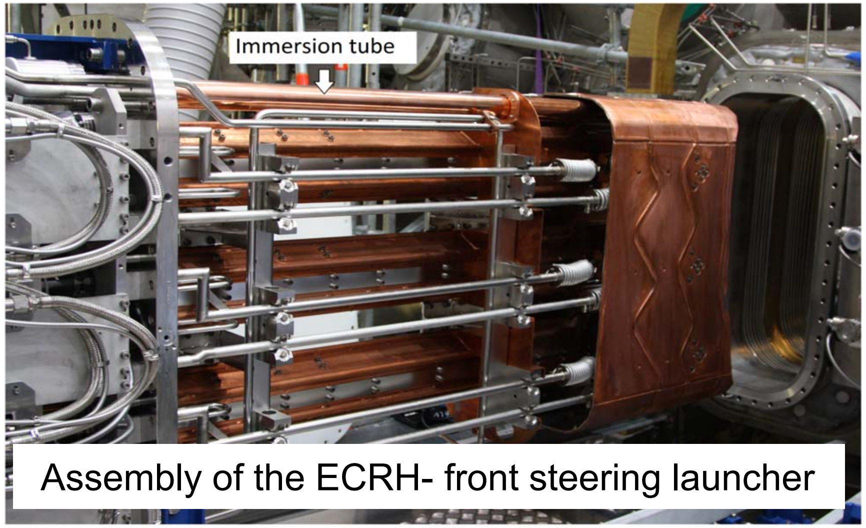


[1] Ongena et al., PoP 2014
[2] Kocsis et al., SOFT2014
[3] Kubkowska et al., EPS-DC2015
[4] König et al., EPS_DC2015

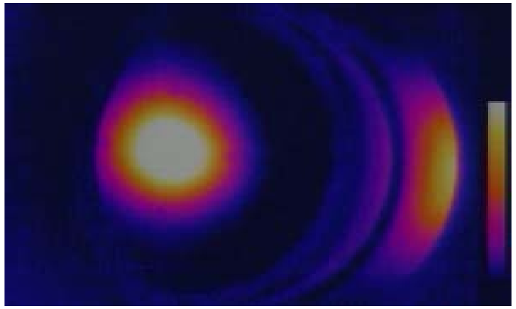
- Context
  - Prepare the European exploitation of W7-X by hardware contributions, support actions and dedicated software developments[4]
  - Focus on fields of strategic interest for bringing the HELIAS line to maturity
- 2014 achievement
  - Diagnostics and Heating hardware prepared under delivery and installation
  - V-band reflectometry, video, imaging software, PHA [3], XICS channel ready for OP1.1.
  - X-ray diagnostics, ICRH underway
  - Enhancement projects launched
- 2015 Outlook & Prospects
  - Operation in OP1.1
  - Enhancement Projects being implemented
  - Feasibility studies being continued

Steady-state heating: ECH on W7-X

EC heating for W7-X: routine operation and tool for physics program



Assembly of the ECRH- front steering launcher



IR Picture of ECRH-beam at a target at the PV-window

launcher (in-vessel view)

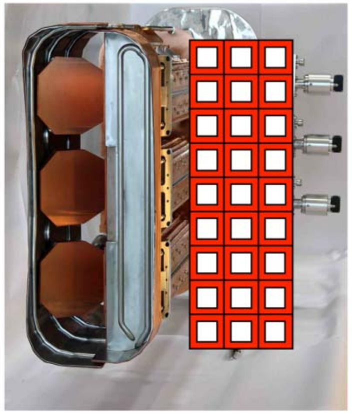
- ECRH Program (in OP1.1)
  - Reliable and routine plasma start-up from day one (incl. break-down)
  - Reliable and routine plasma heating and current drive with X2 mode ($n_e<1.2\times10^{20}\ \mathrm{m}^{-3}$).
  - High density plasma heating with O2 mode ($1\times10^{20}\ \mathrm{m}^{-3} < n_e < 2.4\times10^{20}\ \mathrm{m}^{-3}$)
  - CW operation with X2 and O2.
  - Wall conditioning.
  - Heat wave generation for transport studies.
  - Pressure profile shaping by off-axis heating.
  - Iota profile shaping by local current drive.
  - Edge iota and divertor strike line position control.
  - Impurity control.
  - Fast ion diagnostic CTS

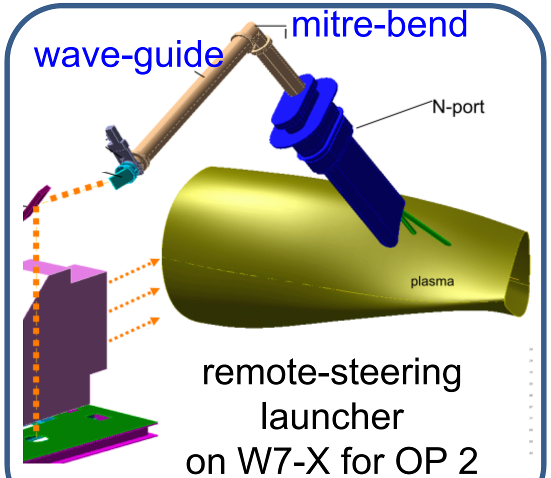
Erckmann FST 2007
Laqua

Steady-state heating: ECH options for FPPs

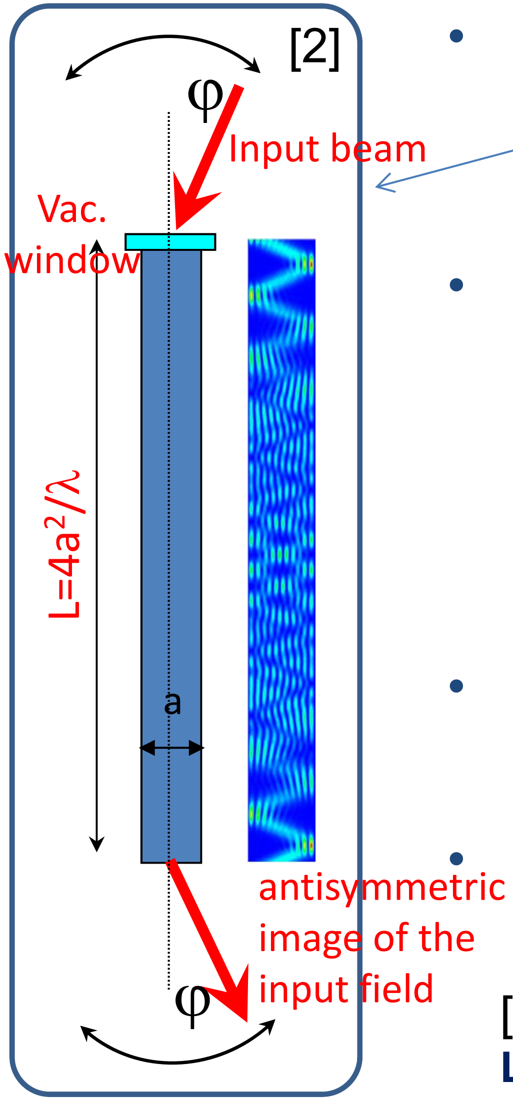
Option for cw-EC heating in harsh environments: remote-steering

