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Title:	Plasma Jet Driven Magneto-Inertial Fusion (PJMIF)
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Plasma Jet Driven Magneto-Inertial Fusion (PJMIF)

Scott Hsu

Physics Division, LANL

Fusion Power Associates 32nd Annual Meeting and Symposium

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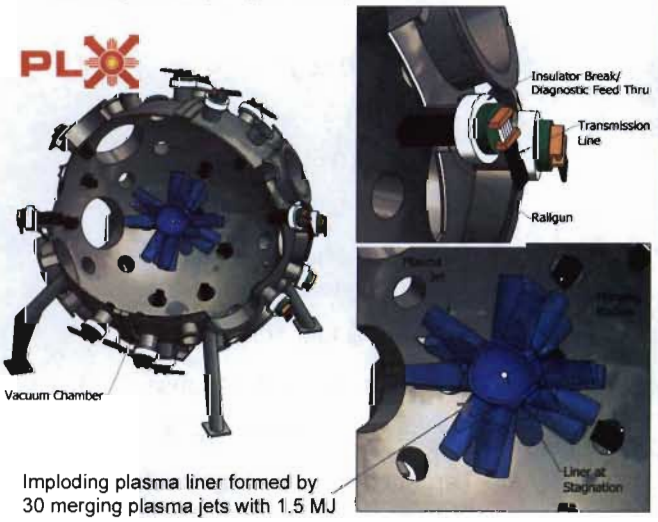
Plasma jet experiments can provide cm/μs/Mbar-scale plasmas for discovery HEDLP science and a platform for laboratory astrophysics

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



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

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

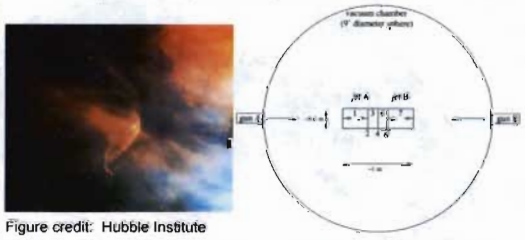


Figure credit: Hubble Institute

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

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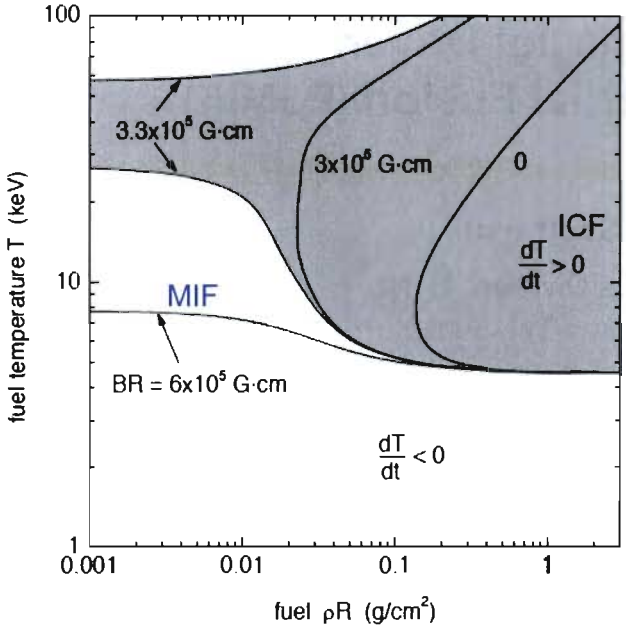
Color CAD drawings courtesy of HyperV Technologies

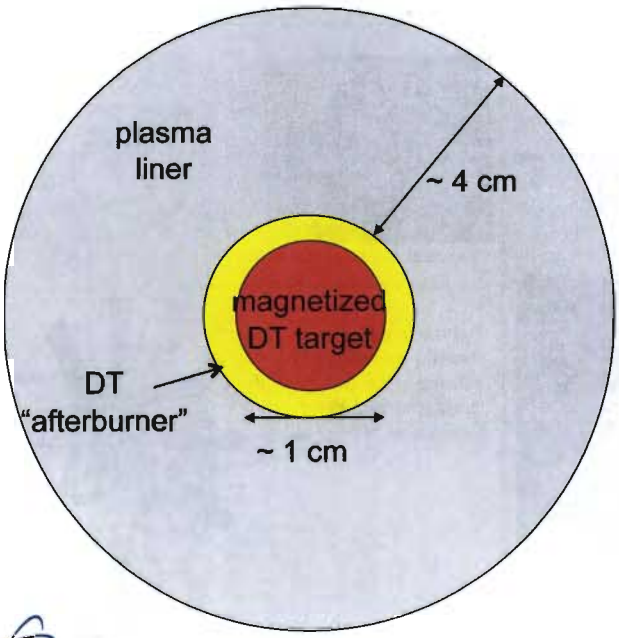
MIF uses a magnetic field in inertially confined fuel to potentially allow fusion burn at modest implosion velocity (<100 km/s) using efficient (η~0.3–0.7) pulsed power drivers



