

FOCUSED
ENERGY

III – The path to commercialization of Inertial Fusion Energy (IFE)

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*Joint EPS – SIF International School on Energy
23 – 28 June 2025
Varenna, Italy*

Summary

- From the NIF experiments to IFE reactors
- Physics and technology requirements
 - Target gain
 - Laser
 - Target fabrication
 - Reactor
- Private companies for an accelerated path to IFE
- Focused Energy activities and roadmap to IFE

The NIF results prove the soundness of two basic elements of inertial fusion:

- laser driven compression
- hot spot ignition, followed by burn propagation

Next: toward Inertial Fusion Energy (IFE)

- **Why?**
- **Who?**
- **What is needed?**
- **How?**

And what is the role of private companies?

Why should we vigorously pursue inertial fusion energy

Advantages of the inertial fusion energy (IFE) concept:

- Scientific energy gain has been demonstrated
- Significantly different technological risks than MFE
- Separable components / Highly modular
- Multiple target concepts with same driver
- Reduced tritium inventory
- Attractive development path
- Technology and science spin-offs
- Multiple sponsors for key technologies (e.g., laser diodes, high neutron yield sources)

Who is pursuing / will pursue / would like to pursue IFE?

- National Initiatives in the US and, above all, in Germany (with smaller funds in the UK)
- [China?]
- A few private companies
- Groups of European scientists from public institutions call for a European initiative (HiPER+)

Note that US, German, UK's programmes explicitly foresee and encourage public-private-partnerships.

IFE: a changing international landscape



The achievement of ignition on the NIF has triggered substantial IFE R&D activities in the US, Germany, UK and France.

In Germany, previously without any ICF activity, ICF/IFE is now an integral part of the national fusion strategy. (*)

In 2024 a new funding programme for nuclear fusion research was announced by Germany's Federal Research Minister Bettina Stark-Watzinger aimed at paving the way for the first fusion power plant to be constructed in Germany by 2040. (**) Such a program has been confirmed by the new government (in power since May 2025)

Germany's new government intends to build the world's first fusion power plants, using two competing technologies. (*)**

(*) see "Memorandum Laser Inertial Fusion", BMBF, May 2023;

(**) BMBF program Fusion 2040 – Research on the Way to a Fusion Power Plant" (370 M€ in 2025-27) for public-private collaborations

(***) <https://www.fusionindustryassociation.org/germanys-new-government-readies-for-a-push-towards-fusion-power/>

<https://www.world-nuclear-news.org/articles/germany-aims-to-build-fusion-power-plant>

Also:

Wörner, J.-D.: *Nuclear Fusion Made in Germany. Options for Building an Innovation Ecosystem for Nuclear Fusion* (acatech IMPULSE), Munich 2024. DOI: https://doi.org/10.48669/aca_2024-16 [German National Academy of Science and Engineering]

Europhysics News 53/1 (2022)

BREAKTHROUGH AT THE NIF PAVES THE WAY TO INERTIAL FUSION ENERGY

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R.H.H. Scott⁹, M. Tatarakis^{10,11}, V. Tikhonchuk^{2,12}, and L. Volpe^{13,14} – DOI: <https://doi.org/10.1051/epn/2022106>

High Power Laser Science and Engineering, (2023), Vol. 11, e83, 31 pages.
doi:10.1017/hpl.2023.80



REVIEW

Future for inertial-fusion energy in Europe: a roadmap

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Inertial Fusion Private Companies



(at least) 10 companies, in alphabetical order:

- Blue Laser (US, laser fusion)
- Ex-Fusion (Japan, laser fusion)
- First Light Fusion (UK, shock driven ICF)
- **Focused Energy (US & Germany, laser fusion)**
- HB11 Energy (Australia. Laser fusion with pB11)
- Laser Fusion X (US, Laser fusion)
- Longview Fusion Systems (US, Laser Fusion)
- Marvel Fusion (Germany, ICF with ultraintense laser)
- **Pacific Fusion (US, MagLiF)**
- **Xcimer Energy Corporation (US, hybrid drive with excimer lasers)**

Only three of them give enough details on their programmes and objectives.

(A few details in the next slide on Xcimer and Pacific, more on Focused Energy later)

Info on Fusion companies: The global fusion industry in 2024. Fusion Industry Association, www.fusionindustryassociation.org. Pacific Fusion and Xcimer not listed there.

Xcimer Energy Corporation

<https://xcimer.energy/>

Hybrid (indirect-direct) drive, using 10 MJ
Excimer (ArF) laser

Ref.: C. A. Thomas et al, Hybrid direct drive
with a two-sided ultraviolet laser,
Phys. Plasmas 31, 112708 (2024)

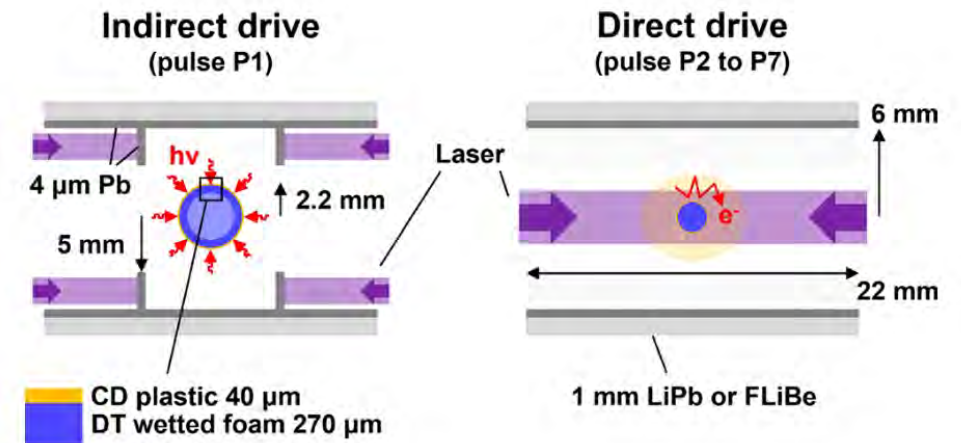


FIG. 2. A diagram of the hybrid target and its two stages in drive: indirect and then direct. The high-Z cavity is designed to protect the capsule from the chamber environment with materials suitable to a power plant, as well as generate a pulse of x-rays.

