



PATH TO ECONOMICAL FUSION REPORT OUTS

Questions: Regions for Economical Fusion

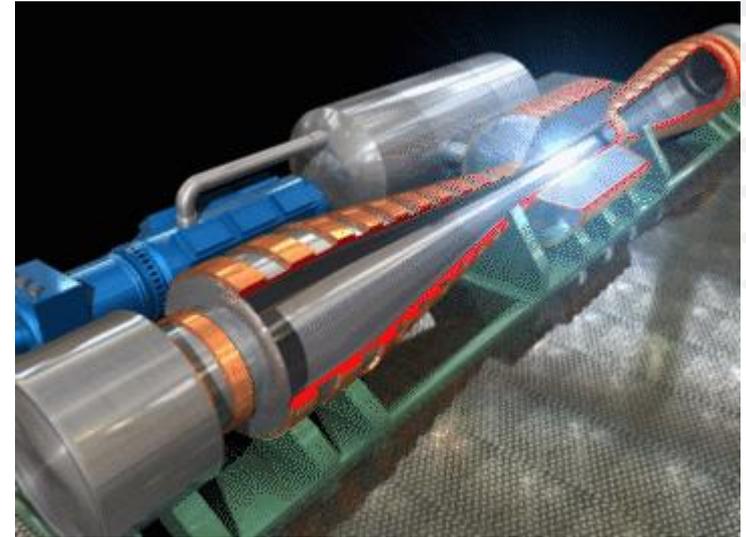
For each concept discussed:

- ▶ Locate the proposed concept in the fusion parameter space
- ▶ Characterize the target
 - *Density, temperature, size, magnetic field, energy*
- ▶ Quantify the critical parameters for the driver
 - *Energy, power density (W/cm^2), velocity, pressure, symmetry, pulse width*
- ▶ What essential technology advances are needed for this concept? Are these advances near-term (within 5 years) or long-term (15+ years)?
 - *For example, technology advances to enable required repetition rate, standoff, first wall, tritium breeding, energy conversion, durability, lifetime, etc.*
- ▶ What is the projected fusion gain for these target and driver parameters?

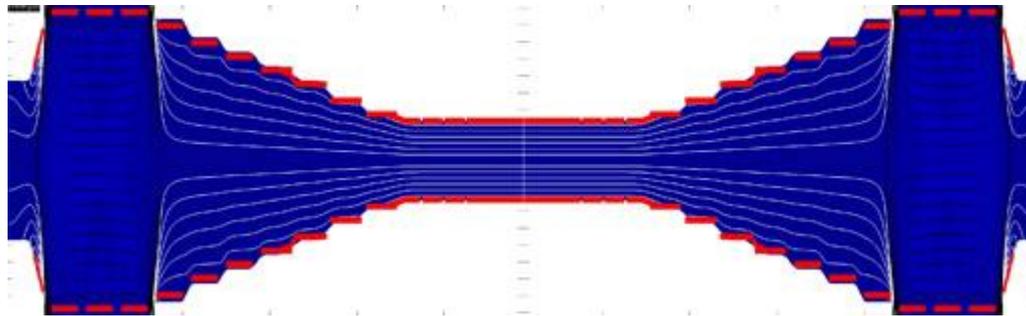
Common Challenges

- ▶ Switches/power electronics.
- ▶ Plasma formation/ achieving correct/desired behavior of plasmas during compression.
- ▶ Code/Modeling: LSP can be useful. ITER code may be useful too, but manpower/resources/etc. needed to make “universal code” useful.
- ▶ Diagnostics: Possible to put 1/3 of funds into diagnostics—are some teams reinventing diagnostics? If a common/general basis of diagnostics existed, it may be enabling.

1. **Formation** – Two FRC plasmoids are dynamically formed by sequential field reversal
2. **Acceleration** – FRC plasmoids are accelerated to high velocities (>300 km/s)
3. **Merging** – Two supersonic plasmoids collide and merge converting kinetic into ion thermal energy
4. **Compression** – FRC is adiabatically compressed to fusion temperatures
5. **Energy Generation** – Spent plasma, fusion ions, and neutrons are converted to energy



Artist's animation of the FE





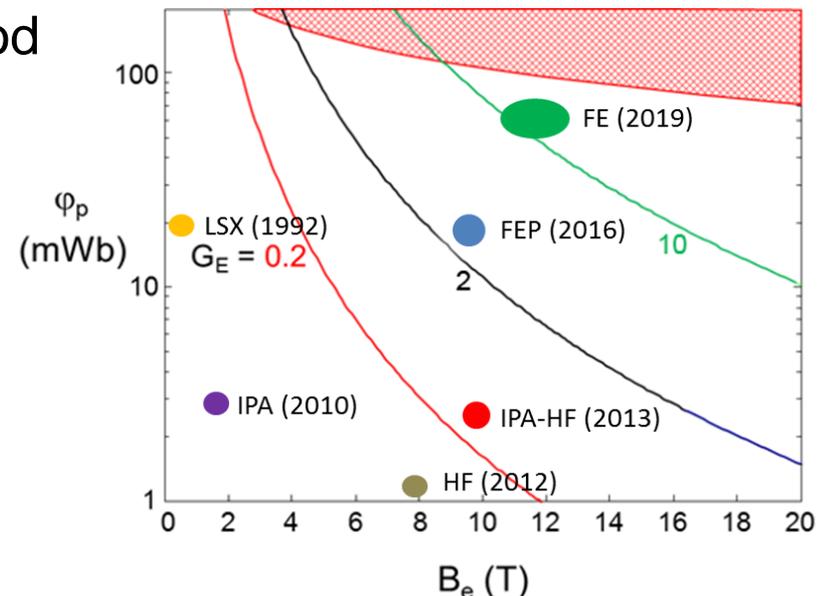
#1 Priority – Reduce Development Risk to Enable a Commercial Power Plant

How to get to a Fusion Reactor

1. Develop end-to-end system design that can will be much less than 10 yrs & 1 \$B total
2. Prove confinement scaling and breakeven
3. Demonstrate MW energy output and rep-rated operation
4. Verify key plant systems– fuel cycle, thermal systems, electricity generation

LSX, IPA, and C-2 Scaling are Clear

- FRC stability criteria are well understood
- Trapped flux defines confinement time
- Field compression defines yield



*Gain curves assumes 3 m, 9 keV plasma

ARPA-hard challenges:

- ▶ Recirculating power. Reclaiming 90% of power from the magnetic field into a capacitor. Inductive losses may be significant
- ▶ Need to understand how to do switching for a rep-rated system that lasts for a long time.
- ▶ Wall lifetime: Estimates from 1 month to 1 year.

