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Plasma Jet Driven Magneto-Inertial Fusion (PJMIF)

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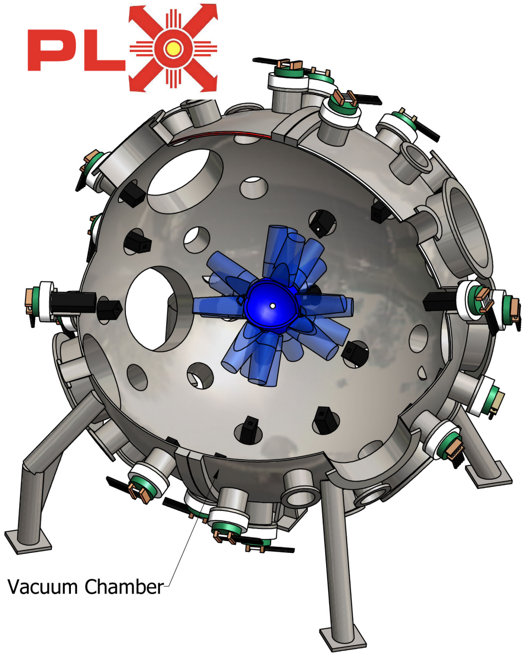
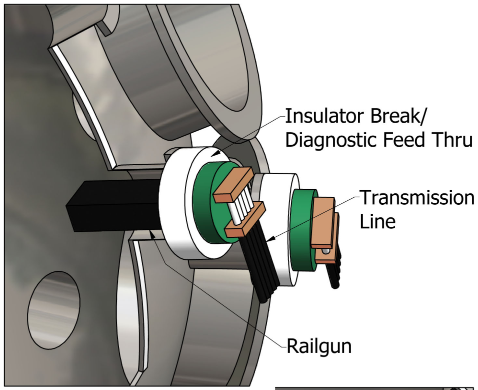
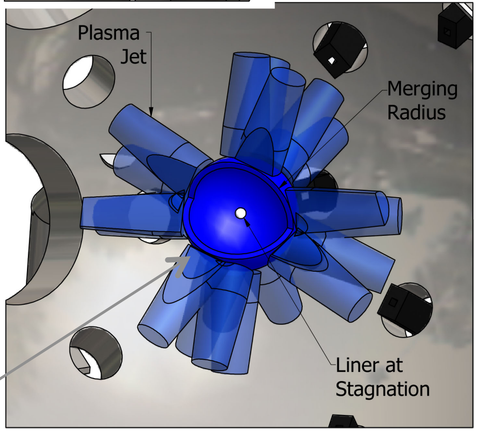
Plasma jet experiments can provide cm/μs/Mbar-scale plasmas for discovery HEDLP science and a platform for laboratory astrophysics

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



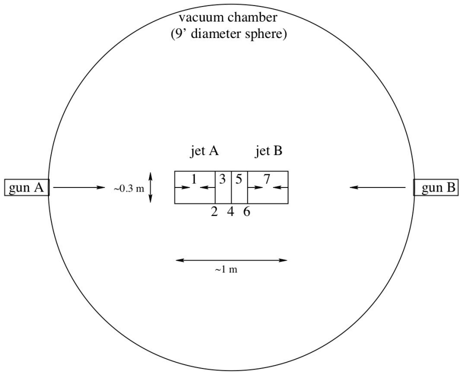




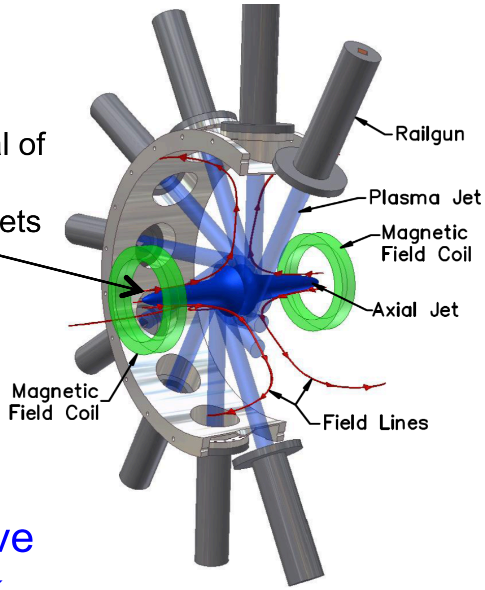
Imploding plasma liner formed by 30 merging plasma jets with 1.5 MJ capacitive stored energy

