The Initial Program of W7-X on the Way to a HELIAS Fusion Power Plant

A. Dinklage[1,*], R. König[1,*], H. Maaßberg[1,*], T. Sunn Pedersen[1,*], F. Warmer[1], R. Wolf[1], A. Alonso[2,*], E. Ascasibar[2,*], J. Baldzuhn[1], C.D. Beidler[1,*], C. Biedermann[1], H.-S. Bosch[1], R. Brakel[1], S. Bozhenkov[1], S. Brezinsek[3], R. Burhenn[1], I. Calvo[2], F. Castejon[2], M. Drevlak[1], V. Erckmann[1], F. Effenberg[4], T. Estrada[2,*], Y. Feng[1,*], J. García-Regaña[1], D. Gates[5], J. Geiger[1,*], O. Grulke[1], D. Hartmann[1], P. Helander[1], C. Hidalgo[2,*], M. Hirsch[1], H. Hölbe[1], W. Kernbichler[6,*], R. Kleiber[1], T. Klinger[1], A. Könies[1], A. Krämer-Flecken[3], M. Jakubowski[1], G. Kocsis[7,*], M. Kubkowska[8,*], H. Laqua[1], M. Laux[1], Y. Liang[3], J. Lore[13], O. Marchuk[3,*], N. Marushchenko[1,*], P. McNeely[1], A. Mishchenko[1], V. Moncada[9,*], O. Neubauer[3,*], J. Ongena[10,*], M. Otte[1], N. Pablant[5], M. Preynas[1], E. Puiatti[11], M. Rack[3], J. Riemann[1], N. Rust[1], F. Schauer[1], O. Schmitz[4], H. Smith[1], T. Stange[1], T. Szepesi[7,*], H. Thomsen[1], J. Travere[9,*], Y. Turkin[1,*], J.-L. Velasco[2,*], A. Werner[1], P. Xanthopoulos[1], K. Tanaka[12], K. Ida[12], S. Kubo[12], R. Sakamoto[12], H.Yamada[12], M. Yokoyama[12], M. Yoshinuma[12] and

The W7-X Team[1,+], The TJ-II Team[2], The LHD-Experiment Team[12]

[1]Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
[2]CIEMAT, Madrid, Spain
[3]Forschungszentrum Jülich, Jülich, Germany
[4]U Wisconsin, Madison WI, USA
[5]Princeton Plasma Physics Laboratory, Princeton NJ, USA
[6]Technische Universität Graz, Graz, Austria
[7]Wigner Institute, Budapest, Hungary
[8]IPPLM, Warsaw, Poland
[9]CEA/IRFM, Cadarache, France
[10]ERM-KMS, Brussels, Belgium
[11]Consorzio RFX, Padova, Italy
[12] NIFS, Toki, Japan
[13]ORNL, Oak Ridge, TN, USA
**EUROfusion Contributor (WPS1/S2)*

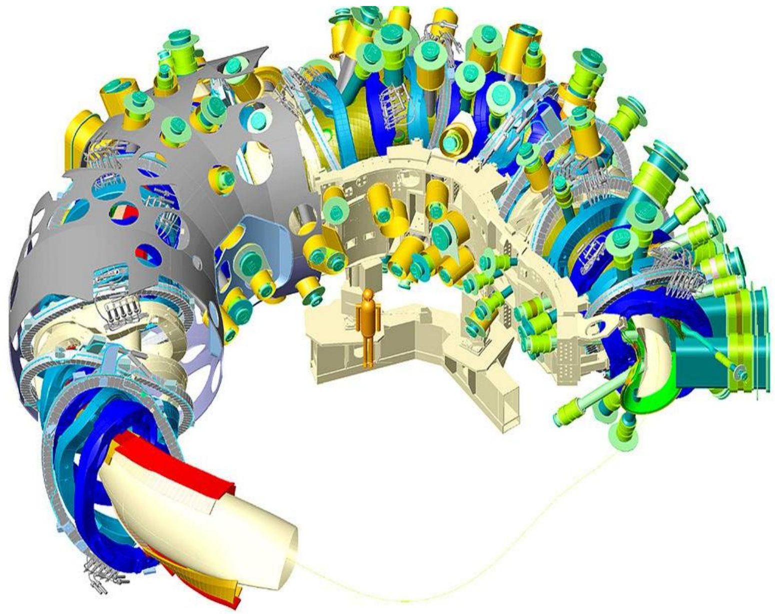
[+]*cf. authors of Bosch, et al. Nucl. Fusion* ***53****, 126001 (2013)*

Outline

- **Stellarators**
- **Towards a HELIAS Fusion Power Plant**
- **Wendelstein 7-X**
- **First Operation Phases (OP)**
- **Programmatic priorities**
- **Summary**

Wendelstein 7-X

Greifswald (Germany) - being commissioned



HELIAS-type stellarator

- N_ϕ=5, R/a = 5.5m/0.53m
  → **30 m³ plasma volume**
- 50+20 **superconducting** coils (2.5T)
- ~8+7MW (**ECRH**, NBI) + ICRH (later upgrades)

Why stellarators[1]?

