First plasma operation of Wendelstein 7-X

R. C. Wolf on behalf of the W7-X Team*)

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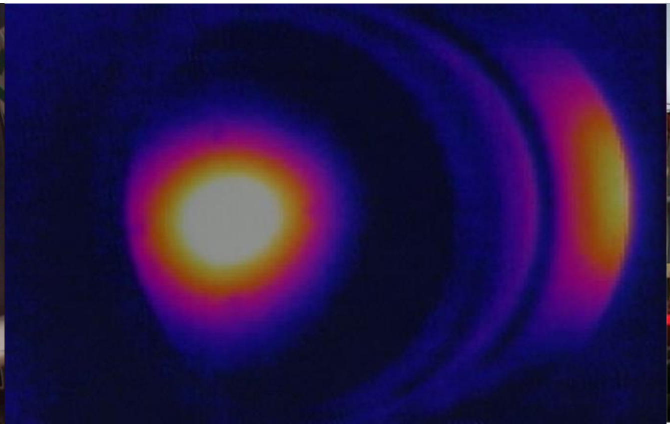

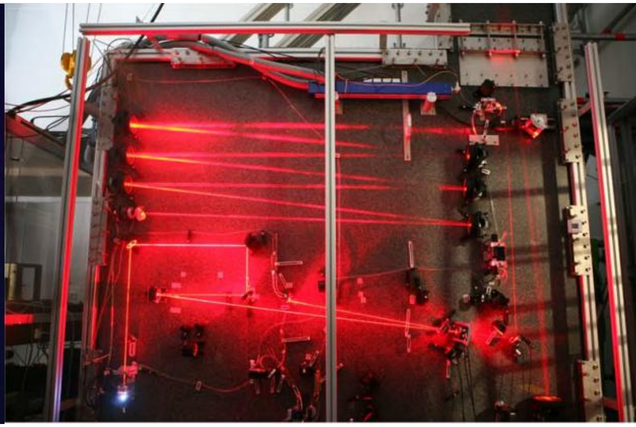

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*) see author list Bosch et al. Nucl. Fusion 53 (2013) 126001

The optimized stellarator Wendelstein 7-X

Main advantage

– **Intrinsically steady-state with benign operational boundaries (w/o disruptions)**

1. Closed magnetic surfaces /sufficiently small error fields
2. Reduced neoclassical transport (thermal plasma); minimization of ε_{eff}
3. Confinement of fast ion (in W7-X ~100 keV)
4. MHD stability at finite β (5%)
5. Equilibrium properties at finite β (5%):
   Low Shafranov shift, small bootstrap current
6. Compatibility of magnetic field and exhaust concept (in W7-X magnetic island divertor at)
7. Feasible modular coils

Special property of W7-X:
Plasma and magnetic field
as far as possible decoupled

Main objective

– **Demonstrate integrated high power, high $nT\tau_E$ steady-state plasma operation**

