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Plasma Liners and the Potential for a Standoff Magneto-Inertial Fusion Reactor

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The focus of this talk

- Is on a fusion energy driver that can potentially
  - Access the “sweet spot” in fusion parameter space
  - Provide a low-cost (i.e., <$500M) R&D path to single-shot reactor-relevant gain
  - Offer an attractive reactor concept, ultimately providing competitive cost-of-electricity (COE)

Outline

- What is standoff and why do we want it?
- Standoff embodiment of magneto-inertial fusion (MIF) using plasma liners
  - Parameter space
  - Forming plasma liners via an array of supersonic plasma jets launched by plasma guns (PJMIF)
  - PJMIF reactor considerations
- Development path

What is a standoff driver and why do we want it?

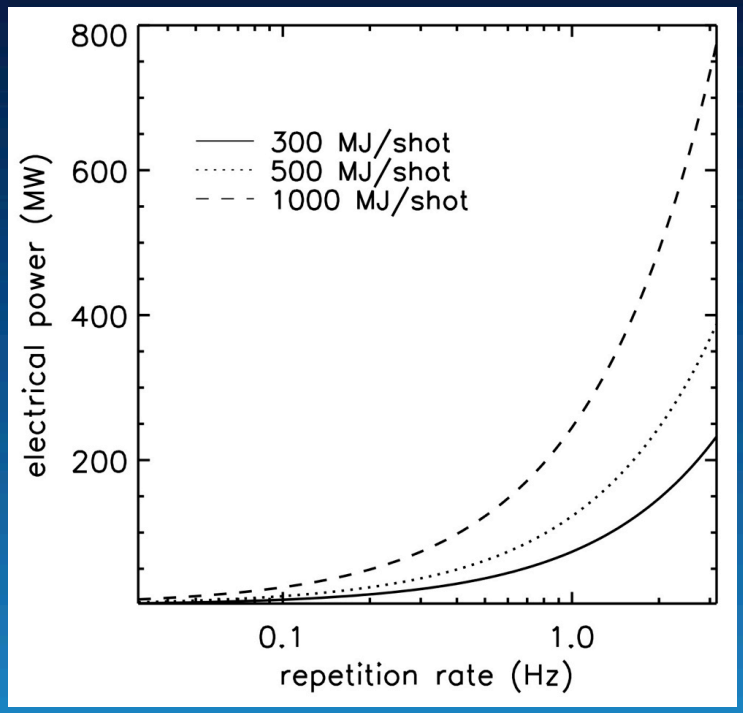
- Standoff places ALL compression driver and target formation hardware far enough away from location of fusion burn to eliminate repetitive hardware destruction

- Easier working conditions → higher shot rate
  - Lower R&D cost
  - Faster rate of scientific progress (100's if not 1000's of shots ultimately needed to identify and overcome problems for MIF)
  - More diagnostic access and possibilities (also needed for identifying/solving problems)

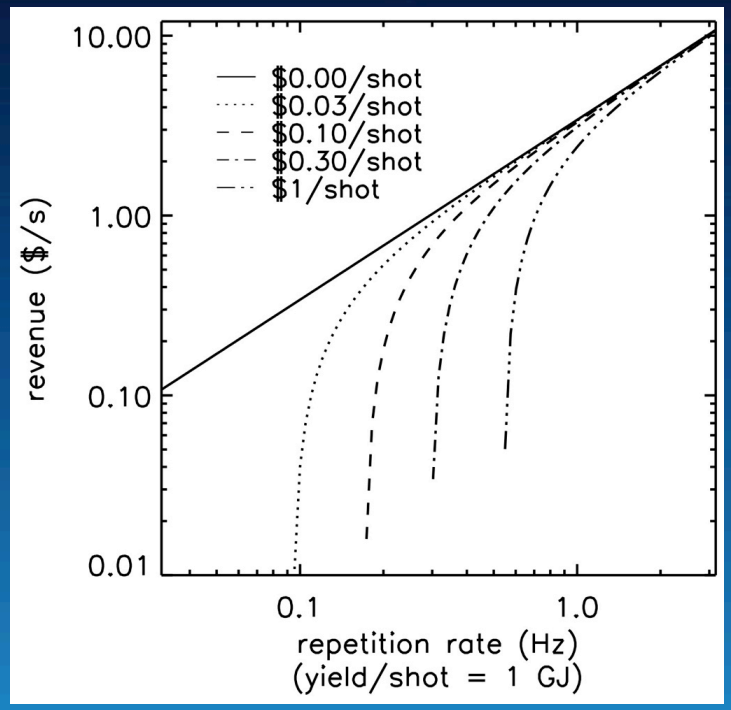
- More reactor friendly (next slide) and more attractive & plausible to potential sponsors/investors as a path to fusion energy

