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Using Bernstein wave emission to measure the current in the tokamak edge

R. G. L. Vann[1], S. J. Freethy[1] , B. K. Huang[2,3] and V. F. Shevchenko[2]

[1] *York Plasma Institute, Department of Physics, University of York, York YO10 5DD, U.K.*

[2] *EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon OX14 3DB, U.K.*

[3] *Centre for Advanced Instrumentation, Physics Dept., Durham University, DH1 3LE, U.K.*

Edge-localised modes (ELMs) are eruptions of the tokamak plasma lasting ~50-200μs which expel large amounts of energy and particles that could be extremely damaging for ITER (Fig.1). Knowledge of the edge current density is critical to test and constrain theoretical models for ELMs, but experimental measurements prior to this work are few.

Figure 1. (left) A tokamak plasma in high-confinement mode (or "H-mode") has a well-defined edge and good confinement of heat; (right) but these plasmas suffer from edge-localised modes (ELMs), which last only about 100μs yet during which over 10% of the total stored energy may be lost. (Images from the MAST tokamak.)

ELMs are driven by pressure and/or current gradients in the edge as shown in Figure 2: between ELMs, the edge pressure gradient increases, which drives the so-called "bootstrap" current there, thereby increasing the edge current density. If the edge pressure gradient (current density) is too large, then the plasma is unstable with the respect to ballooning (peeling) modes. It is thought that the blue, orange and purple cycles correspond to different classes of ELM.

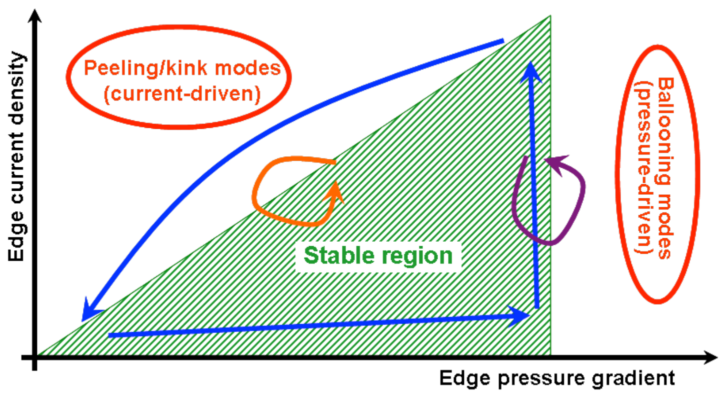

Figure 2. The ELM cycle is an interplay between pressure-driven ballooning modes and current-driven peeling modes. These modes are coupled since the edge pressure gradient drives the bootstrap current there. Thomson scattering can be used to measure the edge pressure gradient; making time-resolved measurements of the edge current density is much more challenging.

Good measurements of the edge pressure profile may be made, using Thomson scattering, but measuring the edge current profile is much more challenging: this is the focus of this work.

We make our measurements of the edge current density on the Mega-Amp Spherical Tokamak (MAST) by observing the directional emission of electron Bernstein waves (EBWs). EBWs are electrostatic plasma waves that occur in hot plasma at harmonics of the electron cyclotron frequency. Electron Bernstein wave emission (EBE) can escape the plasma via mode conversion into electromagnetic waves (Figure 3(left)). The mode-converted EBE is concentrated within a narrow angular cone determined by the magnetic pitch angle and density gradient at the layer where the wave frequency coincides with the plasma frequency (Figure 3(right)). With knowledge of the density profile (from Thomson scattering) we can deduce the field-line pitch. With knowledge of the edge toroidal magnetic field, we can deduce the poloidal magnetic field. By looking at more than one frequency (e.g. by using the simultaneously-acquired upper and lower sideband data), or by deducing the magnetic shear from the shape of the emission window [3] we can deduce the edge current density.

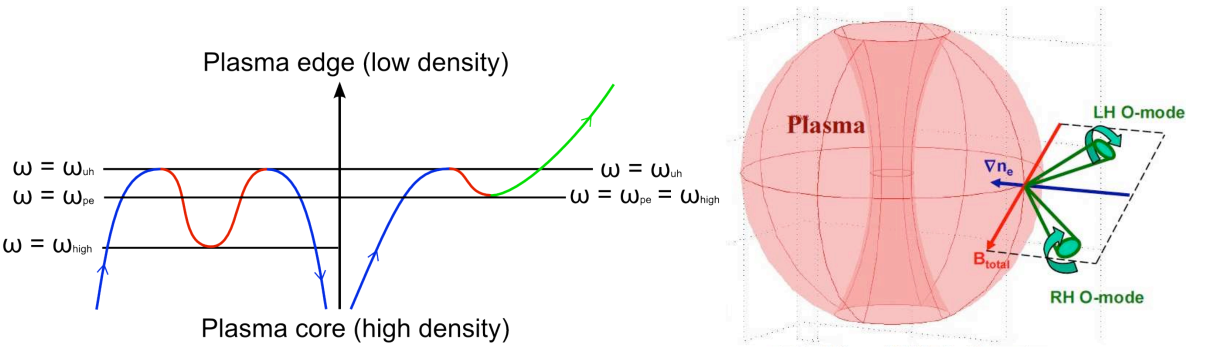

Figure 3. (left) Electron Bernstein waves (blue) are observed only if a degeneracy condition between the X-mode (red) and O-mode (green) is satisfied at the density cut-off surface; (right) this results in two cones of emission, each co-planar with the density gradient and magnetic field at the O-X mode conversion surface.

