# Prospects for Inertial Fusion Energy Systems: Perspectives from Los Alamos National Laboratory


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presented to:

NRC Committee on Prospects of IFE Systems

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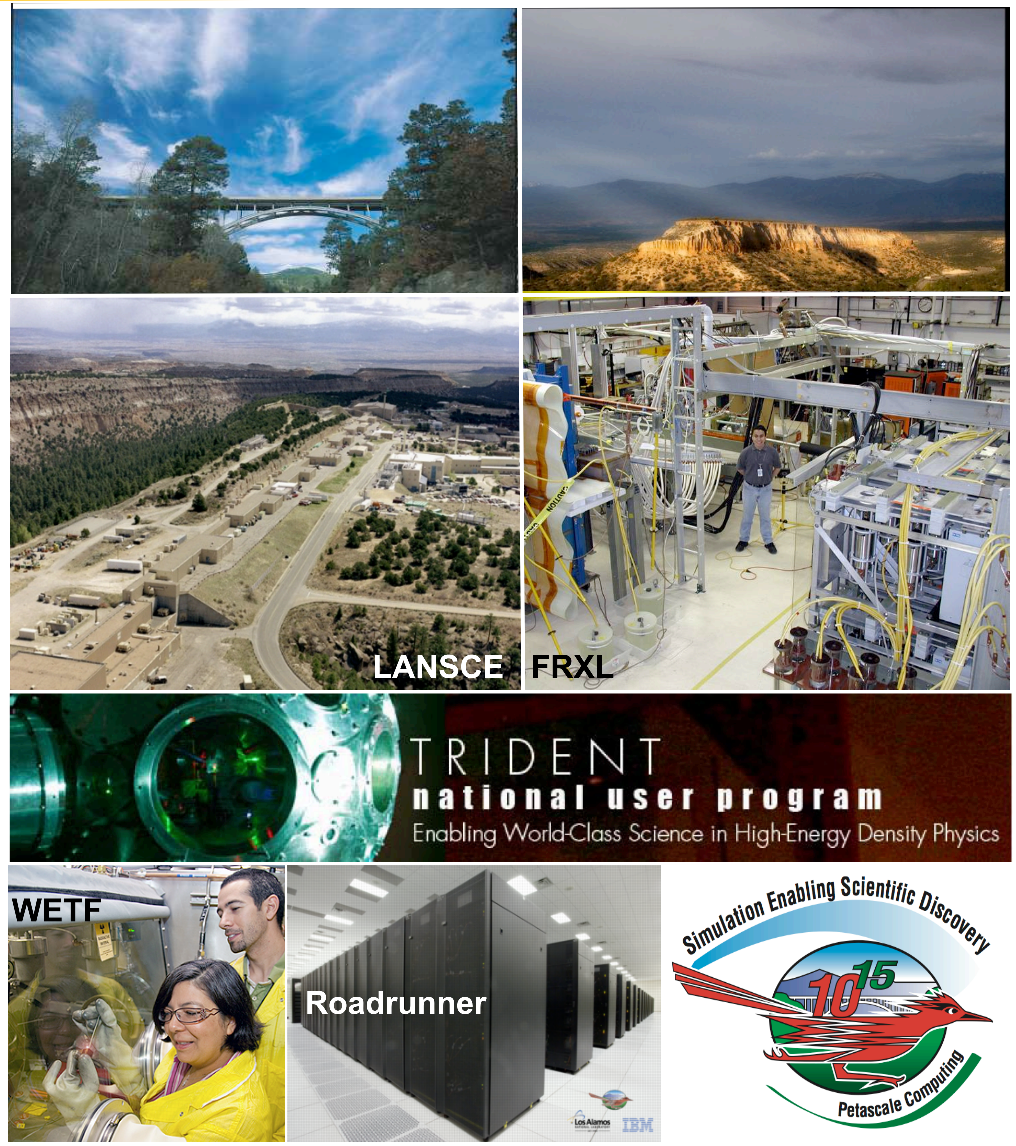


# Outline

- Addressing NRC committee charge
  - Power generation prospects
  - Challenges, cost targets, R&D objectives
  - R&D roadmap
- Support ICF consensus opinion
- Aggressive program to take us from present (TRL = 3 − 4) to a reactor (TRL = 9)
  - Scientifically & technologically diverse, national scale program
- Recommendation: four stage approach for any concept
- Examples of Stage 1 activities
- Summary

Prospects

# LANL fully supports the ICF community common viewpoint on IFE (I)

*Now:*

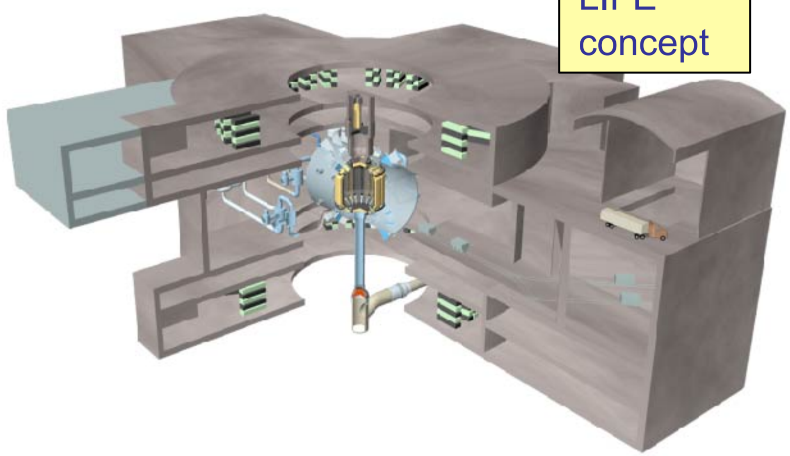
- Demonstrating laboratory ignition will establish that the physics underpinning IFE exploitation is fundamentally sound.
- US is a clear world leader in IFE academically, technologically and industrially.
- We have an opportunity to capitalize on this leadership position over the next few years and leverage prior substantial defense program investment.
- DOE actions to propose a new IFE development program and to secure a stable home for IFE are timely and welcome.


