Simultaneous 2D Doppler backscattering from edge turbulence

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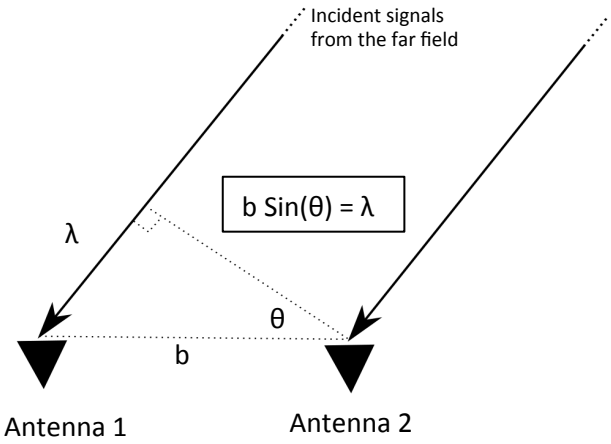
57th APS Division of Plasma Physics, 16th November 2015

The Synthetic Aperture Microwave Imaging (SAMI) diagnostic is first-of-its-kind



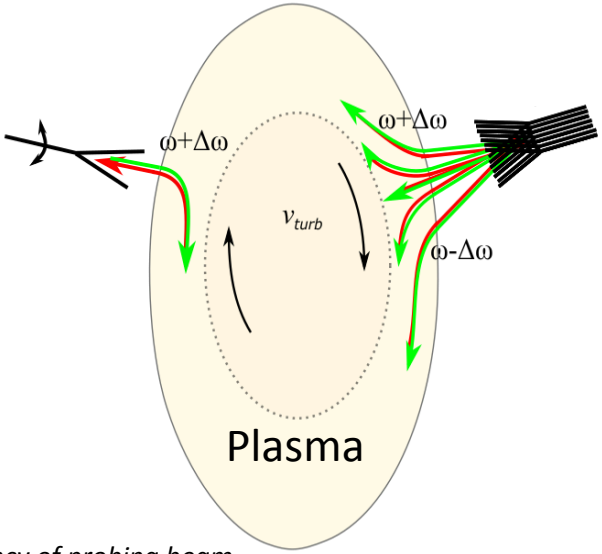
- No optical components
  - Phases and amplitudes from an array of antennas are digitized
- Phase shifts applied to signal data post-shot by software so that constructive interference occurs in a user defined direction
  - Phase shifts applied to each antenna signal individually
  - Enables SAMI to be focused in every direction simultaneously
  - Capability unique to SAMI
- Look at the microwave emission from the plasma – passive imaging mode
  - first ever 2D images of B-X-O mode conversion [1]
  - Insights into electron kinetics during ELMs [2]
- Illuminate the plasma with microwaves – active imaging mode
  - First simultaneous 2D Doppler backscattering (DBS) system

[1] V. F. Shevchenko *et al* 2012. J. Inst. **56** P10016.
[2] S. J. Freethy *et al* 2015. Phys. Rev. Lett. **144**, 125004

SAMI probes multiple locations simultaneously

Conventional DBS

- Narrow launching beam
  - ➢ Backscatters off turbulent structures in the plasma
- Probes a single location
  - ➢ One Doppler shift due to turbulence velocity
- Scattering location can be changed slowly through mechanical steering

