A vision for
Laser Direct Drive
Fusion Energy

John Sethian
Naval Research Laboratory
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Outline

Introduction to direct drive with lasers
- **Advanced target designs (tailored adiabat, zooming)**
- **Lasers-KrF and DPPSL**

Components of Laser Direct Drive Fusion Energy Power plant
- **Why this is an attractive approach to fusion energy**

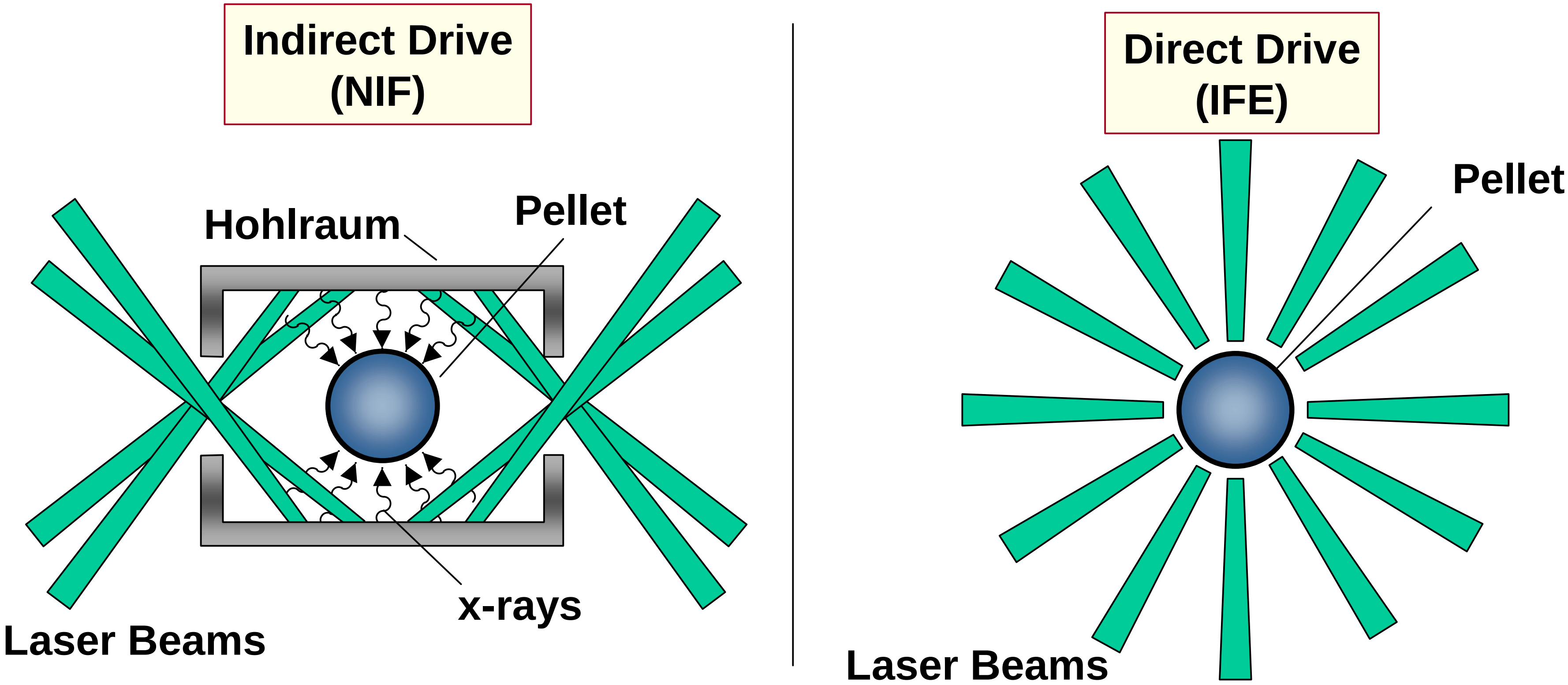
Philosophy for developing fusion energy…*it's the reactor, stupid!*
- **Develop ALL components in concert with each other**
- **Welcome ARIES participation**

Principal technical challenges that require a team effort:
- **Target Injection**
- **Final Focussing Optics**
- **Economics**

The Integrated Research Experiment

Summary

A primer on direct drive with lasers



Advantages of direct drive:

- **Physics is simpler--key issue is hydrodynamic stability**
- **Targets are relatively simple (cheap) to fabricate--key issue is injection**
- **Higher efficiency--better coupling of laser to fuel**
- **No Hohlraum debris to recycle**

High gain Direct Drive requires control of both mass imprinting and subsequent Rayleigh Taylor Growth

Amplitude of
mass modulations

$$A\,(t) = A_o\, e^{gt}$$

Initial mass Modulation

Target non-uniformities

Laser non-uniformities

SOLUTION:

Make targets smooth

Use a Smooth Laser Beam

Rayleigh Taylor growth of modulations

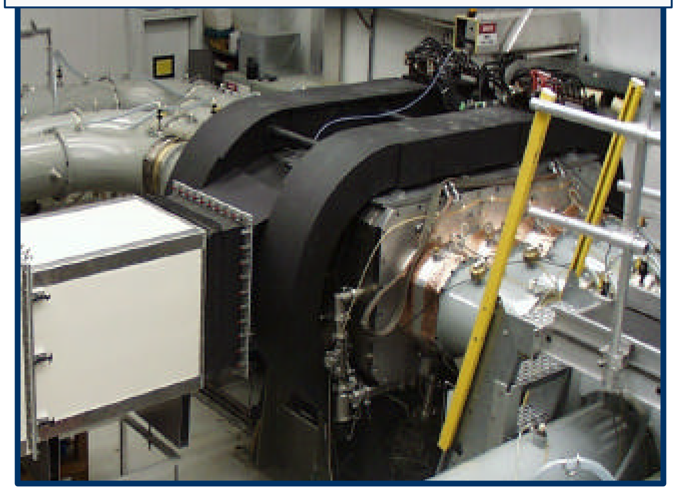
SOLUTION:

