Magneto-Inertial Fusion and Other Intermediate-Density Pulsed Concepts

IAEA Workshop on Fusion Enterprises

• Overview

• Status & challenges

• Survey of private ventures

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Thermonuclear fusion “flow chart”

A necessary but not sufficient condition for a thermonuclear-fusion power reactor is for fusion heating to exceed losses (Lawson criterion):

\[ n \tau_E > 3 \times 10^{14} \text{ cm}^{-3} \text{ s} \]

density \hspace{1cm} energy confinement time

- \( n, B^* \) determine energy loss rate in a thermonuclear plasma
- Lawson criterion sets minimum \( n \tau_E \)
- \( n \) determines whether concept must be pulsed
- Sets minimum plasma size
- Sets energy, heating power, and cost
- Shapes reactor-engineering challenges

*\( B \) is magnetic field strength
The fusion “zoology” is bewildering but need not be

- Thermonuclear
  - Steady-state (lower density)
    - Magnetic confinement
      - Tokamak
      - Stellarator
      - Spheromak, FRC, RFP
      - Mirrors/GDT
    - Electrostatic confinement
      - Fusor
      - Penning trap
      - Polywell
  - Pulsed (higher density)
    - Magnetized
      - Z, θ Pinches
      - Solid-liner MTF
      - MagLIF
      - General Fusion
      - Helion
      - HyperJet
      - Plasma focus
    - ICF
      - Indirect drive (NIF)
      - Direct drive (LLE, NRL)
      - Heavy-ion-beam driven (LBNL)
      - Fast/shock ignition
      - Magnetized ICF

- Non-thermonuclear
  - Low energy
    - Muon-catalyzed fusion
  - High energy
    - Beam fusion
      - Pinches
      - Electrostatic

Energy gain unlikely or impossible for non-thermonuclear
Intermediate density enlarges fusion parameter space and relaxes many technology demands for fusion

Regimes of fusion self-heating in magnetized cylindrical DT fuel

• Adding $B$ to pulsed system
  – Reduces energy transport
  – Enhances DT $\alpha$-particle energy deposition

• Intermediate-density regime relaxes
  – Implosion velocity & heating power (compared to ICF)
  – Size and stored energy (compared to MCF)
  – Many technology requirements (compared to both)

Intermediate density is a “sweet spot” in fusion parameter space, optimizing combination of required energy and heating power

Plasma parameters are approximately geometric mean of MCF and ICF (table from Lindemuth & Siemon, 2009)

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>MTF example</th>
<th>NIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Toroidal</td>
<td>Cylindrical</td>
<td>Spherical</td>
</tr>
<tr>
<td>Cost ($M)</td>
<td>10,000</td>
<td>51</td>
<td>3000</td>
</tr>
<tr>
<td>$n_t$ (/cm$^3$)</td>
<td>$10^{14}$</td>
<td>$10^{20}$</td>
<td>$1.4 \times 10^{25}$</td>
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<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>$4.2 \times 10^{-10}$</td>
<td>$4.2 \times 10^{-4}$</td>
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</tr>
<tr>
<td>$T$ (keV)</td>
<td>8</td>
<td>8</td>
<td>8</td>
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<tr>
<td>$p$ (atm)</td>
<td>2.6</td>
<td>$2.6 \times 10^6$</td>
<td>$3.6 \times 10^{11}$</td>
</tr>
<tr>
<td>$B$ (kG)</td>
<td>50</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>$\tau_L$ (s)</td>
<td>0.9</td>
<td>$9 \times 10^{-7}$</td>
<td>$6.6 \times 10^{-12}$</td>
</tr>
<tr>
<td>$M$ (mg)</td>
<td>350</td>
<td>1.7</td>
<td>0.01</td>
</tr>
<tr>
<td>$a$ (cm)</td>
<td>240</td>
<td>0.6</td>
<td>$3.5 \times 10^{-3}$</td>
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<tr>
<td>$V$ (m$^3$)</td>
<td>$8.3 \times 10^2$</td>
<td>$4.0 \times 10^{-6}$</td>
<td>$1.8 \times 10^{-13}$</td>
</tr>
<tr>
<td>$E_{\text{plas}}$ (J)</td>
<td>$3.2 \times 10^8$</td>
<td>$1.6 \times 10^6$</td>
<td>$9.3 \times 10^3$</td>
</tr>
<tr>
<td>$P_{\text{heat}}$ (W)</td>
<td>$1.3 \times 10^8$</td>
<td>$9.0 \times 10^{10}$</td>
<td>$1.1 \times 10^{14}$</td>
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<tr>
<td>$I_{\text{heat}}$ (W/cm$^2$)</td>
<td>18</td>
<td>1.0 $\times 10^{10}$</td>
<td>$7.5 \times 10^{17}$</td>
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</table>

