

# Turbulence in Wendelstein 7-AS plasmas measured by collective light scattering

## Ph.D. supervisors:

**Henrik Smith**

Ørsted Laboratory, Niels Bohr Institute for Astronomy, Physics and Geophysics  
Copenhagen, Denmark

**Mark Saffman**

Department of Physics, University of Wisconsin  
Madison, USA

**Poul K. Michelsen**

Association EURATOM - Risø National Laboratory  
Roskilde, Denmark



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## Ph.D. committee:

**Mogens Høgh Jensen**

Niels Bohr Institute, Niels Bohr Institute for Astronomy, Physics and Geophysics  
Copenhagen, Denmark

**Dominique Grésillon**

Laboratoire de Physique et Technologie des Plasmas, Ecole Polytechnique  
Palaiseau, France

**Jens Juul Rasmussen**

Association EURATOM - Risø National Laboratory  
Roskilde, Denmark



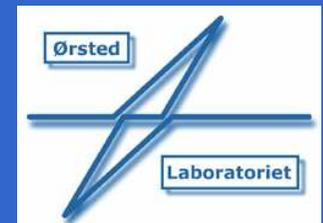
# Turbulence in Wendelstein 7-AS plasmas measured by collective light scattering

Nils P. Basse

Ørsted Laboratory, Niels Bohr Institute for Astronomy, Physics and Geophysics  
Copenhagen, Denmark  
Association EURATOM - Risø National Laboratory  
Roskilde, Denmark

- The Wendelstein 7-AS (W7-AS) stellarator
- The localised turbulence scattering (LOTUS) diagnostic
- Experimental results:
  - I) Fast confinement transitions
  - II) Slow confinement transitions
- Conclusions

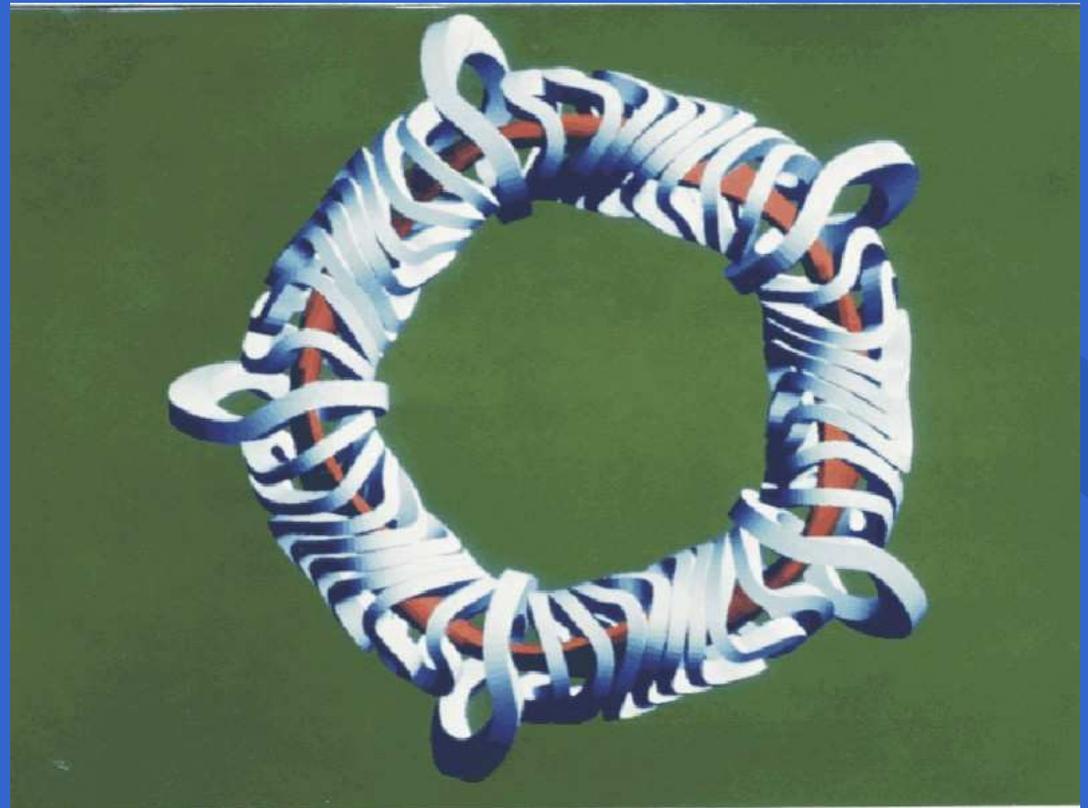
July 1<sup>st</sup>, 2002



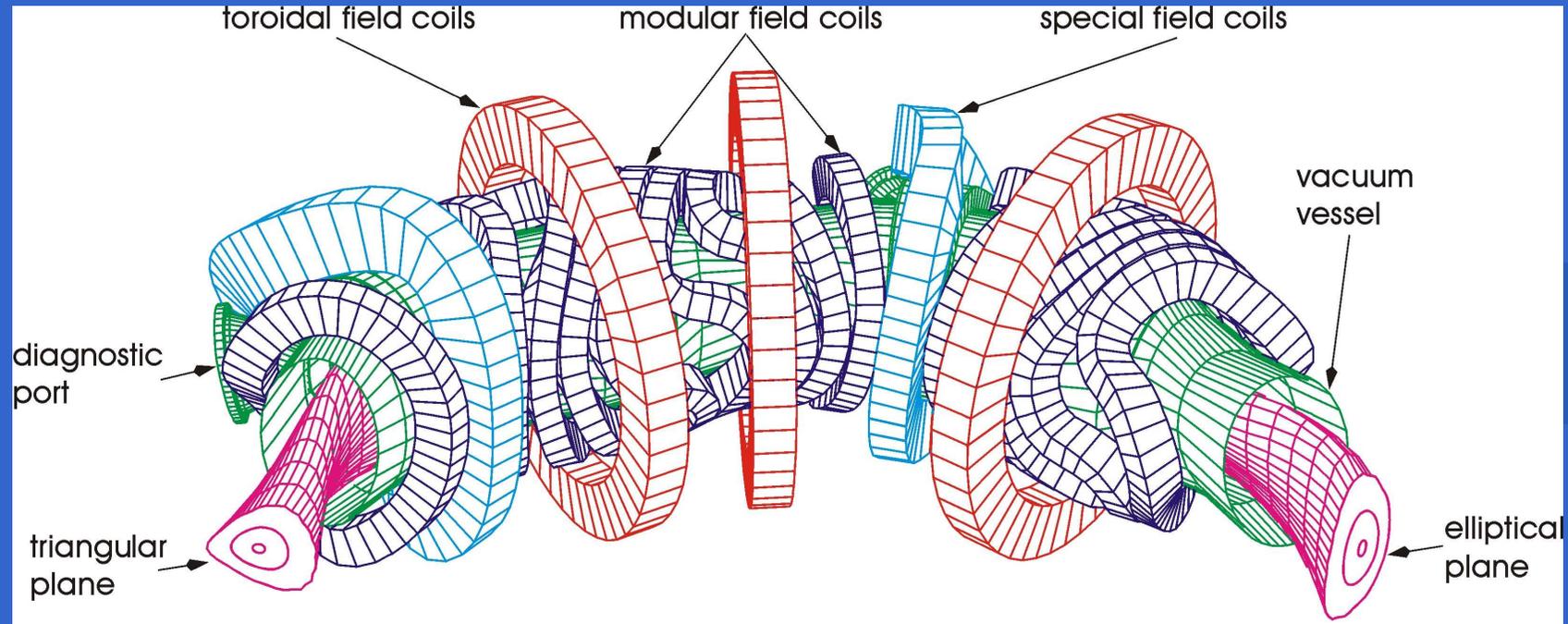
Optics and Fluid  
Dynamics

# The Wendelstein 7-AS stellarator

- Concept proposed by Lyman Spitzer, Jr., at Princeton in 1951.
- W7-AS initial operation in 1988.
- 45 modular coils create the confining magnetic field.
- 10 planar coils and vertical field coils allow experimental flexibility.
- Maximum toroidal field on axis  $B_0$  is 2.5 T.

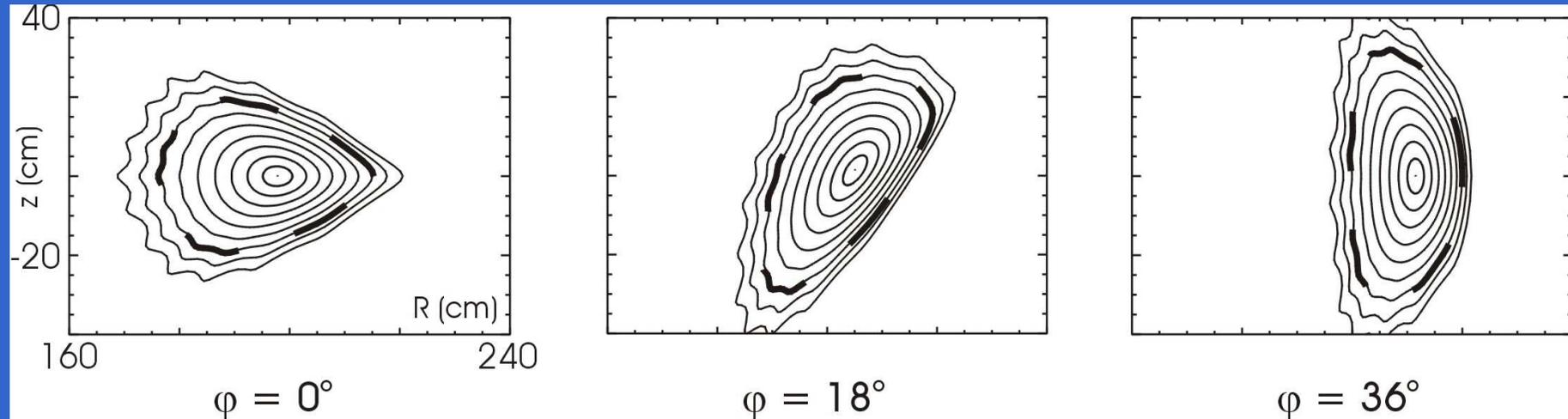


# The Wendelstein 7-AS stellarator



- Major radius  $R_0$  is 2 m, minor radius  $a \leq 18$  cm.
- Flux surfaces are elliptical in the corners and triangular in the straight sections (non-axisymmetric).

# The Wendelstein 7-AS stellarator



- The poloidal cross sections of flux surfaces above are shown for 3 different toroidal angles;  $0^\circ$  is the straight section and  $36^\circ$  is the corner.
- The plasmas are externally heated by up to 2.5 MW ECRH, 4 MW NBI and 1 MW ICRH.
- The working gas is H or D and the plasma volume is  $1 \text{ m}^3$ .

