17th International Stellarator / Heliotron Workshop

Princeton, USA

Overdense Plasma Operation in WEGA Stellarator

Matthias Otte,
H.P. Laqua, S. Marsen, Y. Podoba,
T. Stange, D. Zhang, F. Wagner and the WEGA-team

Max-Planck-Institut für Plasmaphysik, Greifswald branch, EURATOM Ass.

Wendelsteinstr. 1

D-17491 Greifswald, Germany

Outline

- Motivation on over-dense plasma generation
- Overview WEGA
- Setup of 28GHz ECRH system
- Results from OXB mode heating
- Summary and outlook

Overview of actual WEGA results will be presented on poster P-D02 during workshop's poster session from Monday till Wednesday.

Motivation

Why OXB Mode Heating ?

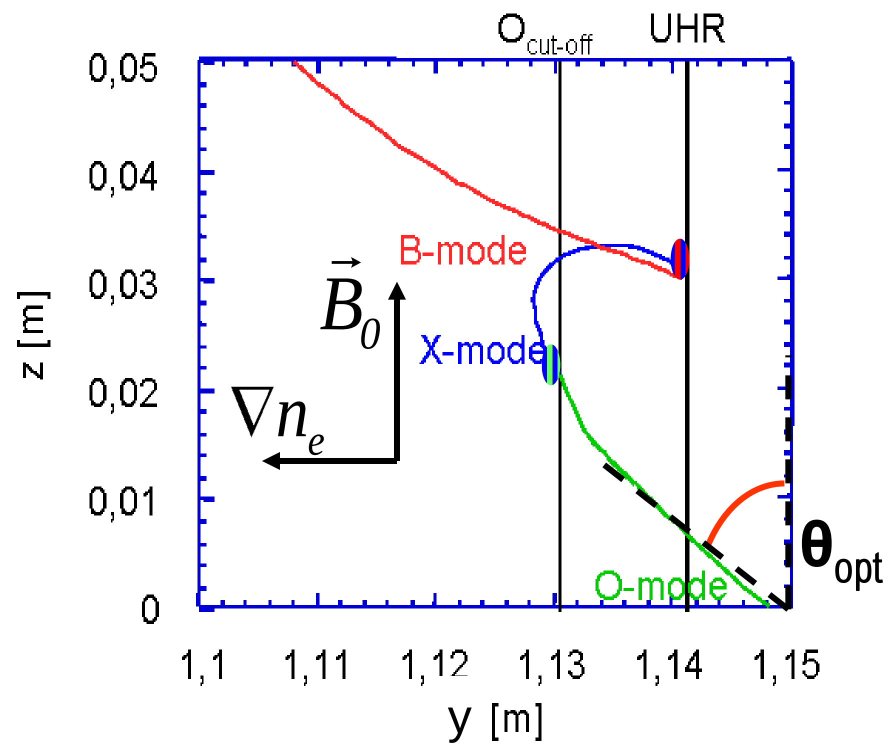
- Electromagnetic waves used for resonant electron or ion cyclotron heating can not penetrate the plasma above associated cut-off density
  ➽ problem for high-density operation
- Electrostatic Bernstein waves (EBW)
  - no density limit but need a medium for propagating
  - damped on electrons at fundamental or harmonic Doppler-shifted electron cyclotron resonance
- Plasma is optically thick for EBWs even at low temperature (<10 eV)
- Interesting physics:
  - Wave field physics
  - Generation and confinement of fast electrons
  - Current drive in overdense plasmas

Requirements

- O-wave launched with θ_{opt} in respect to the magnetic field vector
  - correct polarisation
  - angular window width ~ $1/k_0L_n$ (inverse normalized gradient length)
- Density n_e above cut-off density $n_{e,cut}$
- Existence of UHR ($\omega > \omega_c$)

Example:

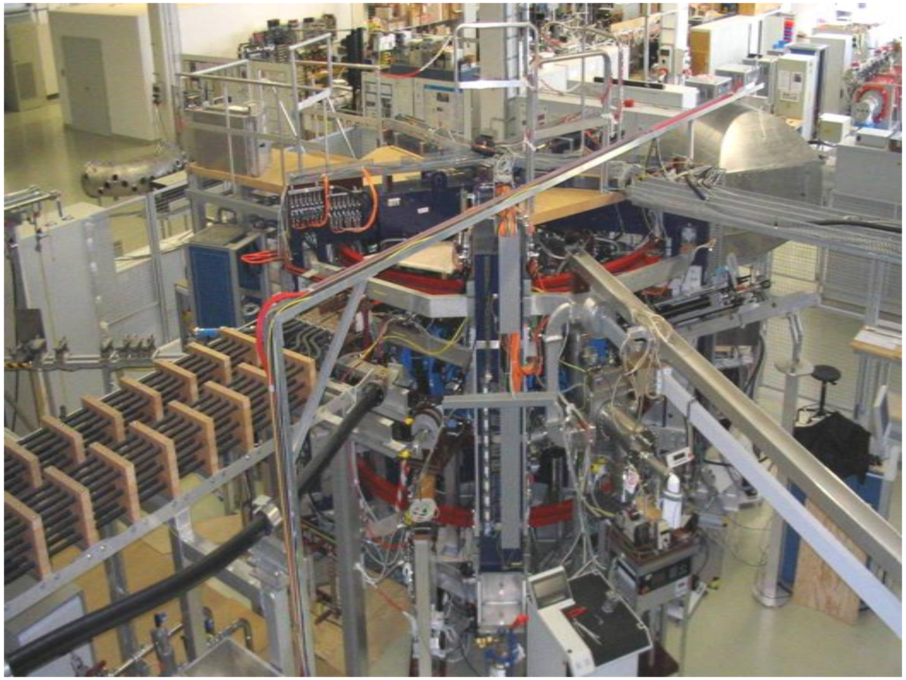
Ray tracing calculation of slow X-mode conversion process at W7-AS



