

First results from Wendelstein 7-X

**Thomas Sunn Pedersen
for the W7-X Team***

Professor of Physics and
Director of Stellarator Edge and Divertor Physics
Max-Planck-Institut für Plasmaphysik, Greifswald

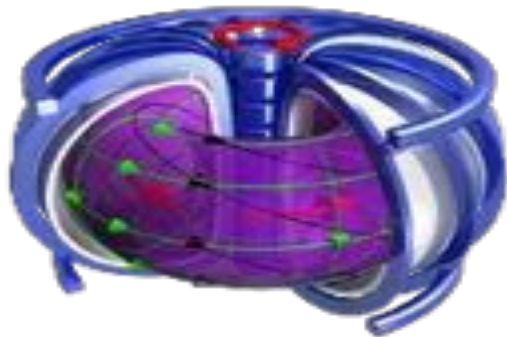
* List of contributors on last slide



- Introducing the Wendelstein 7-X stellarator
- Time line and goals for operation phases 1.1, 1.2, and 2
- Some details about OP1.1
- OP1.1 results:
 - Flux surface measurements
 - First plasmas
 - Scrape-off layer physics
 - Top performance discharges in He and H
- Plans for the rest of OP1.1
- Conclusions

Tokamak and stellarator

- twisted magnetic field
- strong toroidal current in plasma



- Excellent plasma confinement
- Plasma instabilities require control
- steady-state confinement requires strong current drive

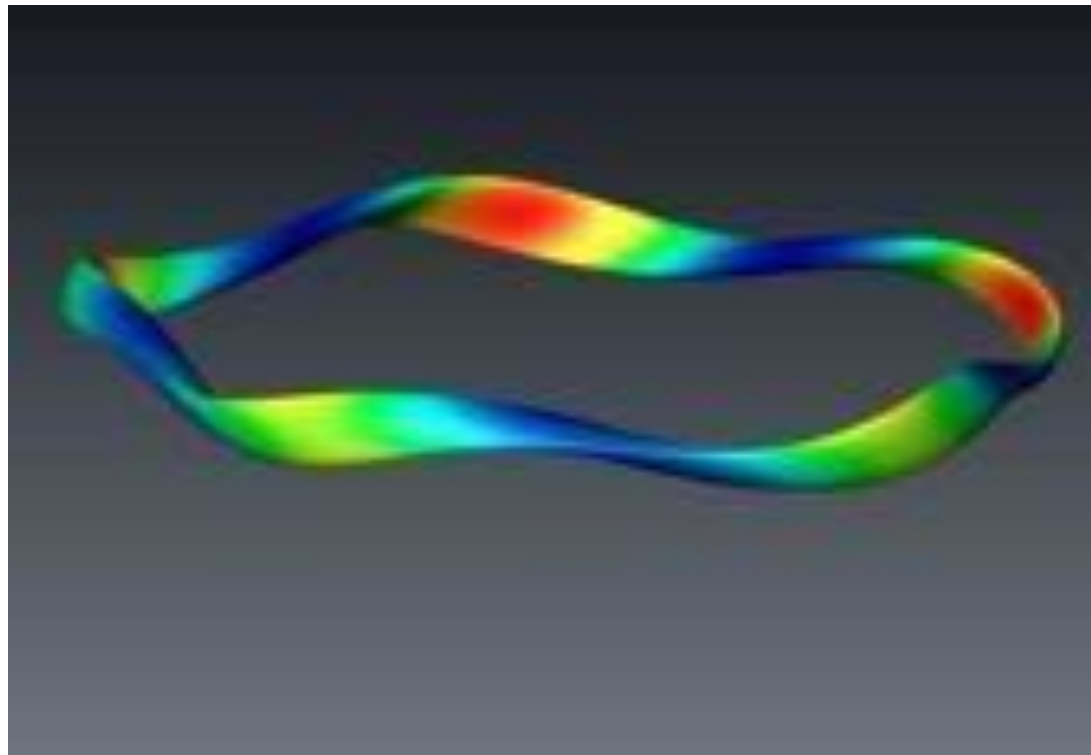
- twisted magnetic field
- weak, self-generated toroidal current



- Excellent plasma confinement to be proven
- more stable plasma conditions
- steady-state capability

Magnetic field optimization

Advances in our understanding as well as in supercomputer power has allowed a comeback for the stellarator concept.



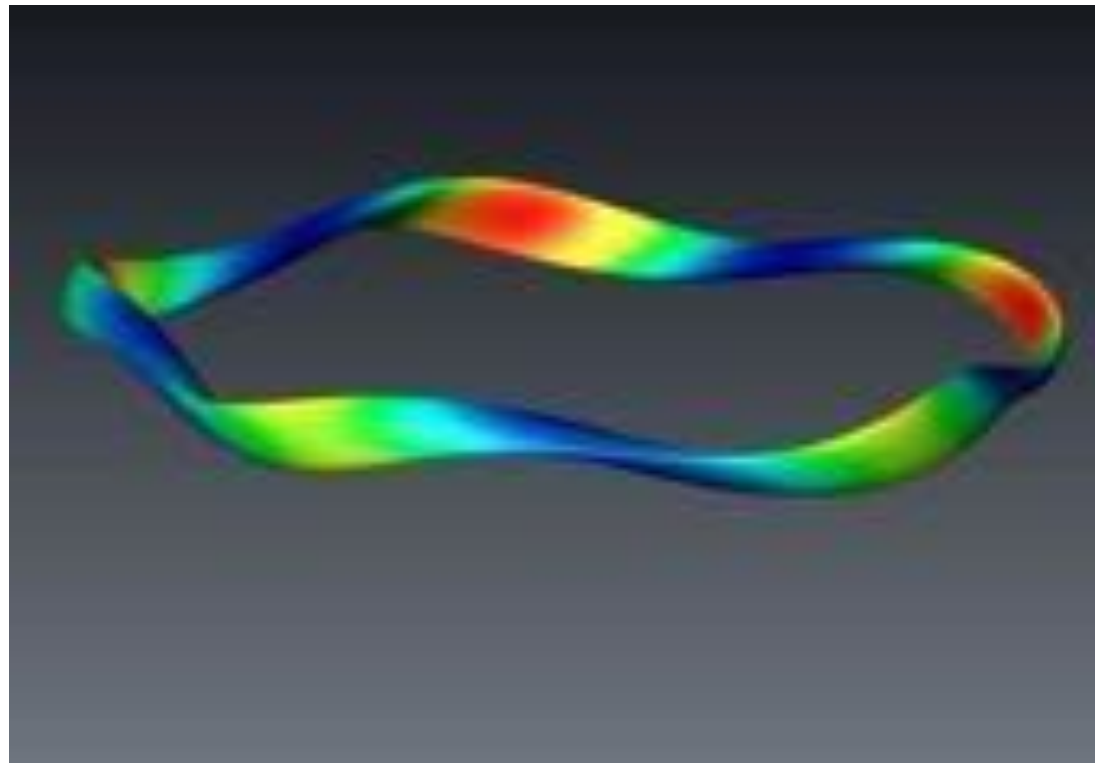
- Poloidally closed contours of $|B|$ ensure that the magnetic drifts do **not** lead to prompt orbit losses
 - Recall that the magnetic drifts lie on the $|B|=\text{const}$ surfaces:

$$\vec{v}_{\nabla B + R_C} = \frac{2mv_{\parallel}^2 + mv_{\perp}^2}{2B} \frac{\vec{B} \times \nabla B}{qB^2}$$

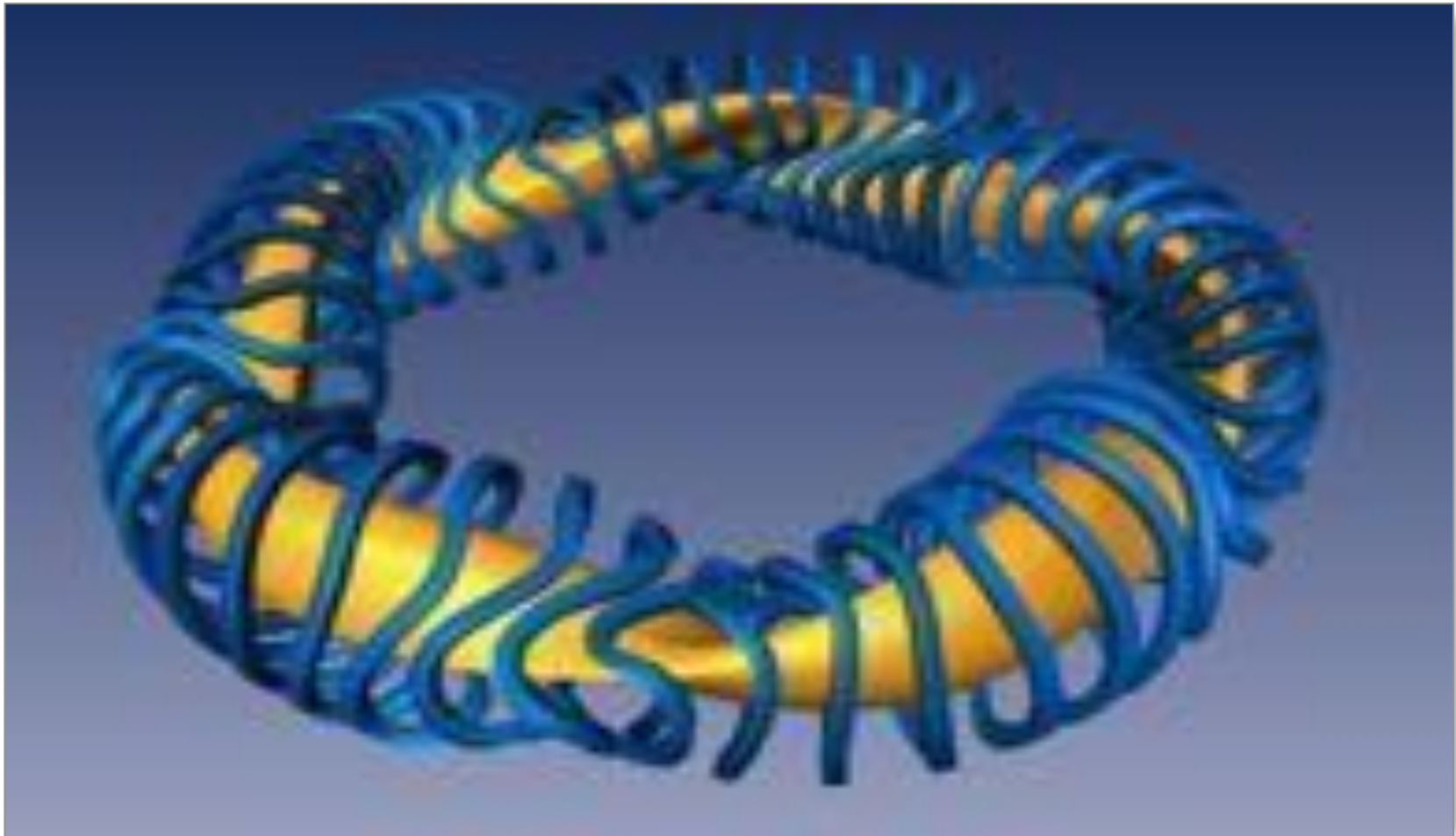
- Other optimizations introduce a non-trivial (quasi-) symmetry so that the magnetic drifts average out for almost all particles
 - HSX (quasi-helical symmetry)
 - NCSX/QUASAR (quasi-toroidal symmetry)
 - Tokamaks: toroidal symmetry

Magnetic field optimization

(The movie again: illustrating the B-field strength symmetry)



Design of magnetic field coils



Design of the stellarator

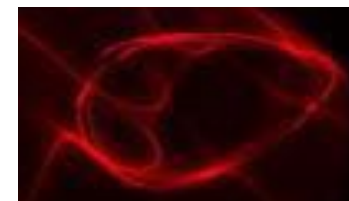
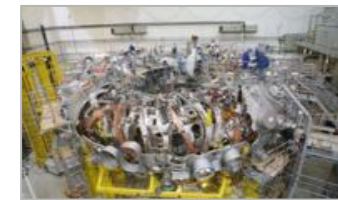


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(2015)

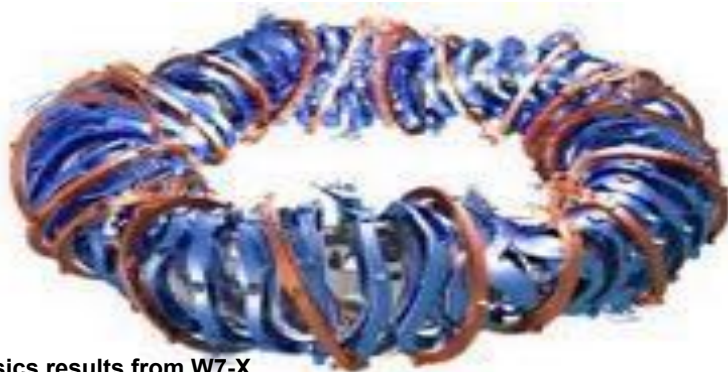
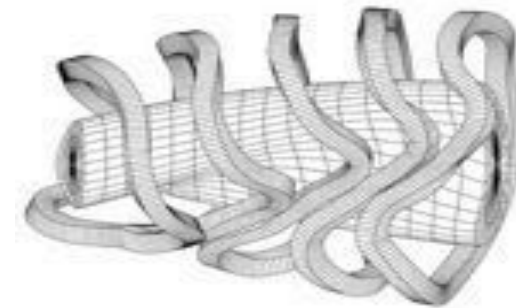
First physics results from W7-X

