Measurements and analysis of turbulence in fusion plasmas

Nils P. Basse
Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139
USA

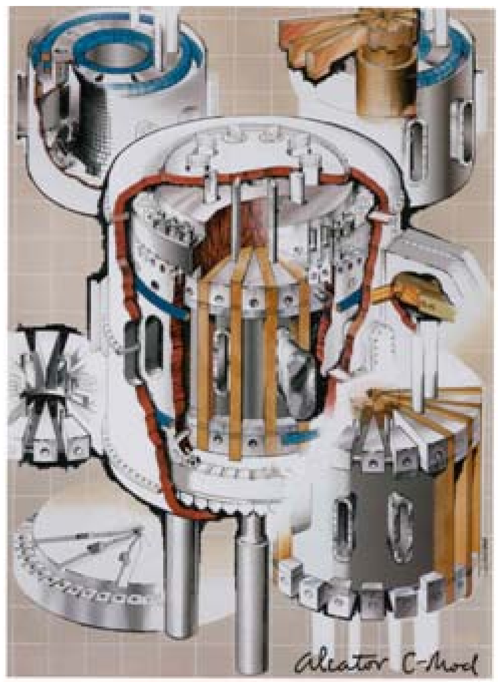

ABB seminar
November 7th, 2005

Curriculum vitae

1. 2002-2005: Postdoctoral Associate at the Massachusetts Institute of Technology, USA
2. 1999-2002: Ph.D. in physics from the Niels Bohr Institute at the University of Copenhagen, Denmark, including a total of two years work at IPP-Garching, Germany. The title of my Ph.D. thesis is: 'Turbulence in Wendelstein 7-AS plasmas measured by collective light scattering'.
3. 1996-1998: M.Sc. in physics from the Niels Bohr Institute at the University of Copenhagen, Denmark, including a one-year stay at JET, England, where I made my Master's thesis.
4. 1993-1996: B.Sc. in physics (mathematics 2nd topic) from the Niels Bohr Institute at the University of Copenhagen, Denmark

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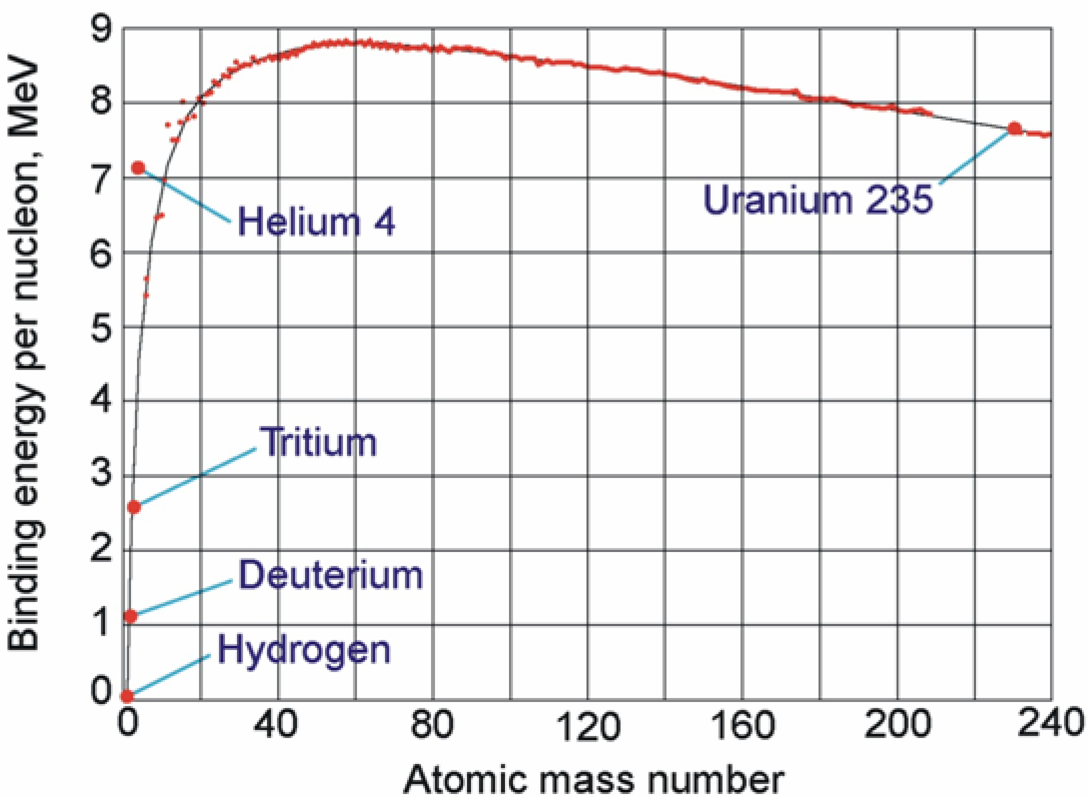
Outline

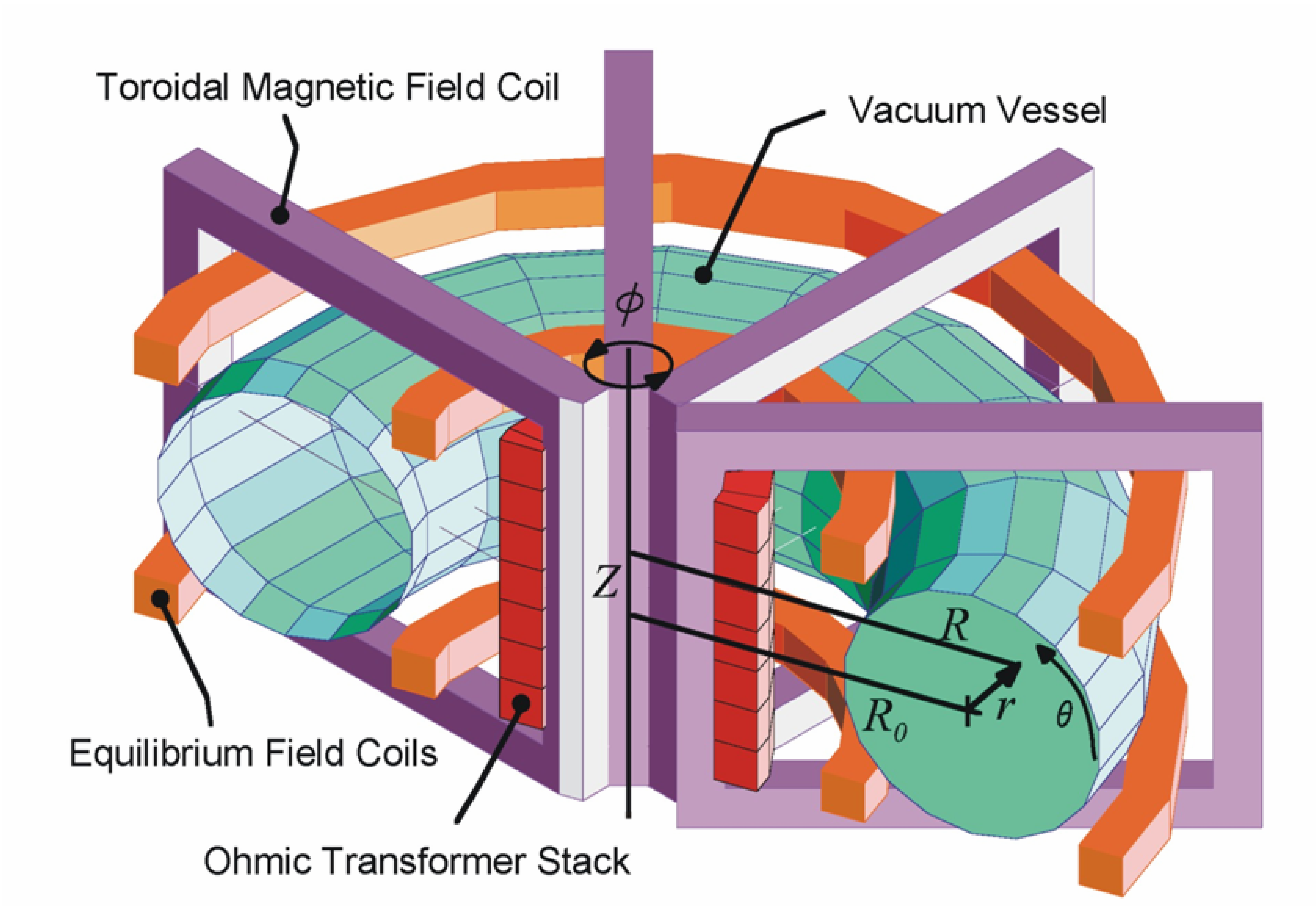
- Fusion energy
- The Alcator C-Mod tokamak
- Anomalous transport
- The phase-contrast imaging (PCI) diagnostic
- The low (L) and high (H) confinement modes
- Analysis of turbulence in L- and H-mode

