Design of a Four-Pin Triple Langmuir Probe for the Pi3 Spherical Tokamak at General Fusion Inc.

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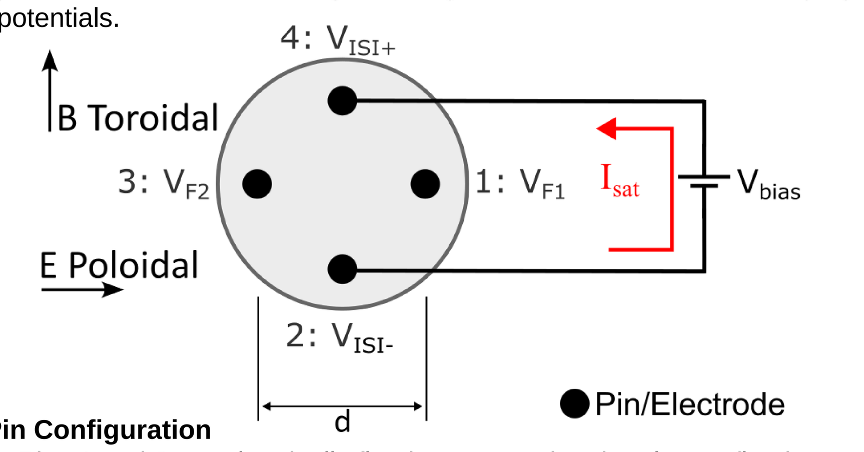
Introduction

General Fusion endeavors to generate power at commercial scale through Magnetized Target Fusion (MTF) via a liquid metal liner compressing a plasma target [5; A. Mossman et. al., Poster **UP11.00144**; C. P. McNally et. Al., **Poster UP11.00006**]. The Plasma Injector 3 (Pi3) is a spherical tokamak with lithium coated walls generating plasma by Coaxial Helicity Injection (CHI). The Pi3 experiment aims to characterize the confinement and stability properties of target plasmas to be compressed by a liquid lithium liner in the Fusion Demonstration Program (FDP) at Culham, UK. We have designed and employed a four-pin triple Langmuir probe on Pi3 to study the effects of lithium wall conditioning on plasma properties in the Scrape Off Layer (SOL) up to the Last Closed Flux Surface (LCFS).

Pi3 Experiment Parameters			
Major Radius	0.64 m	Te	270 eV
Minor Radius	0.35 m	Heating	Ohmic
Magnetic field at Axis	0.37 T	Wall Conditioning	Solid Lithium (~5um)
Plasma Current	350 kA	Pulse Time	~25 ms

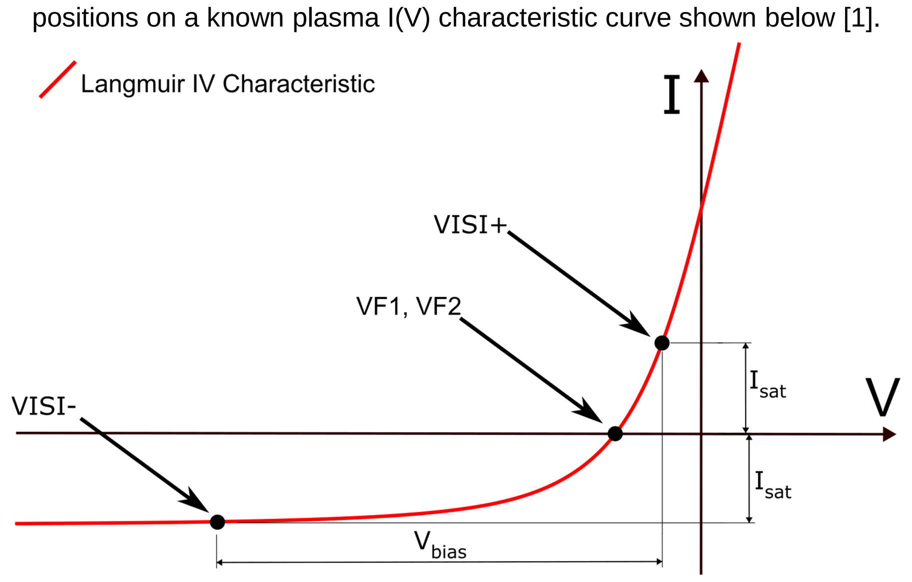
Four-Pin Triple Langmuir Probe Theory

A Langmuir probe is a physical diagnostic making direct contact with the plasma. We have employed a four-pin triple Langmuir probe which takes plasma measurements using four tungsten electrodes biased to varying potentials.