Milestones

Ministerial decision	1993
Official start of the project	1996
Start of construction	1997
Move into new building	2000
Termination of predecessor W7-AS	2002
Arrival of first magnet	2004
Start of magnet assembly	2005
New timeline agreed	2007
Arrival of the last magnet	2010
Magnet system complete	2013
Last weld seam on the vessels done	2013
Start commissioning	2014
Technically ready for plasma operation	07.2015
Start plasma operation	12.2015



1. high quality of vacuum magnetic surfaces
2. good finite equilibrium properties @ $\langle \beta \rangle = 5\%$
3. good MHD stability properties @ $\langle \beta \rangle = 5\%$
4. reduced neoclassical transport in $1/\nu$ -regime
5. small bootstrap current in Imfp-regime
6. good collisionless fast particle confinement
7. good modular coil feasibility



First physics results from W7-X

- Non-planar coils (blue)
 - Standard configuration
- Planar coils (red)
 - Iota changes
 - (De)optimization

Facts and figures



- 735 t mass with 435 t cold mass
 - 70 superconducting NbTi coils
 - 2.5 T on axis (coils rated to 3 T)
 - 254 ports of 120 different types
 - 30 m³ plasma volume
 - $R=5.5$ m, $a=0.5$ m
- five magnetic field periods
 - modular non-planar coils
 - optimized
 - low bootstrap current $O(30$ kA)
 - high iota and low shear

Some key figures

Cost of actual device	370 Mio. €
Other investments	150 Mio. €
Personnel costs (19 y)	310 Mio. €
Running costs (19 y)	230 Mio. €
Total (1996-2014)	1060 Mio. €

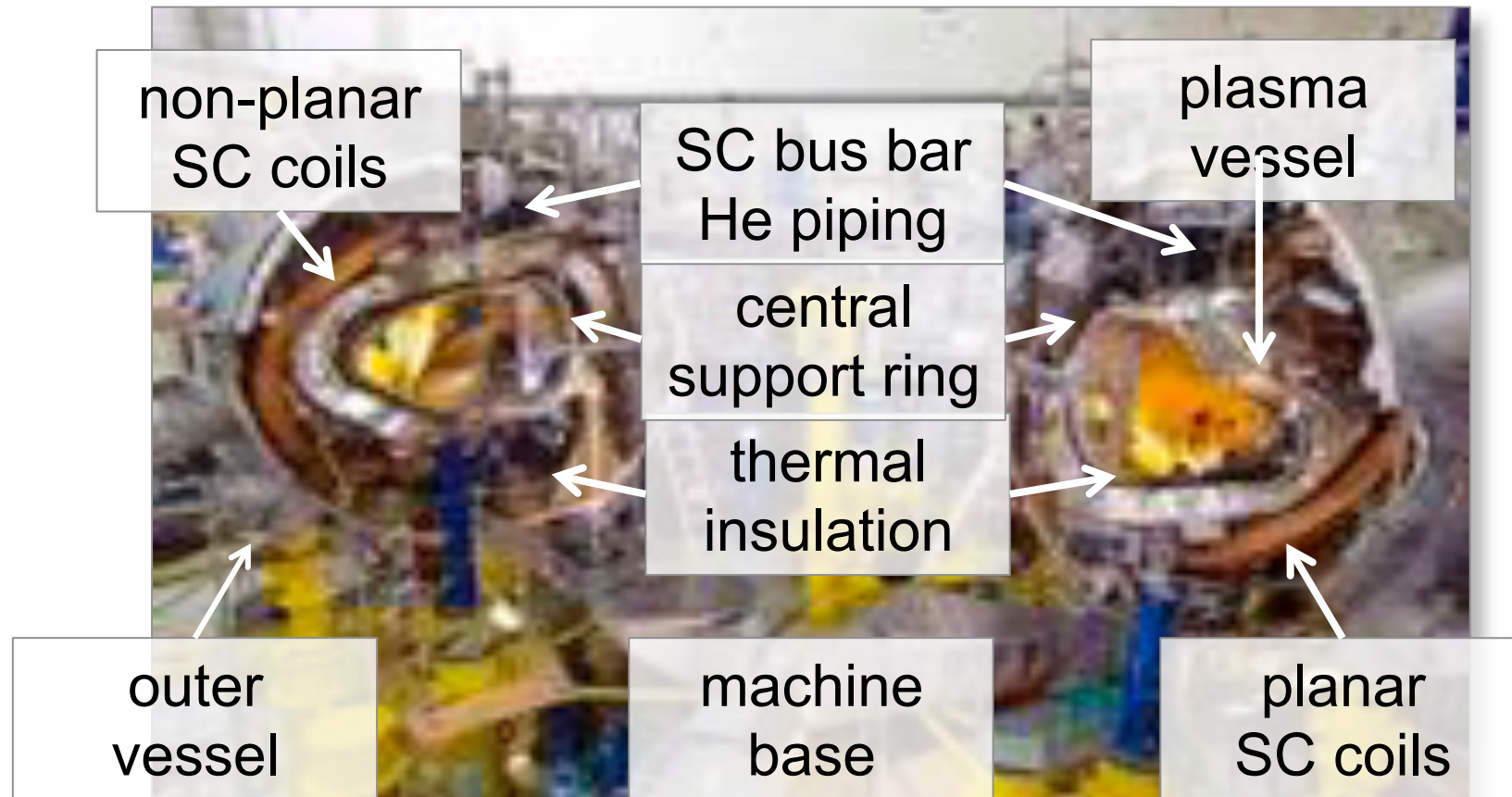


First physics results from W7-X

A magnet module

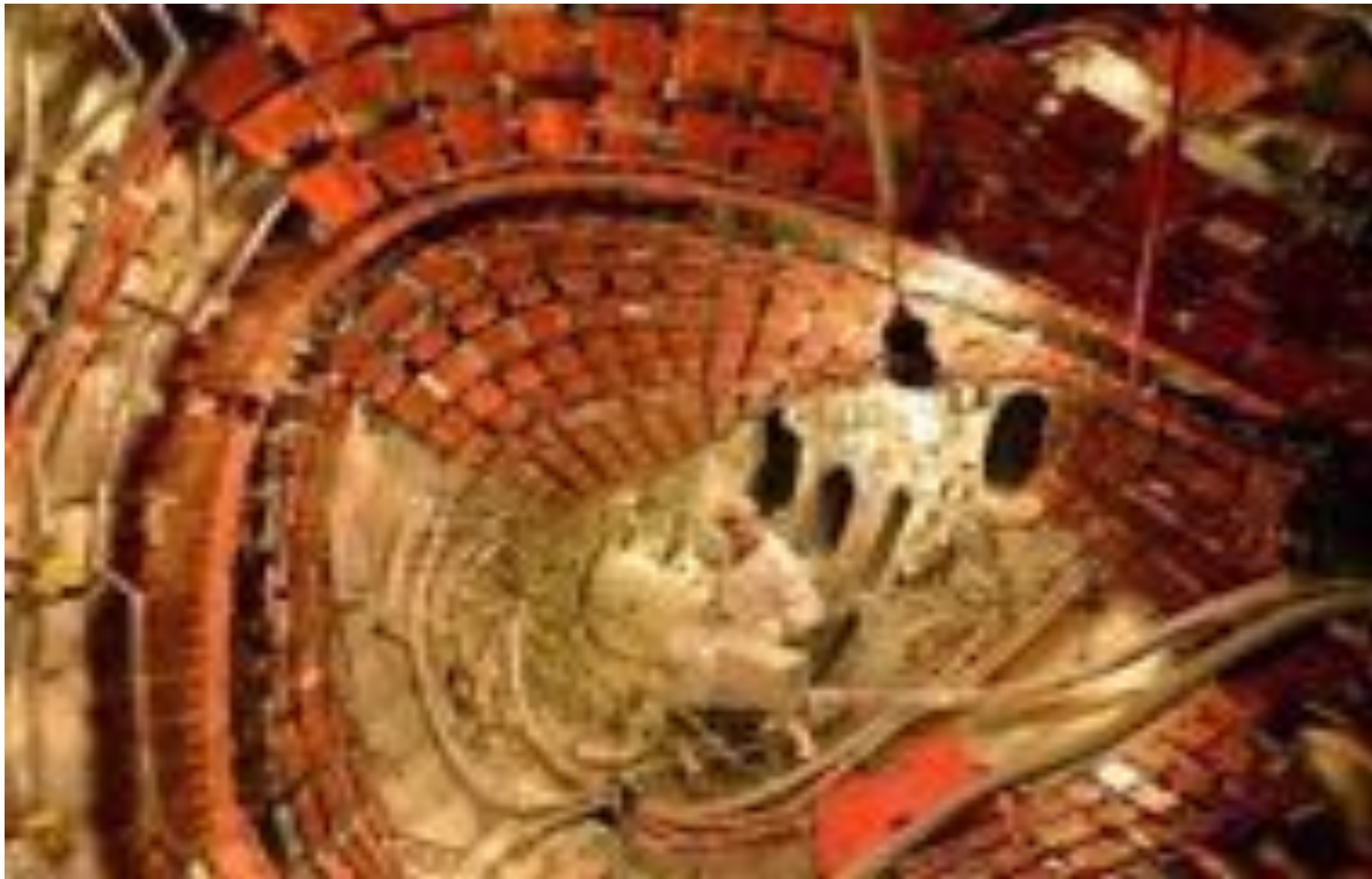


During device assembly

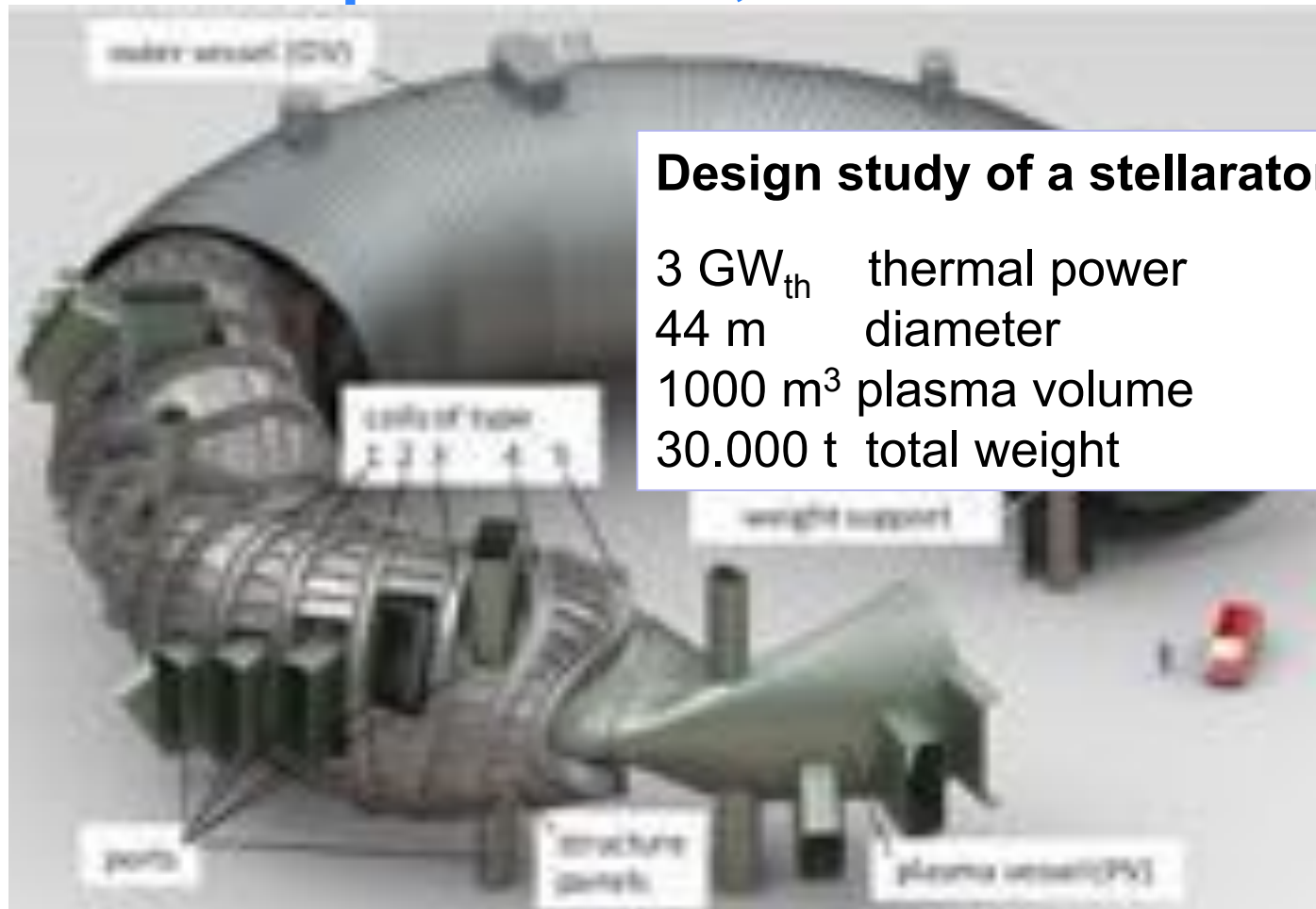




A view inside the device



Power plant vision, W7-XXL



Design study of a stellarator reactor

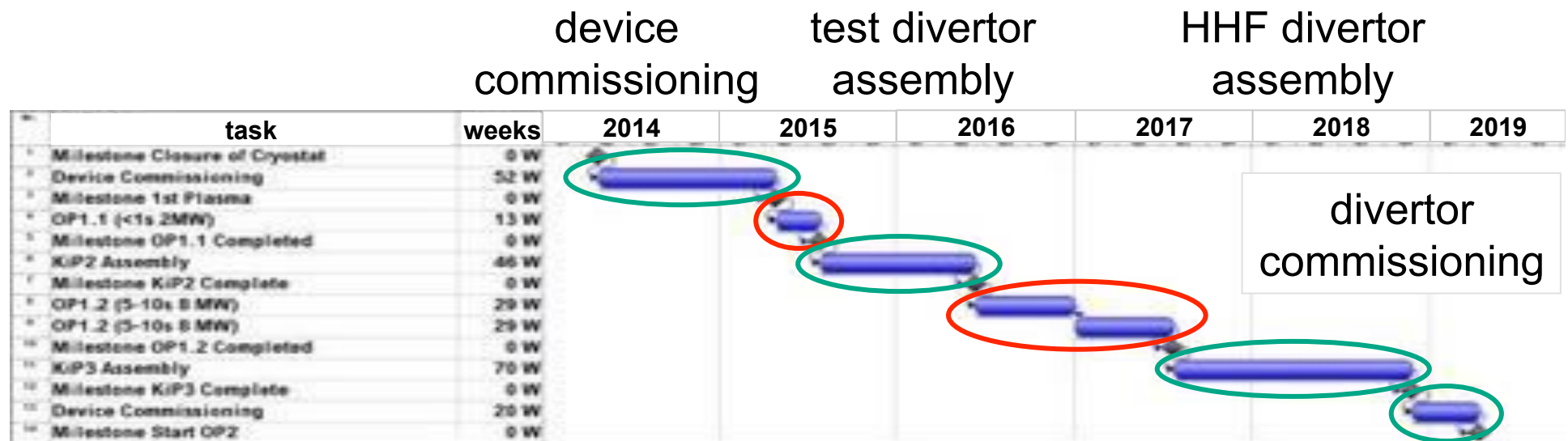
3 GW_{th} thermal power
44 m diameter
1000 m³ plasma volume
30.000 t total weight

