Overview of Experimental Results from the WEGA Stellarator

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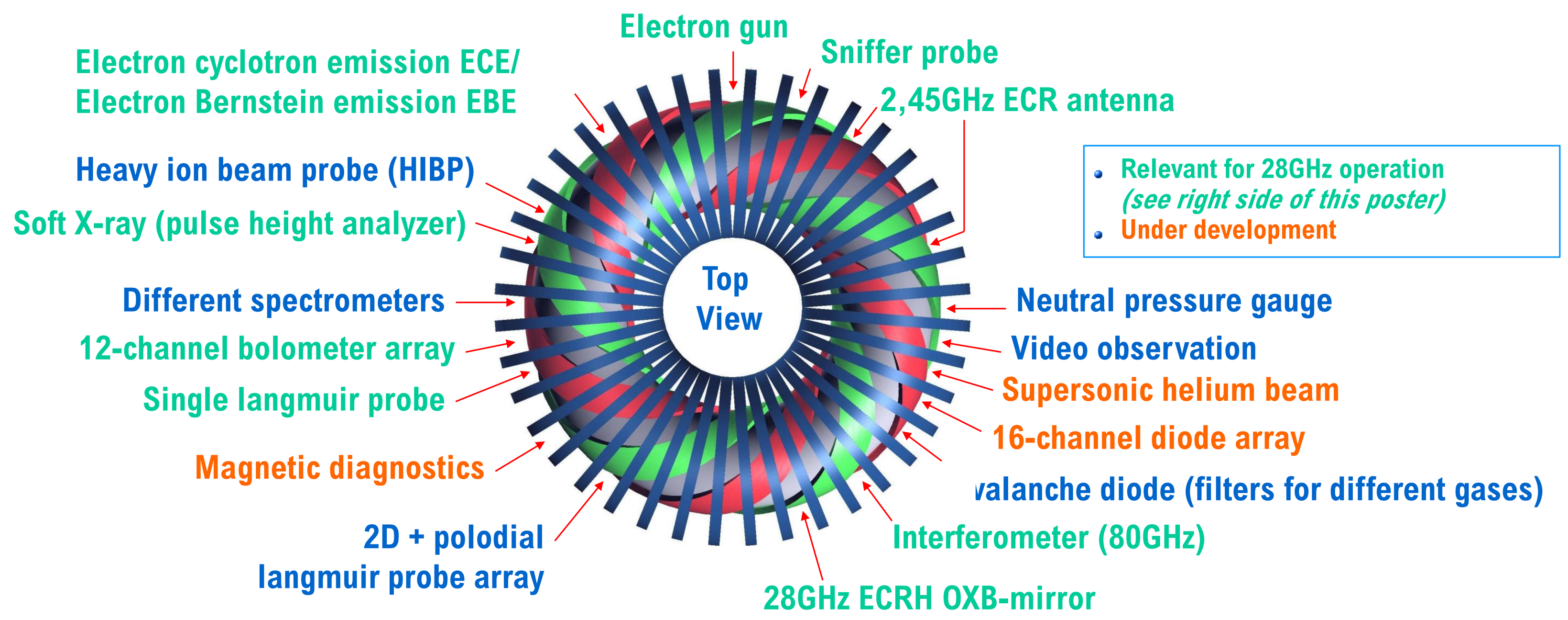
Introduction

- WEGA - **W**endelstein **E**xperiment in **G**reifswald zur **A**usbildung (for education)
- Hybrid-experiment (Tokamak operation also possible) => extremly flexible machine
- Emphasis on:
→Education of young academics
→Diagnostic development for Wendelstein 7-X (*see left side of this poster*)
→Fundamental research of wave heating & transport in plasmas (see *right side of this poster*)
- Testbed for prototype control system of W7-X

Diagnostic Overview



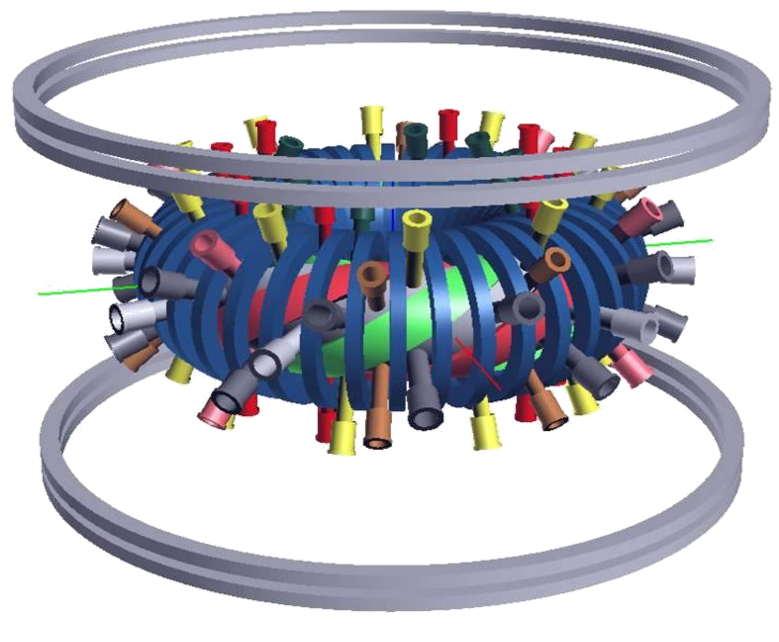
WEGA Stellarator

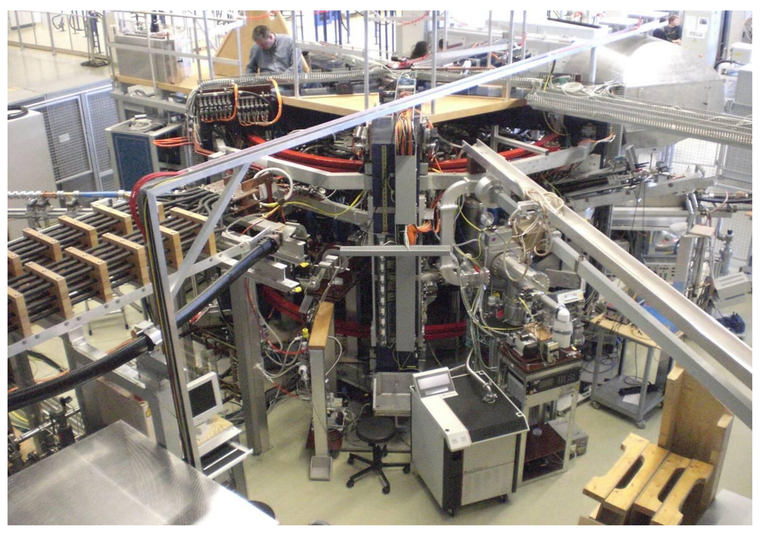
Vacuum vessel:
- Two half-tori with R = 72cm, r = 19cm
- 100 ports (max. diameter of 92mm)

Magnetic field:
- 40 toroidal and 4 helical (l = 2, m = 5) coils
- Vertical field and error field compensation coils
- B_{max} = 0.35T (cw) and 0.9T (pulsed operation)

Plasma radius / volume:
- a_{max} = 11cm, V = 0.16m³ (limiter configuration)
- a ≤ 5cm (high iota configuration $\iota/2\pi > 0.5$)