Fusion energy

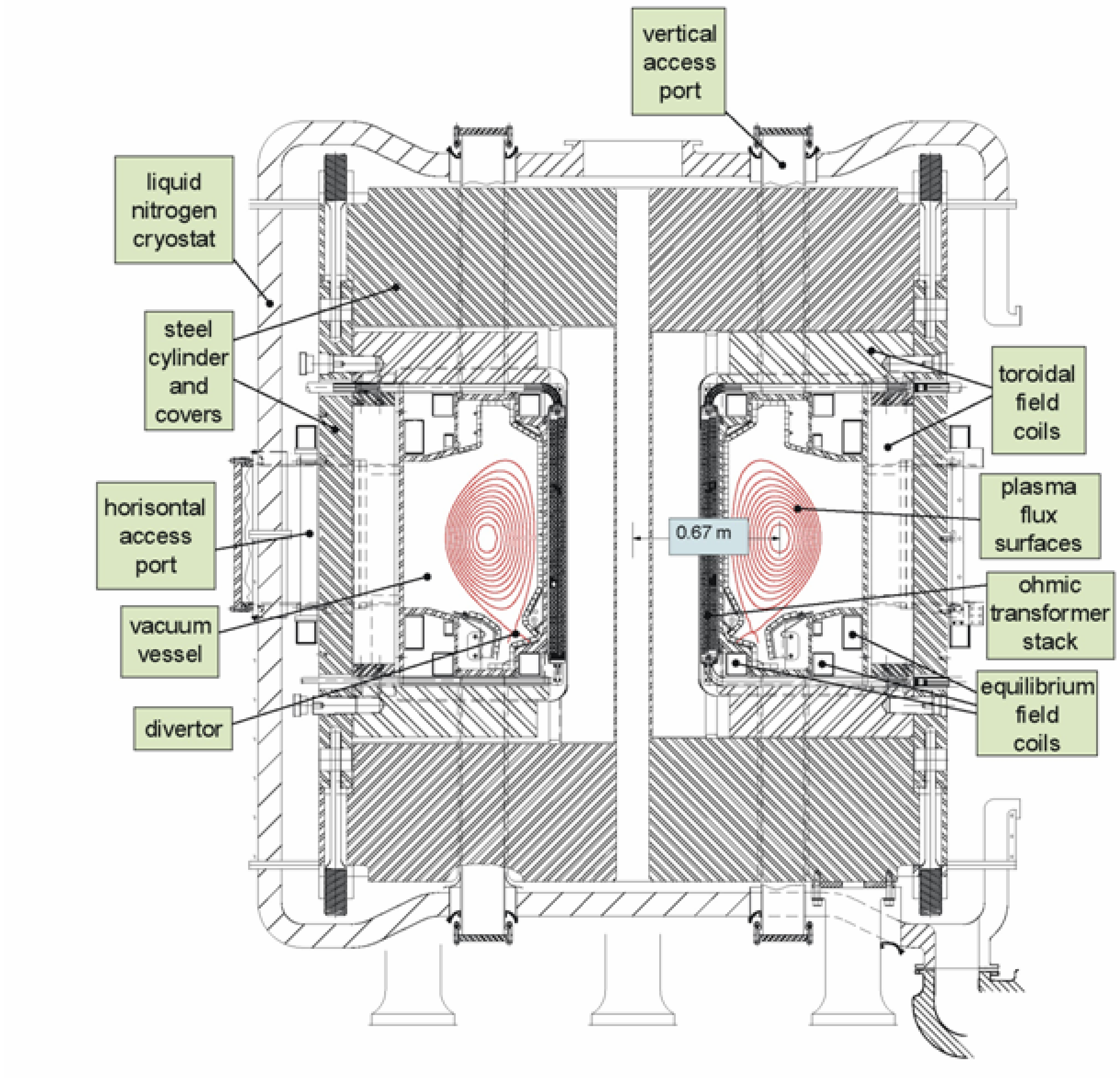


- Candidate fusion reactions on Earth:
- D+T $\rightarrow$ ^{4}He (3.5 MeV) + n (14.1 MeV)
- D+D $\rightarrow$ ^{3}He (0.82 MeV) + n (2.45 MeV)

