Conceptual Design of a Magnetized Target Fusion Power Plant

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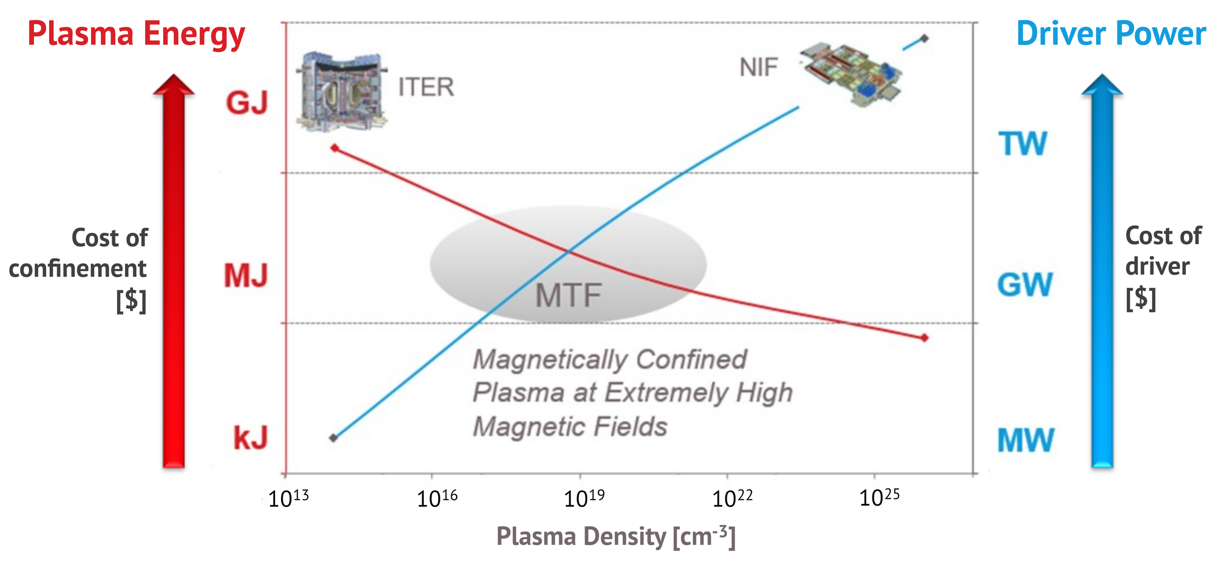
General Fusion's MTF Concept

General Fusion (GF) is developing magnetized target fusion (MTF) as a practical means of producing deuterium-tritium fusion power. In GF's concept, a spherical tokamak plasma target is formed by coaxial helicity injection (CHI) into a rotating liquid lithium flux conserver (liner) and mechanically compressed to fusion conditions [1]. The rotation of the liquid liner generates a cylindrical cavity into which the plasma is formed and stabilizes fluid instabilities during compression. The mechanical compression is driven by high pressure gas and requires no superconducting magnets or high power lasers. The short compression timescale (~40 ms) and compressive heating remove the need for any auxiliary heating, fuelling, or external current drive after formation.



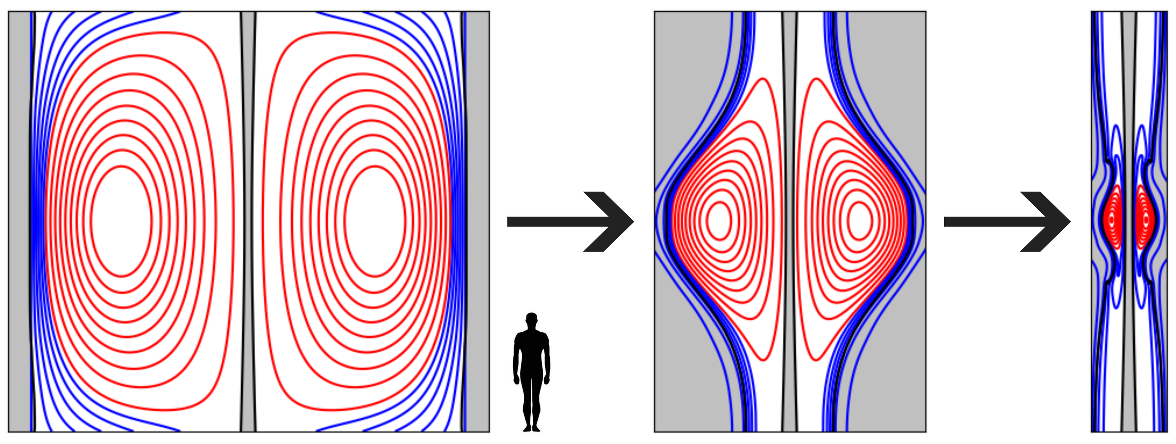
Above: MTF aims to avoid the high cost and complexity of steady-state active confinement in MCF and the high power drivers of ICF, all while retaining the benefits of strong magnetic fields.

