FOCUSED ENERGY

The roadmap of Focused Energy to inertial fusion energy

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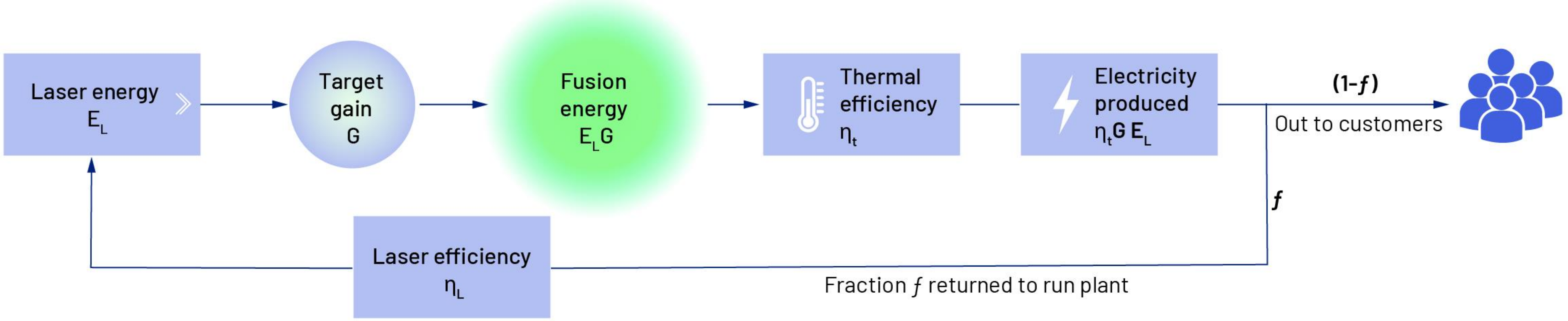
LMJ-PETAL User Meeting
June 8-9, 2023

Focused Energy was founded in July 2021

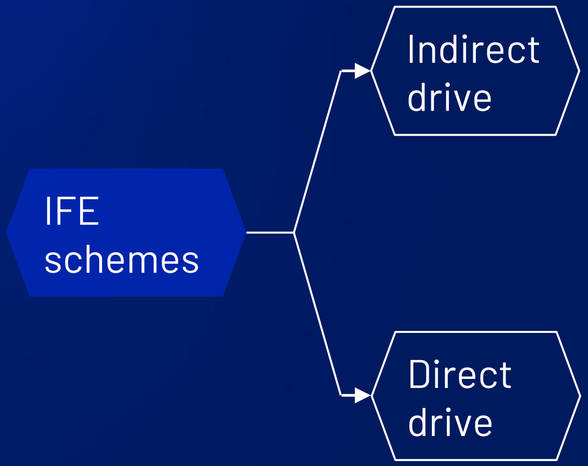
- We are a U.S. Inc. company and a German GmbH with offices in Austin, Texas and Darmstadt, Germany
- We will develop and build a Fusion Pilot Plant by the end of the 2030s, based on an **advanced inertial confinement fusion (ICF) concept, proton fast ignition (PFI)**

For IFE, we need to get target gain of ~ 100 at about 10 Hz to run a power plant



- Energy to run the laser is E_L/η_L-
- Energy produced is $E_\text{L}.G.\eta_t$
- If we keep recirculating power frac. to less than 25%, then $\eta_L \eta_t G > 4$
- If $\eta_t \approx 0.4$, then, $\eta_L.G > 10$
- If $\eta_L \approx 0.1$, then, $\boldsymbol{G > 100}$
- For ~ 750 MW out to the grid, then repetition rate needs to be about **10 Hz** for 2.5 MJ laser

FE has taken a thorough down-select on the fusion scheme



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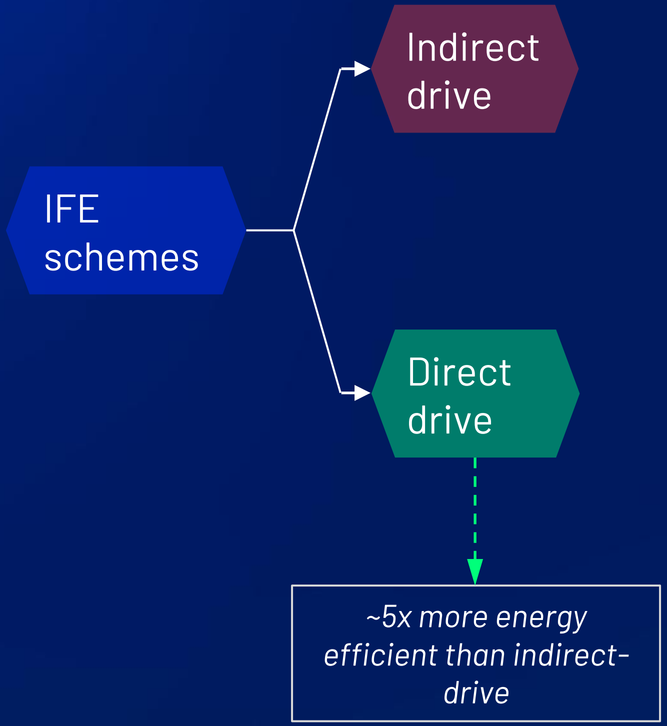

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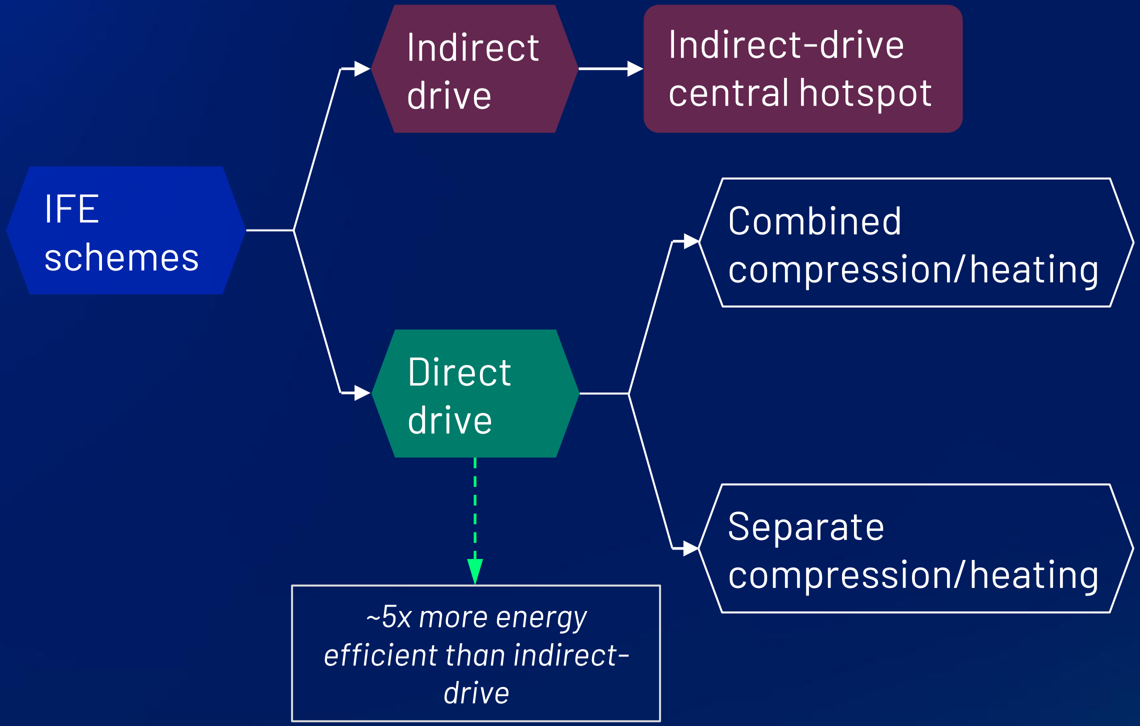

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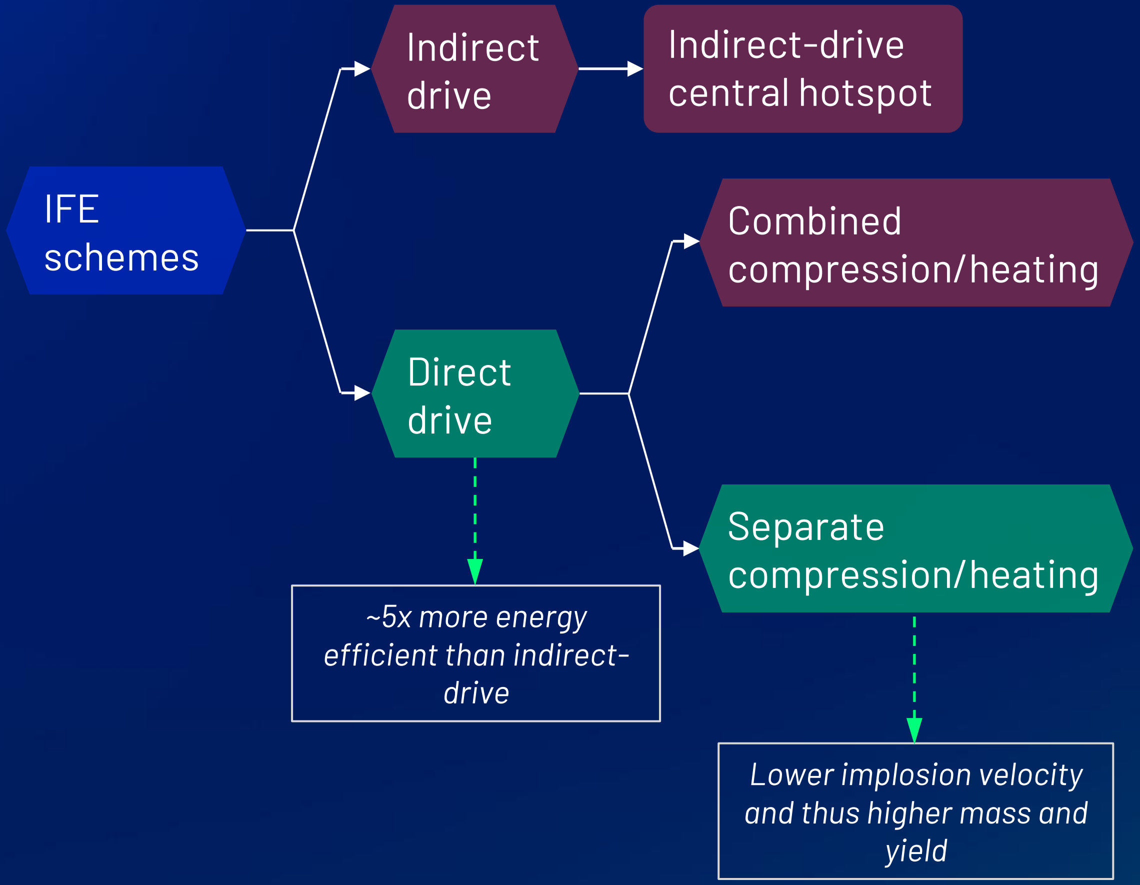

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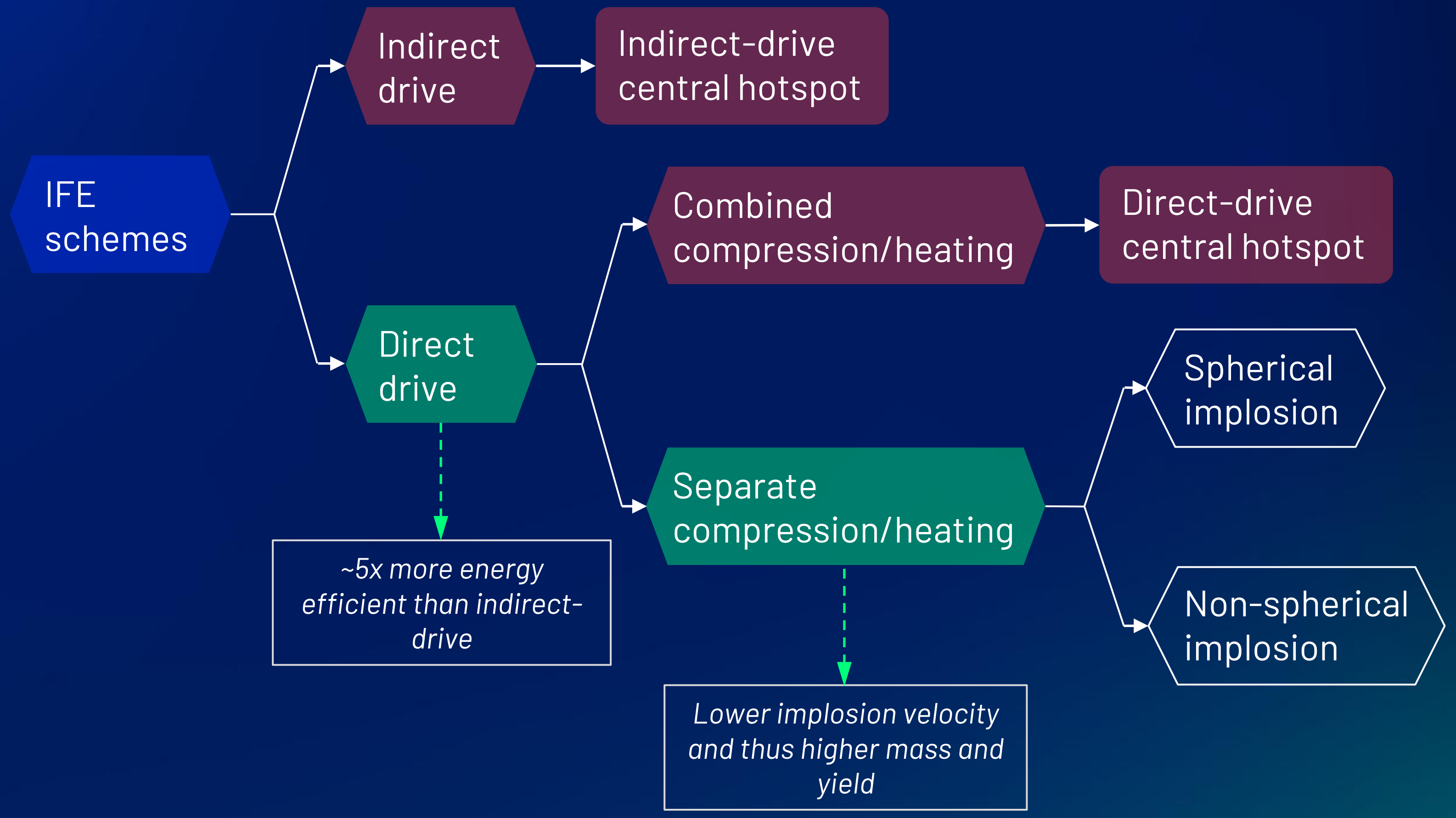