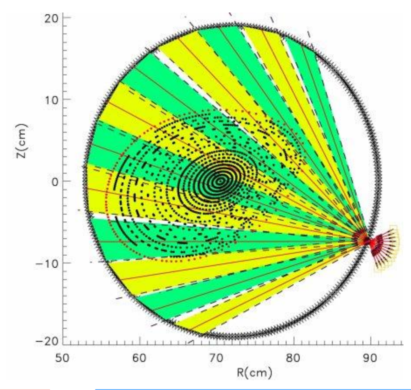
Working gas:
- H_2, He, Ne and Ar





Plasma heating:
- 20 magnetrons @ 2.45GHz (cw)
- 6kW magnetron @ 2.45 GHz (cw) and modulated (max. modulation frequency = 50 kHz)
  λ_0 = 12.2cm, B_{res} = 87mT,
  $n_{e,cutoff} = 7.5\cdot10^{16}$m^{-3}
- 10kW gyrotron @ 28GHz (cw)
  λ_0 = 1.1 cm, B_{res} = 0.5T (second harmonic),
  $n_{e,cutoff} = 5\cdot10^{18}$ m^{-3} (X2 mode)
- OH – transformer with 0.44Vs
- Typical pulse length >20s

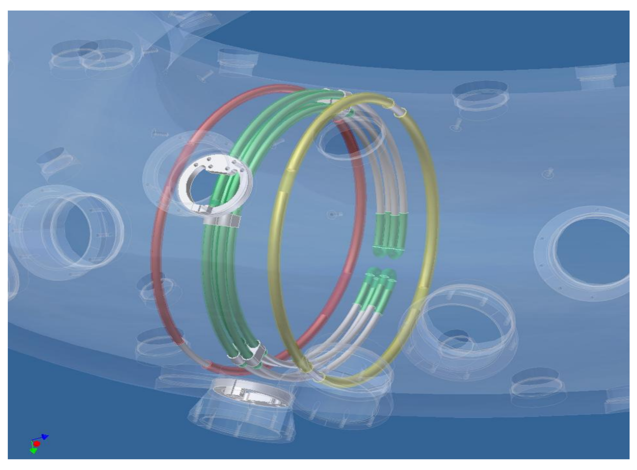
Bolometer



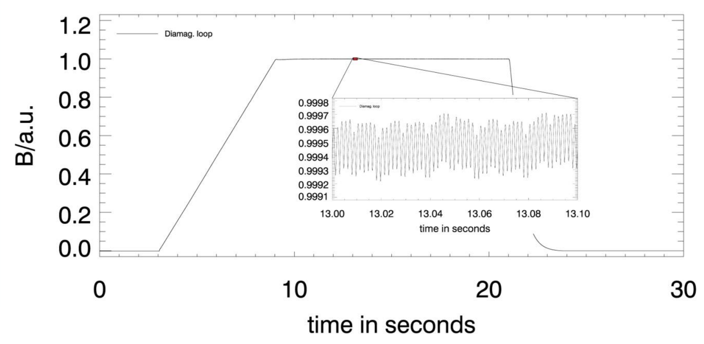
- Integrated plasma radiation is measured along 12 lines of sight
- Profiles are achieved from reconstruction (magnetic field is well known)
- Development of 16-channel diode array (similar to bolometer but better sensitivity in UV-range)

Magnetic diagnostics

- Rogowski coils and hall probe measure current in torodial, helical and vertical field coils
- Plasma current is measured by an additional outer Rogowski coil and OH-transformer coils
- New inner Rogowski, diamagnetic and compensation loop under construction



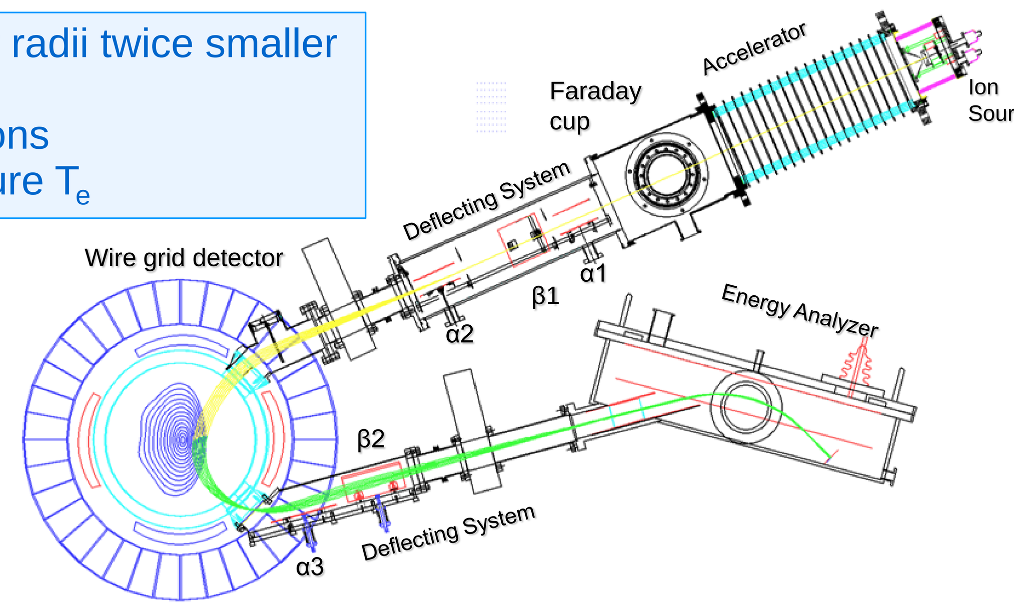
- New digital integrator developed for long pulse discharges at Wendelstein 7-X was successfully tested at WEGA
- Integrator uses chopped input stage followed by a digital integration
→Better common mode rejection, reduced drift behavior, higher dynamic range [1]



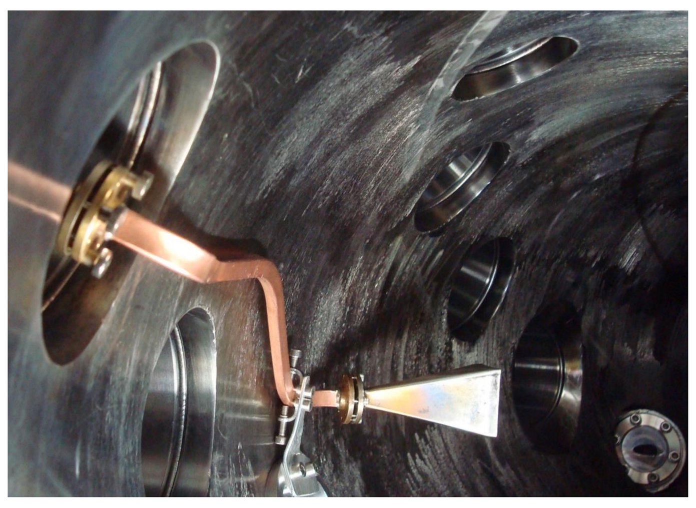
Heavy Ion Beam Probe

- Ionization Ion⁺ → Ion⁺⁺ => Larmor radii twice smaller
- Localized measurements of
→Plasma potential Φ_p and fluctuations
→Density n_e and electron temperature T_e