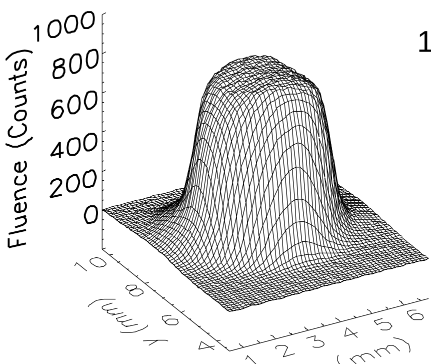
Raise Isentrope of ablator

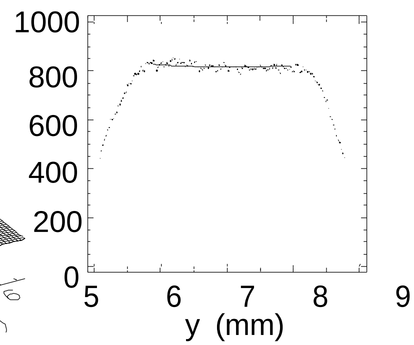
Nike Krypton Fluoride (KrF) Laser has outstanding beam uniformity, with architecture that can be scaled to an IFE-sized system

Beam uniformity

NRL NIKE Laser Main amplifier



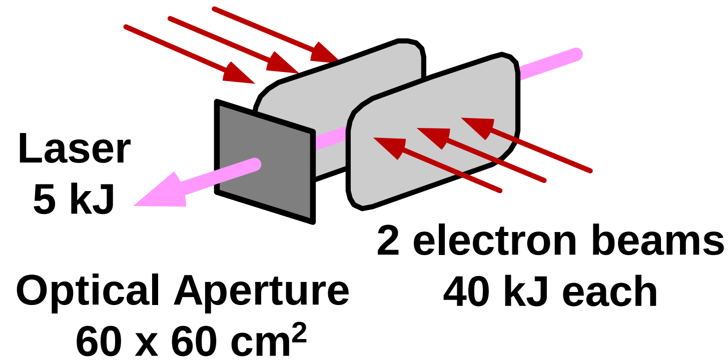




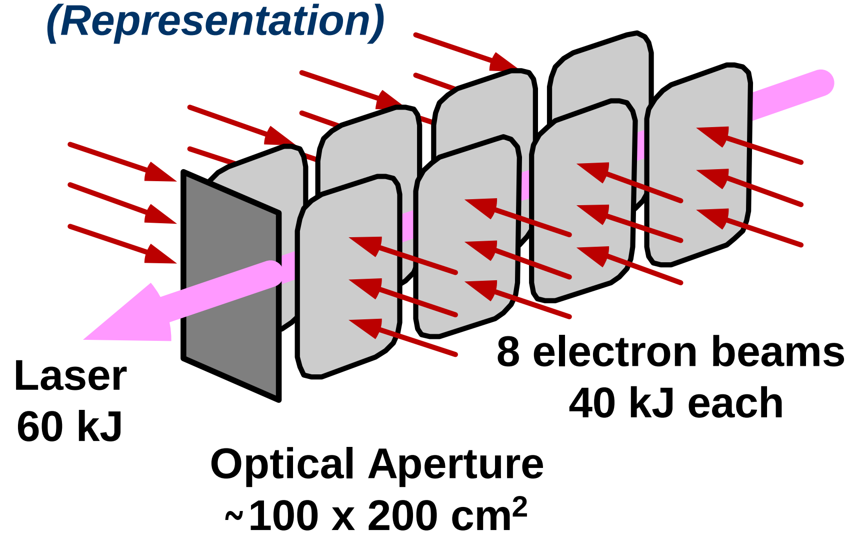
1.2% spatial non-uniformity per beam
0.3% non-uniformity, overlapped beams

Scalable to IFE-size systems

Nike 60cm Amplifier



IFE-sized Amplifier
(Representation)

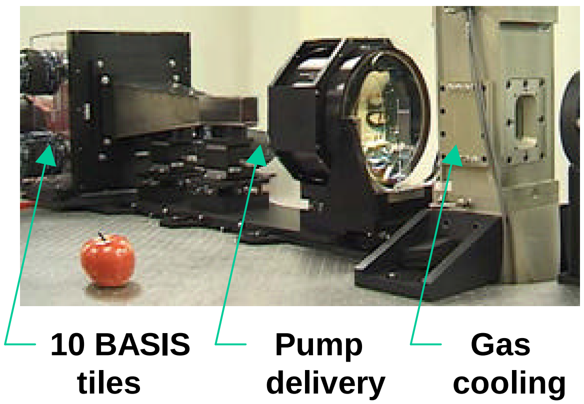


The challenge is to achieve the required cost, rep-rate, durability, & efficiency

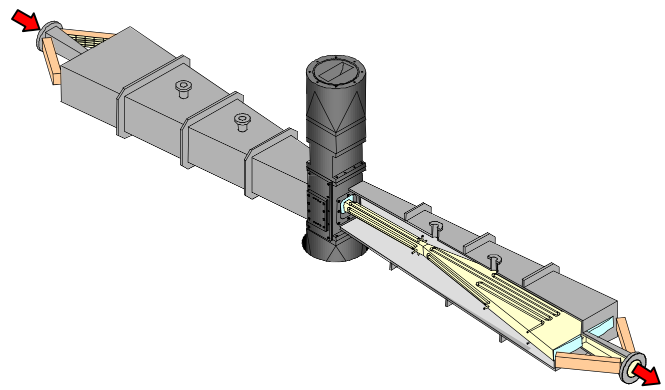
Diode Pumped Solid State Lasers (DPSSL) are another approach for an IFE driver

Mercury Laser is progressing toward our goal of 100J/10Hz/10%

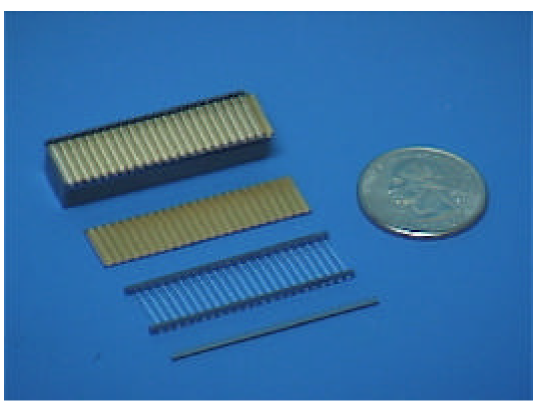
- Gas-cooled head vibration-free; gain and wavefront (surrogate Nd:Glass slabs) consistent with modeling