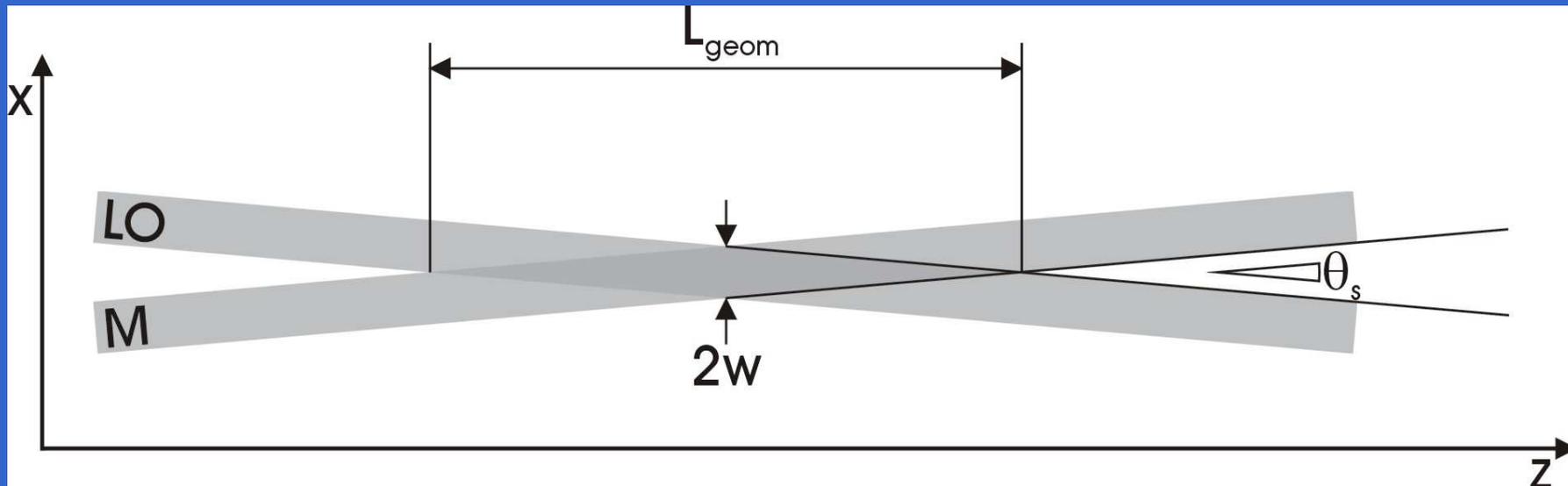
# Transport in fusion plasmas

- Large cross-field „anomalous“ transport observed.
- Anomalous transport is thought to be due to turbulence.
- Turbulence manifests itself as fluctuations in various plasma parameters, for example the density.
- Having measured fluctuations, these can be correlated to calculate transport relevant quantities, e.g. the radial particle flux  $\Gamma$ :

$$\Gamma_e^E(\omega) = \frac{\langle \delta E_\theta(\omega) \delta n_e(\omega) \rangle}{B_\varphi} = \delta n_e^{\text{RMS}}(\omega) \delta \phi^{\text{RMS}}(\omega) |\gamma_{n_e \phi}(\omega)| \frac{k_\theta(\omega)}{B_\varphi} \sin \alpha_{n_e \phi}(\omega) \quad (5.15)$$



# The LOTUS diagnostic



- Measurement volume length  $L_{\text{geom}} \approx 4w/\theta_s$ .
- Measured wavenumber  $k = 2 k_0 \sin(\theta_s/2) \approx k_0 \theta_s$ ,

where  $k_0 = 2\pi/\lambda_0 = 5933 \text{ cm}^{-1}$  is the wavenumber of the laser radiation.

# The LOTUS diagnostic

- The photocurrent  $i_k(t)$  at a given wavenumber  $k$ :

Defining

$$\gamma = \frac{e\eta}{\hbar\omega_0} \sqrt{\frac{\epsilon_0}{\mu_0}} \lambda_0 r_e \epsilon_0 \mathcal{E}_{LO}^*, \quad (2.28)$$

equation 2.24 in its final guise is

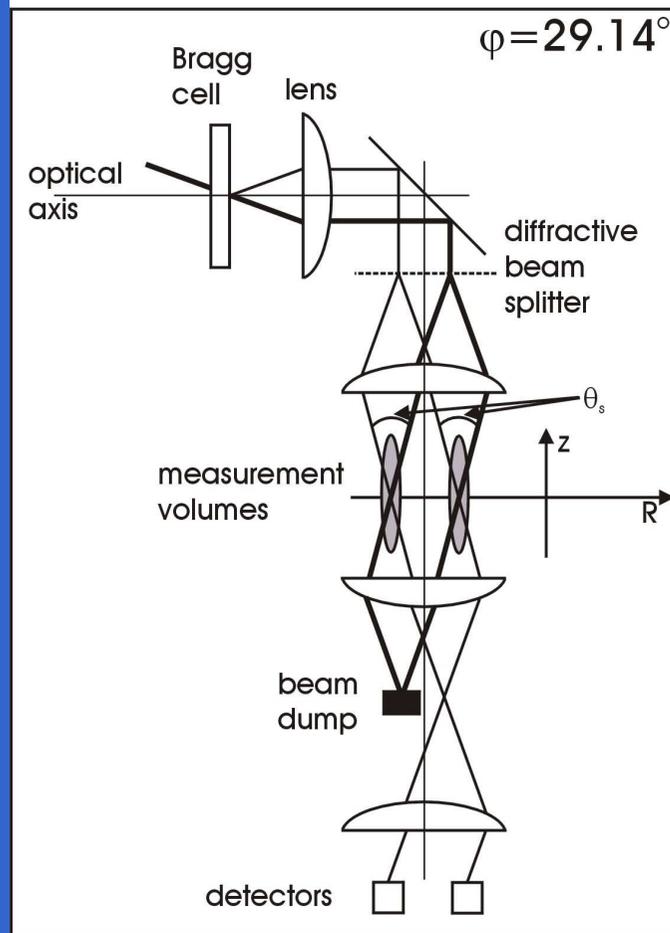
$$i_k(t) = i[\gamma e^{i\omega\Delta t} (n(t)U)_k - \gamma^* e^{-i\omega\Delta t} (n(t)U)_k^*] \quad (2.29)$$

$$\begin{aligned} i_{d,\text{complex}} &= [i_{d,2} - i i_{d,1}]_{\text{LPF}} = \\ &= \frac{1}{2} (\text{Re}[\gamma (n(t)U)_k] - i(-\text{Im}[\gamma (n(t)U)_k])) = \\ &= \frac{\gamma}{2} (n(t)U)_k \end{aligned} \quad (2.35)$$

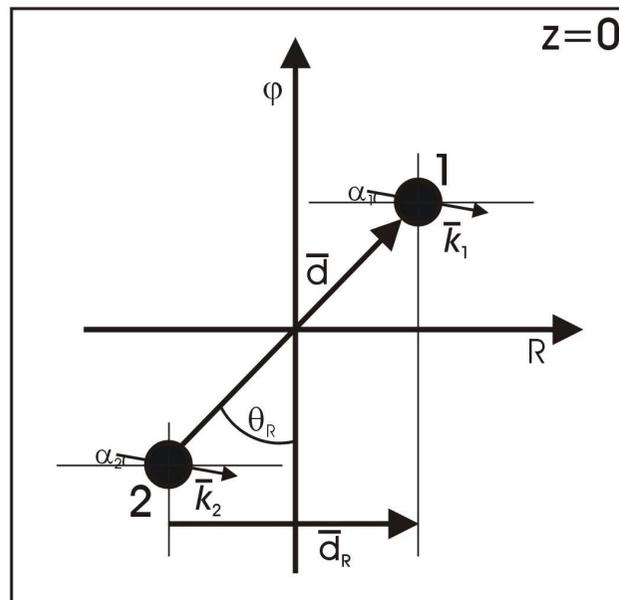


# The LOTUS diagnostic

Side view

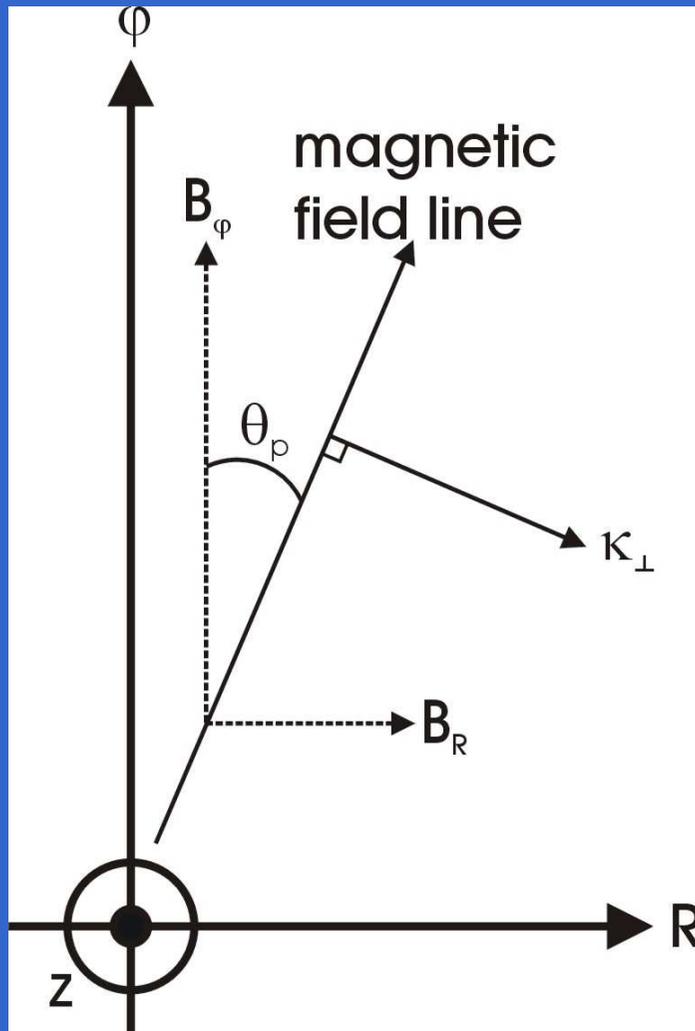


Top view



- Simplified sketch of the optical setup.
- In the side view, M beams are represented by thick lines, whereas LO beams are symbolized by thin lines.

