4 kHz high-dynamic-range Thomson scattering on LM26

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Simon Coop[1], Vincent Carrat[2], Léo Bourgue[2], Filiberto Braglia[1], Akbar Rohollahi[1]

[1]General Fusion Inc., Vancouver, British Columbia, Canada

[2]Bertin Technologies, Aix-en-Provence, 13290, France

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LM26 – Lawson Machine 2026

LM26 is a machine designed to demonstrate General Fusion's magnetised target fusion (MTF) technology. LM26 combines the extant Pi3 plasma injector with an electromagnetically-actuated solid lithium compression system. Pi3's Marshall gun will inject a deuterium plasma into the LM26 vacuum vessel. Then toroidal coils outside the vacuum vessel will be pulsed to create a Θ-pinch which will compress the lithium liner radially inwards. Simultaneously, a current is pulsed through the liner to trap the plasma. The collapsing liner will compress the plasma to high temperature and density, ideally reaching fusion conditions 3 ms after the liner starts moving. The initial plasmas will be the same as the plasmas on Pi3, with temperatures of around $T_e = 300-400$ eV and densities of around $n_e = 1-5\times10^{19}\mathrm{m}^{-3}$. We predict the peak-compression plasmas will be around $T_e = 10$ keV, $n_e = 0.5-1\times10^{23}\mathrm{m}^{-3}$. See poster 4.2.22 for further description of LM26.

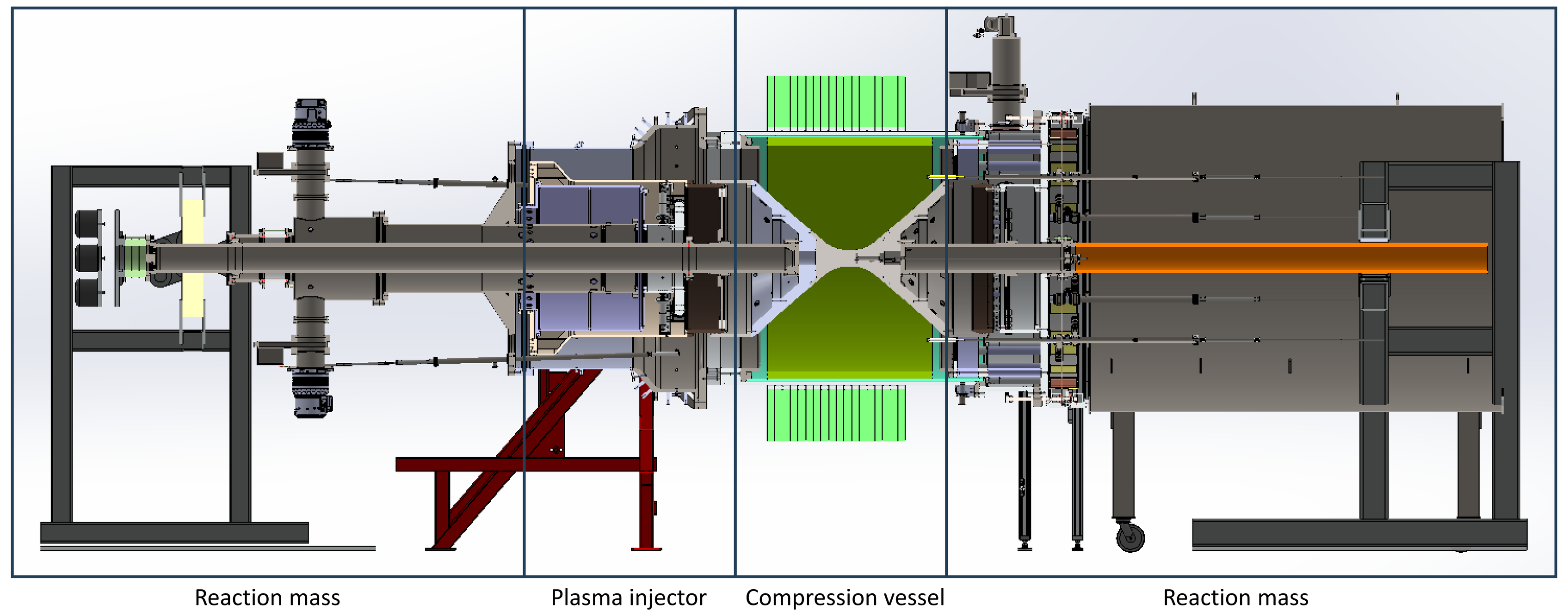

Fig. 1: Prototype schematic of LM26. The central "dogbone" is sacrificial and expected to be replaced every shot.