Stellarators:
the main alternative magnetic confinement concept to the tokamak.

external coils generate rotational transform: 3D-confinement w/o plasma current

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

- 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

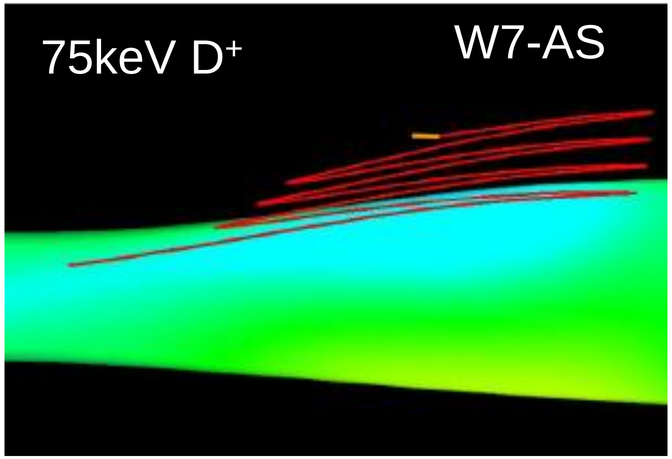
to pave the way to a Fusion Power Plant

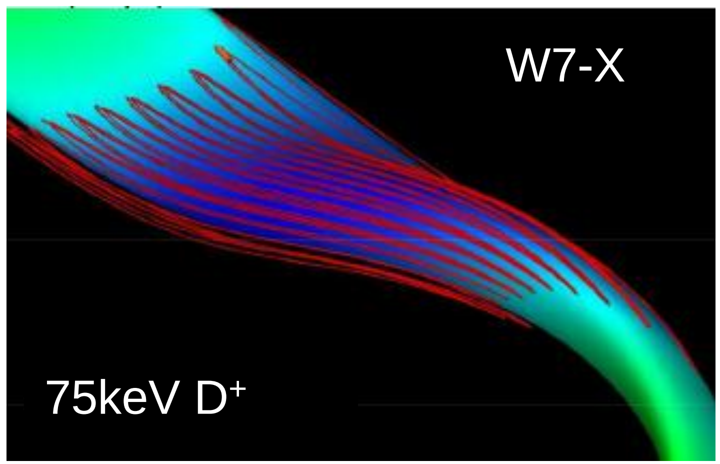
[1] *Helander, Rep. Prog. Phys.* ***77****, 0877001 (2014),* [2] *Nührenberg, Zille, Phys. Lett.* ***A 144****, 129 (1986)*

W7-X: Stellarator Optimization

HELIcal Axis Advanced Stellarator (Neoclassical Optimization)

