DIAGNOSTICS FOR THE GENERAL FUSION LM26 MACHINE

Filiberto Braglia, Patrick Carle, Akbar Rohollahi, Stephen Howard, Myles Hildebrand
General Fusion, Richmond, BC V7B 1B4, Canada

1 Introduction

General Fusion is pursuing the fastest, most practical path to bringing fusion energy to market using its Magnetized Target Fusion (MTF) technology. In this scheme, a rotating liquid metal liner forms the plasma boundary and outer flux conserver in an evacuated target chamber. The centrifugal force pushes the liquid metal outward, creating a stable vortex about the axis of the machine. A Marshall gun forms a magnetized plasma ring of spherical tokamak configuration in this vortex cavity. An array of pistons surrounding the liquid metal liner is actuated to initiate the collapse of the liner to compress the plasma to fusion conditions. Neutrons are released from deuterium-tritium fusion and deposit their energy into the liquid metal, which is circulated through a heat exchanger to generate steam to power a turbine to generate electricity[i].

This approach offers several advantages:

- The liquid metal liner shields the machine structure from fusion neutrons.
- A liquid metal liner is expected to give a high tritium breeding ratio.
- The heated liquid metal can be pumped out of the vessel and used for relatively straightforward power generation
- Mechanical compression is an economic way of heating the plasma.

2 LM26

General Fusion is fast-tracking its technical progress to provide commercial fusion energy to the grid by the early to mid-2030s by building a new MTF fusion machine at its Canadian headquarters. The machine, called Lawson Machine 26 - LM26 - is designed to achieve fusion conditions of over 100 million degrees Celsius by 2025, with a goal of achieving scientific breakeven equivalent by 2026.

LM26 will use a Marshall gun to inject a deuterium plasma into a target chamber as shown in Figure 1. The target chamber's outer wall is a solid lithium liner contained within a cylindrical composite vacuum vessel. Toroidal coils mounted on the outside of the cylindrical vessel are pulsed and push on the liner to initiate compression. As the liner collapses, the plasma is compressed to higher density and temperature. The duration of the compression is about 3 ms.

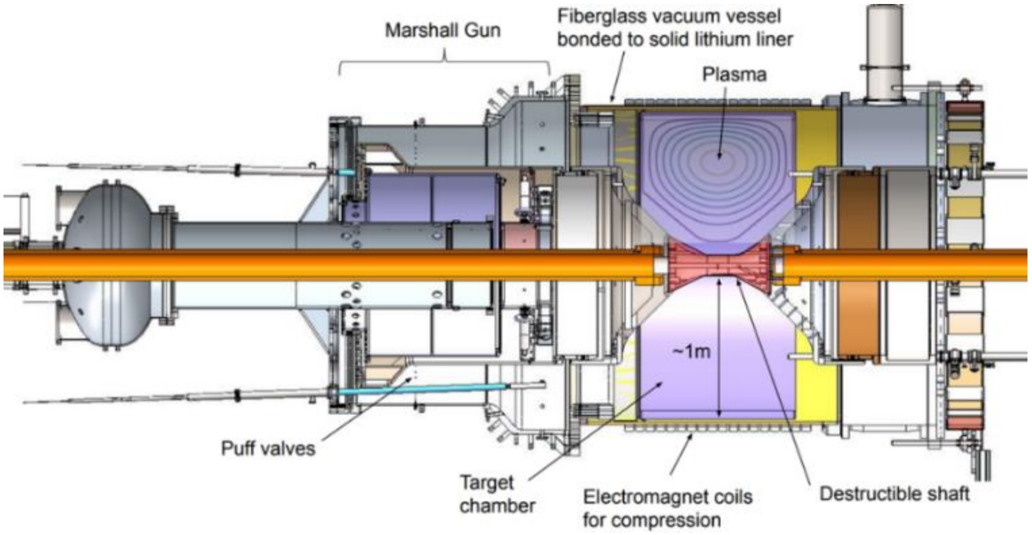

Figure 1: LM26 cross section. Poloidal flux contours of the pre-compressed plasma are shown.