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

Figure credit: Hubble Institute



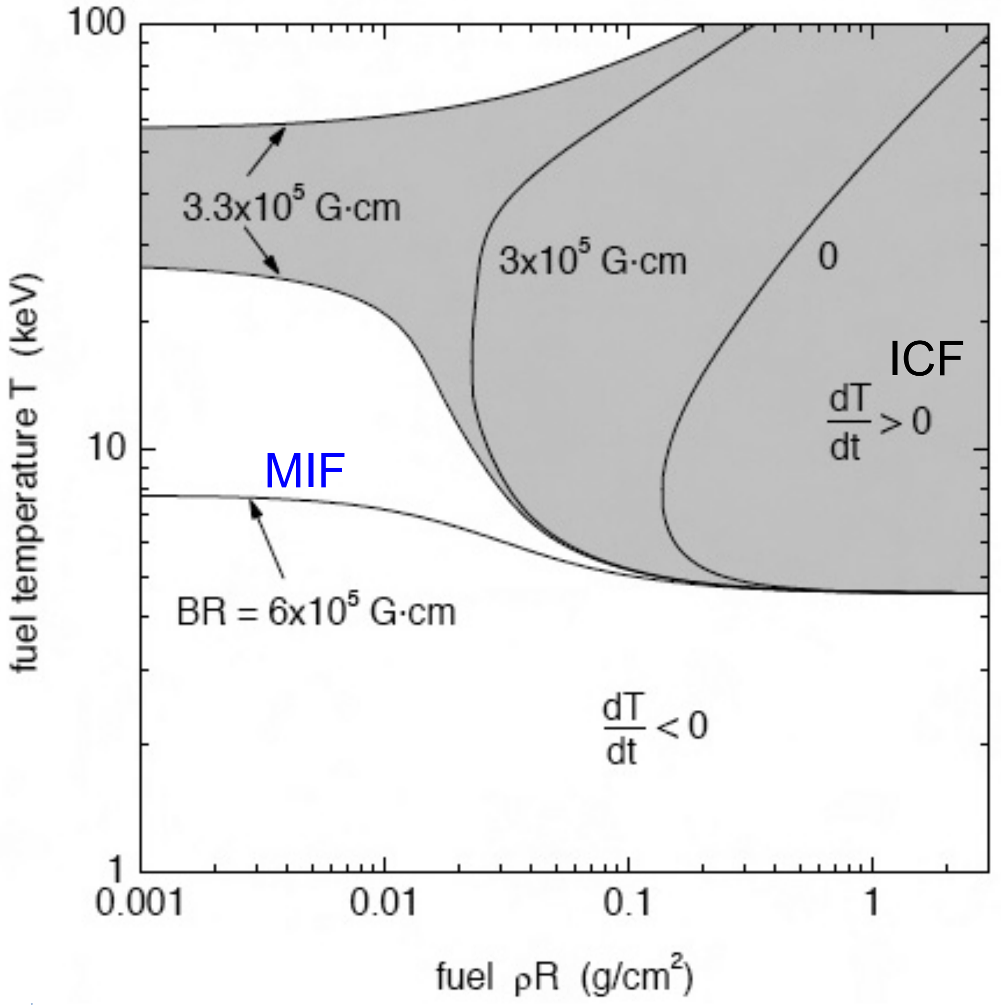
Accretion disk experiment using ~12 plasma guns, with goal of emergent formation/ collimation of plasma jets