Time-lapse movie of construction



First physics results from W7-

Near-term planning



plasma commissioning
diagnostics/control
first investigations

1st plasma
w/o divertor

1st divertor
plasmas
science

steady-state
plasmas

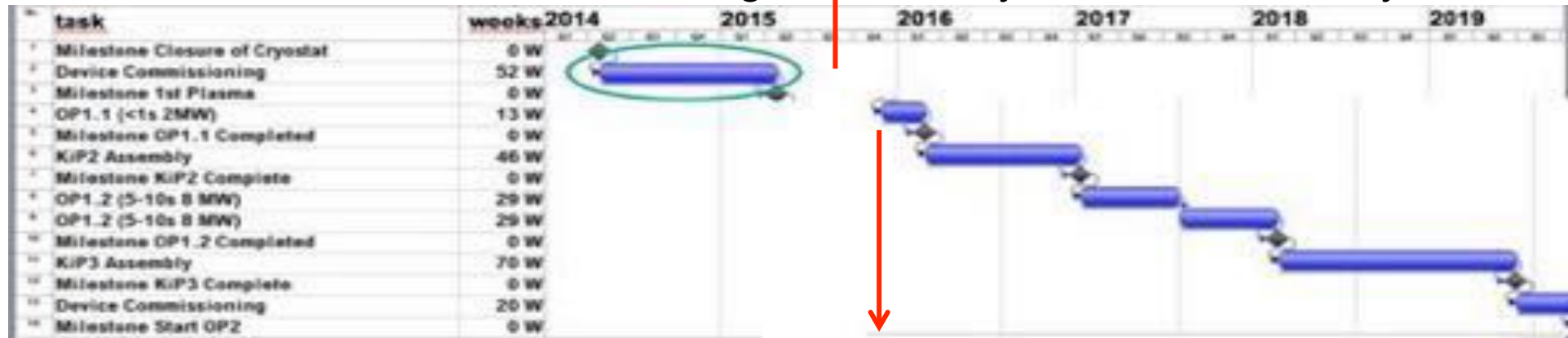
Near-term planning „updated“

Technically ready for 1st
plasmas in July 2015

device
commissioning

test divertor
assembly

HHF divertor
assembly



Dec. 10, 2015

1st plasma
w/o divertor

1st divertor
plasmas
science

steady-state
plasmas 2020

plasma commissioning
diagnostics/control
first investigations

First Operation Phases (OP) in Figures

OP 1.1 2015-16 3 months

Pulse limit: $E_{\max} \sim 2\text{ MJ}$
Graphite limiters, uncooled

$P_{\text{ECRH}} \sim 5\text{ MW}$
6 gyrotrons

$T_e^{\text{NC}} \sim 4\text{ keV}$
 $T_i^{\text{NC}} \sim 1\text{ keV}$
 $n \sim 2 \times 10^{19}\text{ m}^{-3}$
 $\langle b_{\text{NC}} \rangle \sim 1\%$

OP 1.2 2017 2*5 months

Pulse limit: $E_{\max} \sim 80\text{ MJ}$
Graphite divertor, uncooled

$P_{\text{ECRH}} \sim 8\text{ MW}$
 $P_{\text{NBI}}^{\text{H}} \sim 7\text{ MW}$
 $P_{\text{ICRH}} \sim 1.6\text{ MW}$

$T_e^{\text{NC}} \sim 5\text{ keV}$
 $T_i^{\text{NC}} \sim 4\text{ keV}$
 $n \sim 1.6 \times 10^{20}\text{ m}^{-3}$
 $\langle b_{\text{NC}} \rangle \sim 3\%$

OP 2 2020

Pulse limit: $E_{\max} \sim 18\text{ GJ}$
 $= 10\text{ MW}$ for 30 minutes
 20 MW for 10 seconds at a
time
CFC water-cooled divertor

$P_{\text{ECRH}} \sim 10\text{ MW}$
 $P_{\text{NBI}}^{\text{D}} \sim 10\text{ MW}$
 $P_{\text{ICRH}} \sim 4\text{ MW}$
 $P_{\text{tot}} < 20\text{ MW}$

$T_e^{\text{NC}} \sim 5\text{ keV}$
 $T_i^{\text{NC}} \sim 5\text{ keV}$
 $n \sim 2.4 \times 10^{20}\text{ m}^{-3}$
 $\langle b_{\text{NC}} \rangle \sim 5\%$

PFCs for first plasma operation (OP1.1)



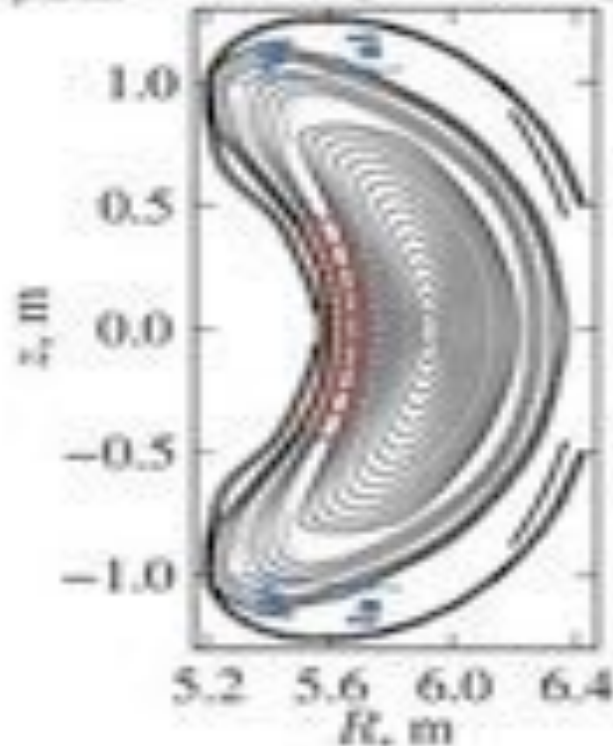
First physics results from W7-X

- Wall protection (SS)
- Heat shields (CuCrZn heat sinks)
- No divertor in the first phase
- 5 graphite limiters at the inner wall
- Must intersect convective plasma heat loads
- Designed for $5 \cdot 0.4 \text{ MJ} = 2 \text{ MJ}$ per pulse





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

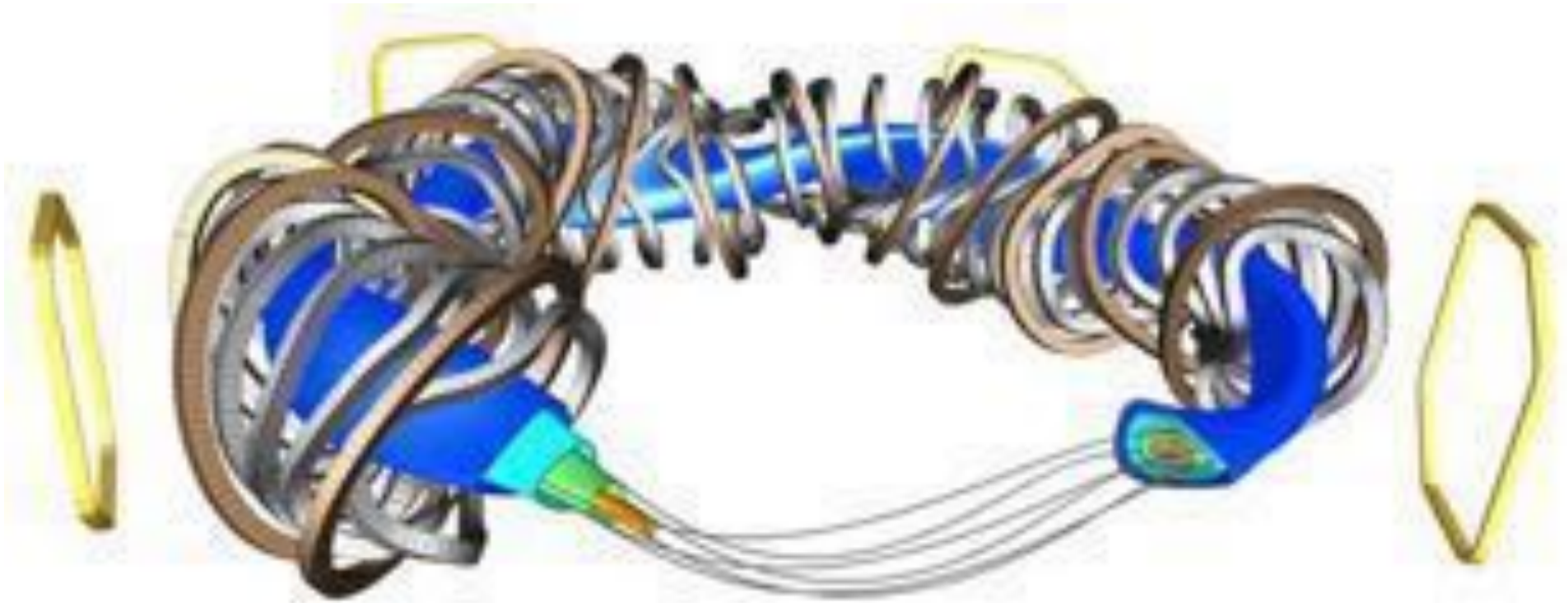


- Make sure limiter intersects >99% of the heat load: Vary iota using planar coils:

- Avoid large islands at the edge
- Avoid stochastic regions at the edge
- Limit several cm of good flux surfaces
- Robust against field errors (in particular 1/1)

