Optimising the Design of a New Turbulence Probe for MAST-U

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IOP Institute of Physics

ONLINE EVENT

47th IOP Plasma Physics Conference

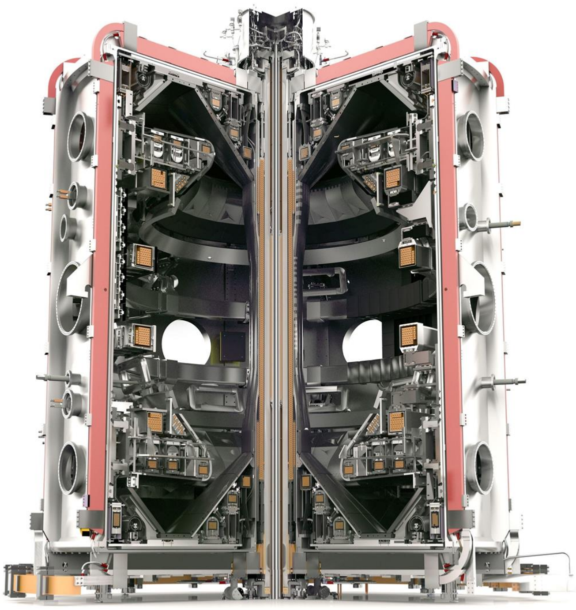
6-9 April 2021

http://plasma2021.iopconfs.org

OUTLINE OF MAST-U, THE SCRAPE-OFF-LAYER, AND PROBES

MAST-U

Mega Ampere Spherical Tokamak Upgrade (MAST-U) is the result of a large upgrade of the previous device, MAST. The upgrade includes a ground-breaking advanced divertor configurations with the aim of reducing exhaust heat flux incident onto the machine walls. To facilitate this, MAST-U has an extended divertor region and additional magnetic coils allowing the machine to create novel divertor field geometries such as a super-x, snowflake, and enhanced leg amongst others. The combination of novel field geometries and the extended divertor region should allow MAST-U to demonstrate detachment, in which the diverted plasma is detached from the core plasma, allowing the injection of neutral particles to aid in further cooling and radiate the excess heat away.



With a new divertor capable of a multitude of configurations comes a need to study the effects of these on scrape-off-layer dynamics, namely how this will affect the filament transport mechanisms. It is imperative to explore filaments in these scenarios to enhance our understanding with a new probe targeted at measuring filaments.

MAST Upgrade new parameters:

Parameter	MAST	MAST Upgrade 1st Stage	MAST Upgrade Final Stage
Major radius (m)	0.85	0.85	0.85
Minor radius (m)	0.65	0.65	0.65
Plasma current (MA)	1.3	1.5	2.0
Magnetic field at R=0.85m (T)	0.52	0.6	0.75
Total NBI power (MW)	3.8	3.5	5.0
On-axis NBI power (MW)	3.8	2.0	2.5
Off-axis NBI power (MW)	0.0	1.75	2.5
Pulse length (s)	0.6	2	5

Table (1): Key parameters of MAST that are planned to be upgraded for the 1st and final stages of MAST-U.

MAST-U achieved first plasma in November last year and the 1st experimental campaign is scheduled to start at the end of April.

