Integrated Research Experiment (IRE) Design of Diode-Pumped Solid-State Laser Driver for Fusion Energy: Venus Laser

Department of Energy • University of California

Lawrence Livermore National Laboratory

Science in the National Interest

Steve Payne

Design Team: Andy Bayramian, Ray Beach, Camille Bibeau, Al Erlandson, Bob Kent, and Ken Skulina

Snowmass Conference, July 2002

The 5-year plan for DPSSL development has several parallel efforts in place

CY 2001 | CY 2002 | CY 2003 | CY 2004 | CY 2005

Mercury Laser (100 J at 10Hz)

Component Development → Build laser → 1ω Activation

- Wavefront Correction
- Bandwidth (SRS suppression)
- Average Power Frequency Converter

3ω Activation

Beam-Smoothing

IRE Component Development (multi-kJ system)

15 cm S-FAP Crystals and Edge Cladding →

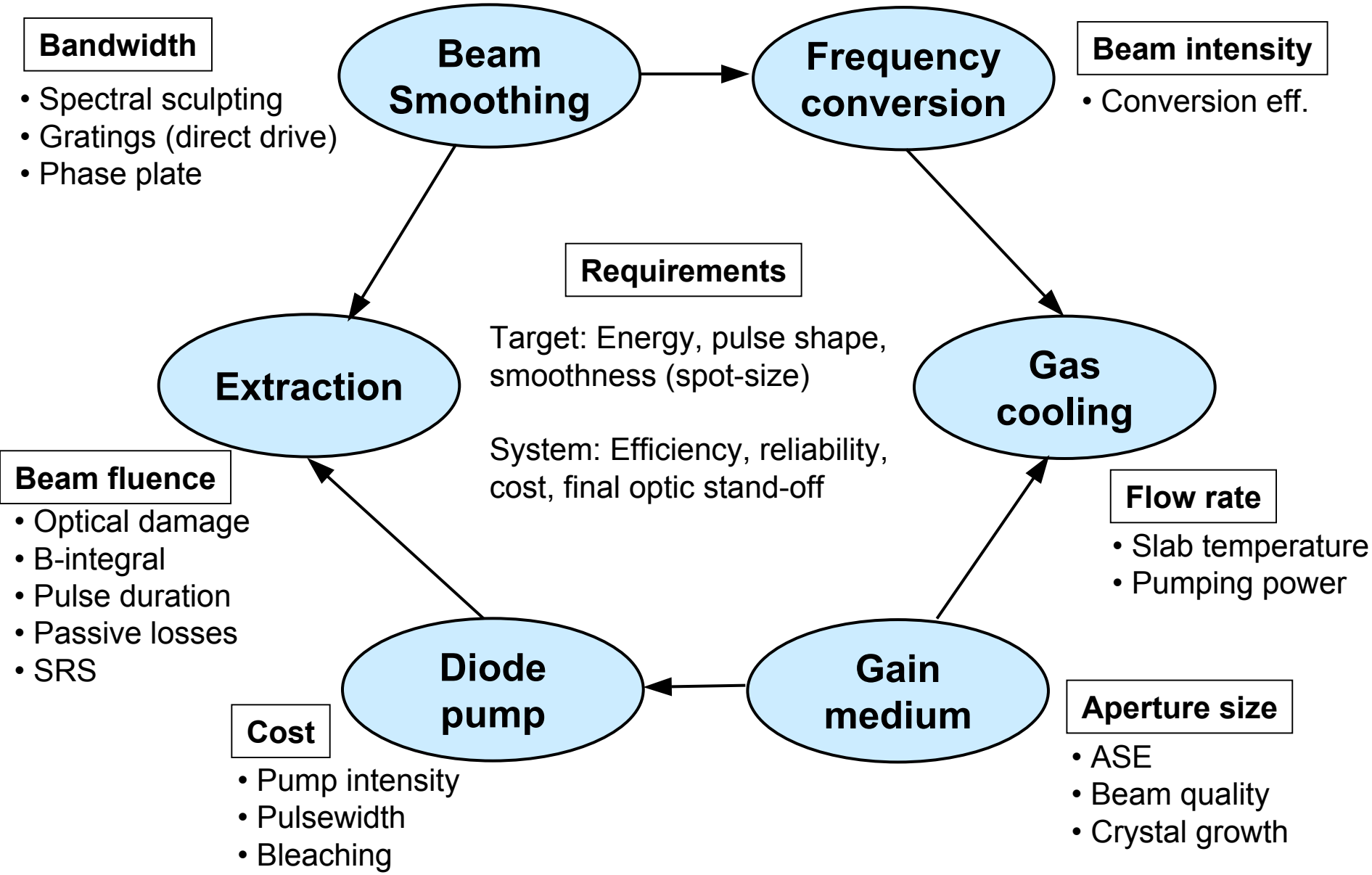
Pockels Cell and Driver →

> 200 W Diode bars →

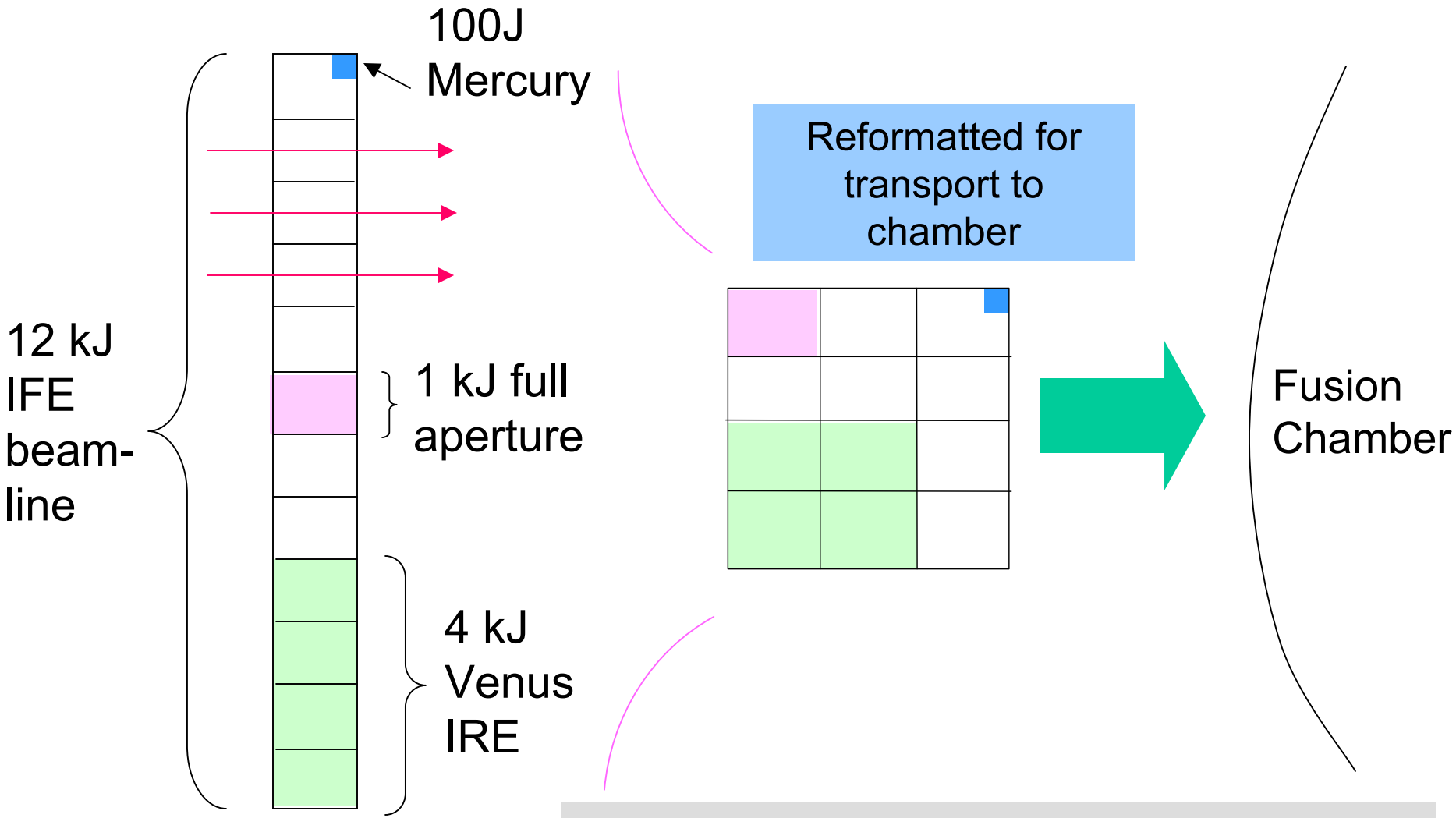
IRE Architecture

System Design Requirements and Cost Scoping → IRE Design

Fusion laser designs are predicated on target and system-level requirements



The Venus Laser is the "Integrated Research Experiment" or IRE follow-on to the Mercury Laser

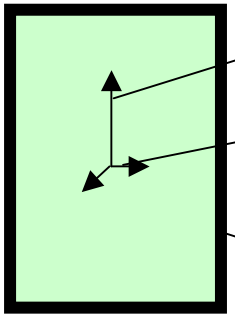


- How large should the aperture be?
- What beam quality is required of the laser?

The amplified spontaneous emission (ASE)-limited aperture of the Yb:S-FAP amplifier is ~10x15 cm^2

- ASE Code has been benchmarked to NIF slab physics
- Stored energy density = 1.1 J/cm^3 (optimized for quasi-three level laser)
- ASE multiplier: $M_{ASE} \cdot k_{em} = k_{ASE}$ causes emission enhancement