Standoff's ultimate purpose is to improve power plant economics

Standoff allows higher repetition rate and lower yield per shot → greatly simplifies reactor engineering



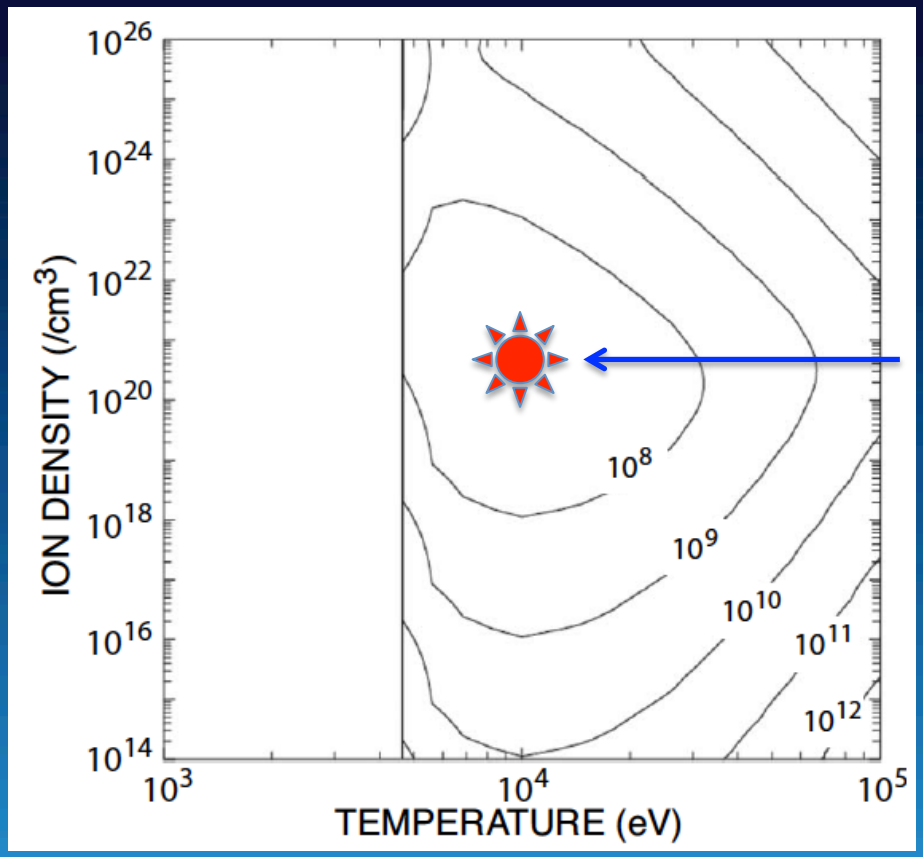
Without standoff → hardware cost per shot quickly erodes power plant revenue



Assumes electrical conversion efficiency=0.35, recirculating power fraction=0.3, market value of electricity=$0.05 per kw-h.

MIF seeks to access "sweet spot" in thermonuclear fusion parameter space

Minimum facility cost (US$) for magnetized fuel satisfying Lawson condition:

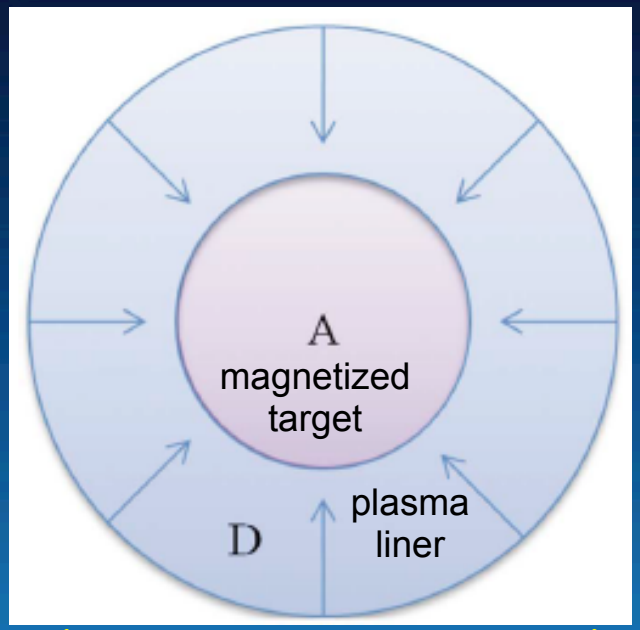


M_{fuel} ~ few mg
R_{fuel} ~ 1 cm
E_{fuel} ~ several MJ
P_{heat} ~ 0.1 TW
Driver cost<$100M

Figure and parameters are from Ref. 7.