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

Color CAD drawings courtesy of HyperV Technologies

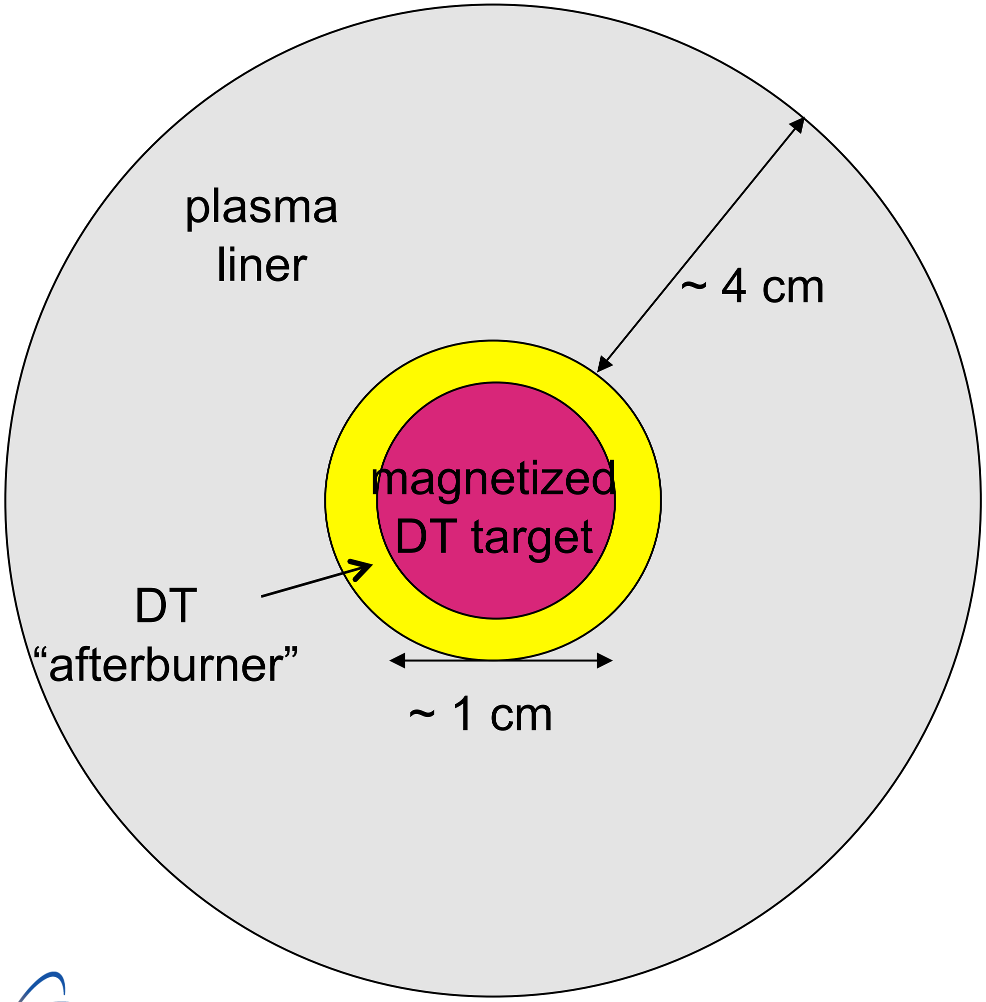
MIF uses a magnetic field in inertially confined fuel to potentially allow fusion burn at modest implosion velocity (<100 km/s) using efficient (η~0.3–0.7) pulsed power drivers



