Technology Challenges in the Development of Inertial Fusion Energy

Seventh IAEA Technical Meeting on Physics and Technology of Inertial Fusion Energy Chamber and Targets

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Experimental results are encouraging – if eventually successful, what are the challenges to developing a practical power source?

\[ E_{\text{ignition}} \sim \rho R^3 T \sim \frac{(\rho R)^3 T^3}{P_{stag}^2} \]

- Increase driver energy and/or coupling efficiency

- Improve implosion “quality” – \( P_{stag}^2 \)
  - Convergence ratio \( \sim CR^6 \)
  - Implosion vel \( \sim \nu^6 \)
  - Symmetry \( \sim S^8 \)

- Challenges
  - Mix and symmetry get harder to control as velocity and convergence increase
  - Hot electron heating – adiabat / symmetry?
Principle of laser IFE power generation

Engine operation of 900 cycles / minute delivers ~ 1 GWe
Most fundamental challenge is to generate more power than consumed by the fusion driver.

Plant electrical gain is a function of four parameters:

\[ \eta_L \times G_F \times G_B \times \eta_T = \frac{P_{\text{Gross}}}{P_{\text{Recirc}}} \]

Recirculating Power:

\[ f_{\text{Recirc}} = \frac{P_{\text{Recirc}}}{P_{\text{Gross}}} = \frac{1}{\text{Plant Gain}} \]
Greatest technology potential is in laser efficiency and fusion gain

- Laser efficiency: < 1% for flash lamp pumped lasers but estimated ~ 15% for diode laser pumped systems

- Fusion gain: higher is better, but how high a gain is needed?

- Fusion blanket gain: constrained by physics and practicalities to <1.2
  - Can be much higher in fusion-fission hybrids

- Thermal to electrical conversion efficiency: <50%, future gains will be hard to come by
Fusion gain drives technology requirements for laser and targets

Design parameter combinations for a 1000 MW fusion power plant

- Assumes: $G_R=1.2$
- $\eta_{\ell}=0.43$
- $\eta_{\ell,\text{c}}=0.16$
Economic analysis shows that greatest benefits accrue between fusion gains of ~30 and 100

Relative cost of electricity as a function of fusion gain and PRF for 1000 MW_E plant
Fusion gain of ~60 needed for energy production

Relative cost of electricity as function of fusion gain and PRF

Assumes:
\( G_e = 1.2 \)
\( \eta_{\gamma} = 0.43 \)
\( \eta_{\text{re}} = 0.16 \)
Power Balance, Electrical Gain 5.1 (example)

Laser
2.3 MJ @ 16 Hz
15% $\eta_L$

37 MW laser

$G_{\text{fusion}} = 65$

2400 MW fusion

$G_{\text{blanket}} = 1.2$

2900 MW thermal

Power cycle
$\eta_{\text{th}} = 44\%$

1275 MWe

1625 MW$_{\text{th}}$

Process heat

1000 MWe

240 MWe
(19% recirc)

30 MWe

Pumps / aux. power

To grid

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Modular design important to mitigating technology risk

Beam-in-a-Box

Laser system availability vs MTBF

“Conventional” Rad-Resistant Steel
Material choices, chamber/plant configuration and RAMI are all inter-related.

The modules don’t need to be physically connected other than via the support structures.

No beam-line connections are necessary.
Chamber gas can be used to mitigate impulse heating of first wall – allowing a 10m scale, steel chamber to be used

Ions are stopped in ~ 10s of cm of xenon gas and x-rays are mostly absorbed

Pb, D, T, α, etc.

First wall heating is low enough to eliminate the need for tungsten coating

Wall is protected from ion and x-ray target output
Since the beam can propagate through lead vapor, complete “chamber clearing” is not required

- Electronic Stimulated Raman Scattering (ESRS) has been observed in Pb
- Metastable states saturate with investment of 20 kJ for $10^{15}$/cc Pb

Chamber clearing of 0.5% is sufficient for a 1.5 g Pb target
An RAFM steel chamber could be utilized at full scale with reduced fusion power (~1100 MW)

- First wall design is balance between temperature ($\eta_{th}$), size and thermal stress

- Based on ASME piping code factors of safety:
  - 3 on ultimate tensile strength
  - 1.5 on yield strength
  - 1.5 on creep rupture strength
  - < 1% creep in $10^5$ hours