Simple costing models* suggest order-of-magnitude (or more) cost reductions for breakeven-scale facility compared to MCF/ICF

Breakeven in the intermediate-density regime may potentially be achieved by compressing magnetized plasma

Magnetoinertial fusion (MIF): liner compression of magnetized plasma

Z pinch: Axial (Z) electrical current in the plasma generates azimuthal field self-compressing the plasma
Advantages of pulsed, intermediate-density fusion

• Compared to ICF
  – Lower density reduces required implosion velocity → lower-cost, high-efficiency pulsed-power drivers
  – No delicate front-end laser optics
  – Reduced repetition rate needed in a power reactor

• Compared to MCF
  – Pulsed, compressional heating eliminates magnets and external heating systems
  – Mitigates or eliminates challenges associated with steady-state plasma-materials interactions (PMI)
  – High solid angle for tritium breeding

• Pulsed system de-emphasizes need for costly, radiation-resistant materials-development program
  – Many MIF/Z-pinch concepts are compatible with thick, flowing liquid first wall and/or blanket; solid plasma facing components (PFCs) are more easily replaced periodically

• Wide parameter space provides room for optimization and flexibility
Disadvantages of pulsed, intermediate-density fusion

• Compared to ICF, the plasma physics has been more challenging (formation, stability, confinement of the fusion plasma)

• Compared to MCF, lack of strong applied $B$-field makes needed stability and confinement more difficult to achieve (though absolute requirements are relaxed compared to MCF)

• Repetitively pulsed system presents different technological challenges from a steady-state reactor
  – e.g., repetitive pulsed-power requirements, thermal-cycling fatigue of solid PFCs (?), handling of very large amounts of liquid metal, etc.

• Much wider parameter space to explore
Fast pulses of intense electrical current are required \(\rightarrow\) high-voltage pulsed-power is the key enabling technology.

- **High-energy-density capacitors**
- **High-voltage spark-gap switch**
- **Ever-improving solid-state switches**

Eventually, need high repetition rate over lifetime of tens of millions of shots.
Outline

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• Survey of private ventures
Convincing proof-of-concept: Magnetized Liner Inertial Fusion (MagLIF) at Sandia (2014)

Implosion speed 70 km/s
2–3 keV ion & electron temperatures
$BR \sim 0.4–0.5$ MG cm

Gomez et al., PRL 113, 155003 (2014)
Schmit et al., PRL 113, 155004 (2014)
Laser-driven “mini-MagLIF” on OMEGA provides a platform to study MIF physics at high shot rate and low cost per shot.

40 compression beams
14 kJ in 1.5 ns

Coils: 4 turns per side
18 kV, 26 kA, $B_z = 10$ T

Preheat beam
180 J in 1.5 ns
Starts at -1 ns

CH cylinder filled with $D_2$ gas

With axial field and laser pre-heat, $T_i > 2.5$ keV, $Y_{DD} > 10^{10}$ neutrons
Most of the intermediate-density concepts being pursued are still orders of magnitude below the required “fusion triple product”

Continued, aggressive technical progress is needed to fulfill the promise of intermediate-density fusion!
Challenge: Plasma must be stable enough to be compressed to needed density and temperature

Two well-known examples: (a) “sausage” and (b) “kink”
Challenge: Plasma must have sufficient energy confinement time at chosen ion density and implosion speed

Particles “random walk”

Minimum size (cm) for magnetized fuel (neoclassical transport)

Challenge: Plasma must be formed in a manner compatible with economical, repetitive, pulsed operation

Merging hypersonic plasma jets (HyperJet Fusion)

Coaxial helicity injection to form a spherical tokamak (General Fusion)

Merged field-reversed configuration (FRC) (Helion Energy)
Challenge: Implosion must be fast enough to overcome rate of energy and magnetic-flux loss from the plasma

\[ P_{\text{compression}} \gg P_{\text{loss}} \]

\[ B_{\text{amplification}} \gg B_{\text{decay/loss}} \]

over entire implosion
(most challenging at peak compression)

