The Steady-State ECRH-System at Wendelstein7-X

H. P. Laqua¹, V. Erckmann¹, H. Braune¹, H. Maassberg¹, N. Marushchenko¹, G. Michel¹, Y. Turkin¹, S. Ullrich¹,
G. Dammertz², M. Thumm², P. Brand³, G. Gantenbein³, W. Kasperek³,
the W7-X ECRH teams at IPP¹, FZK² and IPF³

ECRH-Team at FZK, the ECRH team at IPF Stuttgart, and the ECRH Team at IPP

W7-X ECRH Operation Scenarios
Gyrotrons, Transmission Line, Launcher
Integrated CW-Tests
Summary
W7-X: Engineering Design
Presently assembly of first Module at IPP

![Image of W7-X stellarator](image.png)

- **outer vessel**
- **machine support**
- **central coil support structure**
- **planar coil**
- **ECRH HFL**
- **ECRH LFL**
- **non-planar coil**
- **plasma vessel**
- **plasma**
- **central coil support structure**
- **machine support**

W7-X Parameters:

\[
\begin{align*}
R &= 5.5 \text{ m} \\
\langle a \rangle &= 0.55 \text{ m} \\
\langle B_0 \rangle &= 3.0 \text{ T}
\end{align*}
\]
W7-X: The scientific objectives

- demonstrate quasi steady state operation at reactor relevant plasma parameters
  \[ T_e = 2-10 \text{ keV}, \ T_i = 2 - 5 \text{ keV}, \ n_e = 0.1 - 3 \times 10^{20} \text{ m}^{-3} \]

- demonstrate good confinement, increase the data base for reactor extrapolation

- demonstrate stable plasma equilibrium at reactor relevant \(<\beta> \text{ of about 5 \%}"

- develop and investigate a divertor for plasma heat removal, particle and impurity control

  - superconducting coil system
  - ECRH with 10 MW steady-state capability
  - Divertor with 10 MW, steady-state heat removal capability, active pumping
  - NBI with \(\geq 5 \text{ MW/10 s (20 MW later)}, \ ICRH \text{ with 4 MW/10 s}\)
W7-X: classification of density ranges for ECRH

\[ n_e = 0.1 - 0.6 \times 10^{20} \text{ m}^{-3} \]
ECRH/ECCD in cw with X2 (X3), up to 10 MW, 
Plasma start-up, high electron temperature, Bootstrap current compensation

\[ n_e = 0.6 - 1.0 \times 10^{20} \text{ m}^{-3} \]
ECRH/ECCD in cw with X2 (X3), up to 10 MW, 
High ion temperature, density control, Bootstrap current compensation

\[ n_e = 1.0 - 2.0 \times 10^{20} \text{ m}^{-3} \]
ECRH in cw (O2, X3), up to 10 MW, difficult power handling 
Divertor operation favorable

\[ n_e = 2.5 - 4.0 \times 10^{20} \text{ m}^{-3} \]
ECRH in cw (O-X-B), up to 10 MW, is subject of research 
‘HDH regime’, divertor operation favourable 
Heating power enhancement necessary
ECRH: Predicted plasma parameters for W7-X

2nd Harm X-mode, ‘Lackner-Gottardi’

140 GHz at 2.5 T

\[ T_e \text{ vs. } n_e \text{ [10}^{20} \text{ m}^{-3}] \]

\[ 0.1, 0.5, 1.0 \text{ [10}^{20} \text{ m}^{-3}] \]

\[ P_{ECRH} \text{ vs. } T_e \text{ [MW]} \]

\[ 0, 2, 4, 6, 8, 10 \text{ [MW]} \]
ECRH: Predicted plasma parameters for W7-X
High density O2-mode and X3-mode ECRH

High density at 2.5 T

O2-Heating
140 GHz 10 MW

rel. absorption [%]

density $10^{20}$ [m$^{-3}$]

thermal roll-over

low density at 1.7 T

X3 single pass absorption
140 GHz 10 MW input

rel. absorption [%]

density $10^{20}$ [m$^{-3}$]

cut-off
Power handling for X3 heating

For secure plasma operation at least one controlled reflection is mandatory.

