Fusion Program
Overview at Los Alamos

G. A. Wurden

Fusion Power Associates Symposium
Fusion Energy: Status & Prospects
Washington DC

Dec. 2, 2009

LA-UR 09-07809

ABSTRACT

OUTLINE:

- General information on Fusion Energy Sciences Program at LANL

- Highlights

- Magneto Inertial Fusion
- Basic Plasma Science
- Ion Fast Ignition

- Fusion materials testing opportunities with MTS and MaRIE

Fusion Energy Sciences (FES)

FES Mission: *The mission of the U.S. Fusion Energy Sciences Program is to advance plasma science, fusion science, and fusion technology − the knowledge base needed for an economically and environmentally attractive fusion energy source. Colloquially, we are trying to "create a star on Earth".*

Priorities at LANL:
- Three legs: Theory & simulation, Experiment, and Engineering
- Fusion Simulation Program (FSP)
- High Energy Density Laboratory Physics (HEDLP)
- Basic plasma science, including possible joint fission fusion materials facility (FFMF)
- Supporting roles on FES machines around the country, and at ITER

Changes for FY2010: (Budget increased to $5.4M + $3M ITER)
- New starts in HEDLP (fast ignition energetic ion production, plasma jets experiment)
- ReNeW style workshops on HEDLP and Fusion/Fission Hybrids
- Formal Trident Laser User Facility proposal submission
- Stimulus money for ICC infrastructure upgrade (200 Mfps camera)
- Increased emphasis on importance of "transient events" in tokamak research

FES 2009 LANL Highlights

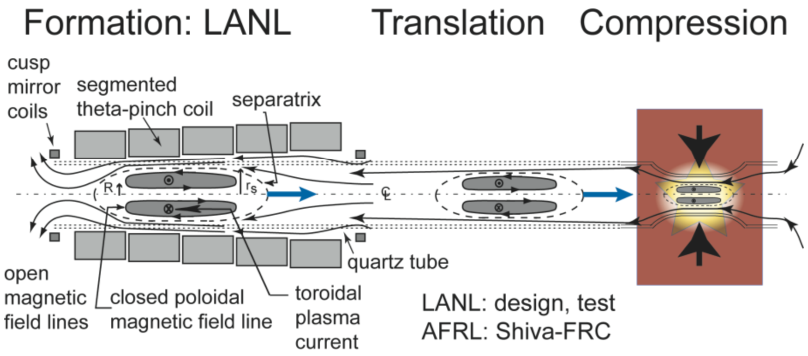
Research:

- LANL has the lead role in demonstrating the physics of magnetized target fusion, collaborating with the Air Force Research Laboratory in Albuquerque. The experiment at LANL is called FRX-L, and at AFRL, it is named FRCHX. The aim is to achieve fusion conditions at 1 Megabar pressures.
- We are studying the generation of MeV ions using the 200 Terawatt Trident laser on ultra-thin foils, and simulating them using VPIC on the RoadRunner supercomputer.
- We collaborate on field reversed configuration plasma physics with the U of Washington, and field diagnostics to study radiation and plasma power balance.
- We collaborate on tokamak research at MIT, on the Alcator C-Mod tokamak, studying plasma wall interactions with infrared imaging equipment.
- Engineering efforts are primarily directed at fueling systems for ITER, and we have 3 LANL personnel stationed at ITER in Cadarache, France.
- Theory work in
    - Temperature relaxation in dense plasmas: HEDLP
    - Magnetic reconnection: space, astrophysics, and magnetic fusion
    - Magnetic self-organization: astrophysics and magnetic fusion
    - Advanced numerical simulation (Fusion Simulation Project is FES equivalent to ASC)

Facilities:

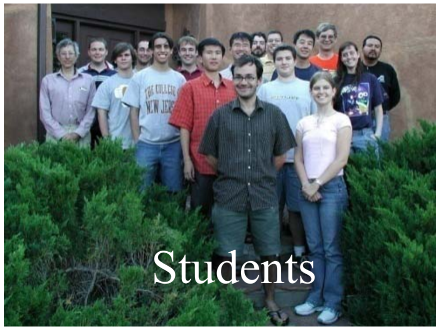
- Magnetized Target Fusion FRX-L plasma
- Inertial Electrostatic Confinement IEC POPs plasma
- Trident Laser for HEDLP fast ion experiments
- Hydrogen gas exhaust processing mockup for ITER

FES @ LANL in Pictures

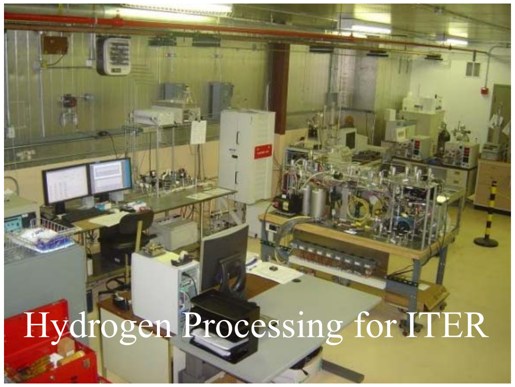


LANL: design, test
AFRL: Shiva-FRC

MTF Team



Students

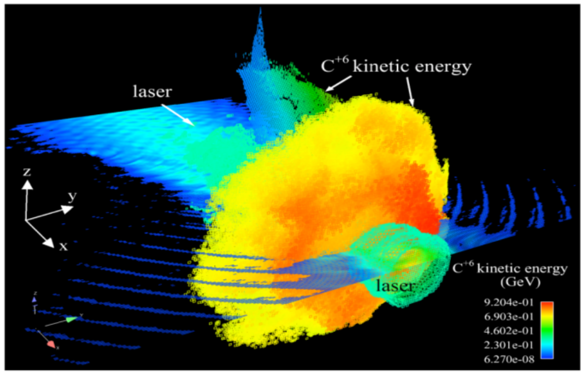


Hydrogen Processing for ITER

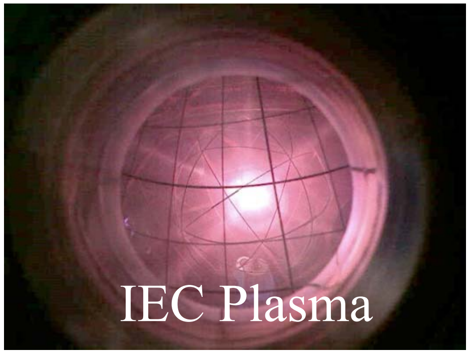
Circular polarization, 30nm C and $I_0=10^{21}$ W/cm² & 312 fs pulse

Our largest simulation to date on ion acceleration (run on Roadrunner base system):

- Physical domain 25x25x20 μm w. solid target density 14×10^9 cells, 21×10^9 particles, 4096 processors
- Contrasting with sim. size at the time of the proposal: 0.5×10^9 cells, 2.2×10^9 particles, 510 processors
- 3D visualization using EnSight server-of-servers mode enables viewing, analysis of very large (multiple-TB) data sets.

