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

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Outline

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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

	W7-X	ITER
Installed Power (MW)	10	27 (incl. Start-up assist)
Power/Gyrotron (MW)	1	1 (EU: 2)
Frequency (GHz)	140	170
Mode of Operation	2nd Harm. (2.5 T) CW (1800 s)	1st Harm. (5.4 T) CW (1000 s)
Transmission System	Optical	Waveguide
Type of Launchers	Front steering/Remote steering	Front steering
Physics Demands	Plasma start up	Start-up assist
	Bulk heating and current drive	Bulk heating and current drive
	q-profile shaping	q-profile shaping
		MHD control
	Net-current suppression	Net-current enhancement

ECH & CD: Operation Scenarios for W7-X
Plasma Density Range

Karlsruhe Institute of Technology

Cyclotron Frequency: $$\omega_c = \frac{eB}{m}$$

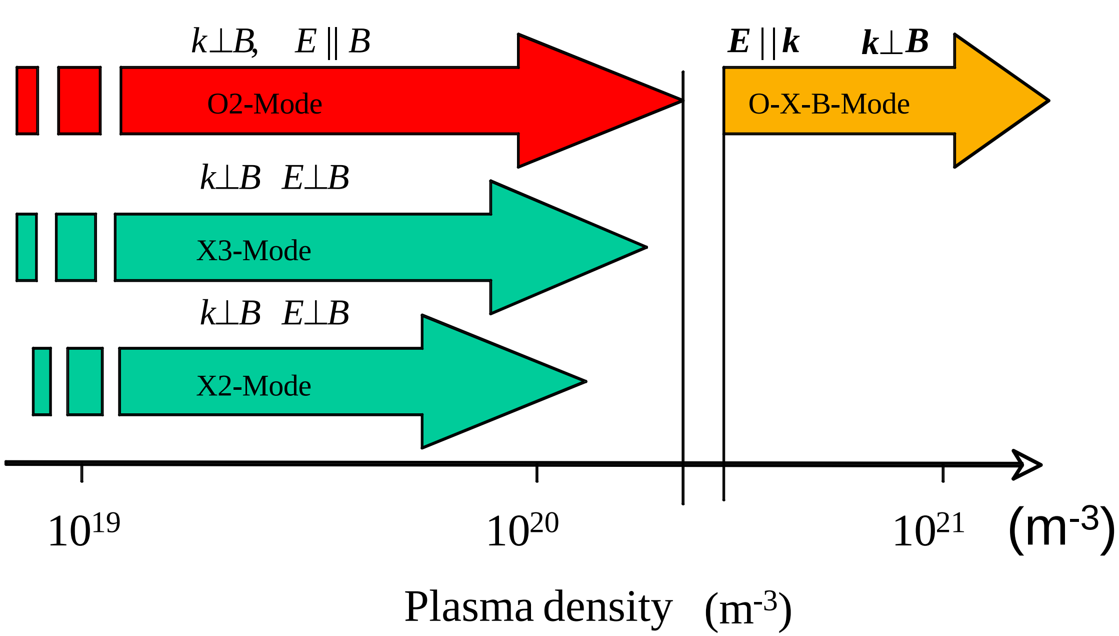
determines the microwave frequency:

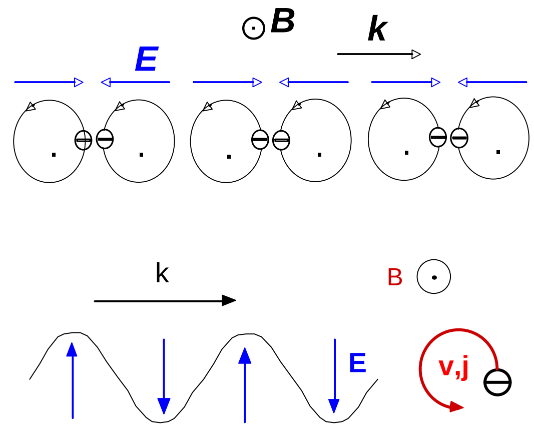
$$\omega - n\omega_c / \gamma - k_{\|} v_{\|} = 0 \qquad \gamma = 1/\sqrt{1 - \frac{v^2}{c^2}}$$

(2.5 T, n = 2, 140 GHz for W7-X)

Plasma Frequency: $$\omega_p^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}$$

determines the density range



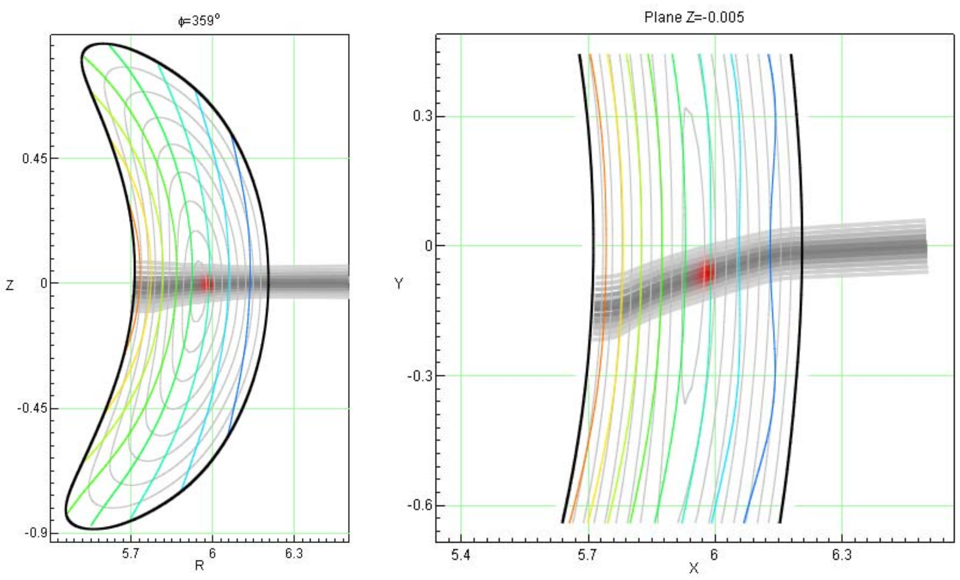


ECH: Predicted Plasma Parameters for W7-X (I)

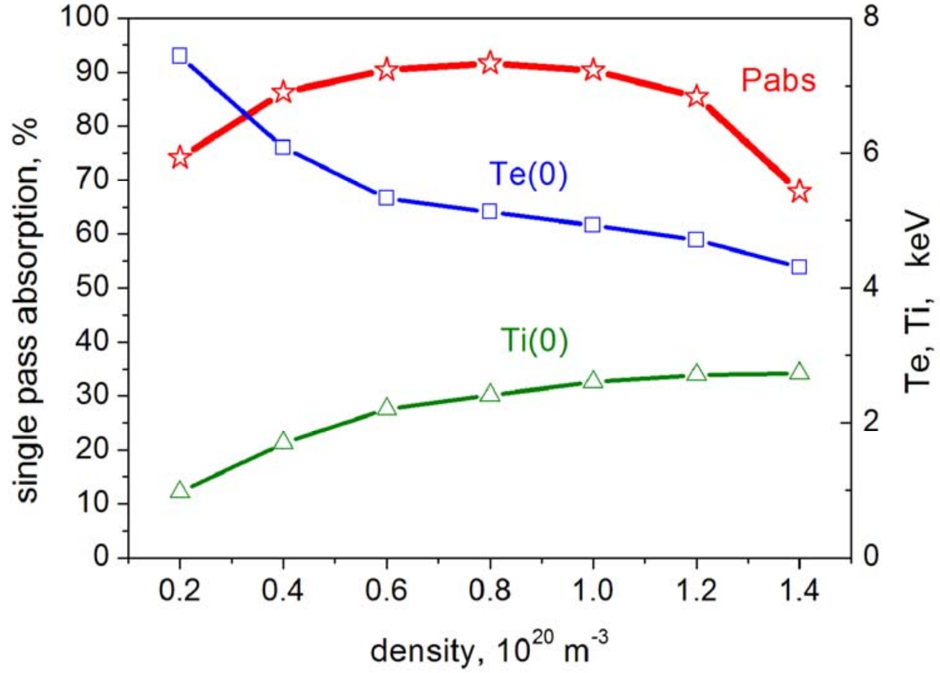
3rd harmonic X-mode, 140 GHz, $B_{res} = 1.67$ T, $n_{e,crit} = 1.6 \cdot 10^{20}$ m^{-3}