SOL

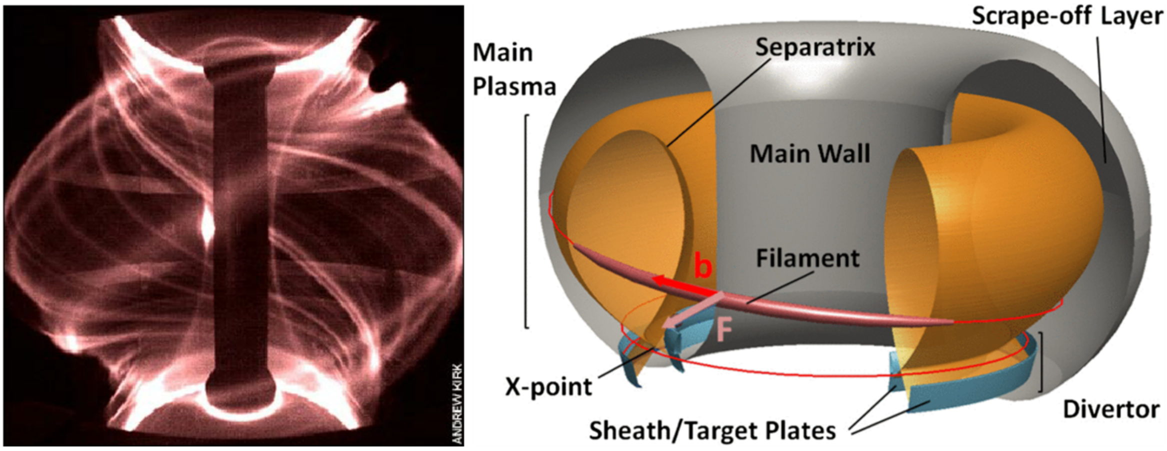
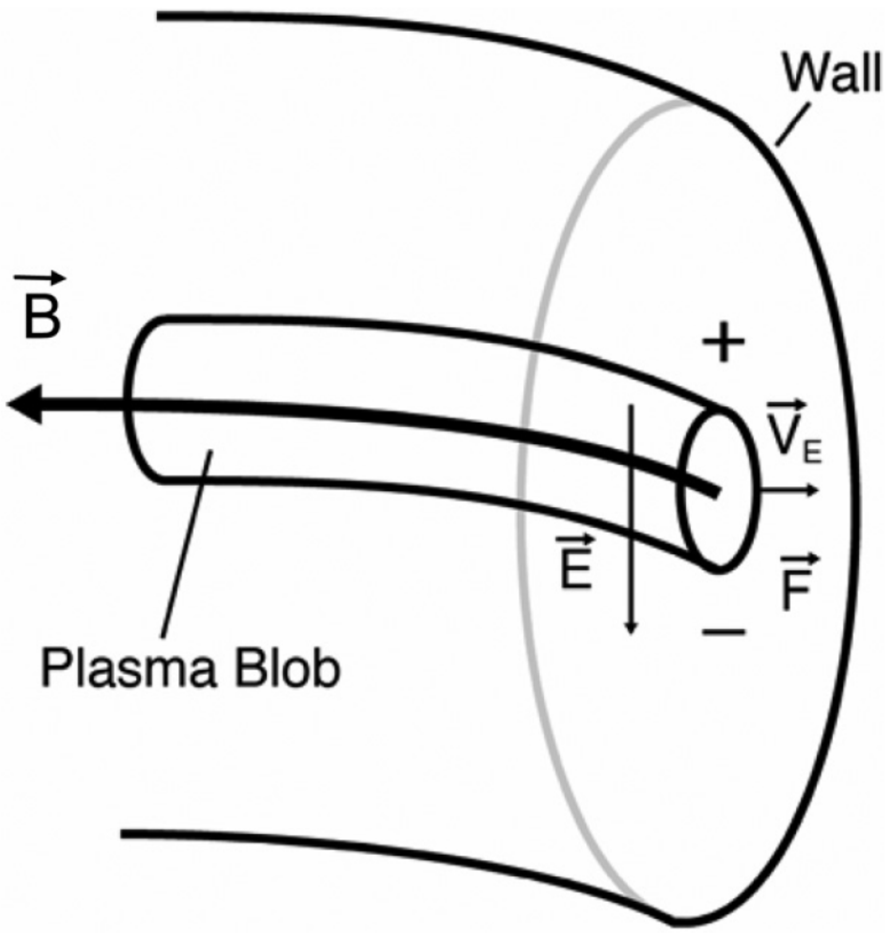


Figure (2): Left is a fast-shutter image of filaments in MAST. Right is a schematic showing a filament propagating in the SOL of a tokamak.

The scrape-off-layer (SOL) in a tokamak is the region just outside of the last closed flux surface. The SOL is a very turbulent region of the tokamak with turbulent modes existing in a broad range of length scales. Fast moving, density profiles known as filaments, blobs, or intermittent plasma objects dominate particle and heat transport in this region. To maintain consistency, we will refer to these fluctuations as filaments. Filaments are field-aligned regions with a density higher than the background plasma density, they propagate toroidally at high speeds and radially with an ExB drift, on the order of several km/s [D'Ippolito paper].