Pin Configuration

- Pins 1 and 3 are electrically floating, measuring the plasma floating potential.
- Pins 2 and 4 are held at a constant potential difference inducing current to flow between the pins through the plasma. The current is known as the Ion Saturation Current (Isat).
- The voltages and currents developed by the electrodes correspond to positions on a probe I(V) characteristic curve shown below [1].



$$I = n_\infty e A_p \left(\frac{T_e}{m_i}\right)^{1/2}\left[\frac{1}{2}\left(\frac{2m_i}{\pi m_e}\right)^{1/2}\exp\left(\frac{eV_0}{T_e}\right) - \frac{A_s}{A_p}\exp\left(-\frac{1}{2}\right)\right] \quad [1]$$

- The IV characteristic is valid for the ion saturation region in which the probe operates. Time-resolved plasma characteristics can then be extracted by fitting the IV characteristic to the electrode data via the triple probe method [2].

Plasma Parameter Equations and Assumptions

$$T_e = \frac{V_{ISI+} - V_f}{\ln 2}$$

$$n_e = K I_{sat} T_e^{\left(\frac{-1}{2}\right)}$$

$$V_p \approx V_f + 3.3T_e$$

$$E_\theta \approx \frac{V_{f1} - V_{f2}}{d}$$

$$\Gamma = < \tilde{n}_e \frac{\tilde{E}_\theta}{B} >$$

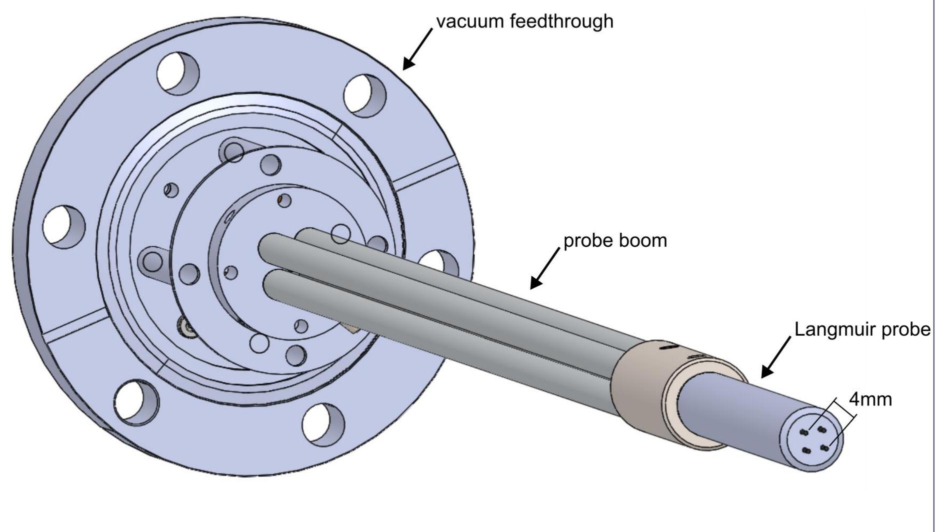
T_e	Electron Temperature
n_e	Electron Density
V_p	Plasma Potential
E_θ	Poloidal Electric Field
Γ	Crossfield Particle Flux

- Electron temperature calculation assumes electrons obey a Maxwellian distribution and V_{bias} remains on the same order of magnitude as T_e in electron volts.
- The density expression depends on a geometry factor, K, which must be adjusted for sheath effects around the electrodes. Further analysis is required to properly correct for sheath effects.
- The poloidal electric field calculation assumes that the electron temperature is uniform across the probe face.
- The cross-field particle flux is estimated based on the correlation of the density and poloidal electric field fluctuations.

Mechanical Design

The vacuum-facing assembly consists of three components:

- A plasma-facing probe composed of a boron nitride head and tungsten electrodes.
- A boom supporting the probe and providing electrostatic shielding.
- A vacuum feedthrough interfacing with a vacuum bellows system to position the probe within the vacuum vessel.

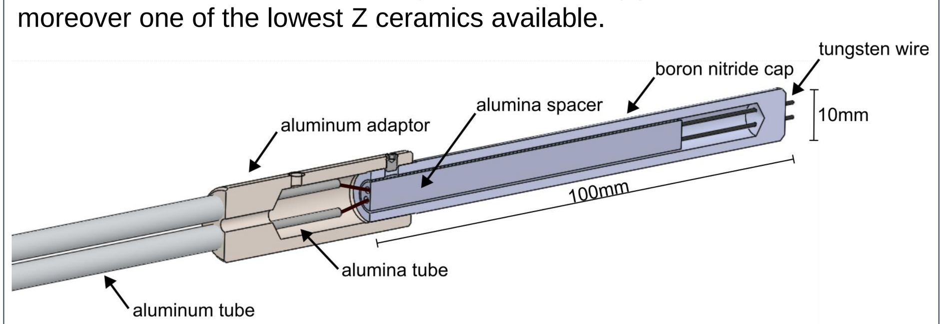


- The probe boom and bellows system is dimensioned such that the probe can be protected behind a gate valve during lithium coating.