The use of liquid lithium as first wall provides several benefits:

- Liquid is ideally suited for cyclical compressions and will not degrade with exposure to fusion plasmas.
- The lithium wall is sufficiently thick (~3 m) to absorb essentially all fusion neutrons, directly capturing fusion energy and facilitating tritium breeding.
- The use of lithium as a plasma facing surface improves plasma confinement due to its chemical gettering, low Z, and low recycling properties.

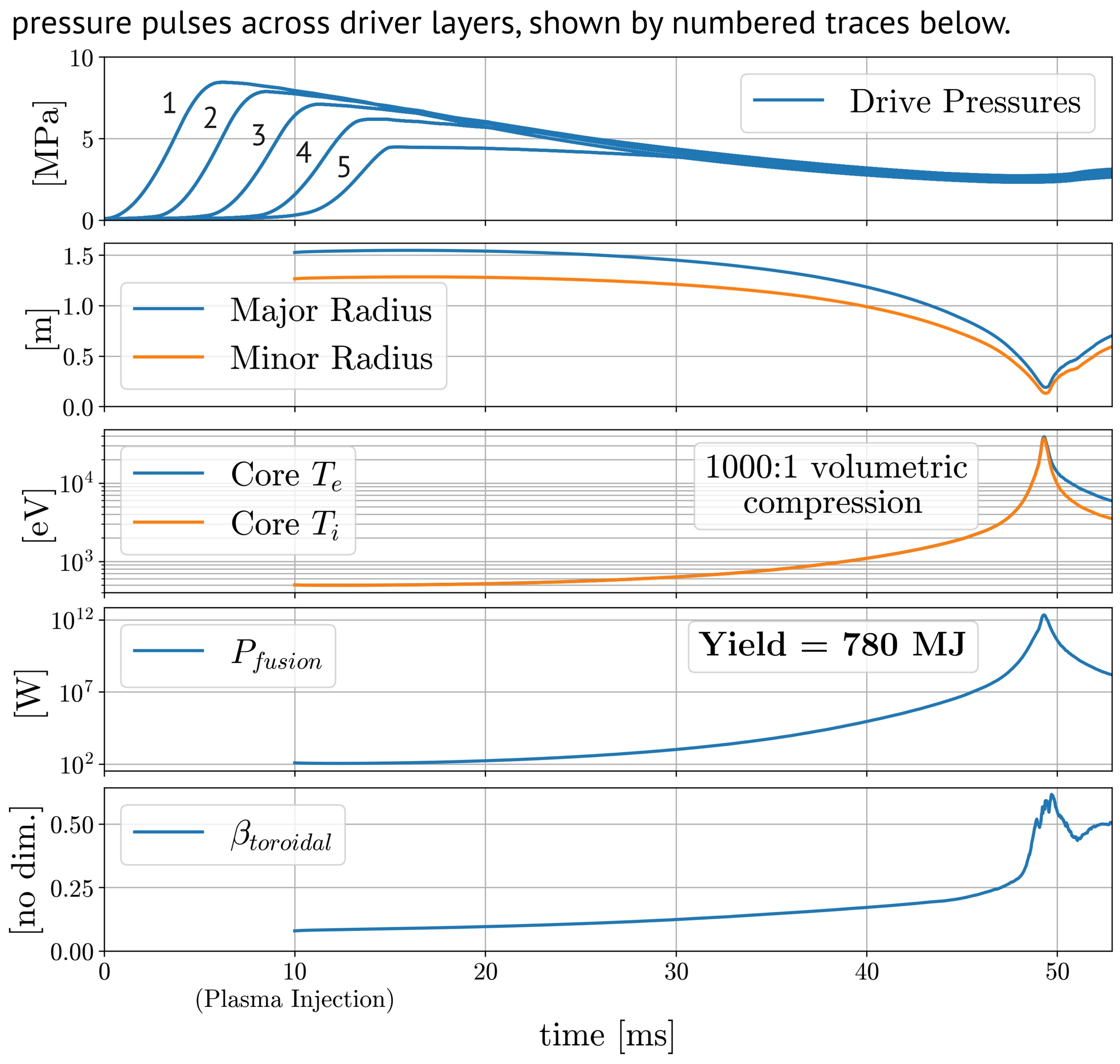
GF has extensive experience forming magnetized deuterium plasmas by CHI, including sub-scale explosive-driven MTF experiments (PCS) [2], formation of plasma in the presence of liquid lithium (SLiC) [3], and large scale plasma formation with evaporatively coated lithium walls (Pi3) [4].