✓ $I_{\text{planar}} = 0.13$ chosen

Magnetic flux surfaces



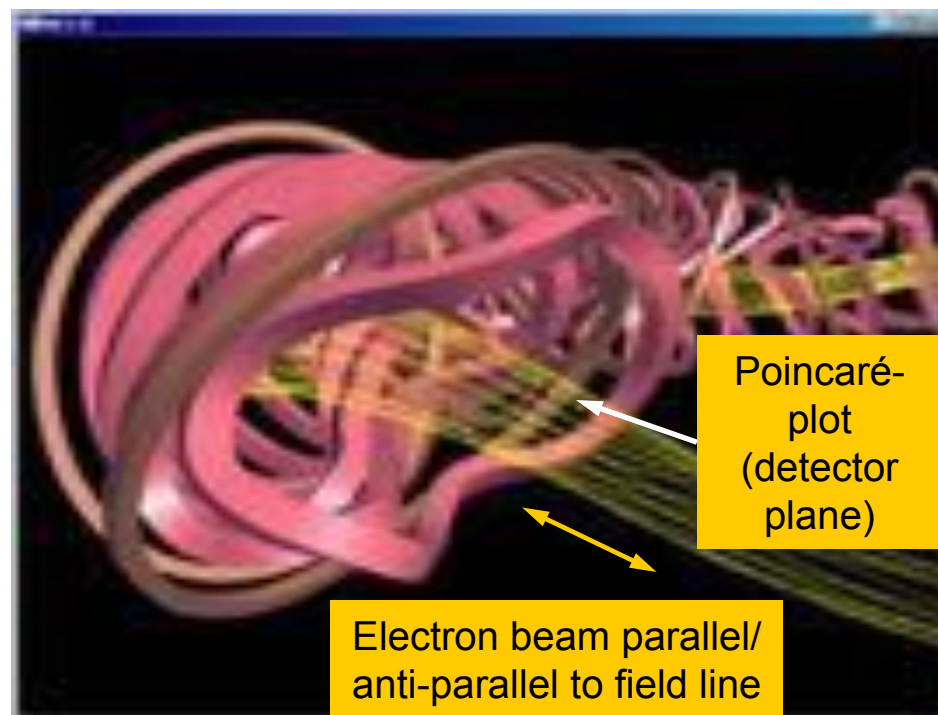
First physics results from W7-X

FSM: Basic Concept

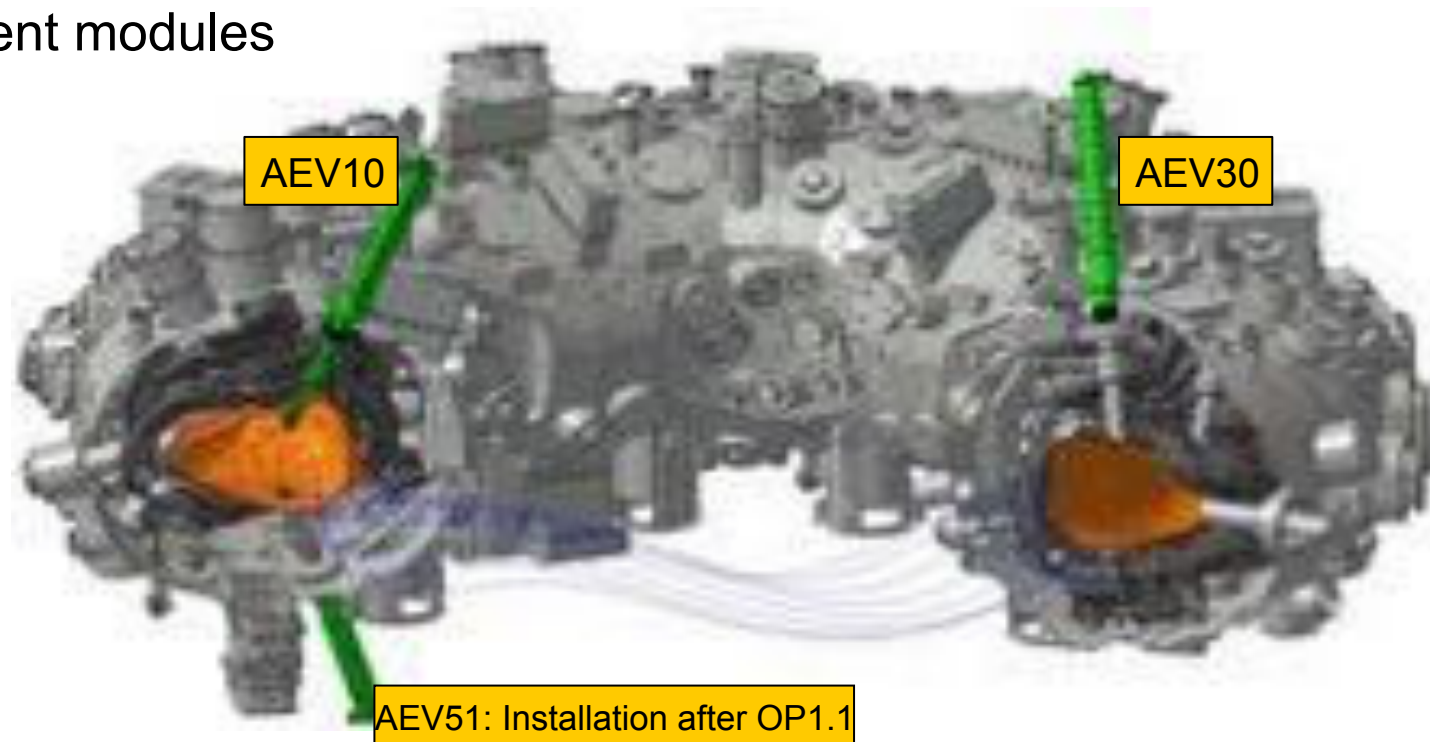
Prerequisites:

- Evacuated plasma vessel $<10^{-5}$ mbar and magnetic field of >50 mT
- Electron beam emitted parallel/ antiparallel to magnetic field line
- Optical detection of the e-beam by interaction with
 - background gas $\rightarrow$ 3D structure of the field line in whole torus

First physics results from W7-



- Three manipulators designed, manufactured and tested
- Two manipulators installed (AEV10 & 30) for measurements in two different modules



First physics results from W7-

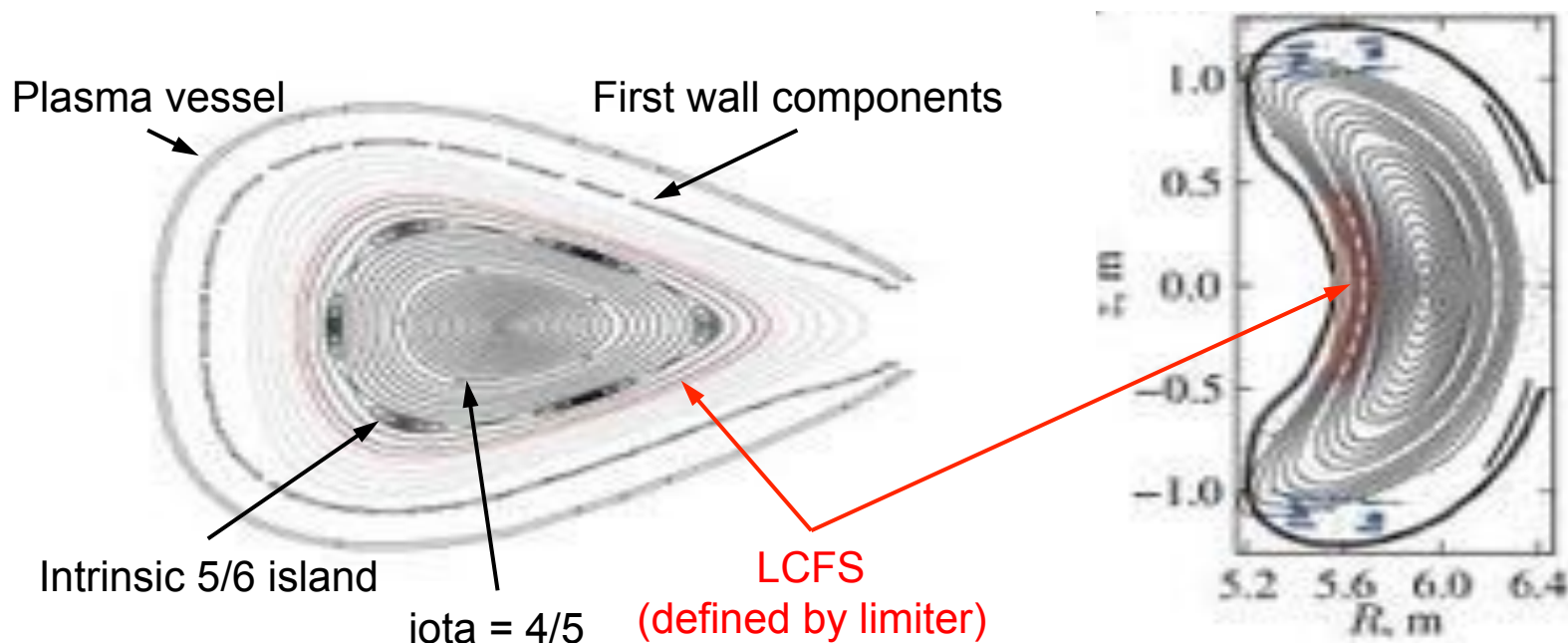


Configuration for OP1.1 plasma operation



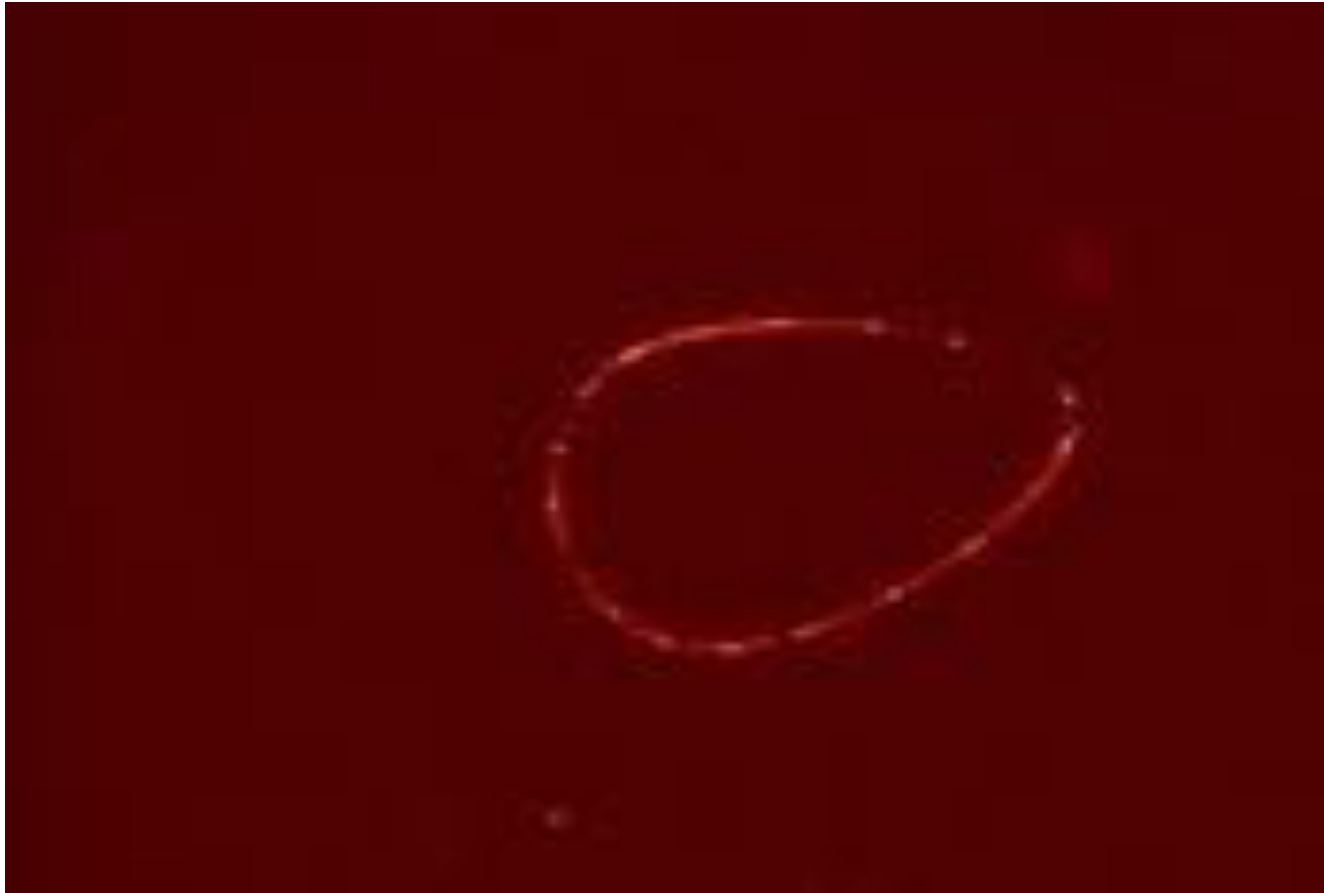
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für Plasmaphysik

- Low order rational $n/m=5/6$ inside confinement region, but insensitive against potential $n=1$ error fields

