Fusion Power Program at LANL

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ICF program manager

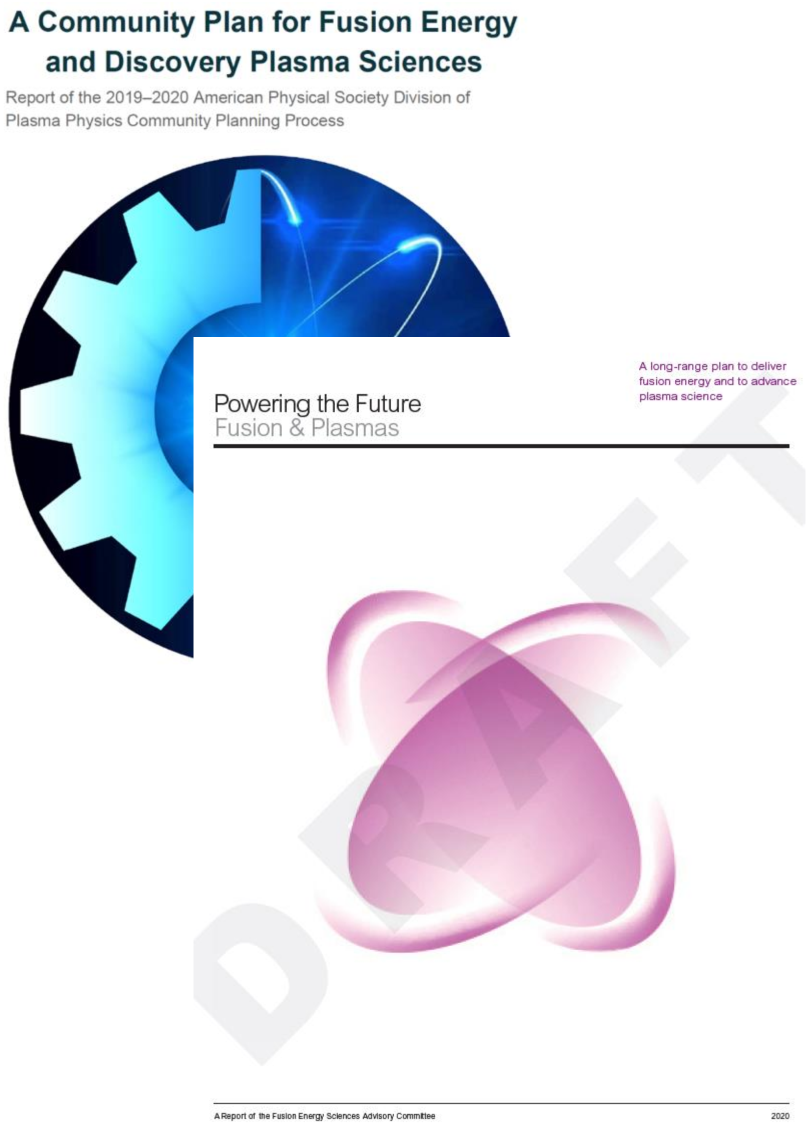
Dec 17th, 2020

Thanks to: E. Pitcher, G. Wurden, X. Tang, L. Chacon, O. El Atwani, & J. Dumont

LANL is poised with its Capabilities and opportunities to support the key recommendation from the 2020 FESAC report

FESAC report extracts:

- **Pivot** the research and development focus **toward fusion materials and technology**
- **Immediately establish the mission need for an FPNS** facility to support development of new materials suitable for use in the fusion nuclear environment, and pursue design and construction as soon as possible
- **Significantly expand** blanket and **tritium research** and development
- **Close fusion pilot plant design gaps** by utilizing research operation of DIII-D and NSTX-U, and **collaborating with other world-leading facilities**
- **Expand existing and establish new public-private partnership programs** to leverage capabilities, reduce cost, and accelerate the commercialization of fusion power and plasma technologies
- **development of innovative ideas** that could lead to more commercially attractive fusion systems and address critical gaps with entirely new concepts



Pivot towards fusion materials:

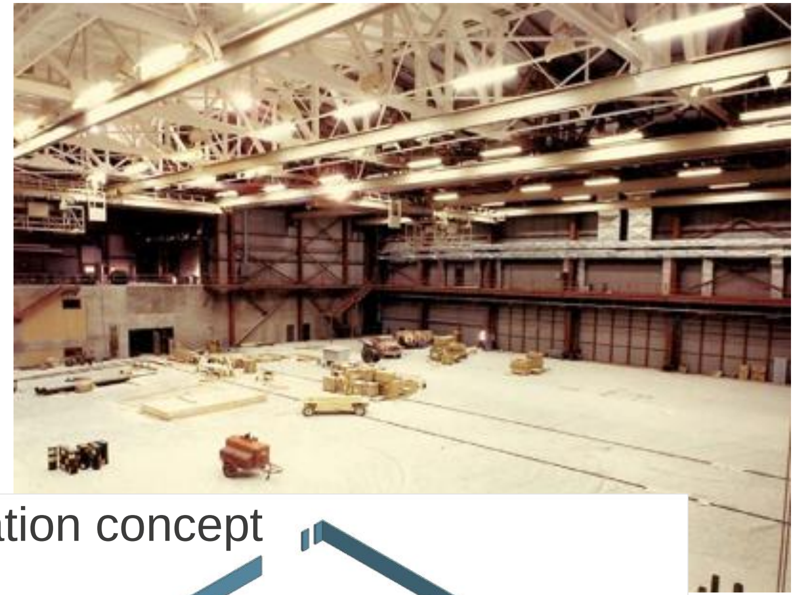
- **Materials:** **a pivot toward research and development of fusion materials** and other needed technology. Emphasis is needed on fusion materials science, **plasma facing components**, tritium-breeding blanket technology and the tritium fuel cycle. A number of key experimental facilities are recommended. **The Fusion Prototypic Neutron Source (FPNS)** will provide unique material irradiation capabilities

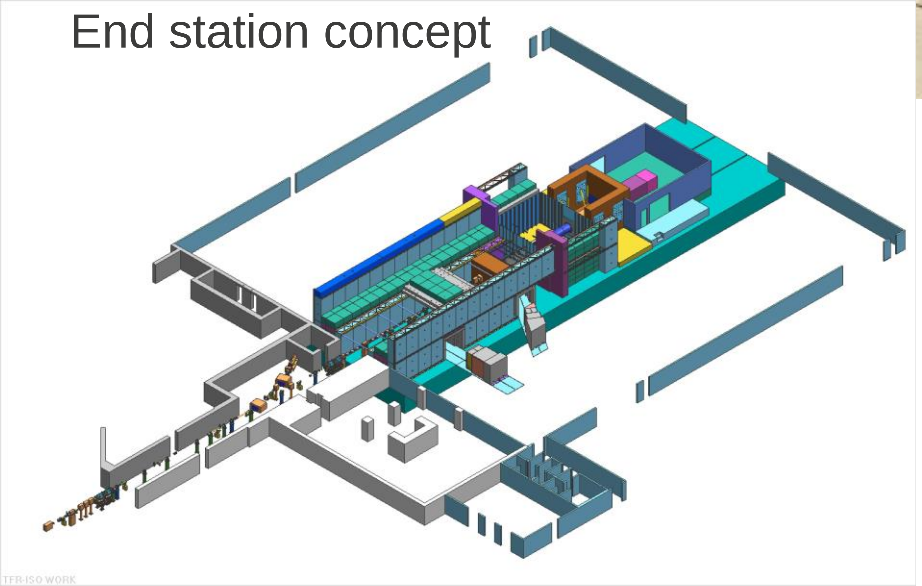
- **Tritium Processing:** Closure of the fusion fuel cycle via successful breeding and **extraction of tritium will be critical** for the sustained operation of an FPP. … understand fundamental tritium transport properties and phenomena in solid and liquid breeder materials, and **associated modeling and model validation efforts. Tritium technologies related to fueling and exhaust from the plasma, and subsequent processing,**

LANSCE can deliver 1 MW of 800-MeV protons to drive a Fusion Prototypic Neutron Source (FPNS)

- LANSCE accelerator delivered 0.8-MW proton beam for a quarter century (1972 – 1999)
- Large experimental hall is available to accommodate FPNS
- Large quantity of steel and cast iron available on site for beamline and target station shielding
- Two hot cells adjacent to the experimental hall can be dedicated to post-irradiation examination of irradiated samples
- Substantial expertise exists at LANSCE to support the design and construction, safety basis and permitting, and target operations
- Some questions that need to be addressed:
  - *Reliability and run time for FPNS*
  - *Beam time/ space sharing with other programs*
  - *Effects of spallation tail for surrogacy*