Polarization of beam

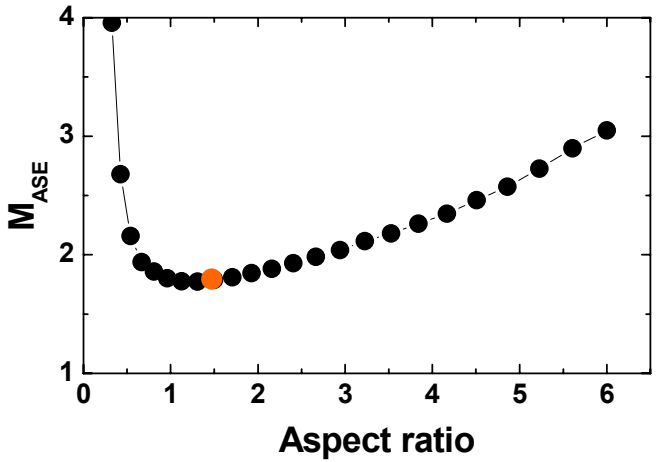


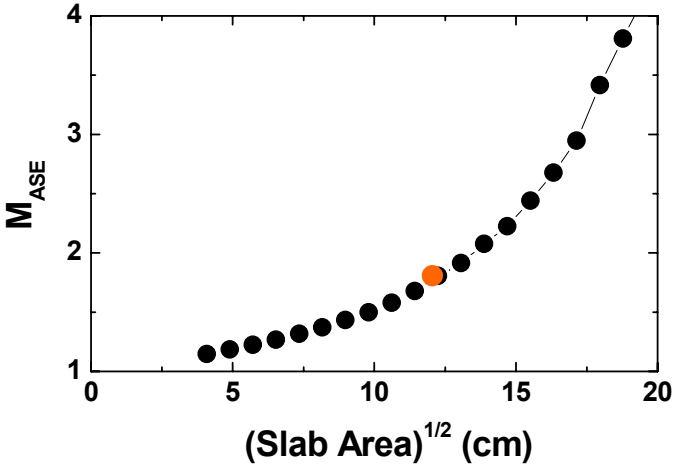
$\sigma_c = 6.0 \times 10^{-20}$ cm^2

$\sigma_a = 1.7 \times 10^{-20}$ cm^2

1.047 μm absorbing edge-cladding

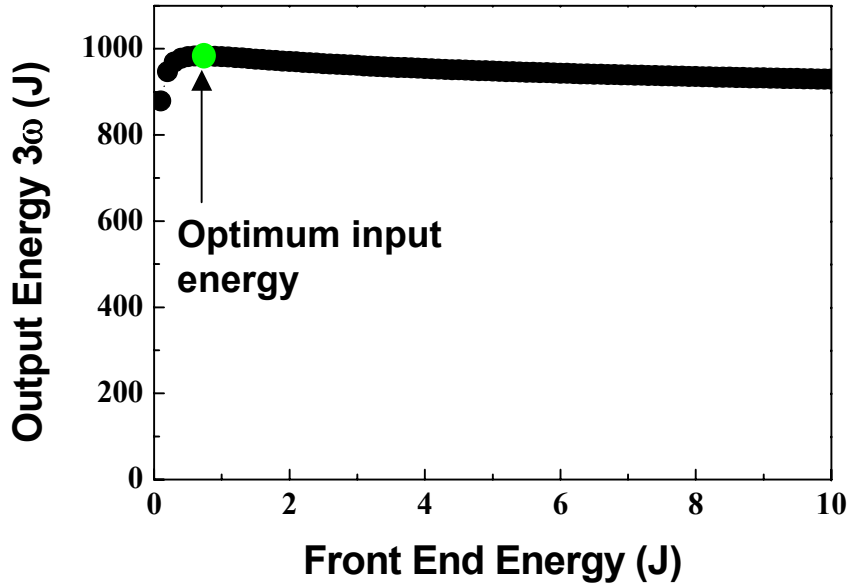
$\sigma_a < \sigma_c$ is advantage for one dimension of slab, leading to rectangular shape

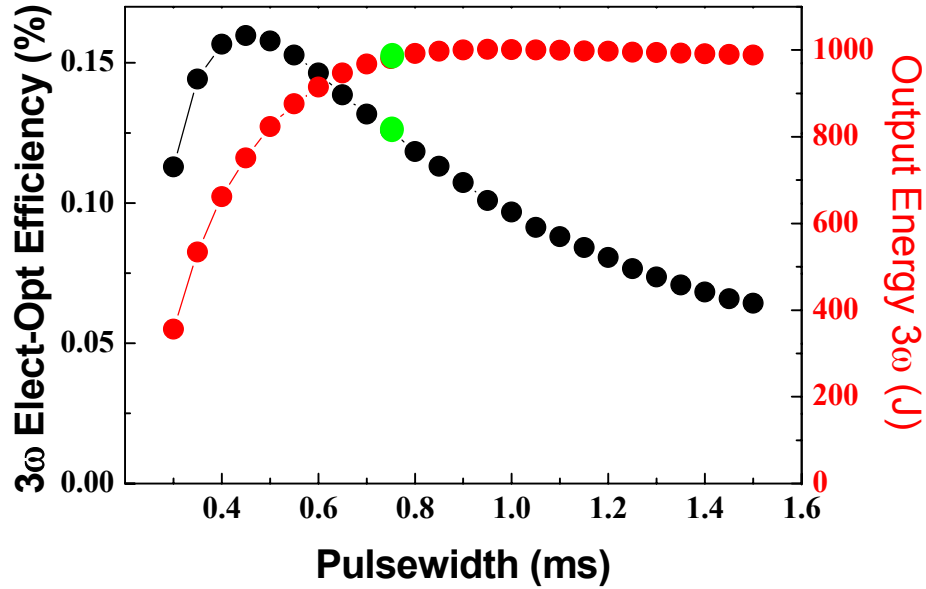




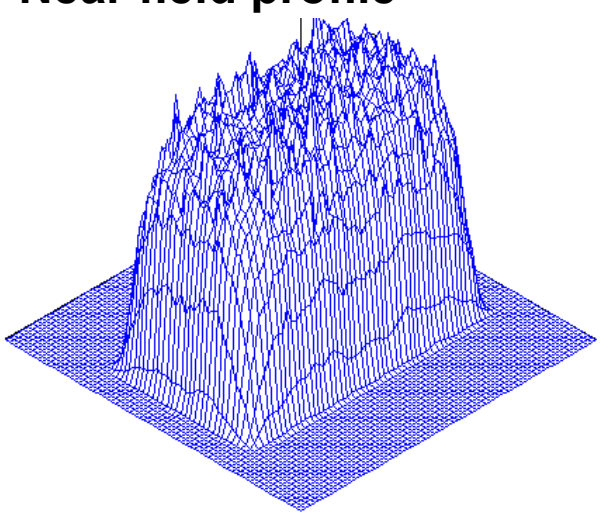
Aperture is calculated to be 10 x 15 cm^2

10x15 cm^2 aperture is predicted to produce ~1 kJ beam at 3ω





Near field profile



Results:
- **12% electrical-to-optical efficiency**
- **76% of energy in 1.0 TDL aperture**

Efficiencies used in 1-D calc'n:

$\eta_{xfer} = 0.90$

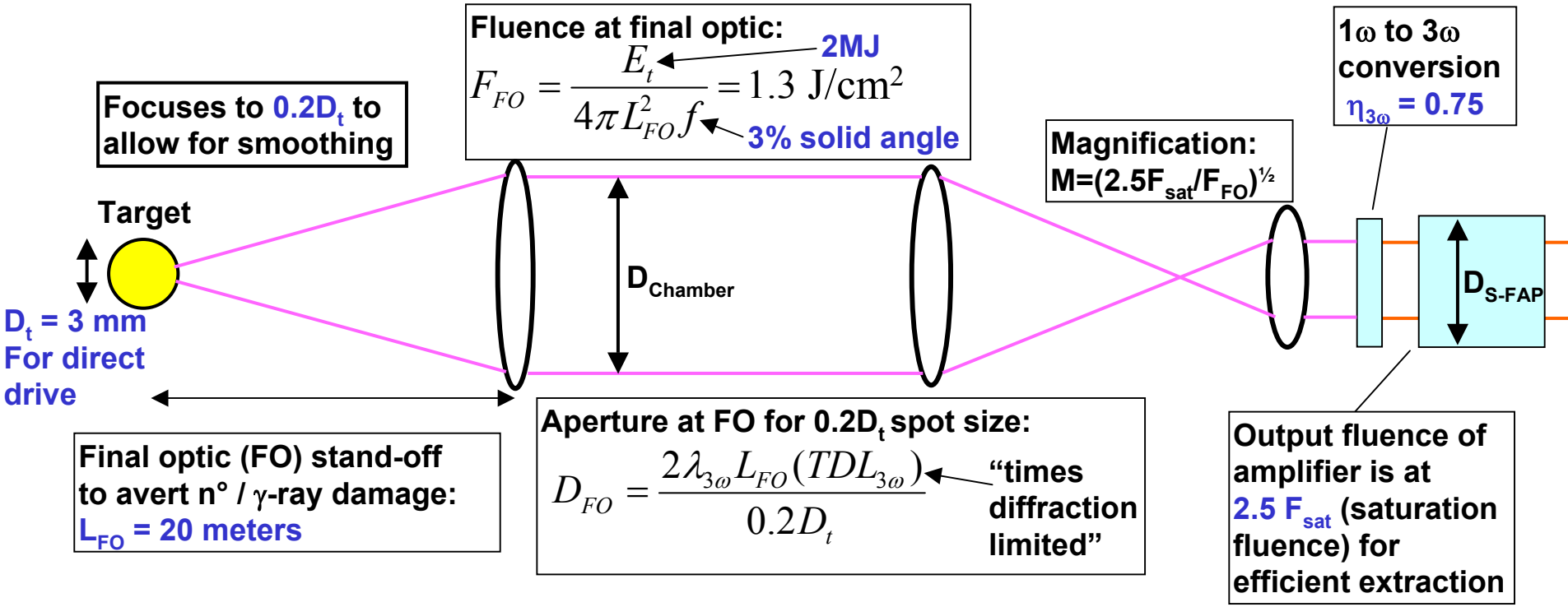
$\eta_{3w} = 0.75$

$\eta_{diode} = 0.60$

$\eta_{fill} = 0.95$

1D calc'ns used

Beam quality requirement for solid state laser is derived from target requirements



- Other equations and information
  - $\lambda_{1\omega}\ TDL_{1\omega} = \lambda_{3\omega}\ TDL_{3\omega}$
  - F_{sat} = 3.8 J/cm² (allows for 1 THz at 3ω)
  - Aperture of amplifier is limited by ASE, $D_{S\text{-}FAP}$ = 12.2 cm
- $$TDL_{1\omega} = \frac{(0.2D_t)D_{S-FAP}}{2\lambda_{1\omega}}\left(\frac{4\pi f \eta_{3\omega}(2.5F_{sat})}{E_t}\right)^{1/2} = 4.0$$

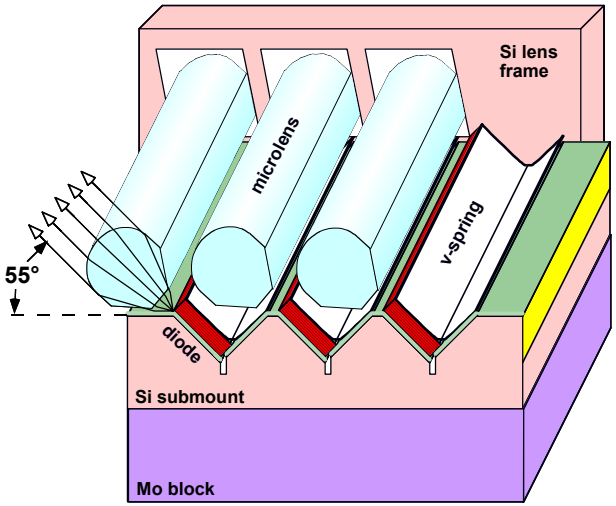
Using reasonable inputs, a basic calculation indicates that the laser beam must be < 4.0 TDL

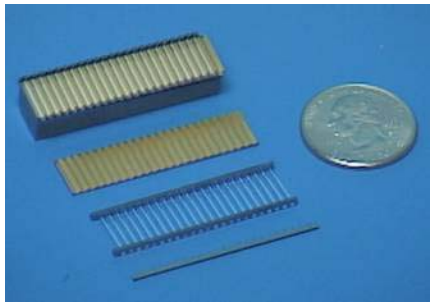
Diode pump arrays are comprised of three technologies: semiconductor diode bars, heatsinks, and backplanes

Diode bars

- Bars yield 100 W peak

23-bar 'tile'