The optimized stellarator Wendelstein 7-X

Magnetic field
3 T

Superconducting coils
70

Cold / total mass
425 t / 700 t

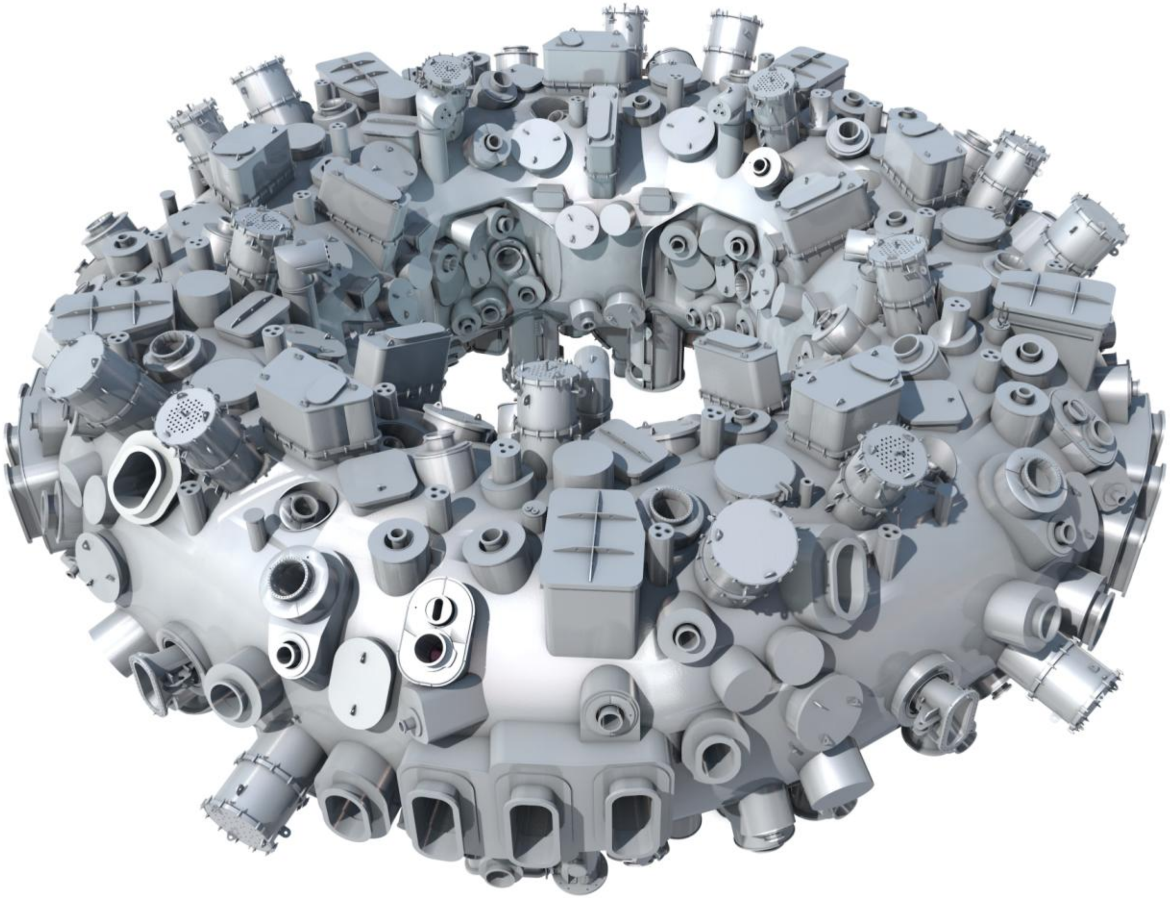
Magnetic field energy
600 MJ

Plasma volume
30 m^3

Plasma duration
30 minutes

Heating power
10 MW

Maximum heat load
10 MW/m^2



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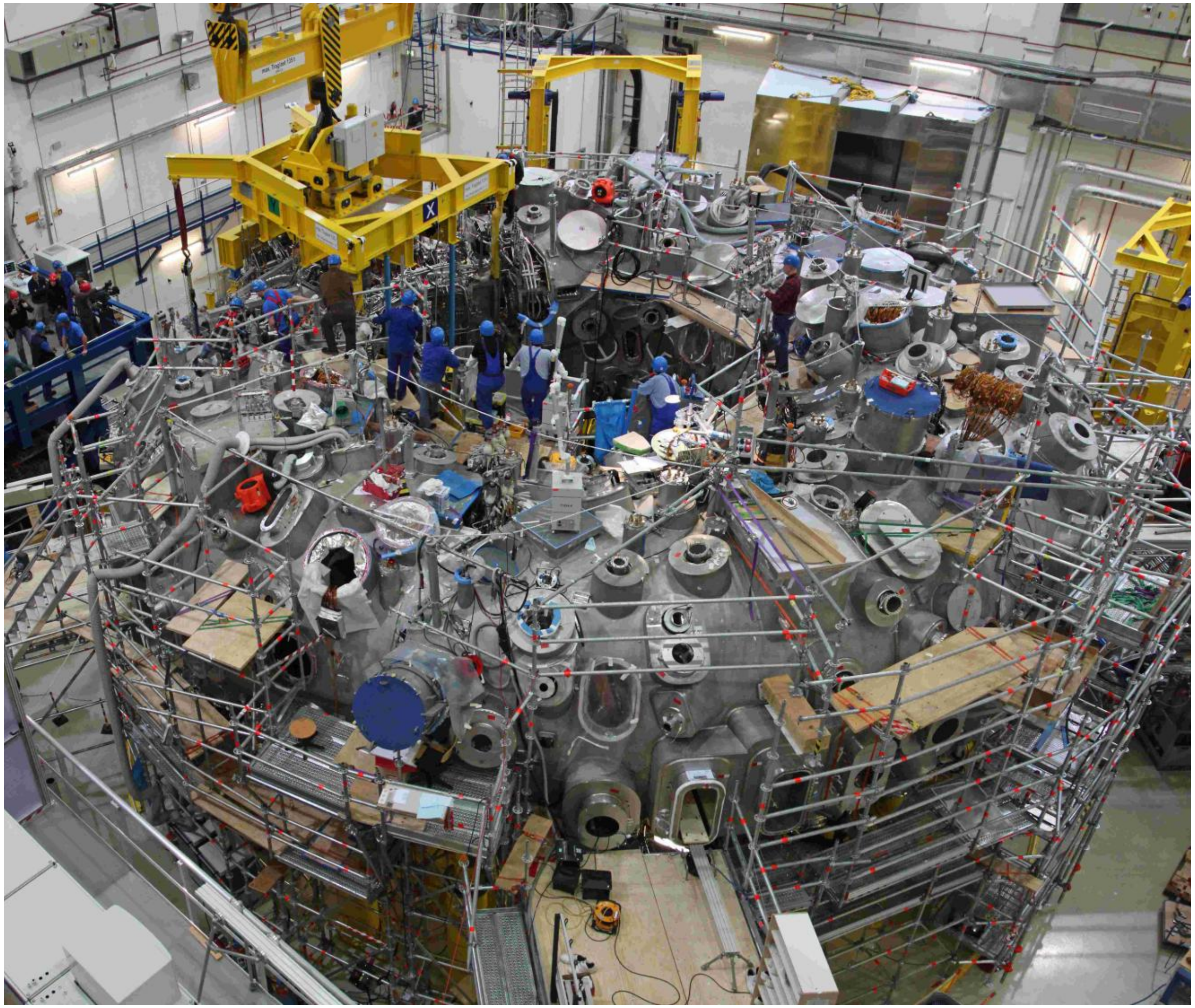
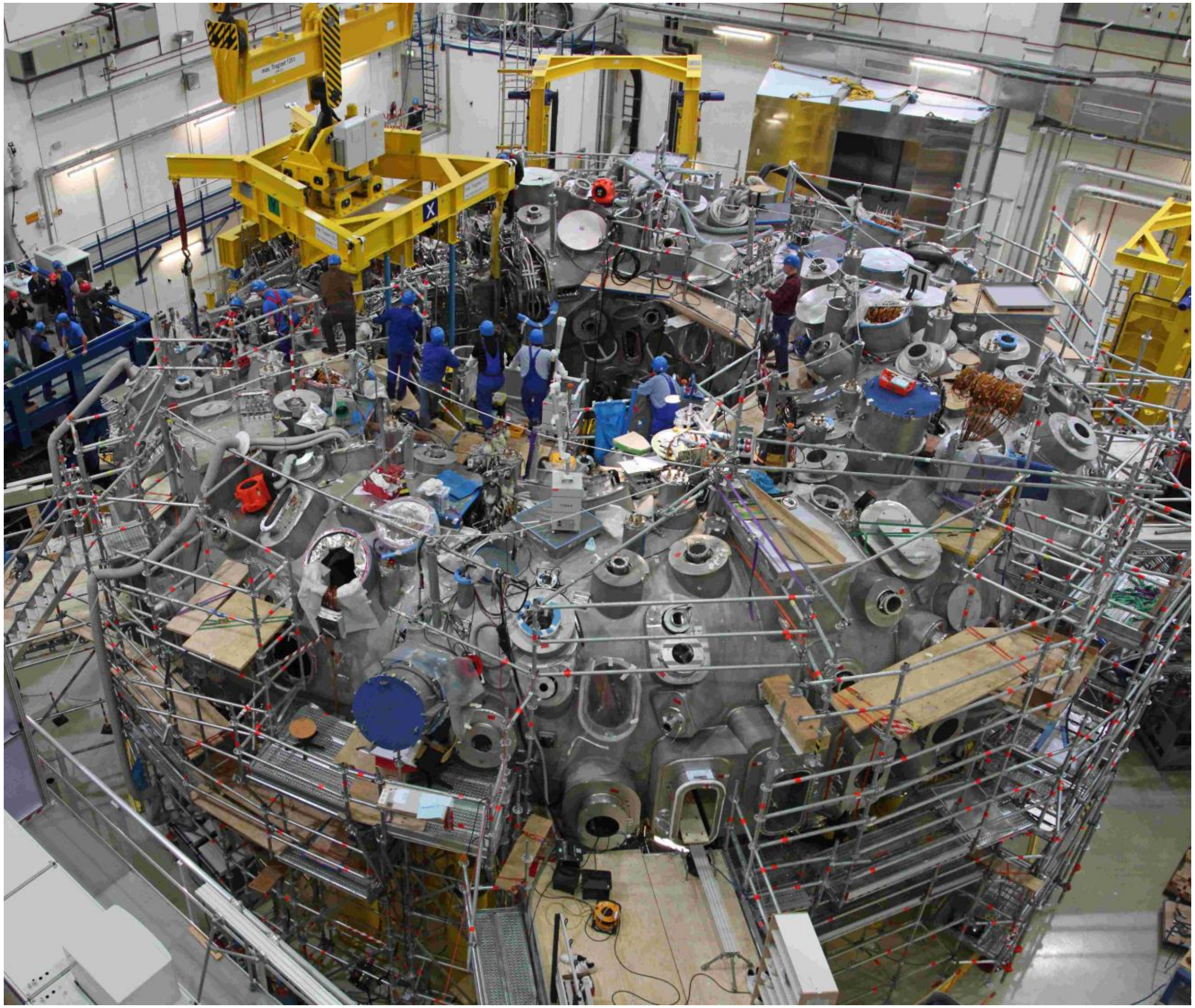


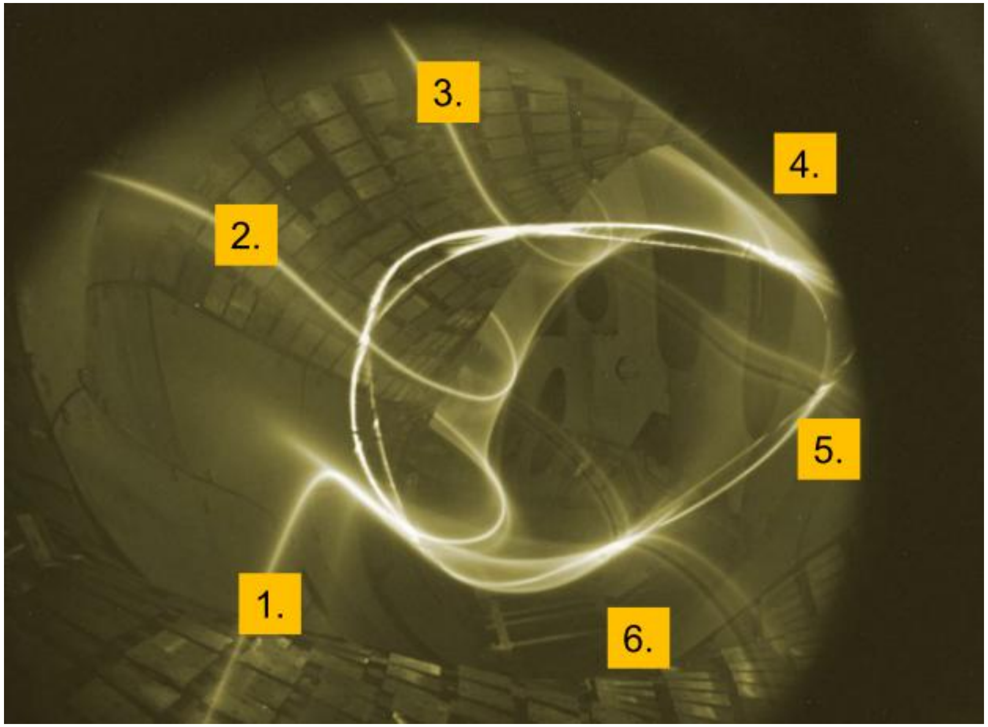
The optimized stellarator Wendelstein 7-X

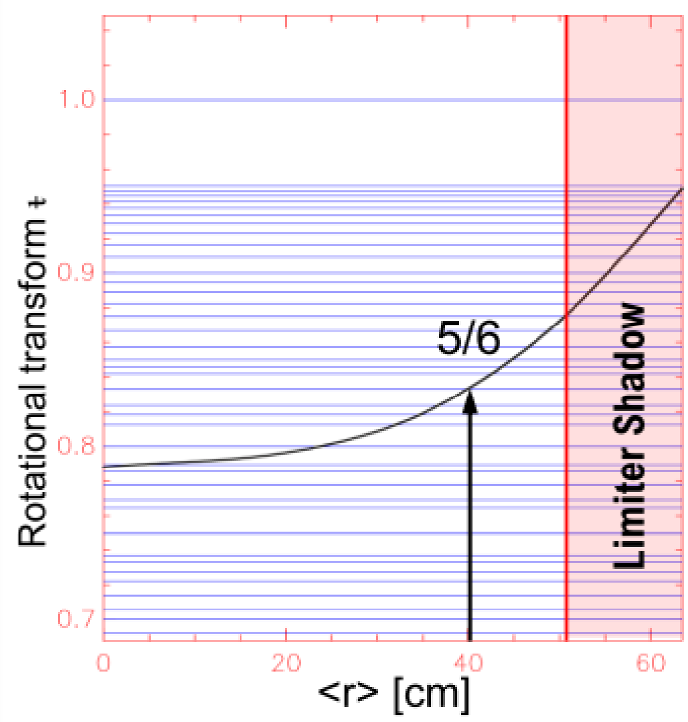
- Assembly of basic device completed in 2014
- Commissioning 2014 – 2015
- First plasma operation 10 Dec 2015 until 10 March 2016



Bosch, PD

Confirmation of flux surfaces and low error fields





- Flux surfaces / field line traces measured with electron beam
- Island chain at m/n = 5/6 corresponds to ɩ = 5/6 : Movement of ɩ = 5/6 position consistent elastic deformation of modular coils when magnetic field is applied
- From dependence of central island width of ɩ = ½ configuration on deliberately applied error field an intrinsic error field of $b_{21} \approx 5\times10^{-6}$ is deduced

