Architecture of a thermo-mechanical-optical model of a laser amplifier for laser fusion applications

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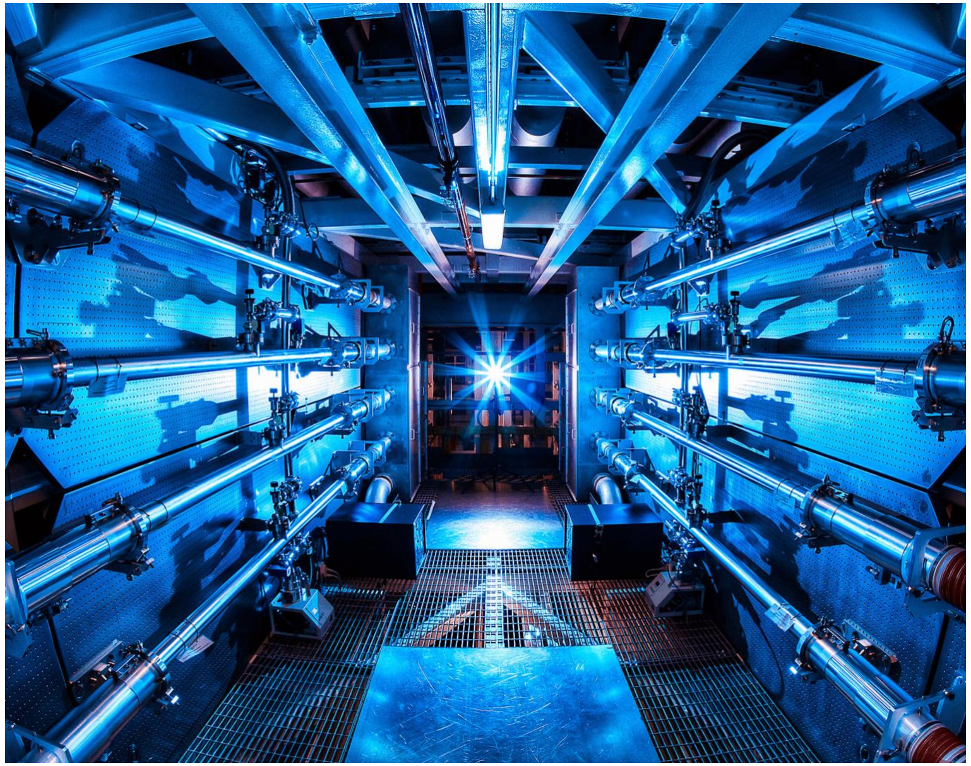
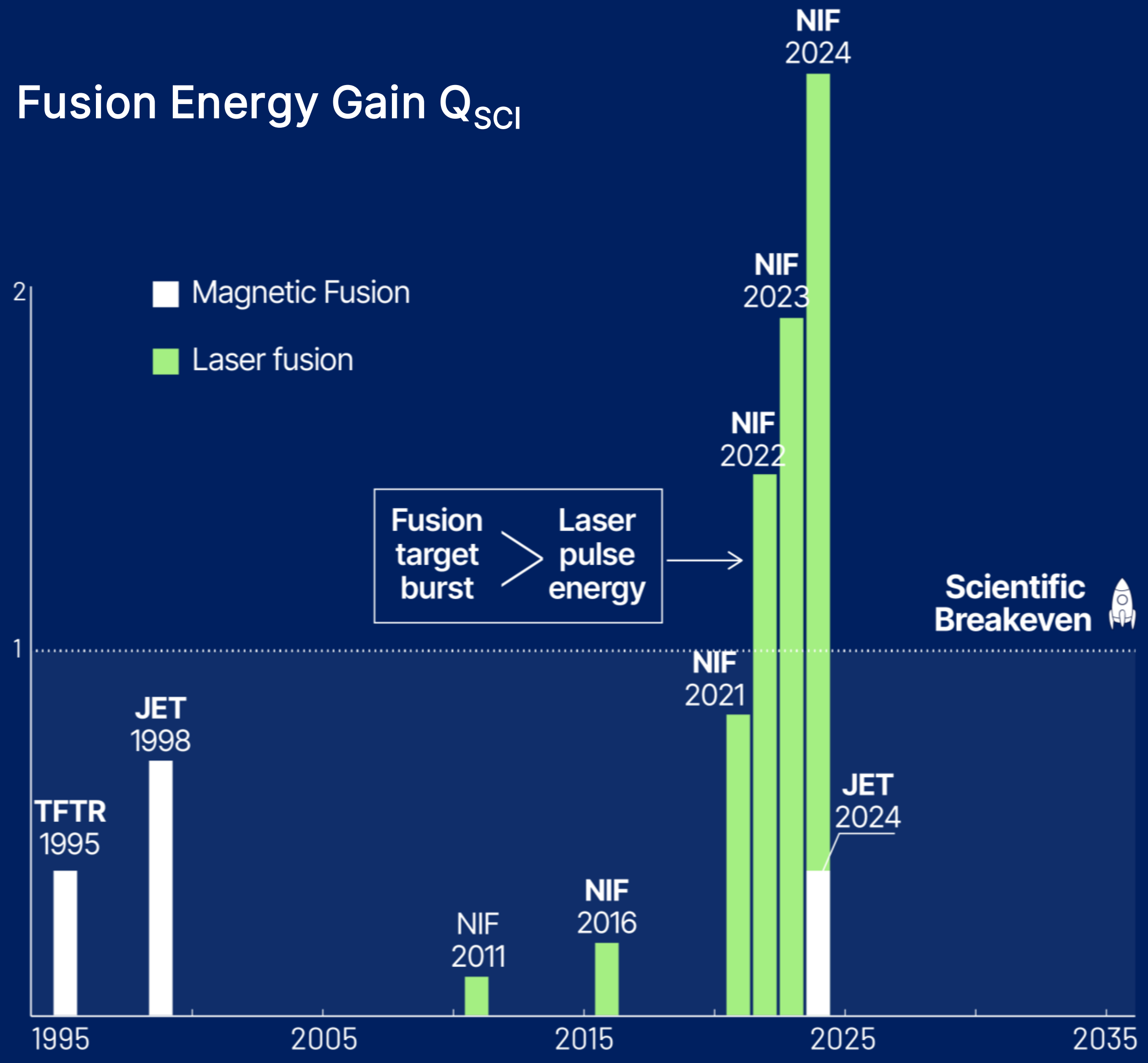
IFE Breakthroughs have burst open the door for Commercial Laser Fusion Power