taming locally trapped particles



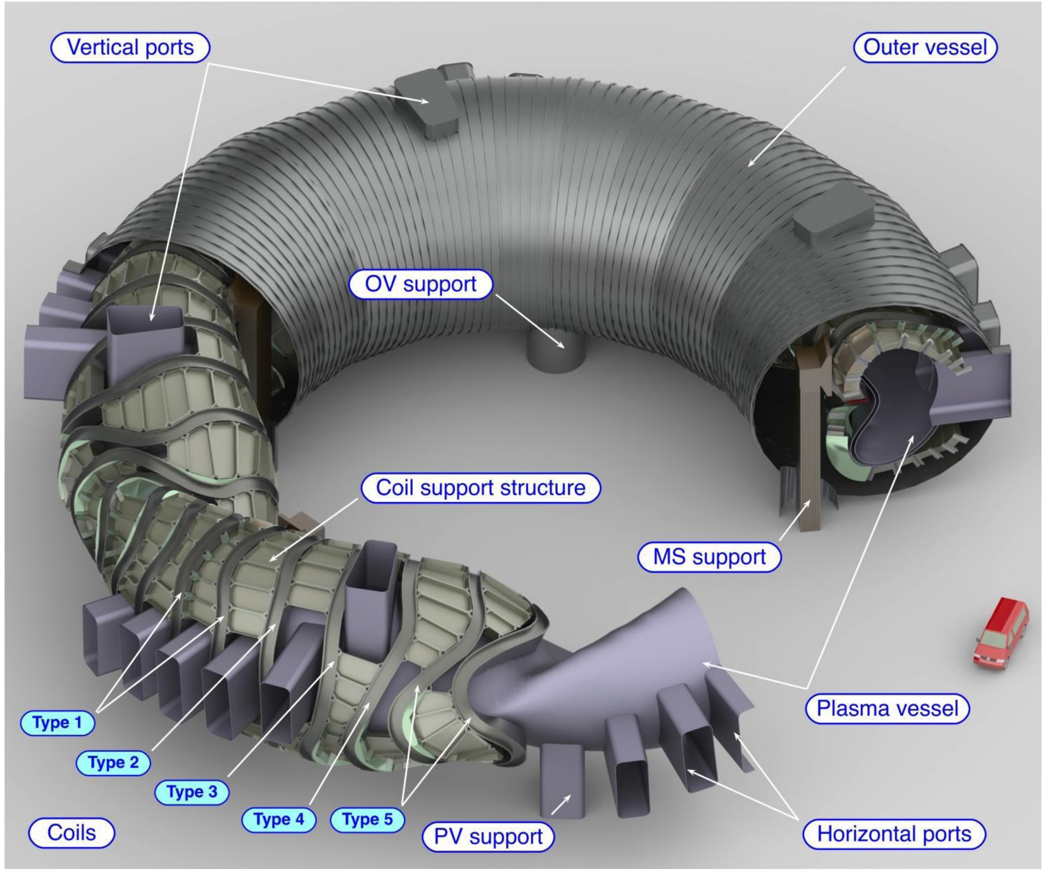


3D plasma physics

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

The Way to a HELIAS Reactor

Engineering Study HELIAS 5-B

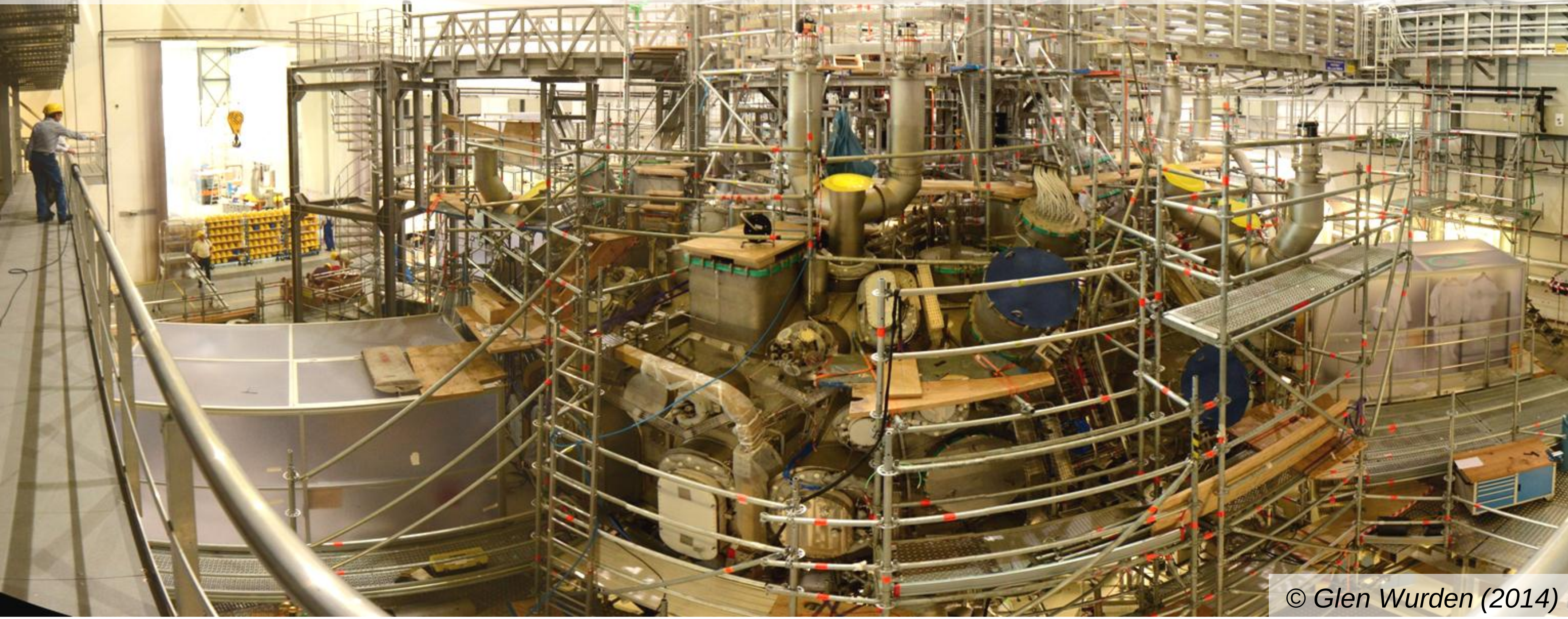


electro-mechanical feasibility of HELIAS fusion-power plants

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

Wendelstein 7-X: Status

Wendelstein 7-X Torus Hall (Greifswald, Germany, Aug. 2014)



- main-device assembly finished (May 2014) ✓
- device commissioning on track ✓
- **first plasma planned for summer 2015**

W7-X: First Operation Phases (OP) in Figures

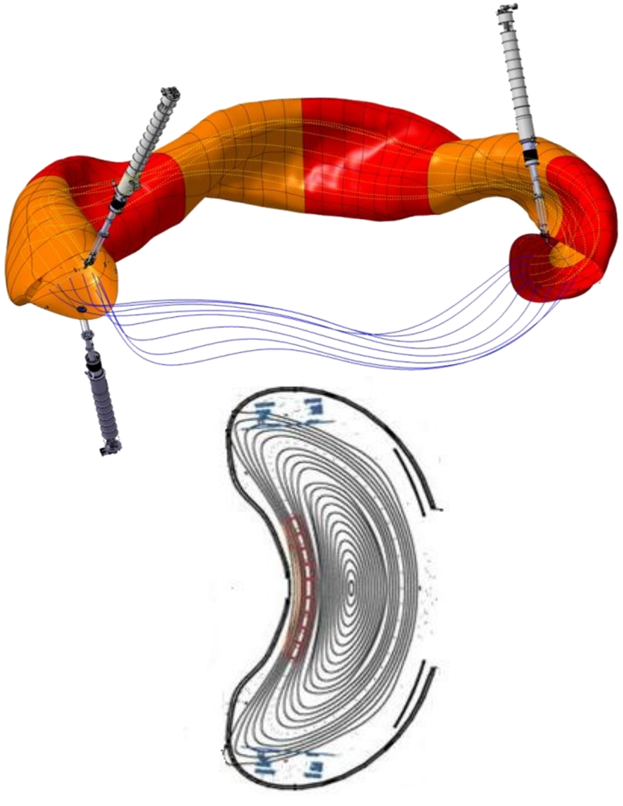
OP 1.1 **2015** 13 wks	**uncooled carbon limiter** He, (H) **pulse** limit: E_{max} < 2MJ $\tau_{Pulse} \lesssim 1$ s	**P_{ECRH} ~ 2 MW** (…5MW) gas puff surveillance diag. magnetics basic *n*, *T*, imp. Diagnostics	T_e^{NC} < 3.5 keV T_i^{NC} < 0.9 keV n < 2 x 10^{19} m^{-3} β_{ISS04} < 0.6% **β_{NC} < 1.6%**
OP 1.2(a) **2016** 29 wks	**uncooled test-divertor (C)** H, (D) **pulse** limit: E_{max} < 80 MJ $\tau_{Pulse} \lesssim 10$s … 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 x 10^{20} m^{-3} β_{ISS04} < 1.2% **β_{NC} < 3%**
OP 1.2(b) **2017** 29 wks	**test scraper element**	+ P_{ICRH} ~ 1.6 MW **$P_{tot} \lesssim 10$ MW** + blower gun + diagn. upgrades	
OP 2 **>2019**	**actively cooled divertor (CFC)** **steady-state capable** D, H technical limit: 30 min/10MW P_{target}/A < 10 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 x 10^{20} m^{-3} β_{ISS04} < 2 % **β_{NC} < 5 %**