# LANL fully supports the ICF community common viewpoint on IFE (II)

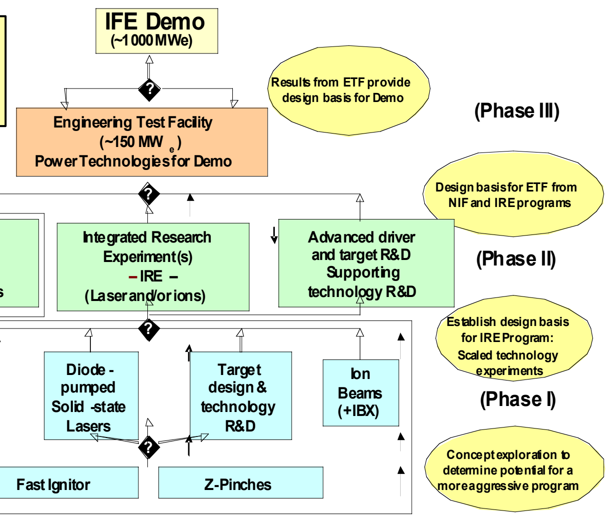
*Forward:*

- Program needs to focus on the requirements of an operating power plant, with design choices managed at a systems-level.
- The inherent modularity and separability of IFE provides significant benefits in power plant development, operations and evolution.
- Taking advantage of significant prior research, future development activities need to include IFE scale science and technology development and demonstration.
- IFE is a national scale program requiring a coordinated effort by academic, Laboratory, and industrial partners.
- A phased program with competition and unambiguous selection criteria is needed.

LIFE concept



Snowmass 2002



Program

# An aggressive IFE development program is timely and welcome.

- An optimum roadmap to a power reactor minimizes developmental stages with prudent risk management.
- Technical Readiness Levels (TRLs) used by NASA, DoD & DOE are helpful in defining R&D and developmental stages.
- Our assessment: IFE as a whole is at a TRL of 3, on the verge of 4, as evidenced by 10>*G*>1 ignition campaign @ NIF, & development of lasers, targets and associated technologies and facilities.
- *IFE is more than drivers and targets.* There are huge gaps to in other critical areas such as materials science and nuclear engineering, largely unaddressed by the ICF program. These challenges are as difficult and important as achieving a burning plasma.

**Technical Readiness Levels provides a basis for assessing the development strategy**

*From F. Najmabadi, UCSD (2009)*

| Level | Generic Description | |
|---|---|---|
| 1 | Basic principles observed and formulated. | Basic & Applied Science Phase |
| 2 | Technology concepts and/or applications formulated. | Basic & Applied Science Phase |
| 3 | Analytical and experimental demonstration of critical function and/or proof of concept. | Basic & Applied Science Phase |
| 4 | Component and/or bench-scale validation in a laboratory environment. | Basic & Applied Science Phase |
| 5 | Component and/or breadboard validation in a relevant environment. | Basic & Applied Science Phase |
| 6 | System/subsystem model or prototype demonstration in relevant environment. | Basic & Applied Science Phase |
| 7 | System prototype demonstration in an operational environment. | Validation Phase |
| 8 | Actual system completed and qualified through test and demonstration. | Validation Phase |
| 9 | Actual system proven through successful mission operations. | |

Increased integration

Increased Fidelity of environment

**Goal: Reactor (TRL 9) by 2050**

# We advocate a four-stage approach in the IFE program

1. Subscale key science and technology development.
2. Module Development at or near full-scale.
3. Integrated Fusion Test Facility (FTF) that brings all necessary subsystems to at least TRL-6.
4. Prototype Reactor that is full-scale relative to a commercial power plant and supplies electricity to the grid, demonstrating extended, reliable, safe operation, and building confidence in economics of commercial systems.

Why these and why four?

- Building upon the 2002 Snowmass plan and our 2010 interactions with the broader ICF community, we believe it optimizes opportunity, cost, benefit, & risk.
- Recognizes that different concepts have different timelines for the four phases and that not all concepts are in the same phase at the same time
- Provides a phased program with competition and unambiguous selection criteria
  - Exploits benefits of IFE modularity and separability
  - Enables most mature concepts to advance towards a reactor
  - Encourages R&D (~ 25% level of total program seems about right) to mitigate the risks identified by the most advanced concepts

Program

# Stage 1: Subscale key science and technology development

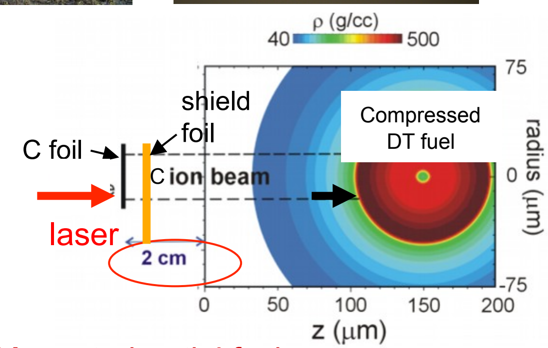
Sample tasks:

- System studies to estimate requirements for full size modules of key technologies for FTF and a Prototype Reactor (PR)
  - including definition of the number of driver lines required and the individual driver line requirements.
- High-gain target designs based on at least 2-D codes, for FTF and a prototype reactor, demonstrating projected target gains sufficient to meet the $\eta G > 10$ requirements for a viable IFE system.
- Sub-scale driver modules that demonstrate performance and lifetime of operation that scales to a prototype driver line for FTF
- Initial design of the tritium processing system for the blanket and the chamber for FTF and a Prototype Reactor

