

Laser Fusion – an Update and Opportunities for Canada

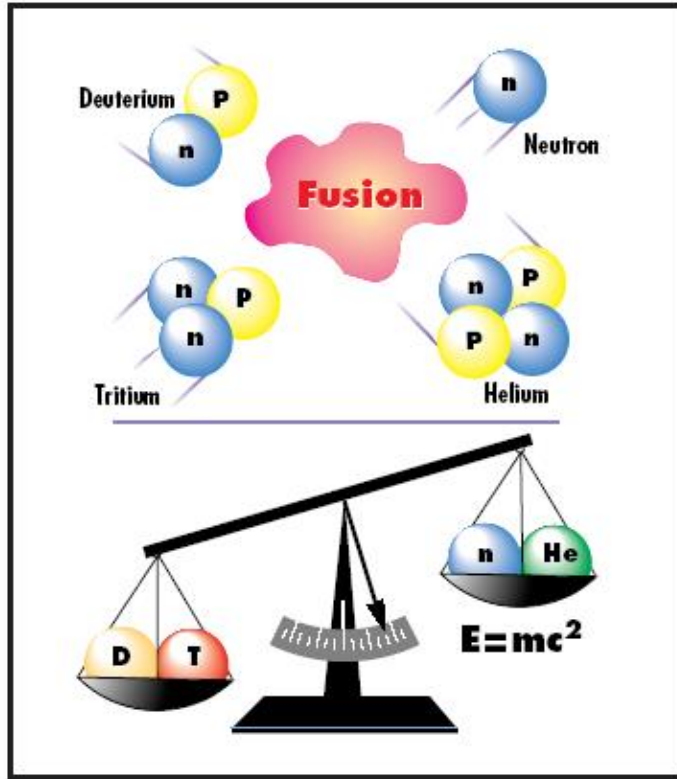
Robert Fedosejevs

*Department of Electrical and Computer Engineering
University of Alberta*

Presented at the Canadian Nuclear Society Meeting,
Ottawa, June 23-26, 2019



Fusion Energy



Energy Release:

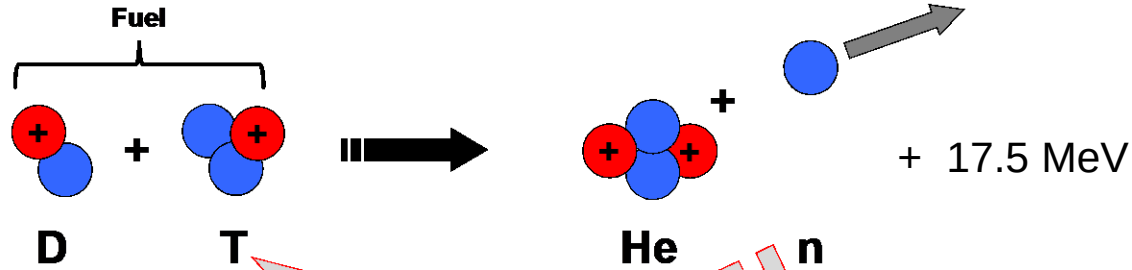
14 MeV neutron
and

3.5 MeV alpha particle (He)

**91 kg of deuterium and tritium
converted to helium to produce
1 GW of power for one year**

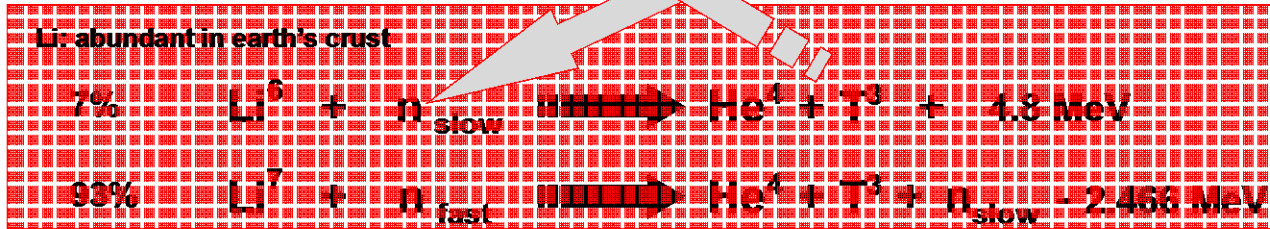
Fuel Cycle

Deuterium plentiful
in seawater
(1 part in 6400)



TBR > 1.1

Breed tritium from lithium



Breed tritium from the neutrons reacting with lithium
in a blanket surrounding the reactor core

Fusion Confinement Mechanisms

3 main confinement mechanisms

Requires Extreme Plasma Conditions:

Temperatures:

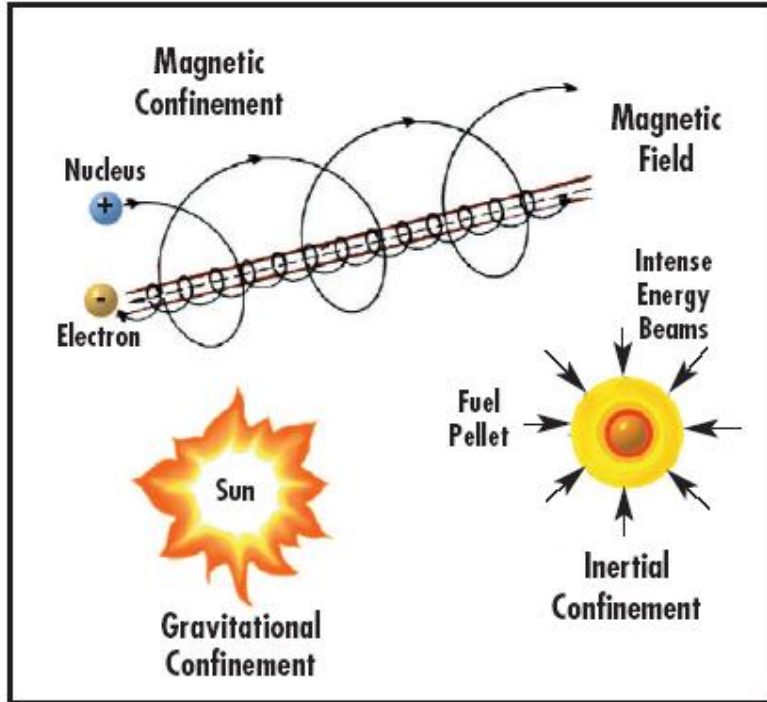
$$T_e \sim 5 - 10 \text{ keV (55 - 110 MK)}$$

Net energy production requires densities and energy confinement times satisfying the Lawson Criterion:

