First physics results from Wendelstein 7-X

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for the W7-X Team

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• The entire W7-X Team
• In particular those contributing directly to the work highlighted in this presentation:
  • T. Szepesi, G. Kocsis, Wigner RCP, Hungary
  • G. Wurden, LANL
  • S. Lazerson, N. Pablant, PPPL
  • L. Stephey, T. Barbui, F. Effenberg, O. Schmitz, U Wisc. Madison
  • P. Traverso, U. Auburn

First physics results from W7-X
• 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: Discharge development and collapse
  • Top performance discharges in He and H
  • Scrape-off layer physics
• Summary and conclusions
Advances in our understanding as well as in supercomputer power has allowed a comeback for the stellarator concept.
Design of magnetic field coils
## Major milestones of the project Wendelstein 7-X

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<td>1993</td>
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<td>Official start of the project</td>
<td>1996</td>
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<td>Start of construction</td>
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<td>Start plasma operation</td>
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Design study of a stellarator reactor

- 3 GW<sub>th</sub> thermal power
- 44 m diameter
- 1000 m<sup>3</sup> plasma volume
- 30,000 t total weight
Time-lapse movie of construction

First physics results from W7-X
Planning (status mid-2015)

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plasma commissioning

1st plasma w/o divertor

1st divertor plasmas

steady-state plasmas

diagnostics/control

First investigations

First physics results from W7-X
Updated planning

Technically ready for 1st plasmas in July 2015

device commissioning → test divertor assembly → HHF divertor assembly

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<th>task</th>
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plasma commissioning
diagnostics/control
first investigations

1st plasma w/o divertor

1st divertor plasmas

steady-state plasmas 2020

Dec. 10, 2015

First physics results from W7-X
## First Operation Phases (OP) in Figures

### OP 1.1
**2015-16**  
**3 months**  
Pulse energy: $E_{\text{max}} \sim 2\text{MJ}$  
Graphite limiters, uncooled  
- $P_{\text{ECRH}} \sim 5\text{ MW}$  
- 6 gyrotrons  
- $T_{e NC} \sim 4\text{ keV}$  
- $T_{i NC} \sim 1\text{ keV}$  
- $n \sim 2 \times 10^{19} \text{ m}^{-3}$  
- $<b_{NC}> \sim 1\%$

### OP 1.2
**2017**  
**2*5 months**  
Pulse energy: $E_{\text{max}} \sim 80\text{ MJ}$  
Graphite divertor, uncooled  
- $P_{\text{ECRH}} \sim 8\text{ MW}$  
- $P_{\text{NBI}}^H \sim 7\text{ MW}$  
- $P_{\text{ICRH}} \sim 1.6\text{ MW}$  
- $T_{e NC} \sim 5\text{ keV}$  
- $T_{i NC} \sim 4\text{ keV}$  
- $n \sim 1.6 \times 10^{20} \text{ m}^{-3}$  
- $<b_{NC}> \sim 3\%$

### OP 2
**2020**  
Pulse energy up to $\sim 18\text{ GJ}$  
- $10\text{ MW}$ for 30 min  
- $20\text{ MW}$ for 10 s at a time  
CFC water-cooled divertor  
- $P_{\text{ECRH}} \sim 10\text{ MW}$  
- $P_{\text{NBI}}^D \sim 10\text{ MW}$  
- $P_{\text{ICRH}} \sim 4\text{ MW}$  
- $P_{\text{tot}} < 20\text{ MW}$  
- $T_{e NC} \sim 5\text{ keV}$  
- $T_{i NC} \sim 5\text{ keV}$  
- $n \sim 2.4 \times 10^{20} \text{ m}^{-3}$  
- $<b_{NC}> \sim 5\%$

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First physics results from W7-X
PFCs for first plasma operation (OP1.1)

- Wall protection (SS)
- Heat shields (CuCrZn heat sinks)
- Water-cooled (starting OP 1.2)
- No divertor in the first phase
- 5 graphite limiters at the inner wall
- Must intersect convective plasma heat loads
- Designed for >5*0.4 MJ=2MJ per pulse

First physics results from W7-X
Magnetic configuration for limiter operation

- 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)

\[ I_{\text{planar}} = 0.23, \quad \iota_0 = 0.75, \quad \iota_a = 0.81 \]

\( I_{\text{planar}} = 0.13 \) chosen

First physics results from W7-X
FSM: Basic Concept

• Electron beam emitted parallel/antiparallel to magnetic field line
• Intersected in one cross-section by rod covered with a fluorescent powder
• Poincaré cross-section appears on time-integrated photograph

First physics results from W7-X
• Three manipulators designed, manufactured and tested
• Two manipulators installed (AEV10 & 30) for measurements in two different modules

