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19th Topical Meeting on the Technology of Fusion Energy

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19th Topical Meeting on the Technology of Fusion Energy
Las Vegas, NV, United States
November 7, 2010 through November 11, 2010

LLNL-PRES-462119

LIFE

Laser Inertial Fusion Energy

Compact, Efficient Laser Systems Required for LIFE

Topics on Fusion Energy
American Nuclear Society 2010 annual meeting
November 10, 2010

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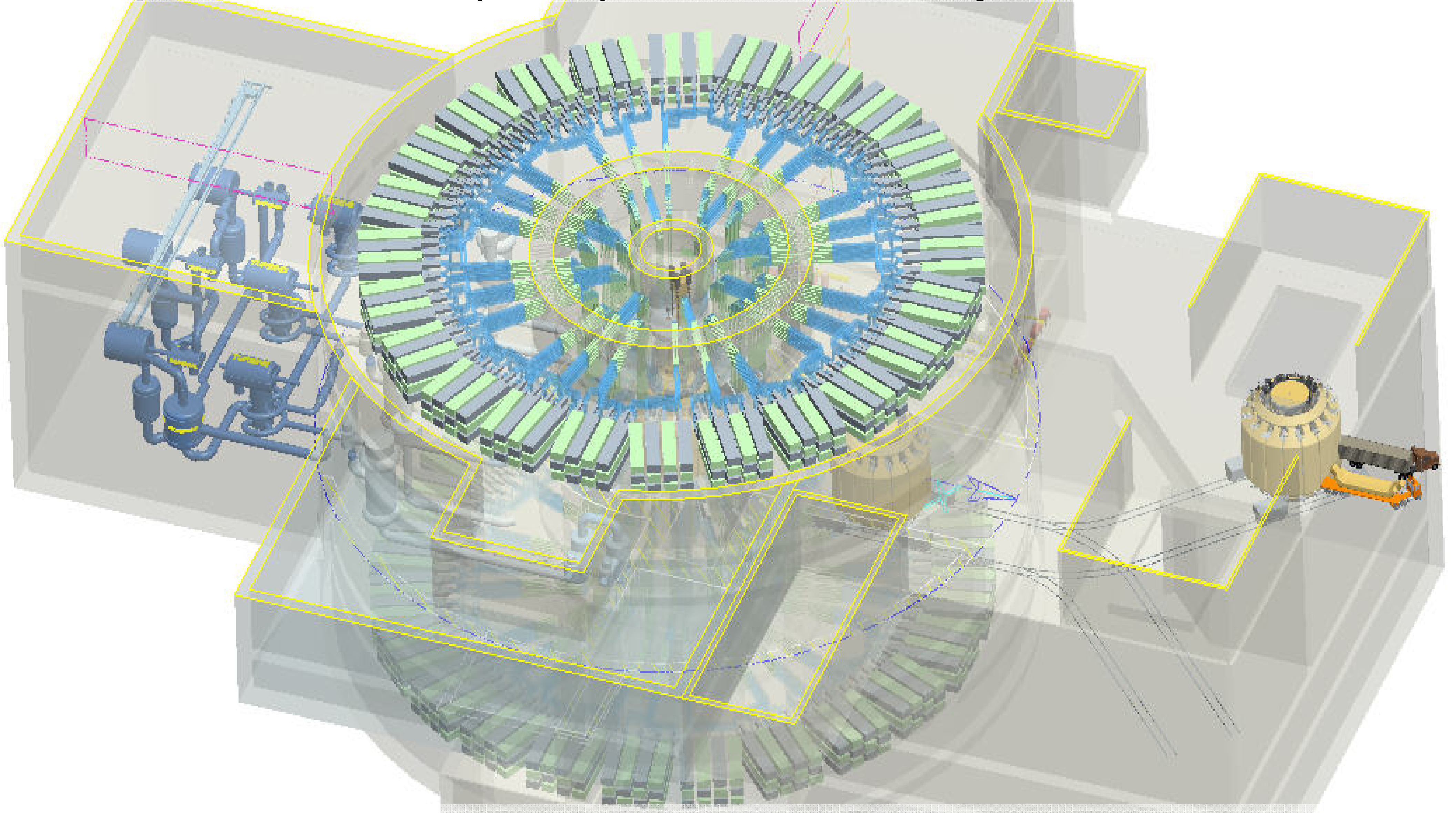
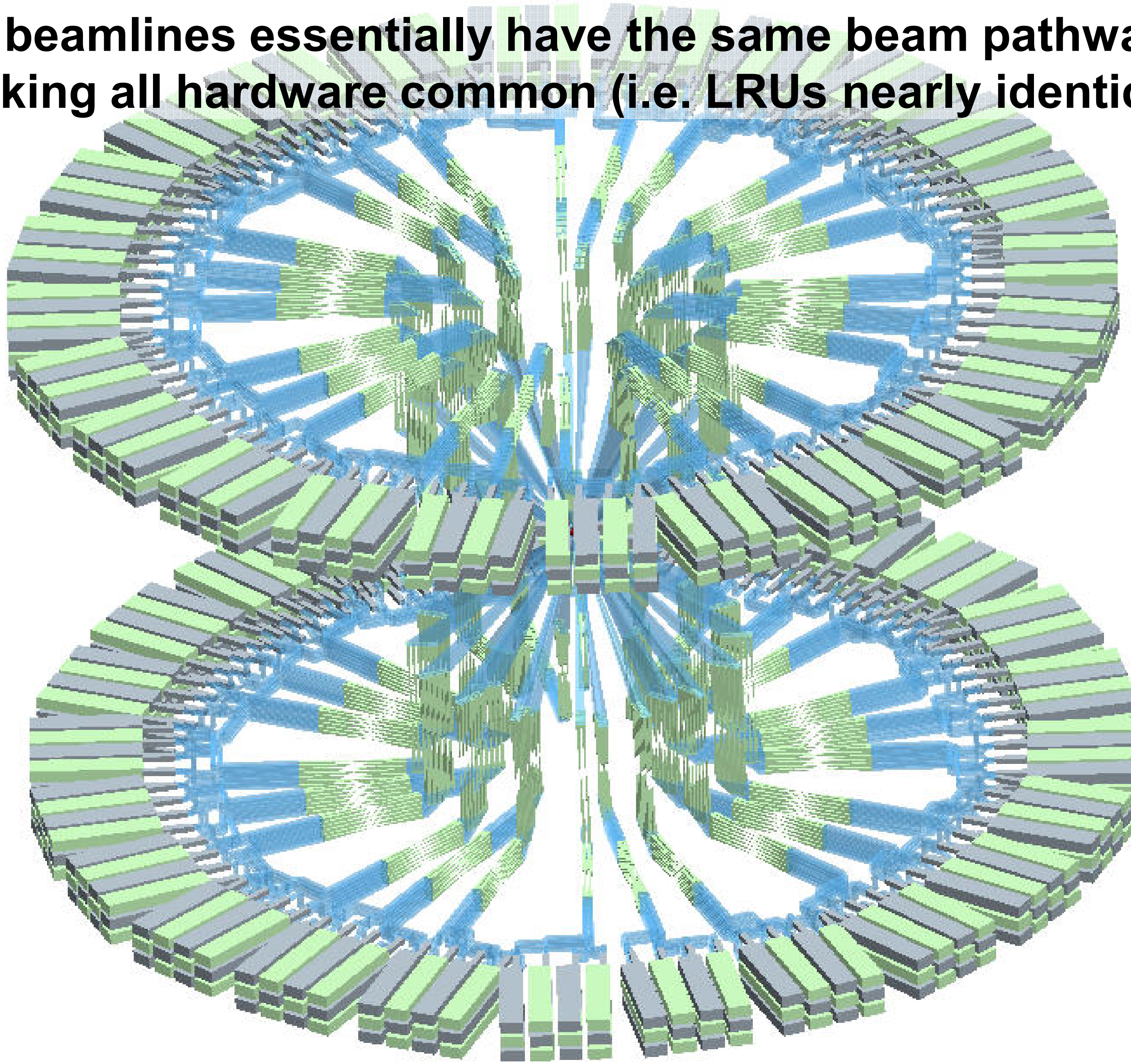
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

This architecture is designed so that all of the hardware Line Replaceable Units (LRUs) are deliverable by truck or smaller



This architecture eliminates the switchyard necessary to transform a rectangular laser array to the target geometry

All beamlines essentially have the same beam pathway making all hardware common (i.e. LRUs nearly identical)



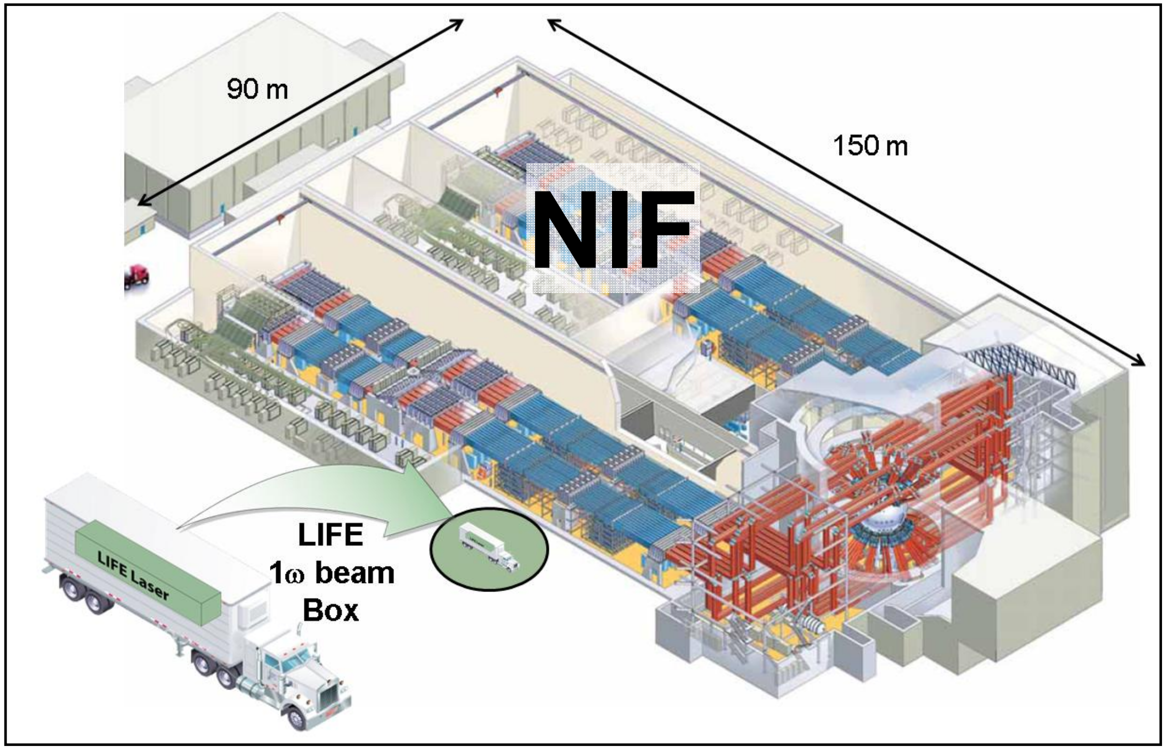
The laser requirements for LIFE are an extrapolation of NIF ignition and power plant requirements

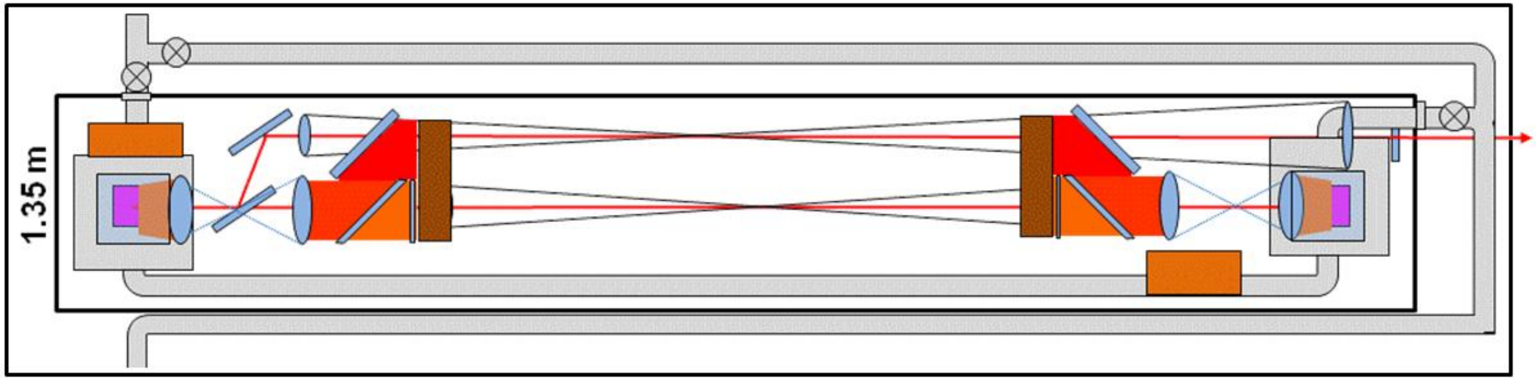
Characteristic	Requirement
Total laser energy	2.41 MJ
Total peak power	694 TW
# beamlines	576 (48 x 12)
Energy per beamline (3ω)	4.3 kJ
Wallplug efficiency	12%
Repetition rate	14.8 Hz
Lifetime of system	15 x 10^9 shots
Availability	0.99
Maintenance	< 8 hrs
Beam pointing	113 μm rms*
Beam-to-beam energy stability	8% rms
Beam to beam simultaneity	30 ps rms
Focal spot size (w/o CPP)	1360 μm, rms*
Spectral bandwidth	10 Angstroms
Prepulse (20 ns prior to main)	< 10^8 W/cm^2

* Larger target - scaled 2.25X from NIF requirements

Our LIFE laser beamline folds into a transportable box, enabling an efficient & cost-effective supply chain