The central shaft on the axis of the machine serves several purposes. Current is run down the shaft to generate toroidal field, which lifts the safety factor (q) profile of the plasma above q=1. The shaft also stabilizes the plasma against tilt instabilities. At peak compression, the shaft is the only way to obtain line of sight to the plasma and thus is an important diagnostic point of access.

Between compression shots, the compressed lithium liner will be extracted from the target chamber to be recycled for subsequent liner cylinders and any damaged components can be replaced. Once the machine is under vacuum again, the inner surfaces of the liner and target chamber will be evaporatively coated with lithium to provide a fresh surface for high vacuum operations. The target is to run a compression shot once per week. We expect to begin 10 keV compression experiments in mid-2025.

The initial goal of LM26 is to compress deuterium plasma from a pre-compression temperature of 300 eV to greater than 10 keV at peak compression. Detailed simulations are a work in progress, but the compression trajectory from a simplified model is shown in Figure 2 and rough plasma parameters are given in Table 1. The extended goal for LM26 is to approach the Lawson criterion and scientific breakeven equivalent for DD fusion reactions. Measurement of density, temperature, and energy confinement time are a top priority.

Table 1: LM26 plasma parameters for a 10 keV compression.

	Pre-compression	**Peak compression**
Major radius	0.6 m	0.08 m
Minor radius	0.5 m	0.03 m
Core temperature	350 eV	10 keV
Core density	5×10^{19} m^{-3}	10^{23} m^{-3}
Core B-field	0.5 T	100 T

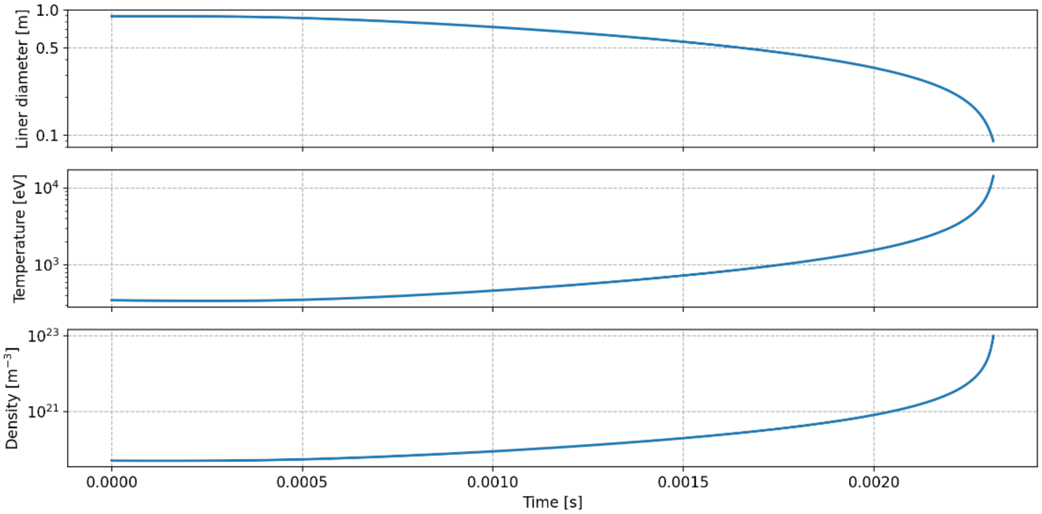

Figure 2: LM26 compression trajectory from a simplified 0-dimensional model. Note the steep rise in density and temperature in the last few hundreds of microseconds before peak compression.

3 LM26 Diagnostics

The LM26 diagnostics suite must be sufficient to understand the performance of a compression shot. Of particular interest is the plasma density, temperature, and energy confinement time before compression and at peak compression. We have prioritized a set of diagnostics to work towards this goal.

3.1 Ports

Due to the machine geometry and compression trajectory, diagnostic access will be limited to the inner sections of the machine. The available surfaces are further defined as two reusable conical sections and a disposable cylindrical shaft.