Plasma Facing Materials Requirements

- Materials must have high working temperatures
- Materials must be highly resistant to thermal shock
- Materials must be vacuum compatible
- Low Z (atomic number) materials are preferred

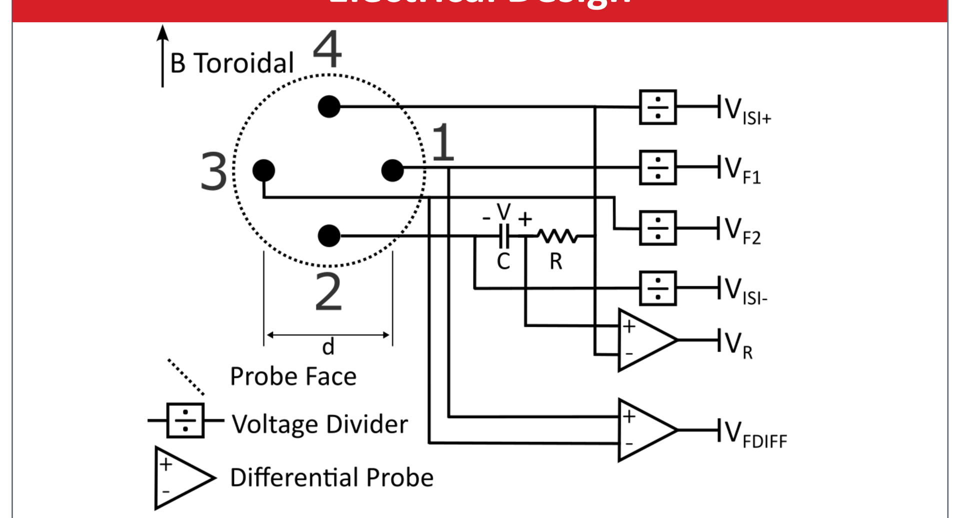
Tungsten electrodes have proven robust. An alumina ceramic head was initially employed, but the alumina shattered during operation. Thermal modeling suggests thermal shock as the failure mechanism. Hexagonal boron nitride (BN), with its higher thermal conductivity, was chosen to better withstand the shock heating occurring during plasma shots. BN is moreover one of the lowest Z ceramics available.



Internal structure

- Maintains electrical isolation and shielding for each W electrode.
- Avoids incurring thermal stress upon rapid non-uniform heating of probe components.

Electrical Design

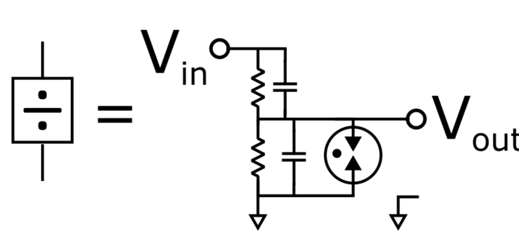


Langmuir Probe Bias and Readout Circuitry

- Maintains a stable 50-100 V bias potential using a 2mF capacitor bank.
- Measures a 5-1000mA ion saturation current by sense resistor, R = 10 Ohm, rejecting common-mode fluctuations on the order of 200V.
- Prevents crosstalk, EMI, and common-mode voltage swings from obscuring the probe's signals via continuous electrostatic shielding and passive signal conditioning.
- Maintains isolated grounding referenced to Pi3's vessel wall.

Passive High Voltage Dividers

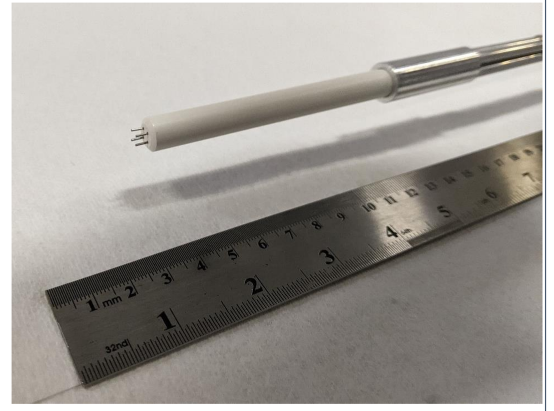
- 20:1 voltage division
- Capacitively compensated for frequency-independent operation up to 20 MHz.
- Gas Discharge Tube (GDT) for scope protection.



Langmuir Probe

Mechanical Assembly

- Probe components were first cleaned and baked out in preparation for vacuum.
- Boron nitride's graphite-like fragility required extreme care during assembly.
- Several BN heads were broken before a successful assembly procedure was developed.