Pacific Fusion

<https://www.pacificfusion.com/>

MagLiF (magnetized liner inertial fusion) scheme

Ref: C. L. Ellison et al., Opportunities in Pulsed
Magnetic Fusion Energy

<https://doi.org/10.48550/arXiv.2408.15206>

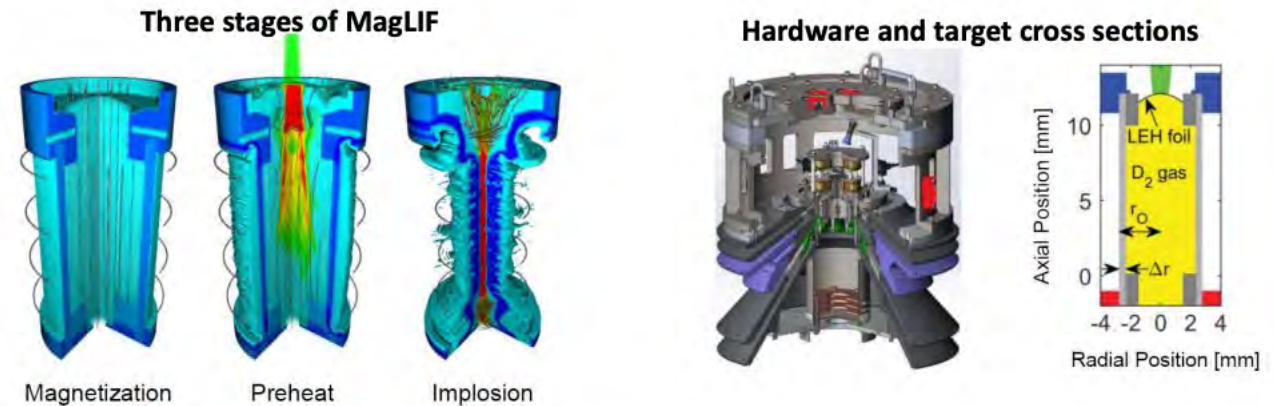


Fig 1. Three-dimensional simulation demonstrating the three stages of MagLiF (left) and load hardware and target cross sections (right)

Focused Energy (FE)

developing commercial fusion energy, using laser direct-drive

Established in 2021, based in Germany and in the US
60 people at the end of 2024 -> 100 by end 2025
200 M\$ raised, series A in progress.

Funded by private investors + competitive public funds [Germany (BMBF, SPRIND) and US (PPP, US INFUSE program)]

Focused Energy works on all areas requiring development:

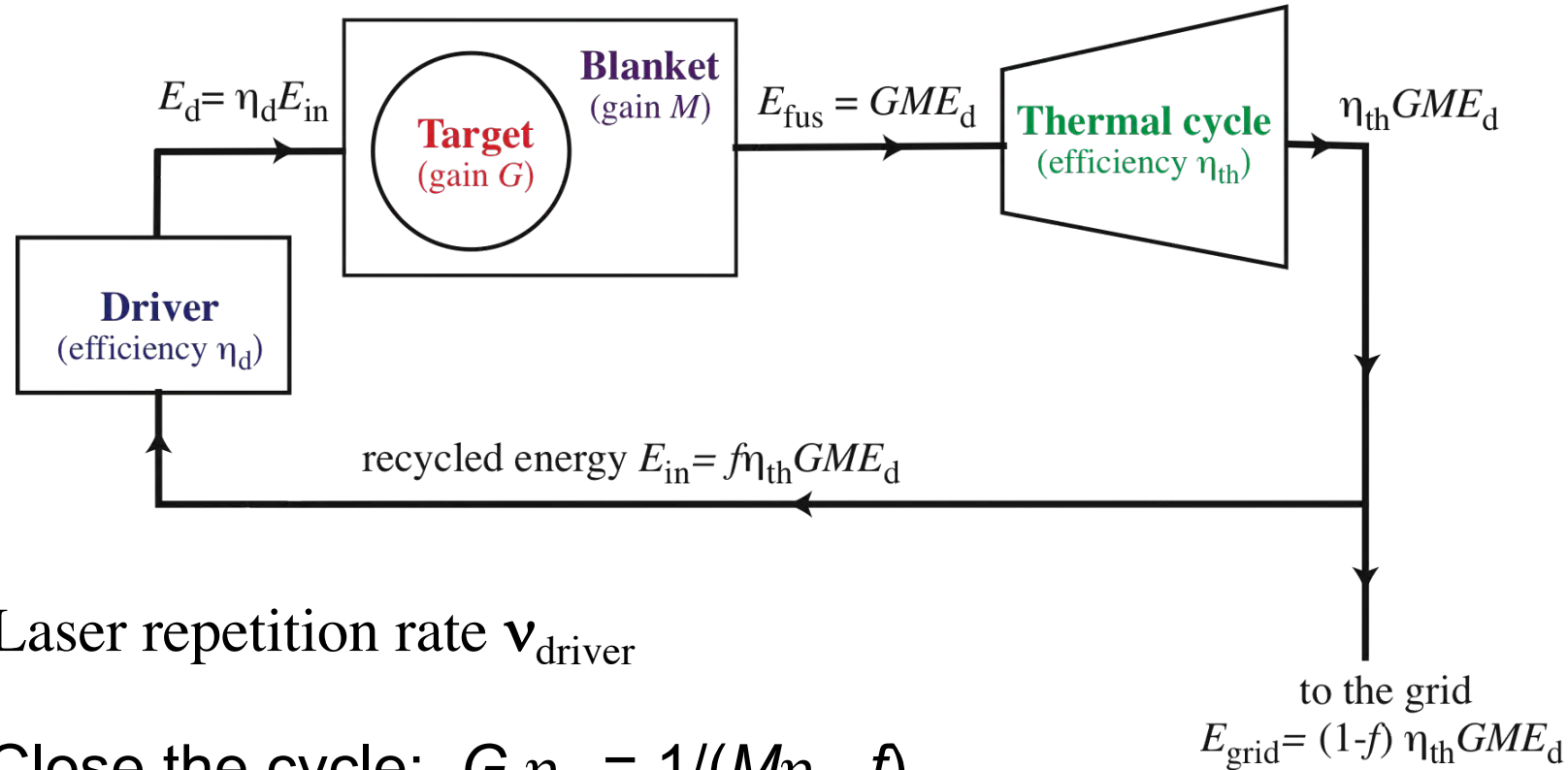
- **IFE Physics**: target design and experiments on key issues
- **Laser**: developing proprietary high efficiency, high-rep rate, scalable modules
- **Reactor**: addressing all system issues,
- **Targets**: developing proprietary mass fabrication techniques

- Fast path toward fusion energy
- Leverage on decades of basic research
- Develop compatible **solutions for the whole system**, i.e. fusion physics, target production, laser, reactor, ... (with proprietary IP)
- Market-oriented, **scalable solutions**
- Collaboration with national labs (PPP programmes), development of supply chain of specific fusion technologies, involvement of utilities, of major energy industries