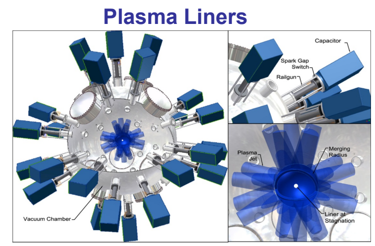
**Examples of Stage-1 Science & Technology at LANL**

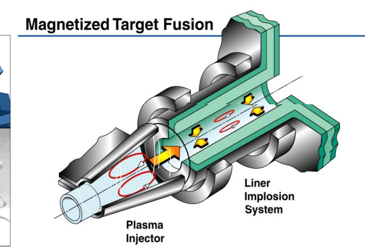


Fast Ignition with laser-driven ion beams

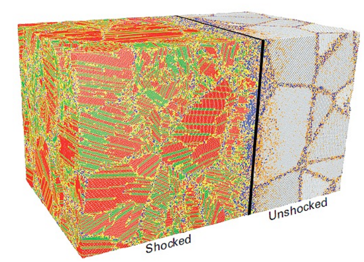



Magneto-inertial fusion




Diagnostics


Material-dynamics under extremes

# Potential criteria for Stage 1 completion: Subscale key science and technology development

- Driver and target combination meets projected technical and economic requirements for an FTF.
- Credible pre-conceptual designs for a complete FTF system
  - target fabrication & manipulation, optics/power coupling to target, reaction chamber, tritium breeding, power conversion.
- Credible scale-up path from FTF to an economically and technically attractive full scale reactor (*e.g.,* sufficient $\eta G$ and a cost of electricity of overall approach).
- For drivers: Sub-full-scale tests are promising for meeting performance criteria (efficiency, durability).
  - At a minimum, must demonstrate days of continuous operation with precise control of critical parameters (energy, pulse shape) but without damage.
  - Demonstrated driver technology must be of sufficient size and nature to be directly scalable to a full size system.
- Premium assigned to lower overall costs for the FTF.

Program

# Stage 2: Module Development at or near full-scale

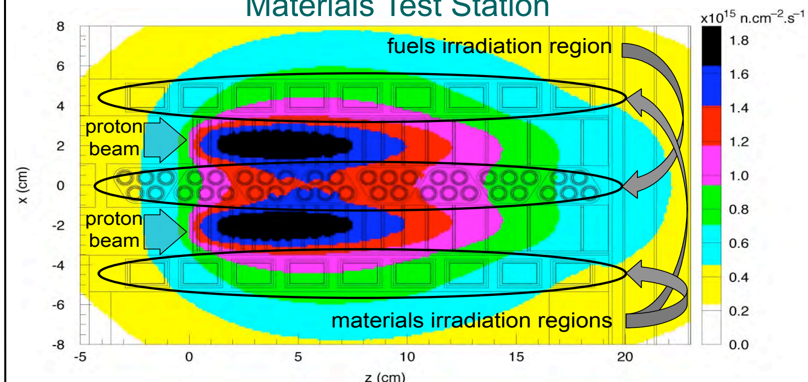
Sample tasks:

- Develop experimental facilities to qualify materials for the FTF.
- Subscale demonstrations of chamber materials (especially first wall) that survive the threats of target yield.
- Experimental validation of the underlying physics of high gain on available devices, including ignition if possible.
- Build one or more full-scale prototype driver modules for each selected driver technology that demonstrates the performance and expected lifetime of operation appropriate for FTF

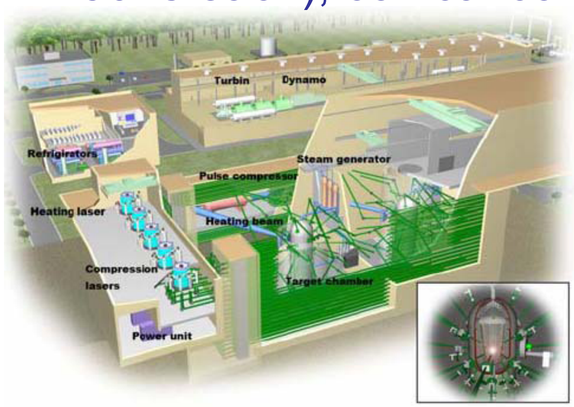
Examples:

- Extend neutron-damage studies of materials beyond LANL MTS

Neutron-irradiation of materials at the LANL Materials Test Station




- Demonstrate a laser-driven ion acceleration module for ion-fast ignition (one of 20 lasers, ~5 kJ, ~50 fs each), conical configuration




Koyo-F Fast Ignition reactor concept, 100 kJ short-pulse ignitor laser

Program

# Potential criteria for Stage 2 completion: Module Development at or near full-scale

- Integrated approach (driver, target, and other key components) must be on a highly credible cost-effective development path to practical commercial fusion power.
- Prototype drive module demonstration at stable continuous operation for months
  - No performance deterioration or significant wear, or equivalent with component hot swap.
  - Analysis of the design and experimental results must credibly extrapolate to 12 months continuous operation at a reliability of 95% and more than ten years operational lifetime
- FTF subsystems -- e.g. target fab & manipulation, final optics/power coupling, first wall & reactor chamber materials must be sufficiently developed & tested.
- Conceptual design for FTF should include:
  - ability to breed its own tritium, test all critical components and procedures for a full scale power plant, and serve as a fusion materials test facility;
  - structural parts with overall design life greater than 20 years with either first-wall replacement required no more than every 2 years, or replacement scheme allowing 95% reliability;
  - capability of long continuous run times (>30 days), with 50% reliability; and
  - provide minimum of 100 MW fusion thermal power to test components.
- Desirable that FTF be capable of generating net electrical power beyond its own needs.
- Size and cost matter -- smallest possible size reduces time and cost of Stage 2 effort.