First physics results from W7-X
A cut through a magnetic flux surface

First physics results from W7-X
First physics results from W7-X
In OP1.1 we have a slightly lower iota than the future “standard configuration”
   • The planer coils are hooked up to lower iota
We could not easily access a high iota configuration before OP1.1
Iota=0.5 is also resonant with n=1 field errors (iota=n/m=1/2), and can be accessed with the polarity used in OP1.1
Thus, an m=2 island should be measurable with FSM
Trim coils can be used to create well-defined n=1 error fields, since the intrinsic error is too small to be measured
   • Shadowing prevents us from measuring small islands
   • (First ten e-beam transits shown)
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
Island width scaling with trim coil current

- Scaling suggests an intrinsic 2/1 island with a width of about 4 cm is present.
- This island size is consistent with the estimated n=1 error originating from construction inaccuracies*: $B_{11}/B_0 \sim 2-3 \times 10^{-5}$

$$w = \sqrt{\frac{R o B_{mn}}{m B_o t'}} \hspace{1cm} B_{mn} \propto I_{trim}$$

*T. Andreeva et al., EPS 2012

*First physics results from W7-X
First Helium Plasmas
Observed with camera diagnostics

Early plasma 15.12.2016
First plasmas end in a radiation collapse

- 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
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)
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 ms) frame rate
  • Total movie 0.46 s real time

\[ T_e \sim 8 \text{ keV} \]
\[ T_i \sim 1.5 \text{ keV} \]
\[ n_e \sim 3 \times 10^{19} \text{ m}^{-3} \]
Hydrogen Plasmas
High performance in H

• 2 MJ milestone reached on Thursday Feb 18, 2016!
• 1 second 2 MW reference 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

T. Szepesi, G. Koczis
• Since the limiters were not overheated even in 2 MJ discharges, 4 MJ per discharge was allowed during the last weeks of operation
• 6 second discharge shown (1 s 1MW, then 5 s 0.6 MW):

• Discharge terminates peacefully, as pre-programmed

First physics results from W7-X

T. Szepesi, G. Koczis
Core parameters and estimates of confinement times: Preliminary data!!!
Core profiles of $n_e$ and $T_e$: Consistency check

**Thomson scattering and ECE**

![Graph comparing Thomson scattering and ECE](image1)

$\beta_e \approx 2.1\%$

ECE comparison
- For $\beta \leq 0.5\%$ there is a good agreement
- For higher $\beta$ the difference between LFS ECE and HFS ECE becomes larger
- More careful mapping should be used

**Thomson scattering and interferometry**

![Graph comparing Thomson scattering and interferometry](image2)

Interferometer comparison
- In many cases TS and interferometer agree within 10%
- Sometimes there is a discrepancy
- No clear dependence on plasma parameters

First physics results from W7-X
Core transport: on- and off-axis heating

Two comparable, low power (0.6 MW), long-lived plasmas:
- On-axis ECRH
- Off-axis ECRH

Clear and expected response in Te profiles
Density does not hollow out (concern from neoclassical estimates)

Peaked profiles:
- Inward pinch?
- Core fueling ($n_e$ low)
Limiter SOL physics

- 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 $I_{\text{sat}}$ values on Langmuir probes ($n \sim 2 \times 10^{19} \text{ m}^{-3}$)
- A real scrape-off layer has formed
- Is there anything interesting to be learned from a limiter SOL?
Why SOL and $\lambda_q$ studies are important

- The width of the heat deposition region, $\lambda_q$, 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).

- Heuristic model: 
  Goldston, Nuclear 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 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

First physics results from W7-X
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:

\[ D \text{ (m}^2\text{/s)} = \begin{cases} 0.5, & \text{connection length, m} \\ 1.0, & \text{80} \\ 2.0, & \text{60} \end{cases} \]

First physics results from W7-X
Edge Filaments
Fast movie “gas puff imaging”

- Superfast movie shows filamentary structures rotating
- 20 kHz<->50 µs 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
Scrape-off Layer Physics with a Limiter

*Standard limiter configuration*
$L_c$ variation on the limiter explained

First physics results from W7-X

Effenberg, O. Schmitz
Scrape-off layer physics with a limiter

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

Cross field diffusion rate visibly affects heat load patterns

First physics results from W7-X

F. Effenberg, O. Schmitz
Scrape-off layer physics experiments using the trim coils
Trim coils

First physics results from W7-X
Heat load shifts upwards as the n= 1 perturbation trim coil currents with a maximum in Module 3, are increased (while holding the phasing fixed).