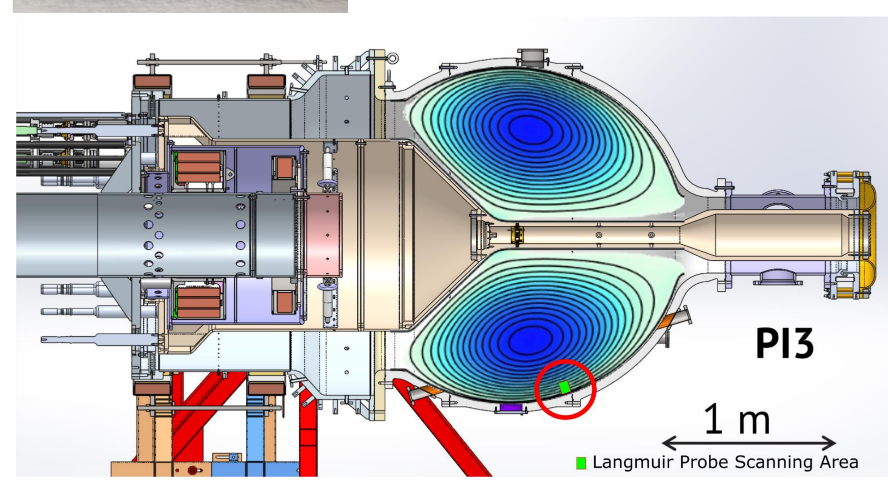


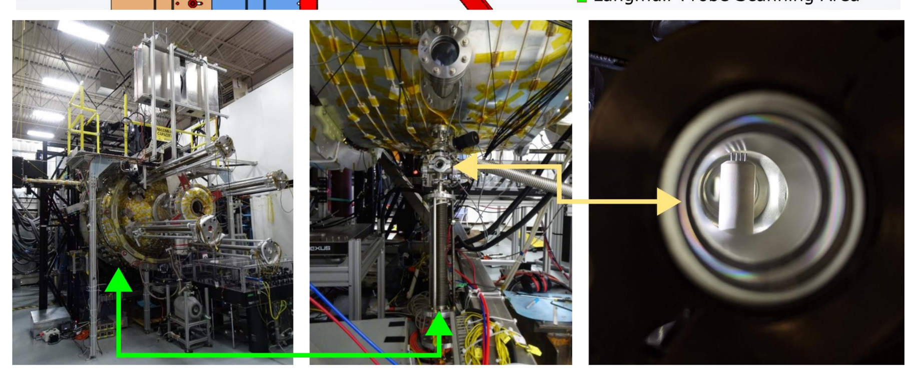
First Operation

- Installed on Pi3, the probe produced its first data on August 22, 2022
- Radial sweeps have been performed under various lithium wall conditions.
- Hundreds of shots later, the BN head and W electrodes show no obvious sign of degradation.
- The success of boron nitride as a plasma-facing probe material validates its use for a planned ion-sensitive probe for Pi3.

Probe Head Parameters

- BN face diameter of 10 mm.
- W Electrode diameter of 0.635 mm.
- Electrode length of 3.0 mm.
- Electrode interspace, d = 4.00 mm (between diagonally opposed electrodes).

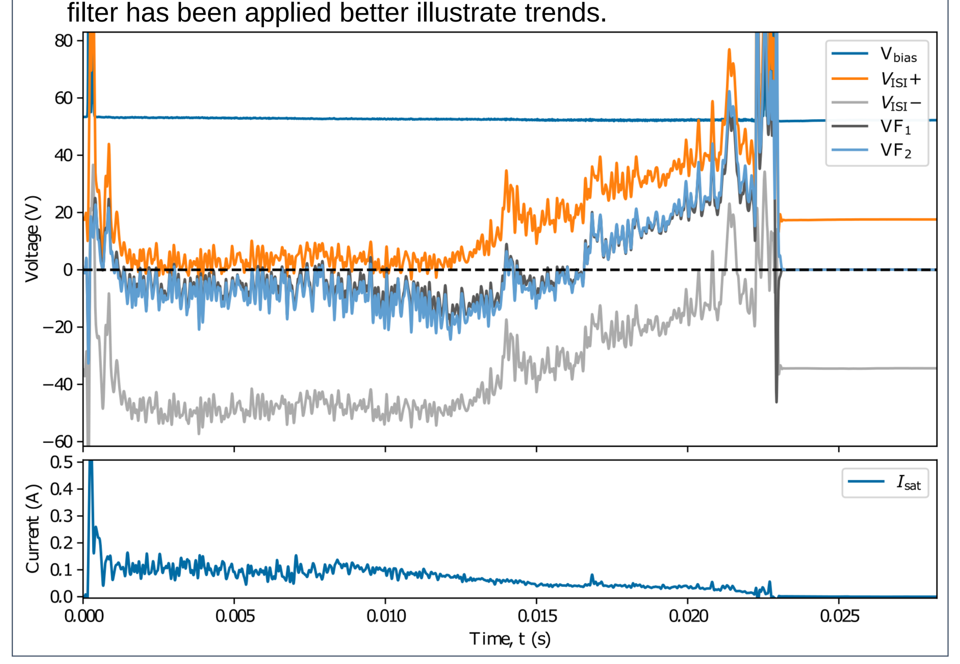




The probe's installation and operating region is illustrated above. The probe's depth is limited by the probe's ability to withstand plasma heat flux and its disturbance to the plasma.

