Turbulence in tokamaks and stellarators

Alcator C-Mod

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Discussions with and measurements from:

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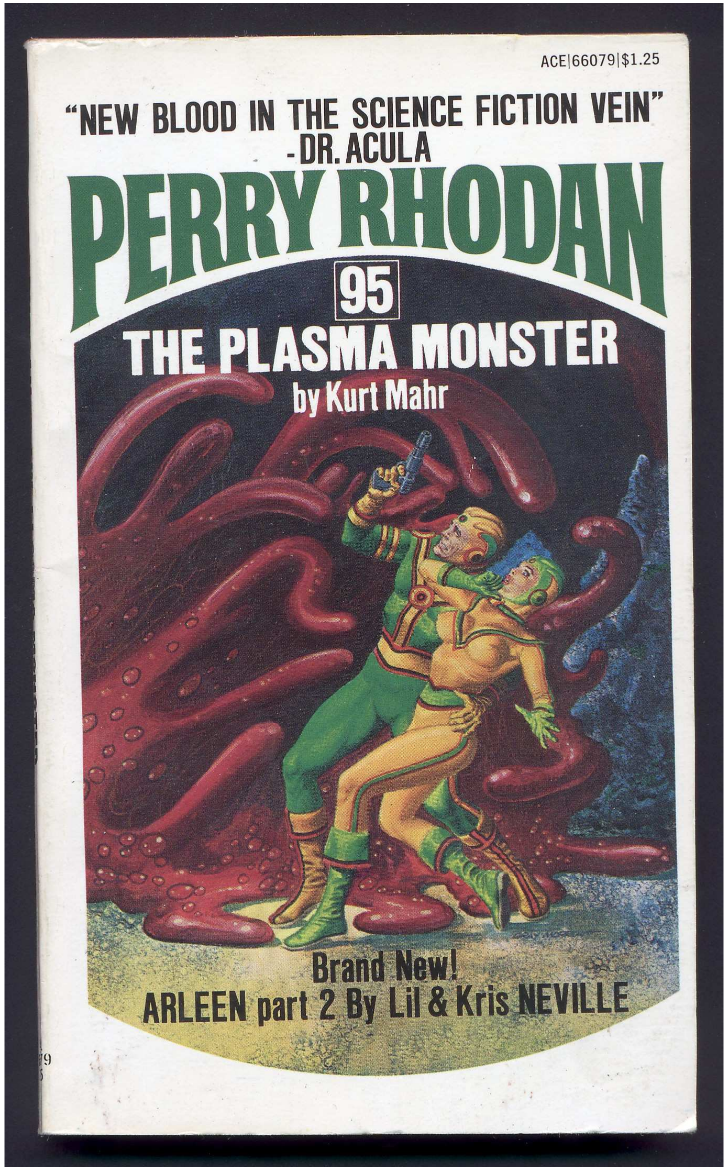
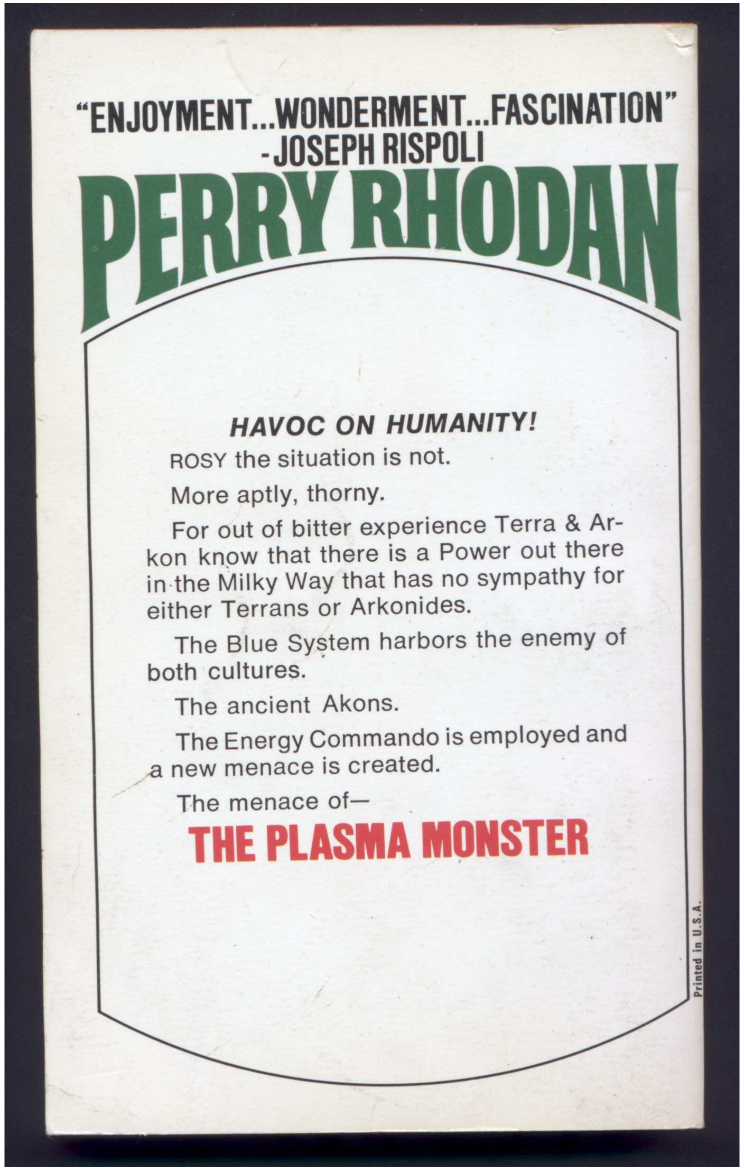
Plasma Physics Colloquium
Columbia University, 1st of October 2004

MIT PSFC

The plasma monster

Alcator C-Mod



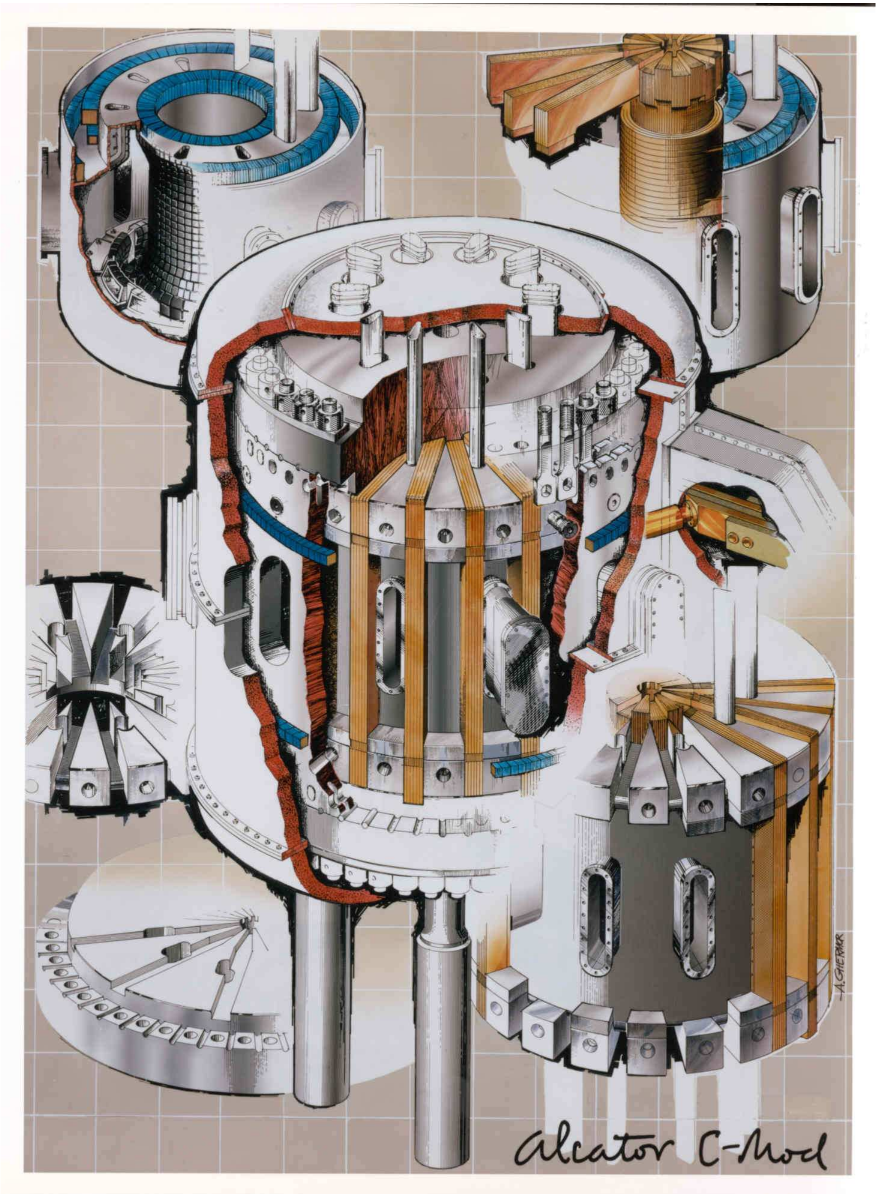


Outline

- Alcator C-Mod tokamak
- L- to EDA H-mode transition in C-Mod
- Wendelstein 7-AS stellarator
- Controlled confinement transition in W7-AS
- Conclusions

L-mode = low confinement mode
H-mode = high confinement mode
EDA = enhanced D_{α}

Alcator C-Mod tokamak



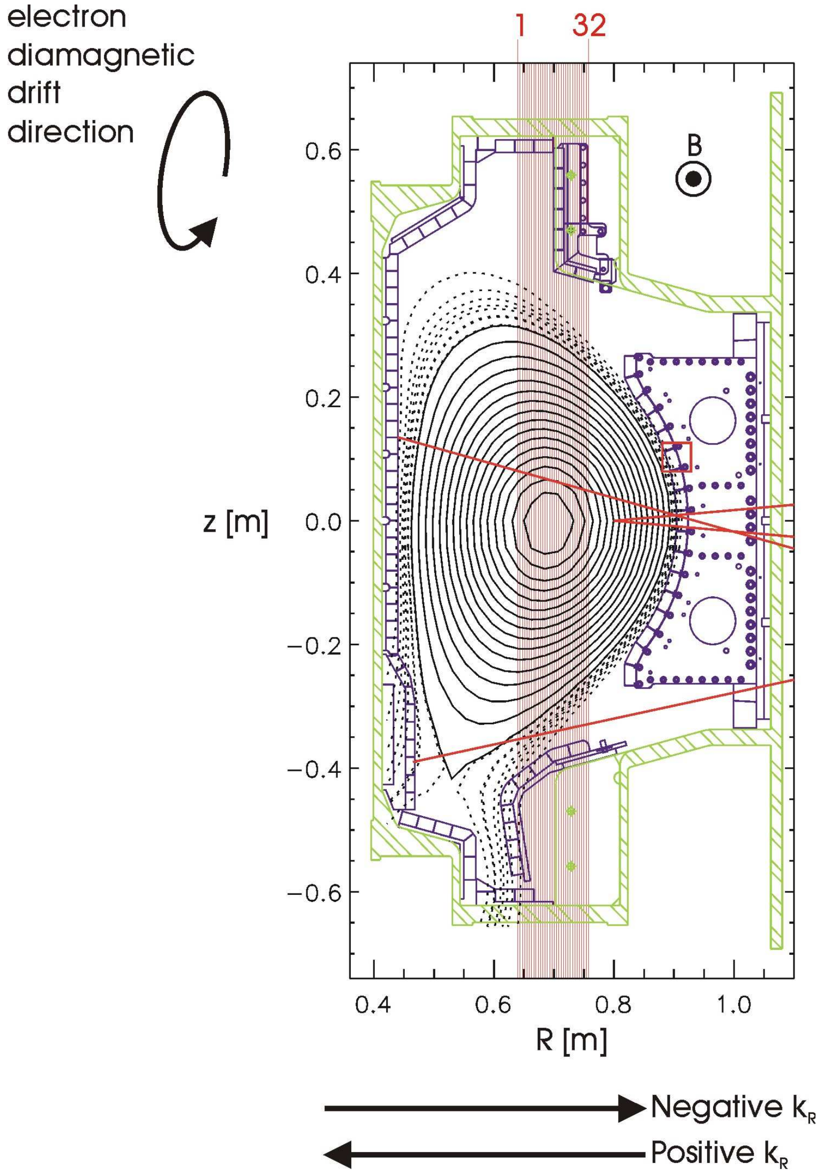
Alcator C-Mod is a divertor tokamak with high magnetic field capability ($B_t \leq 8$ T) in which quite high plasma currents ($I_p \leq 2$ MA) are possible in a compact geometry (R = 0.67 m, a = 0.22 m). Strong shaping options.