Tools exist to calculate these quantities reasonably well (though could be computationally expensive), then need experimental validation (surprises tend to occur)
Challenge: Must mitigate or survive asymmetries and/or mix of impurities into the fuel

Rayleigh-Taylor instability

Electrodes introduce impurities

e.g., plasma guns
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Private companies pursuing pulsed, intermediate-density fusion energy

- General Fusion
- Helion Energy
- ZAP Energy
- Hyperjet Fusion
- MIFTi
- LPP Fusion
- Compact Fusion Systems
## Summary of private fusion ventures pursuing pulsed, intermediate-density fusion

<table>
<thead>
<tr>
<th>Company</th>
<th>Approach</th>
<th>Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact Fusion Systems</td>
<td>Pistons driven by high-pressure gas cylindrically implode a rotating liquid liner on a field-reversed configuration (FRC) plasma</td>
<td>Simon Woodruff</td>
</tr>
<tr>
<td>General Fusion</td>
<td>Pistons driven by high-pressure gas spherically implode a liquid liner on a spherical tokamak</td>
<td>Michel Laberge</td>
</tr>
<tr>
<td>Helion Energy</td>
<td>Pulsed magnetic field cylindrically compresses FRC formed by pulsed-power-driven injectors</td>
<td>David Kirtley</td>
</tr>
<tr>
<td>HyperJet Fusion</td>
<td>Pulsed-power-driven plasma guns form plasma target and imploding plasma liner via merging hypersonic plasma jets</td>
<td>Francis Thio</td>
</tr>
<tr>
<td>LPPFusion</td>
<td>Dense plasma focus (DPF), a Z-pinch variant that radially collapses a high-energy plasma to generate high-energy ions</td>
<td>Eric Lerner</td>
</tr>
<tr>
<td>MIFTI</td>
<td>Staged Z pinch, where a gaseous shell ionized by electrical current is cylindrically imploded onto a shock-heated gaseous target</td>
<td>Hafiz Rahman</td>
</tr>
<tr>
<td>ZAP Energy</td>
<td>Pulsed-power-driven, flow-shear-stabilized Z-pinch, in which sheared axial flows stabilize well-known Z-pinch instabilities</td>
<td>Uri Shumlak</td>
</tr>
</tbody>
</table>
General Fusion Magnetized Target Fusion

a) Vacuum toroidal field from current in liquid shaft
b) Stuffing flux field bubble out
c) Reconnection, spherical tokamak created
d) Liquid PbLi compresses the ST
## General Fusion Magnetized Target Fusion

<table>
<thead>
<tr>
<th></th>
<th>Initial</th>
<th>Final</th>
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<tbody>
<tr>
<td>Density (n)</td>
<td>2e20 m⁻³</td>
<td>2e23 m⁻³</td>
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<tr>
<td>Temperature (T)</td>
<td>120 eV</td>
<td>12 keV</td>
</tr>
<tr>
<td>Major radius (R)</td>
<td>1.2 m</td>
<td>0.12 m</td>
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<tr>
<td>Minor radius (a)</td>
<td>0.8 m</td>
<td>0.08 m</td>
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<tr>
<td>Aspect ratio (A)=R/a</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Plasma current (Iₚ)</td>
<td>2.8 MA</td>
<td>28 MA</td>
</tr>
<tr>
<td>Shaft current (Iₛ)</td>
<td>4.2 MA</td>
<td>42 MA</td>
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<tr>
<td>Magnetic field on axis (B₀)</td>
<td>0.7 T</td>
<td>70 T</td>
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<tr>
<td>Beta (β)</td>
<td>4%</td>
<td>40%</td>
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<tr>
<td>Thermal energy (Eₜₜ)</td>
<td>380 kJ</td>
<td>38 MJ</td>
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<tr>
<td>Magnetic energy (Eₘ)</td>
<td>11 MJ</td>
<td>110 MJ</td>
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<tr>
<td>Compression time (tₖ)</td>
<td>54 ms</td>
<td></td>
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<tr>
<td>Fusion yield (Y)</td>
<td></td>
<td>140 MJ</td>
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</table>
General Fusion Magnetized Target Fusion