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

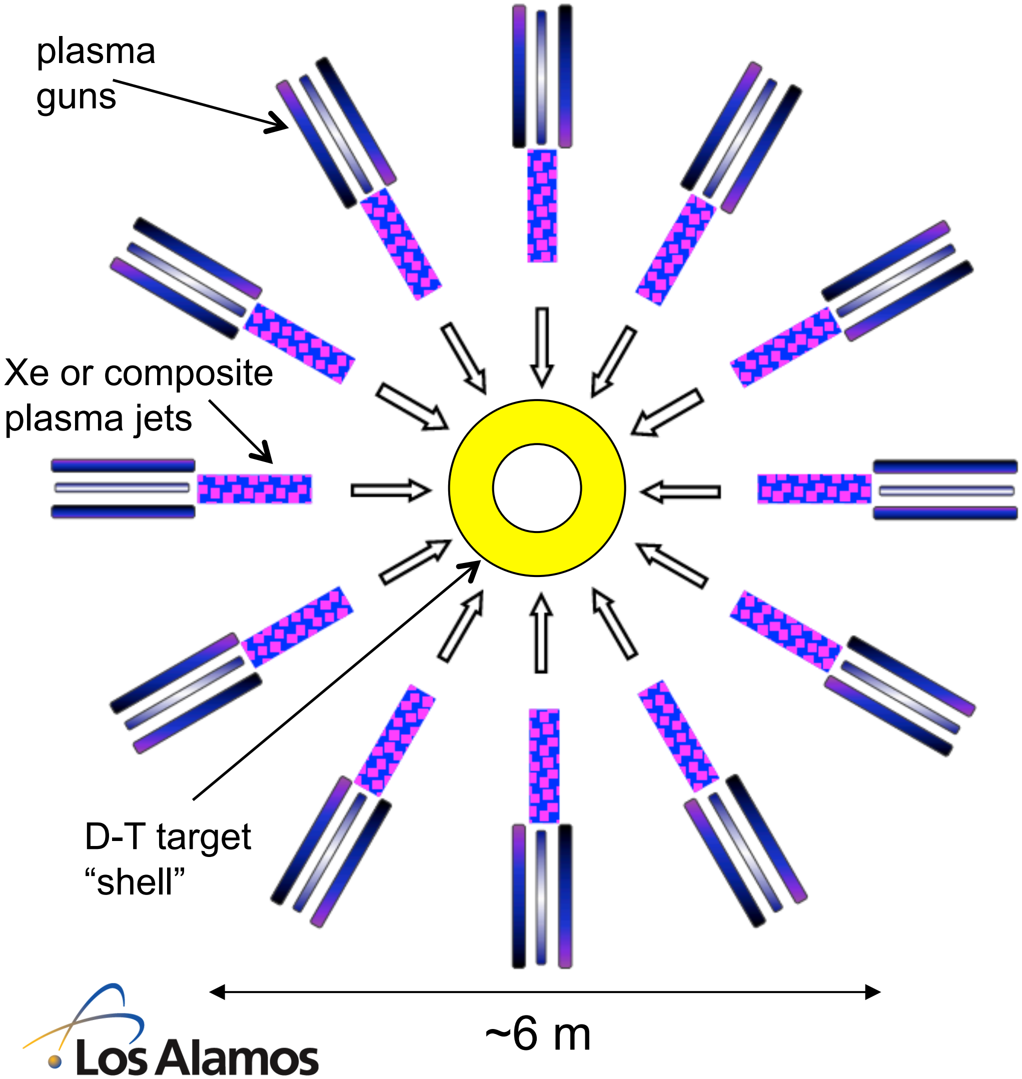
- Magnetic field reduces thermal transport and enhances α-particle energy deposition
  - *Br* instead of *ρr* becomes fusion figure-of-merit
  - “Ignition” possible at *ρr*~0.01 g/cm^2
- Confinement time determined by heavy inflowing liner, not inertia of burning fuel
- High driver efficiency (0.3–0.7) means modest gains ~10–30 are 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
  - ~1.3×10^{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

