Status and Plans at Wendelstein 7-X

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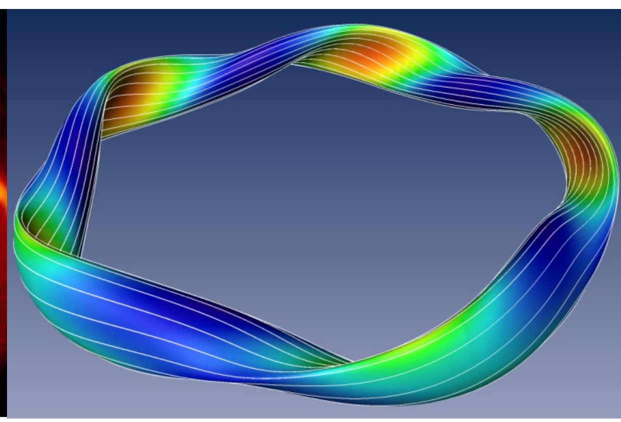
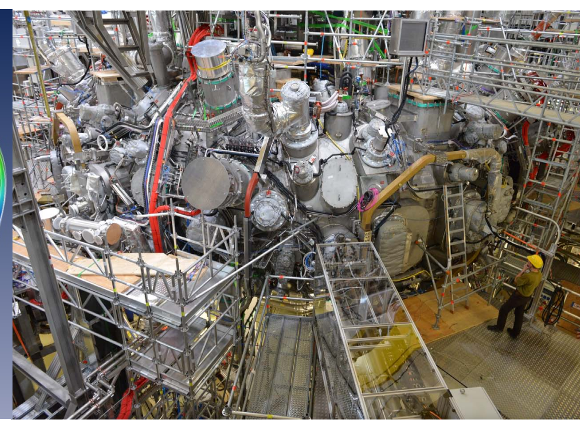
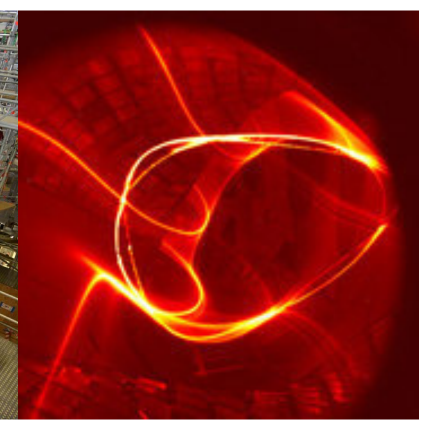
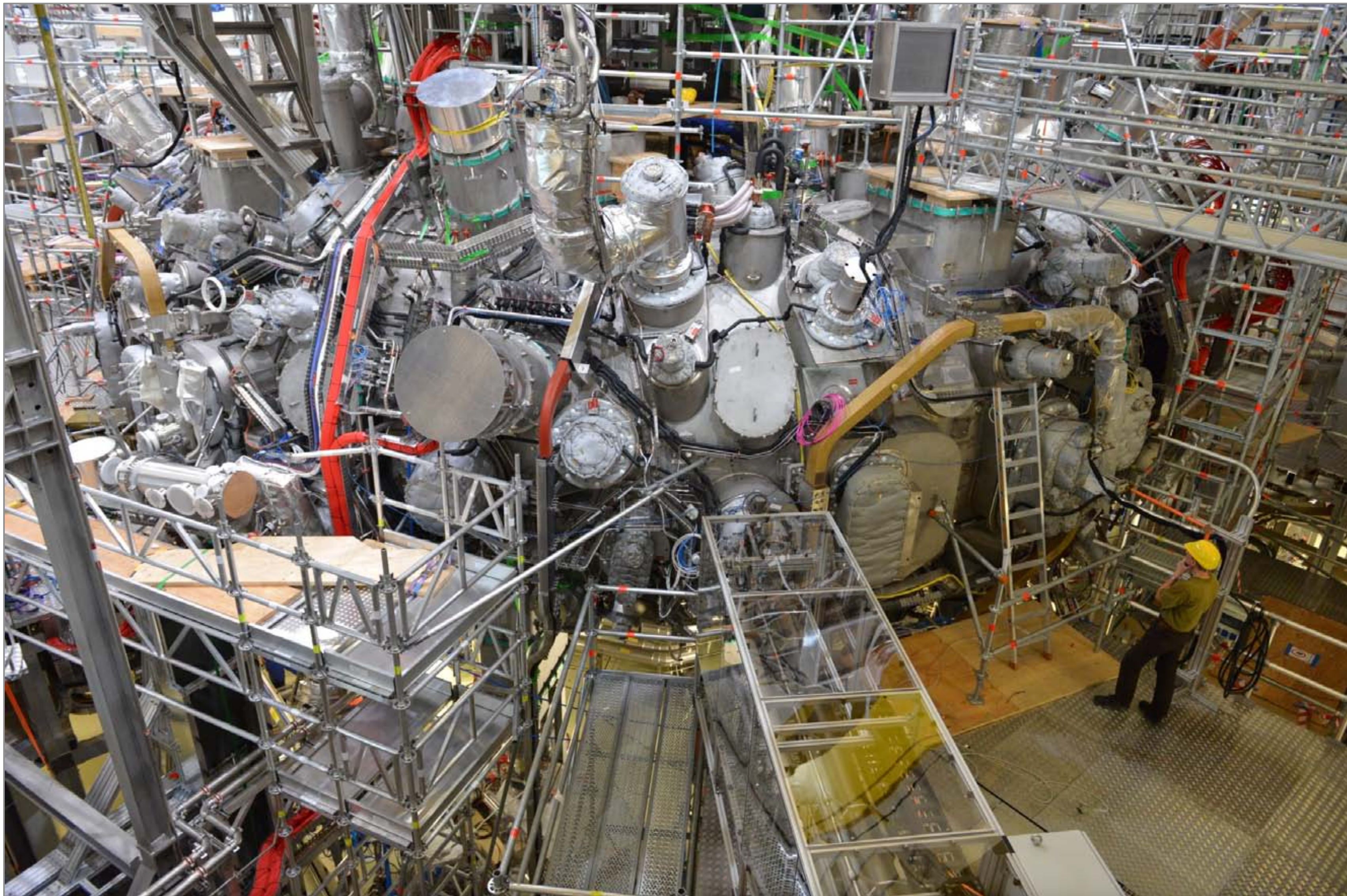
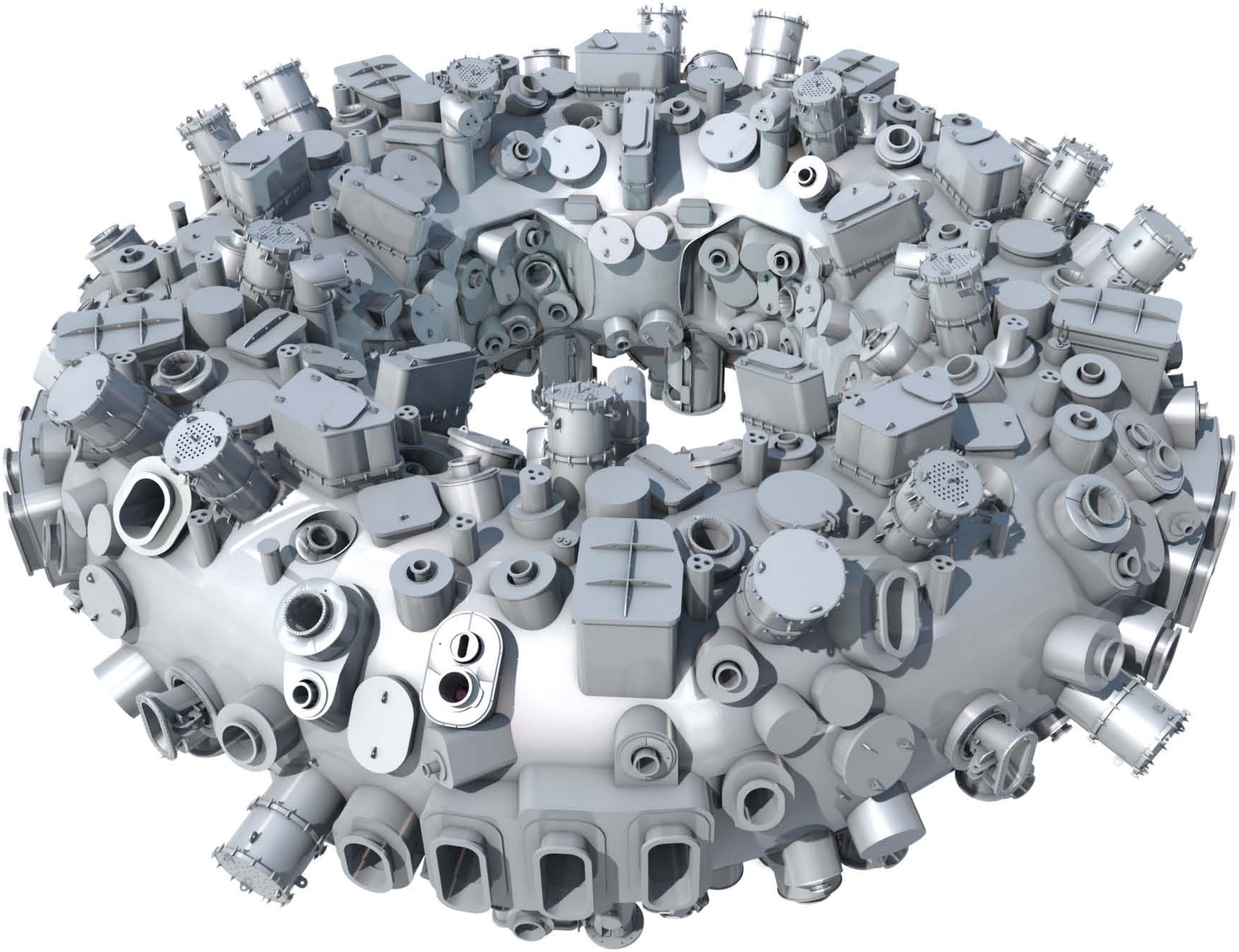
on behalf of the Wendelstein 7-X team

