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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?

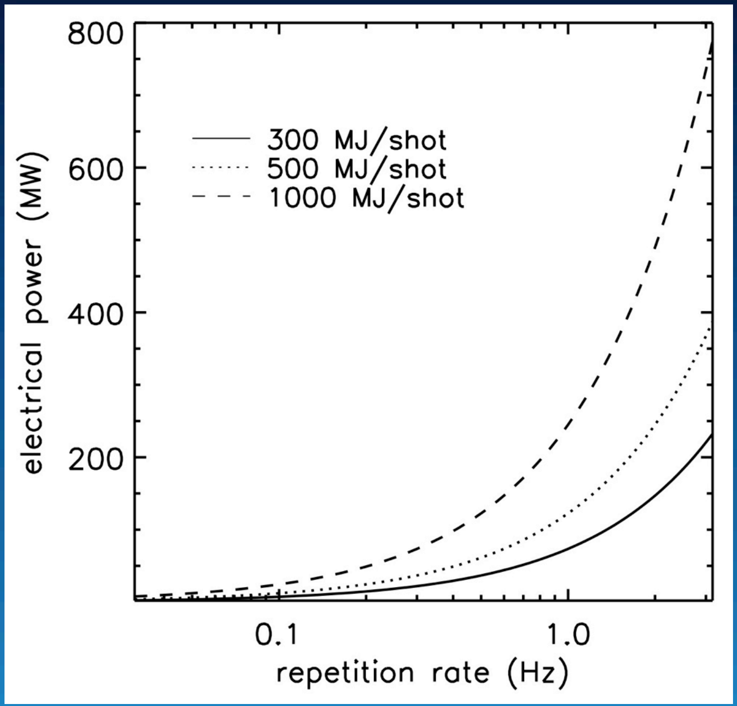
- Standoff places ALL compression driver and target formation hardware far enough away from location of fusion burn to eliminate repetitive hardware destruction

- 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)

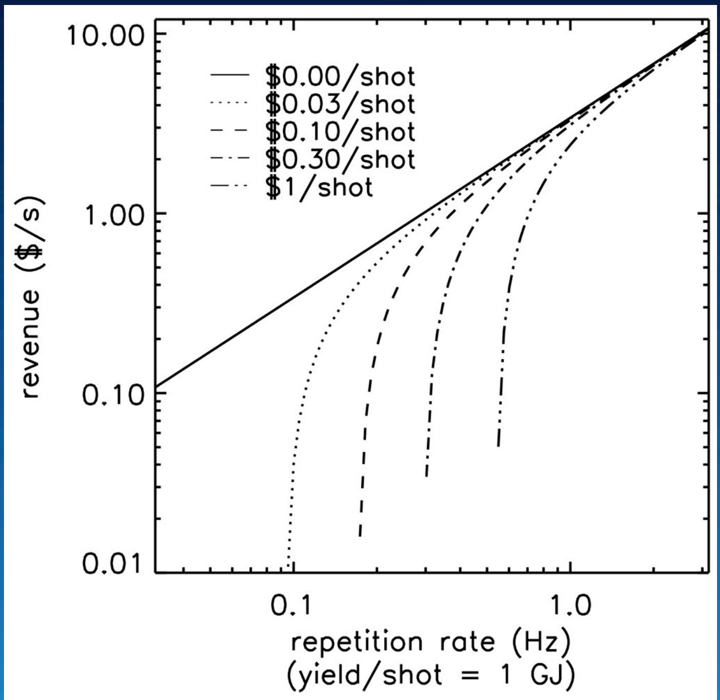
- More reactor friendly (next slide) and more attractive & plausible to potential sponsors/investors as a path to fusion energy

