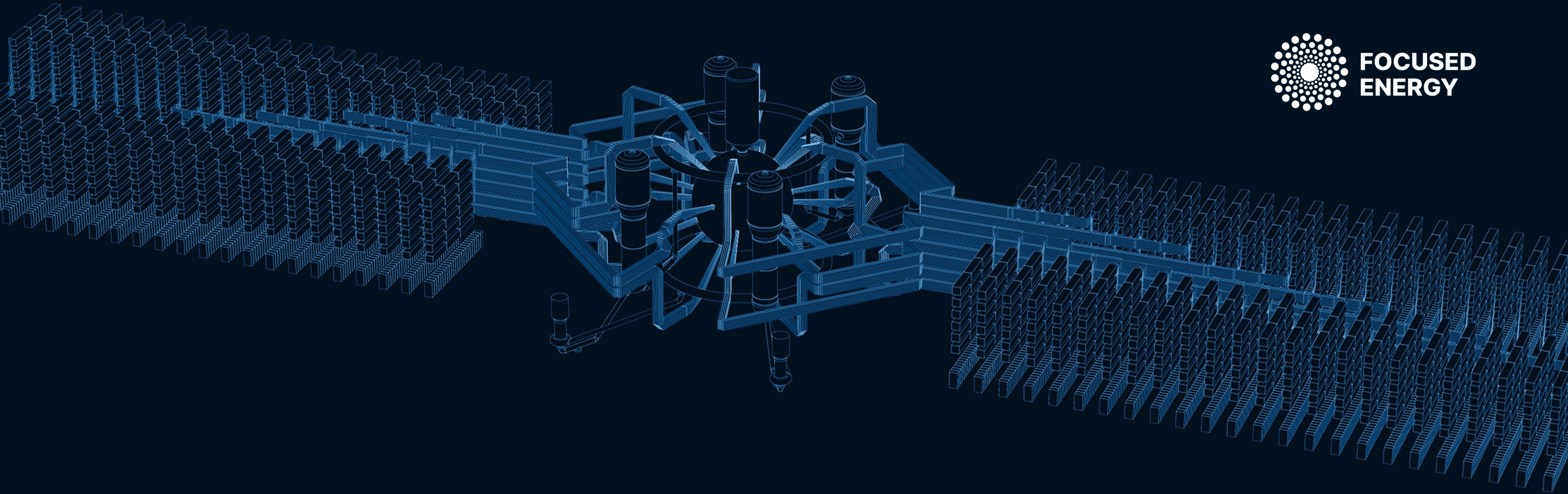


FOCUSED ENERGY

Thermo-Mechanical-Optical Modelling for Laser-Driven Fusion

G. Friedman, C. Paradis, D. Hammond, J. Thoma, A. Loescher, G. Le Touzé,

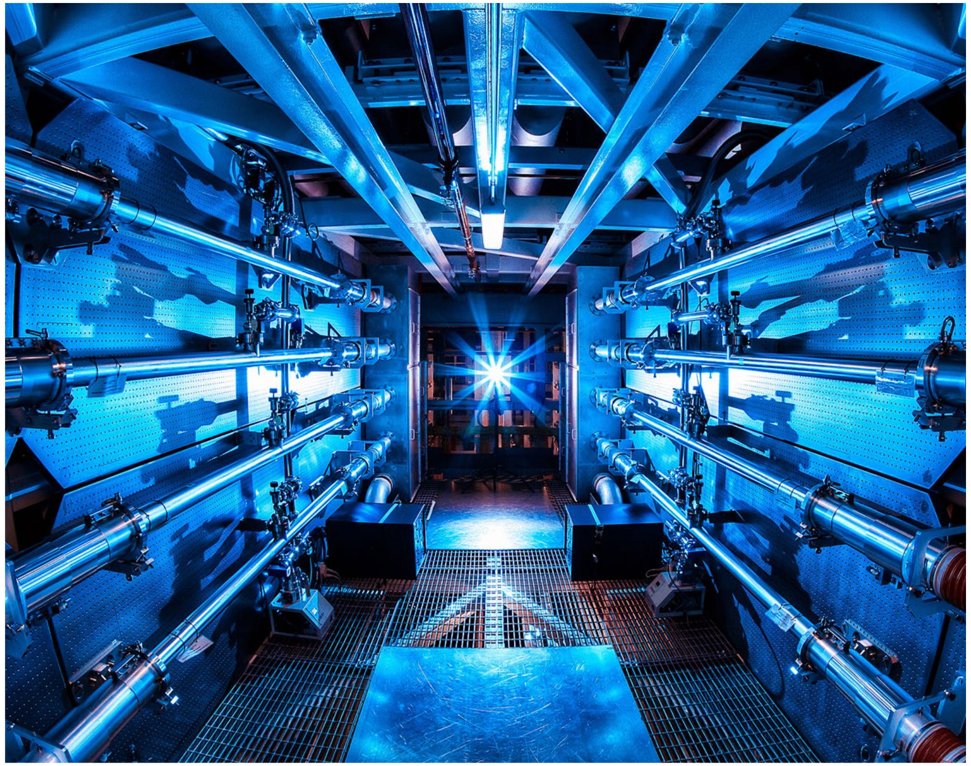
B. Le Garrec, J. Gaffney, P. Patel, G. Chériaux

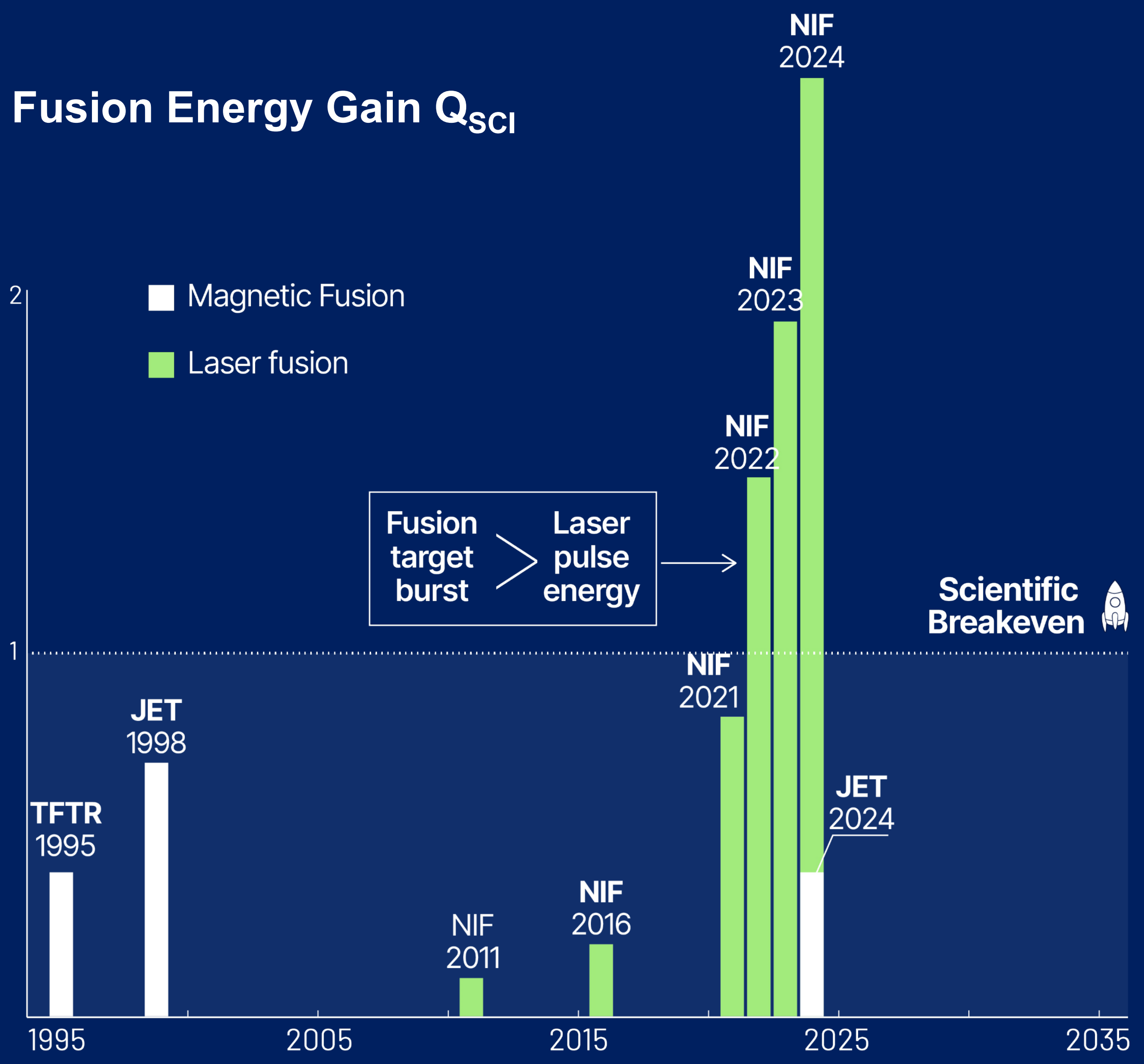
Gavin Friedman

Head of Optical Modelling, Laser Development

COMSOL - 2025 Czechia/Slovakia User Group Mtg

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





FOCUSED ENERGY

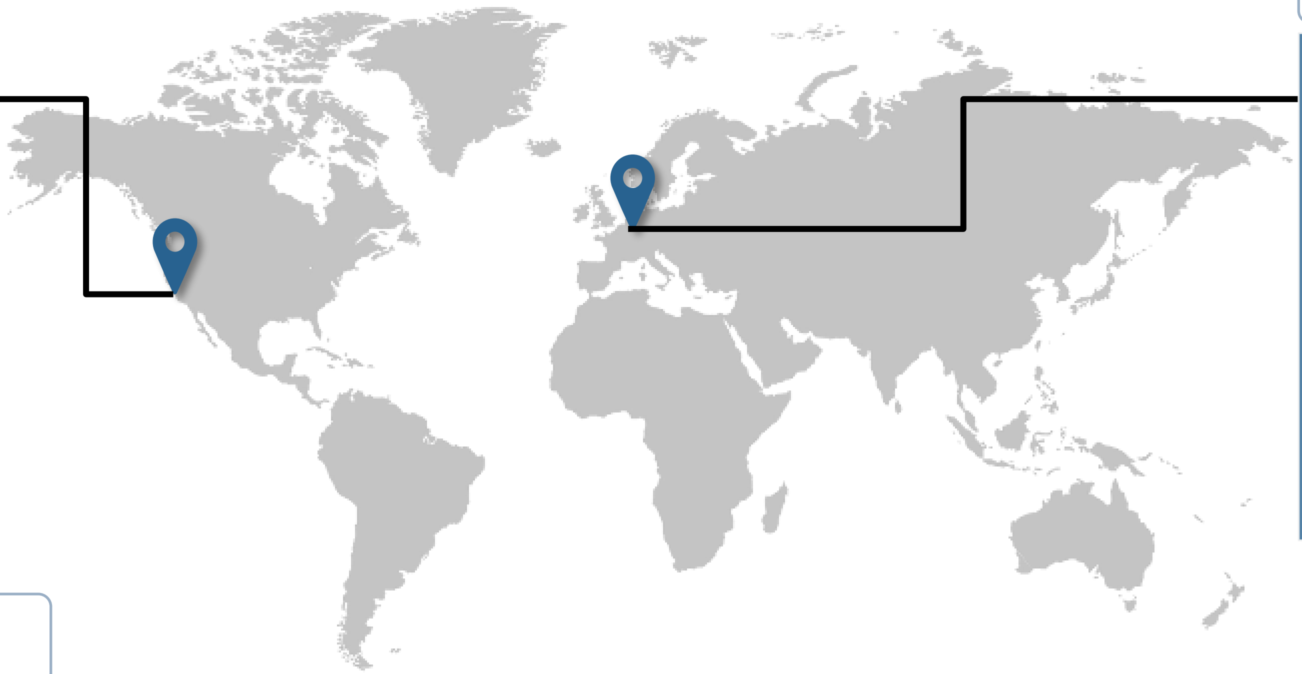
Laser R&D laboratories

FOCUSED ENERGY

Increased development speed and access to worldwide talent pool

Bay Area, CA, US

- ❑ Office headquarters
- ❑ Laser R&D
- ❑ Engineering/physics demonstration

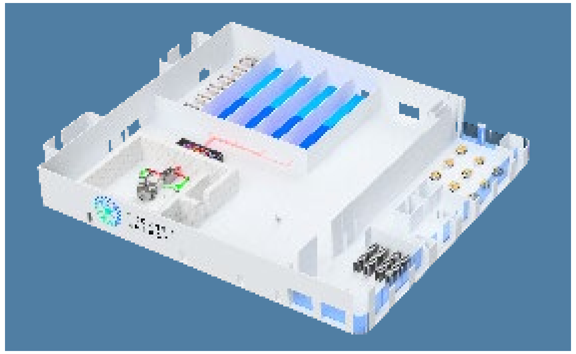


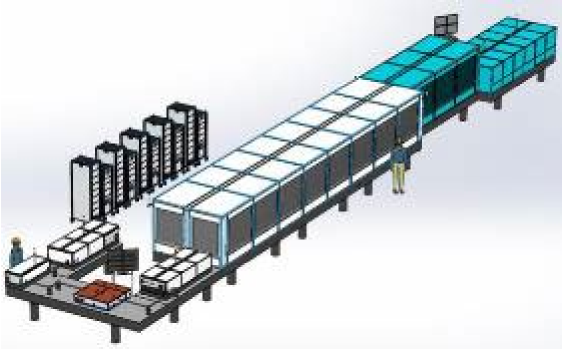
Darmstadt, Germany

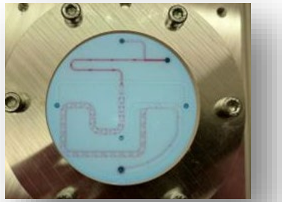
- ❑ Office headquarters
- ❑ Laser R&D Center (FELD Laboratory)
- ❑ Targetry

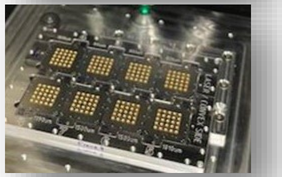
Engineering and physics demonstration

- ❖ **2x 800J laser systems 1 shot/min**
- ❖ **Target area**
- ❖ **Plasma diagnostics**









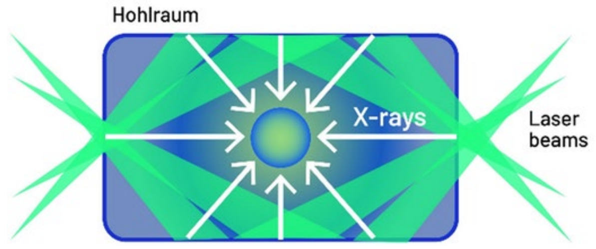
Federal Ministry of Education and Research

SPRIN-D

PULSED LIGHT TECHNOLOGIES

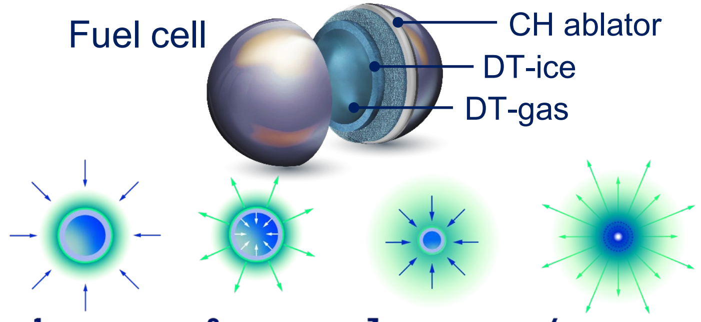
Our Fusion Approach – Direct-Drive Compression with modern Inertial Fusion Energy (IFE) Lasers

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

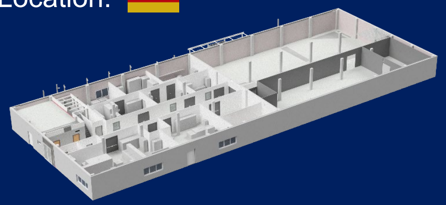


The Next-Generation Driver:
Rep-Rated High-Power Lasers

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

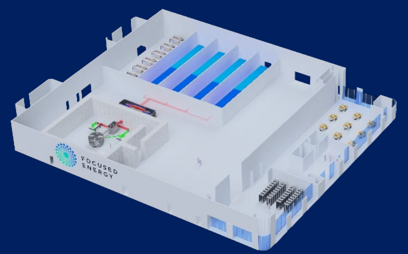
The Focused Energy Roadmap

Target & Laser R&D Lab
Q1 2025
Location: 🇩🇪



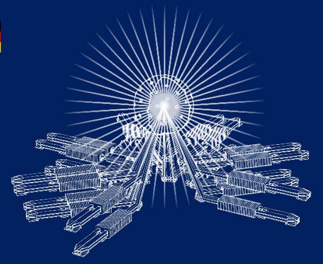
<1kJ →

R&D Facility
Commissioning: 2027
Location: 🇺🇸



~5kJ →

Sub-Scale Facility
Integrated Implosion Facility
Planned: 2030-2032
Location: 🇺🇸 🇩🇪