Figure (3): Drawing of a filament demonstrating charge separation, creating the internal poloidal E field in turn creating the ExB velocity that propagates the filament radially.



Probes

Langmuir probes measure electrical fluctuations in plasma. They operate in three distinct modes.

- Floating potential - where the probe is left electrically floating in the plasma. This measures the floating potential of the plasma.
- Swept mode - sweeping the probe potential with a range of voltages measuring the current creating an IV curve to understand average temperatures and densities of the plasma.
- Biased - a constant bias potential, usually chosen from previous sweep profiles to understand a particular plasma property.

$$V_p = V_f + \alpha T_e \qquad (1)$$

$$I_{sat} = \frac{1}{2} A e n_e C_s \quad \text{where: } C_s = \sqrt{\frac{T_i + T_e}{m_i}} \qquad (2)$$

$$V_+ = V_f + \ln(2) T_e \qquad (3)$$

Langmuir probes are primarily used to directly measure plasma properties such as the electron temperature (T_e) and electron density (n_e) shown in equations (1-3) above. The Ball-Pen probe (BPP) is a novel probe [nick BPP] that can be used to directly measure the plasma potential by reducing the ratio between ion and electron saturation currents to zero with the expression in (4) applied to equation (1) as described in [Walkden, Adamek paper].

$$\alpha \propto \ln \frac{I_e}{I_i} \approx 0 \qquad (4)$$

Common techniques for time series data from Langmuir probes are:

- Probability distribution function (PDF) - its shape is used to infer properties of the plasma
  - To quantify the shape the skew and kurtosis are taken of the PDF.
- Cross correlation and coherence – for probes in close proximity used to gauge if they are measuring the same fluctuations in the plasma.
- Power spectra of probes are typically used to measure the presence of turbulent modes.

MOTIVATION FOR RESEARCH

The MAST-U reciprocating probe system (RP) allows a suite of interchangeable probe heads; Mach probe, Ball-pen probe (BPP) and Retarding Field Analyser (RFEA). These probes are inserted into the plasma to a maximum of 10cm in depth and withdrawn again on a short timescale to prevent damage to the probe and reduce plasma disruption. Of the probe heads available to MAST-U, none are specifically designed for turbulence studies.

Design parameters:

Design Parameter	Constraint
Power supplies available for probes	9
Diameter of probe head	50mm
Shell thickness	6mm
Probe retainer diameter	37.5mm
Probe base diameter	4mm

We want to create a probe for MAST-U specifically targeting turbulence, design based on simulations for optimal data collection of specific turbulent features.

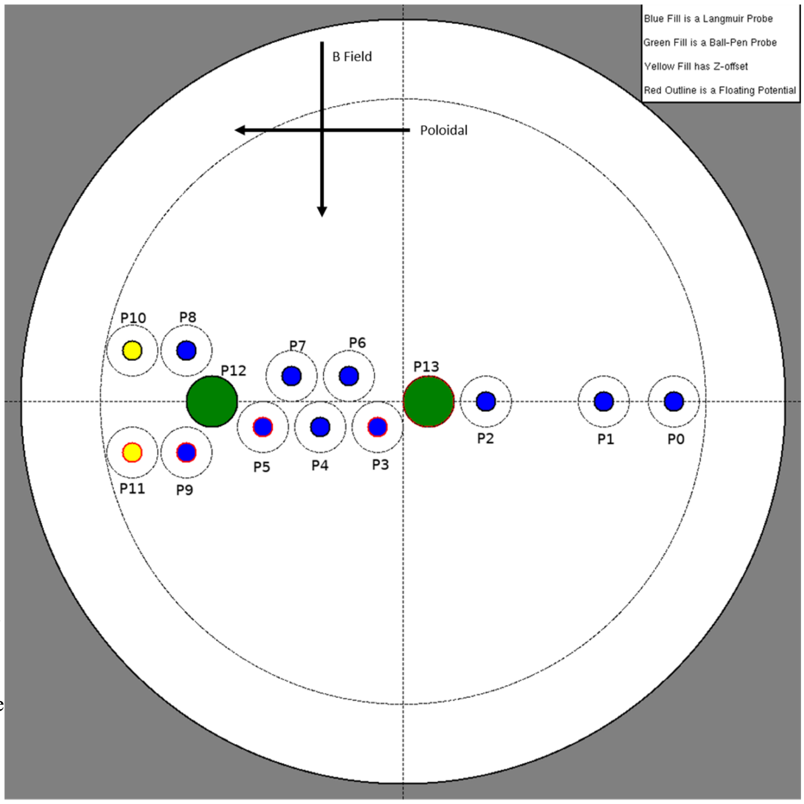
What are we looking for?