Program

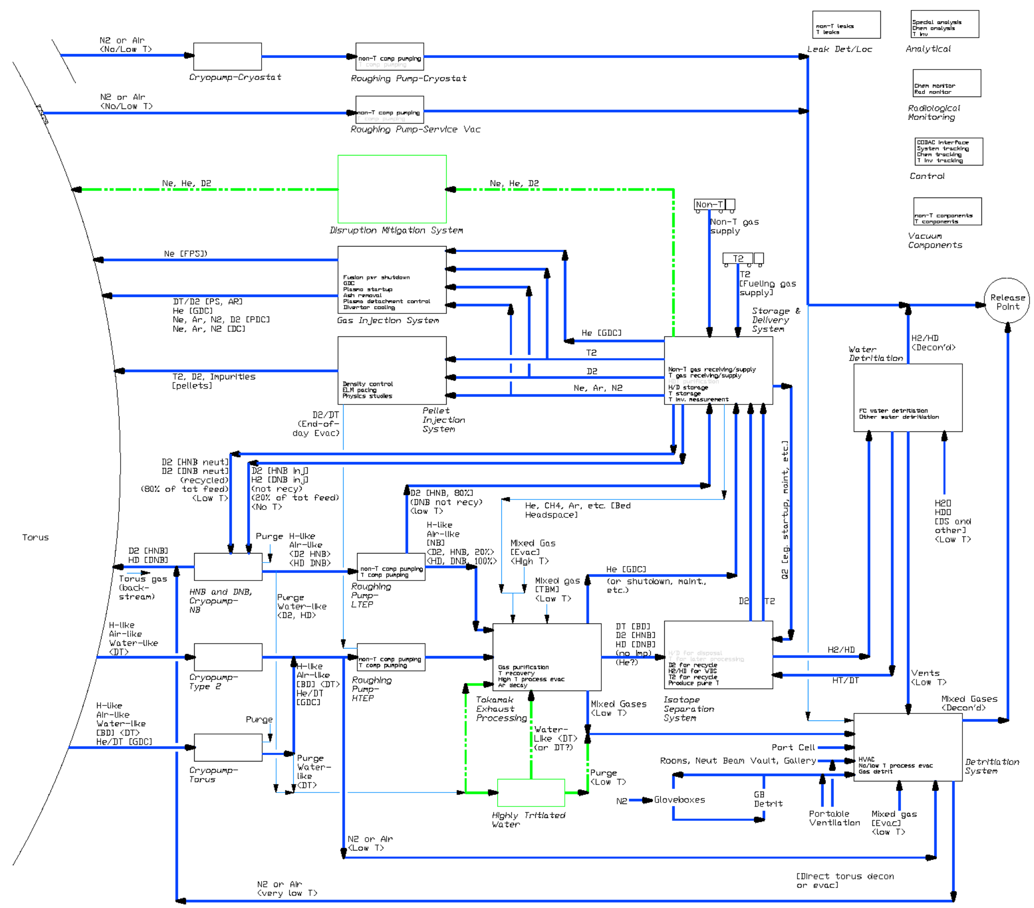
# Stage 3: Fusion Test Facility (FTF) that brings all necessary subsystems to TRL ≥ 6

- FTF Goal: Demonstrate all aspects of a power plant, but at lower yield and scale, with end-to-end tests validating feasibility, availability and cost effectiveness requirements.

- Example Tasks:
  - Verify target performance
  - Demonstrate
    - performance & reliability of drivers
    - performance & reliability of a Prototype Reactor driver line
    - performance and survivability of components

## ITER fuel cycle block diagram:

- 14 highly interconnected, multi-functional systems
- Will occupy 7-story building
- ~5 kg tritium inventory



Program

# Potential Criteria for Completing Stage 3: Fusion Test Facility that brings all necessary subsystems to TRL ≥ 6

- Ignition, burn and expected high net power gain demonstrated in routine long duration operation or demonstrated hot swap at the systems-rated rep rate
- High yield targets for a prototype reactor optimized at necessary gain
- Full-scale (speed, length) drive-target coupling using a scheme appropriate for a prototype reactor, that engages the target at the accuracy appropriate for a Prototype Reactor.
- Critical reactor components performance meet functional, reliability, and lifetime requirements
- Integrated repetitive operation (fusion chamber, tritium breeding, thermal management, and production of high-grade heat flux) including target production demonstrated
- Efficiency, technologies, cost, and economies-of-scale for full-scale driver demonstrated
- First wall for a prototype reactor demonstrated
- Sufficient fuel cycle closure demonstrated (tritium breeding &recovery)
- Prototype reactor conceptual design completed with industry buy-in

# Criteria demonstrated in Stage 4: Prototype Reactor

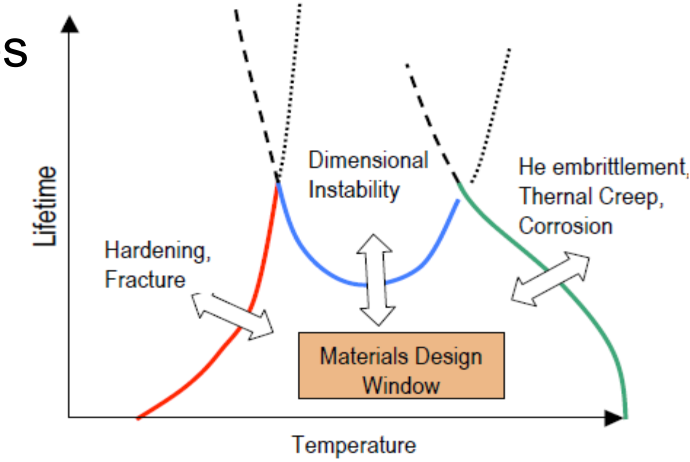
- ES&H:
  - Not require an evacuation plan
  - Generate only low-level waste
  - Not disturb the public's day-to-day activities
  - Not expose workers to a higher risk than other power plants
  - Demonstrate a closed tritium fuel cycle
- Economics:
  - Cost of electricity from a commercial power plant will be competitive
  - Costs of other applications (*e.g.*, hydrogen production) are also attractive.
- Scalability:
  - Use the physics and technology anticipated for the first generation of commercial power plants.
- Reliability:
  - Robotic or remote maintenance of fusion core.
  - Routine operation that meets availability and reliability requirements.
  - Availability of power on the grid that is commercially viable.