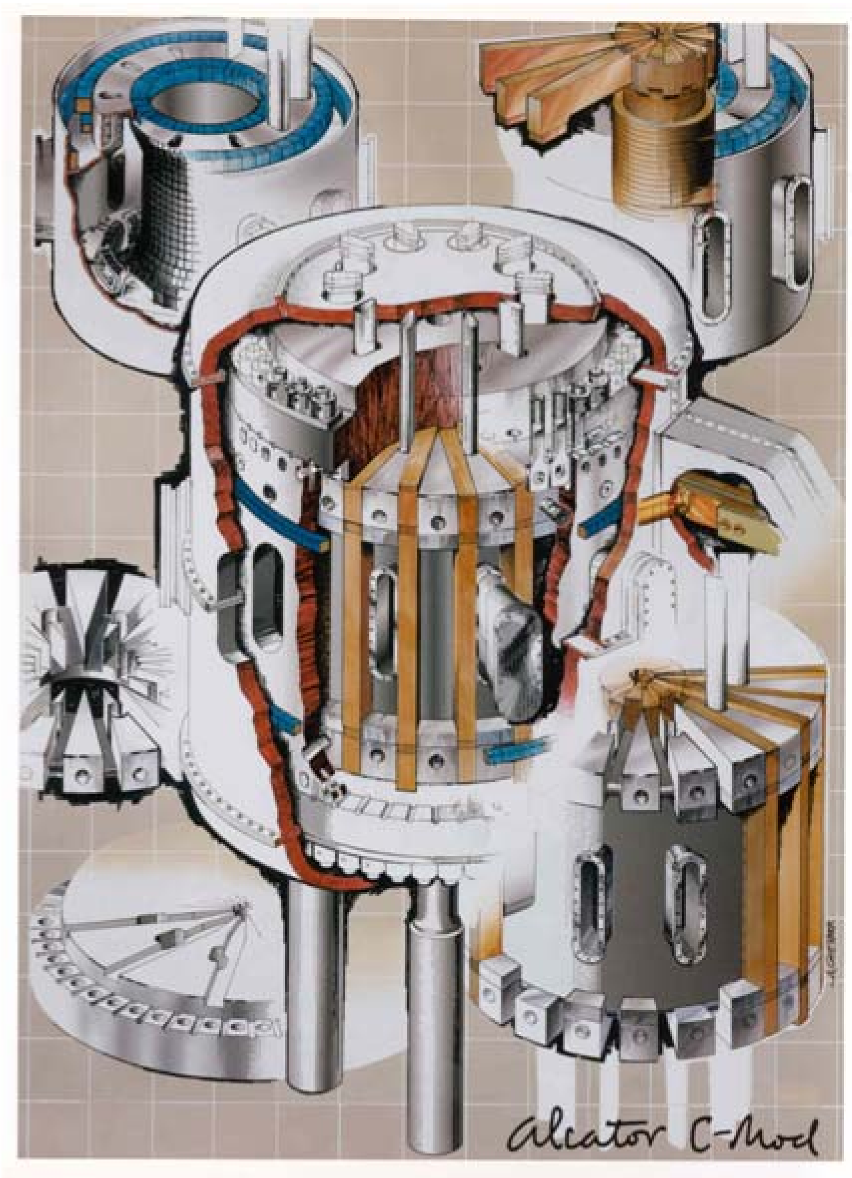
Alcator C-Mod tokamak concept



C-mod structure



C-Mod facts



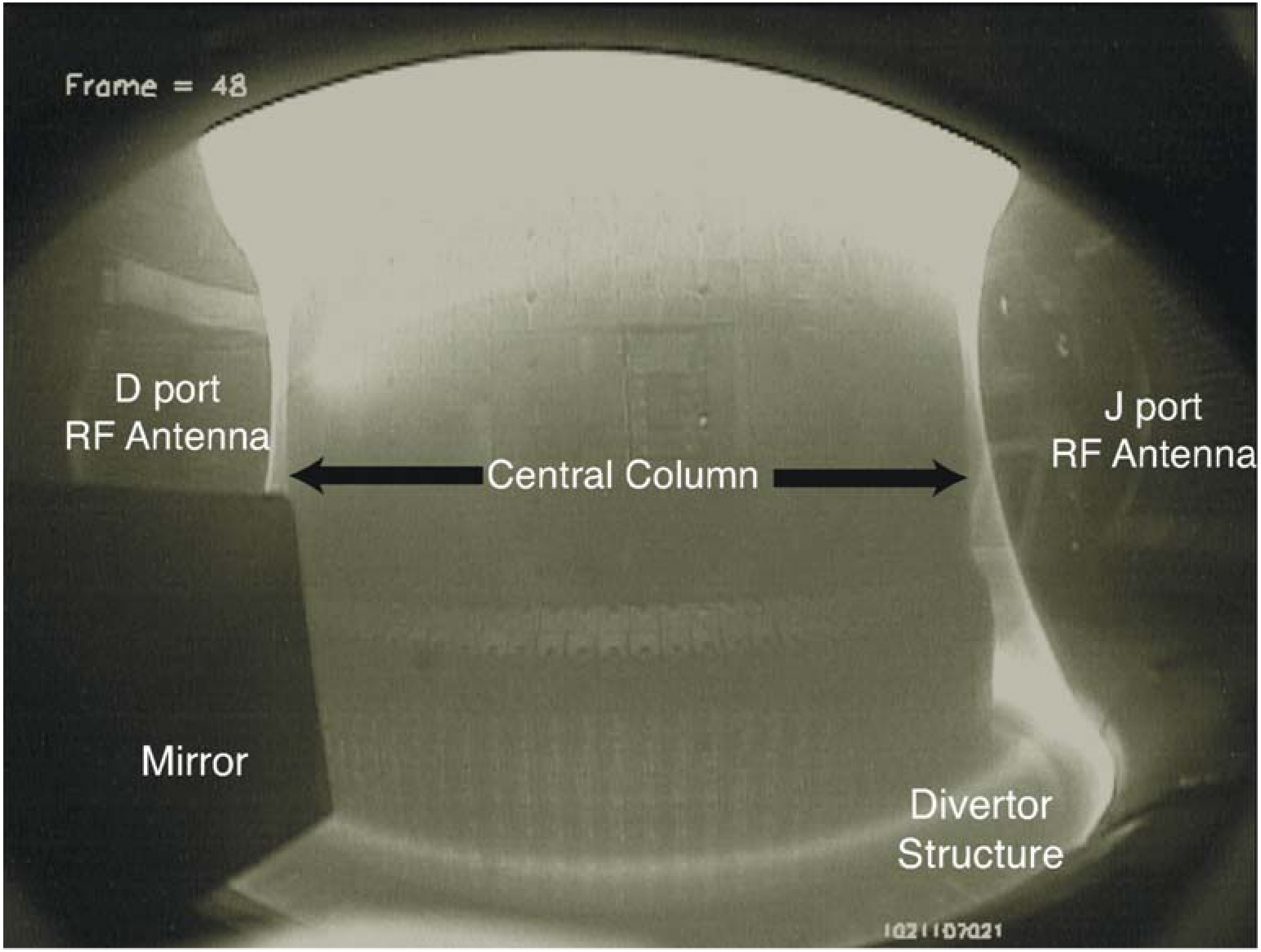
Alcator C-Mod is a divertor tokamak with high magnetic field capability ($B_t \leq 8$ T) in which quite high plasma currents ($I_p \leq 2$ MA) are possible in a compact geometry (R = 0.67 m, a = 0.22 m). Strong shaping options.

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

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

Plasma facing components are made of Molybdenum.

C-Mod plasma



Frame = 48
D port
RF Antenna
Central Column
J port
RF Antenna
Mirror
Divertor
Structure
1021107021

Anomalous transport

Alcator C-Mod

- Plasma transport associated with particle collisions in a toroidal geometry is called neoclassical transport.
- Experimentally, ion heat transport has been observed down to the neoclassical level.
- However, electron heat transport and particle transport is typically 1-2 orders of magnitude above the neoclassical transport predictions:
  - This is called anomalous transport.
- Anomalous transport is thought to be caused by plasma turbulence.
- Turbulence causes fluctuations in most plasma parameters.

Phase-contrast imaging principle

Alcator C-Mod

$$E_{\text{image}} = E_0 + E_0 \frac{\mathrm{i}\Delta}{2} \exp(\mathrm{i}k_R R) + E_0 \frac{\mathrm{i}\Delta}{2} \exp(-\mathrm{i}k_R R) \tag{1}$$

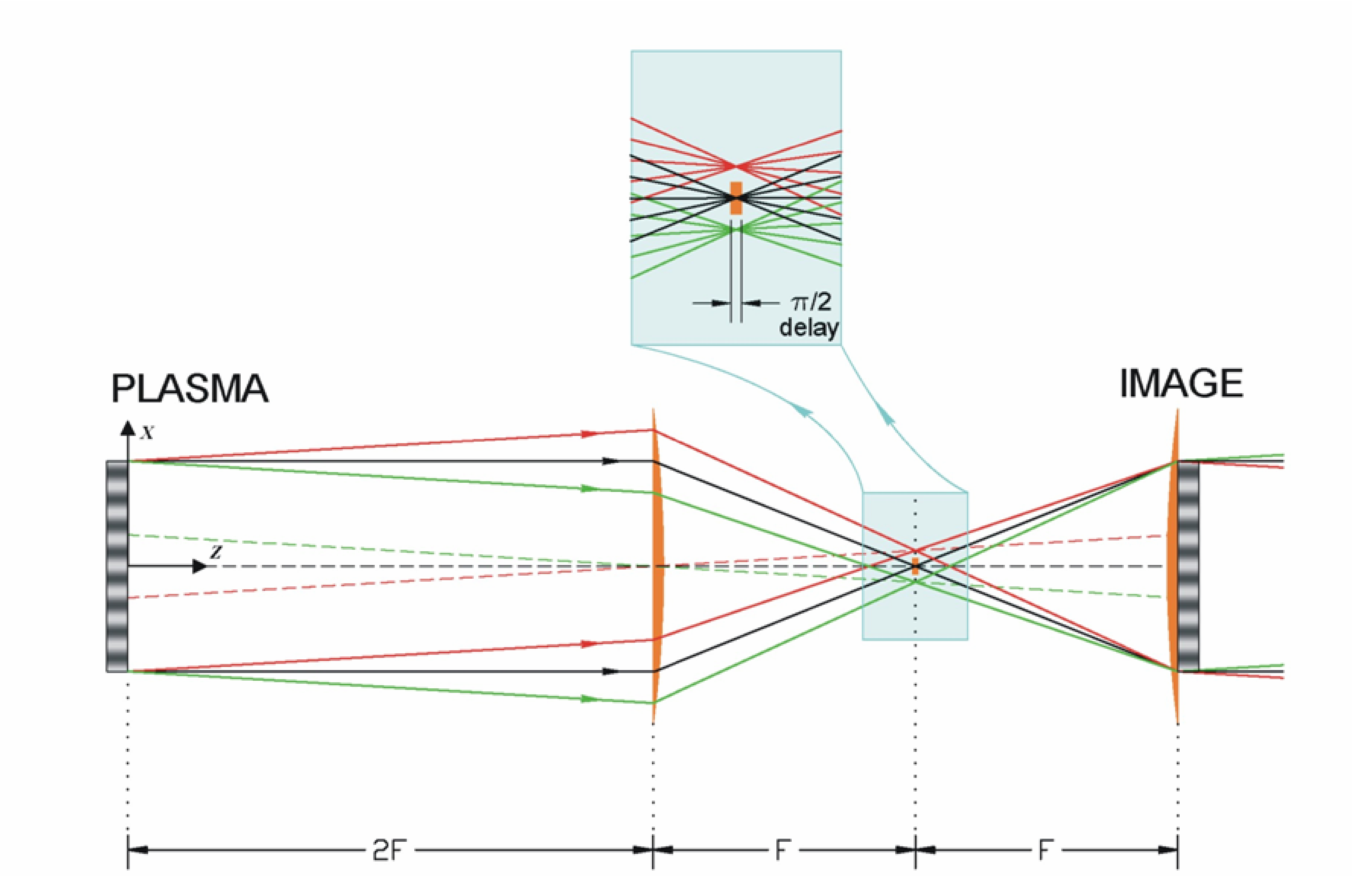
$$I = \frac{\mathrm{c}}{8\pi} |E_{\text{image}}|^2 \approx \frac{\mathrm{c}}{8\pi} |E_0|^2 \tag{2}$$

$$E_{\text{image}}^{\text{PCI}} = \mathrm{i} \times E_0 + E_0 \frac{\mathrm{i}\Delta}{2} \exp(\mathrm{i}k_R R) + E_0 \frac{\mathrm{i}\Delta}{2} \exp(-\mathrm{i}k_R R) \tag{3}$$