OP1.1: the very first operation of W7-X

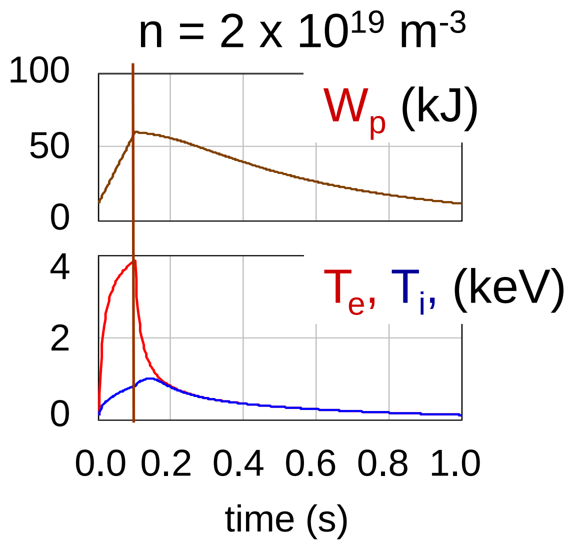
uncooled carbon limiter, He, (H), E_{max} < 2MJ

OP1.1 priorities: integral commissioning and first plasma operation

Vaccum flux-surface measurements



X2-heated plasmas



transport simulations predict high-T_e e-root feature

limiter heat loads: SOL physics

flux-surfaces/error-fields, first X2-heated plasma, limiter SOL

Sunn Pedersen et al., EPS Berlin (2014)

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

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

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-$nT\tau$/high-β@low-$\nu*$ …

2. **employ configurational flexibility**
   optimization

→ **arrange physics topics along these lines**

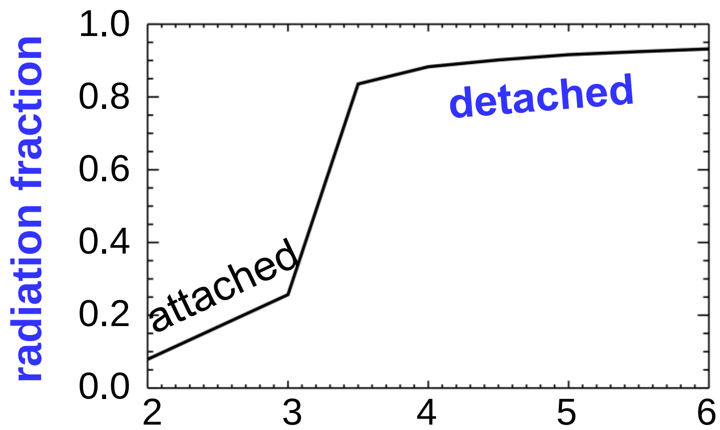
Guiding Principle 1: increase the density

towards safe divertor operation

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

EMC3/EIRENE simulations

detachment in stellarator divertor plasmas

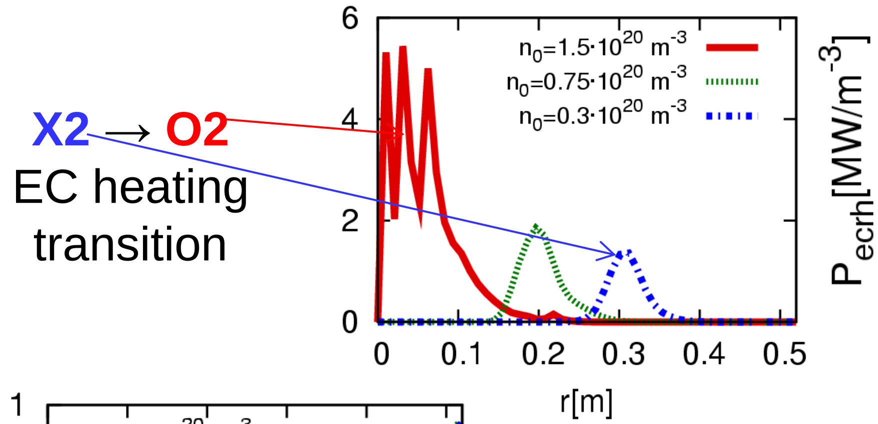


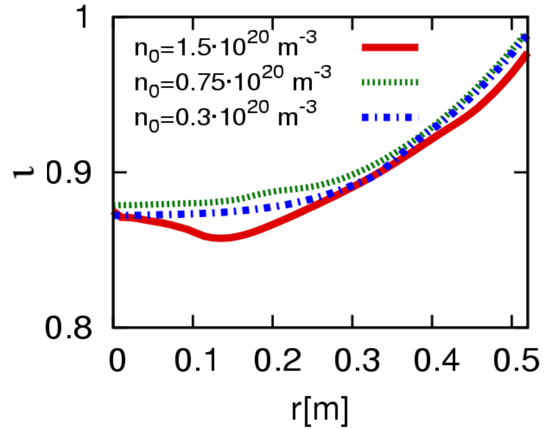
separatrix density (10^{19} m^{-3})

