Electron Bernstein Experiments at the WEGA Stellarator

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EURATOM/IPP.CR Association, 182 00 Prague, Czech Republic

in the EC-16 Workshop
Sanya, China

Why Bernstein Waves?

- Electrostatic waves, no density limit.
  - Heating and current drive in overdense plasmas.
- Plasma is optically thick for EBW´s even at low temperature (<10 eV).
- Interesting physics
  - Mode conversion (OXB)
  - Wave propagation
  - Phase space interaction (current drive, fast electrons)

Outline

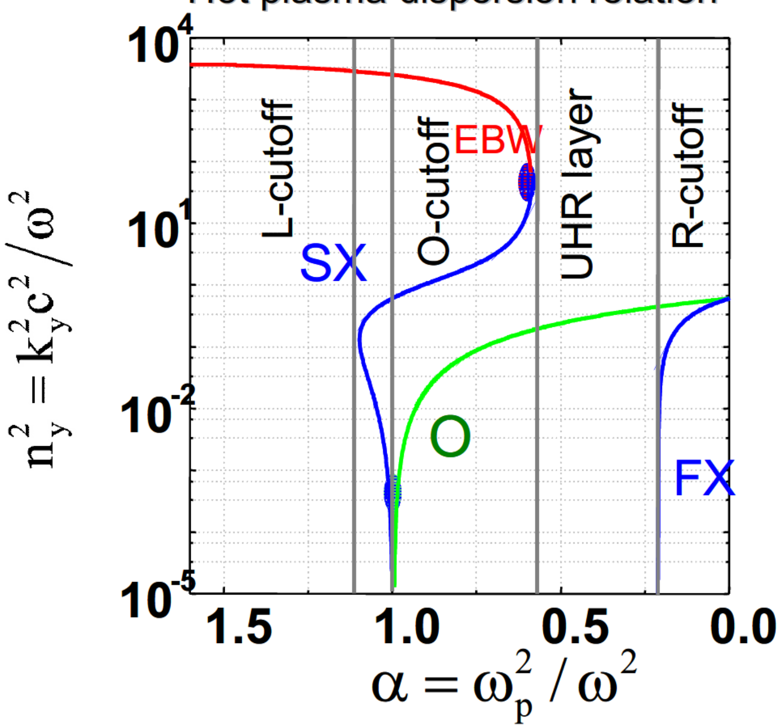
- Introduction
- WEGA and the 28 GHz ECRH system
- OXB heating experiments
- Electron Bernstein wave emission
- Current drive experiments
- Summary and conclusion
  –

OXB Mode Conversion Process

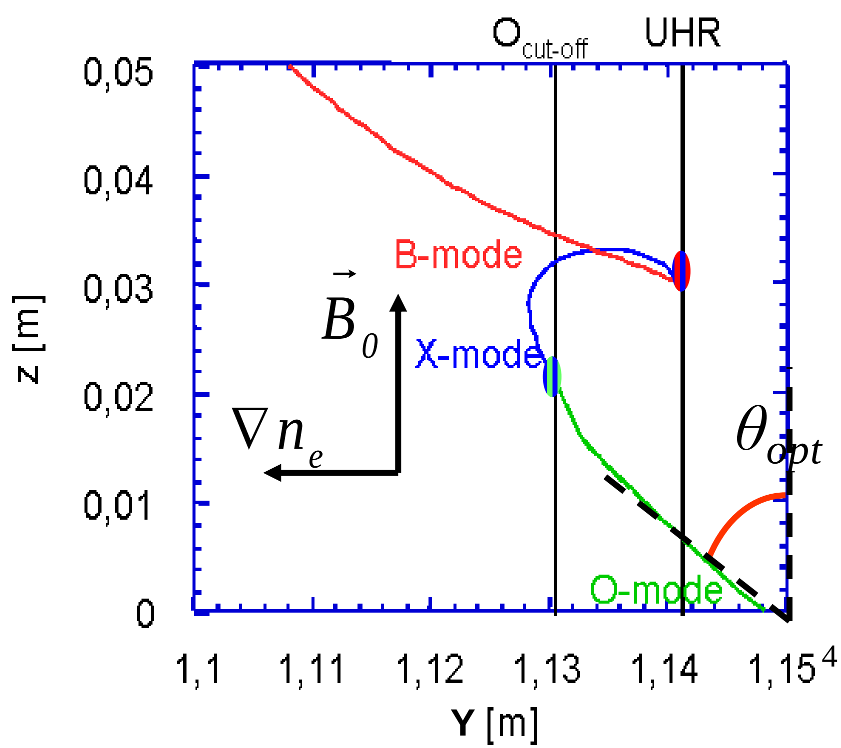
Requires:

1. O-wave launched with θ_{opt} in respect to the magnetic field vector.
   - correct polarisation
   - angular window width **$\sim 1/k_0L_n$**
2. Density above cutoff density.
3. Existence of UHR ($\omega > \omega_c$)

Hot plasma dispersion relation

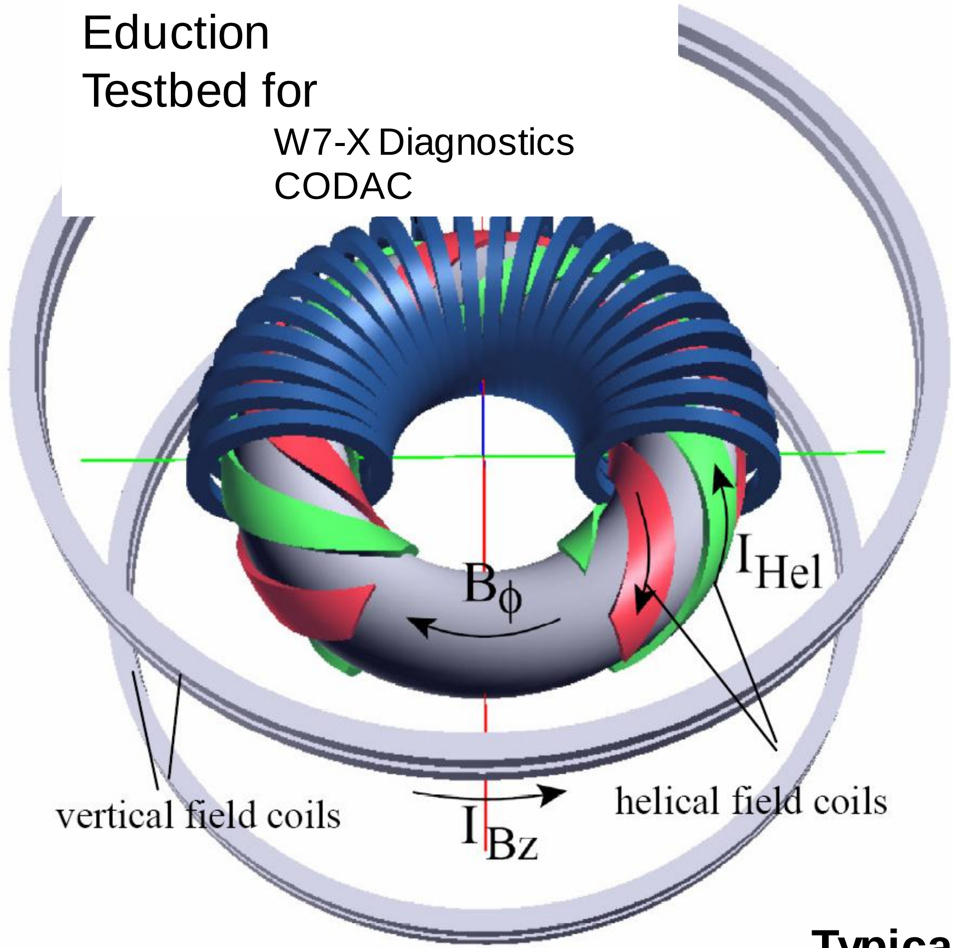


Ray tracing calculations



WEGA Stellarator

Fundamental research
Eduction
Testbed for
W7-X Diagnostics
CODAC



Vacuum vessel:

- Two half-tori with **R = 72cm, r = 19cm**
- 100 ports (max. diameter of 92mm)

Magnetic field:

- 40 toroidal and 4 helical (l=2, m=5) coils
- Vertical field and error field compensation coils

Plasma radius / volume:

- **a_{max} = 11cm,** V = 0.16m^3 (limiter configuration)
- a ≤5cm (high iota configuration)

Plasma heating:

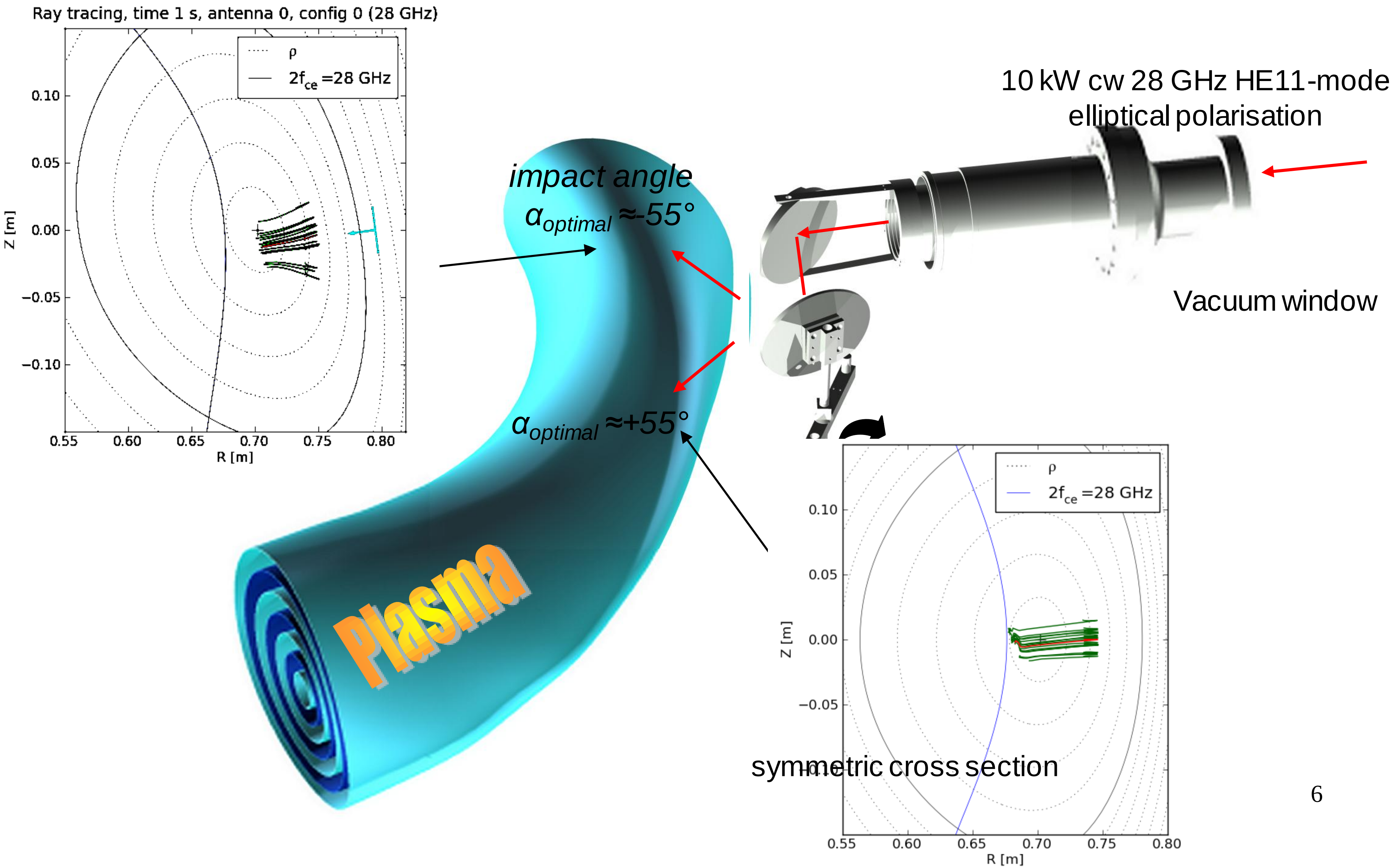
- **20 + 6 kW magnetrons @ 2.45 GHz (cw)**
- **10 kW gyrotron @ 28 GHz (cw)**
- OH – transformer with 0.44 Vs, tokamak operation possible.

Working gas:

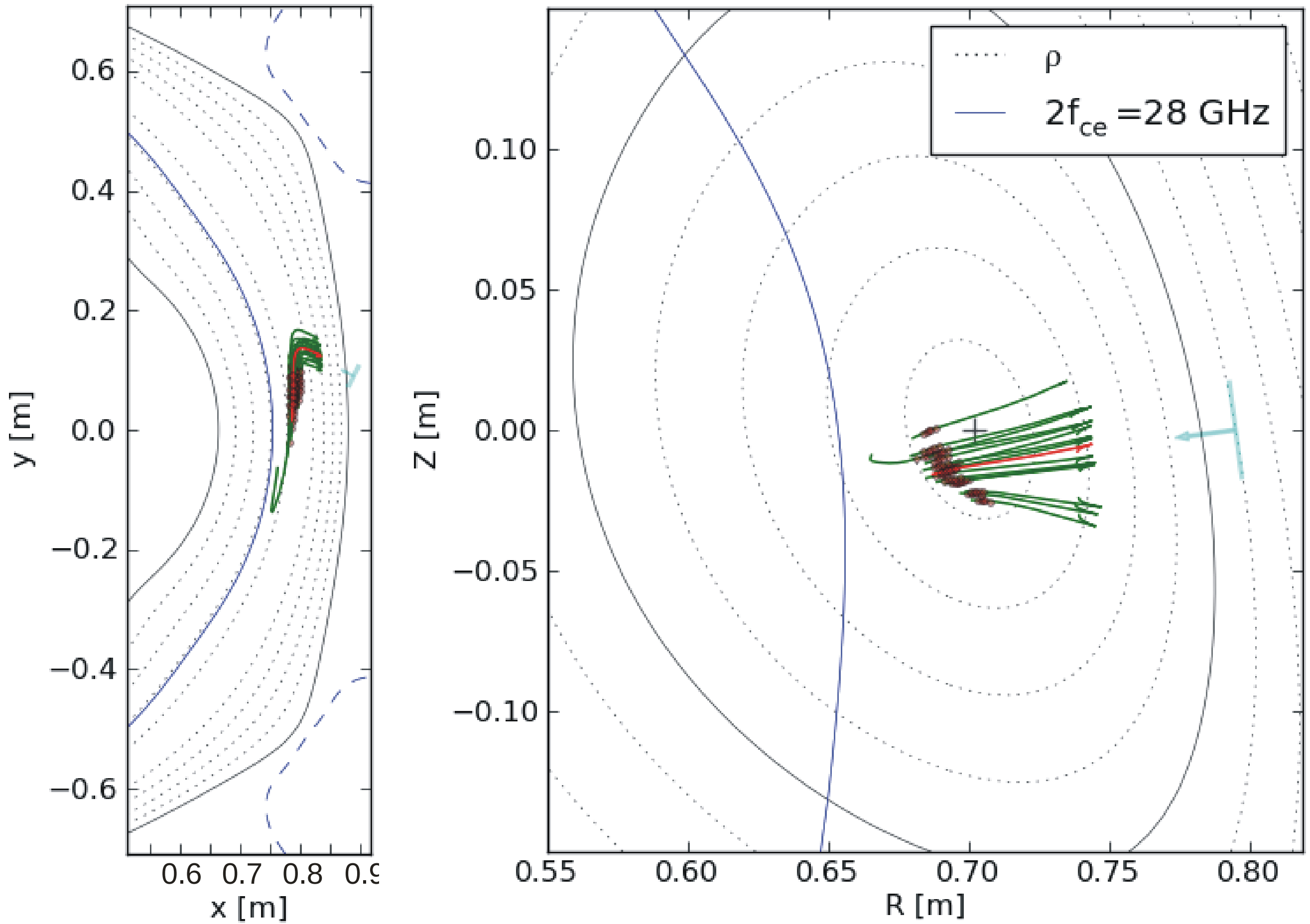
- He, Ar and H_2

Typical pulse length >20s !!!
No toroidal currents needed for confinement!!
No MHD density limit in stellarators.