Basko et al., *Nucl. Fusion*, 2000

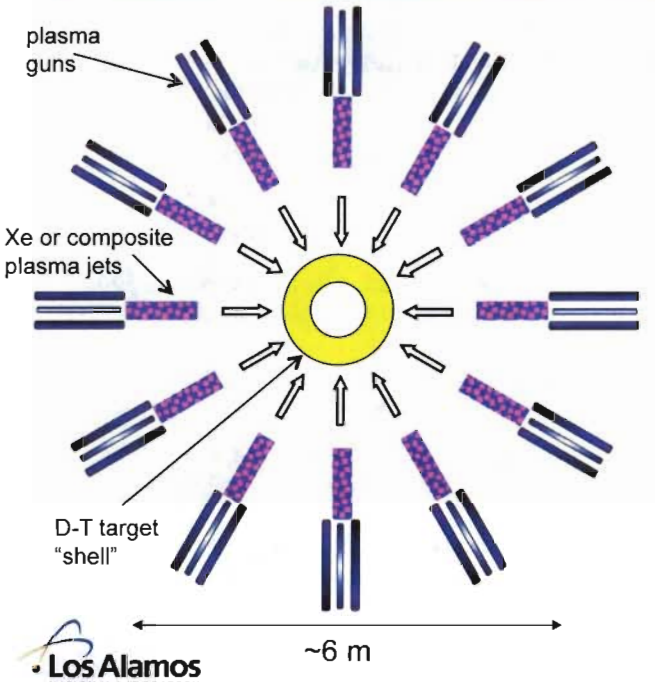
- Magnetic field reduces thermal transport and enhances α-particle energy deposition
  - *Br* instead of *ρr* becomes fusion figure-of-merit
  - "Ignition" possible at *ρr*~0.01 g/cm²
- Confinement time determined by heavy inflowing liner, not inertia of burning fuel
- High driver efficiency (0.3–0.7) means modest gains ~10–30 relevant for fusion energy

PJMIF burn configuration at peak target compression with energy gain > 10



- Target at peak compression
  - n_{DT} ~ 5×21 cm^{-3}
  - $T \approx 10$ keV
  - B ~ 100 T
  - M ~ 10 mg
  - dwell time τ ~ 1 μs
- These conditions would give (not including afterburner)
  - ~10% fuel burn-up
  - ~1.3×20 DT reactions
  - ~ 350 MJ fusion yield
- Target compressed by much heavier (Xe) plasma liner
  - ~30–50 MJ initial kinetic energy
  - 10–30 g @ ~50 km/s

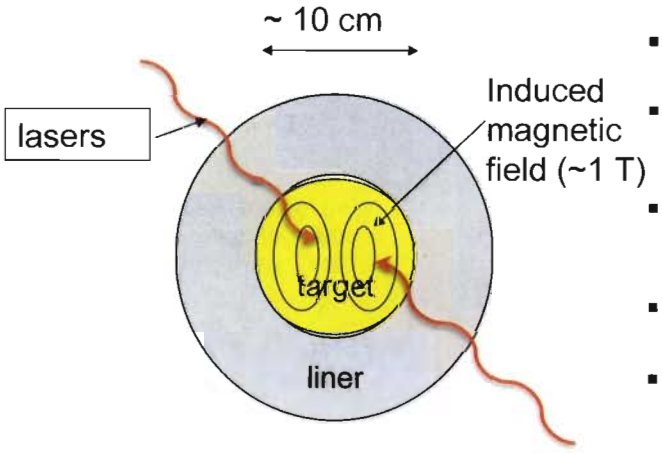
Converging plasma jets may be used to assemble both the target and plasma liner in a standoff manner



- 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 offset laser beams generate beat wave at ~ω_{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)