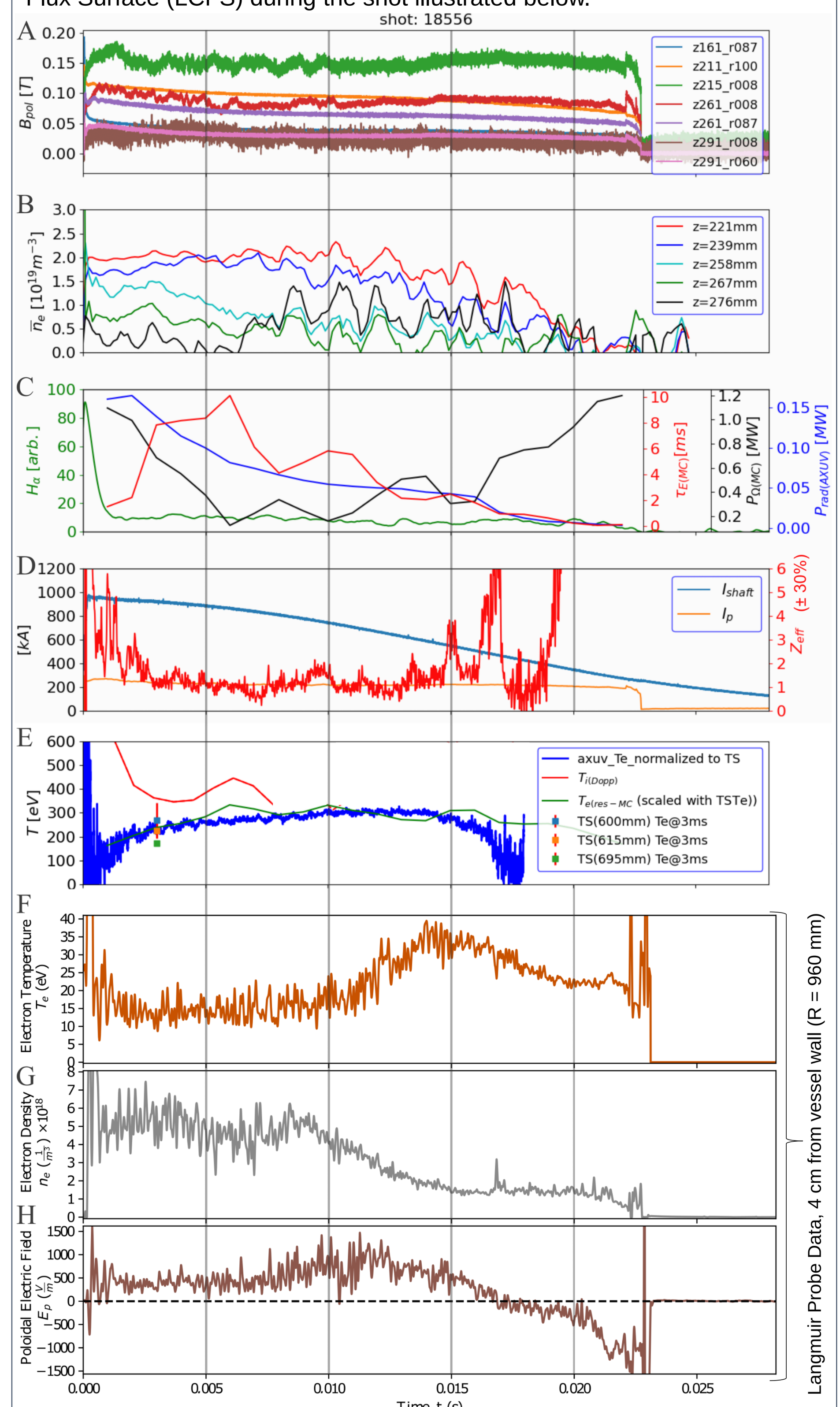
Shot Analysis

- Raw electrode voltages and ion saturation current signals for a Pi3 shot (18556) with a fresh lithium coating and the Langmuir probe protruding 4cm from the vessel wall (R=960mm) are shown. A 10 kHz lowpass filter has been applied better illustrate trends.



Shot Analysis (Continued)