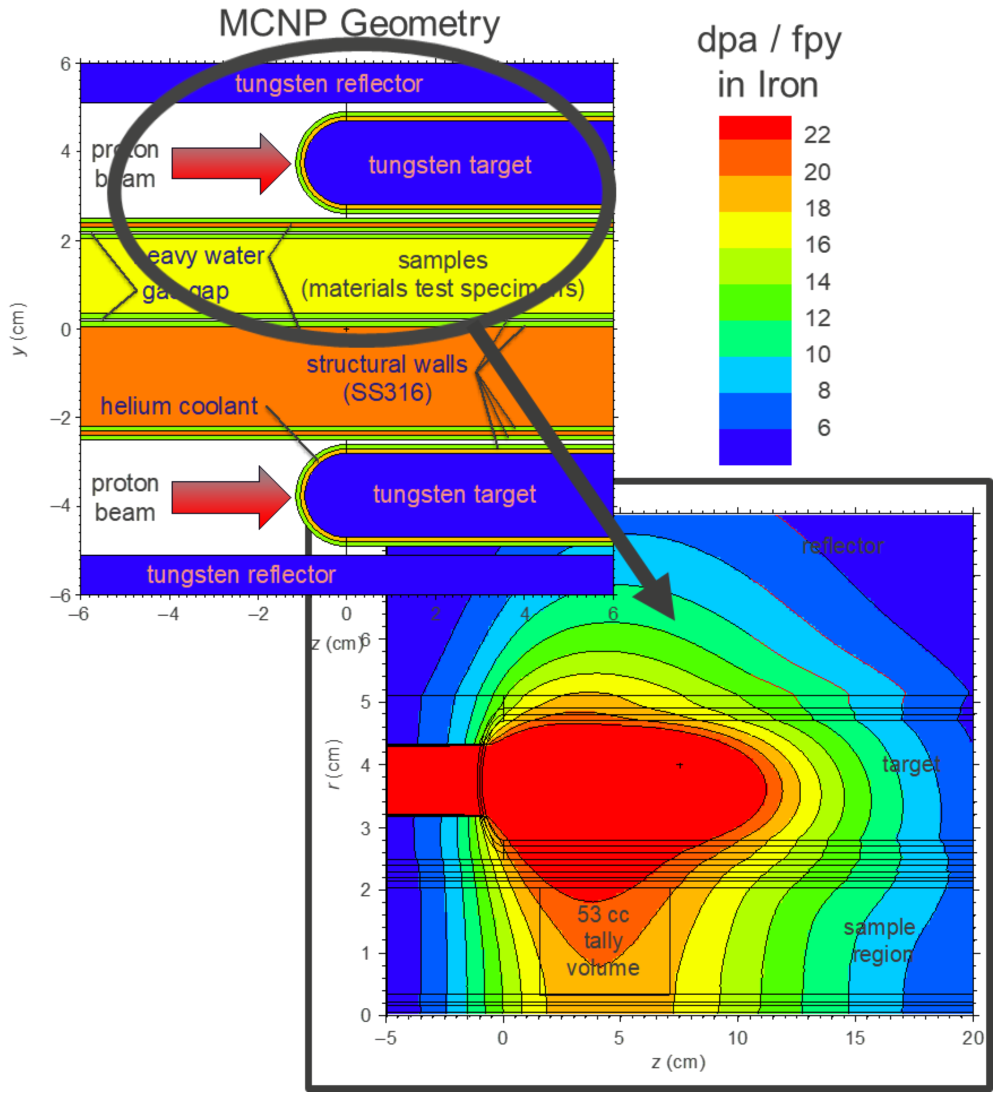
Team: E. Pitcher, Phil Ferguson (ORNL)





End station concept

Proposed design satisfies the desired FPNS requirements



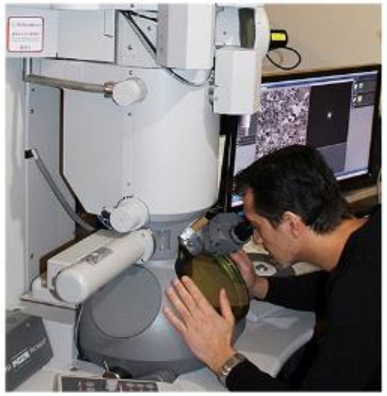
8 dpa/CY for 3400 hours/CY of full-power beam on target with a 14.6 appm He/dpa in the 53 cm³ sample volume