Green tile: center tile of the limiter

FLIR MIR camera
Scrape-off Layer Physics with a Limiter

Increased iota limiter configuration

First physics results from W7-X
Slightly increased iota

- $I_{planar} = 0.10, \nu_0 = 0.80, \nu_a = 0.89$

- 5/5 island chain still in SOL but closer

- Given the large radiated power, this was deemed safe (for the last two days of operation)
  - Limiter shadowing is different – different load patterns
  - 5/6 island chain is deeper in core region
  - Mirror term is larger
    - De-optimized neoclassical transport

First physics results from W7-X
Changing the heat flux pattern between standard original OP1.1 and increased-iota (index 13) configuration

EMC3-Eirene prediction: change in heat load pattern correlated to change in $L_c$ footprint

IR observation shows a clear shift in heat load pattern due to iota variation
Summarizing...
At the end of OP1.1, ~30 diagnostic systems were operational

| QMC: Correlation reflectometry | QRT-h: High-resolution H-alpha | QSV-f: fast video camera |
| QMJ: Single channel interferometer | QSZ: $Z_{eff}$ single line of sight | QRT: Near Infrared limiter observation |
| QTB: Thomson scattering | QSS-f: Filterscope line of sight | QSR: Limiter observation: Hα |
| QME: ECE | Vis. spectroscopy | QRT-h: high-resolution infrared obs. |
| QSX: FZJ crystal spectrometer | QSD: HEXOS (broadband x-ray spectr) | QNC: neutron counters |
| QSW: US crystal spectrometer | QSB: bolometry | QSQ: therm. He-beam obs. systems |
| QXD: diamagnetic loops | QXP: pulse height analysis | CBD-v: NIR-video |
| QXR, QXO: Rogowski coils | QRP: limiter Langmuir probes | CBD-s: Sniffer probes |
| QXM: Mirnov coils | QRG: neutral gas pressure gauges | CBB: gyrotron power measurement |
| QXS: Saddle coils | QRG-p: Penning gauge | QSV: video diagnostic |
| QXE: flux surface measurements | QRN: multi-purpose manipulator | QSQ: thermal He, Ne, Ar, N, -beam gas boxes |
### Status end of OP1.1 (red bold font)

| OP 1.1 | Pulse energy: $E_{\text{max}} \sim 2$ MJ | $P_{\text{ECRH}} \sim 5$ MW | $T_e^{\text{NC}} \sim 4$ keV | 8 keV |
| OP 1.2 | $E$ reached: 4 MJ | $P_{\text{ECRH}} \sim 8$ MW | $T_i^{\text{NC}} \sim 1$ keV | >2 keV |
| 2015-16 | Pulse length: 6 sec | $P_{\text{NBI}}^H \sim 7$ MW | $n \sim 2 \times 10^{19}$ m$^{-3}$ | $5 \times 10^{19}$ m$^{-3}$ |
| 3 months | 6 gyrotrons | $P_{\text{ICRH}} \sim 1.6$ MW | $<\beta_{\text{NC}}^+ \sim 1$% | $\beta_{\text{central}} > 2.5\%$ |
| | 6 gyrotrons in operation, 4.3 MW | | $<\beta >$ to be calculated | |
| | Graphite limiters, uncooled | | |

| OP 2 | Pulse energy: $E_{\text{max}} \sim 18$ GJ | $P_{\text{ECRH}} \sim 10$ MW | $T_e^{\text{NC}} \sim 5$ keV | 8 keV |
| 2020 | $=10$ MW for 30 minutes | $P_{\text{NBI}}^D \sim 10$ MW | $T_i^{\text{NC}} \sim 5$ keV | >2 keV |
| | 20 MW for 10 seconds | $P_{\text{ICRH}} \sim 4$ MW | $n \sim 2.4 \times 10^{20}$ m$^{-3}$ | $5 \times 10^{19}$ m$^{-3}$ |
| | CFC water-cooled divertor | $P_{\text{tot}} < 20$ MW | $<\beta_{\text{NC}} >$ ~ 5% | $<\beta >$ to be calculated |

First physics results from W7-X
Summary of other preliminary results

• Toroidal current measured (bootstrap and ECCD): up to 2 kA
• Confinement time of He in H plasmas ~ 5 seconds
• Confinement changes observed in power-step down experiments
• Electric field profiles measured
• SOL diffusion coefficients and $\lambda_q$ studies started, $D \sim 0.5 \text{ m/s}^2$
• Successful ECRH wall-conditioning in He
• Efficient edge cooling also possible with targeted N injection
• Feed-forward density control successful
• On- and off-axis ECRH, heat pulse propagation studies performed
Conclusions

• Demonstrated good flux surfaces as expected, with error fields $\sim 10^{-5}$
• Managed to increase pulse lengths from initially 10 ms to 6 s
• As wall-conditioning improved, excellent plasma performance achieved:
  4 MJ: $T_e \sim 8$ keV, $T_i \sim 2.0$ keV, $n \sim 1$ to $5 \times 10^{19}$ m$^{-3}$, $\beta_c \sim 2.5$
• Successfully demonstrated functioning of the trim coils
• Confirmed predicted limiter heat load patterns in two limiter configurations
• Many well-diagnosed plasmas made; detailed analysis in progress.