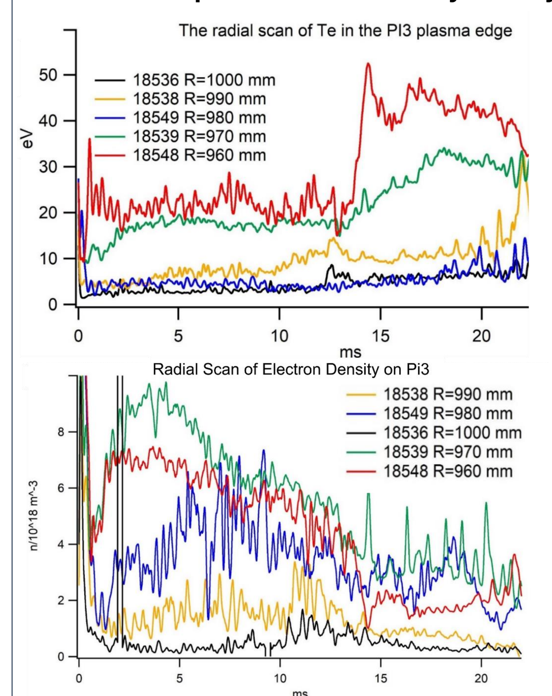
The raw Langmuir measurements are converted to plasma parameters and compared to the plasma parameters inferred by Pi3's other diagnostics. Based on plasma reconstruction, the probe has just pierced the Last Closed Flux Surface (LCFS) during the shot illustrated below.



- **A**–Poloidal B field measurements, see F. Braglia, et al **UP11.00008**.
- **B**–Electron density chords from CO2 interferometer, large fluctuations due to mechanical vibrations.
- **C**–Hα is hydrogen atom spectral emission; τ_E, energy confinement time, from magnetic energy decay model from equilibrium reconstruction. resolved by Monte Carlo method, see Ryan Zindler et al **BP11.00003**; P_Ω is the ohmic heating power in the plasma due to changing magnetic fields estimated from equilibrium reconstruction.
- **D**–Plasma current inferred by Mirnov coils (A); shaft current; Zeff by combining several diagnostics (~30% uncertainty).
- **E**–AXUV T_e is scaled to Thomson scattering measurement at 3ms.
- **F**–Electron temperature measurement begins increasing around 10ms with a peak at 15ms, corresponding to the fastest decay of shaft current. The shaft decay results in toroidal B field decay, inducing a poloidal electric field (~20 V/m) at the plasma edge which may accelerate electrons into a non-thermal distribution. The triple probe method assumes a Maxwellian distribution, leading to an overestimation of temperature in the presence of high energy electrons.
- **G**–Electron density is related by inverse square root to temperature, so an overestimated temperatures leads to an underestimated density after 10-15ms, though we have yet to account for sheath effects.
- **H**–Poloidal electric field is estimated by taking the difference of floating potentials assuming that the temperature across the probe face is constant. The ~500V/m DC component of E_p is much larger than the expected ~20V/m E_p due to B_t decay; however, DC convective structures have been observed near tokamak LCFSs [3] with significant T_e variation over mm scales which could account for the observation. Crosstalk from the current flowing between VISI+ and VISI- or crosstalk from radial E field (~750V/m inferred by V_p radial profiles) may also contribute.
- See poster **PP 11.00090** by C. Ribeiro, et al for an overview of transport studies on Pi3.