	FPNS requirement	1-MW FPNS at LANSCE
Damage rate dpa/fpy (Fe)	~8–11	8 average*
Spectrum He/dpa (Fe)	~10	14.6
Sample volume	≥50 cm³	53 cm3
Flux gradient	≤20%/cm in the plane	<10% in all directions

*Assuming 3400 hours of 1-MW beam on target per calendar year (CY).

Collaborations with the ion beam materials laboratory provides additional unique fusion materials testing with fission reactor research synergies

Better Materials

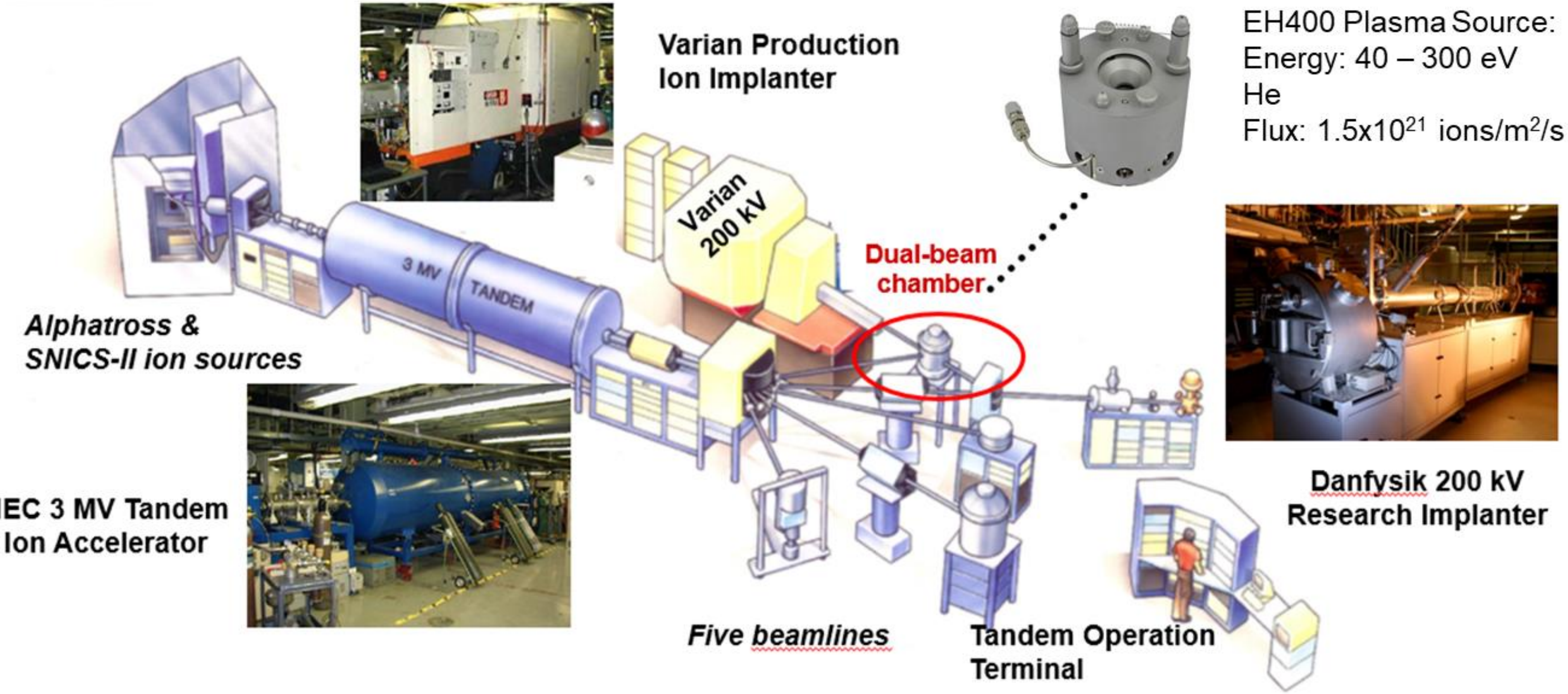


Osman El Atwani, Enrique Martinez (LANL) et al, develop **new tungsten-based alloy** withstands fusion radiation (*Science Advances*, Mar 2019)

Materials-by-design, new fusion nuclear materials.