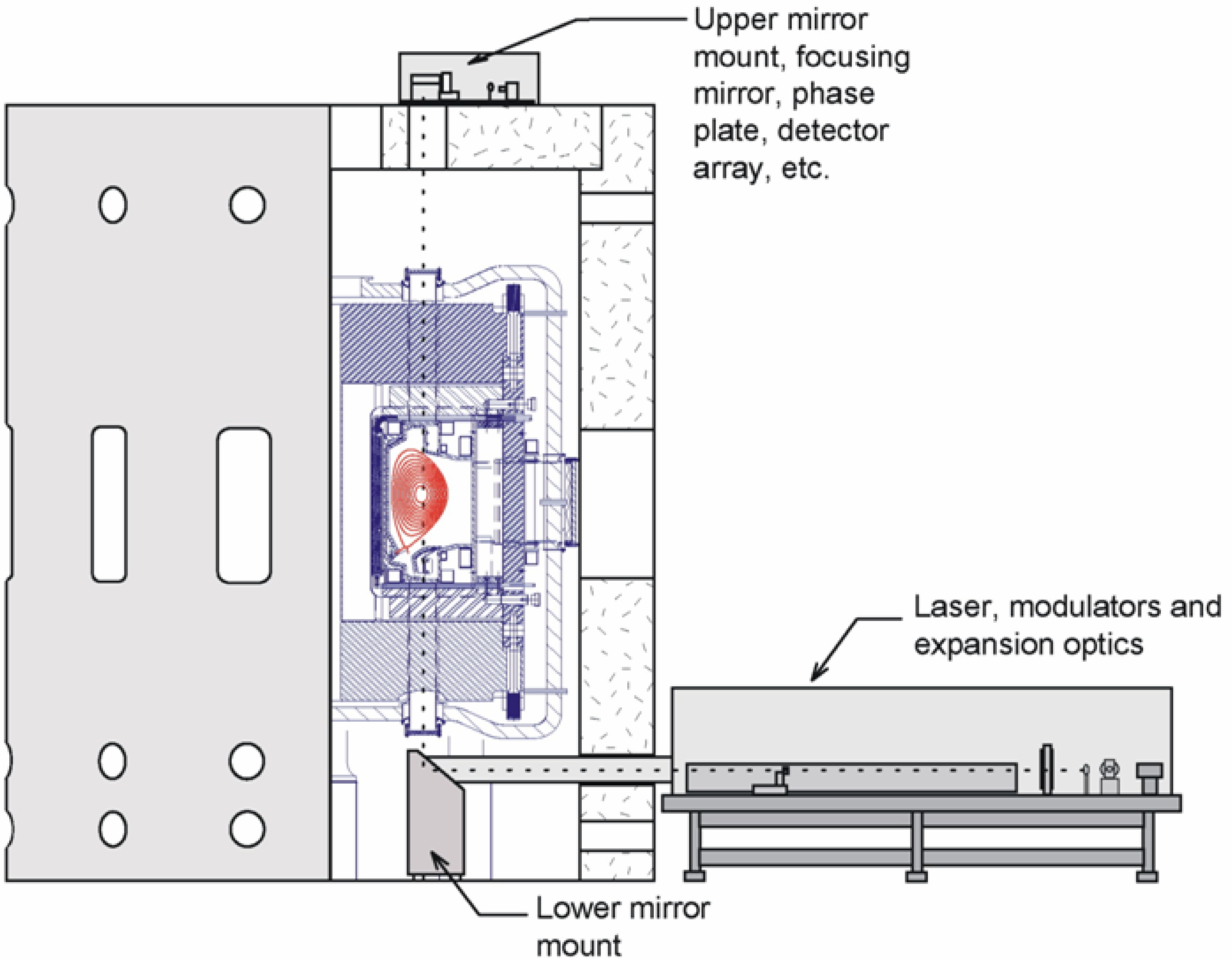
$$I_{\text{PCI}} = \frac{\mathrm{c}}{8\pi} |E_{\text{image}}^{\text{PCI}}|^2 \approx \frac{\mathrm{c}}{8\pi} |E_0|^2 (1 + 2\Delta \cos(k_R R)) \tag{4}$$

- E_0 is the electric field amplitude of the laser radiation
- $\Delta = -\lambda_0 r_{\mathrm{e}} l \tilde{n}_{\mathrm{e}}$ is the acquired phase change, $|\Delta| \ll 1$
- k_R is the fluctuation wavenumber