The Wendelstein 7-X Stellarator



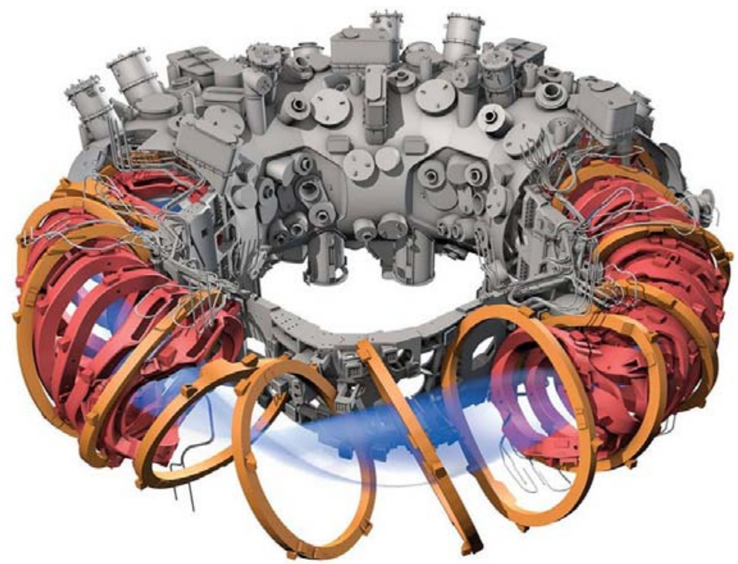
The building blocks of Wendelstein 7-X

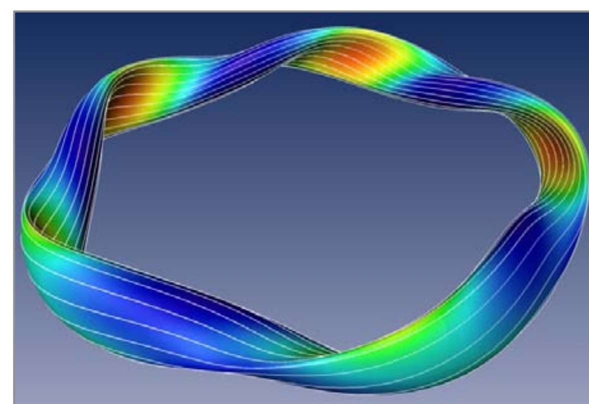


Wendelstein 7-X - facts and figures

- 735 t mass with 435 t cold mass
- 70 superconducting NbTi coils
- 2.5 - 3 T magnetic induction on axis
- 30 m^3 plasma volume
- 254 ports of 120 different types
- 265 m^2 plasma facing components
- 4.5 m height and 16 m diameter
- 1,060 Mio€ full cost
- 1.2 Mio h cumulated assembly time

- five magnetic field periods
- high iota, low shear $\iota = 0.88 \ldots 0.98$
- low bootstrap current O (10 kA)
- optimized plasma equilibrium
- steady-state ≤ 18 GJ injected energy



