Synthetic Aperture Microwave Imaging (SAMI) of the plasma edge on NSTX-U

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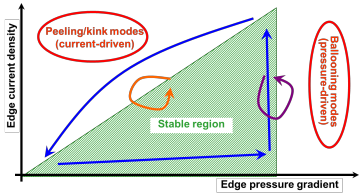
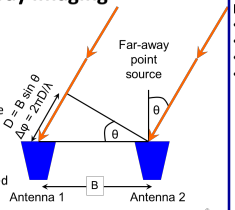
1) Motivation: measure edge current density to understand edge stability



- ELM dynamics are an interplay between the edge pressure gradient and edge current density
- Edge current density cannot currently be directly measured
- SAMI's ultimate goal is to make spatially-resolved measurements of the edge magnetic pitch angle and thence the current density

2a) Methodology: phased-array imaging

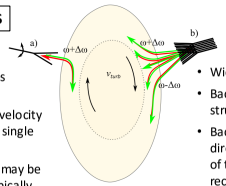
- Aperture synthesis used widely in radio astronomy (e.g. Very Large Array telescope)
- No focusing components: signal illuminates all antennas
- Phase difference between antenna pairs steers beam to arbitrary point on the emission surface
- Cross-correlation between pairs of antennas gives spatial Fourier transform of emission pattern i.e. given a number of antennas, an extended emission pattern can be reconstructed
- Number of "pixels" ~ (number of antennas)^2



2b) Methodology: 2-D Doppler backscattering

Conventional DBS

- Narrow beam
- Backscatters off turbulent structures at single location
- Probes turbulence velocity and amplitude at a single location
- Scattering location may be changed slowly (typically between shots) through mechanical steering



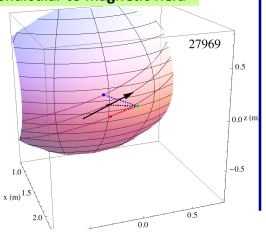
ω = frequency of probing beam
Δω = Doppler shift introduced by turbulent velocity

SAMI

- Wide beam
- Backscatters off turbulent structures at many locations
- Backscattered signal from all directions digitized on each of the antennas in the receiving array
- Probing location selected post-shot using software

Backscattering is strongest perpendicular to magnetic field

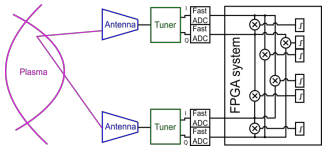
- Turbulent structures are elongated along field lines
- Strongest back-scattering therefore occurs perpendicular to field
- SAMI can locate the points of strongest red & blue shift
- Direction perpendicular to line joining these points gives magnetic field direction



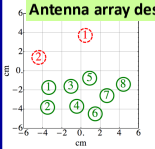
3) Synthetic Aperture Microwave Imaging (SAMI): hardware description

Overview

Unlike "keyed" arrays, SAMI's antennas are independently phased: beam steering is performed post-shot in software.



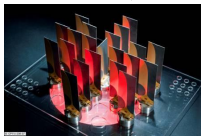
Antenna array design: optimised for main beam efficiency



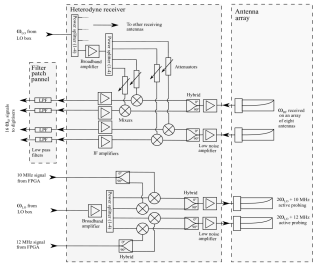
- Array of 8 receiving antennas (green)
- Two transmitting antennas (red) at 10MHz & 12MHz above local oscillator frequency
- Array pattern designed to maximise main beam efficiency (i.e. minimise power in side lobes) [Freethy *et al.*, *IEEE Trans. Ant. Prop.* **60** 5442 (2012)]

Vivaldi PCB antennas are chosen because

- Wide field of view
- Broadband (10 – 35 GHz)
- Excellent polarisation separation
- But the array becomes 3-D i.e. antennas interfere with each other



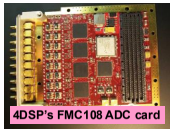
Microwave electronics: 8 receiving & 2 transmitting channels



- Frequency range 10-35GHz in 16 regularly-spaced channels
- Heterodyne down-convertor uses 2nd harmonic mixers
- Need to capture I & Q components for sideband separation: i.e. two data acquisition channels per antenna
- Transmitting circuit provides probing signals at 10MHz and 12MHz above carrier
- Connectorised components throughout enable relative simplicity of assembly

