Status and High Power Performance of the 10 MW, 140 GHz ECH System for the Stellarator W7-X

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Development of Physics and Technology of Stellarators/Heliotrons
en route to DEMO
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Outline

Heating and Current Drive:
- Modes of operation
- Steady state scenarios

The ECH & CD Plant:
- Gyrotrons
- Transmission lines
- In-vessel components

Gyrotron Technology Improvement:
- TFSS at gyrotron collector
### ECH & CD for W7-X and for ITER
#### “Day one“ Heating & Current Drive Systems

<table>
<thead>
<tr>
<th></th>
<th>W7-X</th>
<th>ITER</th>
</tr>
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<tbody>
<tr>
<td>Installed Power (MW)</td>
<td>10</td>
<td>27 (incl. Start-up assist)</td>
</tr>
<tr>
<td>Power/Gyrotron (MW)</td>
<td>1</td>
<td>1 (EU: 2)</td>
</tr>
<tr>
<td>Frequency (GHz)</td>
<td>140</td>
<td>170</td>
</tr>
<tr>
<td>Mode of Operation</td>
<td>2\textsuperscript{nd} Harm. (2.5 T) CW (1800 s)</td>
<td>1\textsuperscript{st} Harm. (5.4 T) CW (1000 s)</td>
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<tr>
<td>Transmission System</td>
<td>Optical</td>
<td>Waveguide</td>
</tr>
<tr>
<td>Type of Launchers</td>
<td>Front steering/Remote steering</td>
<td>Front steering</td>
</tr>
<tr>
<td>Physics Demands</td>
<td>Plasma start up</td>
<td>Start-up assist</td>
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<td>Bulk heating and current drive</td>
<td>Bulk heating and current drive</td>
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<td>q-profile shaping</td>
<td>q-profile shaping</td>
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<td>MHD control</td>
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<td></td>
<td>Net-current suppression</td>
<td>Net-current enhancement</td>
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</table>
ECH & CD: Operation Scenarios for W7-X

Plasma Density Range

Cyclotron Frequency:

\[ \omega_c = \frac{eB}{m} \]

determines the microwave frequency:

\[ \omega - n\omega_c / \gamma - k \parallel v \parallel = 0 \]

\[ \gamma = 1 / \sqrt{1 - \frac{v^2}{c^2}} \]

\( (2.5 \, \text{T}, \, n = 2, \, 140 \, \text{GHz for W7-X}) \)

Plasma Frequency:

\[ \omega_p^2 = \frac{e^2 n_e}{\varepsilon_0 m_e} \]

determines the density range

\[ \omega - \omega_p / \gamma = \frac{1}{2} \]

\[ k \perp B, \quad E \parallel B \]

O2-Mode

\[ k \perp B, \quad E \perp B \]

X3-Mode

\[ k \perp B, \quad E \perp B \]

X2-Mode

\[ k \perp B, \quad E \parallel B \]

O-X-B-Mode

Plasma density \( (\text{m}^3) \): \( 10^{19}, 10^{20}, 10^{21} \)
3rd harmonic X-mode, 140 GHz, $B_{\text{res}} = 1.67$ T, $n_{\text{e,crit}} = 1.6 \cdot 10^{20}$ m$^{-3}$

- Operation at reduced B-field, optically grey
- Toroidal launching angle similar to O2-mode at 140 GHz (12.3 deg.)

$n_{\text{e}} = 1.5 \cdot 10^{20}$ m$^{-3}$

$P_{\text{ECH}} = 10$ MW (12.3 deg.)
2nd harmonic O-mode, 140 GHz, 2.5 T

\[ n_e = 1.8 \times 10^{20} \text{ m}^{-3}, \quad T_e = 2.6 \text{ keV} \]

N. Marushchenko, et al., 2007

M. Thumm et al., "...10-MW 140-GHz ECH ........", ITC-18, Toki, Japan, December 9-12, 2008
Transition of 2nd harmonic X-mode to 2nd harmonic O-mode
- assume neoclassical core confinement with ‘anomalous edge’ -

- Plasma start-up and heating with X2 (5 MW)
- Tuning launching angle (12 deg.) and polarization towards O2
- Increase plasma density
- Increase ECH power (10 MW) and plasma density