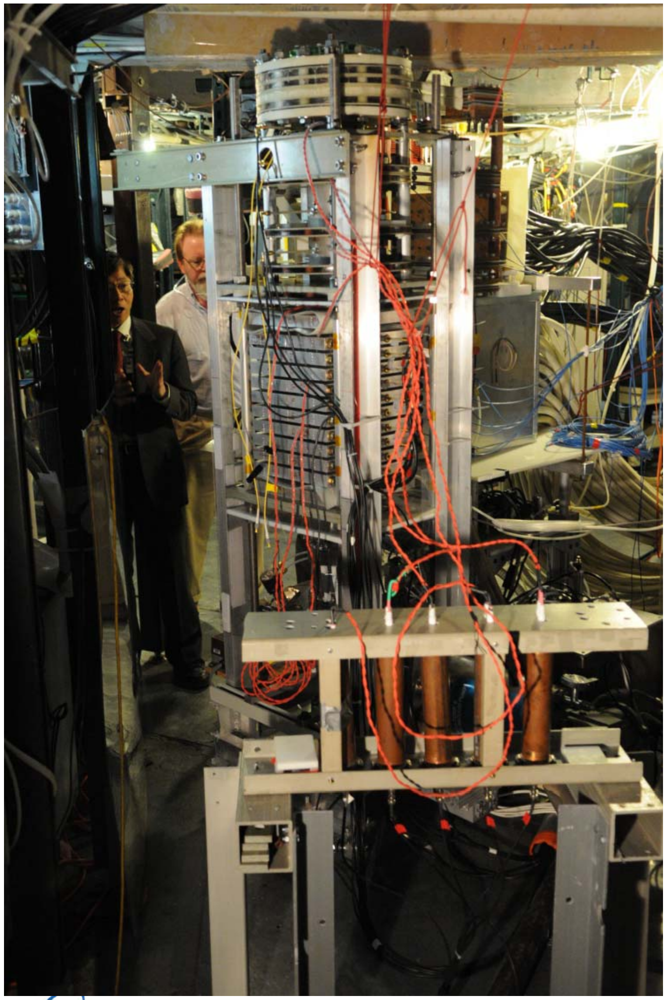


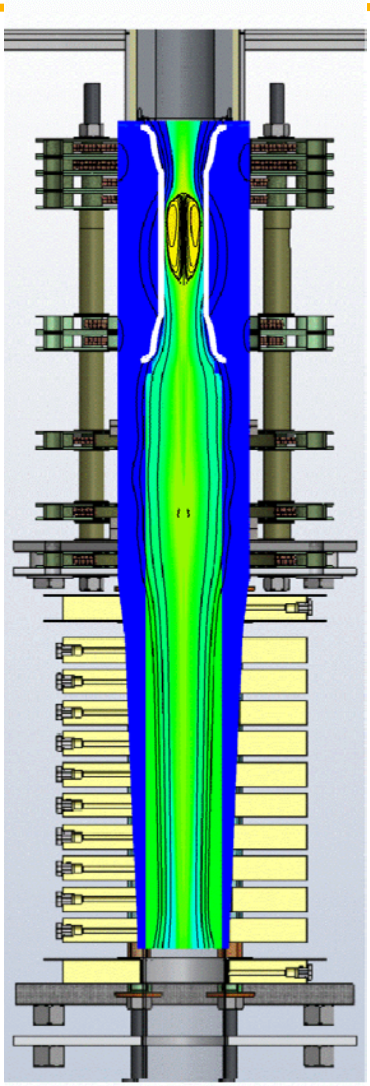
HEDP simulations on the fastest computer

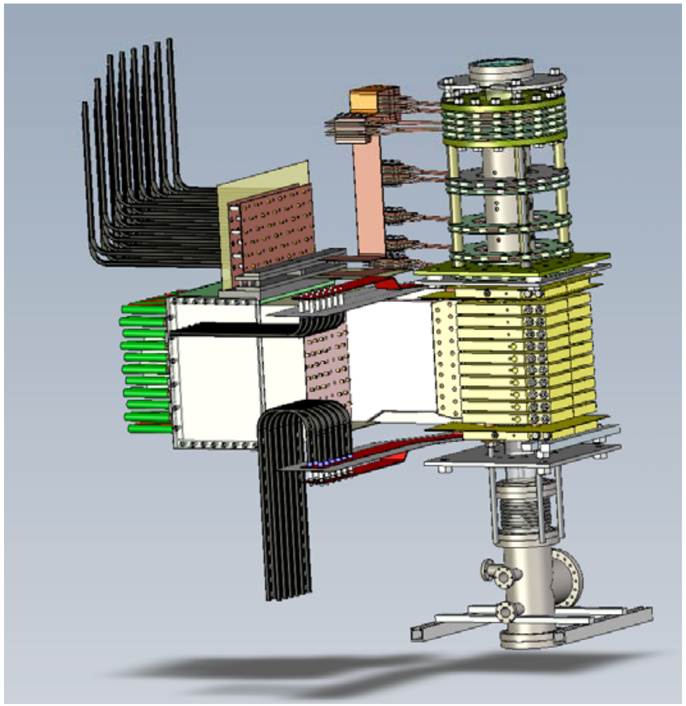


IEC Plasma

Magnetized Target Fusion, LANL/AFRL FRCHX progress



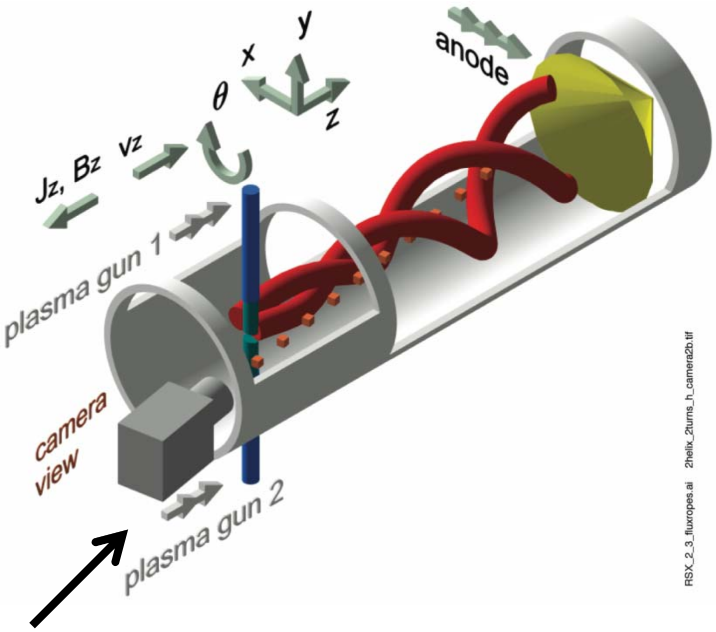




We had 2 engineering tests shots in FY09, and the first full-up plasma liner shot is being prepared now, for March 2010

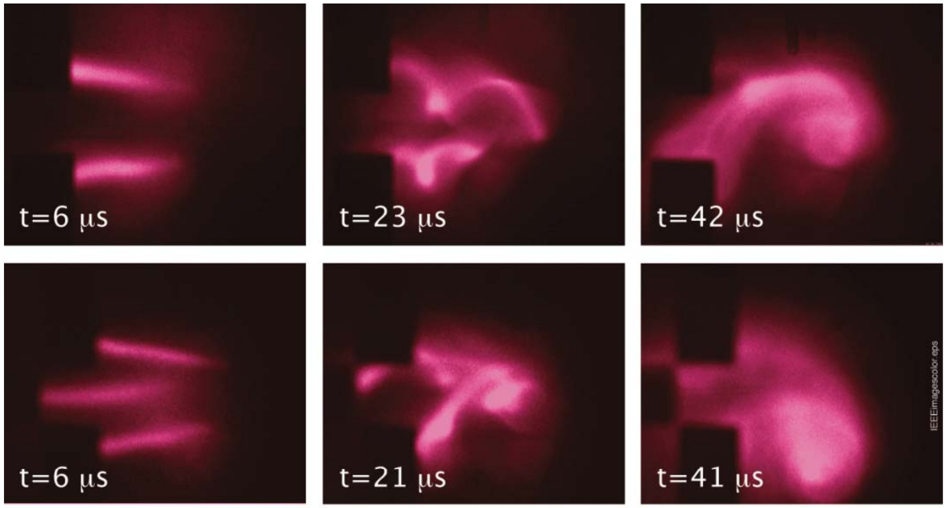
There is NSF/DOE basic plasma science at LANL!