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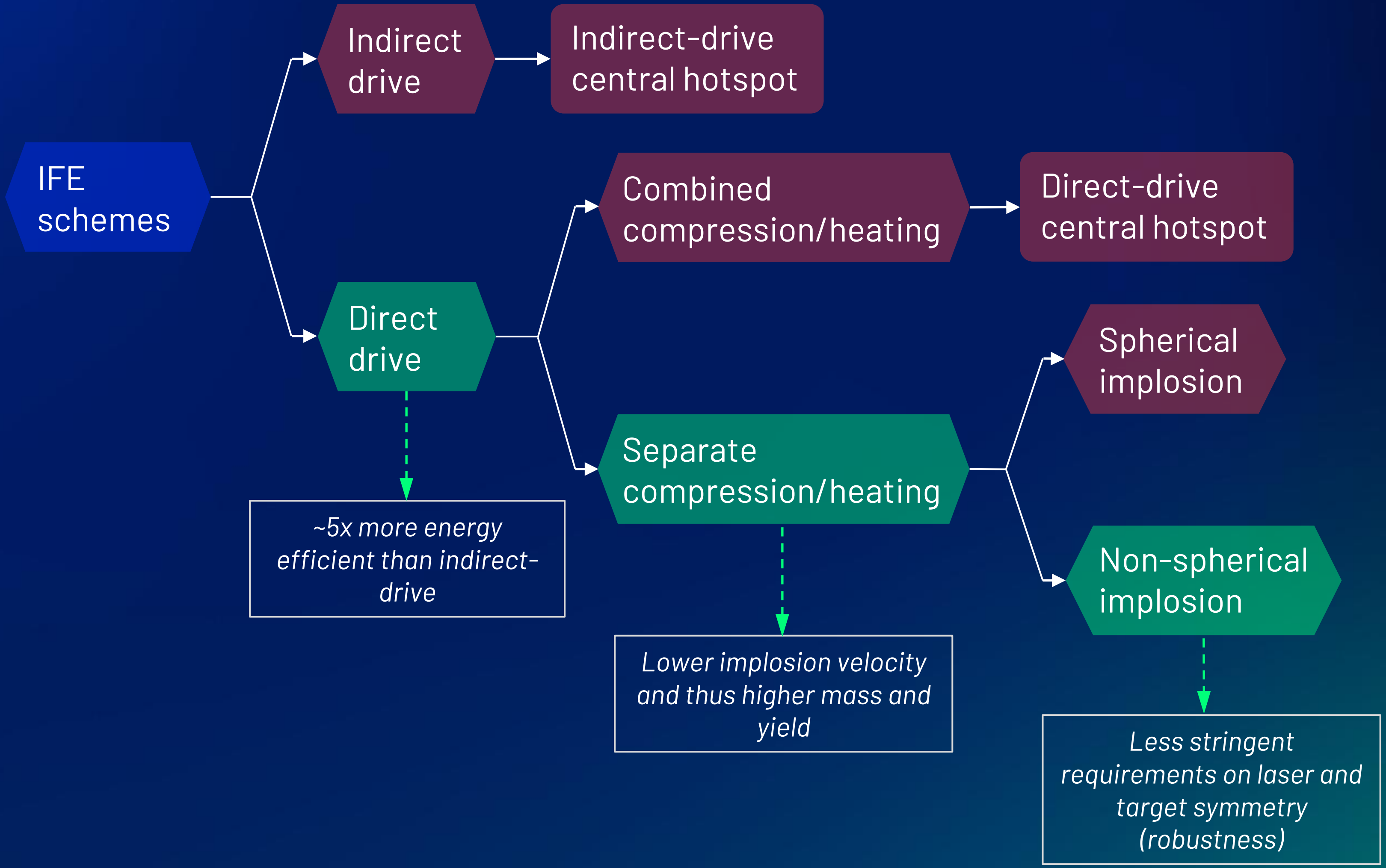

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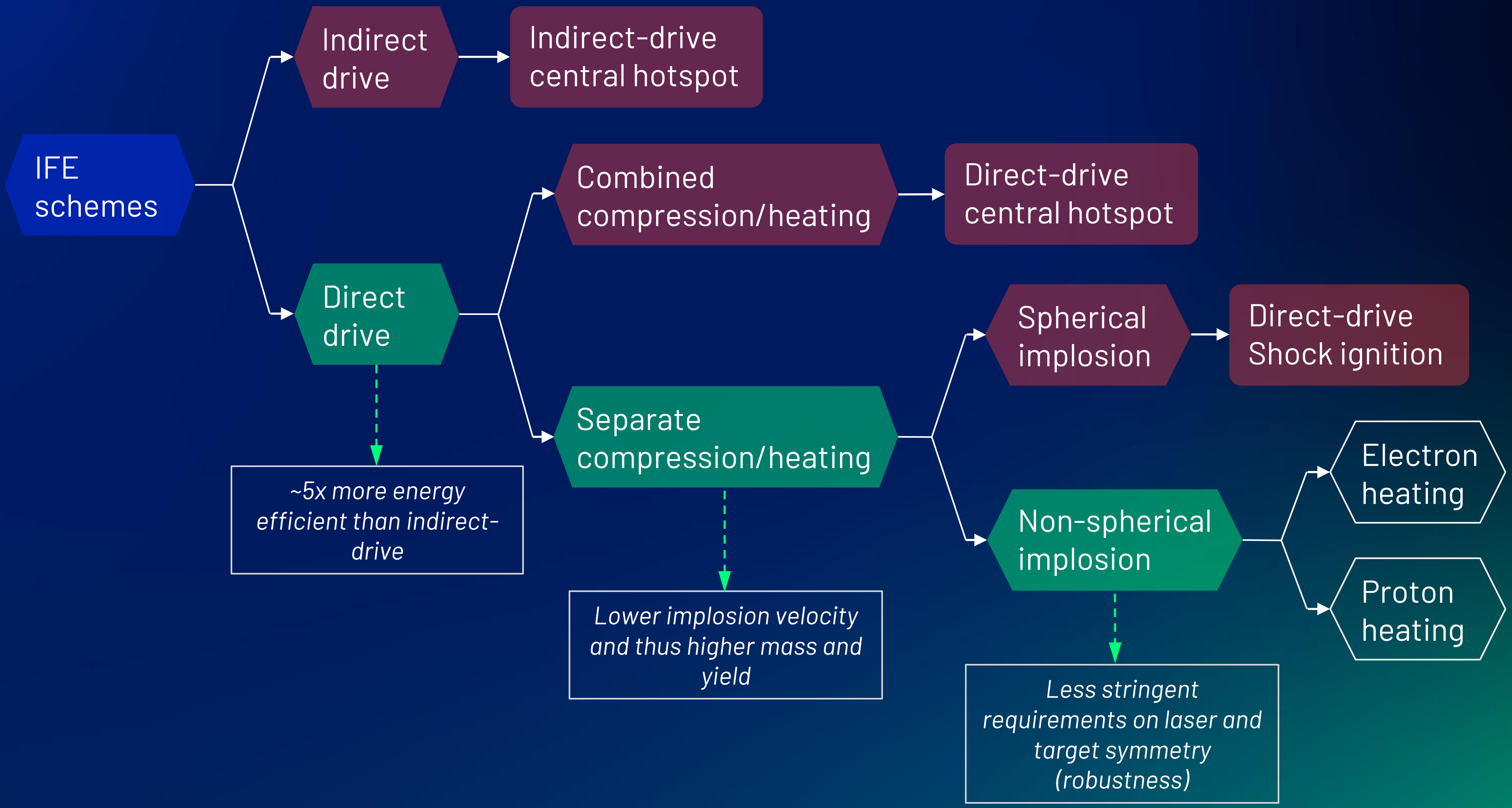

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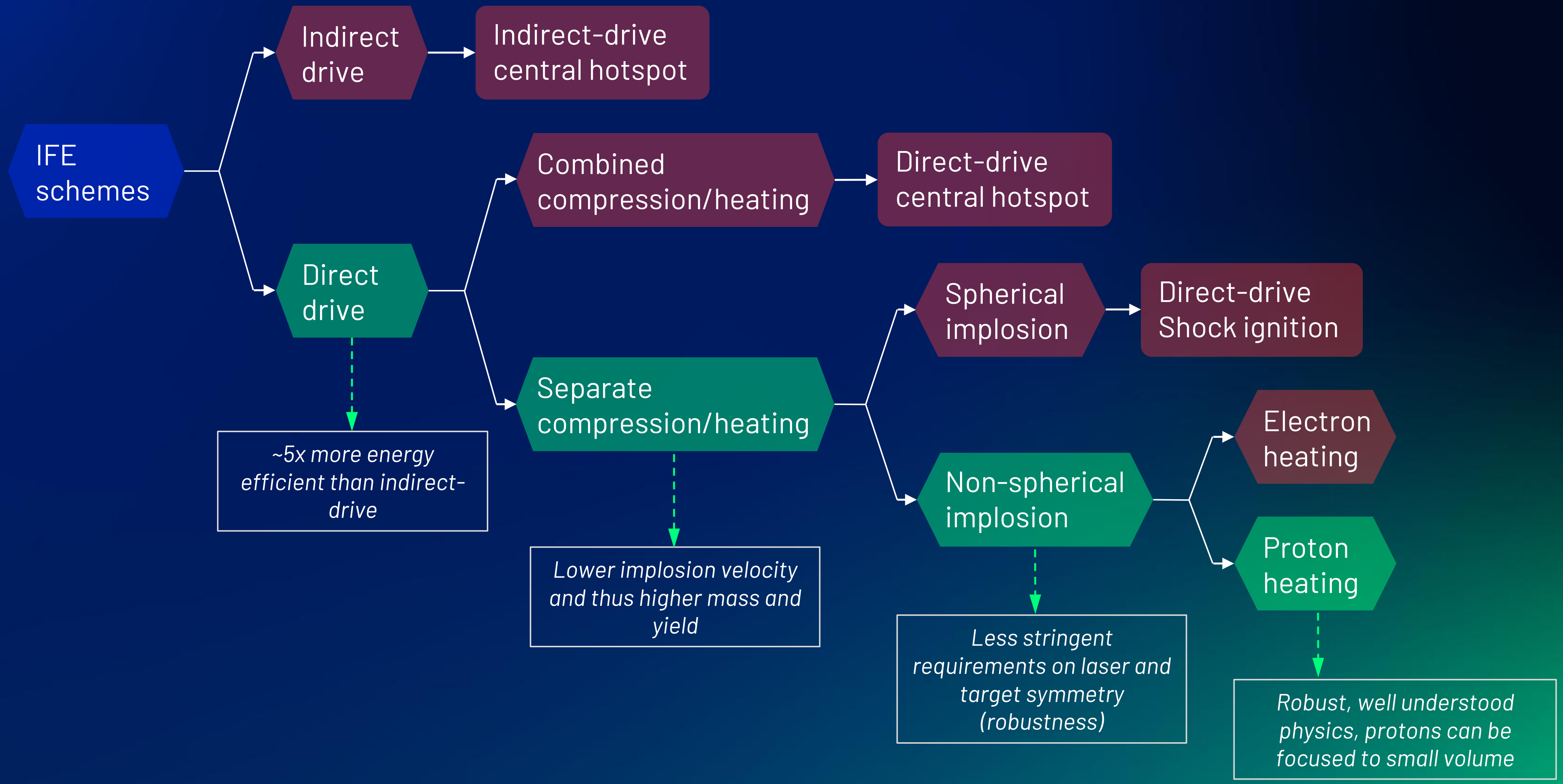