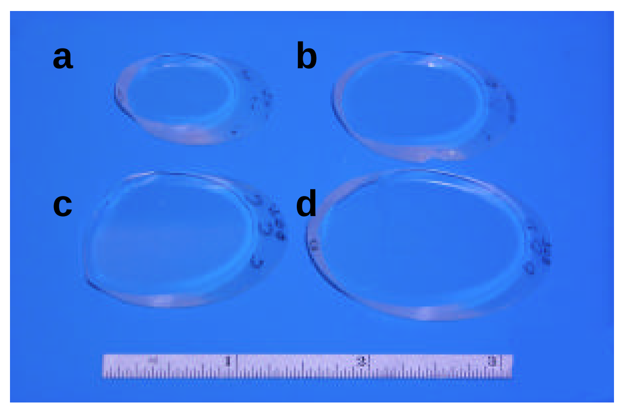
- Improved, robust architecture uses no pump lenses, integrated pump and spatial filter cavities; procurements in process



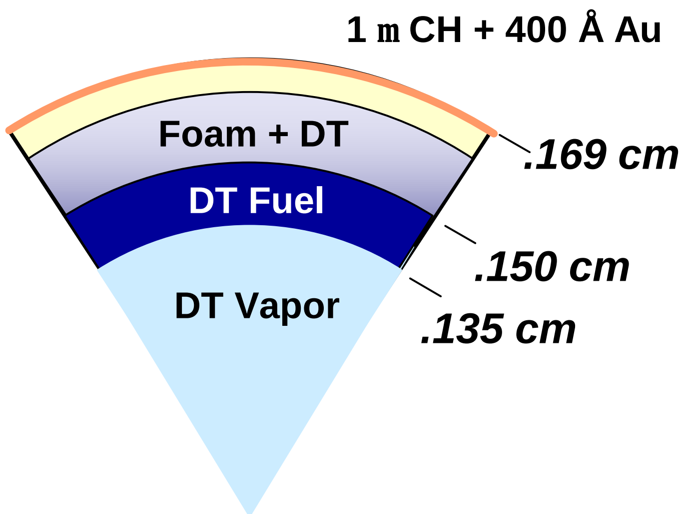
- Diode package is reliable and simple; 13 tiles built since 5/00 operating at 115W/bar



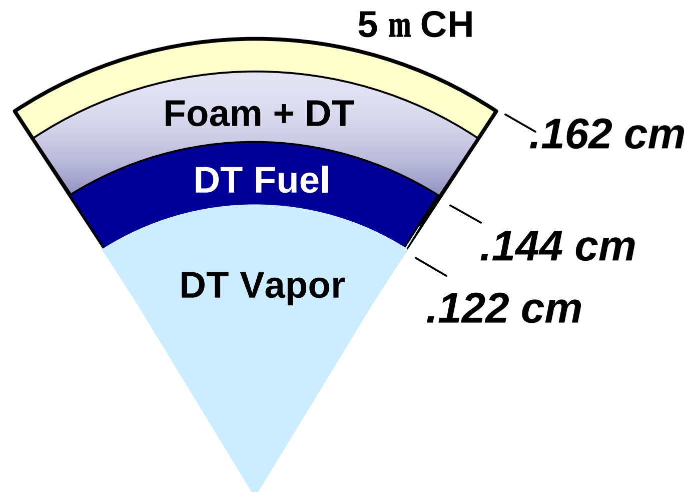
- Yb:S-FAP crystal growth issues are nearly resolved; no bubble core, grain,or smoke; 25% larger boules needed



NRL Advanced target designs show promise for high gain



1.3 MJ laser
124 gain*



1.6 MJ laser
110 gain*

Both designs assume
- **KrF laser (ISI smoothed)**
- **Zooming**
- **Precise laser pulse shape**