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

Y. Feng

plasma scenario development





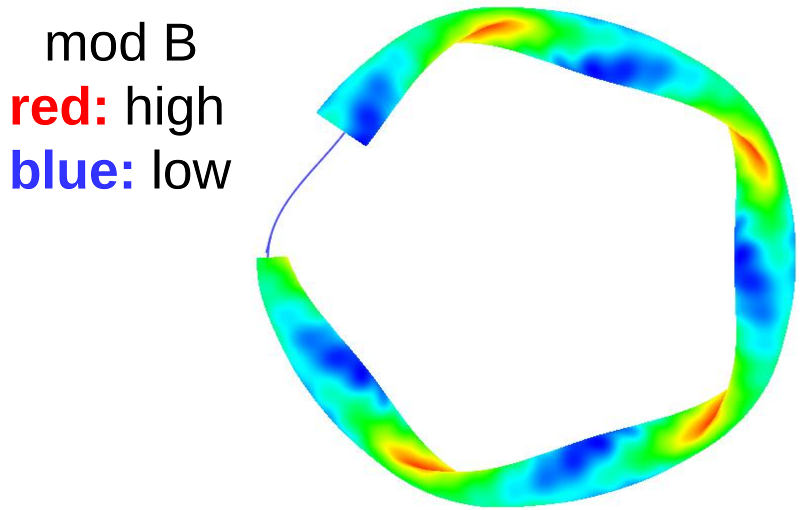
… with stable configuration

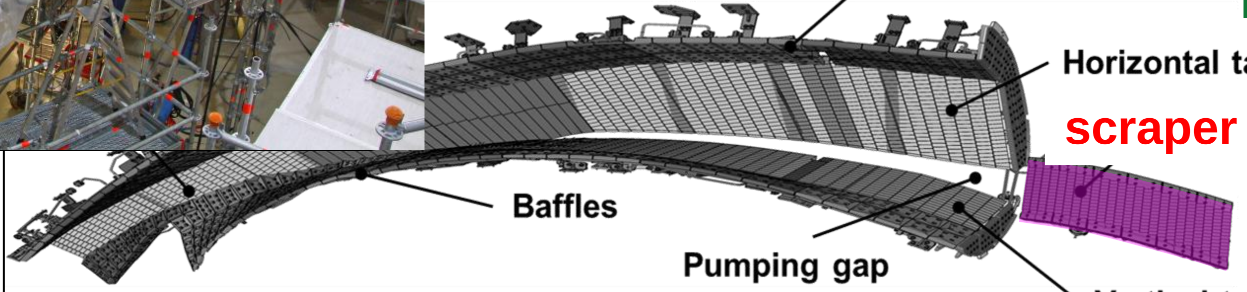
Geiger et al., PPCF (accepted, 2014)

Guiding Principle 2: exploit configuration space

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

Geiger et al., EPS 2014





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

Configurational flexibility: qualify scenarios & address physics topics

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

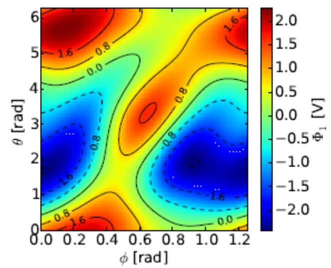
→ mitigation of operation risks with water-cooled PFCs (OP2)

High Priority Physics Topics for OP 1.2

Impurity Transport

avoidance of impurity accumulation

understanding 3D transport (edge/core) and control of sources

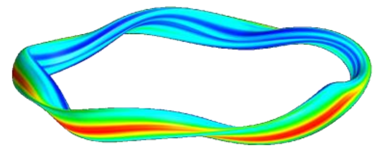


Regana et al, Alonso et al.