An angled, 15 mm diameter port through the shaft will provide an unobstructed view of the plasma core at peak compression as shown in Figure 3. The high plasma density (10^{23} m^{-3}) at peak compression is expected to compensate for the small solid angle through the 2 m long port. We will be limited to only one such port on the central shaft due to structural constraints.

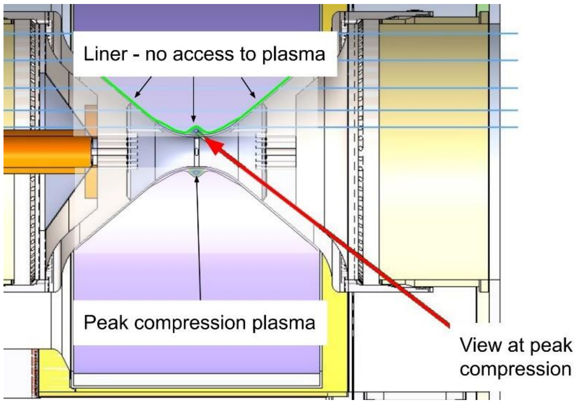

Figure 3: The solid metal liner severely limits access at peak compression, when line of sight to the plasma will only be possible from the shaft such as the red chord drawn in the figure.

There will be 4 evenly spaced toroidal port locations on the cones, each with a set of 6 axial ports (Figure 4). Port diameters are limited by structural constraints and range from 11 mm in diameter at position r=75 mm to 24 mm in diameter at position r=480 mm. A larger 300 mm diameter port at the r=760 mm position, will provide a wide view of the plasma pre-compression.

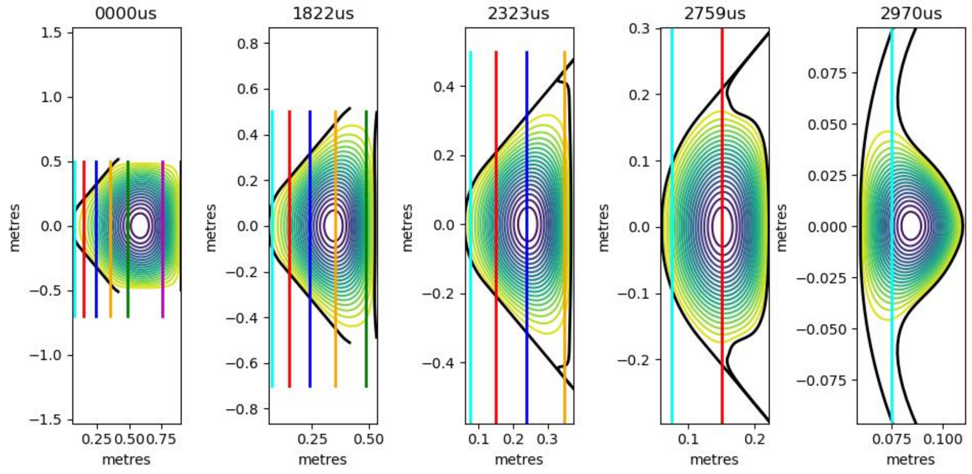

Figure 4: Planned axial port locations for an example compression trajectory. Liner and shaft surfaces in black. Poloidal flux contours are shown for a Taylor state equilibrium at several compression times.

3.2 Diagnostic Priorities

The diagnostic suite of LM26 is aimed primarily at measuring the key physical quantities needed to confirm the scientific outcomes of the project, namely electron and ion temperature (T_e, T_i), electron density n_e, and energy confinement time τ_E. Liner-monitoring diagnostics used to track the quality of the liner compression (position, speed, symmetry, buckling, jetting, etc.) are important but are omitted from this discussion to focus on plasma diagnostics.

A set of magnetic surface probes measuring the poloidal and toroidal components of magnetic field at unique radial-axial positions will be spread out around the cones and along the shaft. The probes are recessed within the shaft and surrounded by a thin metal shield to protect them from the liner and the plasma. This results in a strong frequency-dependent absorption which must be calibrated beforehand.