CMSO and the LANL Reconnection Scaling Experiment



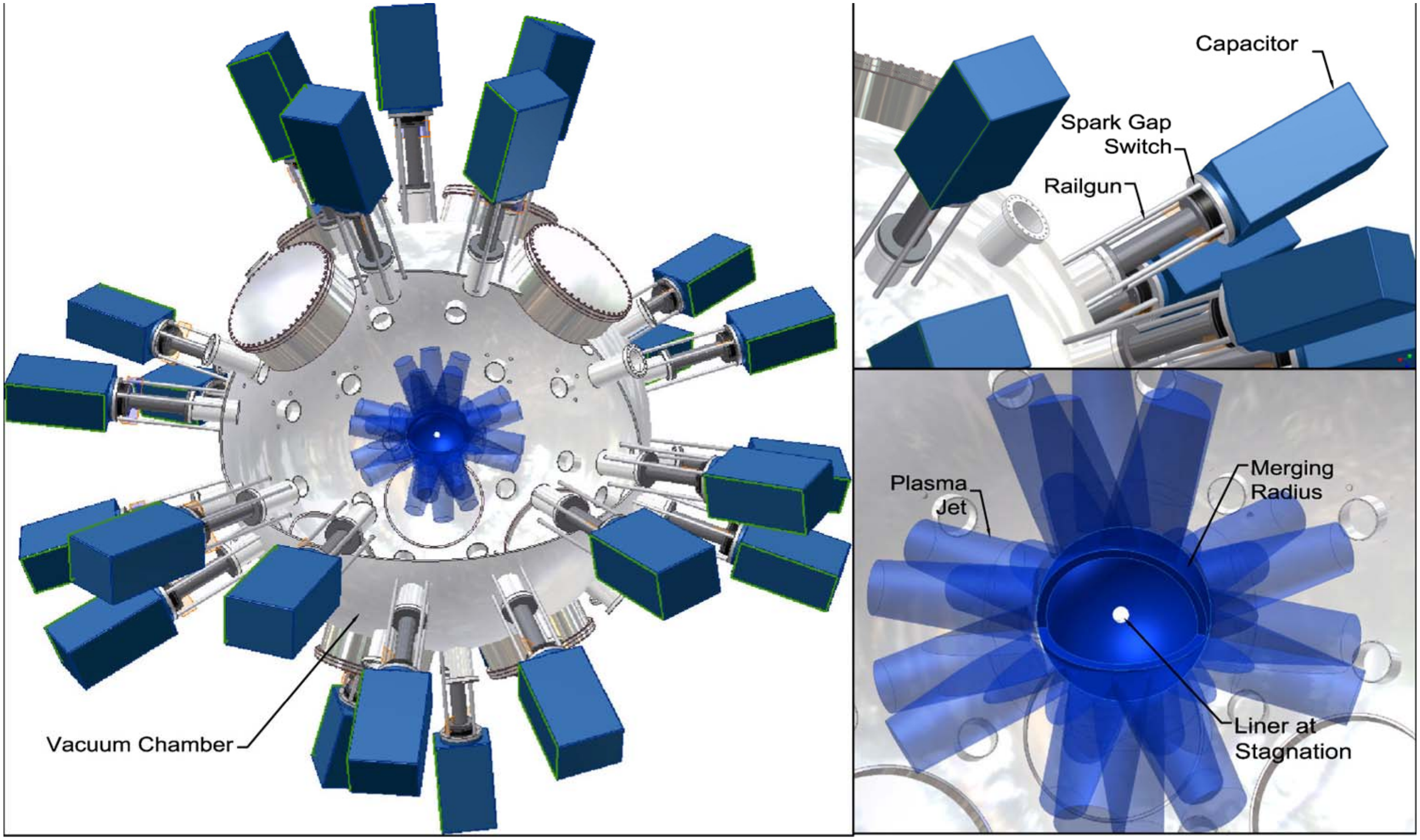
Kinked flux ropes collide ➔ 3D instability driven magnetic reconnection - P-24 Plasma Physics

Intrator *et al*, Nature-Physics **5**, 521 (2009)



End-on camera view perspective

New HEDP project starting at LANL: Merging plasma jets



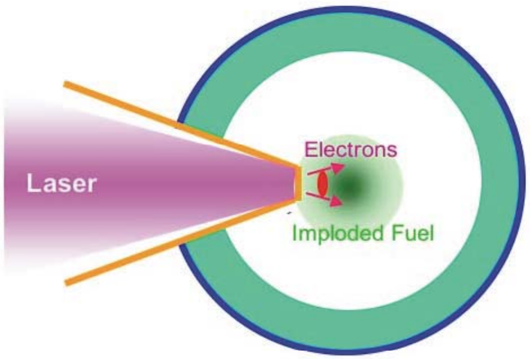
The Plasma Liner Experiment “PLX”

Inertial Fusion: Particle-driven fast ignition (FI)

- FI is isochoric ignition (conventional is isobaric)
- Long-pulse (> 10 ns) driver to compress DT to 300 – 500 g/cm^3 , ρr ~ 3 g/cm^2
- Particle beam must deposit ~ 10 kJ in ~ 25 ps (~ 4 PW) within hot-spot (HS) volume (~ 25 μm)^3 , i.e., ~10^{22} W/cm^3 → high-power laser driver

Alternative schemes:

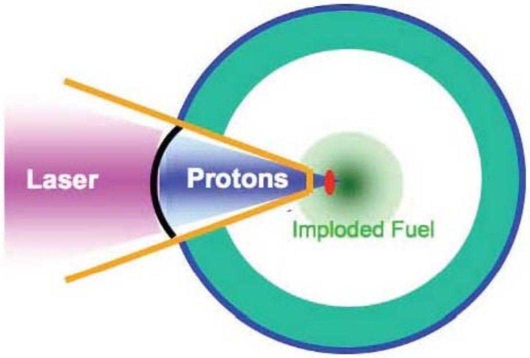
Electron-driven



R. Kodama *et al*., Nature 412 798 (2001)

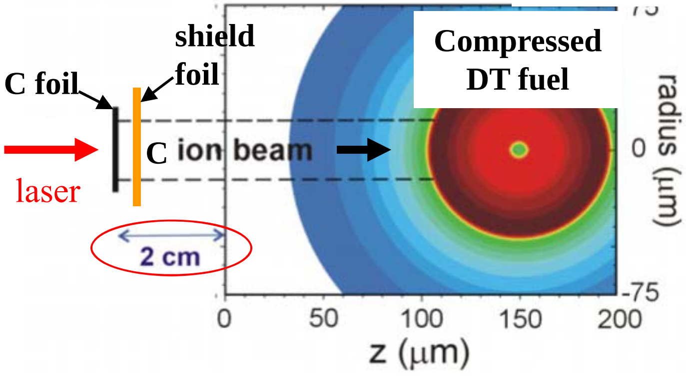
Ion-driven

Maxwellian protons OK → cone
Monoenergetic heavy ions → no cone



M. Roth *et al*., PRL 86 436 (2000)

J. C. Fernández, *et al*., Phys. Plas. 49 (2009) 065004



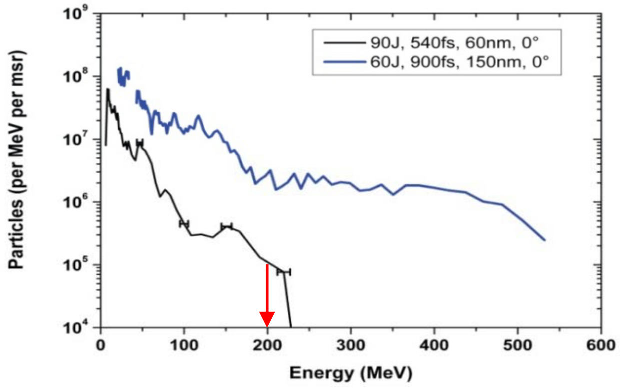
Development of laser-driven C ignitor beam: achieved *separately* required energy, energy spread, efficiency

Ion Accel.

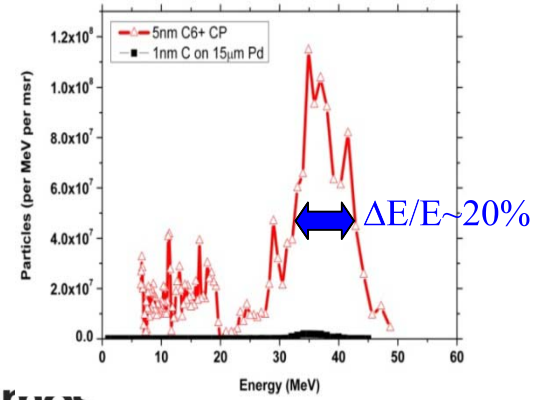
- **Demonstrated**

~ 500 MeV energy

Trident laser @ LANL

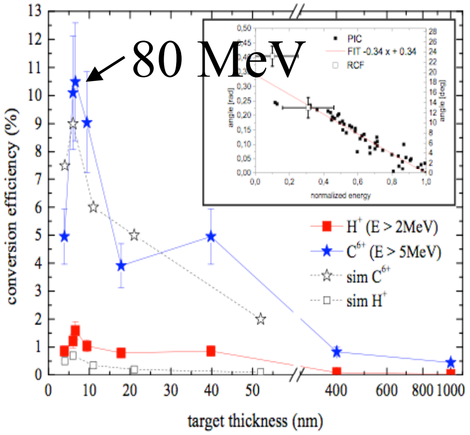


- Demonstrated narrow ion energy spectra (δE/E ~ 20%) at low energy (Trident)