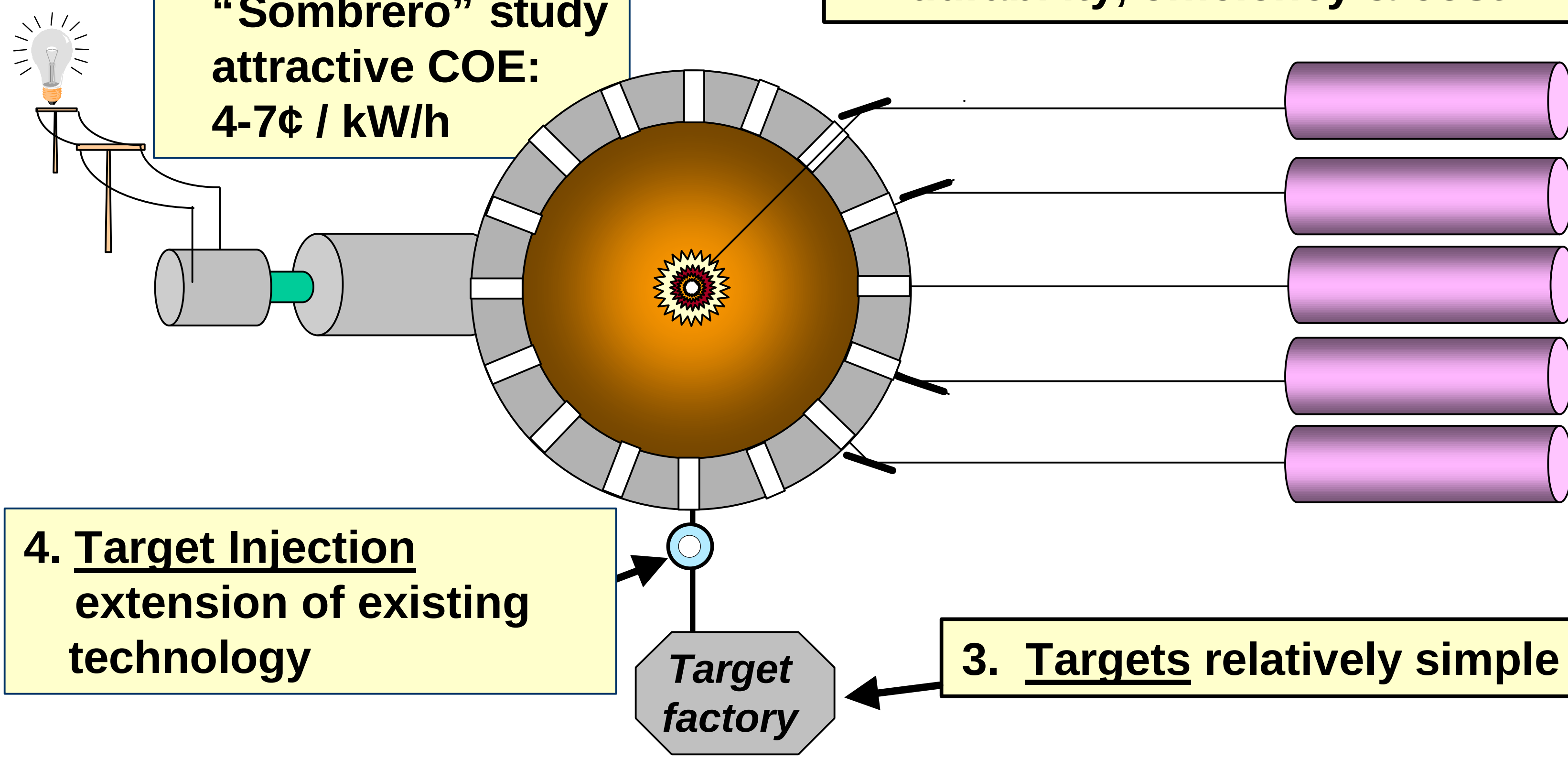
*** gains calculated in 1 D**

Direct Drive with Lasers is an attractive approach for Fusion Energy.

1. Advanced Direct Drive <u>Target Designs</u> show promise for high gain (> 100)

2. <u>Lasers</u> have two promising choices
   KrF (gas) Laser
   Diode Pumped Solid State (DPSSL)
   Both have potential for meeting req'd durability, efficiency & cost

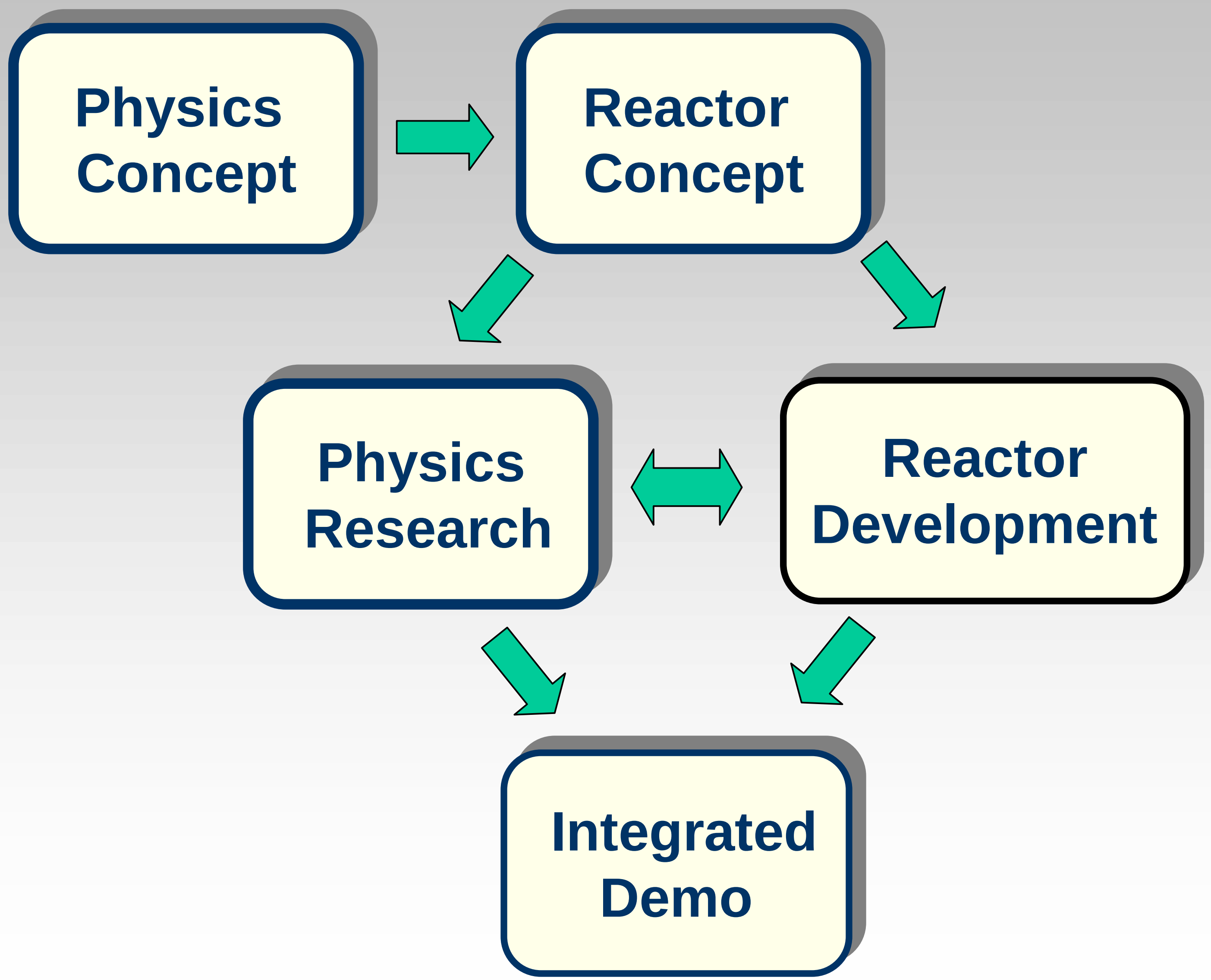
5. <u>Reactor</u>
   "Sombrero" study attractive COE:
   4-7¢ / kW/h



4. <u>Target Injection</u>
   extension of existing technology

3. <u>Targets</u> relatively simple

The RIGHT way to go about developing Fusion Energy

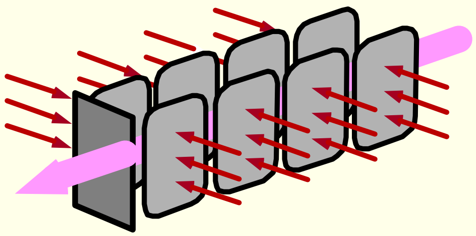


The science and technology for Laser IFE must be developed as an integrated system. Ideal for ARIES