Outside radius (solid)
Shaft radius (dashed)

Temperature (solid) and
Fusion power (dashed)
Sheared-Flow Stabilizes the Z-Pinch

- Pinches sustained for 1000s of growth times
- $n_e \sim 2 \times 10^{17} \text{ cm}^{-3}$, $T_i \sim 1-2 \text{ keV}$, & $B \sim 8 \text{ T}$ (Shumlak et al., PoP 2017, Nuc. Fus. 2009)
- FuZE goal of 300 kA
  - Scientific breakeven $I_{\text{pinch}} \sim 650-700 \text{ kA}$
  - Reactor $I_{\text{pinch}} \sim 1.5 \text{ MA}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>FuZE Design</th>
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<tbody>
<tr>
<td>Cap Bank Energy</td>
<td>$E_{\text{CAP}}$</td>
<td>500 kJ</td>
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<tr>
<td>Charge voltage</td>
<td>$V_c$</td>
<td>10 kV</td>
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<td>Plasma current</td>
<td>$I_p$</td>
<td>300 – 600 kA</td>
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<tr>
<td>Pinch current</td>
<td>$I_{\text{pinch}}$</td>
<td>150 – 300 kA</td>
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<tr>
<td>Pinch radius</td>
<td>$a$</td>
<td>&lt; 1 mm</td>
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<tr>
<td>Pinch length</td>
<td>$l_p$</td>
<td>50 cm</td>
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<tr>
<td>Electron density</td>
<td>$n_e$</td>
<td>$10^{18} \text{ cm}^{-3}$</td>
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<tr>
<td>Plasma temperature</td>
<td>$T_e$</td>
<td>&gt; 1000 eV</td>
</tr>
<tr>
<td>Plasma lifetime</td>
<td>$T_p$</td>
<td>TBD</td>
</tr>
<tr>
<td>Working gas</td>
<td></td>
<td>$H_2$ &amp; $D_2$ mix</td>
</tr>
</tbody>
</table>

Fusion Z-Pinch Experiment: FuZE

100-cm Acceleration Region | 50-cm Pinch
SFS Z-Pinch Reactor Conceptual Design Underway

- Power plant would use multiple cores:
  - Variable output power
  - Eases maintenance
  - Cores share tritium-handling facility
  - Pulsed @ ~10 Hz: 190 MWth each core
  - 1.5 MA pinch lasting ~100 us

- Liquid LiPb outer wall serves as:
  - Outer electrode
  - Heat transfer material
  - Biological shield
  - Tritium-breeding blanket
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. **Magnetic Compression** – FRC is magnetically compressed to fusion temperatures
5. **Energy Generation** – Spent plasma, fusion ions, and neutrons are converted to energy

**Advantages**
- 50 MW - rapid development, low wall heating concerns
- Direct fusion particle energy to electricity – high output efficiency and low gain
- Magnetic/Inductive compression – high input efficiency, minimum capital requirement
- Linear topology – **Divertor** and materials concerns minimized
VENTI - High Field FRC Compression

Grande – FRC heating to fusion temperatures

### Past Programs

- LSX, PhD – Full Scale & Stability
- IPA – Merging
- IPA-C – Heating and compression
- Grande – High field operation

### Current Programs

- VENTI
- FEP

### High Field DT Reactor Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Peak Compression</td>
<td>40 Tesla</td>
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<tr>
<td>Compressed Plasma Radius</td>
<td>6 cm</td>
</tr>
<tr>
<td>Compressed Density</td>
<td>3E17 cm⁻³</td>
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<tr>
<td>Burn Time</td>
<td>1 ms</td>
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<tr>
<td>Average Beta</td>
<td>0.98</td>
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<tr>
<td>Repetition Rate</td>
<td>0.1 Hz</td>
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<tr>
<td>Peak Plasma Energy</td>
<td>40 MJ</td>
</tr>
</tbody>
</table>

Millisecond lifetime
Merged FRC confinement
1 keV D ions, neutrons
5+ keV D ions, neutrons

Small scale, high field
Full scale
HyperJet Fusion Corporation: plasma-jet-driven magneto-inertial fusion (PJMIF)

Merging hypersonic plasma jets merge to form DT target (pink) and high-Z imploding plasma liner (purple)