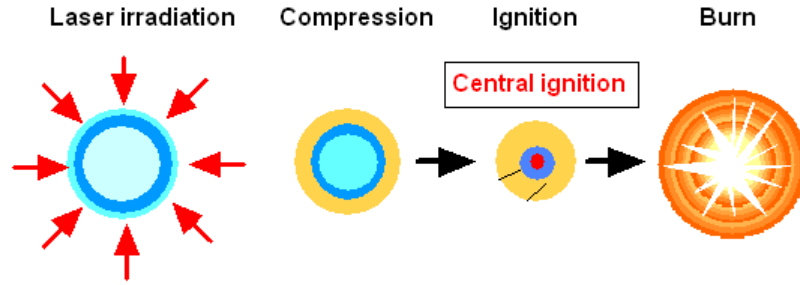
$$n_e \times \tau_c > 2 \times 10^{14} \text{ cm}^3 \text{ s}$$

$$\text{Magnetic (} \tau_c \sim 10 \text{ s, } n_e \sim 10^{14} \text{ cm}^{-3} \text{)}$$

$$\text{Inertial (} \tau_c \sim 10^{-10} \text{ s, } n_e \sim 10^{24} \text{ cm}^{-3} \text{)}$$



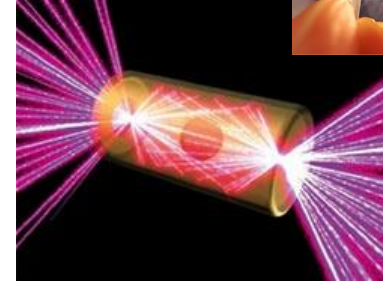
Laser Fusion Energy



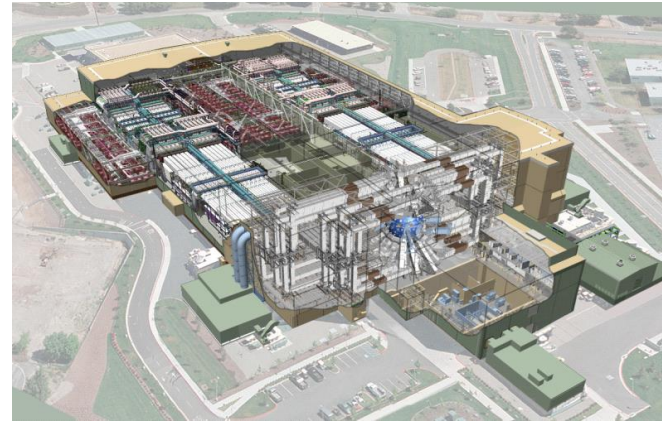
Laser Beams
Compress the Fuel capsule

Fuel Ignites and Fusion wave
Burns through the Fuel

<https://lasers.llnl.gov/about/what-is-nif>



Indirect Drive Converting Laser
Light into X-ray Radiation First



Largest laser in the world - 1.8 MJ / Laser Pulse in 192 beam lines at 353 nm
National Ignition Facility (NIF) at Lawrence Livermore National Laboratory California

NIF Laser Bay

<https://lasers.llnl.gov/about/what-is-nif>



Inside 10 m Diameter Target Chamber

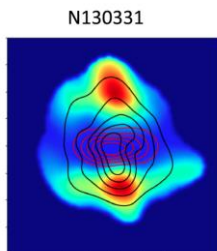
<https://lasers.llnl.gov/about/what-is-nif>



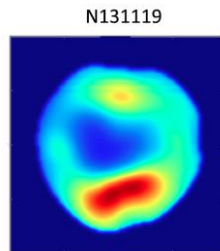
Inside the chamber of the National Ignition Facility, 192 pulses of laser light bombard a target nearly simultaneously. Credit: Lawrence Livermore National Laboratory

NIF Progress 2010-2018

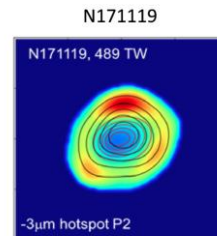
Hurricane et al., Plasma Phys. 26, 052704 (2019)



2010 - 2012

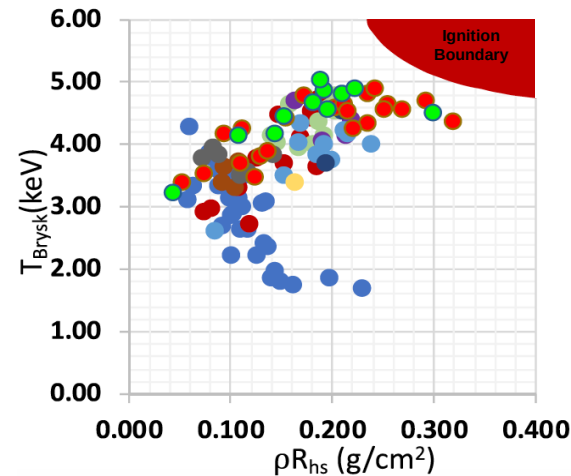
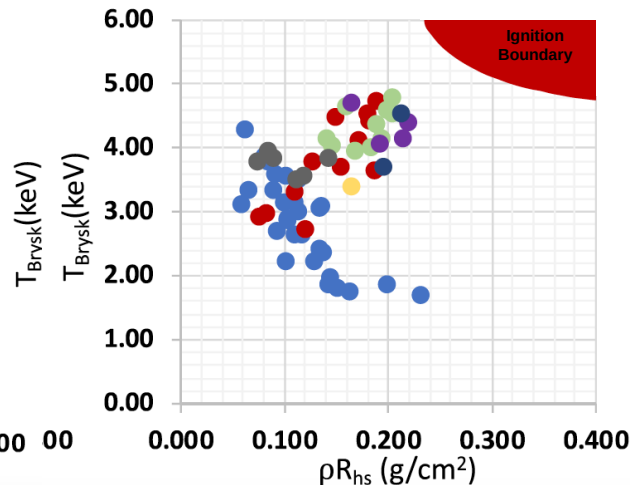
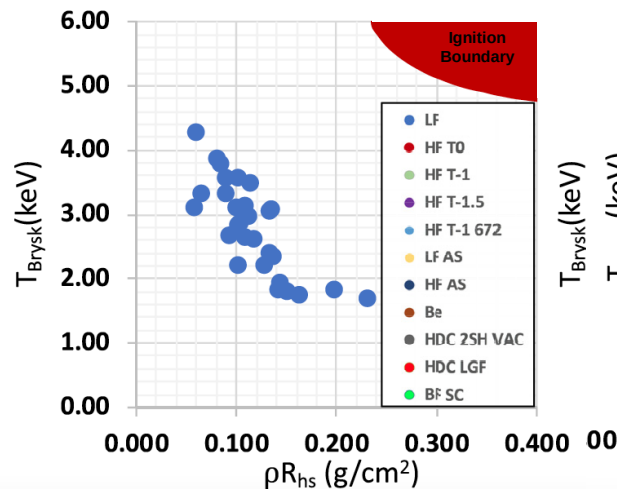


2010 - 2015



2010 - 2018

54 kJ Fusion
Energy Released



Equivalent Lawson Criterion is $\rho R_{hot\ spot} > 0.3 \text{ g cm}^{-3}$

54 kJ fusion yield with 1.5 MJ drive

PHYSICAL REVIEW LETTERS **120**, 245003 (2018)

Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility

S. Le Pape,¹ L. F. Berzak Hopkins,¹ L. Divol,¹ A. Pak,¹ E. L. Dewald,¹ S. Bhandarkar,¹ L. R. Bennedetti,¹ T. Bunn,¹ J. Biener,¹ J. Crippen,² D. Casey,¹ D. Edgell,³ D. N. Fittinghoff,¹ M. Gatu-Johnson,⁴ C. Goyon,¹ S. Haan,¹ R. Hatarik,¹ M. Havre,² D. D-M. Ho,¹ N. Izumi,¹ J. Jaquez,² S. F. Khan,¹ G. A. Kyrala,⁵ T. Ma,¹ A. J. Mackinnon,¹ A. G. MacPhee,¹ B. J. MacGowan,¹ N. B. Meezan,¹ J. Milovich,¹ M. Millot,¹ P. Michel,¹ S. R. Nagel,¹ A. Nikroo,¹ P. Patel,¹ J. Ralph,¹ J. S. Ross,¹ N. G. Rice,² D. Strozzi,¹ M. Stadermann,¹ P. Volegov,⁵ C. Yeamans,¹ C. Weber,¹ C. Wild,⁶ D. Callahan,¹ and O. A. Hurricane¹

¹*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

²*General Atomics, San Diego, California 92186, USA*

³*Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14636, USA*

⁴*Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

⁵*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

⁶*Diamond Materials GmbH, 79108 Freiburg, Germany*

Entering alpha particle heating regime close to ignition

Coupling of x-ray energy to fuel capsule doubled using shaped hohlraums at 1 MJ drive level

Ping et al., Nature Physics **15**, 138 (2019)

LETTERS

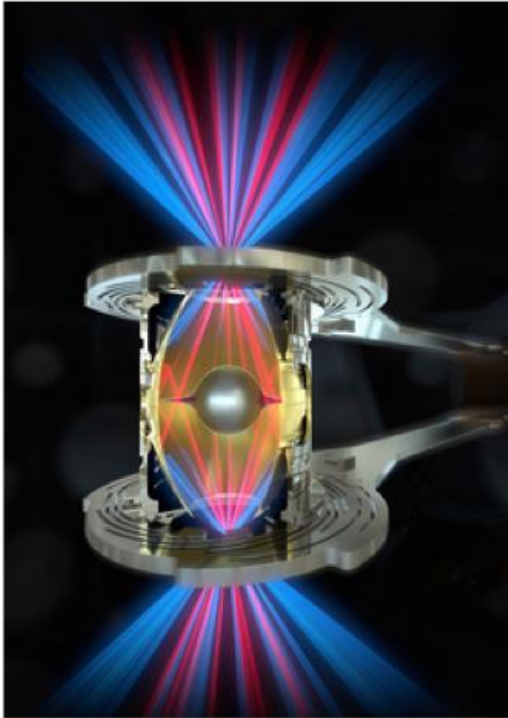
<https://doi.org/10.1038/s41567-018-0331-5>

nature
physics

Enhanced energy coupling for indirectly driven inertial confinement fusion

Y. Ping^{1*}, V. A. Smalyuk¹, P. Amendt¹, R. Tommasini¹, J. E. Field¹, S. Khan¹, D. Bennett¹, E. Dewald¹, F. Graziani¹, S. Johnson¹, O. L. Landen¹, A. G. MacPhee¹, A. Nikroo¹, J. Pino¹, S. Prisbrey¹, J. Ralph¹, R. Seugling¹, D. Strozzi¹, R. E. Tipton¹, Y. M. Wang¹, E. Loomis², E. Merritt² and D. Montgomery²

Could lead to substantially increased energy yield



National Ignition Facility at LLNL – Other Recent Progress

- Indication of capability to fire at 2.5 MJ total energy (in separate amplifier tests) - if necessary
- Addressing issues of Cross Beam Energy Transfer (CBET) which alters the deposited energy distribution
- Addressing issue of hydrodynamic non-uniformity from mounting of the fuel pellet and irradiation asymmetry
- Looking at more advanced target designs such as multi-shell targets using shock impact of an outer shell to drive a smaller inner shell to implosion
- Laser Inertial Fusion Energy (LIFE) project 2008-2013 assessed technologies required to build Laser fusion reactors

Direct Drive 40 kJ Omega Laser Facility at University of Rochester

Laboratory for Laser Energetics

a unique national resource

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About OMEGA

http://www.lle.rochester.edu/omega_facility/omega/index.php

OMEGA stands 10 meters tall and is approximately 100 meters in length. This system delivers pulses of laser energy to targets in order to measure the resulting nuclear and fluid dynamic events. OMEGA's 60 laser beams focus up to 40,000 joules of energy onto a target that measures less than 1 millimeter in diameter in approximately one billionth of a second. At LLE scientists continue to research what will one day become a vast source of power using the ocean's ample storehouse of potential energy.

OMEGA Media Gallery

[Laser Drivers](#)

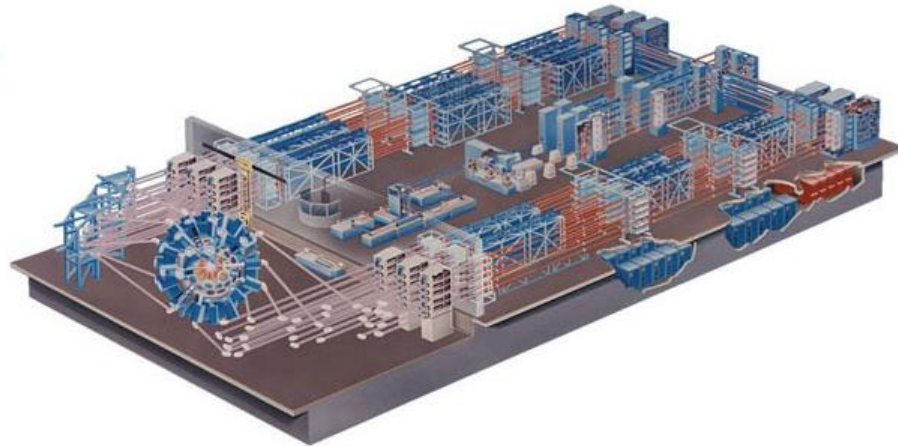
[Amplifiers](#) 

[Power Conditioning](#)

[Experimental Systems](#)

[Control Room](#)

[Targets](#)