W7-X front steering (left) and rem. steer. launcher (to scale)





remote-steering launcher on W7-X for OP 2



- Concept
  - optimized corrugated waveguide[1]: launcher to transform steered beam **outside** the plasma vessel
- Pros
  - compact & high power density (100 MW/m2)
  - much enhanced RAMI avoiding complicated mechanics of fast movable mirrors
  - neutron screening possible (mitre-bend)
- Cons
  - Reduced steering range (<20°)
  - Reduced focusing
- **W7-X**
  - R&D for 1MW cw for OP2
  - High-field side launch

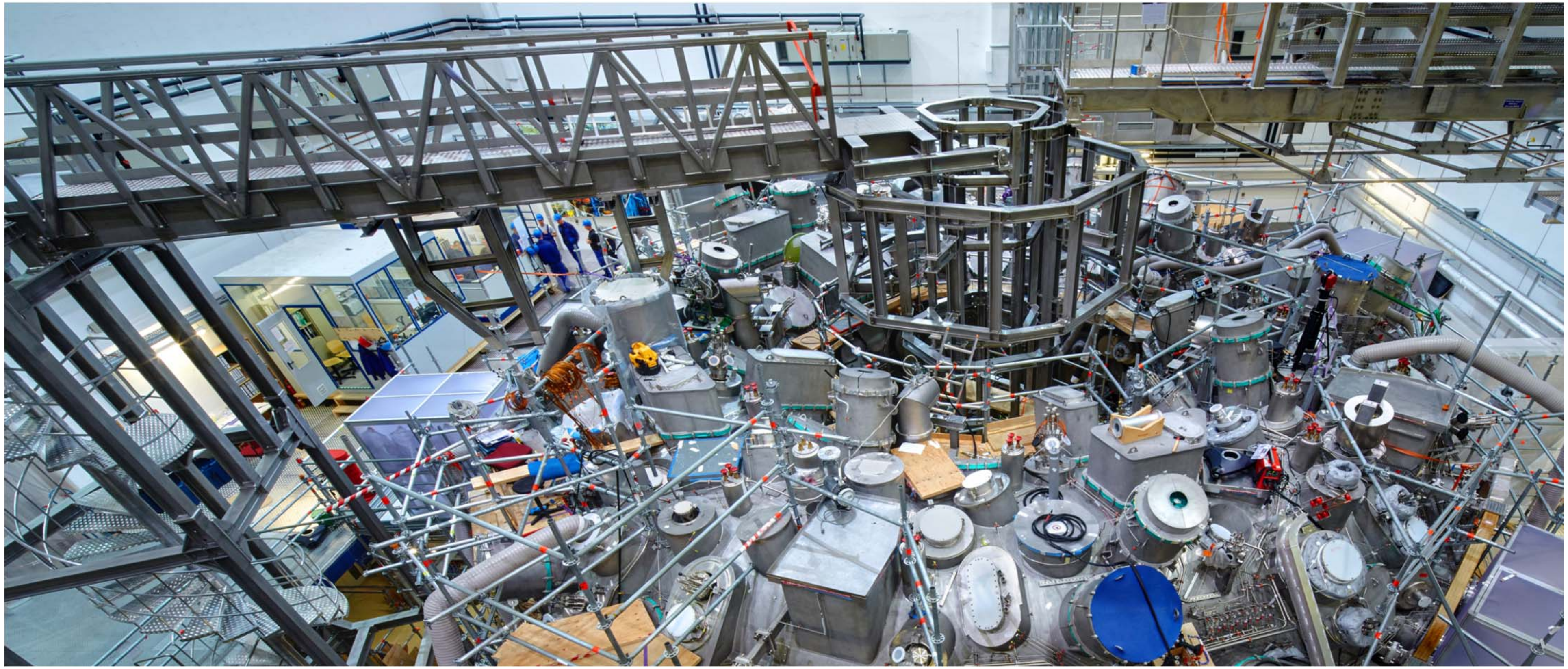
[1] Prater (1997), Kasparek (2003), Laqua, Plaum

OP1.1 is just around the corner...