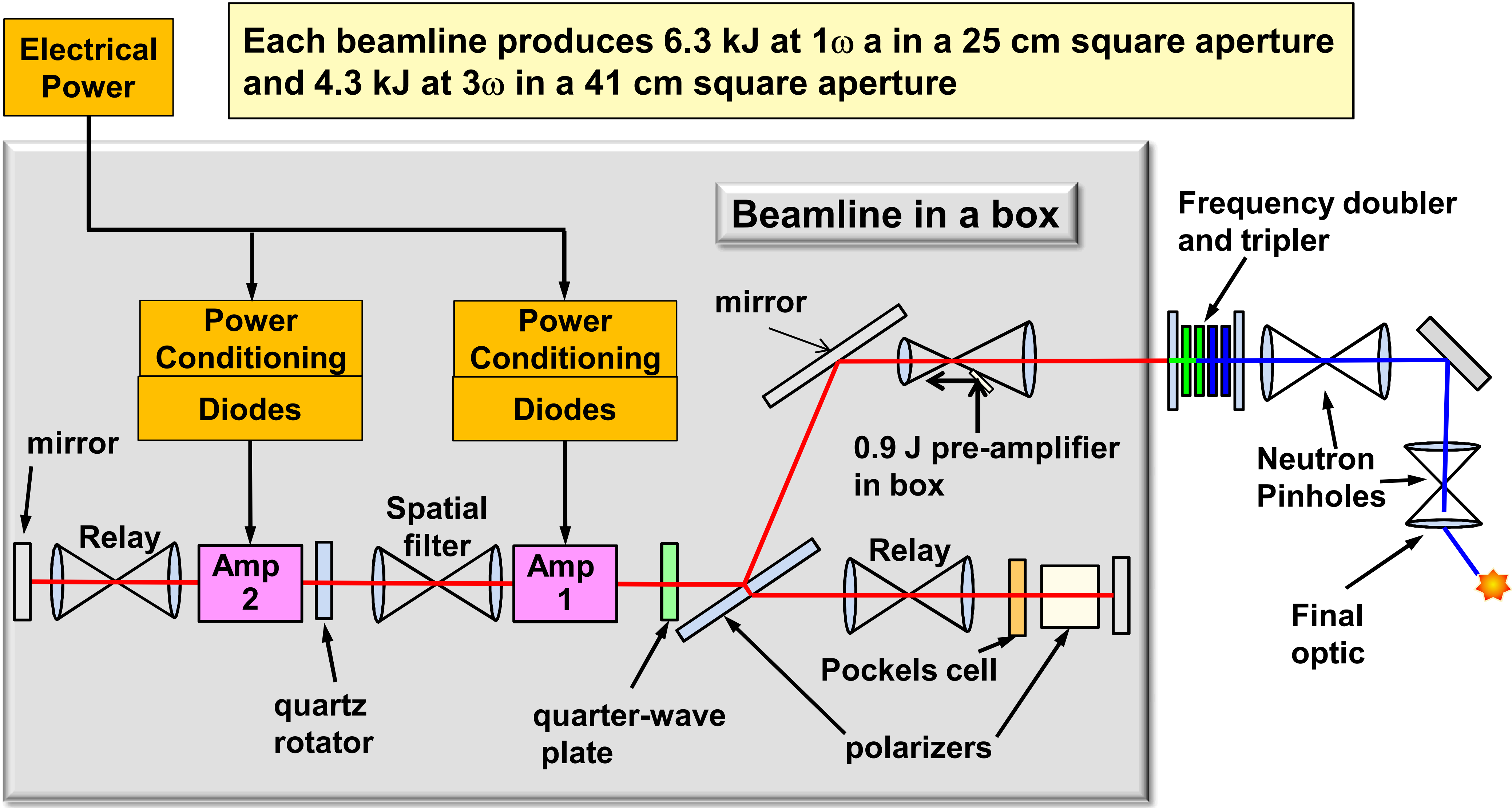
- **Offsite beamline factory**
- **Truck-shippable 1ω beamline**
- **Low-overhead installation**
  - **Kinematic placement**
  - **Few interfaces**





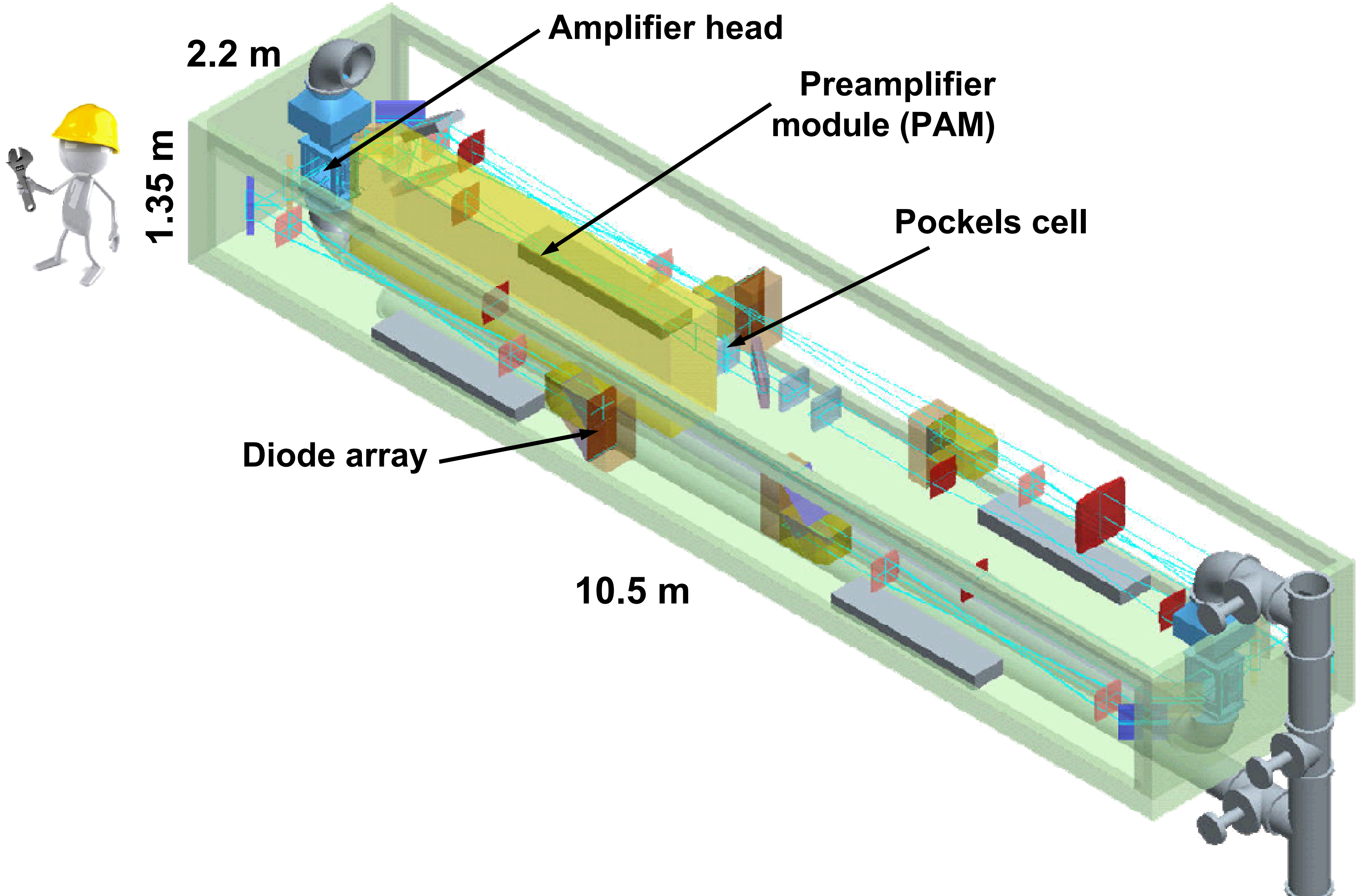
Our baseline design is a passive polarization switched 4-pass image relayed architecture

Each beamline produces 6.3 kJ at 1ω a in a 25 cm square aperture and 4.3 kJ at 3ω in a 41 cm square aperture



Like Mercury, this architecture still needs a Pockels cell for gain isolation, but the average power loading is 40X below a NIF style architecture

The entire 1w beamline can be packaged into a box which is 31 m^3



While no gain media are “ideal” in all aspects, Nd:phosphate glass properties are sufficient for LIFE

	Nd:glass
Storage Lifetime (ms)	0.36 - 0.5
Absorption FWHM (nm)	12.5
Laser Wavelength (nm)	1053
Pump Wavelength (nm)	872
Quantum Defect (%)	17
Sat. Fluence (J/cm^2)	5
Birefringence	None
Thermal conductivity (W/m K)	1
Stress fracture (W/cm)	0.7
Fabrication (cm)	40
Operating Temp. (°C)	25

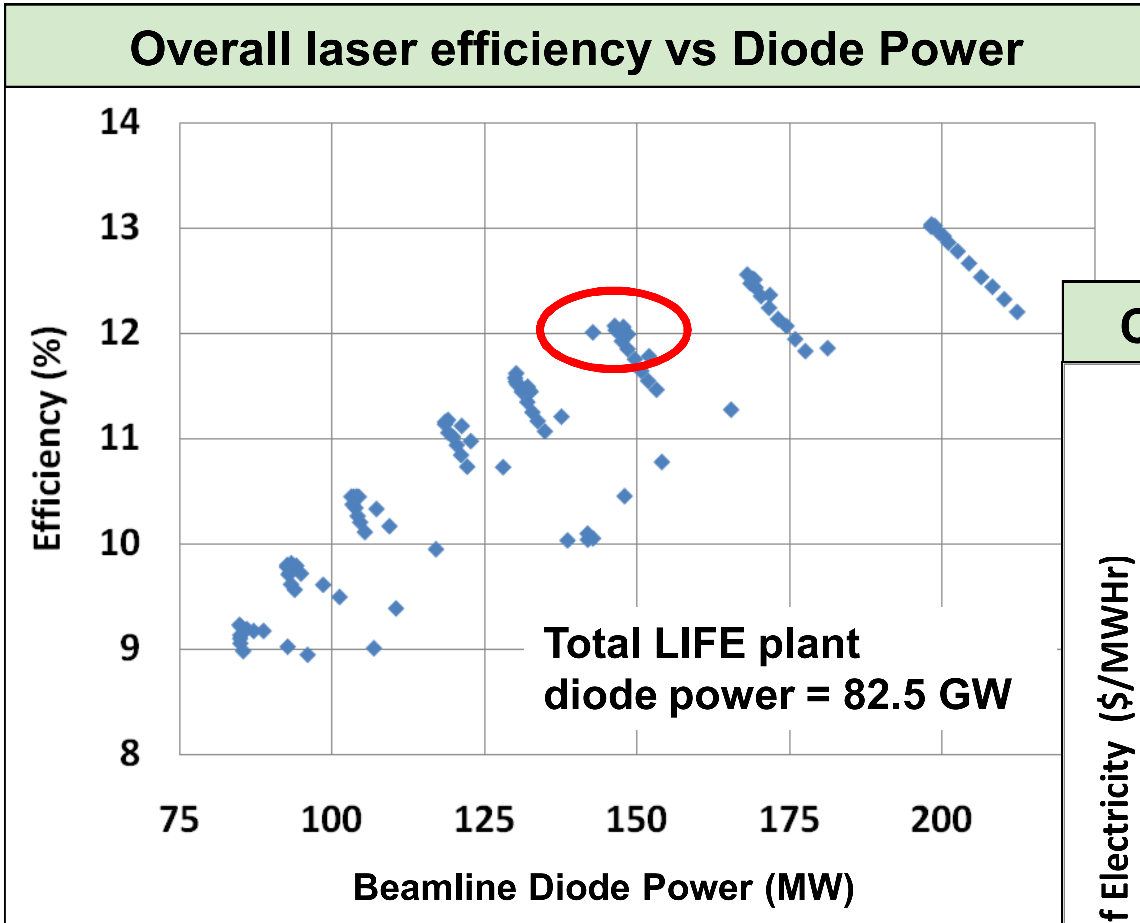
- Diode costs have already dropped making lifetime less of a concern
- Thermal stress birefringence and fracture are issues
- Proper engineering can almost completely mitigate these concerns
- High quality Nd:phosphate glass is available today in large aperture

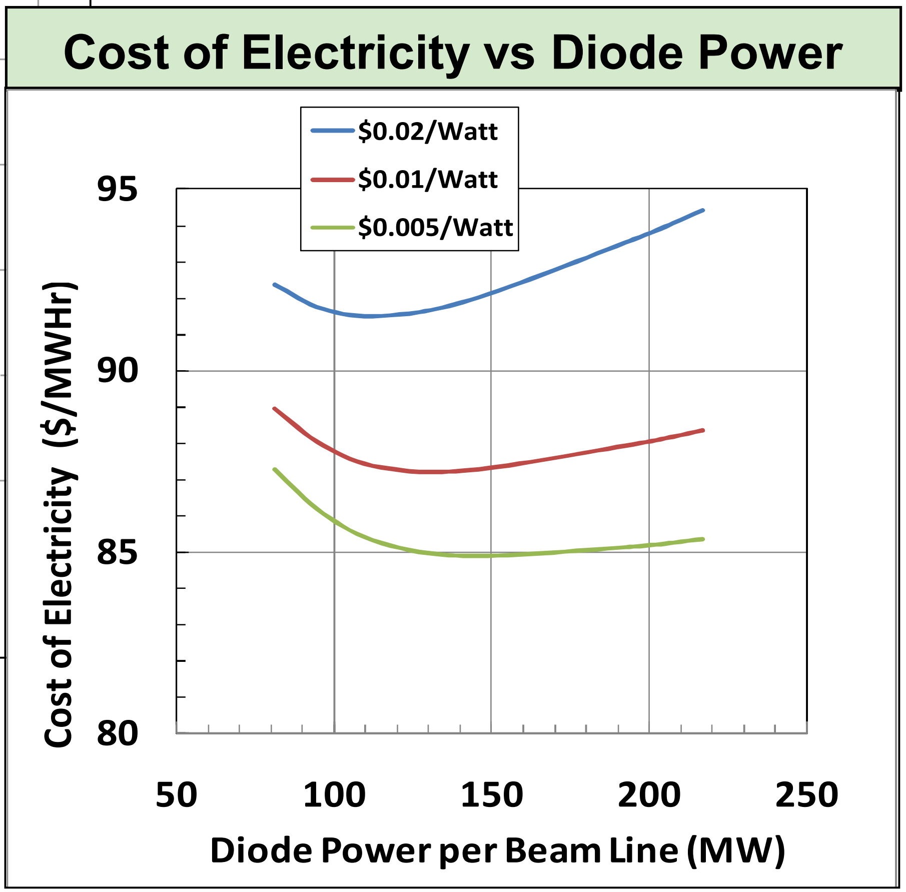
The cost, performance model utilizes analytic models, and empirical fits to analyze the overall system efficiency