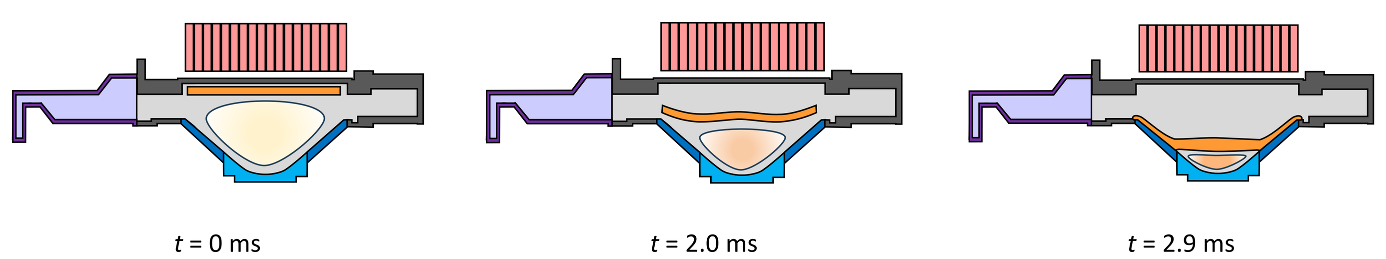

Fig. 2. Lithium wall collapse vs. time

Existing Thomson scattering system on Pi3

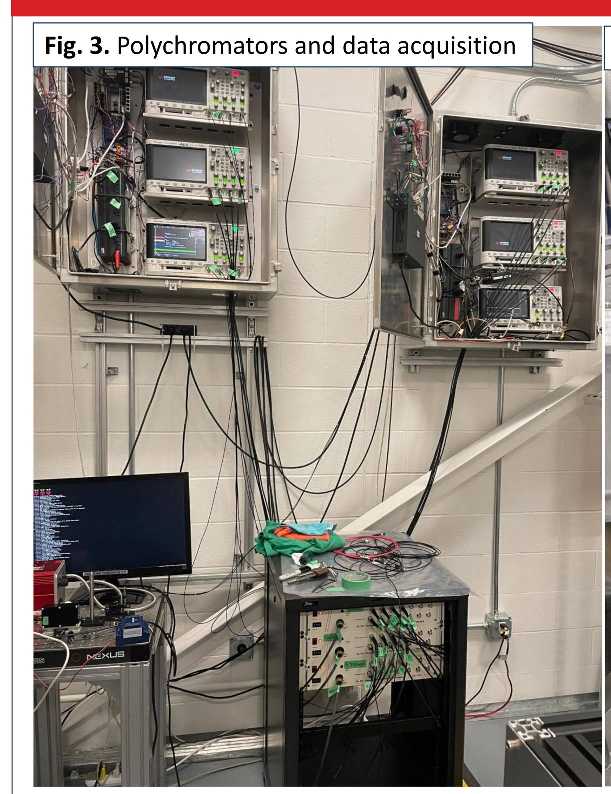

Fig. 3. Polychromators and data acquisition

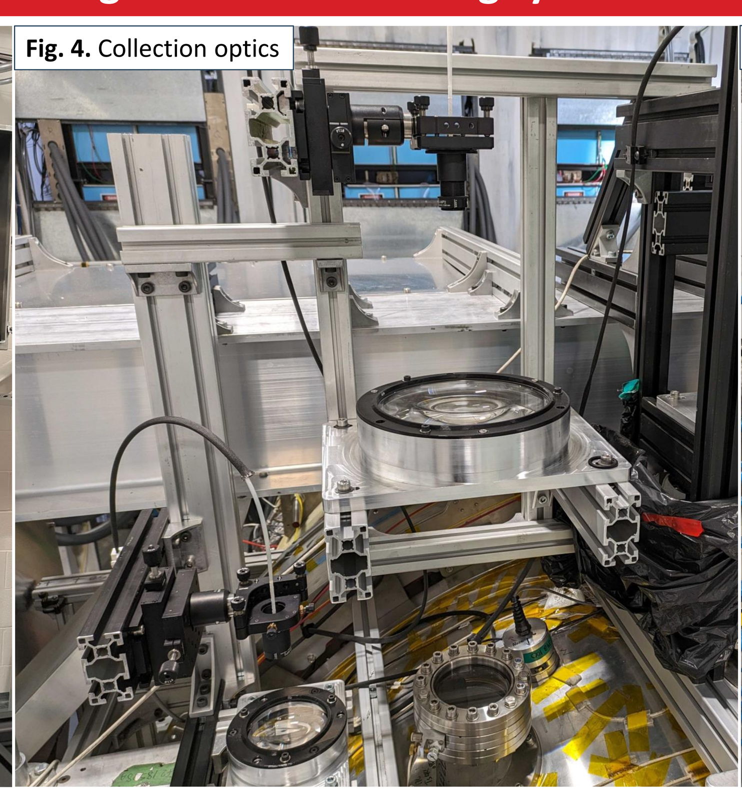

Fig. 4. Collection optics

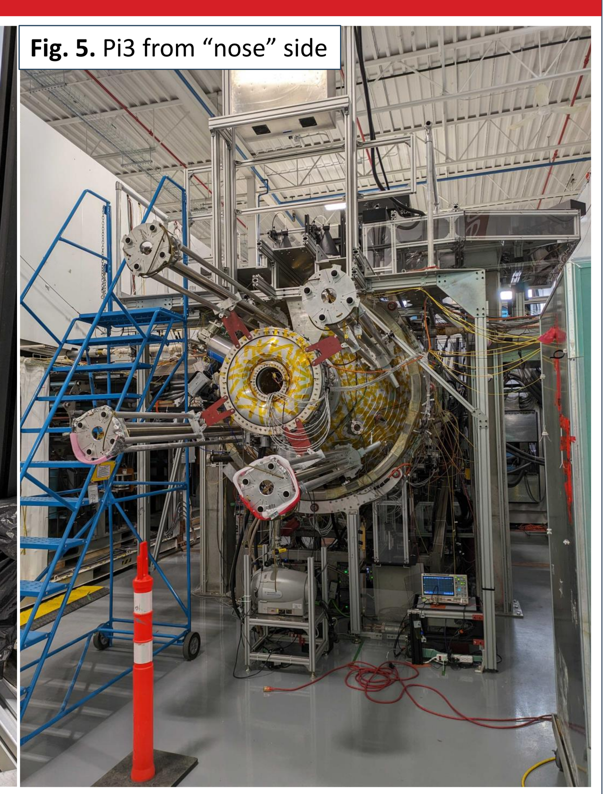

Fig. 5. Pi3 from "nose" side

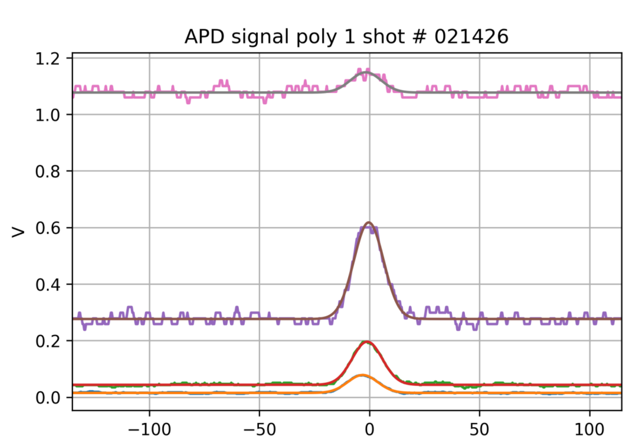

Fig. 6. Typical signal

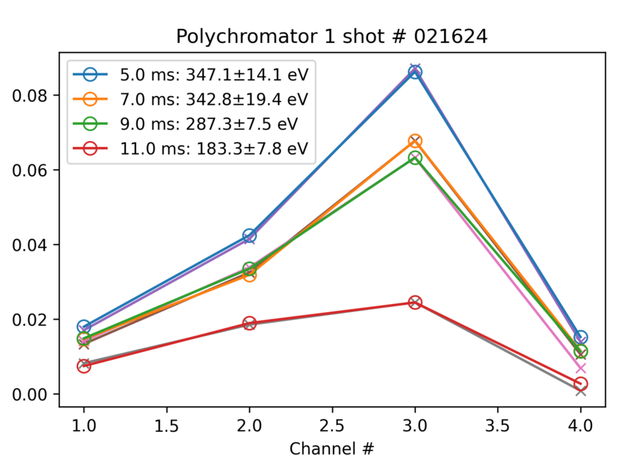

Fig. 7. Multiple shots in a single plasma with burst laser

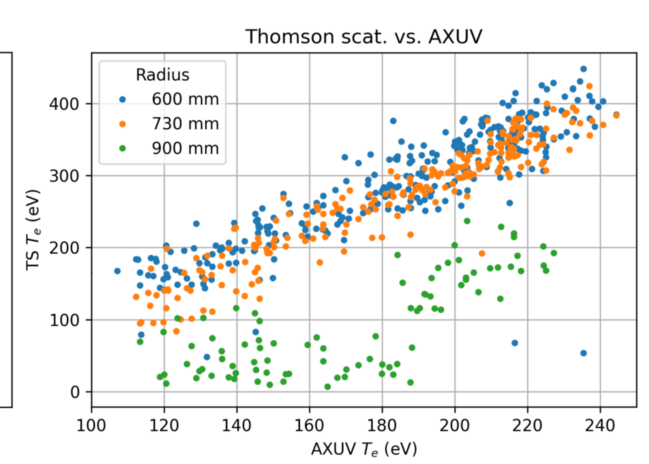

Fig. 8. Comparison with AXUV data

Thomson scattering on LM26

The LM26 Thomson scattering diagnostic will be split into two systems: pre-compression and peak-compression. The pre-compression system will be in principle similar to the existing Pi3 system ($n_e \approx 10^{18}-10^{19}\mathrm{m}^{-3}$, $f/8$), for confirming the plasma is in a state appropriate to trigger the compression system. While the peak-compression system will be designed to measure over a broader range of densities and will be used to confirm the behaviour of the plasma as compression proceeds.

The lasers used are two Innolas SpitLight 1064nm 10ns pulsed lasers capable of burst-firing four 2J pulses each, at either 4kHz or 500Hz. We also have a Spectra-Physics 1064nm 10Hz 2J laser, which might be used for the pre-compression system.