# Standoff's ultimate purpose is to improve power plant economics

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



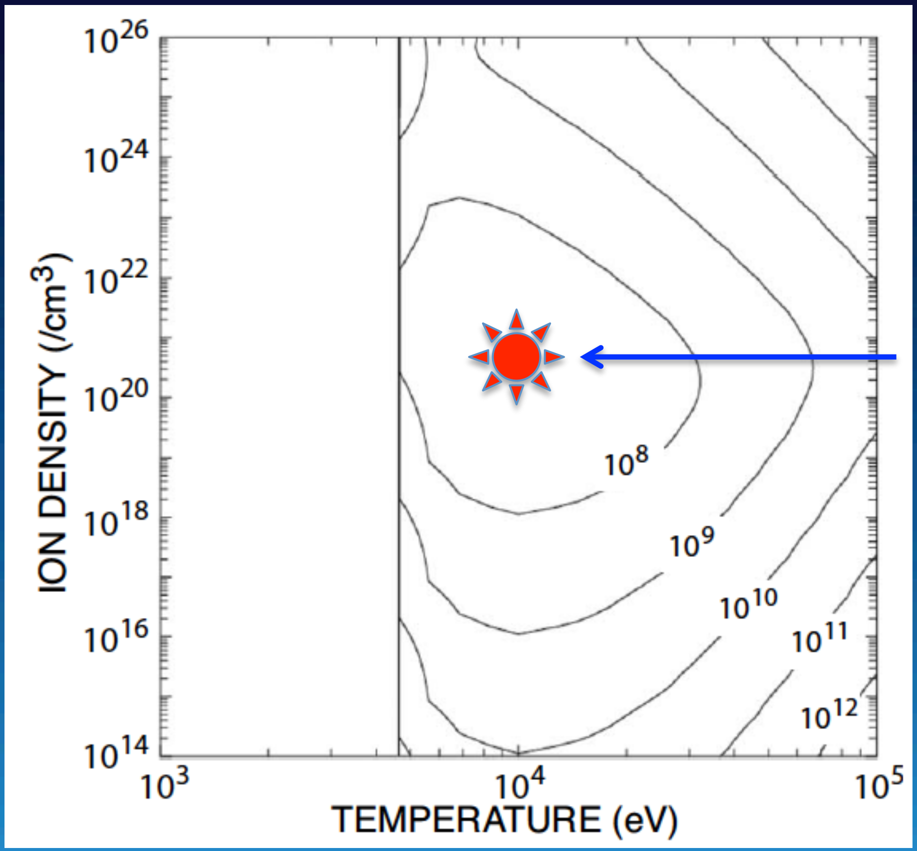

Without standoff → hardware cost per shot quickly erodes power plant revenue




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:

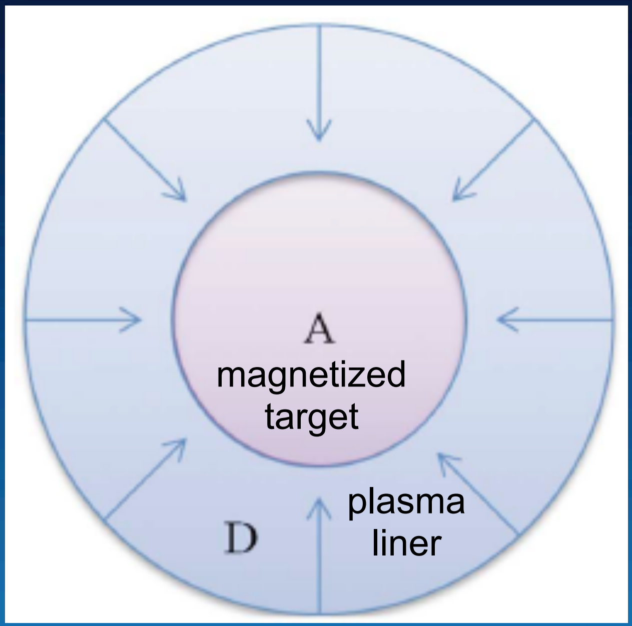



- $M_{fuel}$ ~ few mg
- $R_{fuel}$ ~ 1 cm
- $E_{fuel}$ ~ several MJ
- $P_{heat}$ ~ 0.1 TW
- Driver cost<$100M

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.