Ion Beam Materials Laboratory

IBML
Los Alamos



Utilizing LANL capabilities, we are focusing on high energy alloys as a path to fusion materials (O. El Atwani and E. Martinez)

Scientific Achievement

- Discovery of a single phase refractory high entropy alloy (W-Ta-Cr-V) of nanocrystalline grain size is alternative to pure W
- high hardness to high radiation tolerance under heavy ion irradiation at room temperature or very high temperatures.

Significance and Impact

- This alloy showed no loop formation after heavy ion irradiation up to 8 dpa at RT and 1050 K.
- alloys are suitable for bulk production coupled with the exceptional radiation resistance

Research Details

- Nanocrystalline W-Ta-Cr-V was prepared via PVD.
- In-situ TEM/irradiation was performed at RT and 1050 K using 1 MeV Kr^{++} and showed no sign of loop formation.
- The hardness Cr segregation occurred as confirmed via APT. Nanoindentation showed small increase in hardness after thermal annealing and irradiation.
- DFT and Monte Carlo simulations were in remarkable agreement with the experimental result.

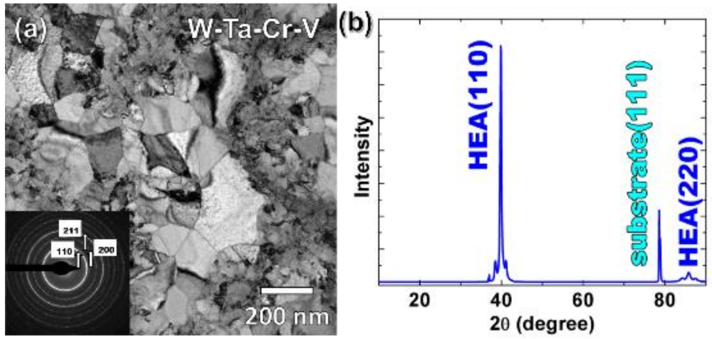


Fig. 1. (a) Bright field TEM micrograph of the HEA. (b) X-ray diffraction results

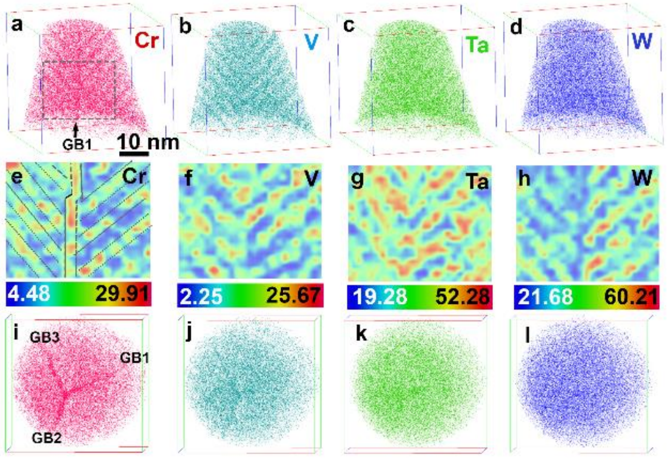


Fig. 3. The 3D distribution of Cr, V, Ta and W in the as-deposited HEA alloy revealed by APT prior to irradiation

O. El-Atwani, *Outstanding radiation resistance of tungsten-based high-entropy alloys*, **Science advances** 5(3) (2019) eaav2002.

O. El Atwani, *Helium Bubble Damage Resistance in W-Ta-V-Cr High Entropy Alloys,* ***Materials Today Energy*** *(2020)* Funded by 20160674PRD3