28 GHz ECRH System



Ray-tracing



0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
y [m]
0.6
0.7
0.8
x [m]
ρ
2f$_{ce}$ =28 GHz
0.10
0.05
0.00
−0.05
−0.10
Z [m]
0.55
0.60
0.65
0.70
0.75
0.80
R [m]

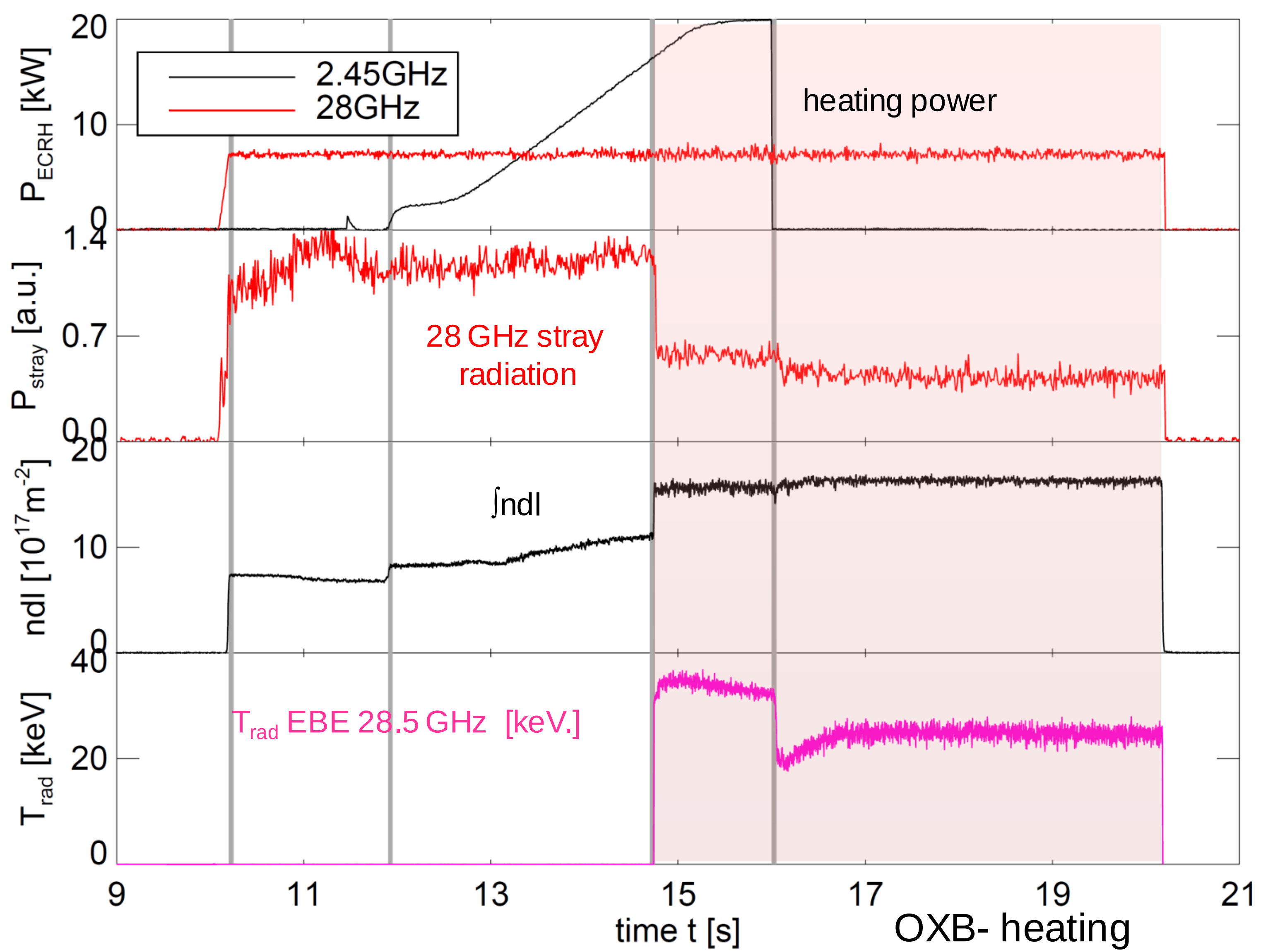
28 GHz Diagnostics

Directional coupler for
forward and backward power.
calibration by calorimetric load.

Sniffer probe for ECRH stray radiation
(OXB conversion efficiency)

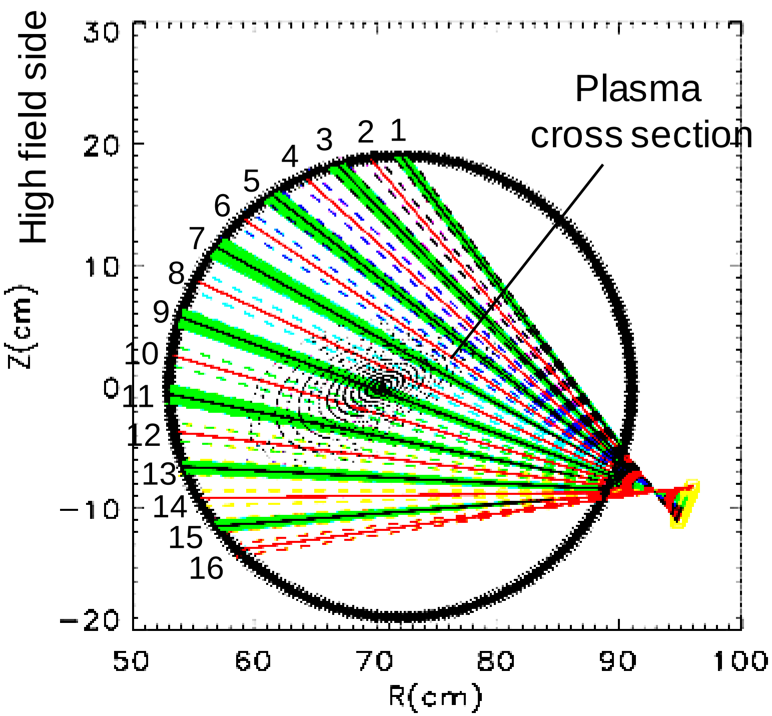
ECE receiver (12 Channel: 22.8-39.6 GHz)
Spectrum analyzer <40 GHz
Horn antennas in perpendicular and **oblique** direction