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

$n_e = 1.5 \cdot 10^{20}$ m^{-3}

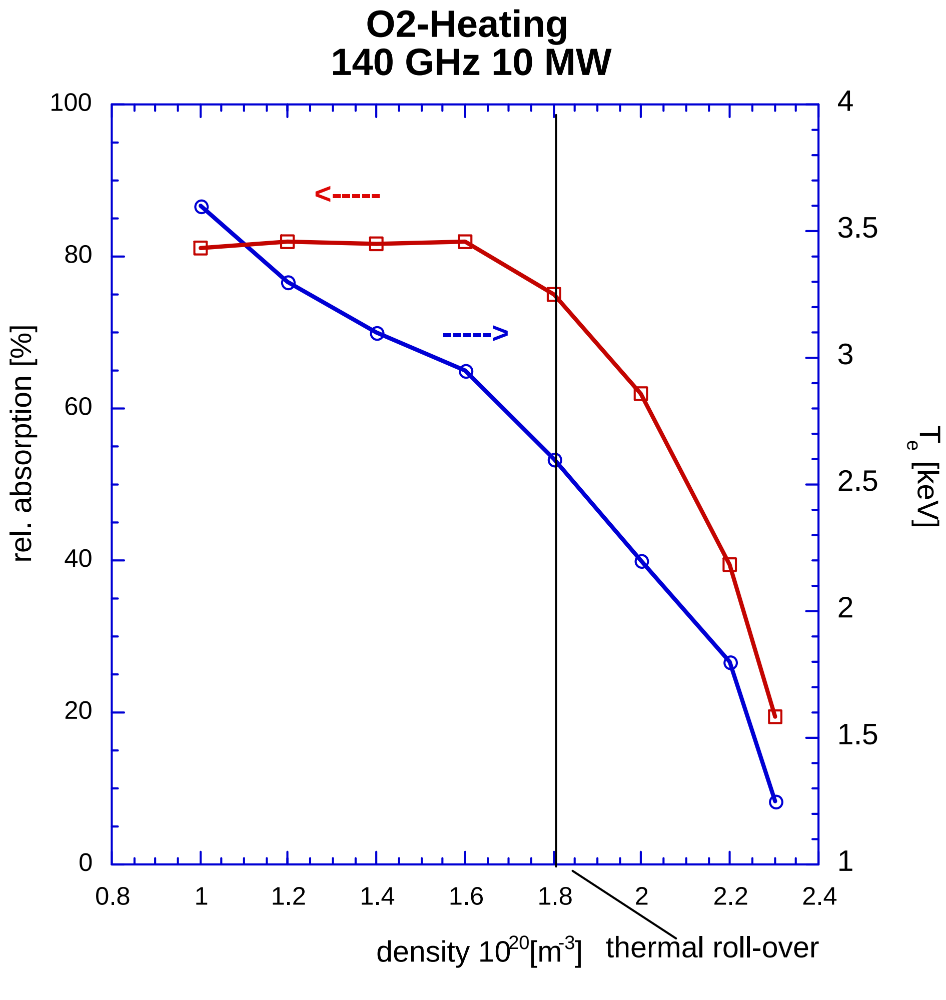


P_{ECH} = 10 MW (12.3 deg.)

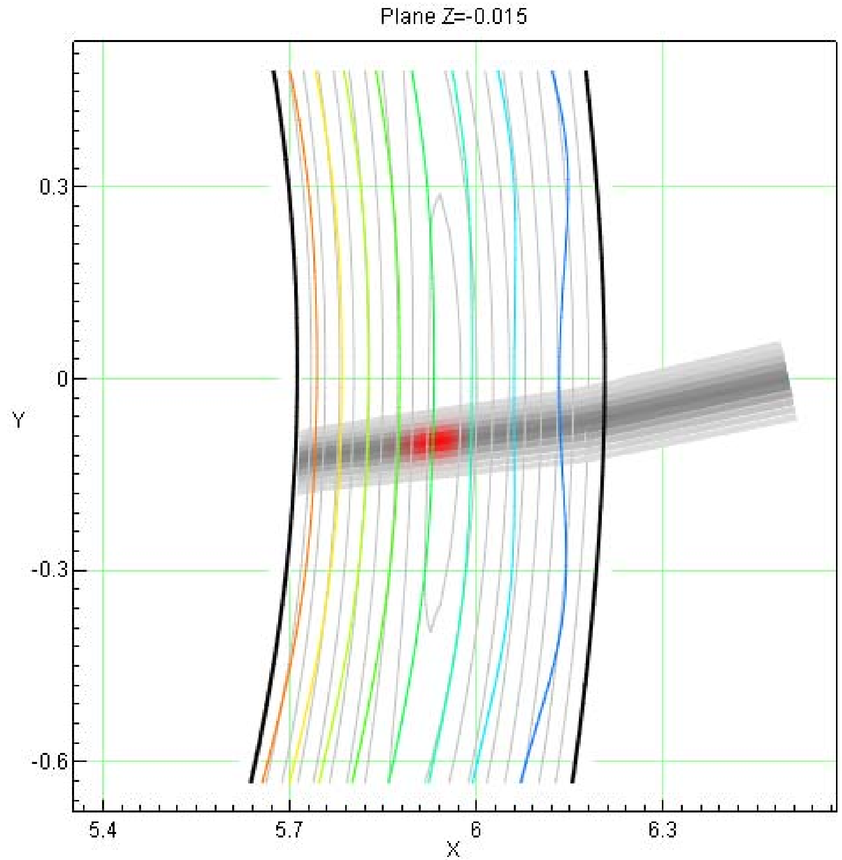


ECH: Predicted Plasma Parameters for W7-X (II)