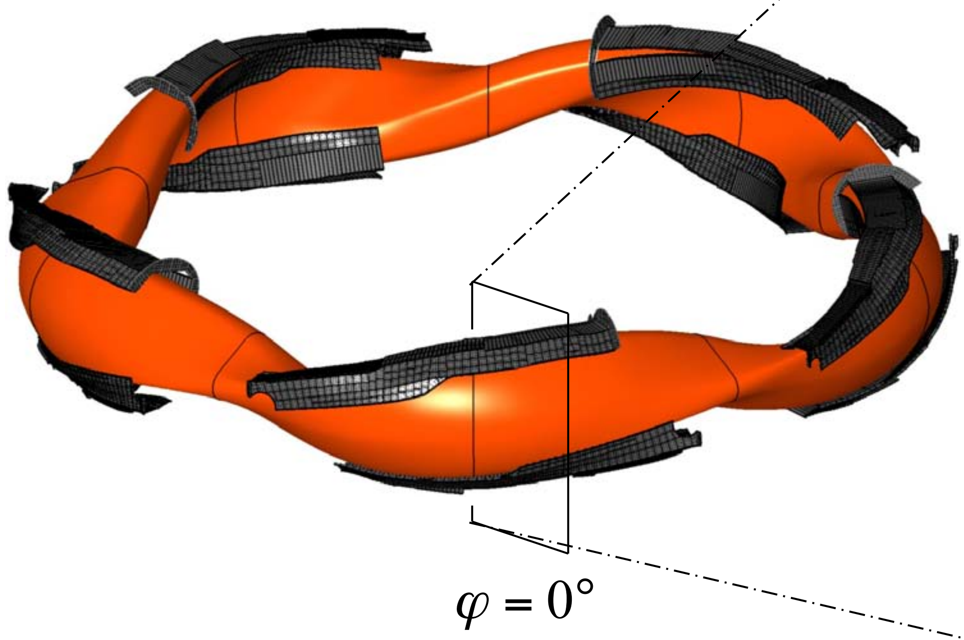


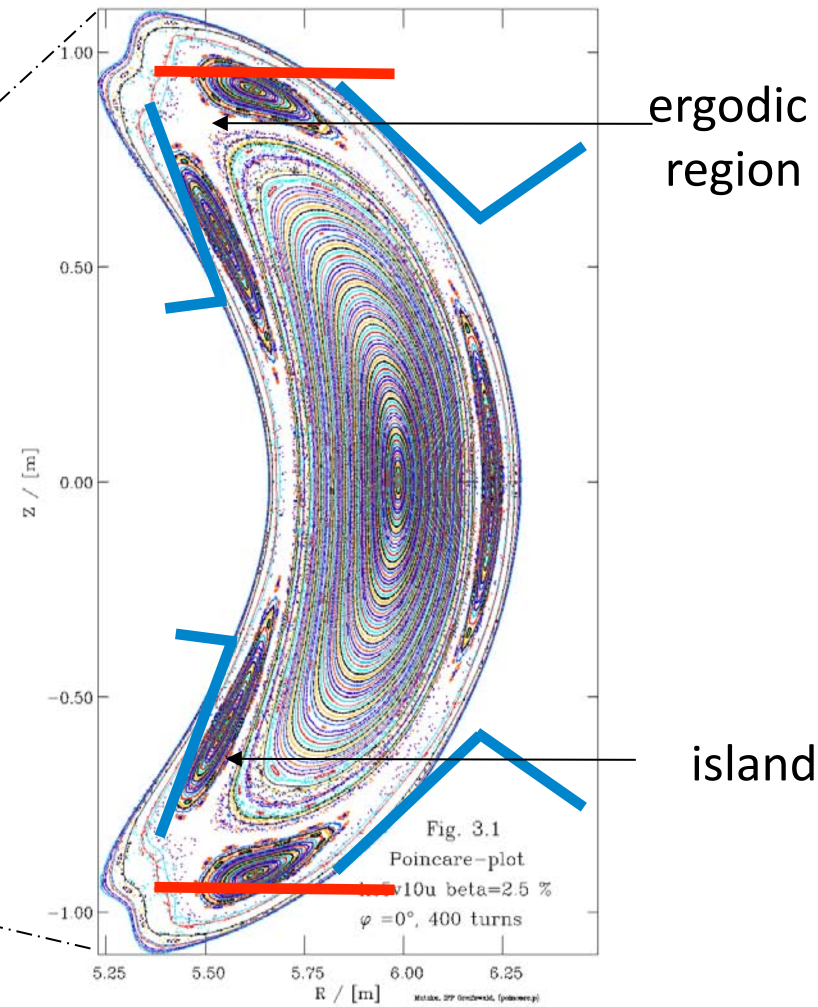
MAX-PLANCK-GESELLSCHAFT

The island divertor concept

The 10 island divertor modules are placed at invariant locations of equilibrium islands. They are used for controlled heat and particle flux as well as reclycling.

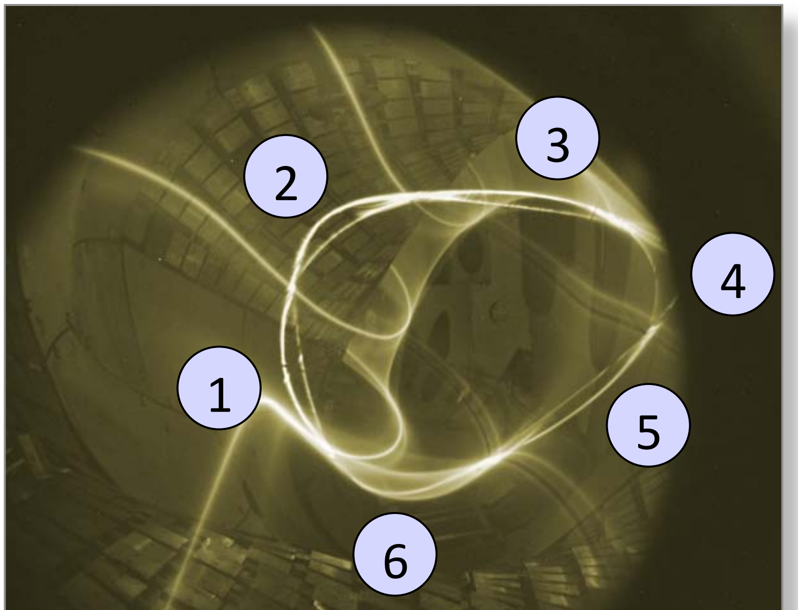
10 island divertor modules

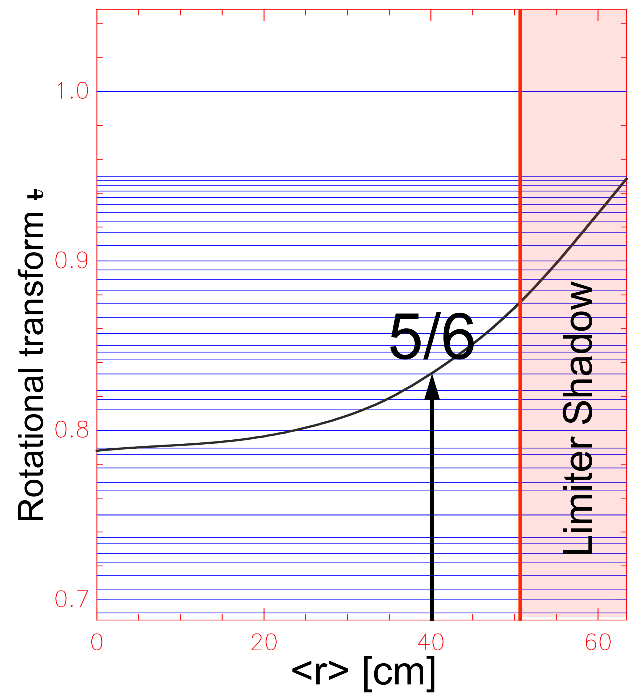




Measurement of the Magnetic Islands

- $\iota/2\pi=5/6$ configuration with 6 magnetic islands
- radial position, orientation and flip symmetry of the islands as expected





- confirms the correct magnet alignment (max. 1.5 mm deviation allowable)
- deliberately applied error field at $\iota = 2\pi / 2$ yields intrinsic deviation $b_{21} / B_0 = 5 \cdot 10^{-6}$

Nature Communications **7** Article No. 13493 (2016)