ΔE/E~20%

- Demonstrated high laser-ion conversion efficiency (~ 12% C)*



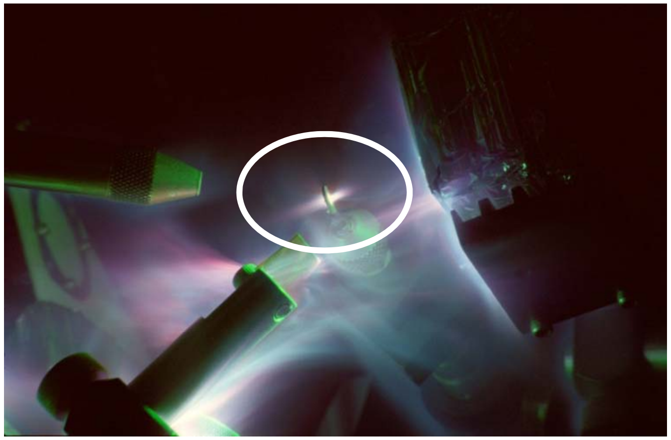
80 MeV

* Steinke, *et al.*, Phys. Rev. Lett. (2009) submitted

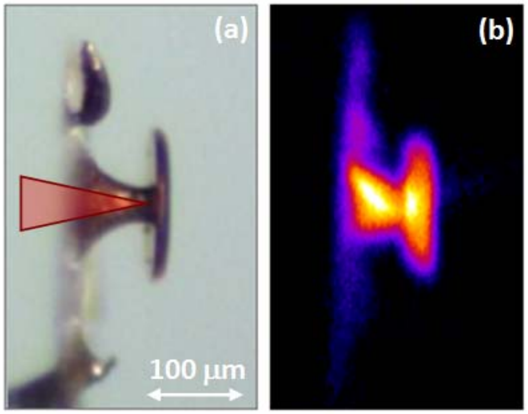
MBI, Berlin
Ti:Sapphire laser:
700 mJ, 45 fs,
3 x 10^{19} W/cm²

Excellent beam quality, contrast & target design enables on Trident the highest proton energy in laser-driven beam.

- Achieved highest proton energy of any laser driven beam: 65 MeV
- Utilized specialized cone-shaped targets
- Pulse energy of 80 J in 0.6 ps, > 10^{21} W/cm^2, > 10^{10} contrast



Visible-light photo (5 sec. exposure) of the experimental setup inside Trident vacuum chamber.



(a) Micro-scale Cu Flat-Top Cone target; (b) Cu K-alpha X-ray image showing the deep penetration of the laser light inside the cone neck.

Forschungszentrum Dresden Rossendorf
Mitglied der Leibniz-Gemeinschaft

Los Alamos NATIONAL LABORATORY EST.1943

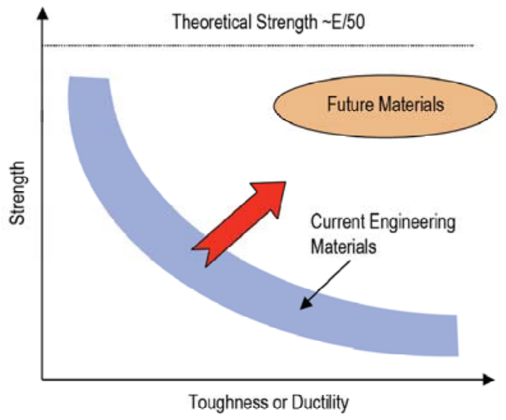
University of Nevada, Reno

Now for an important detour through materials testing and MaRIE *

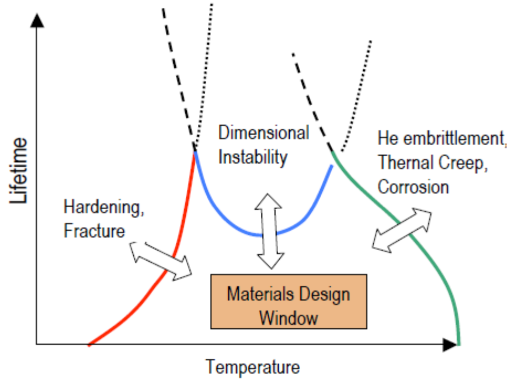
*"MaRIE (Matter-Radiation Interactions in Extremes)"
LANL's proposed flagship facility over the next 10-15 years

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

- There are no known materials for the first wall & blanket structural materials of a fusion system that can withstand the 10-15 MW-year/m2 high neutron & heat fluences in the extreme environments of a fusion reactor.
    - Existing structural materials are not ideal for advanced nuclear energy systems due to limited operating temperature windows
        - May produce technically viable design, but not with desired optimal economic attractiveness
- High heat, neutron fluxes and mechanical stresses result in microstructure & bulk property changes over long time.
    - Voids, bubbles, dislocations and phase instabilities
    - Dimensional instabilities (swelling & irradiation-thermal creep)
    - Loss of strain hardening capability
    - He embrittlement
    - Fatigue, creep-fatigue, crack growth
    - Corrosion, oxidation and impurity embrittlement (refractories)
    - Transient & permanent changes in electrical & thermal properties



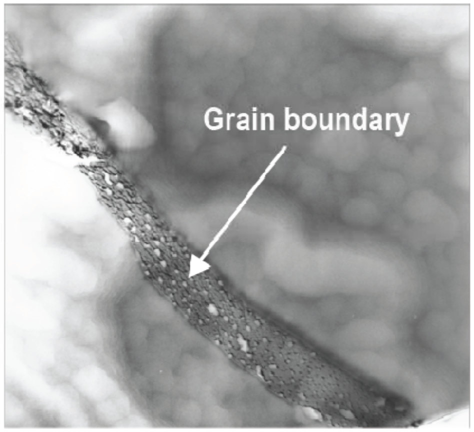
High He may narrow or even close the window



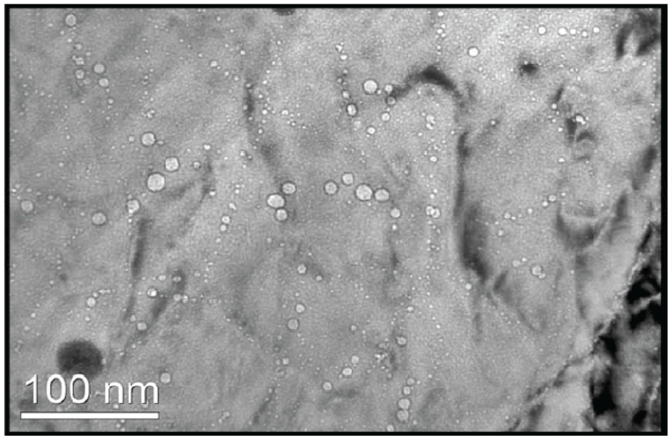
N. Ghoniem & B.D. Wirth, 2002

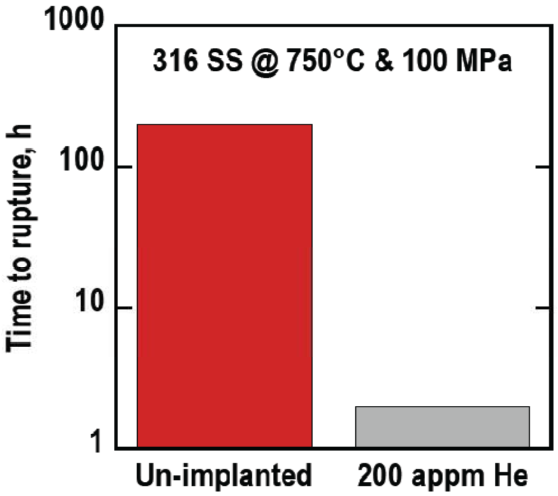
Critical unanswered question is the Impact of H- and He-Rich Environment on Neutron Irradiated Materials