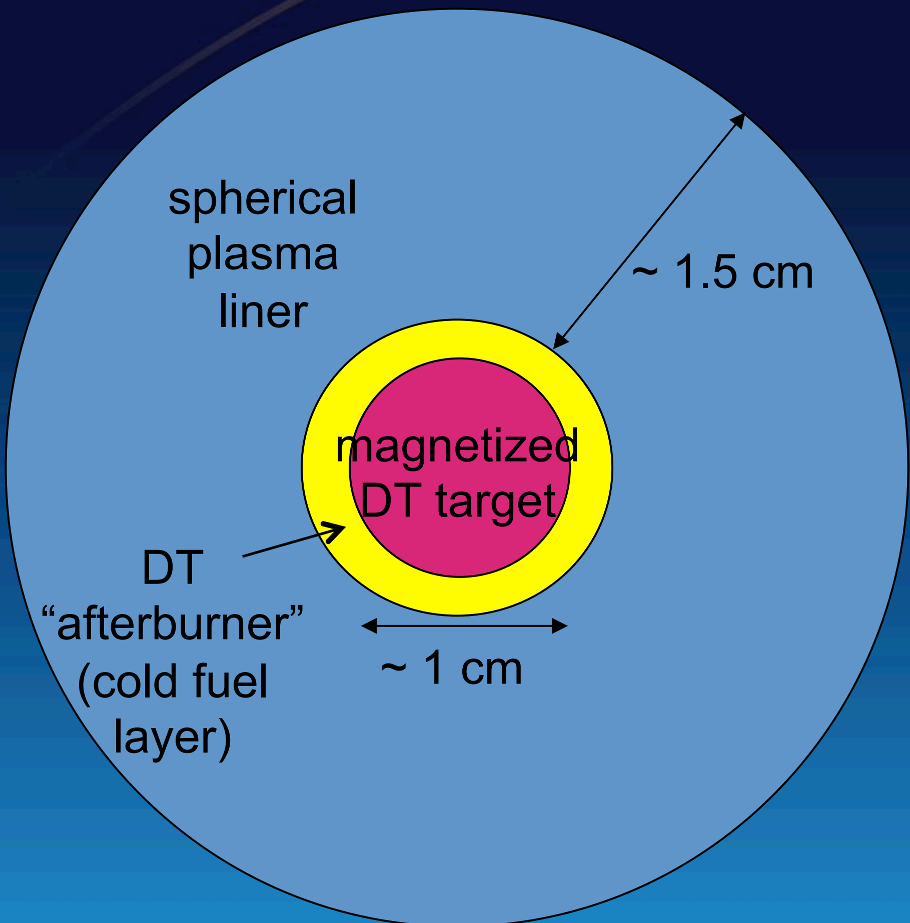



~20 cm
at initiation of target compression

- Plasma liner ram pressure ($\rho v^2$) 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).

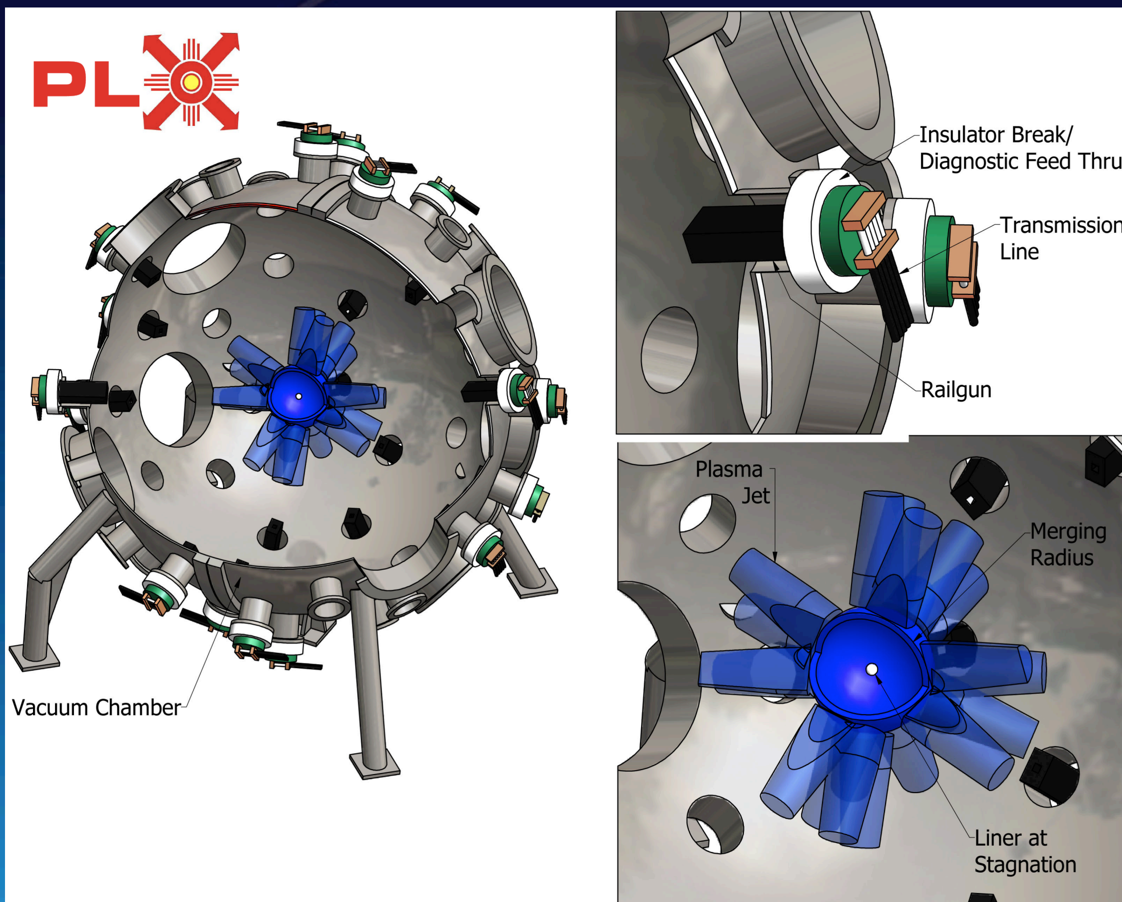
# Example§ from a 1D simulation: Spherical burn configuration with energy gain* ≥ 20