OXB-Transition at 0.48 T

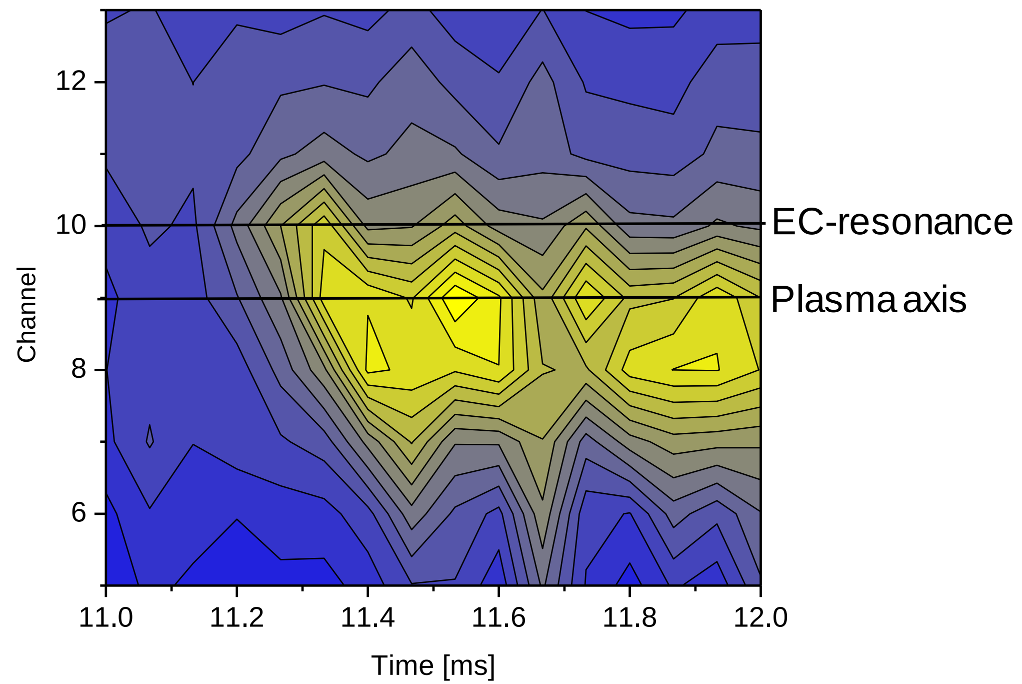


Temporal Development of OXB-Transition

geometry of bolometer diode array

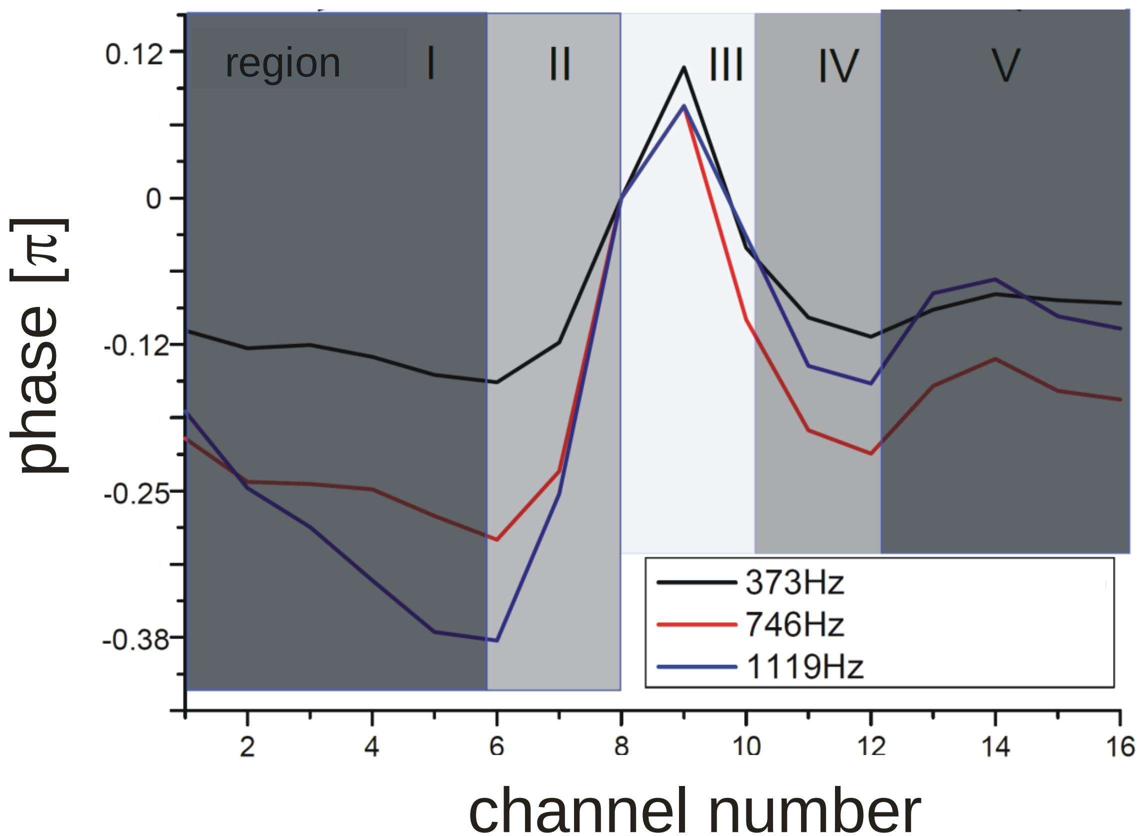


OXB Transition



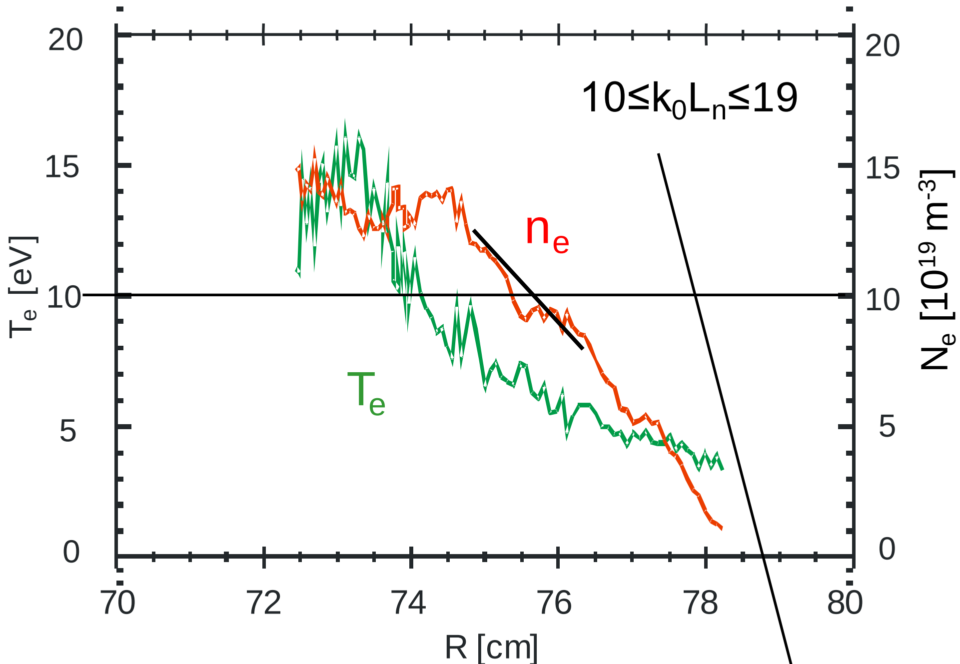
Transition develops at the EC-resonace at high field side.
Very fast overdense plasma expansion within 0.2 ms.
For comparison plasma build-up needs 20 ms.