A set of axial interferometer chords will be the primary measurement of plasma electron density. For the outer chords that will only provide measurements at early compression times, we plan to use a CO2-HeNe (10.6um/633nm) system. For the inner chords and late compression times with high densities (10^{22}-10^{23} m^{-3}), we will use a shorter wavelength 1550/1310 nm system. Some chords will have to make 2 passes through the plasma using reflectors mounted inside the machine, which presents a significant risk due to vibration from the compression.

Thomson scattering will measure core plasma electron temperature pre-compression and at peak compression. The geometry of the laser line and collection optics is a work in progress. Some pre-compression configurations have a relatively poor f/# and would require viewing a large scattering volume. If a beam dump must be used to control stray light, this will have to be located inside the shaft. Signal ratios from filtered AXUV diodes will provide a supporting electron temperature measurement from bremsstrahlung radiation.

An Ion Doppler Spectroscopy designed for UV-Visible range will be employed to measure the ion temperature of pre-compressed plasma. An X-ray imaging crystal spectroscopy system will be developed to measure the plasma ion temperature at peak compression.

Neutron counters such as scintillators, activation foils and He3 detectors will be located outside the machine or inside the shaft. A model of the neutron field will be made to estimate the number of neutrons generated by the plasma. With an estimate of the ion density and the neutron yield, the ion temperature can be calculated. For a direct ion temperature measurement from fusion neutrons at high plasma temperatures, a neutron spectrometer is being developed in collaboration with TRIUMF. The neutron spectrometer measures neutrons' time of flight between two layers of scintillators to determine the neutron energy distribution which is a function of the ion temperature[ii].

It will be important to measure the plasma impurity composition since there is a risk that the collapsing lithium liner injects substantial impurities into the plasma. This will be done with an array of survey spectrometers and filterscopes targeting several lines of interest such as H-alpha, Li-I, Li-II.

Radiated power will be estimated from an array of unfiltered AXUV diodes.

3.3 Diagnostic Challenges

There are several challenges we face in developing diagnostics for LM26:

- Temperature, density changing rapidly during compression. Fast (~5us) diagnostics are required.
- Difficult access to plasma. It is not possible to diagnose the plasma from the outer cylindrical vessel wall due to the surrounding solid metal liner. The compressing liner will also progressively cut off more and more diagnostics, further constraining access to the plasma.
- Shocks/vibration from compression.
- Window/optics protection from lithium coatings.
- Machine at 150C during a compression shot to soften the lithium. Surface temperature of the shaft could be much higher near peak compression.
- Estimation of energy confinement time at peak compression will be affected by limited diagnostic coverage only to the high-field side of the plasma.

4 Tentative Partnerships

- General Fusion is collaborating with TRIUMF, Canada's national particle accelerator centre, hosted on the campus of University of British Columbia and Simon Fraser University to develop the neutron emission spectrometer
- General Fusion is collaborating with University of Lisbon to build and commission a reflectometer to measure electron density
- General Fusion is collaborating with the UK Atomic Energy Authority on the development of multiple diagnostics including Thomson Scattering, magnetic probes and neutron measurement

5 Summary

General Fusion is building its new fusion demonstration machine, Lawson Machine 26 (LM26), at its Richmond, Canada, headquarters. LM26 is designed with the goal of being the first to achieve scientific breakeven equivalent conditions using MTF technology by 2026. It will do so using deuterium fuel and electromagnetic compression of a solid lithium liner.

A suite of diagnostics has been prioritized to quantify the performance of a compression from measured plasma parameters. Several diagnostic challenges have been identified. The most challenging is expected to be a temperature measurement at peak compression when access to the plasma is severely limited.

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[i] Laberge, M. Magnetized Target Fusion with a Spherical Tokamak. J Fusion Energ 38, 199–203 (2019). https://doi.org/10.1007/s10894-018-0180-3

[ii] Carle, P. J. F., et al. "Neutron emission spectrometer to measure ion temperature on the Fusion Demonstration Plant." Review of Scientific Instruments 93.11 (2022). https://doi.org/10.1063/5.0101814