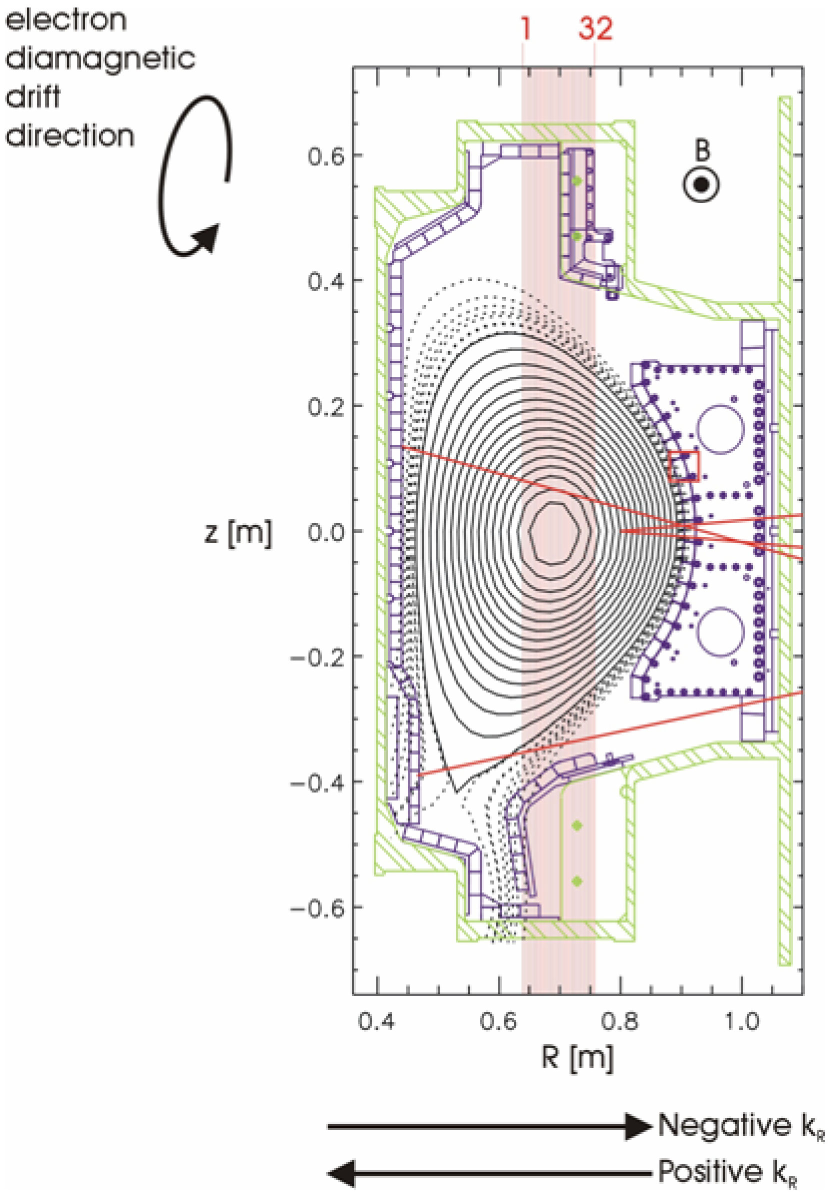
PCI optics



PCI implementation



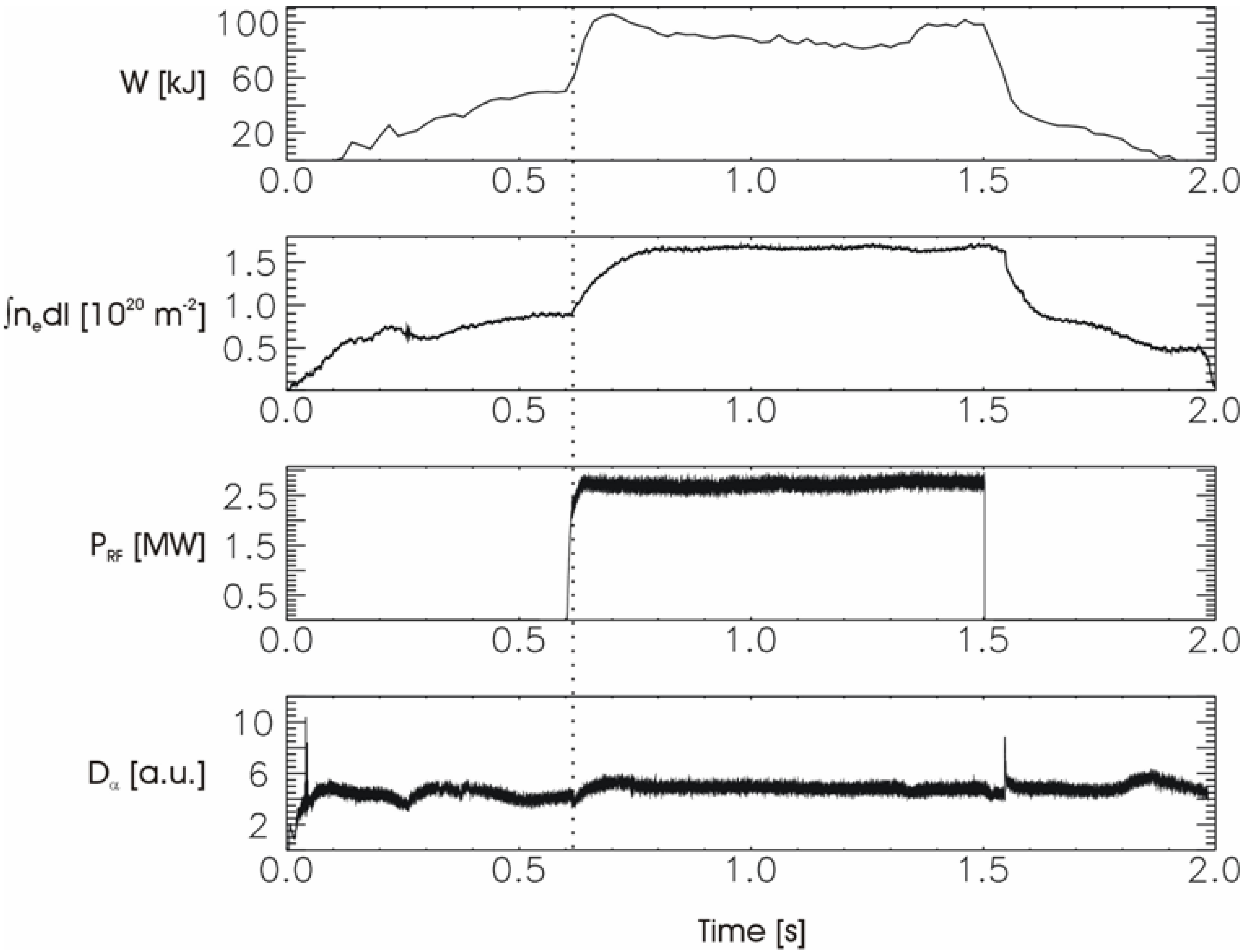
PCI facts



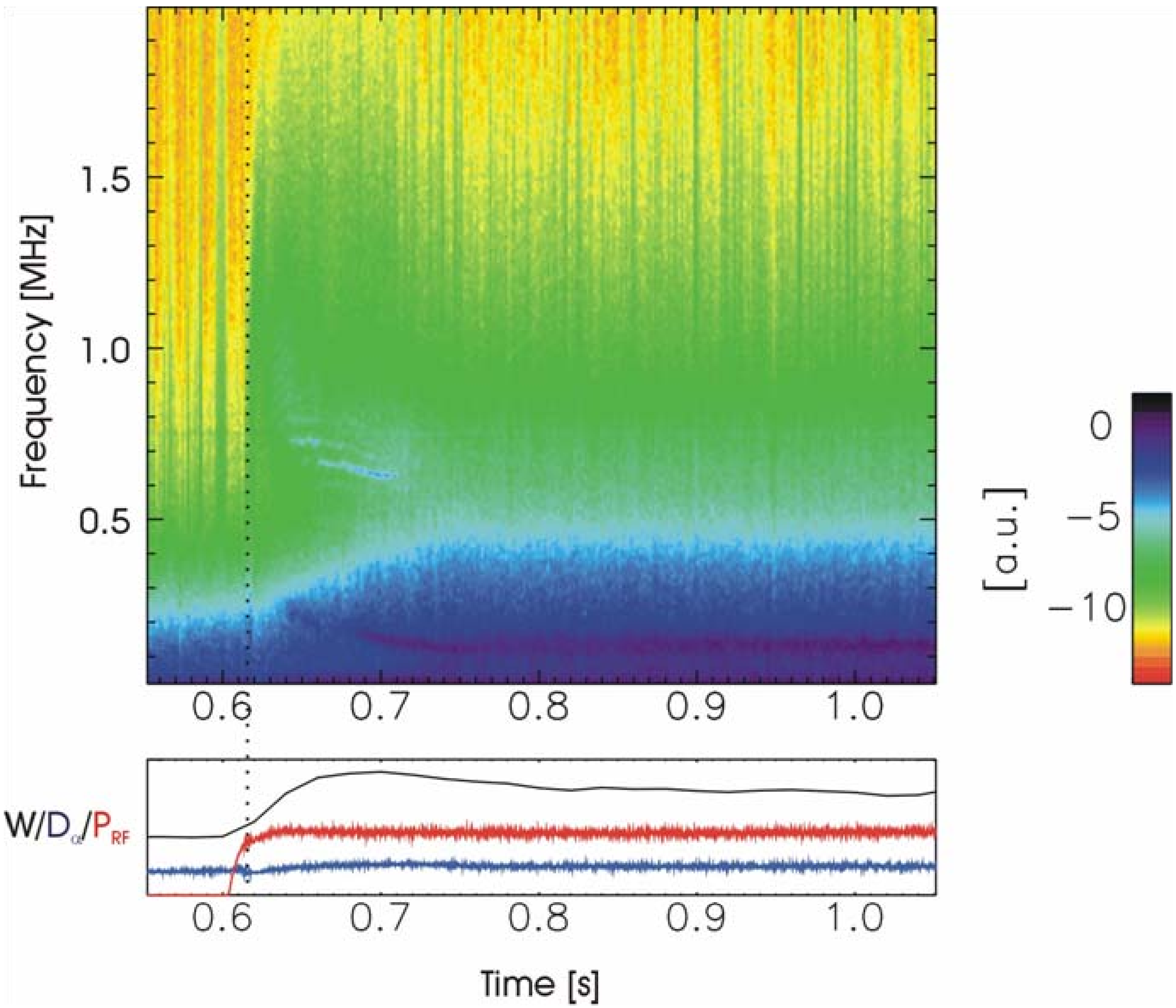
- Measures line integrated electron density fluctuations along 32 vertical chords.
- Sensitive to turbulence from 0.6 to 16.8 cm^{-1}.
- Radiation source is a 25 W CO_2 laser, wavelength 10.6 μm.
- A phase plate converts phase fluctuations to intensity fluctuations.
- Detector is a LN_2 cooled linear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

