First island divertor experiments on the W7-AS stellarator

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Motivation

- Stellarators will need divertors for plasma exhaust.

- Solutions have to be compatible with stellarator configurations.

- Utilize flux diversion by magnetic islands at the edge ----> Island divertor

- W7-X: study of the reactor potential of this concept.

- W7-AS can be operated with similar edge structure, divertor studies can provide preparatory information.

Major studies have been started in March 2001
Divertor geometry in 7-AS: boundary islands

- can be operated with large magnetic islands at the edge
- rad. position can be varied by adjusting the rot. transform
- rad. width can be varied by special control coils

$R = 2 \text{ m}, a \leq 0.16 \text{ m}, B \leq 2.5 \text{ T}$, non-planar coils, five field periods
Divertor geometry in W7-AS

Ten divertor modules

- Targets
- Baffles
- Titanium evaporators

Bottom divertor

- Probe arrays
- Baffles
- Target

Ten divertor modules
Major aims of the programme

To answer the questions:

- Effects of the new divertors on the plasma performance?
- Cold divertor plasmas without too strong cooling of the core?
- Controlled? Compatible with active particle pumping?
- Compatible with improved confinement scenarios (e.g. ELMy H-mode)?

Data shall be used to validate the EMC3-EIRENE code.
Summary of main results

Access to a new regime with NBI at very high density (up to $n_e \approx 3.5 \times 10^{20} \text{ m}^{-3}$) with improved confinement:

- $\tau_E$ steeply increases with density,
- $\tau_p$ and $\tau_{\text{imp}}$ decrease with increasing density ($\tau_{\text{imp}} \approx \tau_E$ at highest density)

$\rightarrow$ Density control already without Ti-gettering,
$\rightarrow$ quasi-steady state operation also including partial detachment,
$\rightarrow$ radiatiation always peaked at the edge.

Record value of $\langle \beta \rangle \approx 3.1\%$ achieved (at $B = 1.25 \ T$)

Plasma heating by HF (EBW 140 GHz) successfully demonstrated.
Plasma performance at high density: trans. to stationarity

- stored energy < 10 kJ,
- radiation increasing with time,
- extremely small edge density
Plasma performance at high density: access to stationarity

\begin{itemize}
  \item \( n_e > 1.8 \times 10^{20} \text{ m}^{-3} \)
  \item improved confinement (IC) quasi steady-state
  \begin{itemize}
    \item stored energy \( \approx 20 \text{ kJ} \)
    \item \( T_e(0) \approx 500 \text{ eV}, \nu^* \approx 0.3 \)
    \item edge density \( \approx 5 \times 10^{19} \text{ m}^{-3} \)
    \item edge temperature \( \approx 100 \text{ eV} \)
    \item radiation edge-dominated
  \end{itemize}
\end{itemize}

\begin{equation}
W_{\text{dia}}
\end{equation}

\begin{equation}
P_{\text{NBI}}
\end{equation}

\begin{equation}
P_{\text{rad}}
\end{equation}

\begin{equation}
P_{\text{NBI}}\quad P_{\text{abs}}
\end{equation}

\begin{equation}
\bar{n}_e
\end{equation}

\begin{equation}
n_{\text{es}}
\end{equation}

\begin{equation}
T_e(0)
\end{equation}

\begin{equation}
T_{\text{es}}
\end{equation}

\begin{equation}
r_{\text{eff}} / \text{cm}
\end{equation}

\begin{equation}
radiated \text{ power}
\end{equation}

\begin{equation}
time / \text{s}
\end{equation}

\begin{equation}
watts / \text{MW}
\end{equation}

\begin{equation}
watts / 10^{20} \text{ m}^{-3}
\end{equation}

\begin{equation}
T_e / \text{eV}
\end{equation}

\begin{equation}
T_{\text{es}} / \text{eV}
\end{equation}

\begin{equation}
radiated \text{ power}
\end{equation}

\begin{equation}
watts / \text{kJ}
\end{equation}
Plasma performance at high density: improved confinement

- IC: steep increase (´jump´) of $\tau_E$,
- low to moderate $\tau_E$ degradation at partial detachment
- steep drop of $\tau_{imp}$
Plasma performance at high density: improved confinement

\[
\begin{align*}
H_{W7-95} &\approx 1.5 \\
H_{ISS95} &\approx 2 \\
H_{NLHD2} &\approx 2 \\
H_{NLHD1} &\approx 2.8
\end{align*}
\]
Plasma performance at high density: plasma radiation

- radiated power fraction low to moderate in attached regimes,
- up to 90% at detachment

- NC: core-dominated radiation, unstationary
- IC: edge-dominated radiation, stationary

Diagram showing the relationship between radiated power fraction and plasma density, with data points for NBI power levels of 1 MW, 2 MW, and 3.5 MW. The graph also includes plots for different effective minor radii over time, indicating the transition between attached and detached states.
Plasma performance at high density: core parameters

NC ---> IC:
- $T_e$ profiles unchanged,
- $n_e$ profiles broadened.