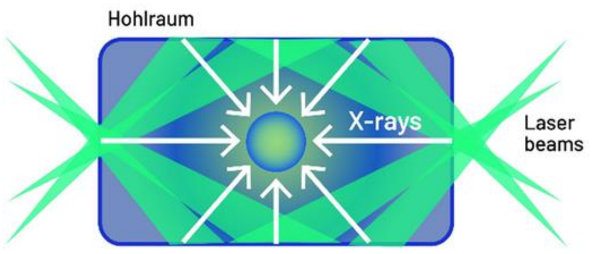


FOCUSED ENERGY

Our Fusion Approach – Direct-Drive Compression with modern Inertial Fusion Energy (IFE) Lasers

The Traditional Indirect Approach

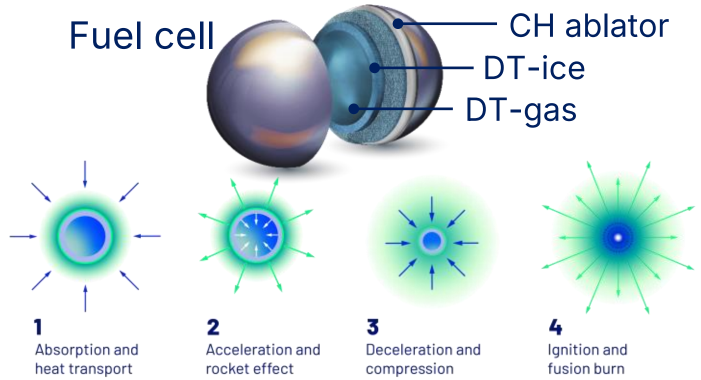
Laser drives X-rays to Compress Fuel



Schema used by NIF for Breakthrough.

The Direct Drive Approach:

Laser *Directly* compresses Fuel Cell



The Next-Generation Driver:

Rep-Rated High-Power Lasers

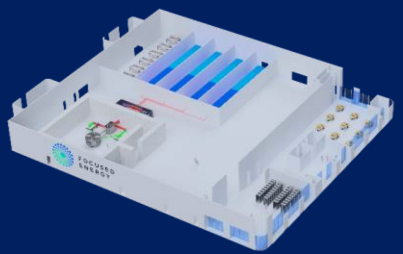
Proprietary IP for high-power, liquid-cooled lasers. First unit in use at the ELI research facility in Prague.