Contents

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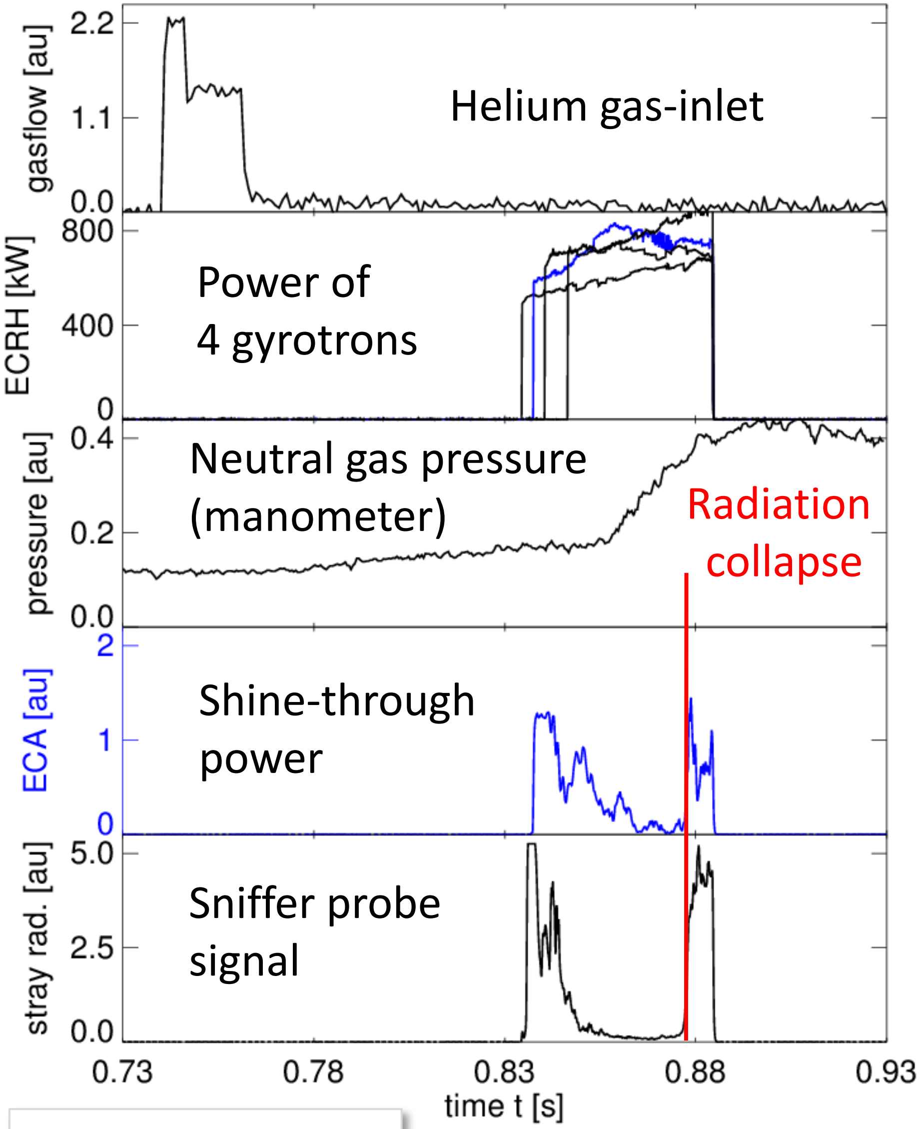
Plasma generation



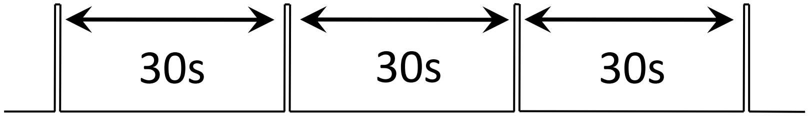
Marsen, EX/P5-13

Boundary conditions

- Limiter plasma restricted to $\int P\,dt \leq 2$ MJ
- Six 140 GHz cw-gyrotrons for central 140 GHz ECRH at 2.5T; total power ≤ 5 MW
- 1 week baking in advance @150° C
- Start with He w/o GDC

First results

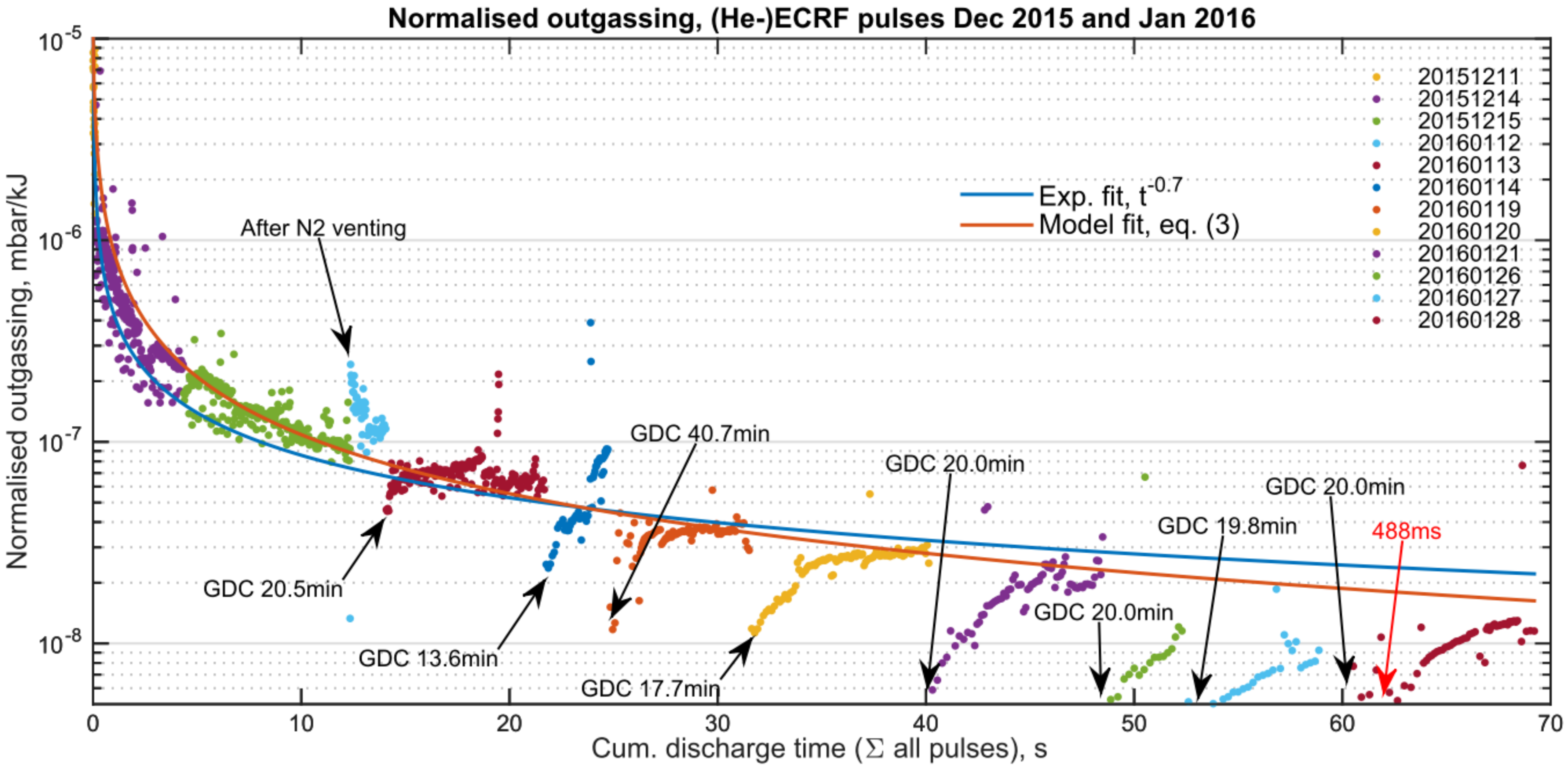
- Plasma break-down within 10ms
- Contamination of wall limits pulse length of first discharges to 20ms (automatic stop by sniffer interlock)
- Hundreds of short ECRH cleaning discharges (3 days corresponding to about 4 sec plasma operation)