From NIF achievements to Inertial Fusion Energy

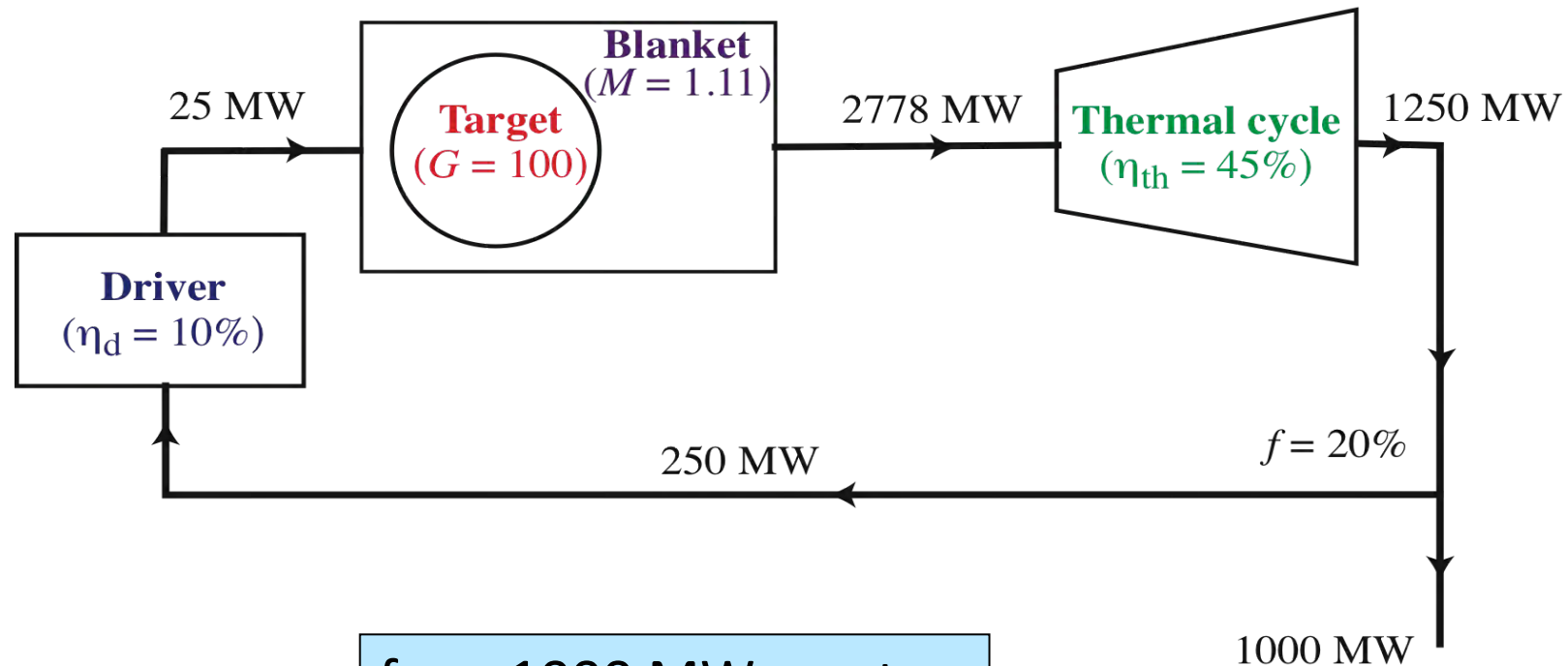
What is needed ?

The main requirements for an IFE plant are obtained from the reactor power cycle



- Close the cycle: $G \eta_d = 1/(M\eta_{th} f)$
- Power production: $P_{grid} = \nu_{driver} E_{grid} = \nu_{driver} [(1-f) \eta_{th} GM E_d]$
- target cost < 20–30 % COE; (COE: cost of energy)

The main requirements for an IFE plant are obtained from the reactor power cycle



To close the cycle

$$\eta_d G \geq 10$$

for a 1000 MW reactor

$$G = 100;$$

$$\eta_d = 10\%$$

$$E_d = 2.5 \text{ MJ}$$

$$\nu_{\text{driver}} = 10 \text{ Hz}$$

Tremendous progress is required

	For IFE	NIF	Required progress
Target gain	100	2.5	40
Driver efficiency	10%	0.7%	15
Driver rep. rate	few Hz	1/day	10^5 – 10^6

cost of target < 30% Cost Of Energy =>

$$\text{cost of target} < 40 \text{ cent} \times \left(\frac{Y_{\text{fus}}}{250 \text{ MJ}} \right) \left(\frac{COE}{5 \text{ cent/kWh}} \right) \left(\frac{\eta_{\text{th}}}{40\%} \right)$$

but potential solutions exist and are actively studied

The issues addressed and the solution proposed by Focused Energy

Progress required, solutions exist: Increasing target gain from $G = 4$ to $G = 100$



NIF target scheme designed 30 years ago, to maximize the chance of achieving ignition with 1990's laser technology and 1990's plasma physics knowledge

- $G \times 4$ possible on NIF, with very small changes [1]
(cfr progress last 4 years; ignition is a bifurcation, a small increase in the Lawson parameter results in a very large change in fusion energy)

- $G \times 5-8$ replacing indirect-drive with **direct-drive**

$$\Rightarrow G = 4 * 5 * 6 = 120$$

- $G \times 2-3$ using **advanced ignition schemes** (fast ignition [2] or shock ignition [3])

$$G > 200$$

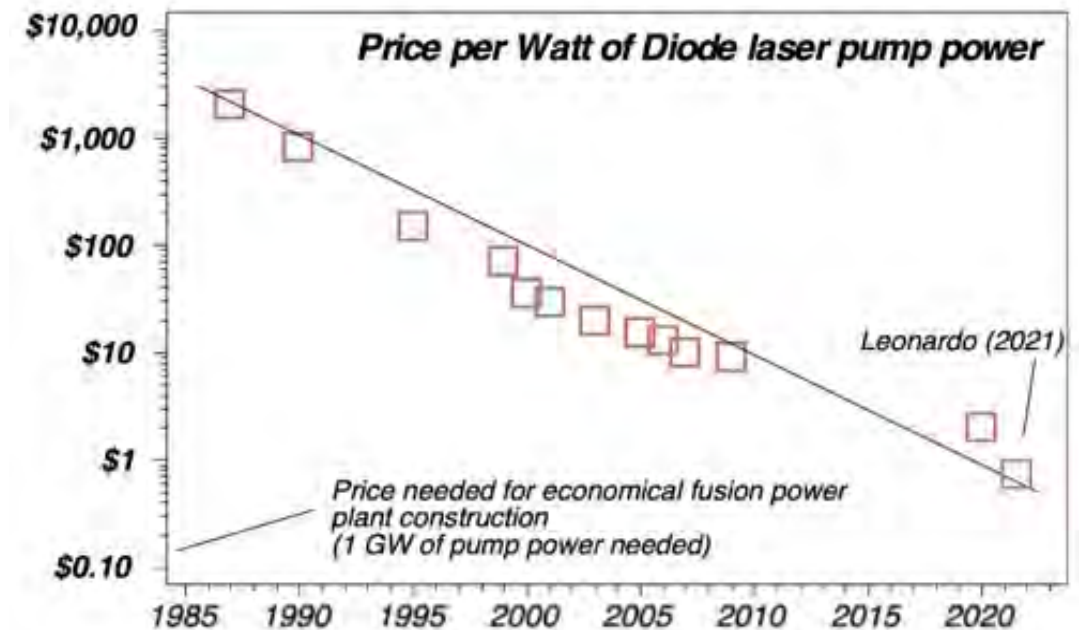
[1] O. Landen et al., *Phys. Plasmas* 31, 062712 (2024); Fratanduono et al, APS-DPP 2024; Kritcher et al, APS-DPP 2024.