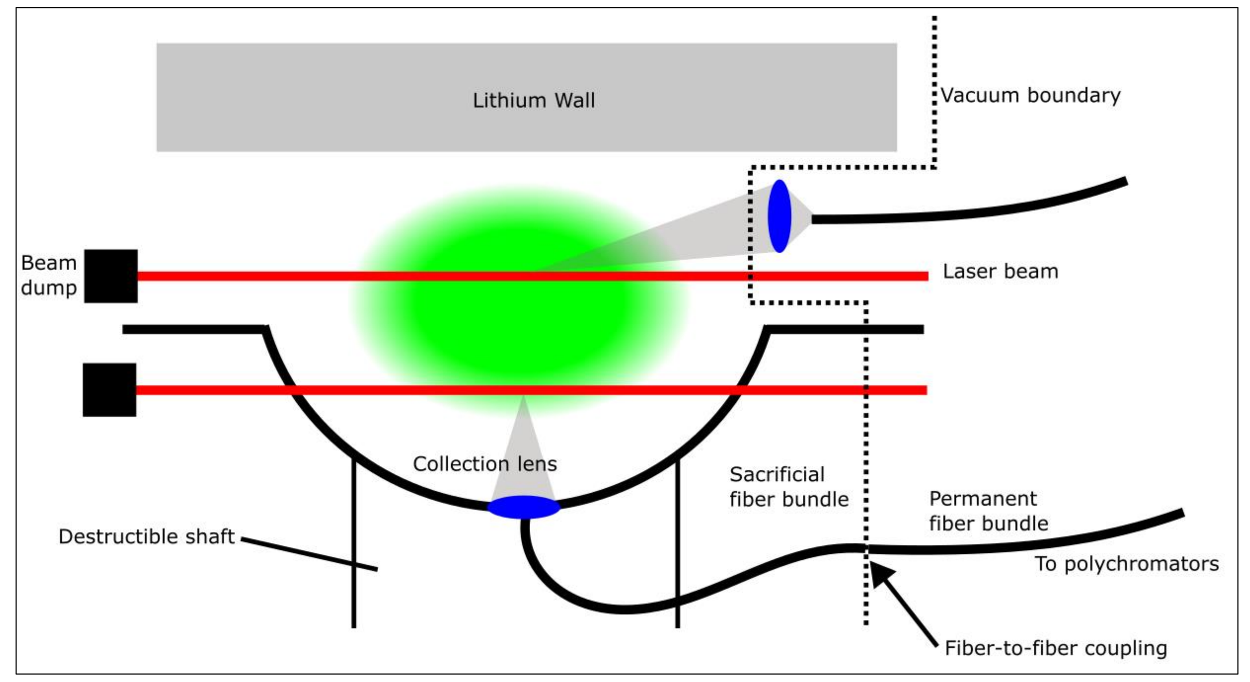

Fig. 9. Conceptual schematic of the two Thomson scattering systems

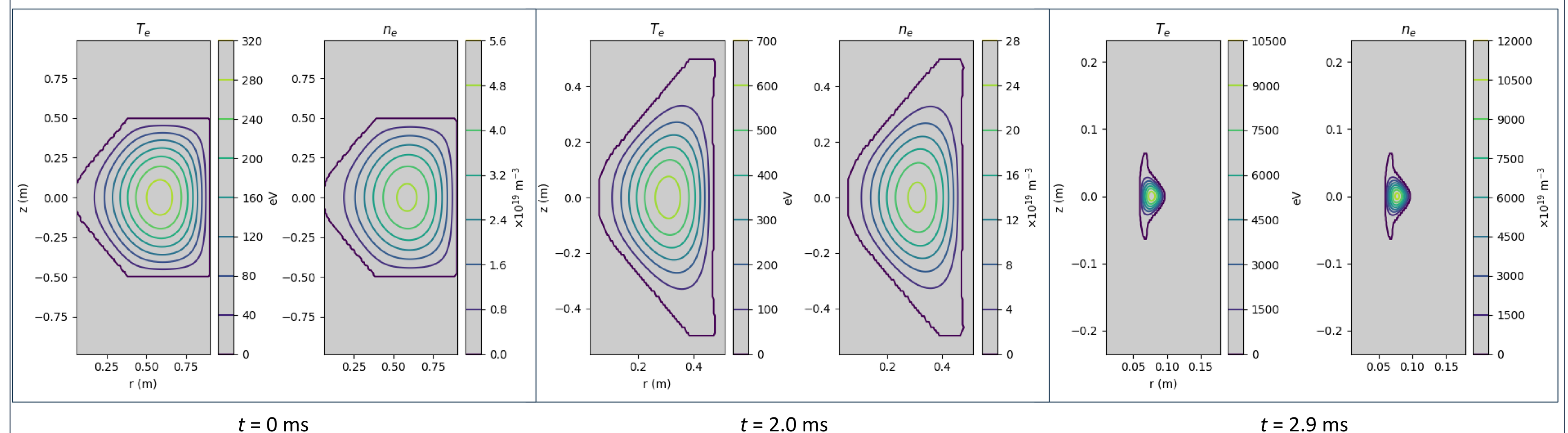

Fig. 10. Preliminary plasma temperature and density distributions vs. time.

Calibration via polychromator channel sensitive to laser wavelength

The lithium liner precludes calibrating the system via the usual Raman scattering technique, as lithium reacts with any diatomic gas. Instead, we have custom UKAEA polychromators with a channel sensitive to the laser wavelength. By