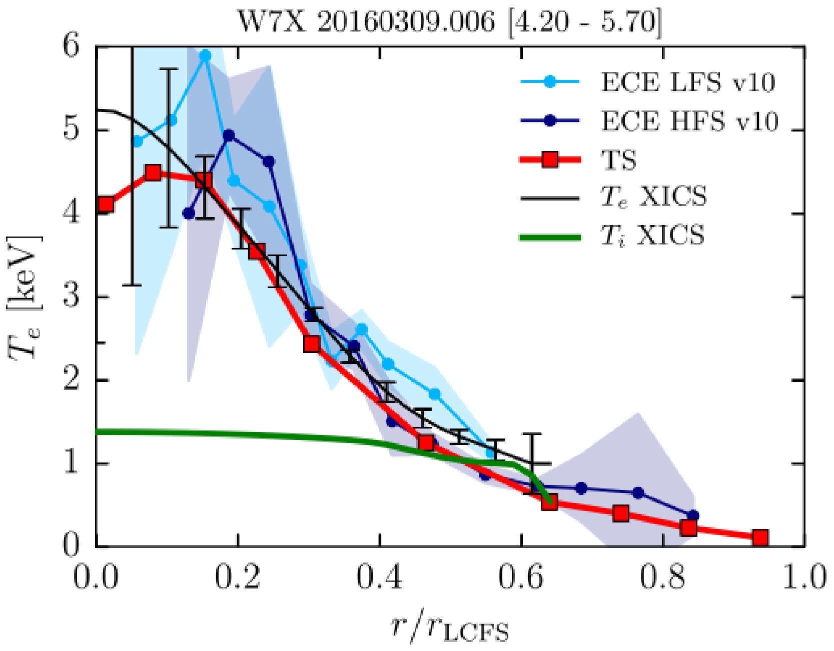
⇒ discharge length extended to ~50ms

Wall conditioning

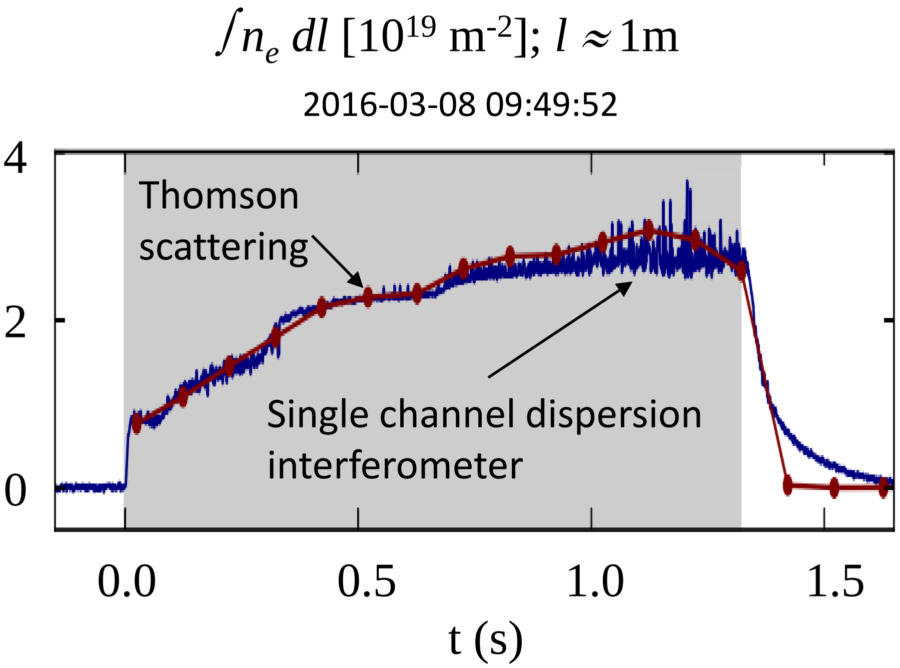
- Wall conditions improved considerably with cumulated discharge time and GDC
- What remained throughout the campaign was the tendency for a radiation collapse terminating the plasma as wall conditioning deteriorates during the day
- The origin of a local neutral gas pressure increase (in module 4) could not be resolved
- Eventually, **600 kW / 6 sec discharges** were achieved (increasing $\int P\,dt$ to 4 MJ)



Plasma parameters



Hydrogen plasma
P_{ECRH} = 0.6 MW, 6 sec



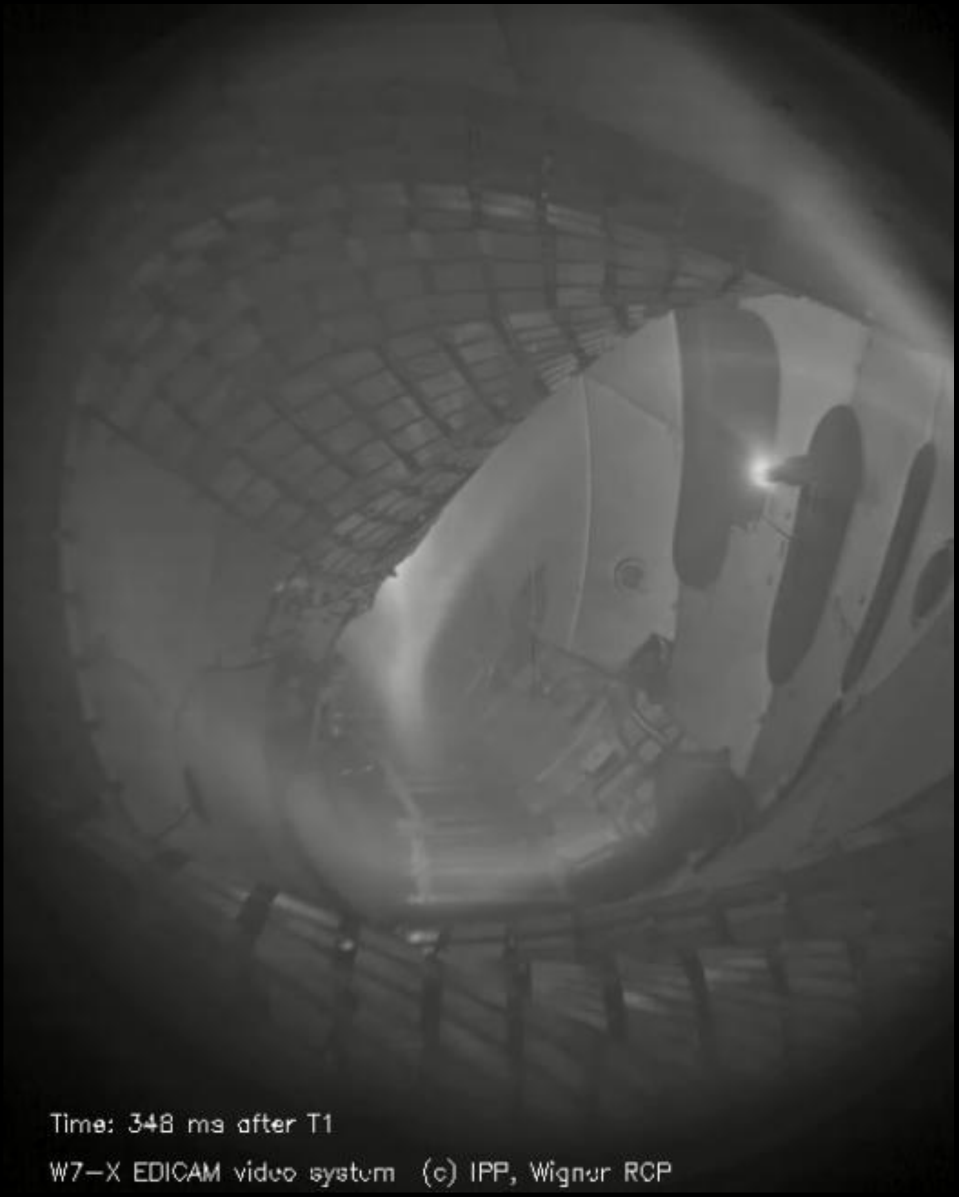
Hydrogen plasma
P_{ECRH} = 4 MW

- At the end of the first W7-X campaign 30 diagnostics were commissioned and provided data
- Low densities and electron heating by ECRH resulted in $T_e >> T_i$
- Results in Core Electron Root Confinement (CERC)

Pablant, EX/P5-6

Langenberg, EX/P5-3

A “typical” hydrogen plasma …



… with mid-plane manipulator in action

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Contributions to / assumptions for power balance

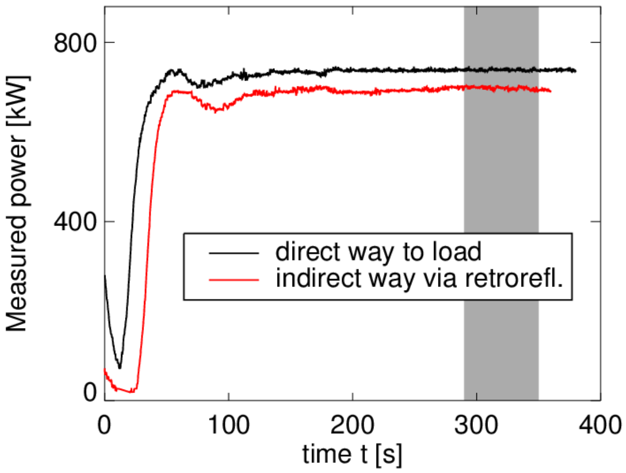
$$P_{heat} - P_{rad} - P_{lim} - \frac{dW}{dt} = 0$$

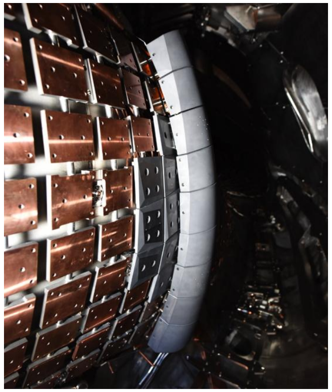
Two Bolometer cameras
– Assuming toroidal symmetry

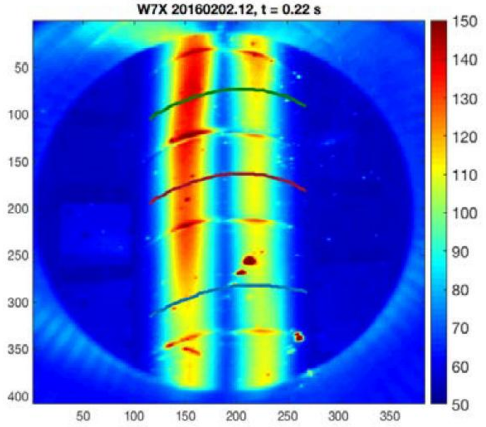
W_{kin} from $T_e(r)$ and $n_e(r)$
– $W_{kin} \sim 1.25\, W_{dia}$
– Impurity content neglected