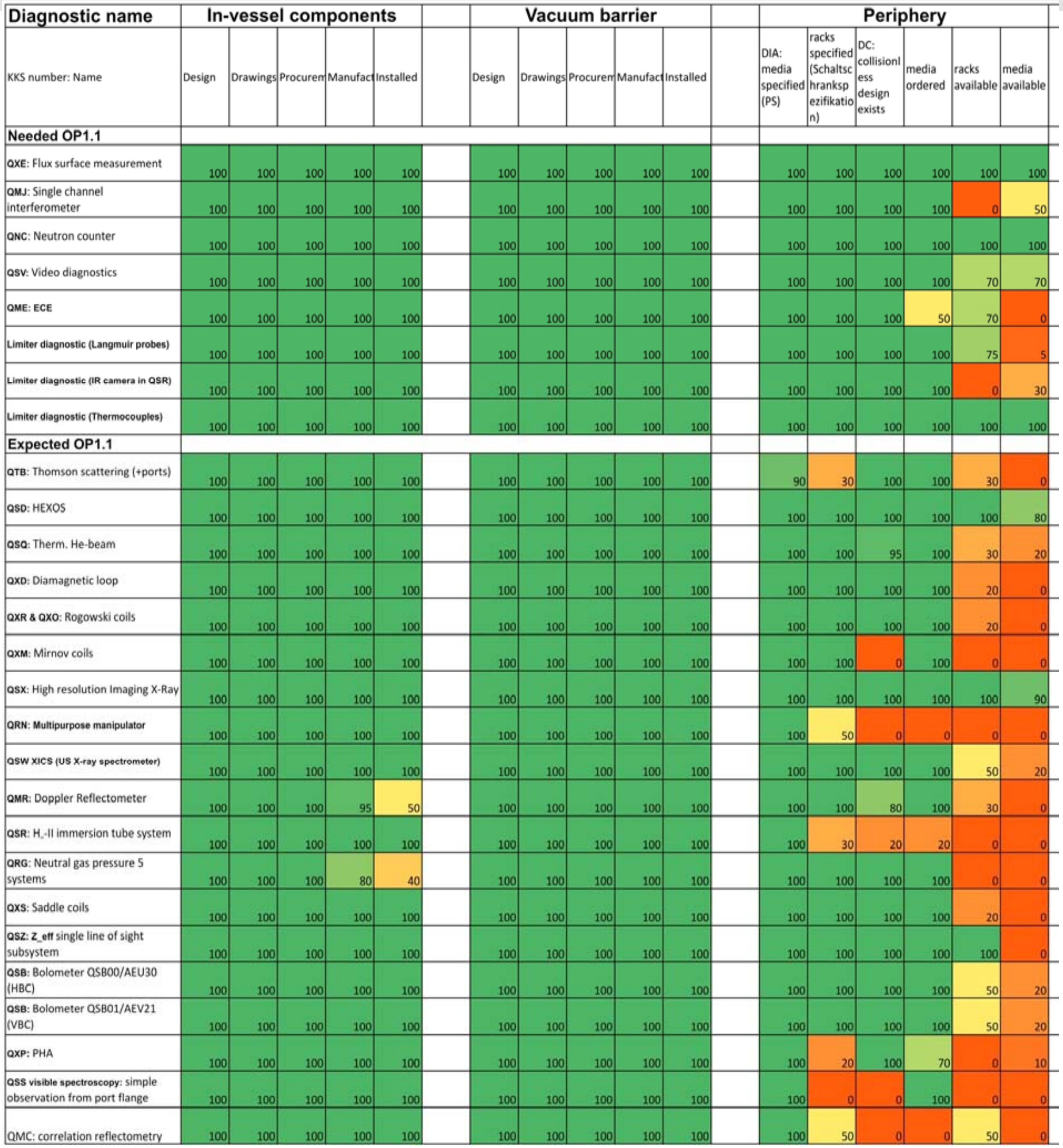
EUROfusion Call for Participation (Apr. 7th). Missions being decided

Three experimental areas:

- Scenario development: safe operation and pulse extension
- ECH Physics
- Scrape-Off Layer Physics



Overview of diagnostic status



Diagnostic name	In-vessel components						Vacuum barrier						Periphery					
KKS number: Name	Design	Drawings	Procurem	Manufact	Installed		Design	Drawings	Procurem	Manufact	Installed		DIA: media specified (PS)	racks specified (Schaltschrankspezifikation)	DC: collisionless design exists	media ordered	racks available	media available
Needed OP1.1																		
QXE: Flux surface measurement	100	100	100	100	100		100	100	100	100	100		100	100	100	100	100	100
QMJ: Single channel interferometer	100	100	100	100	100		100	100	100	100	100		100	100	100	100	0	50
QNC: Neutron counter	100	100	100	100	100		100	100	100	100	100		100	100	100	100	100	100
QSV: Video diagnostics	100	100	100	100	100		100	100	100	100	100		100	100	100	100	70	70
QME: ECE	100	100	100	100	100		100	100	100	100	100		100	100	100	50	70	0
Limiter diagnostic (Langmuir probes)	100	100	100	100	100		100	100	100	100	100		100	100	100	100	75	5
Limiter diagnostic (IR camera in QSR)	100	100	100	100	100		100	100	100	100	100		100	100	100	100	0	30
Limiter diagnostic (Thermocouples)	100	100	100	100	100		100	100	100	100	100		100	100	100	100	100	100
Expected OP1.1																		
QTB: Thomson scattering (+ports)	100	100	100	100	100		100	100	100	100	100		90	30	100	100	30	0
QSD: HEXOS	100	100	100	100	100		100	100	100	100	100		100	100	100	100	100	80
QSQ: Therm. He-beam	100	100	100	100	100		100	100	100	100	100		100	100	95	100	30	20
QXD: Diamagnetic loop	100	100	100	100	100		100	100	100	100	100		100	100	100	100	20	0
QXR & QXO: Rogowski coils	100	100	100	100	100		100	100	100	100	100		100	100	100	100	20	0
QXM: Mirnov coils	100	100	100	100	100		100	100	100	100	100		100	100	0	100	0	0
QSX: High resolution Imaging X-Ray	100	100	100	100	100		100	100	100	100	100		100	100	100	100	100	90
QRN: Multipurpose manipulator	100	100	100	100	100		100	100	100	100	100		100	50	0	0	0	0
QSW XICS (US X-ray spectrometer)	100	100	100	100	100		100	100	100	100	100		100	100	100	100	50	20
QMR: Doppler Reflectometer	100	100	100	95	50		100	100	100	100	100		100	100	80	100	30	0
QSR: H_α-II immersion tube system	100	100	100	100	100		100	100	100	100	100		100	30	20	20	0	0
QRG: Neutral gas pressure 5 systems	100	100	100	80	40		100	100	100	100	100		100	100	100	100	0	0
QXS: Saddle coils	100	100	100	100	100		100	100	100	100	100		100	100	100	100	20	0
QSZ: Z_eff single line of sight subsystem	100	100	100	100	100		100	100	100	100	100		100	100	100	100	100	0
QSB: Bolometer QSB00/AEU30 (HBC)	100	100	100	100	100		100	100	100	100	100		100	100	100	100	50	20
QSB: Bolometer QSB01/AEV21 (VBC)	100	100	100	100	100		100	100	100	100	100		100	100	100	100	50	20
QXP: PHA	100	100	100	100	100		100	100	100	100	100		100	20	100	70	0	10
QSS visible spectroscopy: simple observation from port flange	100	100	100	100	100		100	100	100	100	100		100	0	0	100	0	0
QMC: correlation reflectometry	100	100	100	100	100		100	100	100	100	100		100	50	0	0	50	0

Summary

Wendelstein 7-X in the EU Roadmap

- **achieve steady-state, high-$nT_i t_E$ plasmas**
- **gain predictive capabilites in view of burning 3D plasmas**

Maturity: demonstrate favorable operation + validated capabilities

First Operation Phases (pulsed, lower power):

