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Recent progress with the MAST synthetic aperture imaging radiometer

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Abstract. The MAST Synthetic Aperture Microwave Imaging (SAMI) radiometer is an antenna array designed to image thermal microwave emission from MAST fusion plasmas.SAMI is now installed on MAST and preliminary data has been taken. This data clearly show the presence of electrostatic to electromagnetic mode conversion and the circumstances under which this mode conversion take place are strongly related to the pedestal density gradient and magnetic field. These quantities are valuable in understanding tokamak pedestal behaviour and are especially important to models of the Edge Localised Mode (ELM). This paper describes SAMIs design and construction, as well as fist signals showing the presence of mode conversion.

1. How SAMI works

SAMI employs a technique called aperture synthesis, which is widely used in microwave to radio wave imaging. Some of the more famous examples include the Very Large Array and the SMOS satellite [1]. The Vann Cittert Zernike theorem states that the cross correlation between two points illuminated by a far field source is approximately a sample of the Fourier transform of the brightness distribution [2].

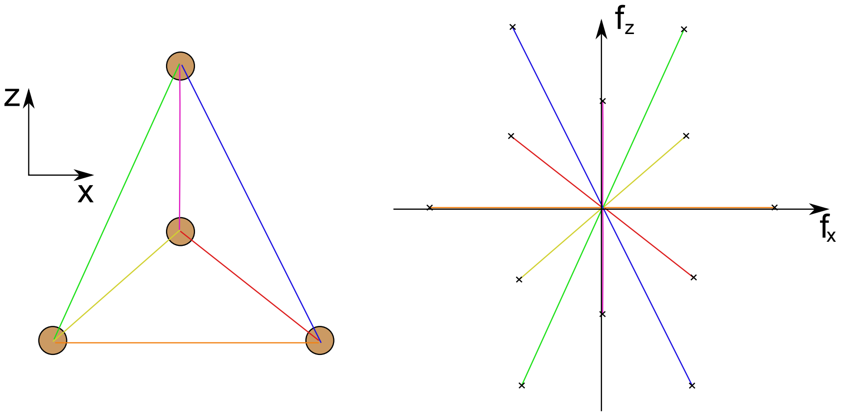

Figure 1. Correlation between pairs of antennas represented by the circles (right) form samples of Fourier space at positions defined by the vector between the pair normalised to the wavelength of the radiation being observed (left). There is π rotational symmetry in Fourier space.

The position in Fourier space at which the sample corresponds is given by the vector between the pair of antennas which are being correlated normalised to the wavelength of the wave being observed, termed baselines, as illustrated by figure 1. Enough pairs of antennas can be used to reconstruct Fourier space which can then be inverted to find the image. The number of pairs for n antennas grows as $n(n-1)/2$ so the number of effective pixels using this technique grows rapidly with the number of antennas.

2. Array shape optimisation and hardware

The problem with measuring only a few places in Fourier space is that this is equivalent to multiplying the Fourier function by a sharply peaked gridding function. The net result being oscillations in real space which are not part of the image. This effect can be mitigated by placing the antennas in such a way that these unwanted oscillations are minimal. By minimising a beam efficiency function which calculates the ratio of power in the central lobe with total power via a simulated annealing approach, reasonable approximations to the optimal layout of antennas were found. SAMI is capable of using sub-microsecond broadband switches to allow switching between groups of antennas in order to enhance its coverage of Fourier space. Figure 2, shows two groups of 8 antennas optimised simultaneously to find complimentary groups of antennas to switch between.

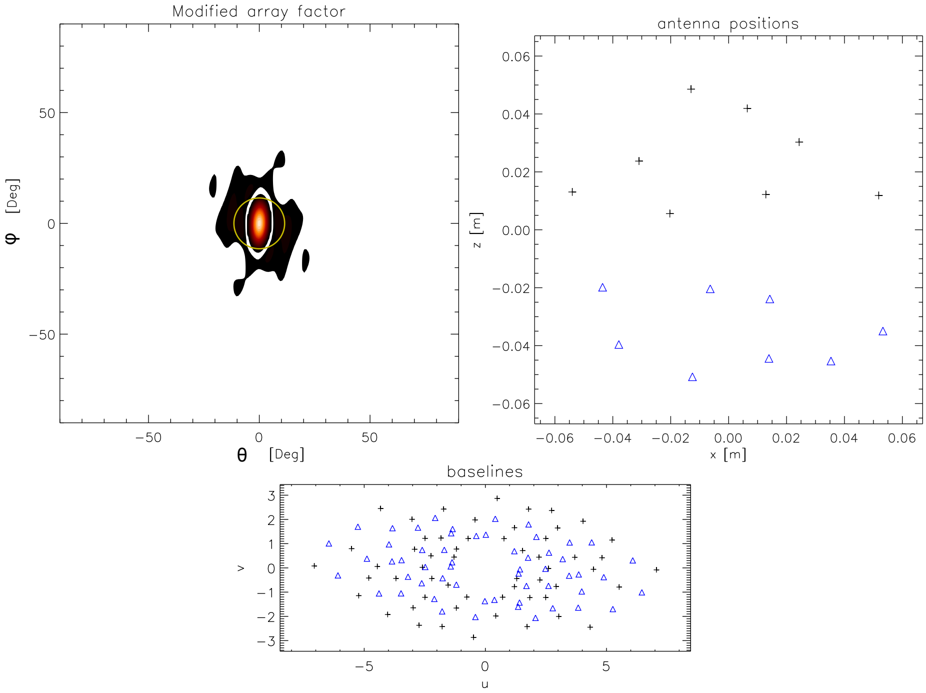

Figure 2. Top left is the synthetic aperture equivalent of an array beam pattern, top right are the optimal antenna positions for two groups of eight antennas and bottom is the coverage of Fourier space for the optimal groups

SAMI employs a full vector heterodyne down converter (see figure 2 left), converting real and imaginary components of the microwave signal for 8 antennas at any of 16 frequencies to a digitsable frequency range. These signals are then digitised by an FPGA controlled digitiser providing 14 bit resolution at 250MSs^{-1}. SAMI uses printed circuit board antipodal Vivaldi antennas which are 2cm wide by 6cm long and can be seen in array form in the top right of figure 2. These antennas are operational from 5 to 35 GHz and were characterised by measurements made at the university of Strathclyde. SAMI includes sub microsecond switches to switch between antenna groups.