2nd harmonic O-mode, 140 GHz, 2.5 T



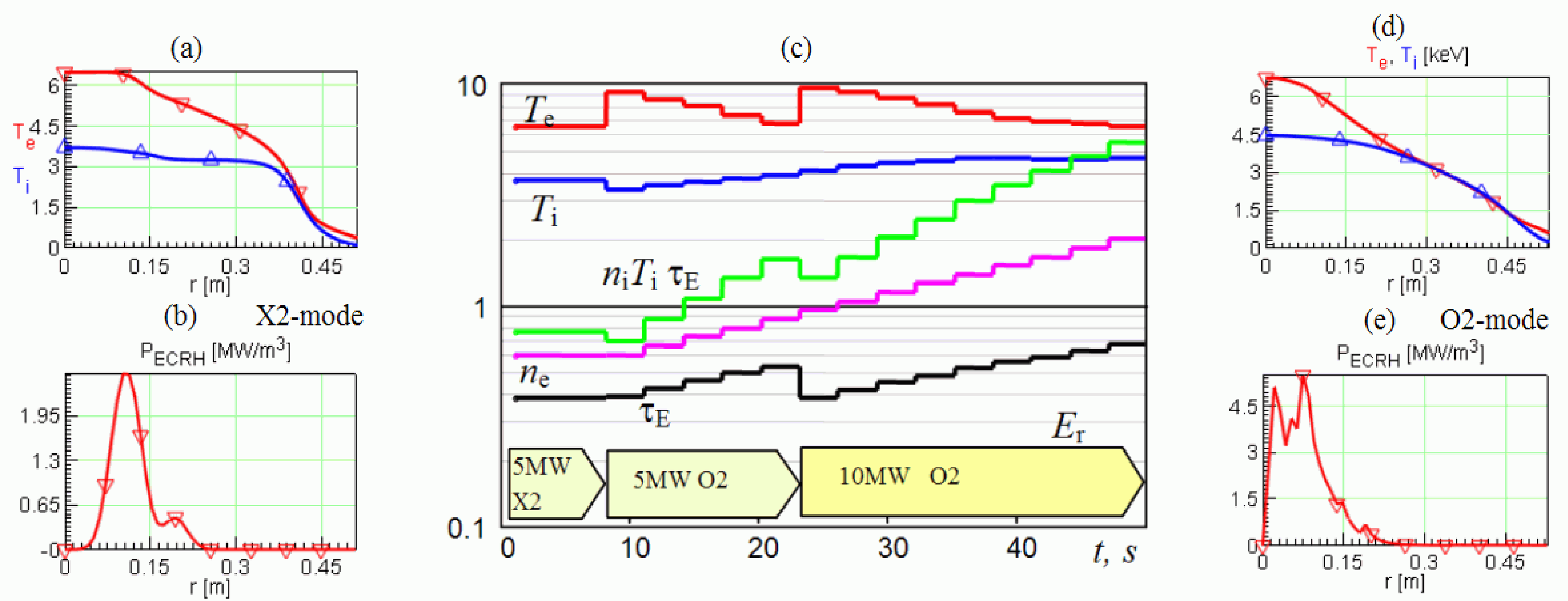
n_e=1.8 ·10^{20} m^{-3} , T_e= 2.6 keV



N. Marushchenko, et al., 2007

ECH: Operation Scenarios for W7-X

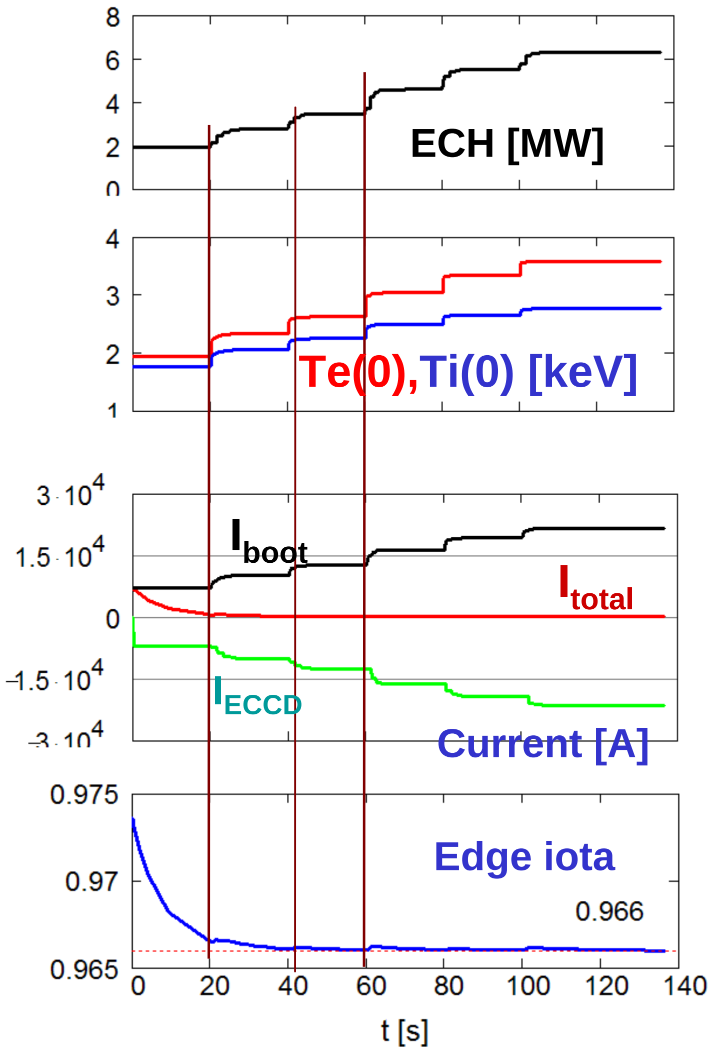
Transition of 2nd harmonic X-mode to 2nd harmonic O-mode
- assume neoclassical core confinement with ‘anomalous edge’ -



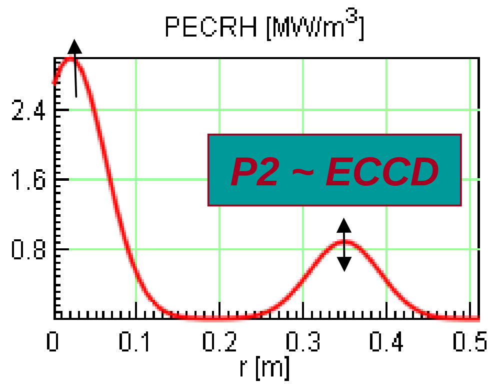
- Plasma start - up and heating with X2 (5 MW) *Y. Turkin, et al., EPS, 2007*
- Tuning launching angle (12 deg.) and polarization towards O2
- Increase plasma density
- Increase ECH power (10 MW) and plasma density

ECH & CD: Predicted Plasma Parameters for W7-X

Steady state operation: Current control by ECCD



- ECCD for bootstrap current compensation
  I_{BS} = 7kA → 22kA
- Adjust power in P1
- Drive current with P2 (launching angle)
- Control edge rotational transform