Laser Driver

KrF: NRL

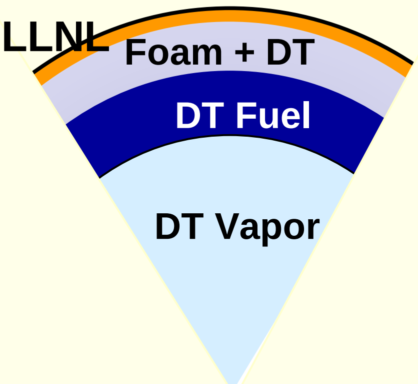
DPSSL: LLNL



Target Design

NRL

LLNL



Laser Fusion Power plant

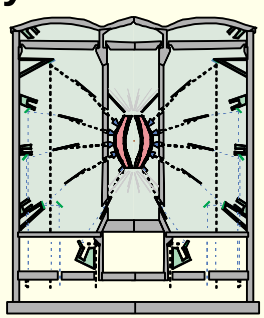
Chamber Studies

Wisconsin

UCSD

Berkeley

LLNL



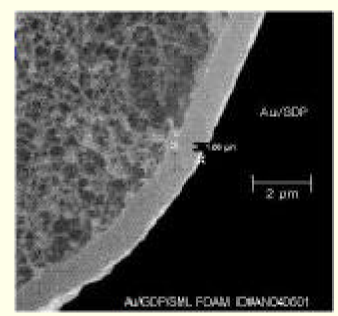
Target Fab & Injection

General Atomics

LANL

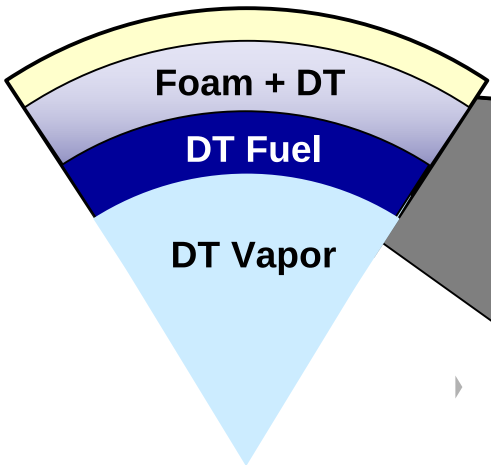
Schafer Corp

NRL

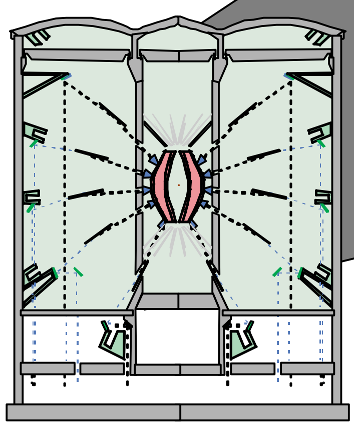


Example: Target gain and power plant studies define laser requirements

High Gain Target Design (>100)[1]



Power Plant Study[2]



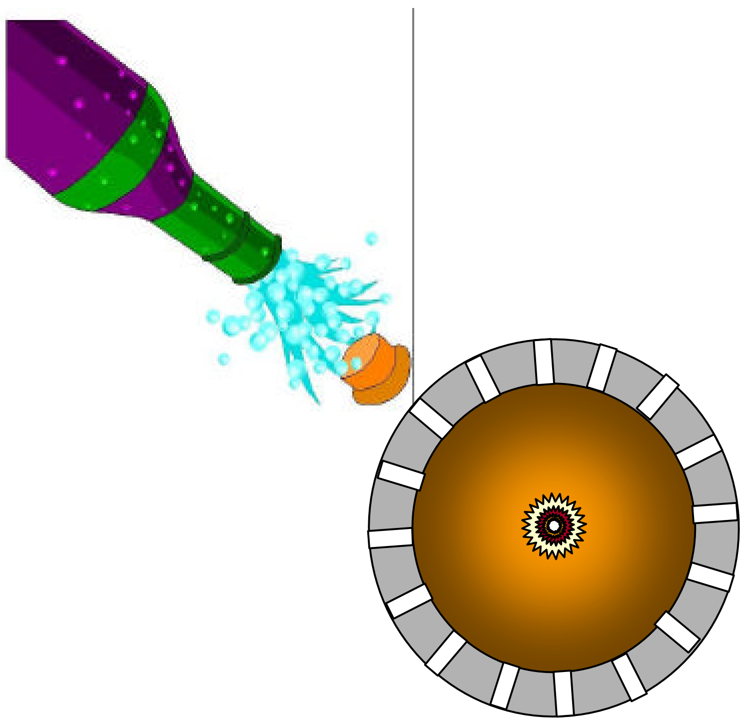
Laser IFE Requirements

	IFE	NIKE
Beam quality (high mode)	0.2%	0.2%
Beam quality (low mode)	2%	N/A[4]
Optical bandwidth	1-2 THz	3 THz
Beam Power Balance	2%	N/A[4]
System efficiency	6-7%	1.4%
Laser Energy (amplifier)	30-150 kJ	5 kJ
Cost of entire laser[1]	$225/J(laser)	$3600/J
Cost of pulsed power[1]	$5-10/J(e-beam)	N/A[3]
Rep-Rate	5 Hz	.0005
Durability (shots)[2]	3×10^8	200
Lifetime (shots)	10^{10}	10^4

1. 1999 $. Sombrero (1992) gave $180/J and $4.00/J
2. Shots between major maintenance (2.0 years)
3. Not Applicable: Different technology
4. Not Applicable: Nike shoots planar targets

1. S.E. Bodner et al, ."Direct drive laser fusion; status and prospects", *Physics of Plasmas* **5,** 1901, (1998).
2. Sombrero: 1000 MWe, 3.4 MJ Laser, Gain 110; Cost of Electricity: $0.04-$0.08/kWh; Fusion Technology, **21**,1470, (1992)

Issue #1:   Target Injection



Problem:

1. Sombrero uses 0.5 T Xe to protect walls
   - Heats target on the way in
   - Asymmetrically heats target
   - Compromises tracking
     - (If gas turbulent-- tracking impossible)
   - Affects laser propagation (> 0.1 T)
2. Chamber wall at 1500 °C heats up target