Y. Turkin, et al., EPS, 2007
ECH & CD: Predicted Plasma Parameters for W7-X
Steady state operation: Current control by ECCD

- ECCD for bootstrap current compensation
  \( I_{\text{BS}} = 7\text{kA} \rightarrow 22\text{kA} \)

- Adjust power in P1

- Drive current with P2 (launching angle)

- Control edge rotational transform

Y. Turkin et al. FS&T 2006
N. Marushchenko, SMSA 2007
ECH & CD: Features Beyond Specifications

2nd frequency at half power: 103.8 GHz

- Gyrotron diamond window transparent at $d = 4\lambda/2$ (140 GHz) ... also at $3\lambda/2$ (105 GHz)
- Two cavity modes can be exited: TE$_{21,6}$ (103.8 GHz) and TE$_{22,6}$ (106.3 GHz)
- However reduced efficiency: 21 - 27%
- RF power limited by collector (<1.3 MW)
ECH: Predicted Plasma Parameters for W7-X

2nd harmonic O-mode, 103.8 GHz, \( B_{\text{res}} = 1.85 \text{ T} \), \( n_{e,\text{crit}} = 1.4 \cdot 10^{20} \text{ m}^{-3} \)

- Operation at reduced B-field, optically grey, reduced power < 4 MW
- Toroidal launching angle similar to O2-mode at 140 GHz, 3-pass absorption
ECH & CD System for W7-X: Schematic

HV-Modules (IPF):
10 delivered and operational

Single-Beam Section Optics (IPF):
Full performance test completed

Multi-Beam Section Optics (IPF):
First full performance test (with single beam) completed

2 rows of gyrotrons with water cooling modules

Spare boxes for future upgrade
ECH & CD Supporting Systems: HV- Supply and Water- Cooling Plant

**HV Modulator: IPF Design (tetrode based)**
- + 30 kV, 0.5 A supply (energy recovery)
- Fast regulator/modulator (20 kHz demonstrated)
- Thyatron crowbar, HV-control system
- All 10 units completed and operational

- Gyrotron cooling modules (< 20 MW)
- Central mirror cooling module (< 0.7 MW)
- Launcher- and dummy load cooling (< 2 MW)
- All units completed and operational
**ECH & CD Plant for W7-X: Status**

- **Gyrotrons...**
  - 8 out of 10 gyrotrons delivered and tested,
  - #2 (2a), #3 (3a), #4 failed to meet the specs, beam tunnel problem (new atten. ceramics), parasitic oscillations
  - #5 presently under test, shifted output beam!

- **Single-Beam Module**

- **Multi-Beam Section**

- **Transmission lines in the beam duct completed (except BMO)**
- Most loaded section tested at full performance (920 kW/30 min)
- Retro-reflectors installed, first integrated tests of the “full-distance transmission”
Integrated CW-Tests with TED- and CPI- Gyrotrons

Reliable 30 min operation achieved (here 5 min + 30 min shots)

All temperature sensors in the gyrotron and transmission line mirrors stationary

Gyrotron output power

- > 0.92 MW (TED)
- > 0.90 MW (CPI)

After transmission through 7 mirrors:

Power in Gaussian mode

- 0.87 MW (TED)
- 0.83 MW (CPI)

(estimated losses are 50 - 70 kW, imperfect BMO, improvement under way)
Thermographic Image of the Output Beam (0.95 MW)

Analysis of measurements with PVC target at several positions

Beam parameters:
- Waist: 18.1 / 18.5 mm
- Waist position: 105 / 51 mm
- Gaussian content: ~ 97 %

Mode purity of all gyrotrons > 95 %
Gyrotrons, Magnets and Loads: Status

- **TED Maquette**: operational
- **TED Prototype**: operational
- **TED #1**: operational, “mothballed”
  full performance 0.92 MW, 30 min
- **TED #5**: presently under test at FZK
- **TED #4, 3a, 2a**: parasitic modes in beam tunnel
  at TED for repair
- **CPI Prototype**: full performance 0.9 MW, 30 min,
  presently under re-test at IPP
  after a vacuum-leak repair
- **All SC-Magnets and PS‘s delivered and operational**