- 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



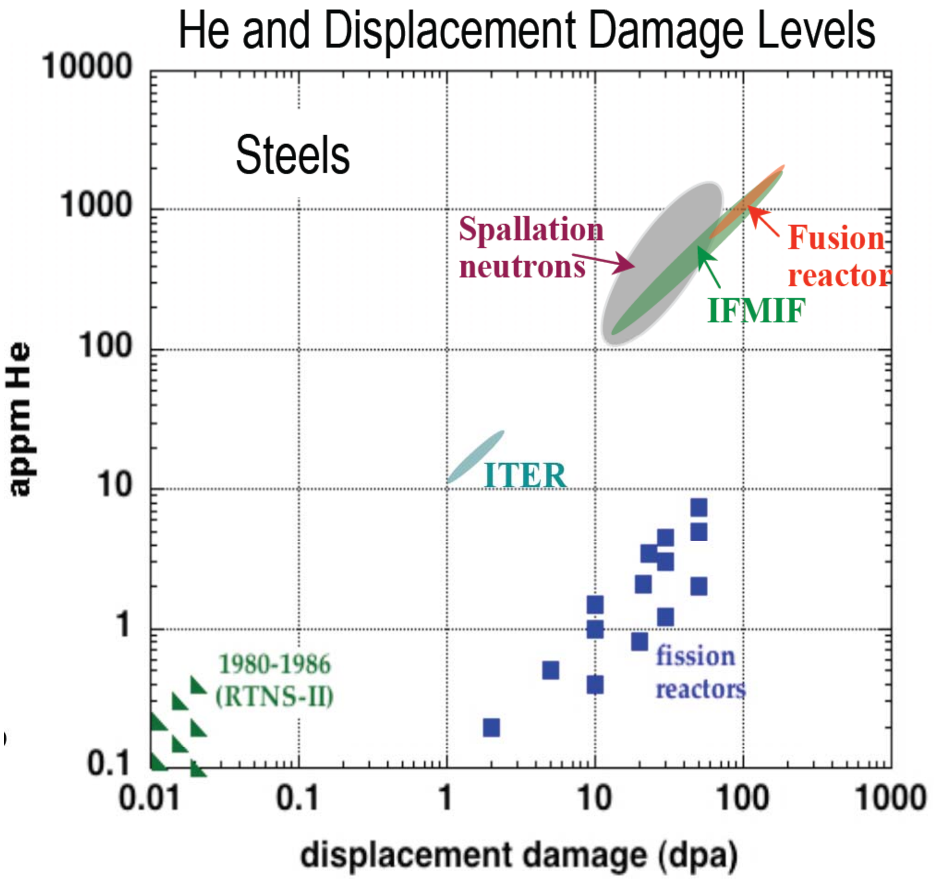


Source: R. Kurtz, M. Mauel, M.Nastasi, R. Odette, S. Sharafat, R. Stoller, S. Zinkle, MFES Research Needs Workshop (Bethesda, 2009)

Facility Performance Gaps

- Finding & validating materials & blanket concepts in a fusion relevant environment is a necessary step for the design, construction, licensing, & safe operation of DEMO, *and* intermediate facilities to be built between the ITER and the DEMO.

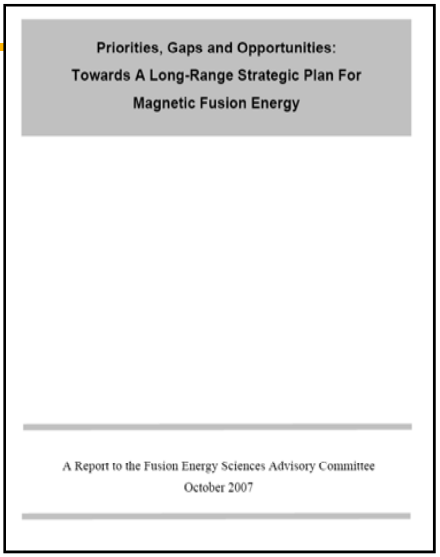
- To test & fully qualify candidate materials for high-fluence service in DEMO, a high-flux source of high energy neutrons needs to be built and operated that simulates service up to the full lifetime anticipated for DEMO and it's prerequisite facilities (*e.g.*, CTF).



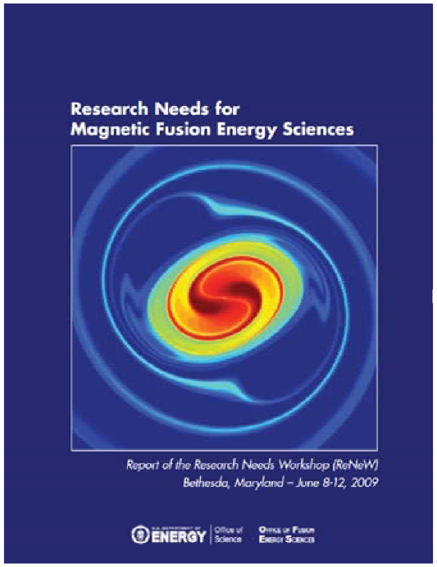
Sources: IFMIF Comprehensive Design Report (IEA, Jan 2004).
R. Kurtz et al., ReNeW (Bethesda, 2009).

The need for a neutron irradiation source has been articulated by the U.S. fusion community

- 2007 FESAC Panel recommended 9 initiatives, including:
  - A materials qualification facility that “would involve testing & qualification of low-activation materials by intense neutron bombardment. The facility generally associated with this mission is the IFMIF. The potential for alternative irradiation facilities to reduce or possibly eliminate the need for the US to participate as a full partner in IFMIF needs to be assessed.”
- 2009 ReNeW recommendations:
  - "An essential requirement to fulfill the mission of (the Materials) Thrust is the establishment of a fusion-relevant neutron source to perform accelerated characterization of the effects of radiation damage to materials."
    - Specific example options cited: (1) IFMF; (2) Materials Test Station (LANSCE); (3) Dynamic Trap Neutron Source.
  - Carefully evaluate options & select the most technically attractive and cost effective approach or combination of approaches.
  - Balance need to obtain relevant bulk material property information with cost, schedule & potential for international participation to leverage investments by the US.
  - Later possibility might be to include large-scale nuclear facility such as the proposed FNSF. However, it must be emphasized that bulk material property data from a fusion relevant n source would inform the design, construction and licensing of such facilities.


Priorities, Gaps and Opportunities:
Towards A Long-Range Strategic Plan For
Magnetic Fusion Energy

A Report to the Fusion Energy Sciences Advisory Committee
October 2007


Research Needs for
Magnetic Fusion Energy Sciences

Report of the Research Needs Workshop (ReNeW)
Bethesda, Maryland – June 8-12, 2009

Current High-Power Accelerators with Spallation Neutron Production Capability

SNS (Oak Ridge)

LANSCE (Los Alamos)

SINQ(Paul Scherrer Inst.)

J-PARC (JAEA & KEK)

ISIS (Rutherford Appleton Lab)

Using a spallation source for fusion materials testing is not a new idea

- Kley, Perlado, et al. (1984-89): EURAC proposal (600 MeV / 6 mA)
- Doran and Leiss (1989): IEA Evaluation Panel Report concluded that d-Li, spallation, and beam-plasma concepts all have the potential to meet flux, fluence, and test volume requirements
- Kondo, et al. (1992): concern over the neutron spectrum in spallation sources extending to several hundred MeV where “neutron data are poorly known, computational tools are inadequate, and radiation effects are poorly understood”
- IEA Evaluation Panel (Kondo 1992) concluded that “A spallation source is not generally favored by the materials community. It is a viable candidate only if it can be attained at much less expense than the alternatives.”

Journal of Fusion Energy, Vol. 8, Nos. 3/4, 1989

Summary

Neutron Source Evaluation Process and Evaluation Panel Report

D. G. Doran[1] and J. E. Leiss[2]

WORKSHOP OBJECTIVES AND ORGANIZATION

This International Energy Agency (IEA) workshop had two primary objectives: (1) to provide an international forum at which the scientific community could present concepts for a potential International Fusion Materials Irradiation Facility (IFMIF), and (2) to conduct an evaluation of such concepts by an international panel of experts in terms of the suitability of such concepts for fusion materials re-

ing. A second set, resulting from the preparatory meeting in Rome, was distributed at the meeting. It differs from the first primarily by trying to quantify the need for large test volumes at modest fluxes. Several presentations at the workshop emphasized that the facility should fill the need for testing of nonmetallics and plasma-facing components, and studies of interactive failure, as well as the more commonly considered alloy development.