*IFE is more than drivers & targets*

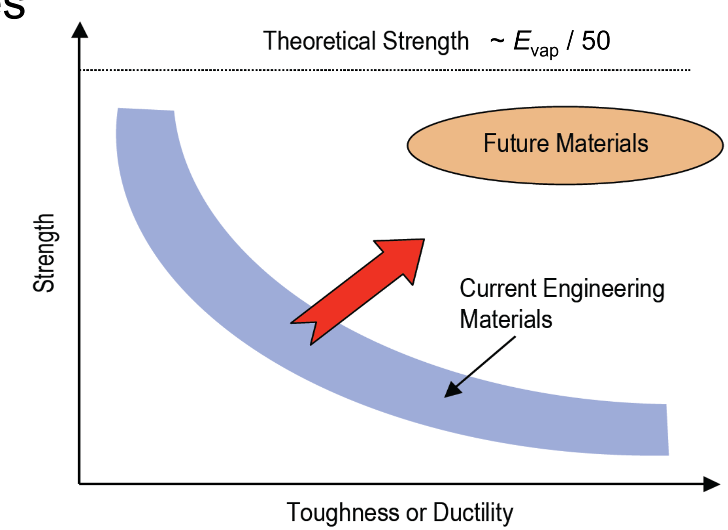
# Fusion reactor materials must function in a uniquely hostile radiation, thermal, & chemical environment

- There are no known solid materials suitable for the first wall & blanket structural materials of a fusion system, able to withstand the high neutron fluences in the extreme environments of fusion reactors.
  - Limited operating temperature windows
  - May produce technically viable design, but not economically attractive
- Heat, neutron fluxes and mechanical stress result in microstructure & bulk property changes over long times.
  - Voids, bubbles, dislocations and phase instabilities
  - Dimensional instabilities (swelling & irradiation-thermal creep)
  - Loss of strain hardening capability
  - Fatigue, creep-fatigue, crack growth
  - Corrosion, oxidation and impurity embrittlement (refractories)
  - Transient & permanent changes in electrical & thermal properties.

High He may narrow or even close the window

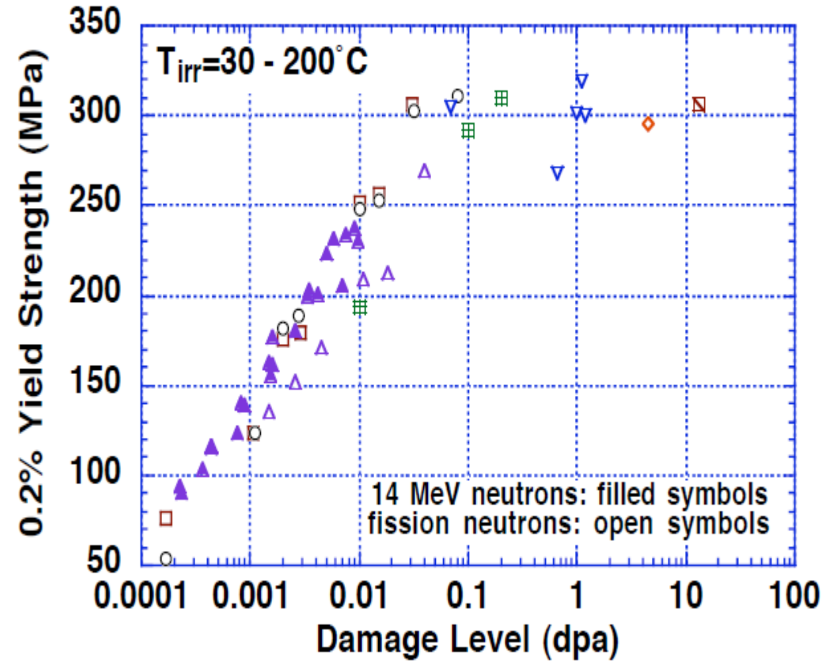


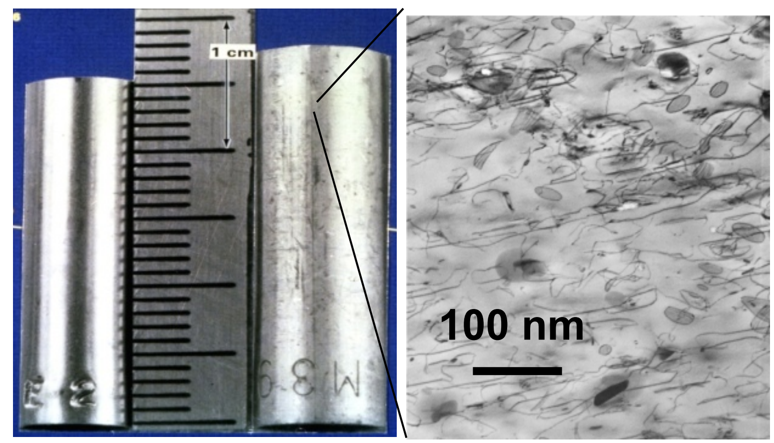

N. Ghoniem & B.D. Wirth, 2002



# Radiation damage can produce large changes in structural materials

- Radiation hardening and embrittlement (<0.4 $T_M$, >0.1 displacements per atom [dpa])
- Phase instabilities from radiation-induced precipitation (0.3-0.6 $T_M$, >10 dpa)
- Irradiation creep (shape changes, <0.45 $T_M$, >10 dpa)
- Volumetric swelling from void formation (0.3-0.6 $T_M$, >10 dpa)
- High temperature He embrittlement (>0.5 $T_M$, >10 dpa)