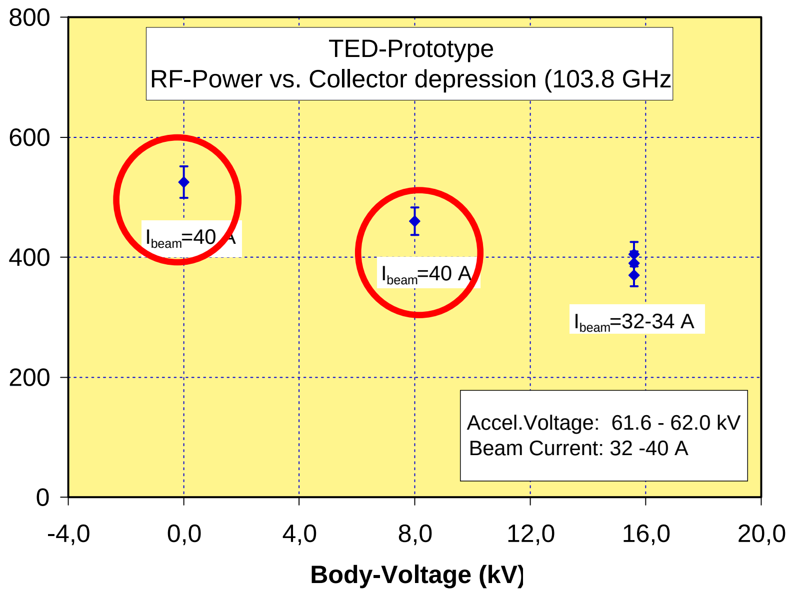


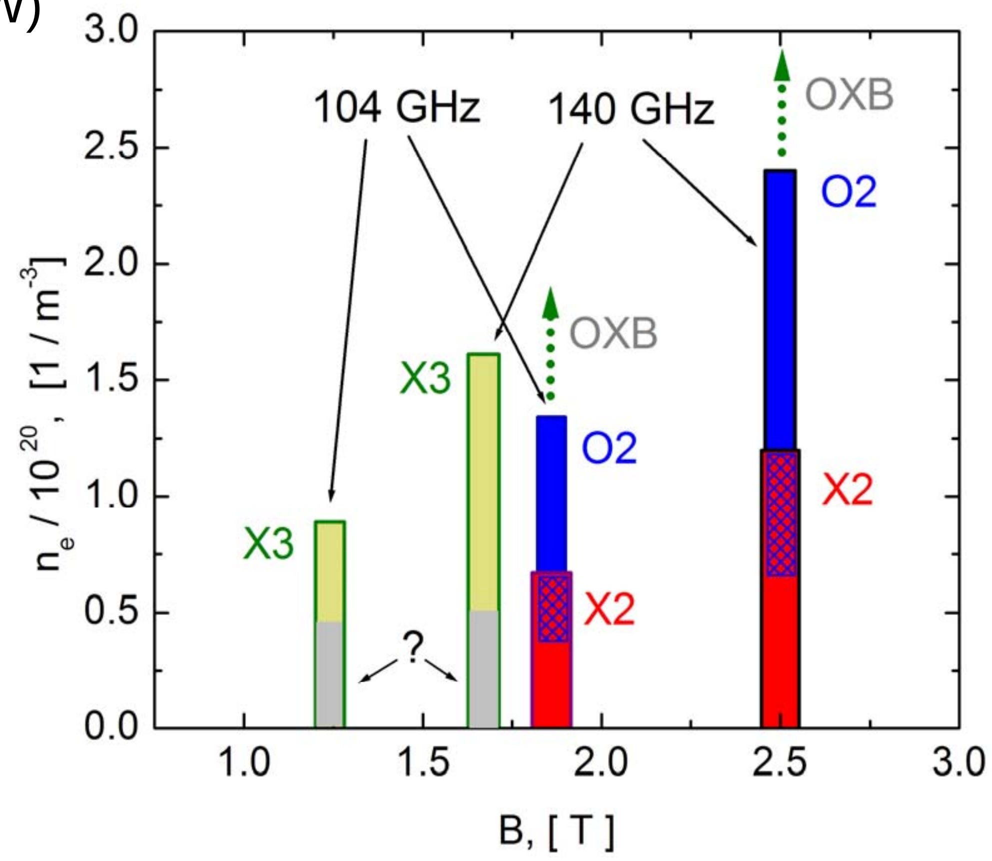
Y. Turkin et al. FS&T 2006

N. Marushchenko, SMSA 2007

ECH & CD: Features Beyond Specifications
2nd frequency at half power: 103.8 GHz

- Gyrotron diamond window transparent at d = 4λ/2 (140 GHz) ... also at 3λ/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)