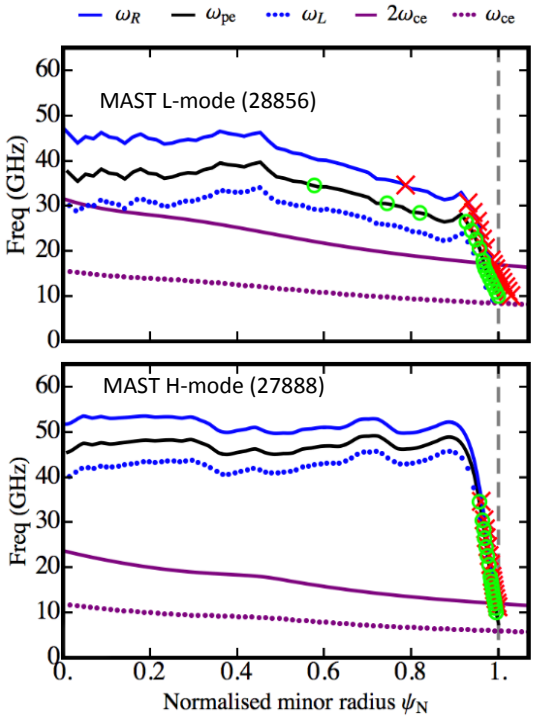


ω: Frequency of probing beam
Δω: Doppler shift introduced by turbulent velocity

SAMI

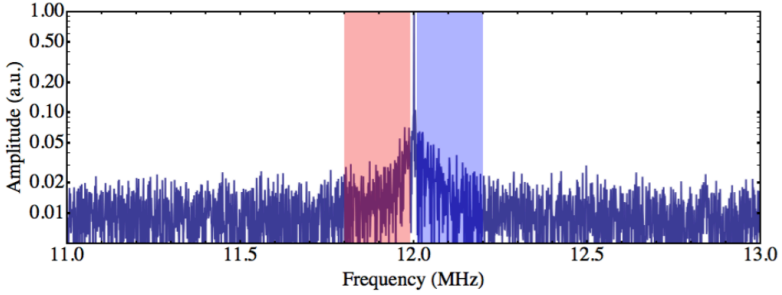
- Launches a broad (±40°) probing beam
  - ➢ Backscatters of turbulent structures at many locations
- Backscattered signal from all directions digitized on each of the antennas
- Can select probing location post-shot using software
  - ➢ SAMI probes multiple locations simultaneously
  - ➢ Constructs Doppler shift map across surface of the plasma

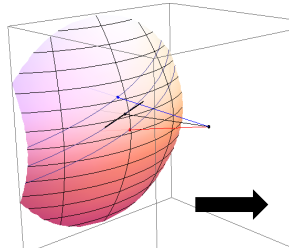
SAMI provides high radial resolution measurements in the edge

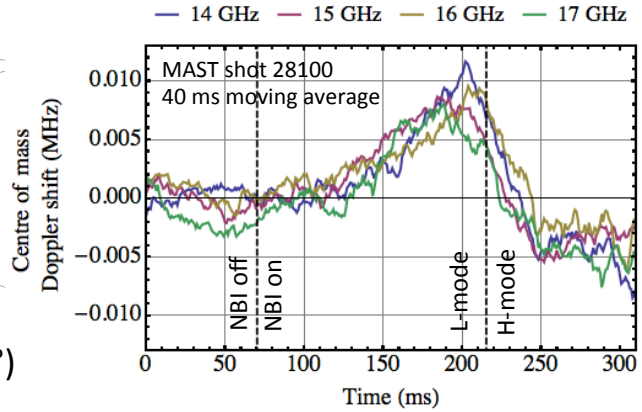


- Normal incidence O-mode and X-mode cutoffs are predominately in the edge
- SAMI probes between 10-35.5 GHz in 16 steps
  - Radial resolution ~3 mm (when acquiring on all frequencies)

SAMI observes phenomena previously observed in conventional DBS





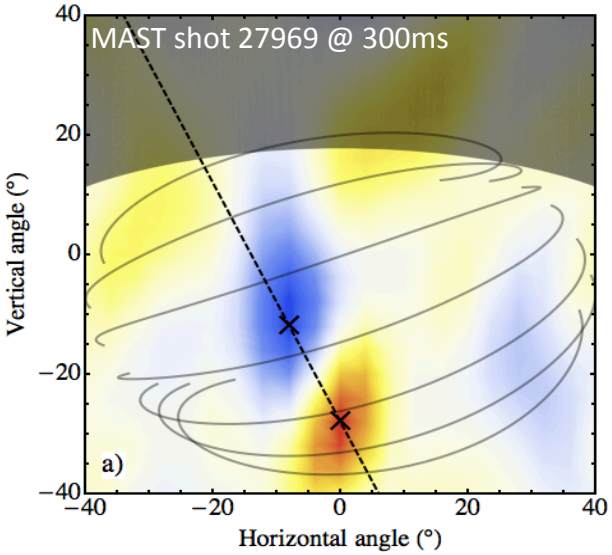


Focused at (-20°,8°)