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

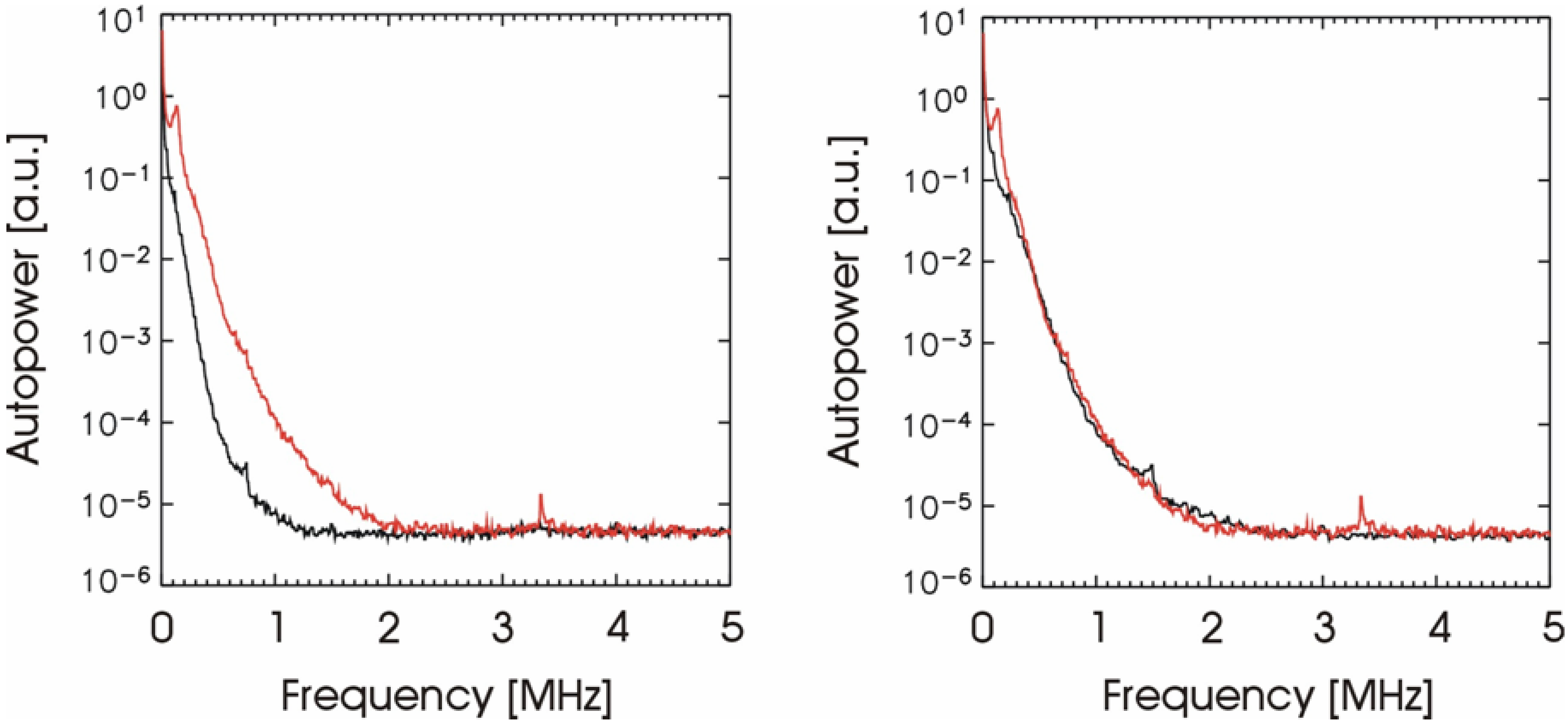
Low- to high-mode transition



Spectrogram
core channel



Autopower spectra
core channel



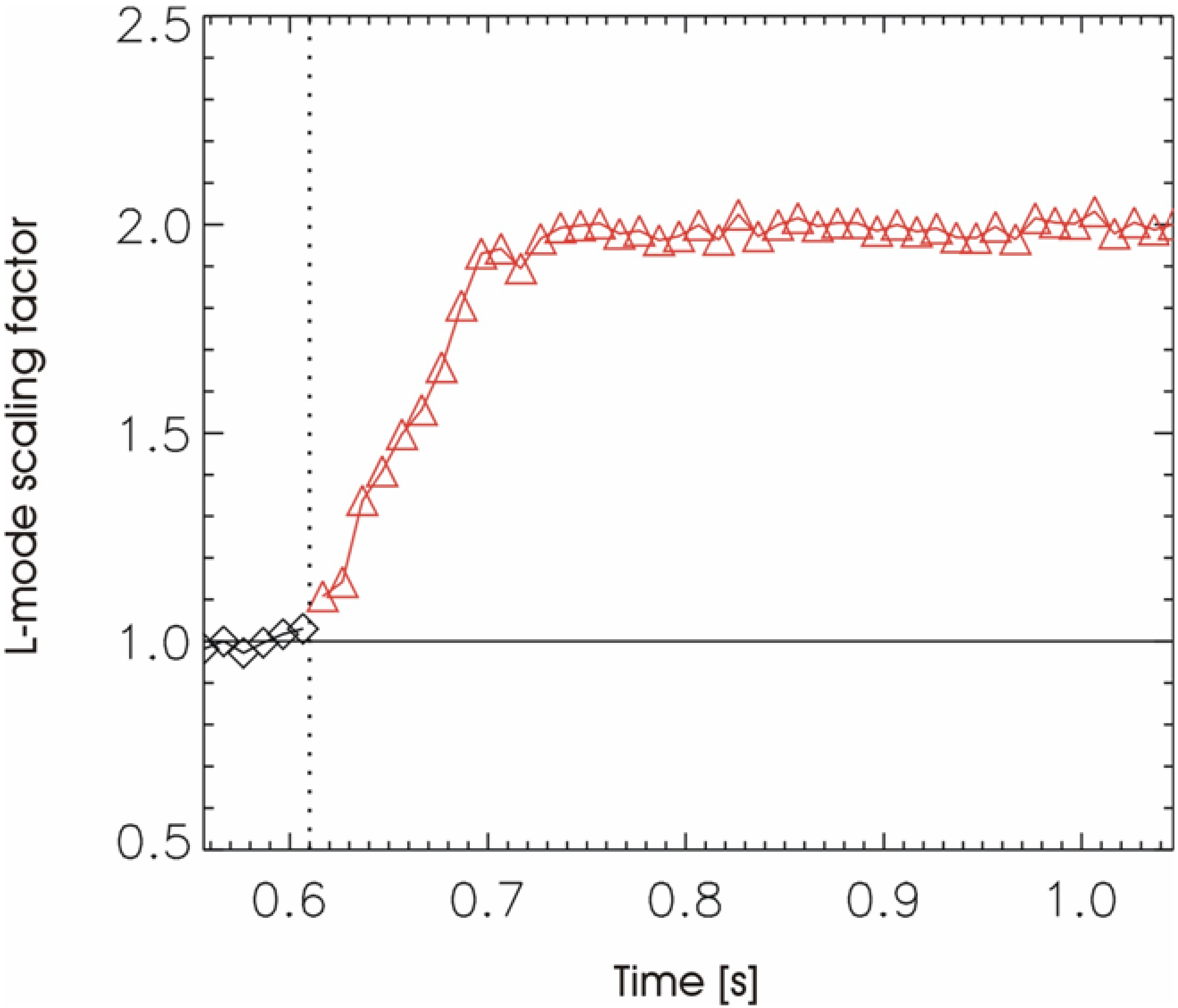
Black is L-mode

Red is H-mode

Black is L-mode,
frequencies multiplied by two.