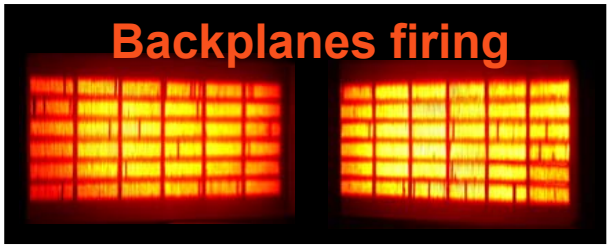




- Heatsink is constructed from silicon to reduce fabrication costs

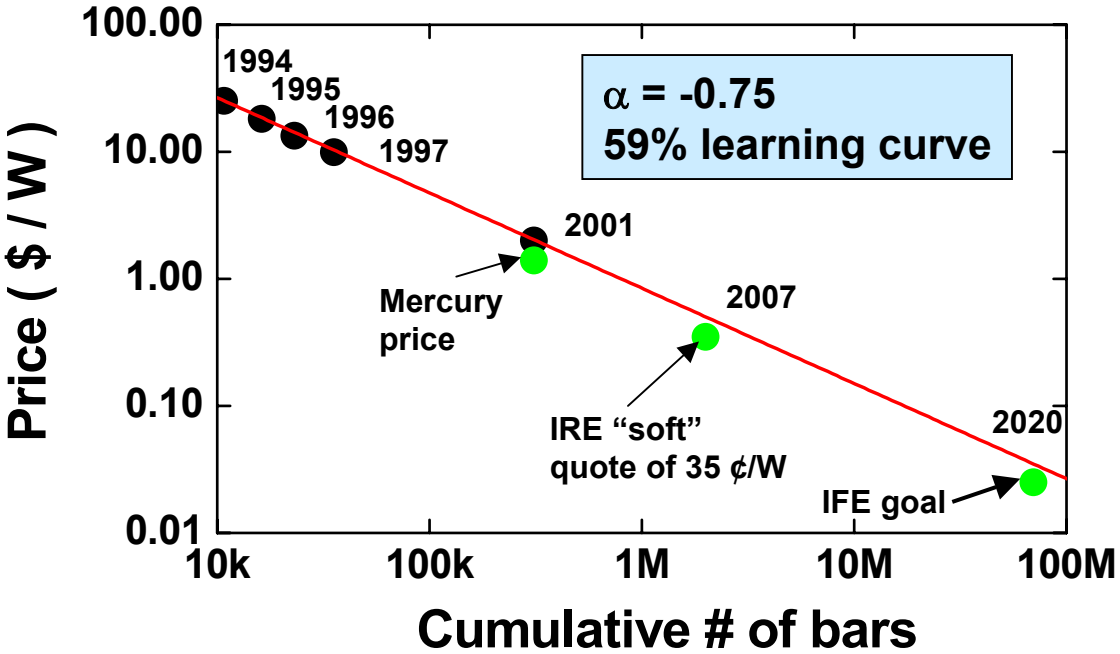
Populated diode backplane

- Tiles are mounted on an isothermal plane with minimum unused space



- **Current diode bar price = $1.60/W for 100 W bars in year 2001**
- **"Soft quote" of diode bar price = $0.35/W for 200 W bars in year 2007**
  - **assumes >20,000 bars/yr preceded by R&D campaign**

Learning curve analysis suggests that diode bar prices will continue to drop



- IFE plant uses ~ 25M bars operating at 400W/bar
- "Bottoms –up" estimate of fusion economy diode bars is 2-3¢/W (price)

Experience in the semiconductor industry is that the price of "minimum function" experiences ~60% slope learning curve *IEEE Spectrum, June 1980, p.45*.

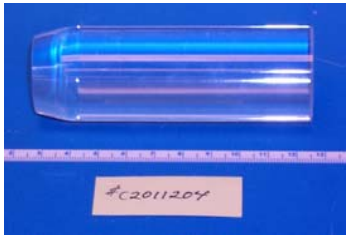
Anticipated diode bar prices for IRE and IFE are judged reasonable from learning curve analysis

Heatsink packaging and diode bar prices – current (2002) and projected to IRE in 2007 and IFE in 2020

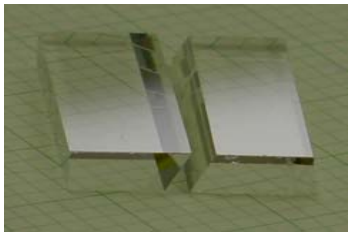
Cost Center	2002-LLNL	2007-Factory
Raw materials	$500	$200
Photolith, etching, dicing, submount, solder	$1,000	$150
Metallization--Ti:Ni:Ag:Au	$500	$60
Solder deposition	$500	$100
Microlensing--etching, dicing, assembly, & attachment	$1,000	$400
Diode bar attachment	$600	$300
Testing	$600	$100
Overhead	$1,000	$100
Tile heatsink cost	$5,700	$1,410
Power per tile	2300W	4600W
Tile cost/W	$2.5/W	$0.31/W
Equipment/W	$1.3/W	$0.1/W
Diode bar/W	$1.6/W	$0.35/W
Total cost/W	$5.4/W	0.76/W
Total price/W	$5.4/W	$1.2/W
Throughput (tiles/yr)	400/yr	5000/yr

- **2002 - LLNL**: Actual "government" costs – **$5.4/W for Mercury**
- **2007 - Factory**: Sustained production, specialized labor – **$1.2/W for IRE**
- **2020 – Factory**: "Bottoms up" estimate, supported by learning curve analysis, yields – **5¢/W for IFE**

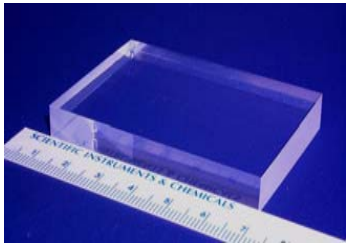
Crystal growth will be scaled up 2X to meet IRE requirements