Design Point – 150 MW$_e$



Above: Snapshots from an MHD-OpenFOAM [5] compression simulation. The liquid wall and centre shaft are in grey, closed field lines in red, and open field lines in blue.

Below: Select integrated modelling outputs. Shaping is achieved by varying pressure pulses across driver layers, shown by numbered traces below.

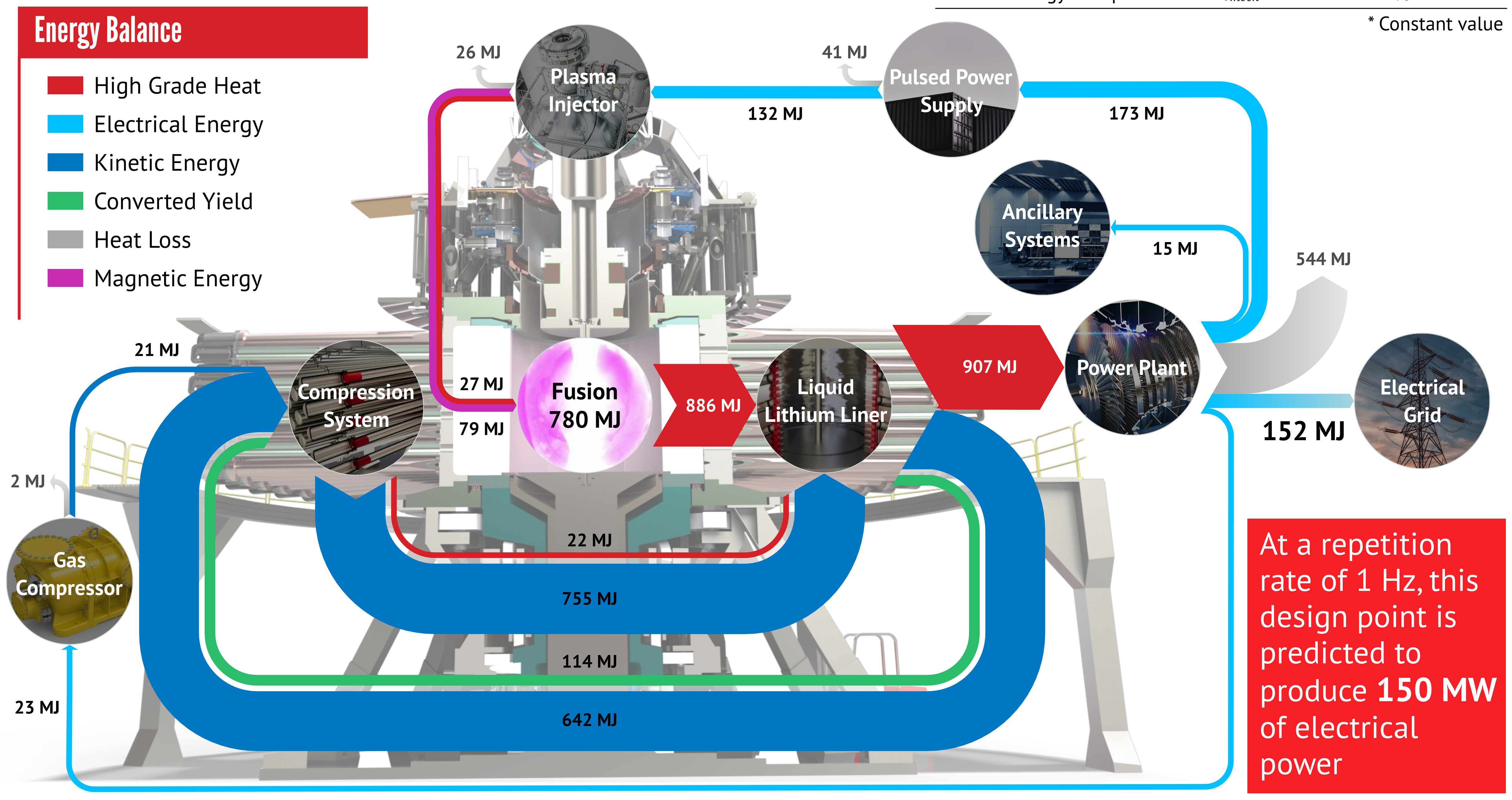


Kinetic energy recovery is a significant benefit of GF's mechanical compression design. After peak compression, a significant fraction of input kinetic energy recharges the compression system. A portion of fusion yield is additionally converted directly to mechanical energy due to vaporization of the liquid surface. Mechanical losses due to shocks, viscous drag, and magnetic diffusion are dissipated within the liner as heat. Ancillary systems include tritium extraction and steady-state rotor drive. Pulsed power and plasma formation require a significant fraction of total energy due to inefficiencies and initial cavity geometry.