Device or Process	Efficiency @ 3ω
DC Power Supply	95
Electrical Pulsers	95
Diodes	73
Diode Micro-Lenses	98
Pump-Light Delivery System	95
Pump-Light Absorption	98
Pump-Light Overfill	96
Quantum Defect	83
Spontaneous Decay	83
ASE	83
Extraction Efficiency	92
Pump-Light Non-Uniformity	98
Beam fill factor	87
1ω transport	80
Depolarization	98
Frequency Conversion	70
3ω transport	99
Efficiency without Cooling	13.9
Cooling System Factor	86.3
Overall Efficiency	12.0

- System design efficiency 12%
- An overall efficiency of >10% is sufficient for power production
- Cost of electricity is a relatively flat function for efficiencies >10%
- Technological developments/learning could yield efficiencies of 16-25%
- Great care in system engineering is required for high efficiency

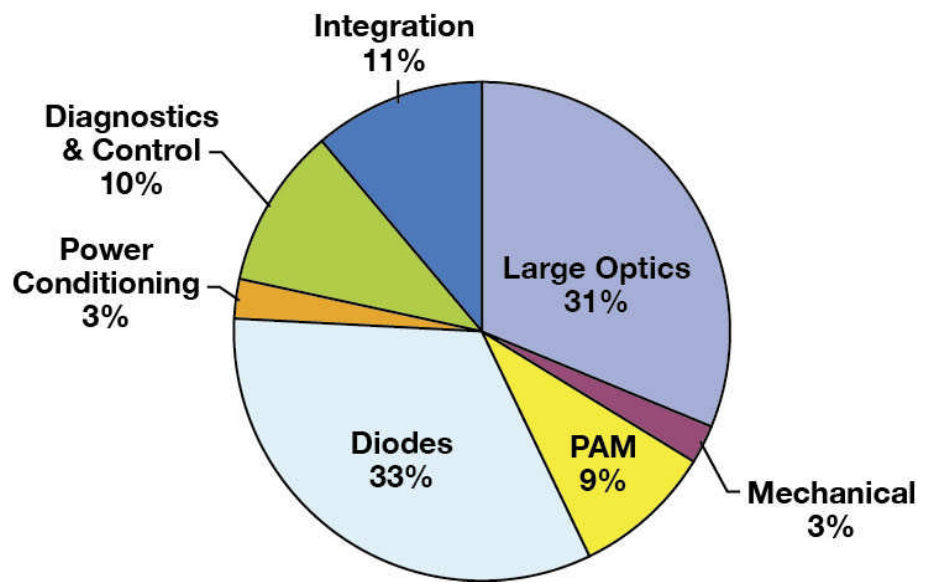
The system design model has been utilized to define the optimum value for diode power vs. efficiency



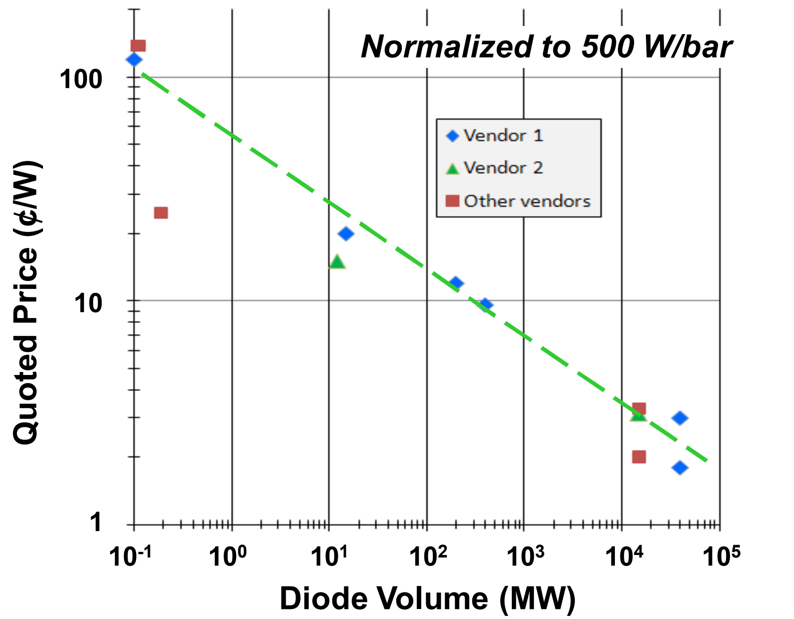


Diodes require close attention as their cost is a significant part of laser cost for LIFE

Nd:Glass Laser System Cost Breakout



2009 Industry Survey:2-3¢/W, no R&D



- 2-3 ¢/W is sufficient for the first plant

We anticipate price points of ~1¢ /Watt for LIFE commercial:

- ~100x greater production volume (“opportunity curve”)
- Improved yields as volumes scale
- Improved power/bar as technology evolves

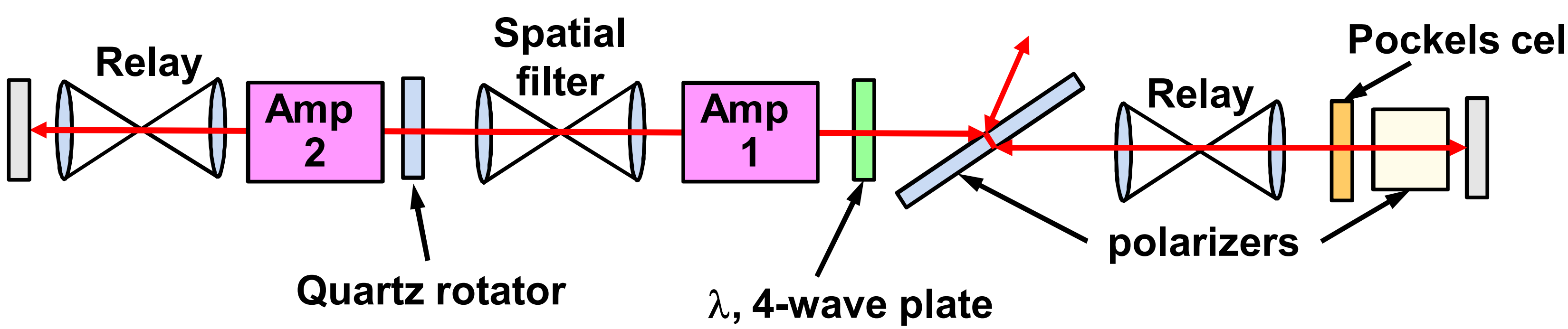
To meet the pump irradiance requirement LIFE diode arrays utilizes high power bars with an aggressive pitch

Characteristic	Specification	Production Status
Diode peak power, bar (W)	500	Industrial
Diode wavelength (nm)	872	Industrial
Diode spectral width (nm)	10	Industrial
Fast axis divergence (degrees)	6	Industrial
Slow axis divergence (degrees)	7	Industrial
Diode lifetime (80%) ($x10^9$ shots)	10	Industrial
Diode efficiency	0.7	Lab scale
Diode pulse length (msec)	200	Industrial
Diode pitch (microns)	200	Lab scale
Bars per tile (stack)	50	Industrial
Tile size (mm)	10x10	N/A
Mounting gap (mm)	1x1	N/A
Effective tile size (mm)	11x11	N/A
Effective array intensity (kW/cm^2)	20.7	N/A

The technology for LIFE diode arrays has been demonstrated.
A focused effort to create industrial production should achieve requirements.

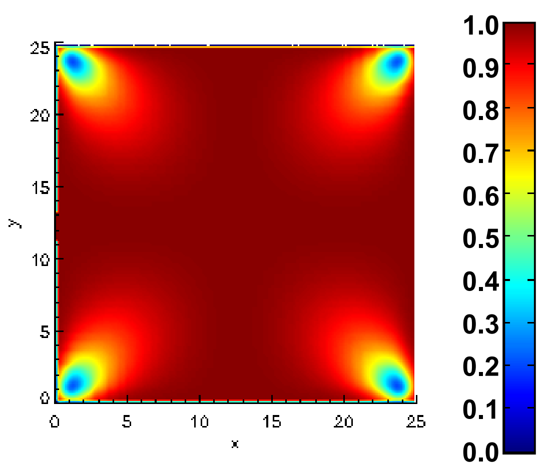
Thermally induced depolarization in isotropic media (Nd:glass) can be minimized with polarization rotation

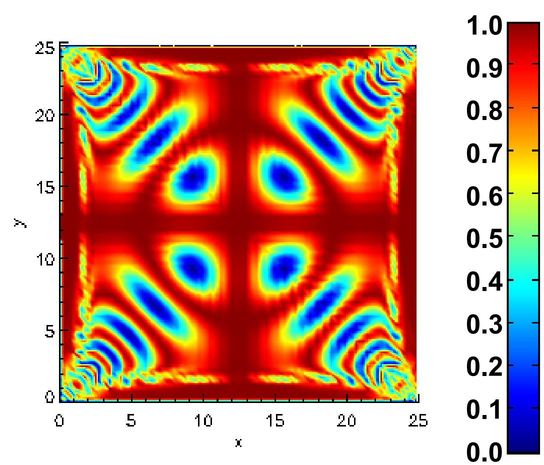
Architecture

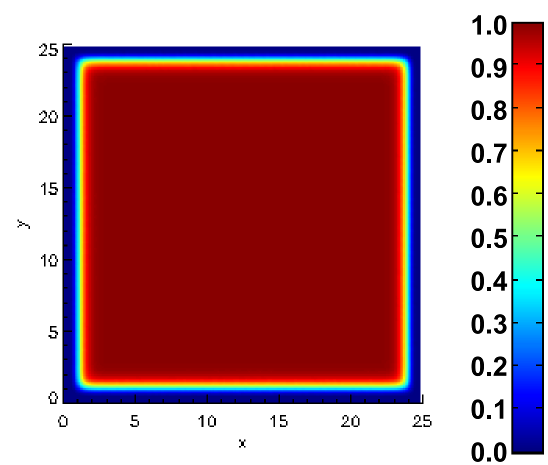


Polarized transmission of amplifier components

1 slab	1 amplifier (22 slabs)	2 amplifiers (compensated)

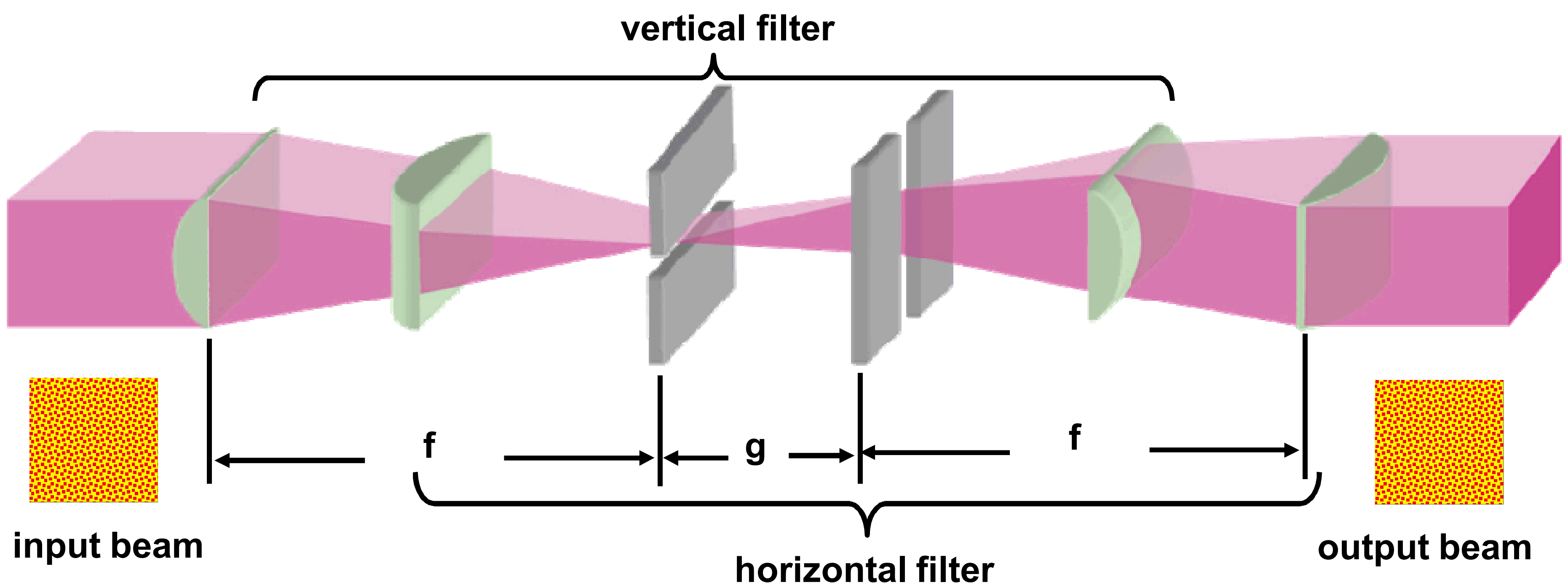






Cylindrical lenses and slit filters potentially offer improved spatial filtering for the LIFE laser