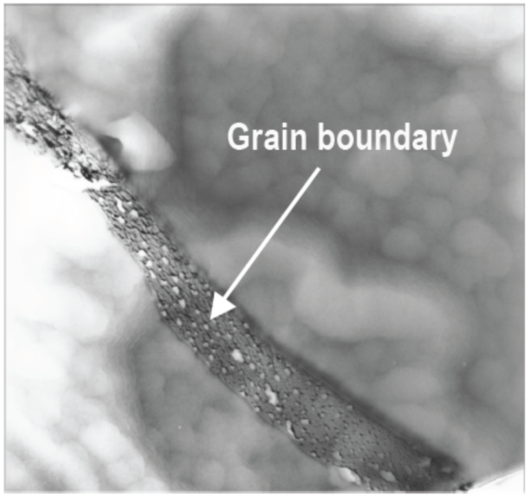

**Dynamic, stochastic processes in extreme environments dominate phenomena, such as swelling, that we do not understand**

Source: S. Zinkle, 23rd SOFE (San Diego, 2009)

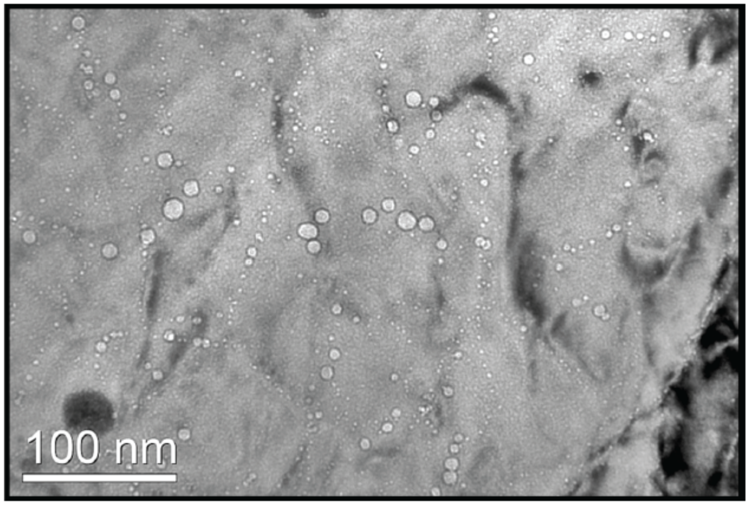
*IFE is more than drivers & targets*

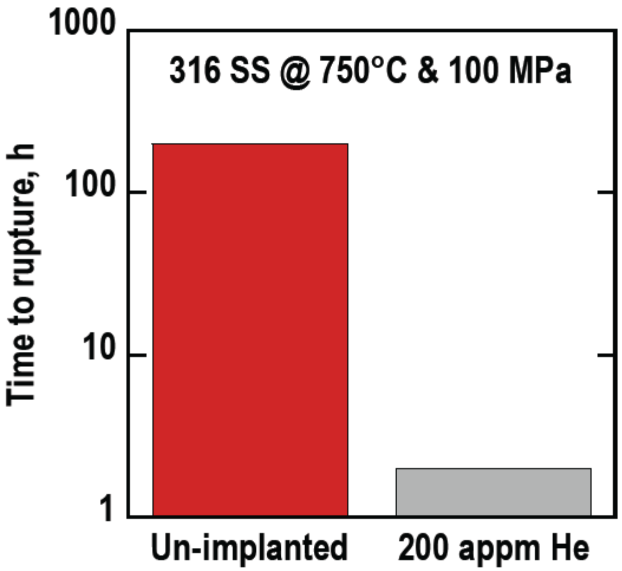
# Critical unanswered question is the impact of H-rich and He-rich environment on neutron-irradiated materials

- A unique aspect of the DT fusion environment is substantial production of gaseous transmutants such as He and H.
- Accumulation of He can have major implications for the integrity of fusion components & structures such as:
  - Loss of high-temperature creep strength.
  - Increased swelling and irradiation creep at intermediate temperatures.
  - Potential for loss of ductility and fracture toughness at low temperatures.




Voids in F82H at 500°C, 9dpa, 380 appm He




Source: R. Kurtz, M. Maule, M.Nastasi, R. Odette, S. Sharafat, R. Stoller, S. Zinkle, OFES Research Needs Workshop ( Bethesda, 2009)

Stage 1

*Example Stage-1 Tasks*

# IFE materials issues can be addressed this decade with existing high-power accelerators with spallation neutron production

SNS (Oak Ridge)

LANSCE (Los Alamos)

SINQ(Paul Scherrer Inst.)


J-PARC (JAEA & KEK)