- Particles Na⁺ → Na⁺⁺
- Beam energy 39.5 keV
- Beam width 5mm
- Penetration depth: 0.4 < r/a < 1 (more central with vertical field) [2]



Electron Cyclotron Emission (ECE) / Electron Bernstein Emission (EBE)



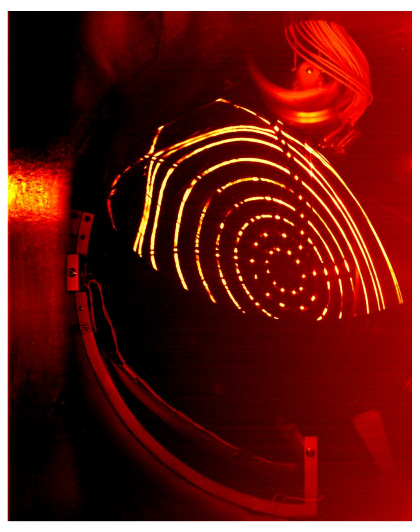
- 12-channel radiometer measures microwave emission from the plasma (22 to 40 GHz):
→Standard ECE perpendicular to magnetic field
→Development of advanced temperature diagnostic using conversion of electrostatic Bernstein waves into an elliptical polarized O-mode (BXO-conversion)
- EBE-antenna orientation under optimal angle of 55° to magnetic field → maximum emission expected
- Spectrum analyzer additionally used for continuous spectra during steady state phase

Visualization of Magnetic Field Lines

Flux surface measurement with fluorescent bar method

Common measurement of the magnetic structure:
- e⁻ beam used as test particles following the field lines
- Intersection point of beam with a fluorescent bar moving in a fixed plane
- Long exposure picture shows 2D cut-view of flux-surfaces (Poincaré-Plot)

→Spatial information on the electron-trajectory is lost in sectional view



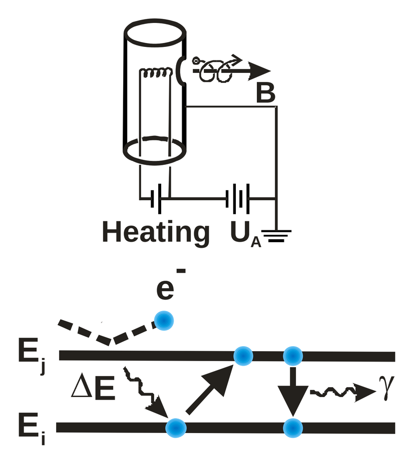
New concept: 3D field line tracing in a background gas

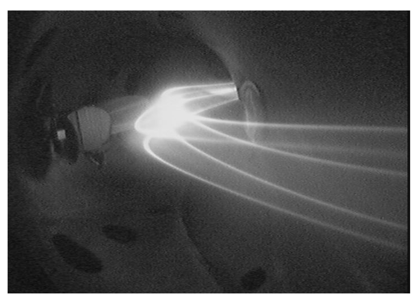
- Luminescent trace in background gas (Ar) by electron-impact excitation
- Deviation of electron drift path with respect to magnetic field line due to gyration and field gradient:
  $r_{beam - field\ line} \leq$ 1,8 mm
- Deviation of luminescent trace with respect to electron drift path due to thermal motion:
  $r_{trace - beam} \leq$ 0,45 mm

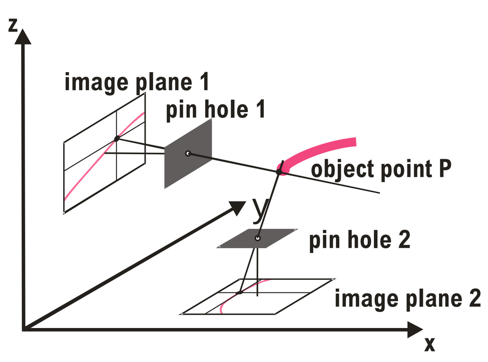
  → luminescent trace ≈ magnetic field line

- Field line visualization with finite range (due to steady energy loss) possible, but no measurement of closed flux-surfaces
  - Observed maximum ranges: WEGA 90 m (0.5T), W7-AS 450m (H2, 2.4T)

- Photogrammetry used for measurement of luminescent trace:
  - Perspective observation from at least 2 angles
  - Tracing the line of sight yields 3D-coordinates at intersection
  - Exact camera position needed for transformation in stellarator coordinates

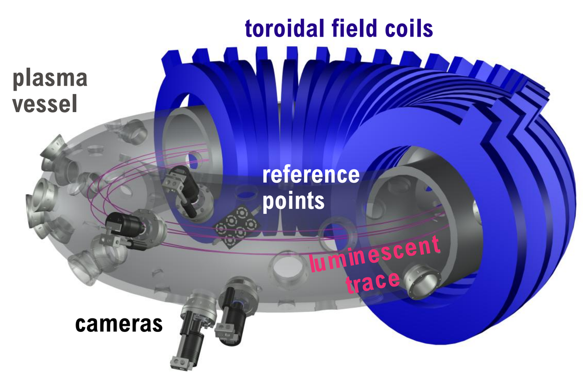






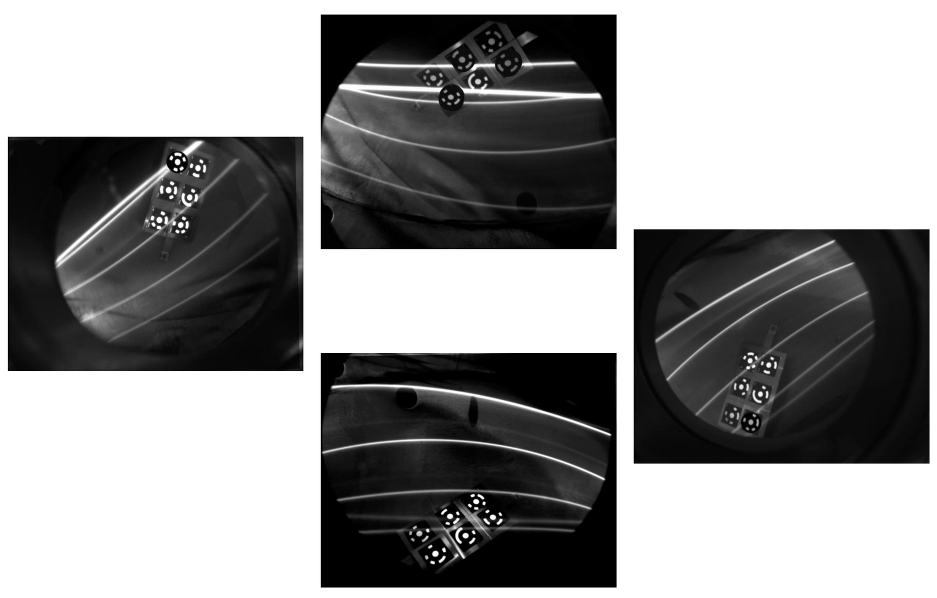
3D field line measurement setup at WEGA

- 4 ports provide sufficiently overlapping fields of view
- Picture analysis with commercial photogrammetry system AICON®
- Reference points in the image background (high field side) in order to determine camera position and transform measured points in WEGA coordinate system