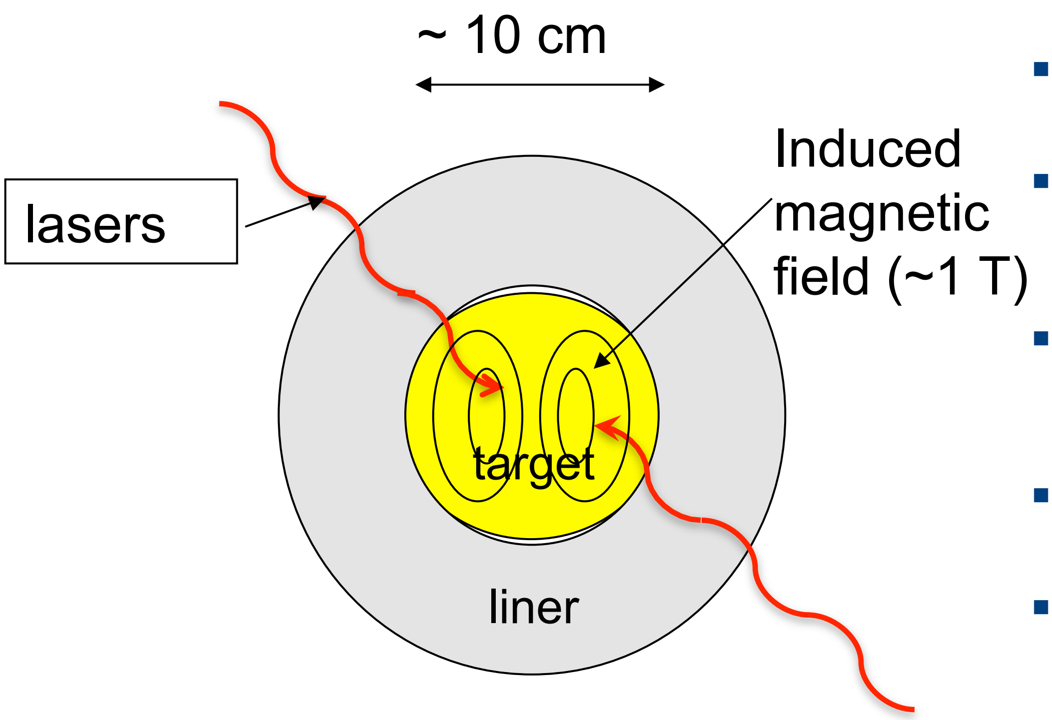


- Option (1): subset of guns fire DT jets forming target shell immediately followed by remainder of guns firing DT/Xe composite jets forming afterburner and heavy liner to compress DT target
- Option (2): all guns fire simultaneously launching composite jets with DT target and afterburner layers in front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