Plasma liner AND its source together constitute a standoff driver for compressing magnetized plasma to fusion conditions near the "sweet spot"

Source hardware can be located several meters away.

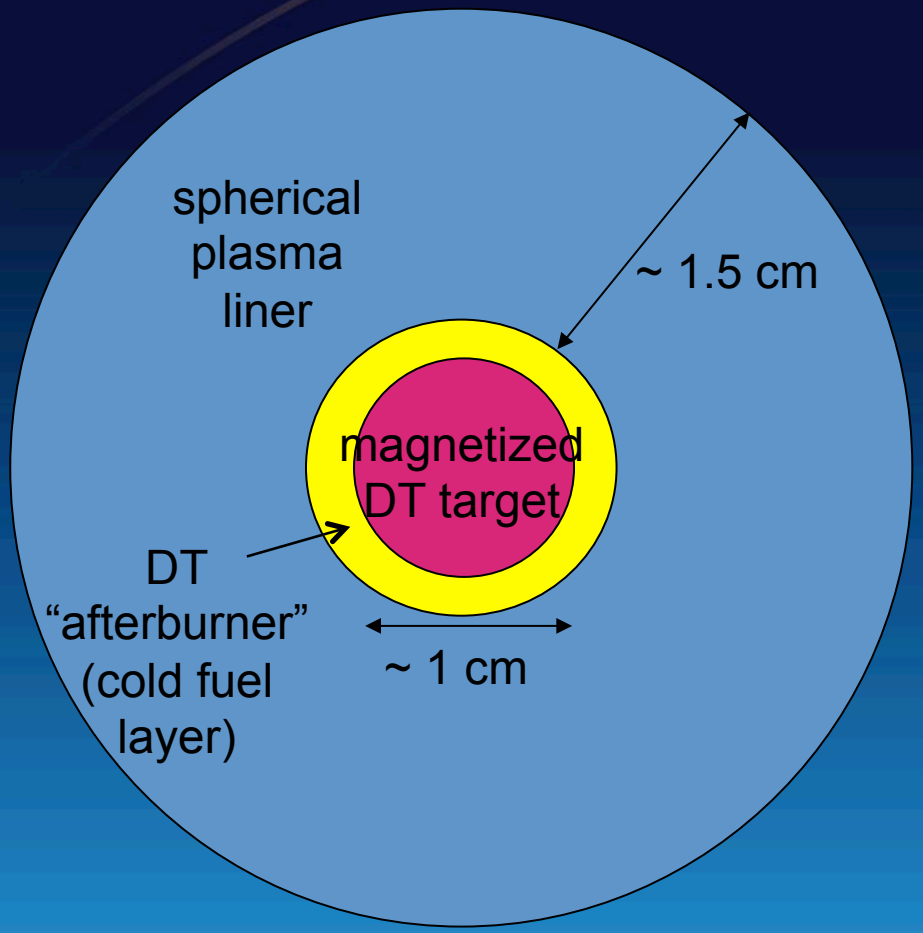


~20 cm
at initiation of target compression

- Plasma liner ram pressure (ρv^2) compresses target to fusion conditions (~100 Mbar @ ~10 keV)
- Desired implosion will have:
  - Cold, fast, high-*Z* liner, i.e., high Mach #
  - Sufficient uniformity (target convergence ~ 10×)
  - Liner thickness & profiles optimized for dwell (burn) time & energy gain

Description of physics and related simulations in Refs. 1–6 (and references therein).