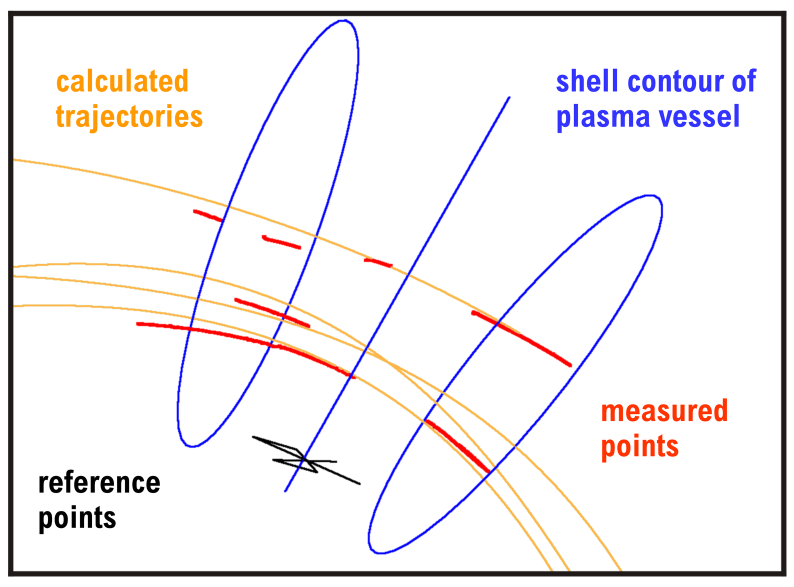
Visualization of a magnetic field line
- Magnetic configuration:
  B_0 = 0.489 T with $\iota/2\pi$ = 0.2039
- Gas: argon at p = 3.9· 10⁻⁴ mbar
- 515x650 effective resolution in 12bit grayscale

- To avoid/correct overlap of the luminescent trace and of the reference marks, pictures were taken sequentially and merged using image editing tool



3D reconstruction and comparison of results
- Numerically calculated trajectories (orange) differ from measured points (red) up to 12mm after 15m beam length (4th revolution)
- Calculated with numerical field line- and drift path-tracing code [3]
- Spatial resolution of measurement technique: 5 mm

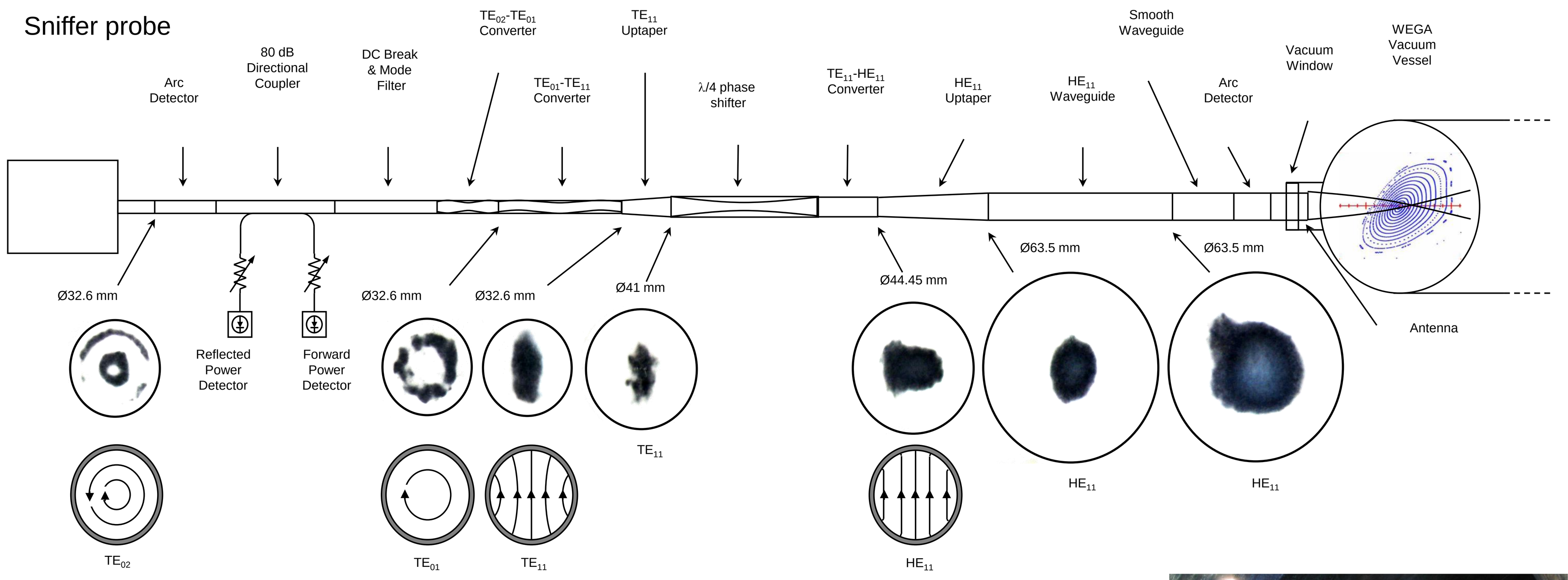
Outlook
- Future application is planed at LHD and W7-X

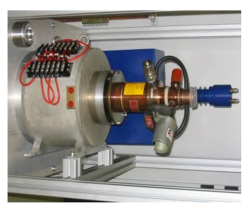


Setup of 28GHz ECR Heating System

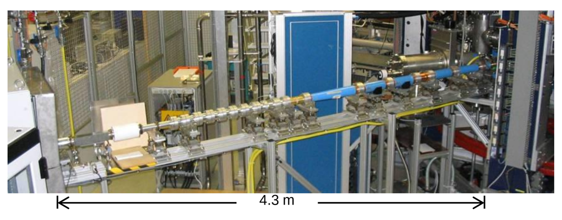
Sniffer probe

- Installation of 28GHz ECRH in cooperation with CIEMAT/Spain & IPF Stuttgart
- HE11 wave generation via mode conversion transmission line
- At B_{res} = 0.5T two different heating scenarios possible
- → Extraordinary wave heating in linear polarization (X2)
- → Bernstein wave heating due to conversion of a left hand side elliptical (λ/4 – phase shifter) polarized ordinary wave (OXB) inside the plasma

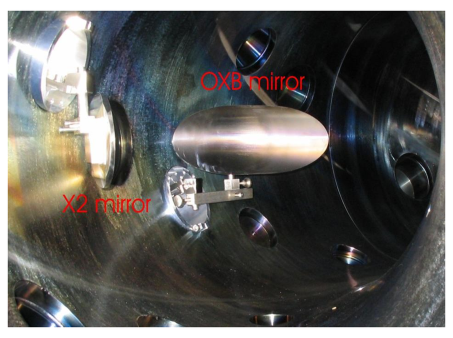




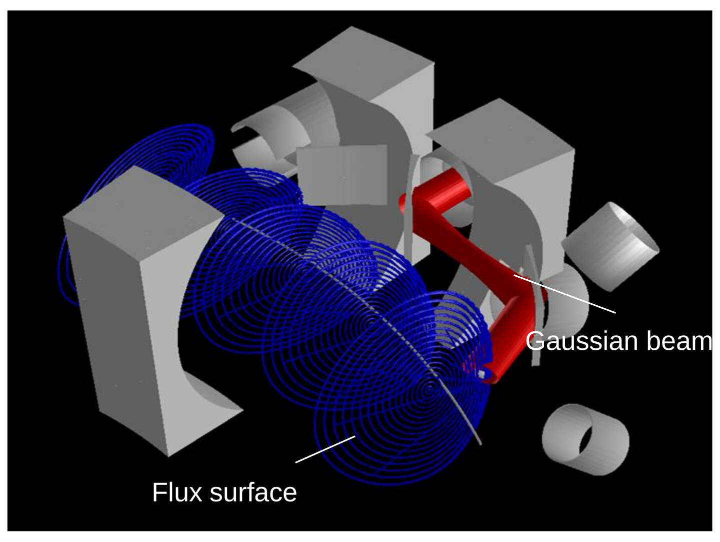
Gyrotron 10kW cw (20 kHz modulation)