The current activity in Japan, centered at the Japan Atomic Energy Research Institute, to secure

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Journal of Nuclear Materials 191–194 (1992) 100–107
North-Holland

journal of nuclear materials

The status and prospects of high-energy neutron test facilities for fusion materials development

T. Kondo [a], D.G. Doran [b], K. Ehrlich [c] and F.W. Wiffen [d]

[a] *Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki-ken, Japan*
[b] *Washington State University Tri-Cities, 100 Sprout Rd., Richland, WA 99352, USA*
[c] *Kernforschungszentrum Karlsruhe GmbH, Postfach 3640, D-7500 Karlsruhe, Germany*
[d] *US Department of Energy, Washington, DC 20585, USA*

The status of progress in the development of facility concepts and the relevant technology is summarized, referring to the

were referred to the anticipated operating conditions for a DEMO reactor. The derived criteria are

(1) neutron flux corresponding to a wall loading of 2 MW/m^2 (0.9 × 10^{18} n/m^{2}s uncollided flux or equivalent to 6 × 10^{-7} dpa/s collided flux for iron),

(2) neutron spectrum as close as possible to that in the first wall in terms of the displacement rate, the energy of primary knockon atoms (PKA) and the transmutation rates,

(3) fluence producing up to 100 dpa in several years,

(4) irradiation volume of 10 liters in high flux region of 2 MW/m^2 or greater, and

(5) other conditions: low flux gradients, accessibility and quasi-continuous time structure of neutron flux.

These criteria made it possible to produce an initial evaluation of several candidate neutron sources [5]. The workshop results stimulated various activities and have been followed by several international events [6–8]. At the latest meeting in Tokyo, the principal topic was the status of d–Li source technology, since this system is currently the most mature. In domestic activities an intermediate size d–Li type irradiation facility, the energy selective neutron irradiation test facility (ESNIT) [9,10], is being designed in Japan. In the US, detailed concepts based on the earlier FMIT program and subsequent advances in accelerator technology have been proposed for energy-selective and modular facilities affording flux-volumes beyond FMIT, and a deuteron accelerator under construction in the United States for near-term non-fusion use has been considered for modification to fusion applications. In Germany a new accelerator-based concept has

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Journal of Fusion Energy, Vol. 8, Nos. 3/4, 1989

Option for Spallation Neutron Sources

J. M. Perlado,[1] M. Piera,[1] and J. Sanz[1]

Spallation reactions are a very important option for efficient neutron sources appropriate for fusion materials testing. An "option of this option" is the EURAC concept, which makes use of short-term accelerator technology in the cheapest way and is proved to provide the needed neutron flux to verify fast experiments on fusion materials performance. Its flexible conception allows an optimum combination of very high fluxes of about 10^{16} n/cm^2/s, with decreasing fluxes along the testing zones in enough volume to perform the correct irradiations. With this assumption, the rate effect can be perfectly analyzed together with the end-of-life conditions assumed in the structural material of the future fusion environments. The possible negative effects of the high-energy neutrons in the spallation spectrum have been taken into account, concluding their non-significance in the desired damage parameters. The EURAC concept can also be considered in light of other purposes like incineration processes, μ production, and, with the appropriate booster, high-flux cold neutron source.

KEY WORDS: spallation; liquid target; proton accelerator; neutron source; high energy; fusion technology; material damage; EOL experiments; atomic displacement; transmutant production; cold neutron.

1. INTRODUCTION

It is a general understanding in the fusion materials research community that the end-of-life of the first wall or blanket materials will be determined by competing complex phenomena.

Due to the non-linear interaction among the different mechanisms involved during the irradiation time to end-of-life conditions, and in the absence of an appropriate synergetic theory on how the damage is accumulated in the material, one cannot extrapolate from low-dose irradiation to end-of-life conditions. Neutron radiation damage can be performed to some extent with charged-particle interaction, D-T sources, or high-flux fission reactors. None of these possibilities have been found to be good for the technological and engineering materials database, recognizing the availability of these sources to obtain results on the basic scientific understanding of some fundamental mechanisms.

According to the present results on the accumulated damage and fluences in the materials at end-of-life, the structural materials of the first wall in conceptual magnetic fusion reactors will handle 40 MW y/m^2 equivalent to 400 dpa. Mattas *et al.*[1] predicted that the lifetime of SS 316 in Starfire (FSW; 1 mm (Be)-1.5 mm SS, 3.5 MW*/m^2, and Tmax = 415°C) will be about 20 dpa or 0.6 years. More recent evaluations[2] on other conceptual reactors and more sophisticated calculational methodology predict damage as high as 1000 dpa for ending life conditions. In the most optimistic case, the fluences will be between 10^{22}–10^{23} n/cm^2 accumulated over a period of 30 years, with fluxes of about 10^{14} n/cm^2/s. To obtain these high fluences in an experi-

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[1] Instituto de Fusión Nuclear, Universidad Politécnica de Madrid, José Gutiérrez Abascal, 2, Madrid 28006.

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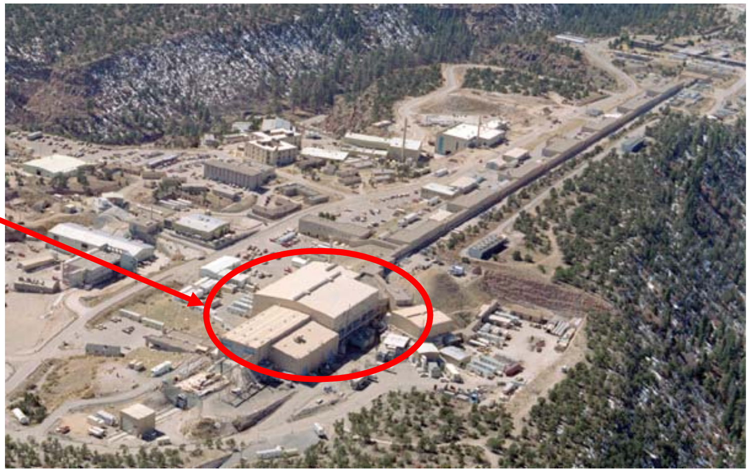
So what’s different today?

- Nuclear data and simulation codes have made significant improvements
  - Nuclear data evaluations now extend to 150 MeV and include both He production and damage energy cross sections
  - Significant improvements in intranuclear cascade, high-energy fission, and evaporation models have been made, e.g.
    - New INCL / ABLA model
    - Improvements in evaporation models that now show better agreement with experimental data on He production
    - New experimental data against which to benchmark the codes

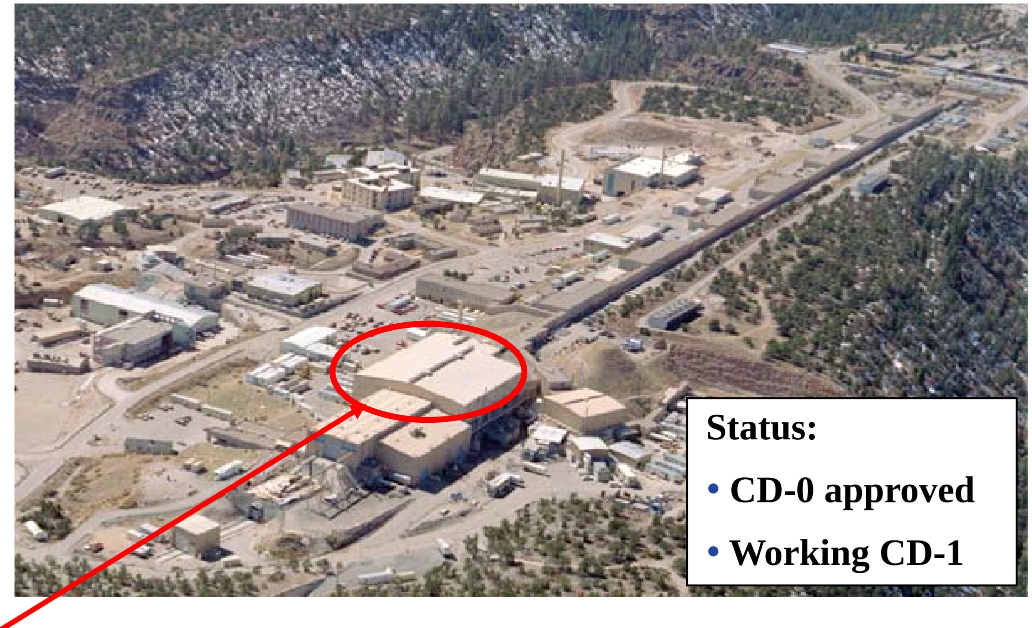
- The Materials Test Station:
  A cost effective spallation source building on existing infrastructure at LANSCE
  - Existing 1 MW proton linac with shared DOE sponsorship
  - Existing experimental hall with all needed utilities
  - Target designed specifically for high neutron flux irradiation



