Could we build a miniature sun on earth?

... to provide significant carbon-free energy for humankind.
Fusion energy is attractive, but needs to be timely
Bringing star power to Earth

Use very high power lasers to create fusion – releasing city-scale energy output, safely and sustainably

1,000,000 mi.

2/1000 in.
The fusion fuel — 40 kWhr from a milligram pellet of deuterium and tritium

Or, less than a gram of fuel per person per year for their entire energy needs
Malibu, California — 1960
Ted Maiman  First laser demonstrated on May 16, 1960
John Nuckolls proposed to use lasers for fusion energy.
Recipe for fusion on earth

**Ingredients**
Hydrogen from water

**Directions**
1. Filter out $\text{D}_2\text{O}$, breed tritium
2. Place in 4 Million degree K oven
3. Ablate for a few billionths of a second and bring to fusion conditions
4. Convert mass to copious amounts of clean energy
The NIF facility is the culmination of many decades of US leadership and investment in this field.

NIF can demonstrate full-scale performance for a 1000 MWe plant.
NIF is now operational and ignition campaigns are underway.

NIF is the world’s most energetic laser by 100x.
NIF concentrates all 192 laser beam energy in a football stadium-sized facility into a mm$^3$. 

Matter
Temperature $>10^8$ K
Radiation
Temperature $>3.5 \times 10^6$ K
Densities $>10^3$ g/cm$^3$
Pressures $>10^{11}$ atm
- 10,400 slabs melted
- 430 tonnes of ultra-high purity glass

Partners: Hoya, Schott
Frequency Conversion Crystals (KDP) (2 million carats)

- Rapid growth developed to reduce growth time ~10x
- New record ~380 kg KDP crystal boule
- Over 100 KDP and DKDP boules needed for NIF

Partner: Cleveland Crystals, Inc (CCI)
NIF operational capabilities — laser energy/power

- NIF laser is steadily increasing the laser energy and power
- NIF Laser is operating 24/7 with exceptional reproducibility and reliability (99%)
- Currently supporting the NIC at 1.4 to 1.8 MJ
- We have achieved the 1.8 MJ milestone and a power of 522 TW in a NIC-relevant pulse format
- The NIF has intrinsic capability to continue on this growth path for several more years
The NIF laser is now operating above its original design specifications.
Inside the target chamber
...in the target chamber
50 target diagnostics enable cutting edge science on the NIF

- LLNL
- LANL
- LLE
- NSTec
- U of M
- LBNL
- AWE
- MIT
- CEA
- Duke
- SNL
- GSI

Number of target diagnostics

Cumulative Diagnostic Count

- Optical
- X-ray
- Nuclear

2009 2010 2011 2012
NIF and its evolving capabilities will address compelling scientific questions

- How do supernovae explode?
- How do dust-filled nebulae (stellar nurseries) evolve?
- How do gamma-ray bursts occur?
- What are the characteristics of burning plasmas?
- Do giant planets contain “oceans of diamonds”?
- What is the source of the highest-energy cosmic rays?
Four steps to ignition

We are taking a systematic approach to learning and improving our engineering design to achieve ignition.
On September 2, 2009 NIF conducted first hohlraum experiments

- **Wednesday, Sept. 2**: 1st cryo implosion
- **Thursday, Sept. 3**: 2nd cryo implosion
- **Friday, Sept. 4**: 3rd cryo implosion
  - $P_2/P_0 = -0.04, \ P_4/P_0 = 0.13$
- **Saturday, Sept. 5**: 4th cryo implosion
On May 4, 2011 NIC conducted the first cryo-layered DT target experiment on NIF

“Cryo DT ice layer” at ~19 deg K
Highlights of progress towards ignition

- Build a laser
  - 1.855 MJ
  - 523 TW
  - 300:1 contrast

- Commission hohlraum
  - 330 eV
  - ~85% absorbed energy

- Convergence ratio ~35,
  - $\rho R \sim 1.3 \text{ gm/cm}^2$ (85% of requirement)
  - $V_{\text{implosion}} \sim 350 \text{ km/sec}$

- Commission capsule
  - Pressure ~150 GBar
  - $Y \sim 9 \times 10^{14}$

- Commission layered target implosions
We are now within a factor of 2 to 3 of the required fuel pressures (350 billion atmospheres!)