Solution (Team effort):

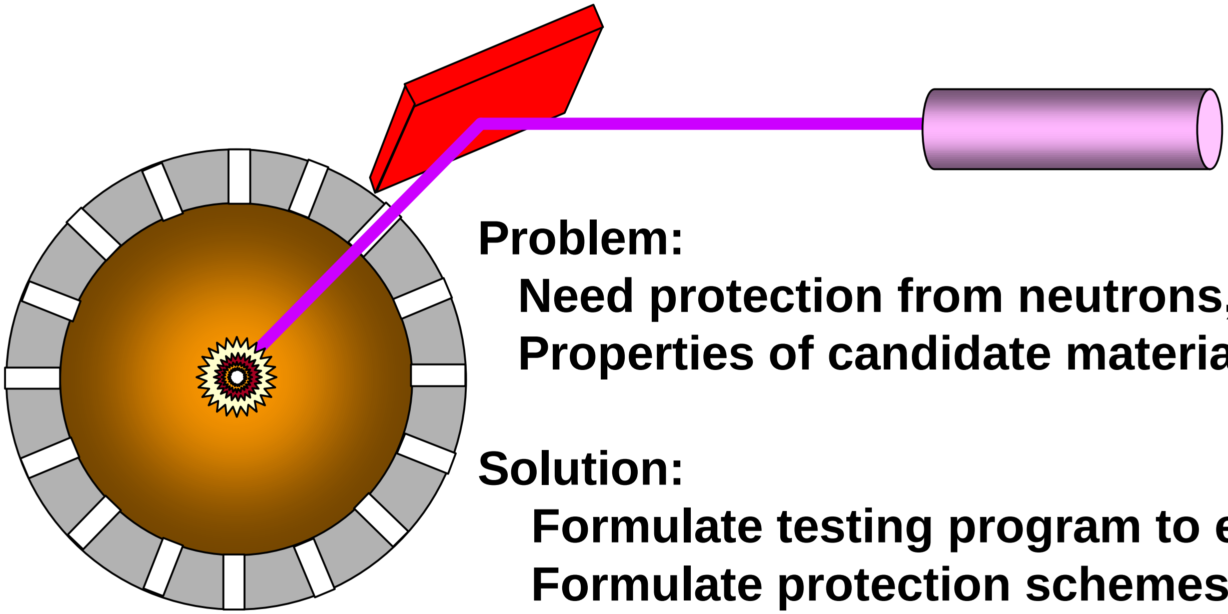
1. Establish true post-burn debris
   - Perkins (LLNL), Schmitt (NRL)
   - Peterson (Wisc), Najmabadi (UCSD)
2. New wall materials
   - Tillack (UCSD), Univ of Wisconsin
3. Effect of rapid (20 msec) warm-up
   - Hoffer (LANL)
4. Target design & fabrication
   - NRL, GA
5. Revisit gas wall protection
   - ARIES

Post burn output energy accounting, at t=100 nsec

From John Perkins, LLNL,
Feb 25, 2000
NRL tailored adiabat target

X-rays		2.14 MJ
Neutrons		109 MJ
Gammas		0.0046 MJ
Burn Product fast ions		18.1 MJ
Protons	0.54 MJ	
Deuterons	4.22 MJ	
Tritons	3.87 MJ	
3He	0.0036 MJ	
4He	9.52 MJ	
Debris Ions Kinetic Energy		24.9 MJ
Protons	0.10 MJ	
Deuterons	10.00 MJ	
Tritons	12.8 MJ	
3He	0.01 MJ	
4He	1.01 MJ	
Carbon	0.72 MJ	
Gold	0.20 MJ	
Residual Thermal		0.013 MJ
TOTAL		154.4 MJ

Issue #2 Final Focussing Optics



Problem:
Need protection from neutrons, x-rays, debris
Properties of candidate materials largely unverified

Solution:
Formulate testing program to evaluate materials
Formulate protection schemes (shutter, magnets, gas, etc)

Sombrero: Grazing Incidence Metallic Mirror (GIMM)
Lifetime depends on (unknown) fluence limit and/or recovery by annealing:
Limit 10^{22} neutrons/cm^2: can last plant lifetime (30 yr)
Limit 10^{21} neutrons/cm^2: requires 90% annealing to last 30 yr

Other options:
Grazing Incidence Liquid Mirror (GILM)--reflectivity not known
Heated fused Silica with self-annealing (OK for DPPSLs, not good for KrF)
Based on models extrapolated from experiments on Sandia SPRIII reactor

Issue #3 Economics

Problem:

How to determine effect of varying cost/ efficiency /performance of one component

Most reactor studies:
Hold *net power constant*, (~ 1000 MWe) and then vary one parameter
But varying one parameter forces others to change as well

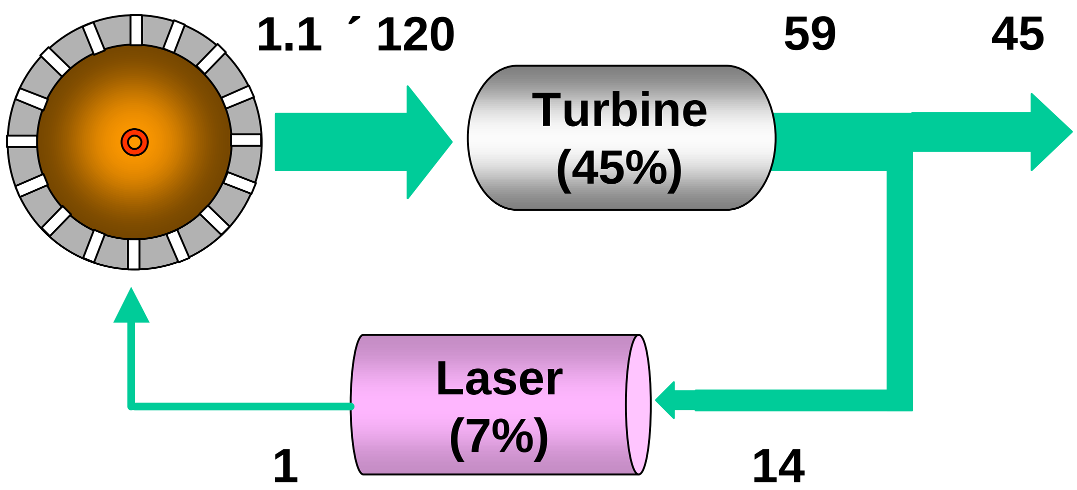
As other parameters are not well known ….results are confusing

Suggested Solution:

Pick a "standard" set of conditions and vary only one parameter.