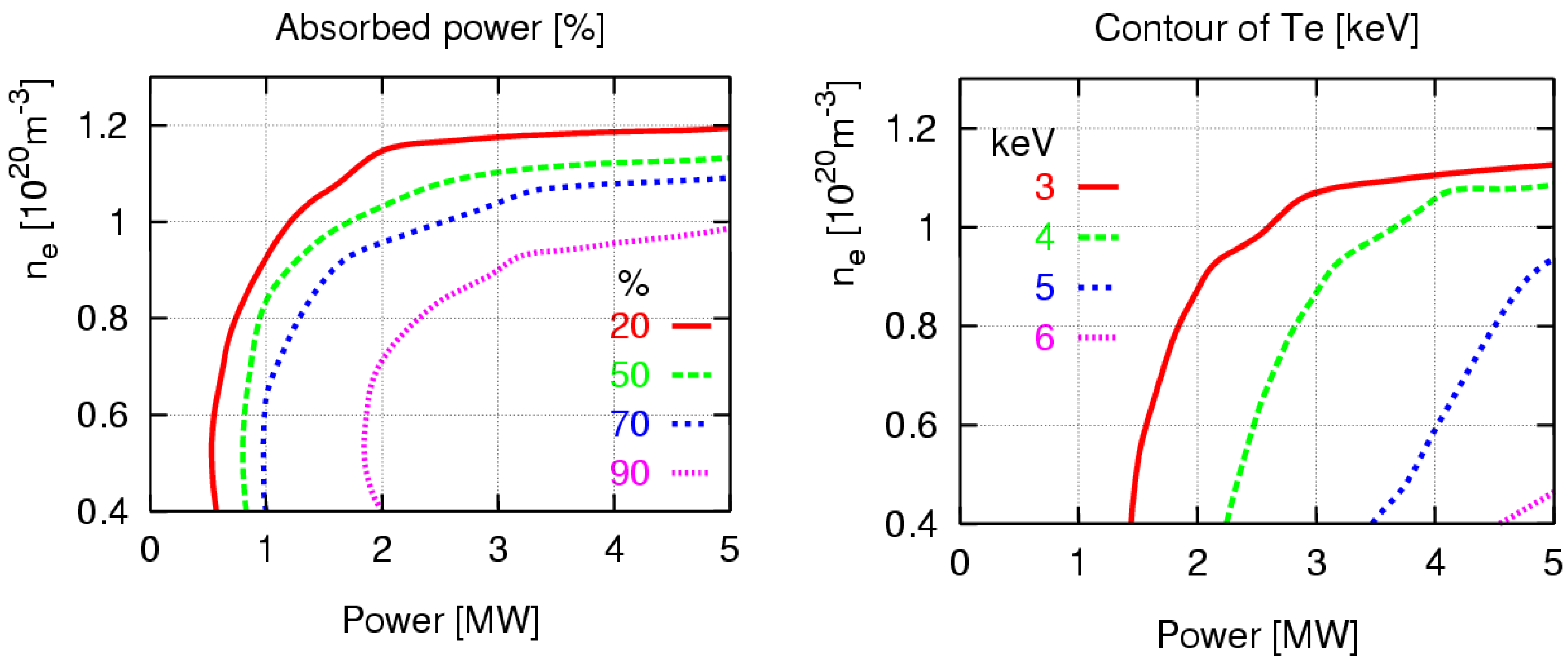




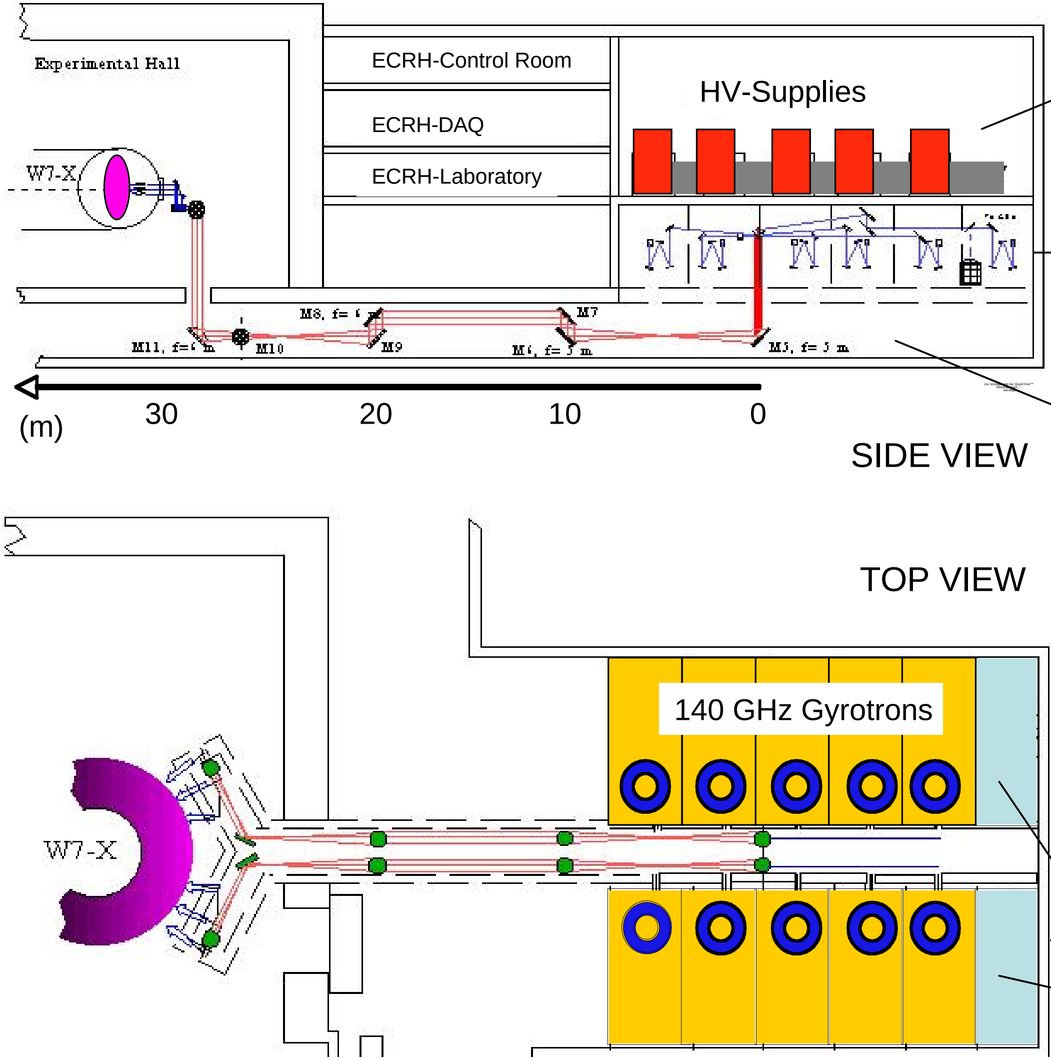
ECH: Predicted Plasma Parameters for W7-X

2nd harmonic O-mode, 103.8 GHz, B_{res} = 1.85 T, $n_{e,crit}$ = 1.4 · 10 ^{20} 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

Karlsruhe Institute of Technology

HV Modulator: IPF Design (tetrode based)

- + 30 kV, 0.5 A supply (energy recovery)
- Fast regulator/modulator (20 kHz demonstrated)
- Thyratron crowbar, HV-control system
- All 10 units completed and operational

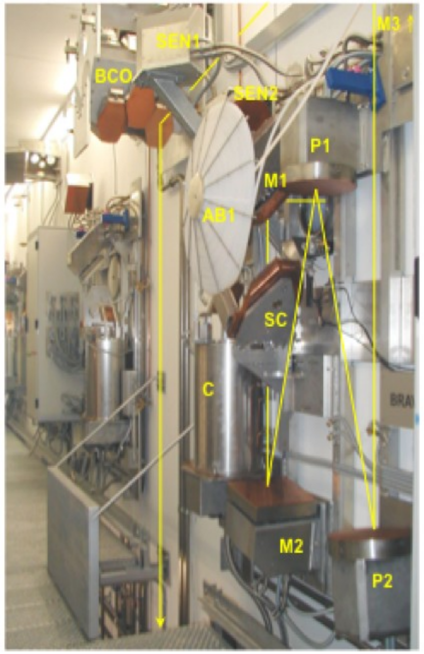
- Gyrotron cooling modules (< 20 MW)
- Central mirror cooling module (< 0.7 MW)
- Launcher- and dummy load cooling (< 2 MW)
- All units completed and operational

ECH & CD Plant for W7-X: Status

Gyrotrons...

....and the quasi-optical transmission system

Single-Beam Module | **Multi-Beam Section**

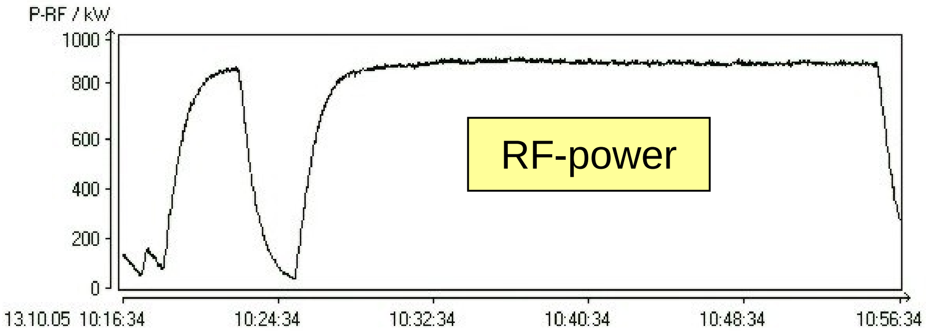


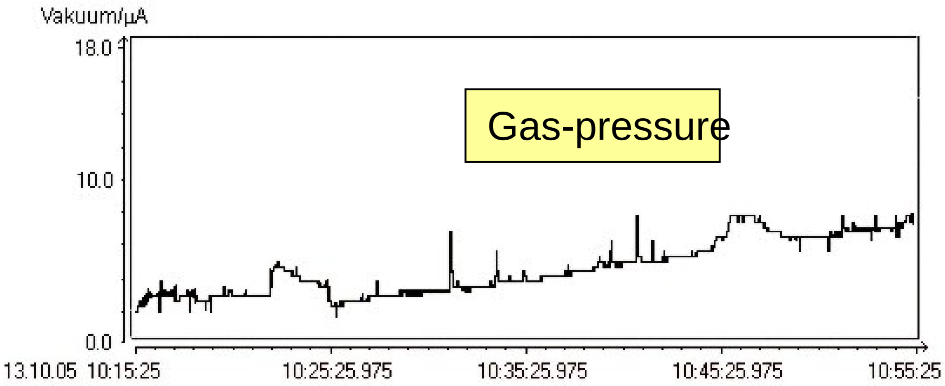
- 8 out of 10 gyrotrons delivered and tested,
- # 2 (2a), #3 (3a), #4 failed to meet the specs, beam tunnel problem (new atten. ceramics) , parasitic oscillations
- #5 presently under test, shifted output beam!