Overview WEGA

WEGA = Wendelstein Experiment in Greifswald zur Ausbildung (for education)

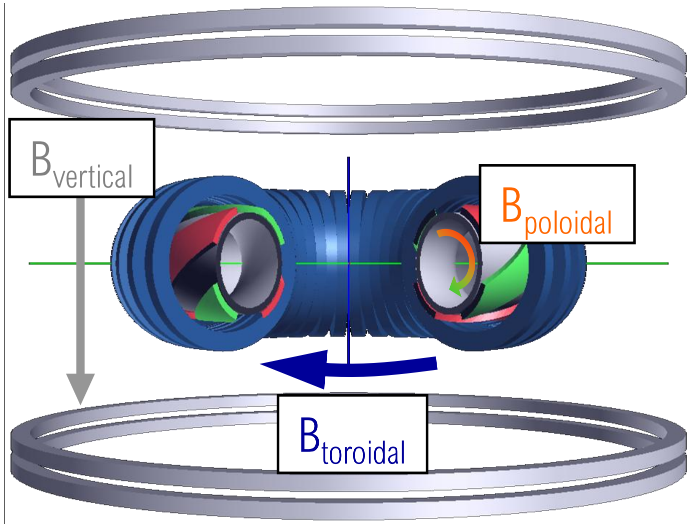
- Hybrid tokamak/stellarator experiment in Grenoble/France in the 1970s and ´80s for development of LH heating
- Installation at IPP Greifswald in 2000/2001 as classical stellarator
- October 2009: about 33000 pulses with typical duration of 10 - 60 s
- 0.5 T operation for 30 s possible
- Up to ~100 pulses / day



Setup and Magnetic Properties

Vessel

- Two half-tori with R = 0.72 m, r = 0.19 m
- 100 ports (∅ ≤ 92 mm)

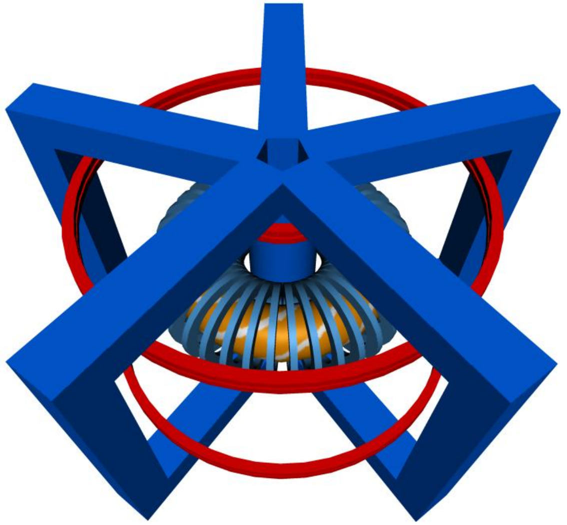


Magnetic field coils

- 40 toroidal field coils: B_{max} (cw) = 0.34 T and 0.9T for pulsed operation
- Helical field coils: l = 2, m = 5
- Rotational transform $\iota/2\pi = 0.1 - 1$
  $a_{max} = 11$ cm, $V_{max} = 0.15\,m^3$ (limiter configuration)
  a <= 5 cm for high iota (separatrix configuration)
- Vertical field and error field compensation coils

Plasma heating

- 20 + 6 kW magnetrons @ 2.45 GHz (cw)
- 10 kW gyrotron @ 28 GHz (cw)
- 5-arm transformer with 0.44 Vs