Questions: Regions for Economical Fusion

- ▶ Locate the proposed concept in the fusion parameter space
 - 6×10^{22} per m^3 , T: 9 keV, mag field: 12 T
 - Two FRC plasmoids are dynamically formed by sequential field reversal
 - Acceleration – FRC plasmoids are accelerated to high velocities (>300 km/s)
 - Merging – Two supersonic plasmoids collide and merge converting kinetic into ion thermal energy
 - Compression – FRC is adiabatically compressed to fusion temperatures
 - Energy Generation – Spent plasma, fusion ions, and neutrons are converted to energy

Questions: Regions for Economical Fusion

- ▶ Characterize the target
 - *Density*: 6×10^{22} per meter³ (after compression)
 - *Temperature*: 9 keV, (after compression)
 - *Size*: 3 meters diameter, (plasma)
 - *Device*: 25 meters by 3 meters,
 - *Magnetic field*: 12 T
 - *Energy*: 10 MJ in the plasma
 - *Compression ratio*: not applicable

Questions: Regions for Economical Fusion

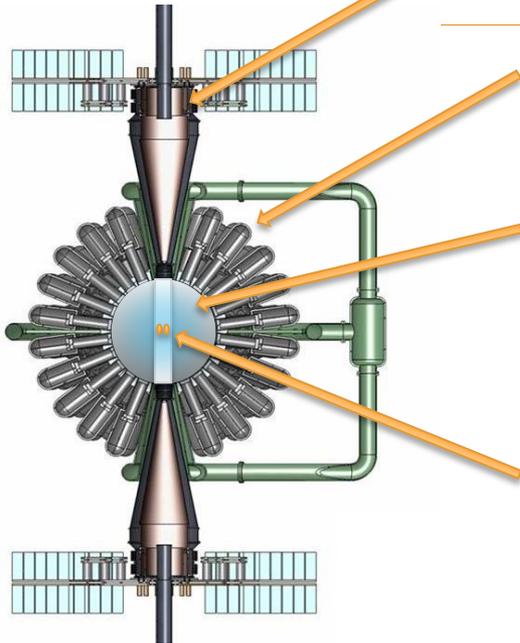
- ▶ Quantify the critical parameters for the driver
 - Magnetic field coils at 25 MJ and 2 Hz. Outstanding question: is it within current solid state technology?
 - *Energy* : 25 MJ
 - *Power density* (W/cm^2): 8 MW/m²
 - *Velocity*: (not inertial—meaningless)
 - *Pressure*: 12 T
 - *Symmetry*: (cylindrical, but not really applicable)
 - *Pulse width*: 3 ms

Questions: Regions for Economical Fusion

- ▶ What is the projected fusion gain for these target and driver parameters?
- ▶ 10, for scientific gain defined as yield/energy in the plasma. Engineering gain? Subject of debate.

Key Features

Spheromak injectors



Compressed gas driver

- Uses power plant working fluid: steam, could also be CO₂ or Helium
- Low cost for driver energy: \$0.2/J compared to >\$2/J for pulsed power

Thick Lead-Lithium blanket

- 300 C inlet, 550 C outlet
- 2 m³/s flow rate
- Neutron flux to structure at 2 MeV and up is **100,000X** lower than ITER
- 4π coverage, n,2n Pb reaction provides tritium breeding ratio of **1.5**

Plasma target

- Liquid wall cannot be destroyed
- Target is plasma only
- Provides a pulsed system with no consumables

Key Challenges

Fusion Yield

- Plasma stability at peak compression
- Plasma / wall interaction

Injector

- Initial plasma confinement quality
- Initial plasma density
- 1 Hz operation (including pulsed power supply)
- Operation at temperature
- Long term reliability

Acoustic Driver

- Impact velocity (**50 m/s target achieved**)
- Impact timing control (**±10 μs target achieved**)
- Smooth vortex collapse
- 1 Hz operation
- Long term reliability

Tritium Handling

- Efficient extraction from PbLi
- Prevention of leakage to environment

ARPA-hard challenges:

- ▶ Plasma implosion and ensuring proper behavior during compression is the hardest challenge.
- ▶ Switching is tough. Semiconductor switches have been tried, but they fry easily. Pulse power, especially the switch, is the problem.
 - Opportunity to invest in switches for pulse power?
 - Work to extend acoustic driver (piston) lifetime.

Questions: Regions for Economical Fusion

- ▶ Locate the proposed concept in the fusion parameter space
- ▶ Characterize the target
 - *Plasma stability at peak compression. Plasma/wall interaction.*
 - *Pressure inside: before pulse, $\sim 10^{-7}$ torr*
 - *Rotational speed: ~ 1 m/sec. Rep rate: 1 hertz.*
 - *Initial plasma (merged spheromak) parameters*
 - *Density: 10^{17} cm $^{-3}$*
 - *Temperature: 100 eV*
 - *Magnetic field: 7 T*
 - *Diameter: 40 cm*
 - *Compressed plasma:*
 - *Density: 10^{20} cm $^{-3}$*
 - *Temperature: 10 keV from compression, ignition to 25 keV*
 - *Magnetic field: ~ 700 T*
 - *Diameter: 4 cm*
 - *Energy: stored energy in plasma is 14 MJ.*

Questions: Regions for Economical Fusion

- ▶ What is the projected fusion gain for these target and driver parameters?
 - 50 MJ provided by acoustic driver array
 - Delivers 14 MJ to the plasma
 - Yields 450 MJ thermal from D-T fusion (Q=32 with ignition) in hot PbLi
 - Heat exchanger converts to 450 MJ hot steam
 - 300 MJ steam drives a turbine to deliver 100 MJ electrical (assume 33% efficiency)
 - 150 MJ steam for acoustic driver next 50 MJ pulse (assume 33% efficiency)
 - Per Pulse Gain (plasma gain, engineering gain, system gain):

$$\frac{\text{Fusion Energy Yield}}{\text{Energy Delivered to Plasma}} = \frac{450 \text{ MJ}}{14 \text{ MJ}} = 32 \text{ (plasma gain)}$$

$$\frac{\text{Fusion Yield}}{\text{Acoustic Driver}} = \frac{450 \text{ MJ}}{50 \text{ MJ}} = 9 \qquad \frac{\text{Electricity Out+Acoustic Driver}}{\text{Acoustic Driver}} = \frac{150 \text{ MJ}}{50 \text{ MJ}} = 3$$

- *NOTE: calculations do not include additional PbLi heating from acoustic driver energy, nor energy from Li fission*

Questions: Regions for Economical Fusion

- ▶ Quantify the critical parameters for the driver
- ▶ Compressed gas driver. Uses power plant working fluid: steam, could be CO₂ or helium too.
 - *Energy: 50 MJ provided by acoustic driver array, Delivers 14 MJ to the plasma, Yields 450 MJ thermal from D-T fusion (Q=32 with ignition) in hot PbLi*
 - *Velocity: 50 m/s target achieved (piston). Liquid velocity is ~2.5 km/sec for layer that delaminates.*
 - *Pressure, : 4 MBar*
 - *Symmetry, : 10:1*
 - *Pulse width: acoustic is 80 microsecond. Rep rate is 1 Hz rep rate*

Questions: Regions for Economical Fusion

- ▶ What essential technology advances are needed for this concept? Are these advances near-term (within 5 years) or long-term (15+ years)?
 - *For example, technology advances to enable:*
 - *Required repetition rate: 1 Hz. Is this a science or engineering challenge? Still need 2 MJ of capacitor. Any pulse driver at MJ and hertz level isn't ready today.*
 - *standoff, first wall ?*
 - *tritium breeding: Challenges are efficient extraction from PbLi; prevention of leakage to environment. Confidential.*
 - *Neutron protection: no concerns either.*
 - *energy conversion: steam, etc. fairly standard.*
 - *durability, lifetime, etc.*
 - *Confinement time for plasma remains challenges: compressing quick instead of slow can be a way to get around this problem..*
 - *Jetting is tricky, but shock-wave is convex, not concave, so it may be solvable.*
 - *Plasma stability in compression is a significant uncertainty.*

ARPA-hard challenges:

- ▶ Modeling: Extracting tritons, understanding ion heating.
- ▶ Diagnostics: THz interferometers, 2D electron temperature measurement,
- ▶ Aspects of RF: Efficient coupling to plasma within chamber

Questions: Regions for Economical Fusion

- ▶ Locate the proposed concept in the fusion parameter space:
 - Note: not an electricity-generating system as presented, but if we made this an electricity-generating system, it would run on D-helium 3, and then do helium-catalyzed D-D fusion.
 - Scaling: This approach can now only give 100 MW total in 1 MW units.
 - Barrier is Helium-3 availability. Very significant barrier.