Plasma jets formed by low-cost, state-of-art coaxial plasma guns
PJMIF aims for both high implosion speed to overcome target energy transport and high repetition rate for reactor economics

**Advantages**
- Standoff: all hardware far from fusion blast
- Low-cost line-replaceable coaxial plasma guns
- High implosion speed to overcome target energy transport
- High repetition rate possible (~1 Hz)

**Disadvantages**
- Non-uniformities due to merging jets is a concern, could prevent good plasma compression
- Potentially high amount of low-grade waste (replaceable first wall, guns) to be stored/recycled
- Plasma-liner and target formation are both challenging

**Status**
- Plasma-gun technology ready for subscale plasma-liner demonstration
- On cusp of demonstrating spherically imploding plasma liner formed by 36 guns/jets (2019)
- Target-formation plans formulated with first modeling and experiments soon to be underway (2018)
Liquid metal piston compression of DT fuel

Figure 1. a) power core consisting of: stainless steel tank (beige); fuel injection ports (copper); pneumatic actuators (purple, green) to drive liquid metal piston (dark blue) radially onto a plasma (pink). b) 150MW, 500MW power core concept. The central region shows the power core consisting of the piston chamber (beige) which also contains the main pneumatic energy store and double-ended fuel injectors (silver). The bio-shield is shown as a transparent box. Shown in blue are the power supplies for making the plasma. Liquid lead, heated by neutrons from the combustion of deuterium-tritium fuel, is pumped (red) to a heat exchanger (yellow). A 6’ person is shown in the foreground [13].

Compact Fusion Systems, Inc

arpa.e
CHANGING WHAT'S POSSIBLE

COMPACT FUSION SYSTEMS
Further work

- Perform Woodruff-Miller FED 2015-level cost analysis (ongoing, with seed investment)
  - Equilibrium \( \rightarrow P_n \)
  - Neutronics \( \rightarrow \) radial build & ME design
  - MHD \( \rightarrow \) stability, realistic power balance
  - Revisit all costing assumptions \( \rightarrow \) calculate LCOE
- \( \rightarrow \) ARPA-E OPEN, or VC for next steps
Staged Z-pinch Fusion Concept

- High-Z plasma liner made from Ar, Kr or Xe Implodes on a D target plasma
- Stagnation of shock waves creates a secondary piston that compresses the target plasma
- Shock waves also preheat the target plasma
- Target plasma remains stable during implosion
- This leads to stable high energy density plasma relevant to fusion conditions

In these experimental images, the effect of the MRT instability is clearly visible on the liner, but the target remains stable.

UCI, 1998

ZEBRA, 2017
Staged Z-pinch Exp. highlights at the 1MA ZEBRA Facility

Reproducible Z-pinches with honeycomb cathodes: $Y_{DD} \sim 10^{10}$ neutrons

**Ag-neutron activation data**

**Honeycomb cathode**

**Neutron time of flight data (nTOF) suggests thermonuclear neutron origin**

**Uniform and stable Z-pinch achieved with only $B_z = 500$Gs**

$12 \text{ mm}$

$t = 78.7 \text{ ns}$

$88.7 \text{ ns}$

$98.7 \text{ ns}$

$97.4 \text{ ns}$

$102.4 \text{ ns}$

# 5239
Advantages of Staged Z-pinch Concept

Advantages:

- Experiments and simulation conducted by three codes match pretty well.
- Compact and scalable machine design (scaling is done with three different codes).
- Does not use extremely complicated technology, like NIF (high power lasers and precision aiming), or stellerators.
- No plasma disruption problems, or runaway electrons like in tokamaks, which might threaten the machine integrity.
- Relatively very low cost machine.

Challenges for staged Z-pinch concept:

- Requires high repetition and highly reliable pulsed power system (capacitors and switches).
- The gas injector system has to be robust to survive higher levels of neutron and associated heat fluxes.
- This is a problem with all fusion concepts, and an additional reason why realistic fusion devices are large: no present day plasma facing material can withstand more than 10 MW/m² neutrons.
- A power SZP reactor will use tritium. Handling of the tritium exhaust each second will impose high additional costs.
LPPFusion (dense plasma focus)
Monolithic W Electrodes