Data acquisition and control: embedded Linux controls FPGAs

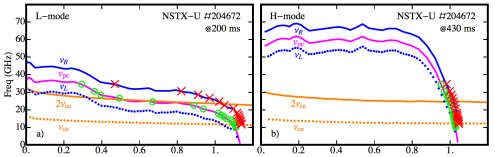
- Data acquisition is demanding: 250Msamples/s; 8 antennas; I & Q components for each; 14 bits per sample = 8GB/s
- Custom solution based on Xilinx's ML605 FPGA board and 4DSP's FMC108 ADC card
- Linux runs on FPGA soft processor providing control of the diagnostic
- Excellent performance and flexibility
- Challenging to program
- Real-time filtering around active probing frequency has now been achieved



4) SAMI installation on NSTX-U

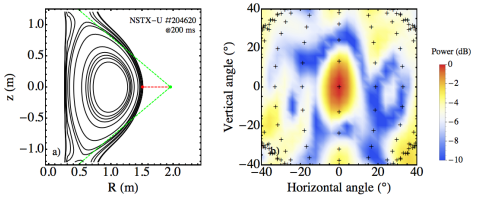
- SAMI was installed on MAST 2011-2013 (with focus on imaging thermal emission)
- SAMI was transferred to NSTX-U and began collecting data in early 2016.

Reflection points ~ 1mm apart for NSTX-U H-mode

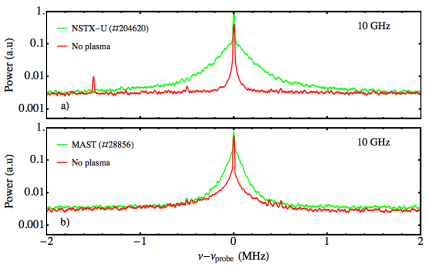


- Reflection locations at SAMI's 16 frequencies are shown by green circles for O-mode and red crosses for X-mode for both L-mode (left) and H-mode (right).
- Proximity of reflection points in H-mode indicates SAMI's potentially excellent spatial resolution.

SAMI has a good view of NSTX-U plasma, albeit near-field effects may become important



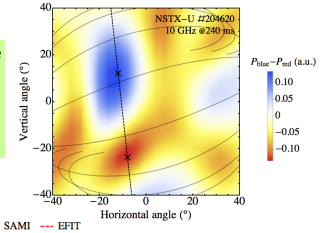
SAMI's proximity to the NSTX-U plasma (compared to MAST) makes 2-D DBS possible even during H-mode

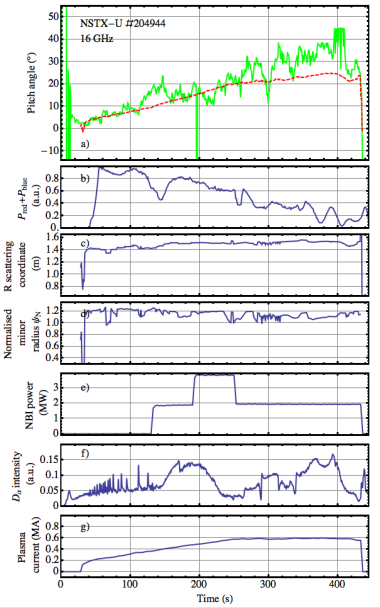


5) Preliminary results from NSTX-U show encouraging comparison with EFIT

Blue-red power imbalance shows well-defined peaks

Magnet field from unconstrained EFIT shown in grey





Principal result: SAMI is able to make time-resolved measurement of the edge magnetic pitch angle, which agrees reasonably well with unconstrained EFIT for this shot.

Conclusion: SAMI has demonstrated the feasibility of using 2-D Doppler back-scattering to measure the magnetic field pitch angle in the tokamak plasma edge. More antennas will be required to make a more sensitive measurement with a better-focused beam.

Future work: In the next NSTX-U campaign, run with two frequencies to attempt a measurement of the rate of change of field line pitch (and thence current density estimate). Simultaneously develop new & enhanced complementary system for deployment at MAST-U.

References: [1] "2 D Doppler backscattering using synthetic aperture microwave imaging of MAST edge plasmas" by D.A. Thomas, K.J. Brunner, S.J. Freethy, B.K. Huang, V.F. Shevchenko & R.G.L. Vann, *Nuclear Fusion* **56**, 026013 (2016)
[2] "Preliminary measurements of the edge magnetic field pitch from 2-D Doppler backscattering in MAST and NSTX-U" by R.G.L. Vann, K.J. Brunner, R. Ellis, G. Taylor & D.A. Thomas, *Review of Scientific Instruments* **87**, 11D902 (2016)

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