- SAMI currently has only eight receiving antennas
  - When focusing SAMI at a single location the returned signal is convoluted
  - Interpretation of 2D data is challenging
  - Further modeling is currently underway (EMIT-3D[1])
  - Move towards turbulent velocity and k-spectra profiles
- First results from a 2D Doppler backscattering diagnostic – center of mass measurement
  - Phenomena have been observed on previous single horn DBS experiments[2]

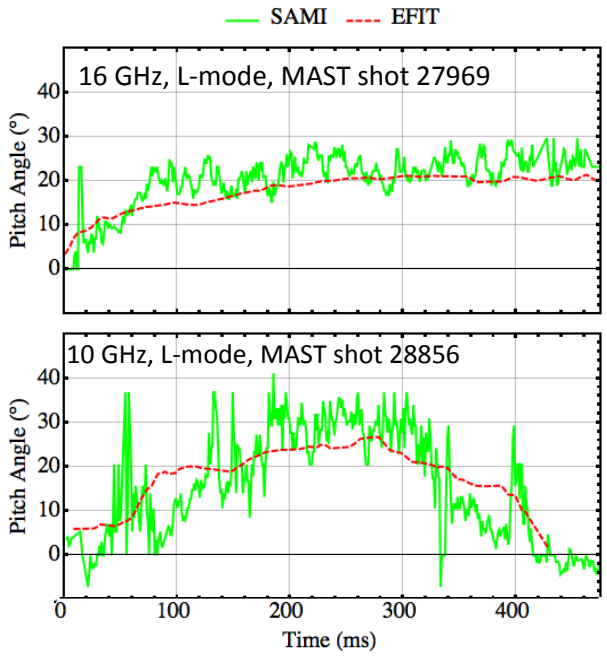
[1] T. R. N. Williams et al 2014. Plasma Phys. Control. Fusion **56**, 075010.
[2] G.D. Conway et al 2004. Plasma Phys. Control. Fusion **46**, 951.

SAMI provides the first ever 2D view of Doppler backscattered radiation off turbulence



- Scattering occurs off turbulent structures elongated along field lines
  - ➢ Backscattering occurs predominately along a path perpendicular to the magnetic field
- Strongest red and blue-shifted signals are aligned perpendicular to the magnetic field – inclination of the magnetic field away from horizontal
  - ➢ A magnetic pitch angle measurement can be made
  - ➢ Made possible because of SAMI's unique **2D** capability

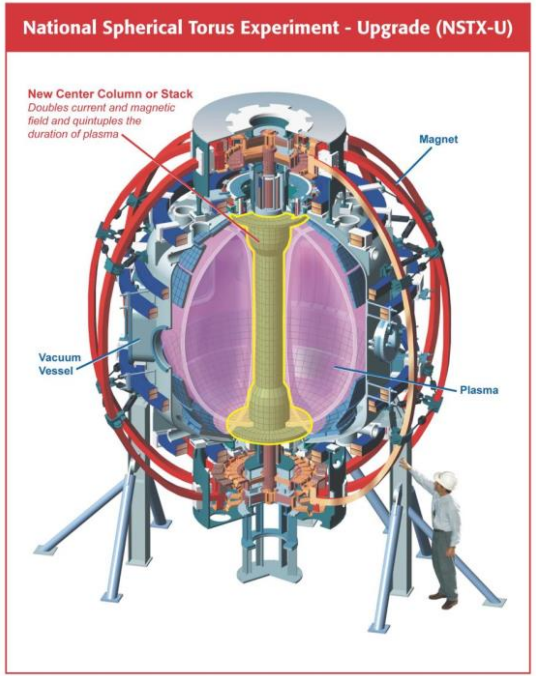
SAMI makes first pitch angle measurements made by a DBS diagnostic



- Pitch angle from SAMI measurements shown in green, Pitch angle from EFIT shown in red
  - Very good level of agreement seen

- High fluctuation level observed
  - We can see that the fluctuation level is lower when probing with 16 GHz than with 10 GHz
    - higher fluctuation level further out in the scrape off layer
  - Receiving array can not separate O and X-modes
    - Interference between modes can give rise to noise
  - Pitch angle may be temporally more variable in the edge than predicted by EFIT