# The LOTUS diagnostic



- It is assumed that the following inequality holds for the fluctuation wavenumber  $\kappa$ :

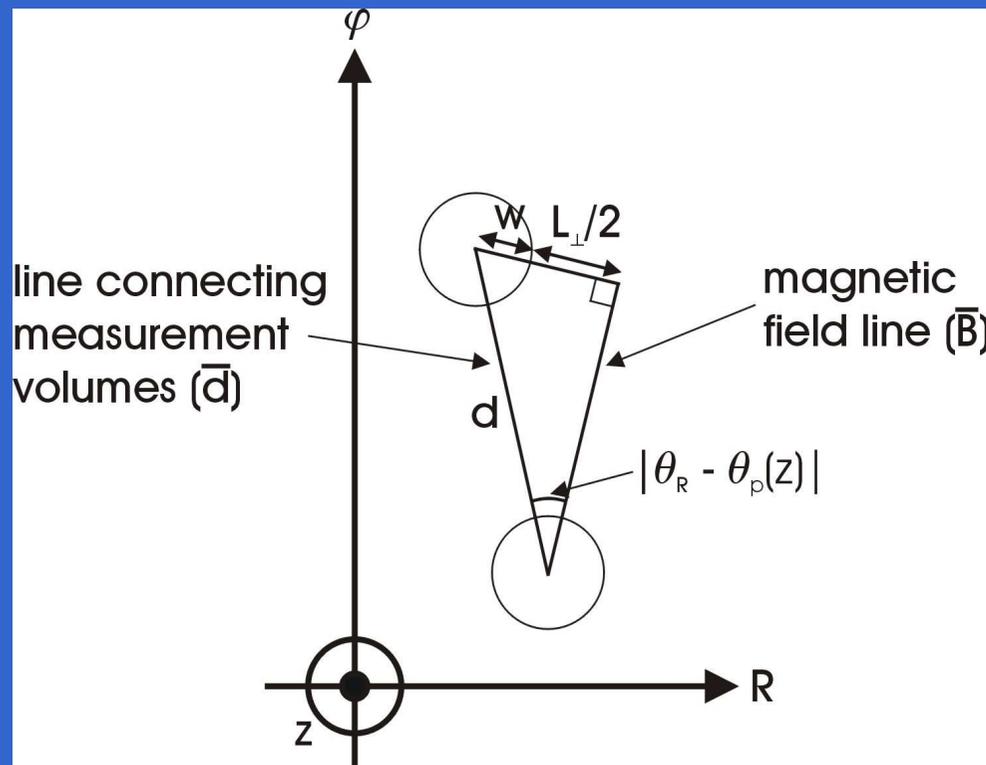
$$\kappa_{\parallel} \ll \kappa_{\perp}$$

- This – along with the analytical autopower formula – enables us to derive the single volume localisation criterion:

$$\Delta\theta_{p,\text{tot}}[\text{degrees}] \gg \Delta\alpha[\text{degrees}] = \frac{2}{kw} \times \frac{180}{\pi} \quad (3.57)$$



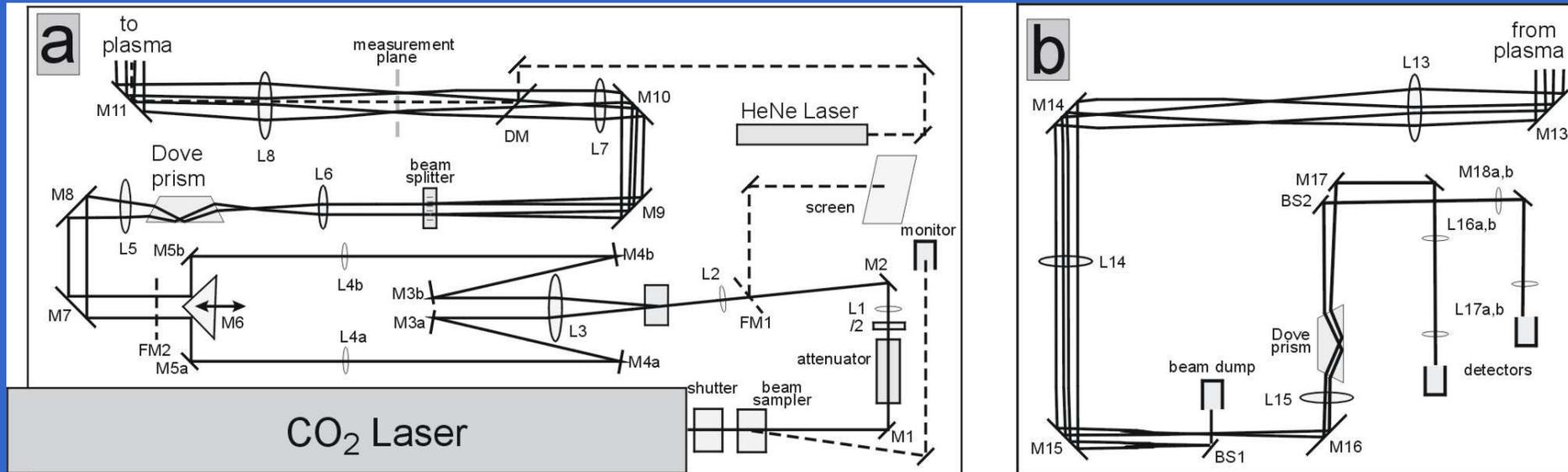
# The LOTUS diagnostic



- For two spatially separated measurement volumes, the crosspower amplitude selects spatially localised fluctuations if the volume separation is large and the cross-field correlation length is small:

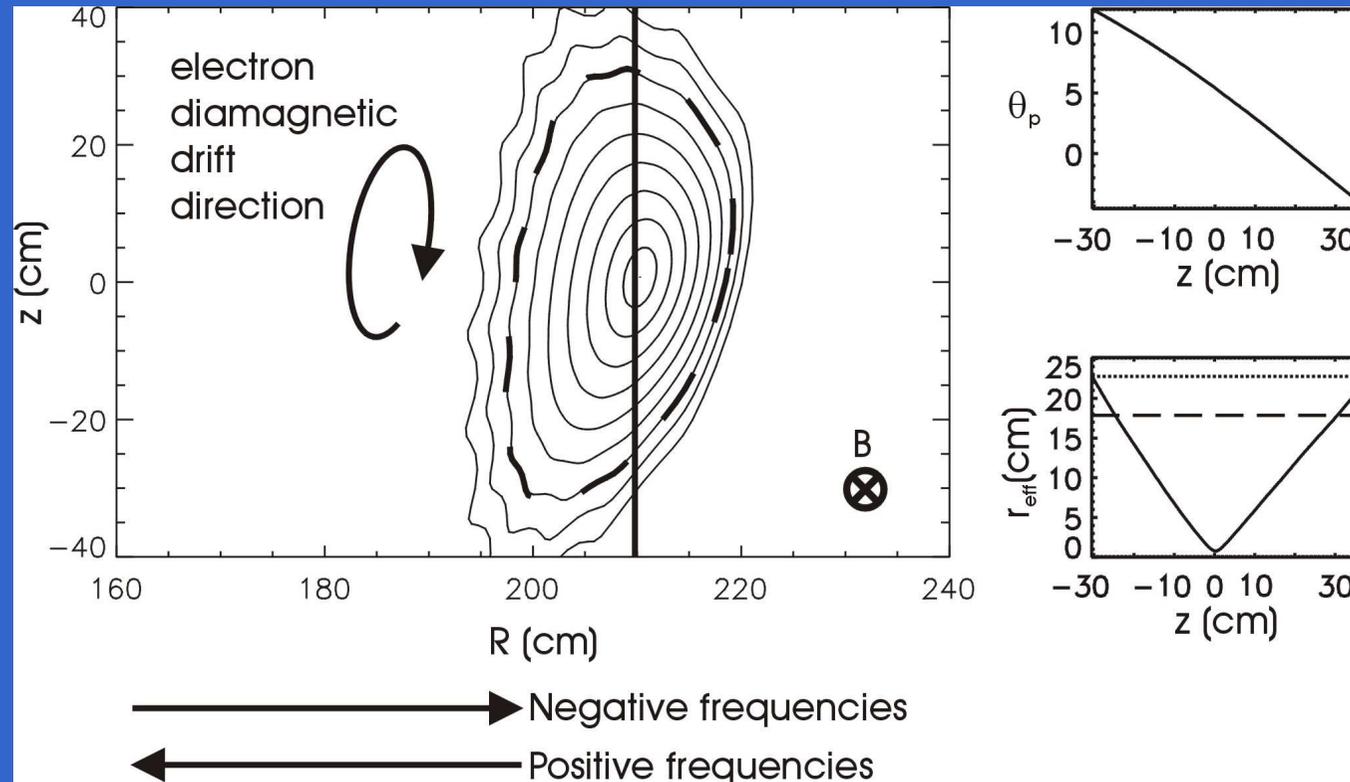
$$\Delta\theta_{p,\text{tot}}[\text{degrees}] \geq \Delta\theta_{\perp,\text{tot}}[\text{degrees}] \gg \frac{w + \mathcal{L}_{\perp}/2}{d} \times \frac{180}{\pi} \quad (3.58)$$

# The LOTUS diagnostic



- Left: Transmitting bench. M6 determines the wavenumber, the Dove prism  $\alpha$  and the beam splitter  $\theta_R$ .
- Right: Receiving bench. The Dove prism rotates the two LO beams so that they have the same height over the table.

# The LOTUS diagnostic



- Flux surfaces at the LOTUS position (vertical line) for a typical plasma. The upper and lower insets show the pitch angle and minor radius versus vertical position.

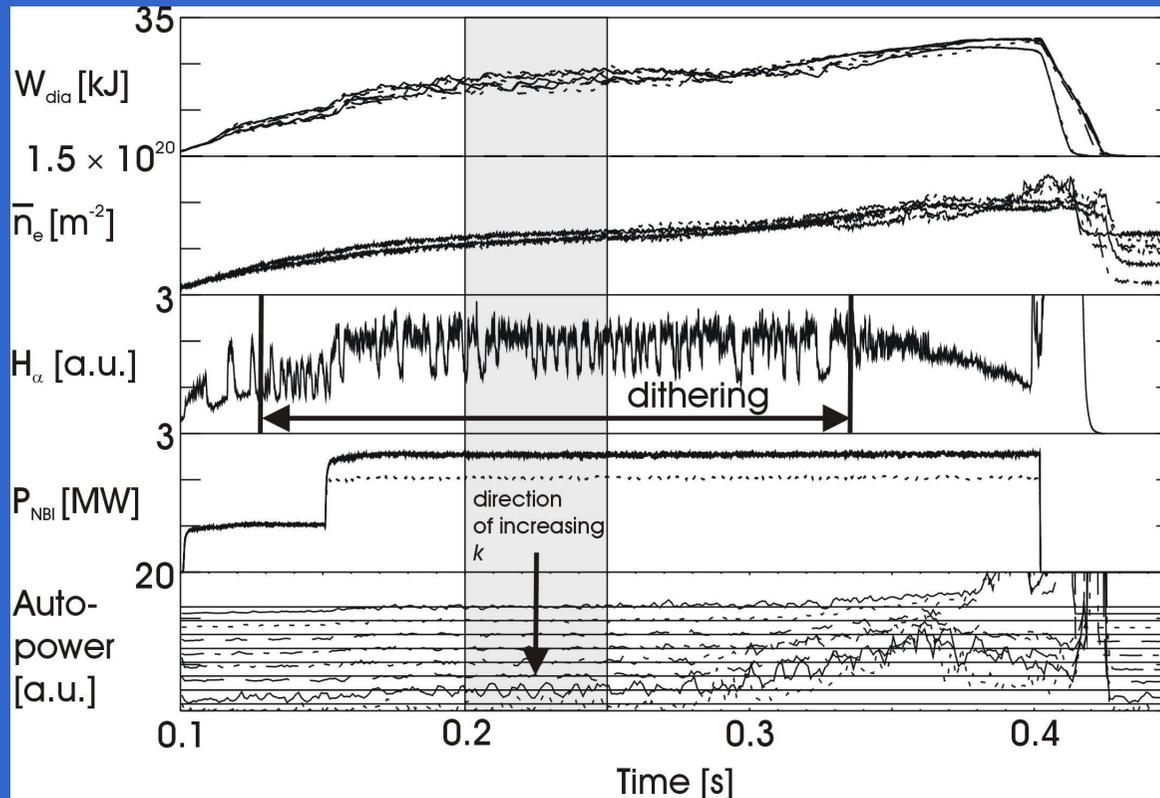
# The LOTUS diagnostic



Photo taken by Sándor Zoletnik [May 2002]