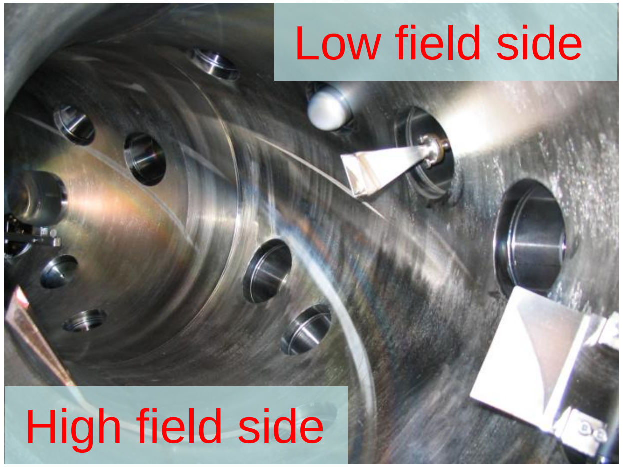
Working gases

- Helium, Argon, Hydrogen

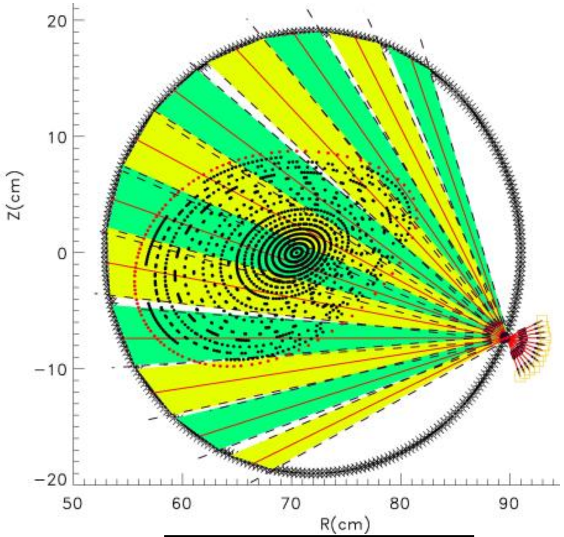
Relevant 28GHz Diagnostics

- Interferometer (80 GHz, single channel)
- Sniffer probe (28 GHz)
- 12-channel bolometer array
- Radiometer with 12 channels (23 – 40 GHz) for ECE, EBE and Reflectometry
- Spectrum analyzer up to 40 GHz
- Soft X-ray (PHA)
- Langmuir probes

Sniffer probe



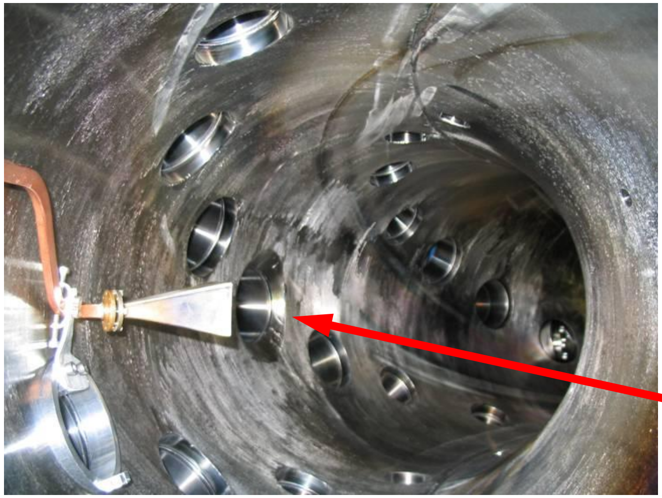
ECE antenna system

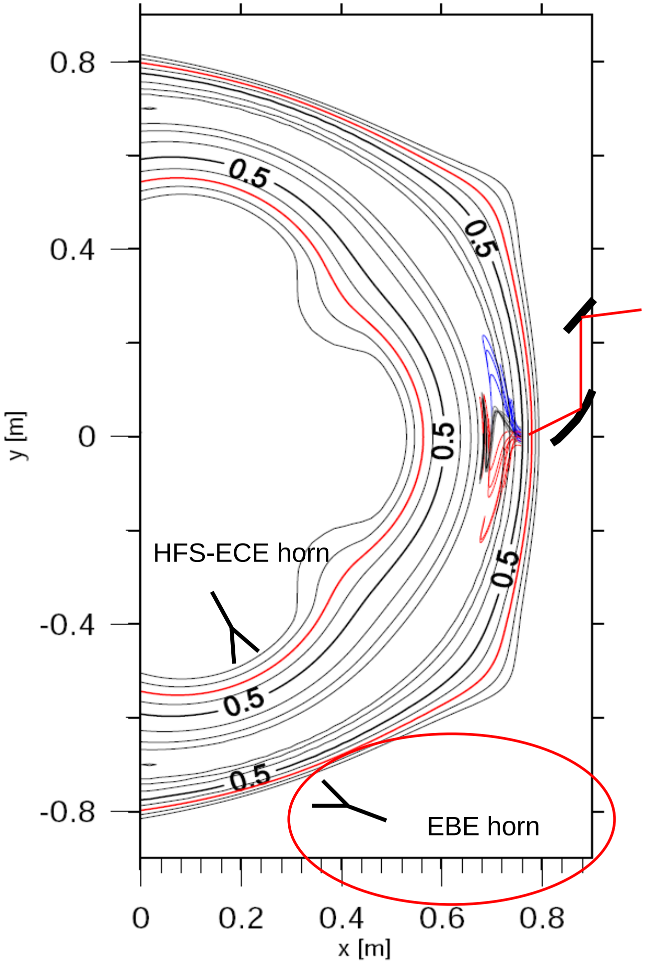


Bolometer array

Temperature measurements

- ECE: problem ➽ over-dense and optically thin
- EBE: accessible via BXO conversion, optically thick even at low temperature, no density limit, oblique alignment of antenna necessary