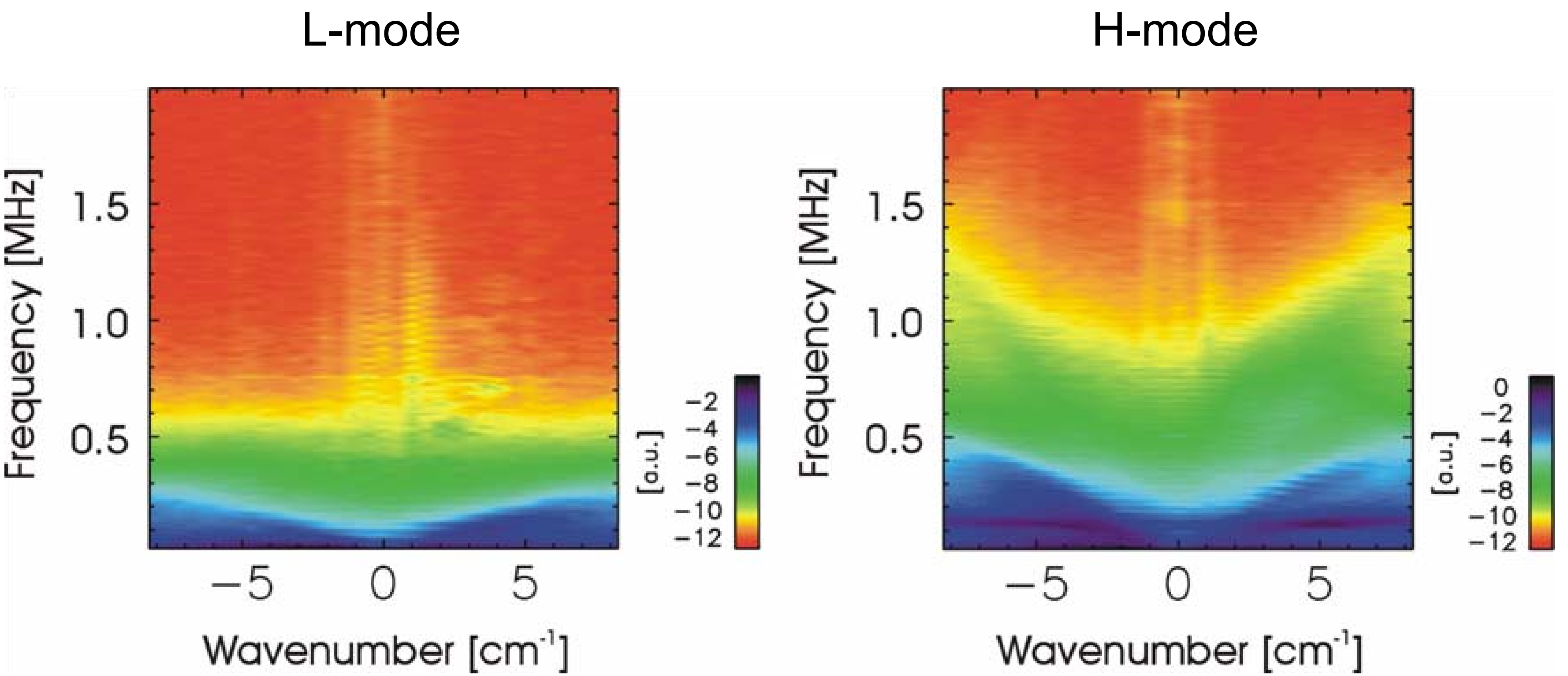
Red is H-mode

L-mode scaling factor
core channel



Frequency-wavenumber spectra

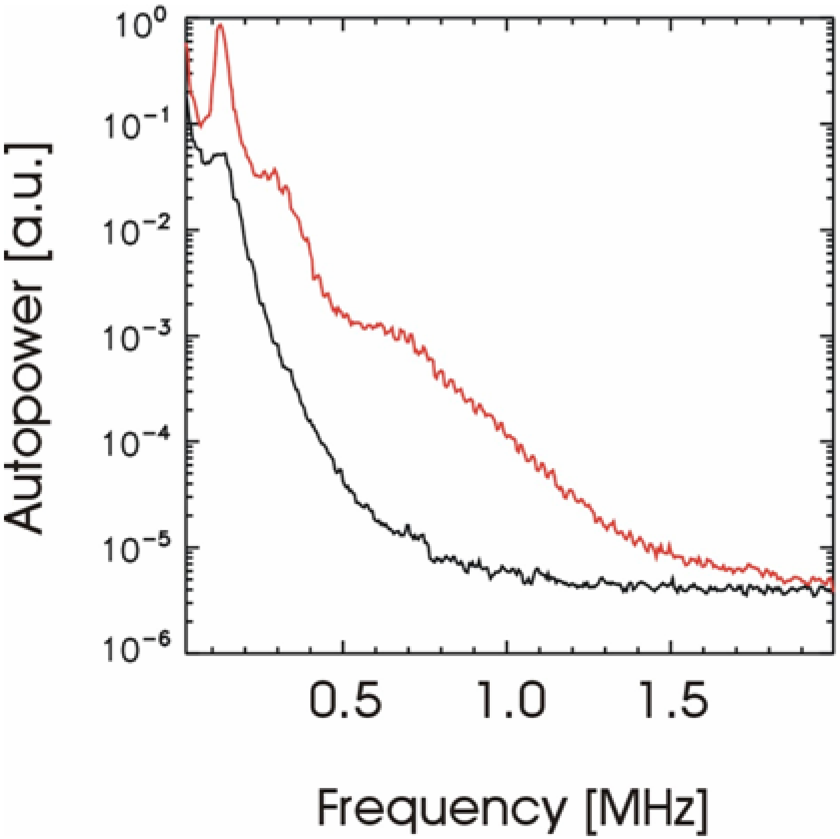
all k_R

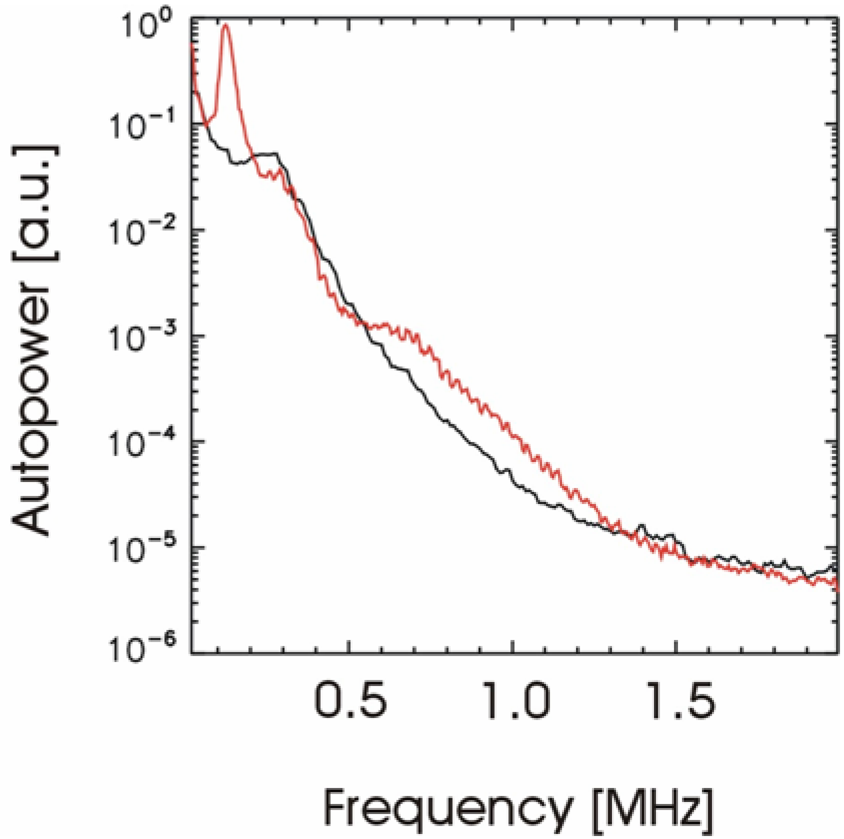


- By performing 2D Fourier transforms on the PCI data from all 32 channels, we arrive at frequency-wavenumber spectra.
- The largest increase in frequency coverage from L- to H-mode is at large wavenumbers.
- Negative (positive) wavenumbers are due to fluctuations travelling outward (inward) parallel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