SAMI's installation on NSTX-U will advance technological and physics objectives



- Longer frequency switching time will allow **radial profiles** of magnetic pitch to be measured
  - Moving closer to edge current density measurements
- Installation of dual polarized sinuous antennas will allow for O/X-mode separation
  - Much improved pitch angle measurements
- 10 fold increase in data acquisition length (0.5-> 5s)
- Investigate numerous other phenomena
  - Near field effects
  - Effect of lithium on the plasma edge
  - Passive emission studies
  - Comparisons with MAST data

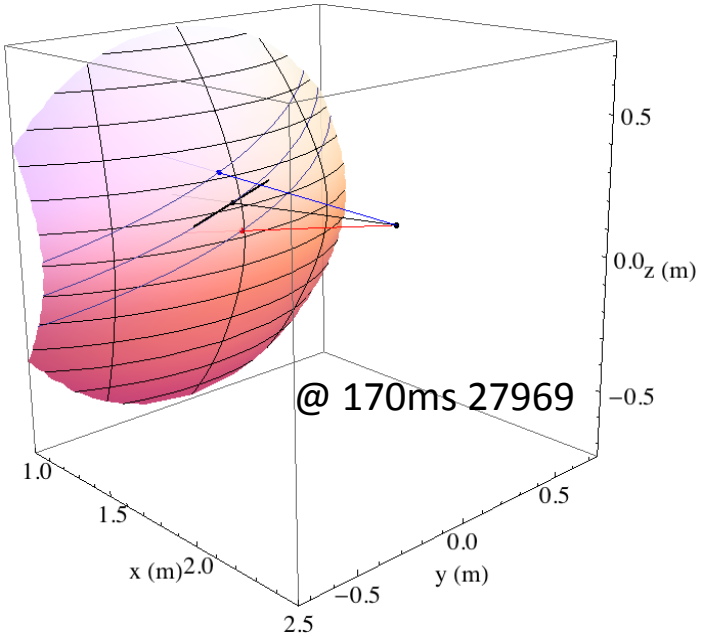
Summary

- SAMI's installation on MAST
  - Reproduced previously observed phenomena from conventional DBS systems
  - First simultaneous 2D image of Doppler backscattering off turbulence
  - Pitch angle measurements

- SAMI's installation on NSTX-U will provide
  - High radial resolution pitch angle profiles in the edge
  - Improved accuracy of pitch angle measurements due to polarization separation

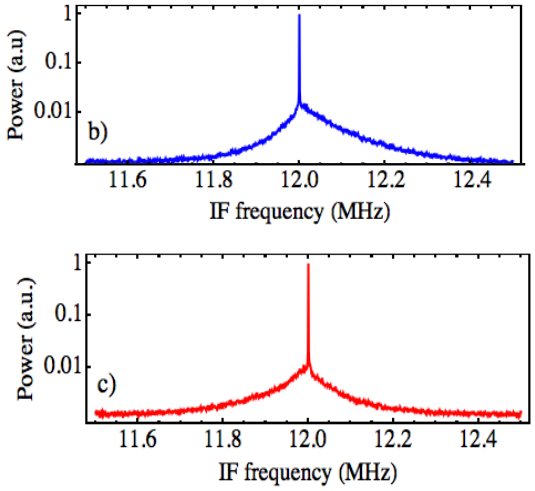
- SAMI has proven the feasibility 2D DBS
  - encouraging for the future development of this field

Comparing SAMI pitch angle measurements with EFIT



- Angle between red and blue maxima bisected
- Ray launched (ray tracing) along the angle between them bisected
- Angle obtained from EFIT at scattering location
- SAMI pitch angle shown in black
- Magnetic pitch angles shown in by blue lines

Data analysis techniques



- SAMI imposes a directional weighting not an absolute spatial filter
- This makes data analysis very different from a conventional DBS experiment
- Plots from location of most red-blue power imbalance aligned at (-8°,-12°) and (0°,-28°) 300 ms into MAST shot 27969
- Large un-shifted power spike
- Continuum of Doppler shifts with low K dominance