[2] M. Tabak et al., *Phys. Plasmas* (1994); SA, *Phys. Plasmas* (1999); M. Roth et al., *Phys. Rev. Lett.* (2001); SA and M. Tabak, *PPCF* (2005)

[3] R. Betti et al., *Phys. Rev. Lett.* (2007); S. Atzeni et al., *Nucl. Fusion* (2014)

Progress required, solutions exist: Lasers

- NIF based on a 30+ year old laser technology
- Today, best performing flash-lamp pumped kJ laser developed with FE IP, and installed at ELI-beamlines (Prague) operate at 1 shot/min
- **Required laser efficiency and rep rate** demonstrated on small scale (100 J, 10 Hz, 10% efficiency) diode pumped lasers;
- **cost of laser diodes** currently rapidly decreasing; likely to be affordable for MJ Hz lasers in less than 10 years, FE is working on them, in collaboration with laser industry (*)



Progress required, solutions exist: Targets, reactor

- Targets for NIF experiments are produced by hands, characterized individually with a time-consuming process => costs are very high
- up to a million low-cost targets per day required by an IFE reactor; FE is working with the final goal of **demonstrating target mass fabrication**; this could lead to a cost decrease analogous to that of VLSI electronics. Serial production of hundreds of simple targets already achieved at Focused Energy laboratory
- **First wall, shielding, breeding, maintenance** being addressed by FE engineers, in collaboration with various labs: easier than in MFE, due to reactor/driver separation
Crucial issues: optics damage, reactor facing optical components

**We are designing high gain reactor targets ($G > 100$),
as well as targets for a Fusion Pilot Plant, FPP ($G > 20-25$)
to identify risks and main physics and technology issues to
be addressed**

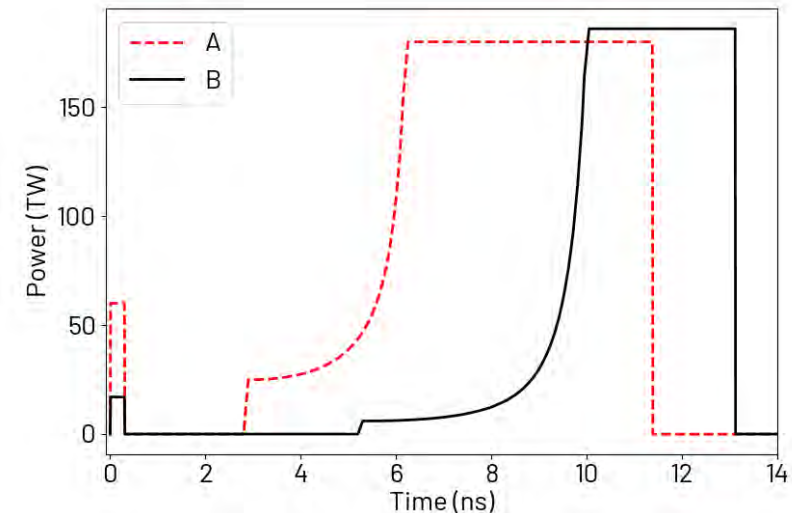
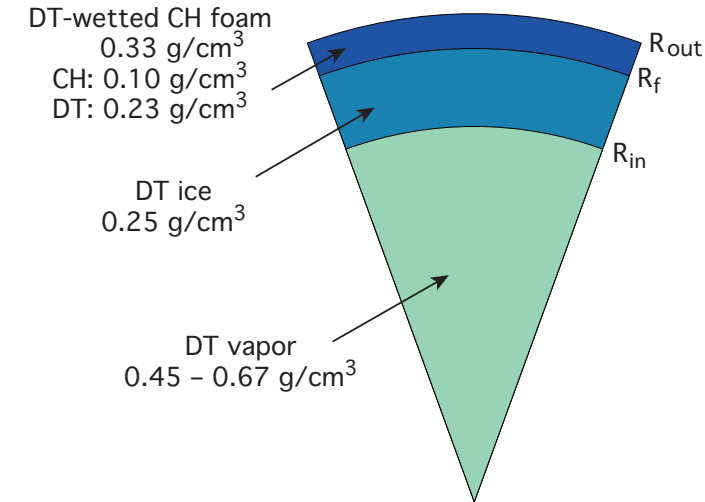
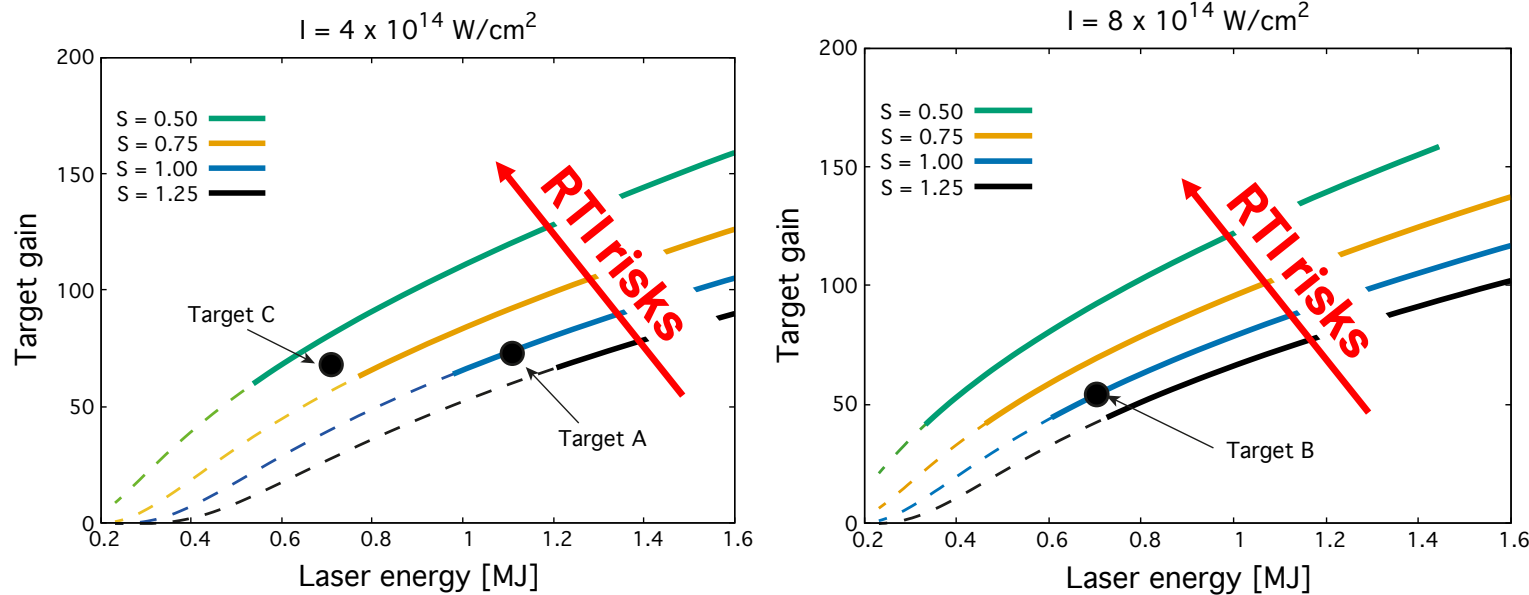
To leverage on available experimental data, **current emphasis is on centrally ignited targets**