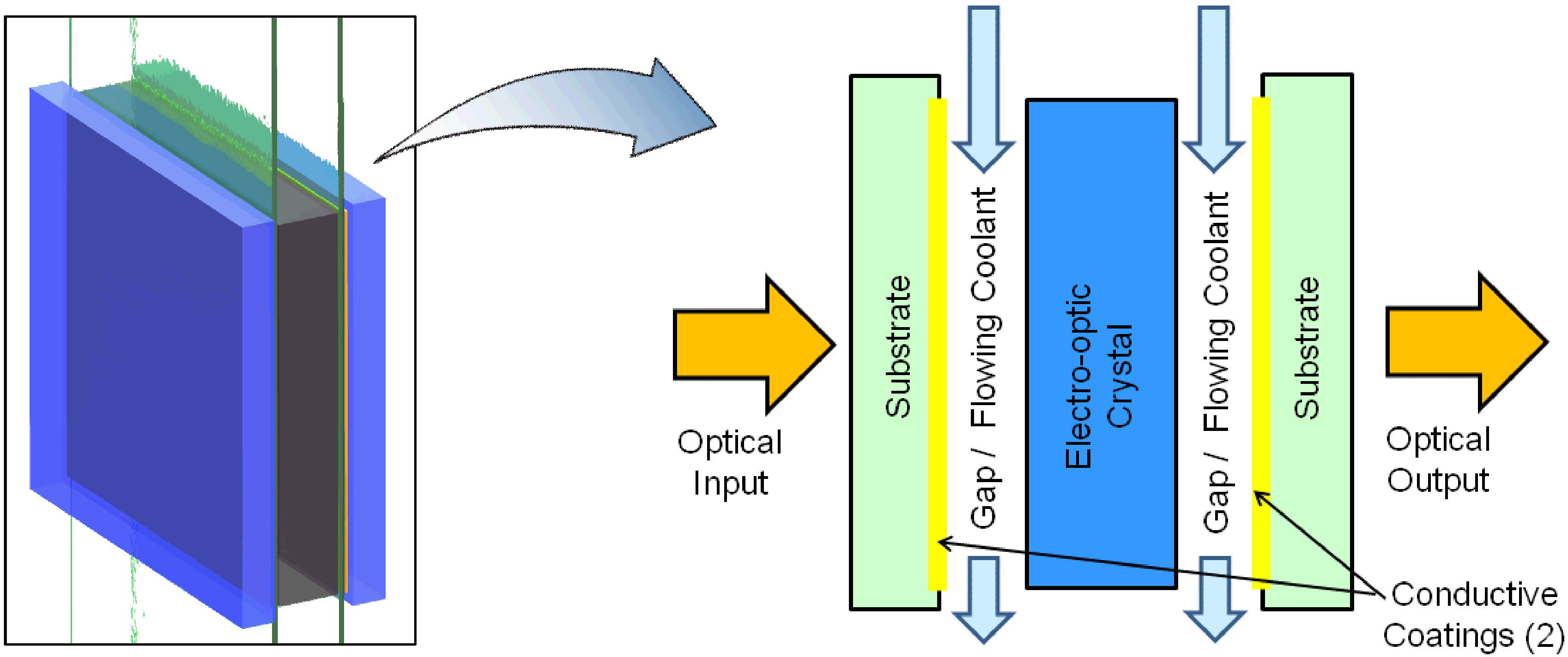
The cylindrical relay spatial filter concept



- Filtering is provided by slits rather than by pinholes
- Intensity at slit edges is several orders of magnitude less than intensity at equivalent round pinhole edges
- Fused silica slits reflect and refract filtered light
- Fused silica has reported surface/bulk damage threshold ~475 GW/cm^2
- Experiments and benchmarked simulation of this method this year

Reduced requirements for LIFE relative to NIF, lead to a simpler Pockels cell architecture

Gap cooled Pockels cell



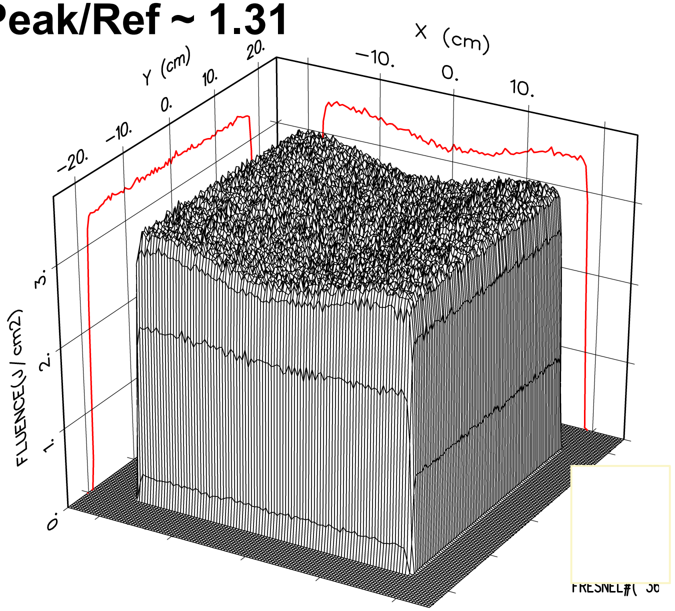
- Operational fluence of 0.3 J/cm^2
- Potential usage of ITO as a conductive coating.
- ITO is expansion matched to sapphire.
- Use of thin flowing Decalin or equivalent coolant
- Operational voltage of ~21 kV
- Aperture scalable to LIFE and even full NIF apertures

Experiments with a scaled aperture of this architecture are planned for this year

Beam propagation using NIF optic aberration data yields an output beam with low contrast and modulation

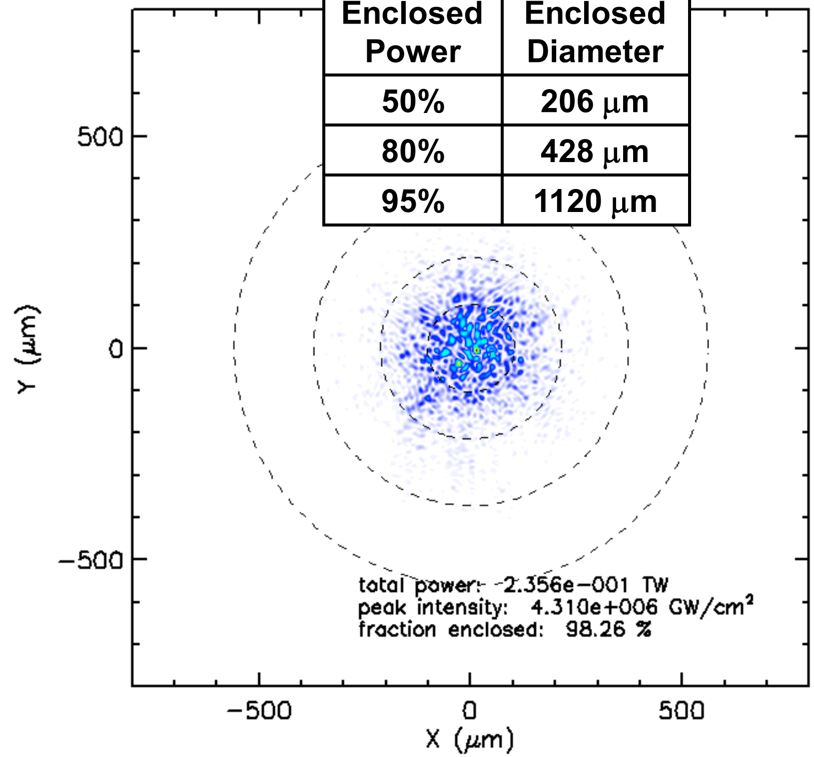
Tripler output

Conversion Efficiency = 74%
3ω = 4.3 kJ
Contrast ~ 4.5%
Peak/Ref ~ 1.31



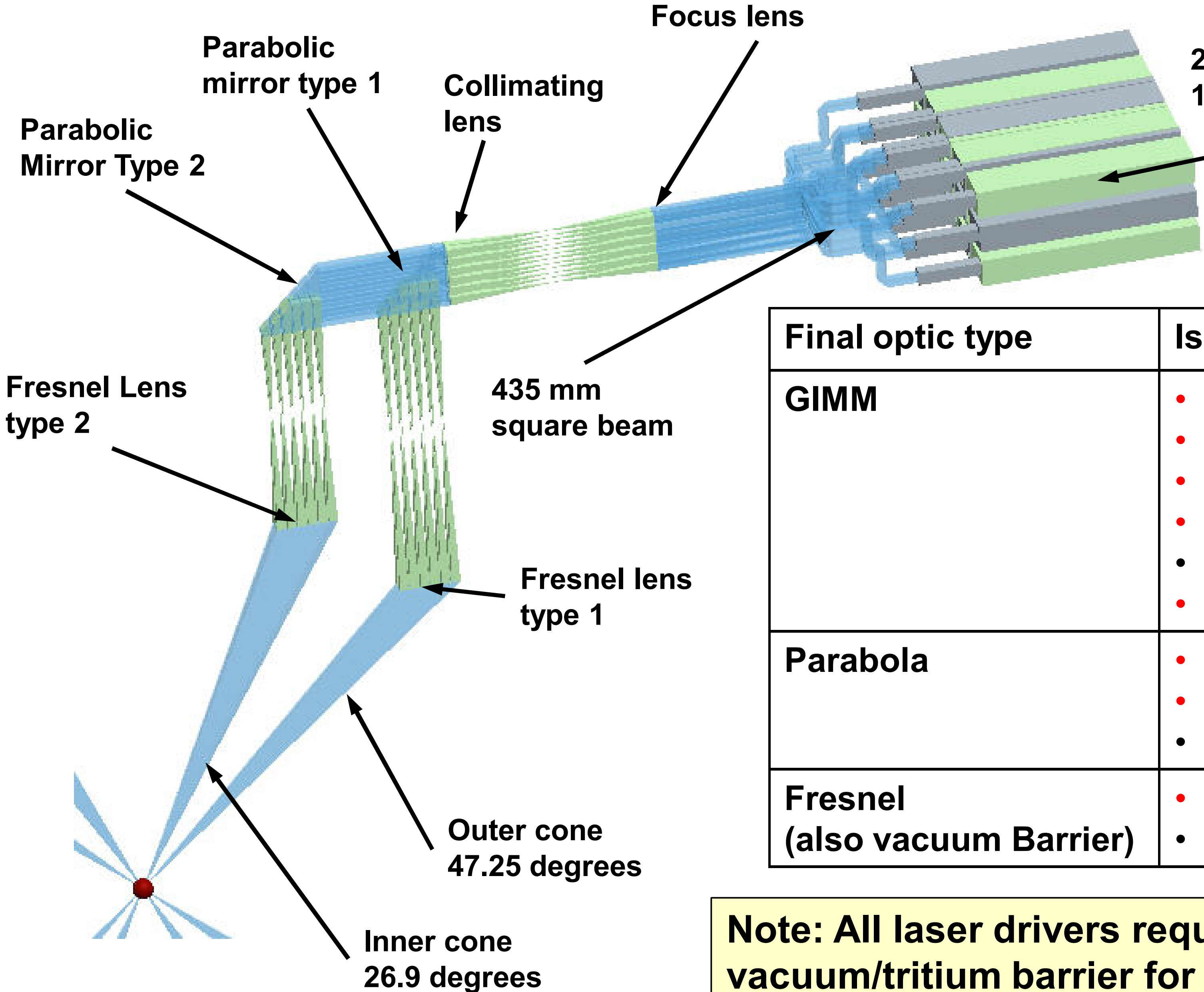
Output Farfield

Enclosed Power	Enclosed Diameter
50%	206 μm
80%	428 μm
95%	1120 μm



- **The output 3ω average fluence is ~3.2 J/cm², to enchance the optical lifetime of these components**
- **The encircled energy meets baseline LIFE requirements**

The final optic is a thin Fresnel lens to minimize the induced optical absorption due to neutron damage



Final optic type	Issues(s)
GIMM	• Very Large size • Damage threshold • Target Shrapnel • Replacement • Wavefront • Pointing
Parabola	• Damage threshold • Pointing • Replacement
Fresnel (also vacuum Barrier)	• Damage threshold • Replacement

Note: All laser drivers require a transparent vacuum/tritium barrier for the plant

The LIFE laser system must be reliable and maintainable

Maintainability	Reliability
• Minimize size and weight • Package integrated functional units as LRUs • Distributed controls • Kinematic replacement • Short replacement time • High availability	• Long MTBF of mechanical subcomponents • Minimize moving parts • Reduced fluence specification for enhanced optical life • Beam expansion after 1w section lowers the fluence to converter and final optics • Use NIF techniques for surface finishing, coating, handling, and cleanliness • Employ optics mitigation techniques to overcome imperfect manufacture of substrates and surfaces • Accelerated testing of components*

* Bayramian, et. al., “A Laser Technology Test Facility for LIFE,” *J. Phys.: Conf. Series*, **244**, 032016, 2010.