- Target at peak compression
  - $n \approx 5{\times}21$ 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

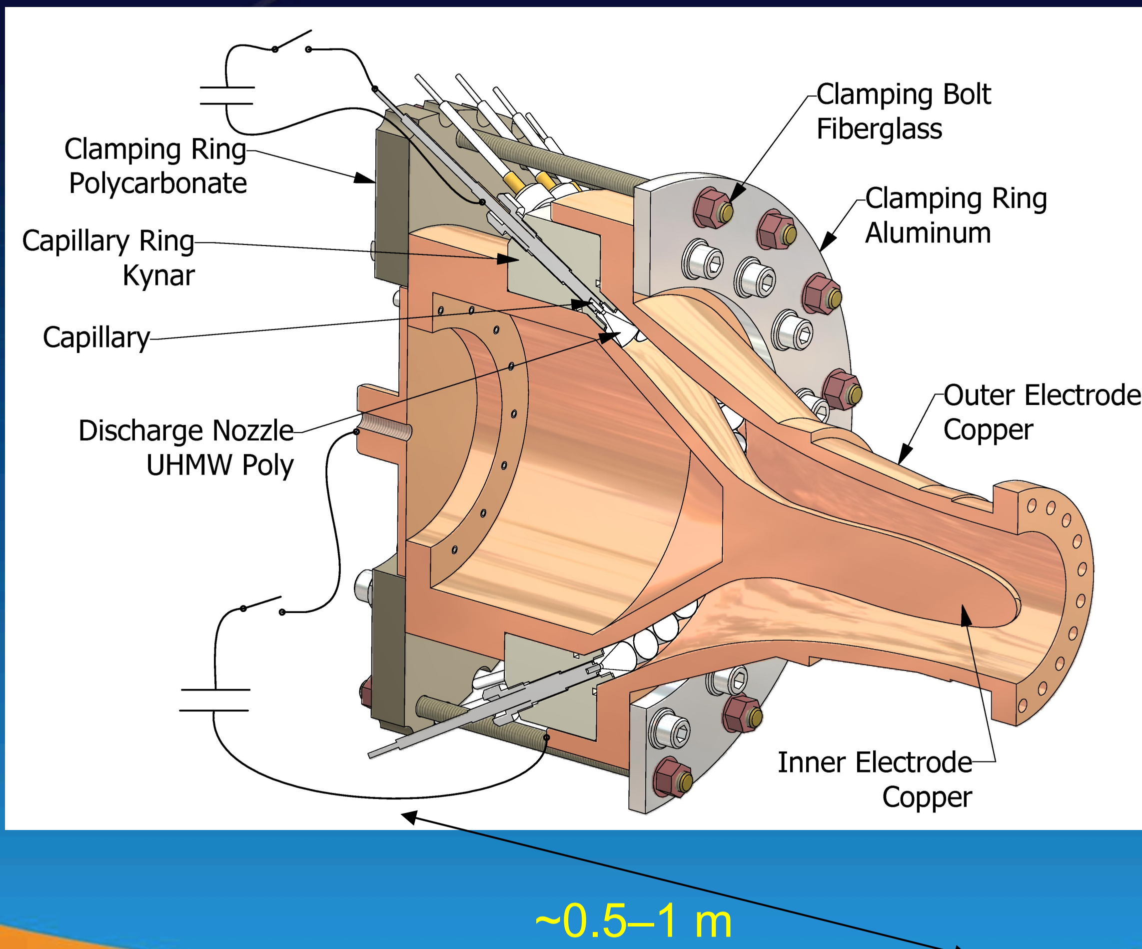
More details in Refs. 4 and 9–11.
*I will not discuss target assembly→ addressed in talks by J. Slough and D. Welch.