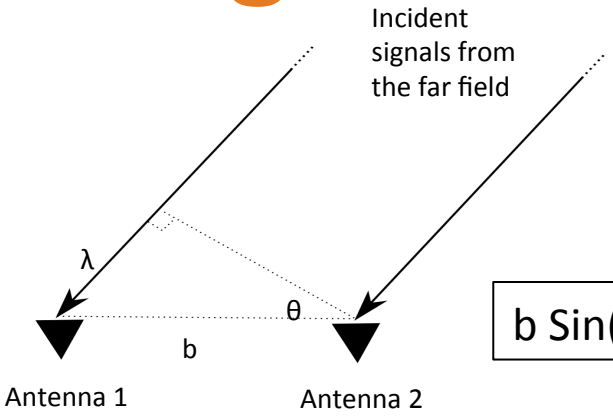
Beam forming

- Phase shifts are applied to each antenna signal such that constructive interference occurs in a specific direction

- Beam is formed by summing together signals from the different antennas with an applied phase shift

$$S^B(t,\ \theta,\ \phi) = \sum_{i=1}^{N} w_i \cdot S_i^A[t; \psi_i(\theta, \phi)]$$

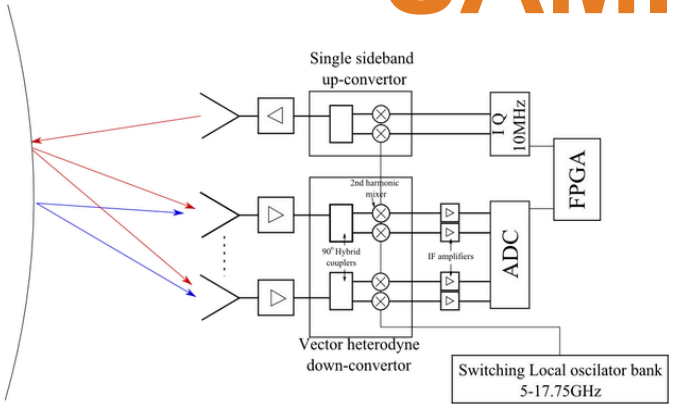
$$I(\theta, \phi) = \left\{ \int_{\Delta t} \mathrm{Re}\left[S^B(t; \theta, \phi)\right] dt \right\}^2$$

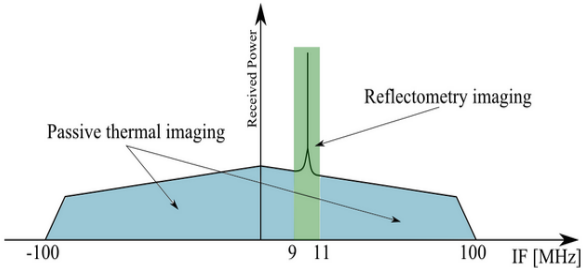


$$b \sin(\theta) = \lambda$$

S_i : signal from the ith antenna
S^B : focused beam signal
θ : horizontal anlge
ϕ : vertical angle
ψ_i : phase difference applied to i^{th} antenna
w_i : normalising weighting factor

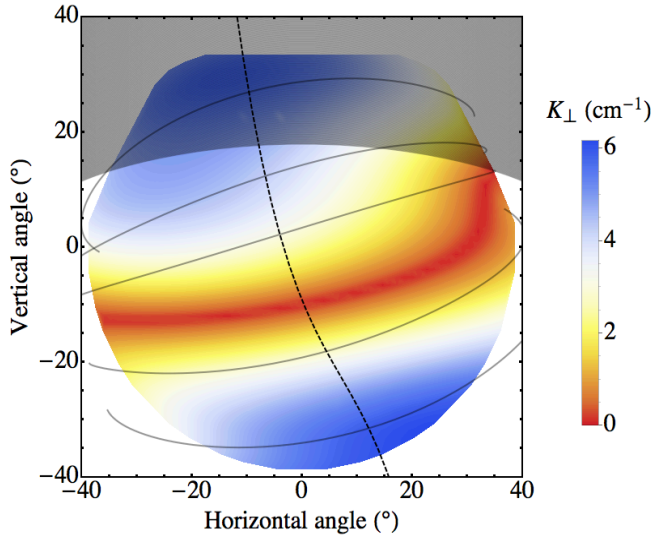
SAMI hardware





- Real and imaginary parts of the electric field are down-converted using a heterodyne receiver and digitised by a 14 bit 250 Mega samples FPGA-controlled digitiser
- A bank of 16 different local oscillators are used allowing imaging 10-35.5 GHz
- 250 Mega sample digitization results in ±100 MHz IF
- Only 1 MHz either side of the active probing signal is used for DBS experiments