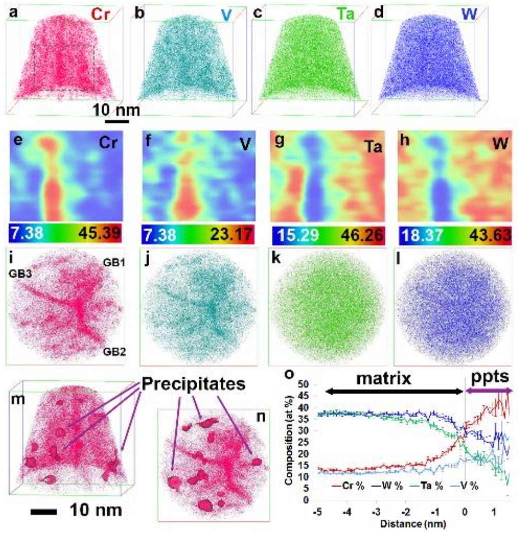
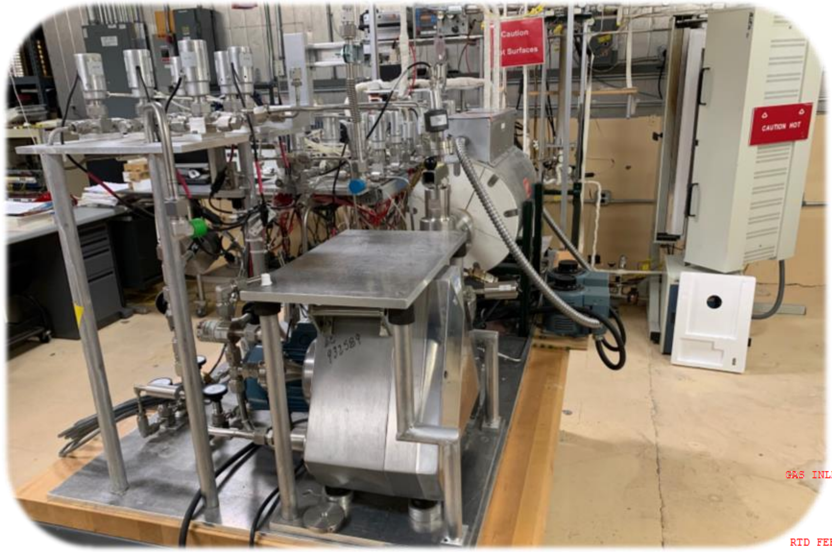


Fig. 4. The 3D distribution of Cr, V, Ta and W in the as-deposited HEA alloy revealed by APT after heavy ion irradiation to 8 dpa.

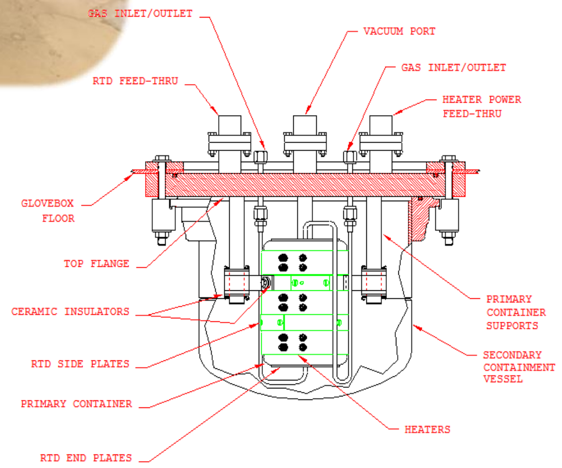
Recent investments upgraded LANL's Hydrogen Processing Laboratory (HPL) to support tritium processing studies for reactors

- **R&D test system for tritium processing/fuel cycle operations**
- **Primary functions are separation and catalysis**
  - Separation of hydrogen streams from other gasses
  - Catalytic removal of hydrogen bound to other species (CH_4, H_2O)
- **Tritium-safe technology**
  - All-metal pumping/seals to prevent permeation
  - Micro-GC for analysis & isotopic resolution
- **High configuration flexibility**
  - Testing of different components alone or in tandem

Hydrogen Processing Laboratory



Team: Victoria Hypes-Mayfield, William Kubic, David Dogruel, Kirk Hollis, Scott Willms, Joseph H. Dumont



<u>**Objectives**</u>:

- Use experimental data to confirm that reported hydriding mechanism is plausible
- Develop a model for design and operations of uranium storage beds