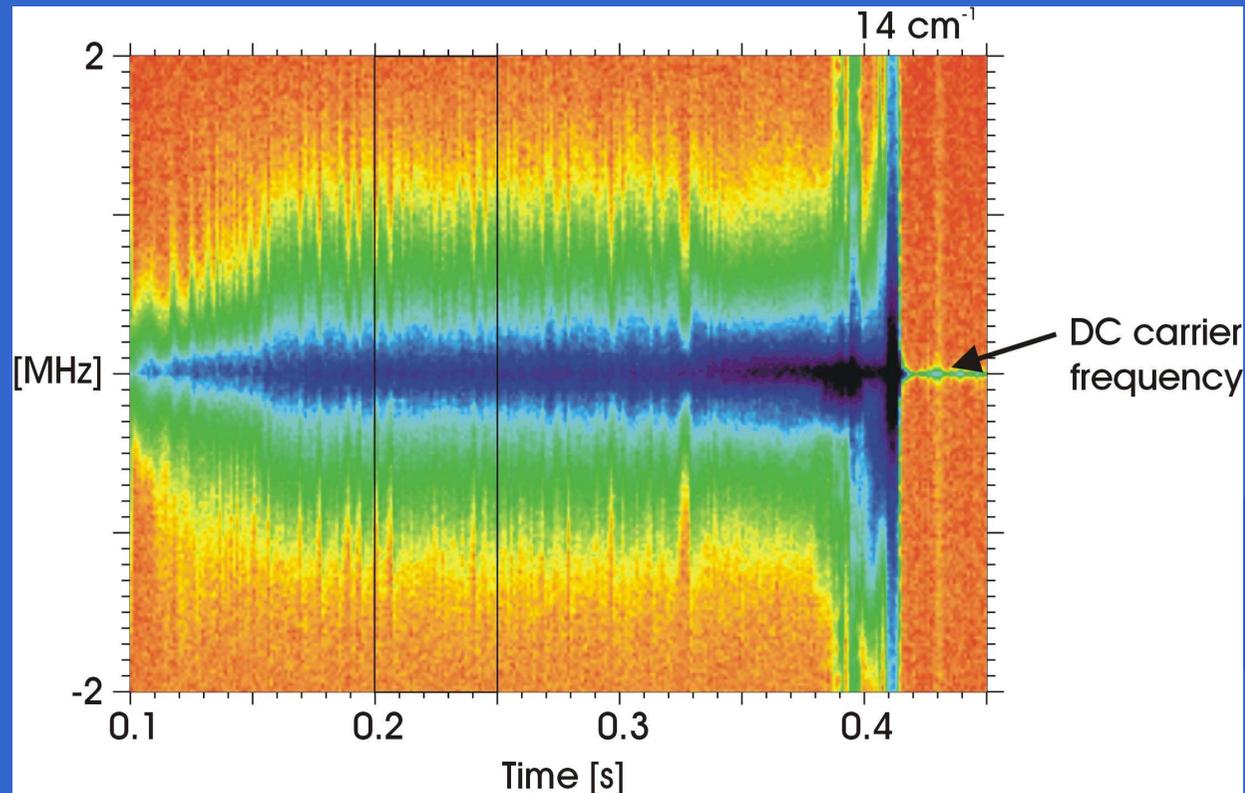


# Fast confinement transitions



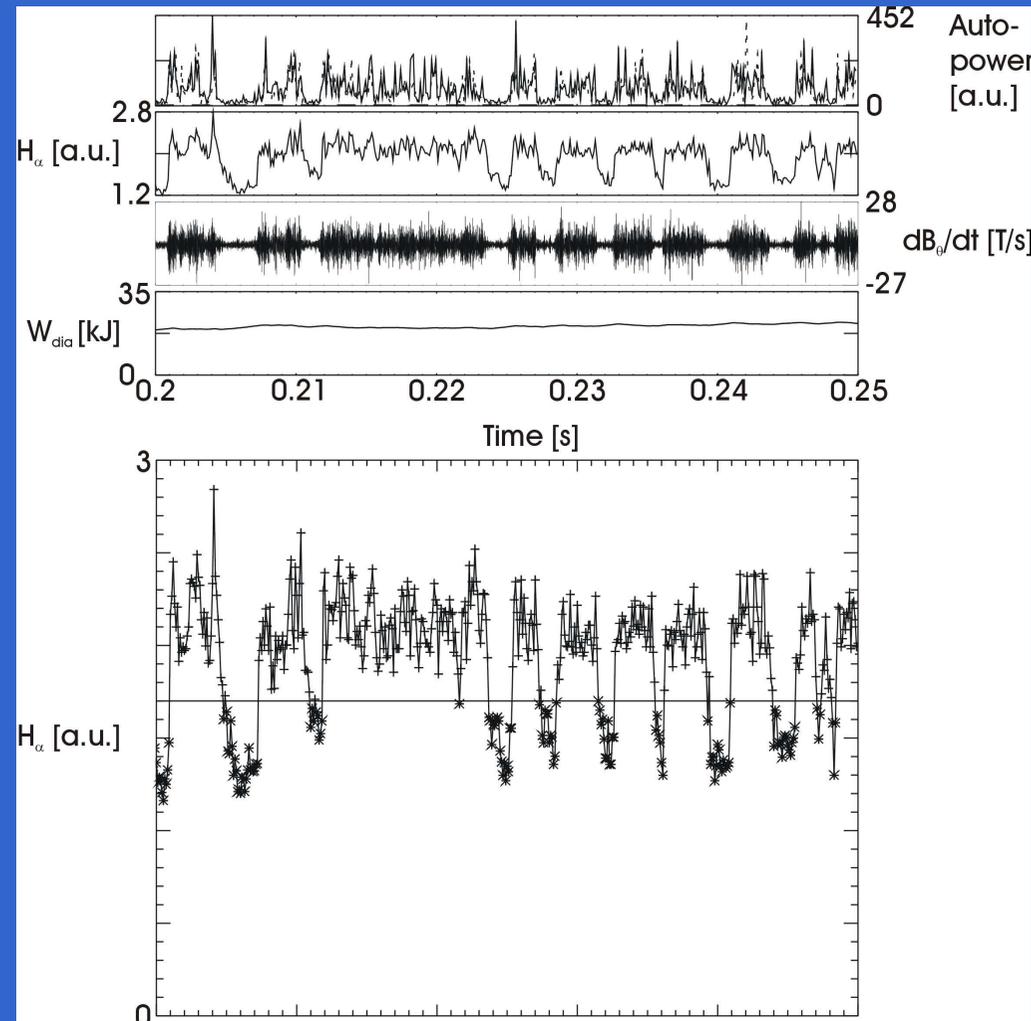
- Plasma waveforms for 8 discharges. Top to bottom:
- Energy, density, Balmer  $H_\alpha$ -light, heating power and density fluctuation power normalised to the analysis time window.

# Fast confinement transitions



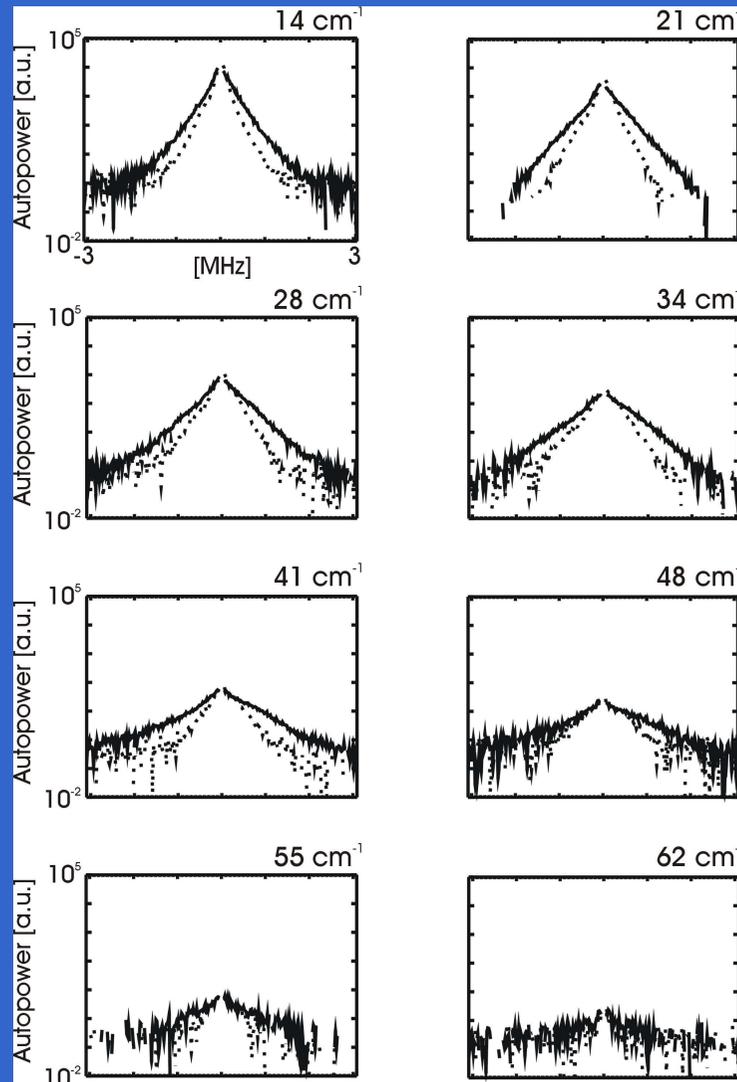
- LOTUS provides full spectral information. The spectrogram shows density fluctuation power versus frequency and time.
- The vertical bursts indicate switching between the low (L) and high (H) confinement mode.