Gets better understanding of varying cost/ efficiency /performance of one component

Example: higher gain lowers COE



BASELINE CASE

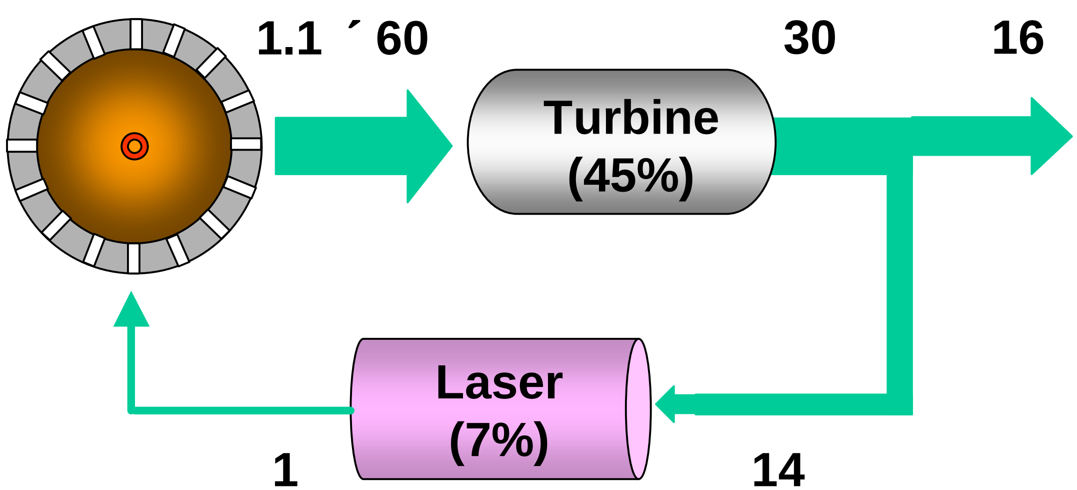
Gain = 120

Laser η = 7%

76% (45/59) **of the output energy available to grid**

COE ≡ $1.00

Fix all parameters, inc laser output, and vary target gain only



Gain = 1/2 = 60

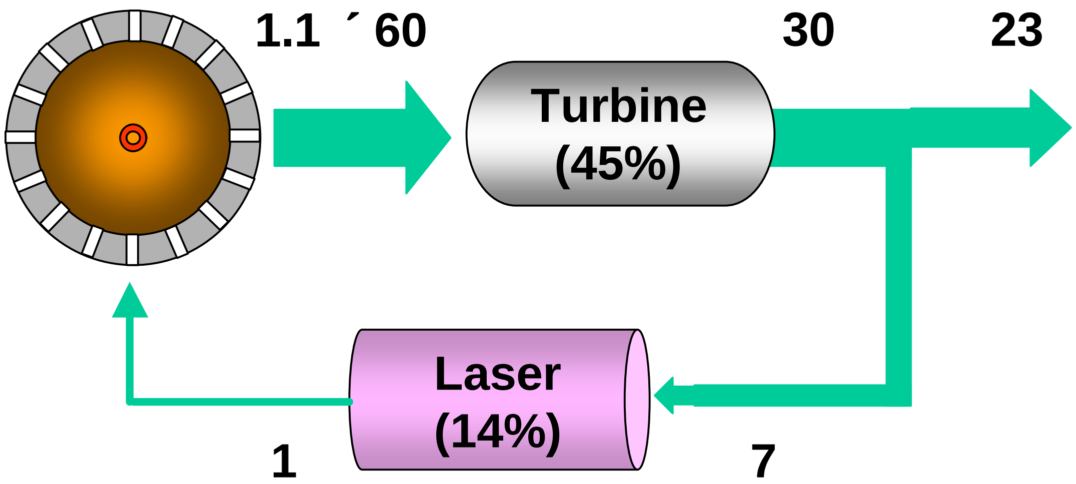
53% of the output energy available to grid

COE = $2.81

Thus, to recover lower cost COE, you need to do something else: More laser energy, higher RR, etc.

Examples from S E. Bodner

Ex 2: Higher laser efficiency does not make up for lower gain



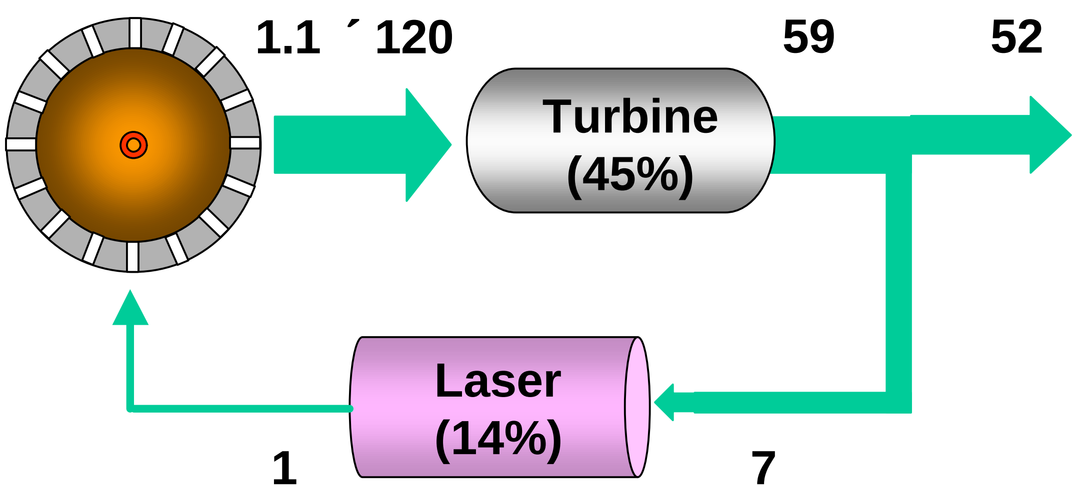
Gain = *1/2* = 60

h = *2x* = 14%

1/2 the output (23/45)