Initial Setup of Wendelstein 7-X

- 10 weeks of operation time, He and H plasmas
- 25 diagnostic systems to be put into operation
- 6 gyrotrons $P_{ECRH} = 5\,\mathrm{MW}$
- no NBI heating
- no ICR heating
- first wall steel panels/heat sinks but no graphite
- 5 uncooled poloidal graphite limiters (no island divertor)
- pulse limit fixed to $E^{\max} = 2\,\mathrm{MJ}$ later $E^{\max} = 4\,\mathrm{MJ}$

expected values

$T_e^{NC} = 4\,\mathrm{keV}$

$T_i^{NC} = 1\,\mathrm{keV}$

$n_{e0} = 2 \cdot 10^{19}\,\mathrm{m}^{-3}$

$\beta_0^{NC} \approx 1\,\%$

major goals

- commissioning of device control, ECRH, diagnostics
- plasma startup in He and H
- plasma heating
- density control
- impurity monitoring, limiter heat loads, edge plasma

First Hydrogen Plasmas

hydrogen plasmas
$T_e \leq 10$ keV
$T_i \leq 3$ keV
pulse length 1- 7 s

International research team

EUROfusion

France
Hungary
Italy
Poland
Portugal
Spain

U.S. DEPARTMENT OF ENERGY

Los Alamos National Lab
MIT
PPPL
U Wisconsin/Auburn U

Overview of the First Operation Phase

The 10 weeks of the first operation phase has exceeded all our expectations.
In the end 30 diagnostic systems were commissioned and delivered data.

$T_e = 1\,\mathrm{keV}$

$T_i < 1\,\mathrm{keV}$

$n_{e0} \sim 2 \cdot 10^{19}\,\mathrm{m}^{-3}$

$t_d = 50\,\mathrm{ms}$

$T_e = 7\,\mathrm{keV}$

$T_i = 1.2\,\mathrm{keV}$

$n_{e0} = 3 \cdot 10^{19}\,\mathrm{m}^{-3}$

$t_d = 250\,\mathrm{ms}$

$T_e = 8\,\mathrm{keV}$

$T_i = 1\,\mathrm{keV}$

$n_{e0} = 2 \cdot 10^{19}\,\mathrm{m}^{-3}$

$t_d = 6\,\mathrm{s}$

10.12.2015
1st He Plasma

2 MJ

3.2.2016
1st H Plasma

4 MJ

$T_e = 8\,\mathrm{keV}$

$T_i = 2\,\mathrm{keV}$

$n_{e0} = 3 \cdot 10^{19}\,\mathrm{m}^{-3}$

$t_d = 500\,\mathrm{ms}$

$T_e = 10\,\mathrm{keV}, 7\,\mathrm{keV}$

$T_i = 1\,\mathrm{keV}, 2.1\,\mathrm{keV}$

$n_{e0} = 5 \cdot 10^{19}\,\mathrm{m}^{-3}$

$t_d = 1\,\mathrm{s}$

~ 1000 experiments

On the 10th of March 2016 the operation was suspended as planned.

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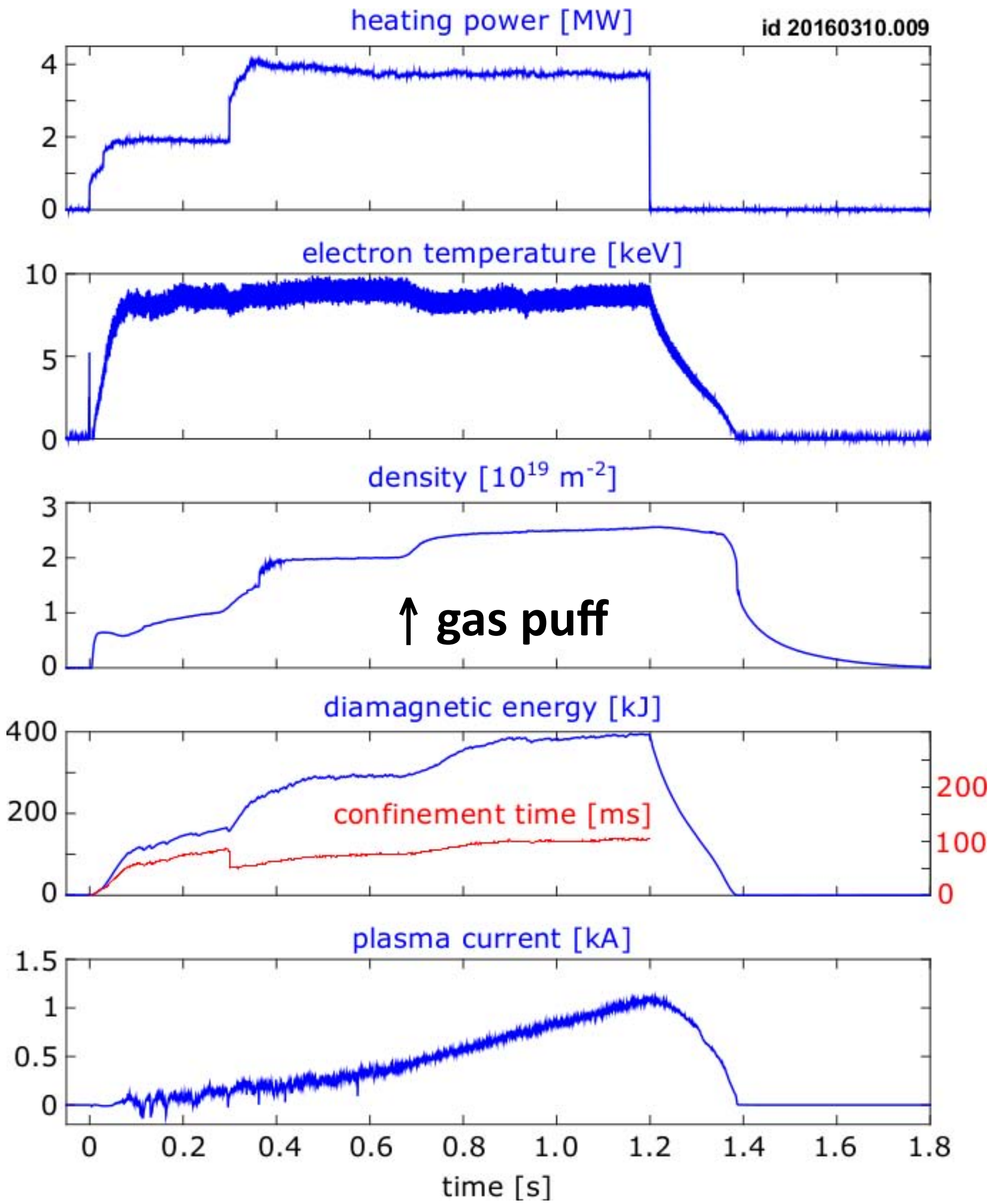
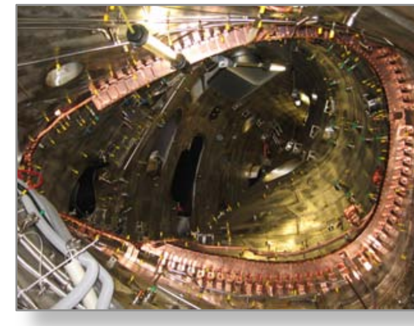
A High-Power Hydrogen Discharge