Solid state lasers have demonstrated long life in many commercial and laboratory applications

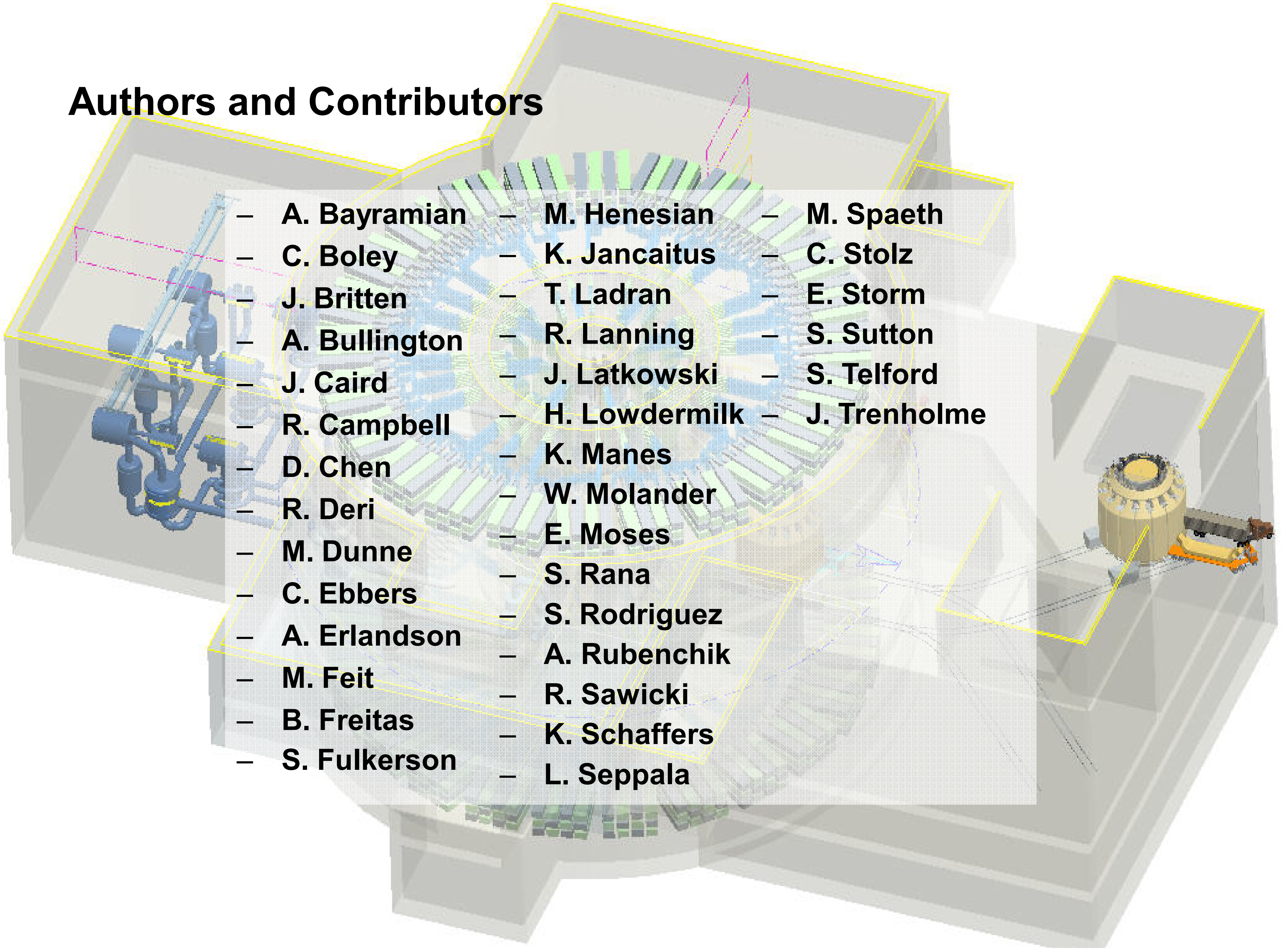
Manufacturer/ Model	Power (W)	Energy (mJ)	Repetition Rate (kHz)	MTBF (hrs)	Max Shots ($x 10^9$)
LLNL laser systems					
AVLIS solid-state laser			20	4000	288
Commercial Diode Pumped Solid State Laser Performance					
Newport / Pulseo (3w)	20	0.2	100	10000*	3600
Northrup Grumman / Patara (2w)	100	10	10	10000*	360
Northrup Grumman / Presencia (1w)	400	40	10	10000*	360
Coherent / Avia (2w)	45	0.375	120	10000*	4320
Coherent / Avia (3w)	28	0.254	110	10000*	4320
Coherent / Evolution (2w)	45	45	1	10000*	36

* Warranteed MTBF from manufacturers

IFE power generation in 2020's is within reach… if we start now

- LIFE laser Reliability, Availability, and Maintainability has driven the engineering of new solutions relative to NIF and Mercury systems:
  - Beamline architecture
  - Laser materials, coating technologies
  - Diode fabrication, packaging, and lensing
  - Diode power conditioning
  - Pockels cell, frequency conversion
  - Final Optics
  - Target pointing and tracking
- Development has already begun in FY2010:
  - Assessment of basic properties of several new laser glasses
  - Purchase materials for characterization
  - Self consistent compact beamline design
- Several sub-scale prototype experiments will be conducted in FY2011
  - Reduction to practice of new Pockels cell technology
  - Measurement of gain saturation fluence for diode pumped laser glass
  - Scaled cylindrical filter test to assess viability
  - Nearfield spatial filtering tests
  - Basic properties of some of the new materials including absorption, scatter, bonding, interface reflectivity, damage threshold

Authors and Contributors



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LIFE

Laser Inertial Fusion Energy

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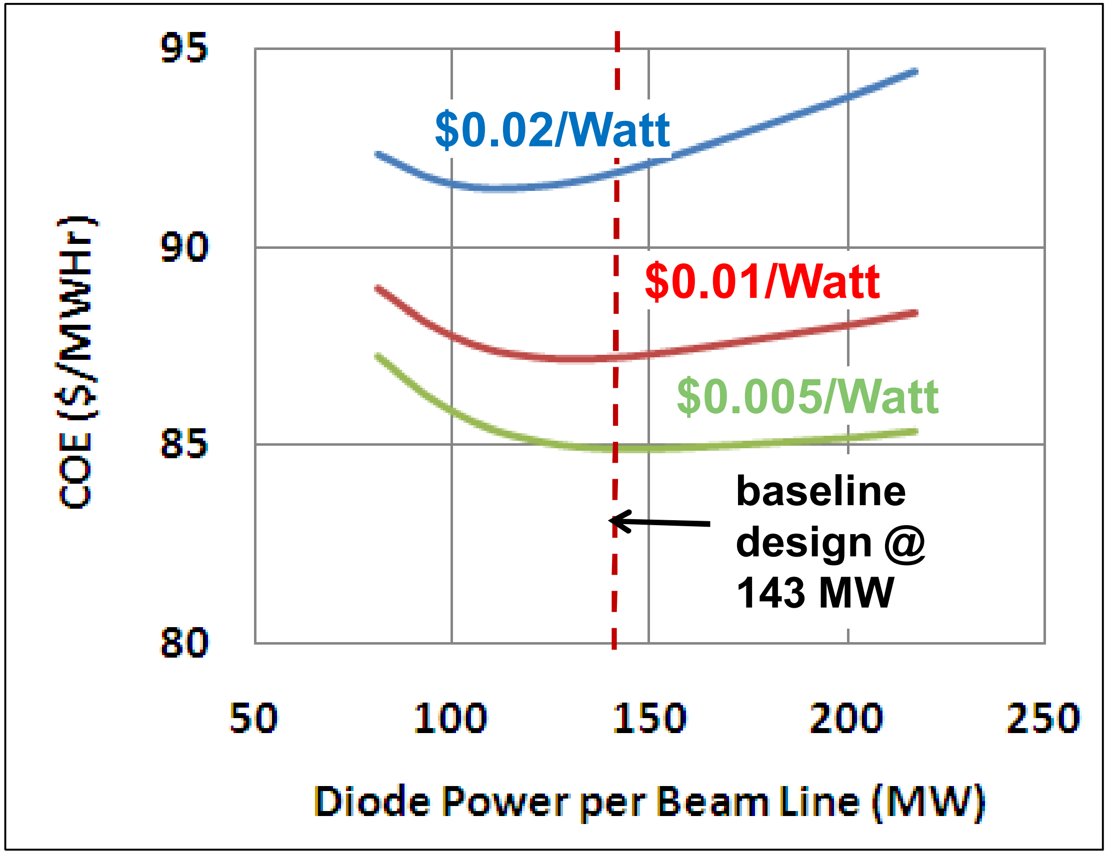
Our choice of diode power per beamline nearly minimizes cost of electricity



- 10th-of-a-kind power plant was modeled with Tom Anklam's Integrated Project Model
- Cost/watt is for LIFE.2, before learning
- Cost rises on the left due to increased electrical power delivered to the laser
- Cost rises on the right due to increased number of diodes
- Pump pulse duration varies with diode power but other parameters are held constant

The laser requirements for LIFE are an extrapolation of NIF ignition and power plant requirements

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Focal spot size (w/o CPP)	1360 microns
Spectral bandwidth	10 Angstroms
Prepulse (20 ns prior to main)	< 10^8 W/cm^2

Inertial Fusion Energy (LIFE) is an extension of Inertial Confinement Fusion (NIF)

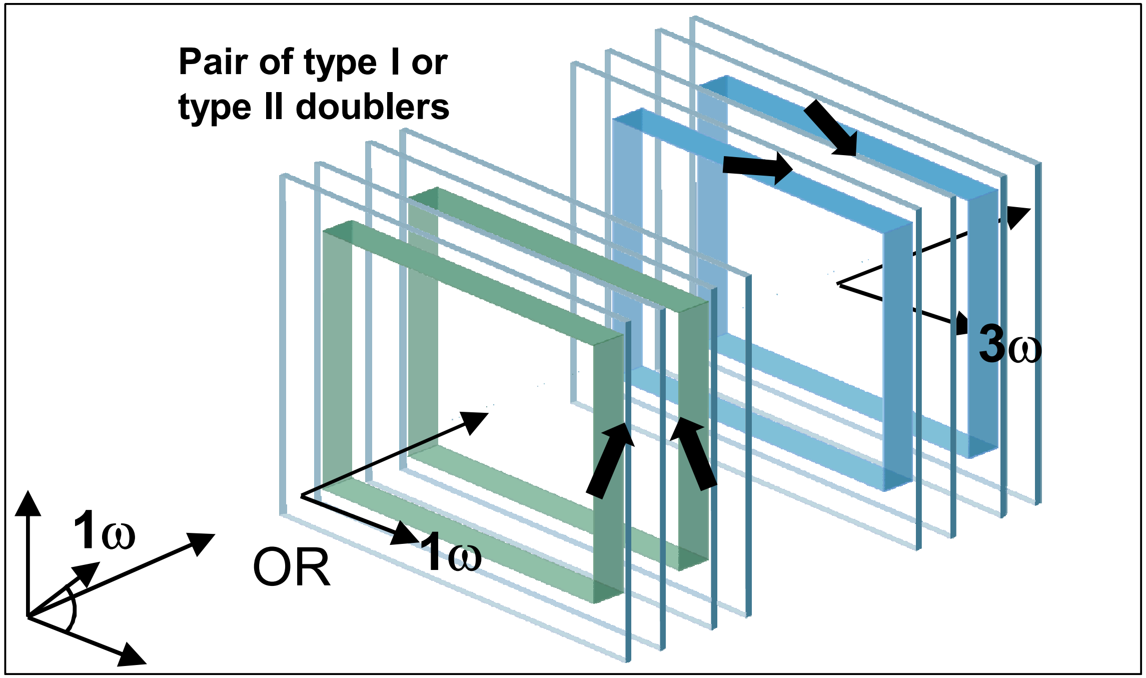
General

- Balance of plant
- Liquid neutron absorber , tritium breeder
  - FLiBe, PbLi, Li, etc.
- Target chamber structure
  - Heating
  - Radiation
  - Pressure wave
  - Weight of fluids
- Target chamber environment
  - First wall integrity
  - Turbulent gases
- Target
  - Tracking
  - Heating
  - Acceleration
  - Mass production , cost ($)
  - Gain

Laser Specific

- Laser average power issues
  - Wavefront
  - Stress birefringence
  - Stress fracture
  - Gain isolation
- Diode lifetime
- Optics lifetime
  - Drive laser optics
  - Final optics – neutrons, photons, pressure, temperature
- Cost of Electricity
  - Capital cost of hardware and size of hardware
  - Efficiency – recycled energy needed
  - Reliability , availability
  - Serviceability and maintainability

High efficiency four-crystal KD*P (98%) frequency converter designs have been simulated



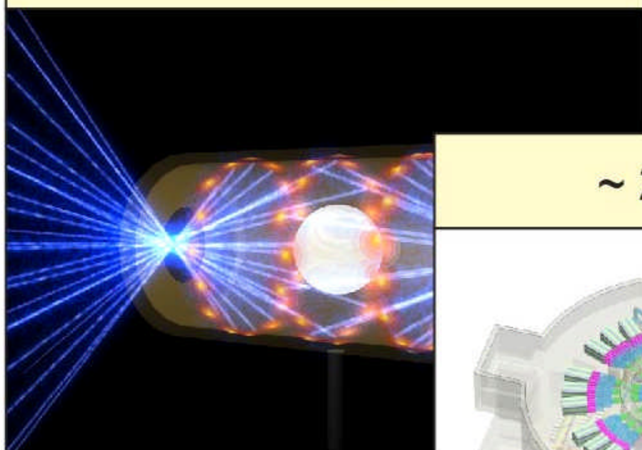
- Average power operation requires He gas cooling between glass or sapphire windows and crystal surfaces.
- Alternate-z crystal axes are also proposed.