For more details, please see T. J. Awe et al., *Phys. Plasmas* **18**, 072705 (2011) and S. C. Hsu et al., *IEEE Trans. Plasma Sci.*, to be published (2012).

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 ~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

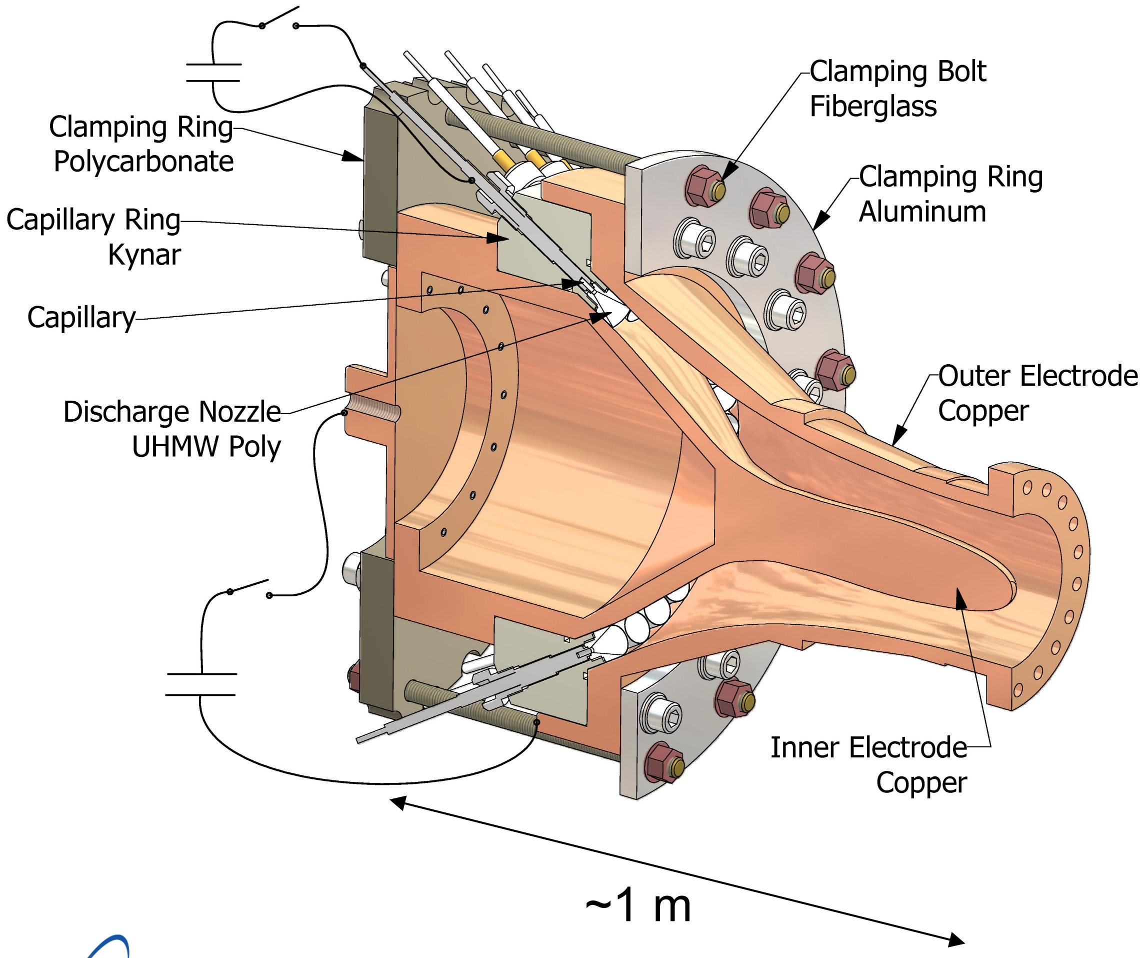
Preliminary and highly idealized 1D hydrodynamic simulations* are exploring/identifying G>5 possibilities