- **qualify safe divertor & develop steady-state scenarios**
- **start to address the physics of optimization**

prepare steady-state operation

EUROfusion Research Strategy

- **address high-priority fields in view of Mission 8**

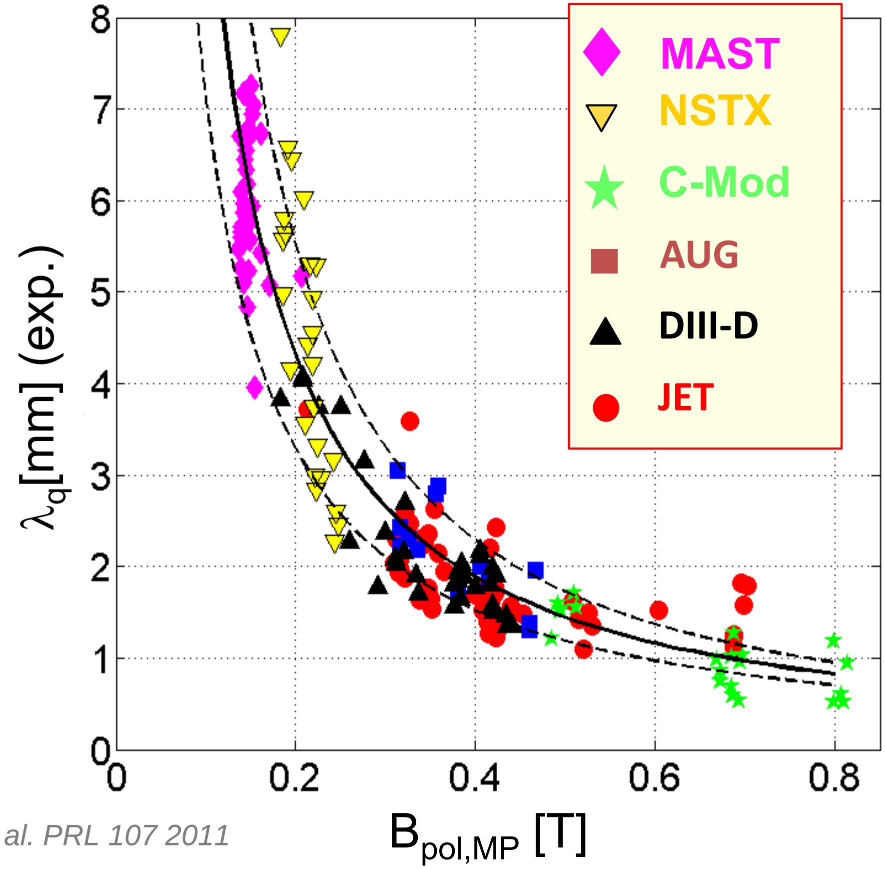
optimization, steady-state/divertor, impurities, fast particles, density control, turbulence

2015: preparatory actions & 1st W7-X plasma operation
to qualify steady-state capabilities

Back-up slides

Why SOL and λ_q studies are important

•The width of the heat deposition region, λ_q, scales with $1/B_p$ in tokamaks , and NOT with machine size, leading to a prediction of $\lambda_q \leq 1$ mm for ITER and DEMO (problematic).



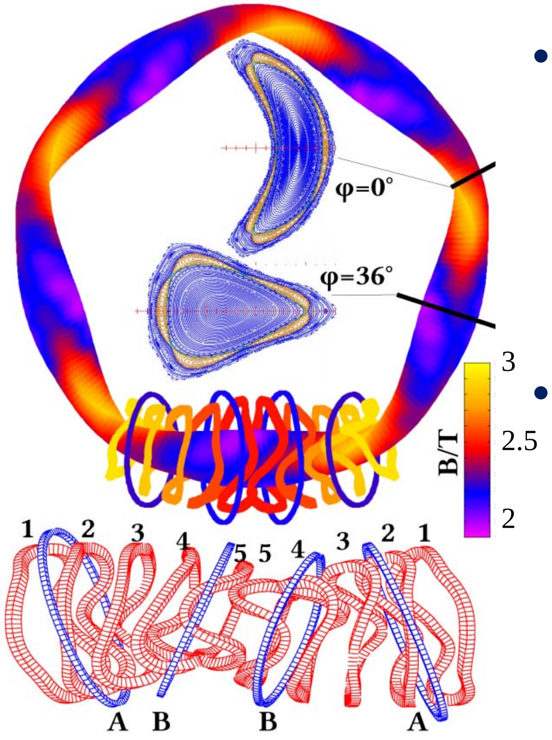
T. Eich et al. PRL 107 2011

- Heuristic model:
  Goldston, Nucl. Fusion 52 013009 (2012)
  - $\lambda_q \sim L_c * v_D$
  - In tokamaks, L is proportional to $1/B_p$ leading to B_p scaling
  - In a stellarator, L_c is not related to B_p but to the inclination of the divertor respect to the field lines
  - Limiter operation gives data points at L_c ~30-80 m
  - Divertor operation will give data at L_c ~100-500 m

Predictive Modelling for W7-X

OP1.2

Navigating the configuration space of optimized stellarators



5MW O2
1.5x10^{20}m^{-3}

mod B on last closed flux surface + vacuum edge magnetic field

individually charged coils

coil set for one W7-X module

Specific high-mirror configurations to minimize residual bootstrap currents with good confinement properties and edge magnetic field (divertor)[1]

[1] Geiger et al., EPS2014, PPCF 2015

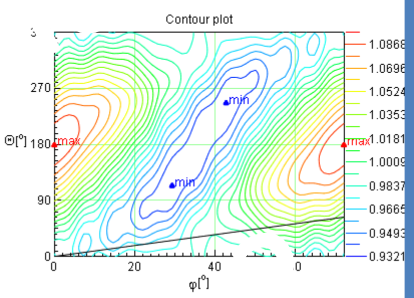
[2] Sunn-Pedersen et al., EPS 2014

[3] Dinklage et al., IAEA 2014

- Context
  - goal: steady-state operation of optimized stellarators @ high-β, low-ν^*, low-ρ^*
  - qualify safe SS divertor operation with robust PFCs (uncooled test-divertor)
- 2014 achievement
  - target configuration (core plasma) low-bootstrap current/good confinement for high-density operation identified
  - OP1.1[2] and OP1.2[3] experiment strategies
- 2015 Outlook & Prospects
  - Integration core/SOL plasma
  - Broaden discharge scenarios port-folio
  - Employ modelling for interpretation (OP1.1.)