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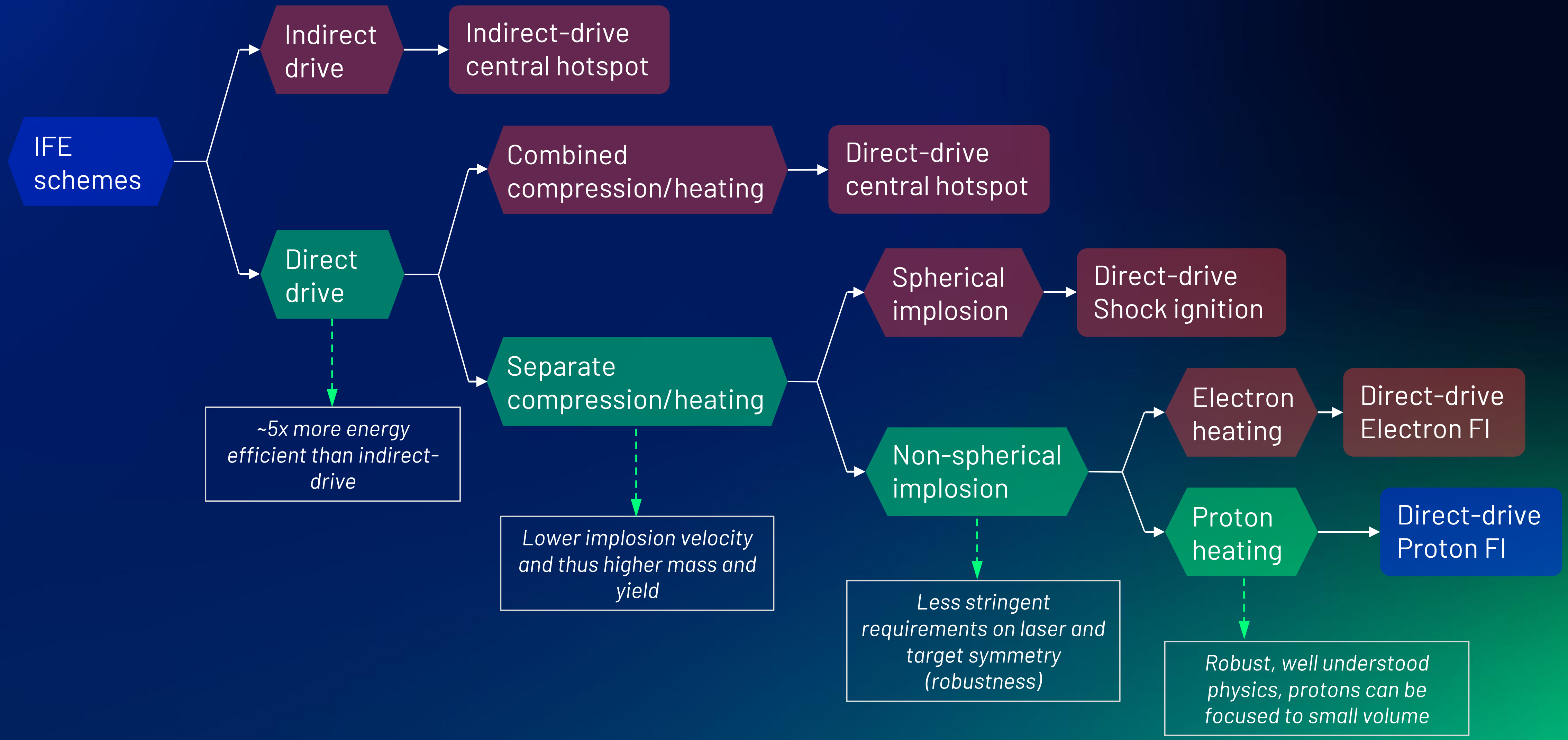
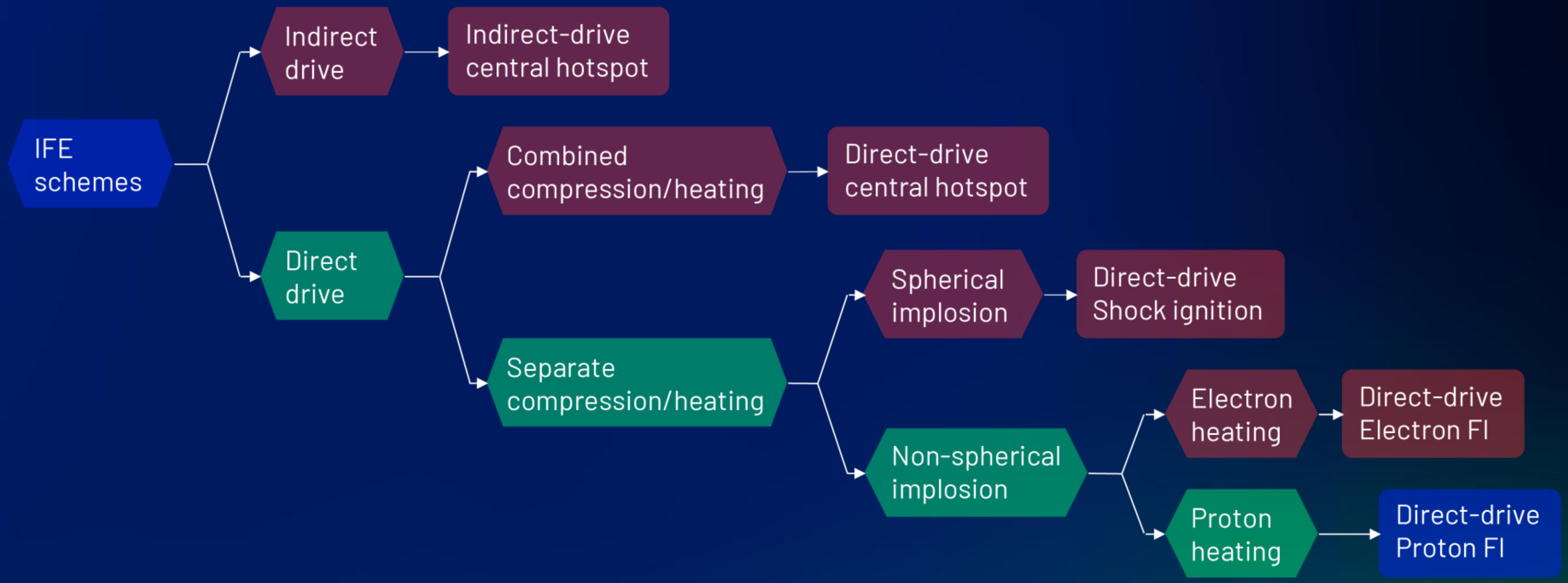


Fast ignition has the potential to reach >100 energy gains



Use direct drive to improve coupling

Use lower (x0.5) implosion velocity to drive more fuel mass (x4) at constant E_{kin}

Increase burn efficiency by increasing fuel areal density

NIF recent result: G = 1.5 → x5 → x4 → x5 → **Potential gain: G = 150**

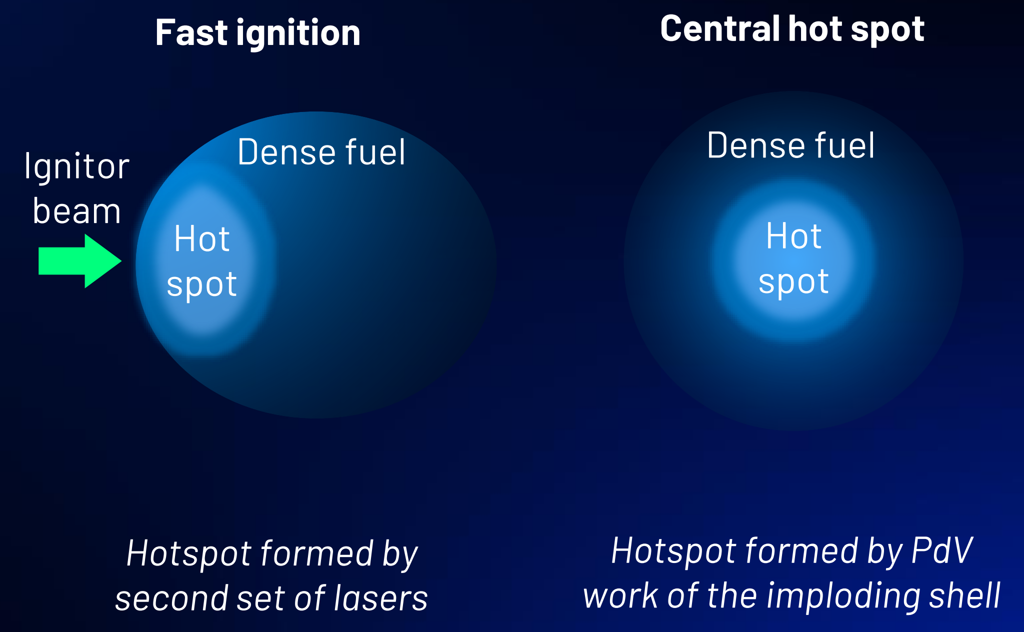
Fast ignition is potentially far more robust to both symmetry and hydro-instability

Symmetry

- Inherently an *asymmetric* implosion scheme
- External source for generating hotspot
- Reduces the requirements on laser drive uniformity, target sphericity, laser and target pointing tolerances, etc.

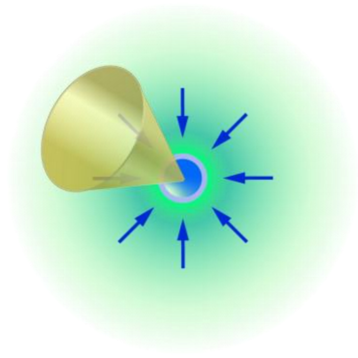
Hydro-instability

- Uses a thick shell driven at low velocity at lower convergence ratio
- Inherently far more stable to growth of hydrodynamic instabilities

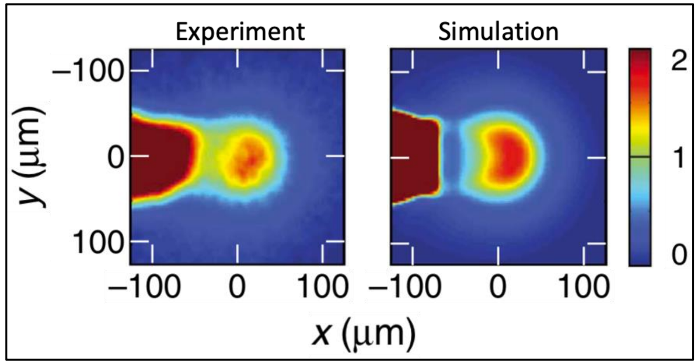


These features of **high target gain** and **robustness** make FI an attractive concept for commercial IFE

Steps needed for proton fast ignition have been demonstrated individually but not at scale or together

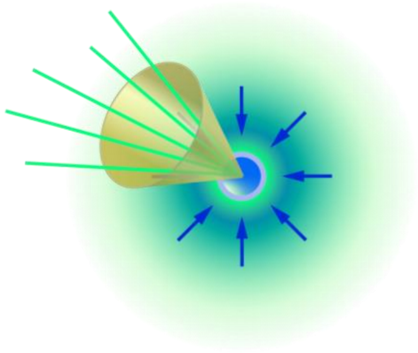


Direct drive compression of a cone in shell target

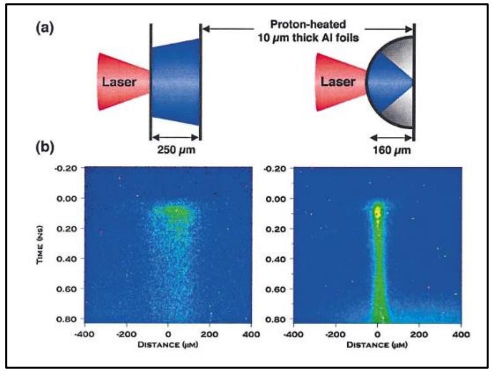


Generation of dense core has been demonstrated by imploding cone-in-shell target

W. Theobald *et al.*, Nature Comm, 5:5785 (2014)



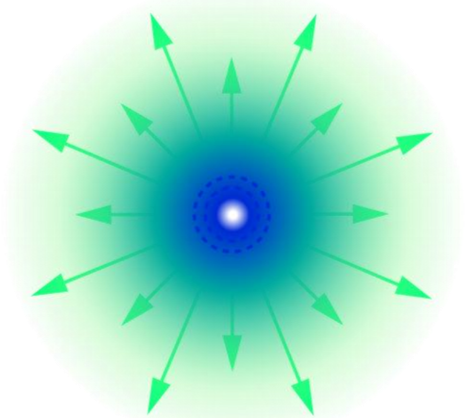
Proton generation and focusing



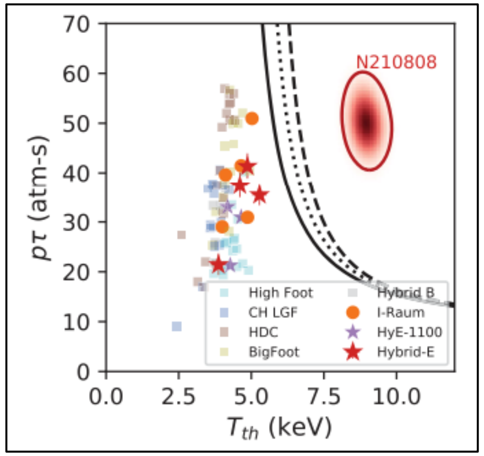
Demonstration of:

- Up to 15% conversion efficiency into protons
- Ø40 µm focused proton beam

P. Patel *et al.*, PRL **91**, 125004 (2003)
C. Brenner *et al.*, Appl. Phys. Lett **104**, 081123 (2014)
T. Bartal et al., Nature Physics **8**, 139 (2012)



Ignition by Lawson's criteria



Abu-Shawareb *et al.*, PRL **129**, 075001 (2022)
Kritcher *et al.*, PRE **106**, 025201 (2022)
Zylstra *et al.*, PRE **106**, 025202 (2022)

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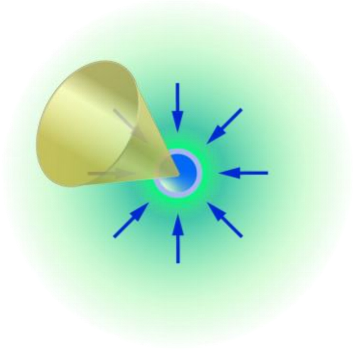
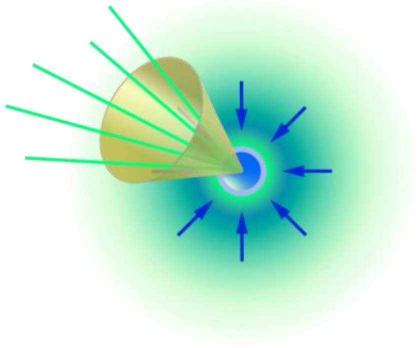


Direct drive compression of a cone in shell target

Use 2ω light to reduce cost and complexity

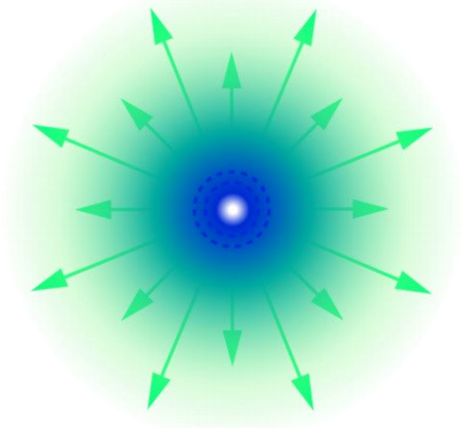
- Effect on LPI and coupling?
- LPI mitigation techniques?