IPP



magnetic diagnostics



~ 30% radiation loss

τ_E ~ 150 ms ~ ISS04 scaling

$\langle\beta\rangle = 0.2\%$

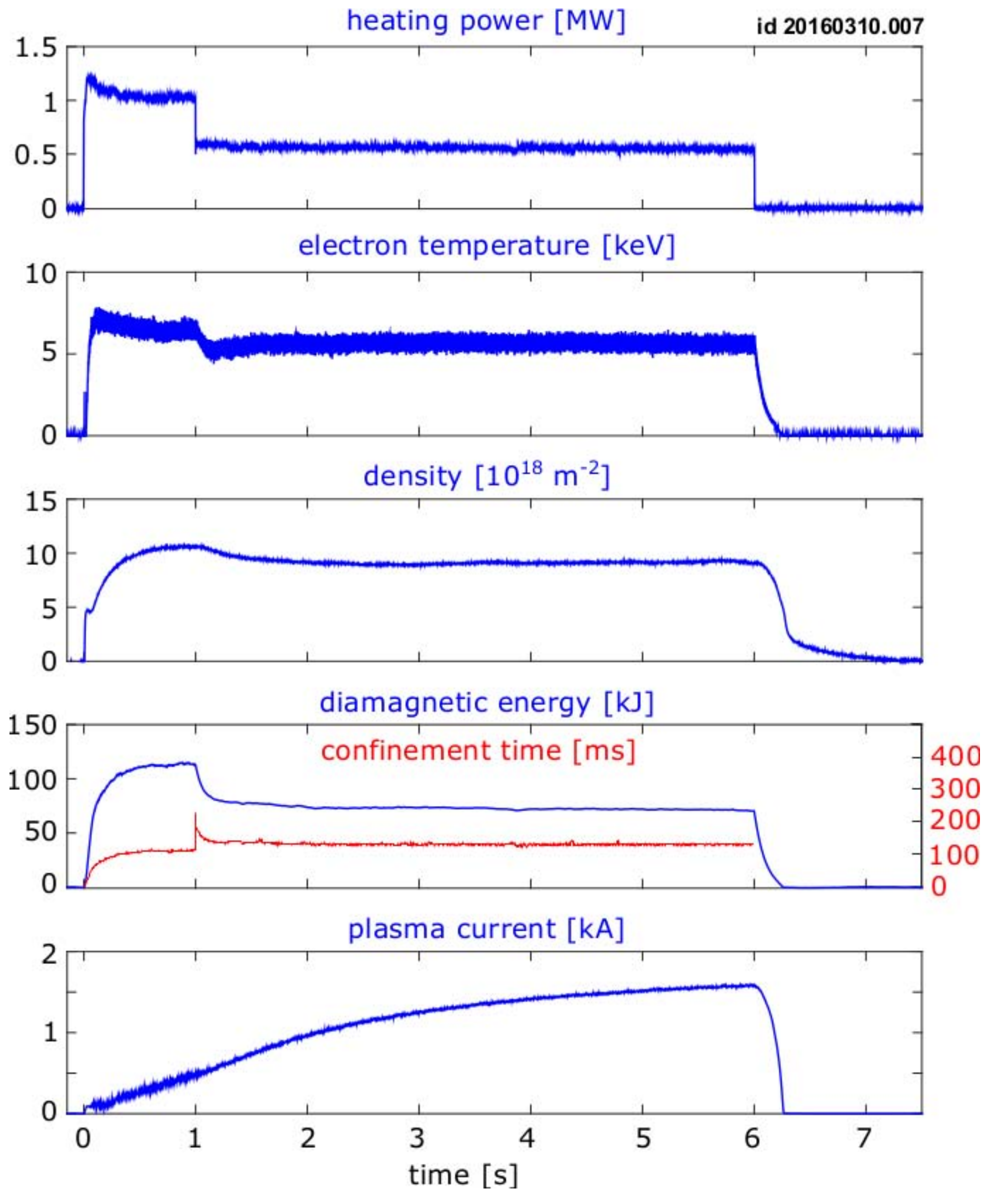
diamagnetic energy

$E_{dia} \leq 400$ kJ

toroidal current

$I_{BS} \leq 1000$ A

A Long-pulse Hydrogen Discharge



wall conditioning

- 10 glow discharge electrodes
- ECR wall conditioning
- decisive for density control

diamagnetic energy

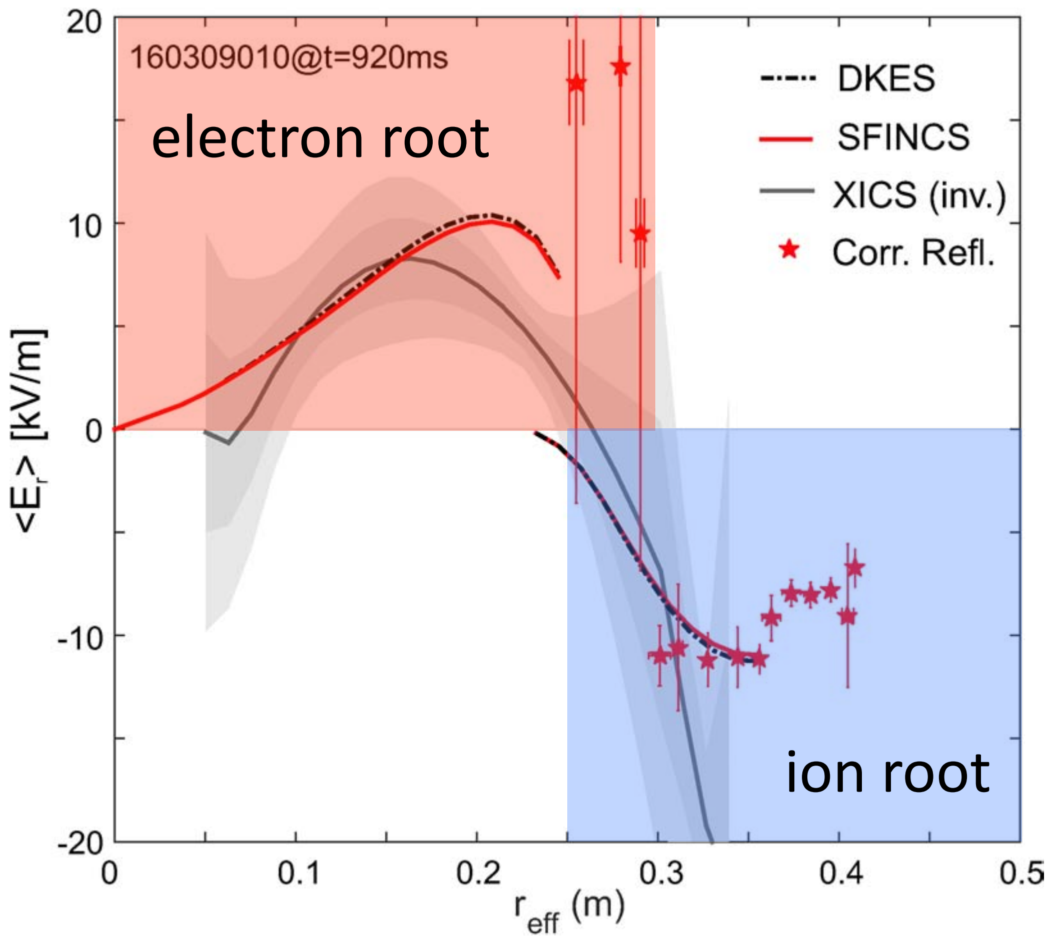
$E_{dia} \leq 100$ kJ

toroidal current

$I_{BS} \leq 1800$ A (still rising)