# Fast confinement transitions



- Switching between the L- and H-mode confinement states is visible in most quantities. From top to bottom: Density fluctuations,  $H_\alpha$ -light, magnetic fluctuations and energy.
- The separated plot shows how L- and H-mode time windows can be separated.

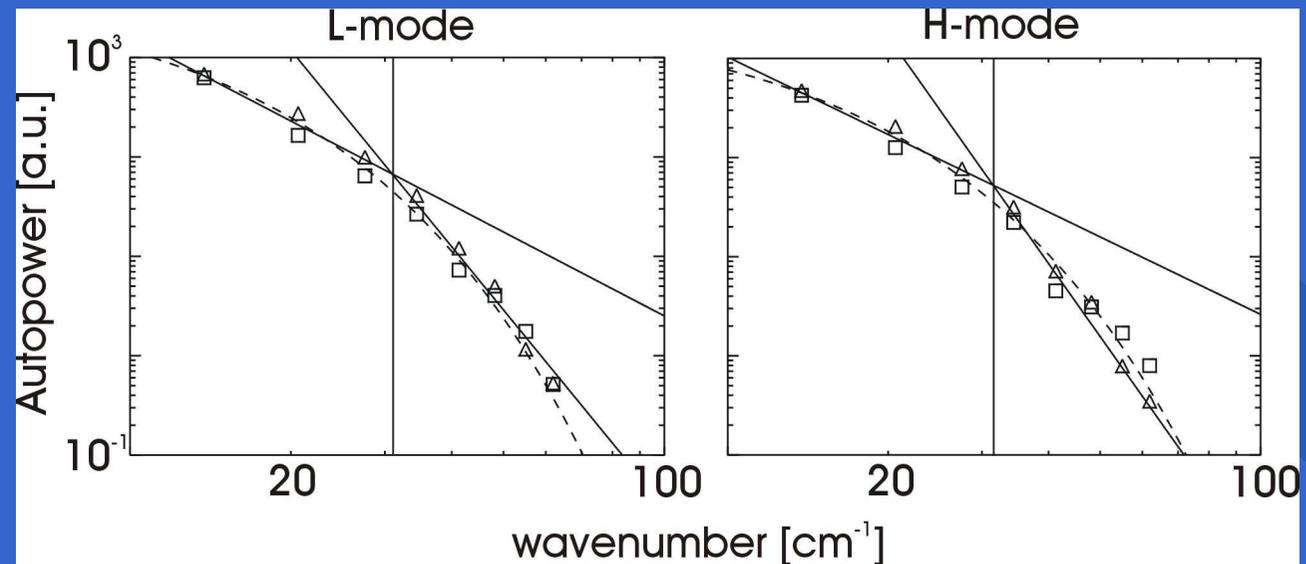
# Fast confinement transitions



- Autopower spectra can be calculated for a series of L- or H-mode time windows.
- In the figure, L-mode spectra are solid lines and H-mode spectra are dotted lines.
- H-mode spectra occupy a smaller frequency range and decrease faster as a function of frequency.
- All spectra decrease rapidly with wavenumber.

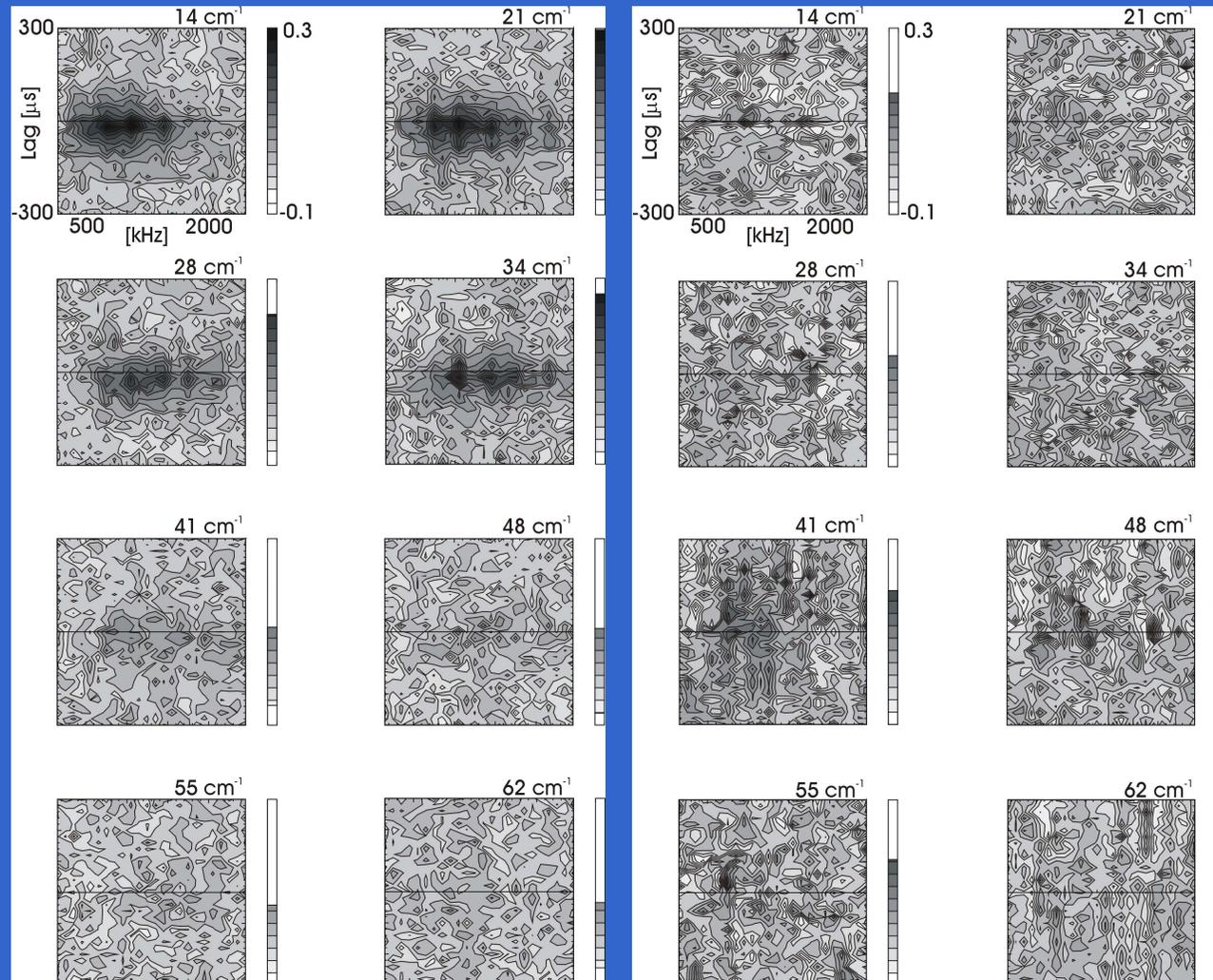
# Fast confinement transitions

- Wavenumber spectra can be constructed by plotting frequency integrated autopower versus wavenumber.
- This is shown for L- and H-modes in the figure.



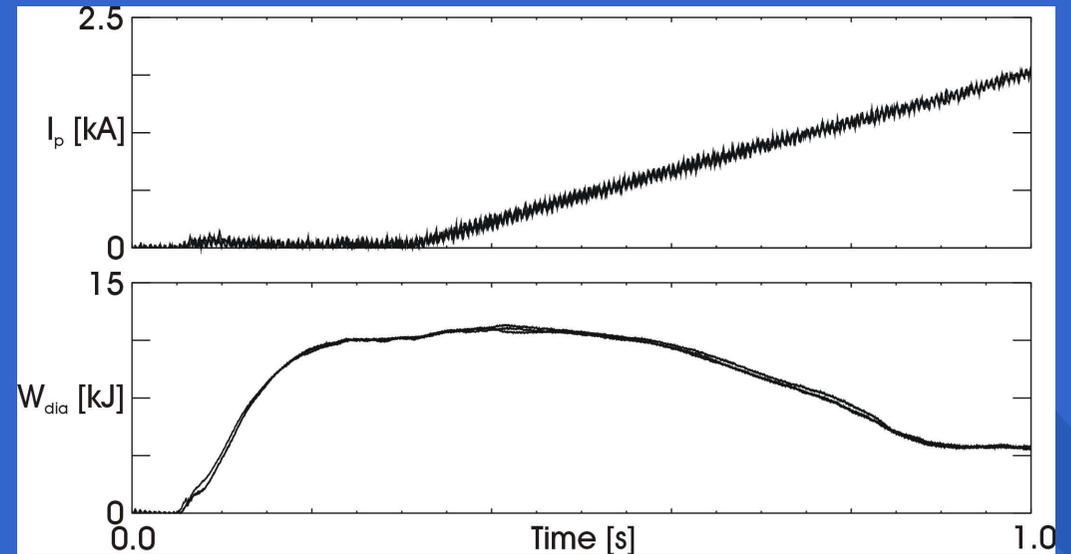
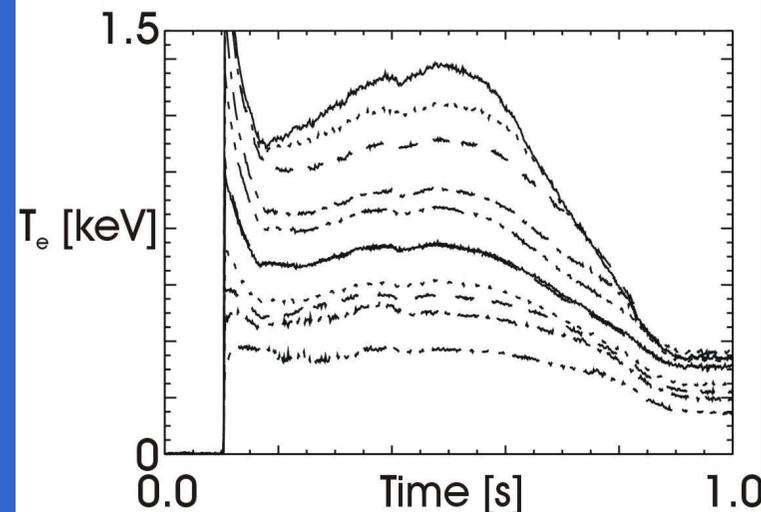
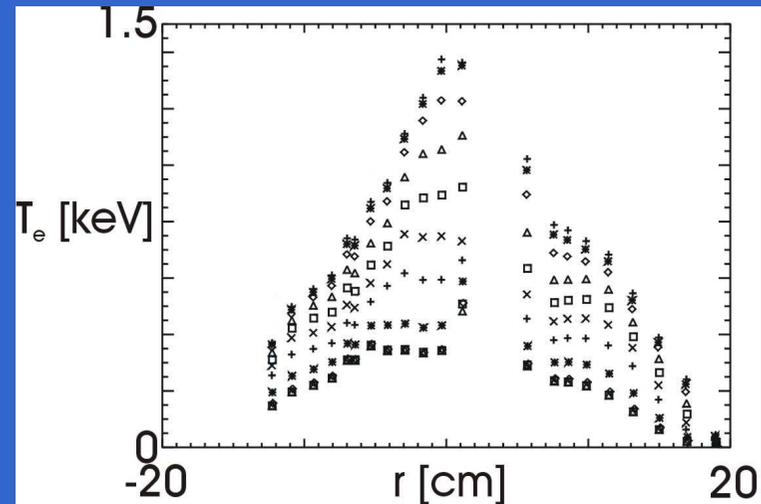
- The wavenumber spectra can be fitted to power-laws or exponential functions. In both cases, the exponents are almost identical for L- and H-mode.