Grow boule

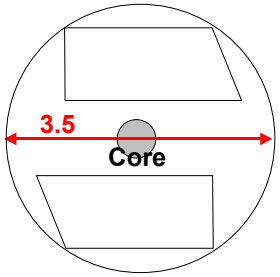


Harvest half-slabs

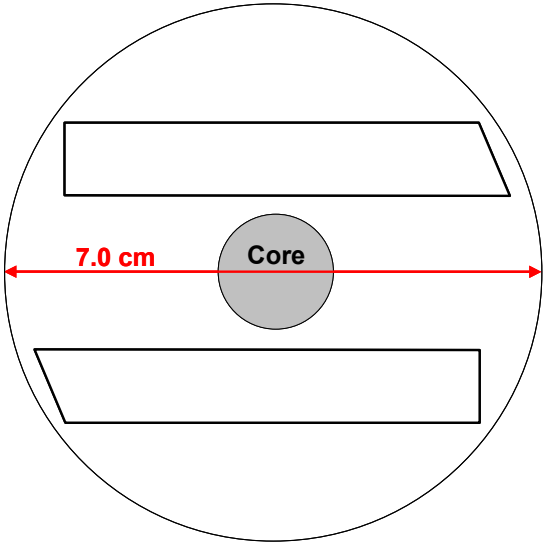


Bond into full-slabs

Mercury Laser (100J)



Venus Laser (1 kJ aperture)



- Very detailed understanding of chemistry
  - temperature gradients, phase diagram
  - five types of defects
- Bonding techniques need to be improved
  - scale-up of diffusion-bonding
  - exploring potential of "glass glues"

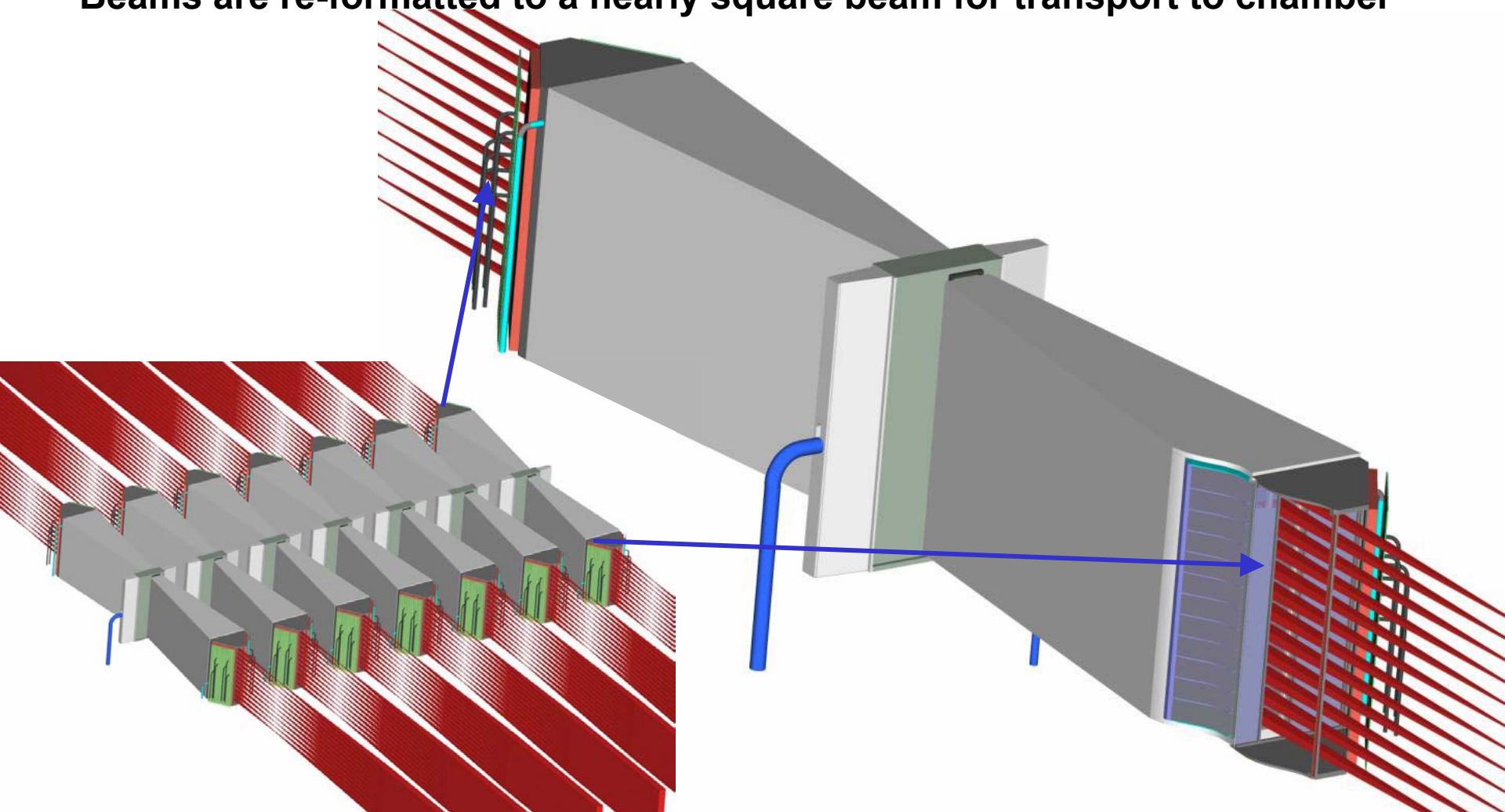
	Mercury (100 J)	IRE (4 kJ)	IFE (2 MJ)
Size (cm^2)	4 x 6	11 x 16	11 x 16
# Slabs	14	56	28,000
# Beams in bundle	1	4	12
# Bundles	1	1	168

Mercury Laser campaign addresses most laser physics and engineering issues, while Venus resolves issues in scaling