However, advanced ignition schemes are considered, too, for their potentially higher gain

Scaled down targets will be tested on the Implosion Test Facility currently being designed

Proposed targets for an FPP, trading risks between laser plasma instabilities and hydrodynamic instabilities

LPI's risks



The Focused Energy roadmap

Steps

- Build and operate a first laser facility (in progress)
- Design (in progress), build, and operate a sub-scale implosion facility
- Design, build and operate a Fusion Pilot Plant by 2040
(preconceptual design in progress)

Most activities in cooperation with national labs, academy, etc.

Spin-offs:

- Laser driven radiation (X,n) sources for non-destructive diagnostics
- Modular advanced lasers

FE roadmap for a scalable approach to fusion energy



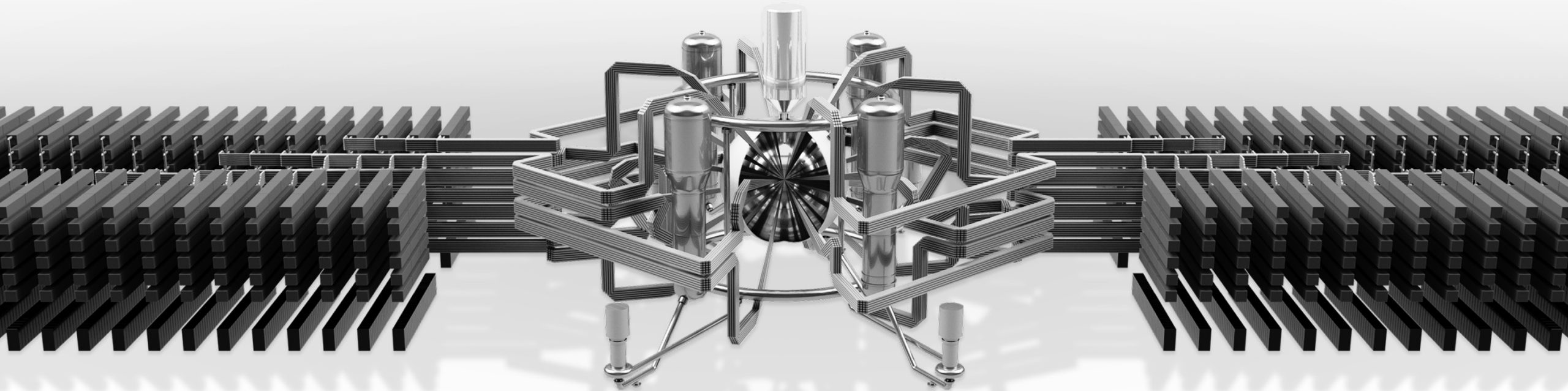
Fusion Architecture

● Modular Stacked Laser Array

● Target Chamber

● Fuel Injection System

● Beam Transport



● Pearl™ Fuel Capsule

Introducing, a first of a kind laser fusion energy system designed to power the grid:

Key Advantages

1. Laser Fusion Works

Closest architecture to the only scientifically proven system

2. Designed for Manufacturability

Components designed to be mass produced and shippable

3. Power Plant Grade Reliability

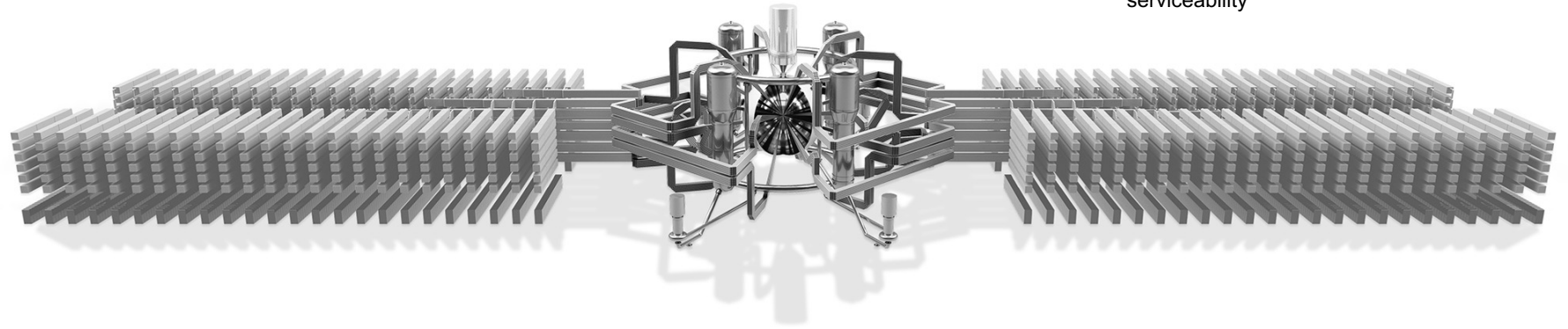
Highest reliability and serviceability of any fusion system

4. Simplified First Wall Challenge

Physical separation between plasma and first wall

5. Low Tritium Inventory

10x higher burn up fraction



Stacked laser arrays use bundled modular lasers for ease of manufacturing and hot-operation serviceability

Hardware separated from chamber limits damage from high temperatures and radiation

Target chamber - pulsed first wall creates 10x longer lifetime than magnetic approaches