- Pre shock tuning
- Post 1st pass shock tuning (June 2011)
- 5.75mm hohlraum CHSi capsule

~60x Increase
NIF can demonstrate full-scale performance for a power plant based on Laser Inertial Fusion Energy (LIFE)
LIFE: A sustainable, carbon-free source of safe baseload electricity

- Security of supply (reducing our reliance on foreign oil imports)
- No enrichment, no reprocessing, and no high-level radioactive waste
- Global commercial competitiveness from a U.S.-led solution
- Compatibility with existing grid infrastructure
LIFE: An integrated approach to plant design

- Based directly on NIF performance
- Modular, factory built design for high plant availability
- Use of available materials and technologies
- Attractive safety bases enabling simplified licensing
Consultation with the end-users is our starting point

- Charles "Chip" Pardee (Chairman) — SVP and COO, Exelon Generation
- William Fehrman (Vice-Chair) — President and CEO, MidAmerica Energy Company
- David Christian — CEO, Dominion Generation; President, Virginia Power
- Brian Debs (Member in residence) — former SVP, Ontario Power Generation Corp.
- John Herron — President and CEO, Entergy Operations
- Steve Kuczynski — President and CEO, Southern Nuclear Operating Company
- Michael Sellman — CEO, Nuclear Management Company (Retired)
- Joseph Callan — Former Executive Director, U.S. Nuclear Regulatory Commission
End-user requirements for operations & licensing

- Grid compatibility
- Plant availability
- Economically competitive
- Sustainable (e.g. water use)
- Conventional M&O regime
- Simple regulatory path
- Timely

- Focus on pure fusion, utility-scale, power producing plant
- Use of commercial materials, technologies and delivery mechanisms
How we meet the energy challenge has profound implications for our economy and security.
Principle of LIFE plant operation

Laser driver

900 cycles / minute provides ~ 1 GWe output
LIFE Power Balance (example)

Laser
2.3 MJ @ 16 Hz
15% $n_L$

37 MW laser

G$\text{fusion} = 65$

2400 MW fusion

G$\text{blanket} = 1.2$

2900 MW thermal

Power cycle $\eta_{th} = 44\%$

1275 MWe

1625 MW$_{th}$

Process heat

1000 MWe

Pumps / aux. power

30 MWe

To grid
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To grid

240 MWe (19% recirc)
NIF performance, and LIFE’s modular architecture is what enables commercialization in a relevant timeframe

Modular fusion chamber reduces lifetime requirement from 60 years to < 4 years

Modular laser, optics and processing equipment enables maintenance without plant shutdown

Fusion chamber can use conventional steel rather than wait for new radiation-resistant alloys to be developed
A LIFE beamline folds into a transportable box, enabling an efficient & cost-effective supply chain

- Offsite beamline factory
- Truck-shippable $1_\omega$ beamline
- Low-overhead installation
  - Kinematic placement
  - Few interfaces

Ability to “hot swap” beamlines during plant operations.
LIFE box in NIF laser bay
LIFE is economically viable over a range of plant sizes.

Economic Performance as a Function of Plant Size

- **Capital Cost**
- **Cost of Electricity**

![Graph showing economic performance as a function of plant size](image_url)
Oxford Economics have calculated the potential impact of domestic rollout on GDP and new jobs

- 4 to 12 B$ annual federal and state tax revenue
- Substantial jobs impact in the high-tech sector

### Domestic Rollout GDP Impacts
- **17 – 47 B$ / year GDP impact**

### Domestic Rollout Employment Impacts
- **155 – 425,000 average jobs**

Similar industrial scale to:
- Aircraft manufacturing (230,000)
- Machine shops (246,000)
- Semiconductor manufacturing (182,000)

Low / High scenarios are for 10 or 5 year doubling times
We have been consulting with a range of environmental groups on the sustainability of LIFE.
Recent TV / documentary coverage of NIF and LIFE

- BBC with Steven Hawking
- National Geographic
- Horizon with Brian Cox
- Discovery Channel’s NOVA
International activity in this area

USA - NIF Laser

China - SG-III

France - LMJ

UK - ORION

Russia - ISKRA

EU - HiPER

Japan - FIREX

Korea
Fusion energy – soon enough to make a difference

National Ignition Facility

Performance

Market Entry Plants

Integration

Mature LIFE Technology

1,000 MW\text{th}

2020’s

400 MW to 1,600 MW\text{e}

2030’s
Achieving ignition on NIF can be a defining moment for the world’s energy future
The capsule starts at 2mm diameter
Re-emission sphere measures early time x-drive symmetry

Bang time – 19 ns

1 billionth of a second into the laser pulse
Radiography measures the shape of the capsule in-flight

N121004
Bang time – 600 ps

~ 2 mm diameter
Radiography measures the shape of the capsule in-flight

N121004
Bang time – 300 ps

~ 2 mm diameter

Early hot spot formation
Compton radiography probes fuel shape at stagnation

N121005
Bang time

~ 2 mm diameter
The hot spot looks quite round!

DT shot N120716
Bang time

~ 2 mm diameter
Compton radiography probes fuel shape at stagnation

N121005
Bang time

Preliminary data!

~ 2 mm diameter
Experiments are working on the P4 (diamond) shape

Nominal length hohlraum

-0.3 mm

9.4 mm

+ 0.3 mm

N121219

N121210

N121218

800 μm

-300 μm

+300 μm

X-ray drive symmetry must be controlled to the ~1% level
Radiography reveals possible signature of ablation front instability growth from tent

- Perturbation is larger than predicted
- Motivates
  - Thinner tent / alternate mounting
  - Experiments to study

Bang time – 640ps
BT– 430ps
BT– 340ps

BT± 50ps
150 μm

Tent
~40 nm