Plasma Jet Driven Magneto-Inertial Fusion (PJMIF)

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Plasma jet experiments can provide cm/μs/Mbar-scale plasmas for discovery HEDLP science and a platform for laboratory astrophysics

Plasma jets forming imploding plasma liners on the Plasma Liner Experiment (PLX), funded by DOE-FES:

Head-on collision of plasma jets for collisionless shock experiments, funded by LANL-LDRD:

Figure credit: Hubble Institute

Imploding plasma liner formed by 30 merging plasma jets with 1.5 MJ capacitive stored energy

Accretion disk experiment using ~12 plasma guns, with goal of emergent formation/collimation of plasma jets

Higher jet/liner energies can also potentially have fusion energy applications ➔ focus of this talk

Color CAD drawings courtesy of HyperV Technologies
MIF uses a magnetic field in inertially confined fuel to potentially allow fusion burn at modest implosion velocity (<100 km/s) using efficient ($\eta \sim 0.3–0.7$) pulsed power drivers.

- Magnetic field reduces thermal transport and enhances $\alpha$-particle energy deposition
  - $Br$ instead of $\rho r$ becomes fusion figure-of-merit
  - “Ignition” possible at $\rho r \sim 0.01$ g/cm$^2$
- Confinement time determined by heavy inflowing liner, not inertia of burning fuel
- High driver efficiency (0.3–0.7) means modest gains $\sim 10–30$ are relevant for fusion energy

Basko et al., *Nucl. Fusion*, 2000
PJMF burn configuration at peak target compression with energy gain > 10

- Target at peak compression
  - \( n_{DT} \sim 5 \times 21 \text{ cm}^{-3} \)
  - \( T \approx 10 \text{ keV} \)
  - \( B \sim 100 \text{ T} \)
  - \( M \sim 10 \text{ mg} \)
  - dwell time \( \tau \sim 1 \text{ \mu s} \)
- These conditions would give (not including afterburner)
  - \( \sim 10\% \) fuel burn-up
  - \( \sim 1.3 \times 10^{20} \text{ DT reactions} \)
  - \( \sim 350 \text{ MJ fusion yield} \)
- Target compressed by much heavier (Xe) plasma liner
  - \( \sim 30–50 \text{ MJ initial kinetic energy} \)
  - \( 10–30 \text{ g} @ \sim 50 \text{ km/s} \)
Converging plasma jets may be used to assemble both the target and plasma liner in a standoff manner

- Option (1): subset of guns fire DT jets forming target shell immediately followed by remainder of guns firing DT/Xe composite jets forming afterburner and heavy liner to compress DT target
- Option (2): all guns fire simultaneously launching composite jets with DT target and afterburner layers in front and Xe layer in rear
- Fuel magnetization discussed on next slide
- Fully standoff fuel assembly and implosion/compression

Method for standoff magnetization of DT fuel is needed: laser beat wave current drive is an attractive option

Lasers fired ~1 μs prior to peak compression:

- Slightly frequency-offset laser beams generate beat wave at $\sim \omega_{pe}$ to resonantly accelerate electrons, which drives current
- Parent frequencies well above cutoff so no accessibility issue
- Has been demonstrated at low density in a tokamak [Rogers & Hwang, Phys. Rev. Lett., 1992]
- ~1 T seed field needed with late stage compression amplifying field to ~ 100 T
- Probable lasers needed: ~1 μm, ~1 kJ, ~1 ns
- Exploratory experiments using refurbished 50 J CO$_2$ lasers and PIC modeling are ongoing (UC, Davis and LANL/Voss Scientific, respectively)

Use of electron beams and fundamentally different methods also need to be evaluated
Preliminary and highly idealized 1D hydrodynamic simulations* are exploring/identifying G>5 possibilities