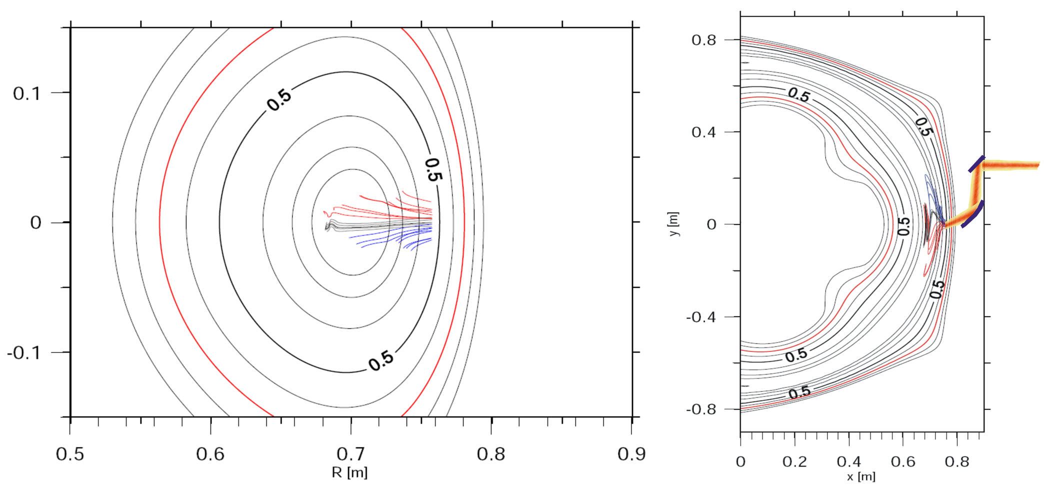


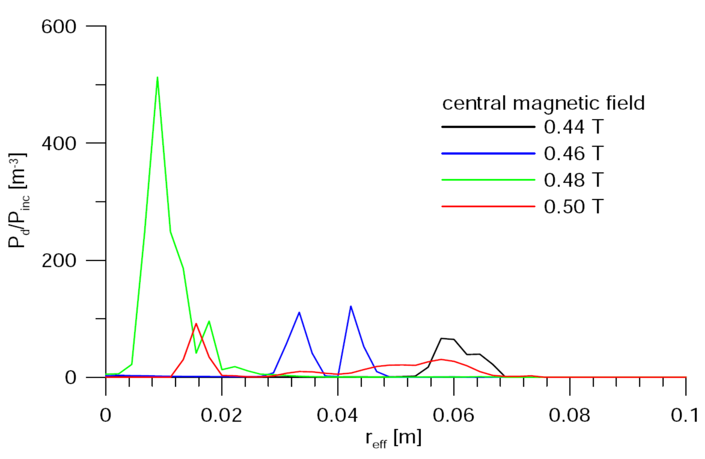
λ/4 phase shifter



Ray Tracing Calculations of Bernstein Wave Heating



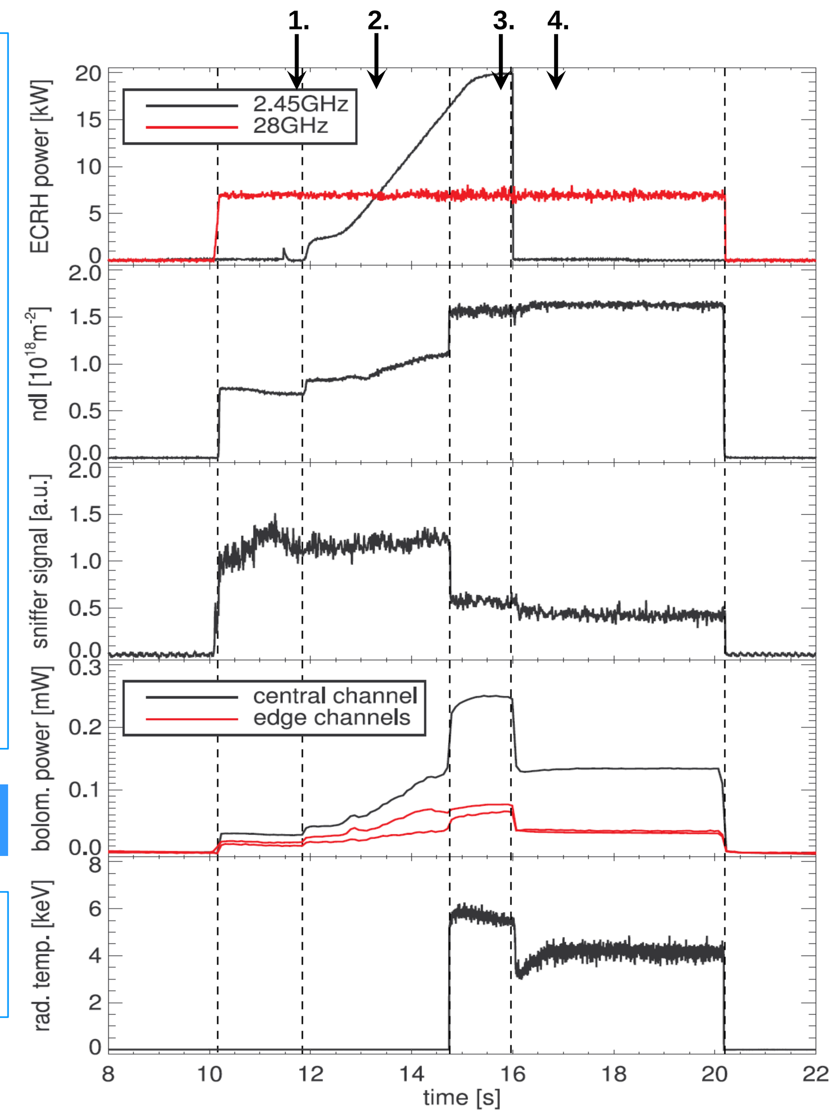




- Quasi-optical OXB-mirror provides oblique beam launch at 55° in respect to magnetic field optimized for OXB-conversion
- → High conversion predicted (>90%)
- Mode conversion at toroidal position with symmetrical plasma cross section (vertical elongation)
  - → Optimum density scale length k_0L_n=12 (maximum angular window)
  - → Minimum Doppler-shift => no current drive
- Central deposition at B_{center} = 0.48T predicted [4]