2 GW

Fusion Energy Output

1 GW

Power to the Grid

1 kg

Fuel Burn per Day

\$0.05

Price kWh LCOE

Modular, manufacturable, solid-state lasers



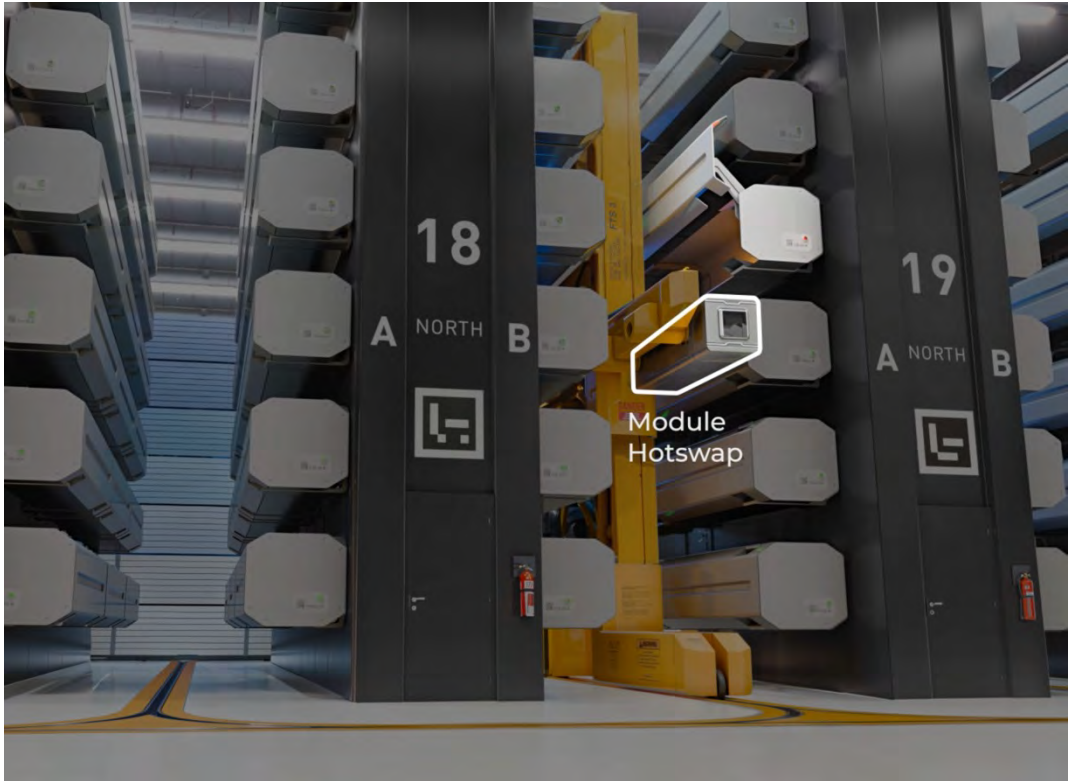
Laser technology has progressed vastly since NIF's design freeze in 1993 Solid-state lasers are 30x more efficient than the flashlamp-driven systems at NIF, and tiny in comparison



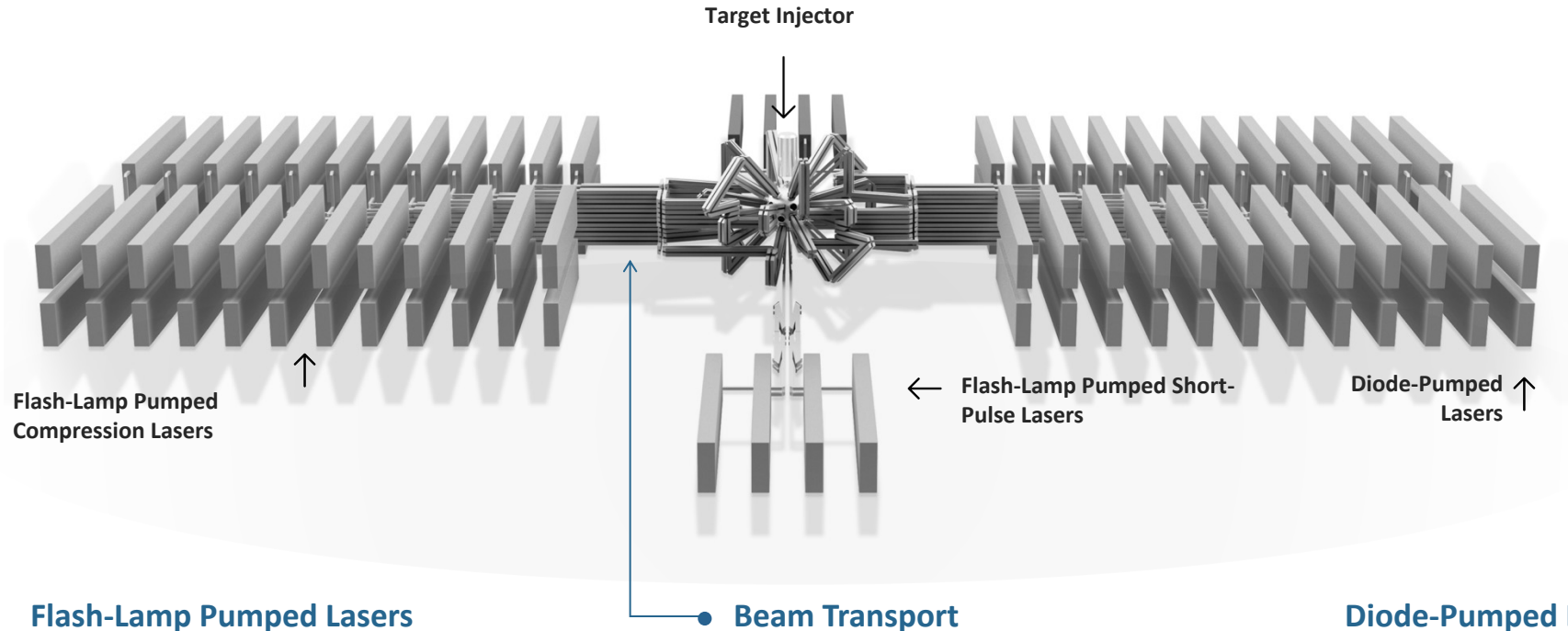
Size Comparison



FOCUSED High Average Power Fusion Laser Module



The NIF laser bay and a solid state fusion laser size comparison on display inside the bay



Flash-Lamp Pumped Lasers

- ▶ Beamline out of 4 individual lasers @ 200 J
- ▶ 3,072 laser glass slabs for 8 cm aperture
- ▶ 1,920 laser glass slabs for 10 cm
- ▶ 80 laser glass slabs for 18 cm
- ▶ 56 laser glass slabs for 30 cm
- ▶ 4,800 flashlamps
- ▶ 3,840 mirrors @ 10 cm 40 @ 30 cm
- ▶ 768 non-linear crystals
- ▶ 384 pockels cells