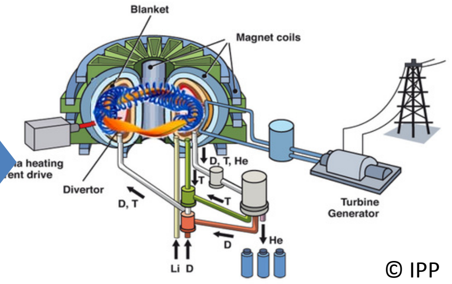
W7-X in the Roadmap

Mission 8: bring the HELIAS line to maturity



- proof optimization: NC, α, bs, stability, …
- qualify steady-state, high-performance operation
- gain predictive capabilities
- pursue optimization in line w/ findings

be ready for surprises!



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IPP Max-Planck-Institut

International Energy Agency

iea

…

WENDELSTEIN 7-X

Strategic benefit for Europe

- Flagship science project
- Synergies and risk mitigation in an integrated fusion road-map
- Physics and technological leadership in 3D MCF

W7-X within EUROfusion: Mission, high-level goals and research objectives

Mission 8 in the European Roadmap:
Bring the HELIAS line to maturity by
the exploration of *reactor capabilities of optimized stellarators* with W7-X

prepare the decision point: is an intermediate-step device (burning-plasma HELIAS) required?

WPS1: identify and implement experimental and theoretical actions in view of M8
Concept: theory driven experimental exploitation

- *3D configuration effects and optimization*
  - ⇒ demonstrate optimization targets:
    improved 3D confinement, MHD stab. (β=5%), beyond NC: 3D turbulence, …
  - develop plasma scenarios with theory models
    (and validate them in experiments to arrive at reliable predictive capabilities)

- *steady-state operation (high $nT\tau$, β, low $\nu*$, $\rho*$)*
  - ⇒ qualify heating, power exhaust & safe divertor operation
    (towards FPP IVCs, sufficient f_{rad})
  - steady-state operation elements: safety, control, cw heating (ECRH), diagnostics
  - demonstrate high-power, high-density steady-state discharges

WENDELSTEIN 7-X

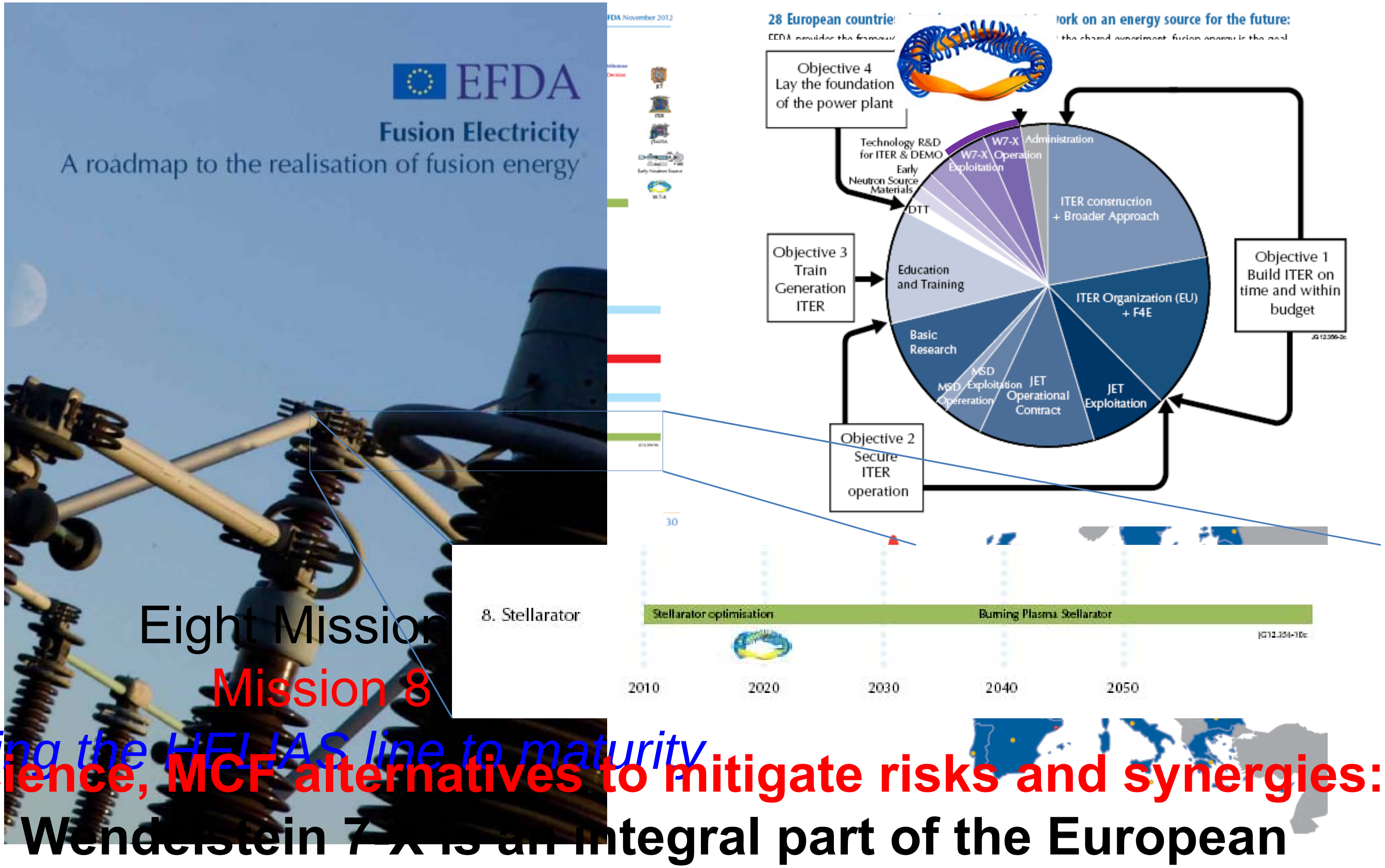
W7-X within EUROfusion:
high-level goals and research objectives