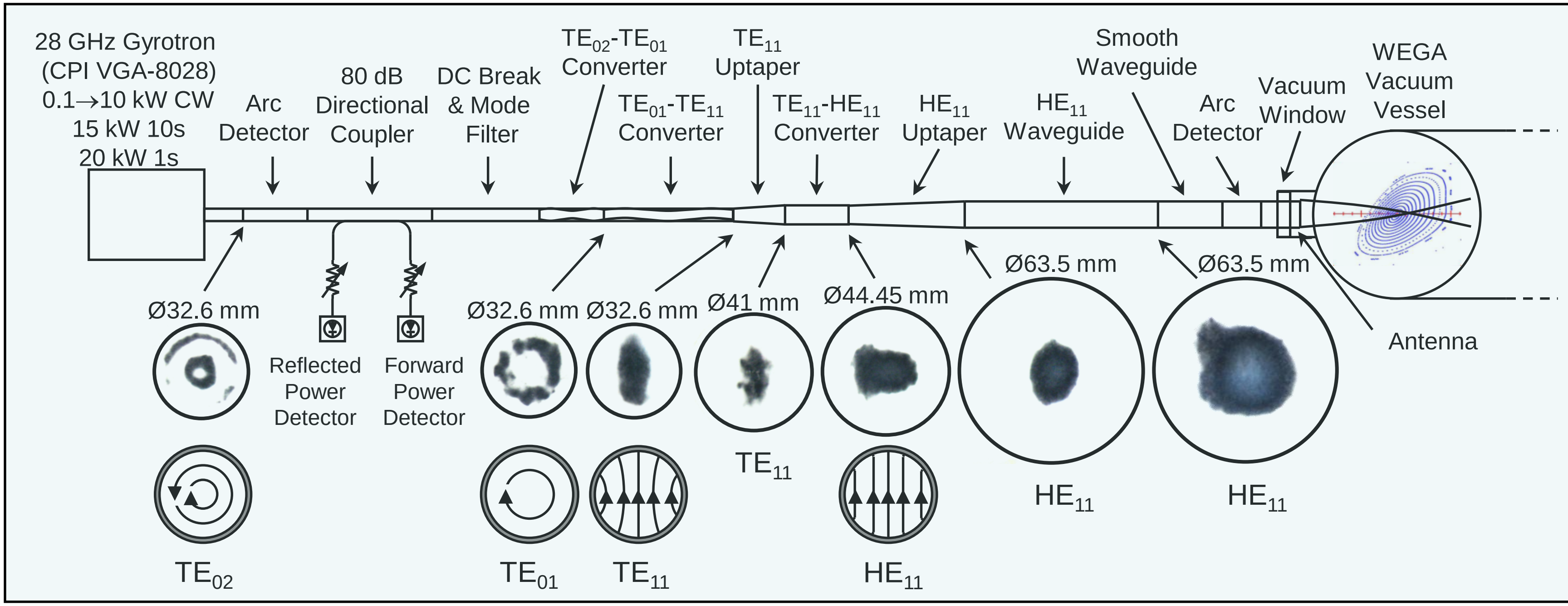


Oblique alignment of EBE antenna (55°)

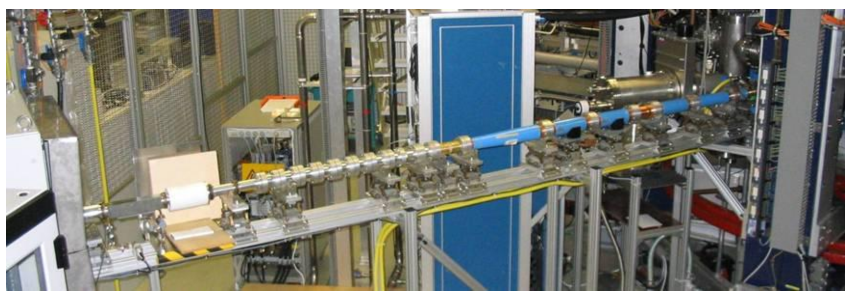
Setup of 28GHz ECRH system

ECRH Components

Installation of a 28GHz ECRH for B_0=0.5T operation in cooperation with CIEMAT/Spain and IPF Stuttgart

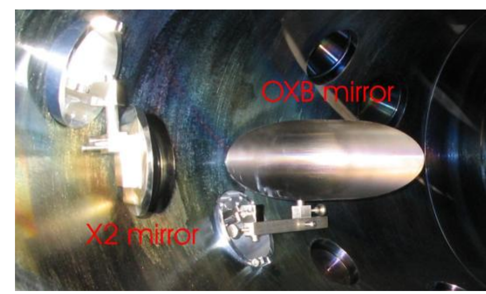


Gyrotron 10kW cw
(20 kHz modulation)