Plasma densities well above 1×10^{21} m^{-3} have been obtained, but more typically the average density is in the range $(1\text{-}5)\times10^{20}$ m^{-3}.

Auxiliary heating: Up to 6 MW ICRF (3 antennas, frequency between 50 and 80 MHz).

Plasma facing components are made of Molybdenum.

Phase-contrast imaging

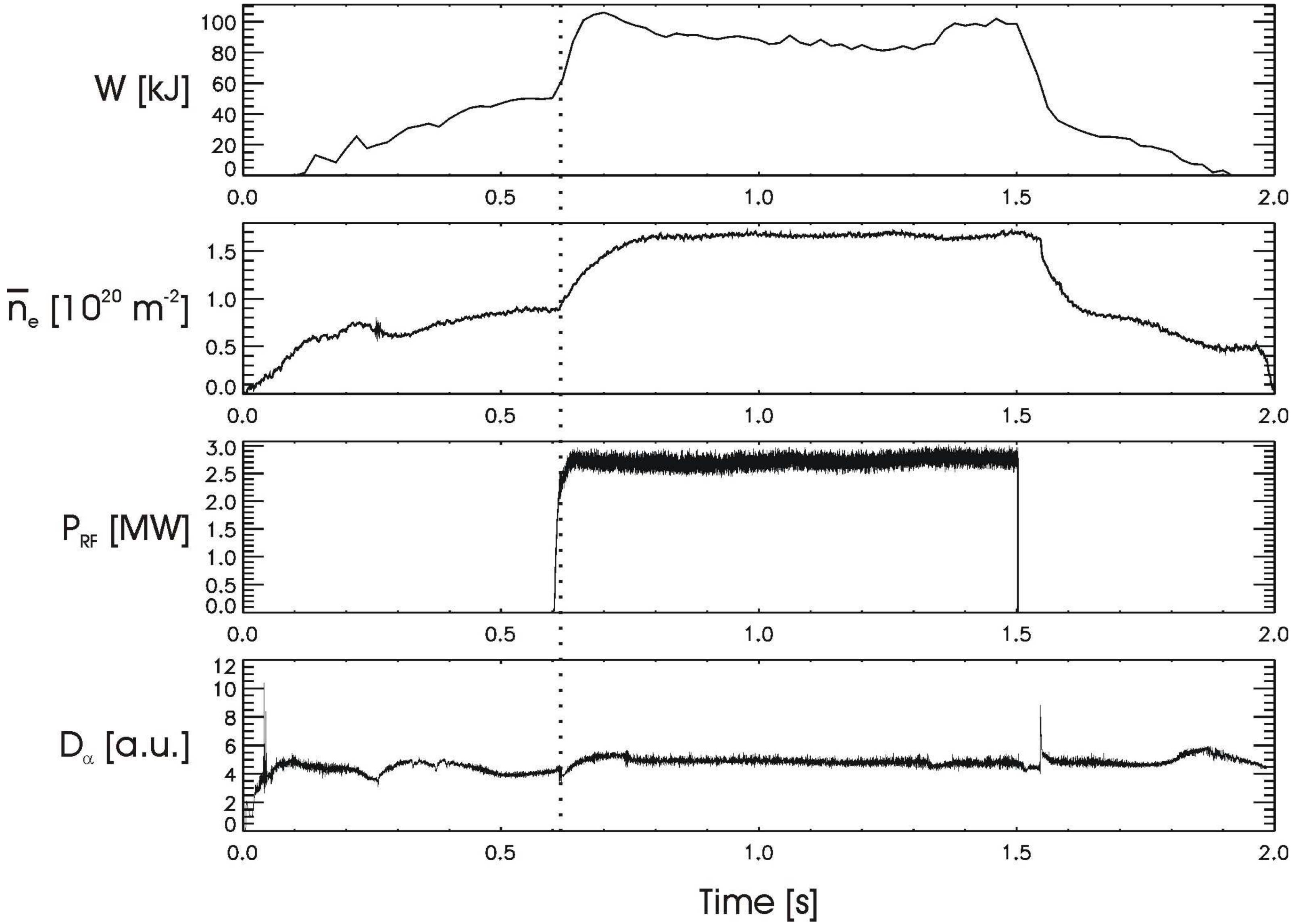


- Measures line integrated electron density fluctuations along 32 vertical chords.
- Sensitive to turbulence from 0.6 to 16.8 cm^{-1}.
- Radiation source is a 25 W CO_2 laser, wavelength 10.6 μm.
- A phase plate converts phase fluctuations to intensity fluctuations.
- Detector is a LN_2 cooled linear array of photoconductive elements.

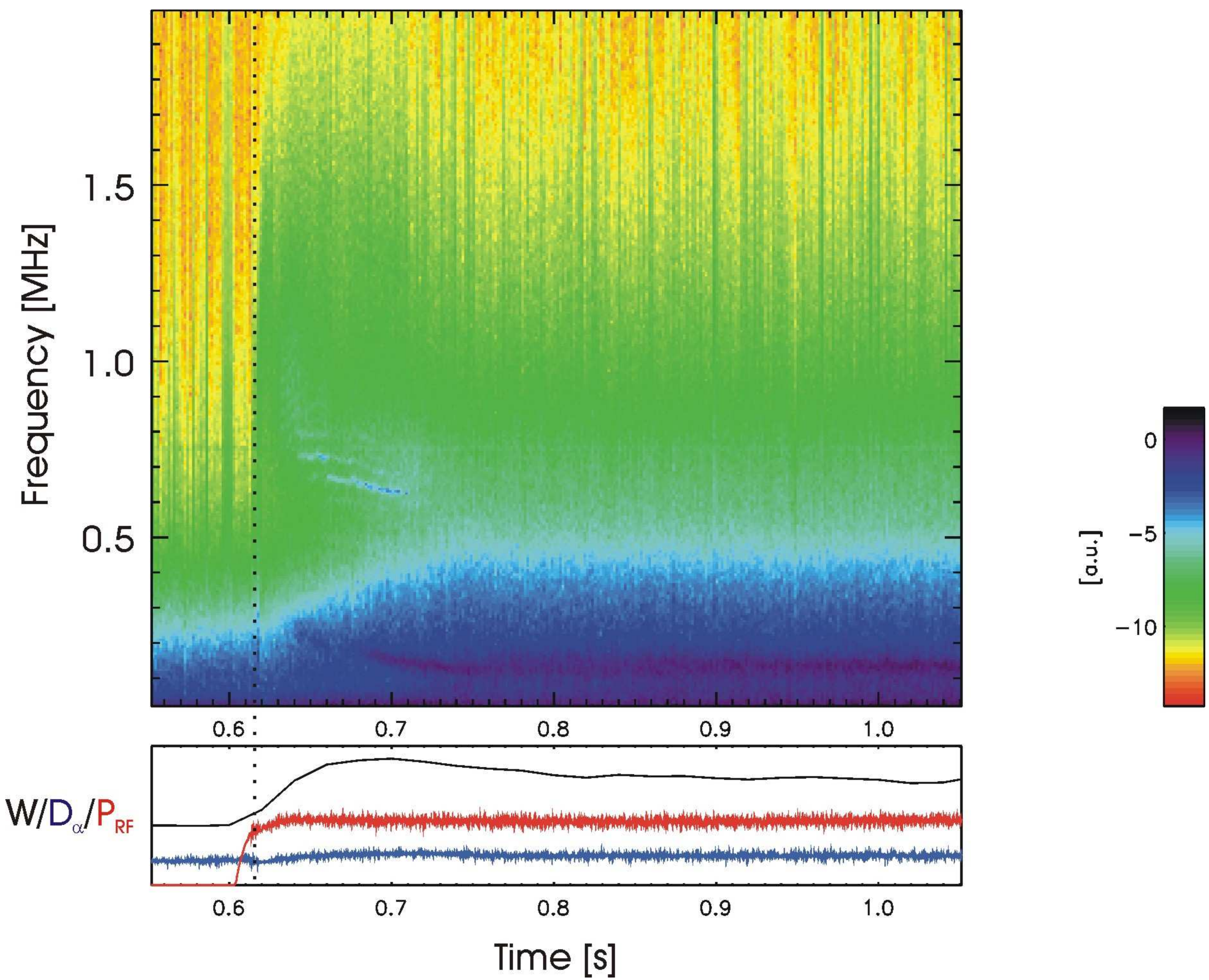
- D_α-light diode viewing inner wall.
- Poloidal magnetic field probe on outboard limiter.