	Single pulse	Foot pulse	Drive pulse	Foot+Drive
Type I, Type II:	60.15 %	61.69 %	71.19 %	68.82 %
Crystal lengths(cm):	1.4, 1.1, 1.0, 1.0	1.3, 0.9, 0.9, 0.9	1.3, 0.9, 0.9, 0.9	
Angles(μR):	280,-240,30,-30	280,-240,30,-30	280,-240,30,-30	
Type II, Type II	65.86 %	68.54 %	75.91 %	74.07 %
Crystal lengths(cm):	1.1, 1.1, 1.1, 1.1	0.9, 0.9, 0.9, 0.9	0.9, 0.9, 0.9, 0.9	
Angles(μR):	30,-30,30,-30	30,-30,30,-30	30,-30,30,-30	

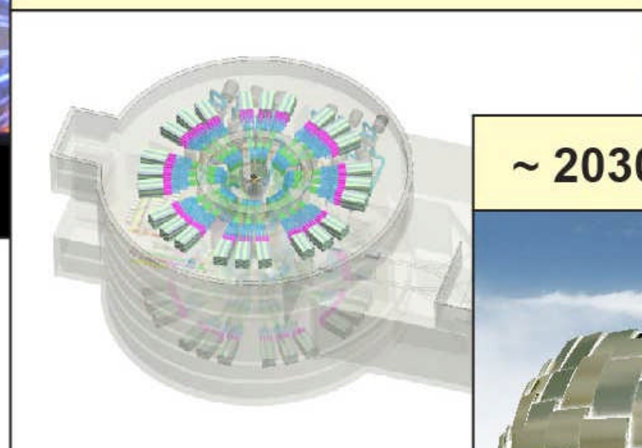
Effective "foot" + "drive" conversion efficiency: 69.0 - 74.0 %

Roadmap — Laser Inertial Fusion Energy (LIFE)

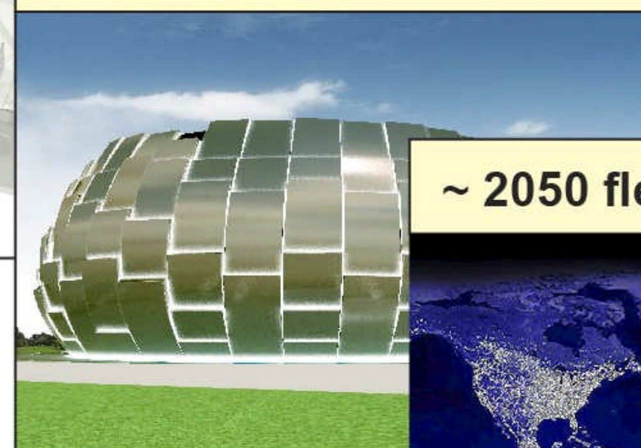
~ 2010 NIF Ignition



~ 2020 LIFE.1



~ 2030 LIFE Commercial



~ 2050 fleet incorporated

The key next step for LIFE and IFE is NIF ignition

LIFE lessons

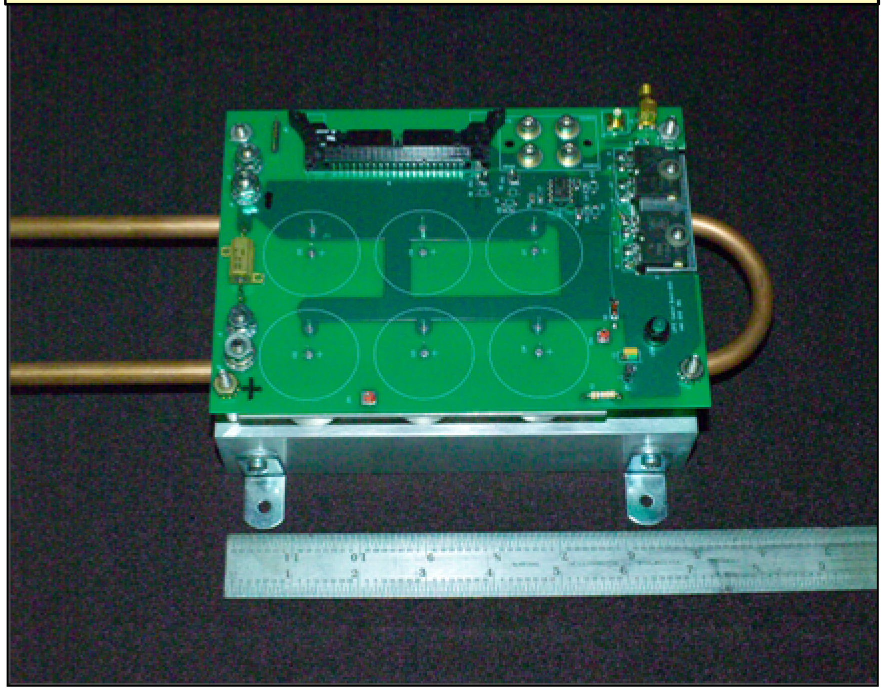
- Leverage ICF success on NIF
- Leverage basic average power demonstrations on Mercury
- System optimization to assess importance of subsystem optimization
- Make decisions based on cost and efficiency
- Incorporate maintainability and availability of the laser system in cost and efficiency models

Diode laser test station recent progress

Laser diode array testing requirements

Property	Value
Peak optical power per bar (W)	500
Electrical to optical efficiency	0.6
Bars per tile	25
Pulse width (us)	200
Pulse repetition frequency	15
Diode current (A)	398
Operating voltage (V)	100
Equivalent series resistance (mΩ)	50
Stored energy (J)	90
Pulser efficiency	0.914

Compact 500-amp diode pulser

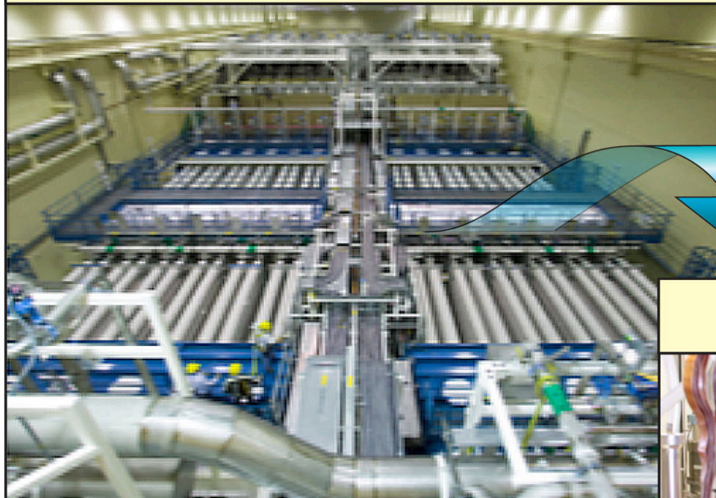


Advanced pulser components exist which could allow full miniaturization and >91% wallplug efficiency

LIFE beamlines are an evolution of NIF and Mercury technology

- He cooling enables average power
- Diode pumping enables efficiency

NIF

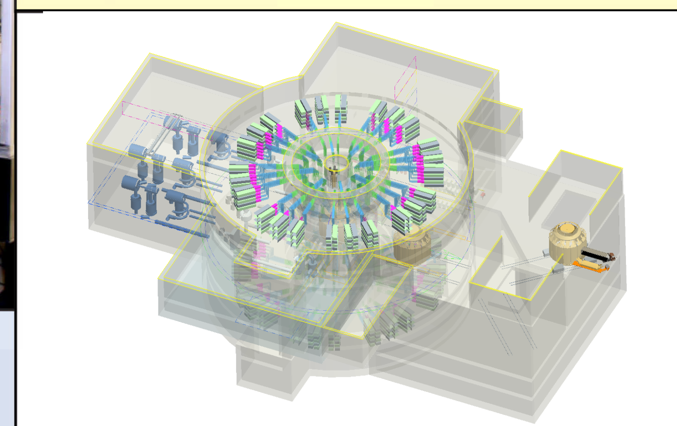


Repetition rate 10^{-4} Hz
Efficiency < 1%
Duration > 10^4 shots
Cost ~ baseline
Availability: science campaigns

Mercury

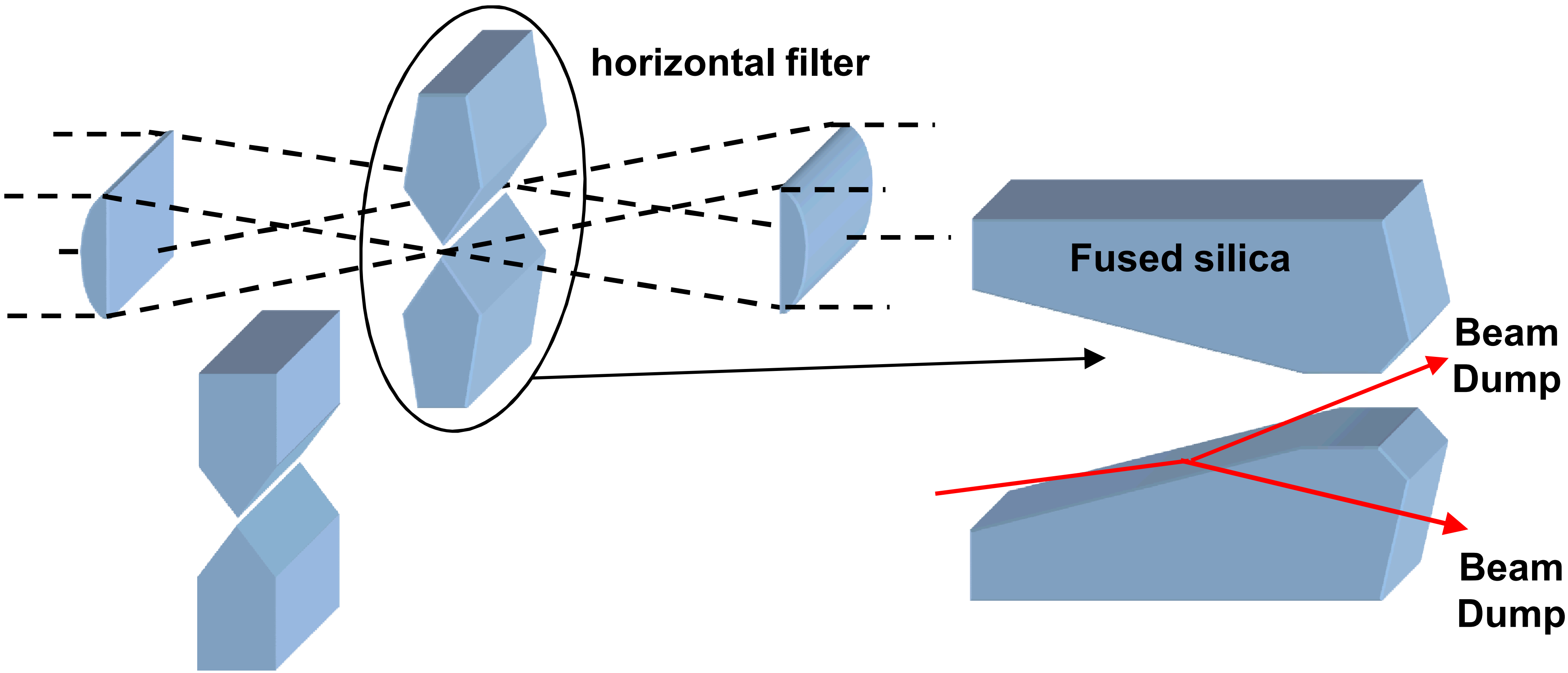
Repetition rate 10 Hz
Efficiency 6%
Duration > 3 x 10^5 shots

LIFE



Repetition rate 10 ~ 20 Hz
Efficiency > 10%
Duration > 10^{10} shots
Cost ~ low wrt balance of plant
Availability: 24, 7

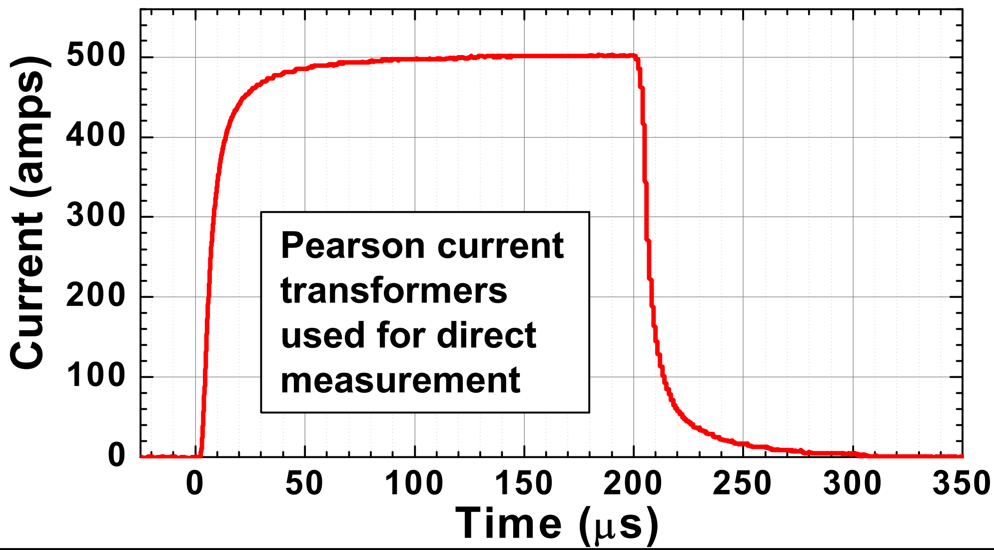
Fused silica slit filters could operate with zero ablation



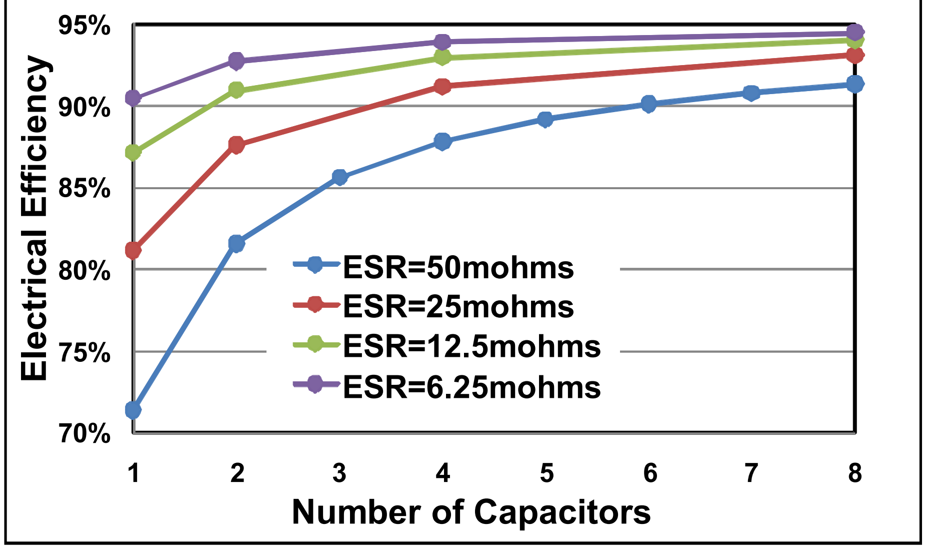
- Fused silica slits reflect and refract filtered light
- Low absorption (0.3 dB, km) gives rise to low heating (~<2 mW)
- Fused silica has reported surface/bulk damage threshold ~475 GW/cm^2
- Experiments and benchmarked simulation of this method this year