# Fast confinement transitions



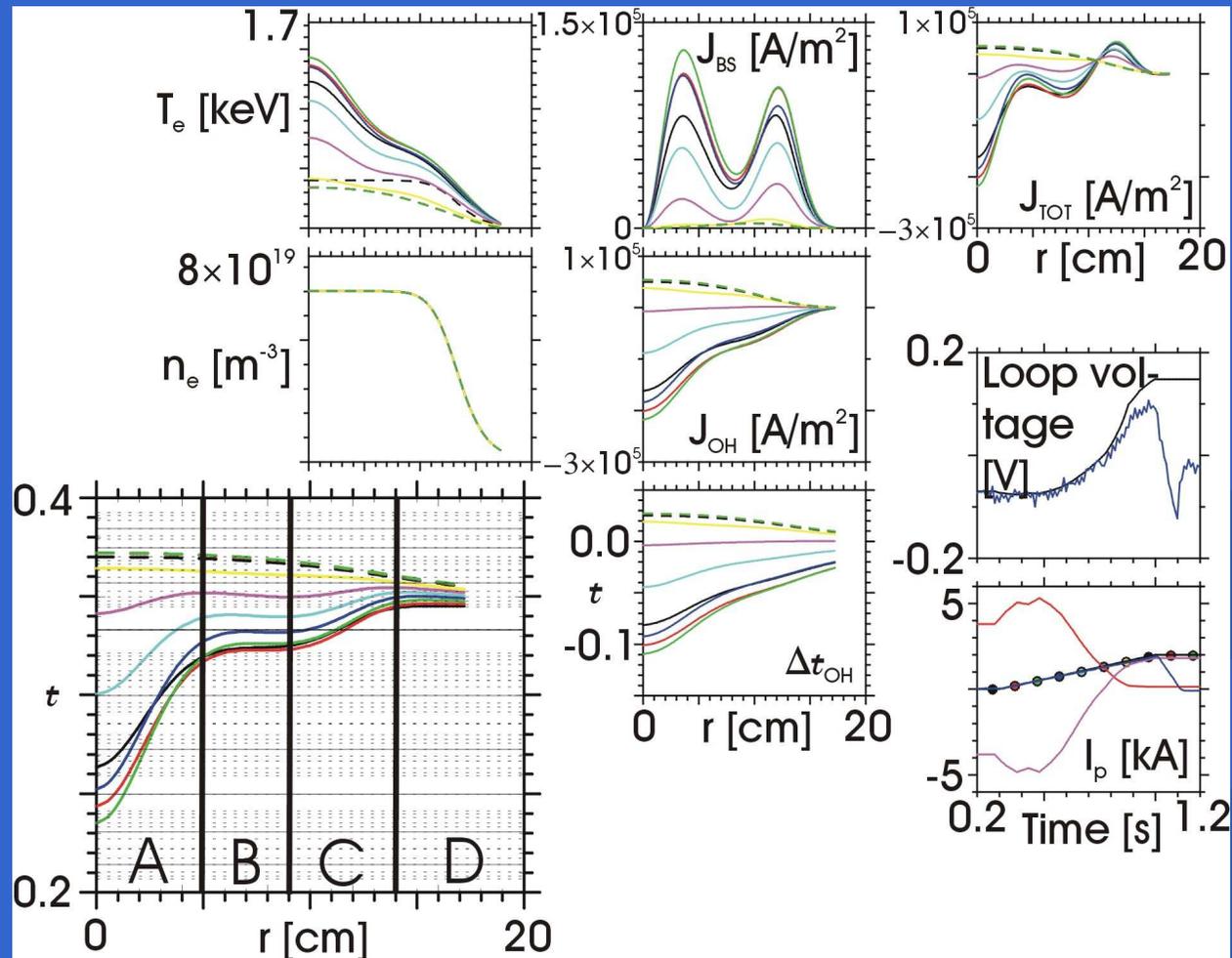
- Correlations between magnetic and density fluctuations have been calculated with time lag steps of  $20 \mu\text{s}$ .
- Correlations exist in L-mode but vanish in H-mode.

# Slow confinement transitions



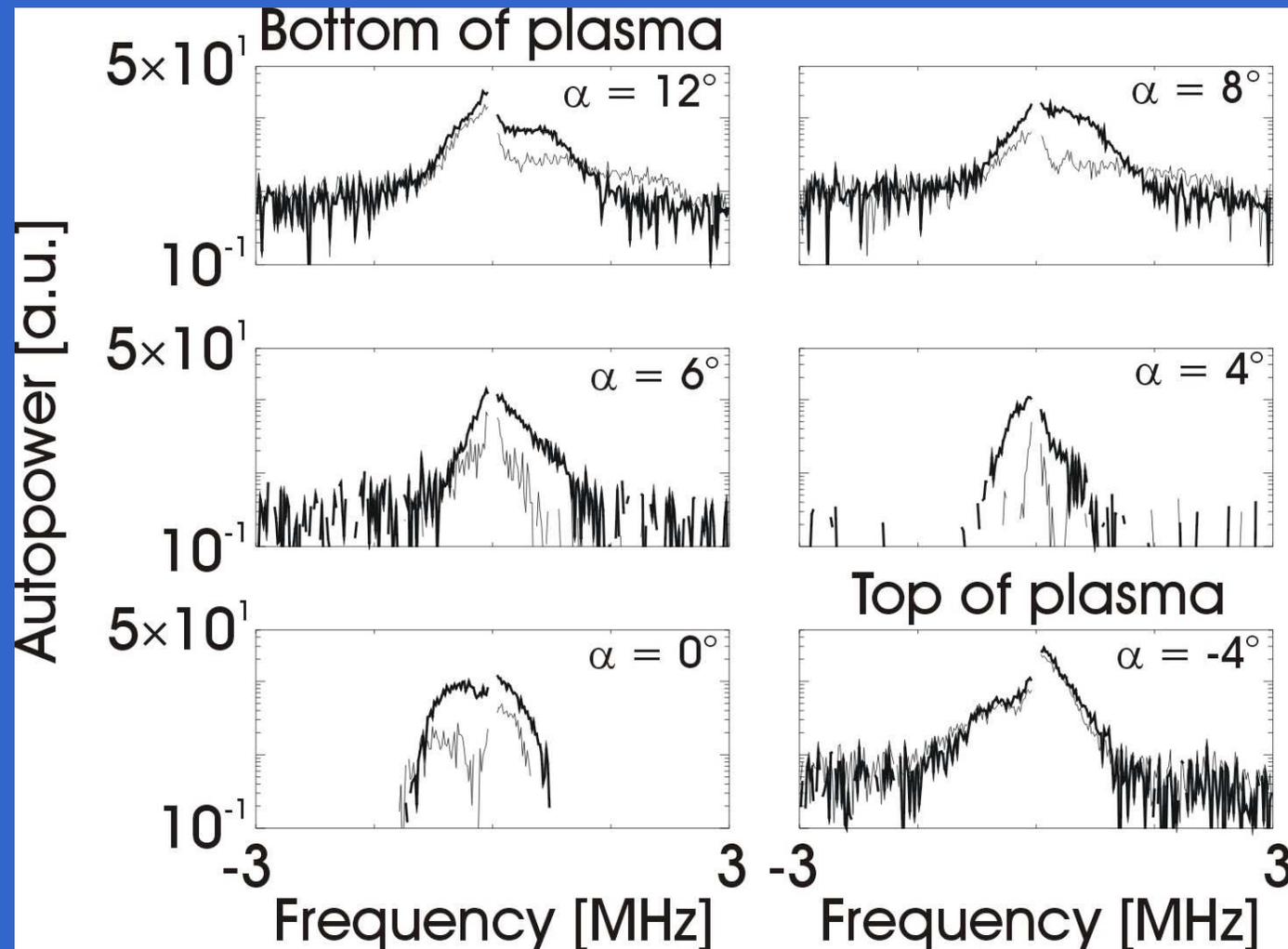
- Confinement in W7-AS is very sensitive to the rotational transform profile and value.
- The rotational transform can be varied by the external coils or an internal plasma current.

# Slow confinement transitions



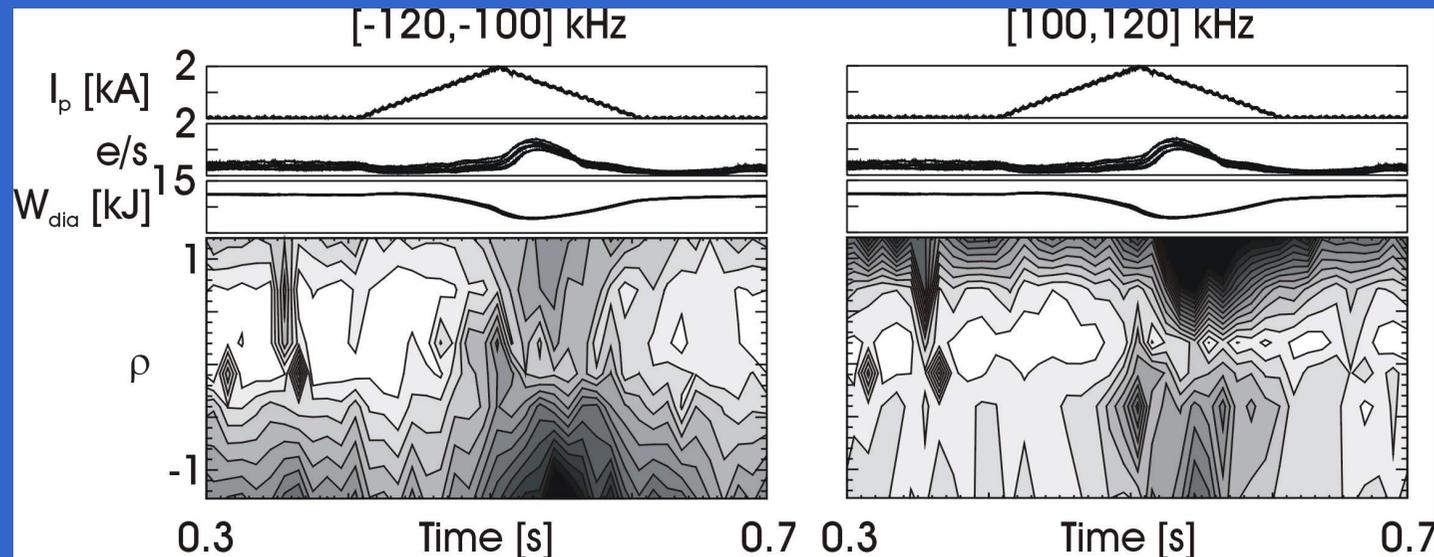
- Current densities and the resulting rotational transform profile (large figure) can be modelled and fitted to measured data.
- Low shear and the presence of low-order rationals are linked to bad confinement.