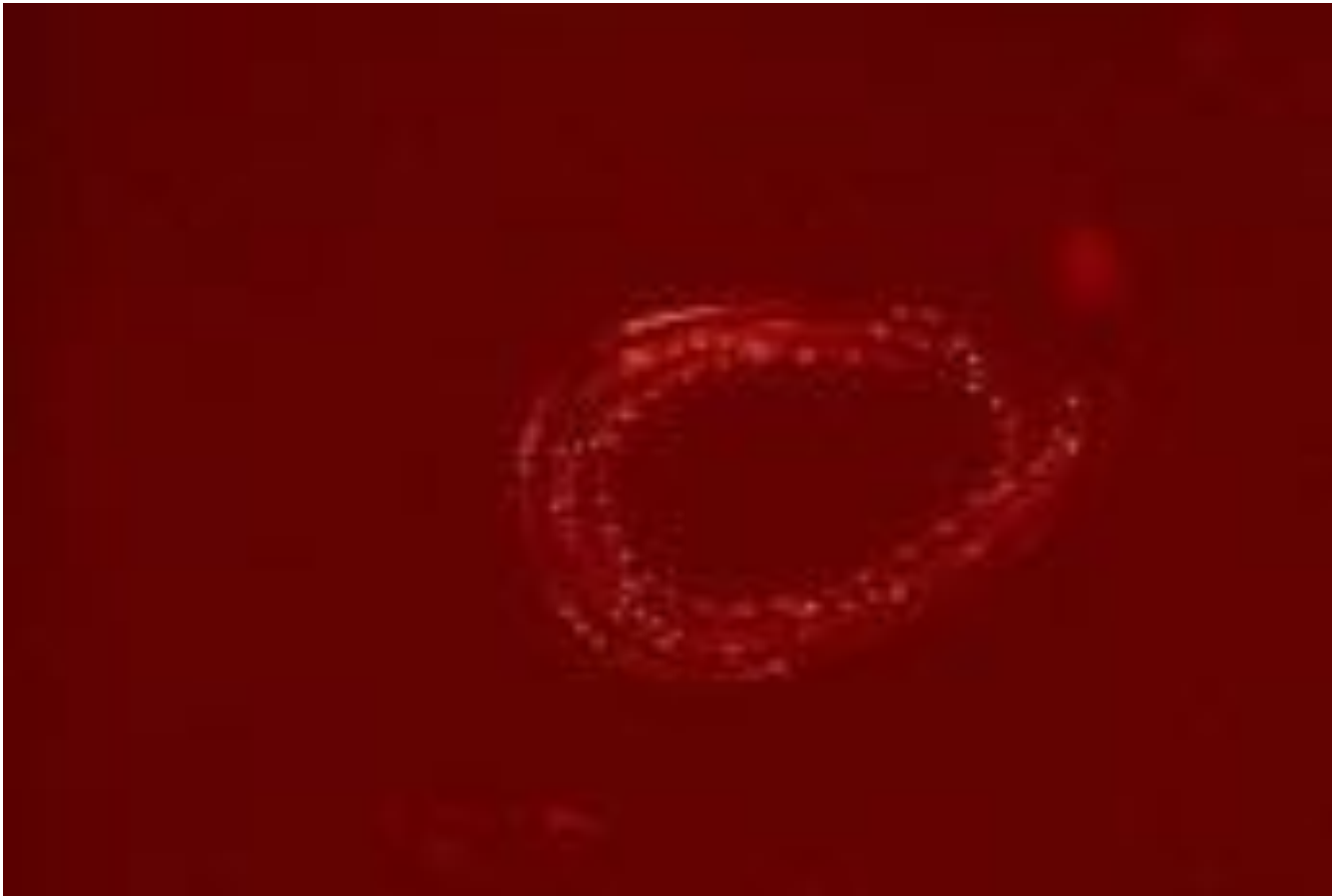


First physics results from W7-

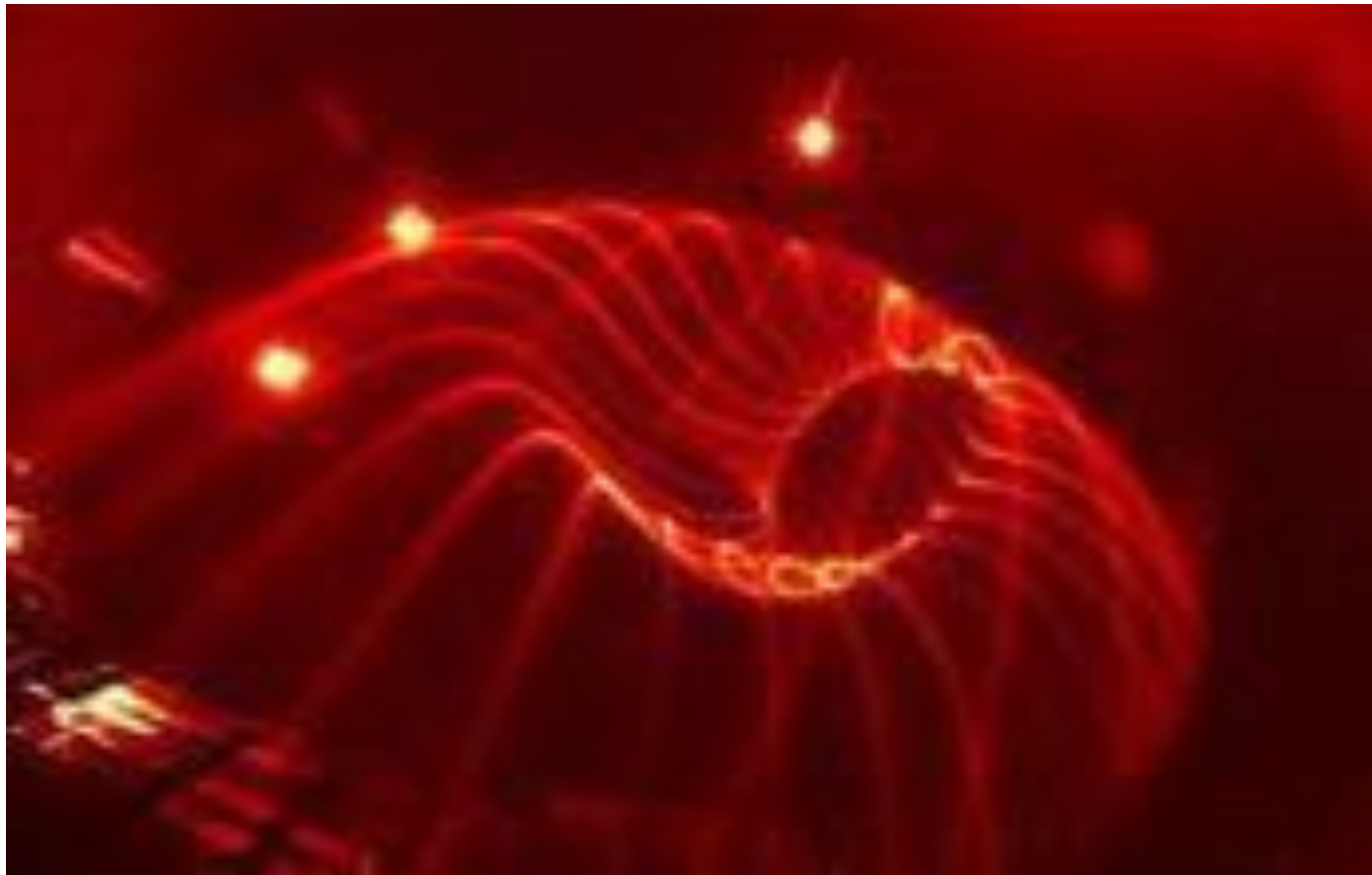
A cut through a magnetic flux surface



More magnetic flux surface

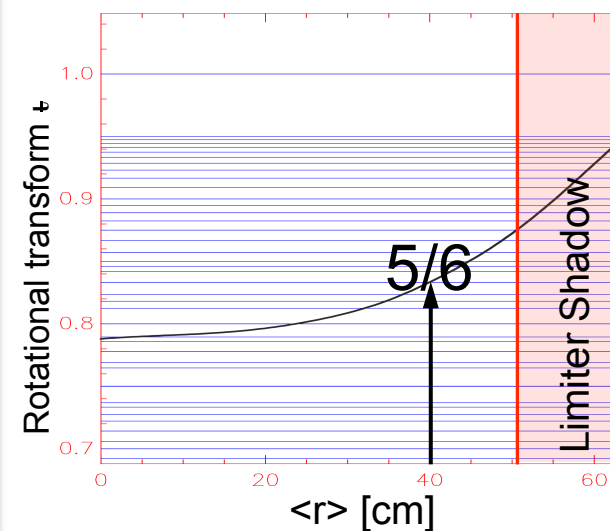


3D magnetic field lines visualized



Intrinsic $n/m = 5/6$ island chain

- Combination of field line tracing and flux surface measurements by moving the fluorescent detector within 65s (Poincaré plot)
- Radial position, orientation and flip symmetry of islands as expected

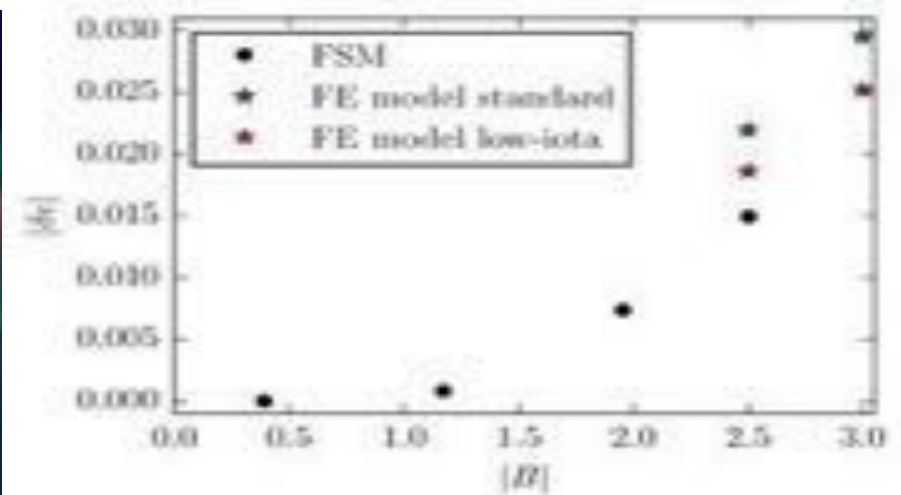
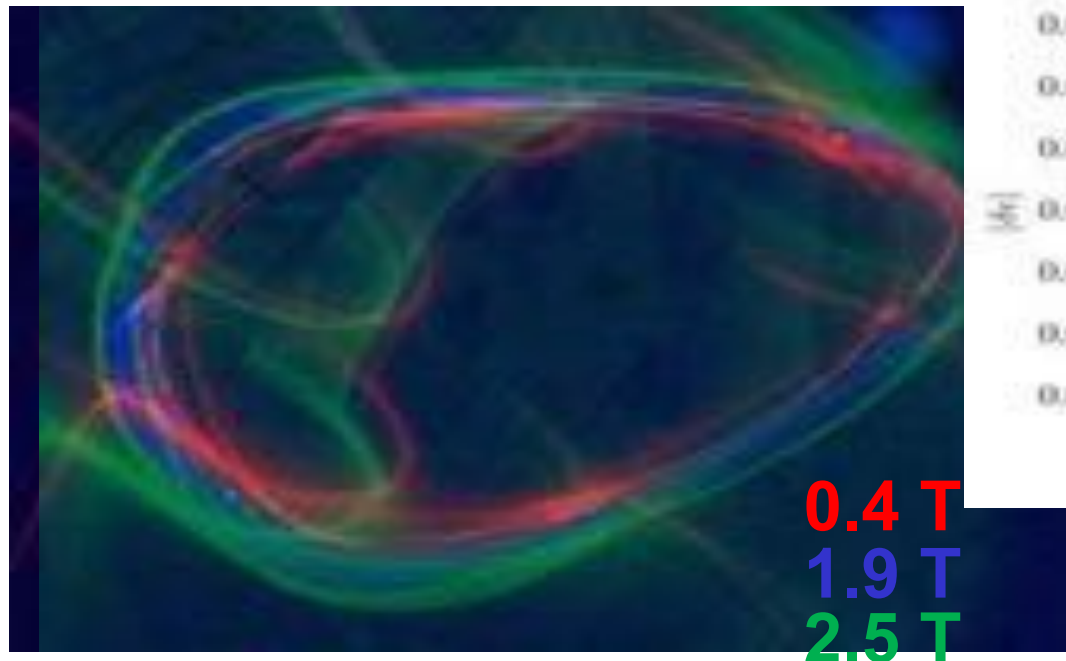


First physics results from W7-

Iota vs. Field Strength 1

Radial outward shift of 5/6 island chain with increasing field strength due to decrease of rotational transform

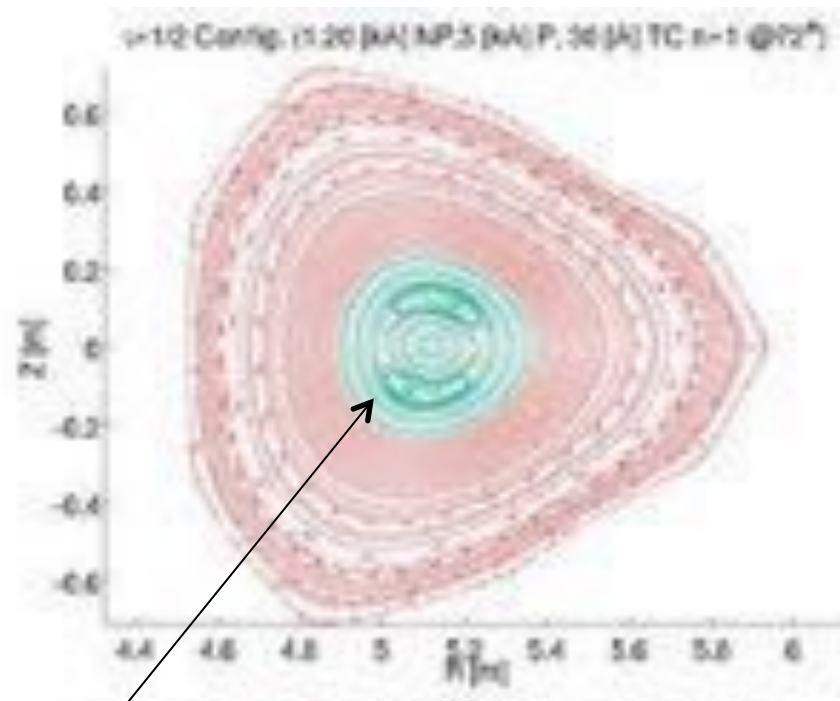
→ Confirmation of expected elastic deformation of non-planar coils by FEM simulations



First physics results from W7-X

- Before OP1.1, we did not want to change the polarity of the planar coils
- Can lower iota, but not increase it above the standard configuration iota
- Iota=0.5 is also resonant with n=1 field errors (iota=n/m=1/2)
- Iota=0.5 near the axis can be created by reduced current in non-planar coils, allowing dramatic decrease of iota at modest planar coil current
- Shape of flux surfaces is substantially different from limiter configuration (therefore the small volume of visible surfaces)
- Add error field with trim coils (30 A/turn!)
- Phase and amplitude of n=1 error still visible