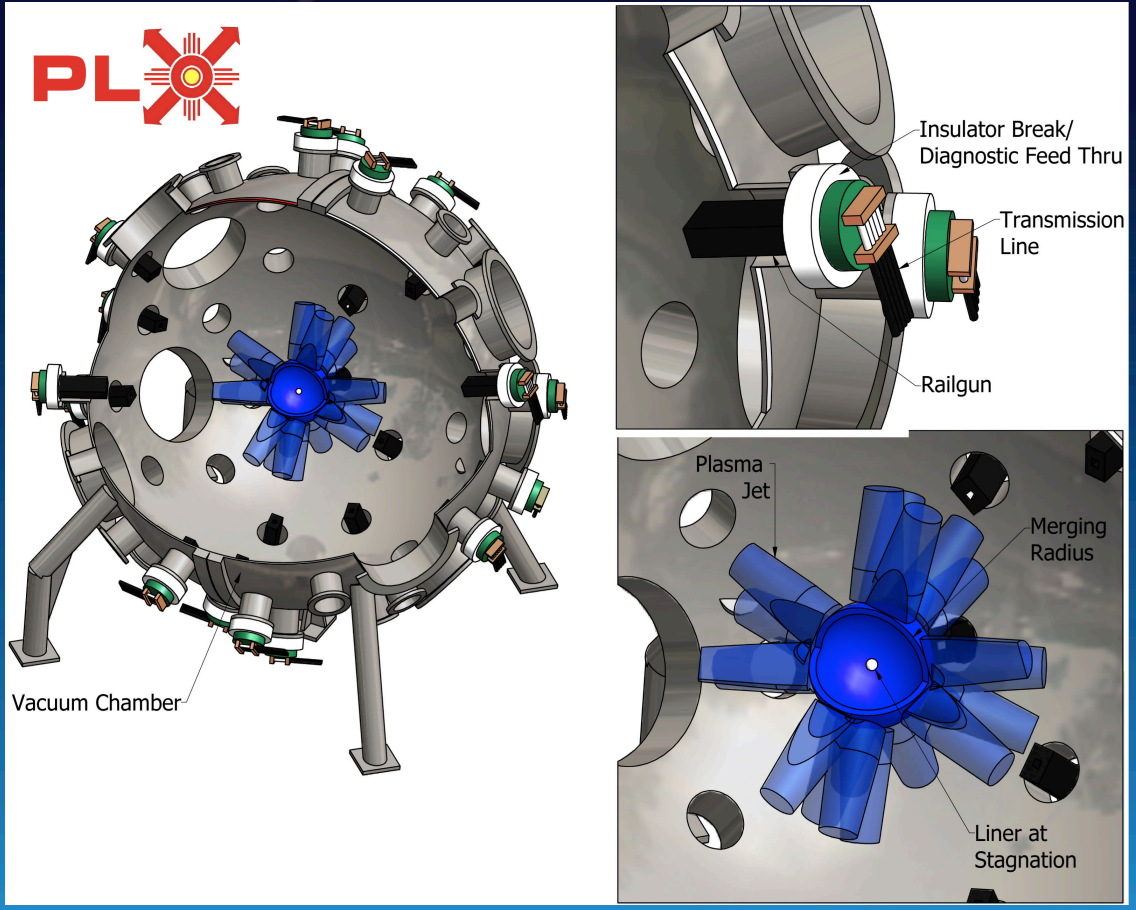
Example§ from a 1D simulation: Spherical burn configuration with energy gain* ≥ 20



- Target at peak compression
  - $n \approx 5\times21$ cm^{-3}, $T \approx 10$ keV
  - $p \approx 150$ Mbar
  - $R \approx 0.4$ cm, $M \approx 5$ mg
  - $B \approx 300$ T
  - dwell time $\tau \approx 0.3$ μs
- These conditions would give (target only):
  - ~8% fuel burn-up
  - ~130 MJ fusion yield
- Xenon liner:
  - ~25 MJ initial kinetic energy
  - ~20 g @ 50 km/s
- DT afterburner increases the gain from target by 3× or more

§from 1D hydrodynamic simulations with theoretically-based alpha-energy-deposition fraction (Ref. 8)
*energy gain = (fusion energy)/(total initial plasma energy)

Plasma liners can potentially be formed by an array of merging supersonic plasma jets launched by plasma guns



Illustrations by D. van Doren, HyperV Technologies.

- Jets launched by plasma guns at chamber periphery
  - Merge into spherically imploding shell at merging radius r_m
- Compatible standoff target assembly required*
  - Option 1: DT target formed separately (merging compact toroids or jets)
  - Option 2: DT placed at the leading edge of jets
  - Both options may require novel standoff magnetization method