- 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





40 min

Gyrotron output power	> 0.92 MW (TED)
	> 0.90 MW (CPI)

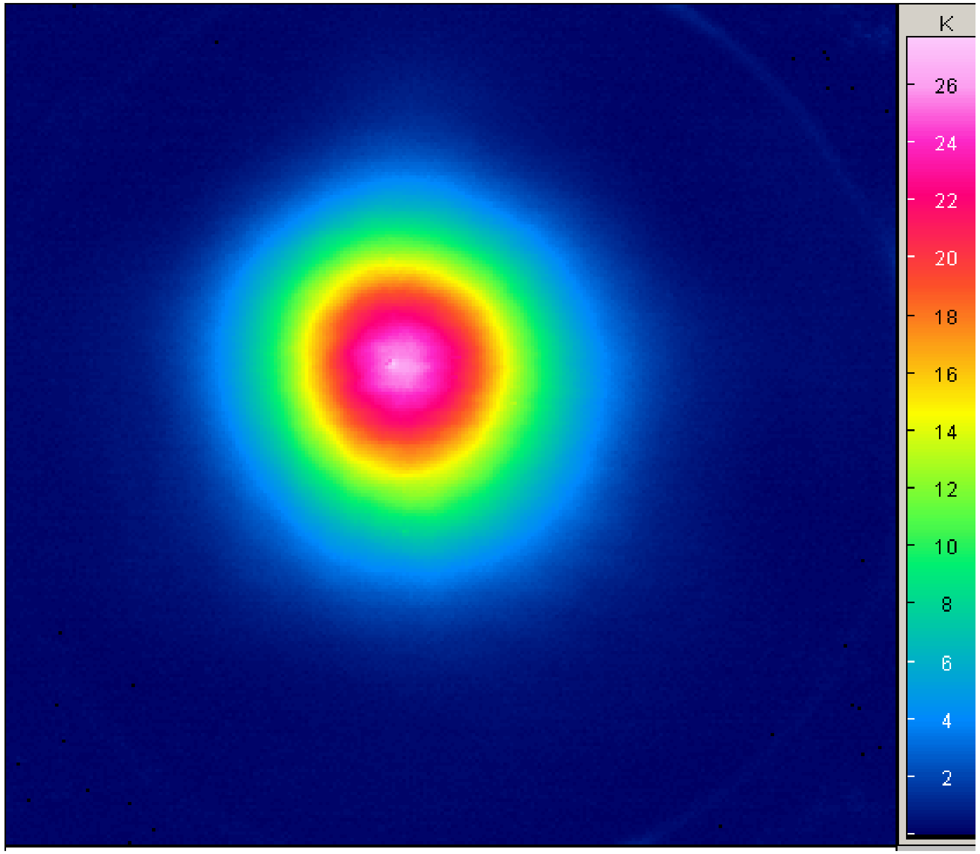
After transmission through 7 mirrors:

Power in Gaussian mode	0.87 MW (TED)
	0.83 MW (CPI)

(estimated losses are 50 - 70 kW, imperfect BMO, improvement under way)

Short Pulse Results of 4th Series Gyrotron

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 %**

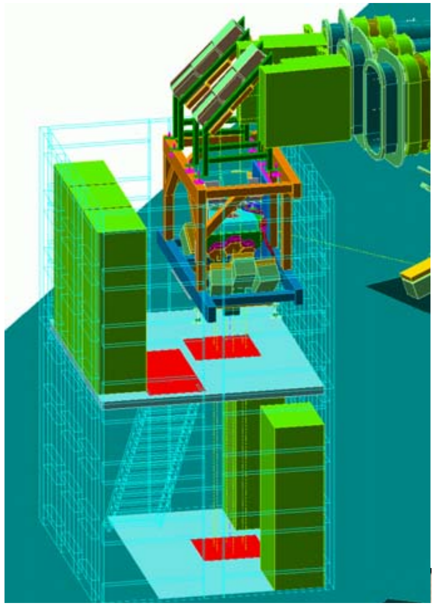
Mode purity of all gyrotrons > 95 %

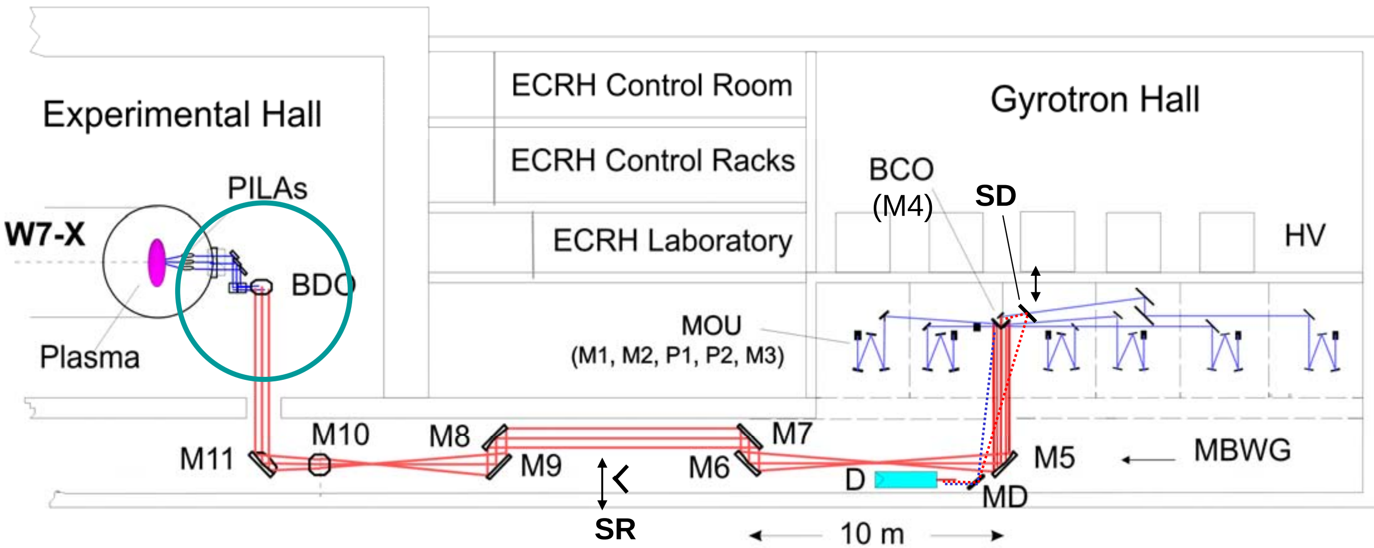
Gyrotrons, Magnets and Loads: Status

- 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

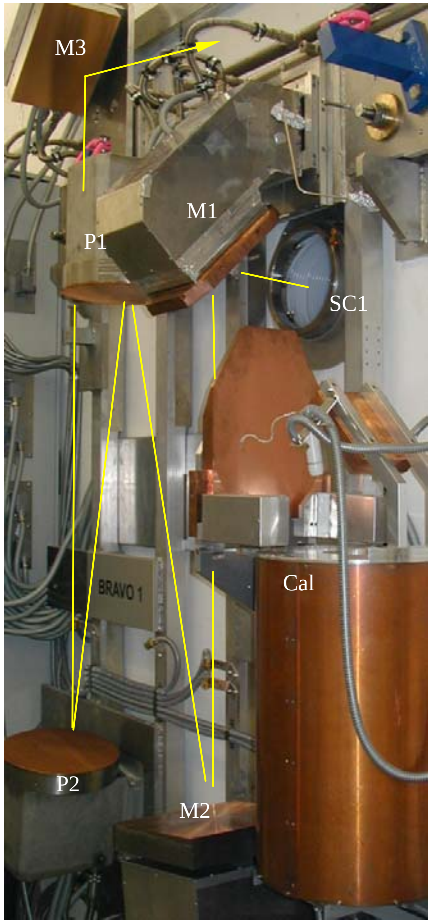
ECH: Near-Torus Transmission: The ECH&CD Towers