University of Rochester Omega Laser Direct Drive 40 kJ Laser Facility

Tripled yield in direct-drive laser fusion through statistical modelling

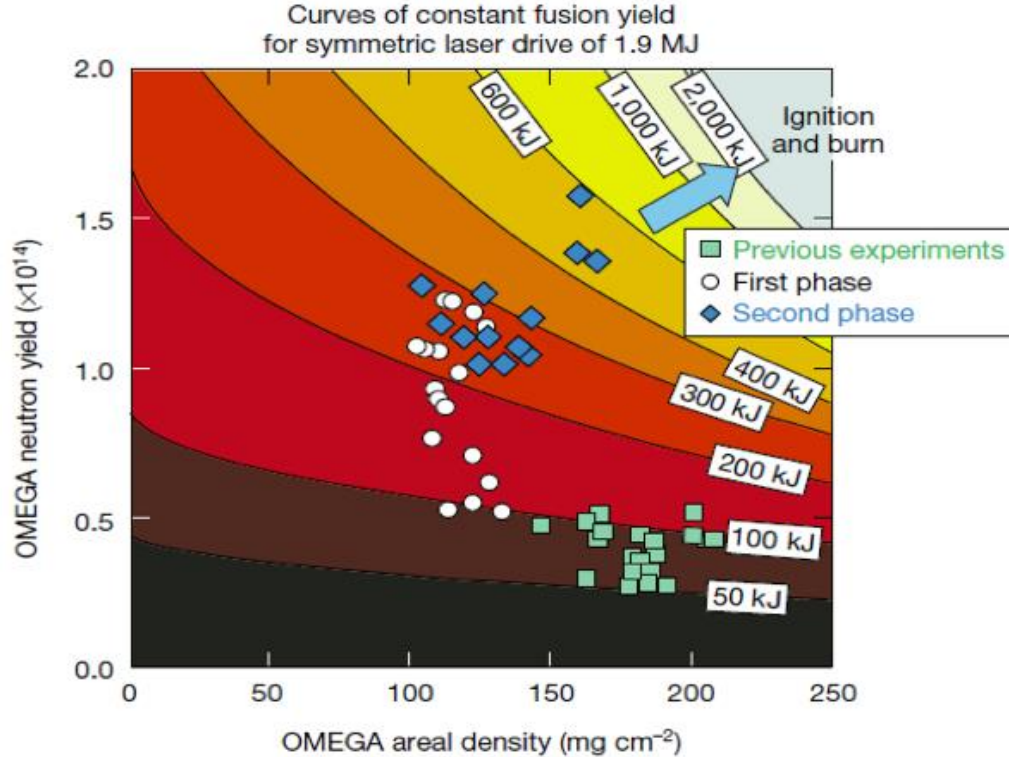
V. Gopalaswamy^{1,2*}, R. Betti^{1,2,3}, J. P. Knauer¹, N. Luciani^{1,2,4}, D. Patel^{1,2}, K. M. Woo^{1,3}, A. Bose^{1,5}, I. V. Igumenshchev¹, E. M. Campbell¹, K. S. Anderson¹, K. A. Bauer¹, M. J. Bonino¹, D. Cao¹, A. R. Christopherson^{1,2}, G. W. Collins¹, T. J. B. Collins¹, J. R. Davies¹, J. A. Delettrez¹, D. H. Edgell¹, R. Epstein¹, C. J. Forrest¹, D. H. Froula¹, V. Y. Glebov¹, V. N. Goncharov¹, D. R. Harding¹, S. X. Hu¹, D. W. Jacobs-Perkins¹, R. T. Janezic¹, J. H. Kelly¹, O. M. Mannion^{1,3}, A. Maximov^{1,2}, F. J. Marshall¹, D. T. Michel¹, S. Miller^{1,2}, S. F. B. Morse¹, J. Palastro¹, J. Peebles¹, P. B. Radha¹, S. P. Regan¹, S. Sampat¹, T. C. Sangster¹, A. B. Sefkow¹, W. Seka¹, R. C. Shah¹, W. T. Shmyada¹, A. Shvydkiy¹, C. Stoeckl¹, A. A. Solodov¹, W. Theobald¹, J. D. Zuegel¹, M. Gatu Johnson⁵, R. D. Petrasso⁵, C. K. Li⁵ & J. A. Frenje⁵

31 JANUARY 2019 | VOL 565 | NATURE | 581

Focusing laser light onto a very small target can produce the conditions for laboratory-scale nuclear fusion of hydrogen isotopes. The lack of accurate predictive models, which are essential for the design of high-performance laser-fusion experiments, is a major obstacle to achieving thermonuclear ignition. Here we report a statistical approach that was used to design and quantitatively predict the results of implosions of solid deuterium-tritium targets carried out with the 30-kilojoule OMEGA laser system, leading to tripling of the fusion yield to its highest value so far for direct-drive laser fusion. When scaled to the laser energies of the National Ignition Facility (1.9 megajoules), these targets are predicted to produce a fusion energy output of about 500 kilojoules—several times larger than the fusion yields currently achieved at that facility. This approach could guide the exploration of the vast parameter space of thermonuclear ignition conditions and enhance our understanding of laser-fusion physics.

Tripled previous Direct Drive fusion yield

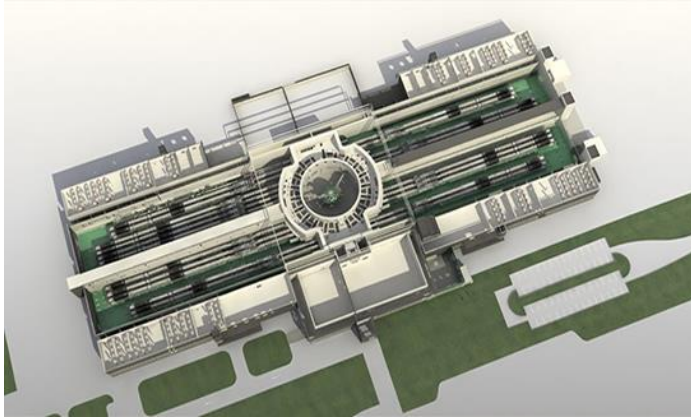
Scaling of Direct Drive Results to NIF Equivalent Laser Energy



Gopalaswamy et al.,
Nature 565, 581 (2019)

**Scaling of Rochester
results to NIF
equivalent results
would predict 500 kJ
energy yield**

Laser Megajoule (LMJ) France



<http://www-lmj.cea.fr/en/lmj/index.htm>

**172 Beamlines 1.8MJ
about 20% operational**



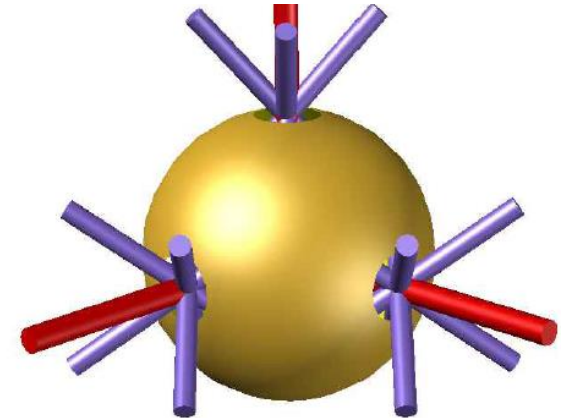
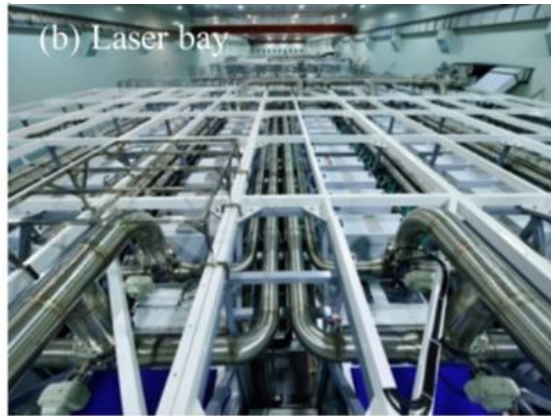
Sheng Guan III Laser Facility China