- *density control and fuelling*
  - ⇒ *develop concepts for high-density steady-state operation*
    develop fuelling techniques to avoid core density depletion
  - pellet, gas-puff (, SSMB, NI) fuelling: deposition mechnanisms
  - preparation of fuelling scenarios, e.g. high-field, low-field side 3D pellet fuelling
- *3D impurity transport*
  - ⇒ develop discharge scenarios without impurity accumulation
  - develop and validate models for high-Z 3D-trasnport
  - implement impurity transport related diagnostics (passive spectr., active LBO)
- *3D fast particle physics*
  - ⇒ *develop predicitive tools for fast particle confinement in 3D fields*
  - generation (NBI, ICRH), diagnostics and validated models
  - predictive capabilities for fast particle confinement and collective effects
- *turbulence, improved confinement modes and isotope effect*
  - ⇒ develop and explore confinement beyond neoclassical transport
  - study the interplay of turbulence , magnetic geometry and E_r (TJ-II, LHD, …)
  - develop predicitve theory for 3D turbulence

\+ *synergies w/ M1-7: support actions (ITER, DEMO), preparation of FPP physics basis*

Priorities: high-level objectives in view of M8, EU expertise,
anticipated impact on W7-X program

Europe and W7-X/W7-X and Europe



Eight Missions

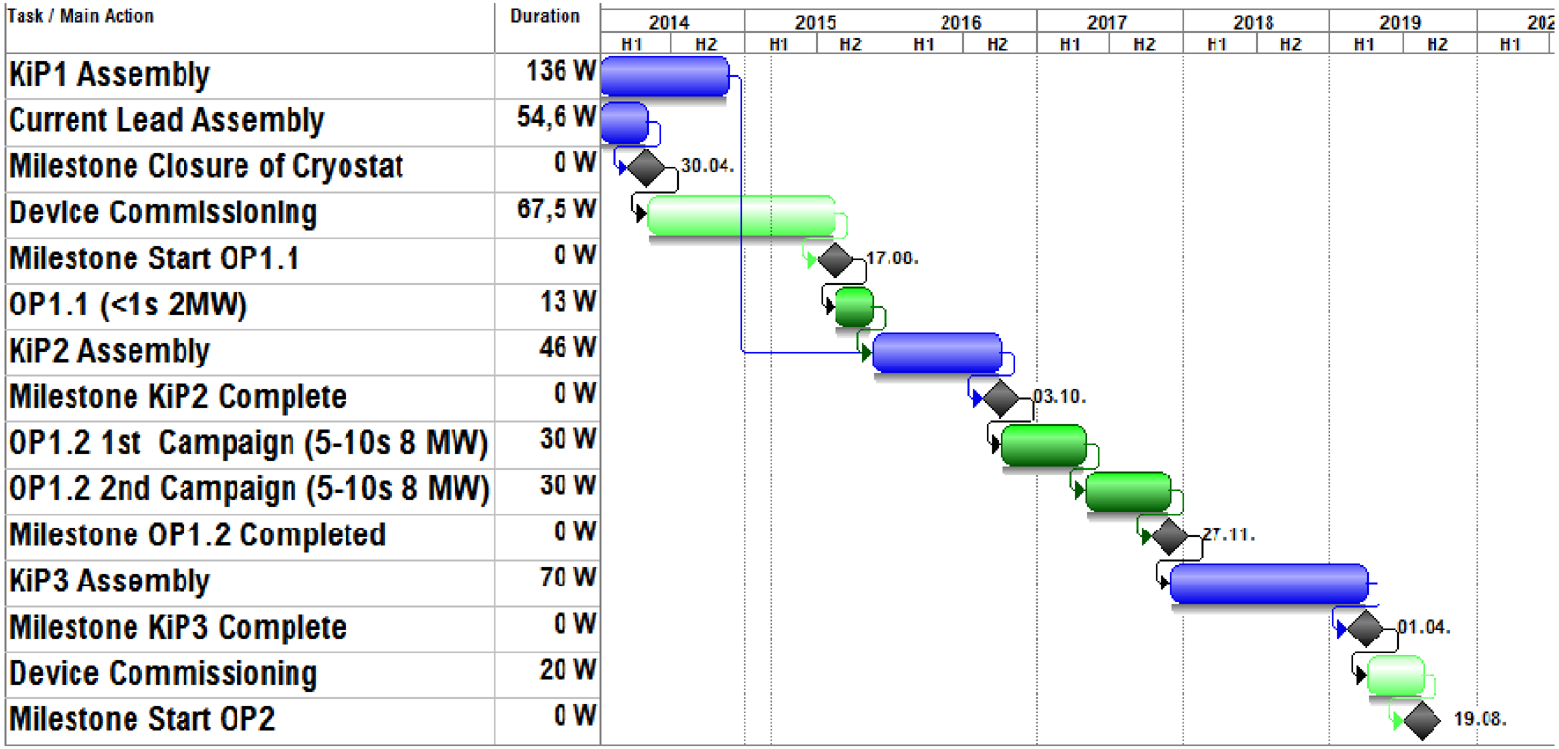
Mission 8

Bring the HELIAS line to maturity

Science, MCF alternatives to mitigate risks and synergies:

Wendelstein 7-X is an integral part of the European fusion development strategy.