ECRH heating power
– Transmission efficiency 94%

IR cameras for limiter loads
– Initial assumptions on asymmetries

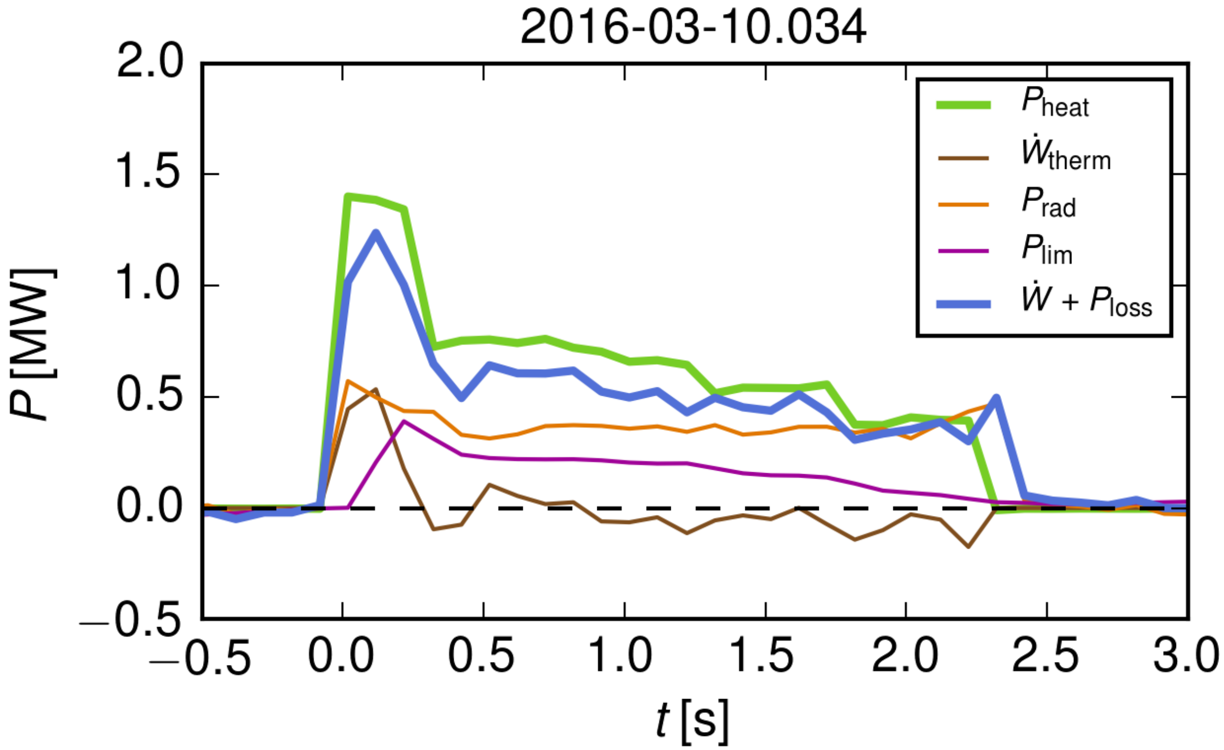






Wurden, EX/P5-7

Fair agreement between heating and loss power



- Power balance shows about 10 – 30% of power which is not accounted for (difference increases with increasing heating power)
- Assumptions are only approximations
- Additional losses could e.g. come from charge exchange processes with background neutrals

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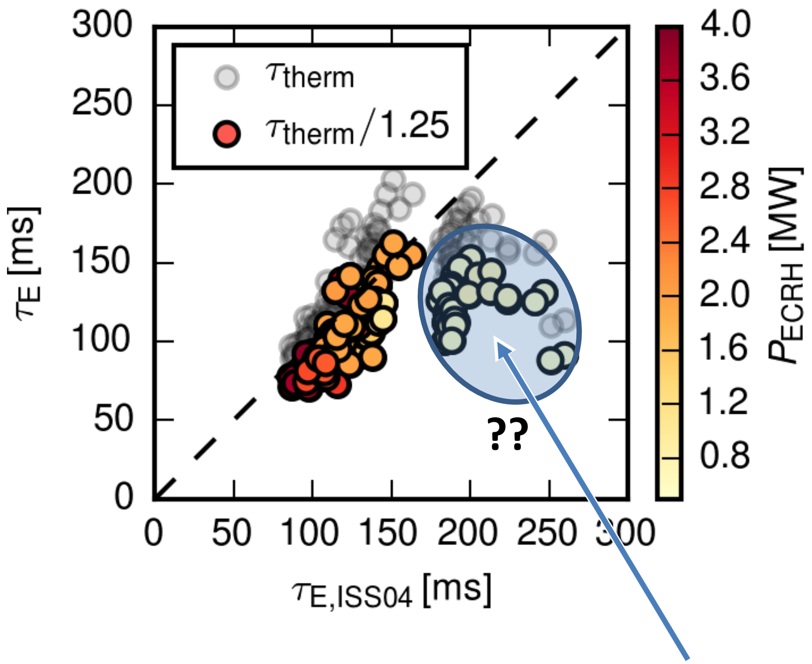
Hirsch, EX/4-5

Comparison with scaling of energy confinement time



Confinement times during 1st W7-X campaign

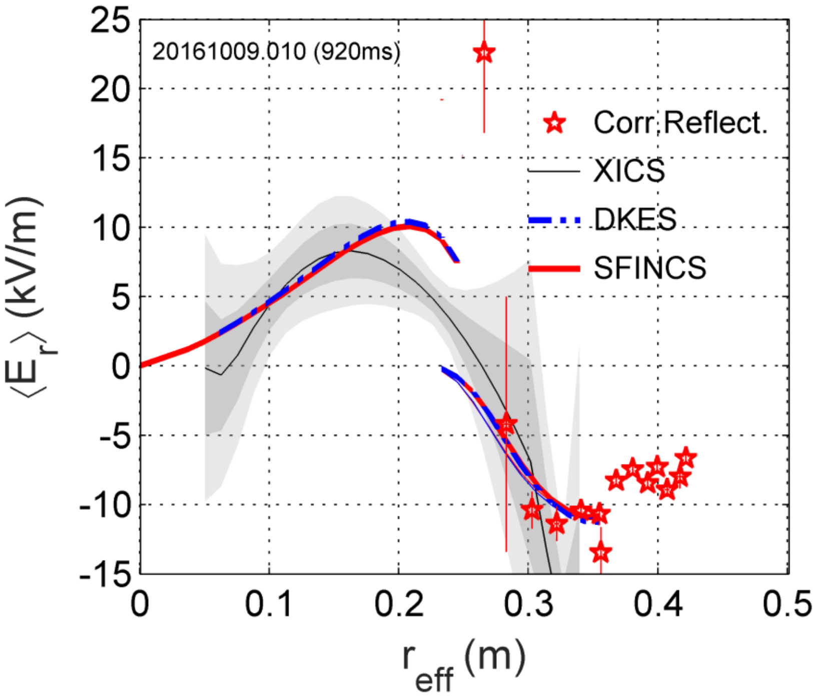
- Best plasmas lie on ISS04-scaling
- Only 16 days of hydrogen operation
- Bare CuCrZr walls
- Conditioning of wall was still ongoing; impurity issues

At low power reduced confinement

- Radiation limit ?
- Density limit ?

Core electron root confinement (CERC)

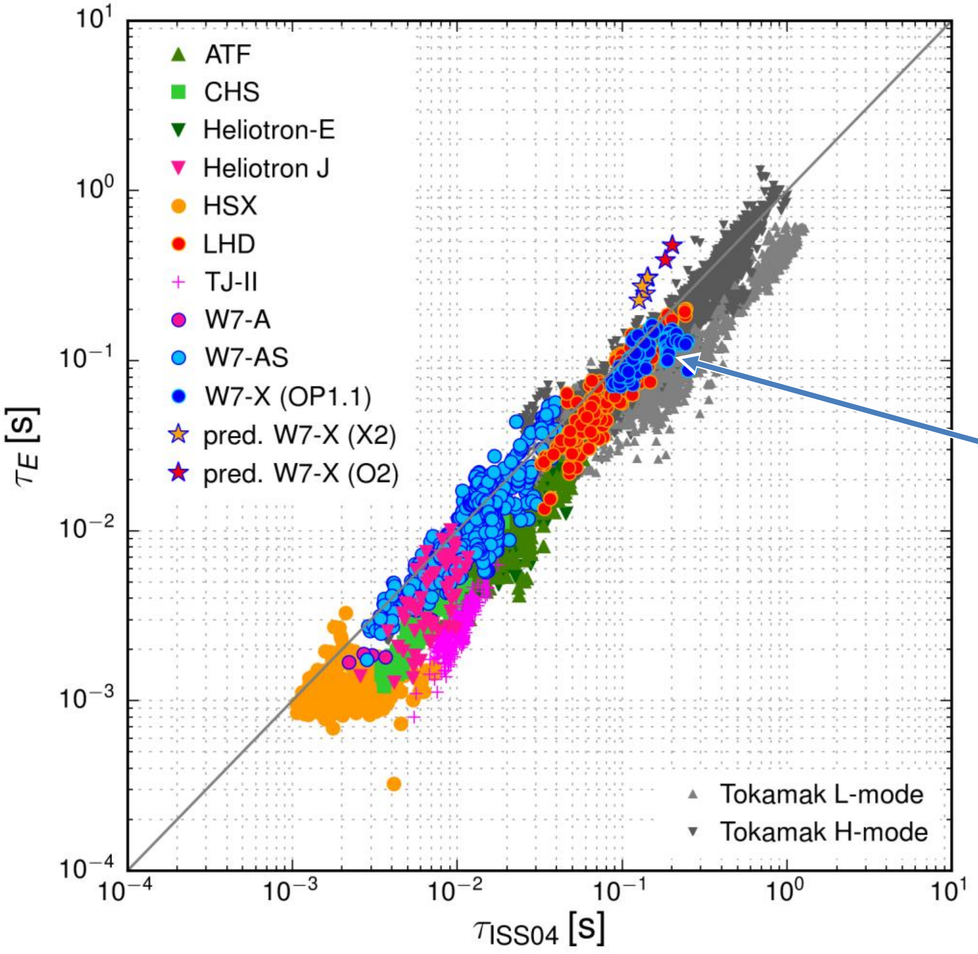
- Deriving neoclassical transport coefficient from measurements of T- and n-profiles (using neoclassical transport codes DKES and SFINCS)
- Radial electric field from enforcing the ambipolarity condition: $\Gamma_e(E_r) = Z\, \Gamma_i(E_r)$



Krämer-Flecken, EX/P5-4

- Clear evidence for core electron root confinement ($E_r > 0$): Region of improved confinement, however, covers only a small fraction of the plasma volume
- Confinement shows only weak dependence on optimization parameter ε_{eff} which is consistent with $\sqrt{\nu}$-transport regime in the presence of an electric field