Questions: Regions for Economical Fusion

- ▶ Characterize the target
 - *Density: $6 \times 10^{14} \text{ cm}^3$*
 - *Temperature: Ti: 100 keV; Te: 30 keV*
 - *Size: Plasma is 25 cm in diameter. Outer dimensions are 2 m by 10 m*
 - *Magnetic field: 5.3 T,*
 - *Energy: steady state, not pulsed.*

Questions: Regions for Economical Fusion

- ▶ Quantify the critical parameters for the driver
 - *Energy: net output, including all inefficiencies, 1.3 MW.*
 - *Power density (W/cm^2), $10^3 W/cm^2$ (power density on wall– radiation power density, not neutron).*
 - *Velocity: doesn't matter*
 - *Pressure: 10 Atm*
 - *Symmetry, Antenna symmetry matters,*
 - *Pulse width: steady state*

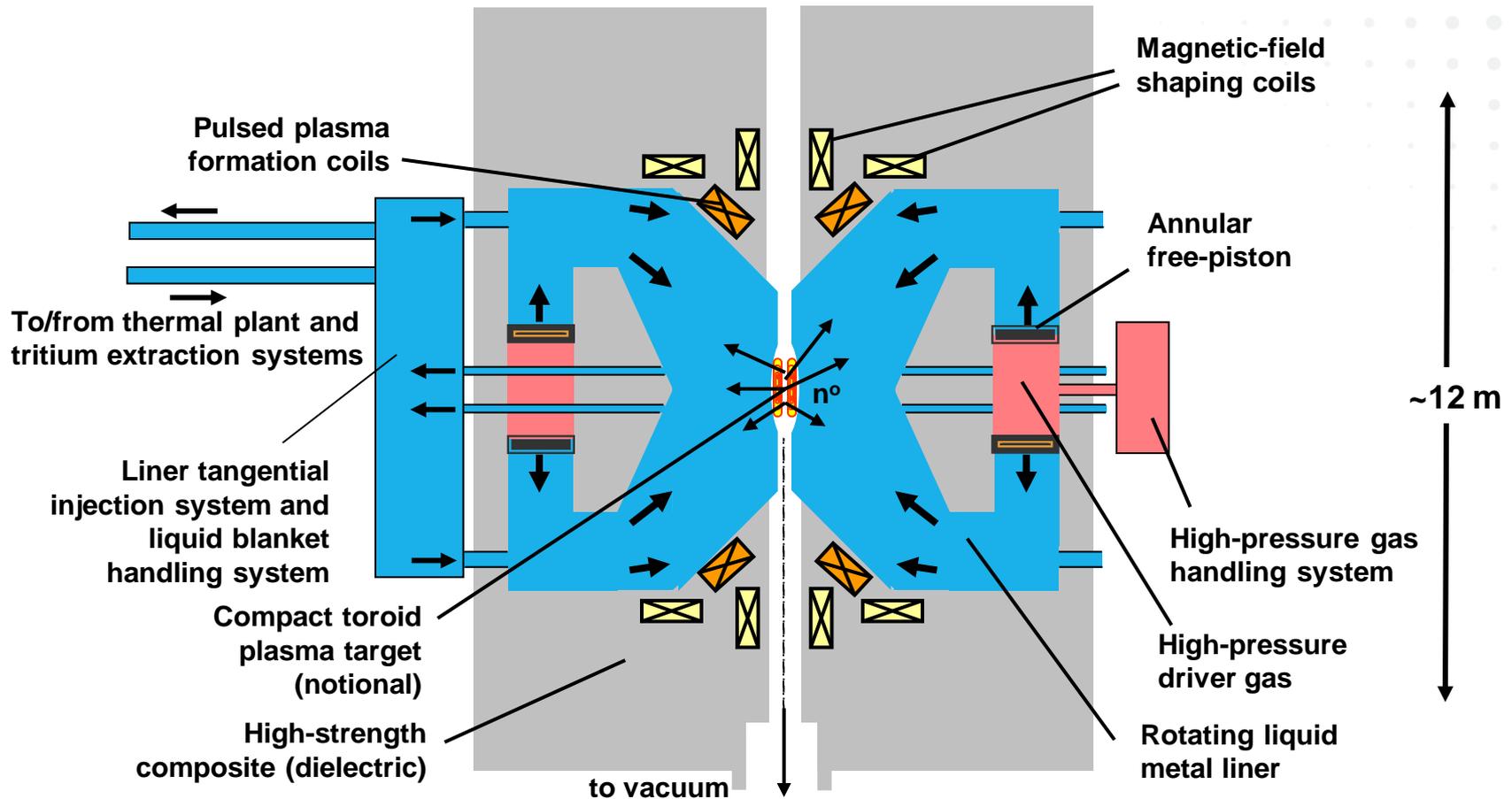
Questions: Regions for Economical Fusion

- ▶ What essential technology advances are needed for this concept? Are these advances near-term (within 5 years) or long-term (15+ years)?
 - *For example, technology advances to enable required repetition rate, standoff, first wall, tritium breeding, energy conversion,*
 - Uses off-the-shelf RF systems. Needs to use controls. Manpower/brain-power needed to figure this out.
 - Need to figure out how to make Boron-carbide walls.
 - Ion heating– need to test approach. Electron heating already observed.
 - Durability and lifetime: no concerns. Neutron-free approach.

Questions: Regions for Economical Fusion

- ▶ What is the projected fusion gain for these target and driver parameters?
 - Engineering gain of about 3.

Schematic representation of fusion reactor based on stabilized liquid liner implosion (LITER)



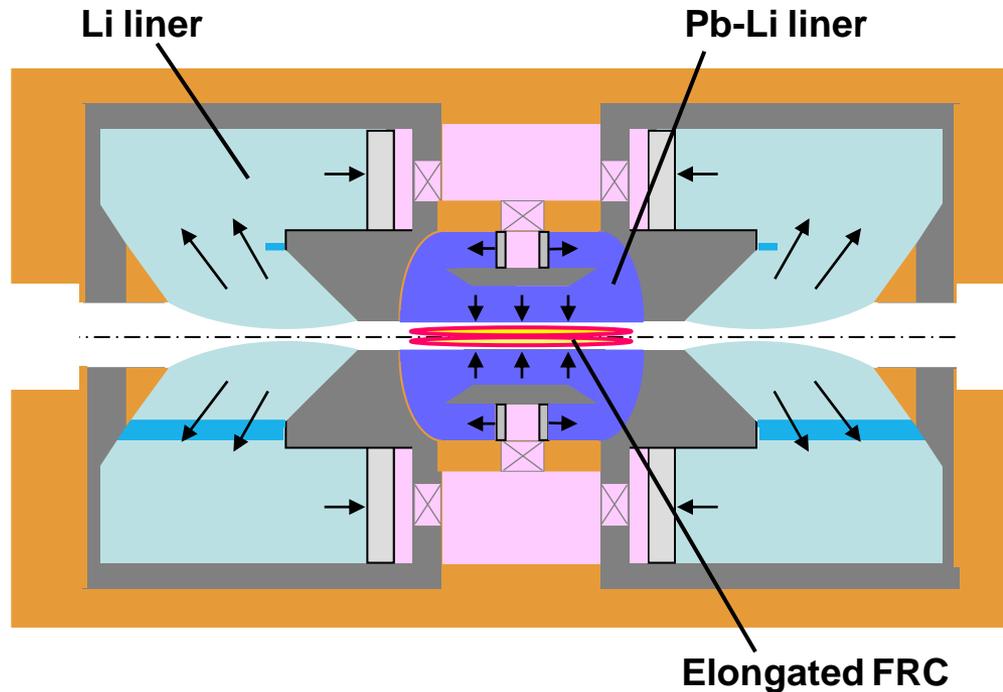
Not shown:

Pulsed power system for plasma formation;
 Power systems for several magnets;
 "Balance-of-plant", including thermodynamic electric generators and chemical processing facilities.

Operating Conditions (at 1 Hz and C = 15%):

Peak (vacuum) magnetic field 1 MG;
 Peak plasma temperature 15 keV; density 10^{18}cm^{-3} ;
 Plasma radial compression ratio 10; target energy 60 MJ;
 Drive pressure 24 kpsi; Stored gas energy 500 MJ;
 Final compression time 75 μsec ; $Q \approx 2-3$; $P_{\text{net}} < 50\text{MWe}$

Most uncertain element is the plasma target. An elongated FRC may offer an alternative to quasi-spherical plasma target, depending on results of plasma effort in parallel with liner implosion development.



In scheme depicted, two liquid lithium liners compress FRCs that then merge inside a separate liner system of Pb-Li. This provides opportunity for plasma elongation and longer burn-time.

To proceed from the liner implosion system to a prototype reactor system, need to combine the stabilized implosion with a plasma target.

Stage 1:

First combination of stabilized liquid metal liner with plasma target

- **Experimental development of plasma target in which liner implosion compresses the plasma, thereby affecting plasma behavior.**
- **Evaluation of liner and plasma behavior at turn-around (after peak pressure)**

Stage 2:

Extension to higher energy for significant deposition of charged-particles in plasma (D-D for 50%: 3.02 MeV p⁺, 1.01 MeV T and 0.82 MeV ³He); equivalent performance for scientific breakeven.

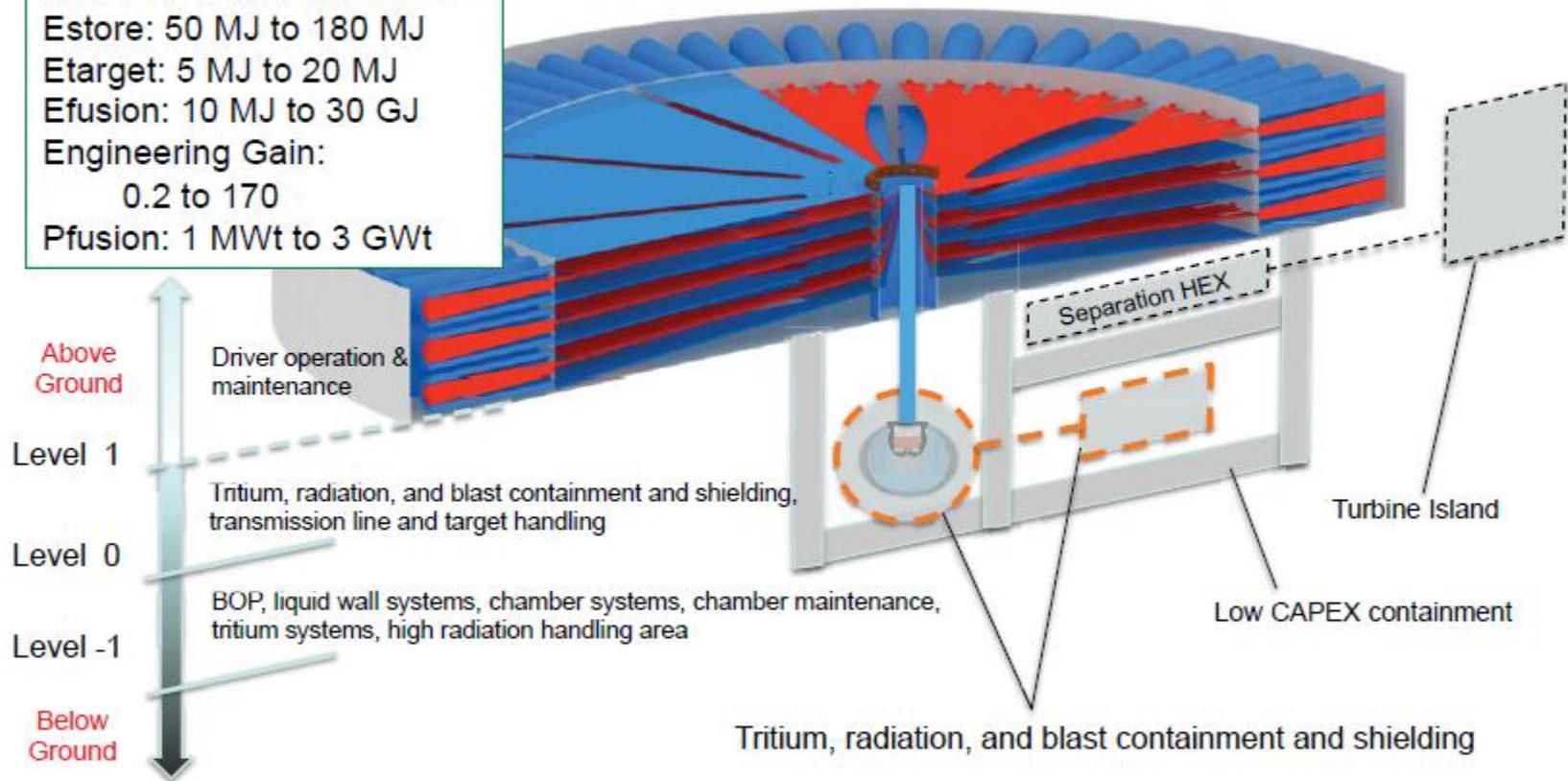
- **Technically significant experiment, without burden of tritium handling.**

Stage 3:

Full assault on nuclear engineering required for fusion reactor, including tritium handling, thermal/chemical processing of liquid liner material, issues of neutron damage/induced radioactivity for prototype reactor demonstration. (Beyond ARPA-E)

Plant functions are segregated on different levels to provide “defense in depth” and inherent safety

Driver Size: 35 m to 100 m
 Estore: 50 MJ to 180 MJ
 Etarget: 5 MJ to 20 MJ
 Efusion: 10 MJ to 30 GJ
 Engineering Gain:
 0.2 to 170
 Pfusion: 1 MWt to 3 GWt



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Pulsed Power IFE Issues: DRIVER-TARGET COUPLING ROADMAP