The Focused Energy Roadmap

Target & Laser R&D Lab
Q1 2025
Location: [German flag]

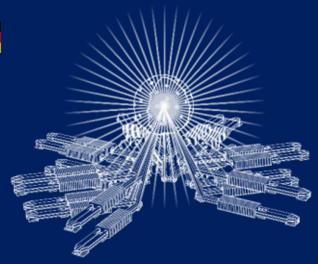
→ <1kJ

R&D Facility
Commissioning: 2027
Location: [US flag]



→ ~5kJ

Sub-Scale Facility
Integrated Implosion Facility
Planned: 2030-2032
Location: [US flag] [German flag]

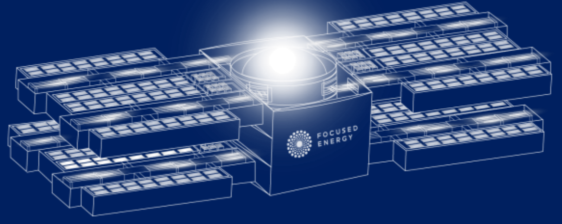


→ 50kJ

Pilot Plant
Commercial Validation
Planned: 2039

→ 2MJ

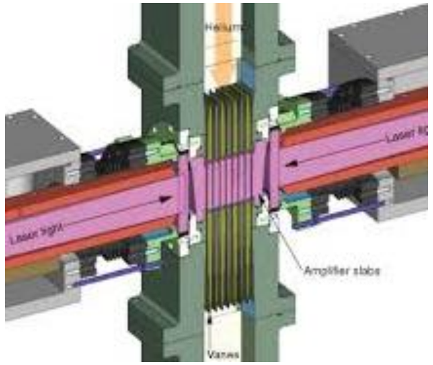
Commercial Plant
Fusion Energy to the Grid
2039 onwards



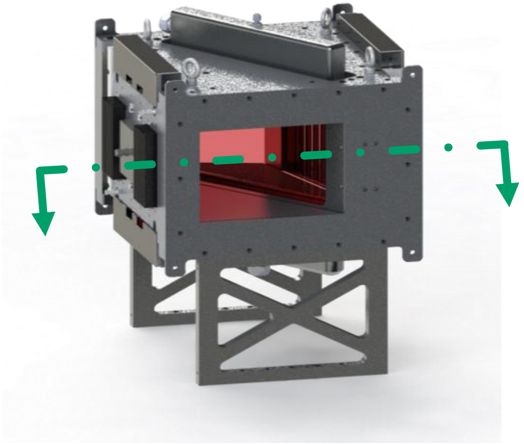
Our Lasers: Cutting-edge light sources and cooling architectures, yet to be seen at scale on existing IFE systems

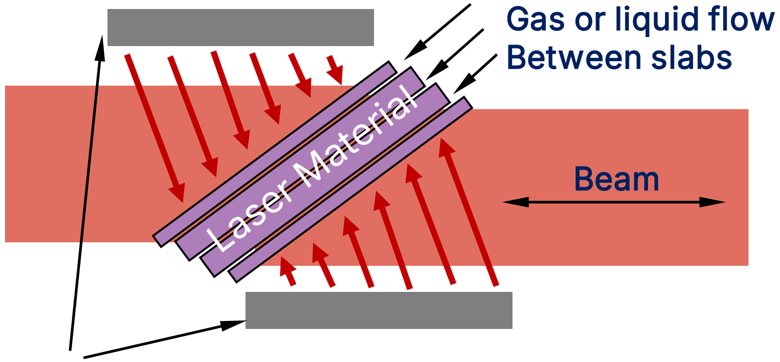
Laser Material

Ion-Doped Glass/Crystal/Ceramic
with Active Cooling



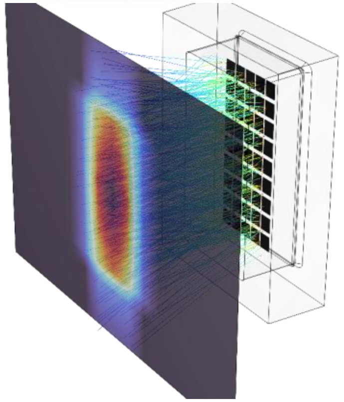
IFE Laser Amplifier Elements





Pump/Excitation Source

Diode or Flashlamp Arrays



Amplifier Thermo-mechanical-optical behavior drives laser quality

Effect 1: Wavefront and Focusability

How does wavefront effect laser quality?