He et al., J. Phys. Conf. Series 688, 012029 (2016); Jing et al., Nuclear Fusion 58, 096017 (2018)



The SG-III laser system with 48 beams (6 bundles)
and the output laser energy of 250kJ/3ns/3 ω and
400kJ/5ns/3 ω

Will investigate Indirect Drive, Direct Drive and Hybrid
Drive fusion with six-sided illumination

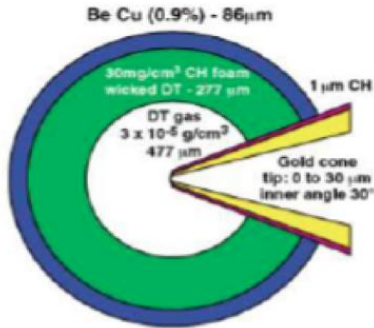


Also ISKRA-6 2.8 MJ Laser Facility under construction in Russia (started 2012)

Advanced Concepts for Direct Drive

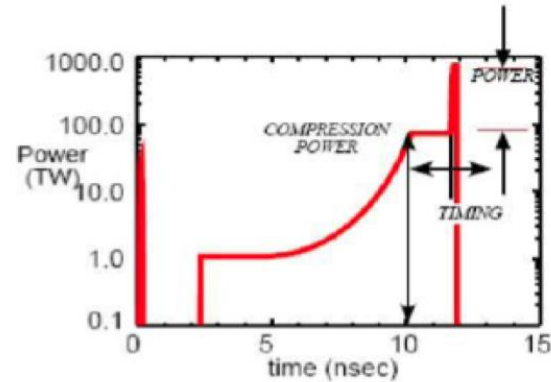
Fast Ignition
Using Separate Ignition Pulse

Fast Ignition



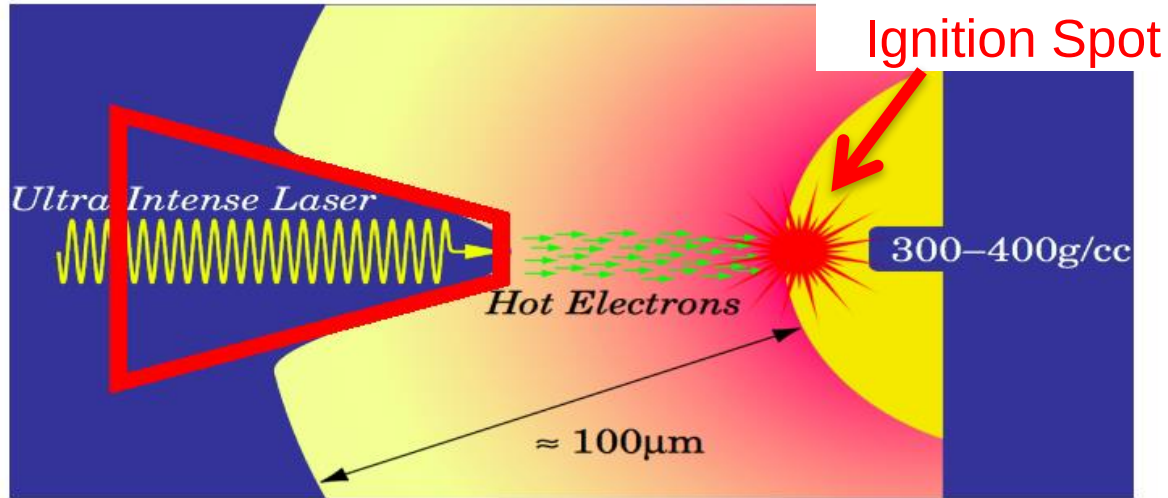
Shock Ignition
Use Strong Shock Spike for Ignition

Shock Ignition



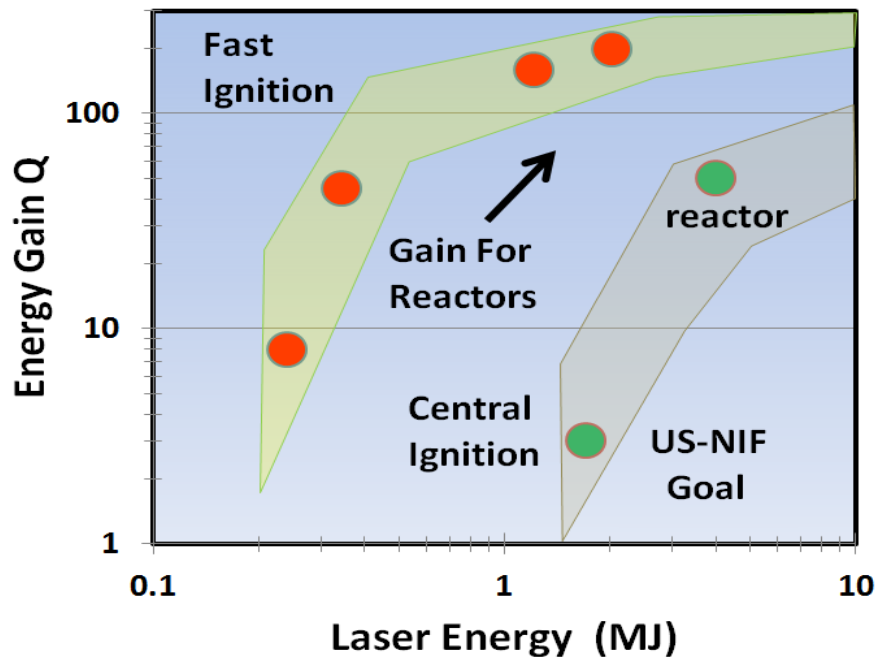
New concepts would require much lower laser driver energy ($\sim 1 \text{ MJ}$)

Fast Ignition



Laser cannot penetrate into the core
Therefore deliver energy in the form of MeV electrons or ions
driven by ultra-intense short pulse laser

Energy Gain Scaling for Fast Ignition



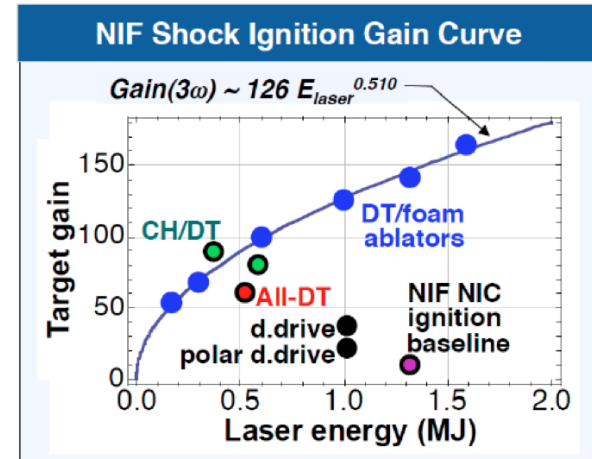
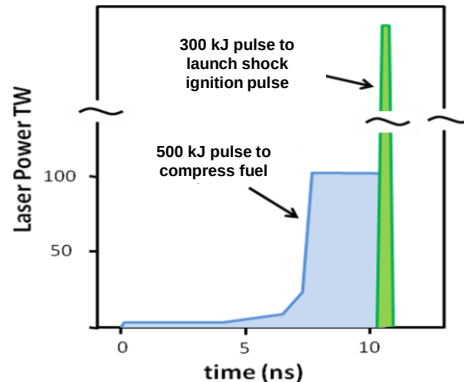
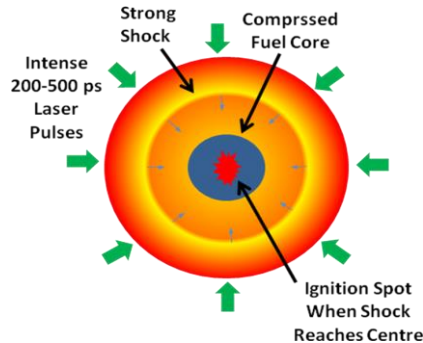
Must control electron transport to the core using strong magnetic fields or use alternative MeV protons to couple energy to the core