spallation source for high-flux neutron irradiation studies

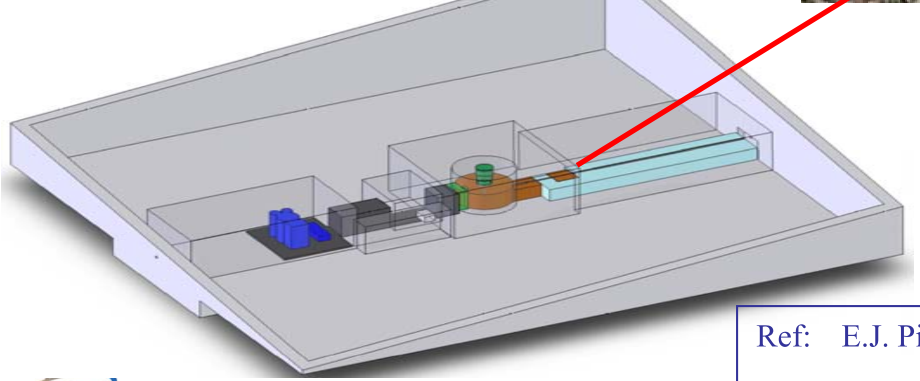
The quickest path to a fast-spectrum fission & fusion irradiation capability.

- Up to 2e15 n/cm^2/s (w/ beam upgrades), appropriate to prove transuranic fuel (e.g., Np, Pu, Am, Cm) performance
- Spectrum relevant for fusion materials testing
- Controlled prototypic temperature, coolant environment
- Prompt data retrieval for experimenters



Status:

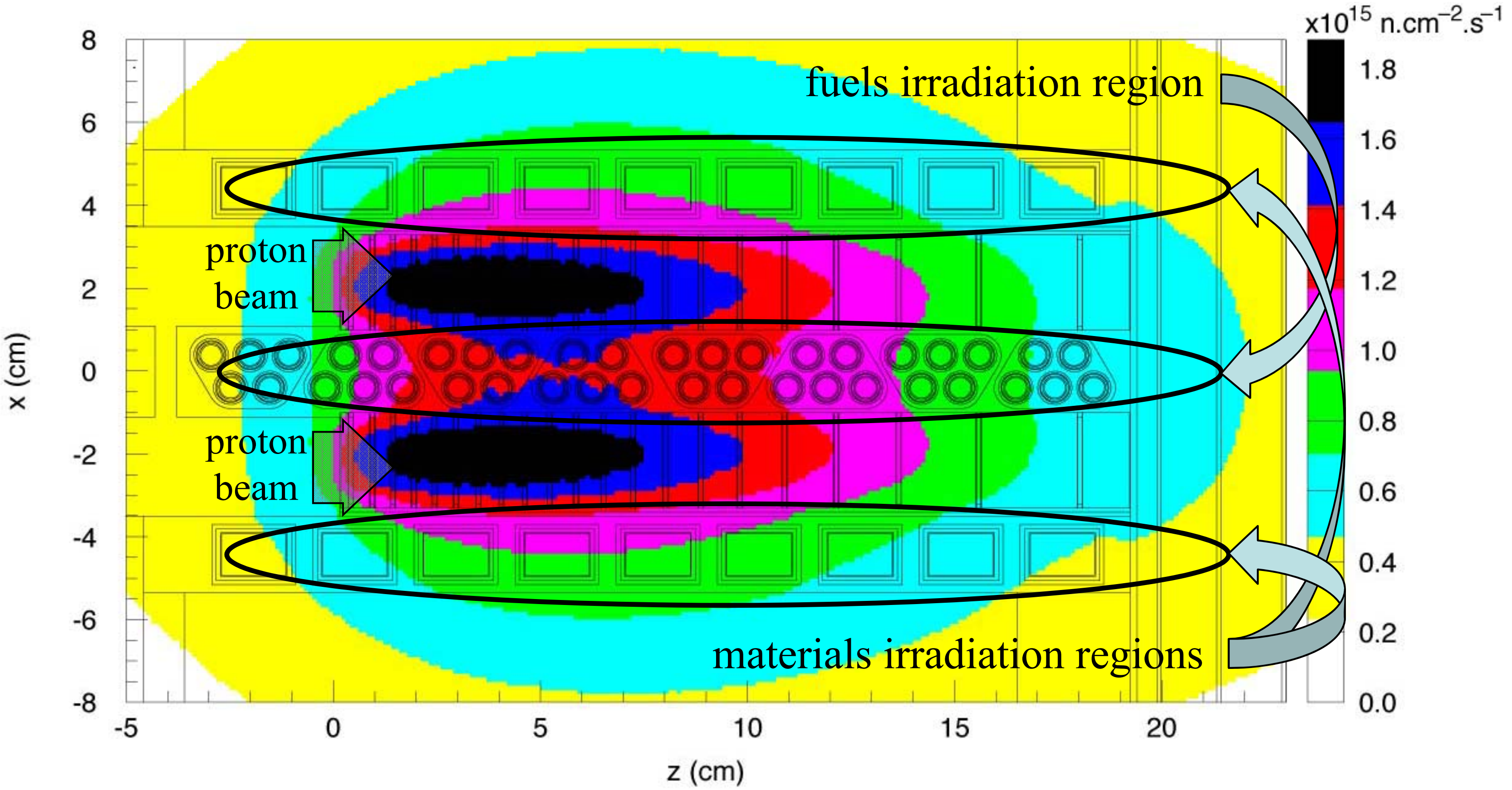
- **CD-0 approved**
- **Working CD-1**



MTS is being built in an existing 3,000-m^2 experimental hall located at the end of the Los Alamos LANSCE linac ,which has successfully delivered 800-kW, 800-MeV beam to this area for a quarter century.

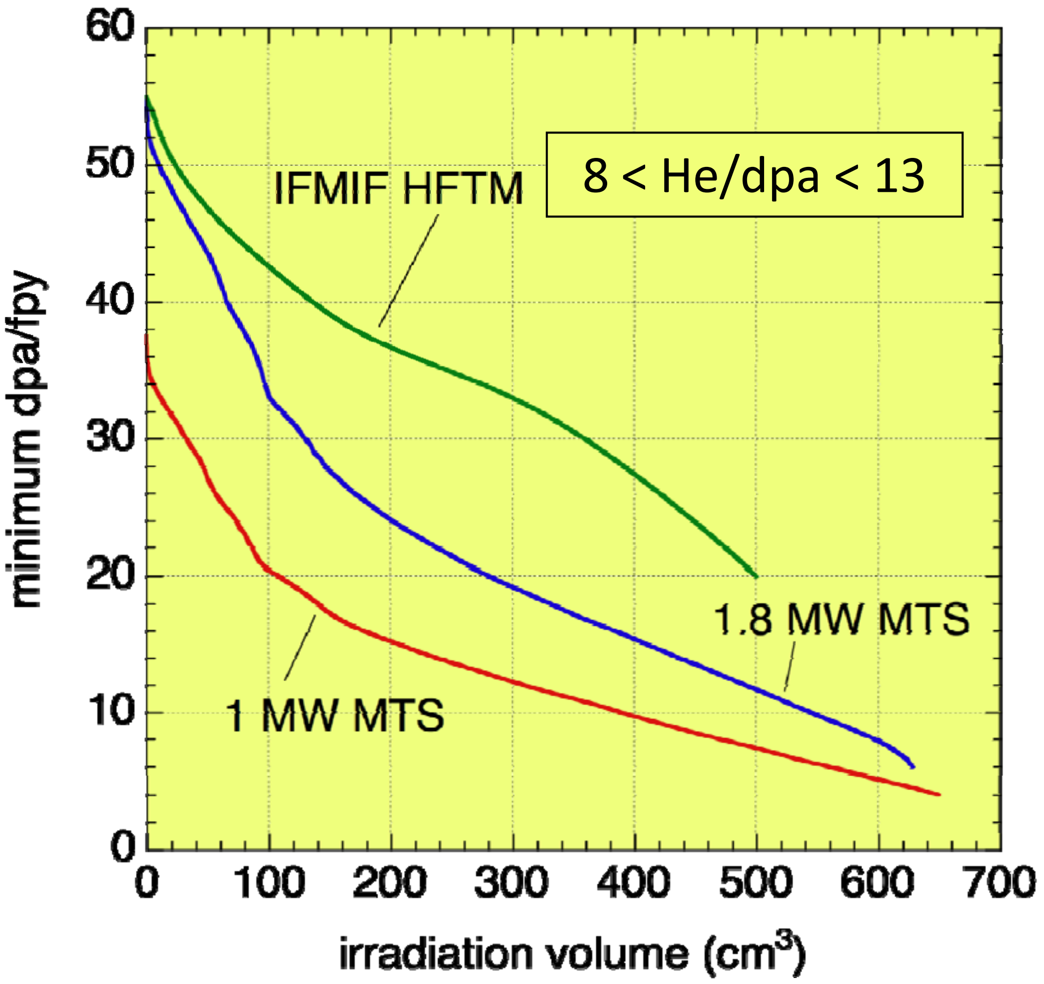
Ref: E.J. Pitcher, in Utilization & Reliability of High Power Proton Accelerators (OECD Publishing, 2008) pp. 427-433.