5/10 natural island
chain



S. Lazerson et al.
(PPPL+IPP)

Error Field Studies at $i=1/2$

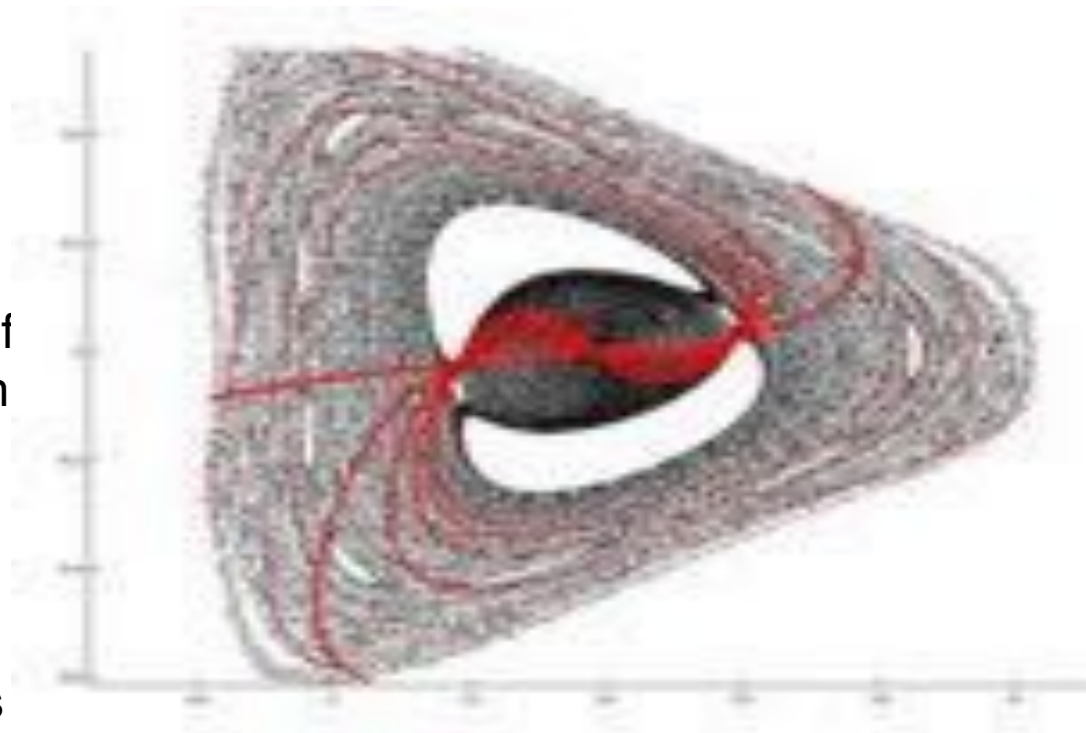
- Shadowing effect of e-gun limits observation at $i=1/2$ to two transits only
→ Potential island chain difficult to detected
- Finite shear is needed, so that the e-beam continues more than two turns



First physics results from W7-X

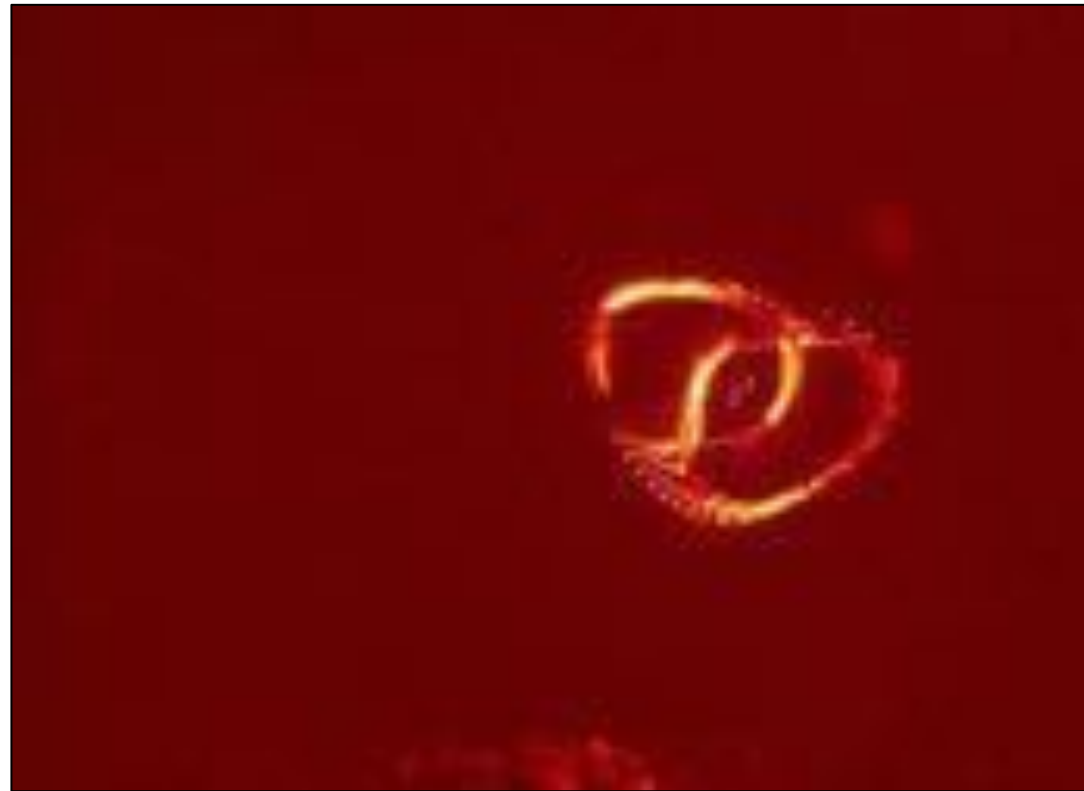


- A configuration was developed that has much more shear
- The first five transits of the e-beam are shown in red
- Inner and outer surfaces should be clearly visible with this configuration



S. Lazerson et al. (PPPL+IPP)

Success! $m/n=2/1$ island measured



2/1 island chain induced by trim coils set to produce $n=1$ error field

First physics results from W7-X

New configuration narrowly misses

- Self shadowing effect of the e-gun for $\iota=1/2$ configuration (e-beam hits backside of e-gun after two toroidal transits)
Increased shear allows the e-beam to “miss” the e-gun on the second transit and begin to trace out the field lines



E-gun near $\iota = 1/2$
rational



With shear, the e-beam (barely) misses
the e-gun on its second toroidal transit

- Scaling shows that an intrinsic 2/1 island with a width of about 4 cm is present

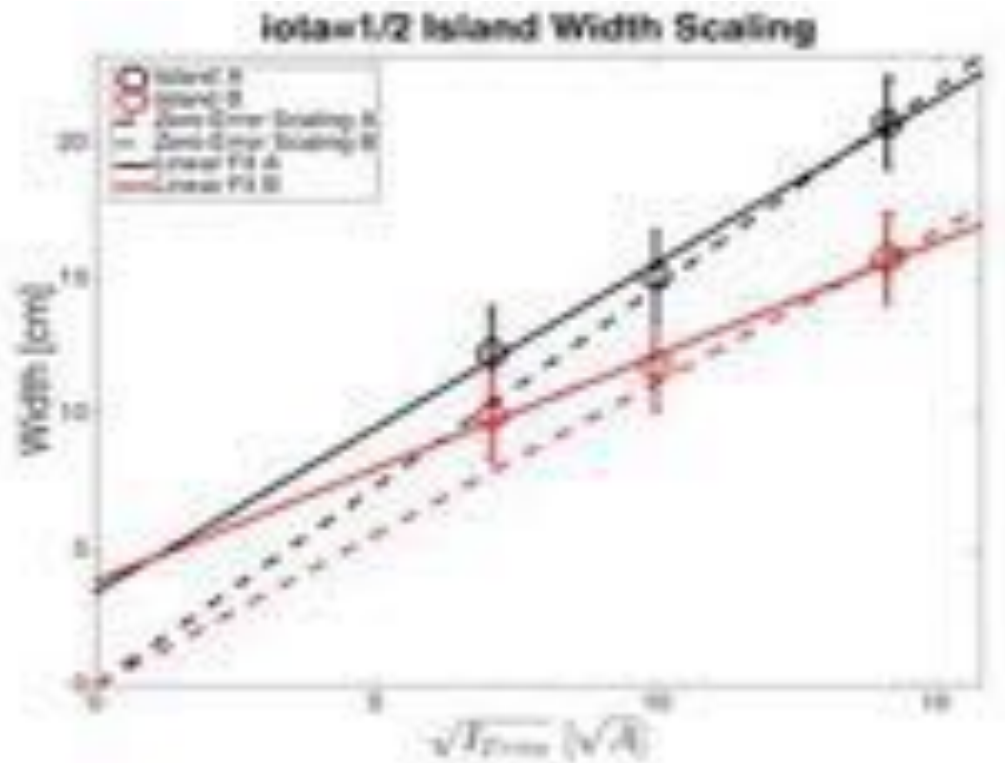
$$w = 4 \sqrt{\frac{R_0 b_{mn}}{m di/dr}} \Leftrightarrow b_{mn} = di/dr \frac{w^2 m}{16 R_0}$$

$$b_{21} \approx 5.4 \times 10^{-6}$$

^a A. H. Boozer, NF 55, 025001 (2015)

- This is consistent with the estimated n=1 error originating from construction inaccuracies^b:
 $B_{11}/B_0 \sim 2-3 \times 10^{-5}$

^bT. Andreeva et al., EPS 2012



Work led by Sam Lazerson, PPPL, USA

First plasma

First plasma (youtube)

First physics results from W7-

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MAX-PLANCK-GESELLSCHAFT

First plasmas end in a radiation collapse



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für Plasmaphysik



- Central ignition
- Expansion from inner to outer magnetic surfaces is slow due to good confinement
- Radiation/ionization layer defines the expanding edge
- Plasma acts as MW UV heater lamp
- UV photons hit the walls, impurities come off the walls
- Impurity radiation kills the plasma from the outside

T. Szepesi, G. Koczis, Wigner
RCP, Hungary

First plasmas “100% edge cooling”



- For these plasmas, the limiters received essentially no convective heat flux
 - 0-2 degree temperature rise
 - Very low limiter Langmuir probe signals
- All the plasma energy was radiated away at the edge – no convective loading
- (Impurity radiation is too intense)

T. Szepesi, G. Koczis, Wigner
RCP, Hungary

Fast movie “gas puff imaging”

- Superfast movie shows filamentary structures rotating
- 20 kHz $\leftrightarrow$ 50 μ s per frame
- The counter-clockwise rotation is consistent with inward-pointing radial electric field
- “Ion root”
- As expected for low T_e plasma
- Reminiscent of tokamak “blob” visualizations using gas puff imaging.

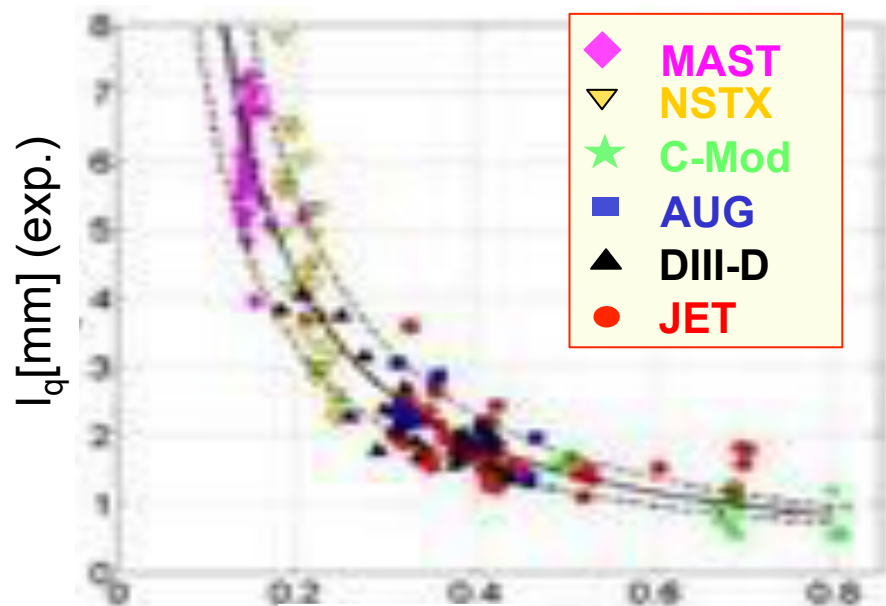
T. Szepesi, G. Koczis, Wigner
RCP, Hungary

First physics results from W7-X



- As the walls progressively cleaned, and the pulses got longer, the plasmas started to touch the limiters
- Several hundred degrees of temperature rise during the longest plasma pulses
- Large I_{sat} values on Langmuir probes ($n \sim 2 \cdot 10^{19} \text{ m}^{-3}$)
- A real scrape-off layer has formed
- Is there anything interesting to be learned from a limiter SOL?

- 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).



$B_{pol,MP}$ [T]