**Reduce laser energy requirements approximately 3-5 times:
Smaller and less expensive initial IFE reactors possible**

Energy Gain Scaling for Shock Ignition

High intensity spike at end of laser pulse drives a strong shock igniting the fusion reactions in the compressed core

Betti et al., Phys. Rev. Lett. 98, 155001 (2007)



JL Perkins (LLNL)

Reduce laser energy requirements 3 to 5 times:
Smaller and less expensive initial IFE reactors possible

U of A Past Research on Laser Fusion

- High power Krypton Fluoride UV laser development
- UV laser driven hydrodynamic studies
- Raman and Brillouin laser-plasma instability studies
- Fast Ignition electron transport experiments at the LLNL Titan laser facility
- Shock Ignition hot electron production experiments at the LLNL Titan laser facility

UofA Current Research on Laser Fusion

- Strong magnetic guide field generation in the laser-plasma interaction using new Orbital Angular Momentum pulses in collaboration with CLPU (University of Salamanca)
- Measurements of laser generated solenoid fields (5-10 MG) in collaboration with CELIA (University of Bordeaux)
- Studies of warm dense matter equation of state (fusion fuel)
- High efficiency diode pumped Yb:YAG laser system development 1 ps, 1 TW at 1030 nm
- Four-colour laser irradiation proposal for reduction of cross beam energy transfer (CBET) and plasma instabilities
- Theoretical studies of laser-plasma interactions

UofA Current Fusion Related Faculty and Resources

- **ECE Department (Engineering Physics Program)**
 - Robert Fedosejevs – Lasers, Advanced Ignition, X-ray and particle diagnostics
 - Ying Tsui – High Energy Density Physics, Warm Dense Matter, Advanced Ignition
 - Manisha Gupa – Optical and X-ray Diagnostics
 - Jason Myatt – Leading expert on theory and simulations of laser fusion processes
 - Allan Offenberger – Emeritus Professor
 - *Approval to expand with 3 additional faculty positions in the Laser/ Plasma/ Fusion area*
- **Physics Department**
 - Strong Computational Plasma Physics Group – Wojciech Rozmus, Rick Sydora, Richard Marchand and Robert Rankin
- **Materials Science**
 - Strong materials science research facilities
 - World class nanofab capabilities, National Institute of Nanotechnology, Surface Science Centre and local MEMS companies (Micralyne, Applied Nanotools, Norcada, etc.)

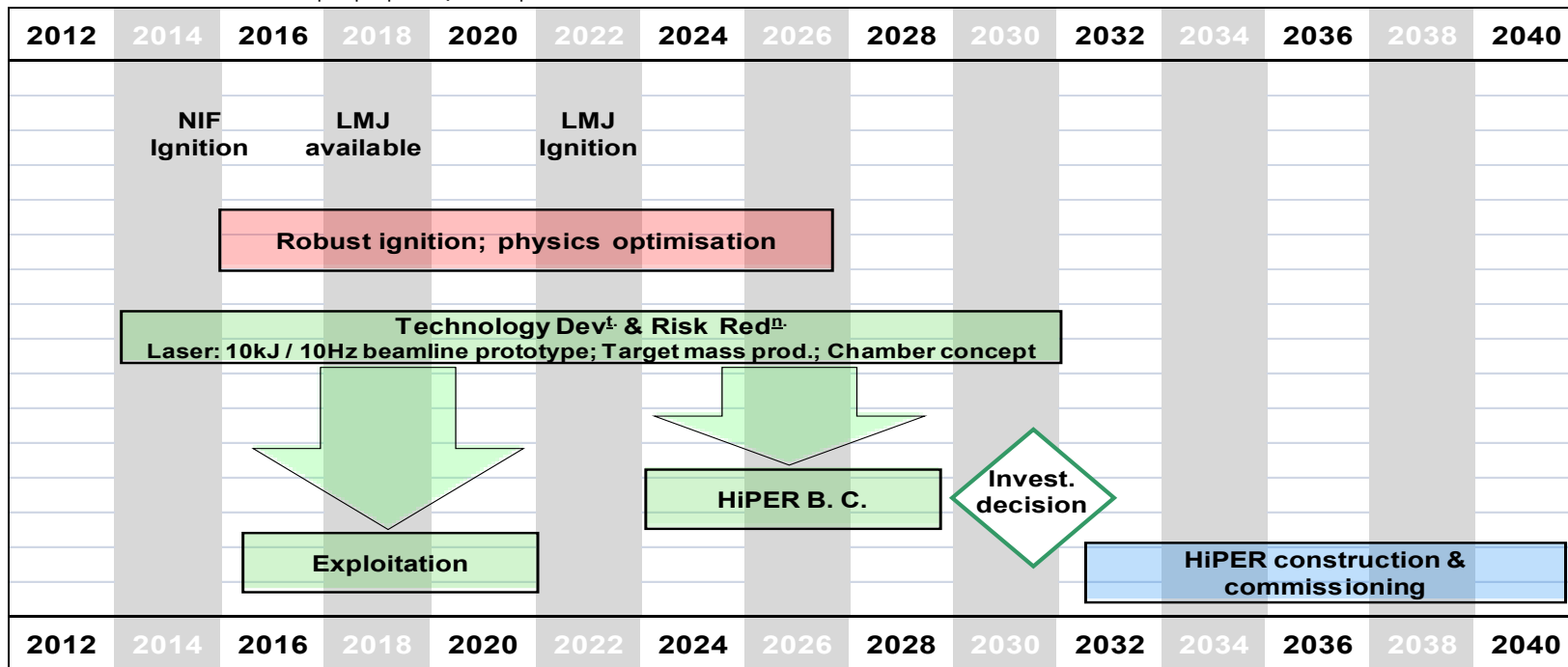
The Way Forward

- We are on the threshold of Fusion Energy
- NIF has a reasonable probability of reaching ignition in early 2020's via indirect drive
- Direct Drive scaling is neck and neck with NIF and also has high chance of showing conditions equivalent to scaled ignition by 2020
- Advanced ignition schemes could improve direct drive efficiency
- France, China and Russia are building Laser Fusion capabilities
- Require large scale facility to study advanced concepts (Shock Ignition and Fast Ignition) for Direct Drive Fusion such as the HiPER proposal in Europe or LIFT proposal in Japan
- Canada should help to lead the way