<table>
<thead>
<tr>
<th>Implosion energy, total yield, target-only yield (MJ)</th>
<th>Ave. initial target (DT) parameters (R-cm, n-cm⁻³, T-eV, v-km/s)</th>
<th>Ave. initial afterburner (DT) parameters (ΔR-cm, n-cm⁻³, T-eV, v-km/s)</th>
<th>Ave. initial liner (Xe) parameters (ΔR-cm, n-cm⁻³, T-eV, v-km/s)</th>
<th>Total gain, target-only gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>20, 416,189</td>
<td>4.1, 3.4e18, 80, 4.0</td>
<td>0.14, 1.2e20, 0.5, 39.2</td>
<td>3.5, 7.3e19, 1.4, 40 (stepped profile)</td>
<td>21, 9</td>
</tr>
<tr>
<td>30, 660, 231</td>
<td>4.1, 4.3e18, 80, 6.0</td>
<td>0.14, 1.9e20, 0.4, 58.8</td>
<td>3.5, 5.0e19, 1.4, 60 (stepped profile)</td>
<td>22, 8</td>
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<tr>
<td>50, 1000, 292</td>
<td>4.1, 4.3e18, 80, 8.7</td>
<td>0.14, 1.7e20, 0.2, 59.6</td>
<td>3.5, 8.2e19, 1.4, 60 (steady-state profile)</td>
<td>20, 6</td>
</tr>
<tr>
<td>50, 2000, 481</td>
<td>4.0, 4.3e18, 80, 6.0</td>
<td>0.14, 1.9e20, 0.5, 58.8</td>
<td>3.5, 7.9e19, 1.4, 60 (stepped profile)</td>
<td>40, 10</td>
</tr>
<tr>
<td>77, 4300, 687</td>
<td>4.0, 4.3e18, 80, 8.6</td>
<td>0.14, 4.3e20, 0.5, 59.1</td>
<td>3.5, 1.3e20, 1.4, 60 (steady-state profile)</td>
<td>56, 9</td>
</tr>
</tbody>
</table>

*Idealized Lagrangian 1D simulations: no thermal conduction, alpha-deposition is adjustable parameter (0.2–0.3 in target; 0.5–1.0 in afterburner), ideal gas EOS; runs are initiated just as liner/afterburner engage the target prior to compression.

Results courtesy of Y. C. F. Thio using the LF1D code
Innovative shaped coaxial guns capable of launching plasma jets of required parameters are key for PJMIF

- Required parameters
  - L ~ 5 cm
  - n ~ $10^{17}$ cm$^{-3}$
  - V ~ 40–80 km/s
  - M ~ 10–60 mg
  - T ~ few eV

- Pre-ionized injection to overcome critical ionization velocity limit and “leaky” snow plow acceleration

- Shaped inner electrode to prevent blow-by of most of the plasma mass

- PJMIF will require such guns operating at few MA, and injection of multiple layers with different species

Main physics challenges for single-shot PJMIF proof-of-principle demonstration

- Forming/launching jets with required parameters/characteristics
  - Density, velocity, mass, Mach number
  - Geometry/profile
  - Impurity level

- Target and liner formation/implosion
  - Requisite uniformity
  - Acceptable levels of convergent instabilities and liner/fuel mix
  - Reaching sufficient peak pressures, densities, temperature, dwell time

- Standoff magnetization
  - Demonstrate physics of beat wave current drive at MIF-relevant density
  - Evaluate current drive efficiency
  - How to obtain desired field strengths and topologies at peak compression
Gains as low as \( \sim 10 \) may generate net electricity due to efficiencies of PJMIF.

To minimize cost-of-electricity, need to examine trade-off space among repetition rate, yield, maintenance down-time, and use of modular reactor cores sharing balance-of-plant systems.
Reactor and technology issues/challenges

- **Repetitive pulsed power** (3.15×10⁷ shots per year at 1 Hz operation)
  - Promising advances by KrF IFE program in repetitive solid-state switching technology (10 million-shot runs have been achieved at 5 Hz operation) [Weidenheimer, *Power Modulator Symposium*, 2006]

- **PJMIF possibly compatible with liquid first wall to avoid costly solid materials development program**
  - However, solid and wetted wall concepts still viable especially due to relatively low heat loading (~1 MW/m² for 100 MW modular fusion core with 6 m diameter chamber)
  - Chamber clearing does not appear to be an issue

- **Gun erosion and surviving fusion blast**
  - Guns will be sacrificial needing periodic replacement
  - Much R&D needed to determine material requirements (e.g., tungsten alloys)

Ron Miller is acknowledged for his inputs on this slide
PJMF presents a potential low-cost (~$300M) R&D path to demonstrating single-shot engineering breakeven in ~decade

Important caveat: This schedule/budget are optimistic in the sense that major S&T problems are assumed tractable.