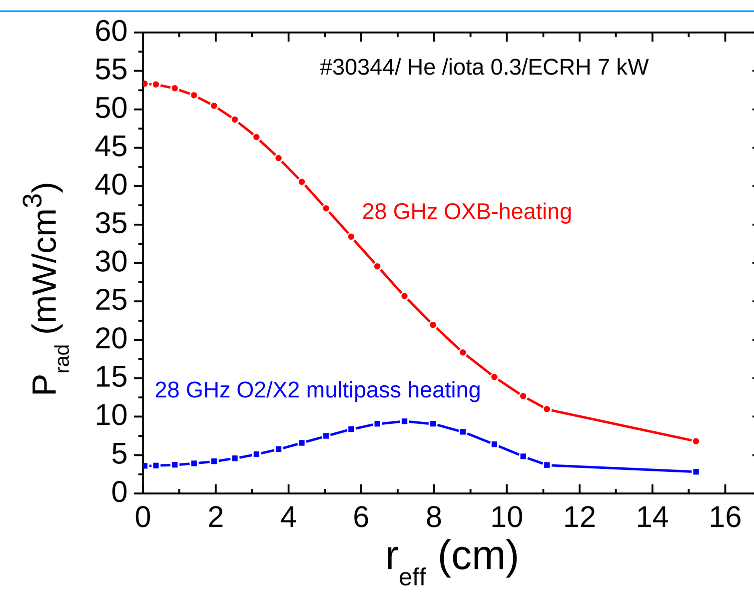
Bernstein Wave Heating Discharge in Helium

1. Plasma generation by multi-pass 28GHz-heating with broad deposition (10%-absorption of X2-mode produced by the wall reflections)
2. Additional resistive 2.45GHz heating (20kW) to overcome power gap above X-cutoff ($0.5\cdot10^{18}m^{-3}$)
3. Overdensed state with density above $10^{19}m^{-3}$ (O-cutoff & threshold for OXB-conversion)
   - → Decrease of 28GHz stray radiation (sniffer) due to high single pass absorption
   - → Increase of central channels of bolometer & EBE radiometer due to central deposition
4. Switch off additional heating
   - → Plasma is sustained by OXB-heating only
   - → Radiation temperature stays at keV-range

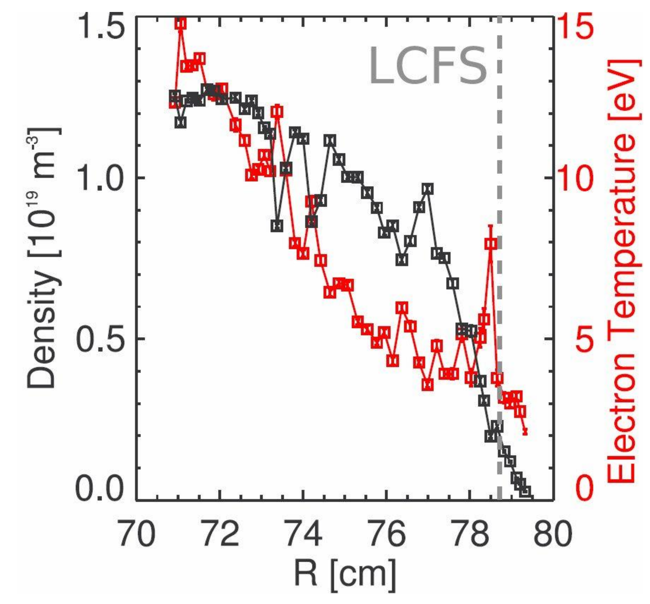


Profile Measurements

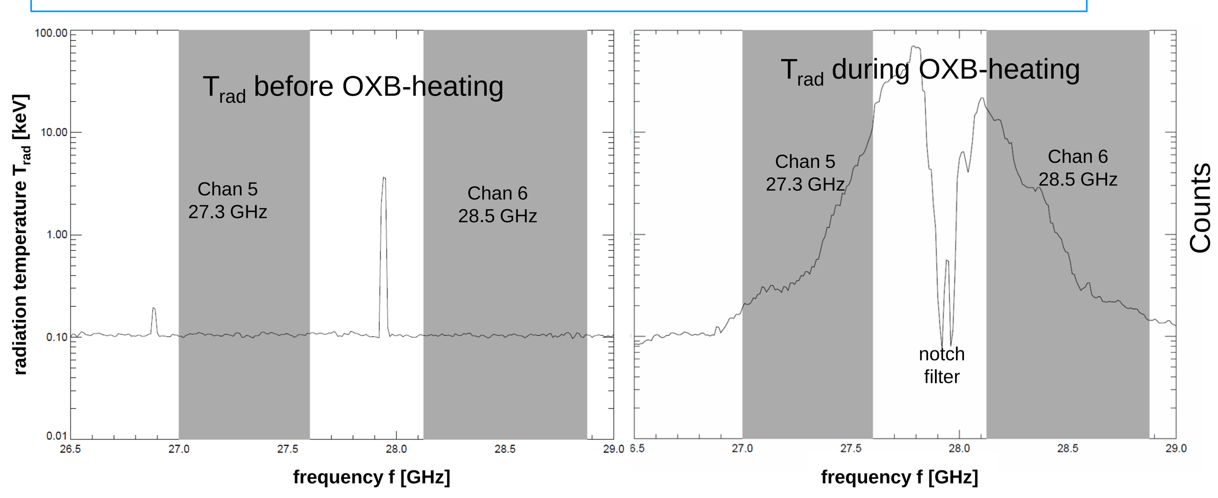
- Bolometer shows strong profile changes (peaking) with achievement of OXB-heating

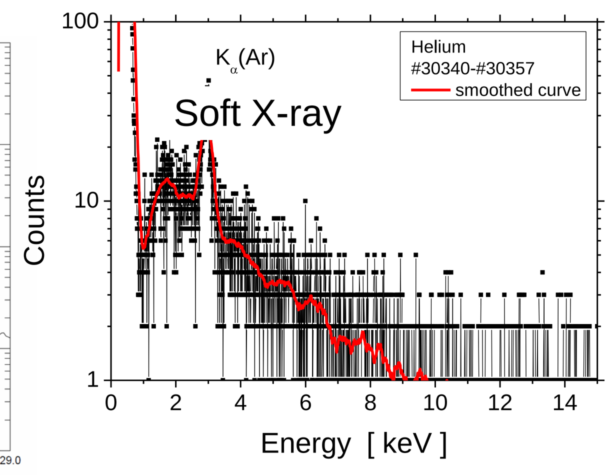


- High density confirmed by Langmuir probes
- Bulk electron temperature of 10eV



- Electron Bernstein emission via BXO-conversion from central plasma column extremely peaked
- → indicating high single pass resonant absorption as predicted by ray tracing code
- → Generation of suprathermal electrons
- Soft X-ray diagnostic measures keV-radiation only during OXB-phase => confirmation of fast particles