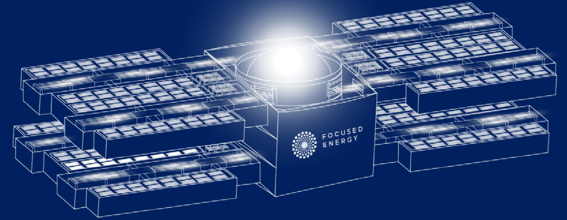


50kJ →

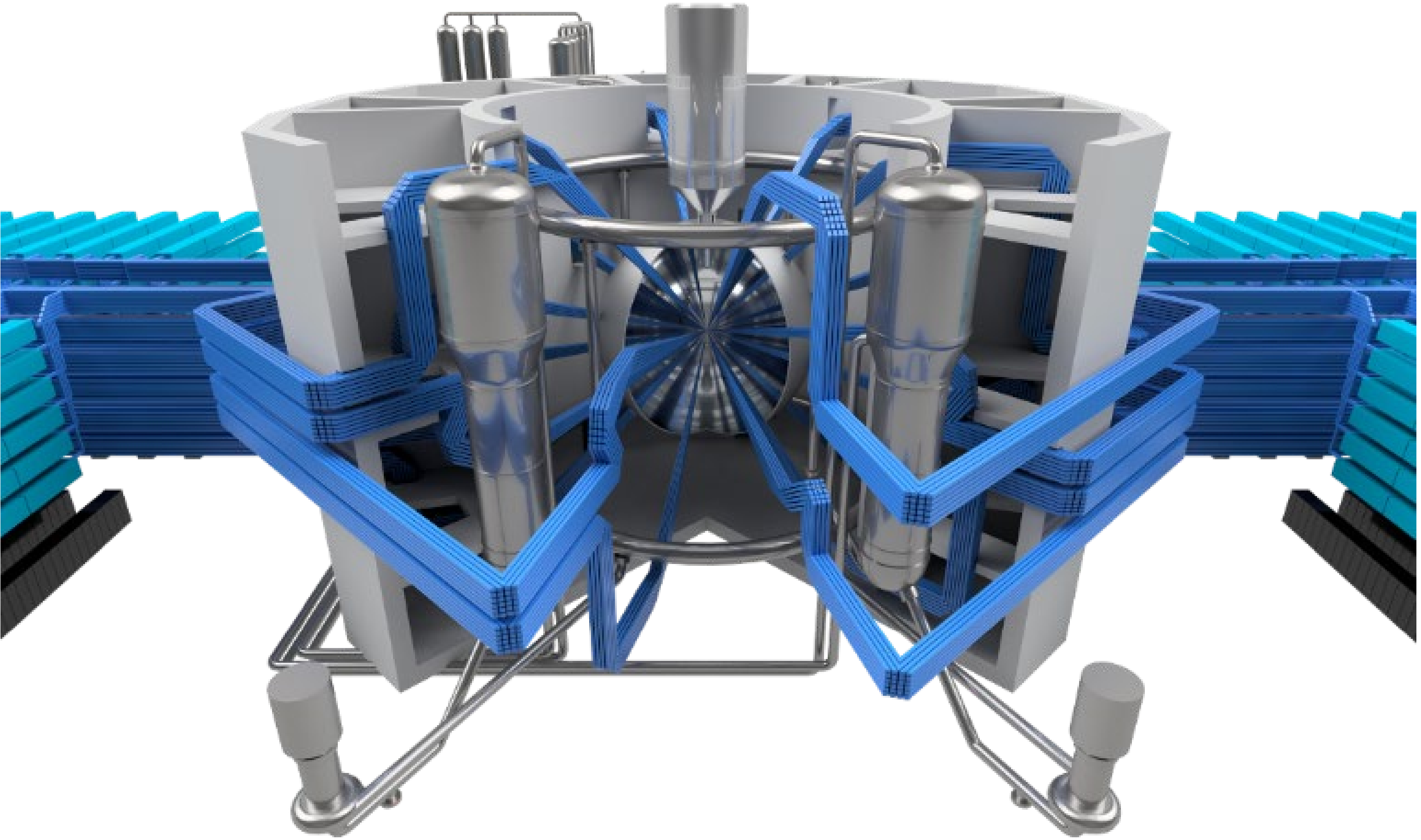
Pilot Plant
Commercial Validation
Planned: 2039

2MJ →

Commercial Plant
Fusion Energy to the Grid
2039 onwards



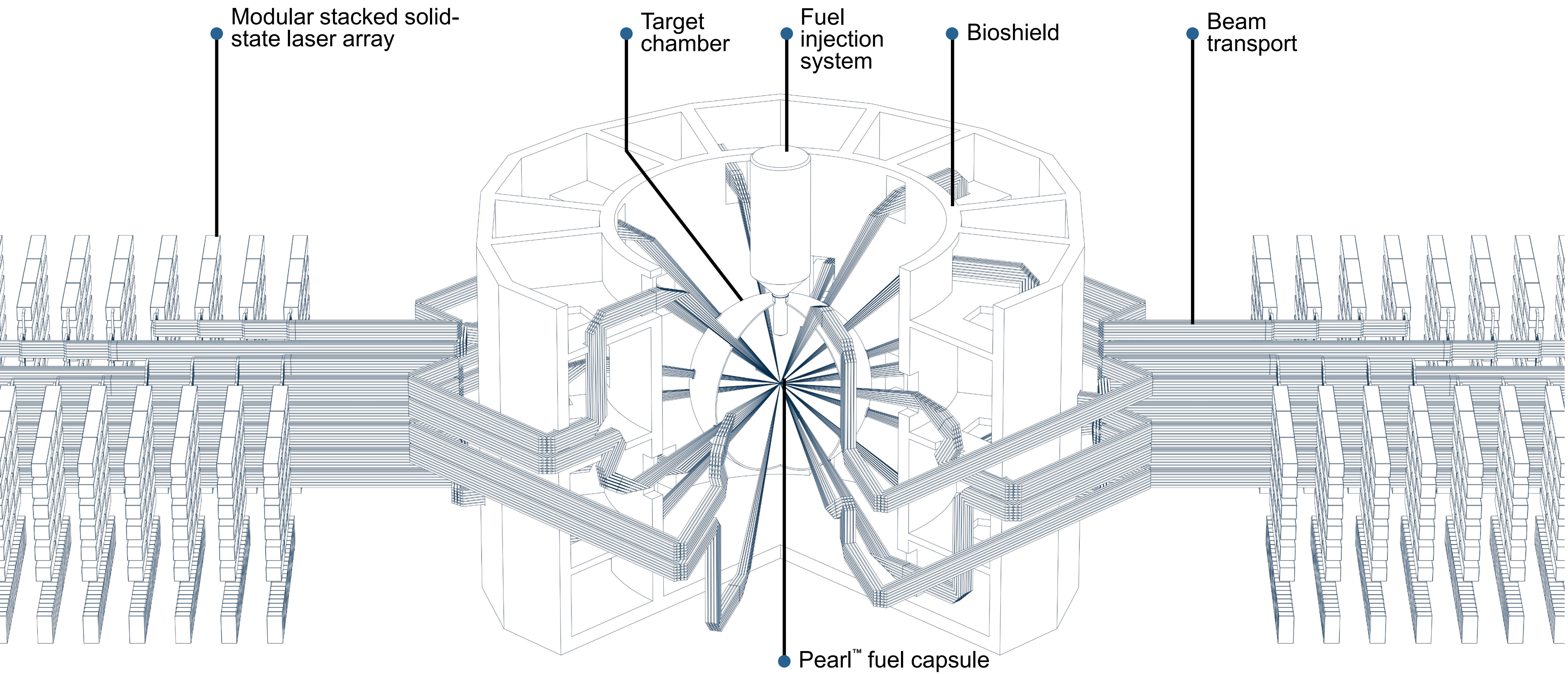
Laser-driven Inertial Fusion Energy: The Next Generation



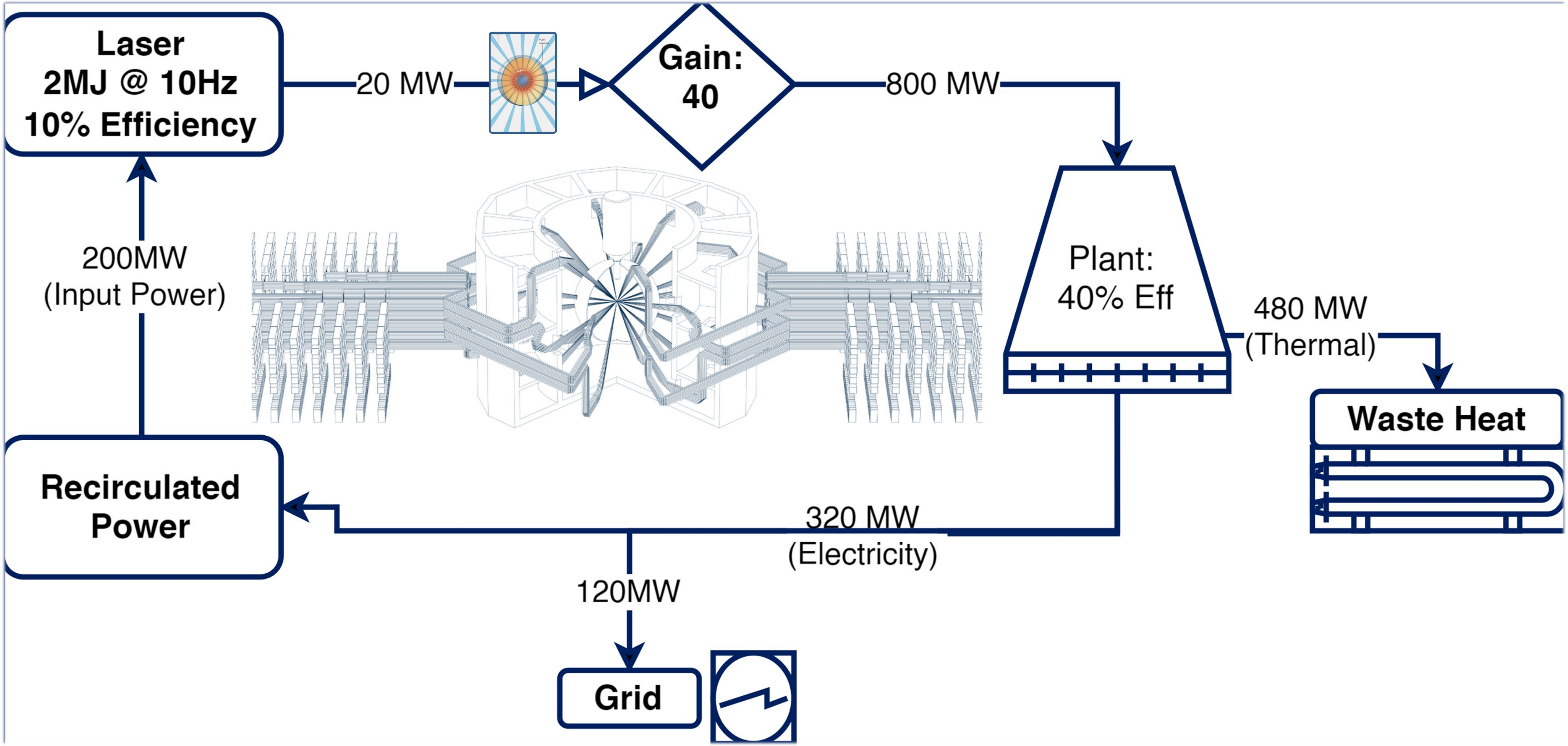
- Experimentally proven gain, Q_{sci}>1
- Standing on the shoulders of giants - built with mature, validated solid-state laser technology
- Known bottleneck ƀ kJ beamlines historically driven by highly-inefficient, performance-degrading flashlamp drivers
- **Switch to Diodes will be much-heralded win for both efficiency and optical performance**

Fusion Power Plant Architecture: From Diode to Deuterium

FOCUSED ENERGY



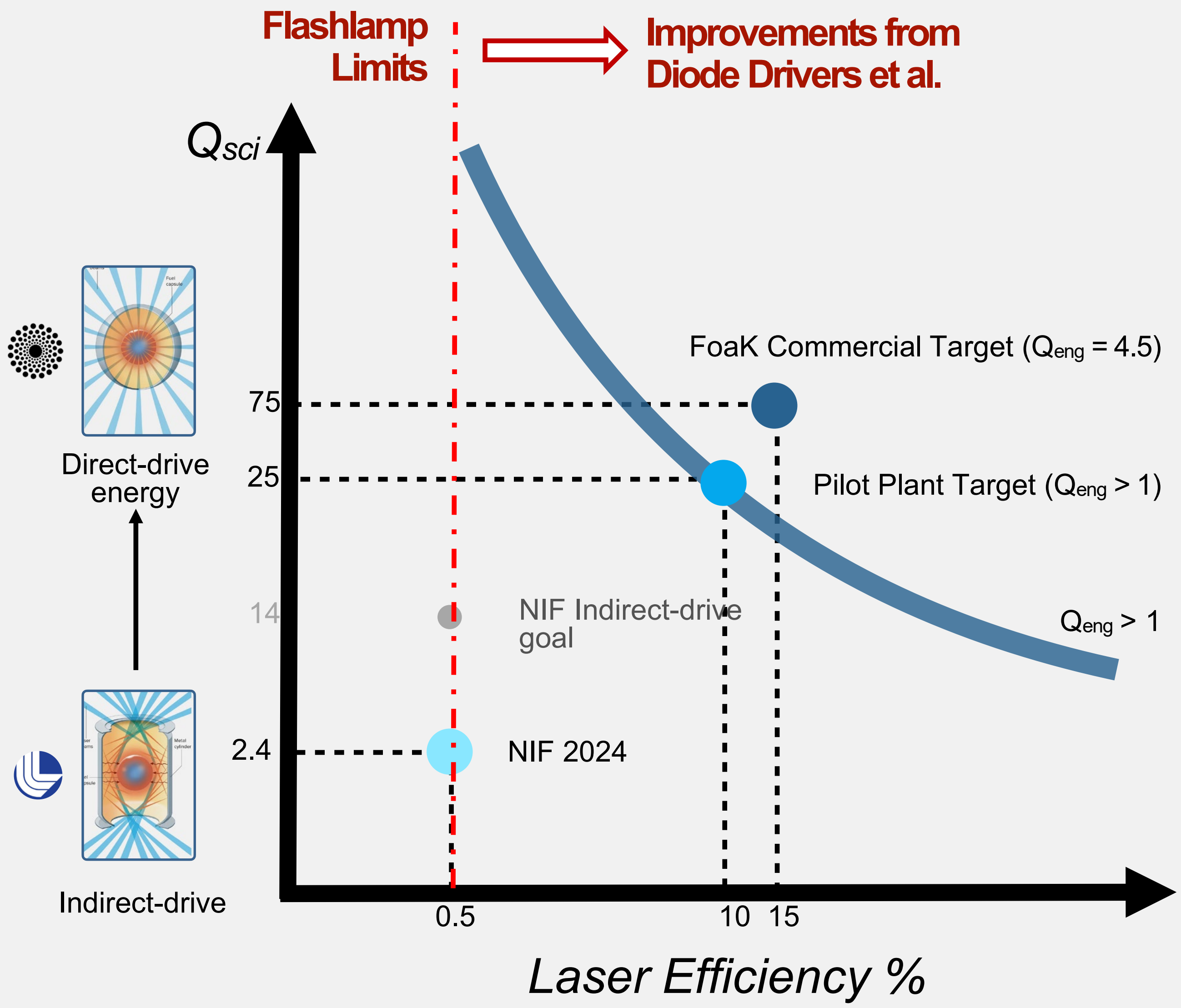
Recirculating Power Schematic of a Fusion Power Plant



Numbers for Illustrative Purposes only

Efficiency gains help derisk target physics for FoaK Facility

FOCUSED ENERGY

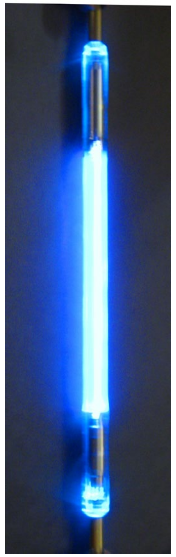


Laser Requirements for IFE Fusion

- **10Hz** Target Feed of mm-sized capsules (Pearl™)
- **True Engineering Gain Q(eng) > 1**
- $\eta_{\text{wall-plug}}$>10%