4.3 m

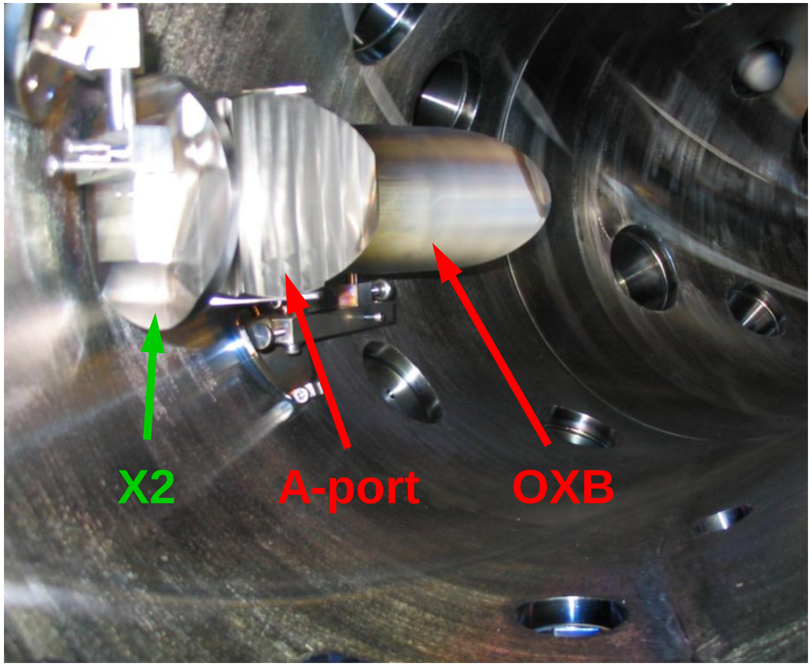
Transmission line

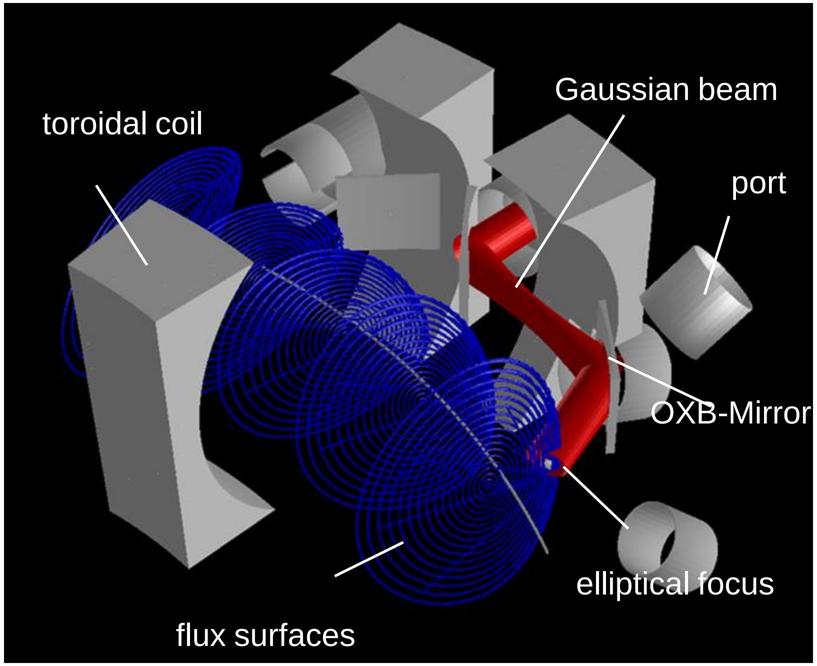


Mirror system inside vessel
for X2 and OXB mode

ECRH Components: In-Vessel Mirrors

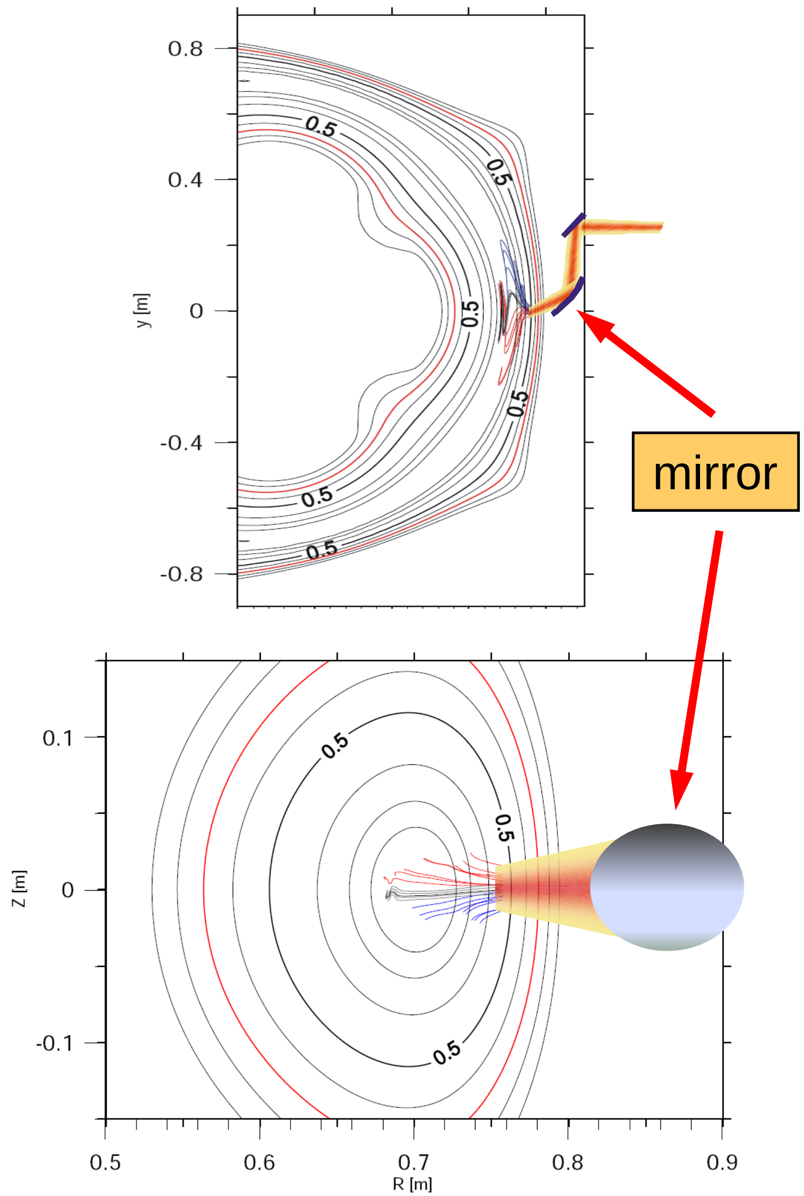
- Switching between X2 and OXB mode heating possible by exchanging A-port mirror
- Quasi-optical Gaussian beam in equatorial plane at vertical elongated symmetry plane (steepest gradient expected) under angle of 55° to magnetic field line
- Steerable OXB-mirror for finding optimum OXB conversion (up to now venting of vessel necessary)