The Radial Electric Field

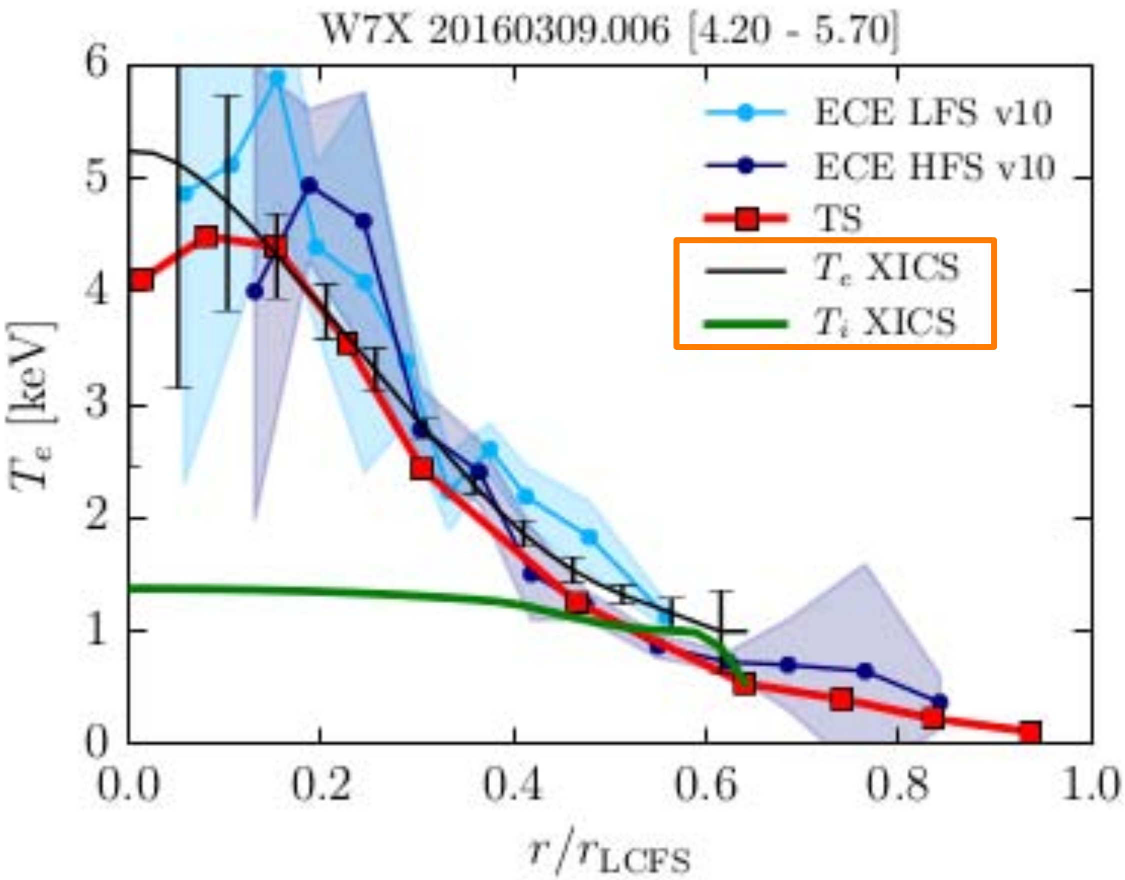
The radial electric field is decisive for necolassical transport and is measured by means of poloidal correlation reflectometry.



U Maryland

Peaked Temperature Profiles

peaked electron temperature profile with $T_e > T_i$



ECE

TS

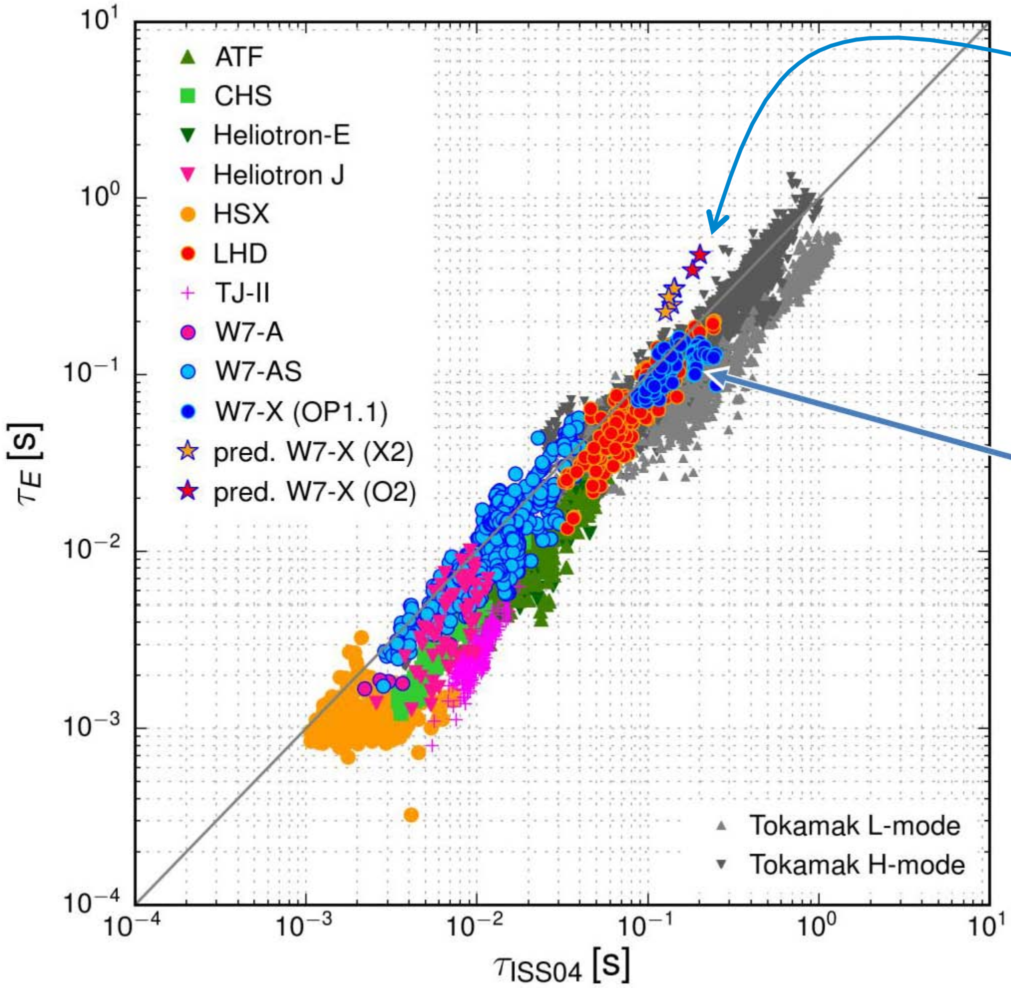
XICS

in good agreement

positive electric field for $r/r_{LFCS} < 0.6$ central electron root confinement (CERC)