Heat Wave Generation by Modulated Central Power Deposition

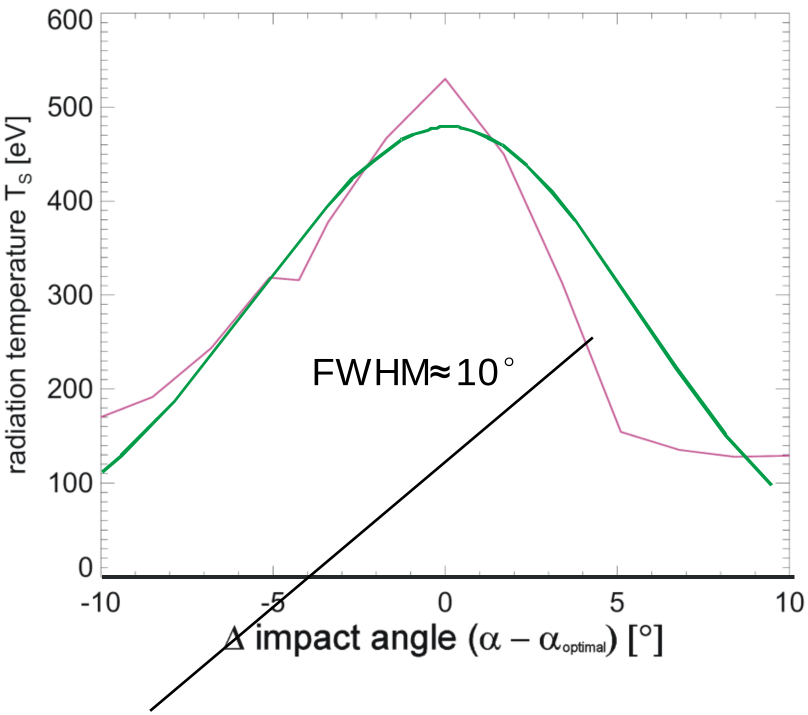


OX-Conversion

Langmuir probe profile measurement



Angular window



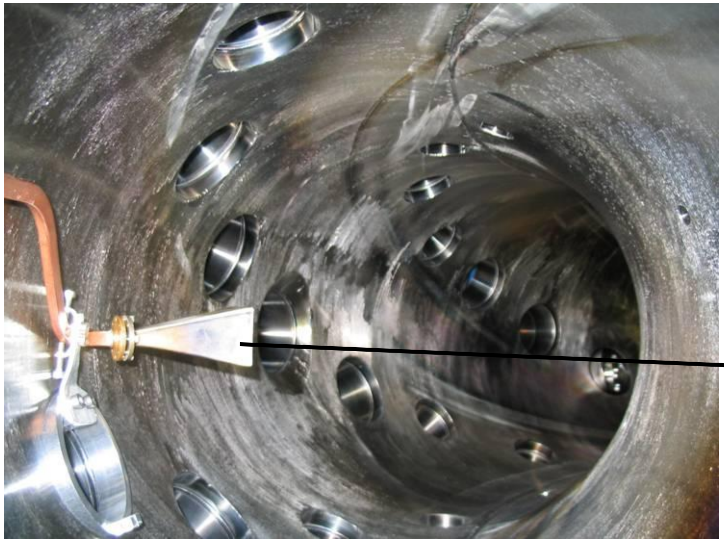
$$\eta_{OX}(N_y, N_z) = \exp\left\{ -\pi k_0 L_n \sqrt{\frac{Y}{2}} \left[2(1+Y)(N_z - N_{z,opt})^2 + N_y^2 \right] \right\}, \quad Y = \frac{\omega}{\omega_{ce}}$$

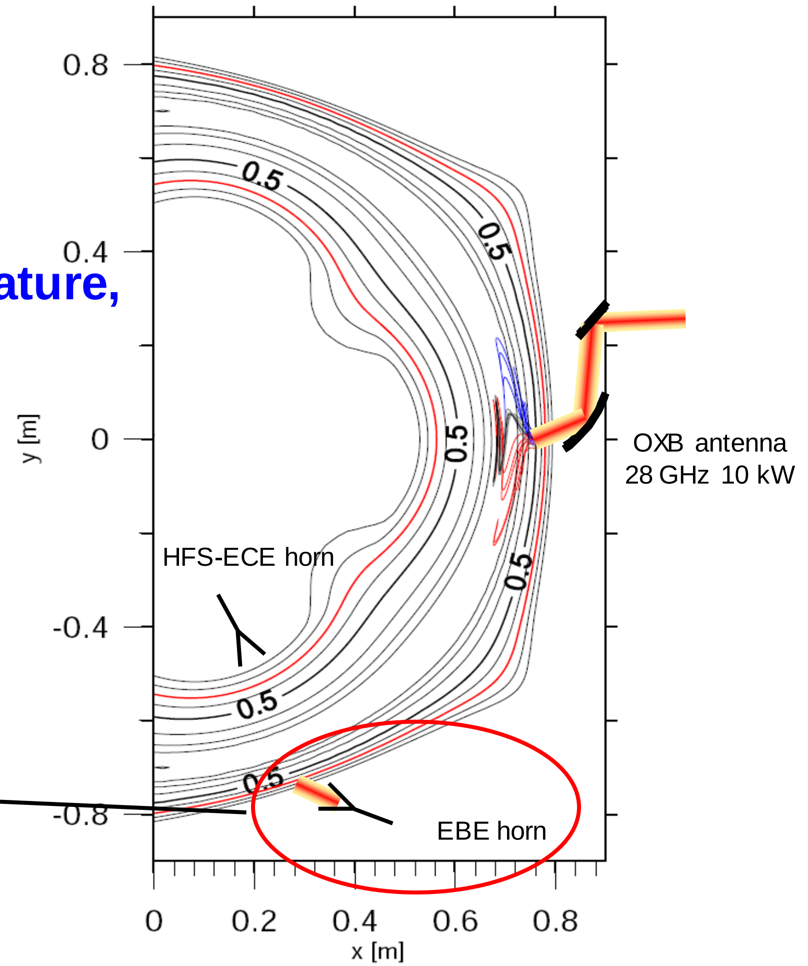
Cyclotron Emission

How to measure Temperature?

probes: perturbation.
Thomson scattering : not available.
ECE: over-dense and optically thin.

EBE: optically thick even at low temperature, no density limit.