3. Initial results

The first results with MAST plasmas have been obtained and we have clear signatures that we are able to see the mode conversion between the electrostatic Electron Bernstein

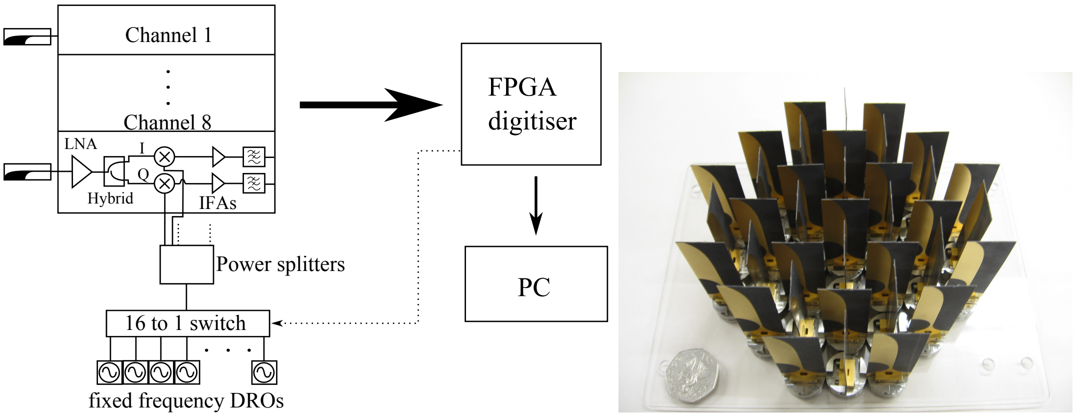

Figure 3. Left: A schematic of the SAMI radiometer. SAMI covers the region from 10GHz to 35GHz. Right: An array of 37 Vivaldi antennas. The antennas are 2cm by 6cm and are operational from 5GHz to 35GHz.

Wave (EBW) and electromagnetic waves. Figure 3 shows power traces from one of our antennas with each frequency plotted with an offset for clarity. Initially the signals develop together in the low density plasma as Electron Cyclotron Emission (ECE). Then the plasma becomes over-dense strongly suppressing the ECE. Note that this appears to happen later for higher frequencies due to the density growing in time. Then the lower frequency channels begin to rise due to the EBW emission mode converting into electromagnetic waves near the plasma edge. Note that the signals are strongest for frequencies from 13 10 18GHz since this range corresponds to the EC resonance. Emission from the second harmonic in this example is weaker, due to the relatively low plasma density being insufficient for mode conversion of these frequencies.

SAMI digitises real and imaginary components in order to perform digital sideband separation, allowing both upper and lower sidebands to be kept. Not only is this far more efficient for estimating the cross correlation phase, it effectively doubles the number of frequency channels. SAMI is able to achieve up to 30dB suppression of sidebands.

4. conclusion

SAMI is an aperture synthetic imaging radiometer designed to obtain the first images of EBW mode conversion, which is sensitive to edge magnetic field and density gradient. The antenna array has been designed explicitly to reduce the sidelobes generated by under-sampling of Fourier space. SAMI performs full vector heterodyne down conversion to allow for digital sideband suppression and image formation. It can switch between any of 16 frequencies in the range of 10-35GHz in sub microsecond time. First data

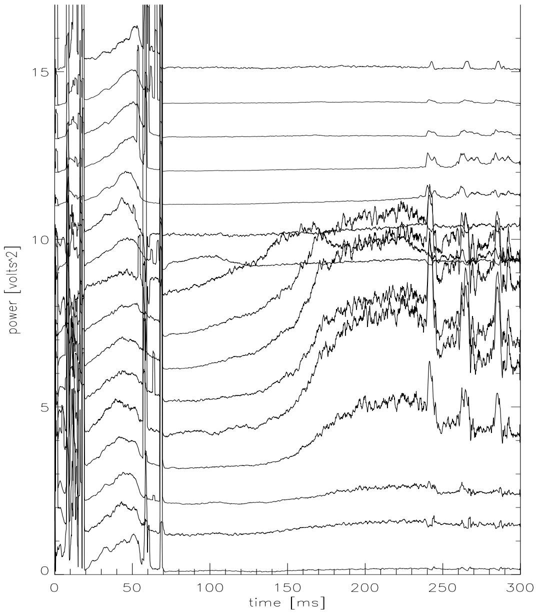

Figure 4. Left: The power received by SAMI for the 1st 200ms of a MAST shot with different frequency channels plotted with an offset for clarity. Right: The reflectometer sweeps up in frequency providing an excellent means to test the sideband separation.

has been taken showing strong signatures of mode conversion and very good sideband suppression capacity.

[1] A Camps et al. Radiometric sensitivity computation in aperture synthesis interferometric radiometry. *IEEE transactions on geoscience and remote sensing*, 36(2), 1998.

[2] A R Thompson, J M Moran, and G W Swenson Jr. *Interferometry and synthesis in radio astronomy.* Wiley - VCH, 2004.