ion temperature profile fairly flat

Energy Confinement Time



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

simulation points

for the ion-root regime

$$\left[\frac{\tau_{\mathrm{E}}}{\tau_{\mathrm{E,ISS04}}}\right]^{\mathrm{W7\text{-}X}} > \left[\frac{\tau_{\mathrm{E}}}{\tau_{\mathrm{E,ISS04}}}\right]^{\mathrm{W7\text{-}AS}}$$

measurement points

$\tau_{\mathrm{E}} \leq 150$ ms ~ ISS04 scaling

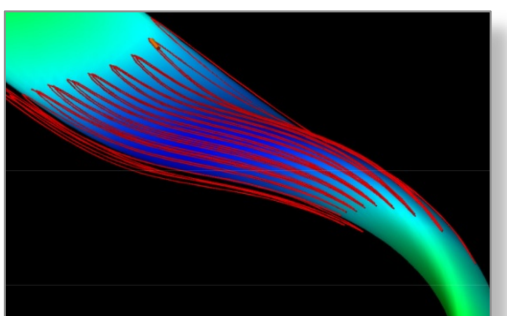
- best values CERC plasma $\propto\sqrt{\nu}$
- 1/3 volume CERC conditions
- 3/4 volume ISS04 conditions
- lower values at low P_h
- wall properties CuCrZr
- wall conditioning imperfect

Science Program – the Big Picture

Major milestones to reach are …

- constructability of a superconducting optimized stellarator ✓
- Tokamak-like confinement in integrated lmfp discharge scenarios
- high plasma density $>2\cdot10^{20}\,\mathrm{m}^{-3}$ microwave (140 GHz) heating scenarios
- full scale divertor performance with neutral and impurity control
- favourable stability and fast particle confinement at $\langle\beta\rangle \geq 4\%$
- very long pulse 1800 s discharges at 10 MW heating power

The key elements are …



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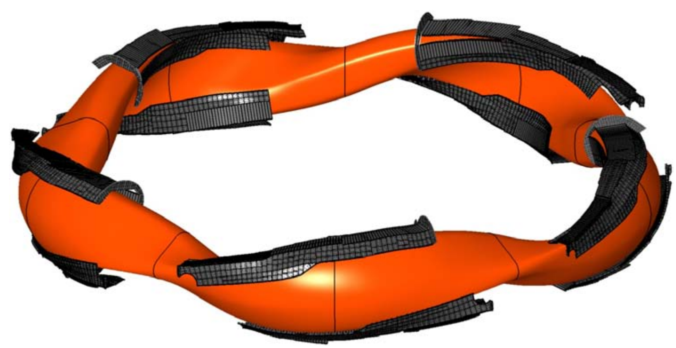
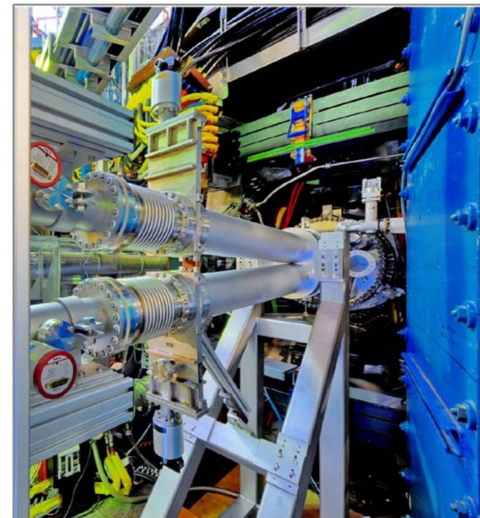


optimized magnetic field **water-cooled island divertor**

Extension in Various Areas

island divertor
graphite wall

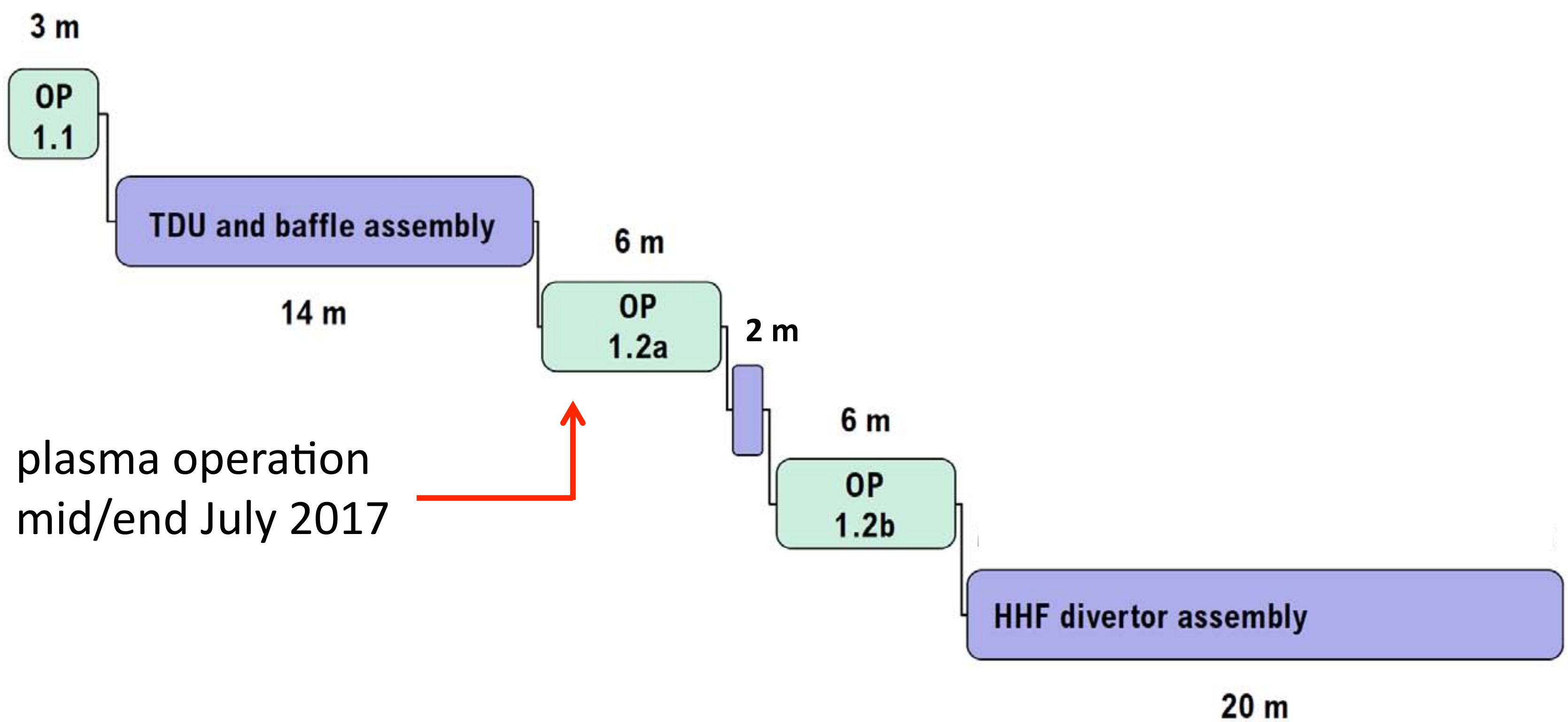


> 20 additional
diagnostic systems

9 MW ECRH
2 MW ICRH
3.5 + 3.5 MW NBI (H^+)

The Coming Years

During the coming years we have a sequence of completion and operation phases.



Staged approach to full performance long-pulse operation starting in mid 2020.