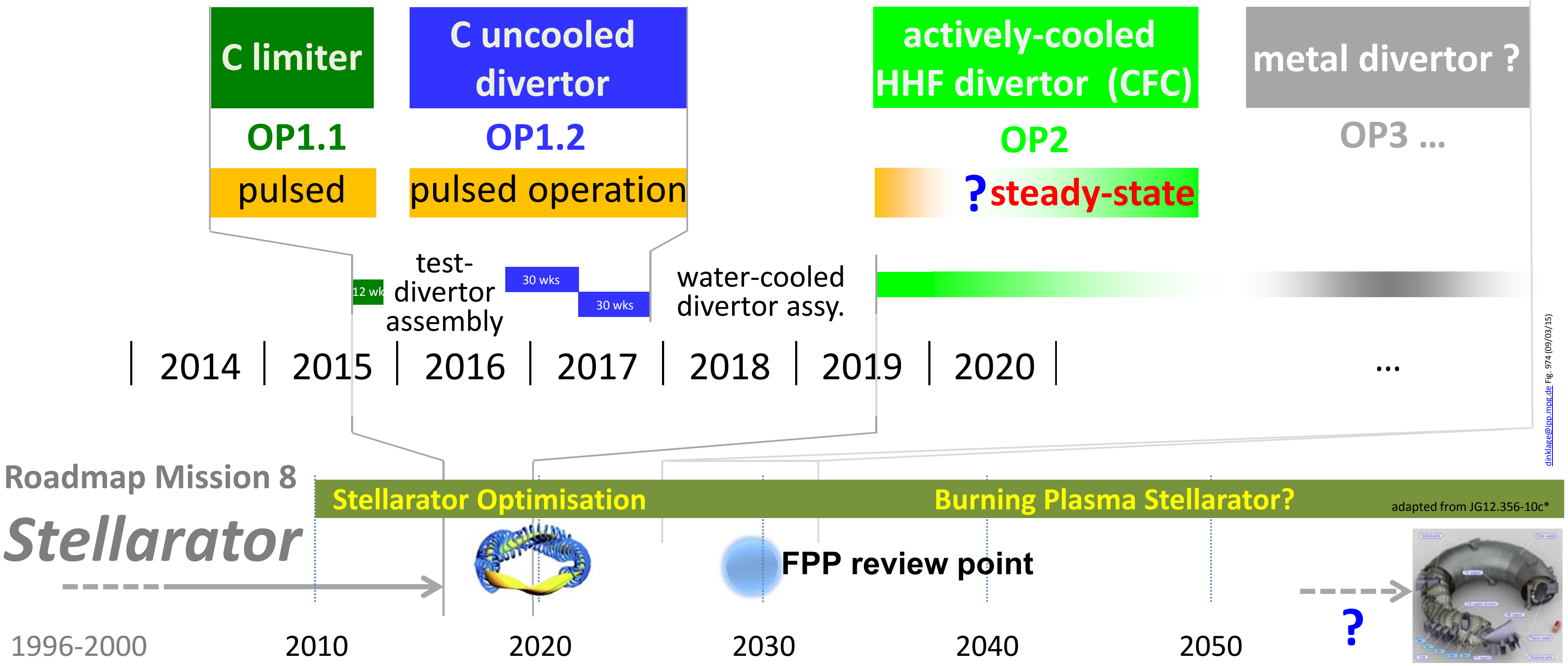
http://www.efda.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf?5c1bd2



Task / Main Action	Duration
KiP1 Assembly	136 W
Current Lead Assembly	54,6 W
Milestone Closure of Cryostat	0 W
Device Commissioning	67,5 W
Milestone Start OP1.1	0 W
OP1.1 (<1s 2MW)	13 W
KiP2 Assembly	46 W
Milestone KiP2 Complete	0 W
OP1.2 1st Campaign (5-10s 8 MW)	30 W
OP1.2 2nd Campaign (5-10s 8 MW)	30 W
Milestone OP1.2 Completed	0 W
KiP3 Assembly	70 W
Milestone KiP3 Complete	0 W
Device Commissioning	20 W
Milestone Start OP2	0 W

A possible time-line

PFC-technology shapes the way to reliable, steady-state, high –$nT\tau_E$ operation



C limiter

OP1.1

pulsed

C uncooled divertor

OP1.2

pulsed operation

actively-cooled HHF divertor (CFC)

OP2

? steady-state

metal divertor ?

OP3 …

12 wk

test-divertor assembly

30 wks

30 wks

water-cooled divertor assy.

| 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | …

dinklage@ipp.mpg.de Fig. 974 (09/03/15)

Roadmap Mission 8

Stellarator

Stellarator Optimisation

Burning Plasma Stellarator?

adapted from JG12.356-10c*

FPP review point

?

1996-2000 2010 2020 2030 2040 2050

Primary target of OP1: preparation for the actively cooled (SSO) divertor

Long term goal: Basis for a HELIAS FPP

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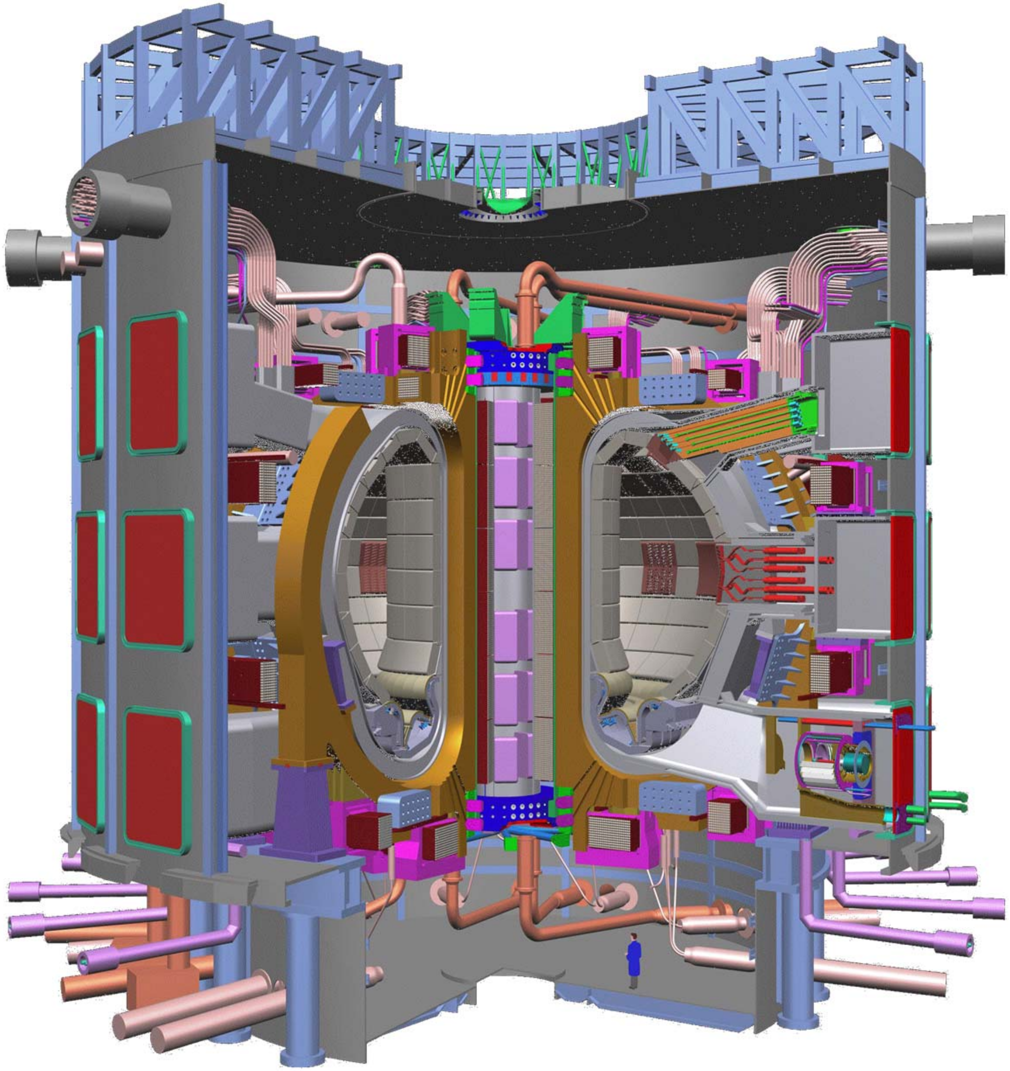
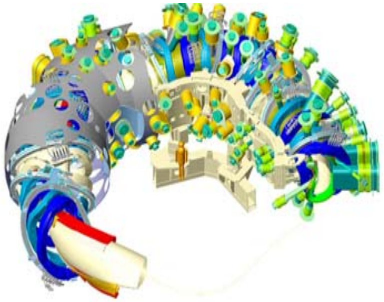
* *from: Fusion Electricity: A roadmap to the realisation of fusion energy (F. Romanelli et al., EFDA, 2012)*