- Optical techniques can only remove a portion of the distortion
- Residual phase reduces size of the final focus → Lower Intensity

→ Amplifier Wavefront or Optical Phase Distortion - S(x,y)

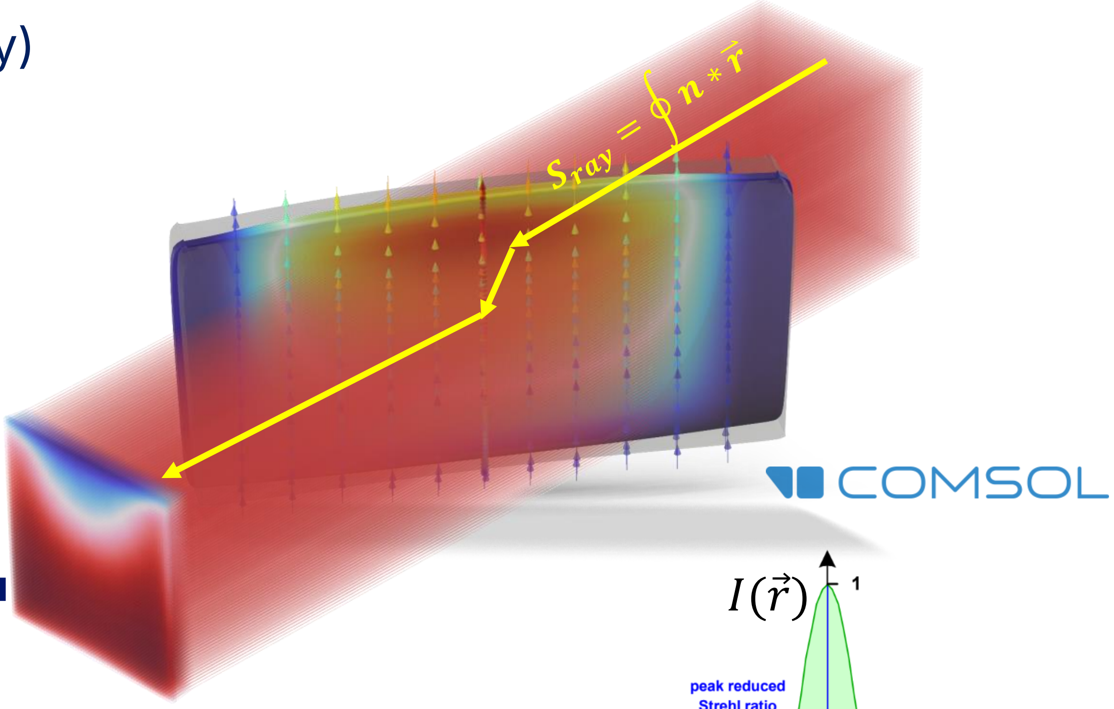
- $S_{ray} = \oint n * \vec{r} \rightarrow ds = r * dn + n * dr$
  - Sum of index (r*dn) and material path (n*dr) changes
- $n_{ij} = n_0 + \frac{\partial n}{\partial T} * \Delta T(\vec{r}) + \sum \left(\frac{\partial n_{ij}}{\partial \sigma_{kl}}\right)_{ijkl} * \sigma_{kl}(\vec{r})$
  - 3x3 Index Tensor based on Polarization (ij)