Bake-out/ Long Chamber

Pre-ionization

TiN coating
Focus Fusion-1
Current Best Achieved Parameters

\[ T_i \quad 260 \text{ Kev} \]
\[ \tau \quad 30 \text{ ns} \]
\[ n \quad 8 \times 10^{19}/\text{cm}^3 \]
Plasmoid Radius 200 \( \mu \)
\[ nT \quad 6 \times 10^{14} \text{ keV s/cm}^3 \]
Device input energy 60 kJ
DD fusion yield 0.25 J
Fill gas density 1 \times 10^{18}/\text{cm}^3
Total project cost to date: $ 6 million

Focus Fusion-1
Planned Parameters

\[ T_i \quad 600 \text{ Kev} \]
\[ \tau \quad 10 \text{ ns} \]
\[ n \quad 2 \times 10^{23}/\text{cm}^3 \]
Plasmoid Radius 20 \( \mu \)
\[ nT \quad 1.2 \times 10^{18} \text{ keV s/cm}^3 \]
Device input energy 60 kJ
pB11 device output 140 kJ
Net electric output per pulse 25 kJ
5 MW at 200 Hz
LPPFusion data

2 kJ Ion beam
Integrated Rogowski
3 Mev by TOF

260 keV ions


Also, (not shown) from x-ray measurements, 155-keV electrons consistent with thermal distribution
• **Advantages**
  – Small, simple, economical device + direct energy conversion = potential for energy source far cheaper than any now existing
  – Using instabilities, not fighting them
  – High density = plasmoid metastability required, not absolute stability

• **Disadvantages**
  – Reduction of electrode erosion to provide repeatable operation
  – Reduce impurities that prevent high-density compression
  – In engineering phase, provide high rate of cooling to anode tip
Preliminary estimates have been made of the overnight capital cost ($0.7B–$1.9B) for 150-MWe power plants.

Caveat: $/W is NOT optimized in this study; 150-MWe was assumed at the beginning.

Conceptual Cost Study for a Fusion Power Plant Based on Four Technologies from the DOE ARPA-E ALPHA Program, Bechtel National Report # 26029-000-30R-G01G-00001.
Key takeaways

• Pulsed, intermediate-density fusion relaxes many of the technological challenges required for fusion by optimizing required combination of stored energy and heating power
  – There are advantages and disadvantages compared to MCF and ICF

• Scientific proof-of-principle (i.e., thermonuclear-fusion conditions that can be further scaled up) has been demonstrated via the MagLIF concept at Sandia

• A broad parameter space and many approaches with different combinations of drivers and plasmas are being explored by private fusion ventures
  – No concept has all the silver bullets; it’s about making conscious tradeoffs
  – Diversifies risk

• There is an opportunity to further develop many of the intermediate-density concepts to see if they can realize their potential in delivering a lower-cost, faster development path toward fusion energy
Backup Slides
Lawson criterion $\Leftarrow$ fusion heating exceeds all losses

For DT fuel

$$P_\alpha > P_{thermal} + P_{brems}$$

$$\frac{1}{4} n^2 \langle \sigma v \rangle E_\alpha > \frac{3n k T}{\tau_E} + C_b n^2 T^{1/2}$$

Ignoring bremmstrahlung and assuming $T = 10$ keV, then

$$n \tau_E > 3 \times 10^{14} \text{ cm}^{-3} \text{ s}$$

For non-magnetized, pure inertial confinement:

$$\tau_E \sim \frac{R}{C_s} \rightarrow$$

$$\rho R > 1 \text{ g cm}^{-2}$$

“breakeven” is easier by about a factor of 5 (use $E_{fus} = 17.6$ MeV instead of $E_\alpha = 3.5$ MeV).
Breakeven-class fusion facility is predicted to have a cost minimum at intermediate density

Based on simple costing model benchmarked to ITER and NIF, plot shows contours in US$ for attaining Lawson conditions $n\tau_E \gtrsim 3\times 10^{14}$ s/cm$^3$

- Broad low-cost minimum at $n \sim 10^{18} - 10^{23}$ ions/cm$^3$ due to reduced heating power compared to ICF and reduced size/energy compared to MCF
- Strong $B$-field is necessary to achieve Lawson criterion at intermediate density
MagLIF’s success motivates work to achieve intermediate-density fusion compatible with low-cost, high-repetition-rate operation

Higher repetition rate allows for lower yield per shot $\rightarrow$ simplifies reactor engineering

Higher repetition rate and low cost per shot essential for viable power-plant economics

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