# Slow confinement transitions



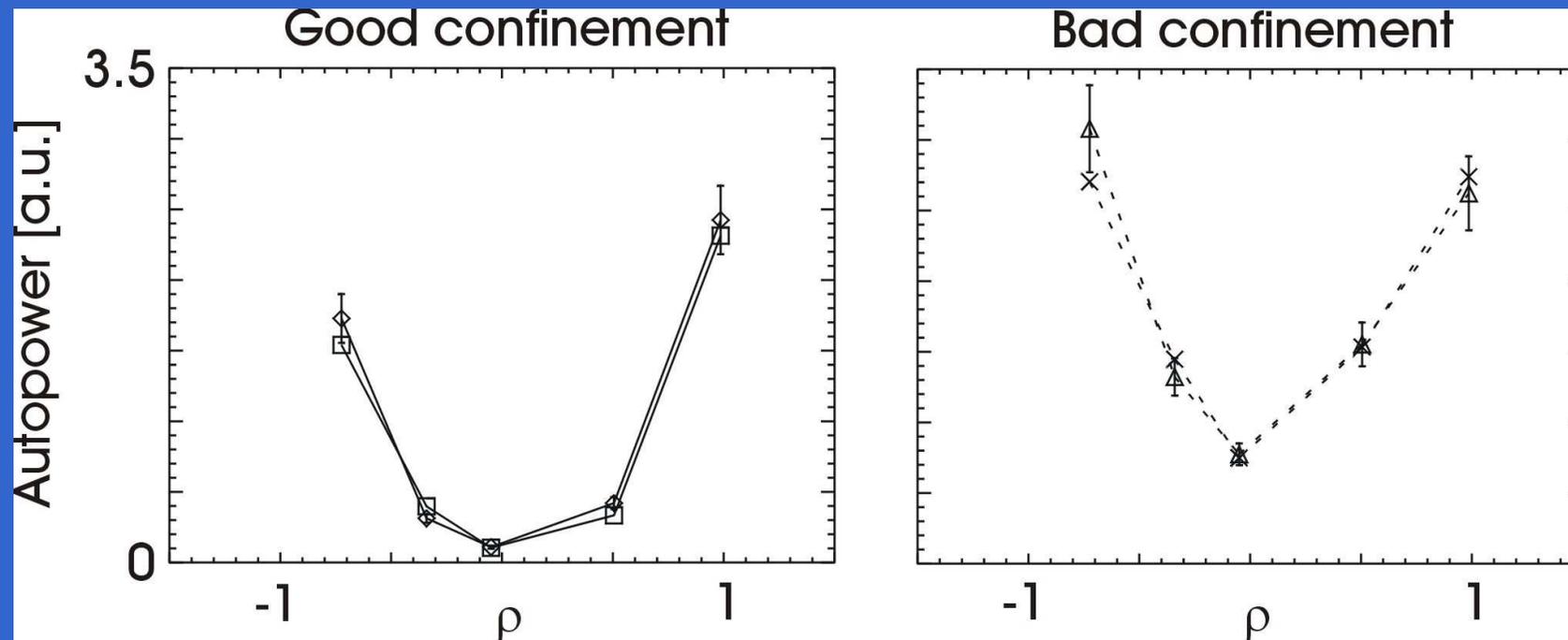
- Single volume localisation.
- Thin lines are good confinement.
- Thick lines are bad confinement.
- 6 localised positions along the measurement volume are shown.

# Slow confinement transitions



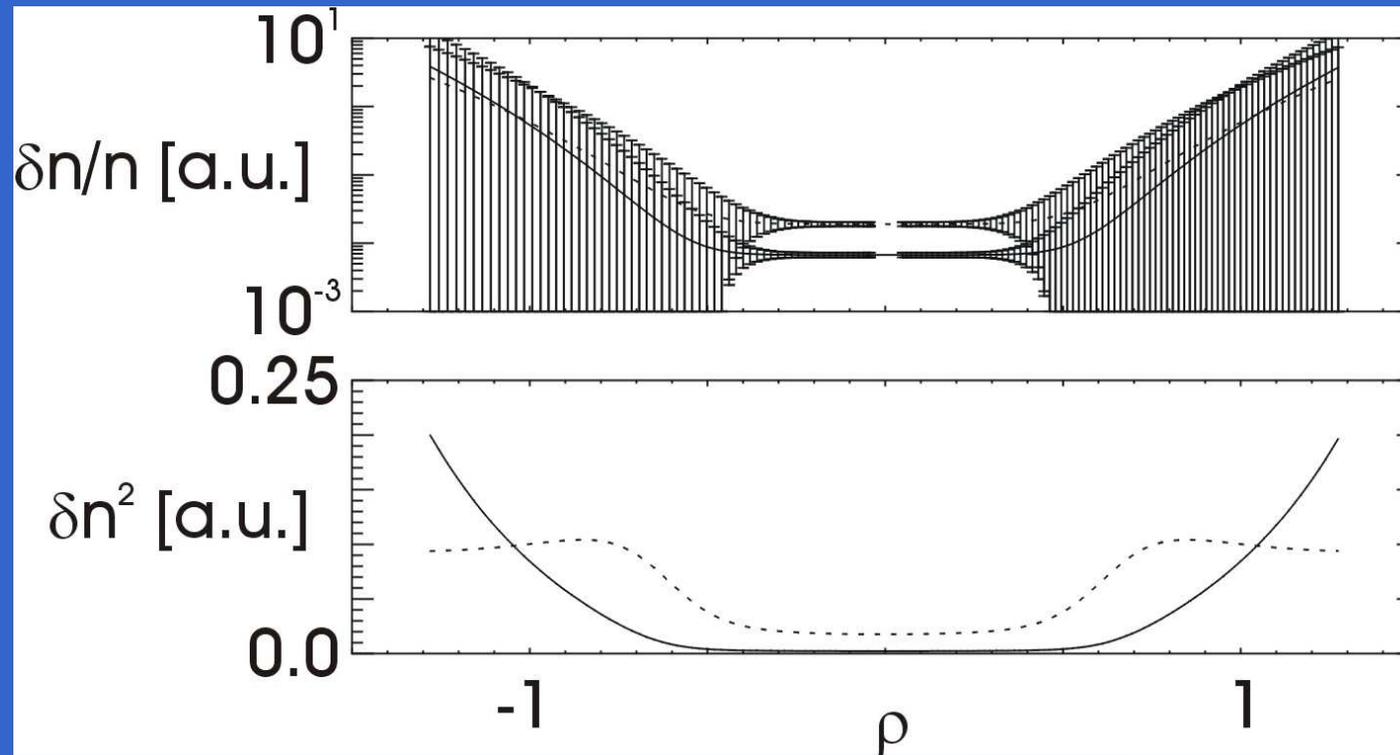
- Top 3 traces: Plasma current, particle fuelling and energy.
- Left contour plot: Low frequency outward travelling fluctuations versus position and time.
- Right contour plot: Inward travelling fluctuations.
- Conclusion: Low frequency fluctuations travel in the electron diamagnetic drift direction.

# Slow confinement transitions



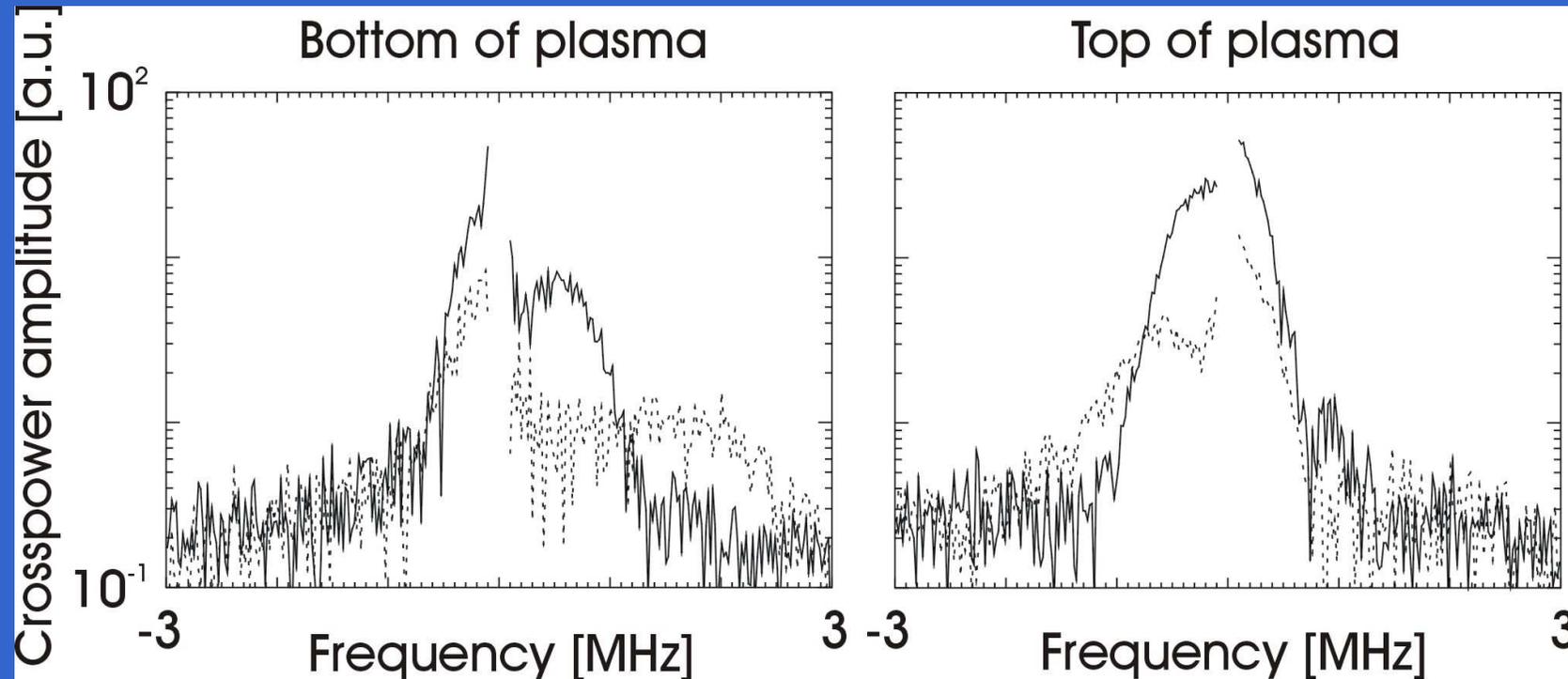
- Left: Measured (diamonds) and fitted (squares) turbulence profiles during good confinement.
- Right: Measured (triangles) and fitted (crosses) turbulence profiles during bad confinement.