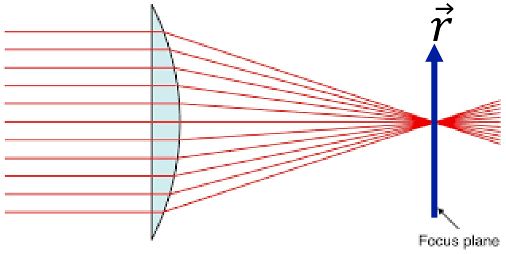
→ The Index Sources - $r * dn$

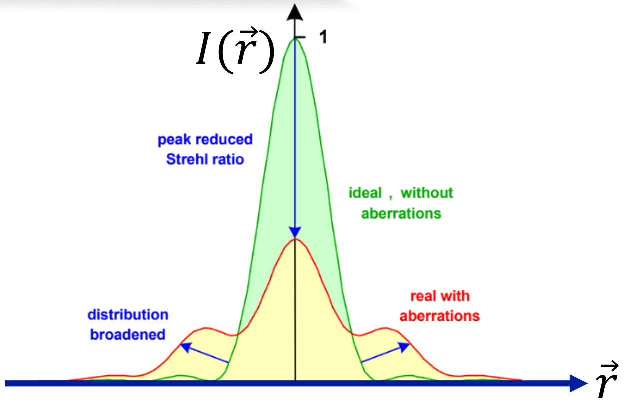
- Stress-Induced Refractive Index Changes: $\sum \left(\frac{\partial n_{ij}}{\partial \sigma_{kl}}\right)_{ijkl} * \sigma_{kl}(\vec{r})$
  - Thermal stress
  - Mechanical Mounting
- Thermally-induced Refractive Index Changes - $\frac{\partial n}{\partial T} * \Delta T(\vec{r})$

→ The Pathlength Sources - $n * dr$

- CTE Expansion
- Index- and CTE-Induced Focusing → New Ray Paths







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Amplifier Thermo-mechanical-optical behavior drives laser quality

Effect 2: Depolarization and birefringence

→ Polarization - $\vec{P}(x,y)$

- Local Stress Tensors rotate local Optical Tensors, often aligning themselves with the Stress Principle Axes

- $$\begin{pmatrix} n_{xx} \\ n_{yy} \\ n_{zz} \\ n_{yz} \\ n_{xz} \\ n_{xy} \end{pmatrix} = \begin{pmatrix} B_{11} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & B_{66} \end{pmatrix} * \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \end{pmatrix}$$

- Index Tensor (n) = Stress-Optic (B) * Stress Tensor (σ)

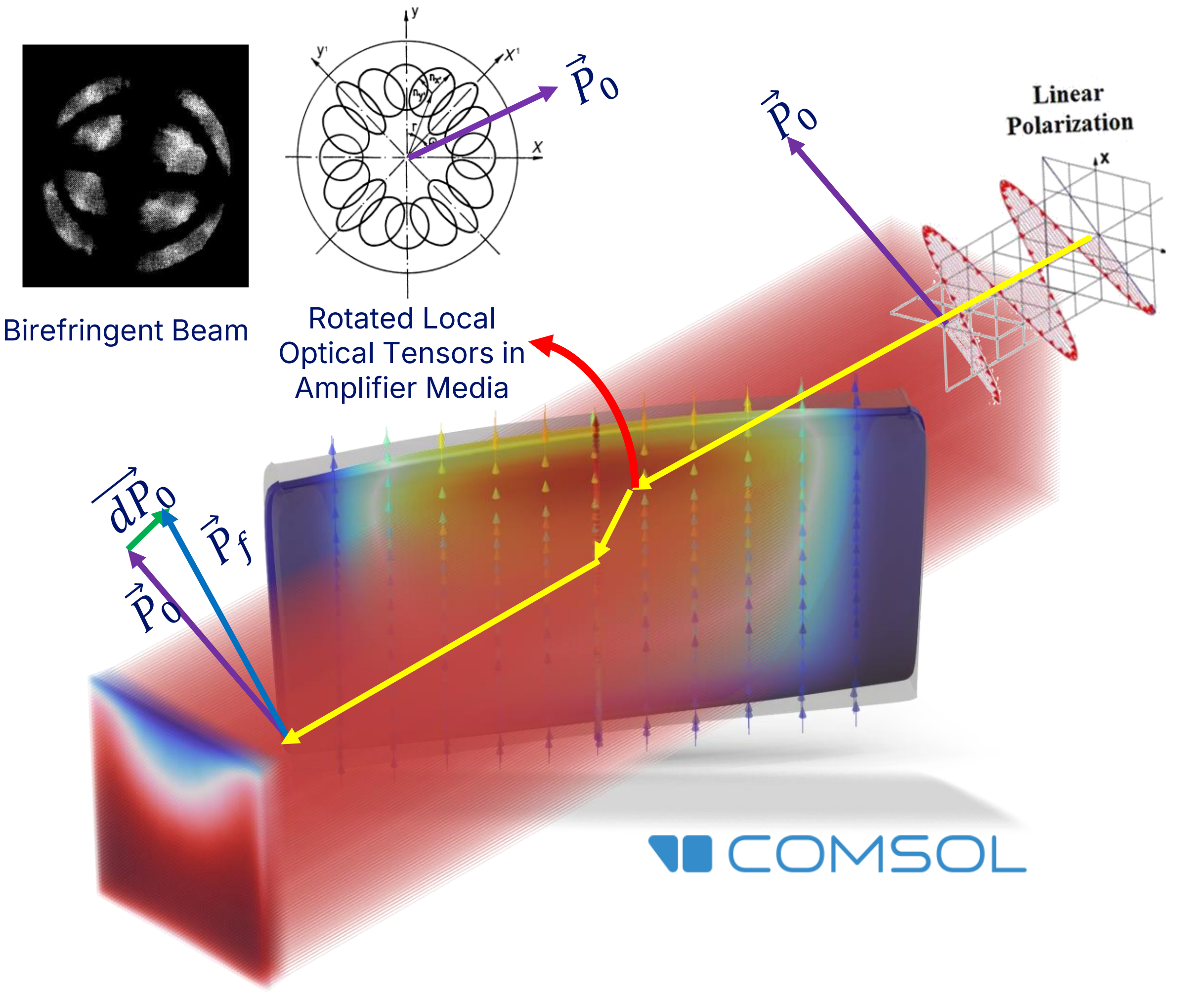
- Local Index Tensor misalignment with Polarization Axis will cause Local Birefringence and Depolarization