measuring the relative spectral calibration ex-situ, and then measuring the absolute sensitivity of the system to 1064nm via in-situ Rayleigh scattering, we will be able to obtain a complete absolute calibration by combining the two measurements. This technique will require careful control and quantification of stray light.

Pre-compression measurement

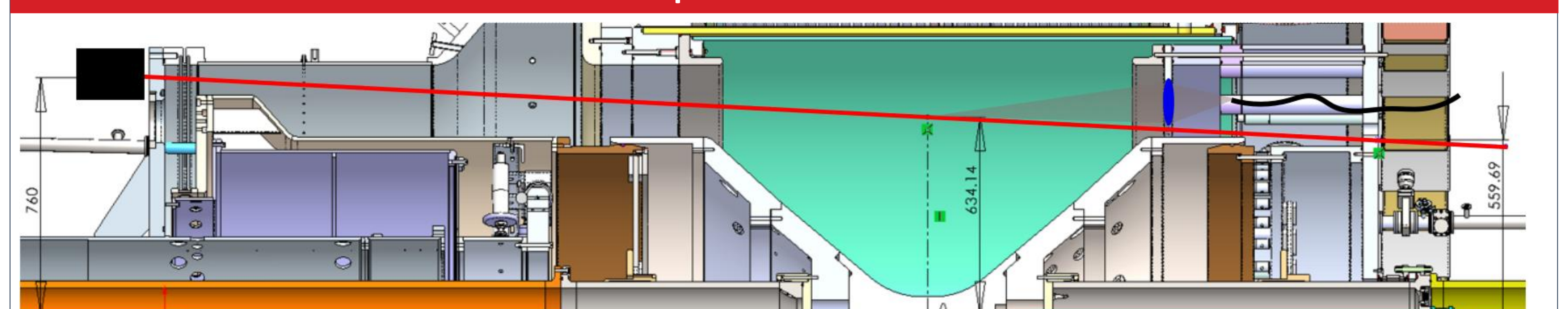

Fig. 11. Pre-compression TS system location and geometry. The collection lens, fiber bundle, and beam dump are in air.

