Pulsed Power Inertial Fusion Energy

Fusion Power Associates

31st Annual Meeting and Symposium

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in collaboration with our colleagues at Sandia National Laboratories
At a high level, all IFE power sources have five major elements:

1. High Fusion Yield Targets
2. High Average Power Driver with Target Coupling
3. Target and Transmission Line Factory
4. Fusion Chamber and Fusion Blanket
5. Power Conversion System
The diversity of drivers, targets, coupling methods, chamber technologies requires *close scrutiny* of systems interface/integration issues

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- IFE has separability built into it from the start (attractive compared to MFE)
- System integration is not trivial
- It is imperative to optimize at a system level, *not just* at a sub-system level
- Efficient coupling needs to be demonstrated and is hard for all options
Pulsed power concepts allow thick liquid wall for long lifetime but require recyclable transmission lines.

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- Direct connection of driver-target
  - simple in concept for low rep-rate, can it be engineered, can yield be high enough?
  - needs to economic, thus recyclable, is this feasible?
  - longer lifetime chamber designs with larger yields?
This system of systems must meet a large number of demands

<table>
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<tr>
<th>Performance</th>
<th>Cost/Schedule</th>
<th>System Engineering</th>
<th>Policy and Politics</th>
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<tr>
<td>Energy rich</td>
<td>Low cost</td>
<td>Reliability</td>
<td>Ease of licensing</td>
</tr>
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<td>High gain</td>
<td>Credible, rapid, development path</td>
<td>Availability</td>
<td>Public acceptance</td>
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<tr>
<td>Efficient</td>
<td>Affordable development path</td>
<td>Maintainability</td>
<td>Acceptability of local or global environmental impact</td>
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<tr>
<td>Scalable/flexible</td>
<td>Credible, rapid, deployment path to mass production</td>
<td>Inspectability</td>
<td>No evacuation plan</td>
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<tr>
<td>Robust</td>
<td>Affordable deployment path to mass production</td>
<td>Manufacturability</td>
<td>No high-level waste</td>
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<td>Closed, on-site fuel cycle</td>
<td>Management of R and D risk</td>
<td>Disposability</td>
<td>Financing</td>
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<tr>
<td>Sufficient rep-rate</td>
<td></td>
<td>Usability</td>
<td>Safety analysis</td>
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<tr>
<td>Handling of high fusion yields</td>
<td></td>
<td>Mass-producability</td>
<td>Infrastructure development</td>
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<tr>
<td>Suppliability</td>
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This table outlines the various demands that a system of systems must meet, categorized under Performance, Cost/Schedule, System Engineering, and Policy and Politics. Each category lists specific requirements such as reliability, availability, maintainability, and public acceptance among others. The table is structured to clearly display the relationships and importance of each demand.
The first IFE z-pinch study (2004-2006) proposed 10 target chambers at 100 MWe per chamber

- C.L. Olson et al identified the science issues of repetitive drivers, recycled transmission lines, thick liquid wall target chambers

- We concluded 10 units are not practical or economic – too much steel for RTL’s, need higher target yield, system efficiency, and wall plug gain

3 GJ yield per chamber
RR = 0.1 Hz per chamber
300 MWth, 100 MWe/chamber
RReff = 1 Hz
Total power = 1 GWe

31,560,000 RTL’s & targets/year
What is new?

- **Indirect drive targets:**
  - Gwall ~1 (400 MJ yield) required two 60 MA, 60 ns drivers
  - IFE would require >3 GJ yields at RR = 1 Hz
  - Required 7.2 to 8.6 MJ absorbed at capsule
  - Required 40 to 100 MJ z-pinch x-ray sources
  - Gave 4.6 GJ yields
  - But required a 100 MA or two 150 MA drivers

- **Direct drive targets:**
  - Higher efficiency target concepts (25X)
  - Higher efficiency driver concepts (2X)
  - 5-10 MJ absorbed energy in target with single 60 MA driver
  - Possibly quite compact Z-sized (7800 ft²) to 10 x Z (85,000 ft²)
  - Higher thermal efficiency cycles (Brayton or Brayton-Rankine)
  - Require G = 500 – 1500, RR = 0.1 Hz for economic IFE
  - 1/10th number of RTL’s and targets at 0.1 Hz
LTDs (Linear Transformer Drivers) are the greatest advance in prime power generation since the invention of the Marx (1924).