$n_e = 0.4 \times 10^{20} \text{ m}^{-3}$

**Graph:**
- **Input single pass**
- **Input double pass**
- **Stray single pass**
- **Stray double pass**

**Diagram:**
- Graphite shield
- Reflectors
- Movable mirrors
- AEE 50
- AEA 51
ECRH: Predicted plasma parameters for W7-X

2nd Harm X-mode, current drive

- residual bootstrap current compensation ($I_{ECCD} < 300 \text{ kA}$)
- modify rotational transform (shear) locally
- Note $\eta_{ECCD} \sim T_e/n_e$ for $T_e < 20 \text{ keV}$
- time scale 10 - 100 s

![Graph showing current drive efficiency vs. electron density for different angles $\phi$]

$\phi = 10^\circ$, $\phi = 20^\circ$, $\phi = 30^\circ$, $\phi = 40^\circ$

$P_{ECCD}$ up to 10 MW
High Field Side Launch N-Port (2 Beams)

Beam propagation along $B=\text{constant surface}$.
-> Phase space interaction

Resonance condition
$$\omega - n\omega_c / \gamma - k_{\parallel}V_{\parallel} = 0$$

Interaction with supra-thermal electrons
-> generation of toroidal flux (current drive)
-> generation of radial flux (electric field)
electron root and transport barriers
-> supra-thermal electrons as tracers for fast particle confinement
-> phase space physics (unstable distribution function)
-> ECRH-Beams for collective Thomson scattering
ECRH: Gyrotrons and Transmission system

- optical transmission system (mirrors only) at atmospheric pressure
- low cost, easy maintenance
  Approved concept (W7-AS)
- Modularized System
  (2 x 5 Gyrotrons)

Single Beam Section

Multi-beam section for long distance transmission
The W7-X Gyrotron

Specifications

- 140 GHz, 1 MW, cw, diode type
- Internal q.o. mode converter (Gaussian mode)
- Single stage depressed collector, $\eta > 45\%$
- Diamond window (106 mm, 1.88 mm thick)
- Collector sweeping
- Collector at ground potential
  - cathode at -55 kV, 40 A (max. -65 KV 50A)
  - body at +30 kV, 10 mA (max. 33KV 500mA)
The W7-X Gyrotron: European R&D, TED

Stage 1: Maquette (available at IPP Greifswald, now)

- Tests at FZK completed by end 2001
  - 1.0 MW, 10 s, eff. 48 %
  - 0.9 MW, 45 s
  - 0.75 MW, 100 s

- R&D successfully terminated by end 2002
- contract for 7 Series Gyrotrons placed with TED, 1st delivered, under test
  - 0.92 MW, 3 min, eff. 42 % (44 A) at load
  - 0.8 MW, 12 min, eff. 42 % (34 A) on-going

- contract for 8 SC-magnets placed with Cryomagnetics in 2003, 4 delivered

Stage 2: Prototype 1 (at FZK for further tests)

- Tests at FZK completed (Oct 2002)
  - 0.9 MW, 3 min, eff. 42 % (40 A)
  - 0.5 MW, 15 min, eff. 39 % (26 A)
Factory test results:

0.9 MW for 3 ms, $\eta = 37\%$ (43 A)

(test-stand limitation: < 45 A for few ms)

0.5 MW for 600 s, $\eta = 33\%$ (26 A)

(test stand limitation: < 30 A in cw)

Test results at IPP:

Conditioning towards full power, cw operation started June 2004 at IPP

Completed March 2005

0.83 MW (at load) for 1800 s, $\eta = 33\%$ (44 A)
Status Modulators

Tasks:  
- Voltage regulation  
- Matching circuit  
- Protection (crow-bar)  
- Cathode heater  

Development of IPF-Stuttgart

B1-Box  “Garching-type” Modulator  
E5-Box  Prototyp Modulator  
E1-Box  Modulator Series 1  
D5-Box  Modulator Series 2
Transmission System

All Single Beam Mirror modules are installed

Consists of beam-matching optics (2 Mirrors)
Corrugated polarizers (2 mirrors)
Calorimeter (short pulse) with switching mirror
Imaging mirror (N-Port switch mirror for B1 and B5)
Full remote control
Transmission system: CW-Tests with CPI gyrotron

Beam path:

SBWG          Beam Combining Optics          MBWG and CW-load
ECRH-Towers

- support BDO-mirrors, Launcher feeding optics,
- mirrors for h.f.s.launch
- retro-reflectors for beam line testing.
- Provide absorbing rf-shield (concrete)
Transmission system
Plug-in Front Steering Launchers

- Wide steering range: toroidal < 50° (-15° < _ < 35°), poloidal < 50 °(±25°)
- Engineering design going-on, simplified mock-up ready for cyclic tests of the
  - driving mechanics under vacuum and heat loading
Water Cooling of Front Steering Launcher

Water line + Push-pull bar

Cycling test: 10000 cycles with max. angle until break to find the safety margin.