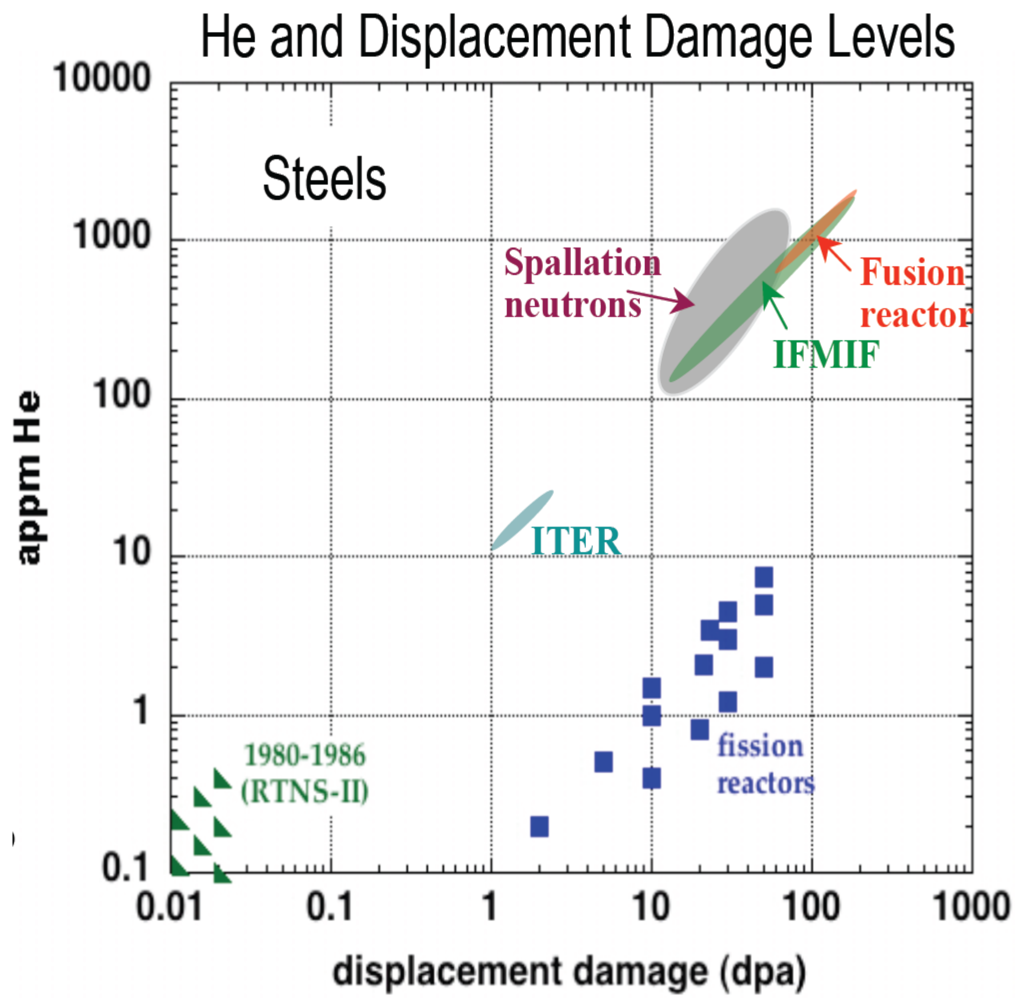
ISIS (Rutherford Appleton Lab)

**Stage 1**

# Material issues should be addressed in Stage-1, long before building the first IFE high-flux neutron source

- Finding & validating materials & blanket concepts in a fusion relevant environment is a necessary step for the design, construction, licensing, & safe operation of an IFE reactor.

- To test & fully qualify candidate materials for high-fluence service a suitable high-flux source of high energy neutrons needs to be built and operated that simulates service up to the full lifetime anticipated for a reactor.




Sources: IFMIF Comprehensive Design Report (IEA, Jan 2004).
R. Kurtz et al., ReNeW (Bethesda, 2009).