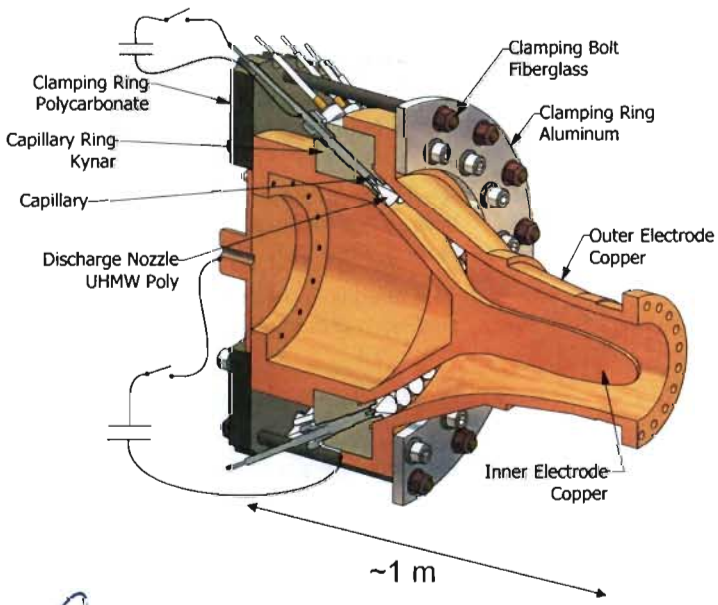
Use of electron beams and fundamentally different methods also need to be evaluated

Preliminary and highly idealized 1D hydrodynamic simulations* are exploring/identifying G>20 possibilities

Implosion energy & yield (MJ)	Ave. initial target (DT) parameters (R-cm, n-cm^{-3}, T-eV, v-km/s)	Ave. initial afterburner (DT) parameters (ΔR-cm, n-cm^{-3}, T-eV, v-km/s)	Ave. initial liner (Xe) parameters (ΔR-cm, n-cm^{-3}, T-eV, v-km/s)	Gain
20, 560	4.1, 3.4e18, 80, 4.0	0.14, 1.5e20, 0.5, 39.2	3.5, 7.3e19, 1.4, 40 (stepped profile)	28
30, 660	4.1, 4.3e18, 80, 6.0	0.14, 1.9e20, 0.4, 58.8	3.5, 5.0e19, 1.4, 60 (stepped profile)	22
50, 1000	4.1, 4.3e18, 80, 8.7	0.14, 1.7e20, 0.2, 59.6	3.5, 8.2e19, 1.4, 60 (steady-state profile)	20
50, 2000	4.0, 4.3e18, 80, 6.0	0.14, 1.9e20, 0.5, 58.8	3.5, 7.9e19, 1.4, 60 (stepped profile)	40
77, 4300	4.0, 4.3e18, 80, 8.6	0.14, 4.3e20, 0.5, 59.1	3.5, 1.3e20, 1.4, 60 (steady-state profile)	56

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

Innovative shaped coaxial guns capable of launching plasma jets of required parameters are key for PJMIF



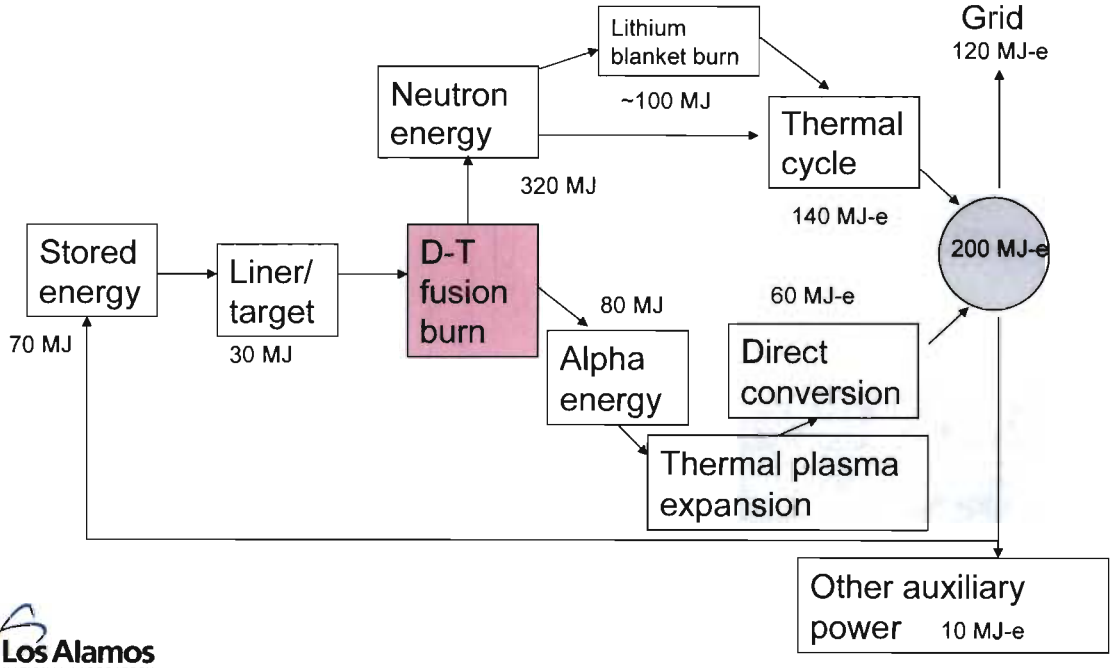
- Required parameters
  - L ~ 5 cm
  - n ~ 10^{17} cm^{-3}
  - V ~ 40–80 km/s
  - M ~ 10–60
  - T ~ few eV
- Pre-ionized injection to overcome critical ionization velocity limit and "leaky" snow plow acceleration
- Shaped inner electrode to prevent blow-by of most of the plasma mass
- PJMIF will require such guns operating at few MA, and injection of multiple layers with different species