Comparison with scaling of energy confinement time



$$\tau_E^{\mathrm{ISS04}} = 0.134 a^{2.28} R^{0.64} P^{-0.61} \bar{n}_e^{0.54} B^{0.84} \iota_{2/3}^{0.41}$$

Confinement times during 1st W7-X campaign

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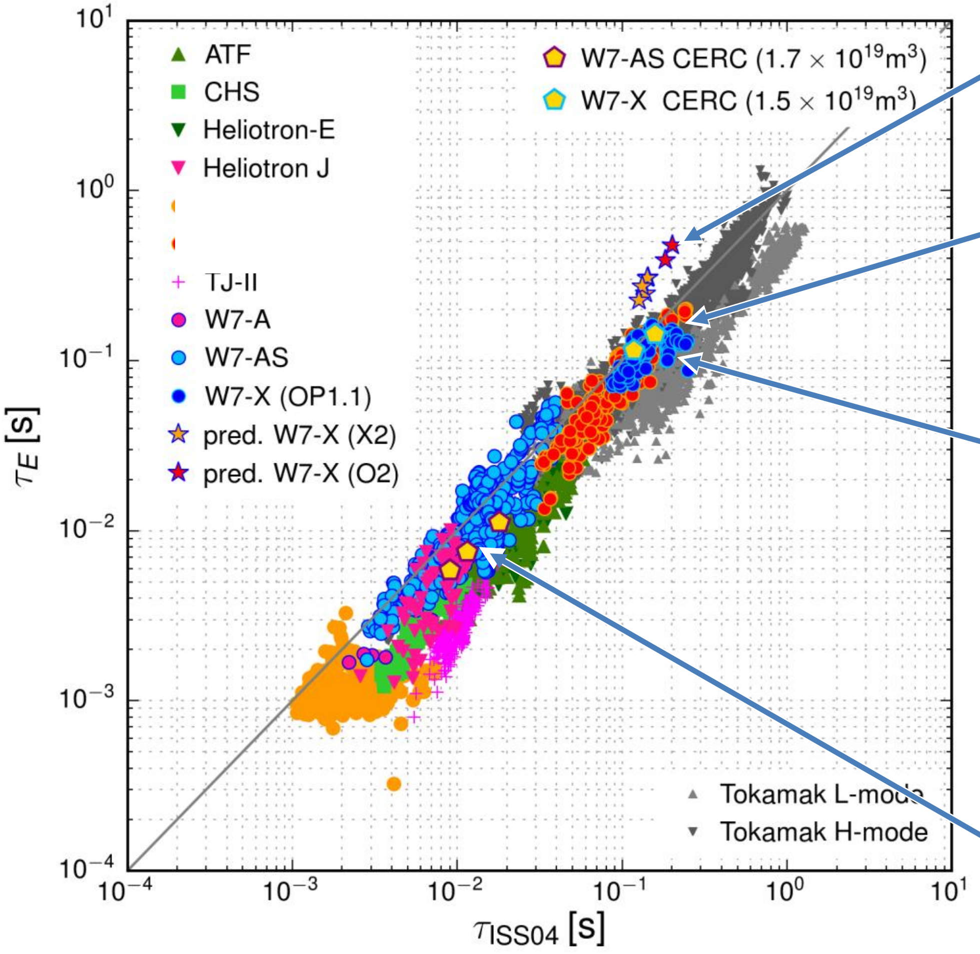
Comparison with scaling of energy confinement time



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Optimized confinement time as predicted for W7-X in the ion-regime (for $1/\nu$: $\varepsilon_{\mathrm{eff}}^{3/2}$ dependence)

W7-X CERC plasmas (more like $\sqrt{\nu}$-regime, only weak $\varepsilon_{\mathrm{eff}}$ dependence)

- ¼ of volume shows CERC
- ¾ of volume at “ISS04 conditions”

Confinement times during 1st W7-X campaign

- Best plasma lie on ISS04-scaling
- Only 16 days of hydrogen operation
- Bare CuCrZr walls
- Conditioning of wall was still ongoing; impurity issues

Comparison of W7-X and W7-AS CERC plasmas at similar densities

$(\tau_E/\tau_{E,ISS04})^{W7X} > (\tau_E / \tau_{E,ISS04})^{W7AS}$

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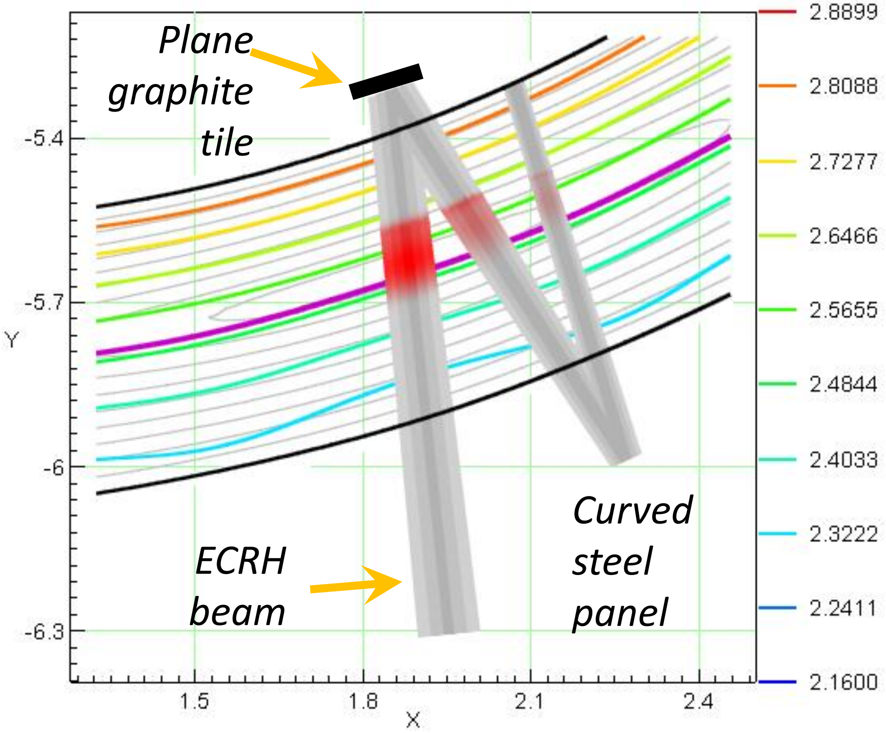
Demonstration of O2-ECRH

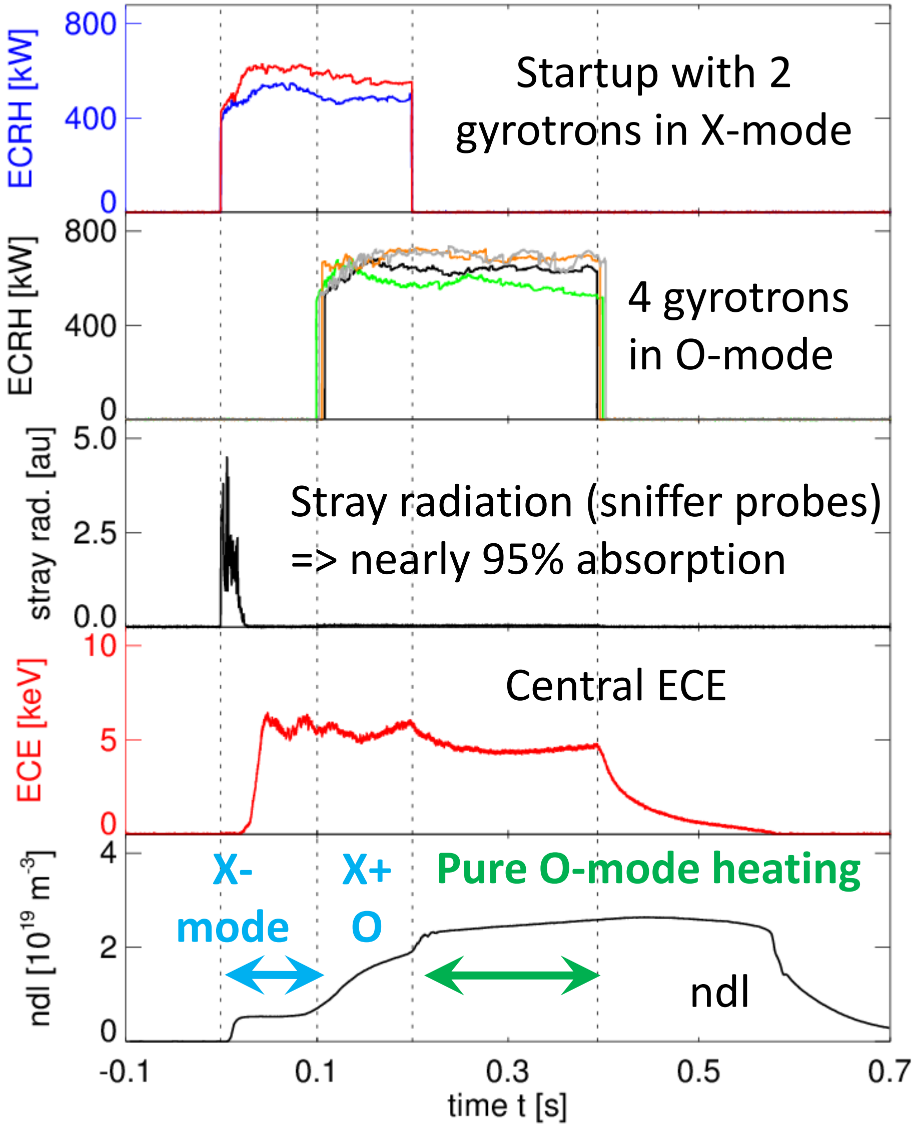
- Standard heating scenario for first campaign: 2nd harmonic X-mode
- Densities between 1.2×10^{20}m^{-3} and 2.4 $\times10^{20}$m^{-3} require O2-heating scheme
- Because of unfavourable temperature scaling of neoclassical confinement, optimum confinement conditions require high plasma density
- At low power single pass absorption up to 70% measured at 5 keV comparing ECA with and w/o plasma agrees well with theoretical predictions
- Multi-pass absorption scheme gives an overall absorption value of 95%