Discharges of B_0=0.5 T up to 30s at $\iota/2\pi$ <= 0.4

Ray-tracing calculations by J. Preinhaelter and J. Urban (IPP-Prague) predict high efficiency central heating at densities above 1×10^{19} m^{-3} and no Doppler-shift



Challenge

How to reach $1{\times}10^{19}$ m^{-3} (28 GHz O-cutoff) ?

- $0.5{\times}10^{19}$ m^{-3} is already reached with X2-mode (X-cutoff)

Additional energy sources available

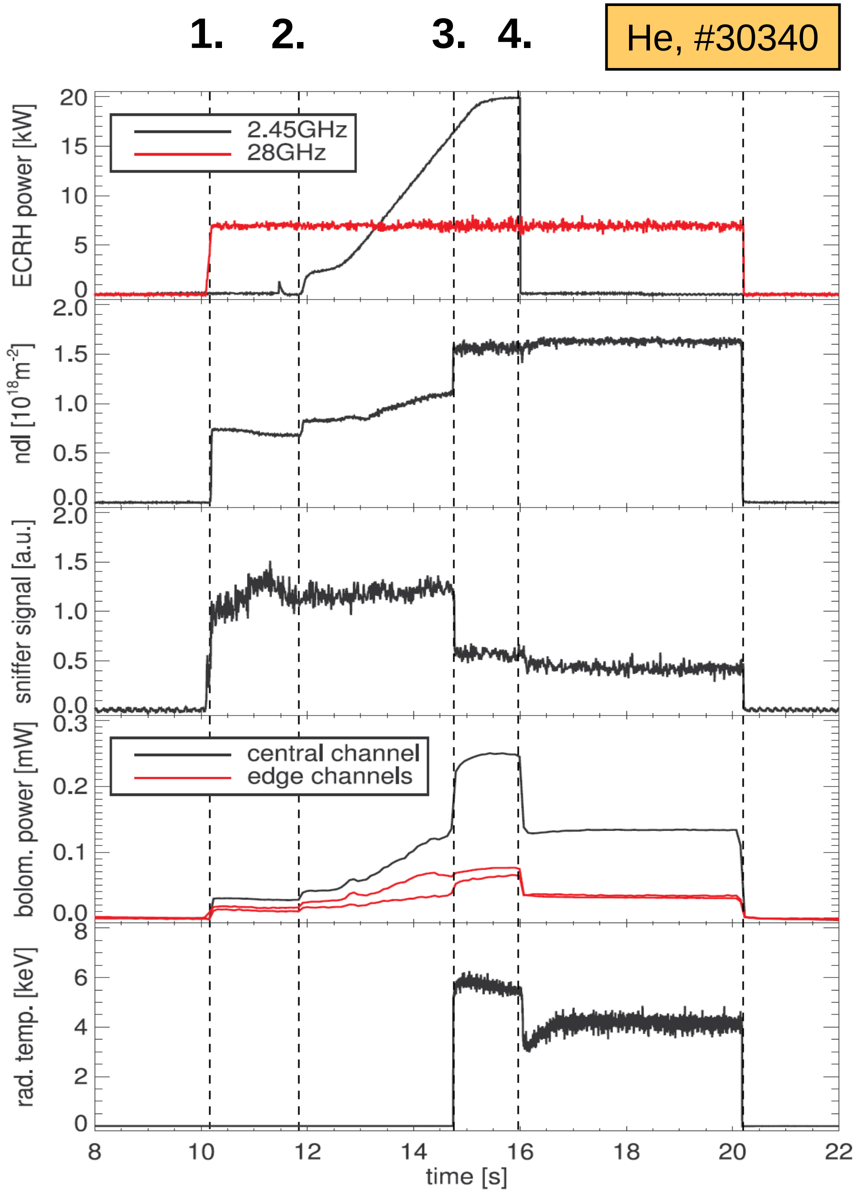
- 20 kW 2.45 GHz resistive R-wave heating at 0.5 T
- Ohmic heating with transformer