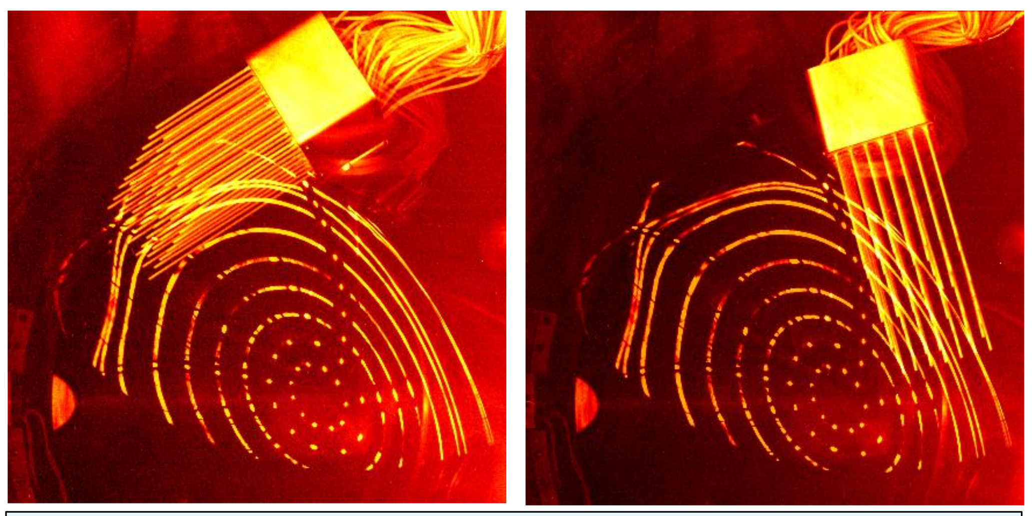


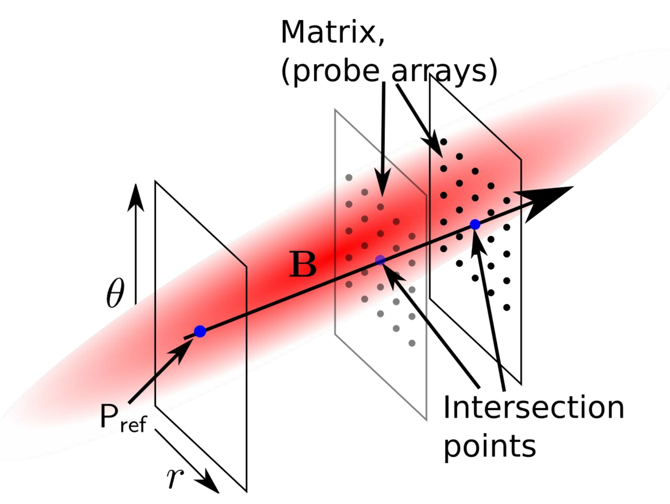


Aspects of Turbulence Addressed in WEGA

- Access to whole plasma cross section with probes – high spatial & temporal resolution, simple
- Study details on parallel dynamics – precise knowledge of field topology from particle tracing experiments
- Toroidal and poloidal asymmetries observed – curvature driven effects inside LCFS
- Turbulence in the region of magnetic islands – unique feature of ability to manipulate islands

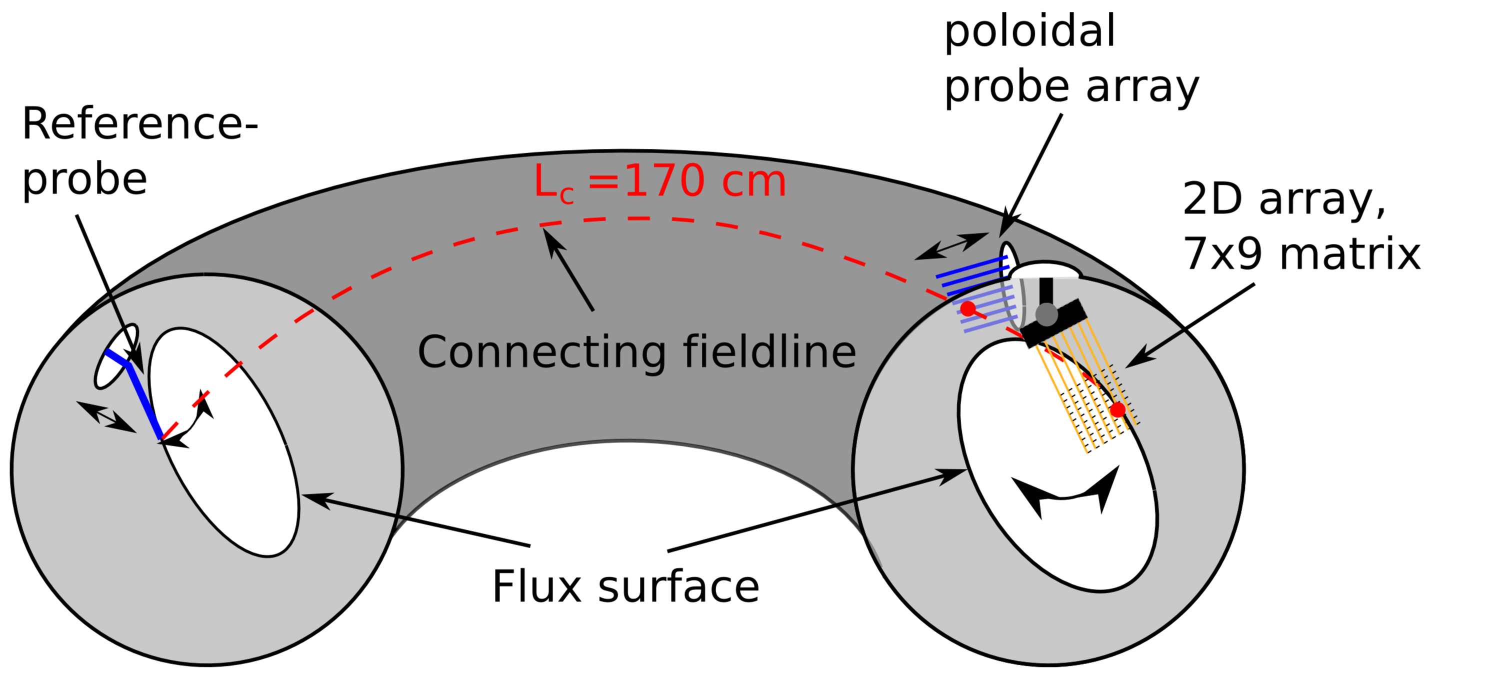
Probe Setup for Turbulence Studies





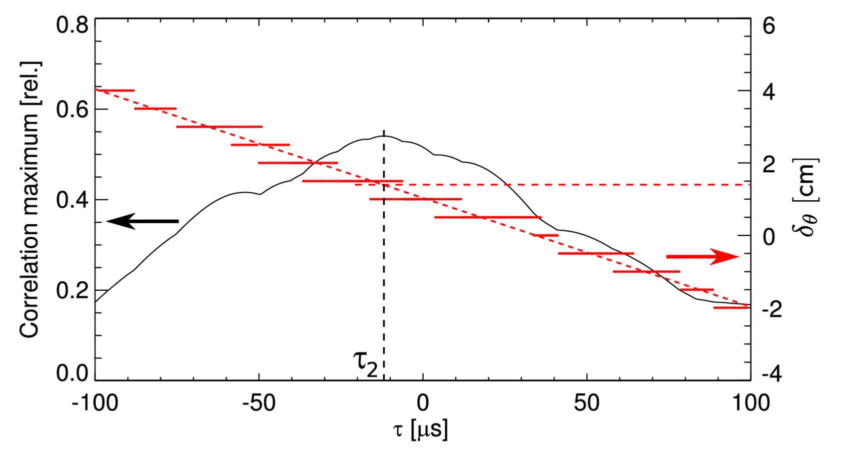
- 2d array with 7x9 probes in a poloidal plane
- Can be placed on low- and high-field side