- Filaments
  - Density fluctuations
  - Temperature fluctuations
  - Plasma potential
  - Velocity
- Other Turbulent Features
  - Broad band turbulent structures

APPROACH

The current design consists of:

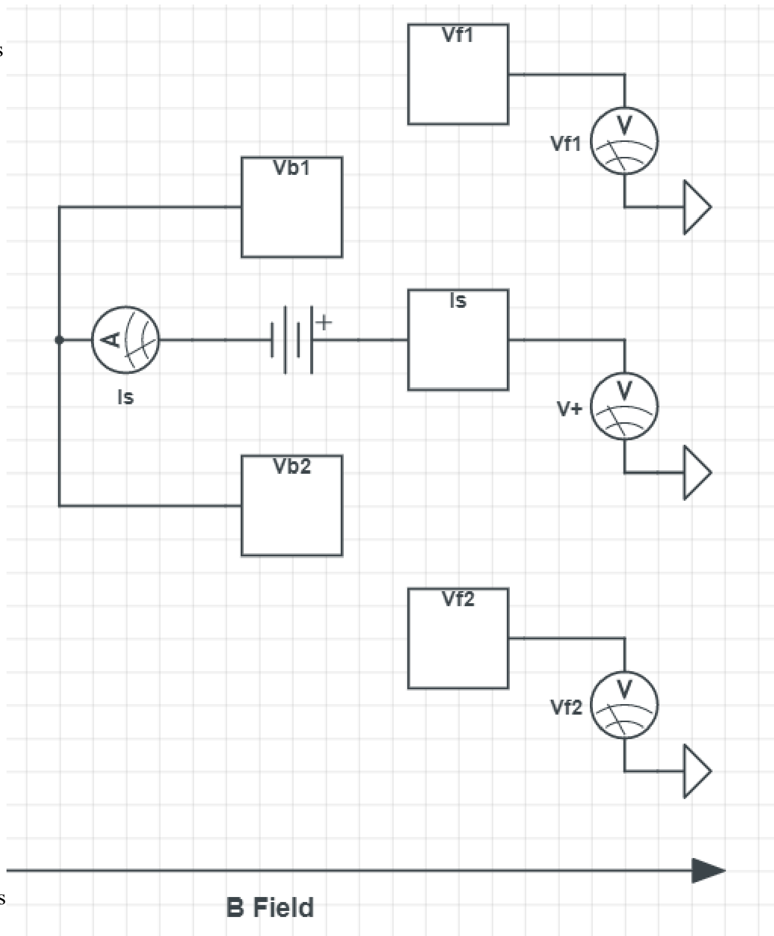
- 14 probes 7 are powered.
- Roughly log-spaced probes along poloidal axis, increases turbulent scale resolution.
- Biased ball-pen probe to directly measure plasma potential, floating BPP to estimate T_e.
- 5-pin balanced triple probe array between BPPs. Array allows increased accuracy of T_e measurement hence improved accuracy for density and plasma potential calculations.
- Radial offset probes add radial dimension to measurements, additionally allow decoupling of radial velocity from velocity measurements.



Along the poloidal axis there are several probes logarithmically spaced such that the scale resolution of turbulent modes is increased. Two BPP are located on the probe one biased, to measure plasma potential directly from equation (1). The other left floating allows an estimation of T_e.

Between these is a 5-pin balance triple probe array [ref Nicola, Tsui paper] wired in such a fashion as seen in the schematic (5).