SITAR analysis of Al emission:
- marginal change of diffusion coefficients,
- reduction of $v_{in}$ at the edge by a factor of 4 - 5.
Plasma performance at high density: H-mode?

H-mode signatures during transition to IC,

- only small spin-up,
- no evidence for ETB

\[ \dot{n}_e / 10^{20} \text{ m}^{-3} \]

\[ \text{stored energy /kJ} \]

NBI, 1 MW

NBI, 1 MW density scan

#51791, 51793, 51794, 51801

\[ \text{time /s} \]

\[ \text{density scan} \]

# 51791

# 51794

# 51793

# 51801

dithers

single ELMs

no ELM-like characteristics

\[ H\alpha \]

IC: - only small spin-up, - no evidence for ETB

grassy

# 51791
Plasma performance at high density: edge parameters

NC ---> IC ---> detachment:
- edge density $n_{es}$ increases steeply
- drops at detachment

- edge temperatures $T_{es}$ and, hence, upstream pressures drop already prior to detachment
Divertor plasma regimes

The plasma-target interaction concentrates mainly at helical stripes

\[ H_\alpha \] traces

Region D: rollover and detachment of energy and particle flux at high density

Region A: attached spots even at highest density
Divertor plasma regimes: downstream parameters

Region D:
- rollover up to detachment of $n_{ed}$, $\Gamma_{pd}$ (confirmed by 2D $H_\alpha$ data)
- $T_{ed} > 2$ eV at detachment (from $H_\alpha/H_\gamma$)

Peak densities and temperatures from probe array

- $n_{ed}$ top, $n_{ed}$ bott.
- $T_{ed}$ top, $T_{ed}$ bott.

NBI 2 MW
Divertor regimes: downstream parameters

Peak densities and temperatures from probe array

- Downstream peak $T_{ed}$ stays above 20 eV
  --> attached spot
- Inconsistent with low $T_{es}$
  --> inhomogeneous $T_{es}$?
Divertor regimes: stable partial detachment

Example for stable partial detachment

- $\bar{n}_e = 3 \times 10^{20} \text{ m}^{-3}$
- $T_e(0) = 400 \text{ eV}$
- $T_{es} = 20 \text{ eV}$
- radiated power fraction up to 80%
- radiation peaked at the separatrix position
- outer peak in region A attached
Divertor regimes: controlled transition to part. detachment

- radiated power fraction $\approx 85$
- edge radiation dominated,
- peak of C II radiation shifts in controlled way towards the x-points.

Controlled transition to 'stronger' partial detachment

- $n_e$, $\bar{n}_e$ (bolometer)
- separatrix position
- radiation profile
- C II 5140 Å

Imaged by spectrometer
Thermal load patterns on target, discharge #51321
(3D calculation from thermography)

$t = 0.35\ s$, attached

$t = 0.65\ s$, partially detached
Divertor regimes: asymmetries

Neutral pressures inside divertor subvolume show strong up/down asymmetry.

- Asymmetry may even invert,
- radiated power fraction is an ordering parameter

![Graph showing neutral pressure and electron density over time](image)

![Graph showing ratio of bottom to top pressures vs. radiated to NBI power fraction](image)
Operational ranges and density limit

Variation of $a_{pl}$ and $\Delta x$ by control coil currents

NBI, 2 MW:

- Access to IC independent of $\Delta x$,
- partial detachment at $\Delta x \geq 2.4$ cm
- partial detachment extends accessible density range

density limit SUDO et al.
Operational ranges and density limit

\( \frac{1}{q_c} = 2 \frac{RI_{eq}}{5a^2B} / [1 + \kappa^2(1 + 2\delta^2 - 1.2\delta^3)] \)

\( \bar{n}_G = \kappa \bar{J} = \frac{I_{eq}}{\pi a^2} \)
- Access to a new NBI, high-density regime (up to $n_e \approx 3.5 \times 10^{20} \text{ m}^{-3}$) with high $\tau_E$ and low $\tau_p$ and $\tau_{\text{imp}}$

- Full density control already without Ti-gettering,

- Quasi-steady state operation also including partial detachment,

- Edge-dominated radiation, radiated power fractions are low to moderate in attached and high (up to 90%) in detached regimes

- Detachment is partial: it does not extend over the full target area, and the particle and energy fluxes stay finite ($T_{\text{ed}} > 2 \text{ eV}$)

- Improved confinement in all separatrix-bounded configurations,

- Stable part. detachment restricts to configurations with larger distance between x-points and targets (divertor configurations).