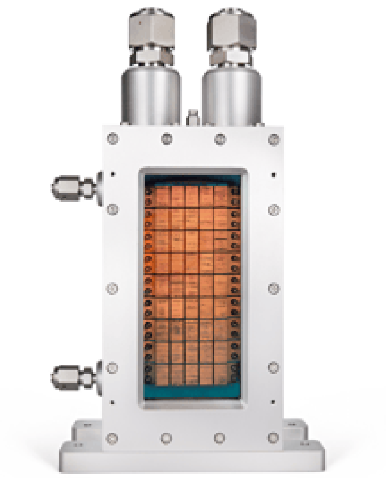
OLD: Flashlamp Drivers

$\eta_{\text{wall-plug}}$<1%



New: Tuned Diode Modules

$\eta_{\text{wall-plug}}$>60%

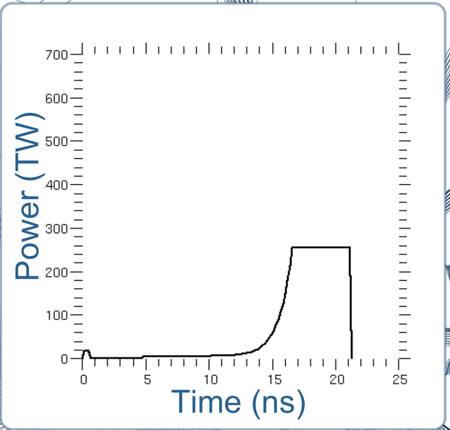


Competing Drive Pulse Shapes to be tested by Targetry Division

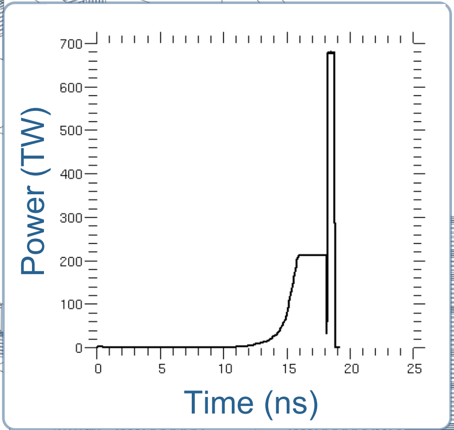
Laser requirements

- **MJ-class facility**
- **Thousands of kJ-class laser systems**
  - High volume for mass manufacturing
  - Reduced aperture to relieve stress on supply chain
  - Power balance, smoothing
- **10 Hz repetition rate**
  - Multi-kW average power
- **Large spectral bandwidth**
  - As part of beam smoothing for laser imprint and LPI mitigation
- **Precise temporal pulse shaping**
- **>10% wall-plug efficiency**

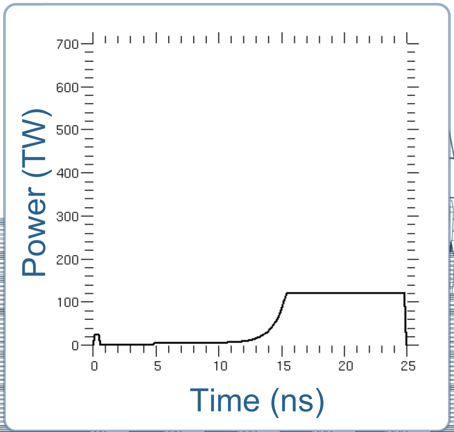
Central Hot Spot



Shock Ignition



Proton Fast Ignition

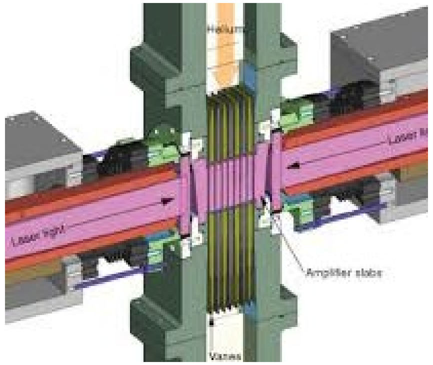


100+ PW ps pulse, high contrast for ignition

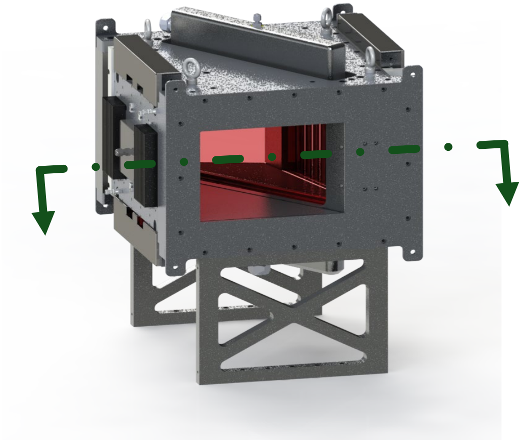
Our Lasers: Cutting-edge light sources and cooling architectures, yet to be seen at scale on existing IFE systems

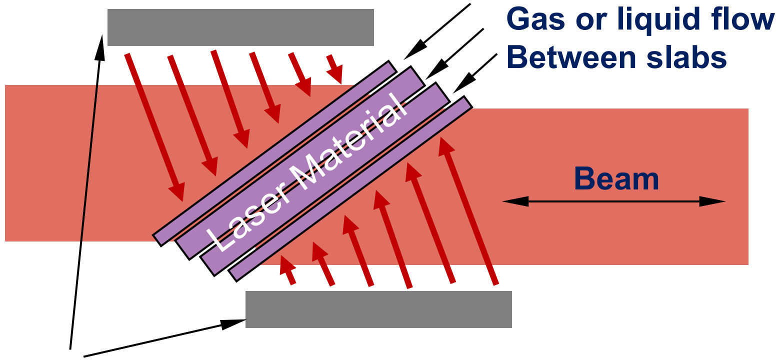
Laser Material

Ion-Doped Glass/Crystal/Ceramic with Active Cooling



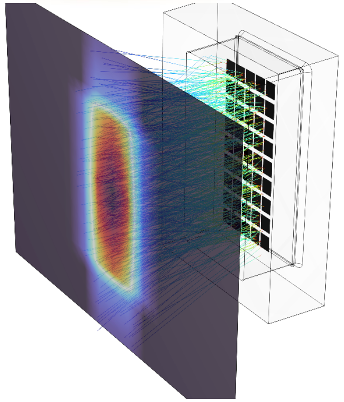
IFE Laser Amplifier Elements





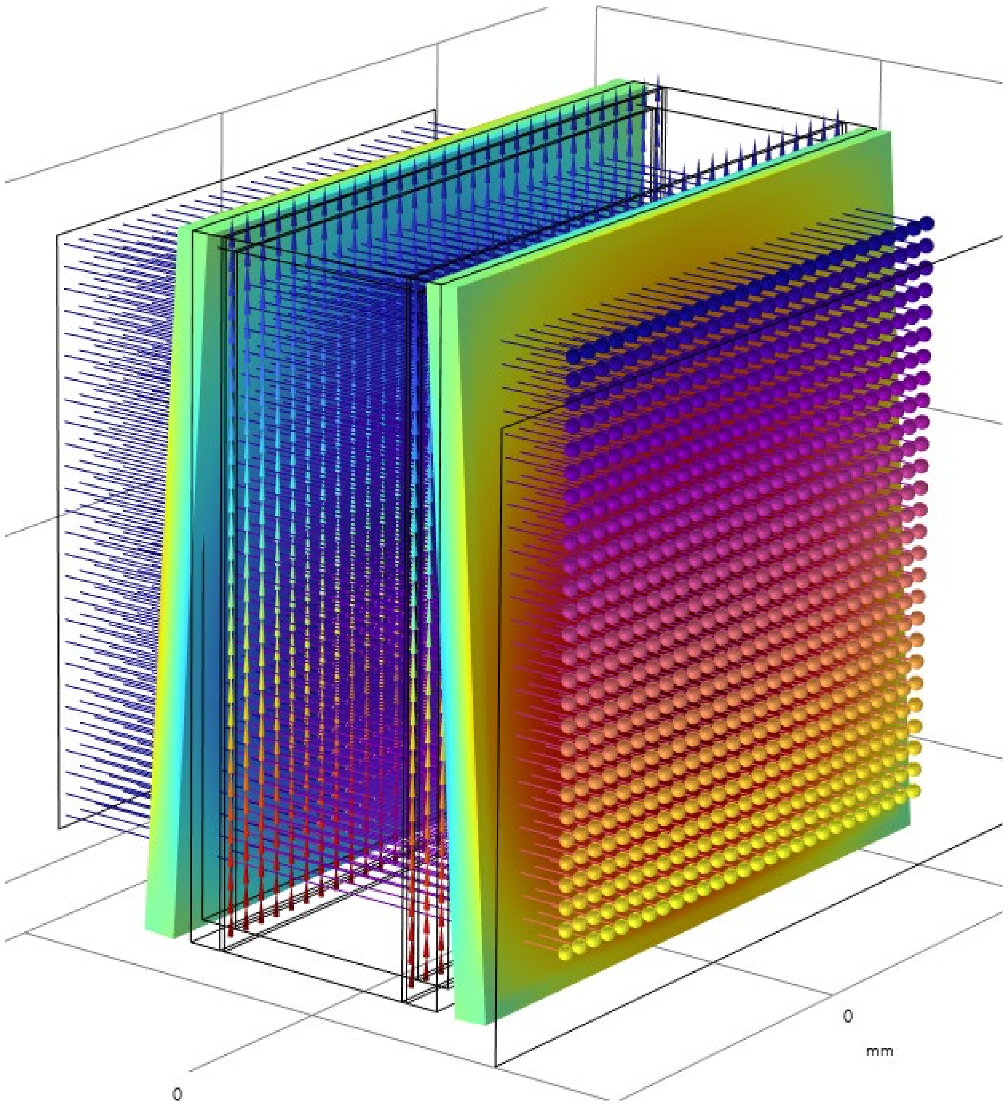
Pump/Excitation Source

Diode or Flashlamp Arrays

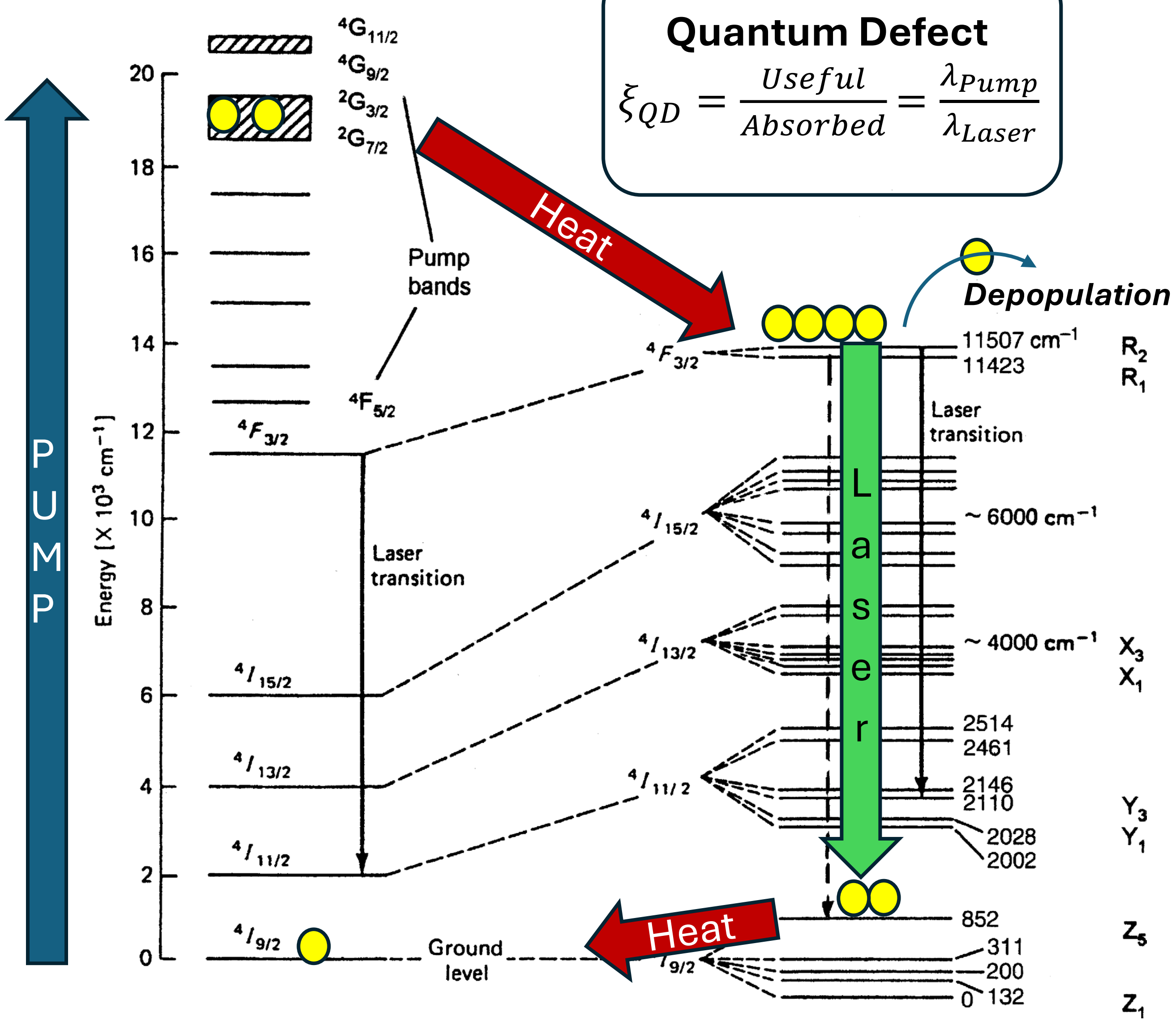


Why COMSOL?

- Custom Ray Tracers exist BUT Propagation models inside materials specific to common industry application (fiber optics, GRIN Lenses)
  - Apply use-case specific simplifications (e.g. Axisymmetric or Small Angle Assumption)
- High Power Laser Amplifier Design is highly multi-disciplinary
  - Electrical, Thermal, Mechanical, Design for Manufacturability, Optics (Ray+Wave), PDEs for Custom Energy Evolution, and more
- Codes developed in past are 30 years old and written in FORTRAN, sometimes C++

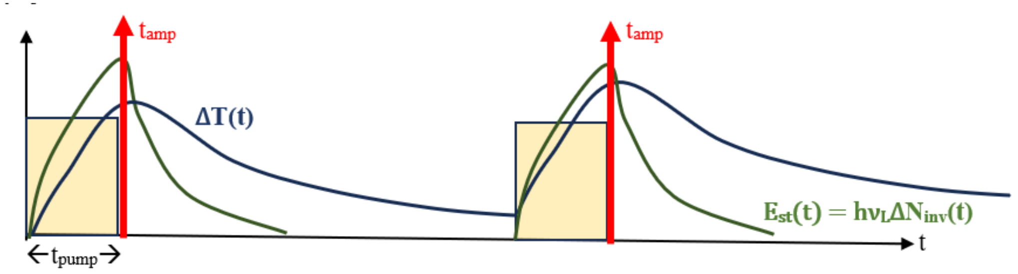


Laser Heat Sources are mix of intrinsic Quantum Energetics and Realities of Engineering Hardware



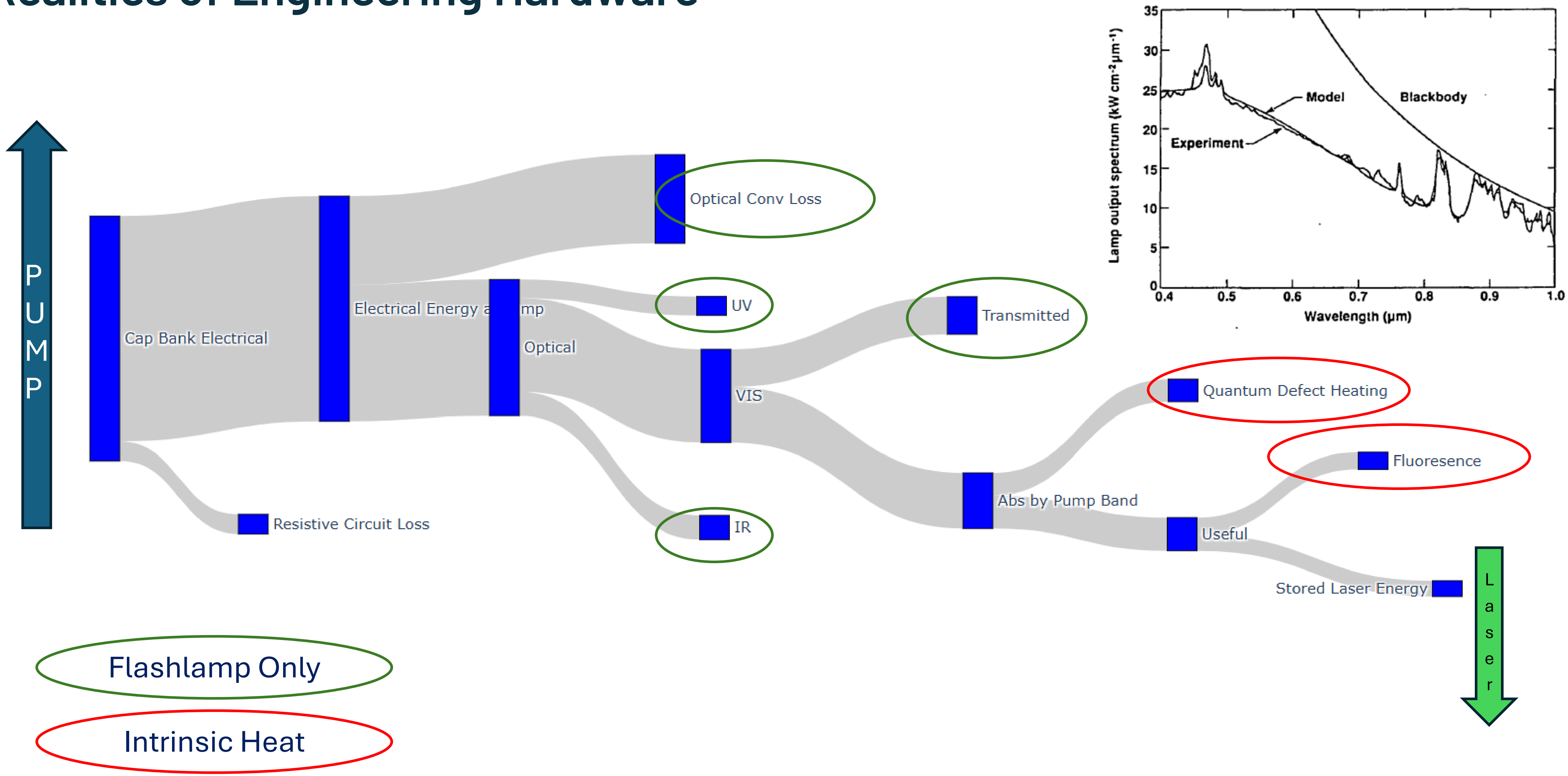
Quantum Defect

$$\xi_{QD} = \frac{Useful}{Absorbed} = \frac{\lambda_{Pump}}{\lambda_{Laser}}$$



- Lasers use multiple Energy Levels with one slow “forbidden” transition to achieve Inversion
- Necessitates Exciting Ions to Pump Band with Higher Energy than Terminal Level creating Excess Heat
- Energetics Modelled on us timescale to get precise picture of Inversion during Laser Transit