- Stage 1
 - Engineering: ½ scale RTL demo of vacuum, mechanical, automation
 - present status: proof of principle designed and purchased
 - funded by LDRD, not tested
 - need funding for a demo (LDRD, ARPA) (500 K/year for 3 years, funding needed)
 - Physics: Single shot power flow scaling on Z facility and development of validated models for scaling (1000 K/year for 3 years, funding needed)
 - Some synergies in power flow with NNSA funded programs, but mostly has to be APRA, VC, energy-directed, LDRD funded
- Stage 2 (iff above are successful, and iff fuel gain ≥ 1 successful)
 - Full scale RTL design with prototype fabrication methods, cassette delivery, vacuum, mechanical, power flow, debris isolation
 - Testing of debris isolation features on the Z facility
 - RTL fabrication pilot plant design with industry
 - Some synergies of debris isolation with NNSA funded programs, but most of this would have to be VC, energy program, LDRD funded
- Stage 3
 - Demo final RTL designs on Z-300 on or about 2020

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SAND2013-9794C

Pulsed Power IFE Issues: DRIVER TECHNOLOGY ROADMAP



- Status of technology
 - Demonstrated 5 GW brick, 160 GW cavity at scale needed for these drivers, for 2000 shots
 - Other cavities demonstrated at 10,000 shots
 - Demonstrated rep-rate of 0.1 Hz
- Stage 1,2 (LTD CAVITY COMPONENT COST, PERFORMANCE, and LIFETIME)
 - Cost: presently 11\$/Joule, LDRD funded (1 M\$/year for 3 years) to drive cost to needed target of 4\$/Joule for NNSA-directed goals.
 - Switch lifetime: gas switch lifetime presently 50,000 shots. Meets NNSA requirements. Multiple ideas exist to extend the lifetime to up to 3e6 shot (1 year at 0.1 Hz), but funding needed (500 K/year x 3 years, funding needed)
 - Switch lifetime: semiconductor switches should also be developed to meet high voltage and current requirements, with lifetimes > 10e6 shots. Development roadmap needed. Costs are likely much higher than gas switches.
 - Capacitor lifetime: capacitors exist with 80e6 shot lifetimes. Research is needed to reduce the volume of these capacitors by a factor of 3, and explore volume-lifetime-cost tradeoff (500 K/year x 3 years, funding needed)
 - Resistor lifetime: test stopped at 144,000 shots, requirements up to 10-100e6.
- Full module demo needed: presently on track to demo 5 cavities at 3 m diameter, need 33 cavities at 2 m diameter. Estimated cost for demo is 10 M\$. Our goal is to build a case to the NNSA to fund this, leading to the Z-300 facility.

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SAND2013-9794C

Reactor Design? Start from the End Point

- **Consider a 4.1 GigaJoule yield (1 metric ton) from a pulsed MTF device.**
- **Consider a rep-rate of 0.1 Herz, which gives more time to clear the chamber.**
- **Pick a thermal conversion efficiency to electricity of 35%, so one would produce 1.4 GJ electric per pulse (gross, not net), or 140 MW electricity (average).**
- **Use a thick liquid curtains, with liquid pool at the bottom of the chamber. The liquid will absorb neutrons, and breed tritium. Have voids to dissipate shock from the explosion, and cushion the solid backing wall of the system.**



Basic points to consider

(1)

3.6 MJoules = 1 kW-Hour

There are 31.5 million seconds in a year.

10 cents/kWH means 1 GigaJoule of electricity is worth \$27.8

At 35% conversion efficiency, then 4.1 GJ thermal is worth only \$40 of electricity

One metric ton (1000 kg) of high explosive has an energy content of 4.1 GJ

To produce 4.1 GJ from DT fusion, at 17.6 MeV per DT reaction, and $1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joules}$, one has $2.8 \times 10^{-12} \text{ Joules}$ per DT reaction; so you need 1.4×10^{21} reactions per 4.1 GJ released.



Basic points (continued)

(2)

A mole of D₂ is $2 \times 6.02 \times 10^{23}$ D atoms, and same for mole of T₂. So each 4.1 GJ pulse burns up approximately 1 milliMole of D₂, and 1 milliMole of T₂. D₂ has a molecular weight of 4 grams/Mole, and T₂ has a molecular weight of 6 grams/mole

If the fractional burn-up of DT is 10%, then you need 10 milliMoles of each, in the final compressed MTF plasma. At least 20 milliMoles of each in the beginning target plasma, assuming 50% plasma inventory losses during translation from the formation region.

The initial target fuel load must be “preheated” to 200 eV (Te+Ti). This is an energy investment of $2 \times (20 \times 10^{-3}) \times 6 \times 10^{23} \times 200 \text{ eV} = 4.8 \times 10^{24} \text{ eV}$, or $0.75 \times 10^6 \text{ Joules}$, or .75 MJ. Add in a factor of 2x for formation losses, so we are talking 1.5 MJ of energy needed to form the MTF “target” plasma.



Basic points (continued)

(3)

Then the gain is $4100 / 1.5 = 2733$ relative to the initial plasma energy content. Work also had to be done to compress the initial plasma to get it to the final state. The energy content of the final state is defined to be same number of particles, heated up to 8 keV. The temperature increase (energy content increase) is $8000/200 = 40$. Assume the liner drive energy is about 2x the final plasma energy. Then the system has a gain (classic Q_{DT}) ~ 34 .

If the electric-to-liner drive efficiency is $\sim 50\%$, the system gain is reduced to ~ 17 , when considered from wall plug to thermal output. (i.e., you needed to put in 240 MJ into the pulsed energy storage to get 4.1 GJ thermal out from pure fusion). If conversion to electricity is 35% efficient, then electricity output is 1.4 GJ, so the minimum recirculating power is about 18%. If the rep-rate is 0.1 Hz, the average electric output is 140 MW.

So a 10% fractional burn-up is adequate performance from a fusion-only, MTF batch-burn system if the liner coupling efficiency is 50%.



Basic points (continued)

(3)

For a 10% DT fuel burnup fraction, an $n\tau_{\text{dwell}} \sim 2 \times 10^{15} \text{ cm}^{-3}\text{sec}$ at 10 keV is required. For example, a final density of 10^{21} cm^{-3} and a liner dwell time of $1 \mu\text{sec}$ would do the trick. This exceeds our projected initial experiments by a factor of ~ 100 .

Further points:

- The price of all the destroyed components, accounting for their remanufacture, should not exceed 10% of the value of the electricity produced. So, a few dollars per pulse is all that is allowed.
- The value of 100 MW of net electricity, produced for one year, at $\$0.1/\text{kWh}$, is only $\sim \$100\text{M}$. If you need a 30 year payback time on your capital equipment, then the plant cost shouldn't exceed $\$3\text{B}$, at zero percent interest! Increasing the rep rate would be a huge win, but you have to be able to reload and clear the chamber between pulses.



Thick liquid wall recirculation is not a big energy hit

- The chemical composition of pure FLIBE is Li_2BeF_4 .
- If the chamber size is a cylinder, with a radius of 3 meters, and similar length, then the minimum amount of hot FLIBE out on the wall, is about 35 cubic meters.
- FLIBE has a density of 2 gm/cc, or 8.5×10^{22} atoms/cc. This is an exposed blanket inventory of about 7×10^4 kg, or 70 metric tons. If it “falls” under gravity, a distance of, say, 5 meters, then the gravitational potential energy MgH is 3.5 MJ. Under gravity free-fall, it also takes only 1 second for this material to fall 5 meters.
- So you will need to invest 3.5 MW, or even twice that, continuously, to keep it circulating, which adds to the recirculating power we have already discussed, but for our assumed 140 MW average electric power output, is not a big issue relative to the required pulsed power energy storage.