COE = $1.96

Ex 3: Higher laser efficiency does not gain that much



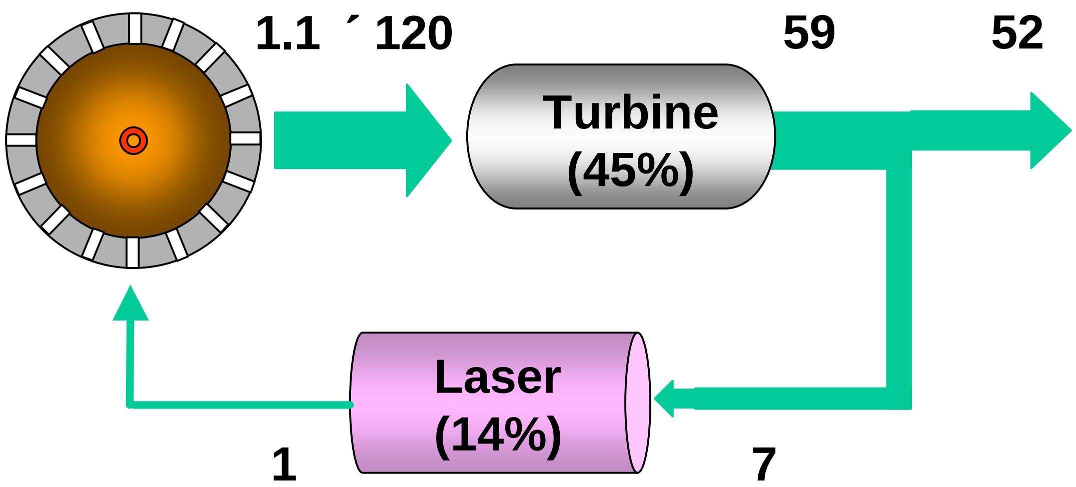
Gain = 120

h = *2x* = 14%

88% of the output energy available to grid

COE º $0.87

Ex 4: Higher laser efficiency at higher price not worth it



Gain = 120
h = 2 x 14%
Laser = 2 x cost

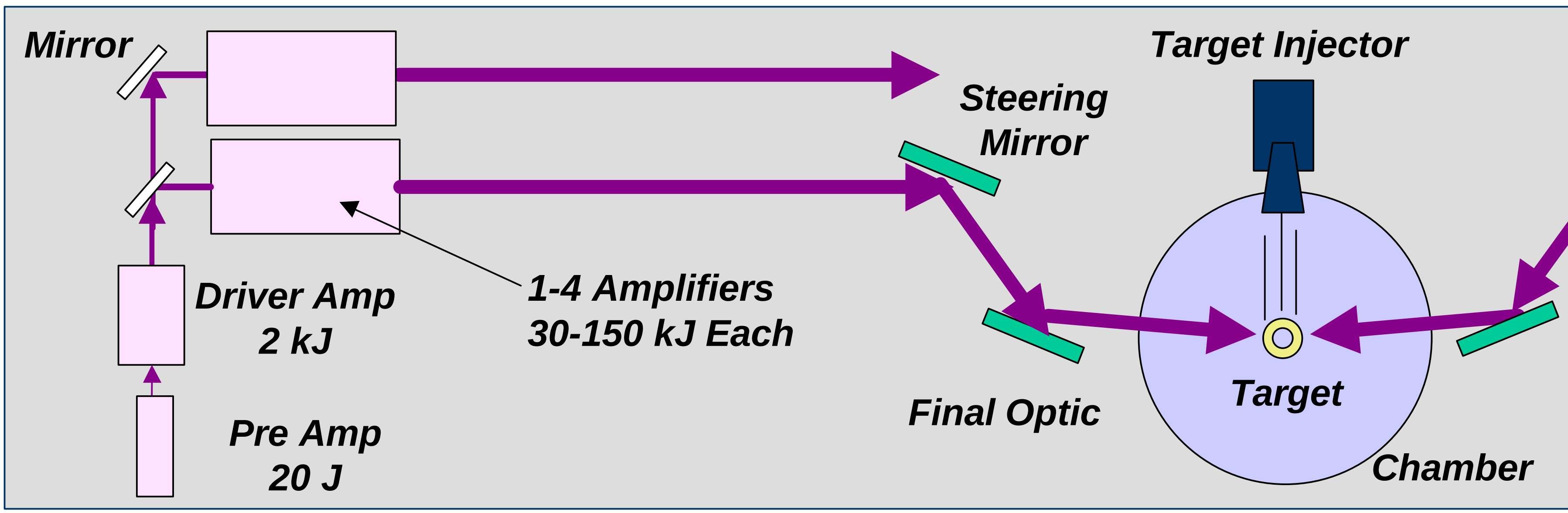
88% of the output energy available to grid

COE º $0.87 x 1.25 = $1.10
(assumes laser = 1/4 cap cost)

(KrF) Laser IFE Integrated Research Experiment

The IRE is envisioned to be an integrated repetitive demonstration that:

1. An IFE target can be injected and survive in a chamber environment
2. A power plant-sized laser can be steered to illuminate the target with the uniformity and precision required for inertial fusion energy.



Amplifier Output/shot	**30-150 kJ [1]**
Efficiency	**6-7%**
Rep-Rate	**5 Hz**
Durability (shots)	**3×10^8**
Lifetime (shots)	**10^{10}**
Cost of entire laser (projected)	**$225/J(laser)**
Beam uniformity	**Goals met**
Beam Power Balance	**2%**
Optics damage threshold-lenses & mirrors	**3 - 8 J/cm^2 [1]**
Final Optic Lifetime (neutrons, x-rays, laser)	**3×10^8**
Beam steering	**TBD [2]**
Laser propagation in reactor environment	**TBD [3**

Summary

Direct Drive with lasers is an attractive approach to IFE
- **Advanced target designs have potential for high gain**
- **Two driver candidates have potential to meet IFE requirements**
- **Target fabrication should be relatively straightforward**
- **Dry wall chamber design seems feasible**
- **Reactor studies show economically attractive**

Science & technologies should be developed as a system, in concert with one another
- **ARIES team participation ideally suited for this**

Biggest issues that require team effort:
- **Target injection**
- **Final focussing optics**
- **Economics**

Integrated Research Experiment proposed
- **Demonstrate key technologies**
- **Reasonable size and cost**
- **“Upgradeable”**