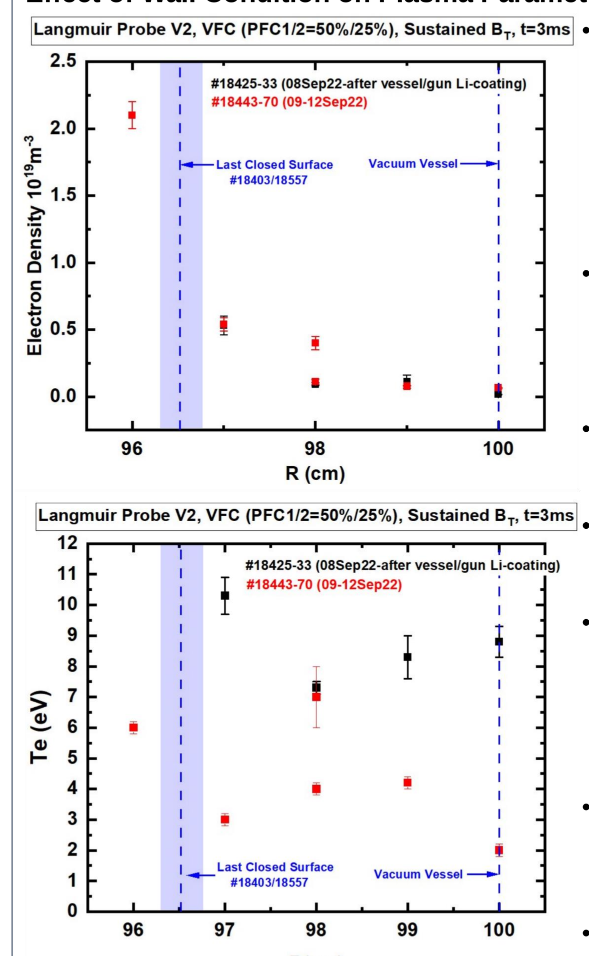
Pi3 Radial Profiles

Electron Temperature and Density at Varying Radial Position



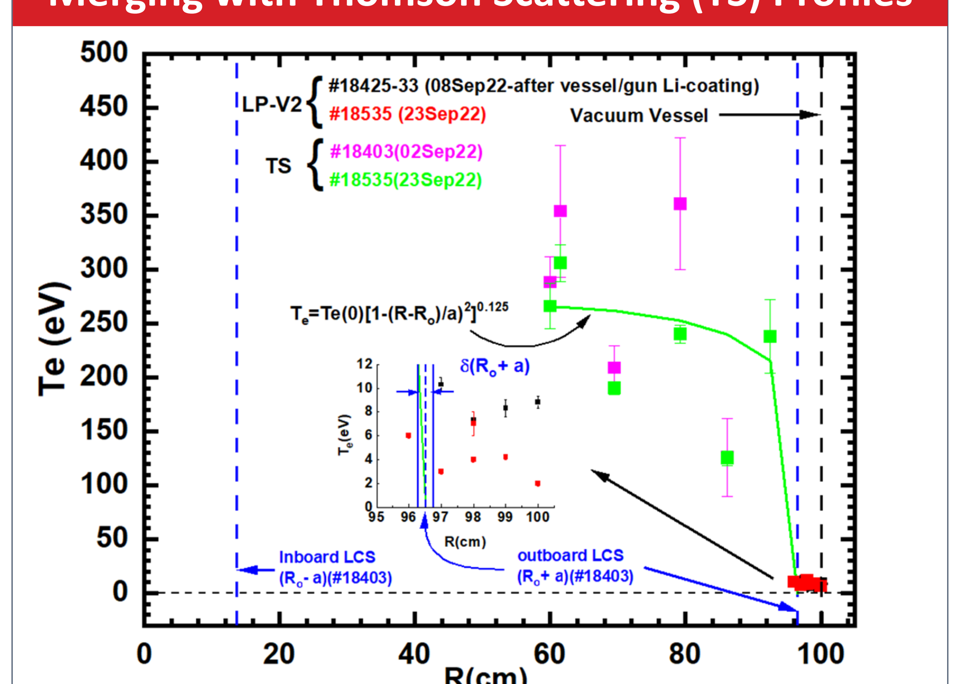
- Radial scans of the SOL can be performed by adjusting the probe's radial position between plasma shots with identical machine settings.
- Shots numbered 18536-18549 were taken after a fresh lithium coat was applied to Pi3.
- We see a monotonic increase in both density and temperature as we approach the LCFS.
- Anomalous increase in T_e after 10-15ms is seen at various probe depths.

Effect of Wall Condition on Plasma Parameters from SOL to LCFS



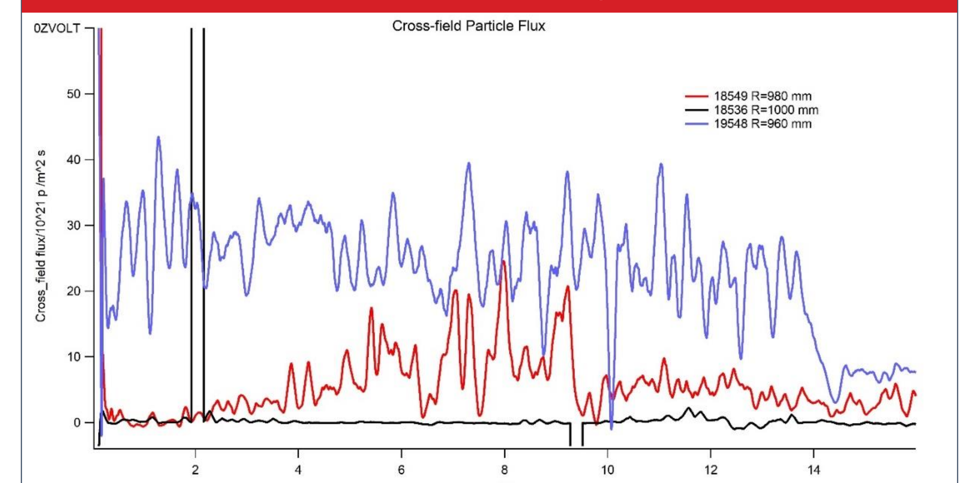
- A radial scan of the plasma with a fresh lithium wall coating (black data points) is compared to a radial scan after that coating has been worn (red data points) under identical machine settings.
- Density is relatively low in the SOL even without sheath corrections, evidence of a low recycling regime.
- The density profile is relatively unaffected by changing wall conditions.
- The electron temperature measurement is higher for the fresh wall coating.
- Based on plasma reconstruction, the Langmuir probe has pierced the LCFS at R=96cm, with an accompanying increase in temperature and density.
- Further experiments are required account for shot to shot variation in these profiles.
- Uncertainty bars based on local parameter variation around t=3ms.