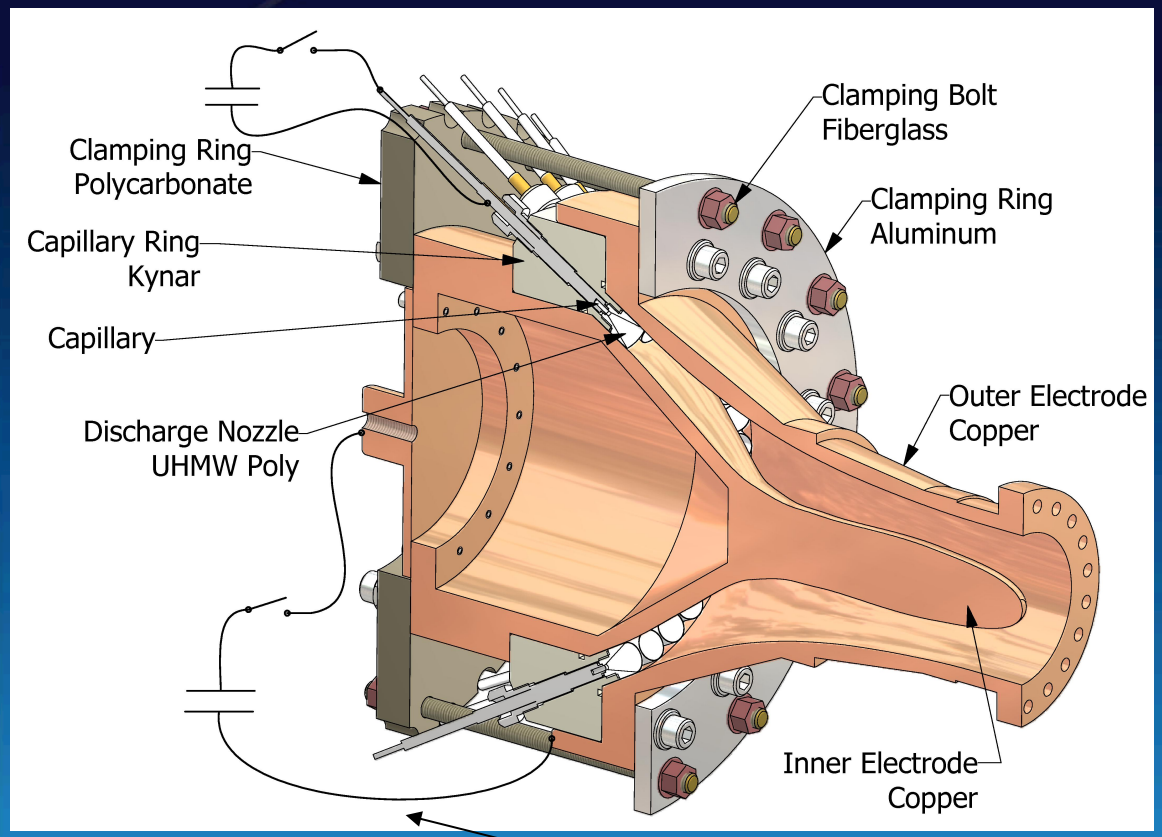
More details in Refs. 4 and 9–11.
*I will not discuss target assembly→ addressed in talks by J. Slough and D. Welch.

Plasma gun requirements are obtained by working backwards from desired fuel parameters

Fuel requirement →	Plasma liner requirement→	Jet requirements (at r_m)
Energy ≈ 5 MJ	≈25 MJ (assuming compression efficiency ~20%)	~40 MJ (all jets) (assuming electrical efficiency ~0.5–0.8)
Pressure ~ 150 Mbar	ρv^2 ~ 150 Mbar (near peak compression)	$\rho_0 v_0^2 = \rho (r_t/r_m)^2 v^2 \approx 0.6$ kbar (assuming r_t/r_m= 0.004m/2m=0.002 and v=constant; corresponds to $n_{Xe} \approx 10^{17}$ cm^{-3} and v=50 km/s→determines pulse length ~10–20 μs)
Temperature ~ 10 keV	Implosion time (~r_{t0}/v) << thermal loss time (~r_{t0}^2/4D)	v>>4D/r_{t0}≈1 km/s (assuming r_{t0}=4 cm and D=10 m^2/s)
Confinement time ~ 0.3 μs	Stagnation time ~ confinement time ~ L/v	L ≈ 1.5 cm (assuming v=50 km/s)
All the above	Mass ~ 20 g (assuming $\rho \sim r^{-2}$ near peak compression)	Mass/jet ~ 20–60 mg (for 300–1000 jets)
All the above	High Mach # to reduce spreading and to reach high pressure	M=50 (Xe with T_e=1 eV) (assuming v=50 km/s)

Many assumptions based on the physics of spherical plasma liner implosions (Refs. 2,3,6); numbers used based on Ref. 8.

Contoured coaxial guns have been designed to achieve the needed jet parameters



~0.5–1 m

- Nominal, required jet initial parameters:
  - L_{jet}≈5 cm
  - n≈10^{18} cm^{-3}
  - V~50 km/s
  - Mass~20–60 mg
  - T~few eV
  - Mach # >10
- PJMIF requires hundreds of guns operating at ~0.5–1 MA, very low impurity levels, and (likely) profile-shaping ability

Contoured coaxial gun, F. D. Witherspoon et al. (Ref. 12) and talk at this workshop.