Liquid Liner Implosion

- ▶ What are options for forming the target?

FRCs. After 40 years what think do now?

Moving FRC years is new (somewhat 10+ years)

Trialpha-1990's big FRC resurgence effort (1-3 ms)

Target need to be closed field magnetically confined (FRC, spheromak)

Merging FRC has been a recent breakthrough—increased magnetic field, life

- ▶ What drivers could be appropriate to implode the target?

Requirement: 3 ms lifetime at density of 8×10^{14} (precompressed)

Present: 0.02 ms lifetime at density of 1×10^{17}

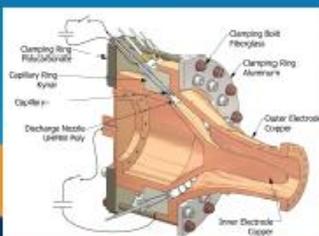
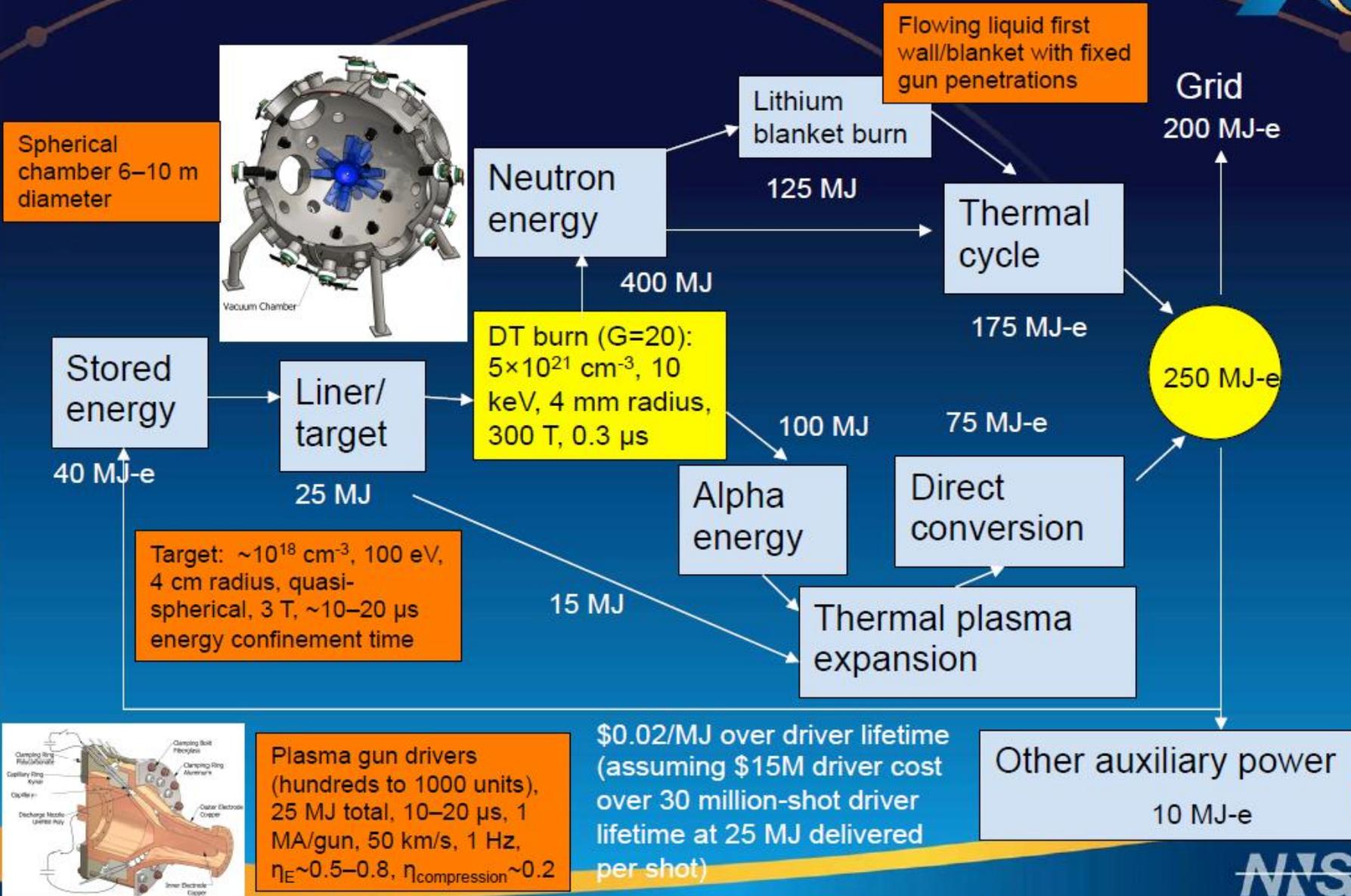
- ▶ What makes these ARPA hard challenges?

Implosion: can one do at 24000 psi (1.6 GPa), material/mechanical—needs hydrocode calcs

What should/could ARPA-E do?

- ▶ Targets (match target lifetime, driver lifetime)
 - Double sided merging FRC compress in theta pinch
 - Laser formed
 - Phi Target [Leeper , ~1979, SNL], electron beam (10^{18} cm^{-3})
 - Deuterium ice fiber z-pinch
 - Laser initiated z-pinch ($10^{18-20} \text{ cm}^{-3}$), [Hammel, ~1984, LANL]
- ▶ Drivers
 - Laser – costly, robustness
 - Rotating liquid liner (LITER)
 - Standoff drivers (e.g. plasma jet)
- ▶ Experiments
 - Scientific breakeven – MagLIF is the best shot – needs to be on a path after (Z is right size) – needs to inform field in MIF – open field
 - Show rotating liquid-wall can be demonstrated at appropriate conditions (higher pressure and speed)
- ▶ Technology/Hardware
 - Pulse power cross-cutting, \$4/J is transformative, decreasing size by 3x, increase coupling efficiency
 - Development of reliable pulse power (3M-50M shots per year)
 - Field coils- combine single pulse performance with (50-100 T field coils) – reduces convergence 10:1

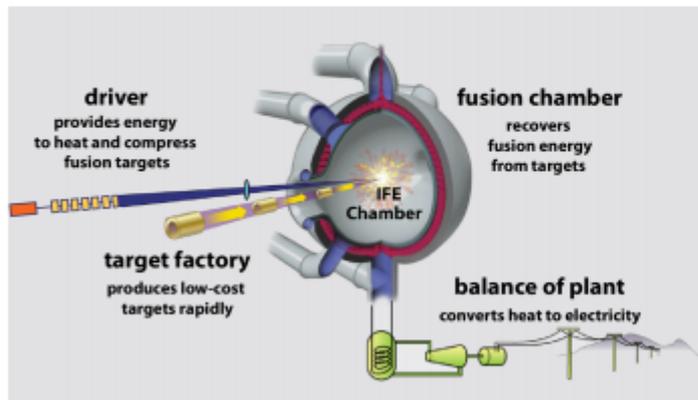
PJMIF sample reactor energy flow



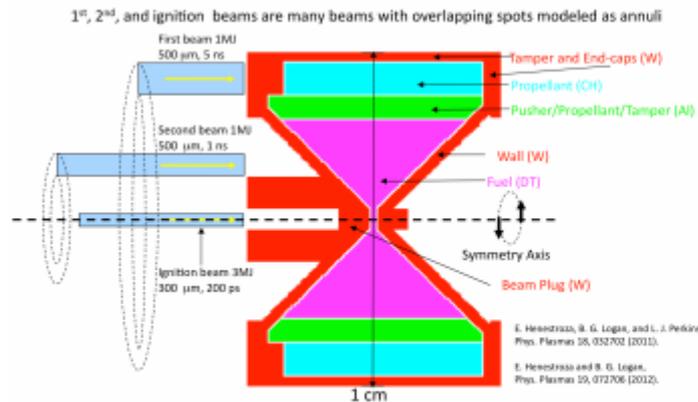
Plasma Jet Fusion

- ▶ Gains
 - Internal gain 100:1
 - Scientific gain: 20:1
 - Engineering gain 12.5:1
- ▶ 1D simulations, not 3D, but you may start with cold fuel
 - Large margin of error on parameters
- ▶ Ion beams might reduce target size and therefore reduce the energy requirement for ignition