Turbulence & Improved Confinement Modes

study the interplay of turbulence, magnetic geometry and E_r

beyond neoclassical transport & improved confinement modes



Helander et al. TH/1-2

3D Fast-Ion Physics

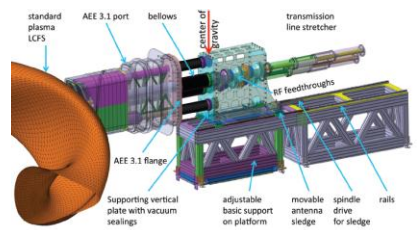
generation, detection and configuration dependencies

qualify and prepare fast-ion physics studies

High-beta, MHD

prepare the assessment of collisionless particle confinement

towards high-beta operation in OP2 and MHD effects



Ongena et al. TH P6/60

begin the physics exploitation of optimized stellarators

Wendelstein 7-X
en-route to a HELIAS Fusion Power Plant

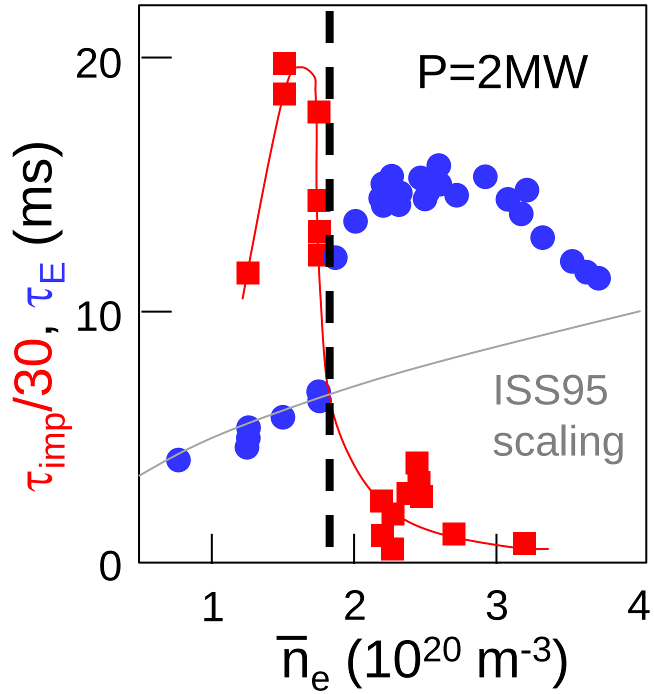
- achieve steady-state, high-$nT_i\tau_E$ plasmas
- gain predictive capabilities

First Phases (pulsed, lower power):

- qualify divertor & develop scenarios
- start to address the physics of optimization

Impurities

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



McCormick et al., PRL (2002)

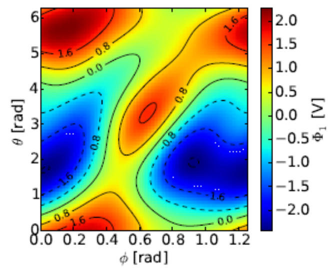
avoidance of impurity accumulation:
employ the interplay of transport, sources (SOL),
and improved operation modes

High Priority Physics Topics for OP 1.2

Impurity Transport

avoidance of impurity accumulation

understanding 3D transport (edge/core) and control of sources



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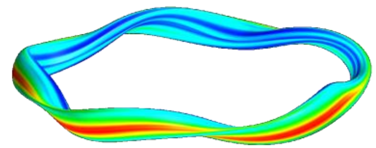

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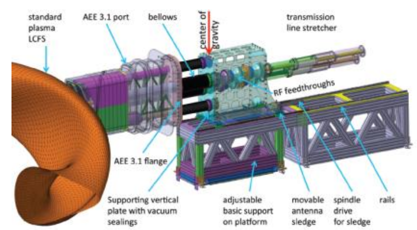

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Wendelstein 7-X
en-route to a HELIAS Fusion Power Plant