L- to EDA H-mode transition

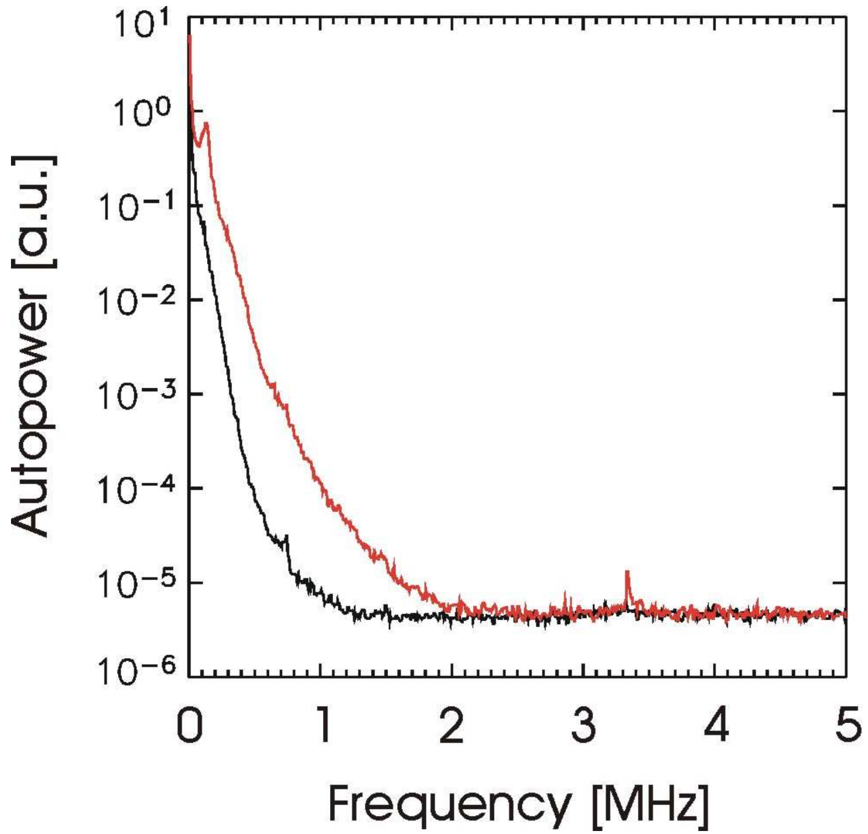
shot 1040310007



Spectrogram
core channel

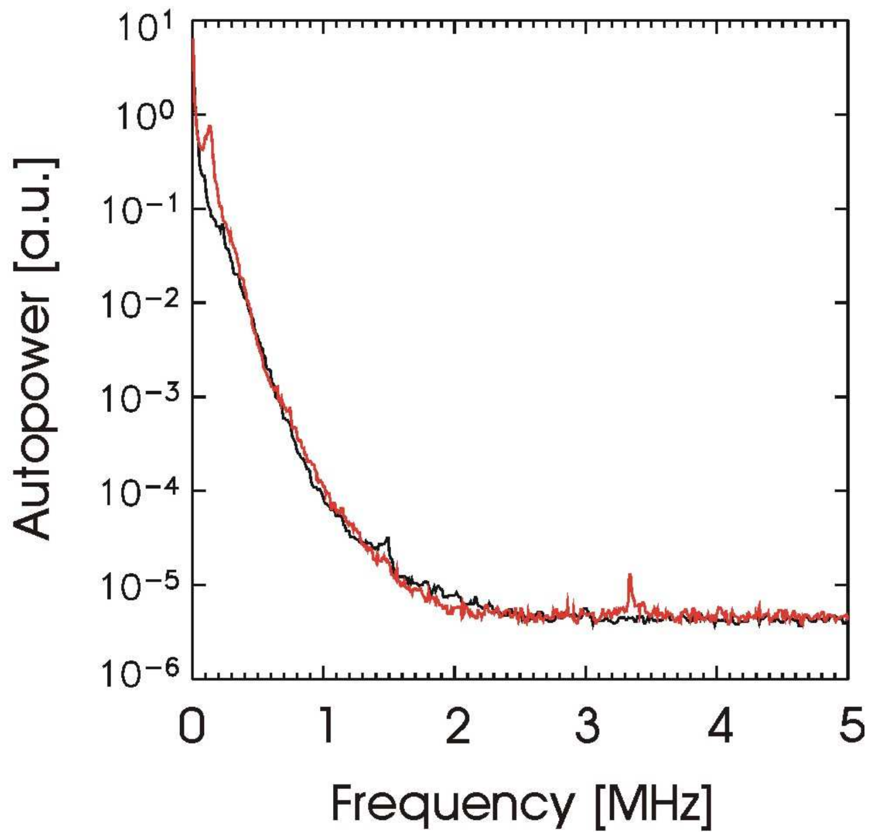


Autopower spectra
core channel



Black is L-mode

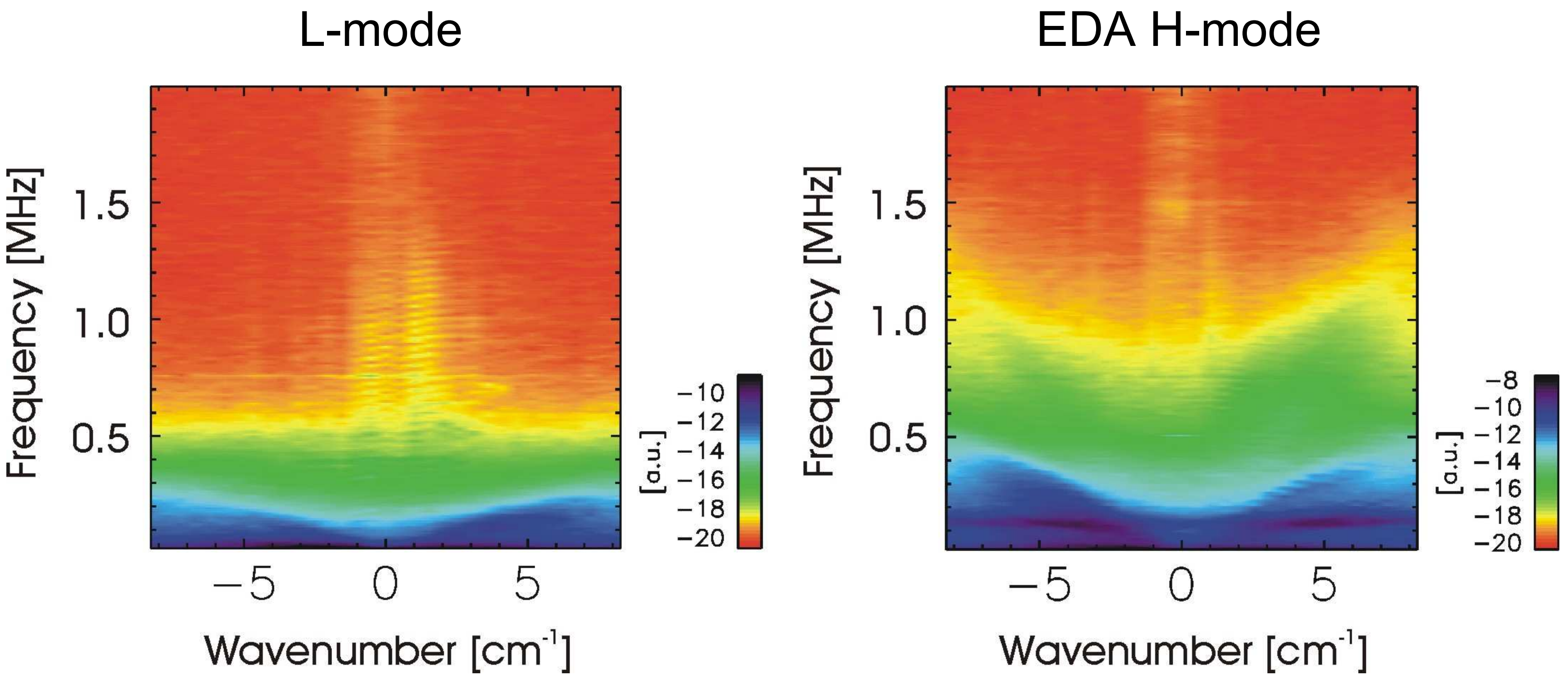
Red is EDA H-mode



Black is L-mode,
frequencies multiplied by two.

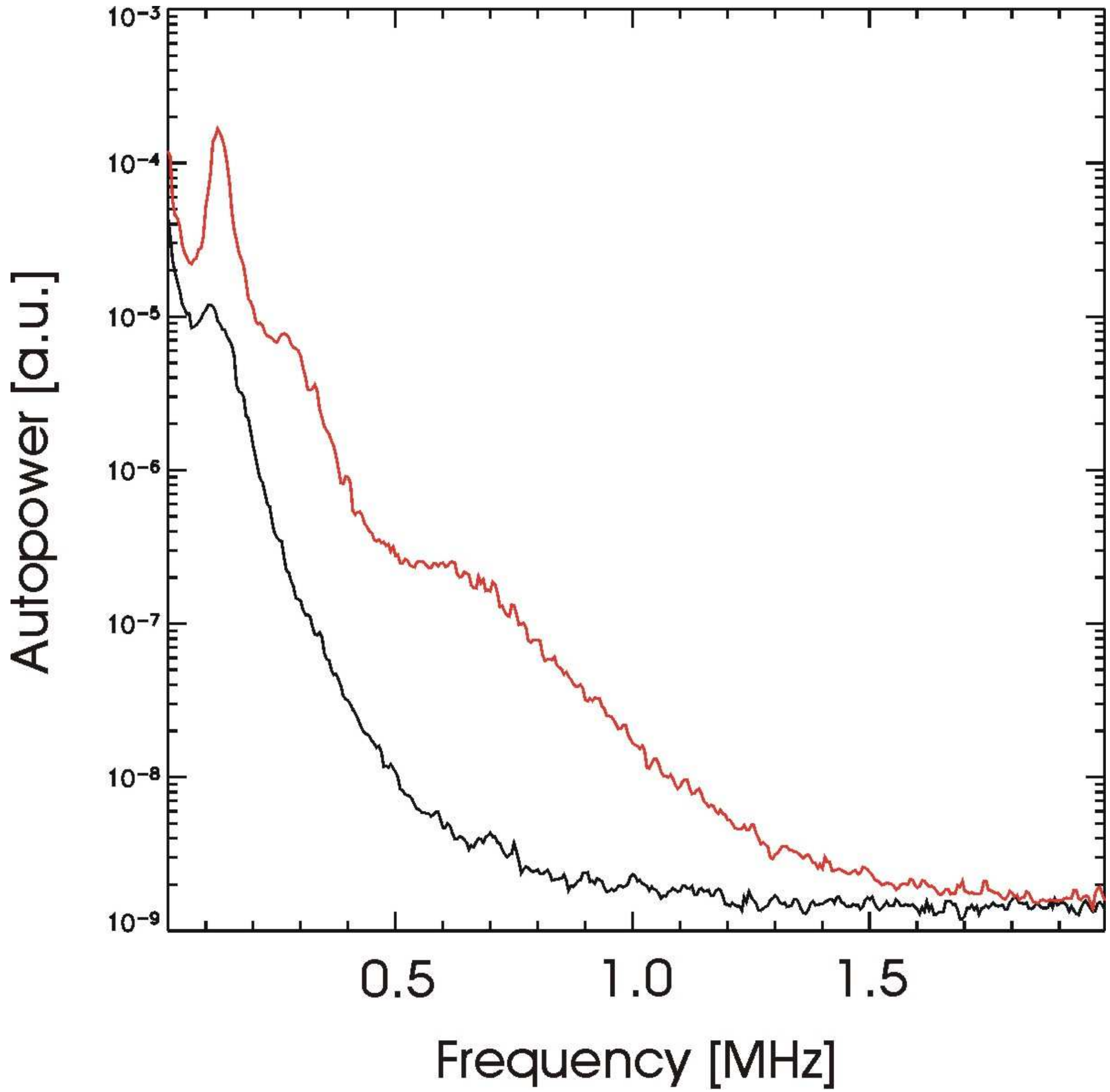
Red is EDA H-mode

Frequency-wavenumber spectra



- By performing 2D Fourier transforms on the PCI data from all 32 channels, we arrive at frequency-wavenumber spectra.
- The largest increase in frequency coverage from L- to EDA H-mode is at large wavenumbers.
- Negative (positive) wavenumbers are due to fluctuations travelling outward (inward) parallel to the major radius.