This technique has already been successfully applied at MAST using a spinning mirror to scan the plasma edge [1]; the time resolution of about 10ms is limited by the rotation rate of the mirror. To reproduce the observed magnetic pitch angle profile requires a double layer current sheath with each layer about 1cm thick and with the currents flowing in opposite directions: the inner layer carries current density of about 3.2MA/m^2 in the same direction as the plasma current and the outer layer current density is about 2.8MA/m^2 in the counter direction.

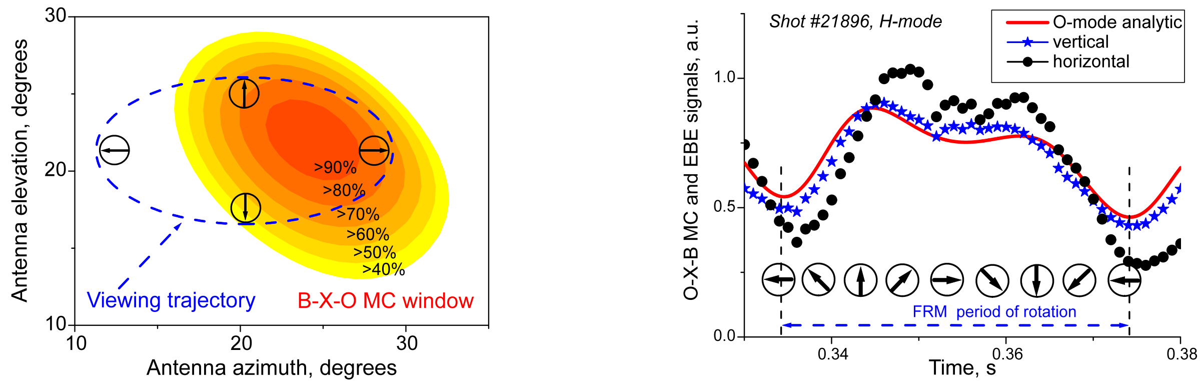

Figure 3. The spinning mirror experiment on MAST scanned an ellipse on the mode conversion surface [1]: (left) the amplitude as a function of position on the ellipse was used to deduce the emission profile; (right) the observed wave was circularly polarised, which is consistent with it being mode-converted EBW emission.

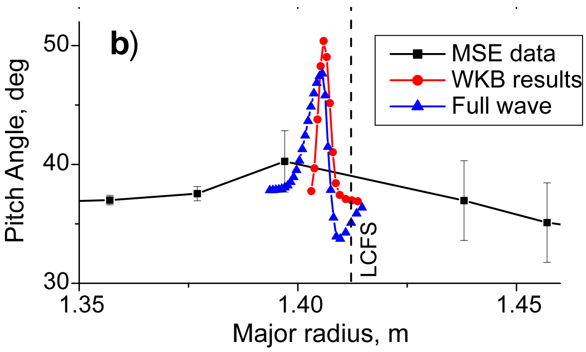

Figure 4. The best fit current profile to the data from the spinning mirror experiment on MAST shows an abrupt change in magnetic pitch angle in the pedestal, corresponding to a double-layer current sheet there [1].

We have now designed and implemented a phased-array microwave imaging system on MAST, the details of which are described elsewhere in these *Proceedings* [2]. This new system is captures the 2-D EBW emission pattern (at each frequency, so perhaps this is 3-D) on a microsecond timescale. We have already obtained preliminary data from this new system, but, being unanalysed, they are not presented here. The new imaging system includes 3 probing antennas which can send signals of 3 different frequencies toward the plasma; this enables active probing, including Doppler reflectometry.

This new diagnostic will probe a wide range of physics by applying a number of capabilities:

- General mode-coupling physics:
  - Testing 2-D mode conversion physics including theories of poloidal asymmetry (i.e. does the emission pattern depend on the symmetry breaking associated with the electrons' gyrodirection?) [4];
  - Pitch angle reconstruction (from multiple frequencies);
  - Magnetic shear (from inclination of ellipse of emission and by using multiple frequencies);
  - Density gradient point measurement (from width of emission window);

    - Polarisation studies of mode-converted EBW emission;
- Fast data acquisition allows spatially and temporally resolved measurements of:
    - EBW / ECE fluctuations
    - Density fluctuations in the mode conversion layer
    - More generally, Doppler reflectometry in the mode conversion layer
    - Temperature fluctuations in the electron cyclotron resonance layer
- Cutting-edge application of FPGA technologies:
    - 16-channels each at 14 bits per sample and 250M samples/s being written to embedded Linux-accessible memory at 8GB/s (using only two FPGAs)
    - Network data download from FPGAs of 4GB in 60s
    - Flexible remote control (including firmware upgrade) via web interface
    - Possibility of real-time signal-processing and synchronisation with other systems

This exciting new diagnostic, the MAST phased-array microwave imaging system, building on the success of the earlier spinning mirror radiometer experiments, will provide a wealth of information about the tokamak plasma, including time-resolved measurements of the edge current density which are so important for understanding the ELM cycle.

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