# Slow confinement transitions



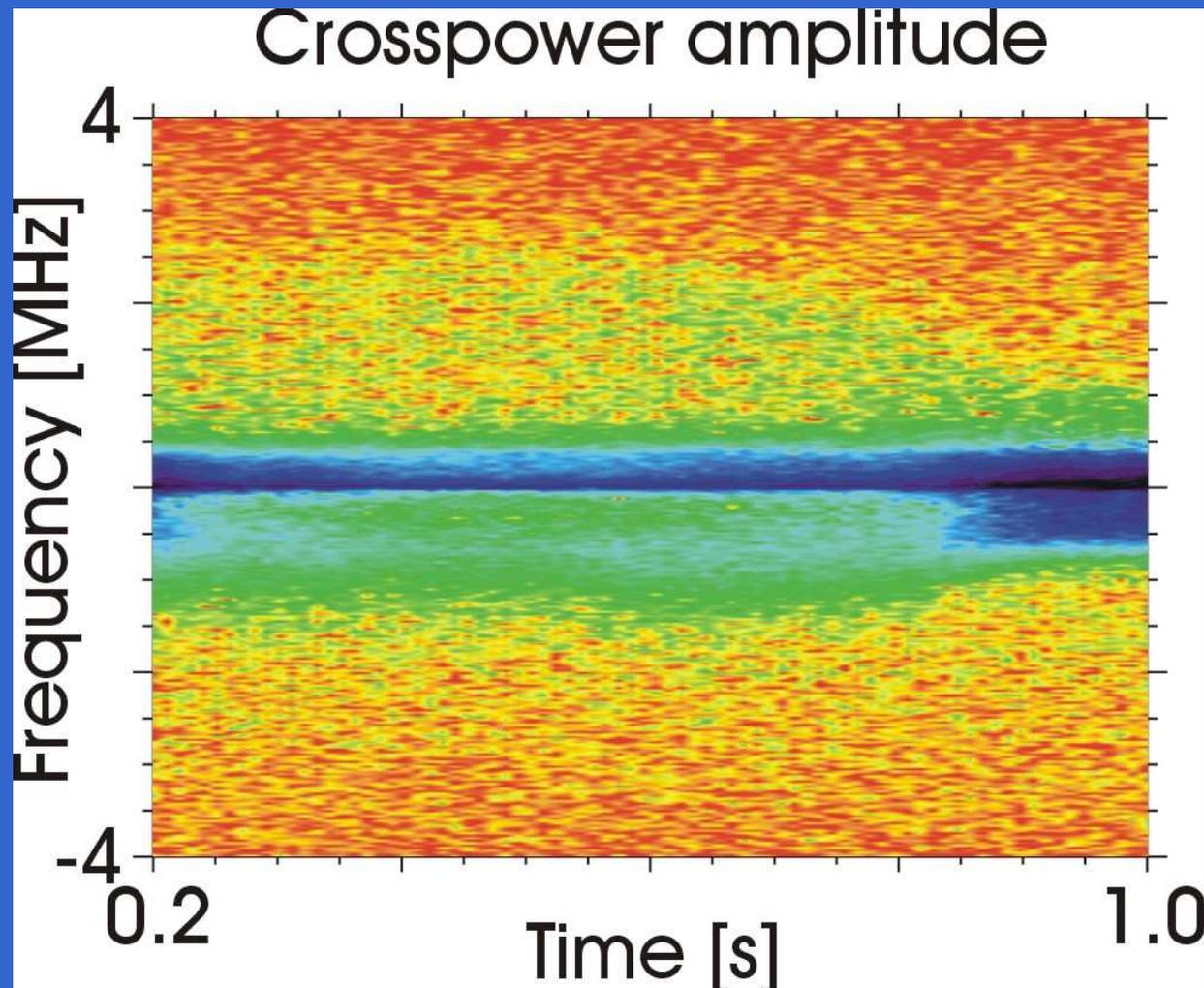
- Top: Relative fluctuation level versus spatial position for good (solid) and bad (dotted) confinement.
- Bottom: Absolute fluctuation level.

# Slow confinement transitions



- Dual volume localisation.
- Dotted line is good confinement, solid line bad confinement.

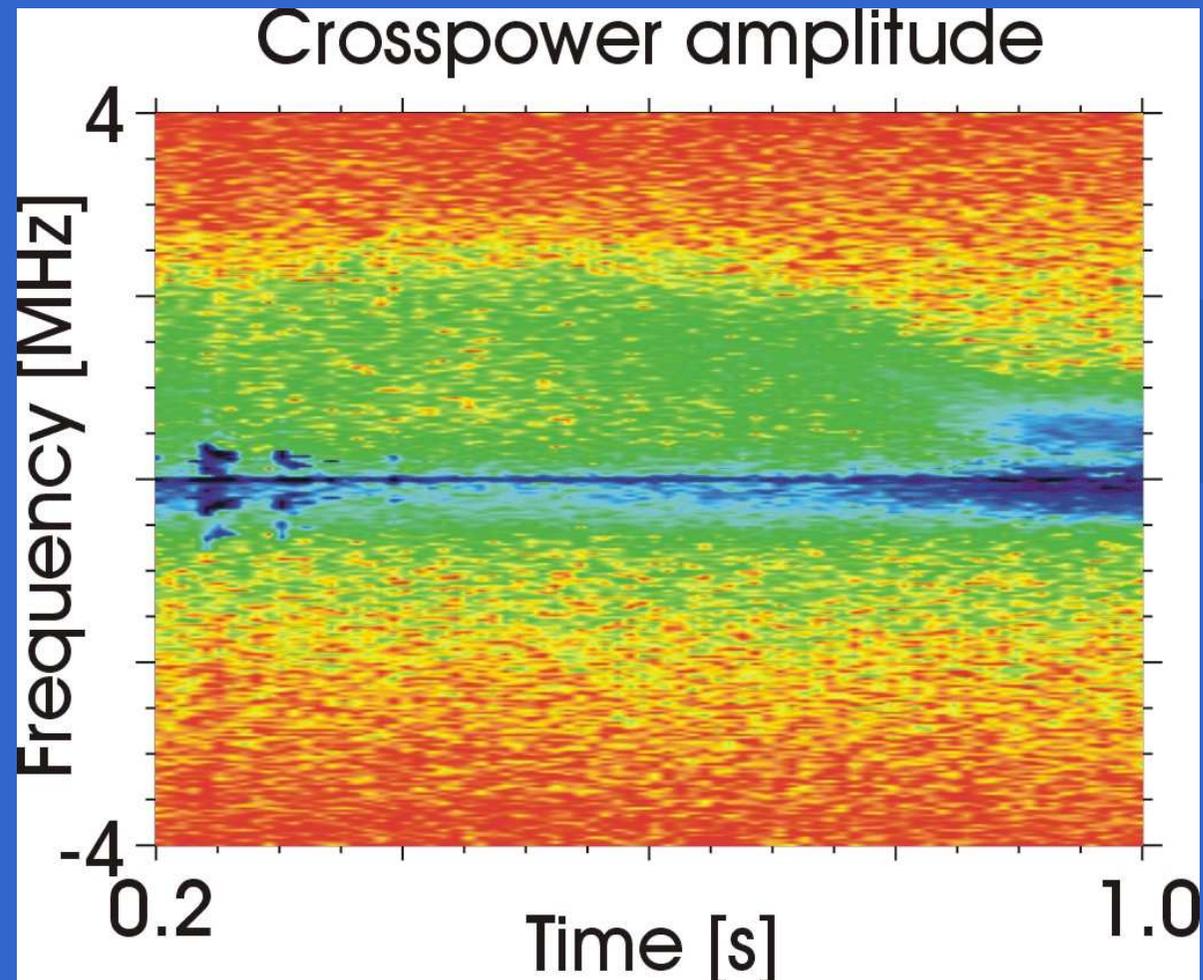
# Slow confinement transitions



- Crosspower amplitude versus frequency and time at the top of the plasma.
- A gradual increase followed by a saturation of the turbulence is observed from good to bad confinement.

# Slow confinement transitions

- Crosspower amplitude versus frequency and time at the bottom of the plasma.
- A gradual increase (and spin down) followed by a saturation of the turbulence is observed from good to bad confinement.



# Conclusions

The LOTUS density fluctuation diagnostic was designed and installed on the W7-AS stellarator [1995-1998].

Turbulence was thereafter routinely measured, and LOTUS was further developed [1999-2002].

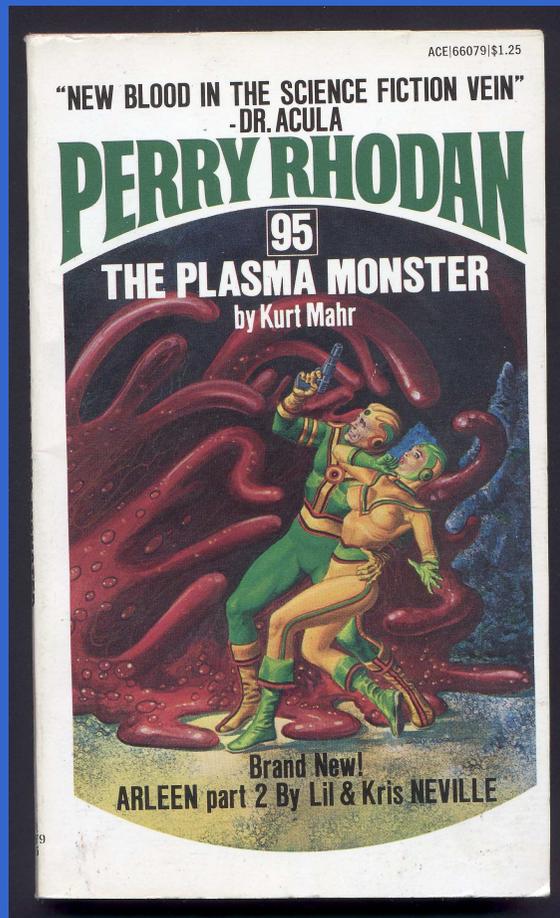
Theoretical expressions for the detected signal have been re-derived and two localisation concepts were elucidated.

The overarching theme of the plasmas diagnosed was „confinement transitions“, both on fast and slow time scales. Two transition types were described and analysed in this talk.

LOTUS has now been dismantled [June 2002] and W7-AS shuts down permanently at the end of July 2002.



# Turbulence in Wendelstein 7-AS plasmas measured by collective light scattering



The plasma monster  
(i.e. turbulence)

versus

the human intellect  
(e.g. Nils P. Basse).