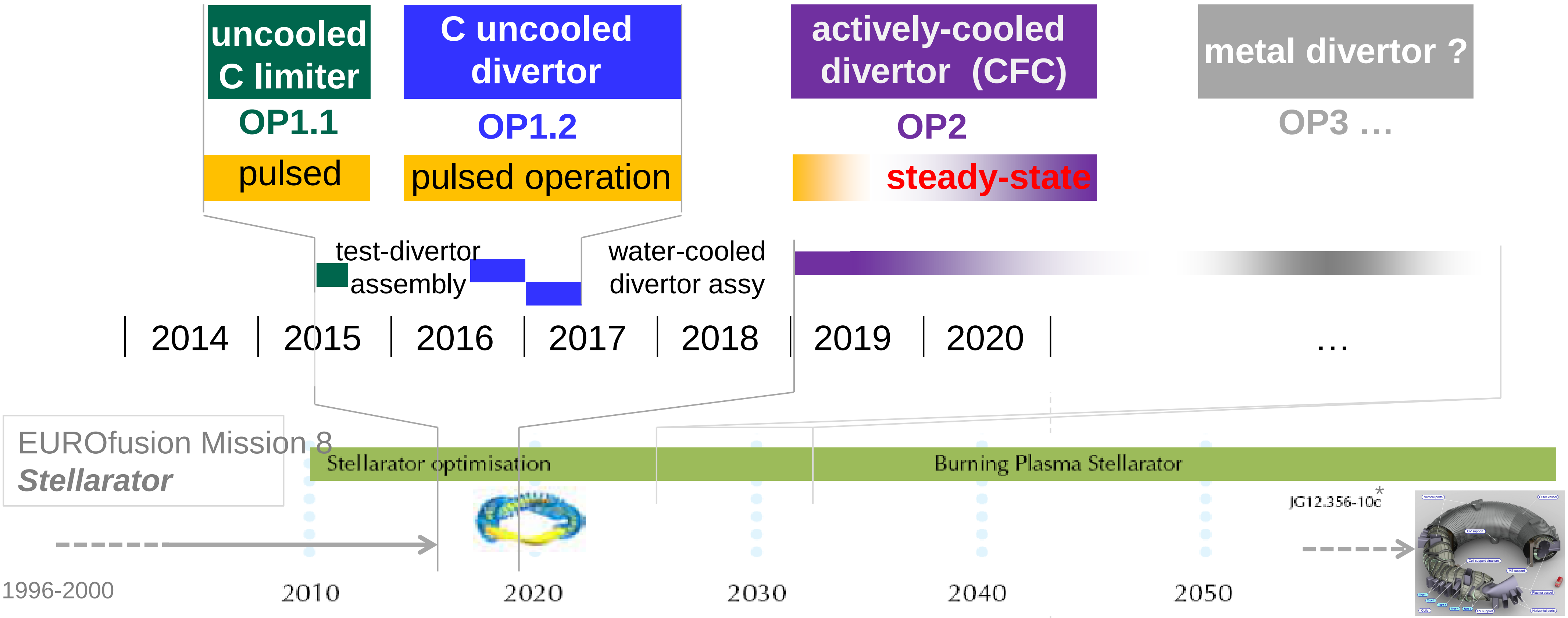
- achieve steady-state, high-$nT_i\tau_E$ plasmas
- gain predictive capabilites

First Operation Phases (pulsed, lower power):

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

W7-X: bring the HELIAS line to maturity

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



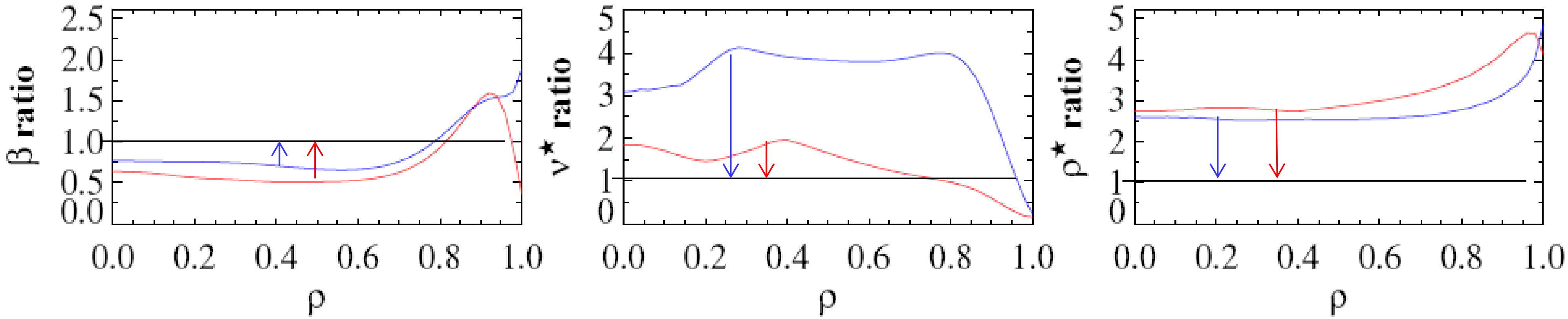
Preparation for the actively cooled divertor is the primary target of the first phase.

Long term goal: Basis for a HELIAS FPP

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

The Way to a HELIAS Reactor

W7-X X2+NBI and O2 compared to $V = 1500$ m^3 Reactor



C.D. Beidler

Wendelstein 7-X – still a large gap
but large enough to assess reactor physics aspects.