MTS produces an intense neutron flux for fast reactor fuels and materials irradiations



While designed for fission irradiations, the MTS environment is well suited for fusion materials testing, short-lived isotope production, transmutation studies, and cross section measurements.

MTS irradiation volume is sufficient for conducting a vigorous fusion materials R&D program



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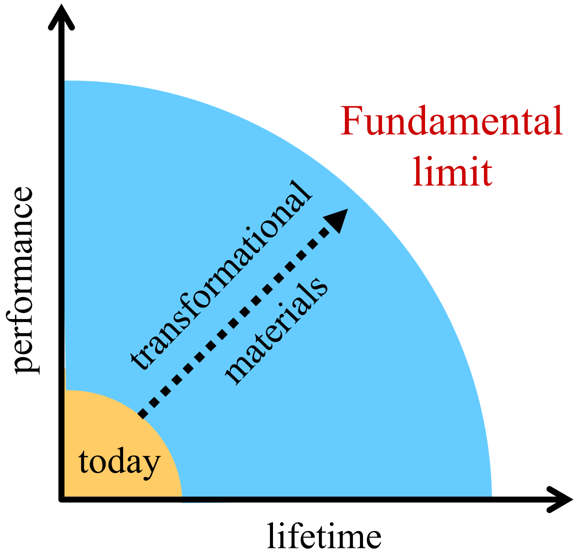
Introduction to the MaRIE Facility Concept: A Transition from “observation & validation” to “prediction & control”



Achieve Transformational Materials Performance

- Solutions require unprecedented control of defects & interfaces

Through Predictive Multi-scale Understanding

- Perform experiments with unprecedented spectral, temporal, and spatial resolution in previously un-accessed extremes

with an emphasis on Radiation-Matter Interactions

- Nuclear is special for LANL and for the world
  - LANSCE is key to our uniqueness in materials-centric national security science

MaRIE will be the first capability with unique co-located tools necessary to realize transformational advances in materials performance in extremes

MaRIE: A comprehensive set of co-located tools to realize transformational advances in materials performance in extremes

First x-ray scattering capability at high energy and high repetition frequency with simultaneous charged particle dynamic imaging

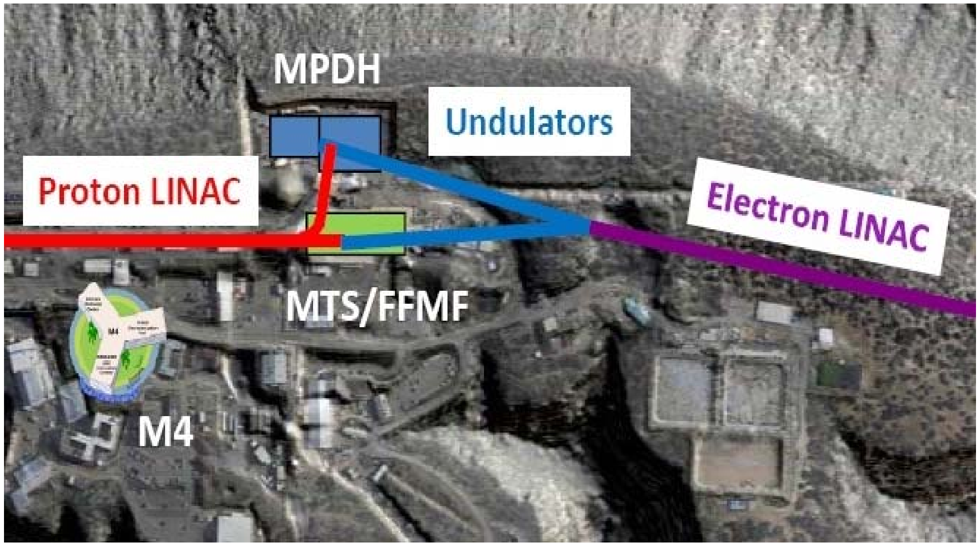
- Multi-Probe Diagnostic Hall (MPDH)

Unique in-situ diagnostics and irradiation environments beyond best planned facilities

- Fission - Fusion Material Facility

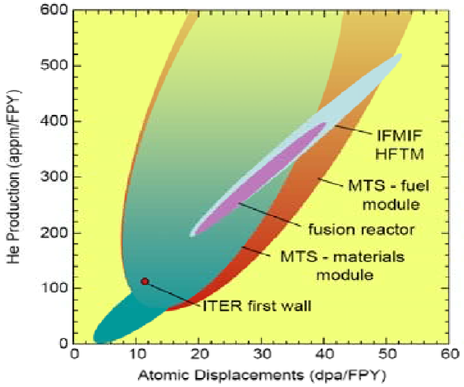
Comprehensive, integrated resource for materials synthesis and control, with national security infrastructure

- Making, Measuring & Modeling Materials Facility (M4)



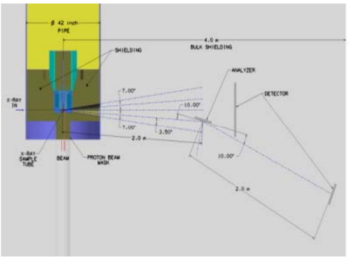
Conclusion: MaRIE can provide solutions to highest priority materials challenges for fusion energy

“Overcoming materials & structures challenges for first-wall, blanket & diverter systems is as difficult & important for fusion energy generation as achieving a burning plasma” - Kurtz & Odette (2009)



MaRIE provides an alternative to IFMIF with a US neutron irradiation facility, years earlier, with lower risk, at a fraction of the cost.

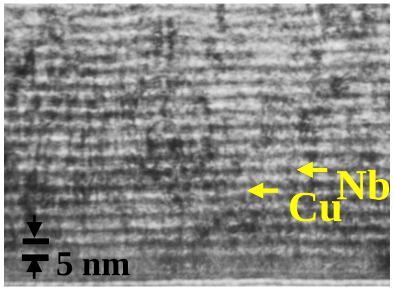
MaRIE enables transition from “observation” to “control,” transforming the science of microstructure, interfaces, & defects, leading to a new class of materials



MaRIE surpasses conventional “cook & look” approaches by providing science-based certification, e.g., in-situ characterization in extreme radiation environments

Users will design, synthesize, & qualify new radiation-resistant structural materials that avoid today’s show-stoppers:

- embrittlement
- phase instabilities
- segregation & precipitation
- irradiation creep & volumetric swelling



Interface/structure manipulation produces enhanced strength & radiation resistance; e.g., nanolayer architectures actively eliminate point defects, producing materials strength that exceeds theoretical “limits” with extreme radiation resistance.

MaRIE provides tools for transformational materials performance in extremes