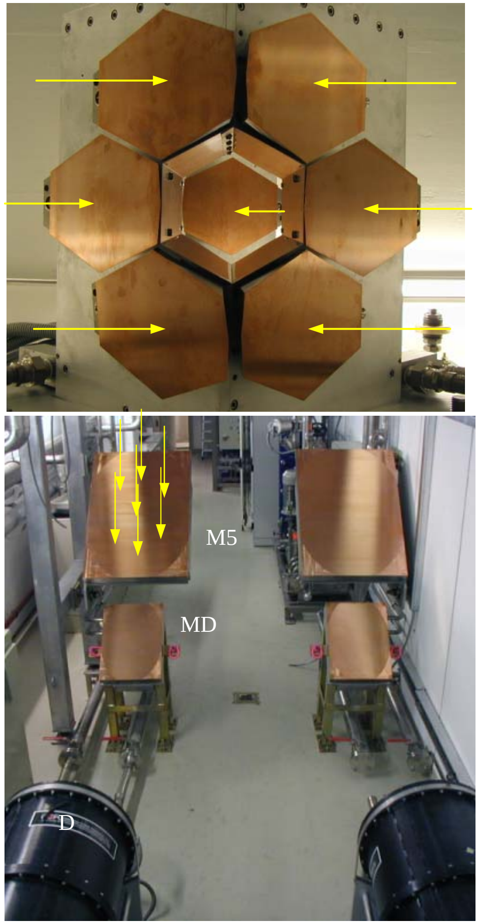




- House of optical elements to distribute and match the RF beams to the 'equatorial-plane' and 'HFS'-launchers
- Heavy granite structure is good mm-wave absorber
- "Towers" completed, presently installation of optical elements, remote control system, cooling etc.

ECH & CD: Integrated CW Tests
Quasi-Optical Transmission, Beam Path



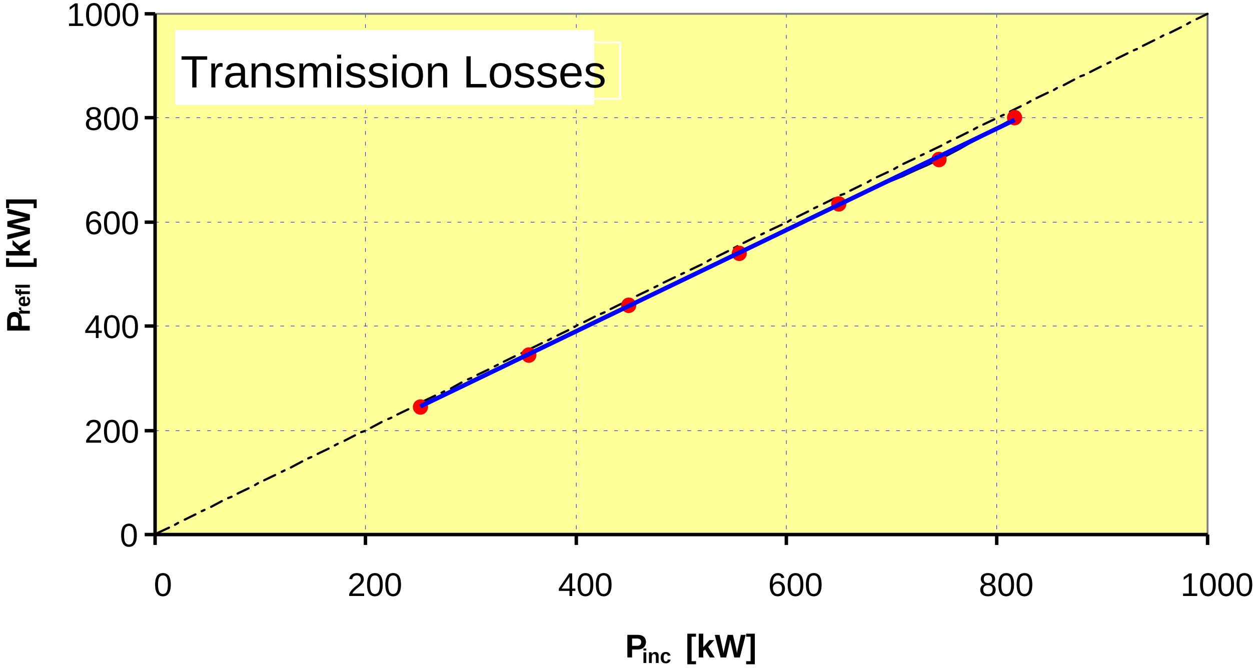


Single-Beam Module

Beam-Combining Optics MBWG and CW Load

- 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



ITEM	OHMIC (%)	DIFFR. (%)	(%)
M5, M6, M7	0.39	0.2	0.59
2 SR	0.26	0.1	0.36
M5, M6, M7	0.39	0.2	0.59
M4	0.13	0.1	0.23
SD	0.13	0.1	0.23
ATMOSPH.	0.68		0.68
SUM			**2.68 %**
MEASURED			**2.7 ± 0.4%**

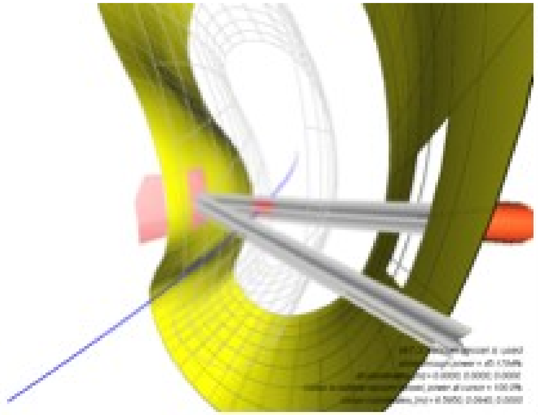
- **Wave beam is transmitted half way to the torus and then reflected by retro-reflector (40 m)**
- **10 mirrors**
- **Beam power measured calorimetrically**
- **Measured losses are 2.7 %, agree with theoretical losses**

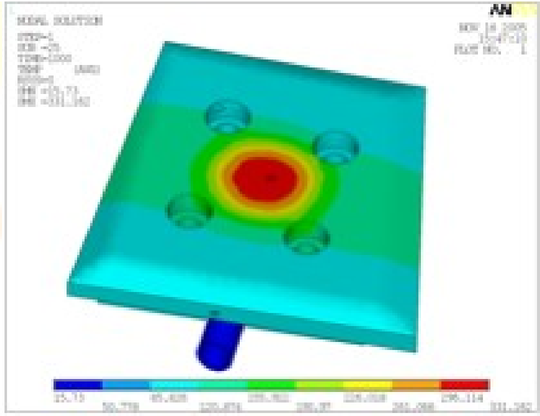
W7-X: The In-Vessel Transmission System
Plug-In Front Steering Launchers

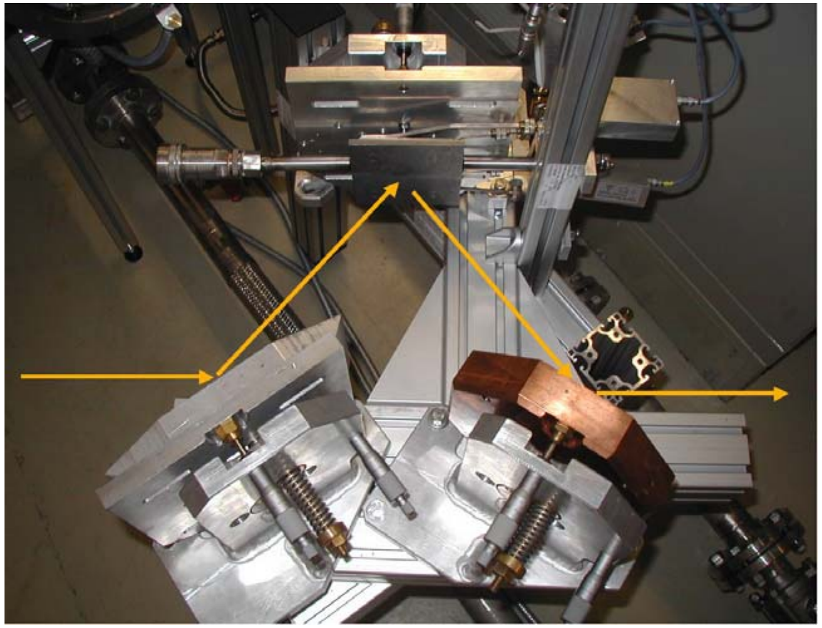
- Combines 3 RF beams per port with wide steering range (O2, X3, O-X-B, ECCD): toroidal < 35° , poloidal < 30 °
- Simplified launcher mock-up tested, concept for in-vessel driving rods and mirror cooling qualified
- Survived 10 000 load cycles
- Tested in MISTRAL facility (mm-wave stray-radiation loading).
- 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