Proton generation and focusing

Most experiments have been done at very small scale

- Scaling of proton CE with laser energy?
- Optimal design to get the highest proton CE?
- How does the compression impact cone/proton foil/beam transport?



Ignition by Lawson's criteria

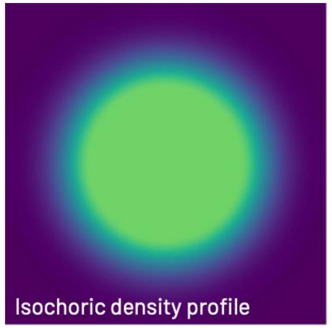
Use a wetted foam to reduce layering time and complexity

- How do the foam and the cone impact ignition?

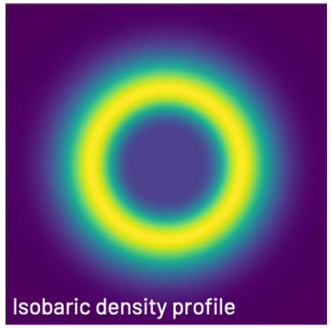
Fast ignition favors isochoric compression designs with thick shells at low velocity

- **Develop capsule design that maximizes areal density (ρr) and density without a hotspot**
  - Using and developing MULTI rad-hydro code in-house [1]
- **Design uses a wetted foam DT layer to reduce layering time and tritium inventory**
  - INFUSE partnership with LLNL on foam modeling (Kemp, Divol)
  - Collaborating with U of Michigan on foam EOS experiments (proposal to LaserNet -- Kuranz)
- **Validate our compression designs through experiments**
  - First as spherical implosion
  - Then adding the re-entrant cone ("cone in shell")
  - Primary measurement is areal density

Fast ignition assembly (1D)



Central hotspot Ignition assembly (1D)



Rendering of a cone in shell target

[1] R. Ramis *et al.*, Comp. Phys. Comm. **49**, 475-505 (1988)

LPI at 2nd harmonic ("2ω") is a concern and we are exploring several mitigation techniques

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Laser Plasma Interactions (LPI) mitigation techniques

- Laser bandwidth (design laser with up to 1% bandwidth)
- Control of laser beam spot size/profile relative to target size [1]
- Reduced laser intensity designs
- Beam smoothing (2-D SSD, polarization smoothing, phase plates)
- Target solutions (e.g., Si doping of capsule)
- Explore "spiked trains of uneven duration" (STUD) pulses [2]

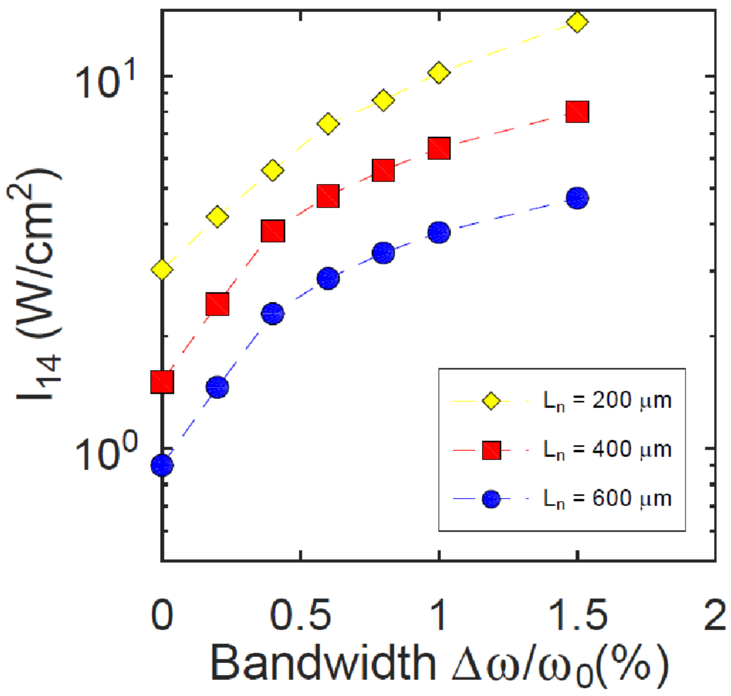
Partnering with community

- INFUSE proposal for LPI PIC simulations with LANL (Albright/Yin)

LPI mitigation experiments at 2ω – start on ELI L4, then FE's T-STAR

- Most of the experimental database is at 3ω (NIF, Omega, Nova, LMJ)
- High repetition rate facilities allow large number of shots in a short period of time (800 shots in a couple of weeks in commissioning)

Stimulated Raman Scatter Threshold

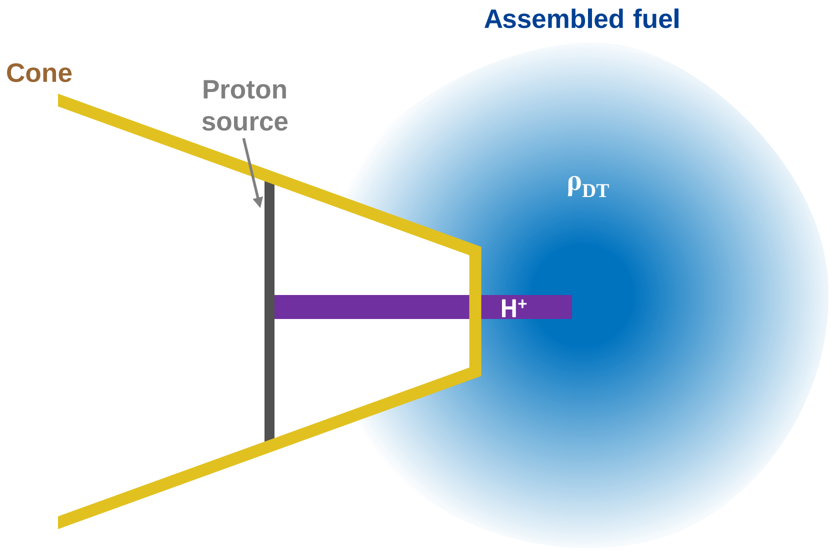


*R. K. Follett et al., Phys. Plasmas 28, 032103 (2021)

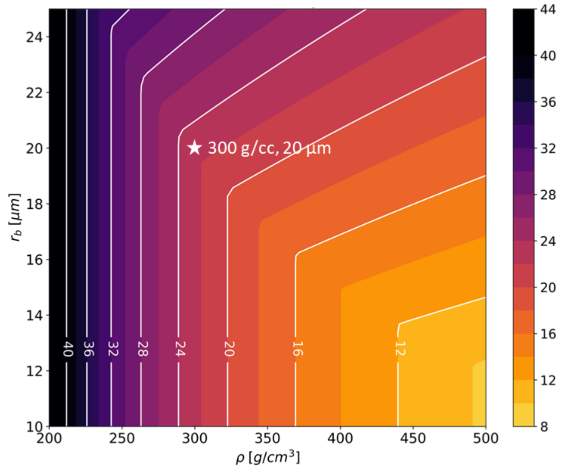
[1] US provisional patent application 63/427,351
[2] B. Afeyan and S. Hüller, EPJ Web of Conferences 59, 05009 (2013).

Point design studies provide the characteristics of the proton beam needed to reach ignition

- Point design studies show that ignition can be met by a **~20 kJ** proton beam of radius **15-20 μm**, with a mean particle energy of **4-9 MeV**, generated no more than **1 mm** from the fuel [1, 2]



Ignition energy VS proton beam radius and fuel density [1]



[1] S. Atzeni *et al.*, Nucl. Fusion **42**, L1 (2002)
[2] J.J. Honrubia *et al.*, Phys. Plasmas **22**, 012703 (2015)

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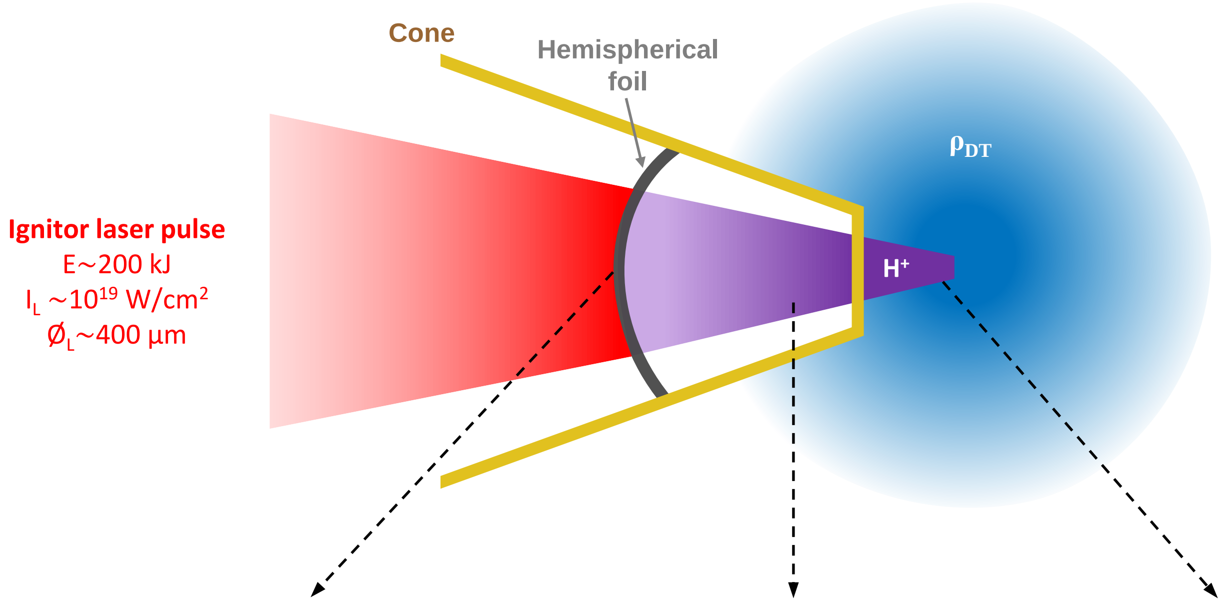
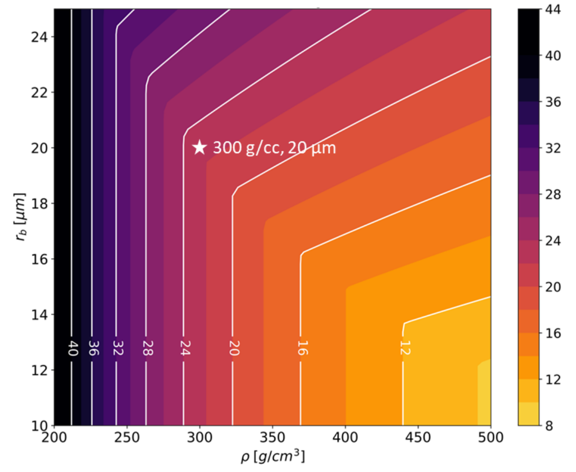




Proton generation (E_b, T_b)

- Multi-beam irradiation pattern
- Temporal laser pulse shaping
- Hemi foil design

Proton focusing (r_b)

- Hemi foil geometry
- Cone structure geometry
- Self-generated B-fields
- Cone tip design

Transport and energy deposition

- Beam divergence
- Stopping power models
- Ignition window and proton beam duration

[1] S. Atzeni *et al.*, Nucl. Fusion **42**, L1 (2002)
[2] J.J. Honrubia *et al.*, Phys. Plasmas **22**, 012703 (2015)