The Three Stages

OP 1.1 12/2015 - 3/2016 10 weeks He and H operation	uncooled graphite limiters no wall coverage $E_{max} = 2\text{ MJ} \rightarrow 4\text{ MJ}$	$P_{ECRH} = 4.3\text{ MW}$	$T_e = 8\text{ keV}$ $T_i = 2.5\text{ keV}$ $n = 4.5 \cdot 10^{19}\text{ m}^{-3}$ $\beta_0 > 2.5\ \%$
OP 1.2 7/2017 - 9/2018 2×16 weeks H operation	uncooled graphite divertor graphite wall $E_{max} = 80\text{ MJ}$	$P_{ECRH} = 8\text{ MW}$ $P_{ICRH} = 1.6\text{ MW}$ $P_{NBI}{}^{H} = 7\text{ MW}$	$T_e{}^{NC} = 5\text{ keV}$ $T_i{}^{NC} = 4\text{ keV}$ $n^{NC} = 1.6 \cdot 10^{20}\text{ m}^{-3}$
OP 2 2020 onwards to be specified H and D operation	water-cooled CFC divertor graphite wall $E_{max} = 18\text{ GJ}$	$P_{ECRH} = 10\text{ MW}$ $P_{ICRH} = 4\text{ MW}$ $P_{NBI}{}^{D} = 10\text{ MW}$	$T_e{}^{NC} = 5\text{ keV}$ $T_i{}^{NC} = 5\text{ keV}$ $n^{NC} = 2 \cdot 10^{20}\text{ m}^{-3}$ $\langle\beta\rangle = 5\ \%$

Numerous Diagnostic Systems

- coherence imaging system
- visible divertor spectroscopy
- divertor bolometer
- divertor infrared cameras
- laser induced fluorescence
- divertor Langmuir probes
- divertor PWI targets
- PWI Si wavers
- alkali metal beam
- H_α cameras
- X-ray tomographic cameras
- pellet injector + mass det.
- probes for manipulator
- phase contrast imaging
- laser blow-off system
- impurity pellets
- C-O monitor
- Z_{eff} profile diagnostic
- CXRS and BES at NBI
- collective Thomson scattering
- profile reflectometer
- imaging bolometer

} **new**

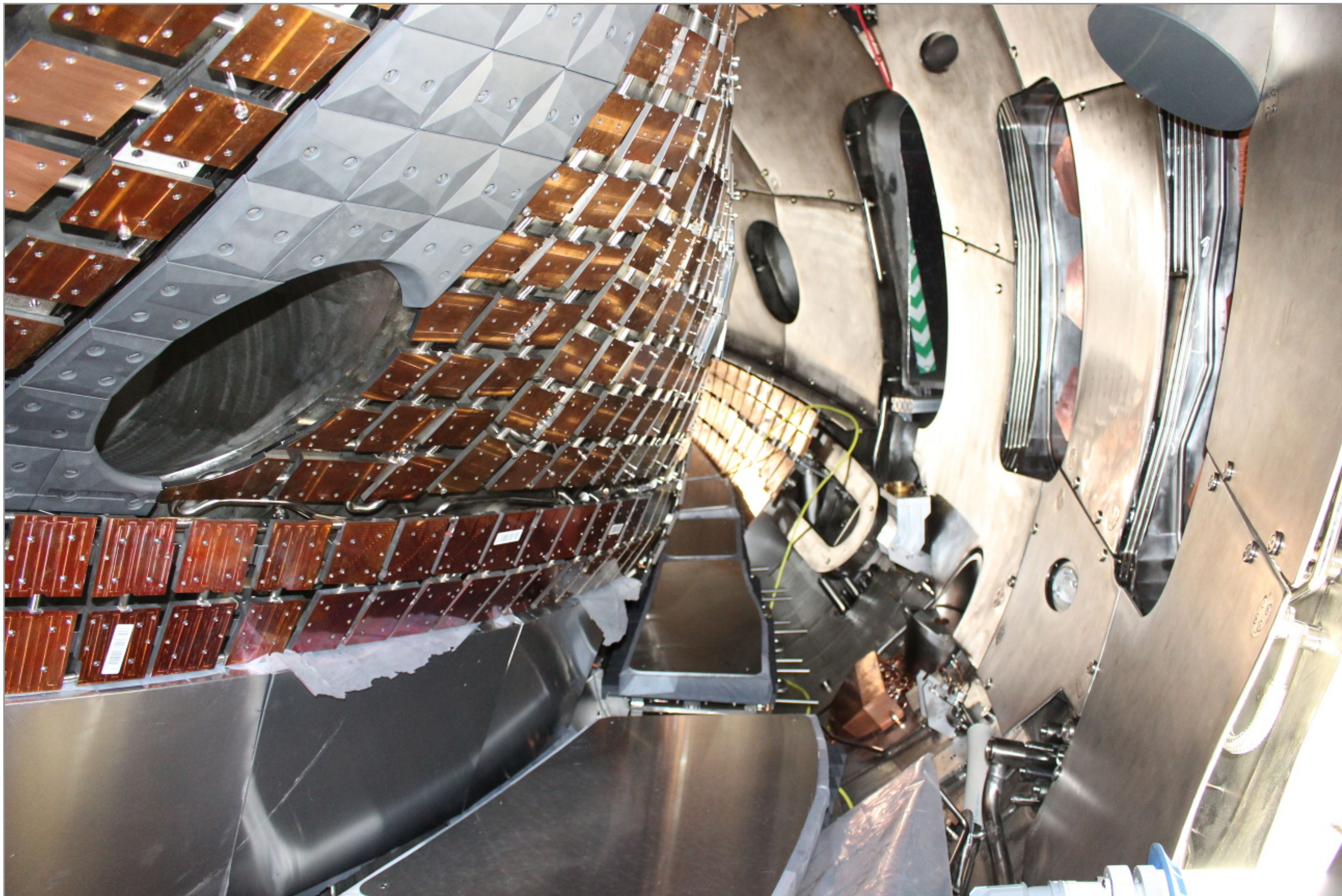
- video camera system
- Thomson system
- ECE system
- Doppler reflectometer
- neutron counter
- magnetic diagnostics
- bolometer systems
- interferometer
- helium beam
- flux surface measurement
- impurity spectrometer
- pulse height analysis
- X-ray imaging camera systems

} **improved**

EUROfusion NIFS

PPPL Los Alamos National Laboratory Est. 1943 Oak Ridge National Laboratory Wisconsin University of Wisconsin–Madison Auburn University Massachusetts Institute of Technology

Current In-vessel Situation (yesterday)



Summary

- Wendelstein 7-X is a physics-optimized SC stellarator
- completed after 15 years of construction (1,060 Mio€ total cost)
- after one year commissioning the machine works perfectly fine
- first 10 weeks of plasma operation suprisingly successful
- now installation of 10 island divertor modules and graphite wall
- allows for increased plasma performance and longer discharges

What did we learn already?

- better plasma parameters and performance than expected
- $T_e > 8$ keV and $T_i > 2$ keV at $n > 4 \cdot 10^{19} \mathrm{m}^{-3}$ yields $\beta_0 \sim 2.5\%$
- 4 MJ microwave energy fully absorbed
- core electron root confinement established
- even more science: crashes, filaments, impurity transport, …