- Secondary Beams can result from this misalignment

- Secondary Beams will not survive optical propagation and is lost energy (Lower Fusion Driver Efficiency)

How does Polarization effect laser quality?

- Laser is optimized for single polarization
- Other polarizations will be quickly removed --> Energy loss



Segregated Solver to capture complete chain of events from pump to propagation

Pumping — COMSOL
- Pump Light Ray-Trace
- Excited State Energy Deposition

Energy Map: $E_{upper}(t,\vec{r})$

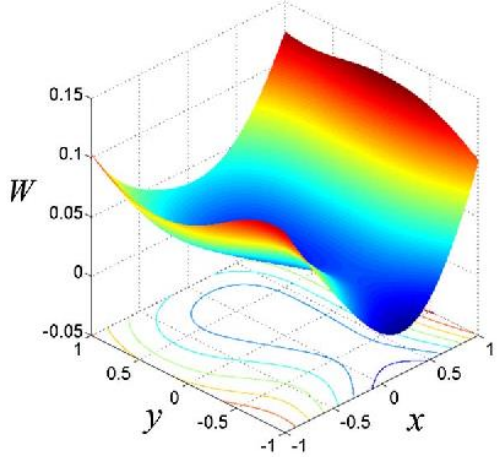
Energetics — CUDA C/C++
- Transient Laser Energetics
- Thermal Energy Storage

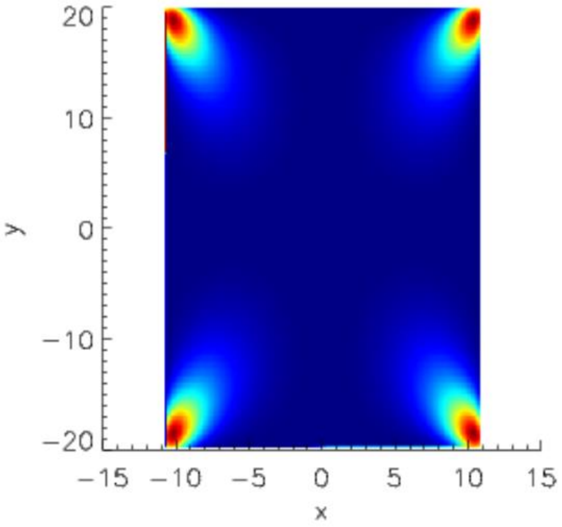
Heat Map: $Q(t,\vec{r})$

Thermo-Mechanics — COMSOL
- Fluid Dynamics
- Conjugate Heat Transfer
- Thermal Stress
- Surface Bowing and Deformations