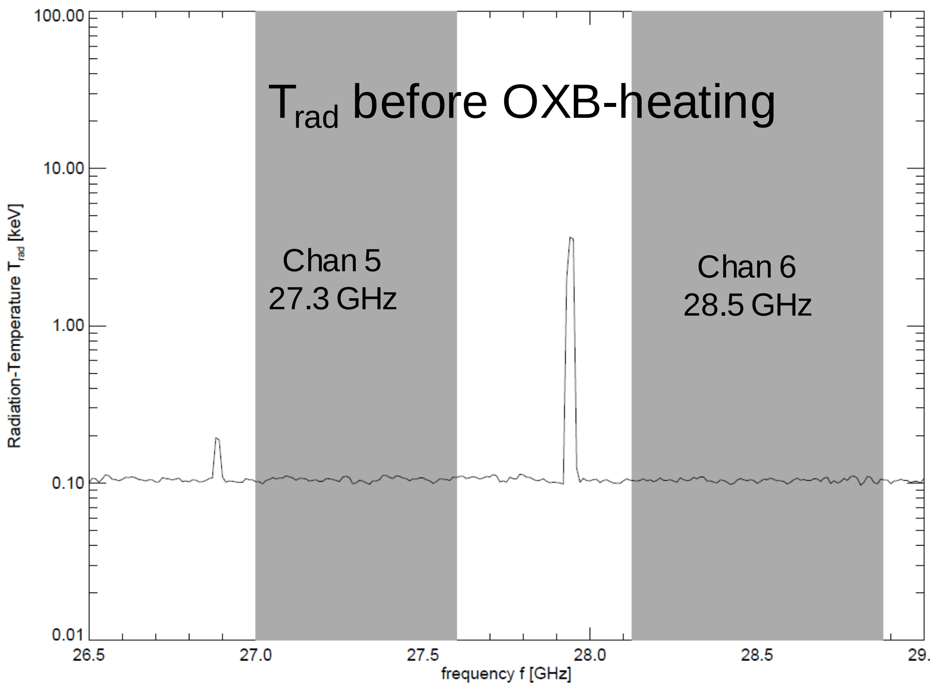


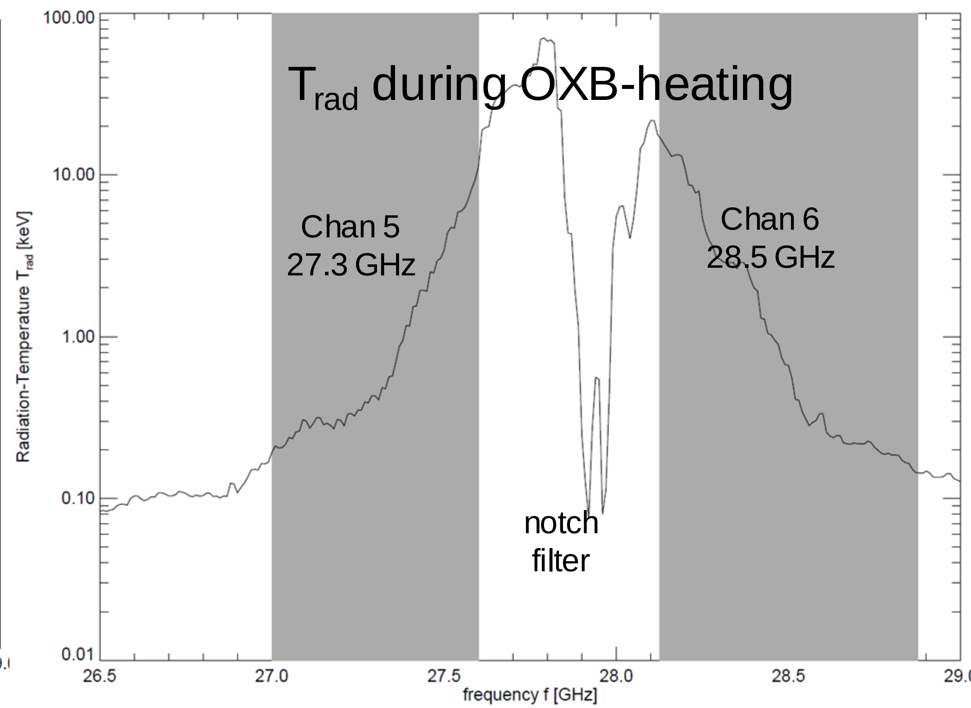
Prove of principle experiment with oblique horn

EBE Radiation Spectrum

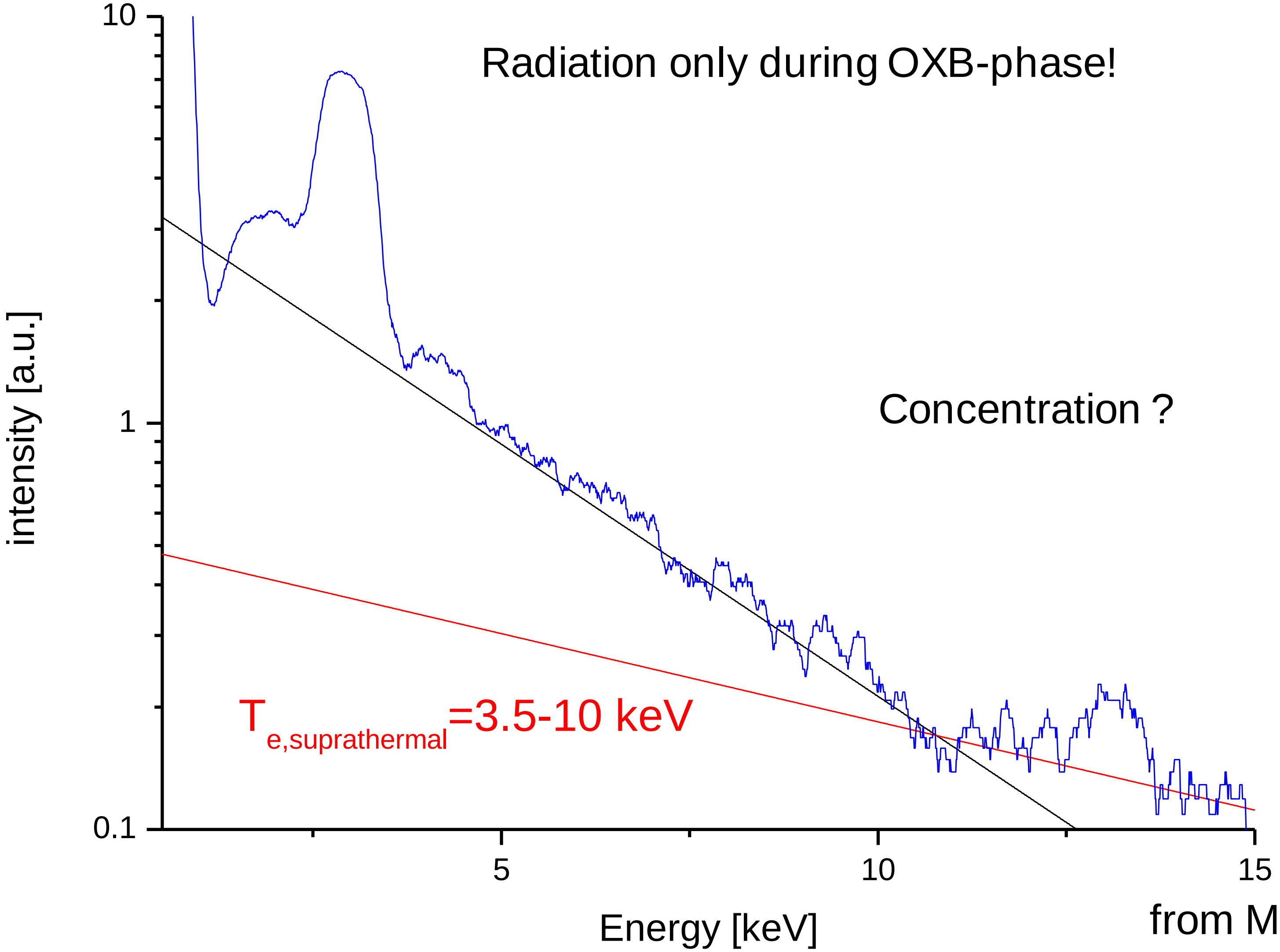
Possible Origins:

Broadband gyrotron emission	NO!
Parametric decay	
line emission	
non-linear power dependence	NO!
Supra-thermal electrons	
15 keV, n_e=1.5 $10^{19}m^{-3}$, 0.5 T, 8 kW ECRH.	Yes!