Implosion energy, total yield, target-only 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)**	**Total gain, target-only gain**
20, 416,189	4.1, 3.4e18, 80, 4.0	0.14, 1.2e20, 0.5, 39.2	3.5, 7.3e19, 1.4, 40 (stepped profile)	21, 9
30, 660, 231	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, 8
50, 1000, 292	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, 6
50, 2000, 481	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, 10
77, 4300, 687	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, 9

*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



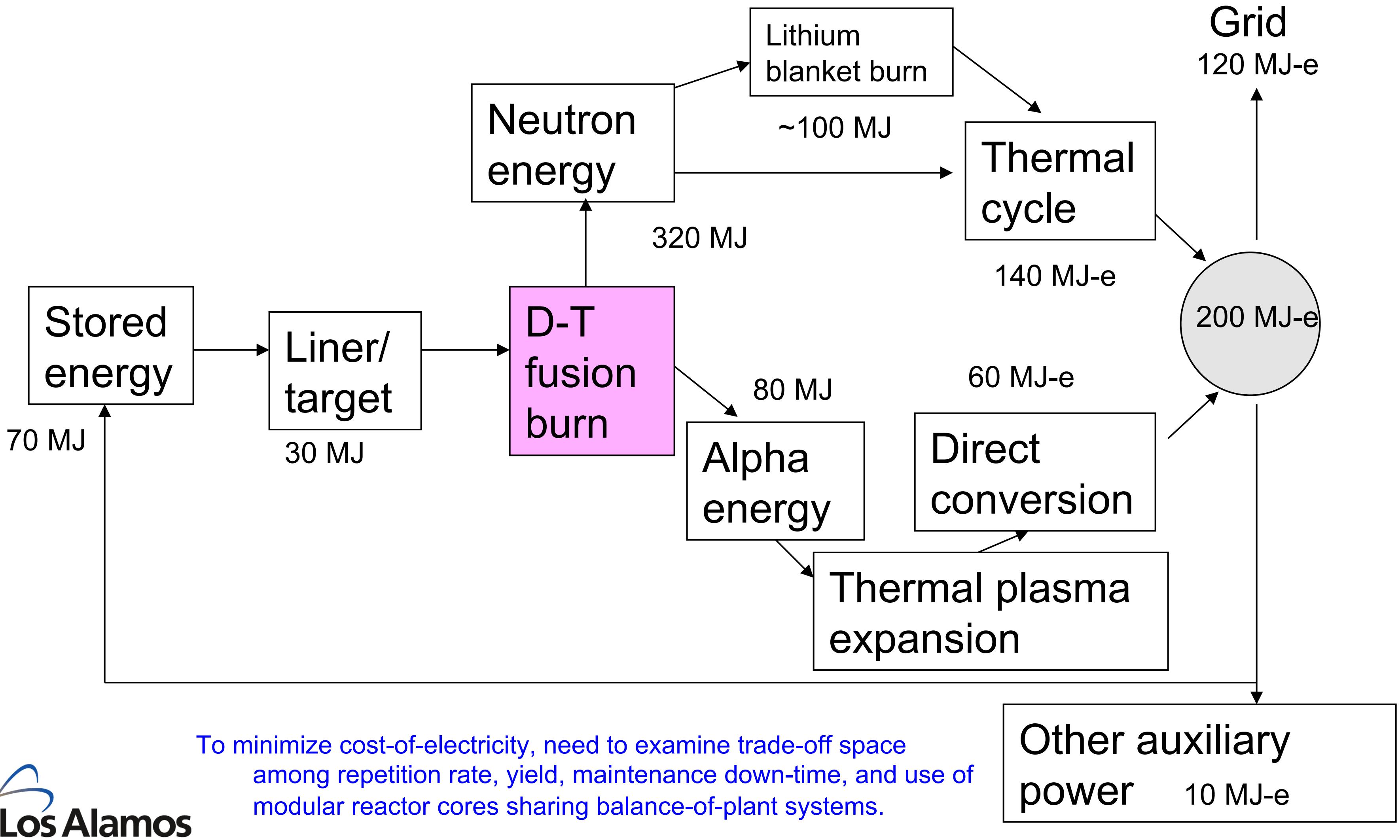
Drawing courtesy of HyperV Technologies
[Witherspoon et al., *Rev. Sci. Instrum.*, 2009]