In this configuration the two outside probes are left floating whilst the centre pins are connected to one power supply and sufficiently biased. This design allows the floating probes to be averaged, reduces the phase delay contribution and to the measurements and allows the measurements to be treated as a single point measurement centred on the Is probe.



From this configuration, equation (3) thus becomes equation (5) as Tsui et al demonstrate [Tsui]. The layout is placed in such a way to reduce shadowing effects along the B field. The 5-pin balanced triple probe array can be used to measure the plasma potential, shown in equation (1). The array is placed tightly between the BPPs aiming to measure the same filaments allowing for a greater confidence in the measurements.

$$V_+ = V_{fav} + \ln(3)T_e \quad \text{where: } V_{fav} = \frac{V_{f1}+V_{f2}}{2} \qquad (5)$$

To try to add further depth to measurements there are two probes that are sunk lower into the probe adding a radial component to measurements. We have also been able to utilise this information in unison with nearby probes to decouple velocity measurements into their radial and poloidal components. Using simple geometry, we calculate these velocities shown in the equations below (6-8).

$$v_\theta = \frac{t_2-t_1}{d_{\theta_{12}}} \qquad (6)$$

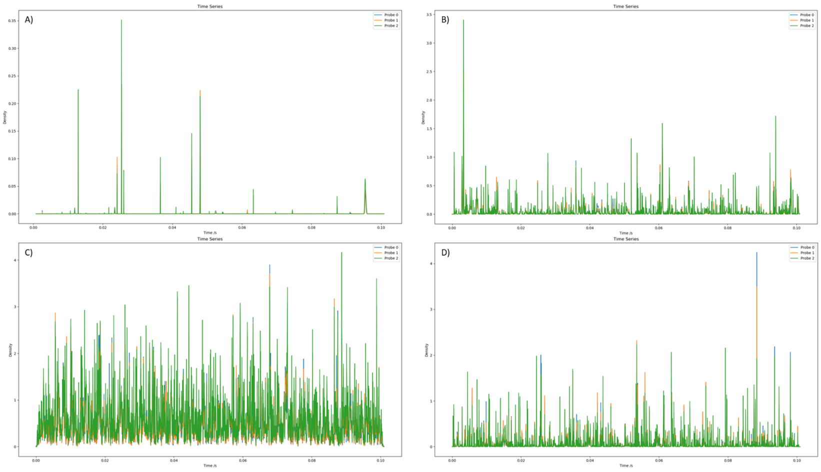
$$v_{rad1} = \frac{t_1-t_{rad}}{\sqrt{d^2_{\theta_{rad1}}+d^2_{z_{rad1}}}} \qquad (7)$$

$$v_R = \sqrt{v^2_{rad1} - v^2_\theta} \qquad (8)$$

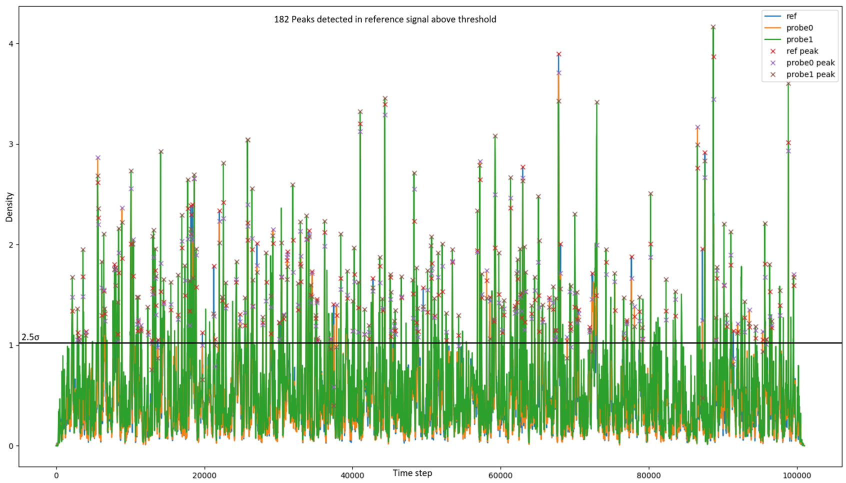
To assess the synthetic probe for filament measurements we are using the Stochastic filament model developed by F. Militelo and J.T. Omotani [Fulvio paper]. The model allows great control with the large parameter space available, making it very suitable for our needs, we can test various scenarios to maximise the confidence in the potential information captured by the probe. We will test the effectiveness of the synthetic probe in high, medium, and low intermittency. Additionally, we will explore the velocity measurement robustness with several suitable modifications to the velocity component distributions.