26 MA, 22 MJ

60 MA, 90 MJ

Doubles electrical efficiency

Single step pulse compression
Rep-rate generator designs use Linear Transformer Driver (LTD) modules have economy of scale mass production

- Double electrical efficiency of conventional architecture (70%)
- Random failure rate of low voltage switches is better than $7 \times 10^{-6}$
- Components have shown 13,000 to 37,000 shots (1.5 to 4.3 days) with no failure

$\eta = \frac{E_{\text{out}}}{E_{\text{store}}} = 70\%$
Tests of a 1 TW rep-rate module are planned at 0.1 Hz at the required energy and technology scale

- 1 MA, 0.2 TW, 25 kJ, two cavity tests planned in FY2011
  - Fire 40,000 shots (\(= 1,600,000\) switch firings) at 6 shots/minute with resistive load
  - Engineer and test a replaceable transmission line system
  - 1 MA, 1 TW, 125 kJ, 10 cavity test planned to follow
- ZR was built for 4$/J. This technology scales more favorably.
- Gen 3 LTD designs have 80% peak current with 50% cavity radius

Prototype costs are:
- $11/Joule
- \(~10^{-4}\) cents/peak watt
LTD modules are integrated into efficient, low cost, compact, high yield scale pulsed power systems

Both systems can deliver 10 to 20 MJ to target regions

- \( E_{\text{store}} = 180 \text{ MJ} \)
- \( I_{\text{peak}} = 68 \text{ MA} \)
- \( \tau_{\text{imp}} = 100 \text{ ns} \)

- \( E_{\text{store}} = 90 \text{ MJ} \)
- \( I_{\text{peak}} = 60 \text{ MA} \)
- \( \tau_{\text{imp}} = 300 \text{ ns} \)

These accelerators consist of capacitors, switches, oil, water, plastic, stainless steel, and air
Concept of operations would allow module replacement during continuous high yield operation

Module Section
- 210 to 500 modules
- Low radiation area

40 m Water Section
- Passive pulseshaping & symmetrization
- Radiation shield

Target chamber
- Liquid wall
- Vaporizing blanket
Repetitive connection of driver and target is achieved by replacing a Recyclable Transmission Line (RTL) at 0.1 Hz

- RTL and the targets are a low mass (<50 kG), low cost, portable vacuum system
- Recyclable so the process can be economic.
- RTL provides coupling of driver and target even with chamber debris from previous event; chamber clearing not required
- RTL can be shaped to shield direct line of sight to driver
There are a number of science and engineering challenges for RTL driver-target coupling

- An applied science and technology R and D program is needed
- The “ilities”: manufacturability, maintainability, reliability, affordability, disposability, usability, availability
Liquid walls and vaporizing blankets could drastically reduce the materials issues that a fusion power plant will face.

- Direct connection with pre-pumped, mechanically-rigid RTL allows thick liquid wall
- Ongoing calculations to determine optimal shielding configuration
- Neutronics: 40 year lifetime chamber
- Initial point design: cyclic material fatigue: 7 year lifetime

M. Sawan, L. El-Guebaly et al., FST (2007)
Prototype RTL’s were manufactured by metal spinning and buckling strengths were measured and modeled.