Quantity	Symbol	Initial	Final
Cavity Height	H	6 m	0.78 m
Cavity Radius	R_a	3 m	0.33 m
Major Radius	R_0	1.5 m	0.19 m
Minor Radius	a	1.3 m	0.13 m
Elongation	κ	2.2	2.0
Electron Density	n_e	2×10^{20} m^{-3}	2×10^{23} m^{-3}
Toroidal Field at Mag. Axis	B_0	0.9 T	70 T
Confinement Time	τ_E	270 ms	3 ms
Thermal Efficiency*	η_{th}	40%	
Kinetic Energy Dissipation*	$1-\eta_{mech}$	15%	

* Constant value

Energy Balance



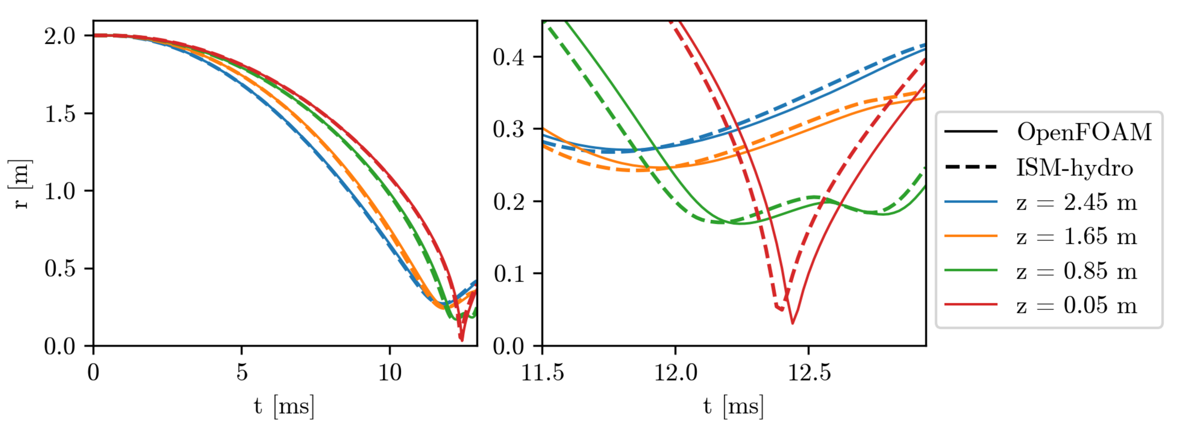
At a repetition rate of 1 Hz, this design point is predicted to produce **150 MW** of electrical power

Integrated Modelling

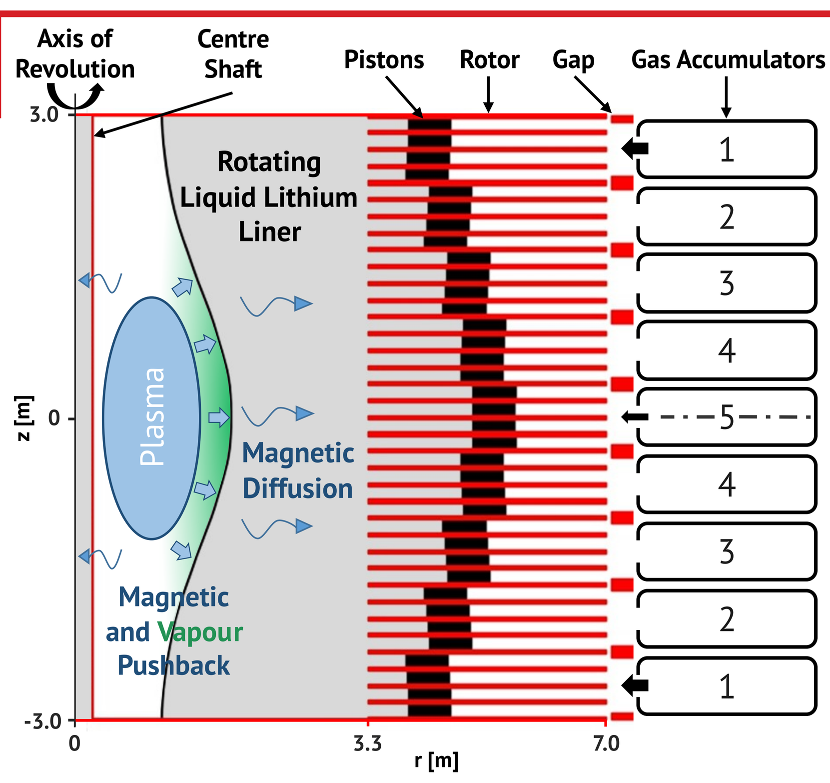
The Integrated System Model (ISM) is an in-house reduced order code capturing most of the subsystems of General Fusion's MTF architecture (see figure to right). This fast code consists of a mixed-dimensionality hydrodynamics and gas network base code (ISM-hydro), a plasma and magnetics module, and a global optimizer.