RESULTS SO FAR

Figure (6) shows the timeseries produced from running the stochastic filament code with 500, 20,000 and 200,000 filaments spawned in A-C, and D shows a timeseries from a simulation containing 20,000 filaments with higher input radial and toroidal velocity distributions. Clearly more filaments spawned by the simulation allows a higher proportion to be detected by the probe array and increasing the filaments velocity distribution allows more filaments to move across the probe array.



The analysis used in figure (7) found 182 peaks in the reference timeseries signal above the 2.5 standard deviations then within a window of 240 timesteps looks for peaks in the other probe signals, selecting the peaks closest to the reference peak. From equations (6-8) above the absolute velocities are calculated as shown in figure (8).



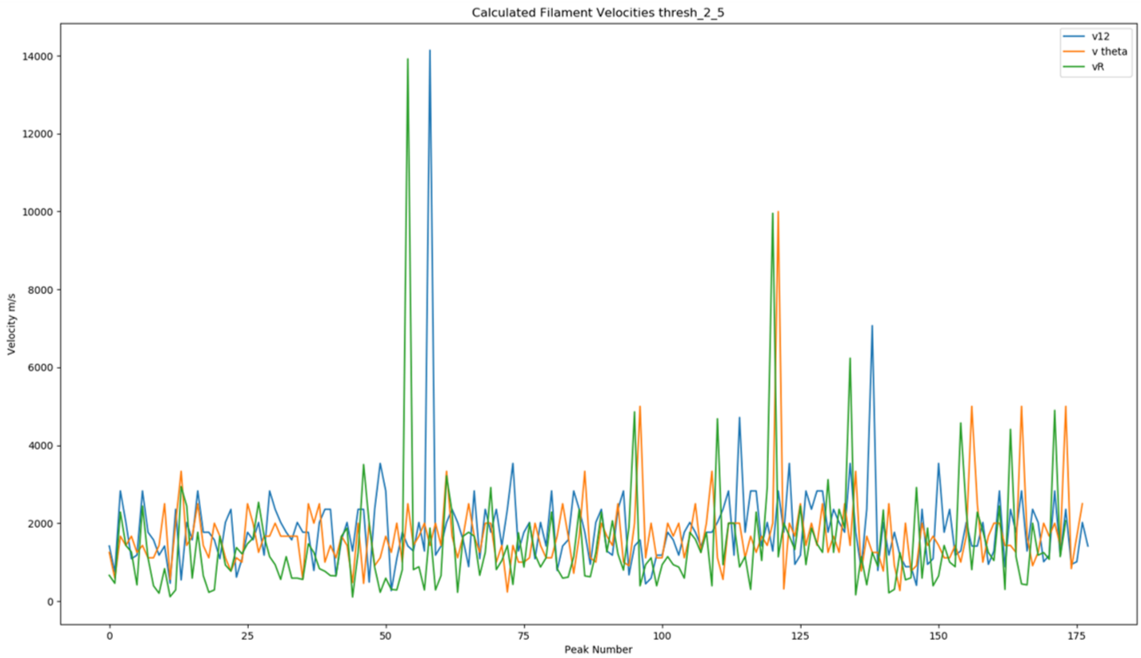


Figure (8): Absolute value velocities calculated via equations (6-8) for the peaks detected in the 200,000-filament run.