The pre-compression TS system will be similar to the existing Pi3 system. The laser will enter the chamber axially, and exit through a window at the top of the Marshall gun. Collection optics will view the laser beam along the same axis with an aperture of about $f/8$. The radius at the measurement point will be 634mm (**Fig. 11**). We expect LM26 to run for several months without firing any compressions, so this system will be used to diagnose plasmas for that time

Veto

The pre-compression system will be used to confirm plasma temperature before firing a compression shot, i.e. the Thomson scattering will veto the compression. This will require data acquisition and analysis in less than 1ms. For this application we plan to use a high-speed SDR board like an AMD RFSoC or similar. The data analysis algorithm will need to be simplified to run in less than 1ms, for detecting a minimum temperature this could be as simple as e.g. "is polychromator channel 3/2 > x". (**Fig. 12**)

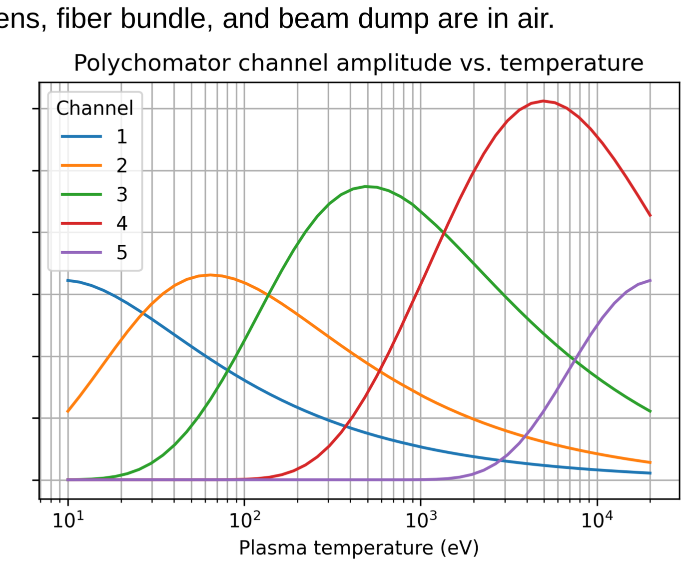

Fig. 12. Polychromator relative signal amplitudes per channel vs. plasma temperature

Peak-compression measurement

Thomson scattering will be one of two diagnostics able to see the plasma at peak compression (the other being the neutron spectrometer, see poster 3.4.45), so it is important that it provides a reliable measurement of electron temperature.

Sacrificial fiber bundles – At the end of a full compression shot we expect the central region of the shaft to be damaged. The fiber bundles inside the shaft will be short ($\sim 1\mathrm{m}$), vacuum-compatible, and coupled to permanent fiber bundles outside the machine via an imaging coupling system.

4 or 8 laser pulses at 4kHz – 4 pulses from a single laser (spanning $750\mu\mathrm{s}$) or 8 pulses from combining two lasers (spanning $1.75\mathrm{ms}$), see **Fig. 14**.

Multiple fiber bundles to increase dynamic range – Due to the uncertainty in the expected signal level close to peak compression, we will have several optical fibers collecting light from almost the same point, which will transport light to separate polychromators with varying levels of attenuation.

Small optics – Preliminary modelling suggests the signal level will be high due to high plasma density ($n_{e,peak} \approx 10^{23}\mathrm{m}^{-3}$) and proximity of the measurement point, so a small ($< 10\mathrm{mm}$) lens will be sufficient. We do not expect this system to acquire a measurable signal in the pre-compression phase of the machine.

Lithium coating protection – LM26 will be lithium-coated periodically prior to running compression shots. Thus the mirror and lens will need to be protected with a remotely controllable cover (not shown in **Fig. 13**).