An X-target-based Heavy Ion Fusion design offers:



The X-Target-Mark2: XMK2
20 GeV Rubidium beams (1.0+1.0+3.0 = 5.0 MJ)
Yield = 1.5 GJ, Gain = 300



- High repetition rate, high efficiency, robust final optics, robust chamber design.
- Single-sided heavy-ion beam illumination with a similar beam for compression and ignition to reduce the complexity of driver and chamber.
- Simple and inexpensive target fabrication.
- Quasi-spherical fuel compression and fast-ignition at high fuel density with burn propagation to low fuel density for high gain.
- Robust RT/RM/KH and mix stability with very small fuel convergence ratios (~ 5 to 7)
- Seeded magnetic field could be compressed during the implosion phase to enhance ignition and burn propagation and reduce hydrodynamic instability growth (RT-RM-KH). This is an extreme example of Magnetized Target Fusion.

The Heavy Ion Fusion Sciences Virtual National Laboratory

EH_ARPA-E WORKSHOP 29-30 OCT 2013



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ENERGY

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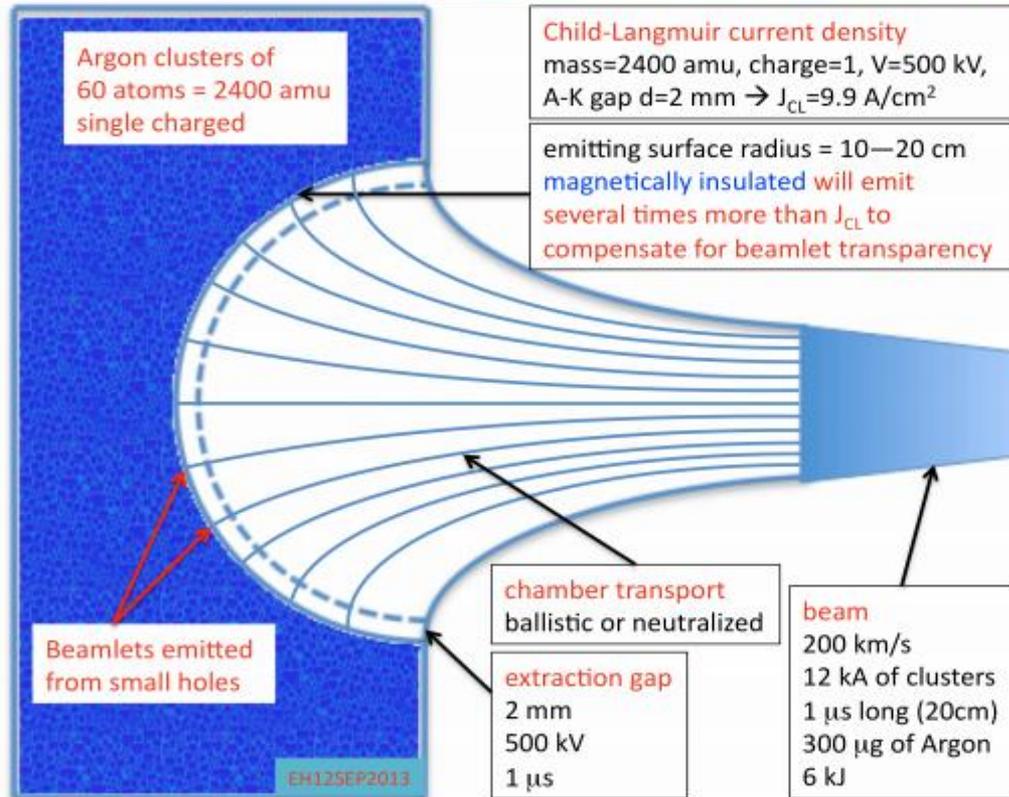
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Assessment of HIF

INJECTOR WITH MAGNETICALLY INSULATED SOURCE

MTF liner will be assembled from 1000 injectors covering a fraction of the area of a 4m-radius chamber

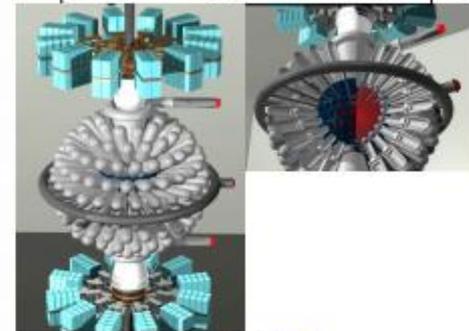
60-atom-Argon-cluster source to extract 300 μg of Argon at 200 km/s in 1 μs



The use of heavy particles like atomic or molecular clusters reduces the required current but increases the particle energy

The addition of drift compression reduces the requirement on extracted current density.
Magnetic insulation might not be needed

REACTOR MODEL FROM GENERAL_FUSION.COM



The Heavy Ion Fusion Sciences Virtual National Laboratory

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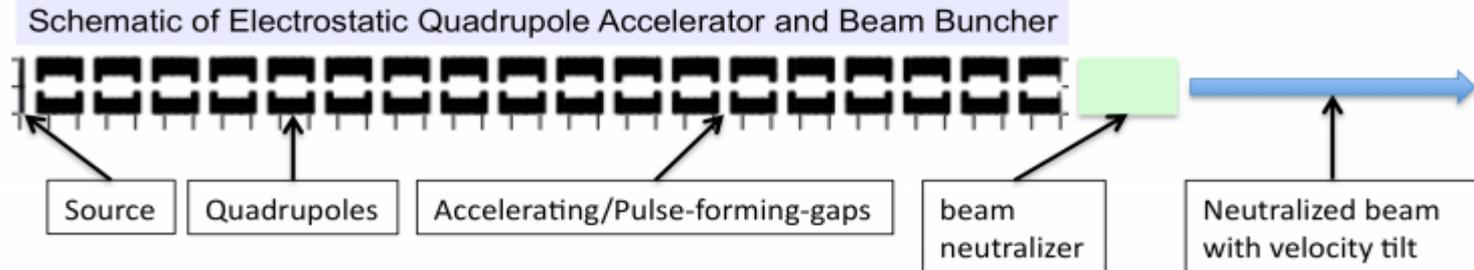
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SUB-MILLIMETER-SIZE INJECTOR WITH ACCELERATION AND BUNCH COMPRESSION

MTF liner will be assembled from 1000 bundles covering a fraction of the area of a 4m-radius chamber (each bundle is made of 10 million injectors)