Water line + Screening of universal joints

There must not be any risk of a water leak!!!
Integrated CW-Tests with CPI gyrotron

Reliable 30 min operation achieved

all temperature sensors in the gyrotron and transmission mirrors stationary.

The beam is transmitted through 7 mirrors (>25 m)
Measured power is the Gaussian fraction of the Gyrotron beam
Estimated losses are 50-70 kW
(mainly imperfect BMO, 30 KW for TED tube)
**CW-Capability of W7-X**

**Thermal Layout**

<table>
<thead>
<tr>
<th>Element</th>
<th>$q_{\text{peak}}$ [MWm$^{-2}$]</th>
<th>$\langle q \rangle$ [MWm$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divertor</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Baffles</td>
<td>0.5</td>
<td>0.25</td>
</tr>
<tr>
<td>Graphite wall protection</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>SS wall protection</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>0.1</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Plasma facing components are designed for 10 MW cw and 24 MW 10s heating power
Up to 200 kW/m² stray radiation is expected.
Concept of the stray radiation chamber

microwave-beam

test volume
ECRH-Strayradiation Test Chamber
build by the diagnostic group

Initial tests showed an homogeneous and isotropic radiation

\[ <P_{\text{stray}} > \leq 40 \text{ kW/m}^2 \]
(later 200 kW/m\(^2\)
A 10 MW cw ECRH will routinely provide the start-up and cw heating of W7-X plasma.
The ECRH heating scenarios will cover nearly the whole operational area of W7-X.
The current drive efficiency is high enough to compensate residual BS-currents.

Localized power deposition will allow profile shaping of temperature and iota (density).
Transport studies by fast modulation (<10 kHz heat waves).
Phase space interaction by N-Port launch. Generation of supra-thermal electrons.
Advanced heating scenarios by mode conversion.
Collective Thomson scattering (Ion distribution function).

ECRH is a part of the experimental program of W7-X
Summary: Technology

- Contracts for 7 TED-Gyrotrons (1 delivered) and 8 Magnets (4 delivered)
- 10 Gyrotrons altogether (TED Maquette and Prototype, CPI, 7 TED Series tubes)
- Transmission system completed (except towers in main hall)
- Tests of launcher prototype started.
- First integrated cw-tests of transmission system and all supporting systems
- Stray radiation chamber in operation.
- Data acquisition and control system under development, first tests
- The project will be realized within the original cost and time frame (2007)
- The ECRH-system already meets the ITER-requirements.

10 MW ECRH will be available for the first W7-X discharge
The IPP Team
ECRH: Predicted plasma parameters for W7-X

2nd Harm O-mode, single pass absorption

- Start up and heating towards $1 \times 10^{20} \text{ m}^{-3}$ with X2
- Change for O2 polarization/launch angle, increase density towards $2 \times 10^{20} \text{ m}^{-3}$
- O2 is thermal unstable below $T_e = 1 - 1.5 \text{ keV}$

$T_{e,crit} = 1.5 \text{ keV}$
X3 ECRH and Start-up at 1.7T

X3 start-up with 10 MW at 0.5 \(10^{19}\) m\(^3\)

- \(P_{\text{absorbed}}\) [MW]
- \(W_{\text{kin}}\)
- \(W_{w7\text{scalig}}\)

\(T_e\) [keV]

Plasma Energy [kJ]

0 2 4 6 8 10

0 50 100 150 200 250 300 350
X3 - Ray-tracing calculation

$n_e = 1.5 \times 10^{20} \text{ m}^{-3}$, $T_e = 2.4 \text{ keV}$

Diffraction effects are small up to $n_e = 1.5 \times 10^{20} \text{ m}^{-3}$
Sealing Gaskets in Microwaves

Viton-gasket was destroyed after 10 s

Viton

AUG-type gasket

DIIIID-type gasket

Data from S. Ulrich and Hildebrandt
Multi-Pass Absorption

Up to 3 controlled passes

Divertor elements
graphite shield
copper reflectors
movable mirrors
Port
AEA 11
AEA 51
SS-liner

0.5 m
Current Drive

Fokker-Planck simulations

HFL

LFL