Results from OXB mode heating

Reaching OXB mode

1. Plasma start-up:
   Plasma generation by 10% X2-mode at resonant field, multi-pass heating with broad deposition
2. Overcome power gap above $0.5 \times 10^{18}\,m^{-3}$ (X2-mode cut-off) by additional resistive 2.45 GHz heating (20 kW)
3. Start OXB conversion above $1 \times 10^{19}\,m^{-3}$ (O-mode cut-off):
   - central deposition due to high single pass absorption
   - density peaking up to $1.4 \times 10^{19}\,m^{-3}$ (33 GHz EBE signal)
   - EBE signal in keV – range (radiation but not electron temperature)

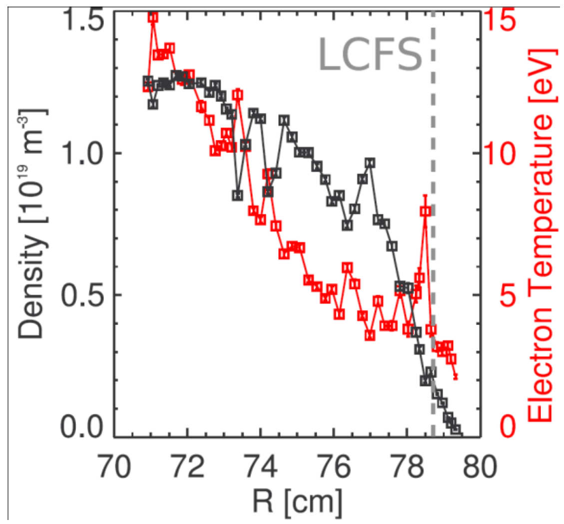
     ➽ **supra-thermal electron component**
4. Switch off additional heating:
   Plasma sustained by OXB-heating only, strongly peaked radiation profiles



Further Results during OXB Phase

Langmuir probe

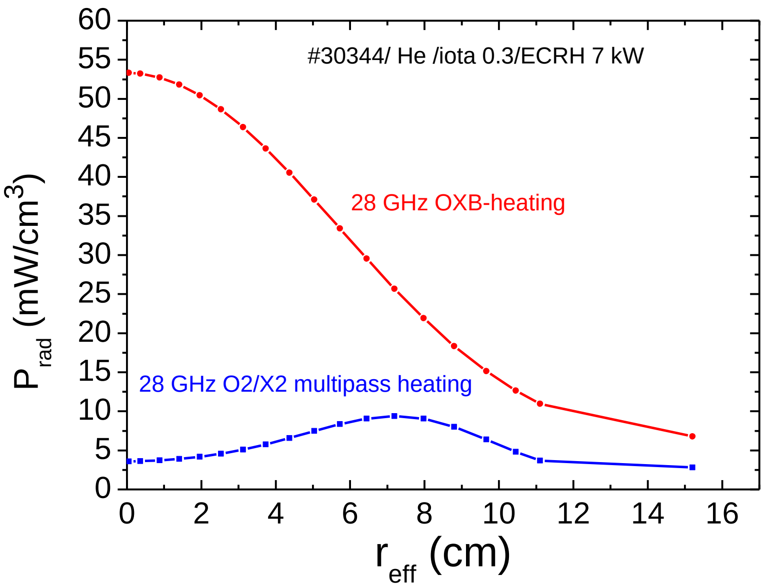
- Peaked profiles with $n_{e,0} = 1.3 \times 10^{19}\ m^{-3}$
- Bulk parameters:
  - $n_e = 1 \times 10^{19}\ m^{-3}$ at R = 75 cm
  - $T_e = 5$ -15 eV
- No sign of supra-thermal component in Langmuir-probe characteristics



12-channel Bolometer camera

Reconstructed radiation power signal:

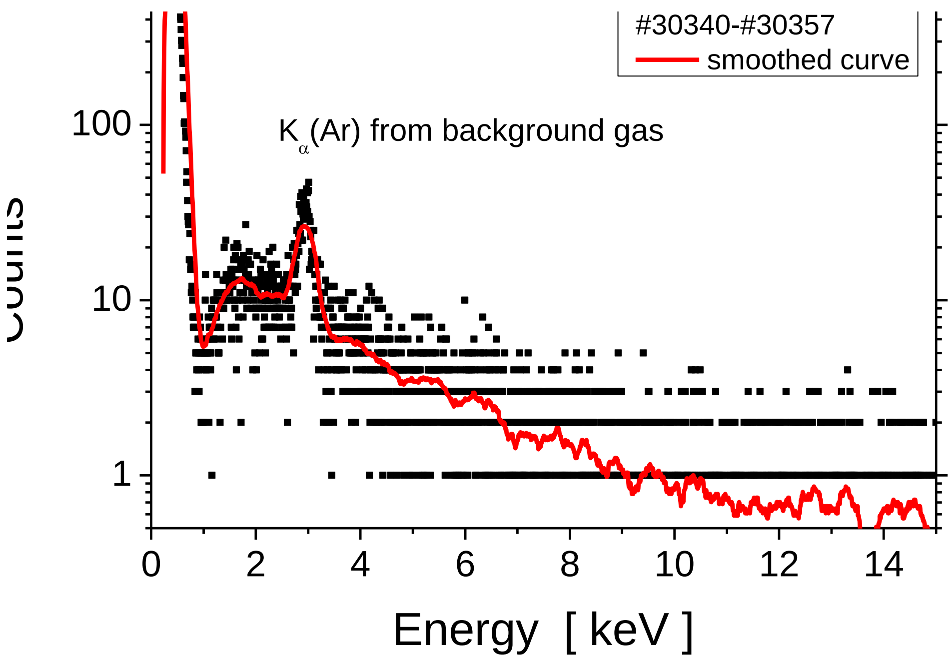
- peaked profile during OXB-phase due to central power deposition
- Broad, flat profile during O2-mode heating due to multi-pass absorption



Soft X-ray

- Pulse height analyzer with range of 0.5keV – 15keV
- Signals above 1keV detected exclusively during OXB phase
- Only Bremsstrahlung, but no characteristic radiation detected (e.g. wall material) except from argon from previous experiments

➽ **supra-thermal electron component arises in center as expected by resonant absorption mechanism**



Optimization

Gas

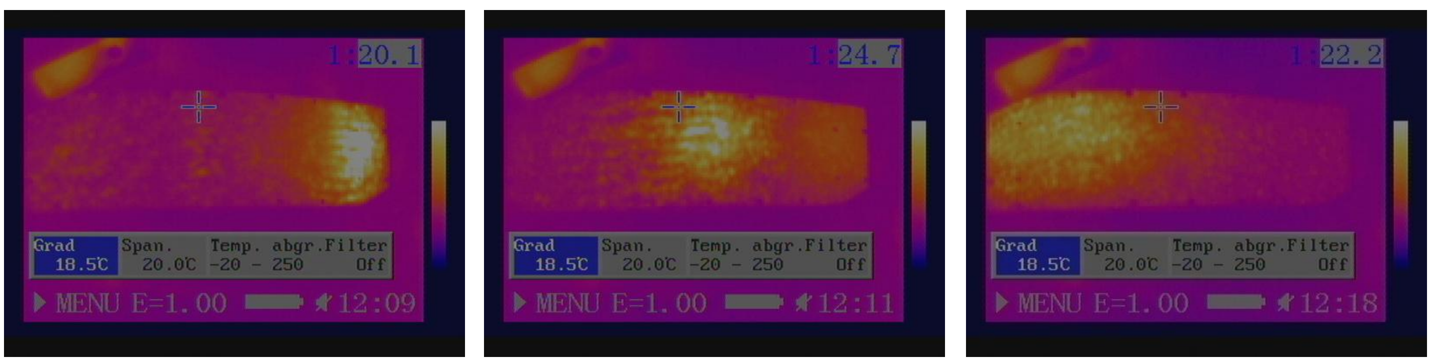
- Analogue results in argon even without additional heating
  but no conversion reached in hydrogen (factor of 3 missing in density)

Rotational transform

- iota (iota↑, confinement↑, but plasma size↓)
- best iota = 0.3 (still limiter configuration, higher iota not accessible)

OXB mirror position

- October 2009: remotely steering of OXB-mirror possible,
  detailed study of emission pattern performed



Thermal emission pattern for varying toroidal position on target installed at vessel high field side

Summary and Outlook

WEGA has reached a new unexplored physics regime!

- Quasi-stationary overdense plasma heated by 28 GHz OXB mode conversion exclusively
- Supra-thermal electron component detected in EBE radiation,
  confirmed by X-rays detector, however quantitative fraction to be determined
- Acceleration mechanism of the supra-thermal electron component
  ➽ auto-resonance cyclotron acceleration of electrons is not limited

Supra-thermal electrons

- Fast particle confinement
- Generation of current drive
- Ray tracing with non-Maxwellian
  ➽ do they exist and how could they be measured?
- Source for highly charged ions

Acknowledgement

The authors gratefully acknowledge the work of D. Aßmus, R. Gerhardt, the colleagues of the W7-diagnostic group and the technical staff of the IPP.

Thank you for your attention!