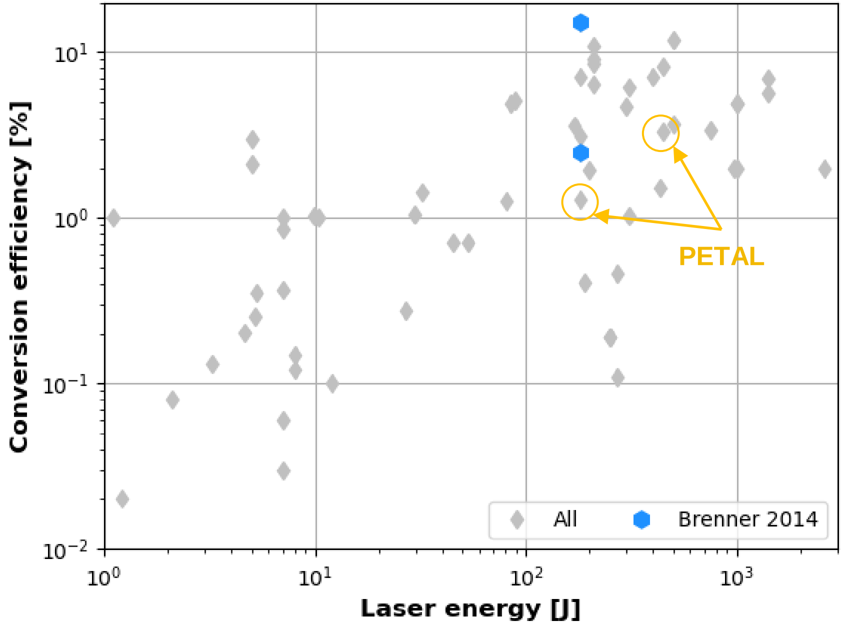
Our goal is laser to proton conversion efficiency of 10-15% at full scale

FOCUSED ENERGY

→ **Data survey shows increasing efficiency with increasing laser energy**

- Highest observed conversion to date is ~15% [1]

Survey of data from many facilities [2]



[1] C.M. Brenner *et al*., Appl. Phys. Lett. **104** (2014)
[2] M. Zimmer *et al*., Phys. Rev. E **104** (2021)

Our goal is laser to proton conversion efficiency of 10-15% at full scale

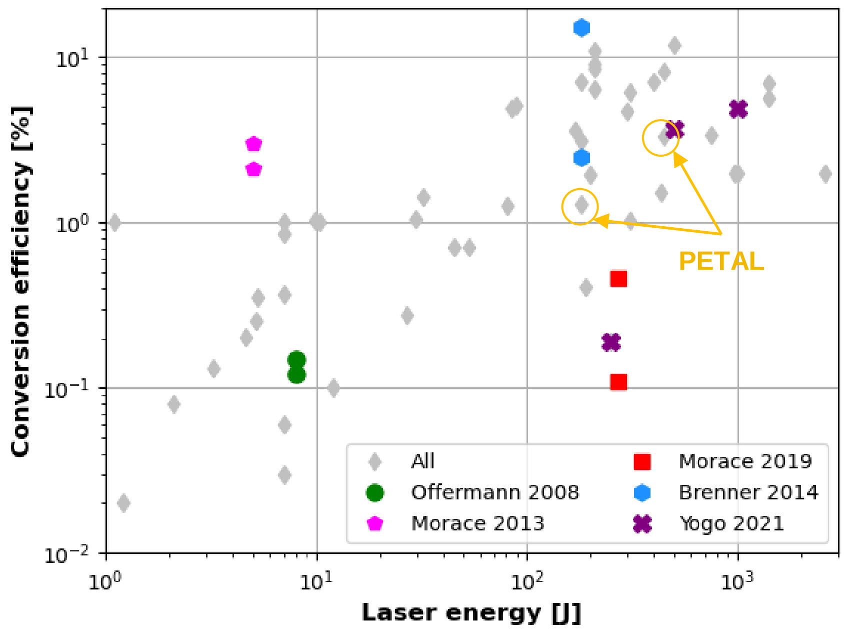
FOCUSED ENERGY

- **Data survey shows increasing efficiency with increasing laser energy**
  - Highest observed conversion to date is ~15% [1]

- **We will investigate and implement multiple approaches to optimize conversion efficiency**
  - Heavy-hydride target coating (ErH_3) [3]
  - Additional target solutions (mass-reduced targets [4])
  - Control of laser energy deposition (multi-ps irradiation [5], large focal spot [6], beam interference [7], temporal contrast, pulse shaping [1,8])

- **Experimental strategy:**
  - Start on external facilities (mostly sub-kJ laser energy)
  - Move to FE's T-STAR (multiple beams, kJ short pulse laser energy)

Survey of data from many facilities [2]



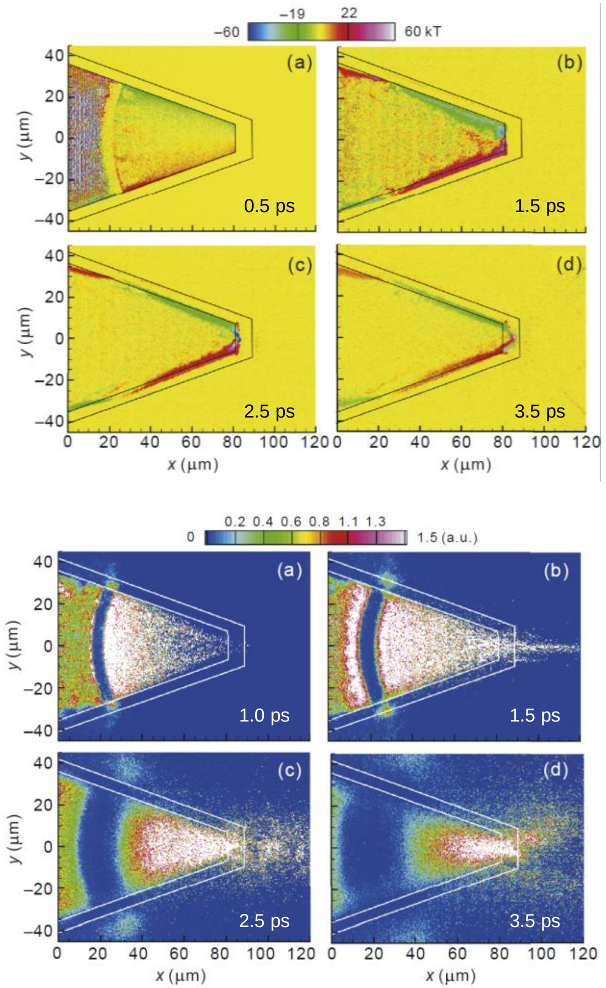
[1] C.M. Brenner et al., Appl. Phys. Lett. **104** (2014)
[2] M. Zimmer *et al.*, Phys. Rev. E **104** (2021)
[3] M. Foord *et al.*, J. Appl. Phys. **103**, 056106 (2008)
[4] A. Morace *et al.*, Appl. Phys. Lett. **103**, 054102 (2013)
[5] A. Yogo *et al.*, Sci. Rep. **7**, 42451 (2017)
[6] N. Iwata *et al.*, Phys. Rev. Research **3**, 023193 (2021)
[7] A. Morace *et al.*, Nat. Commun. **10**, 2995 (2019)
[8] J. Kim *et al.*, Phys. Plasmas **25**, 083109 (2018)

Focusing the proton beam to a small spot is key to minimizing the required proton ignition energy

FOCUSED ENERGY

- A hemispherical foil has been shown to focus the proton beam [1]
- The cone structure also plays a key role in proton focusing:
  - Generation of strong B-fields allows funneling protons to the cone tip [2]…
  - … but B-field structure at the cone tip might enhance proton defocusing [3, 4]
  - Different strategies to mitigate the proton beam divergence are being evaluated (limitation of laser intensity, cone tip design, …)
  - The cone structure may also impact the conversion efficiency
- Experimental strategy:
  - Start on smaller-scale facilities to optimize beam focusing and benchmark PIC simulations
  - Move to FE’s T-STAR to optimize cone geometry at multi-kJ scale with cone-in-shell design
  - Collaboration with UCSD on integrated cone-in-shell proton fast ignition experiment on OMEGA (NLUF proposal, F. Beg)
  - Strong interest of PETAL for proton focusing experiments

B_z field and corresponding proton energy density in a cone target [3]



[1] P. Patel *et al.*, Phys. Rev. Lett. **12** (2003)
[2] T. Bartal *et al.*, Nat. Phys. **8**, 139 (2012)
[3] J.J. Honrubia *et al.*, Matter Radiat. Extremes **2**, 28 (2017)
[4] A. Morace *et al.*, Sci. Rep. **12**, 6876 (2022)

What simulation codes are we using?

- As a company, we currently do not have access to NNSA ICF codes
- Our main tools currently:
  - **MULTI (1-d rad-hydro code)**
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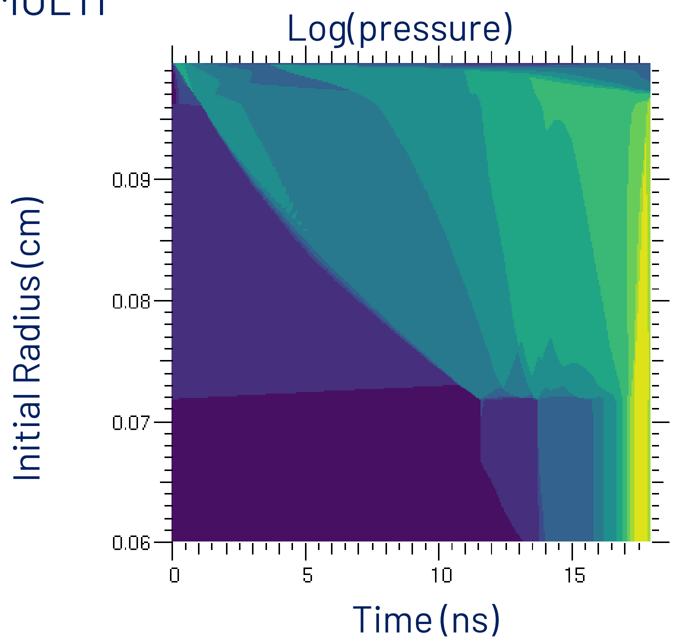
  - **DUED (2-d rad-hydro code)**
    S. Atzeni, Computer Phys. Commun. 43 107 (1986)
    S. Atzeni et al, Computer Phys. Commun. 169 153 (2005)
  - **FLASH (2-d/3-d radiation MHD code)** (Just starting to use)
    flash.rochester.edu

MULTI



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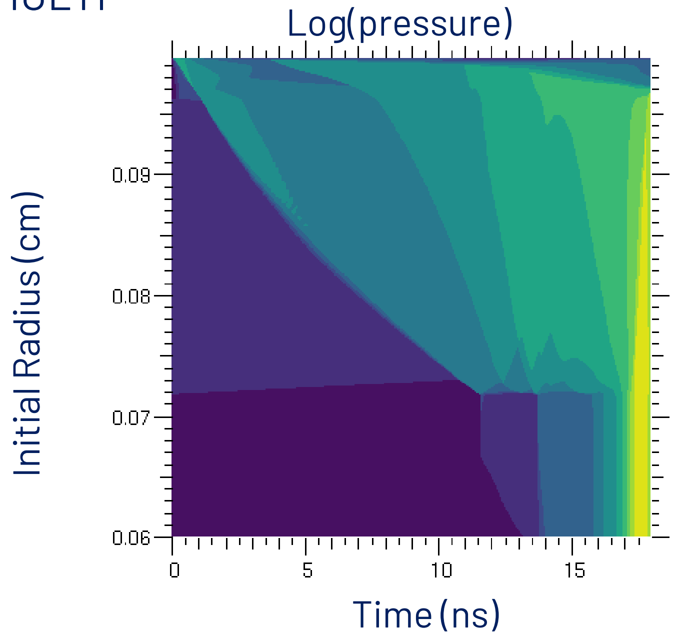
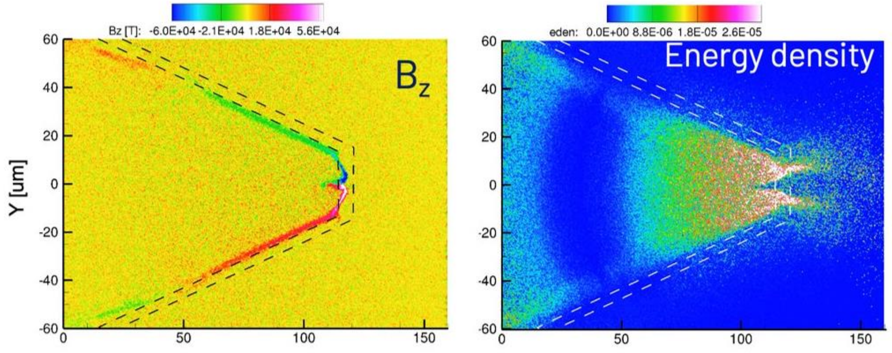
    flash.rochester.edu
  - **EPOCH (2-d PIC code)**
    T. D. Arber, K Bennett, CS Brady, et al Plasma Phys and Controlled Fusion, 57, 1-26 (2015)
  - **PETRA (2-d/3-d hybrid PIC code)**
    J.J. Honrubia and J. Meyer-ter-Vehn, Nucl. Fusion 46, L25 (2006)
- We have indirect access to other codes via collaborations

MULTI



EPOCH (simulation by J.J. Honrubia)