Laser Heat Sources are mix of intrinsic Quantum Energetics and Realities of Engineering Hardware



Amplifier Thermo-mechanical-optical behavior drives laser quality

Effect 1: Wavefront and Focusability

→ 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 - $r * dn$

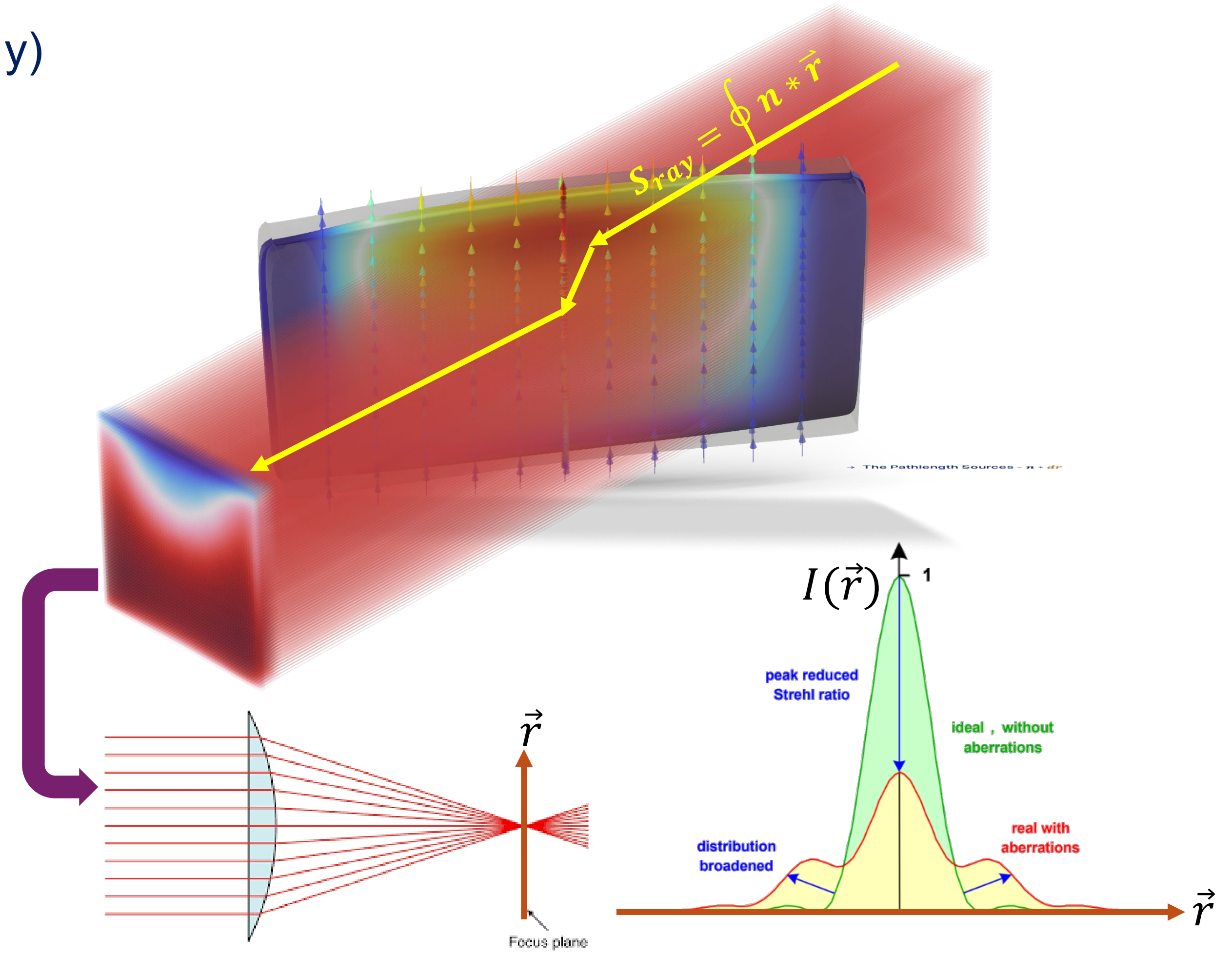
- Stress-Induced Refractive Index Changes: $\sum \left(\frac{\partial n_{ij}}{\partial \sigma_{kl}}\right)_{ijkl} * \sigma_{kl}(\vec{r})$
  - Thermal stress
  - Mechanical Mounting
- Thermally-induced Refractive Index Changes - $\frac{\partial n}{\partial T} * \Delta T(\vec{r})$

→ The Pathlength Sources - $n * dr$

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

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 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)

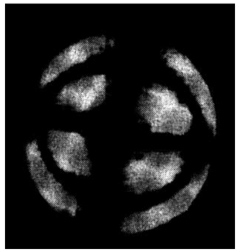
- Local Index Tensor misalignment with Polarization Axis will cause Local Birefringence and Depolarization

- Secondary Beams can result from this misalignment

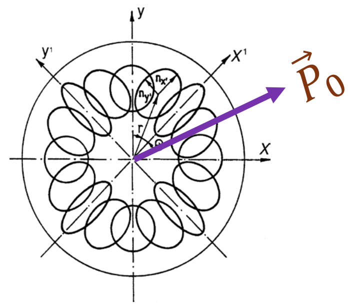
- Secondary Beams will not survive optical propagation and is lost energy (Lower Fusion Driver Efficiency)

How does Polarization effect laser quality?

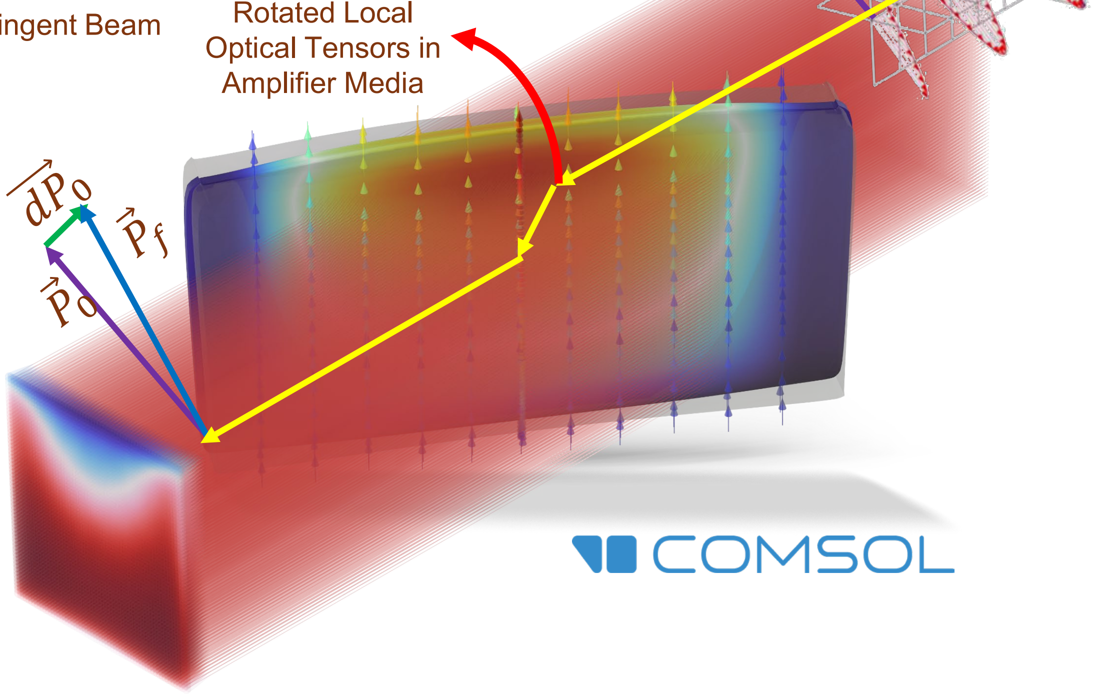
- Laser is optimized for single polarization
- Other polarizations will be quickly removed --> Energy loss



Birefringent Beam



Rotated Local Optical Tensors in Amplifier Media



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

Pumping (COMSOL)
- Pump Light Ray-Trace
- Excited State Energy Deposition

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

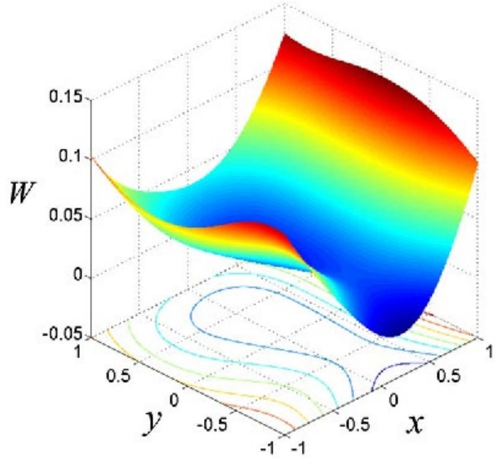
Energetics (CUDA C/C++)
- Transient Laser Energetics
- Thermal Energy Storage

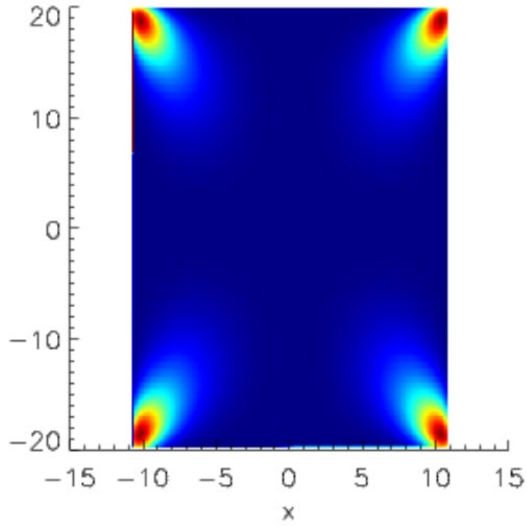
Heat Map: $Q(t,\vec{r})$

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

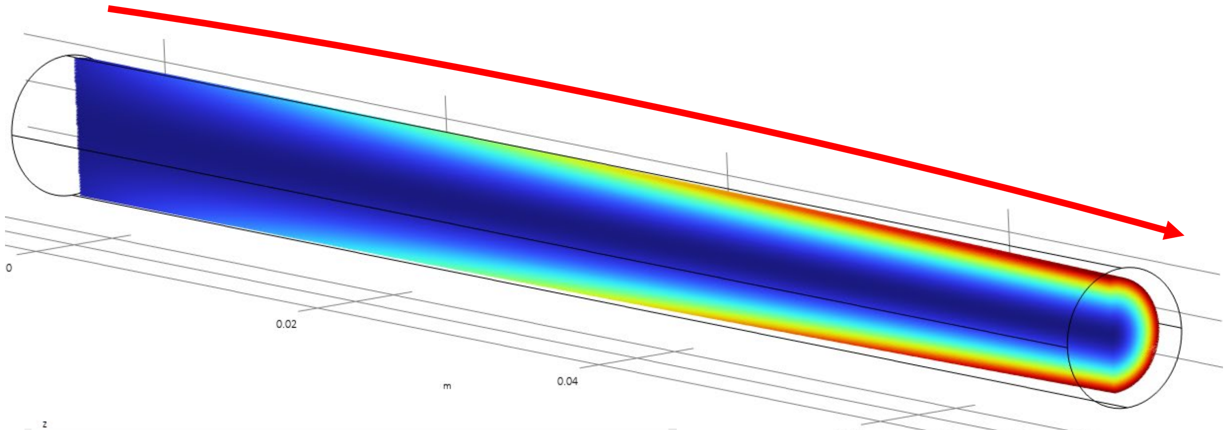
Index of Refraction Map - $n_{ij}(t,\vec{r},\lambda)$
Deformed Optics Surfaces

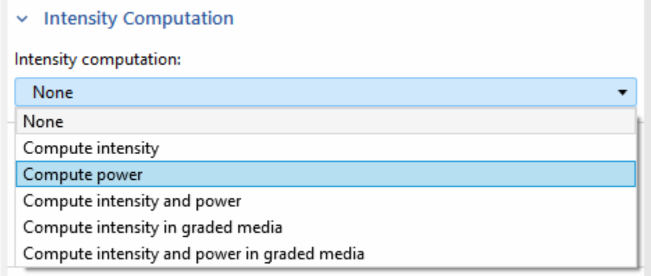
Propagation (COMSOL)
- Thermo-Optic Distortions
- Local Birefringence
- Propagation thru Deformed Optics





“Bending” of Light media requires fine time-stepping within Domain

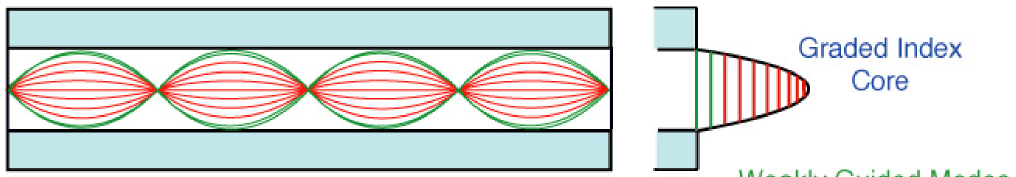




Optics with spatial variation in Temperature, Stress, or Doping have graded index → Curving of Light Rays

- Used for Fiber Optics Communication requiring low modal dispersion

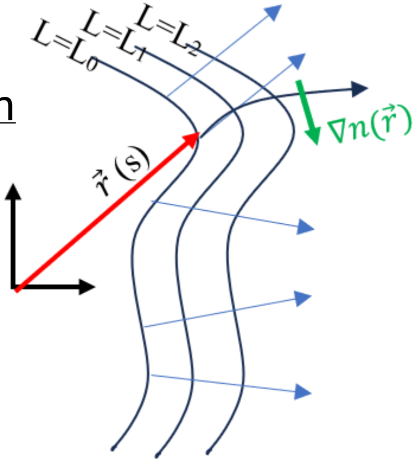
COMSOL provides option to update Intensity/Power of Rays as they converge or diverge from one another

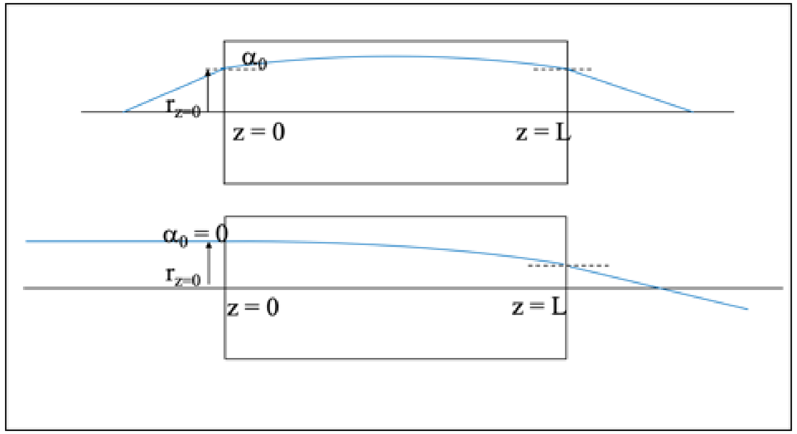


Multimode, Graded Index

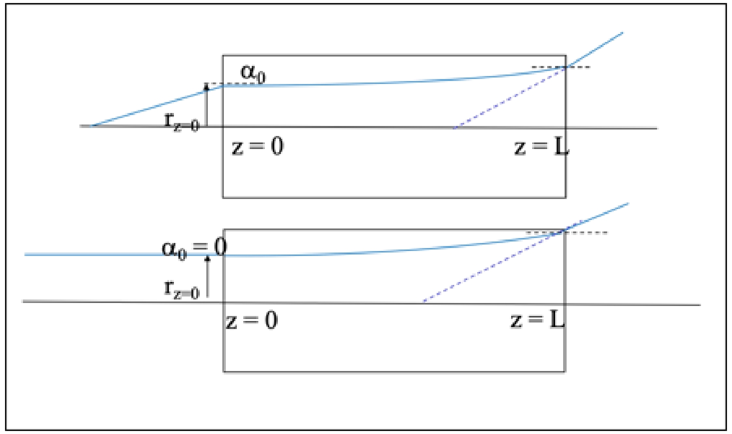
Eikonal Ray Equation

$$\nabla n(\vec{r}) = \frac{\partial}{\partial s}\left(n \frac{d\vec{r}}{ds}\right)$$