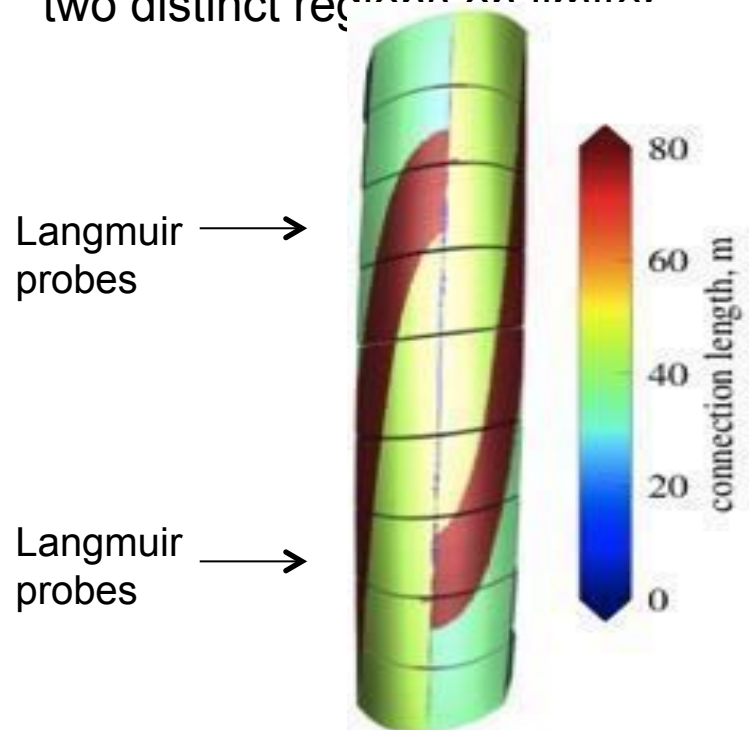
T. Eich et al. PRL 107 2011

First physics results from W7-X

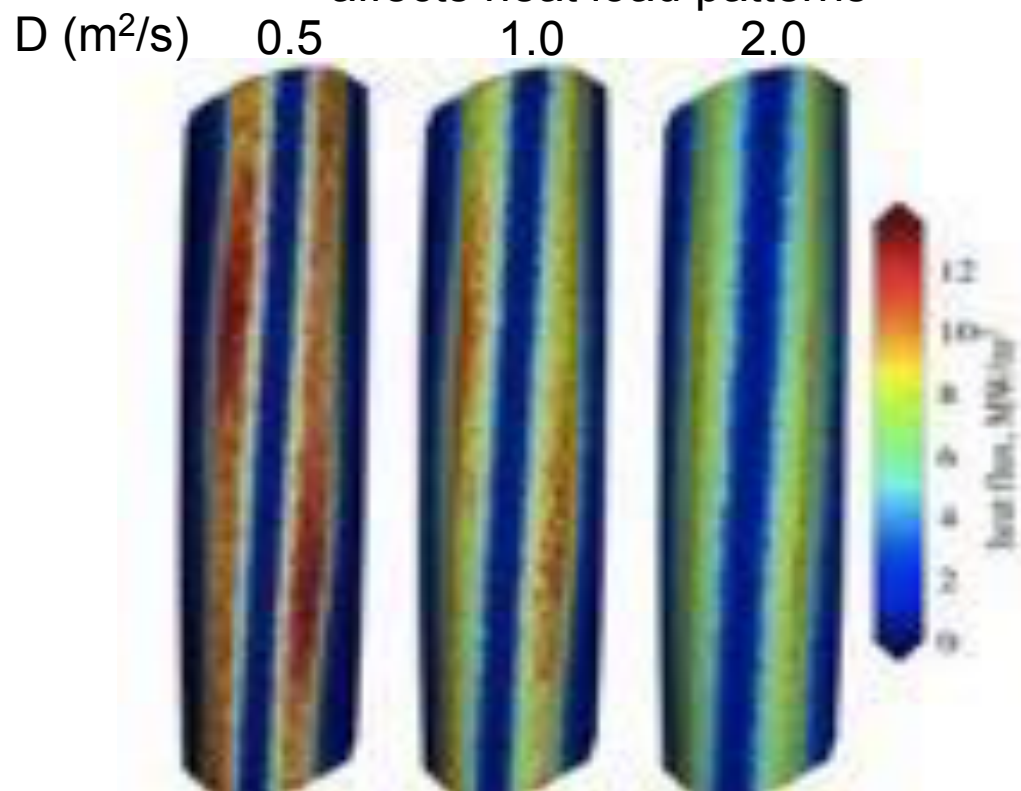
- Heuristic model:
Goldston, Nuclear Fusion 52 013009 (2012)
 - $\lambda_q \sim L_c \cdot v_D$
 - In tokamaks, L is proportional to $1/B_p$ leading to B_p scaling
 - In a stellarator, L_c is not related to B_p but to the inclination of the divertor relative to the field lines
 - Limiter operation gives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

Scrape-off layer physics with a limiter

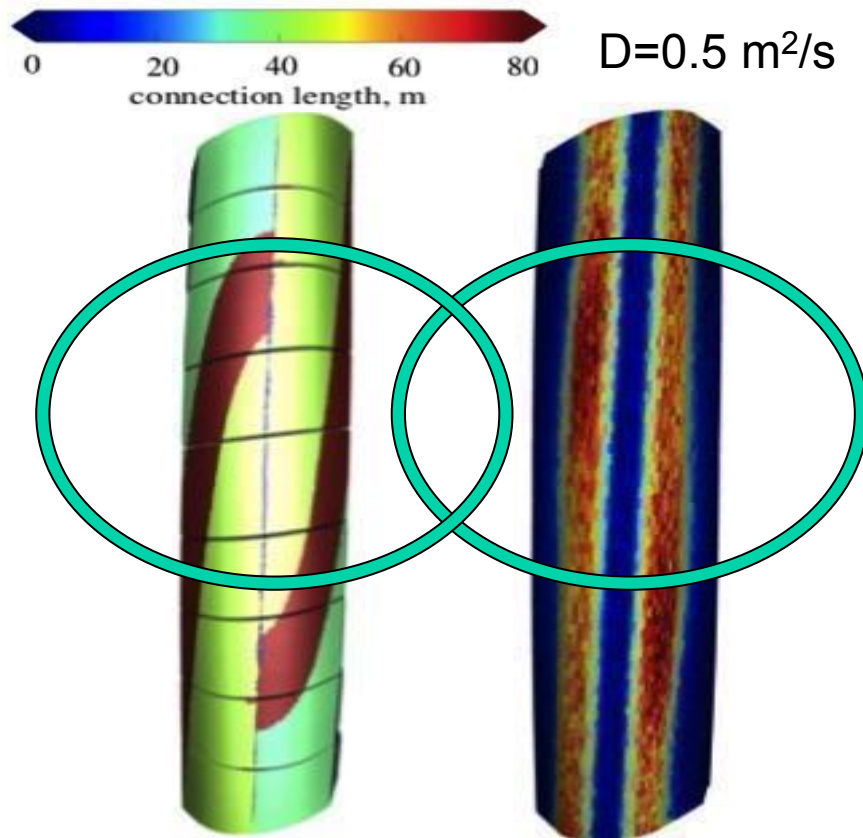
Connection length is short
compared to divertor phase
two distinct regions on limiter



Cross field diffusion rate visibly
affects heat load patterns



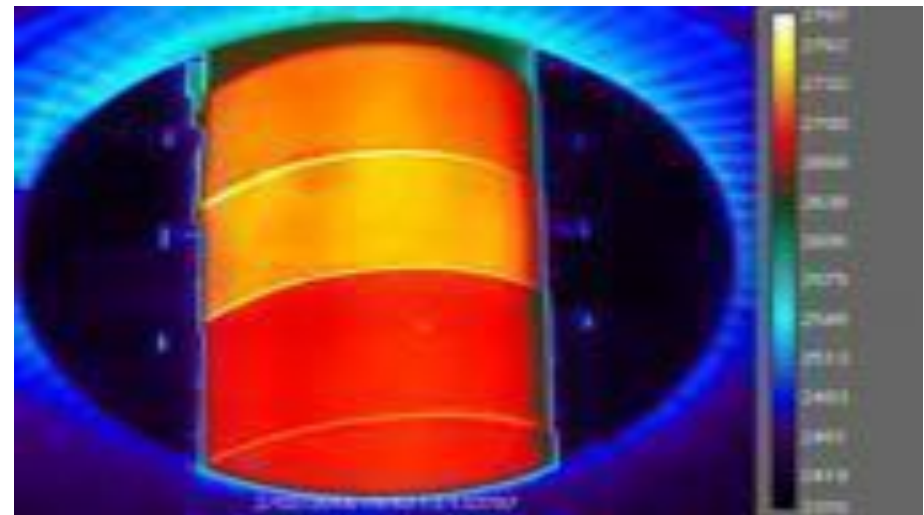
First physics results from W7-X



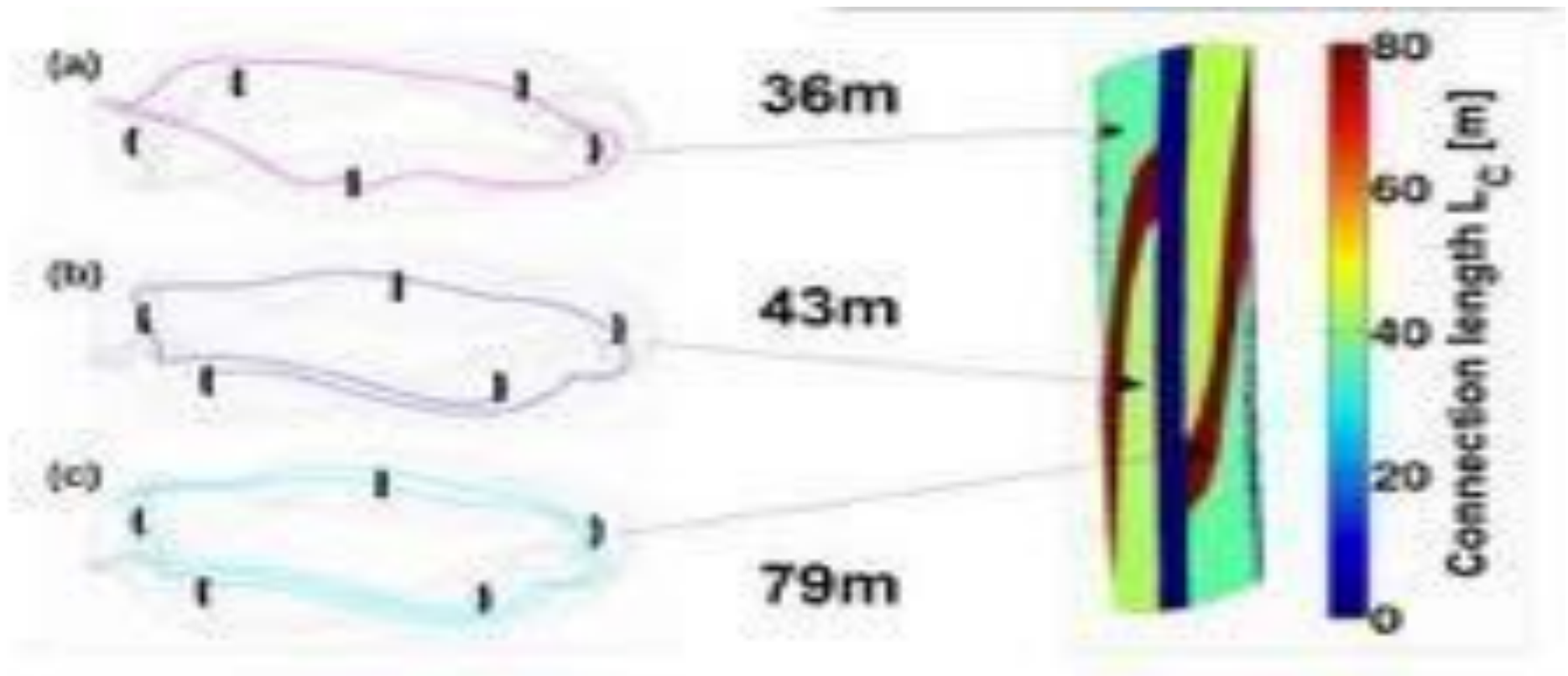
First physics results from W7-X

High-res. IR camera
view directly onto
limiter in module 3

Glen Wurden, LANL



L_c variation on the limiter explained



F. Effenberg, O. Schmitz, U Wisc. Madison

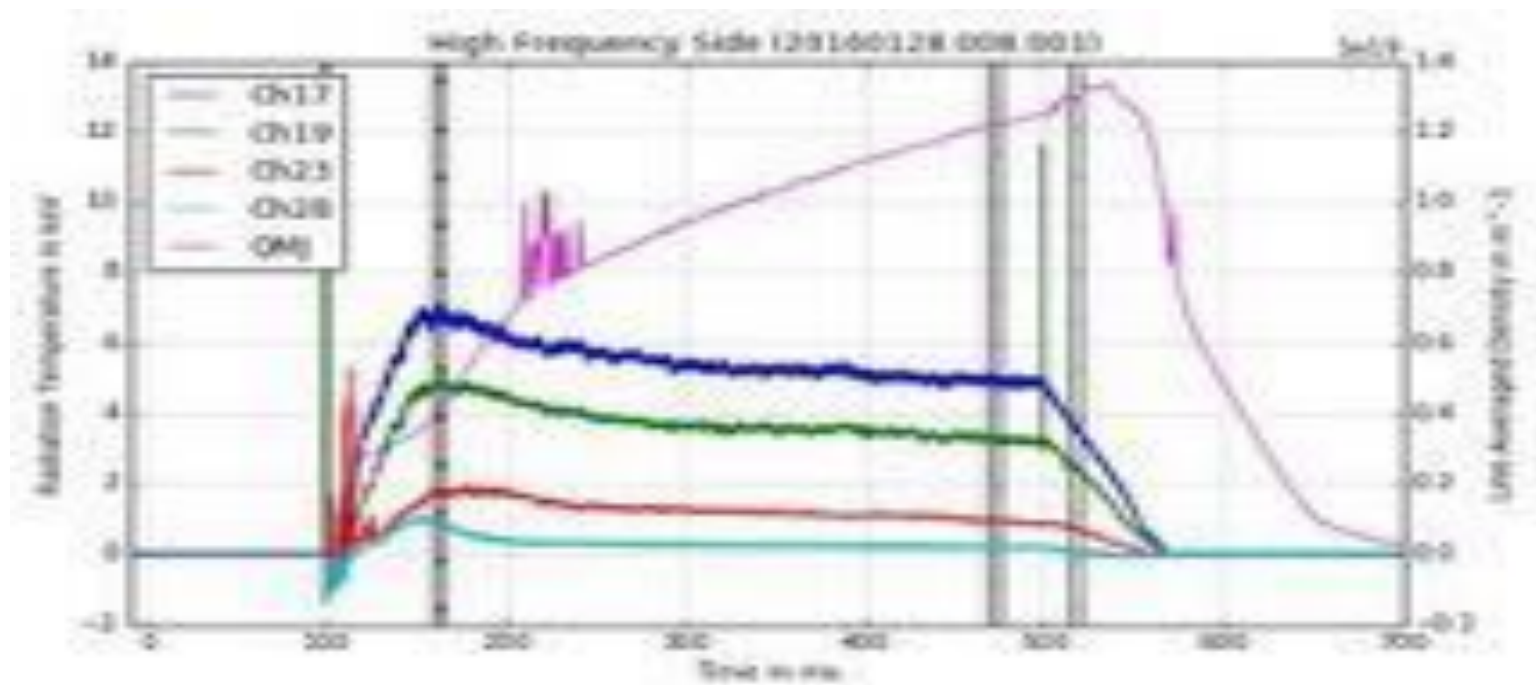
First physics results from W7-X

- Right before switching from He to H plasmas, we achieved plasmas with lifetimes of 0.4-0.5 seconds (28.01.2016)
- The plasma had prolonged contact with the limiters
- Limiter temperature rose to over 300 C
- Movie:
 - 100 Hz
(10 msec)
frame rate
 - Total movie
0.46 seconds
real time