**Dummy Loads:**
- TED load at FZK teststand has water leak (fatigue)
- CCR loads at IPP have reduced performance (< 0.75 MW, CW)
  now operated in tandem configuration
**ECH: Near-Torus Transmission: The ECH&CD Towers**

- **House of optical elements to distribute and match the RF beams to the ‘equatorial-plane’ and ‘HFS’-launchers**

- **Heavy granite structure is good mm-wave absorber**

- **“Towers” completed, presently installation of optical elements, remote control system, cooling etc.**
Transmission lines in the beam duct completed (except BMO)

Most loaded section tested at full performance (920 kW/ 30 min)

Retro-reflectors installed, first high power tests of “full-distance transmission”
ECH & CD: Long Distance Transmission
High Power Measurements on MBWG

- Wave beam is transmitted half way to the torus and then reflected by retro-reflector (40 m)

- 10 mirrors

- Beam power measured calorimetrically

- Measured losses are 2.7 %, agree with theoretical losses

<table>
<thead>
<tr>
<th>ITEM</th>
<th>OHMIC (%)</th>
<th>DIFFR. (%)</th>
<th>(%)</th>
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<tbody>
<tr>
<td>M5, M6, M7</td>
<td>0.39</td>
<td>0.2</td>
<td>0.59</td>
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<tr>
<td>2 SR</td>
<td>0.26</td>
<td>0.1</td>
<td>0.36</td>
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<tr>
<td>M5, M6, M7</td>
<td>0.39</td>
<td>0.2</td>
<td>0.59</td>
</tr>
<tr>
<td>M4</td>
<td>0.13</td>
<td>0.1</td>
<td>0.23</td>
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<tr>
<td>SD</td>
<td>0.13</td>
<td>0.1</td>
<td>0.23</td>
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<tr>
<td>ATMOSPHER.</td>
<td>0.68</td>
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<tr>
<td>SUM</td>
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<td></td>
<td>2.68 %</td>
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<tr>
<td>MEASURED</td>
<td></td>
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<td>2.7 ± 0.4%</td>
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</tbody>
</table>
W7-X: The In-Vessel Transmission System
Plug-In Front Steering Launchers

- Combines 3 RF beams per port with wide steering range (O2, X3, O-X-B, ECCD): toroidal $< 35^\circ$, poloidal $< 30^\circ$
- Simplified launcher mock-up tested, concept for in-vessel driving rods and mirror cooling qualified
- Survived 10,000 load cycles
- Tested in MISTRAL facility (mm-wave stray-radiation loading).
- Fabrication/assembly of all 4 launchers in progress
W7-X: In-Vessel Transmission and Diagnostic

Inner Vacuum Vessel Wall, TZM Reflector

TZM: Titanium- Zirconium- Molybdenum

- TZM tiles for in-vessel reflection qualified with 0.5 MW incident power
- Thermal loading acceptable with polished surface ($T_{surf} < 470 \, ^\circ C$ in CW)

Good knowledge of beam location on TZM tiles required

- ECA diagnostics and beam position control
- Measure non-absorbed power
- Pick-up horn antenna array (120 horns)
- Routing of WGs in progress
W7-X: In-vessel ECA- Diagnostic
Routing of Pick-Up Waveguides to TZM Reflectors

- Pick-up horn antenna array (120 horns)
- Routing of circular WGs towards ports
- Prototype under fabrication, tests soon
Advanced Transverse Field Sweeping System (TFSS)

50 Hz rotating perturbative field

...with small VF-modulation (VFSS)


- TFSS only does not solve the problem completely!
- Combination of conventional VFSS and novel TFSS
- Obtain smooth distribution, increase collector capability (factor of 2)
- Modulated TFSS satisfies the demands for next-step gyrotrons
The project has arrived an advanced state, all major systems are completed and running, presently ECH work concentrates on near-torus and in-vessel components (N-port, ECA).

The series production of gyrotrons still needs close attention. Investigation of different beam tunnel geometries up to mid 2009. SN7 (#10) is expected beginning of 2011.

Extended operation regime: Promising perspective for 2-frequency operation 140 GHz and 103.8 GHz (at half power).

Steady state scenarios under investigation.

First high-power measurements on long distance transmission: losses are very low (2.7 %) and agree with theoretical losses.

Development and test of advanced gyrotron components
• Improved gyrotron collector sweeping