# 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<br>(assuming compression efficiency ~20%) | ~40 MJ (all jets)<br>(assuming electrical efficiency ~0.5–0.8) |
| Pressure ~ 150 Mbar | $\rho v^2$ ~ 150 Mbar<br>(near peak compression) | $\rho_0 v_0^2 = \rho (r_t/r_m)^2 v^2 \approx$ 0.6 kbar<br>(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 ($\sim r_{t0}/v$) << thermal loss time ($\sim r_{t0}^2/4D$) | $v >> 4D/r_{t0} \approx 1$ km/s<br>(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<br>(assuming v=50 km/s) |
| All the above | Mass ~ 20 g<br>(assuming $\rho \sim r^{-2}$ near peak compression) | Mass/jet ~ 20–60 mg<br>(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)<br>(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




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

- 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

# PJMIF reactor challenges are not as demanding as those of IFE

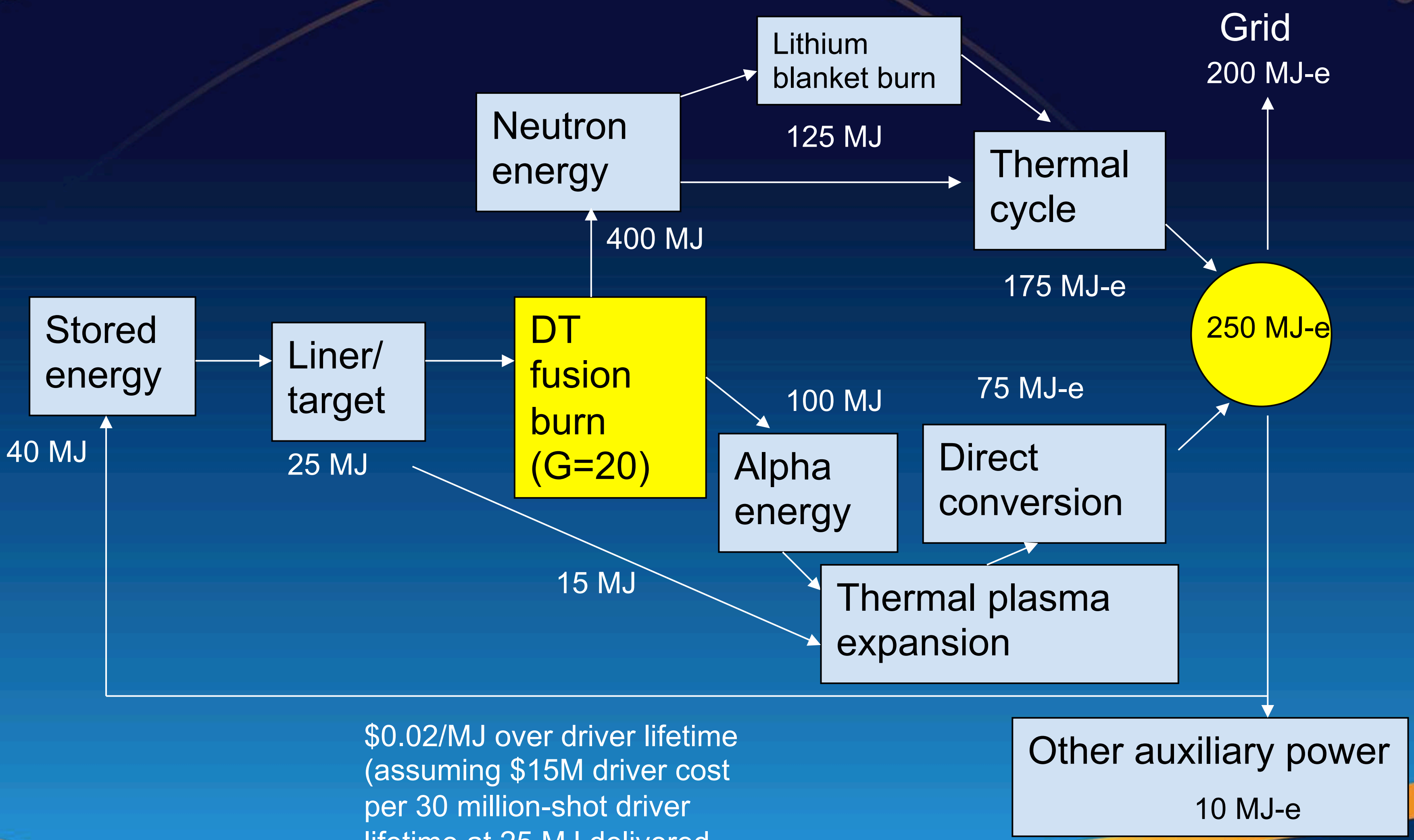
| Parameter / Issue | PJMIF | ICF | Benefit |
|---|---|---|---|
| Pulse repetition rate | ~1 Hz | ~10 Hz | Eases chamber clearing and first wall engineering |
| Fusion pulse time | ~1 μs | ~1 ns | Lowers first wall temperature peaking and no x-ray burst |
| Driver | Robust plasma guns | Vulnerable final 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., $3.2\times10^7$ 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