- 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 ~10 may generate net electricity due to efficiencies of PJMIF



Stored energy

70 MJ

Liner/ target

30 MJ

D-T fusion burn

320 MJ

Neutron energy

Lithium blanket burn

~100 MJ

Thermal cycle

140 MJ-e

80 MJ

Alpha energy

Thermal plasma expansion

Direct conversion

60 MJ-e

200 MJ-e

Grid

120 MJ-e

Other auxiliary power 10 MJ-e

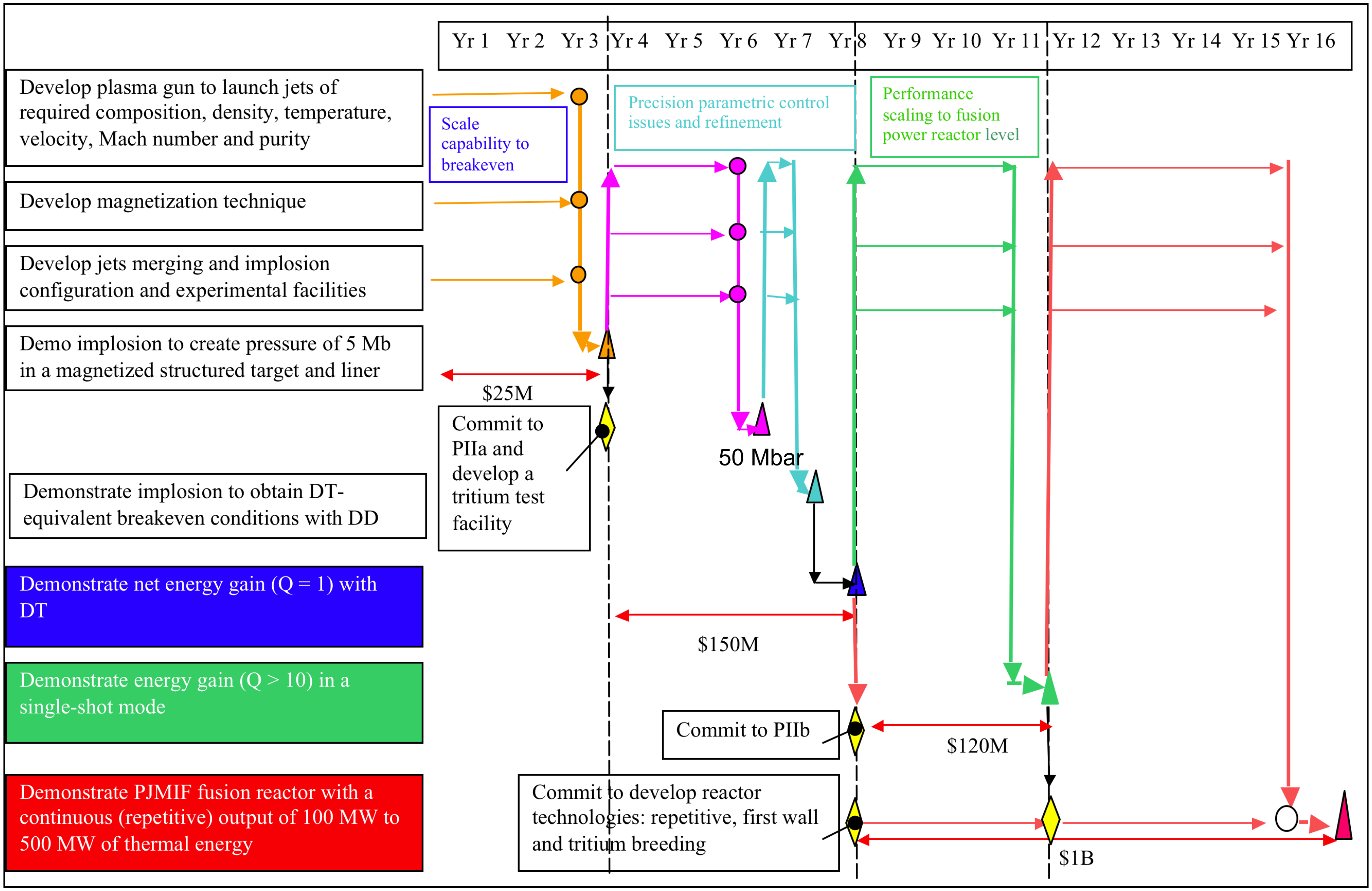
To minimize cost-of-electricity, need to examine trade-off space among repetition rate, yield, maintenance down-time, and use of modular reactor cores sharing balance-of-plant systems.

Reactor and technology issues/challenges

- **Repetitive pulsed power (3.15×10^7 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) [Weidenheimer, *Power Modulator Symposium,* 2006]
- **PJMIF possibly compatible with liquid first wall to avoid costly solid materials development program**
  - Surface vortex liquid flows envisioned for heavy ion beam fusion [Bardet, *Fus. Sci. Tech.*, 1995] potentially well-suited for PJMIF
  - However, solid and wetted wall concepts still viable especially due to relatively low heat loading (~1 MW/m^2 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

PJMIF presents a potential low-cost (~$300M) R&D path to demonstrating single-shot engineering breakeven in ~decade



Yr 1 Yr 2 Yr 3 Yr 4 Yr 5 Yr 6 Yr 7 Yr 8 Yr 9 Yr 10 Yr 11 Yr 12 Yr 13 Yr 14 Yr 15 Yr 16

Develop plasma gun to launch jets of required composition, density, temperature, velocity, Mach number and purity

Develop magnetization technique

Develop jets merging and implosion configuration and experimental facilities

Demo implosion to create pressure of 5 Mb in a magnetized structured target and liner

Demonstrate implosion to obtain DT-equivalent breakeven conditions with DD

Demonstrate net energy gain (Q = 1) with DT

Demonstrate energy gain (Q > 10) in a single-shot mode

Demonstrate PJMIF fusion reactor with a continuous (repetitive) output of 100 MW to 500 MW of thermal energy

Scale capability to breakeven

Precision parametric control issues and refinement

Performance scaling to fusion power reactor level

$25M

Commit to PIIa and develop a tritium test facility

50 Mbar

$150M

Commit to PIIb

$120M

Commit to develop reactor technologies: repetitive, first wall and tritium breeding

$1B

(CE $25M)

(PoP/PE $150M)

(BPX $120M)

(DEMO ~$1B)

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