Index of Refraction Map - $n_{ij}(t,\vec{r},\lambda)$
Deformed Optics Surfaces

Propagation — COMSOL
- Thermo-Optic Distortions
- Local Birefringence
- Propagation thru Deformed Optics





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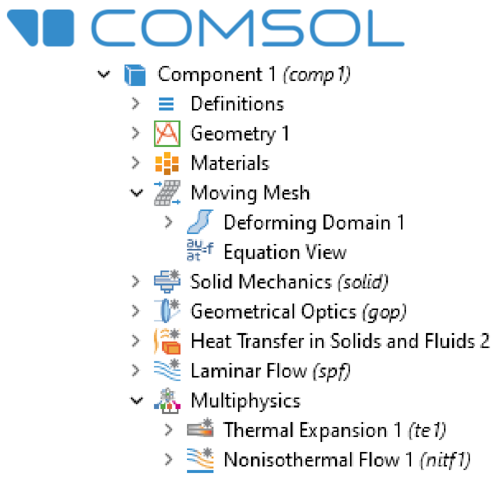
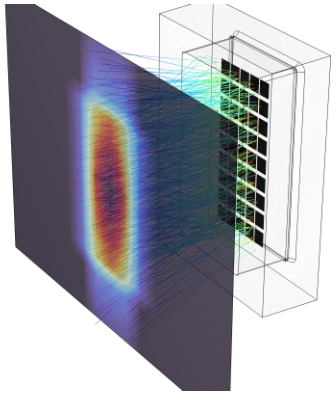
The solution leverages built-in modules with encapsulation of benchmarked laser codes and manufacturing data



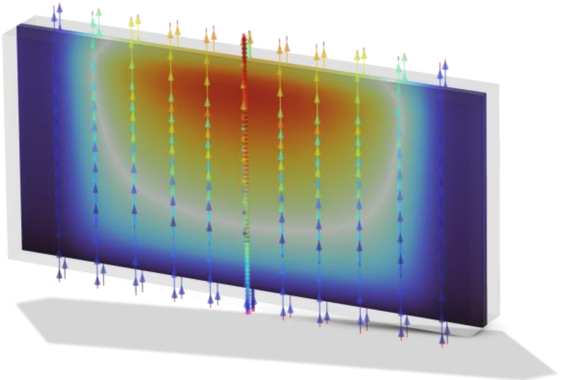
Pump Source Modelling

+Ext Modelling of Diode Characteristics



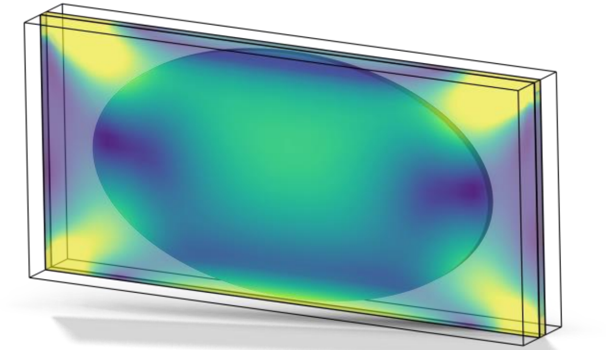
Heat Transfer + CFD

+Ext Module: Diode Excitation to Heat Map



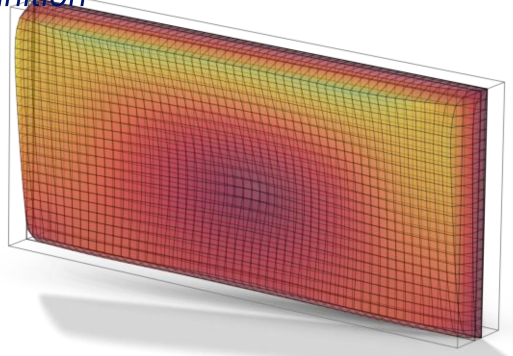
Solid Mechanics

+Mfg Data on Elastic Tensor Axes



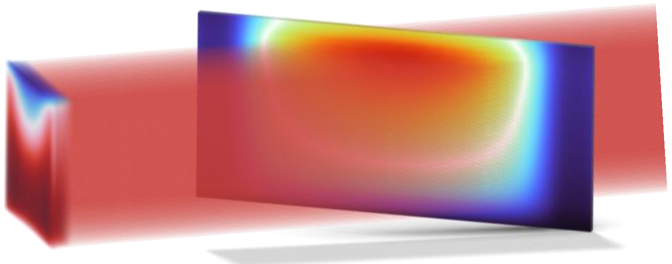
Moving Mesh

+Capture evolving micro-channel & optic definition



Ray Optics

+Mfg Data on Stress-Optical Tensors



Code benchmarking relative to known performance of existing actively-cooled lasers by former system experts in-house