Beam Transport

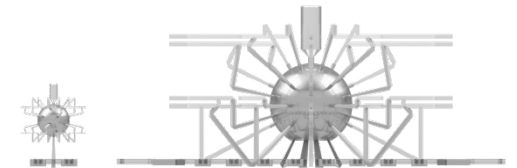
- ▶ 3,840 mirrors for 10 cm aperture
- ▶ 120 mirrors for 20 cm aperture
- ▶ 1,584 lenses for telescopes
- ▶ 396 final focusing lenses + spares
- ▶ 192 debris shields @ 20 cm + spares
- ▶ 32 diffraction gratings 40 x 80 cm
- ▶ 72 mirrors for 30 cm beam
- ▶ 8 off axis parabolas

Diode-Pumped Lasers

- ▶ 288,000 diode bars
- ▶ 240 laser glass slabs @ 30 cm
- ▶ 168 mirrors @ 30 cm
- ▶ 216 lenses
- ▶ 24 non-linear crystals
- ▶ 12 pockels cells

Overview

- ▶ 104 flash lamp pumped beamlines
- ▶ 12 diode pumped lasers
- ▶ 3m target chamber

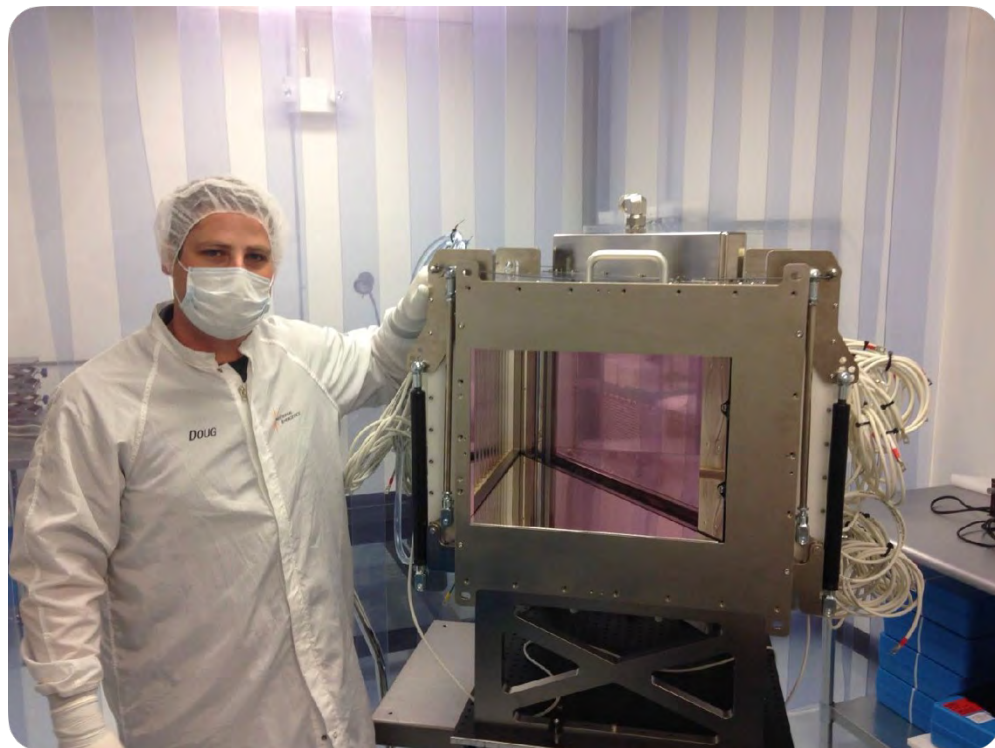


Beacon vs Lighthouse target chamber size comparison

Some of the world's most advanced high energy lasers



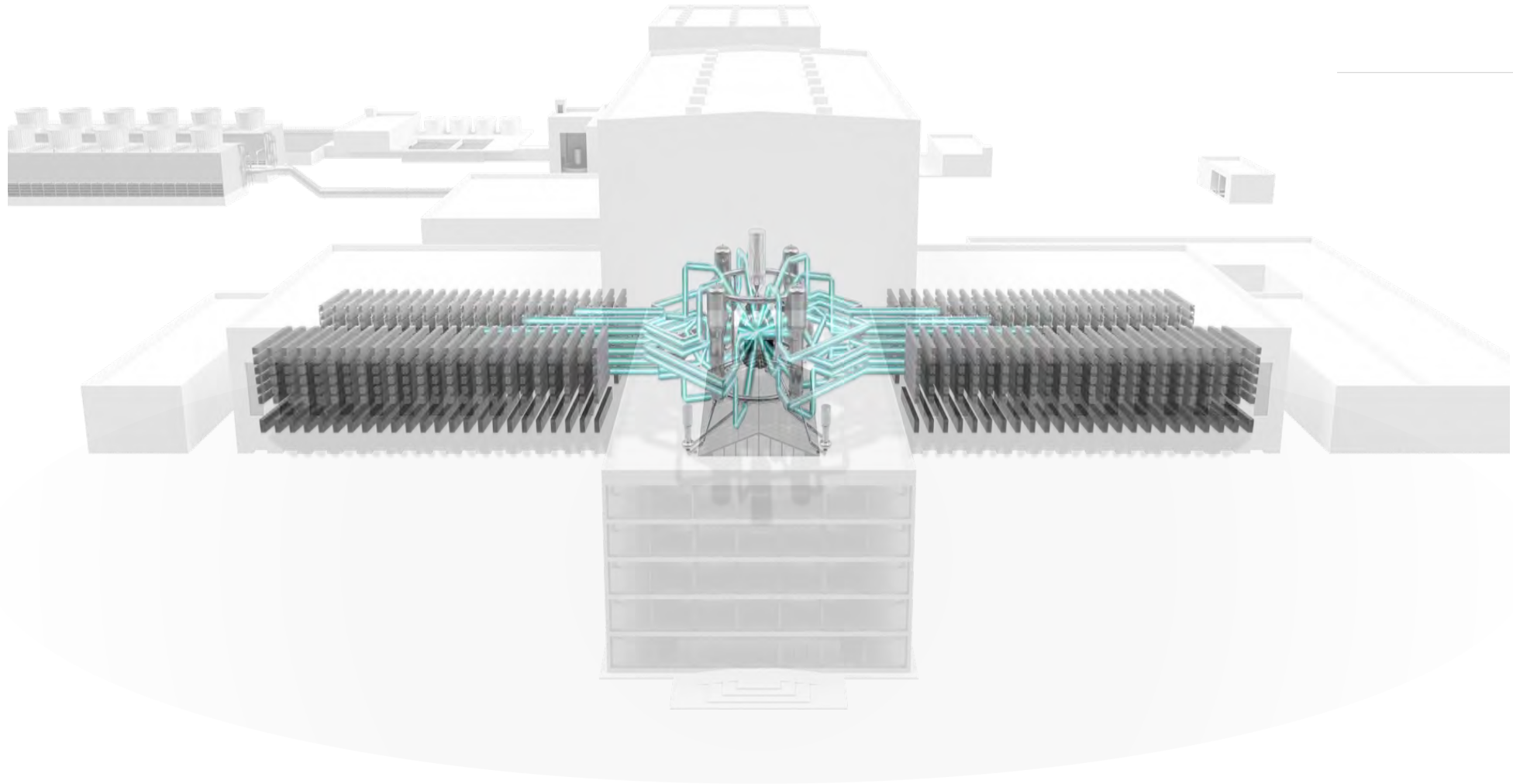
Focused Energy has developed and ordered our IP for our first two private beamlines leveraging our proprietary liquid-cooled high energy amplification technology, with commercial deployment experience and commercial demand as well.