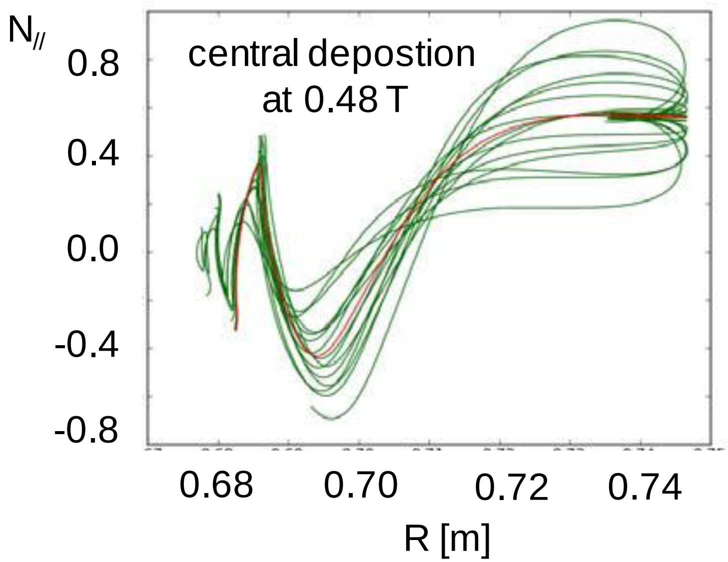
Confirmation of Supra-Thermal Electrons by X-Ray Measurement