Merging with Thomson Scattering (TS) Profiles



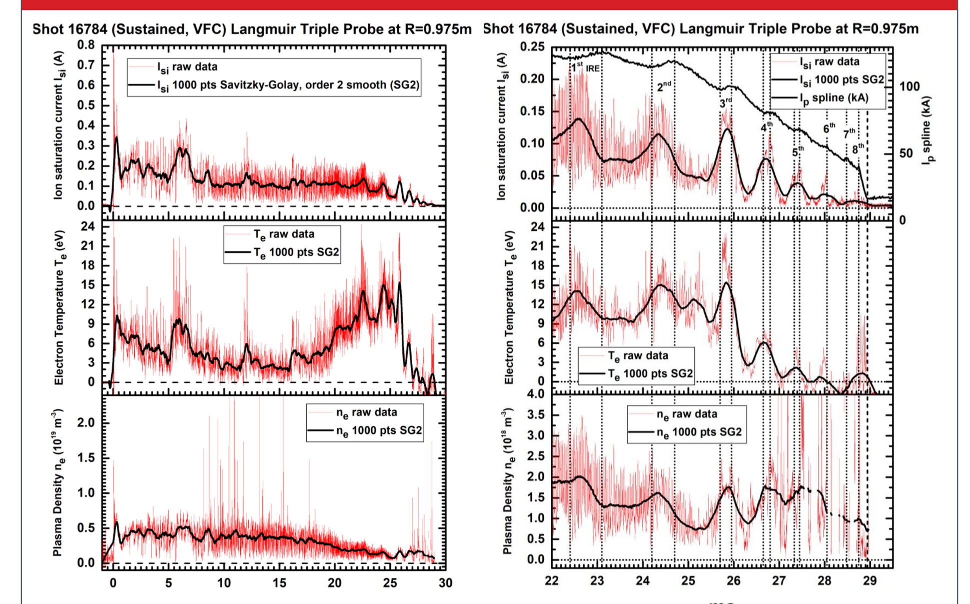
- A flattish Te profile from TS is similar to measurements seen on LTX and provides evidence for a low recycling regime due to lithium coating on both devices [4].
- Further experiments will be required to precisely define to the electron temperature profile throughout the plasma.

Turbulent Transport



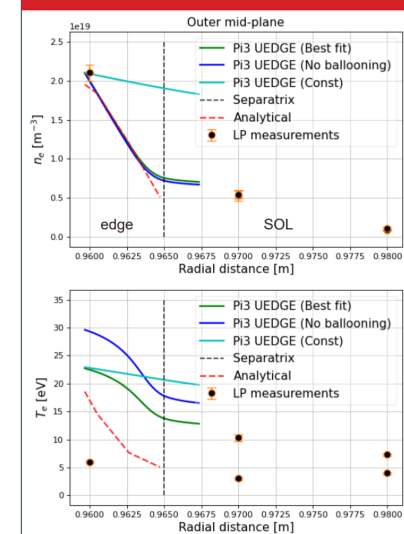
- Correlated fluctuations of the electric field and plasma density may explain anomalous transport observed in tokamak SOLs [6].
- Flux varies a lot within a small radial excursion. This may be evidence for particle losses on limiting sections of the vacuum vessel before they reach the wall at the Langmuir probe's outboard position.

IRE Detection



- Isat identifies Internal Reconnection Events (IREs) at least 0.5ms before identification by Mirnov coils (plasma current, Ip).
- Since IREs can be detrimental to energy confinement time, a monitor based on Isat can be used to predict IRE appearance.
- The use of several probes in different poloidal and radial positions could identify the position where IREs occur using flight-time of the energetic lost particles in combination with an energy particle analyzer (e.g., NPA).

Edge Physics Simulations



- Plasma diffusion models can be developed by combining Langmuir radial scans with UEDGE plasma simulations.
- The best fits simulations suggest a non-trivial spatial dependence of diffusion parameters with enhanced transport in the Scrape Off Layer (SOL) with respect to the core. The increased transport on the edge may be accounted for by plasma turbulence.
- More experimentation is required to develop robust radial profiles.
- See poster **PP11.00037** by L. Carbajal et al for a detailed presentation of edge physics modeling at General Fusion.

Conclusion

Our four-pin triple Langmuir probe design has been successfully commissioned as a diagnostic on Pi3, a lithium-coated spherical tokamak, providing time-resolved electron temperature and density, floating and plasma potential, poloidal electric field, and cross-field anomalous particle transport measurements at adjustable radial positions. It is also an effective IRE monitor. The probe's data is being used for plasma edge transport studies by UEDGE code.

References

[1] I. Hutchinson, *Principles of Plasma Diagnostic*, pp. 55–77 (2002).
[2] S. Chen, et al. *J. Applied Science, 36, 2363* pp. 2363–2375 (1965).
[3] V.P. Budaev, et al. *J. Nuclear Materials 176 & 177* pp. 705–710 (1990).
[4] R. Majeski et al., *PoP 24*, 056110 (2017).
[5] M. Laberge, *J. Fusion Energy 38*, pp. 199-203 (2019).
[6] J.A. Boedo, *J. Nuclear Materials 390-391* pp. 29–37 (2009).