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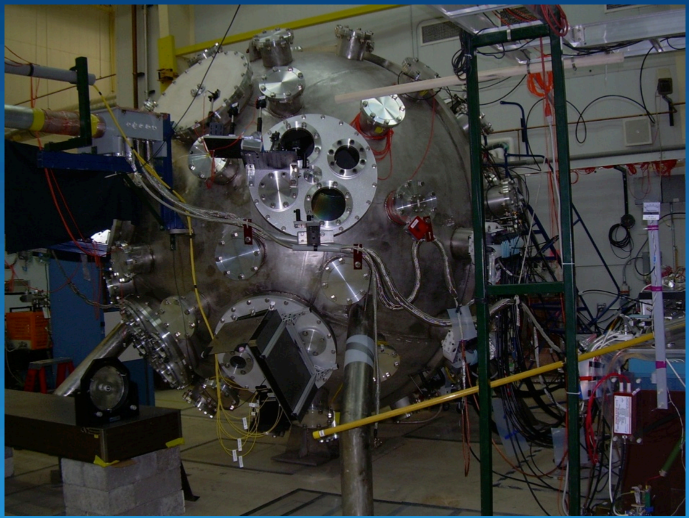
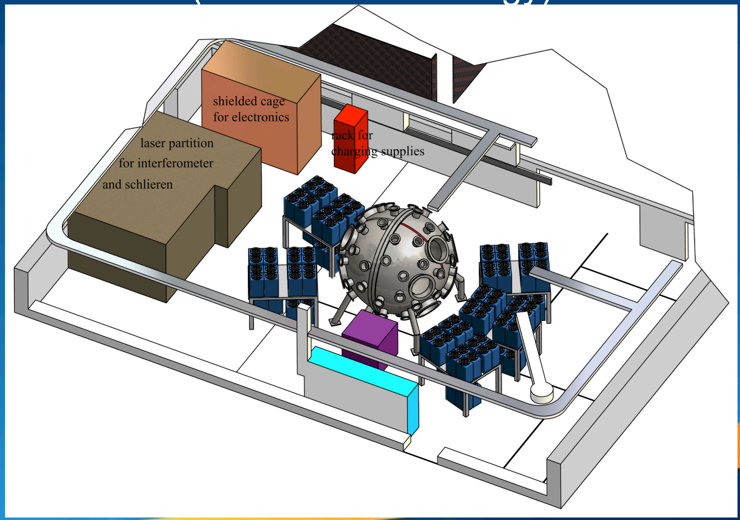
- LANL: A. Moser, E. Merritt, T. Awe, J. Dunn, C. Adams, J. Davis and many student interns
- HyperV Technologies: F. D. Witherspoon, S. Brockington, S. Messer, A. Case, D. van Doren
- UAHuntsville: J. Cassibry, M. Stanic
- Univ. New Mexico: M. Gilmore, A. Lynn
- Many others at Voss Scientific, Prism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



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