from M.Otte

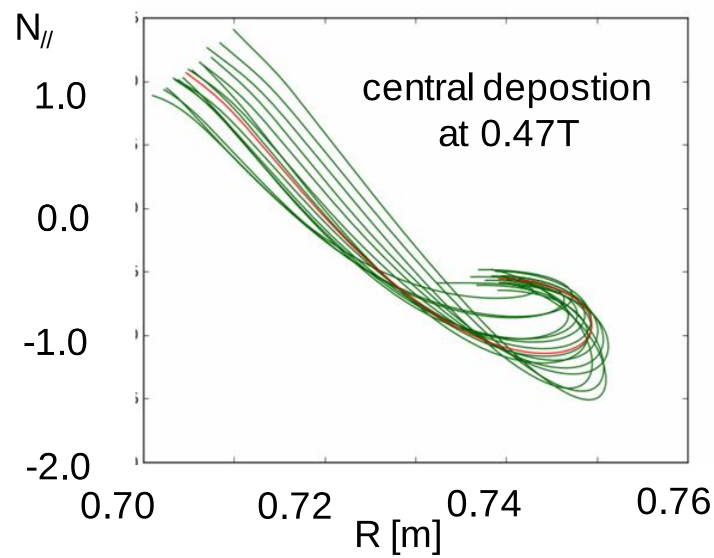
Current Drive
Ray-Tracing Calculations

η_{ECCD}=1-5 A/kW

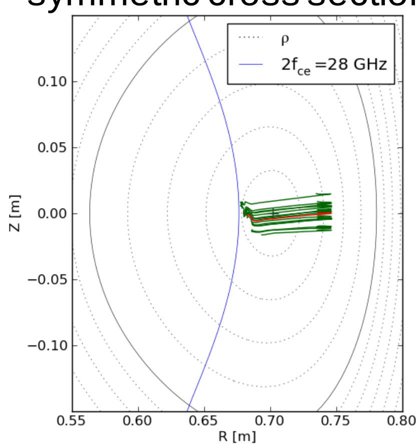


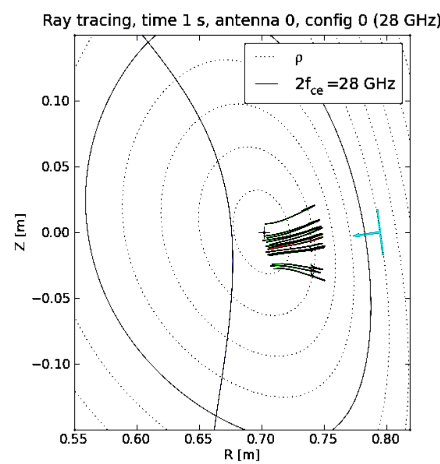
symmetric cross section

η_{ECCD}=55 A/kW



tilted cross section

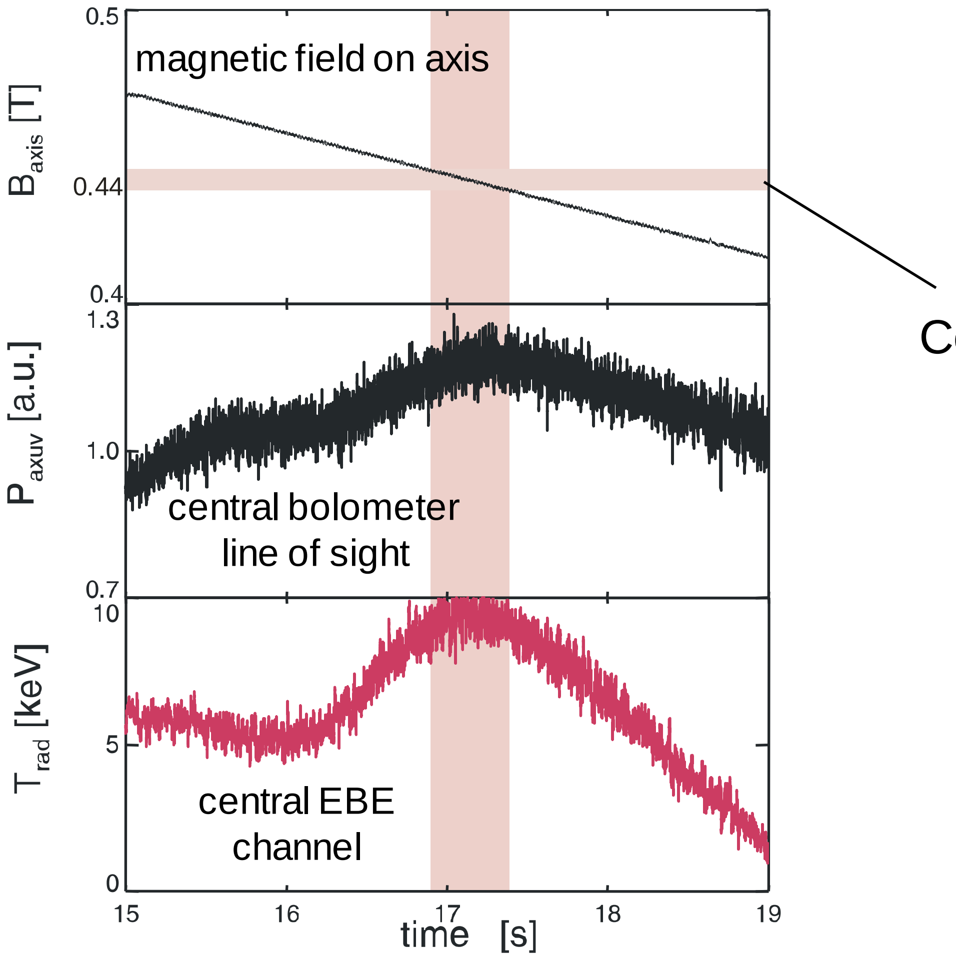




Calculation from:
J. Urban, J.Preinhaelter

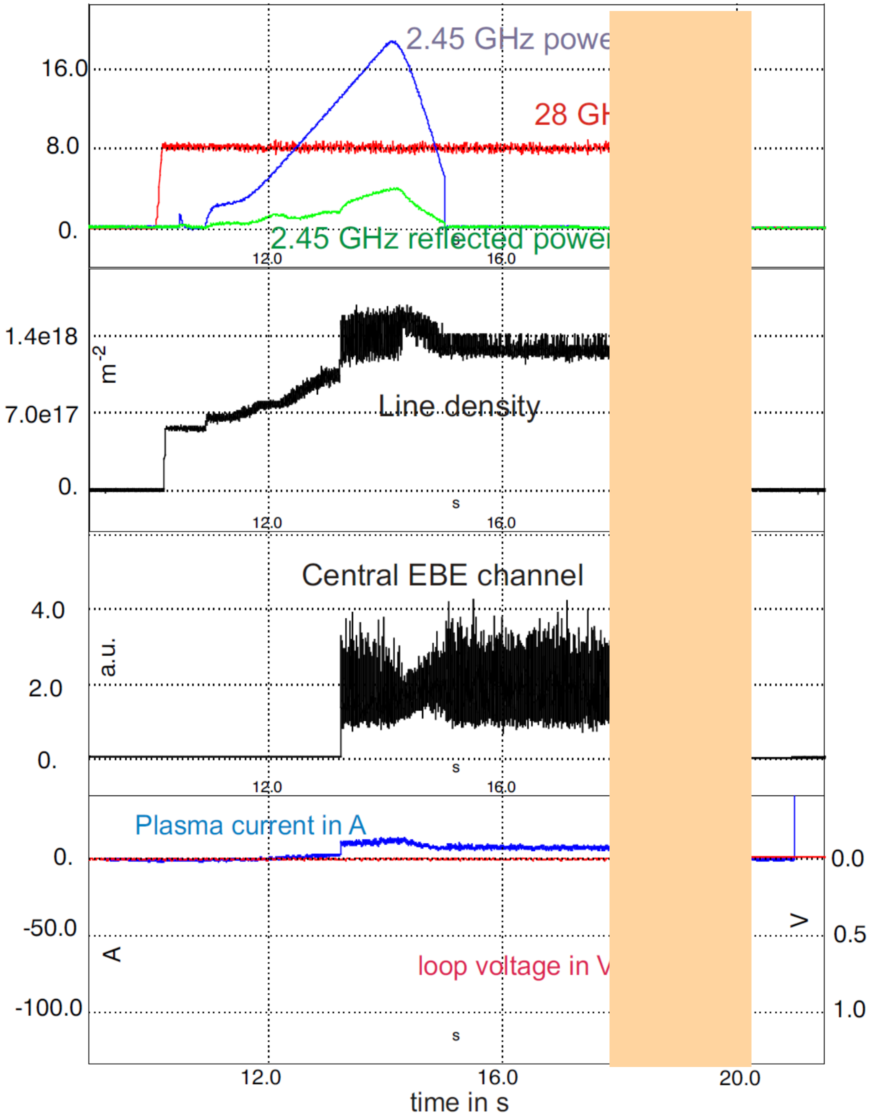
Doppler Down Shift

Variation of central magnetic field strength



Central power deposition at 0.445 T

Current Drive Experiments



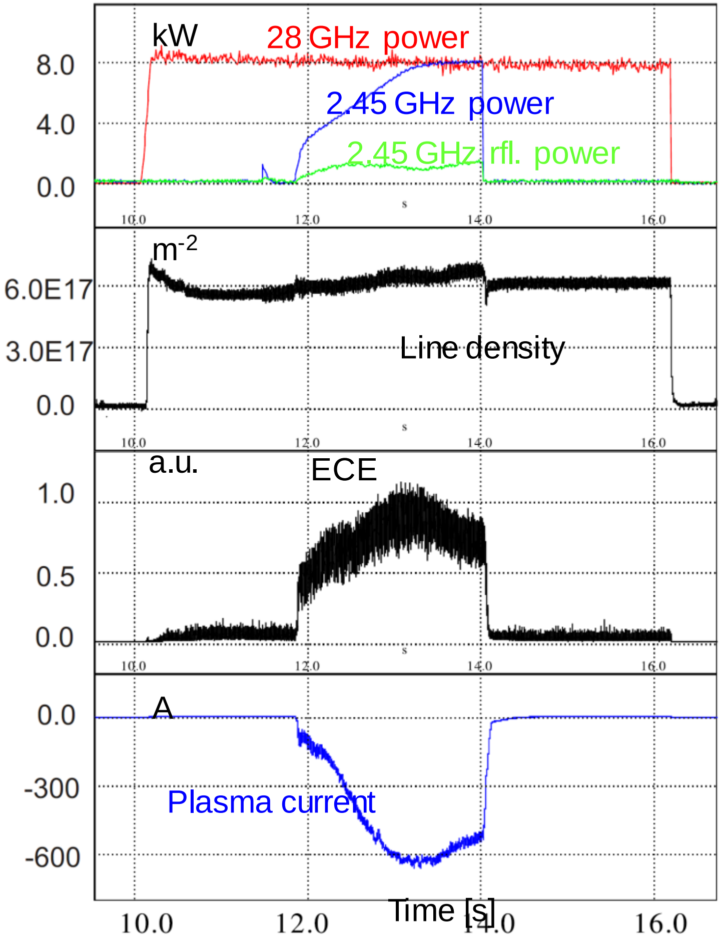
Only 14 A current measured
No difference between
symmetric and tilted launch position

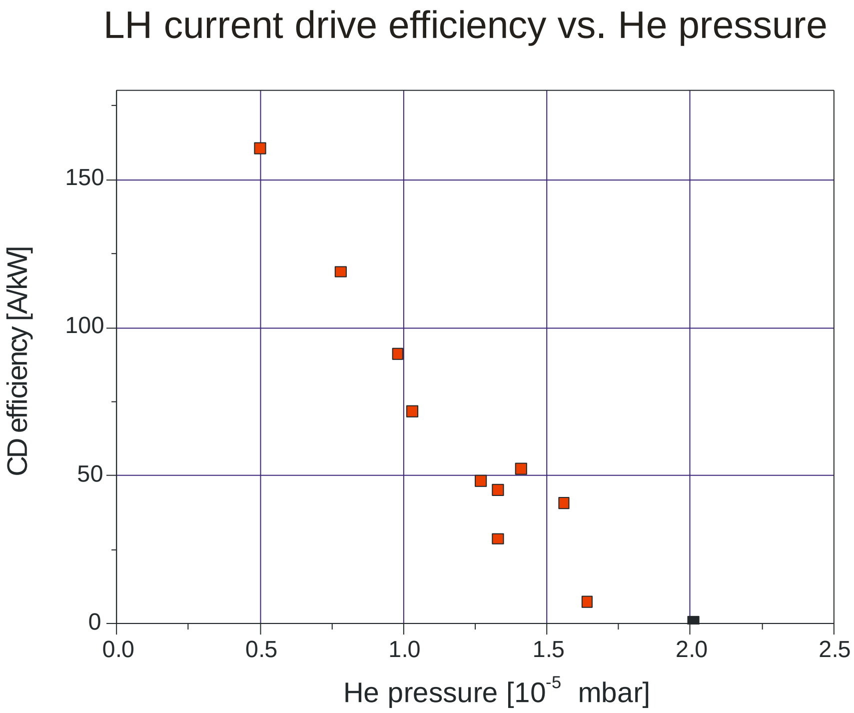
High resistivity measured by inductive current drive
No acceleration of central supra-thermal particles

Why do we do not see predicted current?

Suggestion:
High neutral He pressure prohibits total ionisation
Inelastic collisions prevent generation of
run-away electrons.

Pressure Limit for RF-Current Drive





But for 28 GHz OXB-heating needs 8 $10^{19} m^{-3}$!

Summary

WEGA has reached a new unexplored physics regime!

- Stationary overdense plasma heated by 28 GHz OXB mode conversion exclusively.
- Detailed investigation of OX conversion
  - Angular window.
  - Fast overdense plasma build-up.
- Strong Doppler down shift detected.
- Supra-thermal EBE Radiation detected.
- Fast electron population confirmed by X-rays detector
- Current drive much below ray-tracing prediction.

  (inelatic collisions)

Outlook

- 1T operation (first harmonic OXB).
- Reduction of He-pressure by gas jet.
- Quasi-optical EBE-antennas.
- High resolution X-ray detectors.


Thank you for
your attention

Power Balance