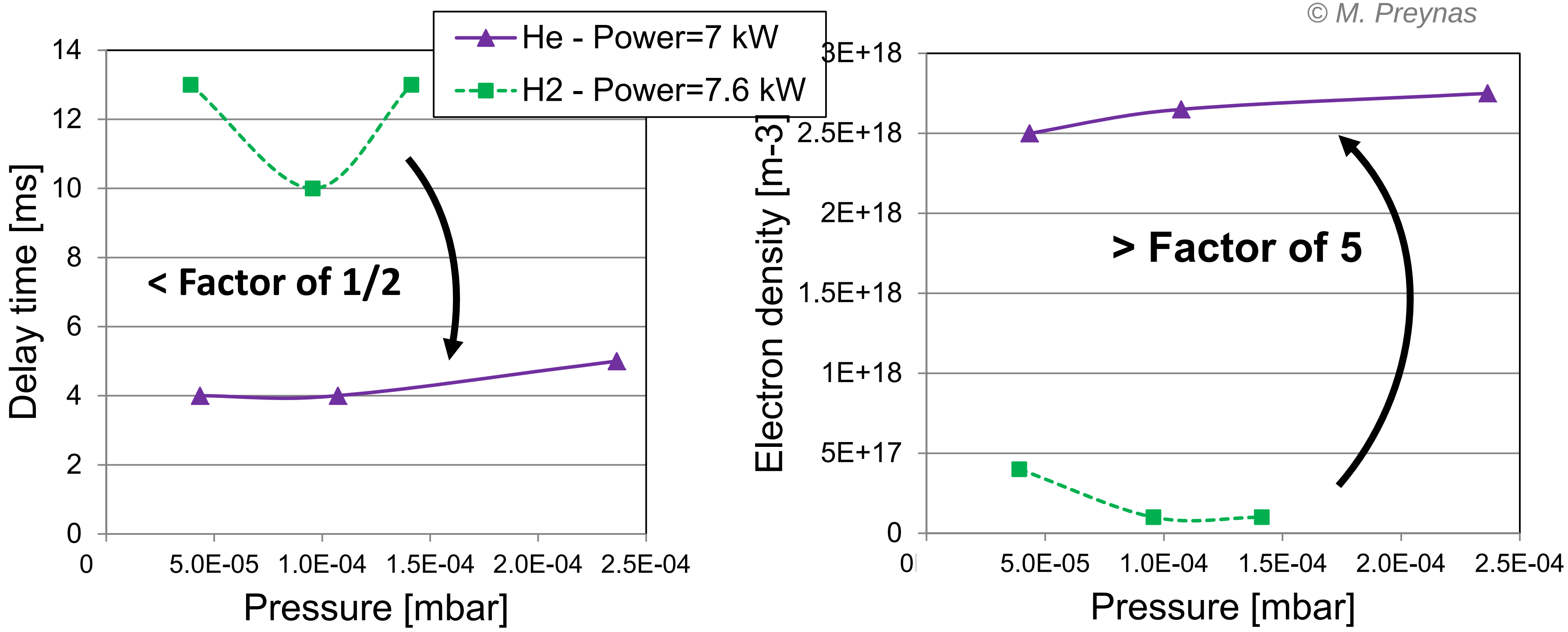
2D/3D MCF





Plasma start up: why helium?

empirical finding in WEGA (in line with Heliotron-J, LHD)



© M. Preynas

- Breakdown easier in He than H
  - NBI start-up model: no dissociative processes +lower vibrational cooling[1]
- Discharges serve to condition the machine

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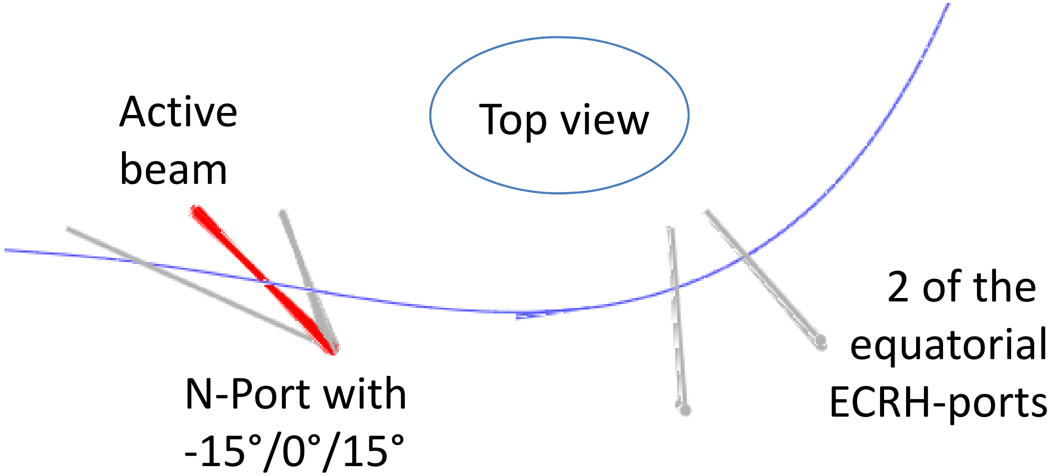
[1] *Gradic et al., Nucl. Fusion* ***55****, 033002 (2015)*

Steady-state heating: ECH options for FPPs



Active beam

2 of the equatorial ECRH-ports

N-Port with -15°/0°/15°