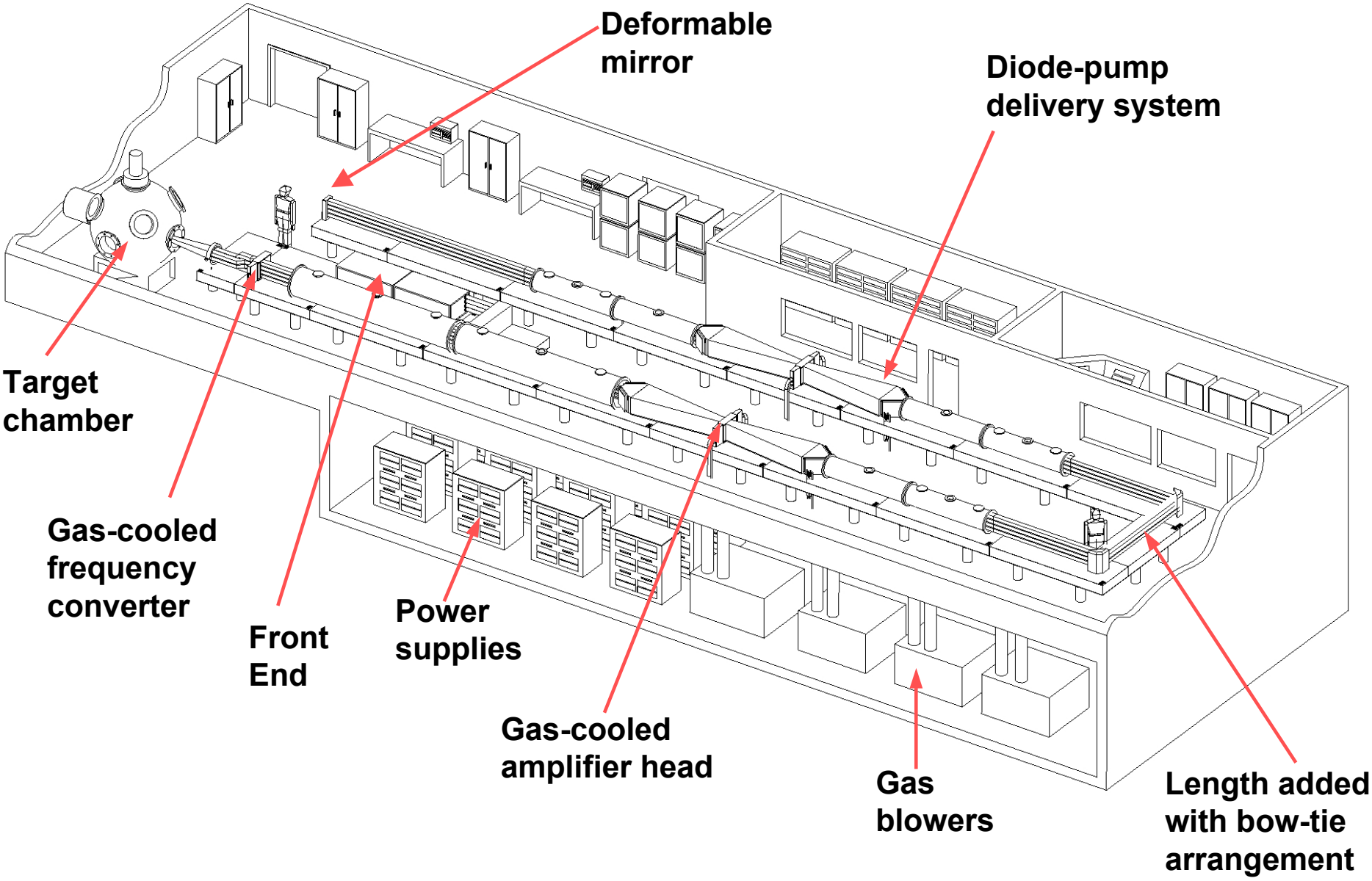
Technology	Mercury (100 J aperture)	Venus (4 kJ "bundle", 1 kJ aperture)
Optical architecture	Demo'd design	Scales with constant F#
Yb:S-FAP crystals	3.5 cm boules; chemistry understood	7 cm boules; requires more growth stability
Diode heatsinks	Designed and fab'd at LLNL	Commercial manufacturer – Tech transfer in process
Diode bars	100 W/bar - Coherent	Natural progression to 200 W
Pockels cell	100 W demo'd (not yet on laser)	Aperture scaling to 1000 W
Front-end	Temporal, spectral, Spatial control	Increase energy with small amplifier
Frequency-converter	3x5 cm^2 planned	10x15 cm^2 do-able
Gas-cooling	Demo'd operation	Larger re-circulator
Aperture "bundling"	Not addressed	Mechanical engineering