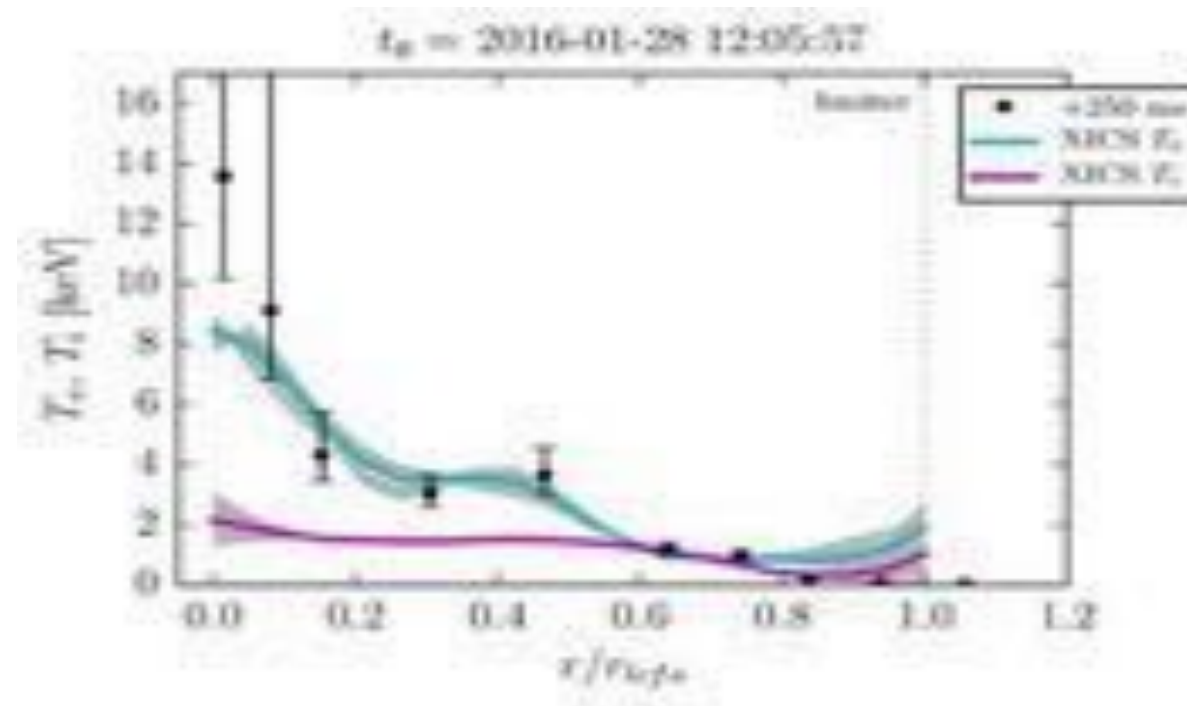
3.20

- Similar discharge (same day)
- Time traces of several ECE channels, and interferometer



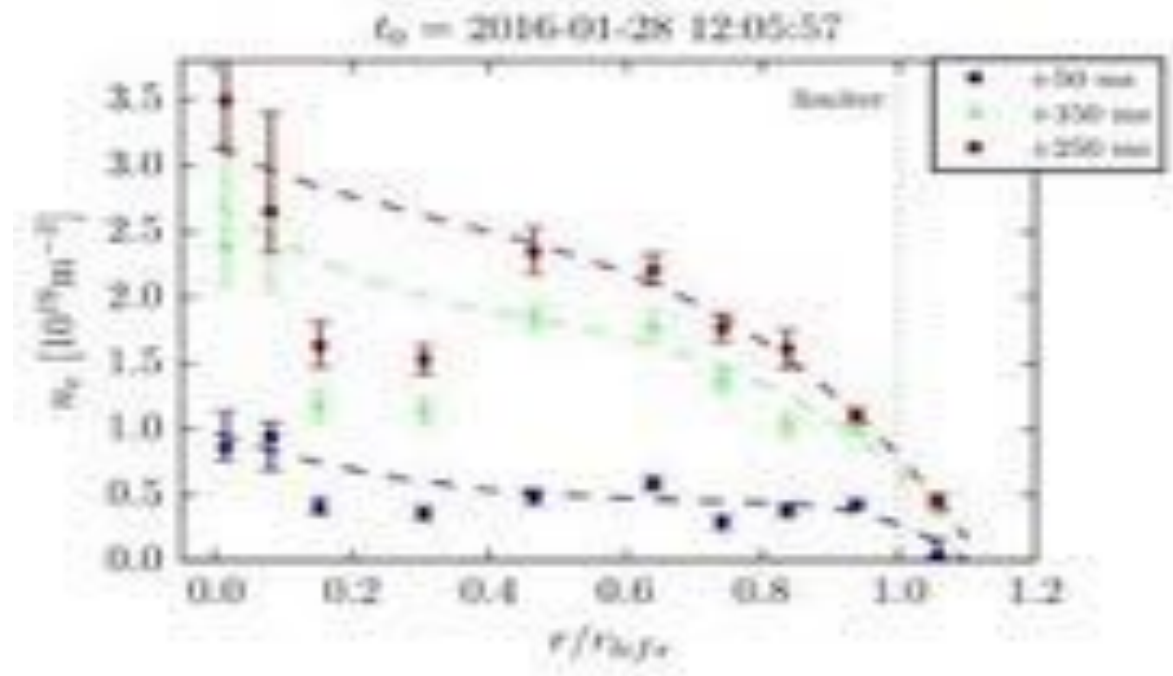
First physics results from W7-X

- Same discharge as before
- Data from Thomson scattering x-ray crystal spectr. (PPPL)



First physics results from W7-X

- Same discharge as before
- **Preliminary** data from Thomson scattering
 - The two channels near $p=0.2$ use a different light fiber type



First physics results from W7-X

Best performance in H

- 2 MJ milestone reached on Thursday Feb 18, 2016!
 - 1 second 2 MW discharge
 - Look closely 1.52 (5.34 msec), 2.21 (744 msec) and 2.90 (944 msec)
-
- 100 Hz/ 10 msec frame rate
 - Total movie 1.2 seconds real time



First physics results from W7-X

Magnetics of 2 MJ shot



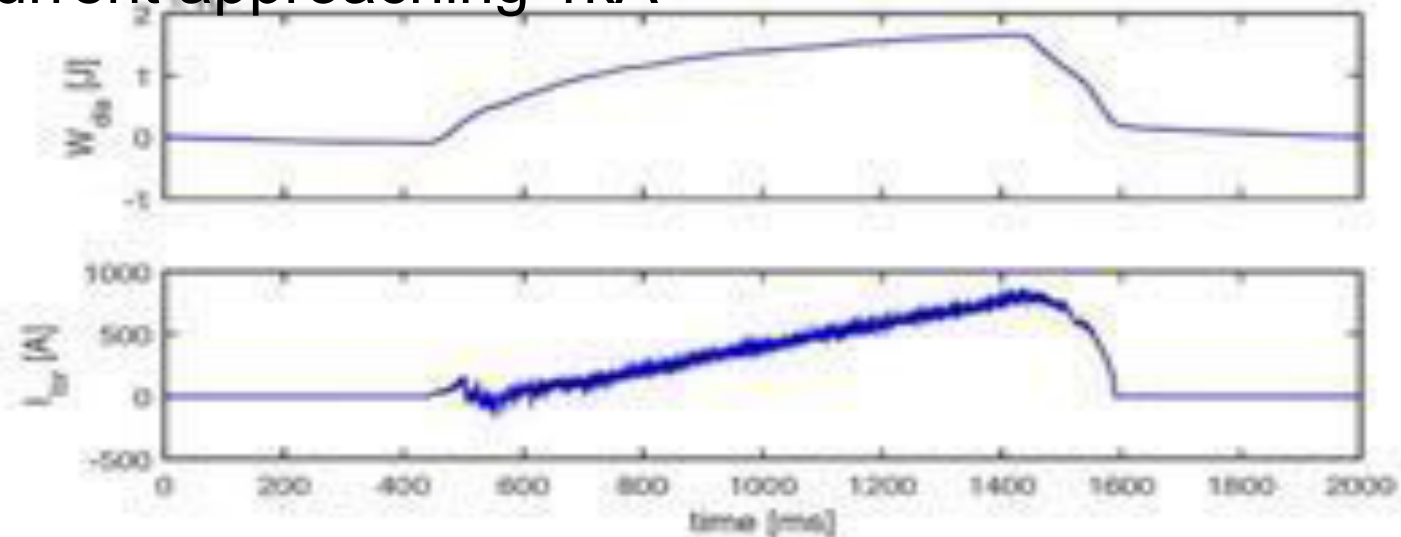
First physics results from W7-X

Magnetics of 2 MJ shot

- Diamagnetic energy still rising at 1 second – $\tau_E \sim 500$ msec
- $200 \text{ kJ}/2\text{MW} = \tau_E = 100$ msec confinement time (inconsistent)
- Bootstrap current approaching 1kA



First physics results from V



Status as of Feb 18, 2016 (**bold font**)

OP 1.1
2015-16
3 months

Pulse limit: $E_{\max} \sim 2 \text{ MJ}$
E reached: 2 MJ
Graphite limiters, uncooled

$P_{\text{ECRH}} \sim 5 \text{ MW}$
6 gyrotrons
6 gyrotrons in operation, 4MW

$T_e^{\text{NC}} \sim 4 \text{ keV}$ **8 keV**
 $T_i^{\text{NC}} \sim 1 \text{ keV}$ **>1.5 keV**
 $n \sim 2 \cdot 10^{19} \text{ m}^{-3}$ **$5 \cdot 10^{19} \text{ m}^{-3}$**
 $\langle \beta_{\text{NC}} \rangle \sim 1\%$
 $\beta_{\text{central}} > 2\%$
 $\langle \beta \rangle$ to be calculated

OP 1.2
2017
2*5
months

Pulse limit: $E_{\max} \sim 80 \text{ MJ}$
Graphite divertor, uncooled

$P_{\text{ECRH}} \sim 8 \text{ MW}$
 $P_{\text{NBI}}^{\text{H}} \sim 7 \text{ MW}$
 $P_{\text{ICRH}} \sim 1.6 \text{ MW}$

$T_e^{\text{NC}} \sim 5 \text{ keV}$
 $T_i^{\text{NC}} \sim 4 \text{ keV}$
 $n \sim 1.6 \times 10^{20} \text{ m}^{-3}$
 $\langle b_{\text{NC}} \rangle \sim 3\%$

OP 2
2020

Pulse limit: $E_{\max} \sim 18 \text{ GJ}$
=10MW for 30 minutes
20 MW for 10 seconds
CFC water-cooled divertor

$P_{\text{ECRH}} \sim 10 \text{ MW}$
 $P_{\text{NBI}}^{\text{D}} \sim 10 \text{ MW}$
 $P_{\text{ICRH}} \sim 4 \text{ MW}$
 $P_{\text{tot}} < 20 \text{ MW}$

$T_e^{\text{NC}} \sim 5 \text{ keV}$
 $T_i^{\text{NC}} \sim 5 \text{ keV}$
 $n \sim 2.4 \times 10^{20} \text{ m}^{-3}$
 $\langle b_{\text{NC}} \rangle \sim 5\%$

- Current drive experiments (ECCD)
- Heating the limiters to above 300°C for better symmetrization experiments (we have 10 near-infrared cameras for that)
- Running a second limiter configuration:
 - De-optimized neoclassical transport
 - Changed heat load patterns on limiters
 - Inward shifted 5/6 island chain
- Further performance extension and global confinement studies
- Electron-root vs ion-root transport (first results last week)
- For more on OP1.1 physics ideas, see:

“Plans for the first plasma operation of Wendelstein 7-X”,
T. Sunn Pedersen et al., Nuclear Fusion 2015 no. 126001 (13 pages)

- W7-X has been built and put into operation in 2015 – marking 8 years of stable schedule
- Flux surfaces are as expected, error fields are below 1:100,000
- Startup robust, also in the presence of the press and Merkel
- First plasma lasted about 10 msec, reached about 100 eV
- Plasma performance improves as wall-conditioning improves
 - $T_e \sim 8$ keV, $T_i \sim 1.5$ keV, $n \sim 3 \cdot 10^{19} \text{ m}^{-3}$, $\beta_c \sim 2.5\%$
- Hydrogen plasmas reached the 2 MJ design value:
 - 1.0 sec at 2MW on 19.02.2016
- Three more weeks of OP1.1!
- Co-authors: see next page

- The entire W7-X Team
- In particular those contributing directly to the work highlighted in this presentation:
 - R. König, M. Otte, B. Standley, M. Endler, M. Jakubowski, M. Krychowiak, J. Baldzuhn, C. Biedermann, P. Kornejew, U. Wenzel, H. Niemann, T. Klinger, K. Rahbarnia, O. Grulke, R. Wolf, H. Laqua, S. Bozhenkov, E. Pasch, A. Dinklage, M. Hirsch, T. Stange, M. Beurskens, D. Hartmann, P. Helander, J. Geiger, S. Bosch, R. Brakel, IPP
 - T. Szepesi, G. Kocsis, Wigner RCP, Hungary
 - G. Wurden, LANL, USA
 - S. Lazerson, N. Pablant, PPPL, USA
 - L. Stephey, T. Barbui, F. Effenberg, O. Schmitz, U Wisc. Madison, USA
 - P. Traverso, Auburn U., USA