CNE400 Pump Laser – Saclay, FR

Flashlamp-Pumped – 400J @ 1054nm

L4-Aton Laser – Prague, CZ

Flashlamp-Pumped – 1500J @ 1054nm

→ Each laser equivalent to 1 of the N Lasers required to compress the fuel pellet for a Laser Fusion Power Plant

→ Next generation of Amplifiers builds upon and extends the performance

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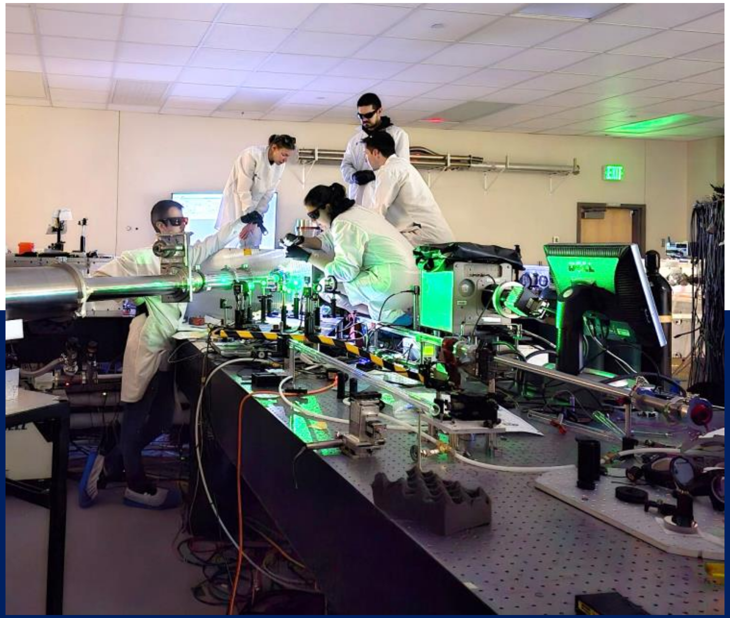
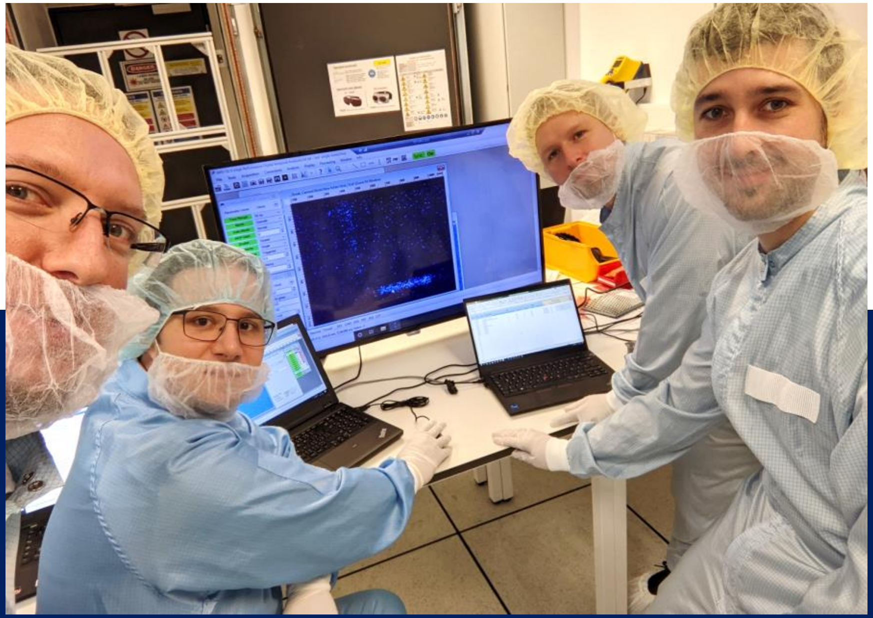
Thanks for your attention and interest in Fusion Energy!

We are happy to field any questions or comments at this time





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