PJMIF reactor challenges are not as demanding as those of IFE

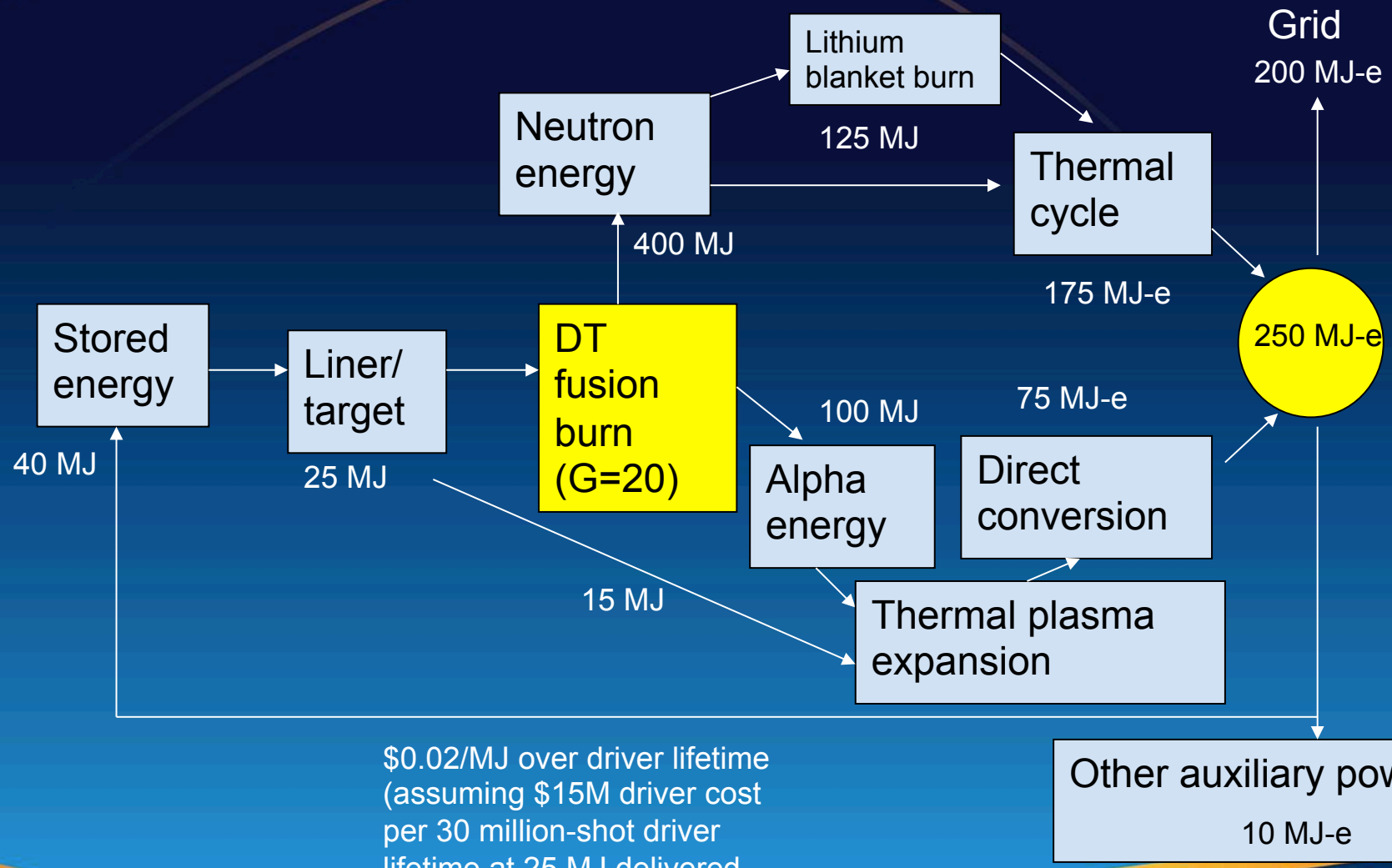
Parameter / Issue	PJMIF	ICF	Benefit
Pulse repetition rate	~1 Hz	~10 Hz	Eases chamber clearing and first wall engineering
Fusion pulse time	~1 μs	~1 ns	Lowers first wall temperature peaking and no x-ray burst
Driver	Robust plasma guns	Vulnerable final optics	Easier maintenance
Driver to target hydro efficiency	~20%	~1%	Decreases driver size/complexity and widens design space
Driver cost / Plant cost	~1%	~30%	Lower capital cost and COE

Table courtesy of John Santarius (University of Wisconsin-Madison).