Autopower spectra
all channels

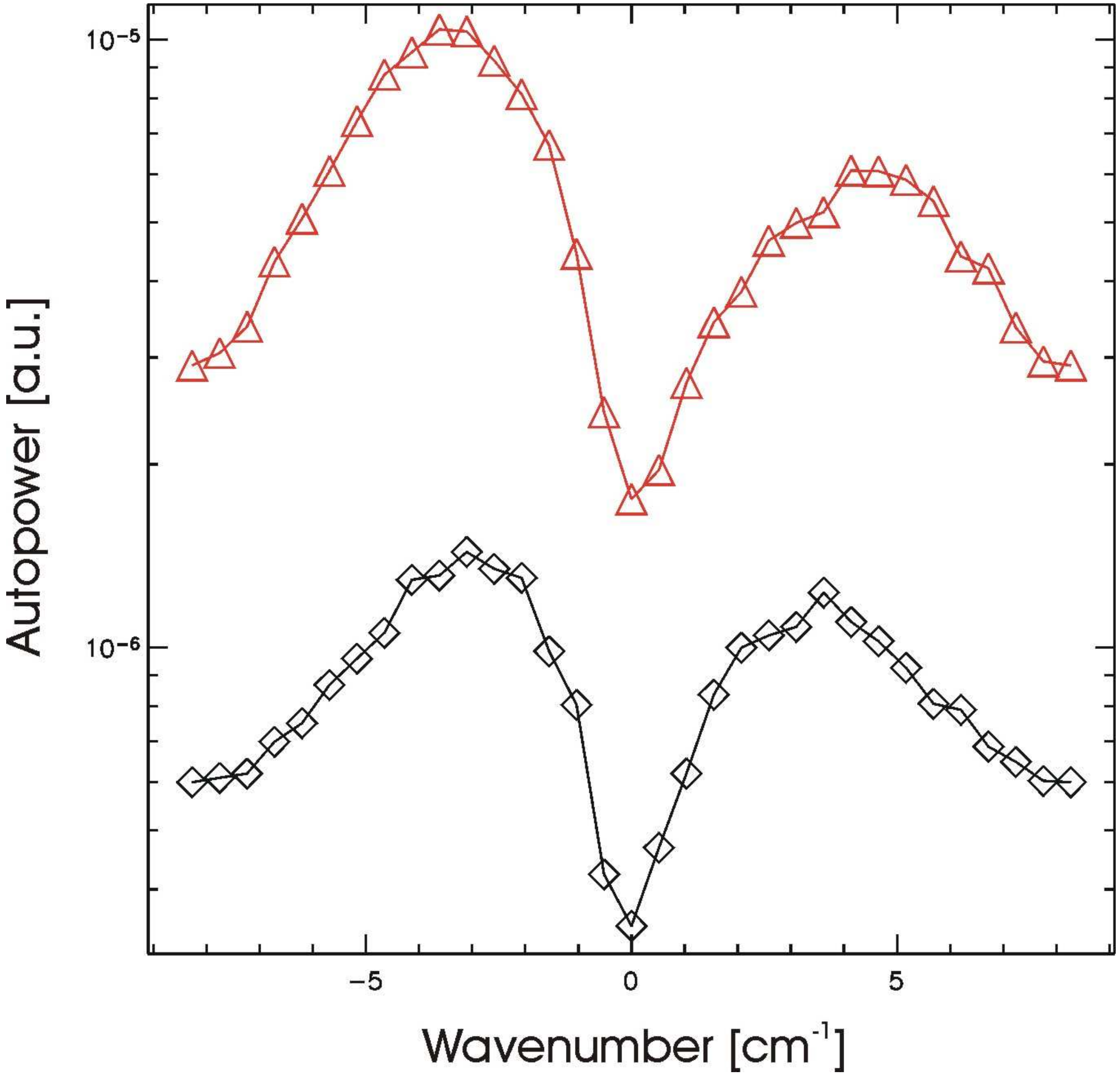


Wavenumber is 4.7 cm^{-1}

Black is L-mode

Red is EDA H-mode

Autopower-wavenumber spectra

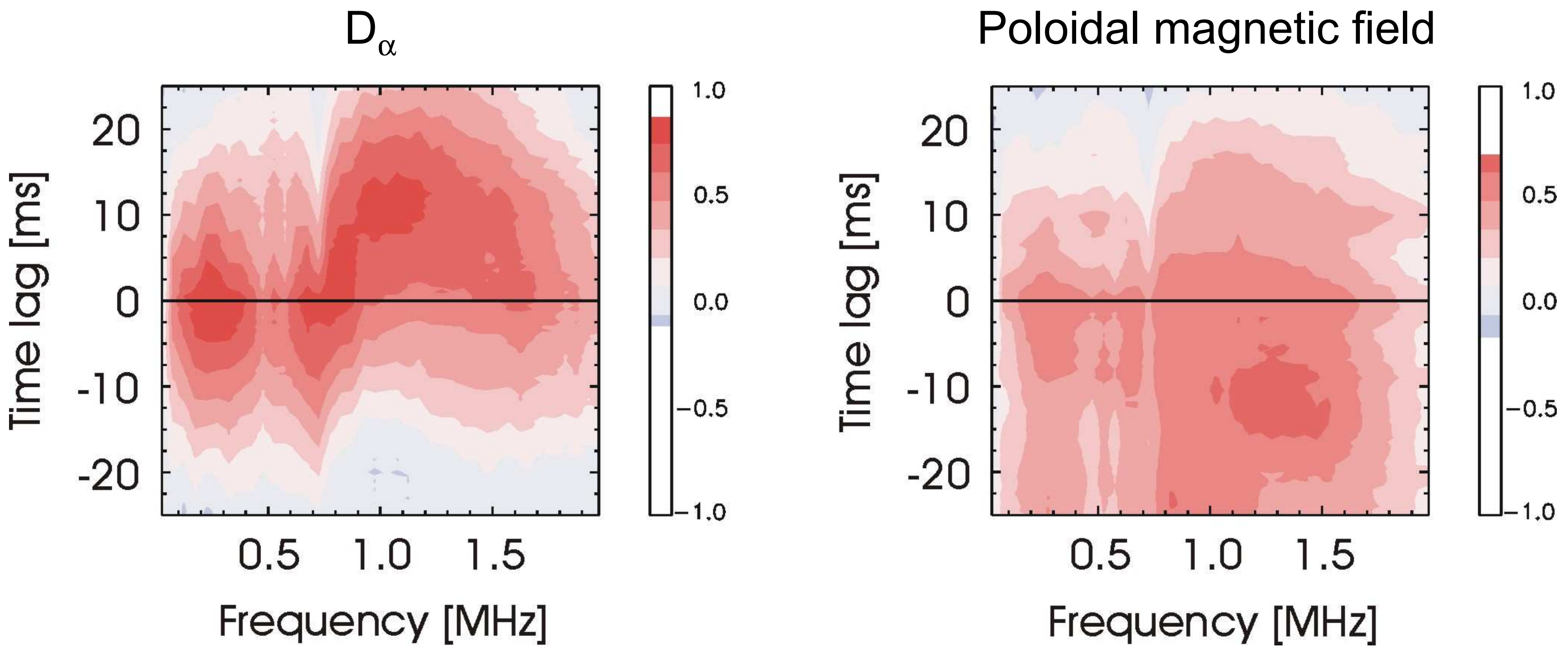


Integrating fluctuations over all frequencies we can plot wavenumber spectra for L- and EDA H-mode.

Black diamonds are L-mode.

Red triangles are EDA H-mode.

Correlation
between PCI and D_α/poloidal magnetic field

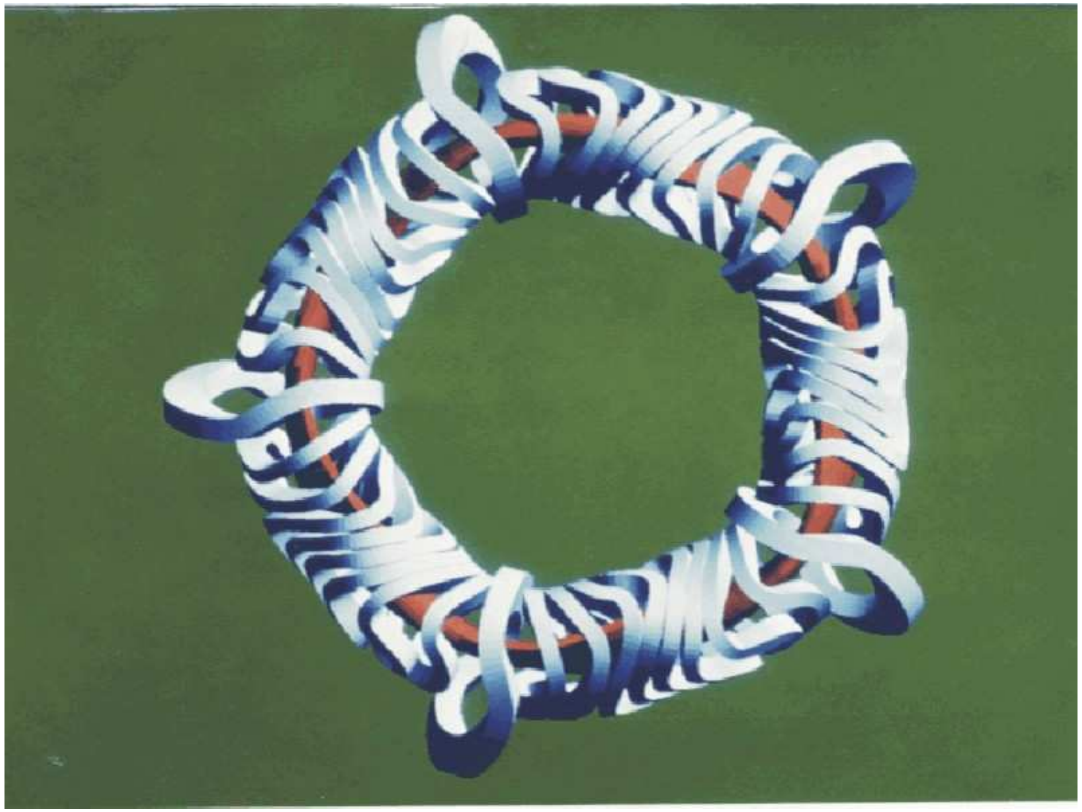


Cross correlation between rms D_α/poloidal magnetic field fluctuations and PCI band autopowers. Band autopower resolution 50 kHz, time resolution 0.5 ms.

Positive (negative) time lag:
PCI fluctuations occur before (after) the D_α/poloidal magnetic field fluctuations.