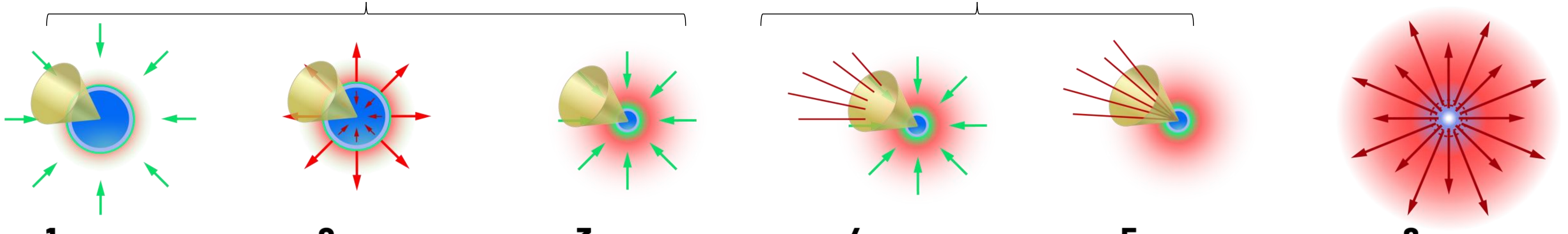


Towards an integrated PFI modeling framework (P. Gibbon)

Compression

Heating

Ignition



1 Absorption and heat transport

2 Acceleration and rocket effect

3 Deceleration and compression

4 Laser-ion beam generation

5 Ion beam heating of dense fuel

6 Ignition and fusion burn

2D/3D wave-fluid & PIC

1D/2D/3D radiation-hydrodynamics

2D/3D particle-in-cell (PIC)

2D/3D particle transport

2D/3D hybrid MC-hydro

Roadmap includes target physics and technology needed for a fusion pilot plant

- Target design with a gain, G>100, demonstrating robust, repeatable performance

→ Scientific validation

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- Target design with a gain, G>100, demonstrating robust, repeatable performance

→ Scientific validation

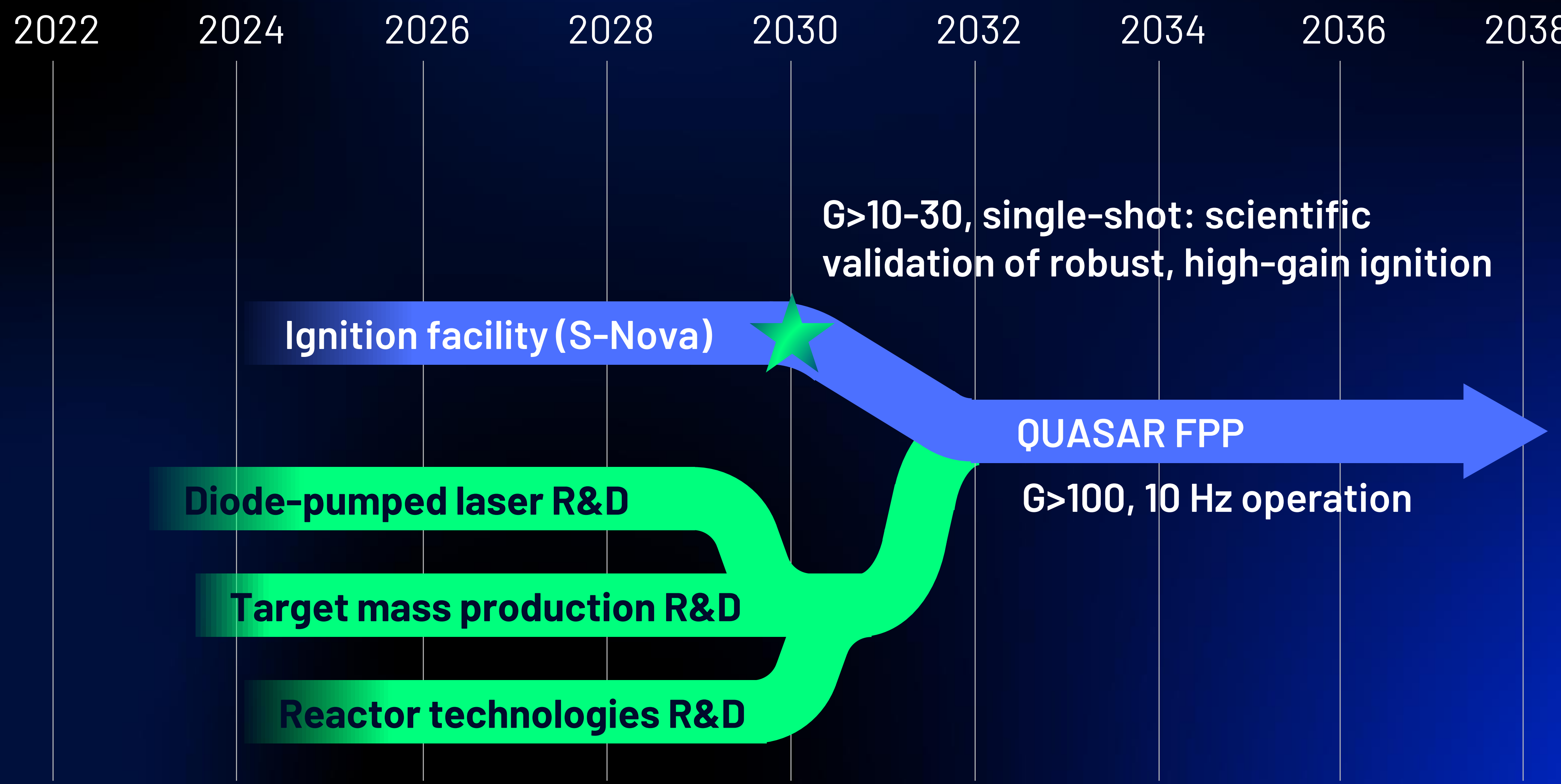
- Diode-pumped laser system operating at 10 Hz with high efficiency, and low production and maintenance costs
- Target mass manufacturing and automated assembly and delivery at low cost
- Target injection system operating at 10 Hz in a reactor environment
- Reactor chamber, first wall design compatible with pulsed neutron, ion, and x-ray source spectrum
- Tritium fuel cycle and minimization of on-site inventory

→ IFE technology development:

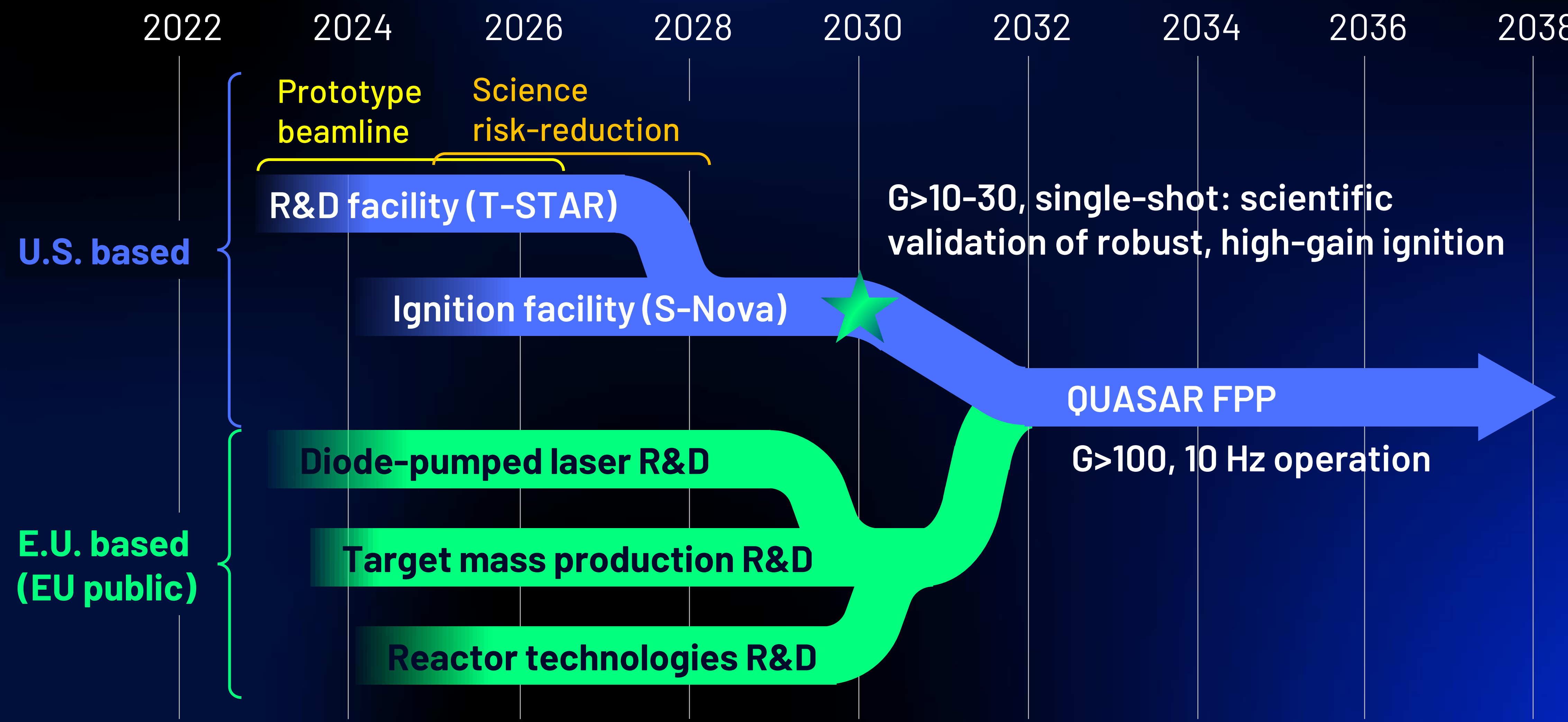
- Laser R&D
- Targetry R&D
- Reactor R&D