PJMIF reactor challenges

- Need repetitive pulsed power drivers (e.g., 3.2×10^7 shots/year at ≤1 Hz operation)
  - Example: KrF IFE program solid-state switching (10^7 shots achieved at 5 Hz operation; see Ref. 13)
  - Ideas to explore: switchless operation, adapting LTD technology (see Mike Cuneo's talk–this workshop), etc.
  - Plasma guns need to survive fusion blast and operate with low impurity levels
- Solid, wetted, and liquid first walls are all viable options
  - Low heat loading (<1 MW/m^2 for 100 MW modular core with 6 m diameter) allows for solid & wetted wall concepts
  - Surface vortex liquid flows envisioned for heavy ion beam fusion (Ref. 14) potentially well-suited for PJMIF; other liquid wall/blanket implementations possible
  - Chamber clearing does not appear to be an issue
- Disposable components open up reactor design space
  - Relatively cheap guns and accessibility allow regular component replacement, i.e., radiation resistant materials to MFE standards not necessary

PJMIF sample reactor energy flow



$0.02/MJ over driver lifetime (assuming $15M driver cost per 30 million-shot driver lifetime at 25 MJ delivered per shot)

Proposed PJMIF development path to single-shot reactor-relevant gain (~$420M)

Task	Milestone	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
	Phase I-A: Concept/driver development, $20M								
1	Demonstrate required reactor-level plasma gun performance (single-shot operation)								
2	Develop physics point design via integrated 3D simulations and perform reactor concept study								
3	Facility design, preparation, and demonstration of targetless plasma liner implosion to ~1 Mbar								
4	Concept exploration of target assembly approaches culminating in engineering design of target facility								
	Phase I-B: Target development, $20M								
5	Demonstrate compatible target at 1e17 per cc, 100 eV, 1 T, 10 µs energy confinement time								
	Phase II: Proof of principle, $30M								
6	Demonstrate integrated liner-on-target implosions reaching ~5 keV, ~10 Mbar								
		Year 9	**Year 10**	**Year 11**	**Year 12**	**Year 13**			
	Phase III: Single-shot engineering breakeven, $200M								
7	Demonstrate plasma conditions (~10 keV, ~50 Mbar) for scientific breakeven using DD								
8	Achieve single-shot engineering breakeven using DT								
	Phase IV: Single-shot reactor gain, $150M								
9	Demonstrate single-shot fusion gain needed for reactor								

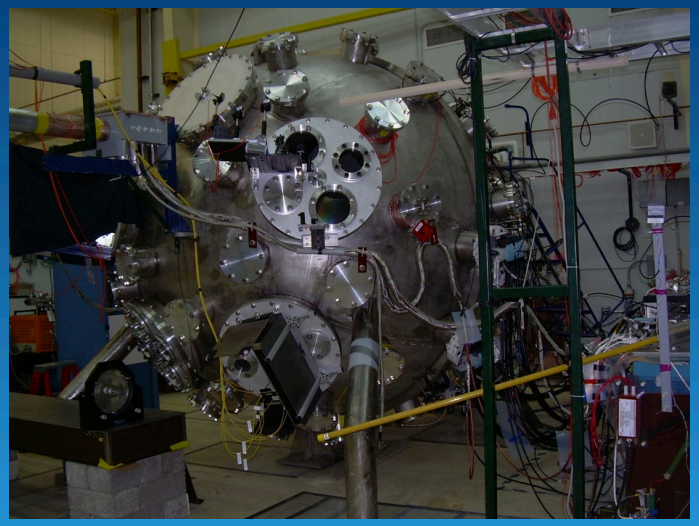
Closing remarks

- Standoff embodiment of MIF avoids destroying significant mass per shot
  - Allows for higher repetition rate, cheaper and faster R&D development path, simpler reactor engineering, and better power-plant economics
  - More attractive & plausible to potential sponsors/investors
- Plasma liner driven MIF has many attractive features:
  - Higher implosion velocity than most liner-driven approaches
  - Potential for liner profile shaping and multi-layered structure
  - Magnetized target could be formed separately or in situ (more options → risk mitigation)
  - Many possible sources could potentially be used to form imploding plasma liners (can benefit from transformative new technologies)
  - Potential compatibility with thick liquid wall or presently available plasma-facing-component (PFC) materials (avoids multi-$B, multi-decadal material development effort ←serious Achilles heel of fusion energy development)
  - Plasma guns are economic candidate sources with many possible technological spinoffs