IFE beamline involves linear bundling of 12 apertures

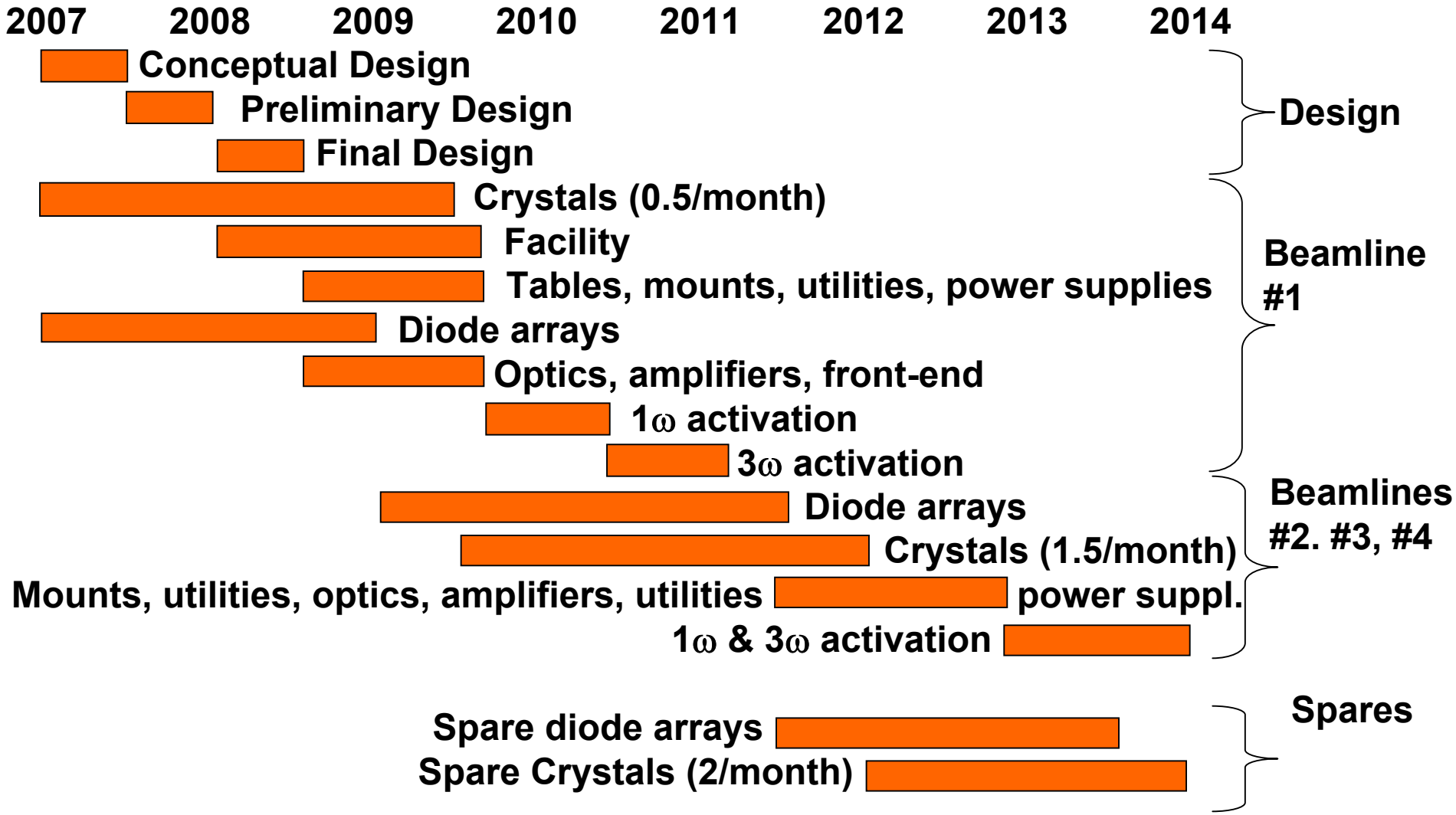
- 12 aperture beamline fed by cooling lines (water and helium), and mounted on space frame structure
- 7 beamlines can be serviced by each water and helium utility
- 168 total bundles in IFE power plant
- Beams are re-formatted to a nearly square beam for transport to chamber



The "Venus Laser" IRE will be comprised of four 1-kJ apertures



Proposed schedule for Venus Laser buildup and activation



Venus can also be configured as a short-pulse fast-igniter laser

Front-end → **Stretcher** → **Venus Laser (single aperture)** → **Compressor (2X mag)** → **1.0 kJ 10 ps**

$\Delta\lambda_p$ = 1.6 nm
τ_p = 2psec

C_p = 105 ps/nm
d_{sep} = 2 m
τ_p = 2 nsec

E_{out} = 1.2 kJ
B-integral limited

C_p = 1254 ps/nm
d_{sep} = 8.6 m
(intentionally stretched to lengthen pulse)

Target/System Requirements	
Total Energy	100 kJ
Final Optic Standoff	20 m

Optical specification	Spot size	
	300 μm	50 μm
Aperture	26 cm	160 cm
% solid angle (no phase lock)	0.15%	5.6%
% solid angle (with phase lock)	-	0.15%

- **Assumptions – Laser has 2X diffraction-limited output**
- **If 36 beamlines can be phase-locked, then there is a 37X decrease in solid-angle for a 50 μm spot size**

Possible experiments to be performed on the Mercury and Venus Lasers

Shots-on-demand mode

- Obtain improved data through averaging – opacity, shocks, equation-of-state, instabilities, laser-plasma interactions, and hohlraum
- Calibrate diagnostics for single-shot facilities
- Evaluate beam-smoothness and its impact on instabilities
- Propagate high-power beams in chamber gasses

Rep-rated mode

- Assess laser driver physics and reliability (thermal effects and beam quality)
- Test first-wall and final-optic with average-power X-ray/fast –ion source
- Determine optical damage limits for fusion-lasers
- Hit targets "on-the-fly"

Short pulse mode

- Explore fast-igniter physics
- Develop improved back lighter
- Generate laser induced fusion neutrons for materials testing

- Synergies with other government programs: laser weapons and γ–γ collider
- Additional science experiments: X-ray laser, radiative shocks, geological EOS

Rough estimated "top-down" cost of the 4-kJ IRE (Venus laser)

IRE breakdown	Cost ($millions)
Diode arrays ($0.5/W)	37
Crystals (incl. fabrication and coating)	16
Facility, utilities, mounts	8
Power supplies + pulsars + cabling	17
Frequency converters	3
Front end	3
Pockels Cell	3
Optics	3
Control system	2
Diagnostics (optical)	2
Diagnostics (chamber)	2
Target chamber + shielding	2
Other small procurements	13
Manpower for design and set-up	12
Manpower for activation	5
Contingency	20
Distributed direct support	12
Other distributed charges	26
Total	185