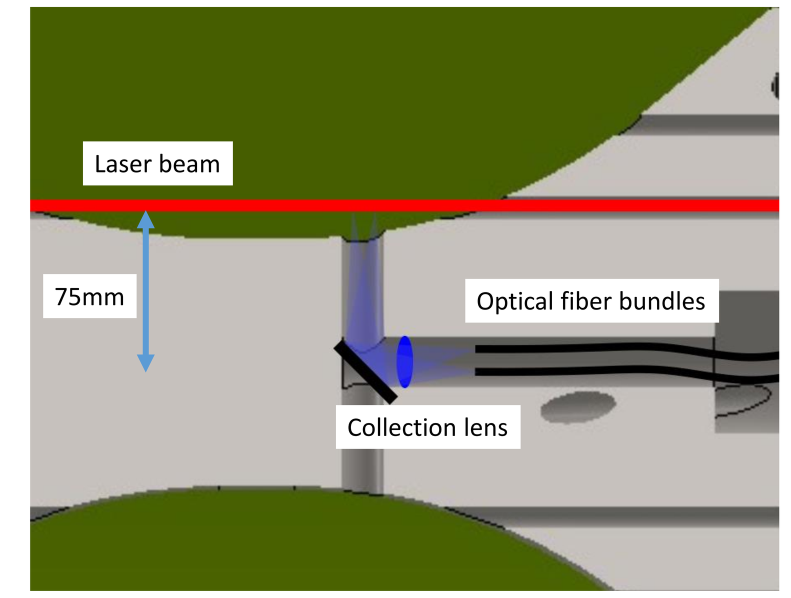

Fig. 13. Closeup of the LM26 shaft showing the peak-compression Thomson scattering laser beam entrance tube and collection optics.

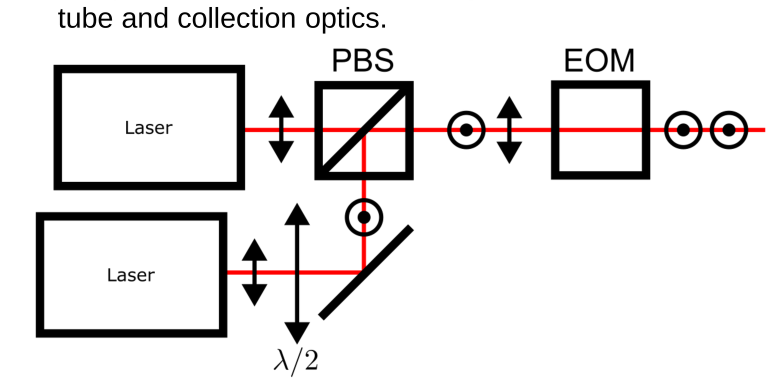

Fig. 14. System to combine two pulsed lasers by dynamically switching polarisation state with an electro-optic modulator

Risks

Background

Line radiation – We already see significant background from line radiation on Pi3 (**Fig. 15**). For small increases in density we expect this background to increase with density *squared,* so the polychromators could easily saturate. We plan to use notch filters at the strong lithium lines, and the line radiation should decrease at much higher temperatures as the plasma becomes more fully ionised. The vacuum on LM26 should also be lower so we hope to reduce radiation from non-Li species.

Bremsstrahlung – Currently on Pi3 we do not measure detectable Bremsstrahlung. While the level should also increase with density squared, the spectrum also blue-shifts with temperature. Modelling is underway to understand what to expect during compression.

Blackbody radiation – The LM26 shaft may momentarily reach high temperature during a compression shot due to the high currents. Above $\sim 700\mathrm{K}$ the amount of light due to blackbody radiation may be significant (**Fig 16**). Testing on a scale model is planned to confirm this effect.