EXAMPLE:

- Maximum transportable current density for ion beam velocity of 200 km/s and quadrupole tip field of 25 MV/m is $\sim 110 \text{ A/cm}^2$ for a quadrupole aperture radius= $10 \mu\text{m}$.
- Accelerator footprint= $100 \mu\text{m}$ by $100 \mu\text{m}$ to make room for accessories.
- For beam radius= $5.5 \mu\text{m}$ the current is $\sim 100 \mu\text{A}$.
- For a 4m-radius chamber, the total surface area is $2e6 \text{ cm}^2$. Therefore we can fit 10 billion injectors in half the surface area. The total current is 1 MA. Further drift compression (e.g., X10) of a $10\mu\text{s}$ beam will provide $10\text{MA}@1\mu\text{s}$ as required.
- If size is increased by a factor of 10, the total current is decreased by the same factor, which could be compensated by an increase in drift compression by the same factor.
- If the particles are carbon fullerenes, we will need 40X compression to attain $40\text{MA}@1\mu\text{s}$ to assemble a liner with 300 mg of carbon. The cluster-beam energy is 150 keV (6MJ).

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U.S. DEPARTMENT OF
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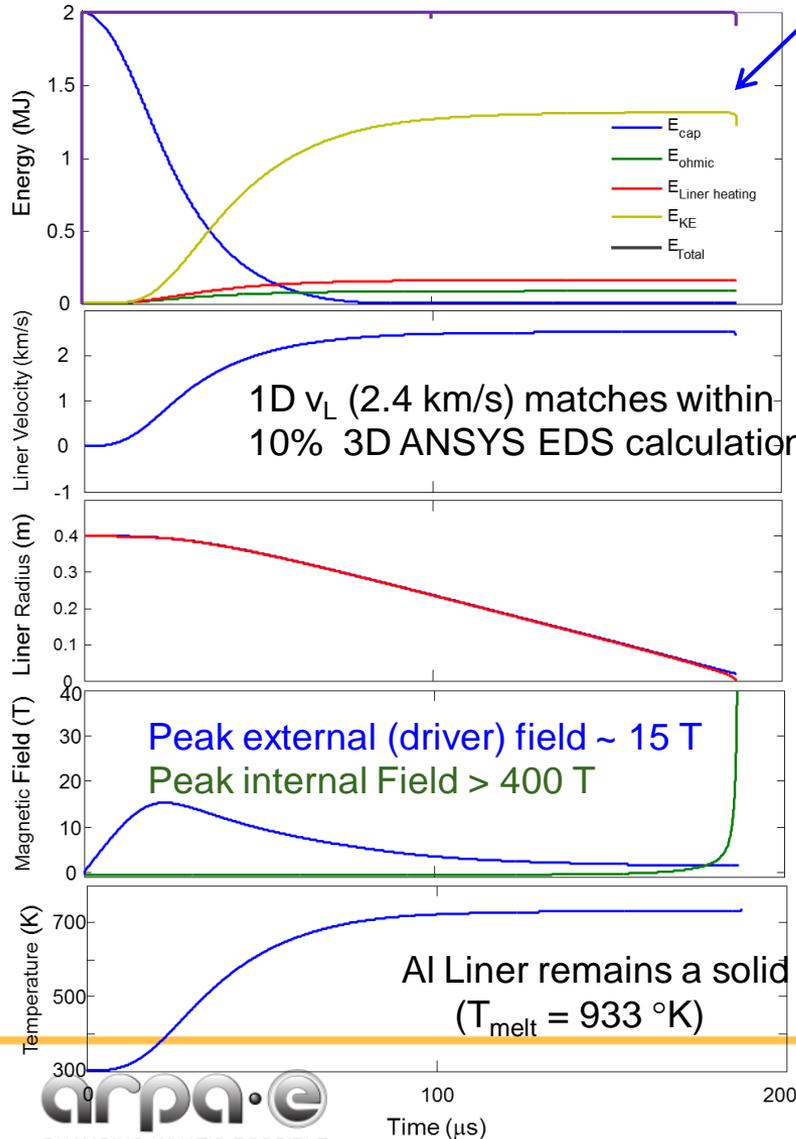
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MIF with Heavy Ion Fusion

- ▶ Magnetic field moves with the plasma, so ion don't need to penetrate through magnetic fields
- ▶ Target alignment critical
 - 3D printing assumed to allow manufacturing

Inductively Driven Liner Fusion – Gain Demo Parameters

Liner System Energetics and Dynamics from 1D Circuit and Field Modeling



- ❖ 67% coupling efficiency of bank energy into liner kinetic energy.
- ❖ With driver magnetic field energy recovery, driver efficiency is **87%**

FRC Plasma Parameters Anticipated for Demo

Adiabatic Law: $P \sim V^{-5/3}$

Rad. P Balance: $P \sim nkT \sim B_e^2$

Particle Cons: $nV = \text{const.}$

FRC ϕ Cons: $\phi \sim r_c^2 B_e (\text{const } x_s)$

$T \sim B_e^{4/5}$

$n \sim B_e^{6/5}$

$r_s^2 l_s \sim B_e^{-6/5}$

$l_s \sim r_s^{2/5}$

Parameter	Merged FRC ($t = \tau_{1/4}$)	Radial FRC Compression	Axial FRC Compression
v_L (km/s)	2.5	~ 0	0
r_L (cm)	22.5	0.9	0.9
r_s (cm)	20	0.8	0.88
l_s (cm)	80	22	3.5
B_{ext} (T)	0.16	100	410
$T_e + T_i$ (keV)	0.12	10	30
n (m^{-3})	5.5×10^{20}	1.3×10^{24}	7×10^{24}
E_p (kJ)	2.2	180	560
E (Pa)	1.5×10^4	6×10^9	10^{11}
τ_N (μs)	600	175	270

FRC adiabatic scaling laws, and (Bottom) Anticipated FRC parameters from merging, a purely radial, and a purely axial compression. During the actual liner implosion the FRC radial and axial compressions would occur simultaneously. They are calculated separately to show their relative effects

Inductively Driven Liner Fusion - Slough

- ▶ Challenge: how do you get around the Koepck problem?
 - AI liner driver
- ▶ Unknown interaction of liner and plasma at high compression

ARPA-E challenges for Drivers

Particle beams

- ▶ Breakdown field optimization at low cost for high energy
- ▶ Ion optics facing plasma

Plasma Jet

- ▶ Injection of compact plasma into breach of coax

FRC

- ▶ Liner target interaction is unknown
- ▶ Neutron bombardment into first wall could create thermal cycling challenges.

ARPA-E challenges for forming targets

Particle beam/Plasma Jet

- ▶ How do you magnetize a target with standoff?
 - Ideas:
 - With beam approach, drop in the coil with the target?
 - Injection of plasma with it's own internal field?

FRC

- ▶ Getting standoff

Costs

- ▶ Driver likely to be order of 10%
 - If not high power laser arrays
- ▶ Target formation likely to be inexpensive
 - As long as it can be magnetized cheaply
- ▶ Balance of plant will likely be largest cost driver

Other big picture discussion

- ▶ Debate on diagnostics being part of a potential program
 - reliance on reduced order models
 - need diagnostics to make sure you're on right path to breakeven (otherwise not likely to get there) and to inform the modeling.
- ▶ If ARPA-E can make a target that's independent of a compact toroid, can get away from many constraints