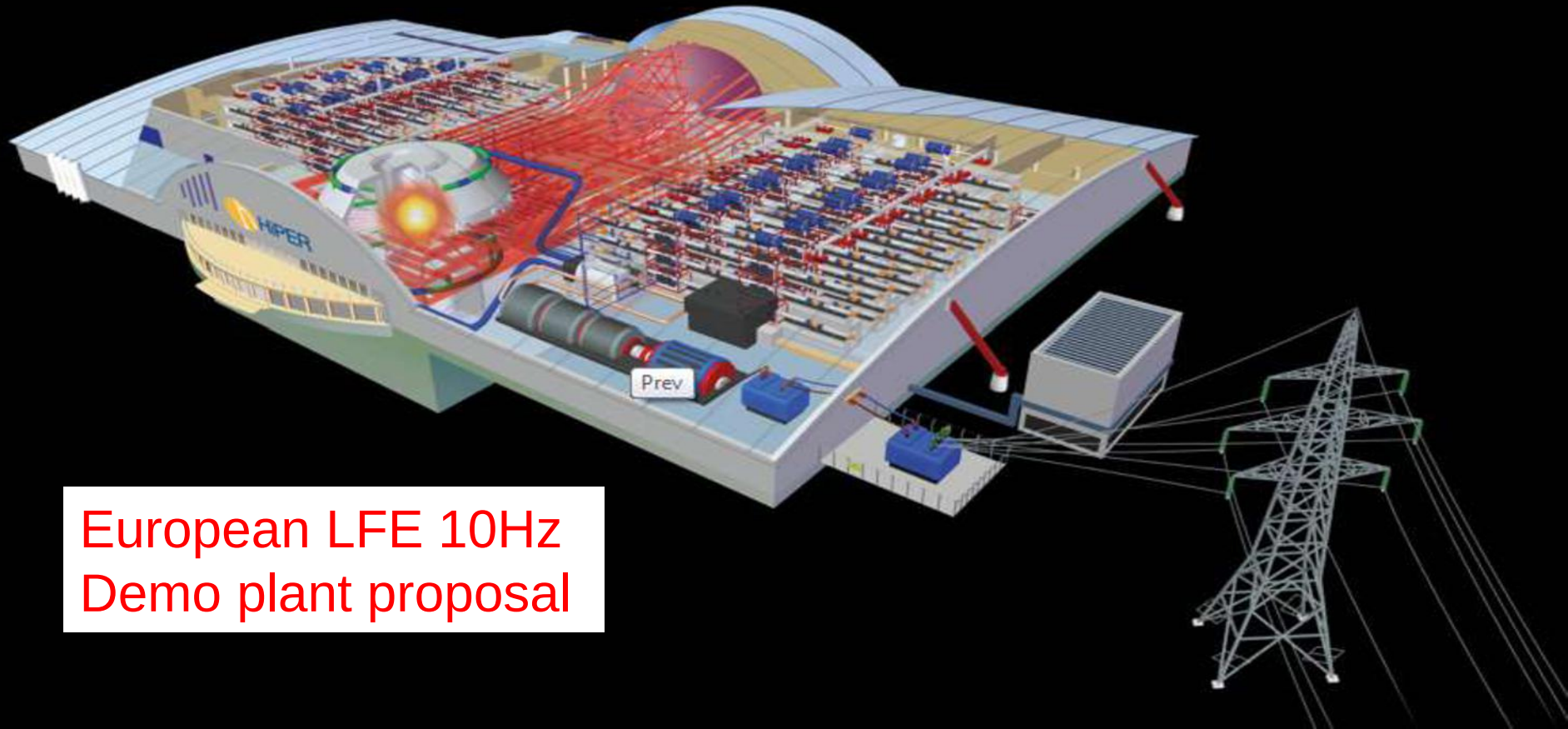
European Inertial Fusion Energy Roadmap

A 2013-2020 roadmap towards Inertial Fusion Energy based on a 2007-2012 watching brief

The *Consultative Committee for the EURATOM specific research and training programme in the field of Nuclear Energy (CCE-FU)* endorsed in 2007 continuation of the keep-in-touch (KiT) activity over civilian research activities in inertial confinement fusion for energy (IFE), as part of the Annual Work Programmes of the involved Associations. To monitor this KiT activity, the CCE-FU set up the *Inertial Fusion Energy Working Group (IFEWG)* from whom annual Watching Briefs, as well as in-depth proposals, are requested.



HiPER



European LFE 10Hz
Demo plant proposal

LLNL LIFE Power Plant Design Study 2008-2013

Addresses Engineering Requirements for a Real Reactor)

Plant Primary Criteria (partial list)
Cost of electricity
Rate and cost of build
Licensing simplicity
Reliability, Availability, Maintainability, Inspectability (RAMI)
High capacity credit & capacity load factor
Predictable shutdown and quick restart
Protection of capital investment
Meet urban environmental and safety standards (minimize grid impact)
Public acceptability
Timely delivery



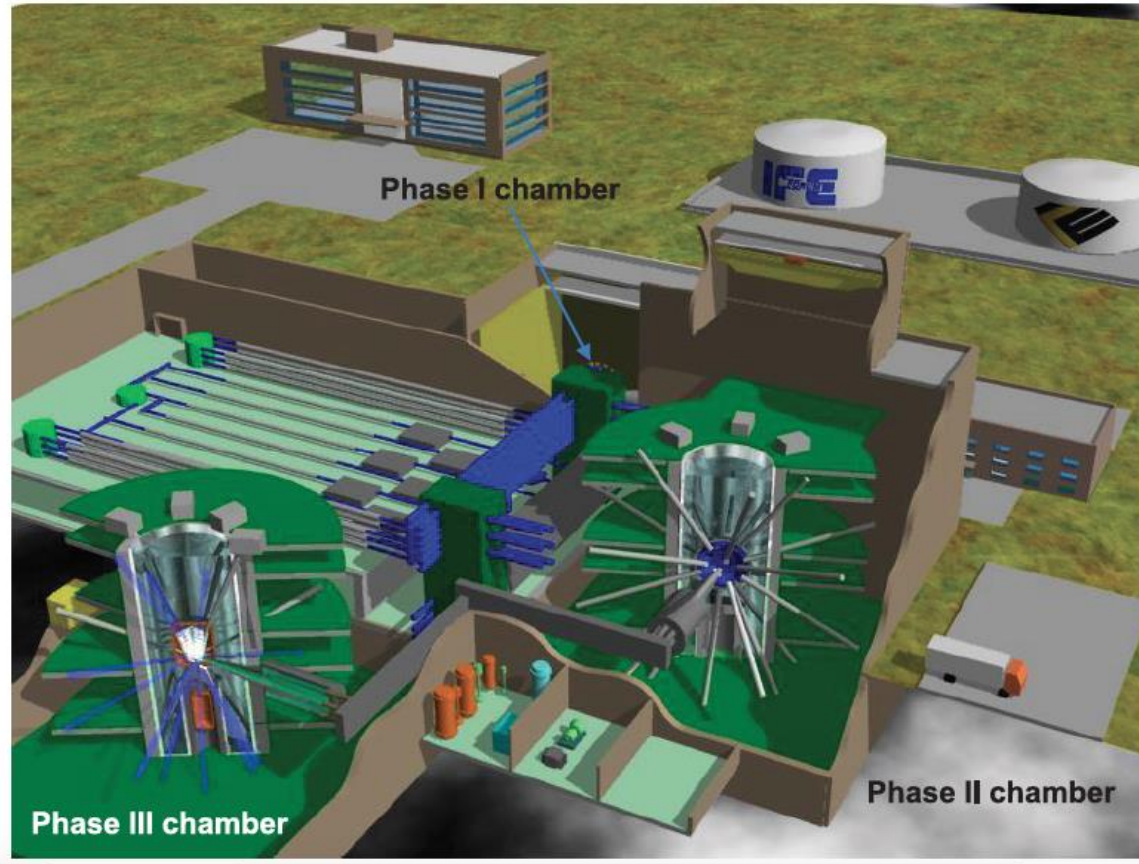
Use of commercially available
materials and technologies