Wendelstein mountain
(1838 m)

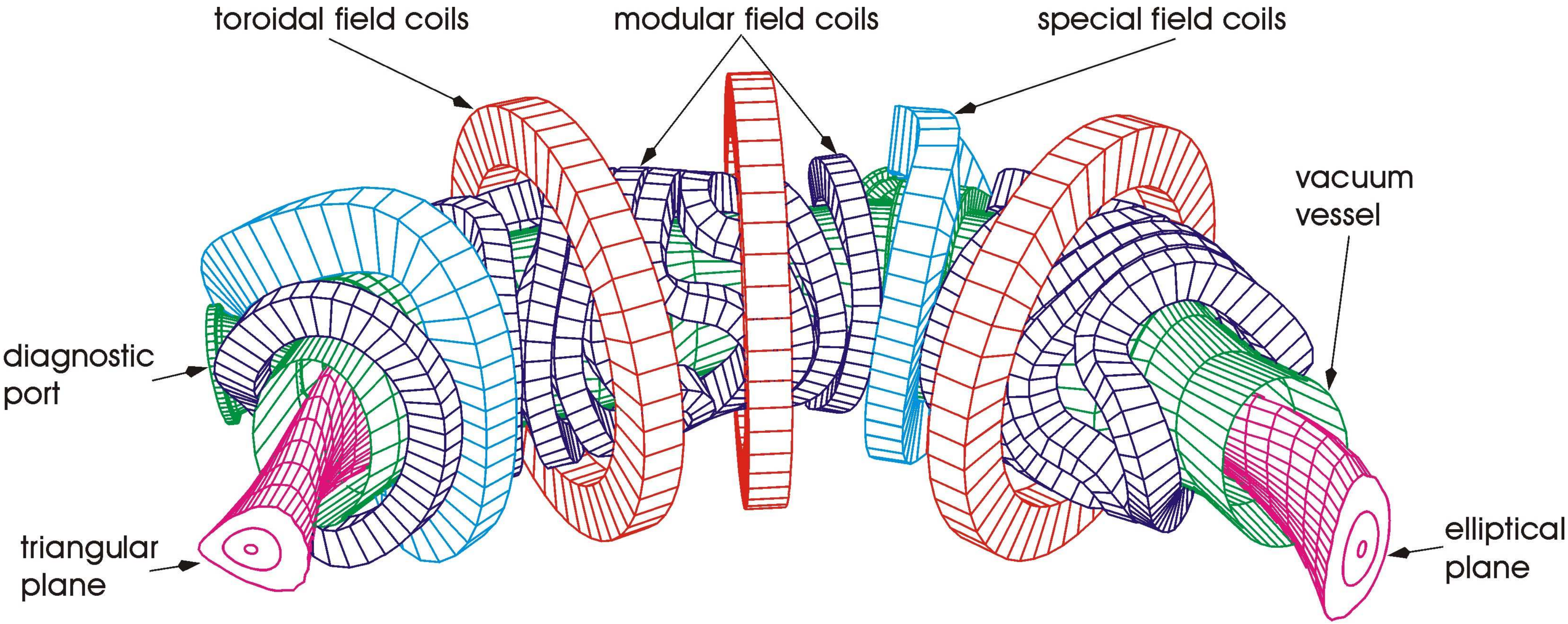
Wendelstein 7-AS stellarator



- Concept proposed by Lyman Spitzer, Jr., at Princeton in 1951.
- W7-AS operation 1988-2002.
- 45 modular coils create the confining magnetic field.
- 10 planar coils and vertical field coils allow experimental flexibility.
- $B_t \leq 2.5$ T.

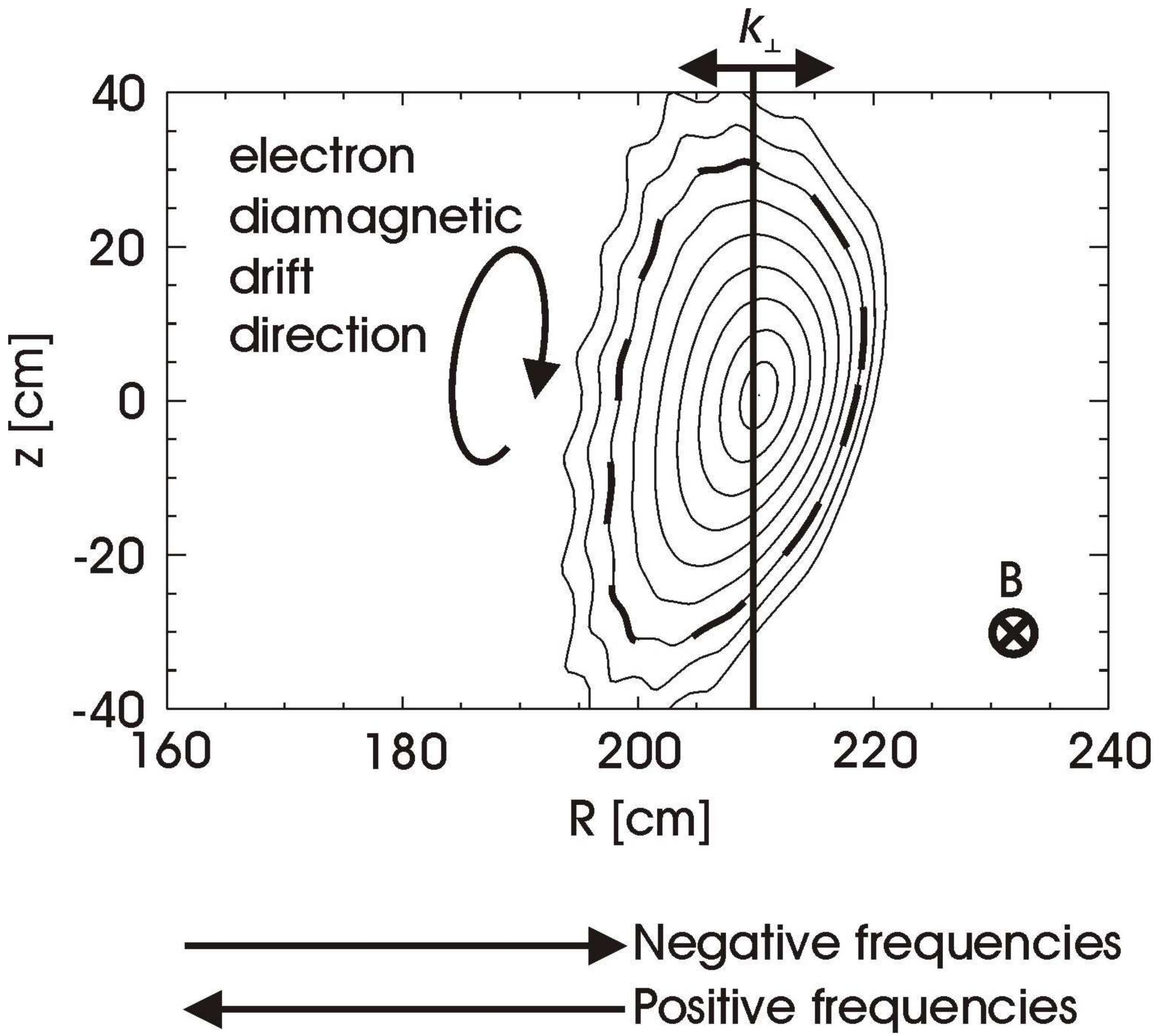
Wendelstein 7-AS stellarator

Alcator C-Mod



- R = 2 m, a $\leq$ 0.18 m.
- Flux surfaces are elliptical in the corners and triangular in the straight sections (non-axisymmetric).

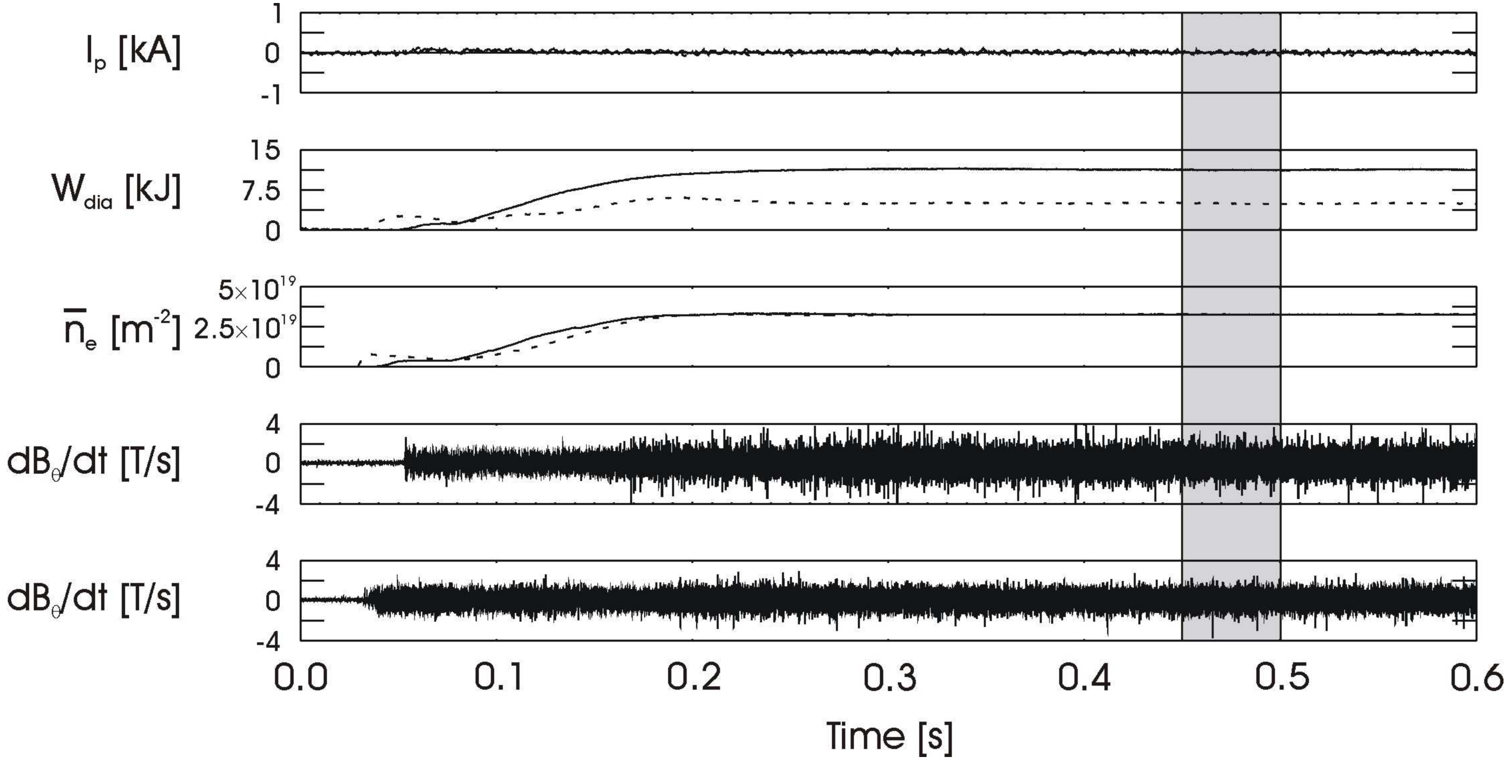
Small-angle scattering



- Measures line integrated electron density fluctuations along 2, spatially separated, vertical chords.
- Fixed wavenumber can be set from 14 to 62 cm^{-1}(in this case set to 15 cm^{-1}).
- Radiation source is a 20 W CO_2 laser, wavelength 10.6 μm.
- Two crossed, frequency shifted, beams define the measurement volumes.
- Detectors are two room temperature photoconductive elements.