Frequency-wavenumber spectra

k_R = 5.2 cm^{-1}





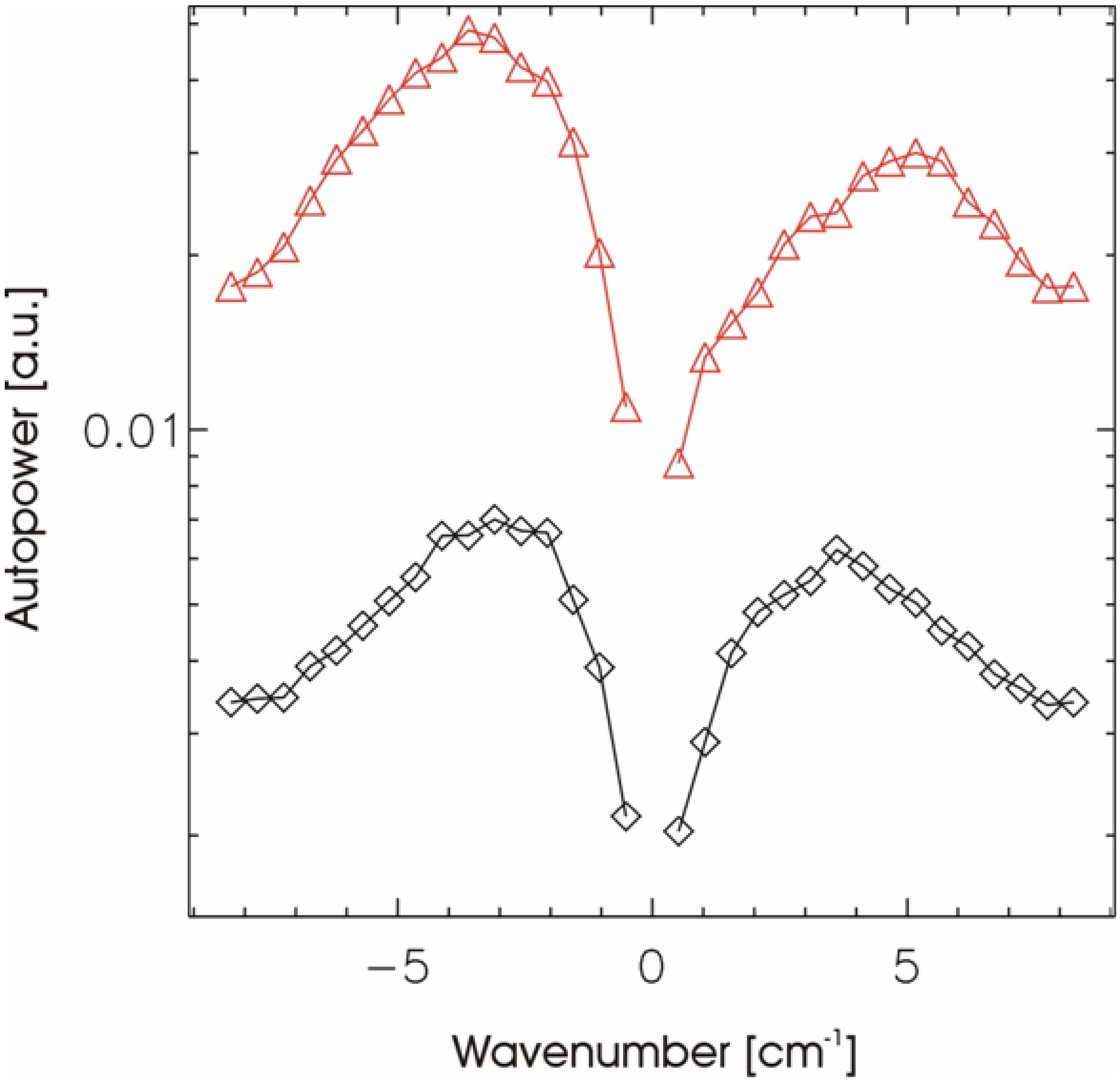
Black is L-mode

Red is H-mode

Black is L-mode, frequencies multiplied by two.

Red is H-mode

Autopower-wavenumber spectra



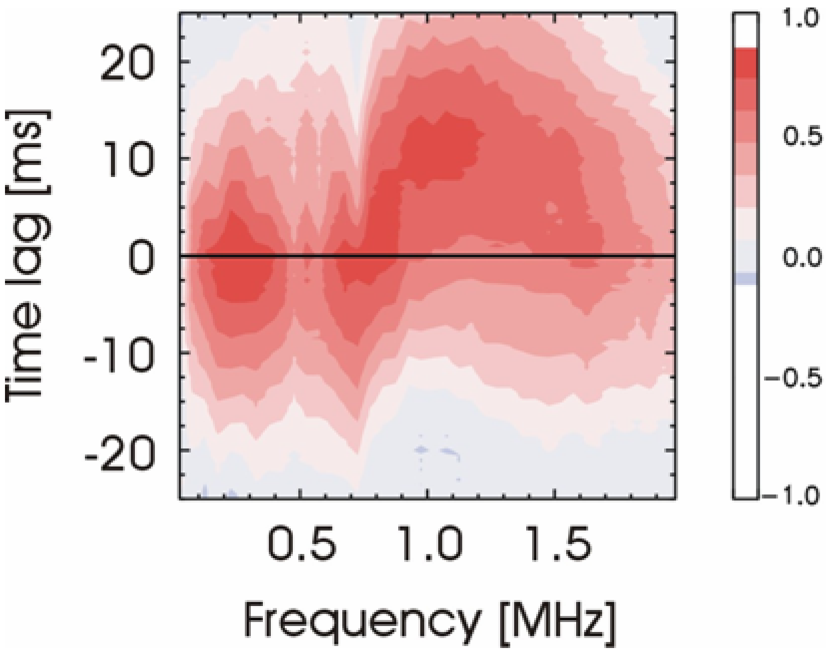
Integrating fluctuations over all frequencies we can plot wavenumber spectra for L- and H-mode.

Black diamonds are L-mode.

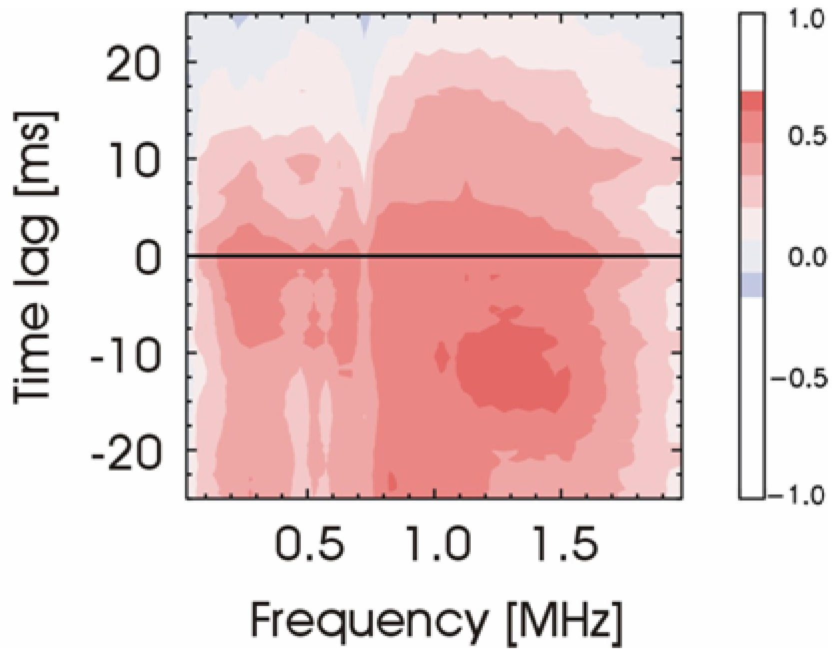
Red triangles are H-mode.

Correlations
between PCI and D_α/poloidal magnetic field

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.

Conclusions

We have in this talk given a brief overview of magnetic confinement fusion and presented an analysis of turbulence measurements at a confinement transition in the Alcator C-Mod tokamak:

•Turbulence is observed up to 2 MHz
•Changes in broadband turbulence averaged over wavenumbers can be explained by Doppler shift (rotation)
•The peaks in the wavenumber spectra indicate a specific forcing scale
•Cross correlations with other fluctuations show two features separated by frequency

The international fusion program is rapidly evolving:

•The Wendelstein 7-X stellarator is being built in Greifswald, Germany
•The international thermonuclear experimental reactor (ITER), a tokamak designed to demonstrate the feasibility of fusion energy, will be built in Cadarache, France