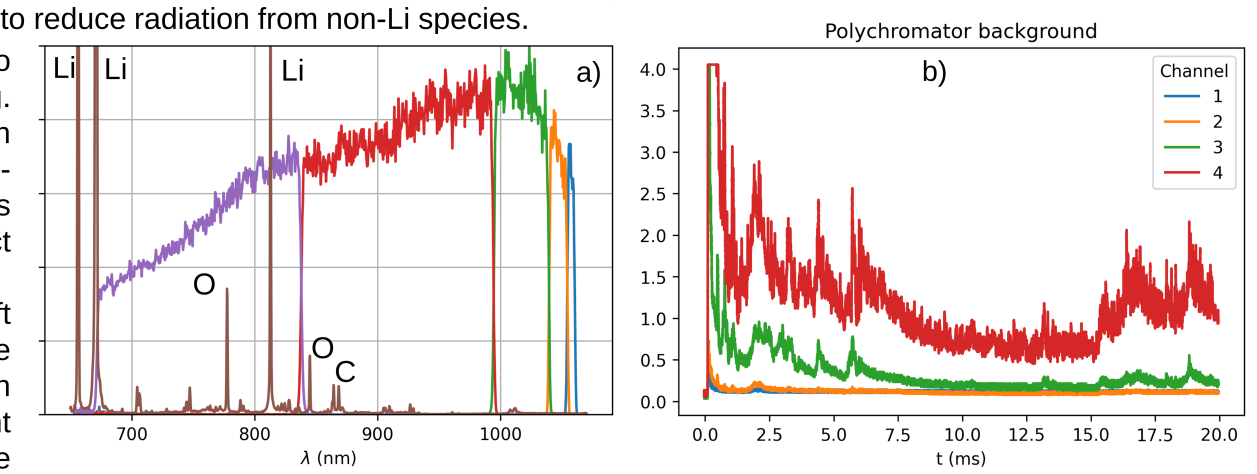

Fig. 15. a) Polychromator channel sensitivity superimposed on an IR spectrometer measurement from Pi3. b) Polychromator background level vs. time in a typical Pi3 shot.

Vibrations

The limited optical access to the plasma means LM26 has tight tolerances regarding vibration-induced misalignment.

Internal reflections

The proximity of the lithium liner to the measurement point near the end of compression means there is a risk of significant reflection of spectrally-distorted scattered light (**Fig. 17**), a problem for temperature measurements.

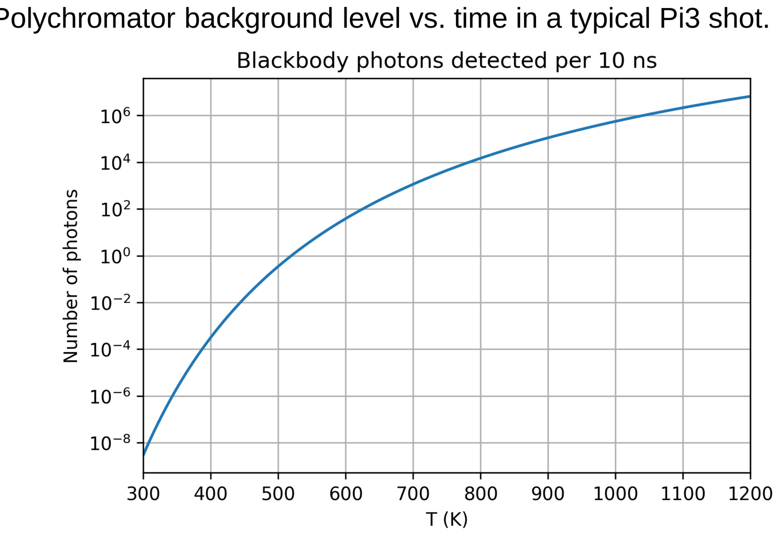

Fig. 16. Estimated number of photons collected per 10ns by a 10mm lens 100mm from a 10mm diameter area blackbody as a function of temperature. For comparison a typical Thomson scattering signal is $\sim 10^3-10^4$ photons

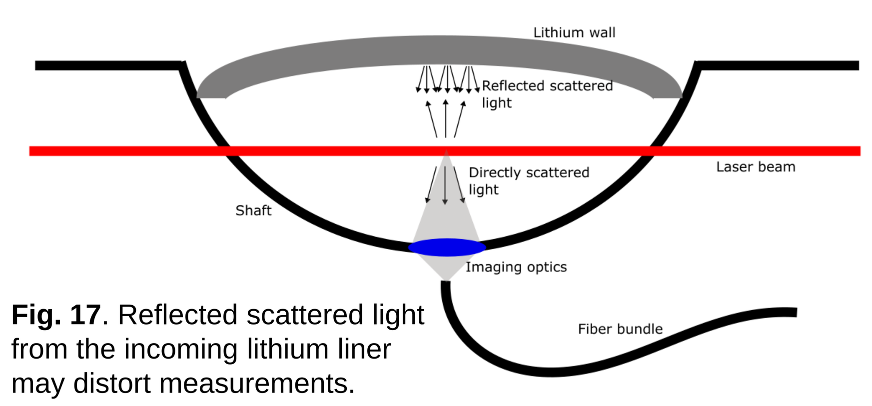

Fig. 17. Reflected scattered light from the incoming lithium liner may distort measurements.