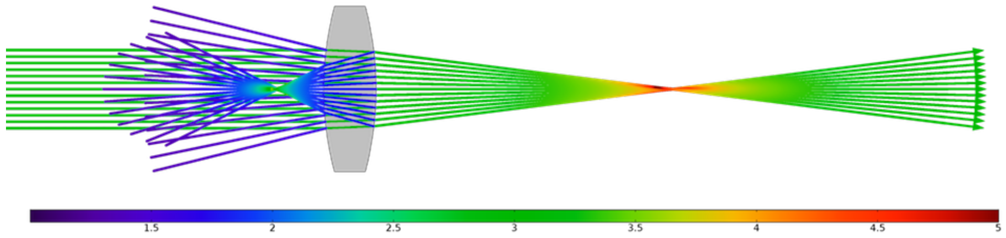


Positive Gradient → Converging



Negative Gradient → Diverging

COMSOL Solves Spectral Version of Eikonal Equation



$$\begin{cases} \dfrac{d\mathbf{k}}{dt} = -\dfrac{d\omega}{dr} \\ \dfrac{d\mathbf{r}}{dt} = \dfrac{d\omega}{dk} \end{cases} \rightarrow \frac{\partial}{\partial t}\begin{pmatrix} kx \\ ky \\ kz \\ rx \\ ry \\ rz \end{pmatrix} = \begin{pmatrix} -\dfrac{d\omega}{dx} \\ -\dfrac{d\omega}{dy} \\ -\dfrac{d\omega}{dz} \\ v_{g,x} \\ v_{g,y} \\ v_{g,z} \end{pmatrix} = \begin{pmatrix} -\dfrac{\partial\omega}{\partial n}\dfrac{\partial n}{\partial x} \\ -\dfrac{\partial\omega}{\partial n}\dfrac{\partial n}{\partial y} \\ -\dfrac{\partial\omega}{\partial n}\dfrac{\partial n}{\partial z} \\ v_{g,x} \\ v_{g,y} \\ v_{g,z} \end{pmatrix} = f\left(\omega\left(k(\lambda), n(r,\lambda)\right)\right)$$

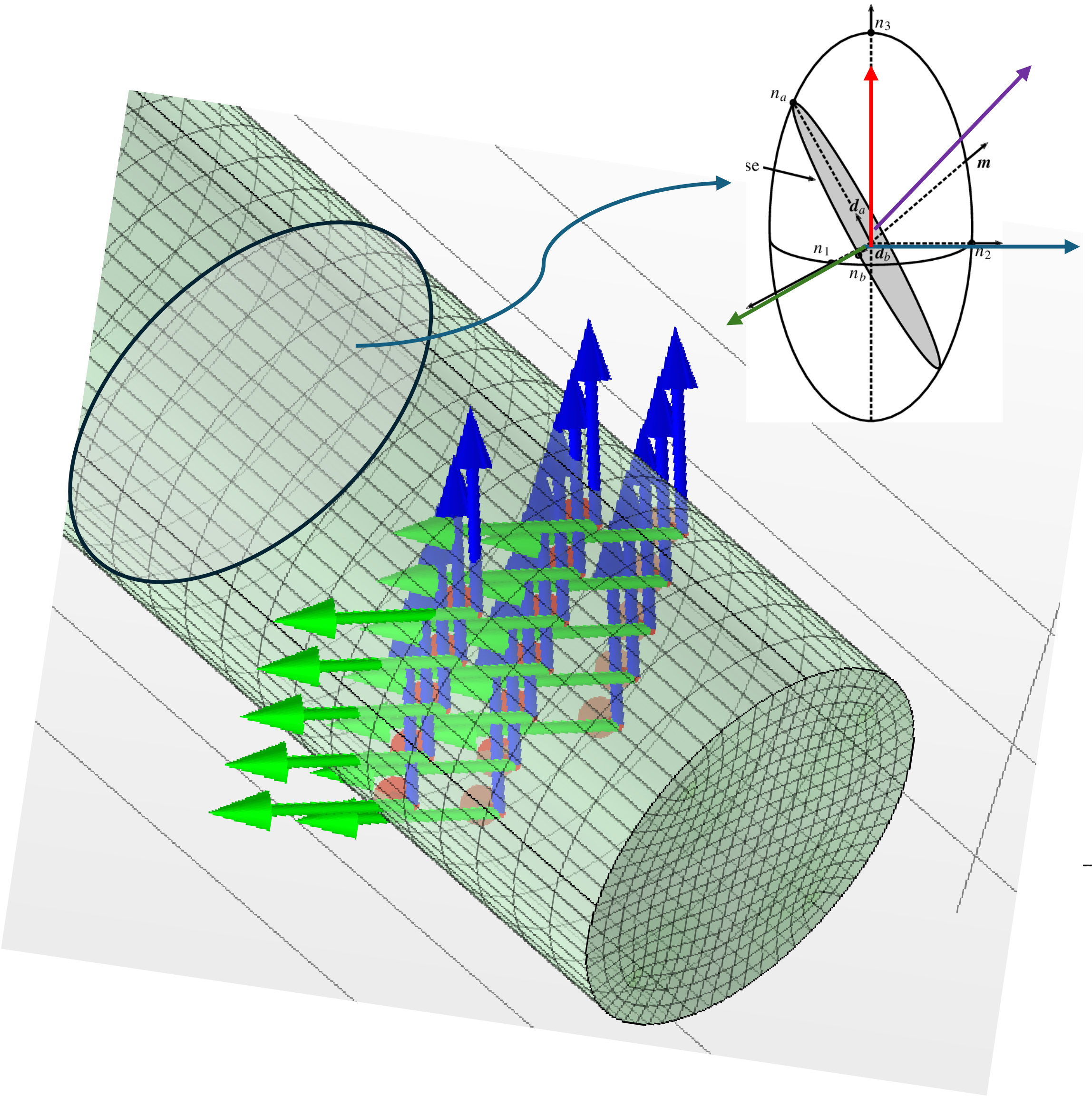
- Equation is only valid for small λ
  - This is generally satisfied for optical wavelengths of interest.

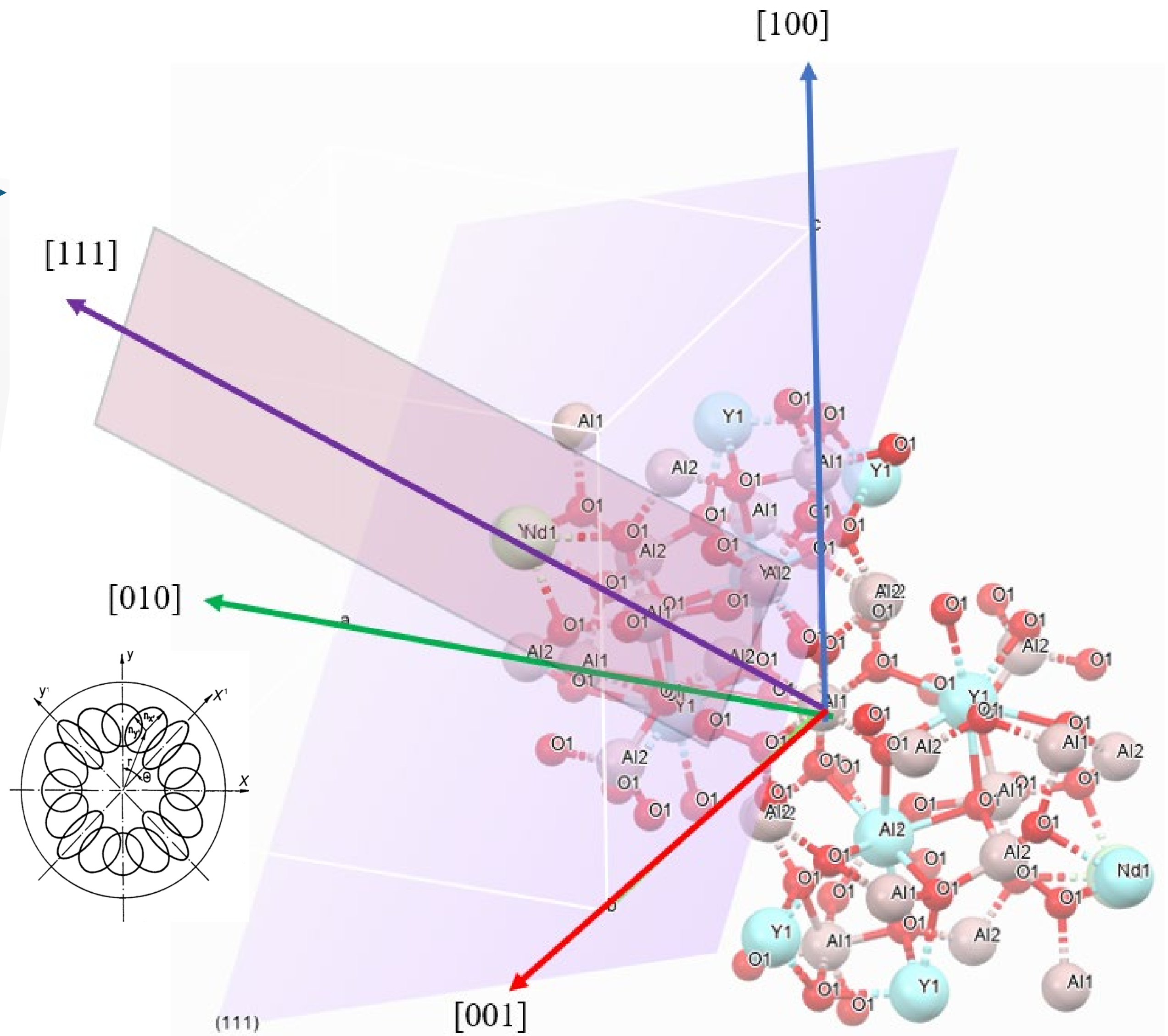
- **Ignores any effects from diffraction, interference, and polarization (Wave Optics Module)**
  - Light rays cross without interaction
  - Cannot intrinsically capture interference physics of coatings (e.g. multilayer dielectrics)
  - Misprediction of far-fields, will not capture diffraction limits at focus
  - Intrinsically assumes a scalar refractive index, independent of polarization

- Assumes infinitesimal extent, or zero thickness, for a ray at any given instant

- Objects must be much larger than the optical wavelength

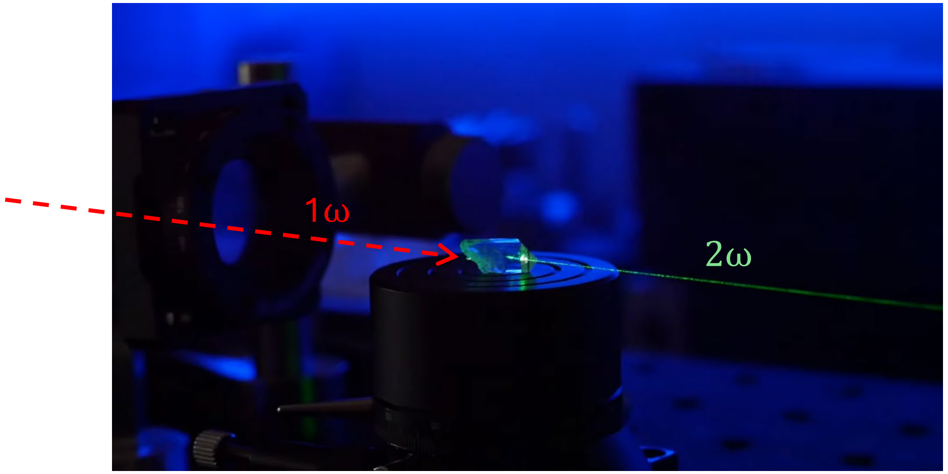
Laser Media requires Tensor Analysis for each local Crystal Axes and k-vector

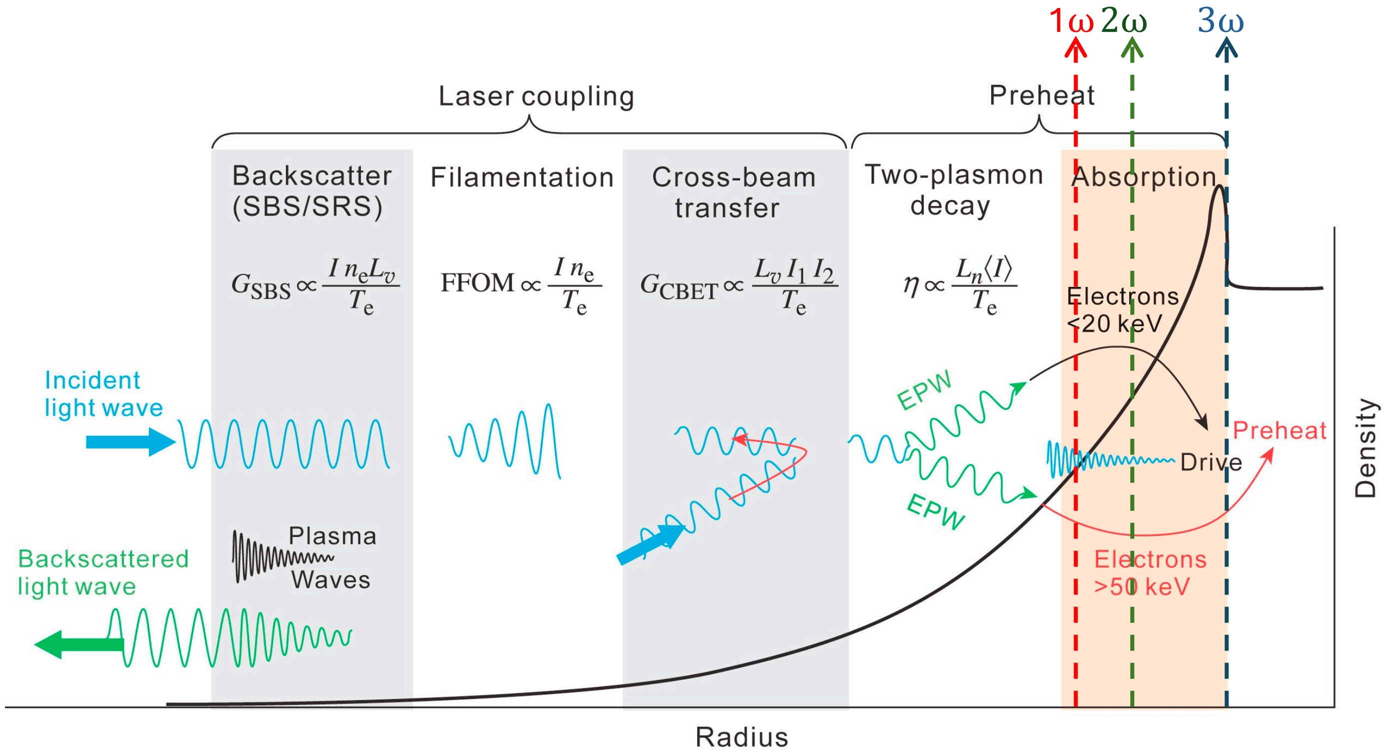


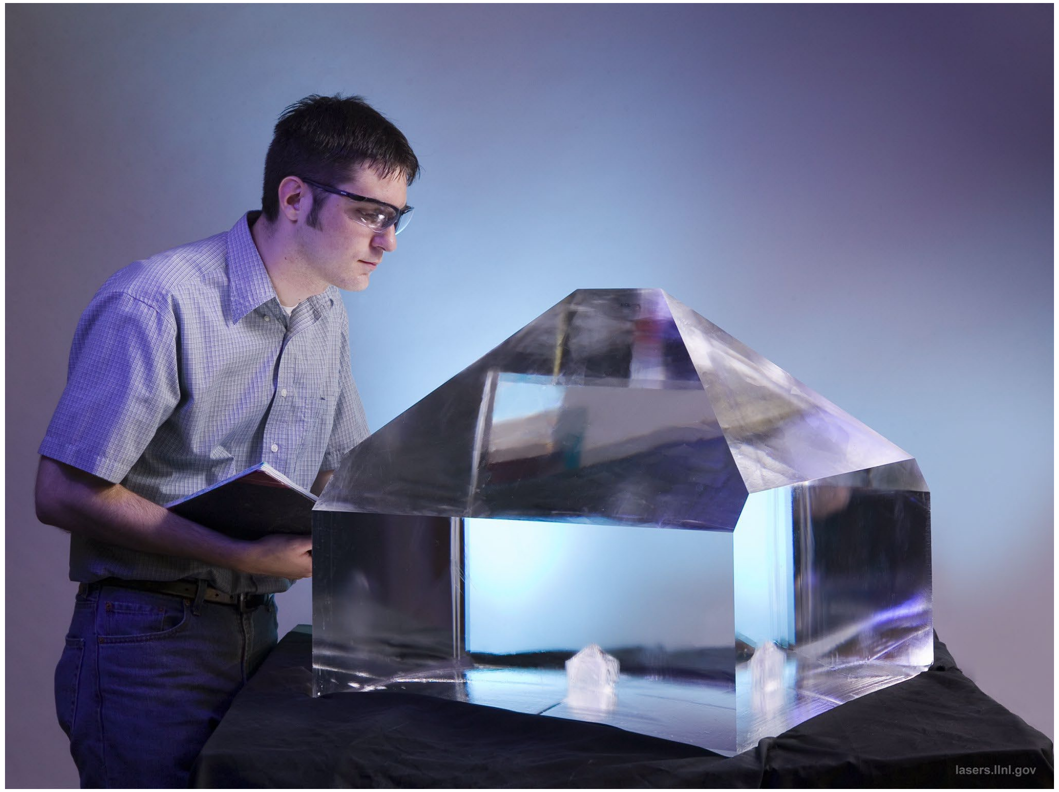


Freq. Doubling Crystals also critical multiphysics process to be modelled

- Shorter Wavelength light (more blue) couples farther into the Target Plasma
  - $n_c = \frac{m_e}{4\pi e^2}\omega_{Laser}^2$
- Frequency Doubling Crystals used as penultimate optical step before focus and fusion
  - Temperature Dependent Efficiency