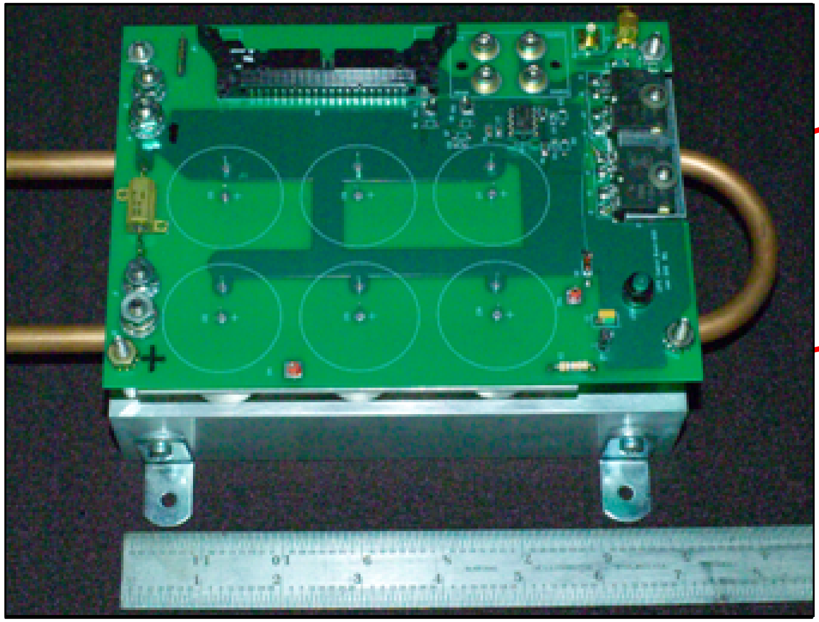
A new compact, efficient diode pulser meets early testing requirements

Output current waveform at the load



Efficiency vs. storage capacitors

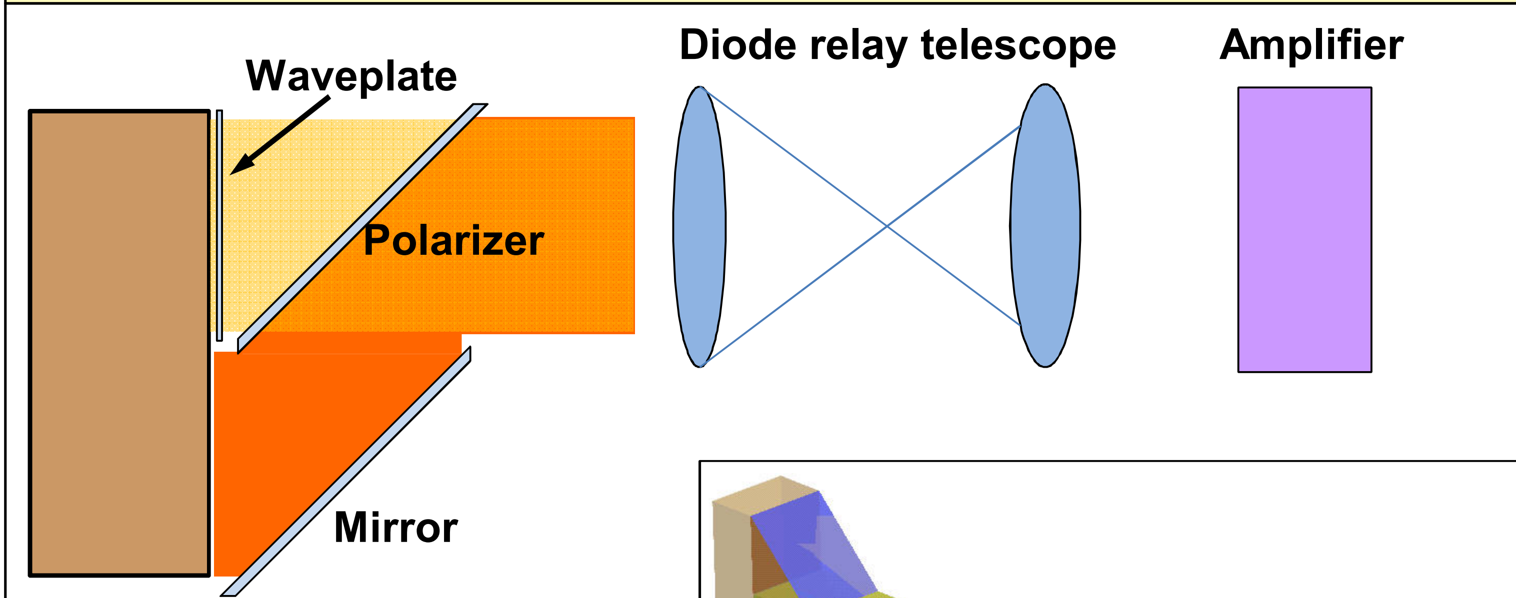


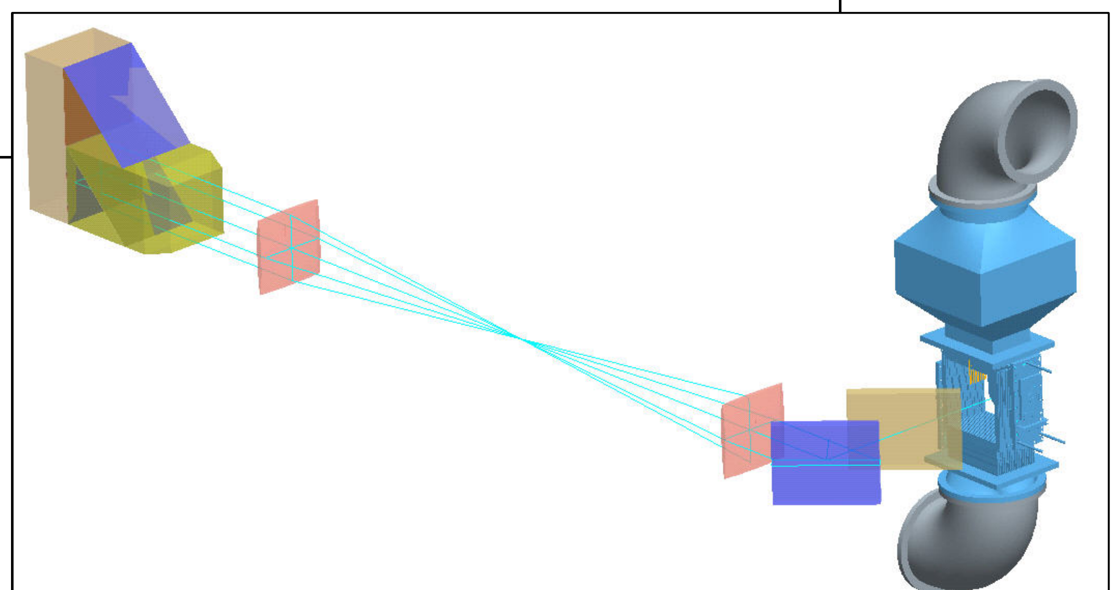


- The new pulser is (2.8x12x18 cm^3 – a 12.7X reduction in volume) and is capable of 1000 Amps, and 100 Hz (25X increase in performance).
- The Mercury pulser box (4.4x46x76 cm^3) held two pulser channels capable of 200 Amps, 20 Hz

Polarization combination makes the diode brightness sufficient for simple ~1:1 relay to the amplifier

Schematic of pump delivery method



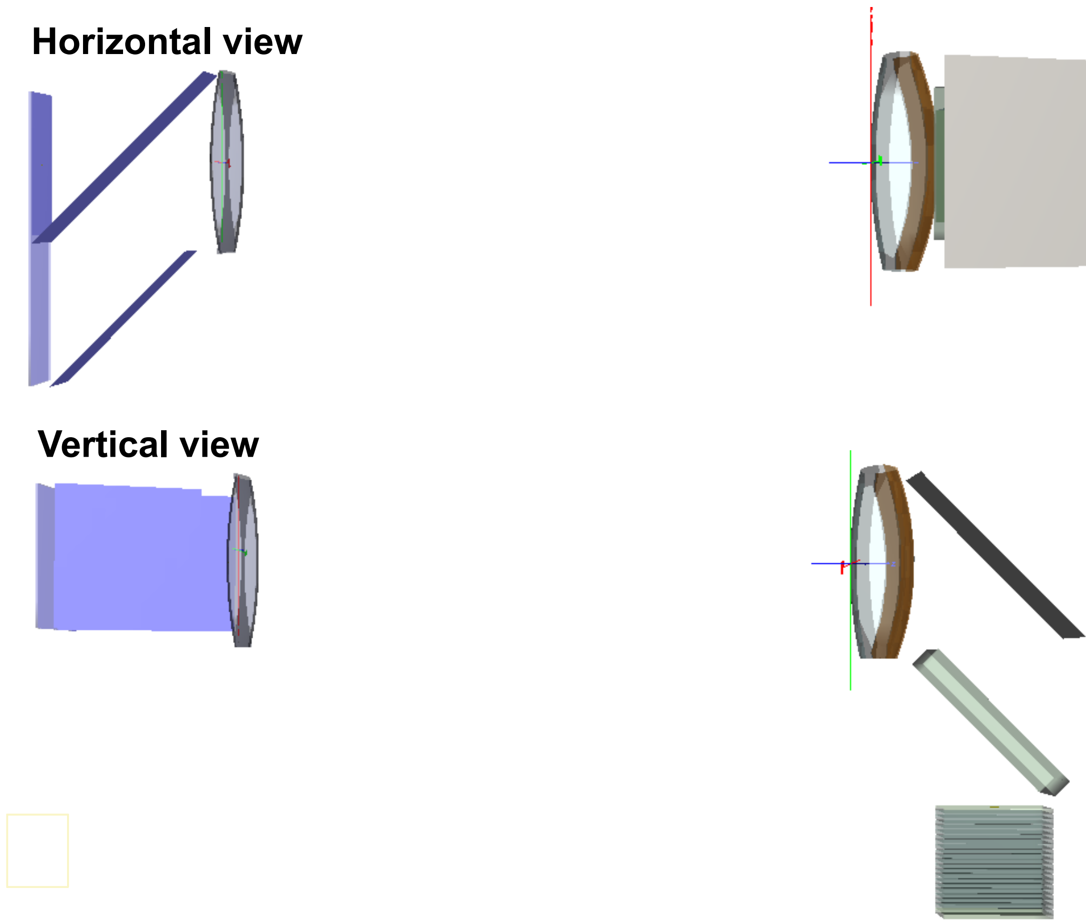


A ray trace model of the architecture shows a smooth pump profile which meets our requirements

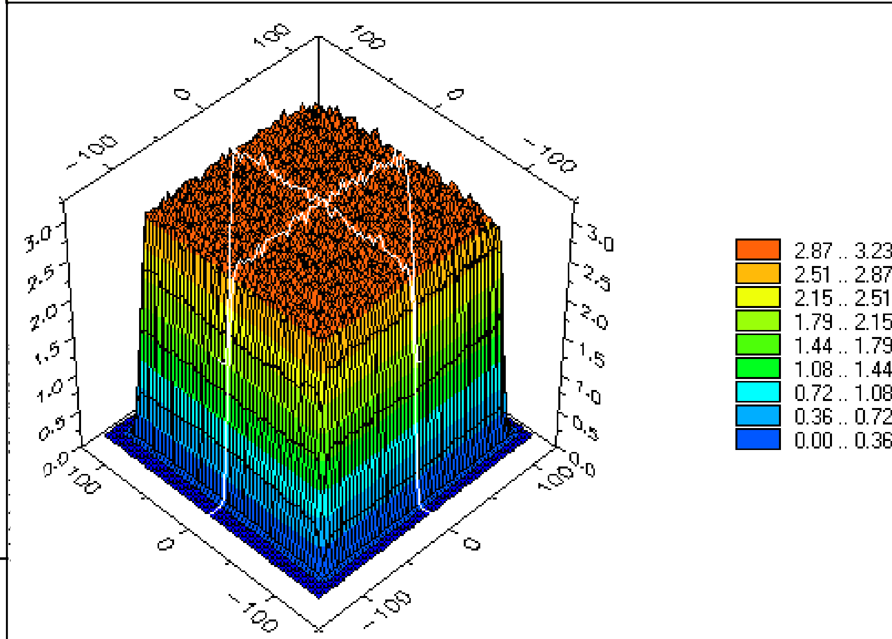
Isometric view of ray trace model in FRED

Horizontal view

Vertical view

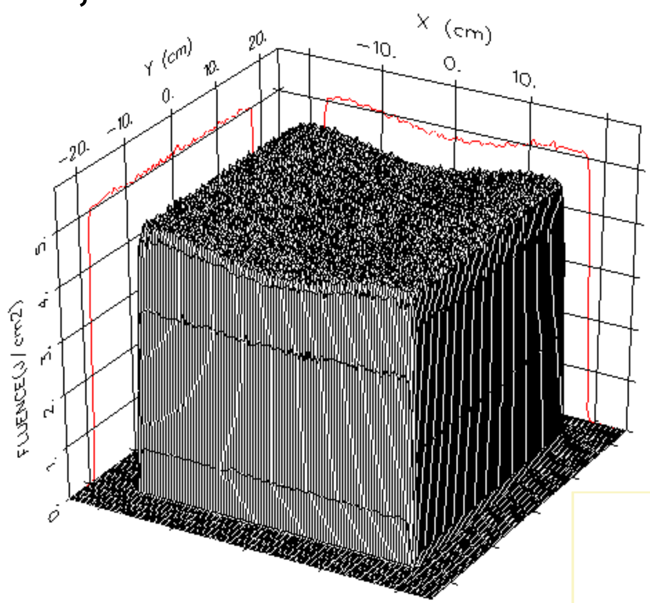


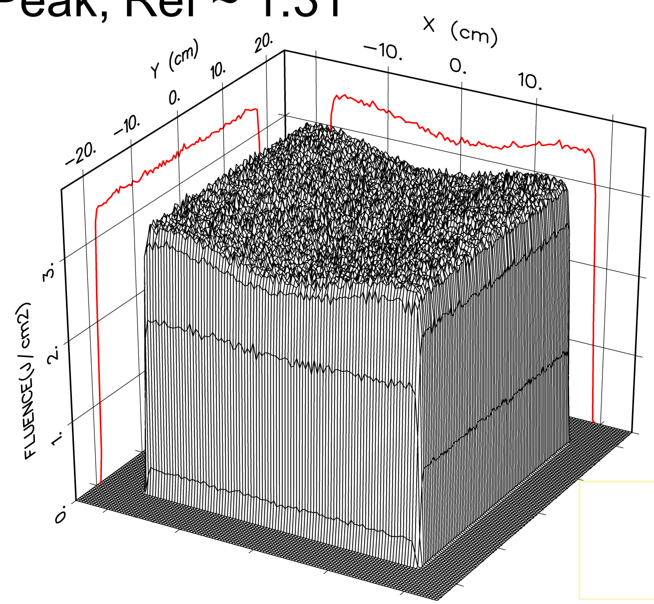
Output ray trace



Beam propagation using NIF optic aberration data yields an output beam with low contrast and modulation