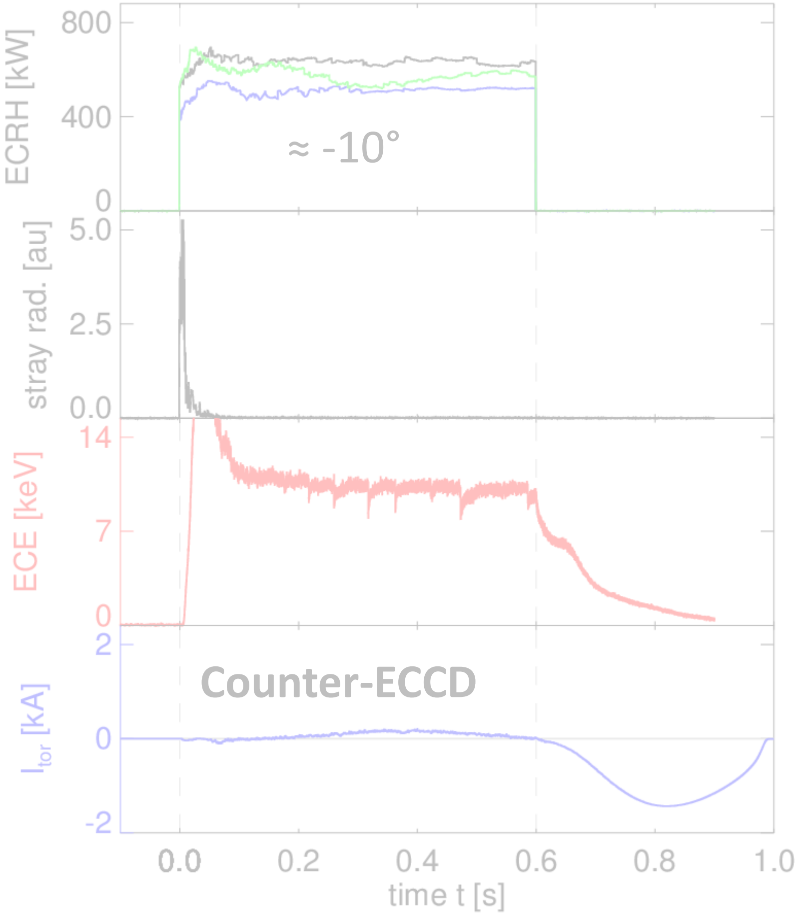
Moseev, EX/P5-11

Demonstration of O2-ECRH

- Plasma start-up in X2-mode
- For $T_e \geq 5$ keV simultaneous X2- and O2-heating
- Finally, sustainment of plasma only applying O2-heating



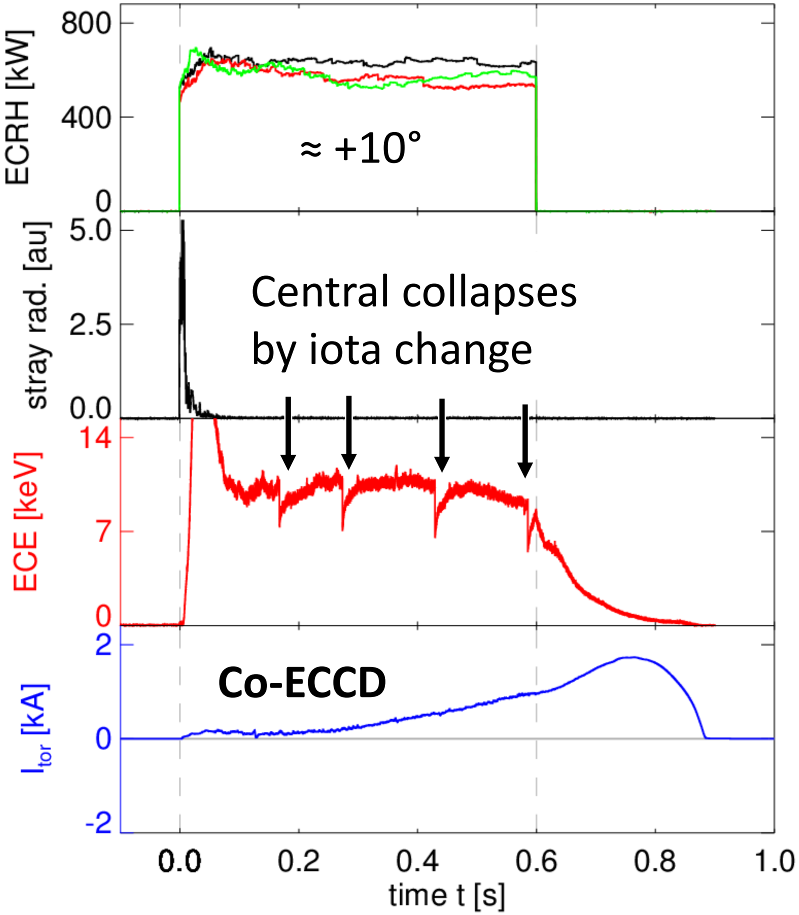
Current drive experiments



2MW ECRH

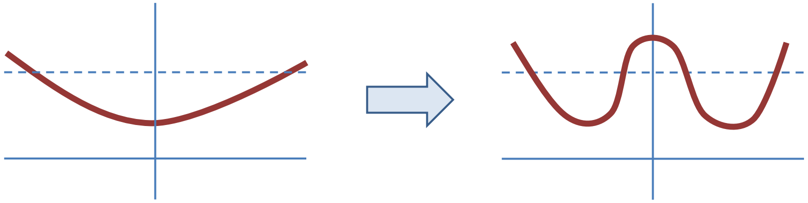
Crashes in central ECE

Agreement with predicted currents



Central collapses by iota change

- Remember: Low shear ι-profile with ɨ ≤ 1
- Central Co-ECCD increases ɨ
- Crashes in central T_e triggered by magnetic resonances generated by ι-change ?



Summary and conclusions

The objective of Wendelstein 7-X is to demonstrate that the steady-state stellarator confinement concept fulfils the requirements for the development to a fusion power plant

- Steady-state operation of a high-power, high performance plasma

The superconducting stellarator Wendelstein 7-X was successfully commissioned, first plasma experiments were very successful

- At P_{ECRH} 4 MW, $\boldsymbol{T_{e0} \approx 8\ \mathrm{keV}}$, $\boldsymbol{T_{i0} \approx 2.2\ \mathrm{keV}}$, $\boldsymbol{n_{e0} \approx 4.2 \cdot 10^{19}\mathrm{m}^{-3}}$, $\boldsymbol{\int n_e dl \approx 3.6 \cdot 10^{19}\mathrm{m}^{-2}}$ achieved simultaneously
- Discharges lasting up to 6 sec ($\int P dt \leq 4$ MJ)
- Integral commissioning including 30 plasma diagnostics and 5 MW of ECRH
- A comprehensive physics programme has been conducted with many interesting results (about half of the 900 discharges dedicated to physics studies)
- This forms a good basis for the continuing completion of the device towards full steady-state capability

Many more results reported at this conference

Device commissioning

- H.-S. Bosch et al., “Final integration, commissioning and start of the Wendelstein 7-X stellarator operation”, FIP (post deadline)

Heating and confinement

- M. Hirsch et al., “Confinement in Wendelstein 7-X Limiter Plasmas”, EX/4-5
- J. Geiger et al., “Plasma Effects in Full-Field MHD-Equilibrium Calculations for W7-X”, TH/P1-1
- N. Pablant et al., “Investigation of initial plasma parameters on the Wendelstein 7-X stellarator using the x-ray imaging crystal spectrometer”, EX/P5-6
- A. Langenberg, “Minerva Bayesian Analysis of X-ray Imaging Spectrometer Data for Temperature and Density Profile Inference at Wendelstein 7-X”, EX/P5-3
- D. Moseev, “Application of the ECRH radiation for plasma diagnosis in Wendelstein 7-X”, EX/P5-11
- S. Marsen et al., “First Results from Protective ECRH Diagnostics for Wendelstein 7-X”, EX/P5-13
- J. Ongena et al., “Physics and applications of ICRH on W7-X”, EX/P5-12
- Y. Kazakov, “ICRH Scenarios for Fast-Ion Generation in Wendelstein 7-X“, TH/P4-22

Many more results reported at this conference

Plasma transport

- O. Grulke et al., “Transport studies during the first campaign of Wendelstein 7-X ”, EX/P5-14
- A. Krämer-Flecken et al., “Investigation of turbulence rotation in limiter plasmas at W7-X with a new installed Poloidal Correlation Reflectometry”, EX/P5-4