Drawing courtesy of HyperV Technologies
[Witherspoon et al., *Rev. Sci. Instrum.*, 2009]

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
  - Materials compatible with repetitive operation
- **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

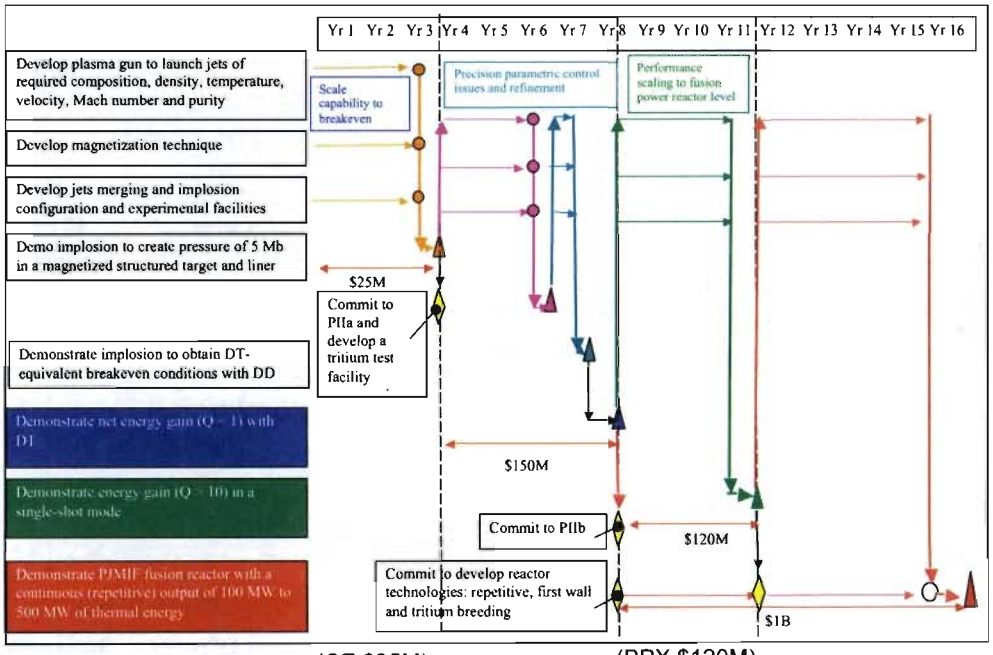
Reactor power flow per shot (example)



Reactor and technology issues

- **Repetitive pulsed power (3.15×7 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)

- **PJMIF possibly compatible with liquid first wall to avoid costly solid materials development program**
  - Surface vortex liquid flows envisioned for heavy ion beam fusion potentially well-suited for PJMIF
  - However, solid and wetted wall concepts still viable especially due to relatively low heat loading (~0.9 MW/m^2 for 100 MW modular fusion core with 6 m diameter chamber)

- **Gun erosion and surviving fusion blast**
  - Guns will be sacrificial needing periodic replacement
  - Much R&D needed to determine material requirements

Development path to PJMIF "DEMO": 100–500 MW fusion proto-type reactor (16 years, 4 phases, ~$1.3B)