Doubler input	Tripler output
1ω = 6.6 kJ **Contrast ~ 3.6%** **Peak, Ref ~ 1.28**	3ω = 4.3 kJ Contrast ~ 4.5% Peak, Ref ~ 1.31

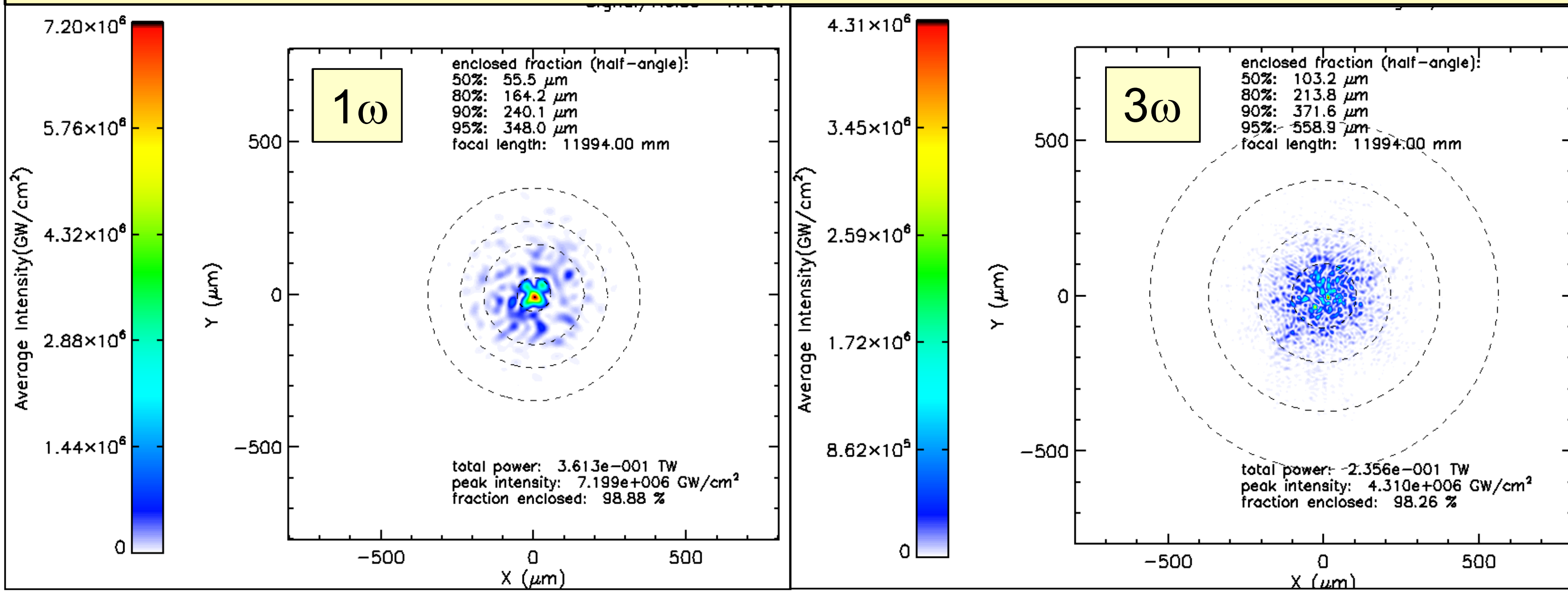




The output 3ω average fluence is ~3.2 J/cm^2, to enchance the optical lifetime of these components

Initial far field simulations using CPP designs for target beam smoothing indicate

Irradiance at Best Focus for Target Chamber Center (12-m focal distance)



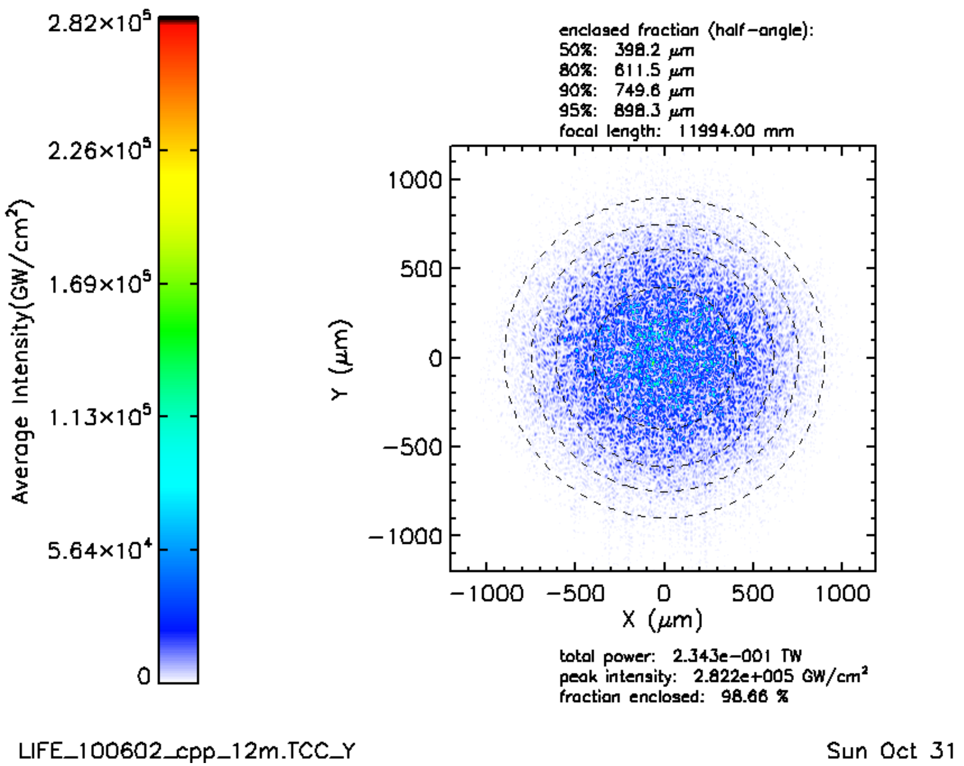
Percentage of Enclosed Power	1ω Power Enclosed Diameter	3ω Power Enclosed Diameter
50%	1110 μm	206 μm
80%	328 μm	428 μm
95%	700 μm	1120 μm

- Simulation includes 39 actuator DM and estimate of wavefront residuals
- LIFE CPP analysis are in process for use at 12-20 meter focus.

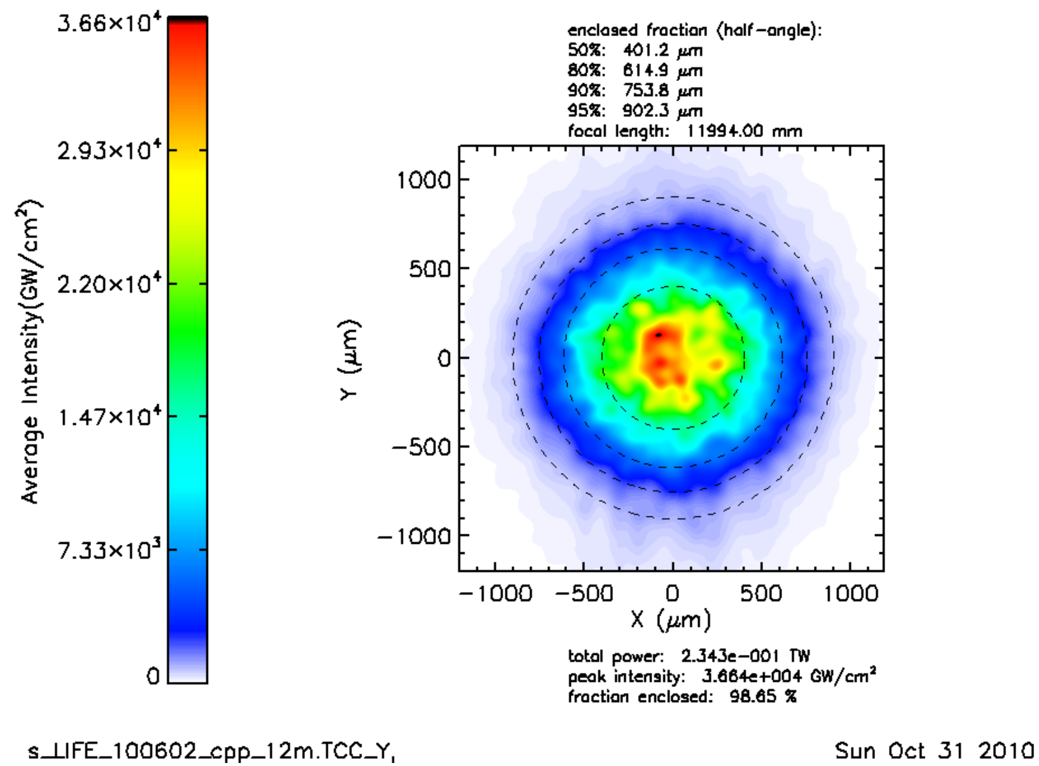
With a scaled NIF CPP design specific to a 50 deg Outer beam we get some encouraging results:

Simulation in plane of the Hohlraum entrance hole at 12-m focal distance:

Without smoothing



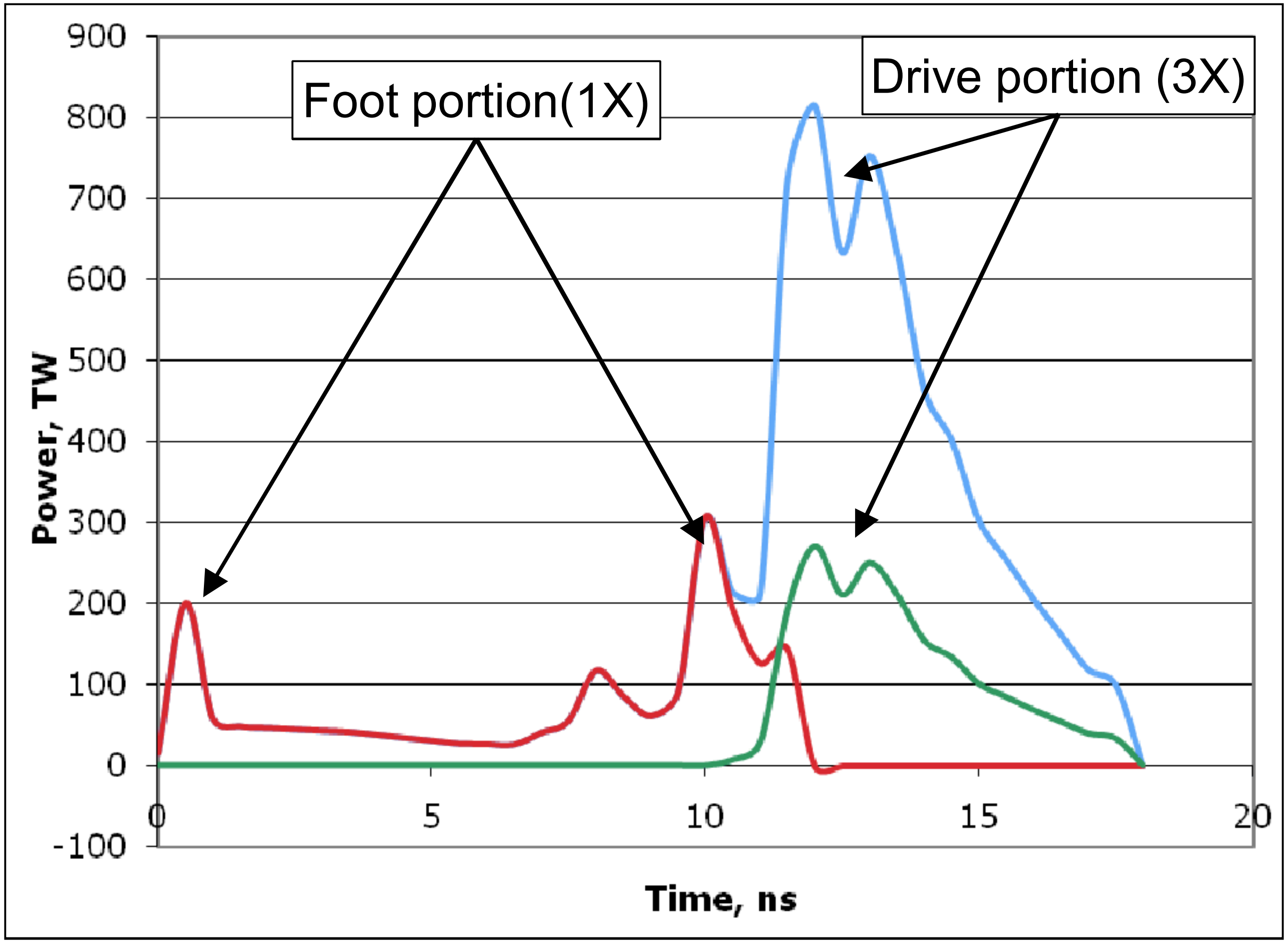
With thermal conduction smoothing



Percentage of Enclosed Power	3ω Power Inside Diameter of	3ω Power (with thermal smoothing)
50%	796 µm	802 µm
80%	1222 µm	1230 µm
95%	1800 µm	1805 µm

LIFE optimized CPP designs in the future will improve the flatness of the focal spot.

Average power frequency tripling efficiency is optimize with separate “foot” and “drive” beams:



The three “drive” beams are co-focused on target with one “foot” beam to create the desired power profile.

Thermally induced depolarization in isotropic media (Nd:glass) can be minimized with polarization rotation

Architecture