Microchannels inherit distortions from Optics – Moving Mesh Implemented

- Treats Domain as “Rubber” that expands according to Boundary Conditions inherited from Solid Mechanics problem
  - Minimizes Strain Energy W

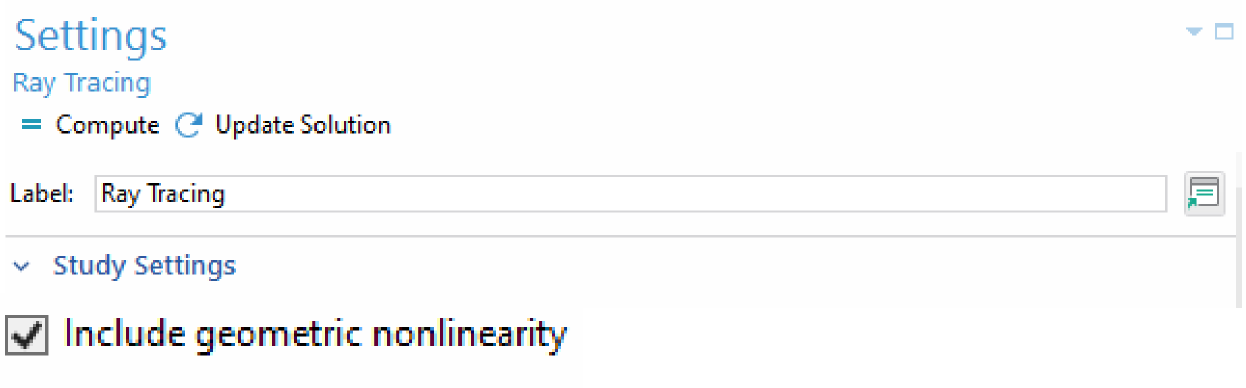
$$W = \frac{1}{2}\int_{\Omega} C_1(I_1-3)+C_2(I_1-3)^2+C_3(I_1-3)^3+\kappa(J-1)^2 dV$$

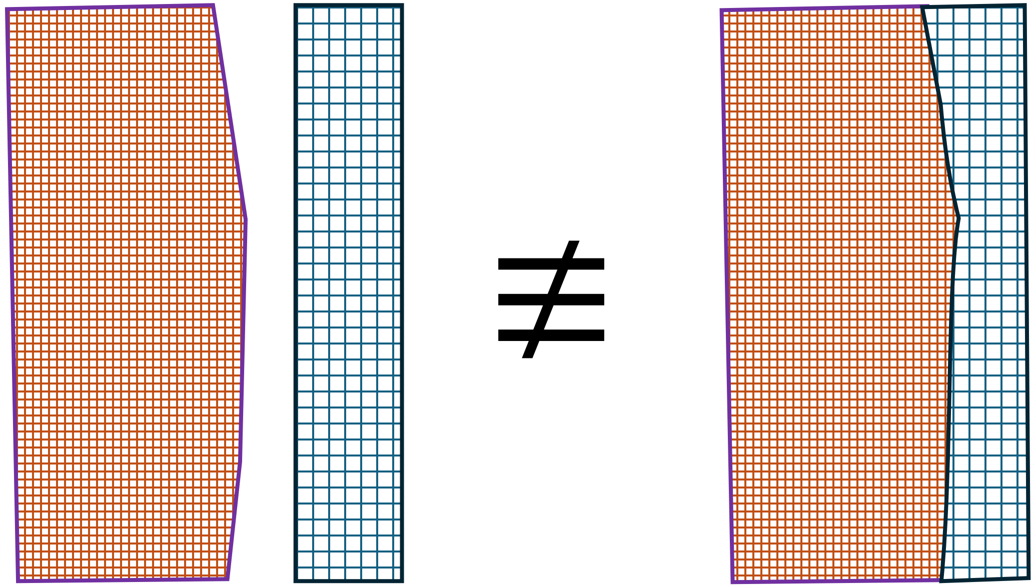
- Necessary to model since laser travels THRU microchannel and must have sub-micron accuracy of the optical pathlength

$$OPD = \sum OPD_{Fluid} + \sum OPD_{Solid}$$

- Light Propagation solved in Material Frame as denoted by “Include Geometric Nonlinearity”
  - Surface locations, refractive index, pathlengths evaluated in Deformed Mesh

$$\mathbf{x} = \mathbf{x}(\mathbf{X}, t) = \mathbf{X} + \mathbf{u}(\mathbf{X}, t)$$

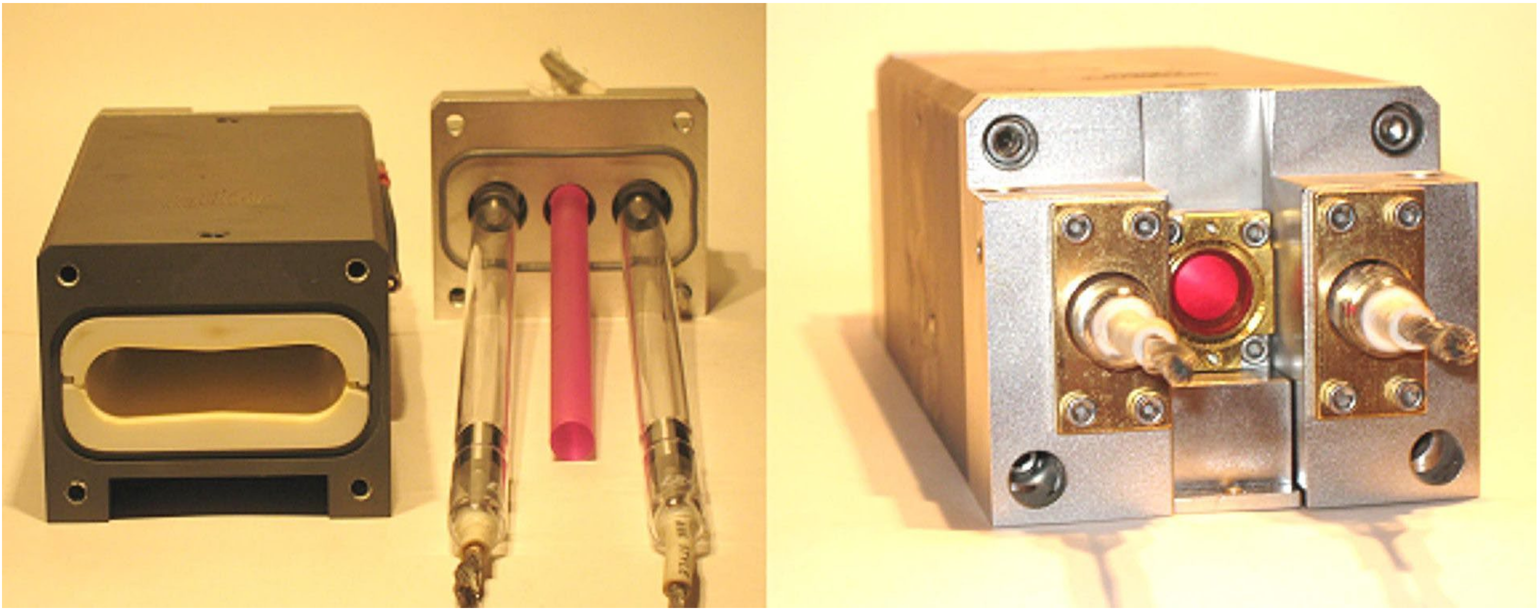


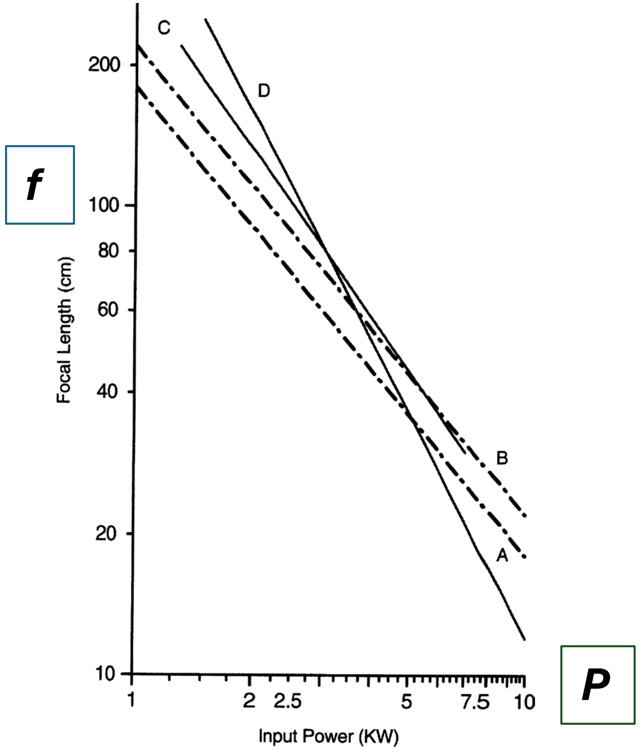


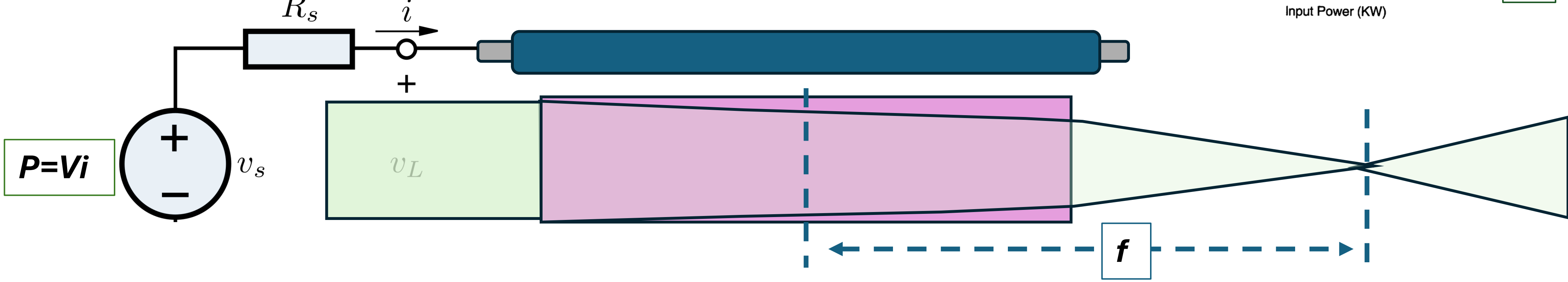
Propagation with Just Solid Mechanics

Propagation with Dynamic Fluid Domains

Code benchmarking relative to known performance of existing Simulation Codes using Rod Amplifier



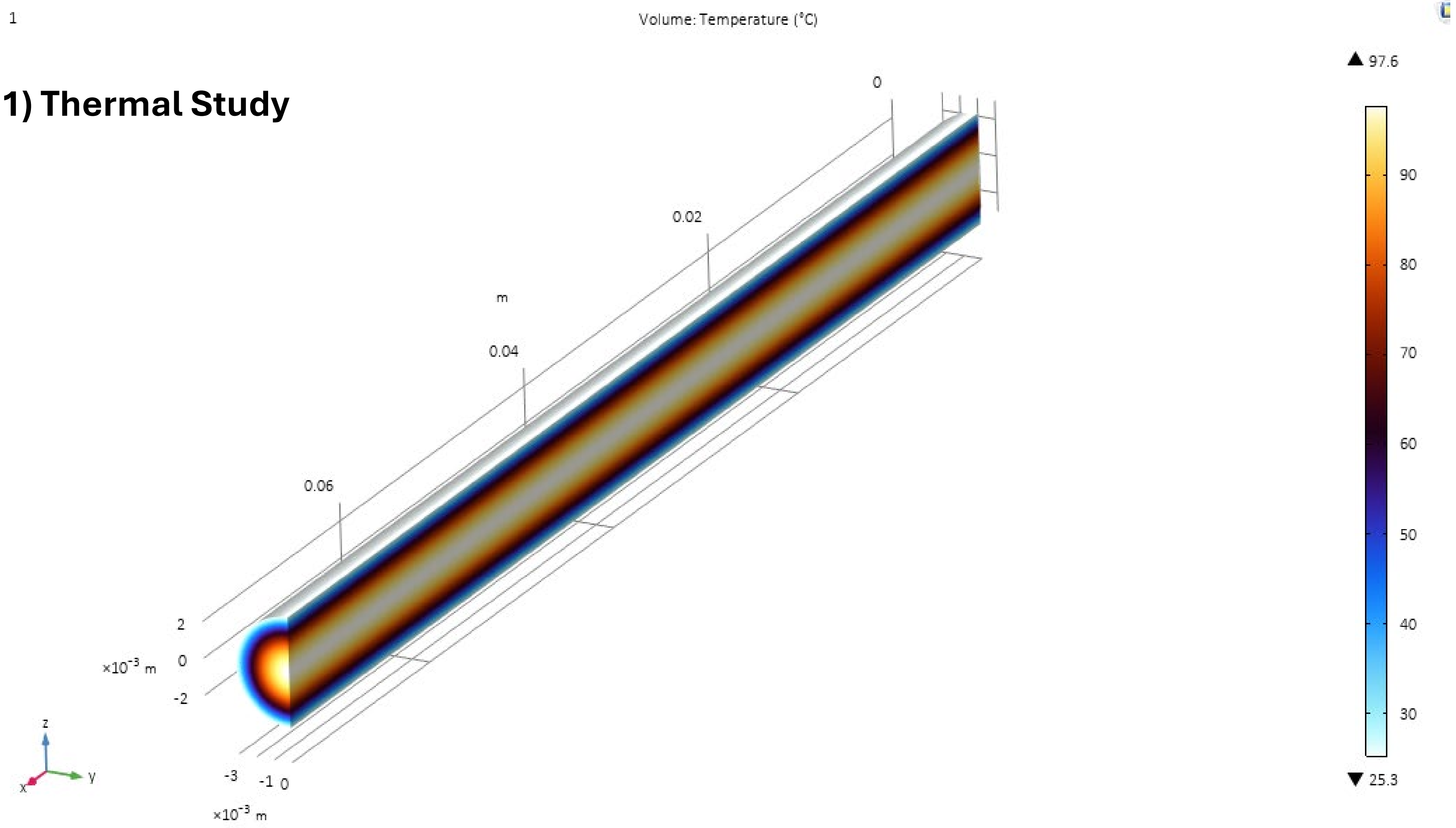




→ Well documented Canonical Case – Simulate-able in Many Commercial Codes

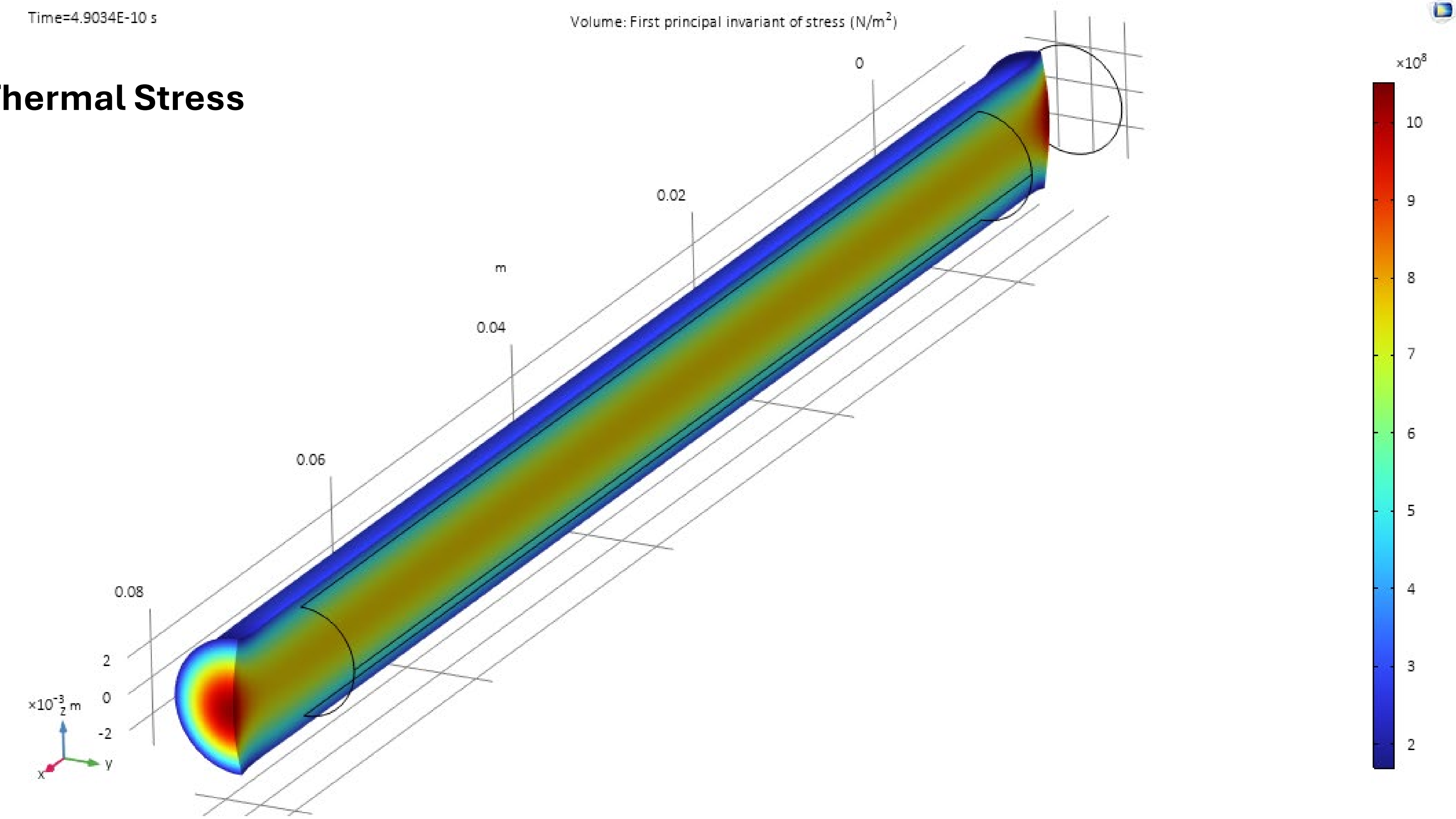
Code benchmarking relative to known performance of existing Simulation Codes using Rod Amplifier