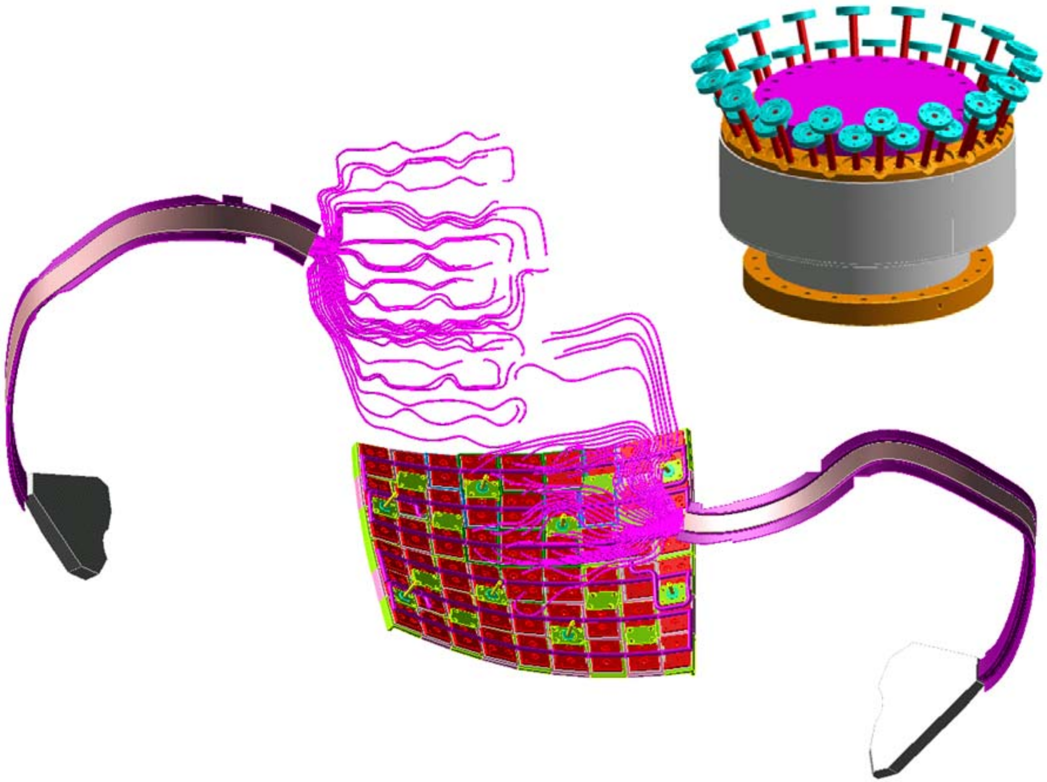
- TZM tiles for in-vessel reflection qualified with 0.5 MW incident power
- Thermal loading acceptable with polished surface (T_{surf}< 470 °C in CW)

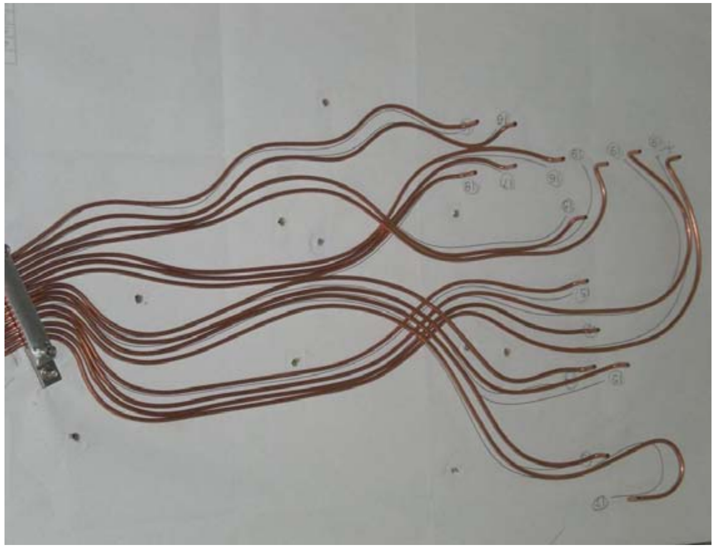
Good knowledge of beam location on TZM tiles required

- 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



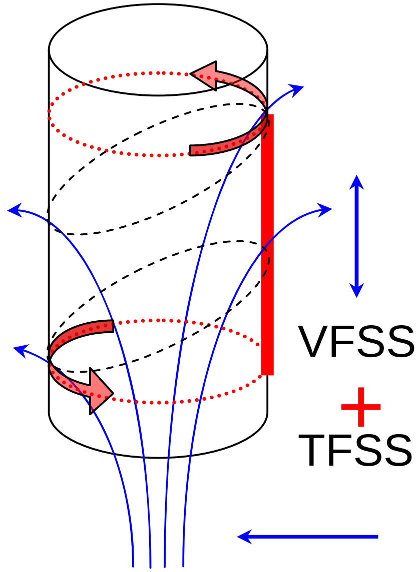


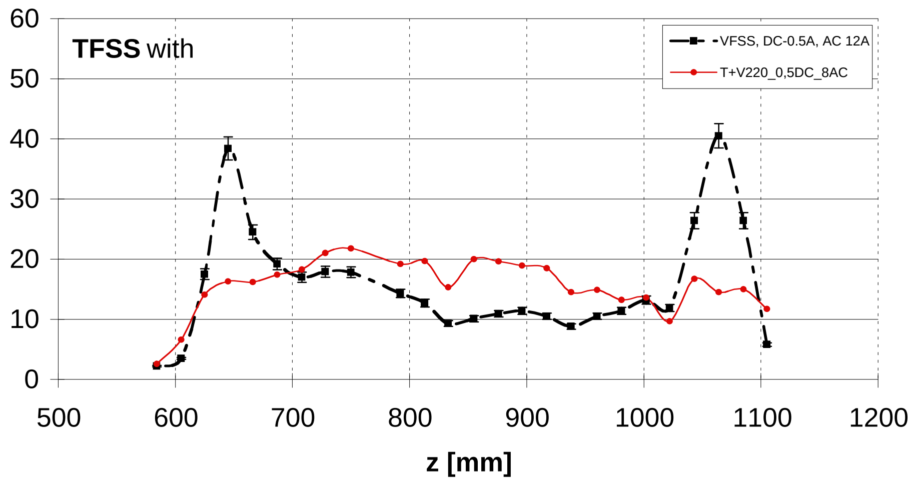
Advanced Transverse Field Sweeping System (TFSS)

50 Hz rotating perturbative field

...with small VF-modulation (VFSS)

(V.Erckmann, G, Dammertz, M. Schmid,. Patent 2007)





- 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

ECH & CD for W7-X: Summary

- 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