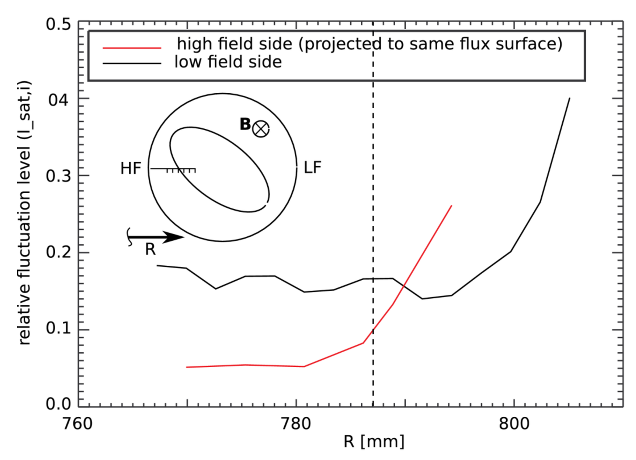
- Multiple probes for 3D structure
- Aligned along a field line

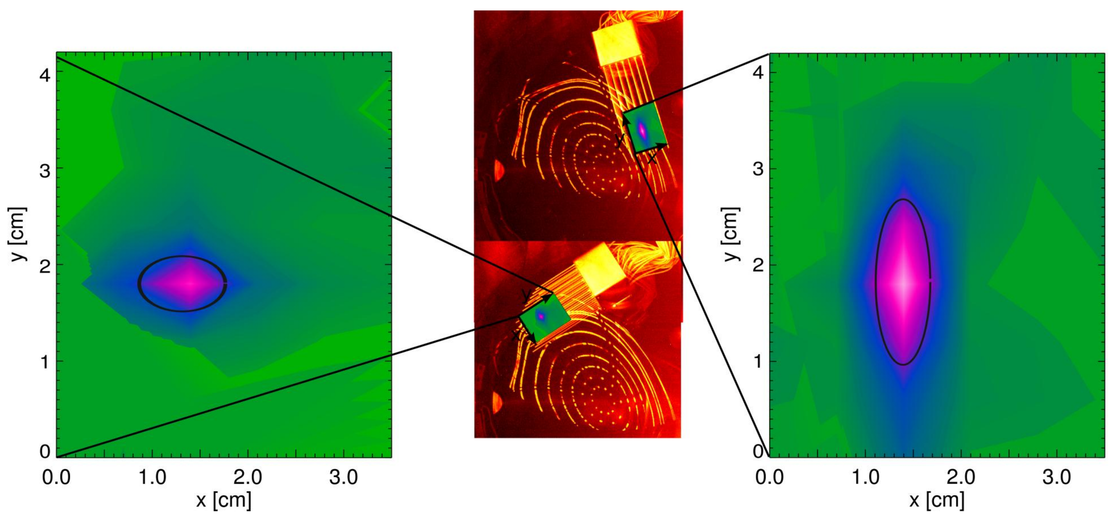


Spatial Asymmetries in Turbulence Activity

- Result from toroidally resolved experiments: turbulent structures preferably arise in a certain region along a field line [55]
- Inside LCFS necessarily linked to poloidal asymmetry (good and bad curvature)
- Lower fluctuation amplitude on HFS
- Smaller averaged structure size on HFS



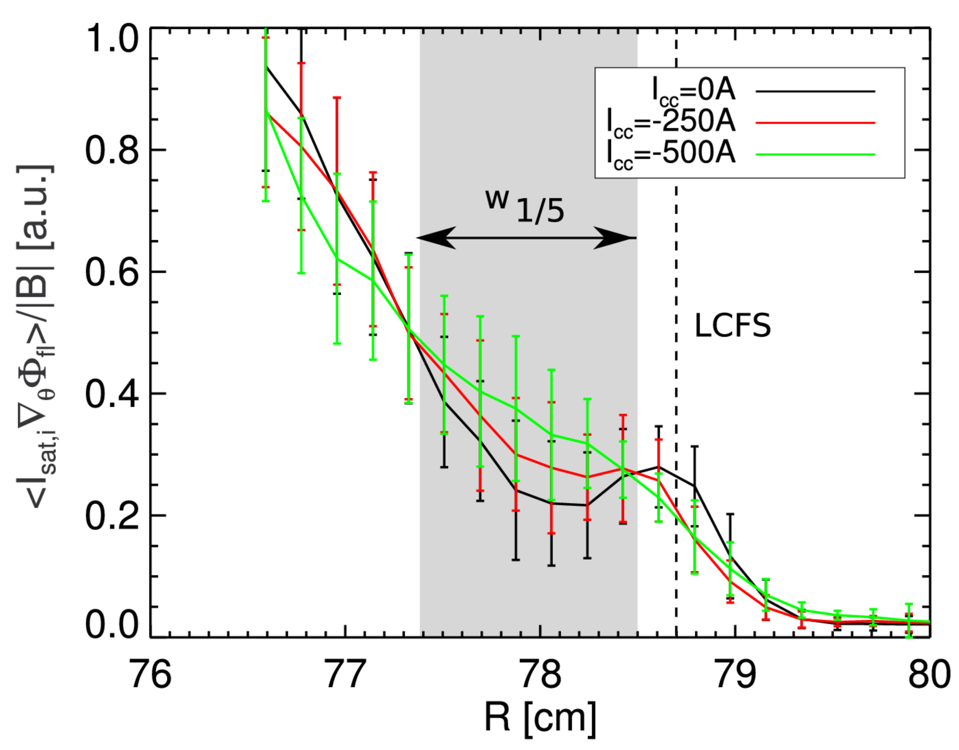




Preliminary Results on Turbulence in Islands

- Error field compensation coil used to manipulate 1/5 island in the edge
- Island width reduced by about 50%
- Local increase of net radial ExB flux in the island region
- Local bump smeared out with reduced island width
- Observed only at low collisionality

- 2D array to investigate turbulence dynamics inside islands
- Compare islands and stochastic regions
- Measure magnetic fluctuations locally in islands



Future Tasks and Experiments

- Detailed plasma generation and heating experiments with different magnetic configurations
- → Third harmonic (X3) Electron Cyclotron Resonance Heating (ECRH) at 0.33T
- → Electron Bernstein Wave (EBW) heating (and diagnostic) at 0.5T
- → Fundamental 28GHz ECRH at 1.0T
- Current Drive experiments → generation and confinement of fast particles

References

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[2] Krupnik, L. I., et.al. "Development of Heavy Ion Beam Probing (HIBP) diagnostic for stellarator WEGA", 15th International Stellarator Workshop, Madrid 2005 poster
[3] A. Werner, private communications to W7 code
[4] J.Preinhaelter and J. Urban, RF conference, Praha 2009
[5] Marsen et al, Plasma Phys. Control. Fusion 51 (2009) 085005

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