First divertor physics studies in Wendelstein 7-X
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Overview

- The path forward for W7-X in terms of upgrades to the PFCs
- The W7-X island divertor concept
- Heat load patterns during attached operation:
  - Spatial patterns
  - Scaling of heat fluxes
- Detachment at lower power, before boronization
- Effects of boronization
- Detachment at higher power, after boronization
- Summary
Successive upgrades to plasma-facing components

**OP 1.1: 2015 - 2016**
Graphite limiter configuration
P < 4.3 MW achieved
∫ Pdt ≤ 4 MJ achieved

**OP 1.2: 2017 – 2018**
Uncooled graphite divertor
P ≤ 7 MW achieved
∫ Pdt ≤ 200 MJ achieved

**OP 2: 2021 ...**
Actively cooled CFC divertor
Pcw ~ 10 MW (30 mins)
Divertor Γ ≤ 10 MW/m²
∫ P dt ≤ 18000 MJ

T. Sunn Pedersen et al., IAEA-FEC Meeting, Ahmedabad, India
Introducing the W7-X island divertor
Introducing the W7-X island divertor
Divertor heat load patterns for attached plasmas

Heat load patterns generally as expected,
See also M Jakubowski et al., this conference

For strike line motion and general issues with those: see J. D. Lore et al., this conference
A look onto a divertor unit halfway through OP1.2

- View into torus after OP1.2a: Visible signs of plasma-divertor contact
- The OP1.2 test divertors are uncooled, robust against overload ⇒ Ideal testbed for later operation with the water-cooled divertor which has a 10 MW/m² heat flux design specification
Attached divertor operation: heat loads are a function of density

- Standard island chain (5/5): scaling to P=10 MW looks good ($L_c \sim 240$ m)[1]
- High iota island chain (5/4): Scaling presents a challenge at low density ($L_c \sim 130$ m)[1]
- Higher density features more desirable scaling
- Primarily due to increased radiation but also indicative of large wetted area (up to 1.5 m$^2$)

Full heat-flux detachment at high $n_e$, low $P \sim 3$ MW

Complete detachment for $t > 2$ s on all 10 divertors (one shown)

Heat flux essentially disappears from target for $t > 2$ s, persisting until end of plasma heating at $t = 4$ s

$t_\epsilon \sim 100$ ms rather constant for over 1 s

Increased radiation near the LCFS

Heat flux derived from IR camera data
But what about the particle exhaust (P~3 MW)?

- For low-power detachment, the subdivertor neutral pressure reaches about $5 \times 10^{-5}$ mbar
  - In OP1.2: $2 \times 10^4$ l/s pumping rate (divertor turbopumps)
- The exhaust rate is therefore about 1 mbar-liter/s~$2 \times 10^{19}$ particles/s
- Compression ratio: About 7.5
- Expected/hoped: compression ratios of more than 30, subdivertor pressure $5-10 \times 10^{-4}$ mbar

Factor 7.5

$5 \times 10^{-5}$ mbar
After boronization: Reduced edge radiation, higher density

- Edge impurity concentrations (relative to hydrogen density):
  - Oxygen reduced by a factor of 10 (or a lot more, in some cases)
  - Carbon reduced by about a factor of 7

- Achieved hydrogen densities increased by factor $>3$:
  - Avoidance of MARFE-like phenomena
  - Achieved confinement times increased by $\sim60$
    - Consistent with the increased density ($\tau_{E,LSS04} \propto n^{0.54}$), so:
  - Boronization was not the direct cause of increased confinement
  - Plasma core generally clean before and after boronization
Post-boronization detachment: Efficient exhaust

- High-density, higher-power (5-6 MW) detachment achieved after boronization
- Strong heat flux reduction
- Triggered in narrow density range in both upper and lower divertors
- Strong neutral compression now (x30):
  - $p_n = 5 \times 10^{-4}$ mbar now ($p_n = 0.5 \times 10^{-4}$ mbar for low-power detachment)
- All divertors detach but a somewhat stronger neutral compression (30%) is seen in the upper divertors.
- The particle removal rate is $\sim 13$ mbar-liter/s$\sim 2.6 \times 10^{20}$ particles/s – projects well to OP2 with divertor cryo-pumps and a 4x higher pumping rate:
  - Should result in $10^{21}$ particles/s removed – about the amount expected to be needed
Why the difference in neutral compression?

Low-power detachment: Factor 7 neutral compr.

High-power detachment: Factor 30 neutral compr.

• **Hypothesis (illustrated with cartoons):**
  - **At low power**, the plasma “runs out of energy” near the edge and radiates its energy away before it arrives at the island and the divertor
  - Oxygen and carbon act as “radiating mantle”
  - Therefore, the plasma does not “plug” the hole – neutrals can escape divertor region
  - See also Florian Effenberg’s talk directly following this one – using neon to trigger the same physics
  - **At high power**, after boronization, the plasma radiation cooling and condensation occurs further out, in the divertor
  - Therefore the plasma effectively “plugs the hole” – neutrals cannot escape divertor region (as designed…!)

• **The surprising thing is that also the low-power detachment can be stable without feedback stabilization.**
W7-X divertor works: Efficient particle exhaust, stable detachment

32 second discharge from last week, detached for the last 28 seconds

- Pulse terminates as preprogrammed – could have been extended
- Energy confinement time ~120 ms constant
- Efficient exhaust
  - Divertor neutral pressure ~ 6-7x10^-4 mbar
- Low impurity content
W7-X in general has very good confinement:
28-second detached discharge had H-L mode confinement

- W7-X discharges lie with the same range that regular tokamak H-mode discharges do.
- The 28 sec detached discharge has confinement between H- and L-mode.
- The triple product record shot (labeled “transient” here) lies above the H-mode scaling, and had reduced turbulent fluctuations (re. Th. Klinger overview talk).
Summary

• **First results with the W7-X island divertor were very successful**
  • The divertor heat load patterns were generally as expected
  • In attached operation, we observe large wetted areas and acceptable heat fluxes:
    • Projects well to future operation with water-cooled divertor
    • An indication of the benefits of long connection lengths
  • Stable detachment was achieved (two varieties)
    • Low-power, volumetric, limited particle exhaust
    • High-power, with high neutral compression, efficient particle exhaust
      • All divertors detached stably for 28 seconds @ 5MW – could have lasted much longer

• **Boronization was key; it enabled:**
  • Strong reduction of oxygen and carbon in SOL
  • Stable high hydrogen density operation
  • Access to detachment with efficient exhaust