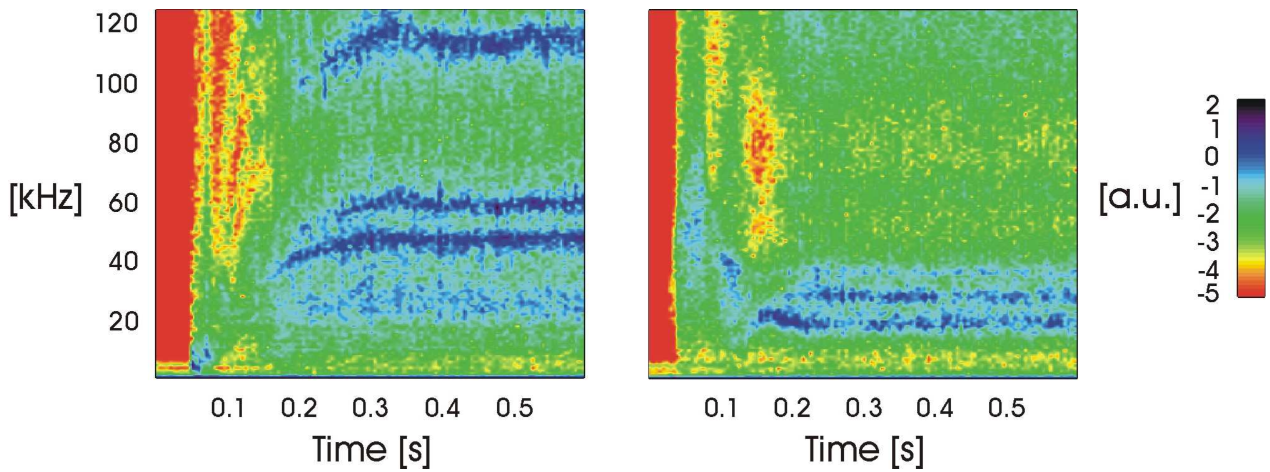
Controlled confinement transition

shots 47941 and 47944

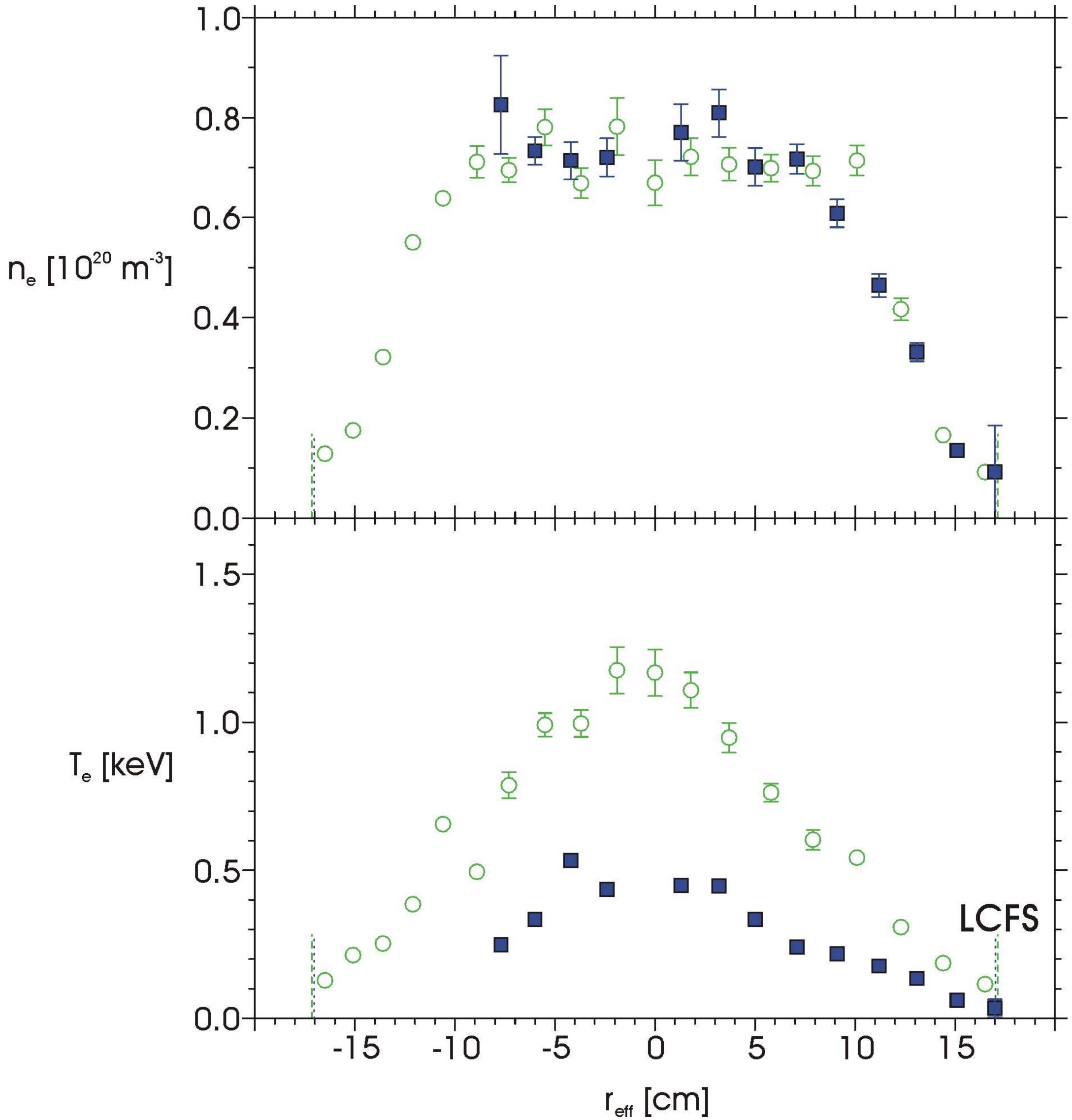


Left-hand plot:
Good confinement

Right-hand plot:
Bad confinement



Density and temperature profiles

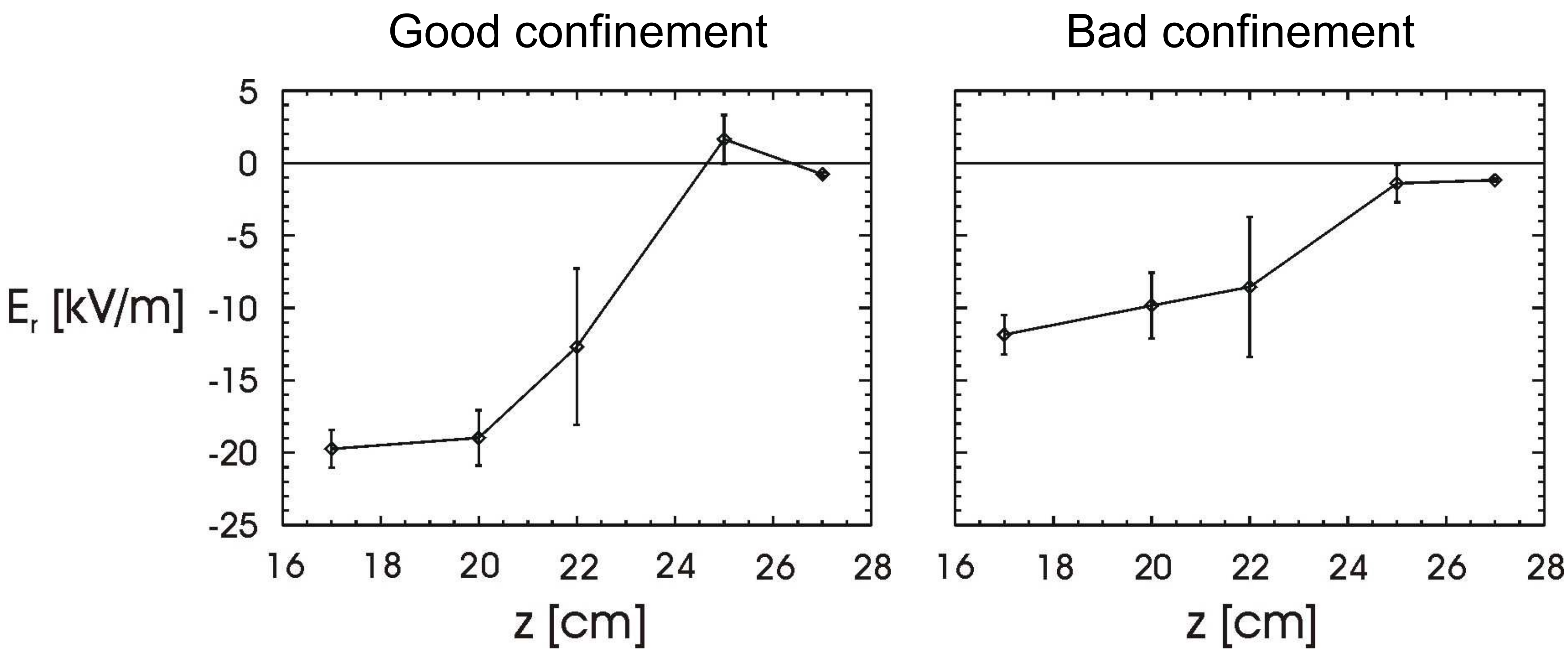


- ι_a (good) = 0.34
- ι_a (bad) = 0.36
- Confinement transition is due to a collapse of the temperature profile.
- Empirical model has been proposed where the electron heat conductivity has three terms:

  1. Neoclassical
  2. Anomalous
  3. Rational surface

- Open green dots are good confinement
- Solid blue squares are bad confinement

Radial electric field profiles

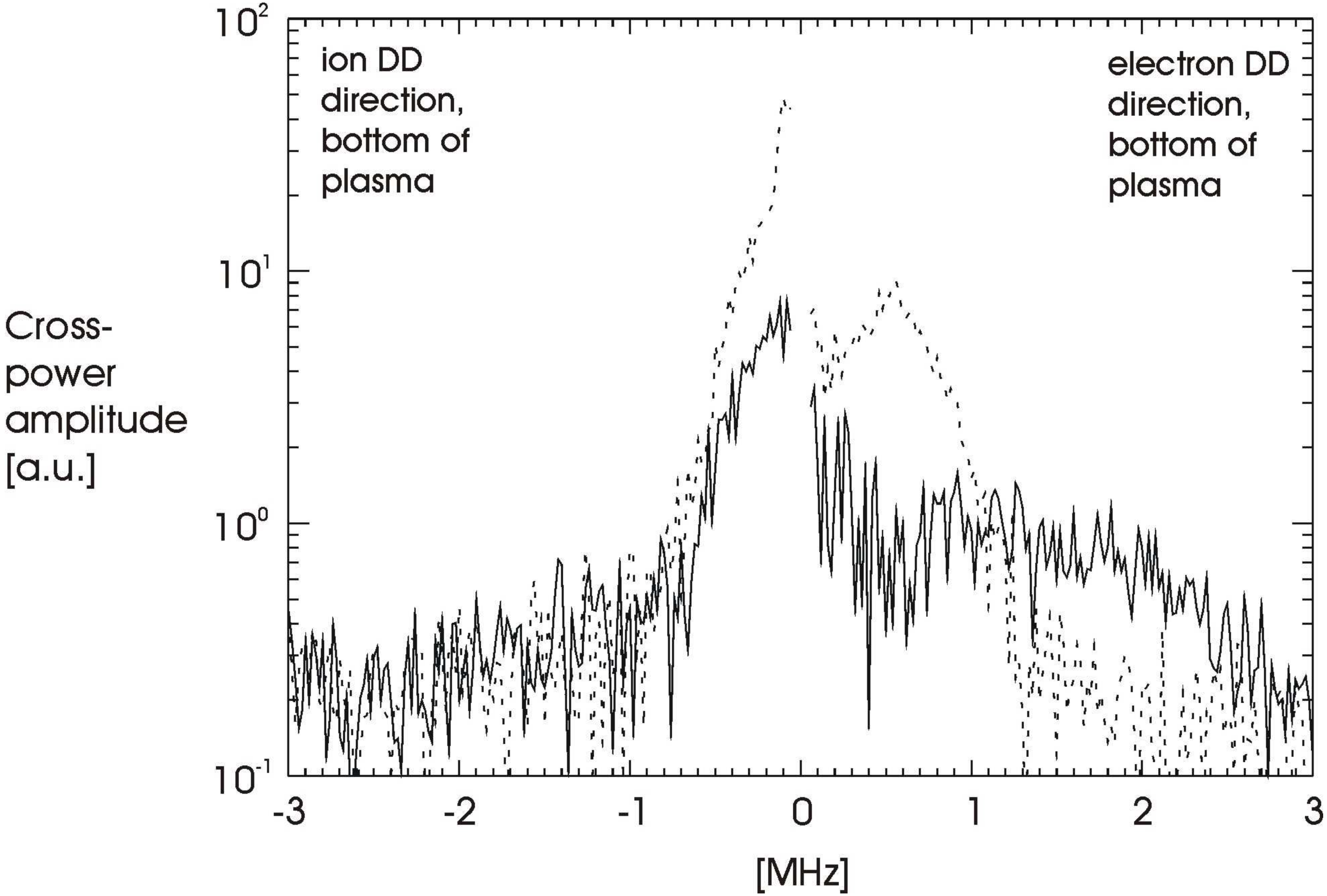


The Doppler shift is in the electron (ion) diamagnetic drift direction inside (outside) the separatrix.