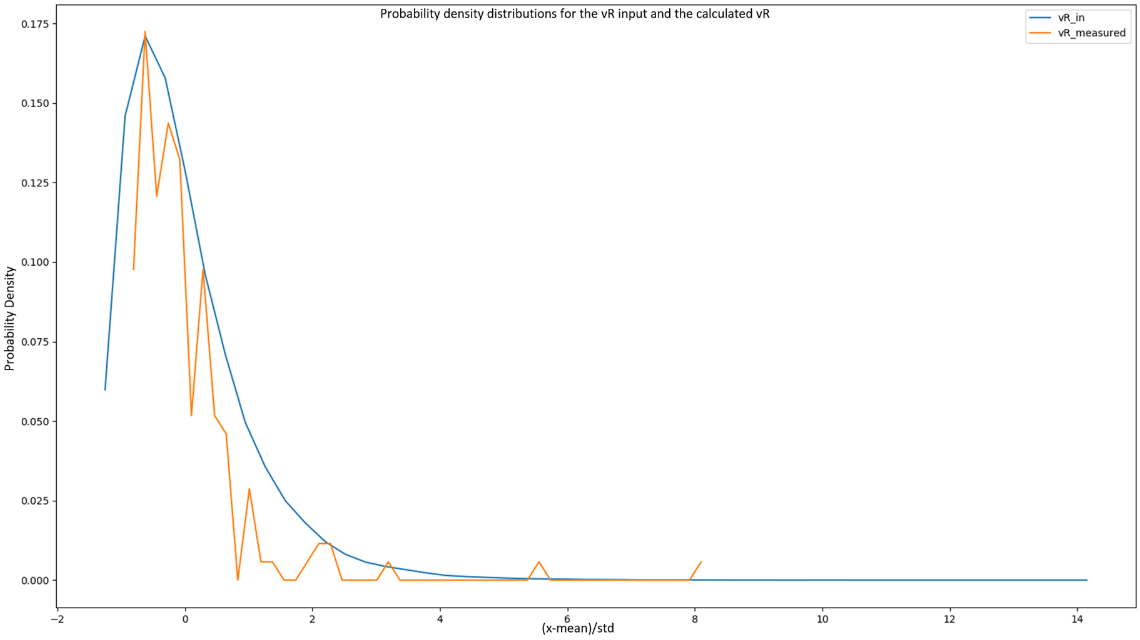


Figure (9): The probability distributions for the radial velocity distribution that was input into the simulation versus the radial velocity distribution calculated from the peaks that were detected in the timeseries data for the 200,000-filament run.

FUTURE WORK

The continued work will further study different design aspects of the probe and how they affect the ability to measure the various turbulence modes discussed previously. Using the probe designs in conjunction with other simulation models to confirm design suitability. There is also scope to test effectiveness of the analytic techniques discussed here on other datasets to ensure they are in good agreement with other analytical work.

Once an informed design is settled upon, the UKAEA drawing office will be consulted and a production design finalised. The completed probe is targeted for experiments in the MAST-U second physics campaign starting around late 2022. The probe will operate on the midplane RP targeting the SOL of MAST-U. These experiments will aim to collect data to assess probe performance and collect information on turbulence in the SOL including filaments.

AUTHOR INFORMATION

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ABSTRACT

With MAST-U's first plasma achieved in November 2020 and one of the key aims of the first experimental programme being to study exhaust physics, there is strong motivation to develop a new probe designed specifically for studying edge turbulence effects in the exhaust region of MAST-U. To create a new versatile probe, the design will be validated synthetically on a variety of edge turbulence simulation data. This study uses both a simple 2D Hasegawa-Wakatani drift wave model alongside a 3D stochastic filament model to test the fidelity of measurements made and to optimise the design of the probe. To quantify the data, a synthetic diagnostic for differing probe geometries and analytic techniques to leverage these different geometries was used based on the wavelet Beall Algorithm analysis. To increase the versatility of the probe several layouts have been factored into the design to allowing the ability to measure a variety of turbulent structures. The probe will be able to directly measure the electric potential of the plasma utilising two ball pen probes [1] in close proximity to a five-pin balanced triple probe array [2] to ensure good agreement. Additionally, probes are generally spaced logarithmically in the poloidal direction allowing an increased scale resolution for detection of various turbulence modes. Included are two radially offset probes close to some non-offset probes adding additional dimensionality. The results of this synthetic analysis will be compared between different probe designs to understand the efficacy of measurements made, and to determine an optimal design before the probe is fabricated. There is scope for additional future simulation studies using the STORM2D module of the BOUT++ model to increase the range of physics models considered, alongside experimental data to aid in validation of the final design.

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Funding

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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