- Outer RTL electrode is susceptible to the buckling instability
- Stiffening rings increase buckling pressure by 3X
- Thicker RTL’s for higher gain and lower rep-rate
- Other materials, other fabrication techniques

ASTM 1008 low carbon steel
Thickness = 0.620 ± 0.02 mm (25 mils)
Buckling ~ 8.3 psi

Buckling ~ 26 psi

RTL’s can be fabricated economically – up to $15/shot can be spent on RTL’s and targets at >10 GJ and 0.1 Hz

Nuclear plants raw fuel costs ~ $3.50 to $5.50 per MWhr<sub>e</sub>

Coal ~ $10 to $13.20 $/MWhr<sub>e</sub>

Only 5 to 10% of COE results from RTL and target costs

2 week inventory (3000 metric tons), yearly throughput (<190,000 metric tons)

Need to develop design of full scale production line with industry (SCHULER)

OCC RTL stamping plant: 160 million
We will manage IFE R and D with Technology Readiness Levels

<table>
<thead>
<tr>
<th>System</th>
<th>TRL level completed</th>
<th>Achievement (by 2014)</th>
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<tbody>
<tr>
<td>LTD Cavity</td>
<td>5</td>
<td>Prototype module costs ~ 11$/Joule</td>
</tr>
<tr>
<td>Switches</td>
<td>5</td>
<td>3,000,000 to 9,000,000 shot lifetime (1 to 3 years)</td>
</tr>
<tr>
<td>Driver Module</td>
<td>5</td>
<td>1 TW sub-scale module testing complete at 2-6 shots/min 40,000 shots with no failure (~ 5 days)</td>
</tr>
<tr>
<td>RTL’s</td>
<td>4</td>
<td>Prototype system demonstrated on sub-scale module at sub-speed for 100 shots Conceptual designs for economic RTL mass production factory</td>
</tr>
<tr>
<td>Target</td>
<td>5</td>
<td>Q ~ 0.5 to 1 DT implosions on Z Cryogenic implosions High gain target designs (&gt;5 GJ) and validated simulations</td>
</tr>
<tr>
<td>Chamber</td>
<td>4</td>
<td>Preliminary thick-liquid wall designs Scaled hydrodynamic shielding experiments</td>
</tr>
<tr>
<td>Breeding</td>
<td>3</td>
<td>Preliminary design of tritium recovery system</td>
</tr>
<tr>
<td>Balance of Plant</td>
<td>5</td>
<td>Preliminary design of Brayton cycle system for inertial fusion energy with primary loop of molten salt</td>
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<td>Net TRL</td>
<td>4</td>
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- Subsystems mature enough to integrate into a viable IFE system have a TRL of 6
Cost of electricity models put requirements on the product of target gain and rep-rate \((G^*RR)\)

First-of-a-kind unit in 2007 $

- 8$/J, 10%  
  - 200 MJ
- 4$/J, 20%  
  - 100 MJ
- 2$/J, 30%  
  - 67 MJ

- Escalate TCC = 2 \times \text{based on MIT nuclear study}
- Cost of $ = 7.8\% \text{ based on MIT nuclear study}
- Learning curves and 10\textsuperscript{th}-of-a-kind units for fusion power economy could lower COE by 30\%
Large yields and low rep-rate may be an attractive path for Inertial Fusion Energy

The logic of the integrated system is compelling

- Compact, efficient, low cost, long-lifetime, repetitive driver
- Advanced, efficient, low cost, robust targets, that are simple to fabricate
- Very large absorbed target energies
- Very large fusion yields
- Allows low rep-rate
- RTL coupling is feasible, engineering development required
- Thick-liquid-wall and vaporizing blanket for long lifetime chamber
- Shielding of line of sight to the driver

Key enabling physics: magnetically-driven-targets
Key enabling technologies: LTD’s and RTL’s
IFE diversification

- Many possible IFE systems (1000’s)

- Don’t up-select too early:
  - Magnetically-driven implosions and pulsed power could be a breakthrough
  - Diversify the risk portfolio for national IFE plan. Diversification is in the national interest.

- Diversification, formally: for a given level of expected return, a portfolio minimizes total variance by diversifying amongst assets with poorly correlated risks.

- Technology adoption lifecycles require 40 years for significant market penetration (25% market share)