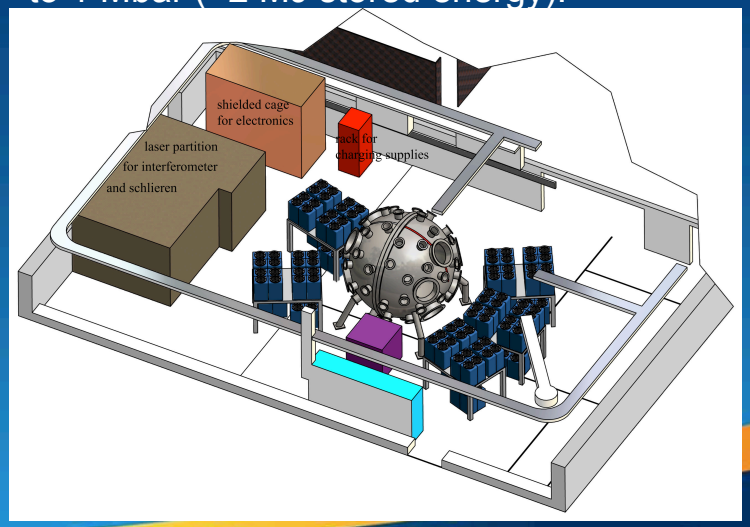
Acknowledgement: collaborators on the multi-institutional Plasma Liner Experiment (PLX) project formerly funded by DOE-OFES

- LANL: A. Moser, E. Merritt, T. Awe, J. Dunn, C. Adams, J. Davis and many student interns
- HyperV Technologies: F. D. Witherspoon, S. Brockington, S. Messer, A. Case, D. van Doren
- UAHuntsville: J. Cassibry, M. Stanic
- Univ. New Mexico: M. Gilmore, A. Lynn
- Many others at Voss Scientific, Prism Computational Sciences, Tech-X, FAR-TECH

Existing PLX facility with two plasma guns:



Proposed 30–60 plasma gun experiment to 1 Mbar (~2 MJ stored energy):



References

1. Y. C. F. Thio et al., "Magnetized Target Fusion in a Spheroidal Geometry with Standoff Drivers," in *Current Trends in International Fusion Research–Proceedings of the Second International Symposium*, edited by E. Panarella (NRC Canada, Ottawa, 1999), p. 113.
2. J. T. Cassibry et al., "Estimates of confinement time and energy gain for plasma liner driven magnetoinertial fusion using an analytic self-similar converging shock model," *Phys. Plasmas* **16**, 112707 (2009).
3. T. J. Awe et al., "One-dimensional radiation-hydrodynamic scaling studies of imploding spherical plasma liners," *Phys. Plasmas* **18**, 072705 (2011).
4. S. C. Hsu et al., "Spherically Imploding Plasma Liners as a Standoff Driver for Magnetoinertial Fusion," *IEEE Trans. Plasma Sci*. **40**, 1287 (2012).
5. J. Santarius, "Compression of a spherically symmetric deuterium-tritium plasma liner onto a magnetized deuterium-tritium target," *Phys. Plasmas* **19**, 072705 (2012).
6. J. S. Davis et al., "One-dimensional radiation-hydrodynamic simulations of imploding spherical plasma liners with detailed equation-of-state modeling," *Phys. Plasmas* **19**, 102701 (2012).
7. I. R. Lindemuth and R. E. Siemon, "The fundamental parameter space of controlled thermonuclear fusion," *Amer. J. Phys*. **77**, 409 (2009).
8. Y. C. F. Thio, manuscript in preparation.
9. S. C. Hsu et al., "Experimental characterization of railgun-driven supersonic plasma jets motivated by high energy density physics applications," *Phys. Plasmas* **19**, 123514 (2012).
10. J. T. Cassibry et al., "Tendency of spherically imploding plasma liners formed by merging plasma jets to evolve toward spherical symmetry," *Phys. Plasmas* **19**, 052702 (2012).
11. J. T. Cassibry, M. Stanic, and S. C. Hsu, "Ideal hydrodynamic scaling relations for a stagnated imploding spherical plasma liner formed by an array of merging plasma jets," *Phys. Plasmas* **20**, 032706 (2013).
12. F. D. Witherspoon et al., "A contoured gap coaxial plasma gun with injected plasma armature," *Rev. Sci. Instrum.* **80**, 083506 (2009).
13. D. Weidenheimer et al., "Scaled-up LGPT (laser gated and pumped thyristor) devices at KrF IFE operating parameters," in *Conf. Rec. 27th Int. Power Modulator Symposium*, 2006, pp. 201–206.
14. P. M. Bardet et al., "Liquid vortex shielding for fusion energy applications," *Fusion Sci. Tech.* **47**, 1192 (2005).