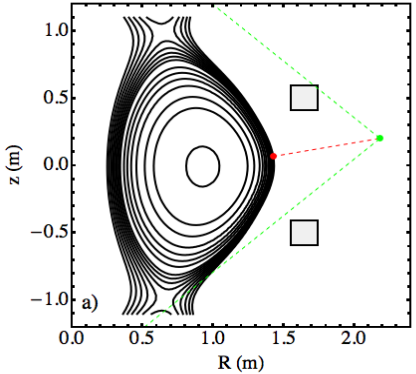
SAMI peak sensitivity K-map



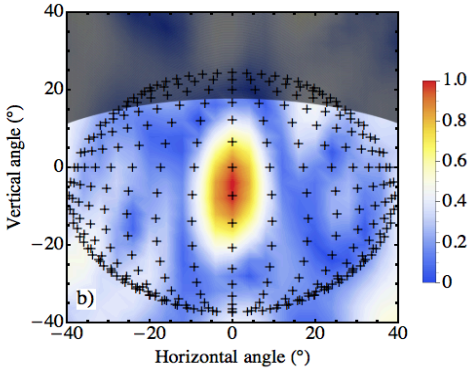
- Backscattering spatially localized at point of minimum wavenumber along path
- Ray tracer code (TORBEAM[1]) used to calculate peak $K_\perp$ sensitivity
- $K_\perp$ shown for 16 GHz probing 230 ms into MAST L-mode shot 27969
- We expect backscattered signal when incident probing beam is incident perpendicular to the magnetic field

[1] E. Poli et al 2001. Comput. Phys. Commun. 136, 90.

SAMI's installation on MAST



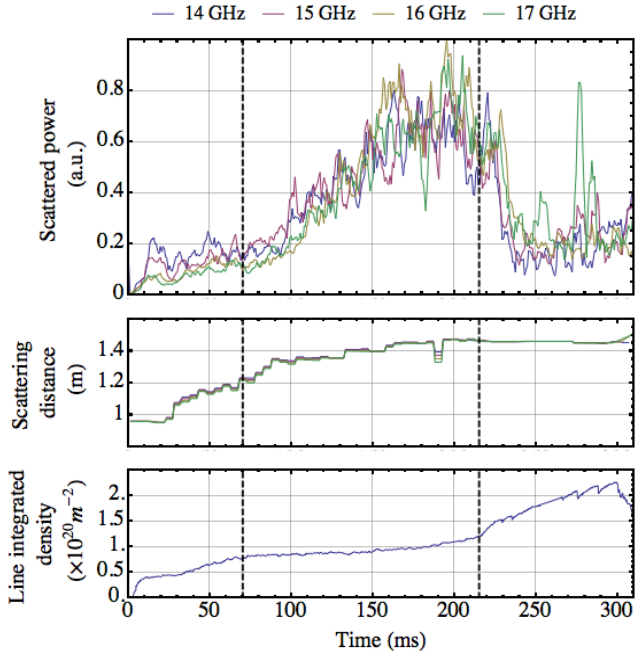
Poloidal-cross section of SAMI's installation on MAST



Normalised intensity of the SAMI point spread function at 16 GHz

- Maxima location accurately reconstructed despite only having eight antennas
- Incomplete side lobe suppression results is signal being measured away from the point source
- Width of beam is defined by the length of the longest baseline
- Effective number of pixels is proportional to the square of the number of antennas

Initial results – backscattered power



- We observed an increase in the power after the NBI is applied (30 ms moving average)
- Scattering distance calculated from TORBEAM
- The increase in the observed power results from the scattering location moving out towards the edge of the plasma and/or the turbulence amplitude increasing
- A sharp drop in the power is observed coinciding with the onset of H-mode
- Caused by suppression in of turbulent structures in the edge region
- Phenomena observed on previous DBS experiments[1]

[1] J. C. Hillesheim et al 2009. Rev. Sci. Instrum. 80, 083507.

Talk structure

- Introduction to the Synthetic Aperture Microwave Imaging Diagnostic (SAMI)
  - Introduction to hardware
  - Using SAMI to conduct Doppler Backscattering (DBS)
- SAMI's installation on MAST
  - O & X-mode cutoffs
- Results
  - Doppler shift off turbulent structures
  - Pitch angle measurements
- Further work & Summary