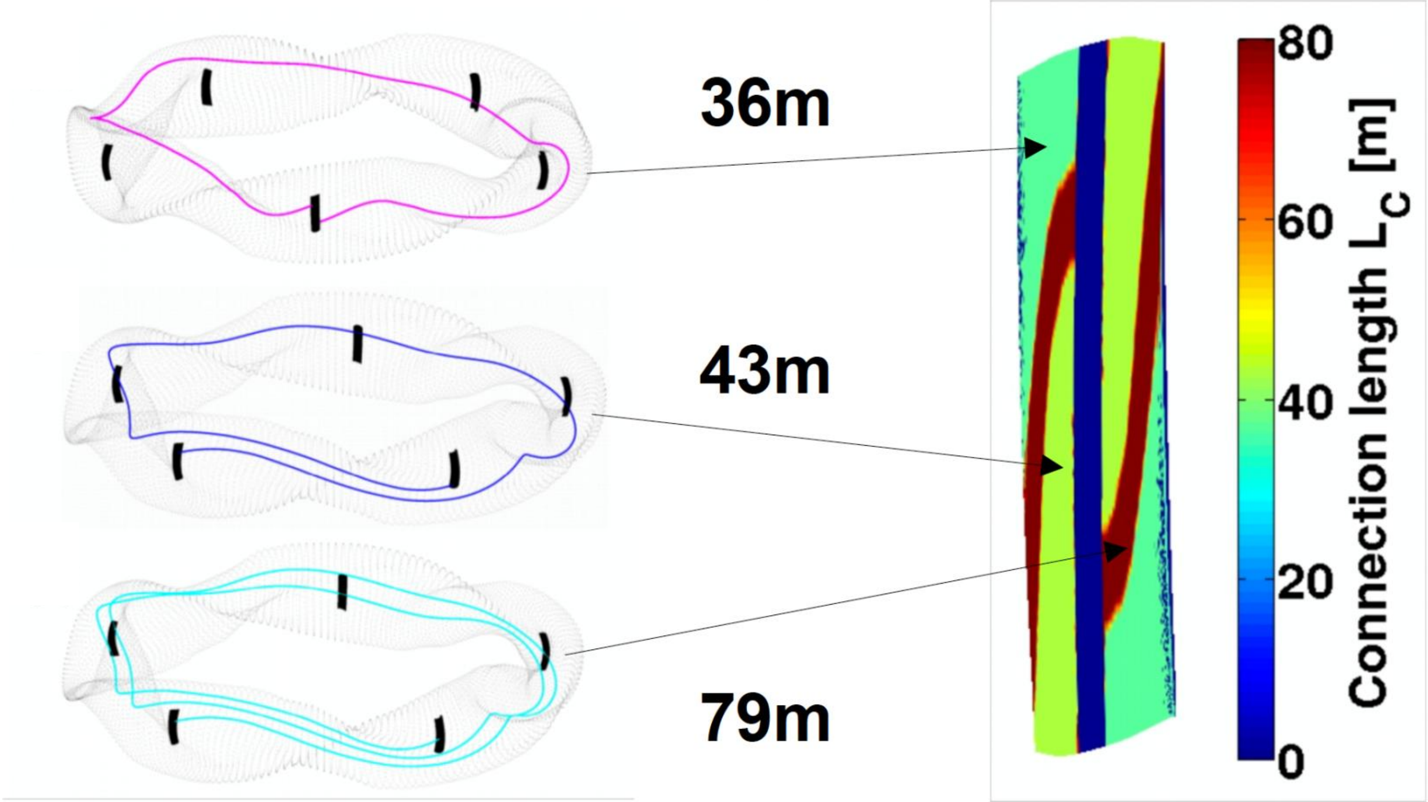
Heat load distribution on limiters and error field experiments

- S. Lazerson et al., “Error field measurement, correction and heat flux balancing on Wendelstein 7-X”, EX/P5-5
- G. Wurden et al., “Limiter observations during W7-X first plasmas”, EX/P5-7
- S. Bozhenkov et al., “Enhancement of W7-X performance by symmetrization of limiter loads with error field correction coils”, EX/P5-8

Plasma edge characterization and plasma wall interaction

- P. Drews et al., “Measurement of the plasma edge profiles using the combined probe on W7-X ”, EX/P5-9
- F. Effenberg et al., “Numerical investigation of 3-D plasma edge transport and heat fluxes including impurity effects in Wendelstein 7-X start-up plasmas with EMC3-Eirene”, TH/P6-11

Special properties of the W7-X limiter configuration



Affected by …

… rotational transform

… cross-field transport

… accuracy of limiter positions

… intrinsic error fields and application of error field correction coils

L_c short compared to divertor phase
Three distinct regions on limiter

Bozhenkov, EX/P5-8

Lazerson, EX/P5-5

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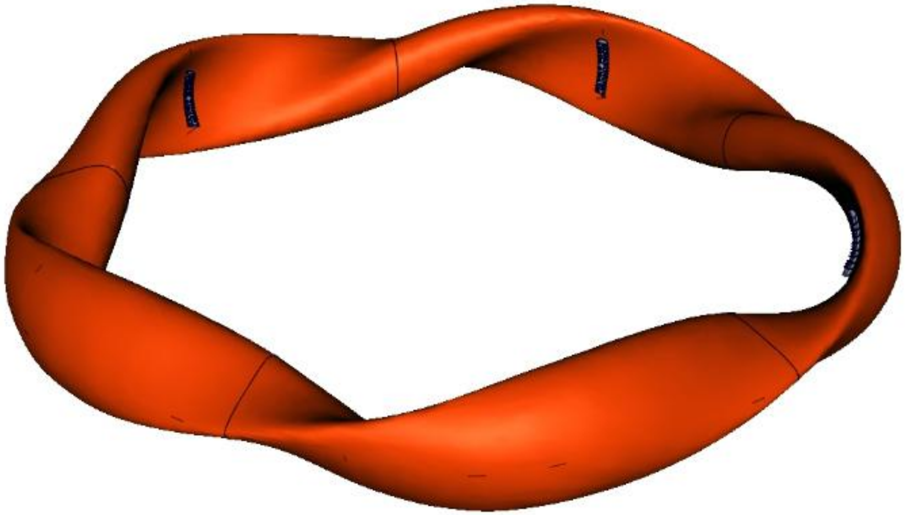
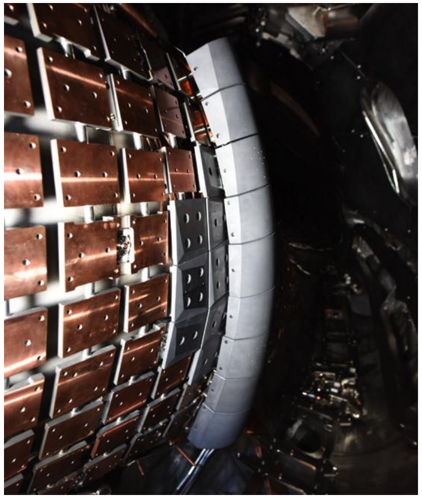
Towards steady-state operation

2015 / 2016
5 MW
4 MJ
6 s



Uncooled
graphite
limiters

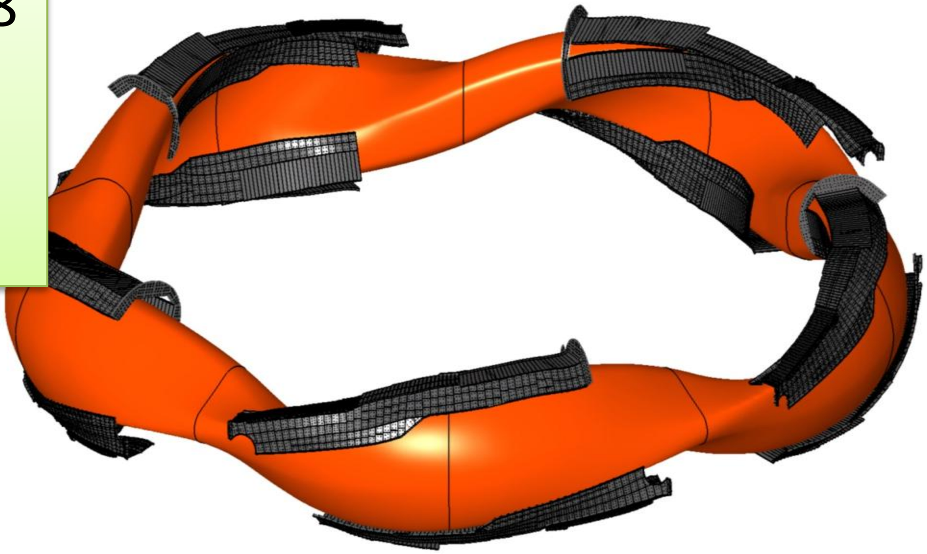
CuCrZr surfaces



Steel panels

Towards steady-state operation

2015 / 2016	2017 / 2018
5 MW	10 MW
4 MJ	80 MJ
6 s	10 s
Uncooled graphite limiters	Uncooled graphite divertor
CuCrZr surfaces	Graphite heat shields and baffles
Steel panels	Steel panels



Ongena, EX/P5-12

Kazakov, TH/P4-12

Towards steady-state operation

2015 / 2016
5 MW
4 MJ
6 s

2017 / 2018
10 MW
80 MJ
10 s

Uncooled graphite limiters

Uncooled graphite divertor

CuCrZr surfaces

Graphite heat shields and baffles

Steel panels

Steel panels

Towards steady-state operation

2015 / 2016
5 MW
4 MJ
6 s

2017 / 2018
10 MW
80 MJ
10 s

2020 …
10 MW…20 MW
18 GJ
30 minutes

Un
gra
lim

Cu

Ste


Water cooled divertor target
10 MW/m²

Actively cooled steady state high heat flux divertor
- **10 MW/m²** -

Graphite heat shields and baffles

Steel panels

Towards steady-state operation

2015 / 2016
5 MW
4 MJ
6 s

2017 / 2018
10 MW
80 MJ
10 s

2020 …
10 MW…20 MW
18 GJ
30 minutes

…

Uncooled graphite limiter

CuCrZr surfaces

Steel panels

Uncooled graphite divertor

Graphite heat shields and baffles

Steel panels

Actively cooled steady state high heat flux divertor - **10 MW/m²** -

Graphite heat shields and baffles

Steel panels

Increase of heating power

Tungsten wall

www.helmholtz.de/fileadmin/user_upload/publikationen/Helmholtz_Roadmap_2015_web_korr_150921.pdf

Acknowledgements

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