Focus on pure fusion,
utility-scale,
power-producing facility

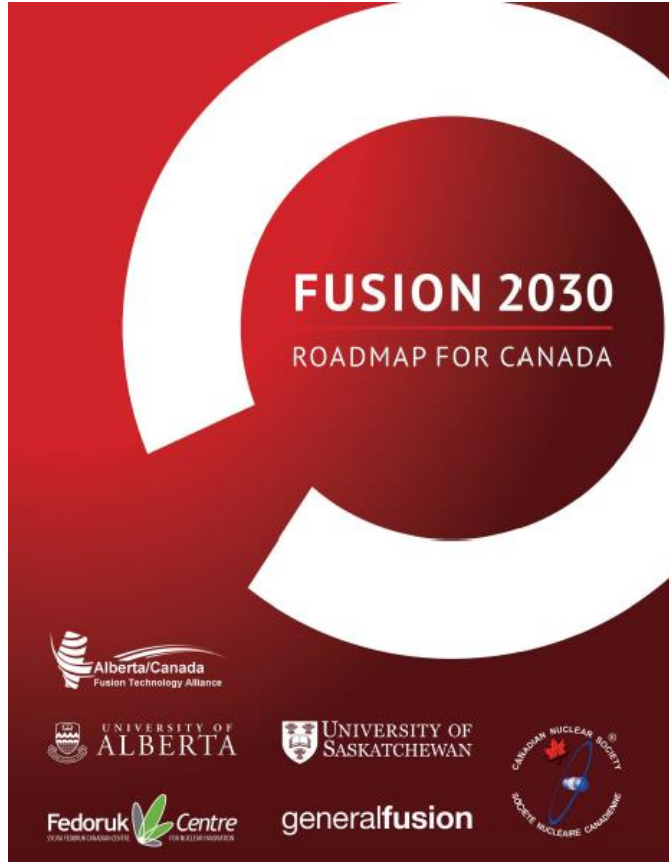
Meier et al., Fusion Engineering and Design 89, 2489 (2014)

Japan Laser Inertial Fusion Test Reactor (LIFT) Proposal

Norimatsu et al., Nuclear Fusion 57, 116040 (2017)



Canadian Fusion 2030 Proposal



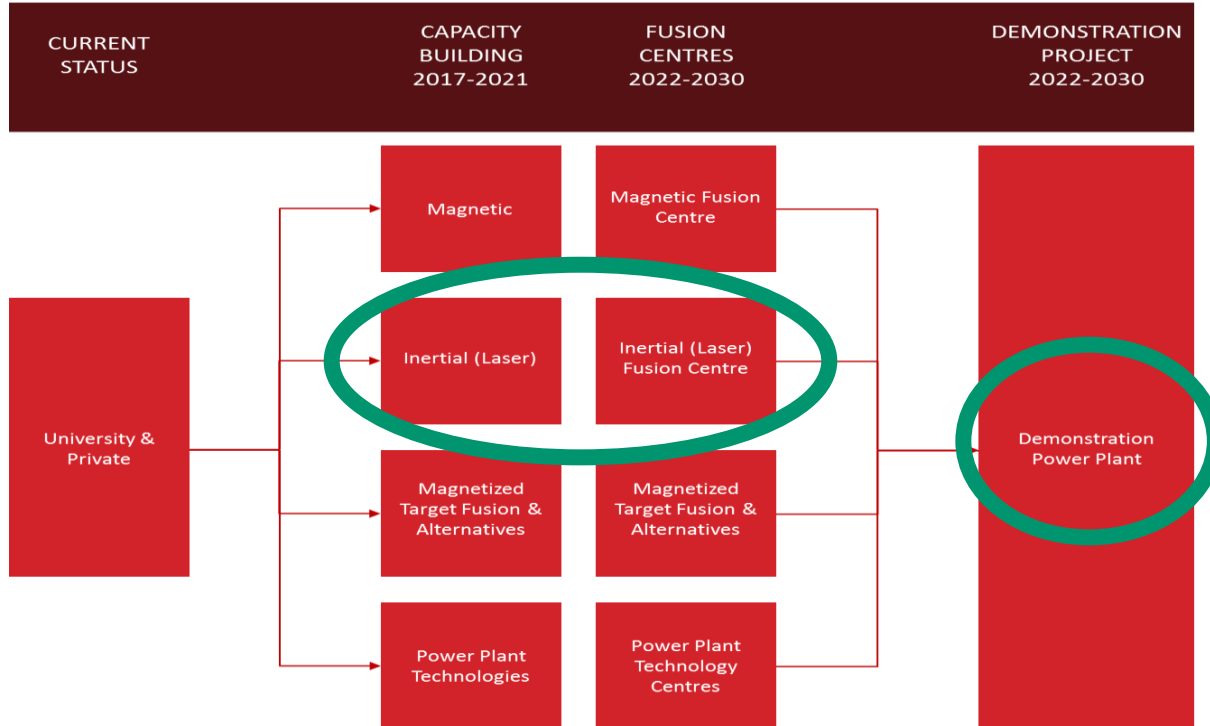
Canadian Fusion Researchers submitted a collaborative proposal by to the Federal government in the Fall of 2016

Available at the Alberta/Canada Fusion Technology Alliance (ACFTA) web site:

<https://acfta.ca>

Alberta's Part – Laser Fusion

PROPOSED CANADIAN FUSION PROGRAM



1. Build Capacity yrs 1-5
Provincial funding
 - People and projects
2. Build Infrastructure yrs 1-5
Federal funding
 - Laser development
 - High power laser interaction facilities
3. Laser Fusion Research Centre yrs 6-13
Joint Provincial and Federal support
 - Fusion research
 - Develop technology and transfer to industry
4. Propose and collaborate on a Demo Reactor Project

Thank You

Questions ?