Our high-level roadmap

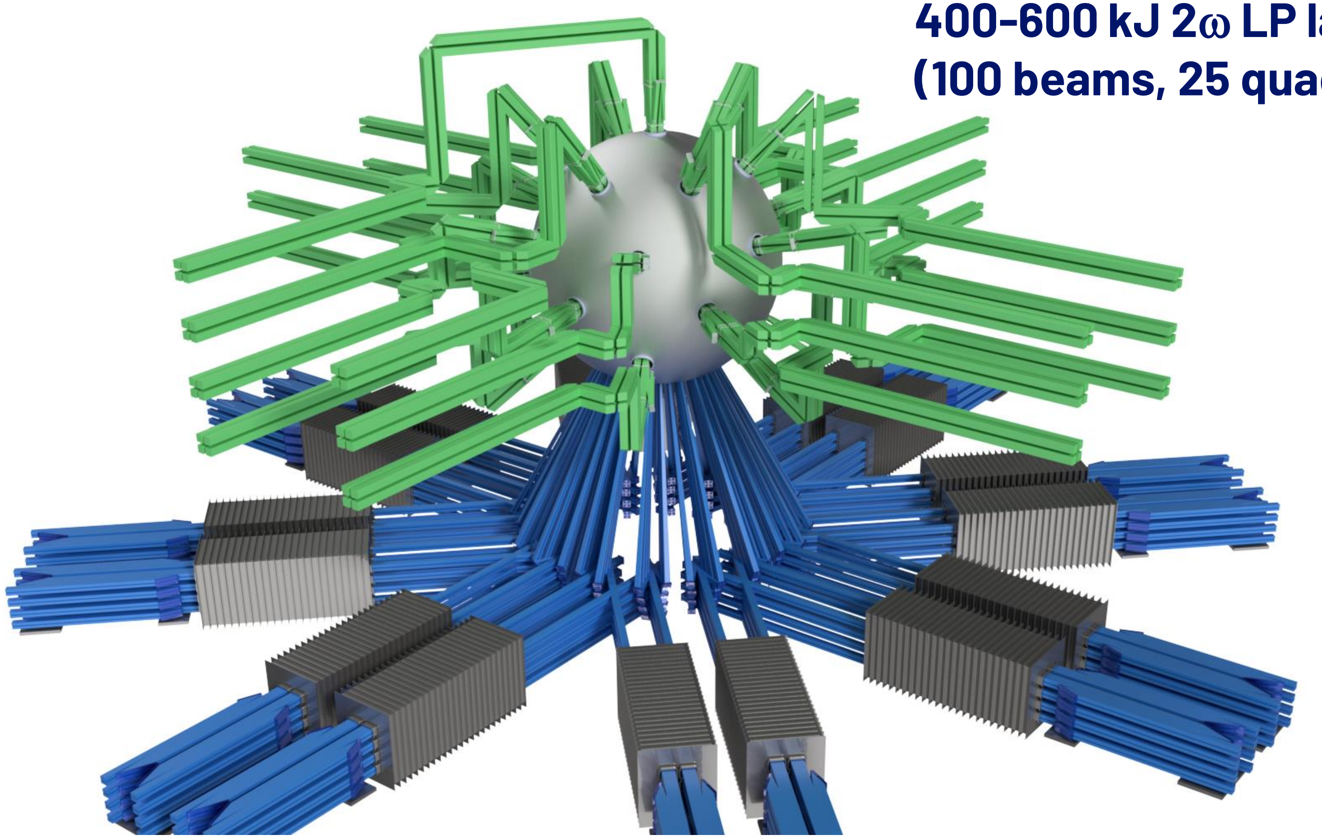
Our high-level roadmap



Our high-level roadmap



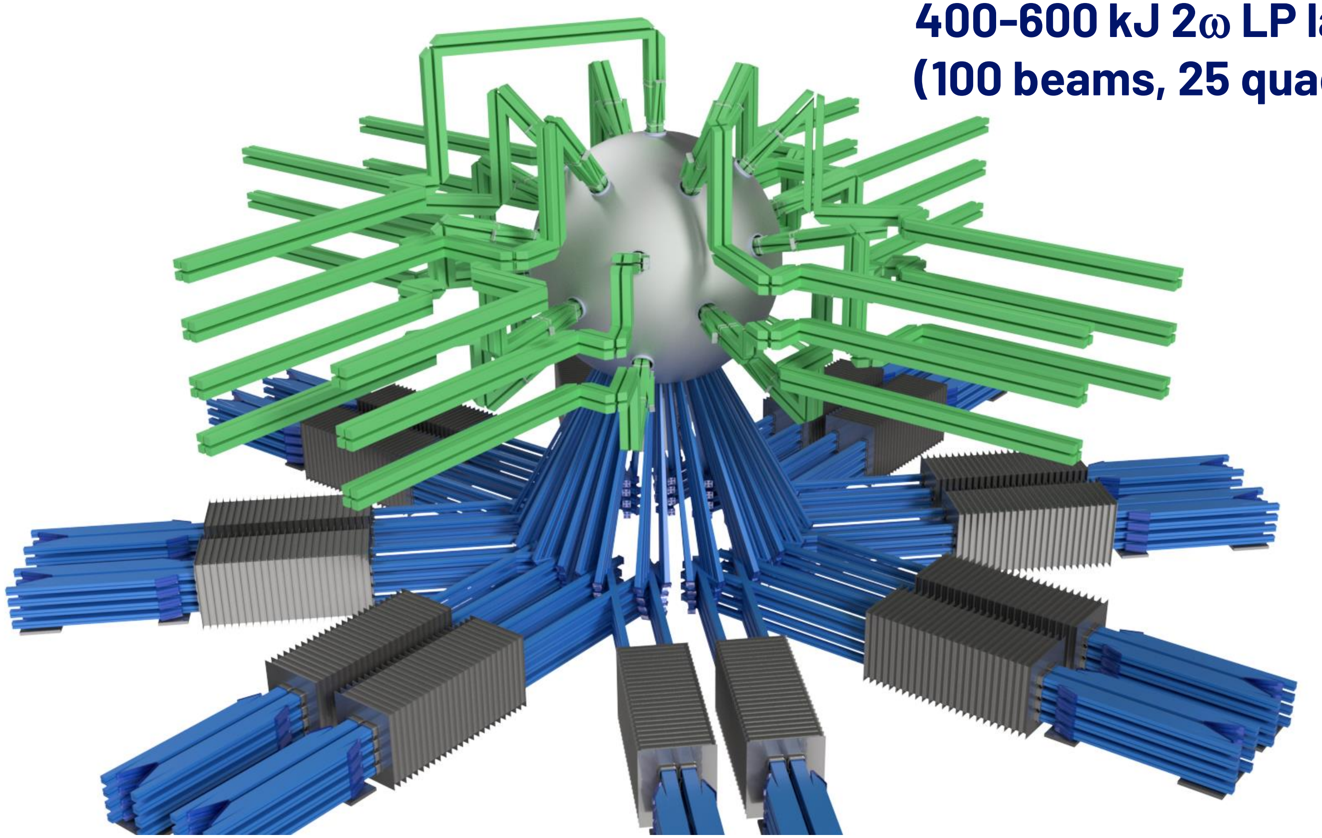
We are currently working on finalizing the PFI target design and conceptual design of the Super-Nova ignition facility



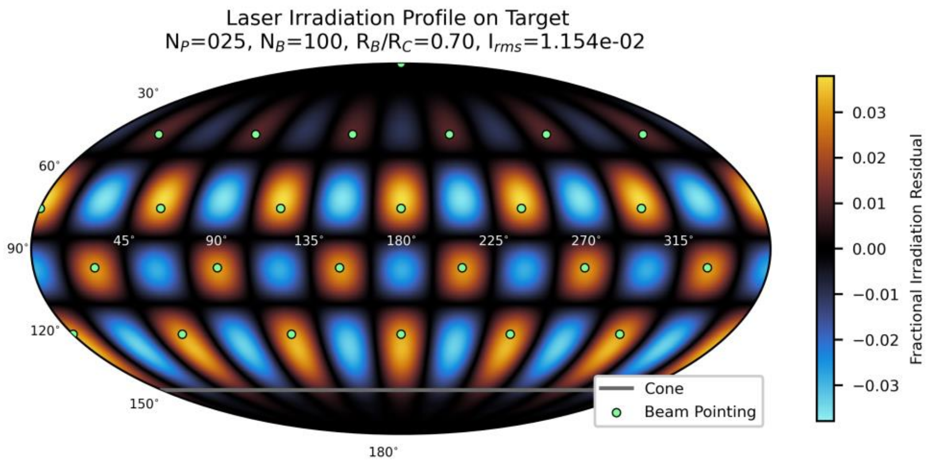
- Super-Nova will be an NIF-like ignition facility capable of **>100 experiments a day** - vastly accelerating rate of progress in target optimization and learning
- It will implement and test key technologies required on the path to a 10 Hz IFE FPP

We are currently working on finalizing the PFI target design and conceptual design of the Super-Nova ignition facility

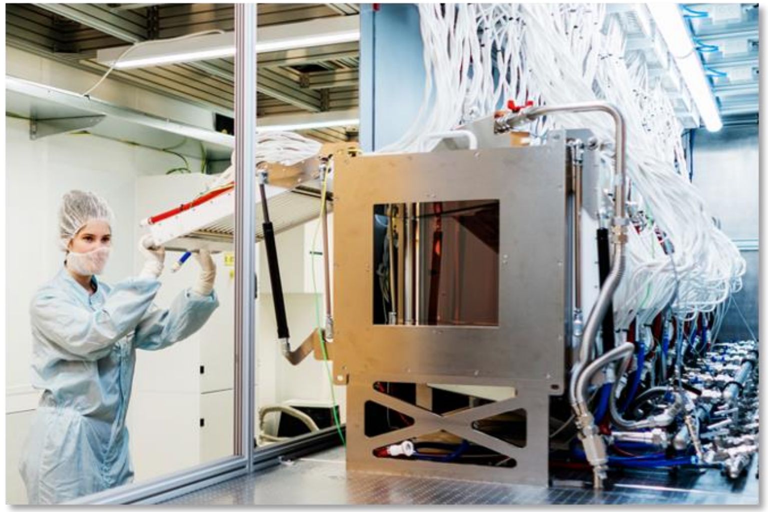
400-600 kJ 2ω LP laser (100 beams, 25 quads)

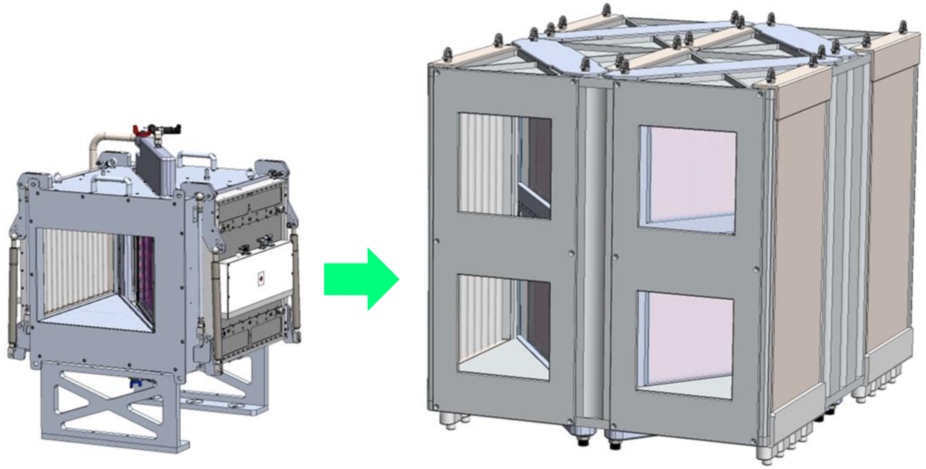


200 kJ 1ω SP laser (140 beams)



The beamlines use modern liquid-cooled amplifier technology that we have already demonstrated and is operational