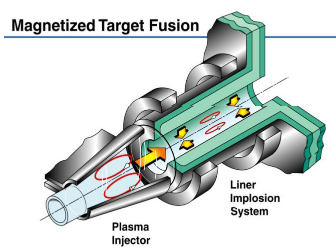
*Example Stage-1 Tasks*

# Magneto-inertial fusion

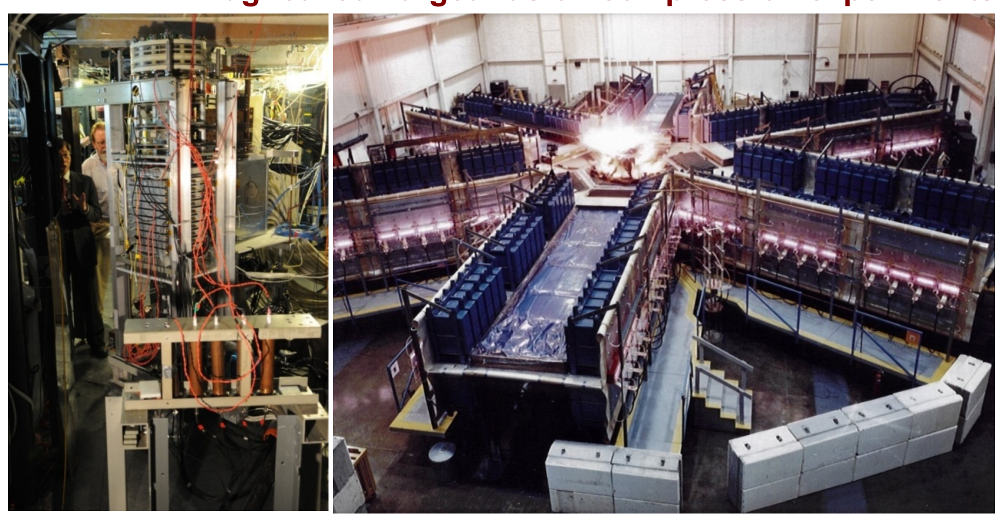
**Stage 1**

## Why magneto-inertial fusion (MIF)?

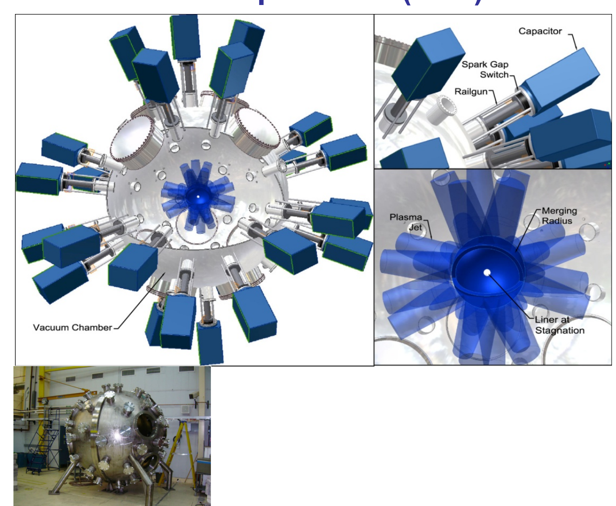
- Reduces *ρr* requirements: lower implosion velocity & lower peak power
- Confines alphas with B-field (*Br* parameter becomes relevant)
- Reduces required compression ratios
- Allows high efficiency, lower cost drivers (pulsed power driving slow & fast liners, plasma liners, … )
- Allows additional targets types (*e.g.*, high density MFE or wall-confined plasmas)
- Enables an intermediate regime: η ~ 0.5, *G* ~ 20, wide operating timescale window (~ 0.1 -- 10 μs)
- MIF is being tested: plasma-source optimization (FRXL@LANL), plasma compression (FRCHX / SHIVA STAR @ AFRL) and plasma liner (PLX @ LANL)
- Complementary research at SNL and LLE.




**LANL-AFRL Magnetized-Target Fusion compression experiments**



**Plasma Liner Experiment (PLX) at LANL**

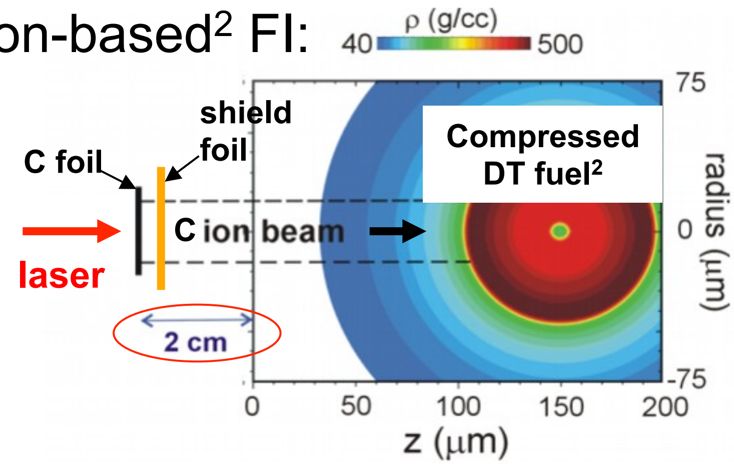


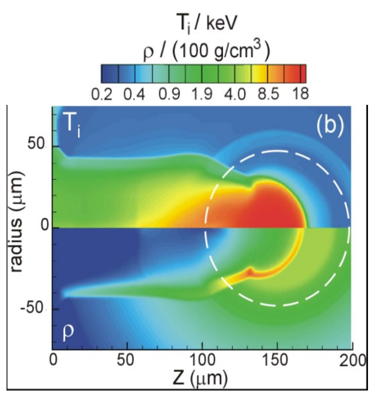
Stage 1

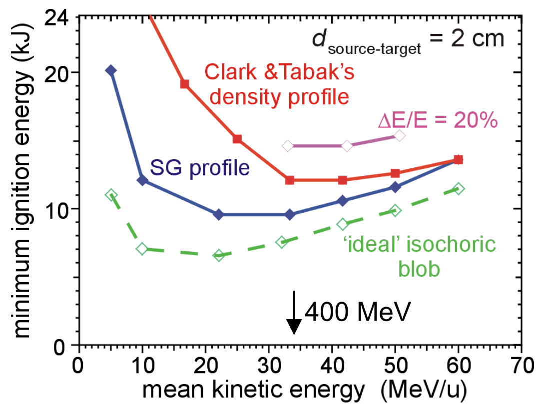
# Laser-produced quasi-monoenergetic low-Z ions (e.g., C) have potential advantages as a fusion ignitor beam.*

- Potential advantages over electron[1] or proton-based[2] FI:
  - Quasi-monoenergetic-ion source may be placed far from the fuel
  - Sharper deposition (higher efficiency)
  - Most robust particle-beam transport
  - Many fewer ions than protons required

No Cones




- Target design study with realistic designs for the compressed-capsule[3] specifies ion-beam requirements

- Modest program to develop required laser-driven ion beams ongoing @ LANL
  - Laser – ion conversion efficiency: ~ 10% desired, up to 12% observed
  - Achieved up to 500 MeV C ion energy, but not desired energy distribution yet
  - Ion beam focusing is not in the present research scope
  - Complementary proton FI program is ongoing.

*J.C. Fernández, *et al.*, Nuclear Fusion 49, 065004 (2009), J.J. Honrubia, *et al.*, PoP **16**, 102701 2009 ; [1] Tabak *et al.*, PoP **1,** 1626 (1994); [2] Roth *et al.,* PRL **86,** 436 (2001); [3] D. Clark & M. Tabak, Nucl. Fus. **24,** 1147 (2007)

# Summary & Conclusions

- LANL fully supports the ICF community common viewpoint.
- While significant investments in ICF over the past 40 years have yielded impressive accomplishments in driver technology and target physics, our assessment is that IFE as a whole is currently at a TRL of 3 and on the verge of 4.
- IFE is more than drivers and targets. There are huge gaps to in other critical areas such as materials science and nuclear engineering, areas that have been largely unaddressed by the ICF program over the years. These challenges are as difficult and important as achieving a burning plasma.
- A four-stage approach optimizes opportunity, cost, benefit, & risk.
  - Performance gates (not necessarily down-selects, no eternal consideration of given idea) to accommodate diverse rates of progress
  - Scientifically & technologically diverse, multi-institutional, national scale
- Prior to the construction of a prototype power reactor, all necessary subsystems should demonstrate performance at TRL ≥ 6.
- We look forward to contributing.