- Demo system could use low-activation ferritic martensitic and accept 10 dpa/100 appm lifetime
Raw materials availability does not appear to be an issue
IFE energy requires new target manufacturing paradigm

**Target for an ICF Experiment**
- Expensive
- Production rate: ~1 per day
- Manual, high-precision fabrication
- Held stationary in chamber

**IFE target**
- Low cost (< 50 cents each)
- Production rate: ~1 million per day
- Automated production
- Injected at ~250 m/s for fusion energy applications

~13 mm
Concepts exist for low-cost, mass manufactured fuel, but development is required

**Die-cast hohlraum components**

**Target component cost breakout**

**Plasma – CVD HD Carbon Capsule**

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**Off-site**
- Fabricate CVD diamond ablator
- Laser-drill fill-hole
- Etch out mandrel
- Die-cast Pb hohlraum parts
- Attach CVD-diamond membranes
- Pre-formed capsule support IR shield LEH window

**In-plant**
- Create inner foam layer
- Assemble hohlraum parts
- Assemble hohlraum halves
- Helium fill
- Cool to ~18K, filling foam

**On-site Target Assembly Plant**
- Fill capsule with DT
- Plug hole
- Place capsule into hohlraum
High throughput process for capsule manufacturing is important to achieving target low cost

Capsules could be stacked in a CVD plasma to increase number of capsules per run

More capsules can be coated per run under a laterally expandable hot-filament CVD to reduce cost
High throughput techniques are also needed for ultra-thin membranes

500 nm thick membranes for experiments are spin-coated. This will not meet high-throughput and low-cost objectives.

Meniscus coating membrane films on a removal layer is estimated by to meet cost and through-put objectives.
Injector must aim target to a point near chamber center within the laser field-of-view

- Laser fast-pointing field-of-view (FOV) is ±500 µm at chamber center.
- Injector must place 99.9% (3.3σ) of targets with ±500 µm of chamber center to allow target to connect with laser (equals laser FOV).
- Target tilt/precession must be less than 40 mrad.
- Tracking and engagement system must track position to ±25 µm and ±50 µm respectively to allow laser to point to target ±100 µm RMS (1σ) interaction specification.
- Tracking and engagement system must measure target velocity to within ±0.2 m/s at a 250 m/s target speed to time laser to a ±12 µm vertical positional error for a final measurement taken 23 µs from chamber center.
- Target tilt must be measured to ±4 mrad.

Target trajectory, velocity and tilt must be measured to meet laser-target interaction specification.
Gas-gun injector is a well-known, high-accuracy acceleration system

Injector prototype:
- 35 m/s
- ±1 mm at 6 m in air

Target loading

Pressurized He forces target into barrel

Barrel clamped at muzzle

10m injector barrel

4 gas guns mounted on turret: Disabled gun can be quickly replaced increasing system reliability
Advancements in tritium technology enable more compact architecture and lower tritium inventory

More than 50% of plant’s T inventory resides in the target fill area

Examples include SRNL’s micro- TCAP technology and use of cryo-viscous compressors
Waste disposal could meet Class-A requirements using high purity steel manufacture

- Waste Disposal Rating ~ 0.1
- Nb, Tb, Ho, Ir contribute ~95%

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<th>Specified impurity (ppm)</th>
<th>Estimated Class A req. (ppm)</th>
<th>Measured Impurity (ppm)*</th>
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Alloy fabrication tests encouraging for Class A disposal
E23-HAPLS builds on technologies demonstrated on Mercury to achieve scalable, efficient, high-average-power operation.
GOLD and ELI are driving demonstration of increasingly capable diode arrays

**GOLD:** 120 Hz, 126 kW

**ELI L3:** 10 Hz, 800 kW
800 kW QCW diode array in action at 10 Hz

- 800 kW peak @ 120 Hz
- 2.4 kW average power
Important Challenges Must be Overcome

- Because inertial fusion is a threshold phenomena, fixed costs are high and minimum economic plant size is large
- While laser technology has alternate, near-term applications, the fusion chamber and several other systems are unique to fusion – likely to require significant, dedicated government funding
- Pulsed nature of IFE generates high cycle fatigue – challenging thermo-mechanical design
- Low-cost fuel concepts exist, but much development work is required
- Final optic radiation damage risk addressed by in-situ thermal annealing – but final optic survival is a high technical risk area