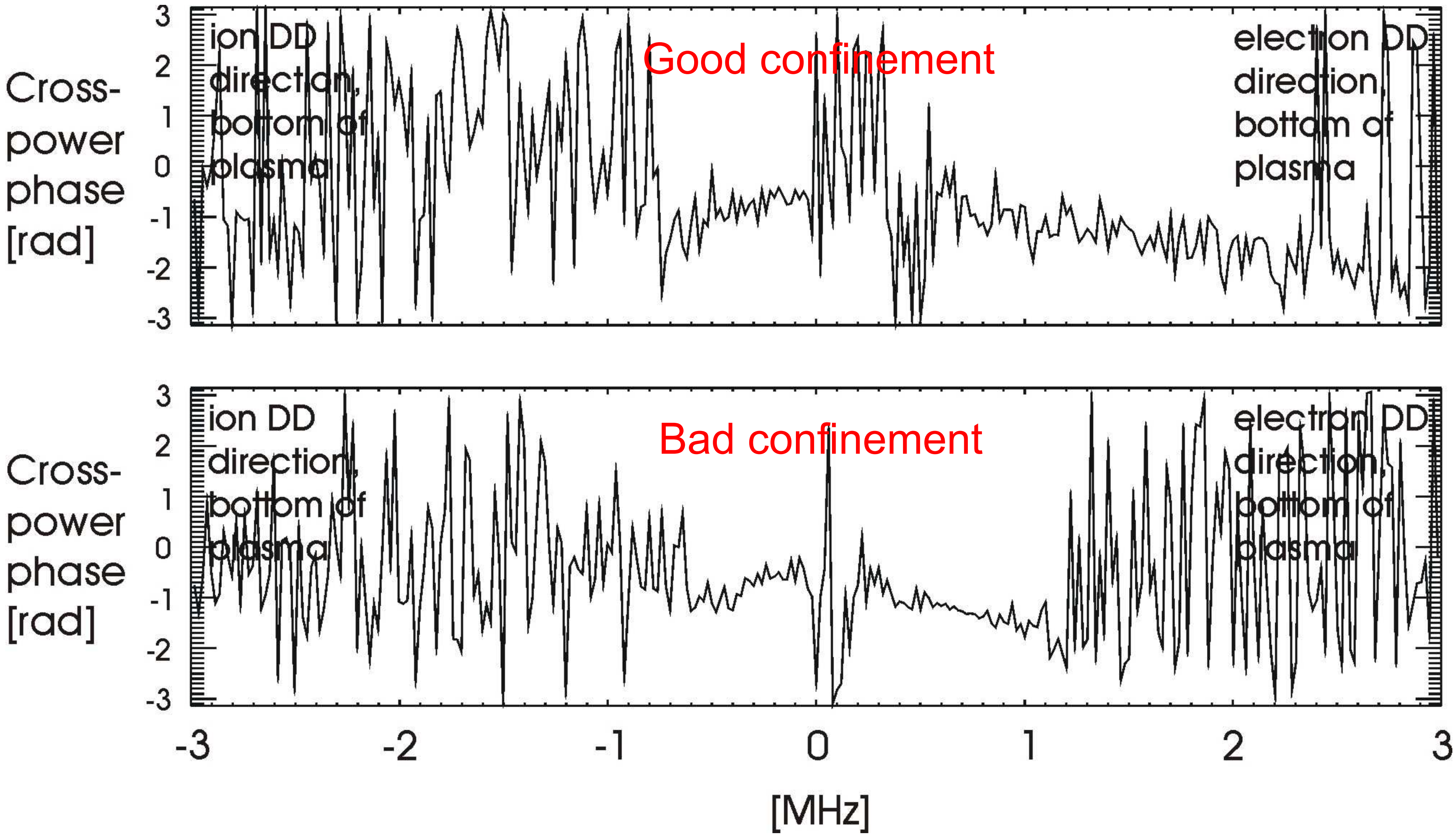
Both the shear and absolute value of the radial electric field inside the separatrix are larger for good confinement.

Crosspower amplitude

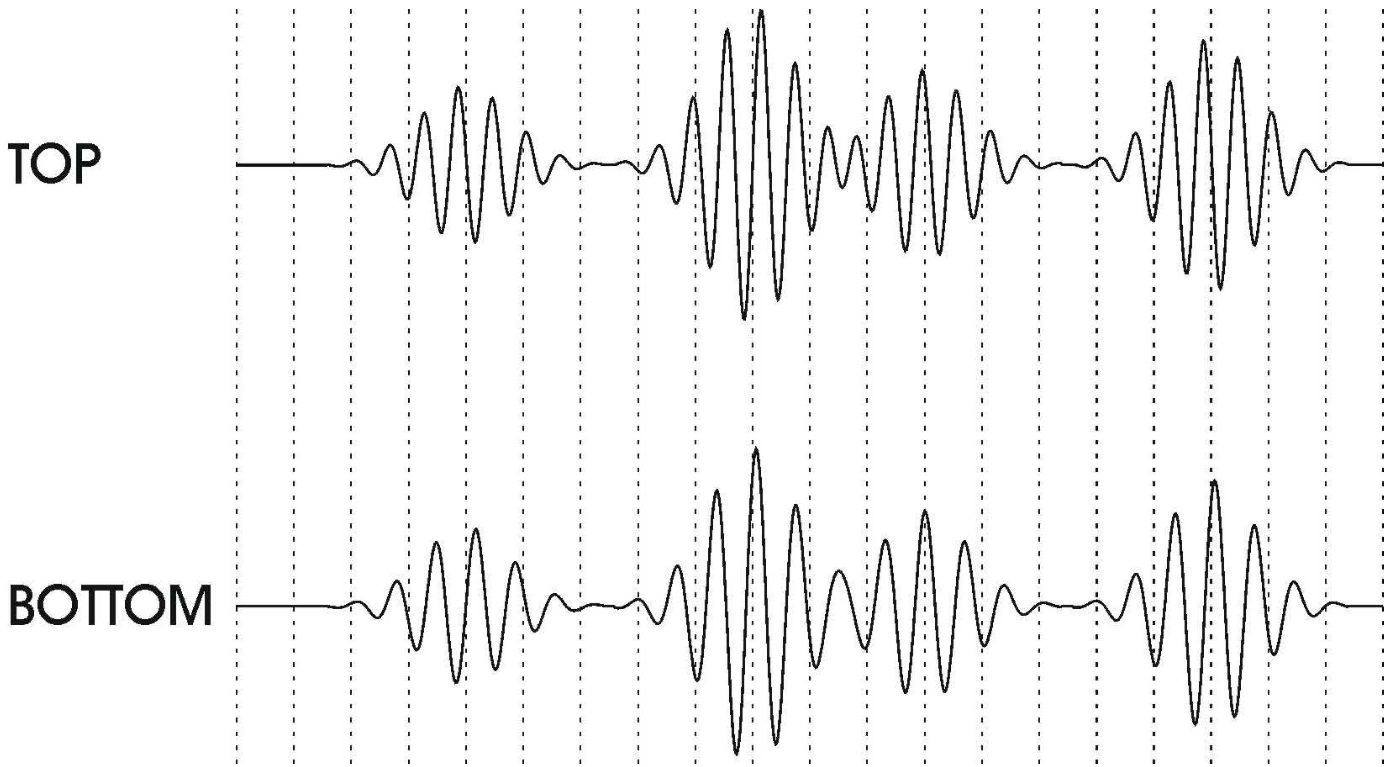
Solid line is good confinement
Dashed line is bad confinement



Crosspower phase

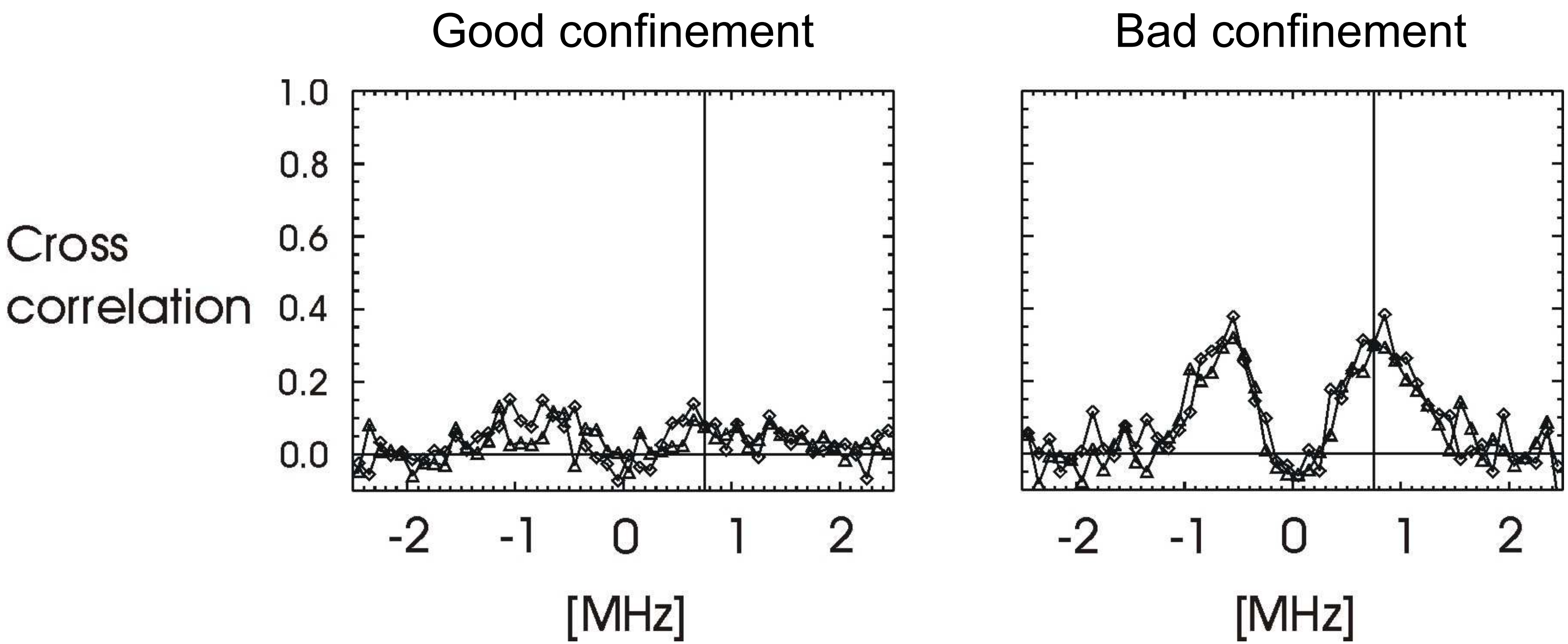


Band autopower correlation



The frequency of the signal at the top is slightly different from the frequency at the bottom, but their amplitude is modulated in a completely correlated way. These two signals exhibit zero correlation (due to their different frequencies) but display high band autopower correlation.