1) Thermal Study

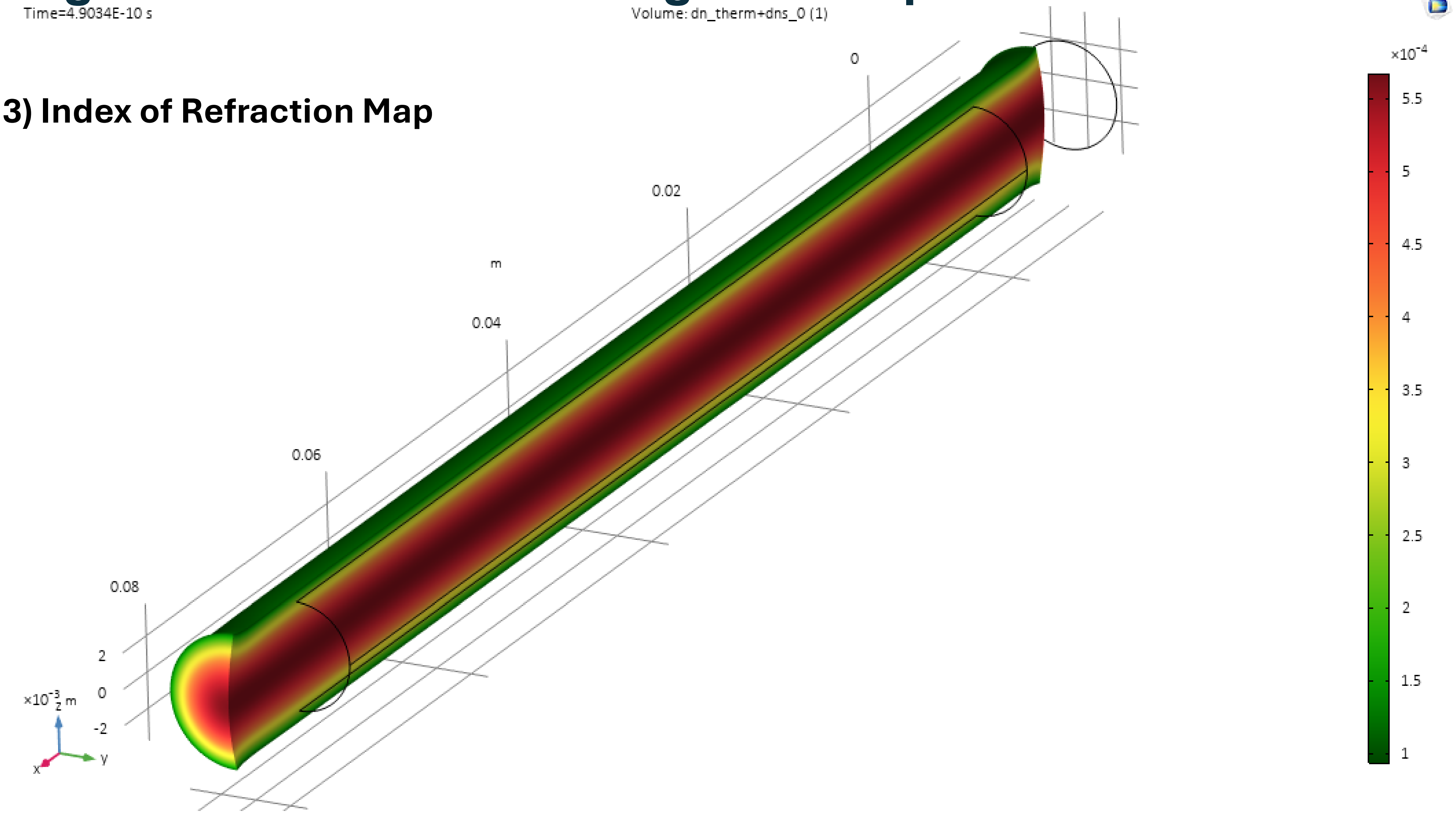


Code benchmarking relative to known performance of existing Simulation Codes using Rod Amplifier

2) Thermal Stress



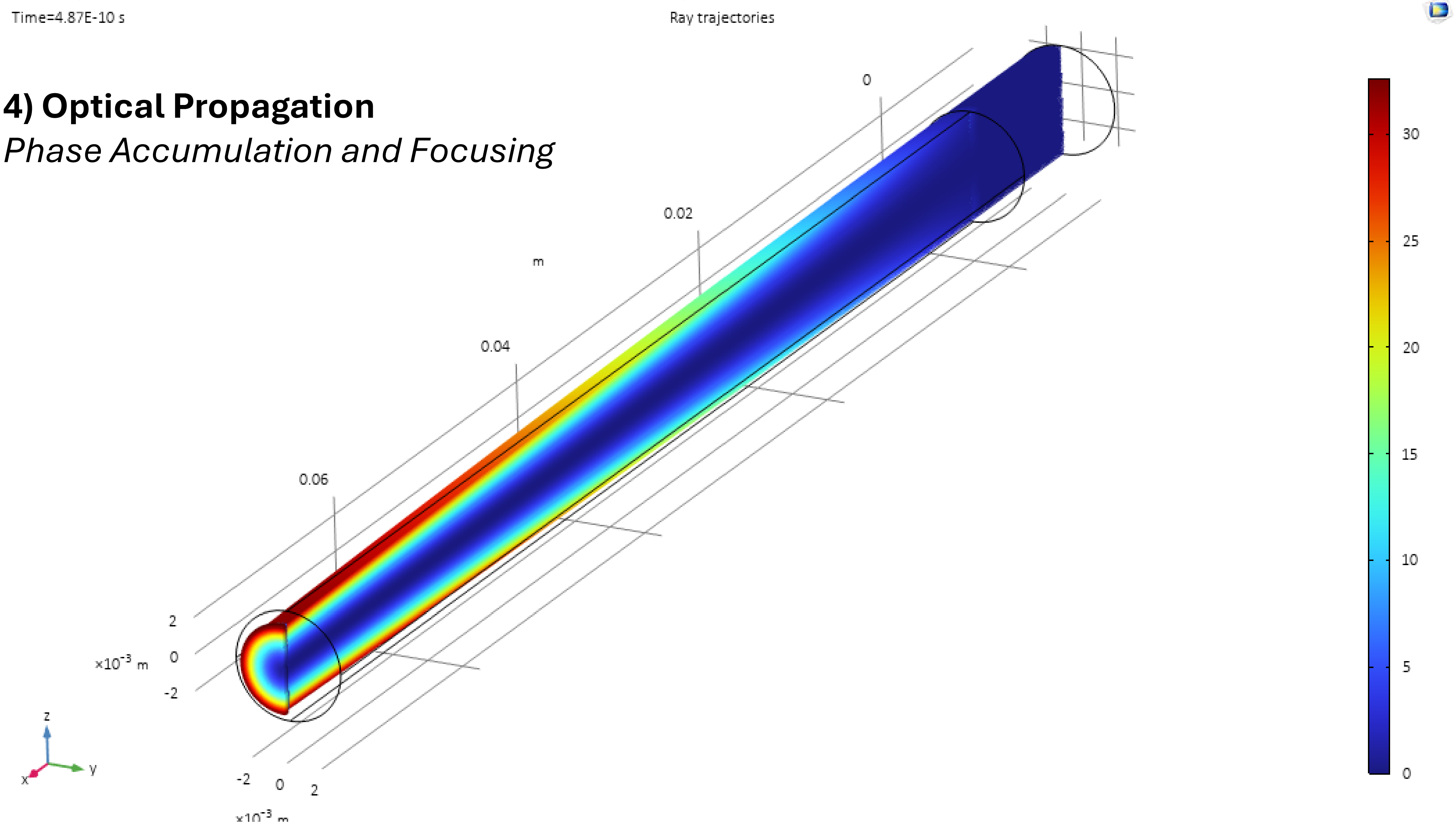
Code benchmarking relative to known performance of existing Simulation Codes using Rod Amplifier



Code benchmarking relative to known performance of existing Simulation Codes using Rod Amplifier

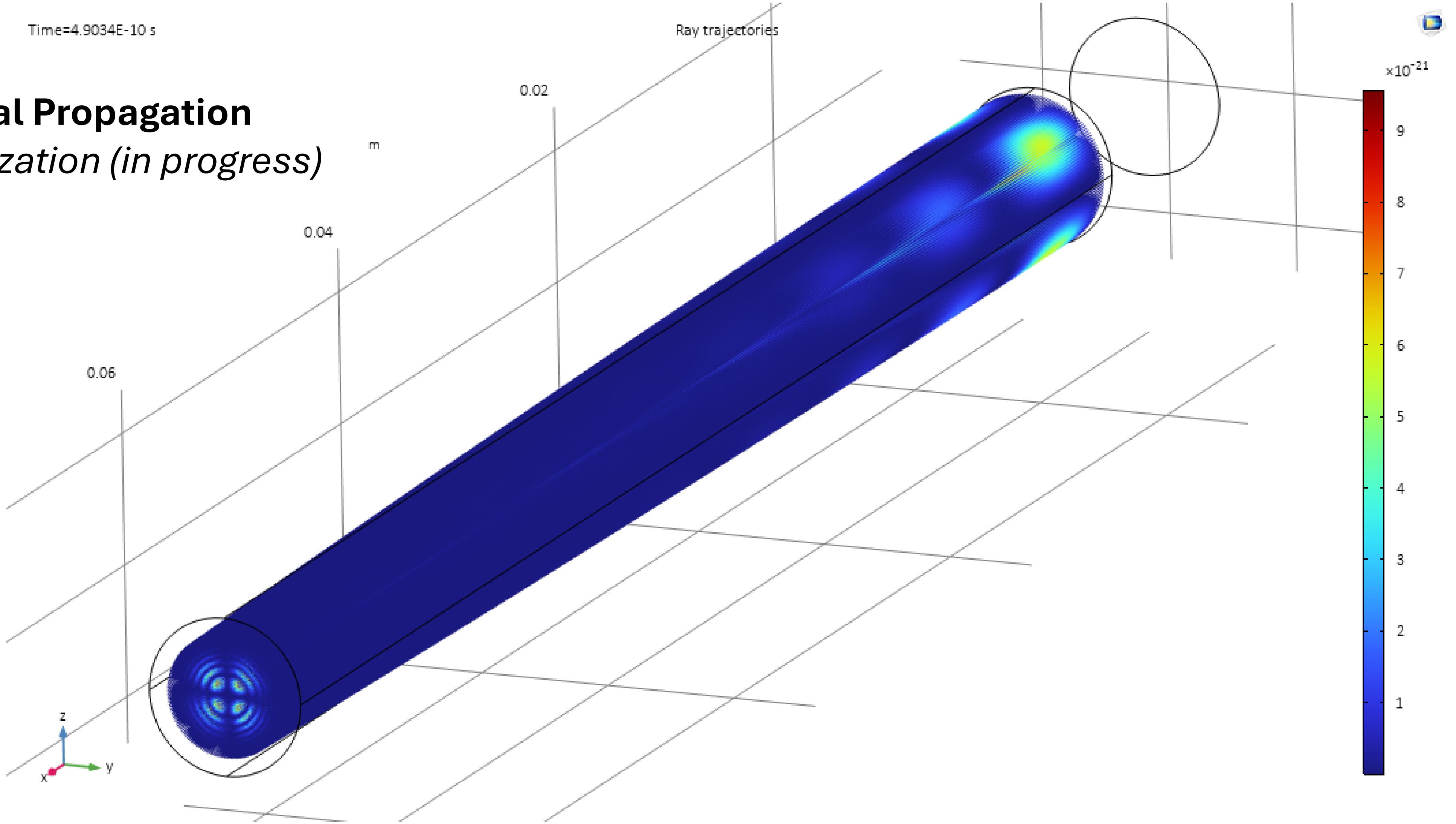
4) Optical Propagation

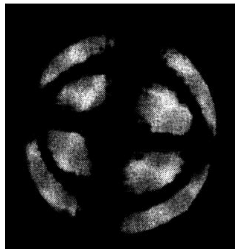
Phase Accumulation and Focusing



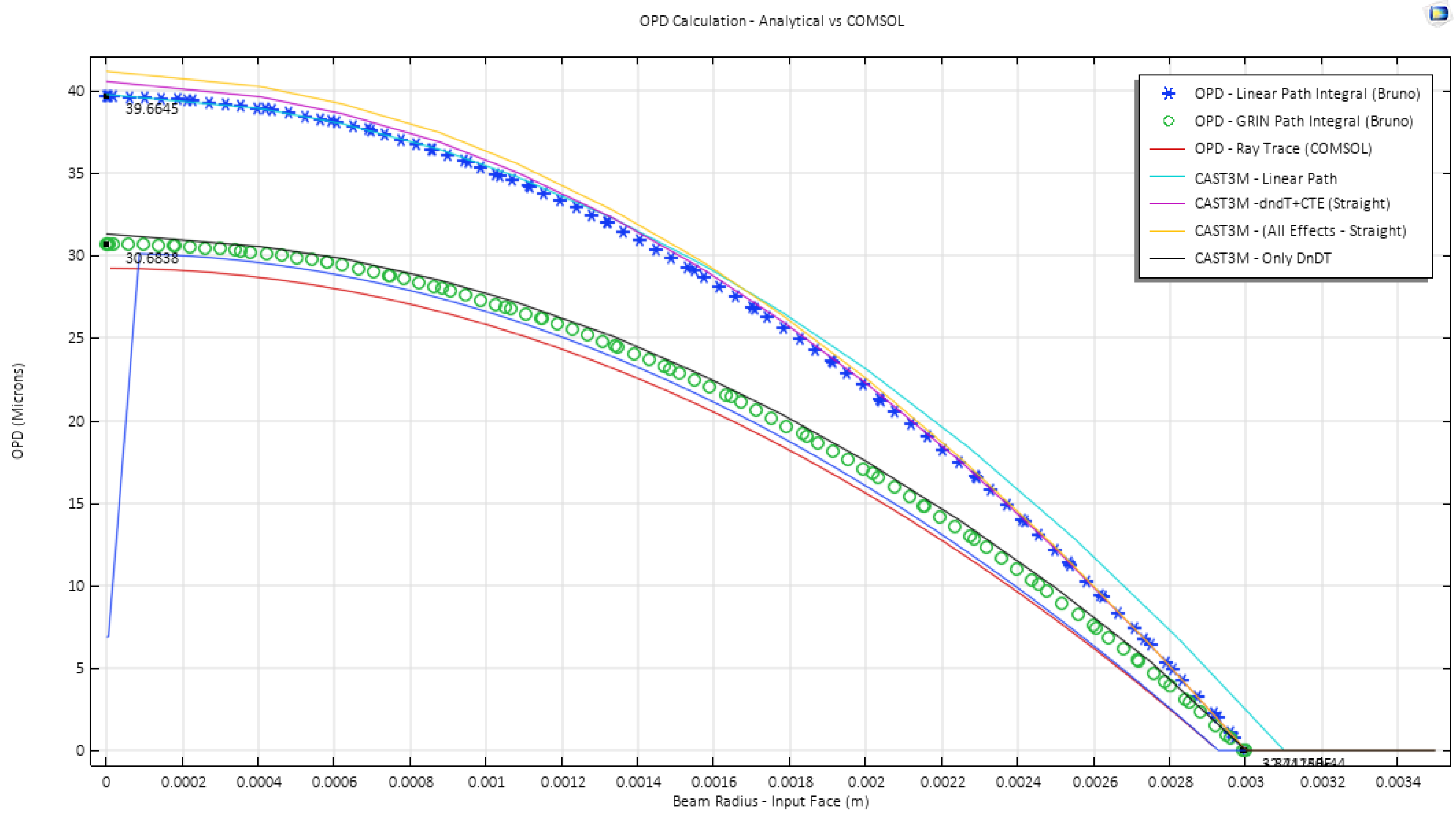
Code benchmarking relative to known performance of existing Simulation Codes