FE liquid-cooled high energy laser amplifier



FE laser amplifier IP installed and operating at 2 KJ at ELI, Prague.
Monetization opportunities exist for FE standalone laser IP including IP licensing interest and full laser beamline LOI's



We plan to address as many of the risks as possible before finalizing the FPP (fusion pilot plant) design

Subscale Implosion Test Facility

Test target physics at subscale with moderate rep rate (shot every few mins)

- Priority for conventional centrally ignited schemes, but also advanced ignition schemes
- INFUSE proposals on LPI with LLE and LANL

Reactor chamber work

Collaborations to develop reactor design

- Blanket design work in progress
- Part of a proposal to study first wall system and materials in Germany
- Collaboration in materials for fusion
- INFUSE proposal with SRNL to design tritium system

Laser development

Develop high energy, broad bandwidth lasers

- Near term facilities use flashlamp pumped (shot every few mins)
- In parallel, develop diode pumped high efficiency lasers with high rep rate
- Partnerships with industrial partners and SPRIND in Germany

Targetry

Develop target fabrication capability for reactor and for near term facilities

- Have in-house targetry lab
- lab moved from TUD to FE building
- Target injection and tracking in near future



FOCUSED



LightHouseTM — Laser Fusion System

Commercializing the world's first proven fusion energy architecture

Deploying and commercializing the essential components of the future fusion ecosystem

With commercial traction today, our business is actively deploying essential pieces of the fusion ecosystem, de-risking our path to commercial power.

Current core technology set



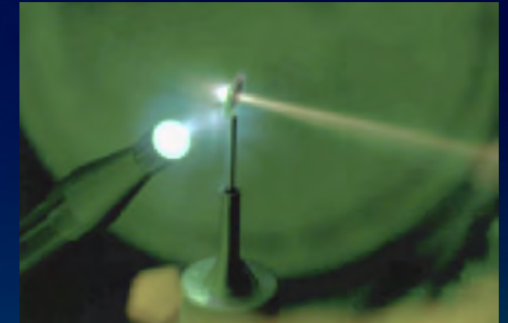
High power lasers

Proprietary IP for high-power, liquid-cooled lasers. First unit installed and in use at the ELI research facility in Prague.



Fusion targetry

One of the most advanced targetry facilities in the world. Target fabrication technologies scalable to mass production and automation



Laser-driven accelerators

High energy imaging and analysis with neutrons and hard x-rays; existing customer (RWE)

A first spin-off

We're helping decommission a fission plant with our laser-driven imaging technology - **today.**

➤ PLANET Facility at Biblis RWE reactor

High energy imaging;
existing customer (RWE);
also funds from German BMFT

We have developed a miniature laser-driven radiation source to enable on-site characterization

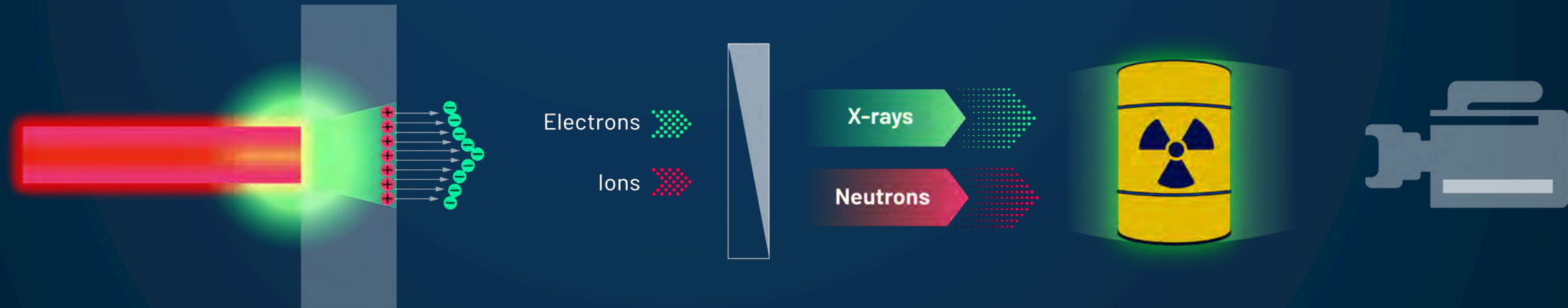
1. LASER

2. TARGET

3. CONVERTER

4. OBJECT

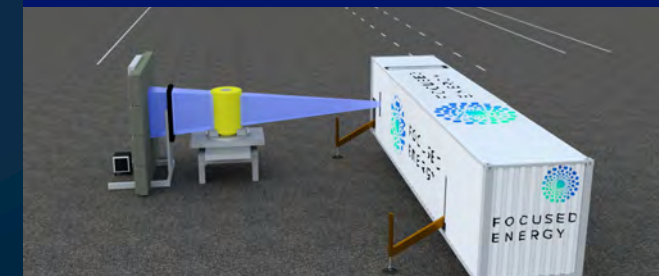
5. DETECTOR



Containers cannot be brought to the existing facilities...



The compact design enables **direct inspection** at the interim storage.



Conclusions

- Two key ingredients of ICF demonstrated: laser-driven compression, hot spot ignition
- Key physics issues for high gain IFE schemes identified and addressed worldwide, a few open issues remain
- Design and interpretation based on synergy between theory, simulation, experiments; crucial role of high-resolution diagnostics
- Transition from basic ICF research to IFE-oriented R&D
- Simultaneously consideration of IFE physics, laser technology, targetry, reactor technology
- Focused energy addresses all the above aspects. FE has developed a roadmap for a scalable approach to IFE



The Future is Fusion.