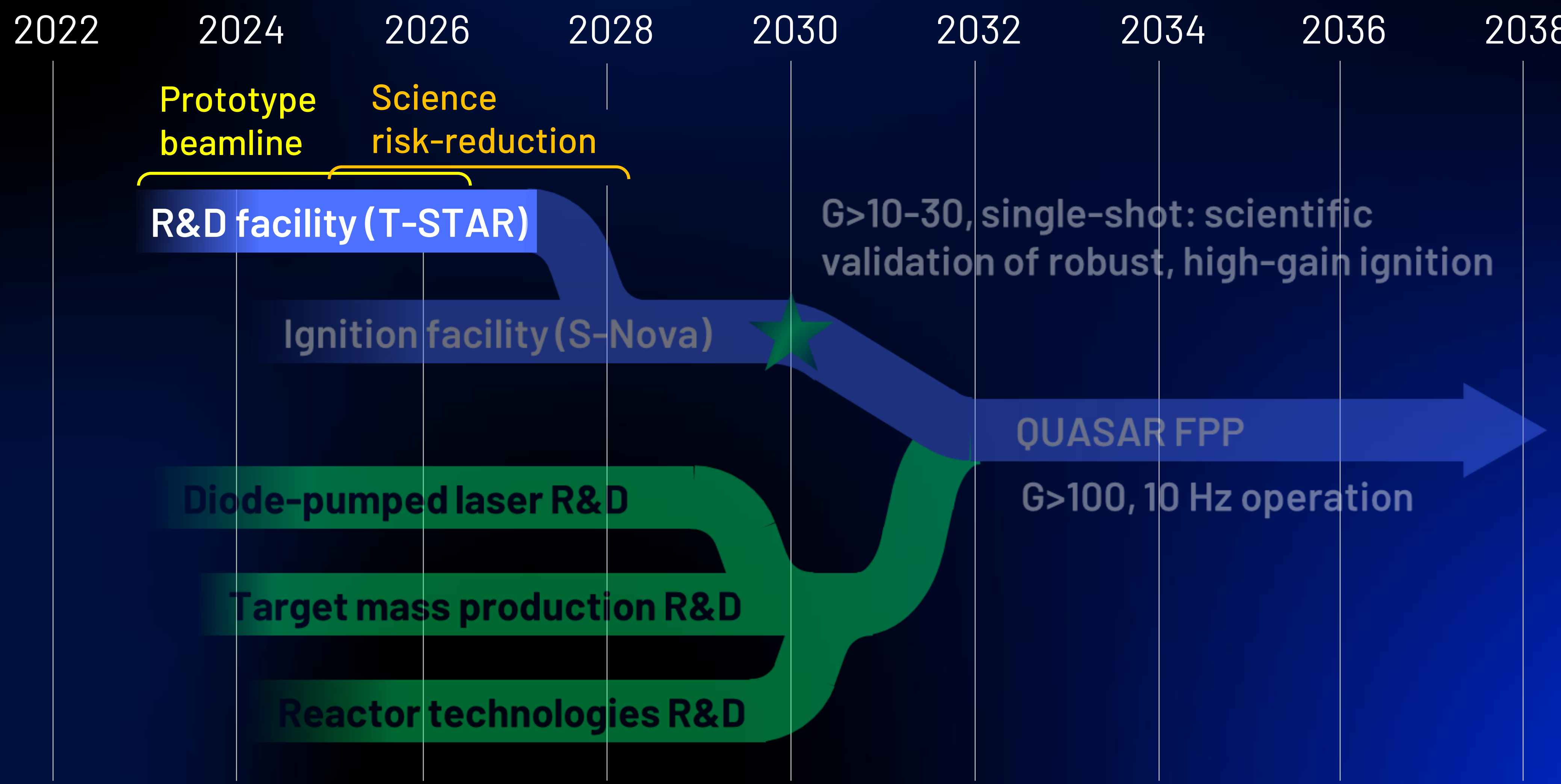




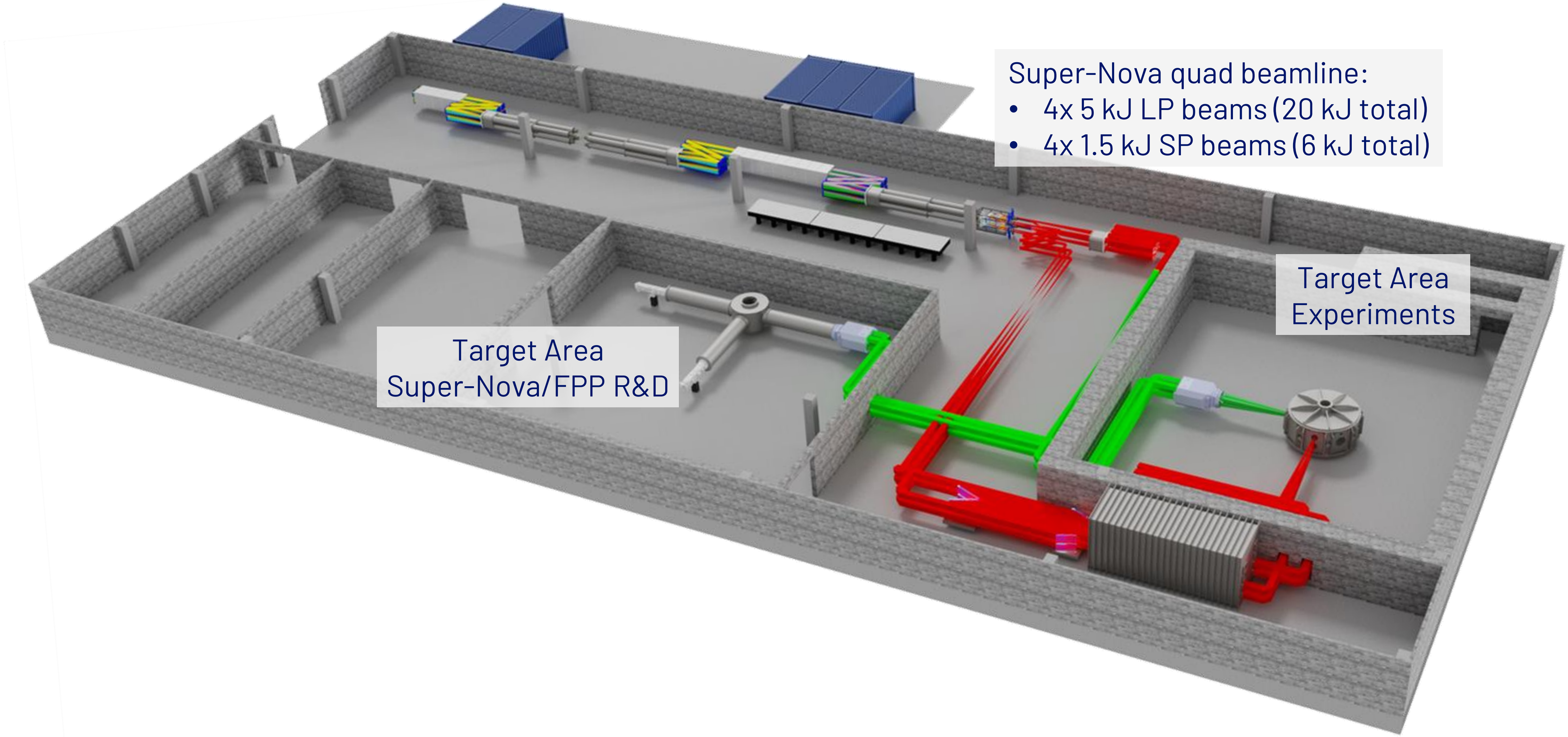
Original L4 design New Super-Nova quad design

- 30 cm aperture liquid-cooled amplifier
- Beamline installed at ELI beamlines (L4), operating at 2 kJ at a shot / 3 minutes
- Super-Nova beamlines will use this same technology, but upgraded to a quad amplifier design, and meeting higher performance specs (fluence, bandwidth, etc.)

Before building Supernova, build a prototype for beamline and for science experiments



T-STAR is a *dual-purpose* R&D facility for Super-Nova technology development & scientific risk-reduction



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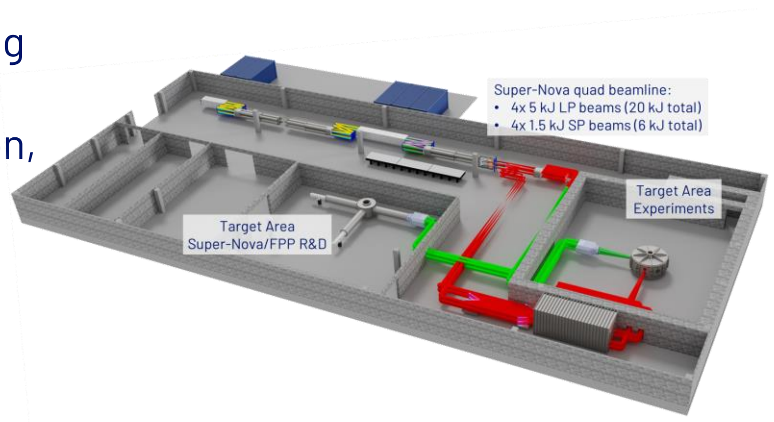
FOCUSED ENERGY

Full Super-Nova beamline prototype

- End-to-end integration, testing, and characterization
- Find and fix any issues before building many beamlines
- Allows for controls system integration, testing, and refinement

Enables integration, testing, and characterization of other key hardware and systems

- Pulse compressors
- Final optics assemblies
- Target insertion systems
- Diagnostics



We also view T-STAR as providing a unique opportunity to engage the broader IFE/HED scientific community in our effort

Science de-risking experiments

- Validation of laser absorption and compression physics at actual Super-Nova laser conditions
- Develop and test LPI and CBET mitigation techniques
- Optimize proton acceleration and focusing at high energy

Prepare for Super-Nova experiments

- Develop and test diagnostics designed for high shot-rate
- Develop machinery for automated data analysis, interpretation, and feedback
- Gain operational fluency in campaigns at 100 shots/day

IFE will benefit from public/private partnerships

FOCUSED ENERGY

- Focused Energy is one of the awardees of DOE's new milestone-based fusion development program

U.S. DEPARTMENT OF ENERGY | Office of Science

Advancing the Bold Decadal Vision: Launching a Milestone-Based Fusion Development Program

In March 2022, the White House held a Fusion Summit that laid out a Bold Decadal Vision for Commercial Fusion Energy. One of five priorities in the White House Net-Zero Game Changers Initiative, commercial fusion energy has the potential to deliver abundant, clean, reliable electricity and many other benefits. With strong support from Congress and the Biden-Harris Administration, the Department of Energy (DOE) is following through on this vision with bold steps forward in our support for fusion energy science and technology.

Please join Secretary of Energy Jennifer Granholm, White House Office of Science and Technology (OSTP) Director Arati Prabhakar, DOE Under Secretary for Science and Innovation Geraldine Richmond, and DOE Office of Science Director Asmeret Asefaw Berhe as we announce the first selections for the new Milestone-Based Fusion Development Program. This innovative new public-private partnership brings together the vibrant U.S. fusion private sector community and the nation's solutions department to resolve key scientific and technological challenges that must be overcome to realize fusion pilot plants in the next decade.

Please join us at energy.gov/live May 31st at 2pm ET to celebrate this exciting announcement.

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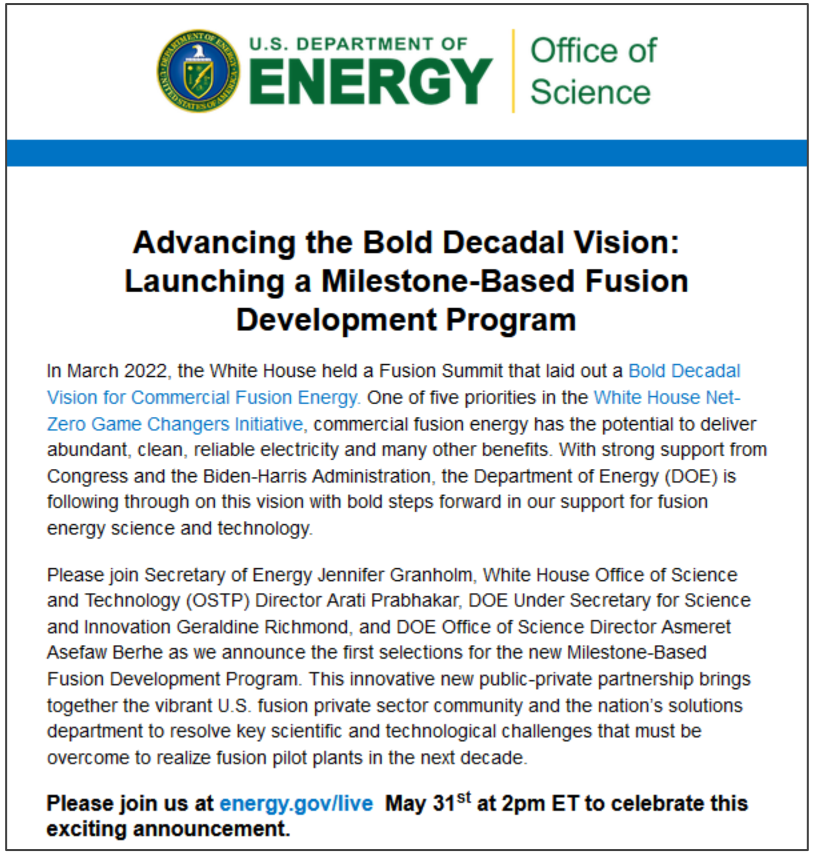

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Federal Ministry of Education and Research

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SPRIND CREATES INFRASTRUCTURE FOR LASER-DRIVEN FUSION

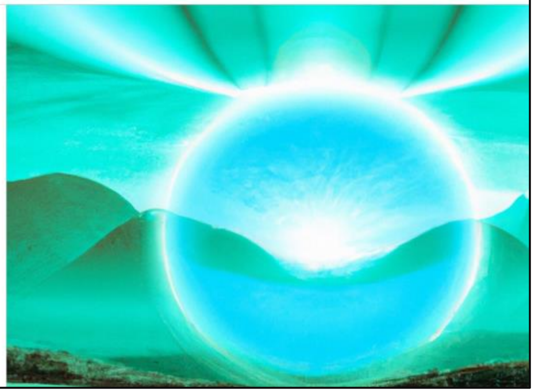
Founding of Pulsed Light Technologies

At a meeting on March 7th, the SPRIND Supervisory Board gave its approval for the founding of Pulsed Light Technologies GmbH (German LLC). The wholly-owned subsidiary of SPRIND GmbH will develop infrastructure for the generation of energy from laser-driven fusion.

"A working and economically-operated fusion power plant would be a truly disruptive innovation," says Rafael Laguna, Director of the Federal Agency for Disruptive Innovation (SPRIND). "Fusion could provide a relatively clean way of generating continuous power independent of local geologic factors and without relying on limited resources. In view of the goal to phase out the use of fossil fuels and the simultaneous rising demand for electrical energy, it makes sense for us to tap into public funds to accelerate the development of this technology."

Pulsed Light Technologies is working on fusion energy issues that need to be solved, but it does not interfere with start-ups' core developments or IP concerning fusion power plants. It expressly does not work on any physical fusion processes. The planned developments in laser technology may also lead to significant advances in other applications, such as in materials studies with high-intensity neutron beams. Licensing regulations will enable the results to be used for other, future applications.

"Like all SPRIND subsidiaries, the GmbH will apply for a loan from the Federal Ministry of Education and Research parallel to its establishment," explains Dr. Antonia Schmalz, designated Managing Director of Pulsed Light Technologies GmbH. "Our plans call for investing up to 90 million euros in the technology over the next five years."



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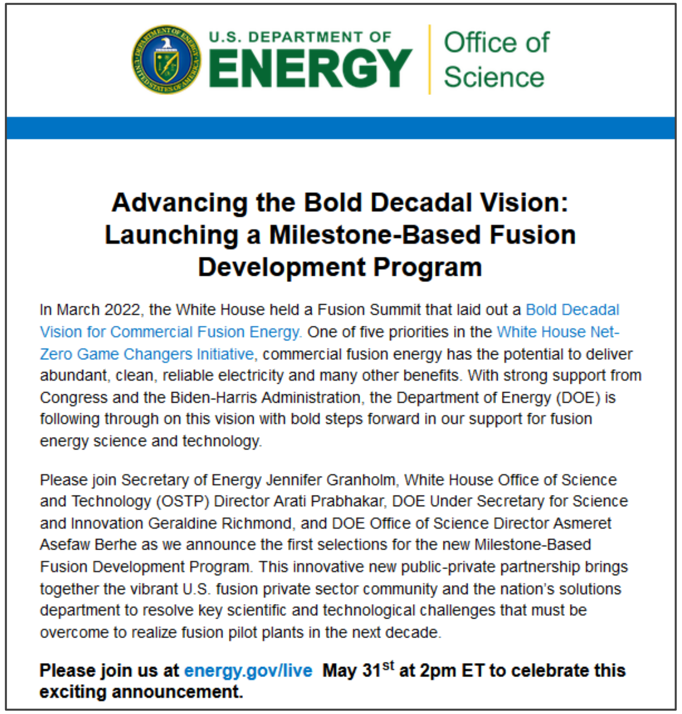
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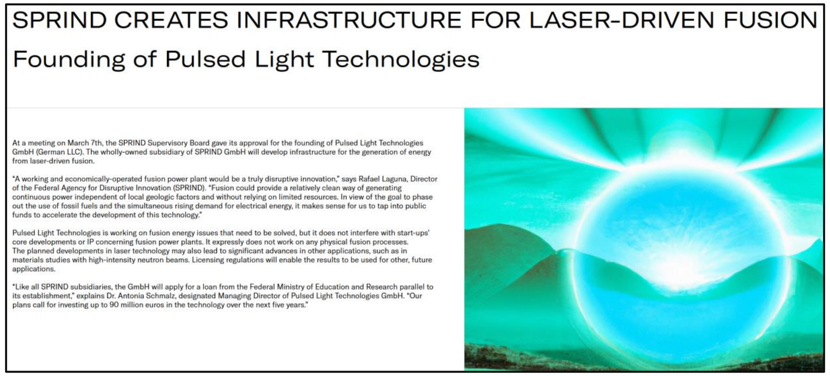
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Partnerships

with the leading companies, experts and national labs for IFE

FOCUSED ENERGY

SUPPLY PARTNERS

LABORATORIES

UNIVERSITIES

Thank you