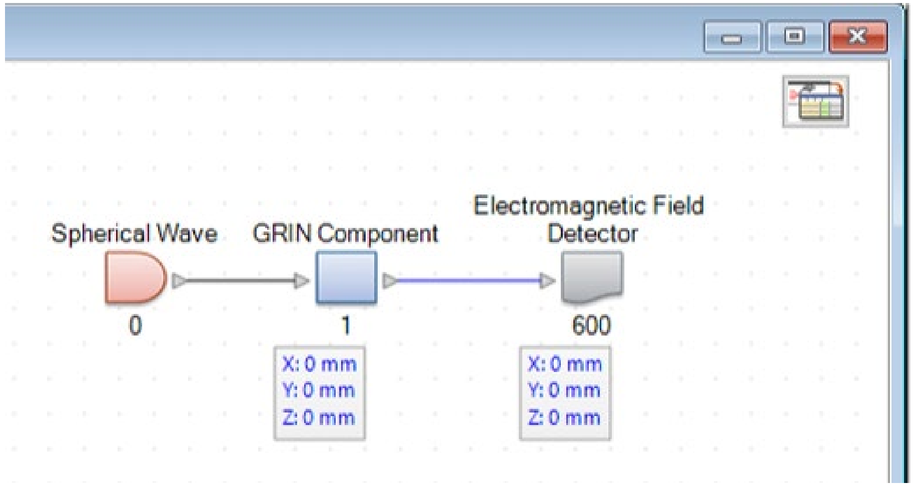
5) Optical Propagation
Depolarization (in progress)

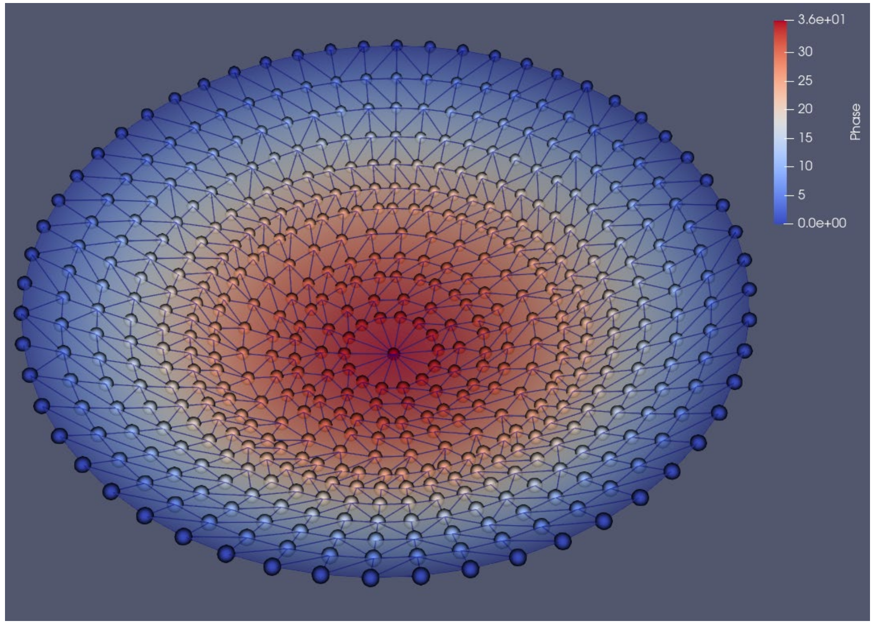




Code benchmarking relative to known performance of existing Simulation Codes

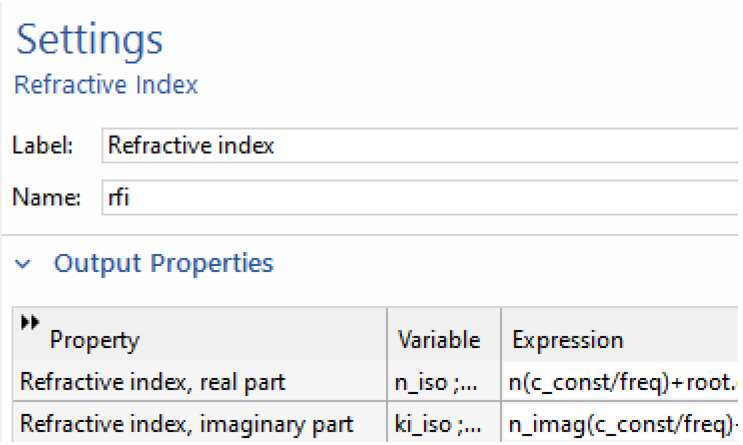




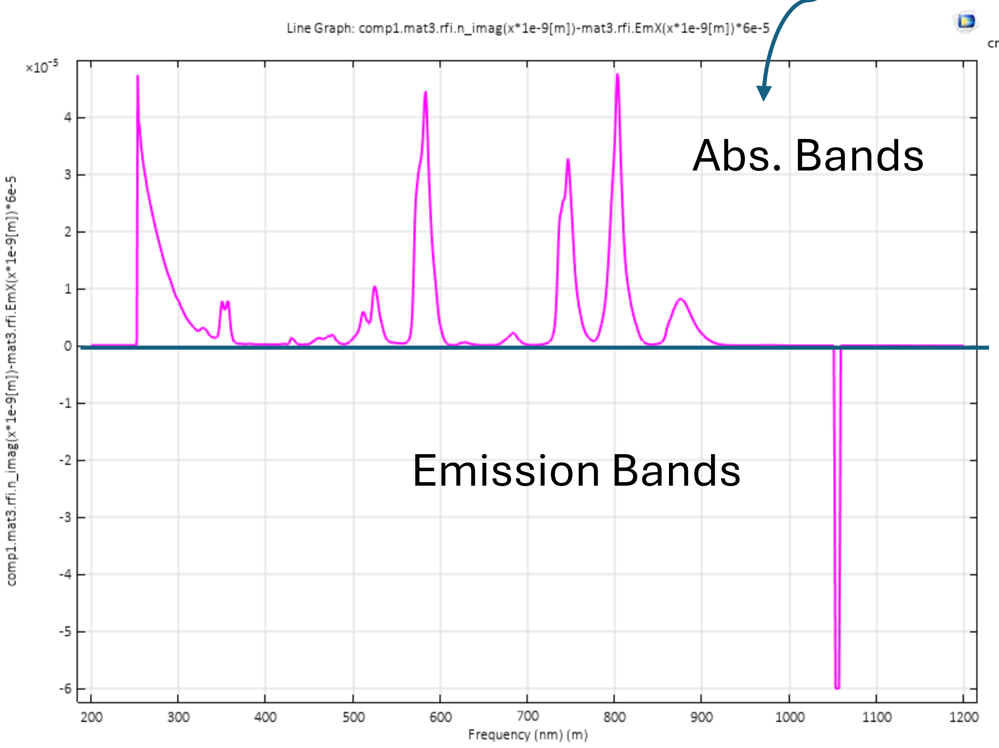


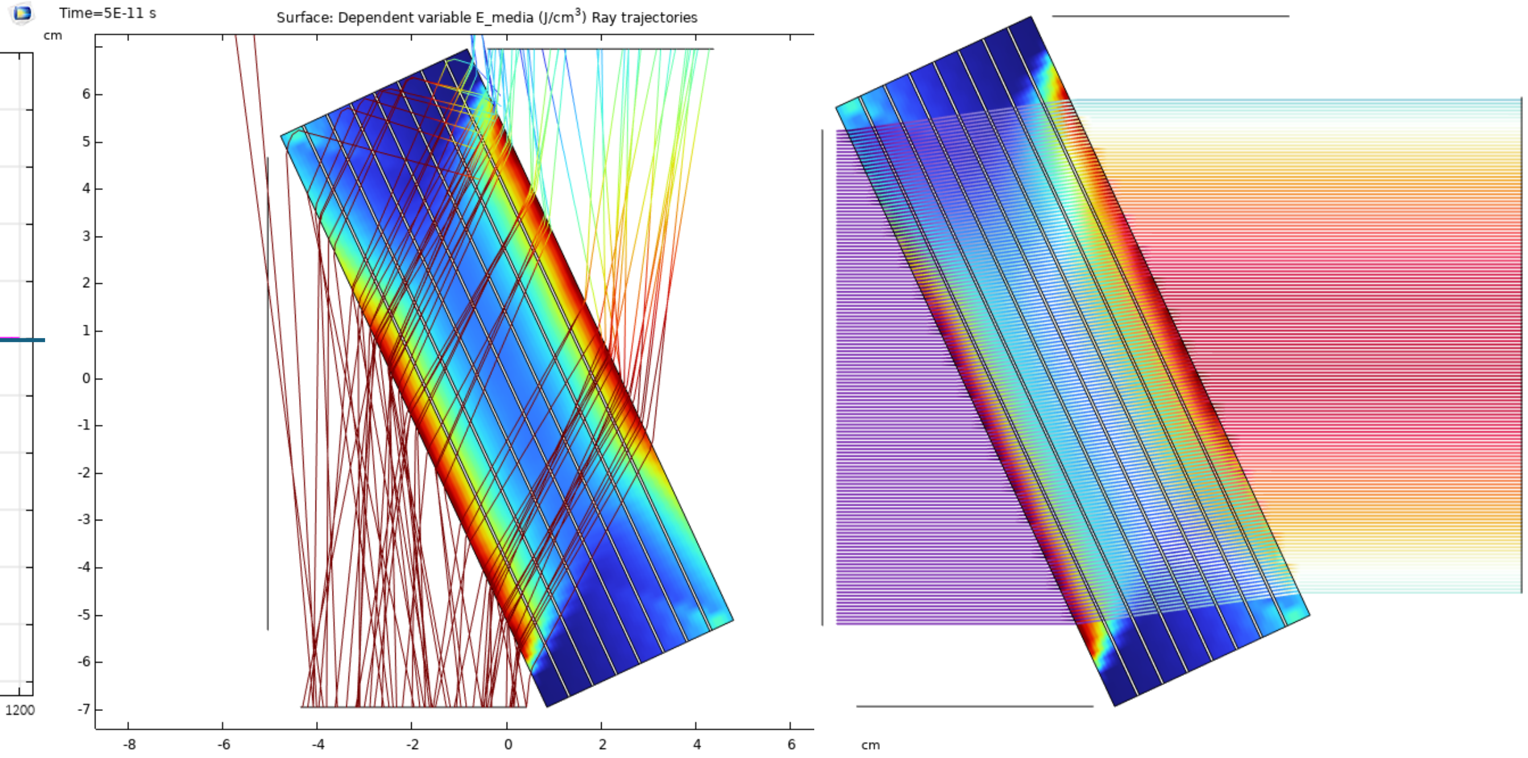
Complex Refractive Index provides Option for Simultaneous Absorption/Gain Modelling

- Resolution of k term as frequency dependent complex number leveraged to include Gain as Laser Performance Metric



$$E = E_0 e^{i\omega t} e^{-i n_0 k_0 z} \boxed{e^{-\kappa k_0 z}}$$





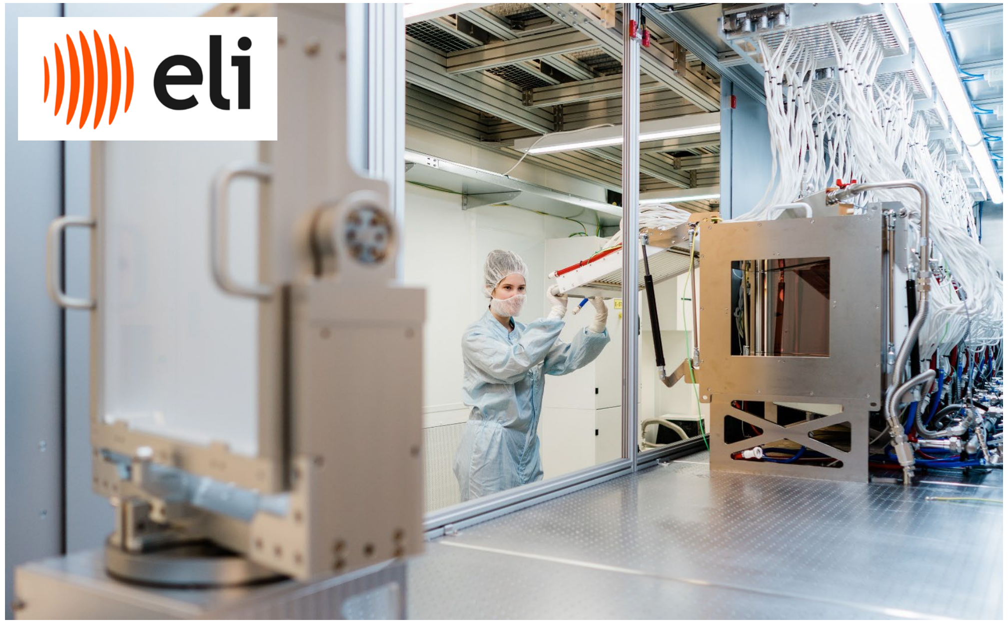
Future code benchmarking relative to known performance of existing actively-cooled lasers

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

Additional Projects: Physics-Informed Discovery of Optimal Power Plant Parameters (Dr. Gaffney and Team)

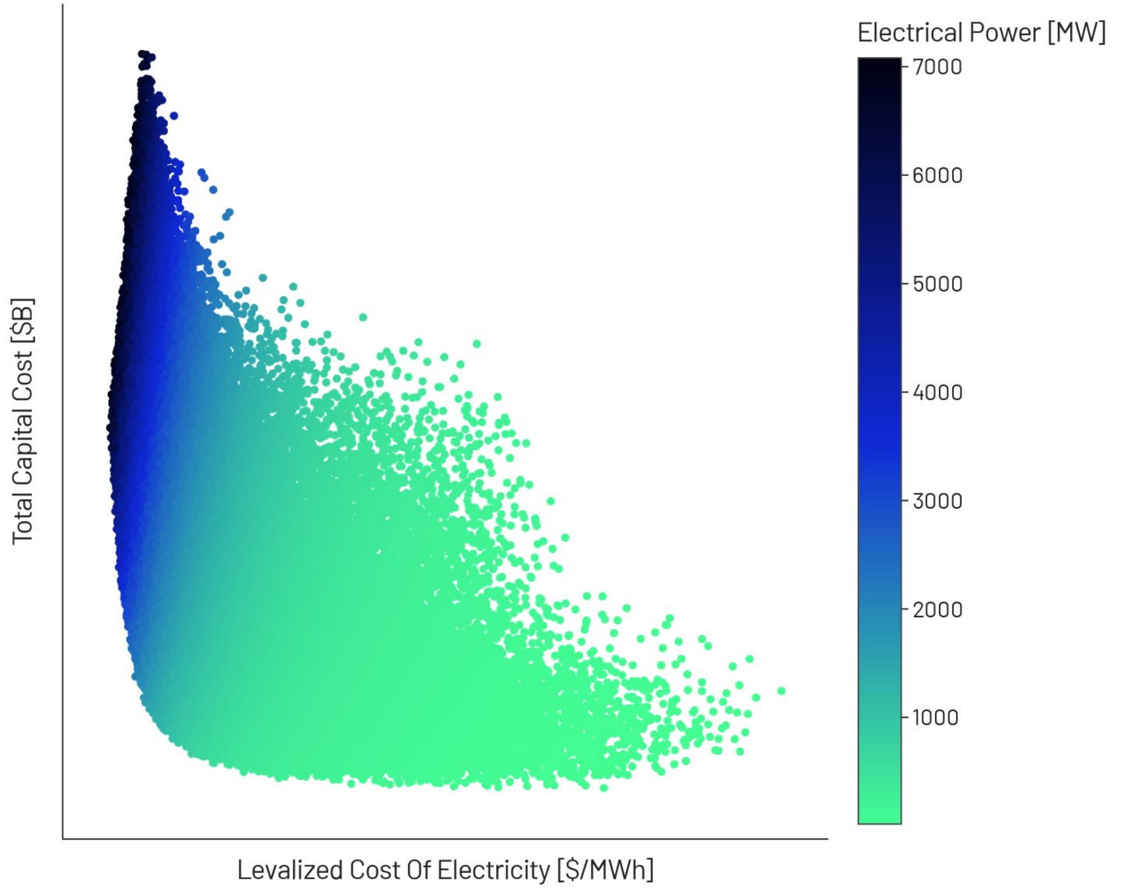
Inputs:

- ❑ Laser specs (energy, pulse shape,ł)
- ❑ Wall-plug and absorption efficiency
- ❑ Cost / kJ
- ❑ Repetition Rate
- ❑ Cost / target

Outputs:

All reactor quantities, but in particular:

- ➢ Power output
- ➢ Total capital cost
- ➢ Cost of electricity



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