ISM-hydro uses a 2D axisymmetric fluid model to predict the liquid lithium compression trajectory. The model uses a mixed Lagrangian-Eulerian approach to solve the compressible Navier-Stokes equations [6, 7].

- This method is tailored to the regime of GF's liner collapse and is thus very efficient, running in less than one minute on a single processing core.
- ISM-hydro has been verified against OpenFOAM CFD [7], which has in turn been validated by results from GF's cylindrical water compressor (CWC) experiment [8].
- The fluid model optionally includes magnetic modelling wherein the vacuum toroidal field is self-consistently advected and resistively diffused into the liner.
- In the regime of a power plant magnetic pressure can significantly alter the liner's trajectory.



Above: Comparison of ISM-hydro and OpenFOAM CFD liner trajectories [7]. The case shown does not include magnetics and was used for verification purposes only. Compression timing and depth differ by less than 1%.



Left: Simplified depiction of GF's core MTF architecture and ISM components. High pressure gas flows from accumulators into rotor bores. Pistons embedded in the rotor drive the rotating liner inward, compressing the plasma target. Cavity shaping is achieved by varying drive gas pressure and timing along the vertical axis.

The ISM plasma model is based upon a series of Taylor state (force-free) Grad-Shafranov solutions of the form:

$$r^2\nabla\cdot\left(\frac{1}{r^2}\nabla\psi\right)=-\lambda^2\psi$$

Each solution is Bateman scaled [9], making it consistent with the vacuum toroidal field. The temperature evolution is derived from:

$$\frac{3}{2}n\dot{T}-T\dot{n}=\nabla\cdot\left(\frac{3}{2}\chi_E n\nabla T\right)+Q$$

Assuming uniform density, uniform thermal diffusivity, and a self similar temperature profile this simplifies to:

$$\nabla^2T=-\lambda^2T\rightarrow\dot{T}=T\left(\frac{2}{3}\frac{\dot{n}}{n}-\lambda^2\chi_E\right)+\dot{T}_Q$$

where λ is the same magnetic eigenvalue from the Taylor state equation above. Density is then directly related to plasma volume with a correction for particle loss due to flux diffusion. Fusion power is calculated following Bosch-Hale thermal reactivities [10]. Subsequent terms for Ohmic heating, alpha heating, and electron-ion equilibration are included.

The plasma poloidal field exerts a pressure concentrated near the equator, naturally enhancing cavity shaping.

Design Point Optimization

The presented design point is a solution of the following many-dimensional global optimization problem:

maximize: **Net energy output**

subject to:
- Plasma stability limits (κ, β, q, etc.)
- Liner Rayleigh-Taylor stability
- Fluid, rotational, and magnetic stress limits
- No centre shaft or piston collisions

Optimization is performed using a two step approach. The input space is first sampled using a low-discrepancy method. Candidate points are then automatically selected from convex regions of the sample set and refined by conventional local minimization methods.

The input space includes, but is not limited to: initial plasma and vacuum magnetic field values, initial rotation speed, initial accumulator pressure and valve timings, number of driver layers, piston stroke length, liquid volume, liquid composition, compression chamber aspect ratio, and overall machine size.

The dimensionality and size of this space is reduced wherever possible by parameterizing inputs, such as driver timing and pressure profiles, applying scaling laws related to machine size and compression timescale, and employing heuristics developed by reduced-dimensionality parameter scans.

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