Cross correlation at zero time lag

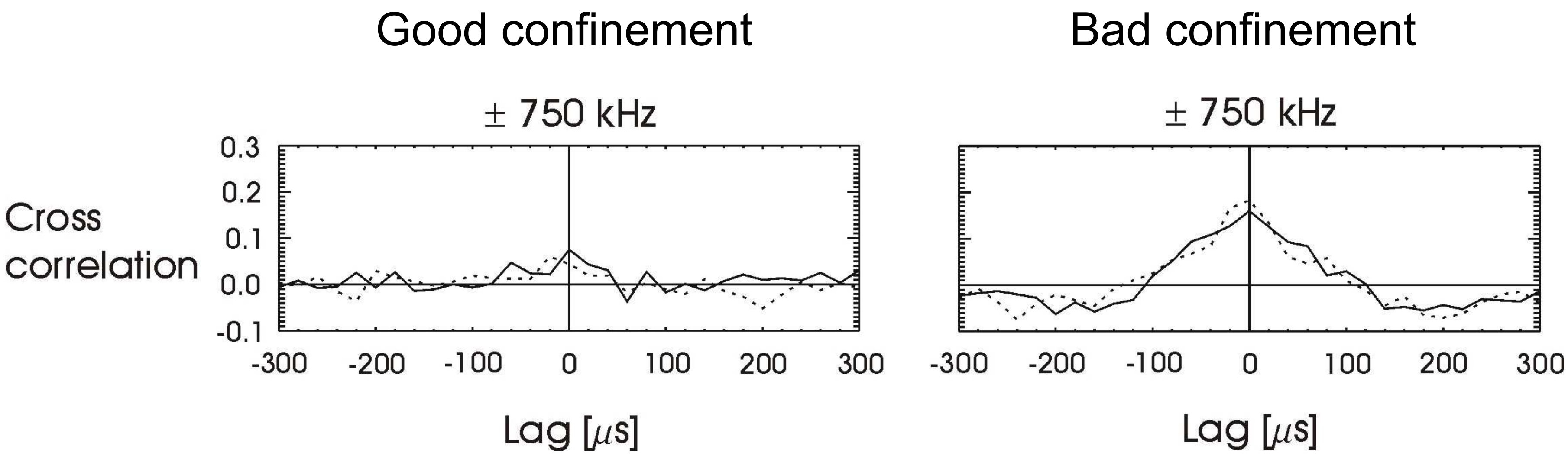


Diamonds: Cross correlation at zero time lag between reference band autopower [700,800] kHz, volume 2, and band autopowers in volume 1.

Triangles: Cross correlation with the volumes switched.

Cross correlation vs time lag

Alcator C-Mod

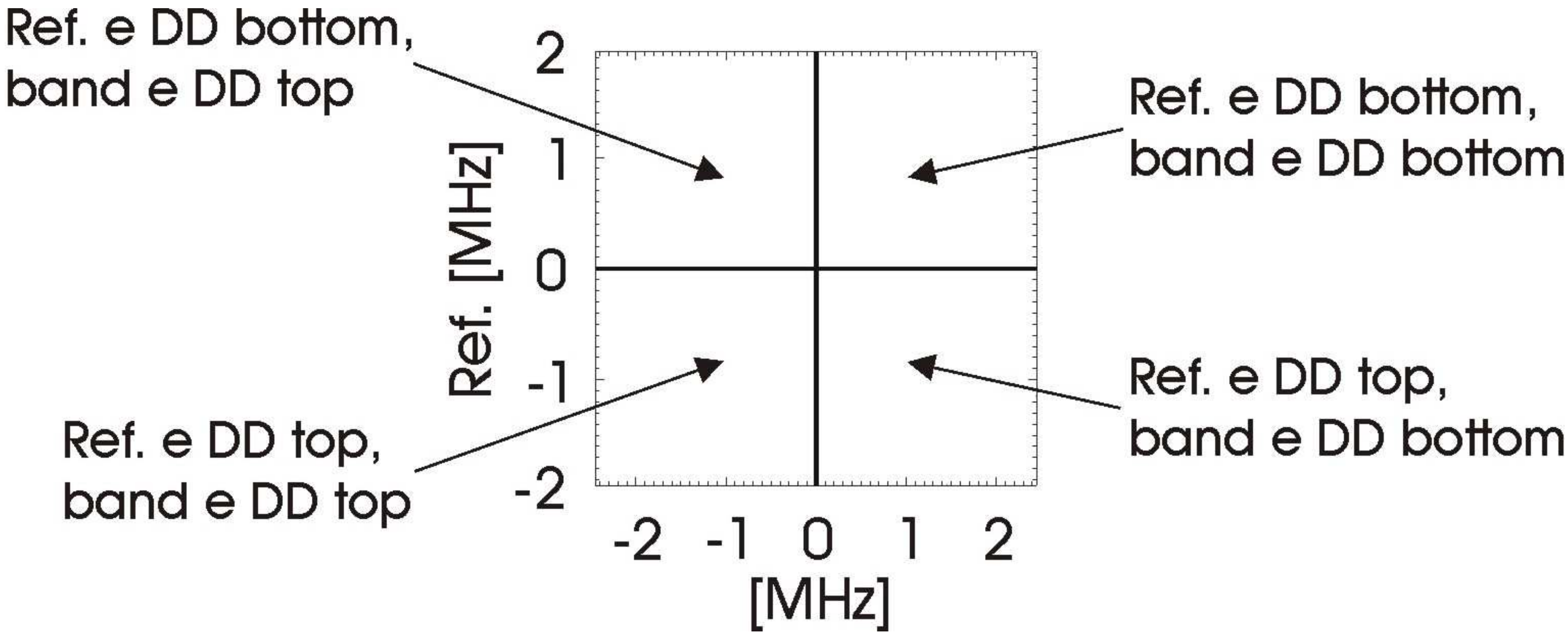


Cross correlation between density fluctuation band autopowers vs time lag (units of 20 μs).

Solid lines: Cross correlation between [700,800] kHz, volume 1, and [-800,-700] kHz, volume 2.

Dashed lines: Cross correlation with the volumes switched.

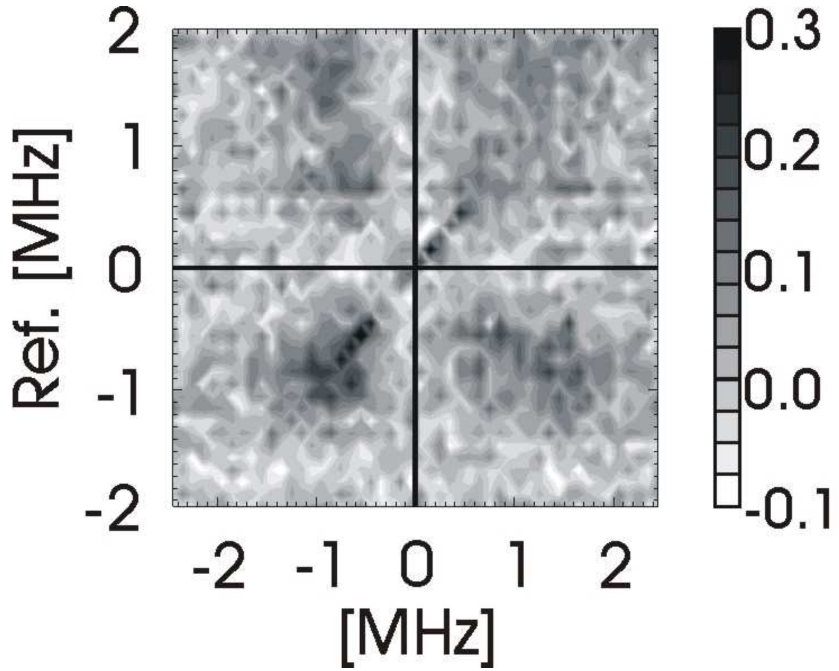
2D cross correlation explanation



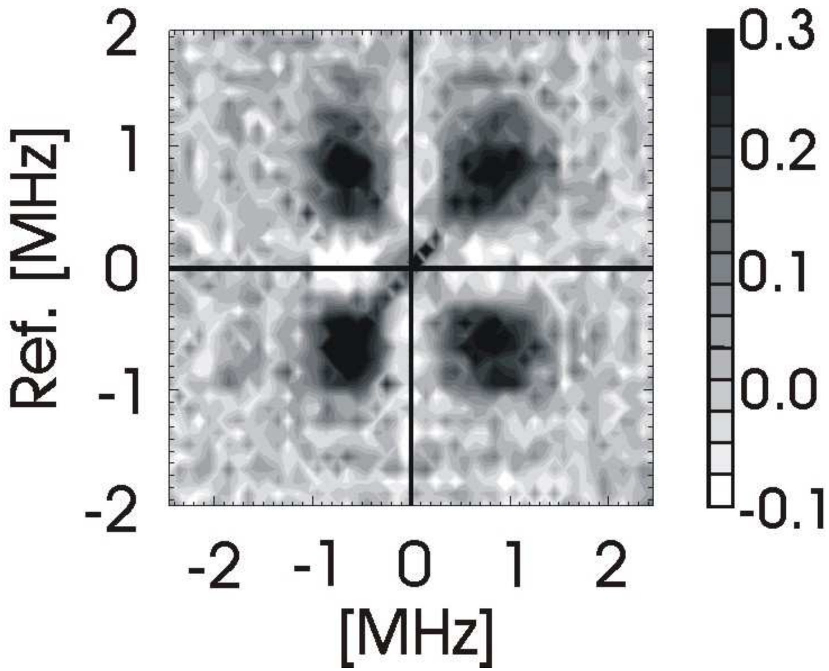
We assume that the correlations observed in the previous two figures are due to fluctuations travelling in the electron diamagnetic drift direction. Combining this with the conventions of the small-angle scattering diagnostic, we conclude that correlations in each quadrant of the grid shown originate from different fluctuation components.

2D cross correlation results

Good confinement

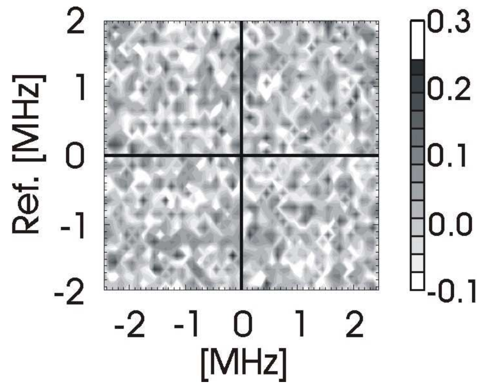


Bad confinement



Cross correlation between reference band autopowers, volume 2, and band autopowers in volume 1.

Background data



Conclusions

•We have in this talk presented an analysis of turbulence at confinement transitions in C-Mod and W7-AS.

L- EDA H-mode transition in C-Mod:

•PCI has been upgraded from 12 to 32 channels, sampling rate from 1 to 10 MHz

•Changes in broadband turbulence averaged over wavenumbers can be explained by Doppler shift (exception: Single wavenumbers)

•Cross correlations with other fluctuations show two features separated in frequency

Controlled confinement transition in W7-AS:

•The electron diamagnetic drift feature is modulated at the top and bottom of the plasma in a correlated way

•The fluctuation amplitude is modulated on an entire flux surface

•It is not clear whether this modulation causes local profile flattenings (ELM-like phenomena) or if it is simply a consequence of the flattening by some other mechanism