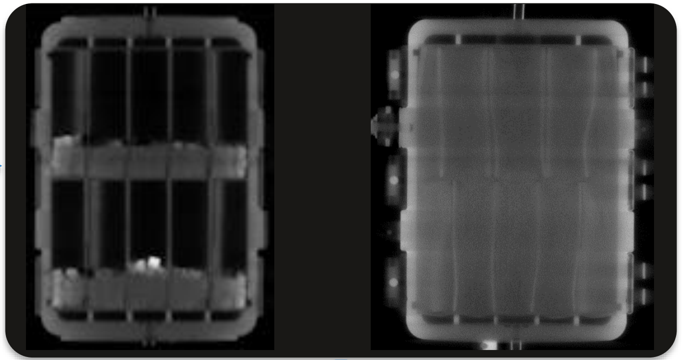
Experimental data using H_2, D_2 with the components of the HPL (pumps, permeator etc.) is used to inform the modelling, T_2-material interaction from micro to macro scale, PMR catalyst performance…

We are using the STACI bed to advance our modeling capabilities to build confidence for ITER and fusion power plant tritium handling

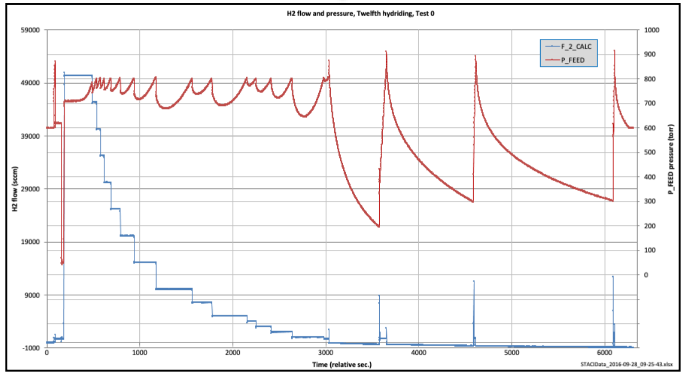
Experimental work
Hydriding/ dehydriding of Uranium

Materials characterization

X-Ray Computed Tomography

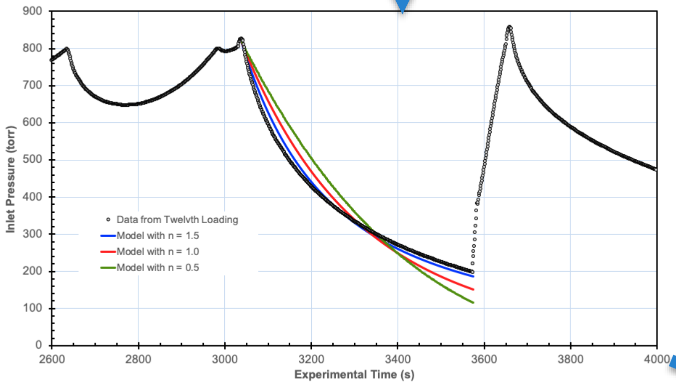


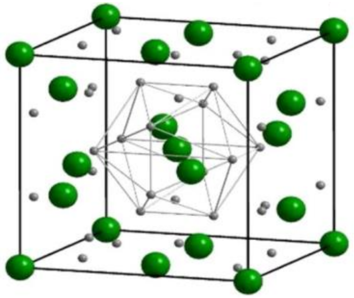
Experimental data

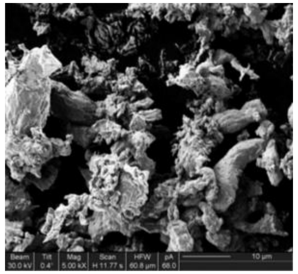


Kinetic model

$$r = \frac{k_o \cdot e^{-E_a/R\cdot T}}{s} \cdot \left(P_{Q_2}^{n} - \frac{1}{K_{eq} \cdot P_{Q_2}^{3/2-n}} \right)$$







Hypes et al., Uranium Bed Design Parameters for Tritium Plants Supporting Fusion Reactors, Fusion Science and Technology (ANS Winter 2020)

Information about material state, surface area, particle size

Continue to advance TRLs and build Public/Private partnerships:

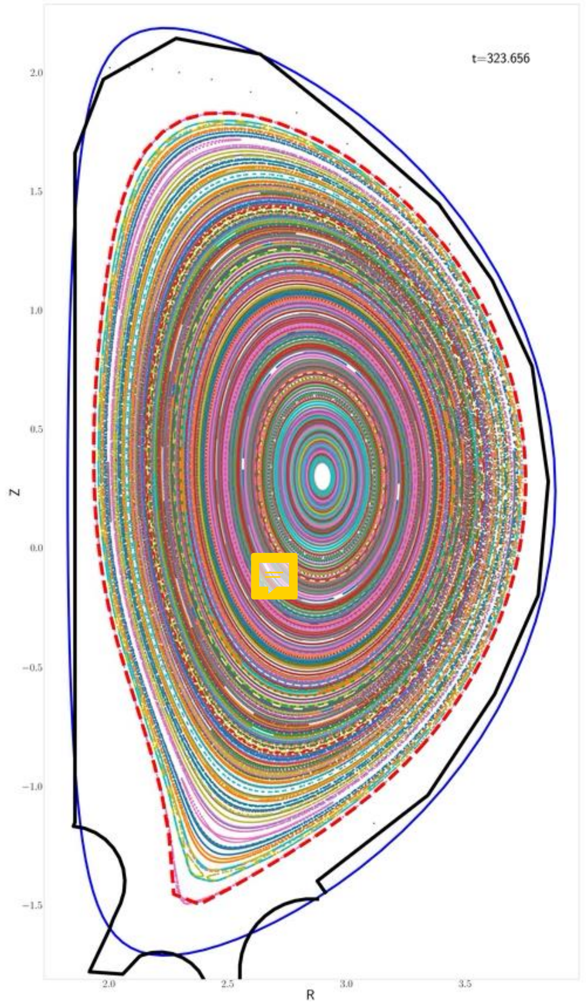
- **Theory/Diagnostics:** This includes the expansion of **theory and modeling efforts that support advancing technology readiness levels** (TRLs), **accelerating development of diagnostics and measurement systems** that will function in fusion nuclear (irradiation-hardened) environments, and rapid maturation of enabling technologies.

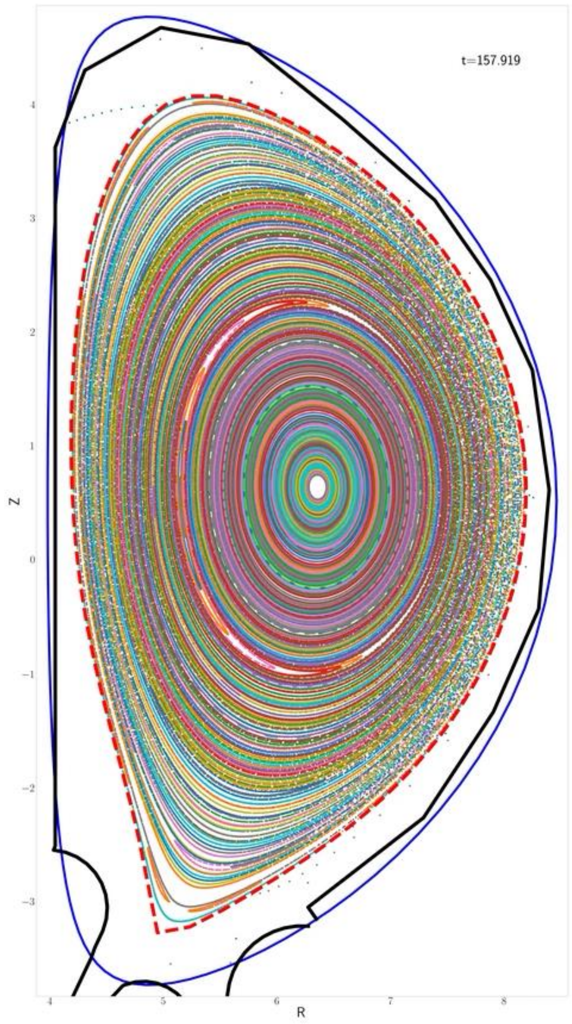
- **Public/Private Partnerships:** **Public-private partnership should be used as a tool to engage and stimulate** industry involvement. DOE Fusion Energy Sciences has already established successful PPP programs, notably the **Innovation Network for Fusion Energy (INFUSE).** These activities should be expanded …

Nonlinear resistive MHD simulations quantify global magnetic field line stochasticization that is responsible for thermal quench.

What sets the thermal quench time scale on ITER

- ***Saturation of 3D MHD instabilities → Global field line stochasticity → decreasing magnetic connection length L_B***
  - ***3D Extended MHD simulations (PIXIE3D) quantify $L_B(t)$ history for different disruption-causing MHD instabilities on ITER***
  - ***Thermal quench time τ_{TQ} can vary greatly depending on L_B (next slide with kinetic calculations)***

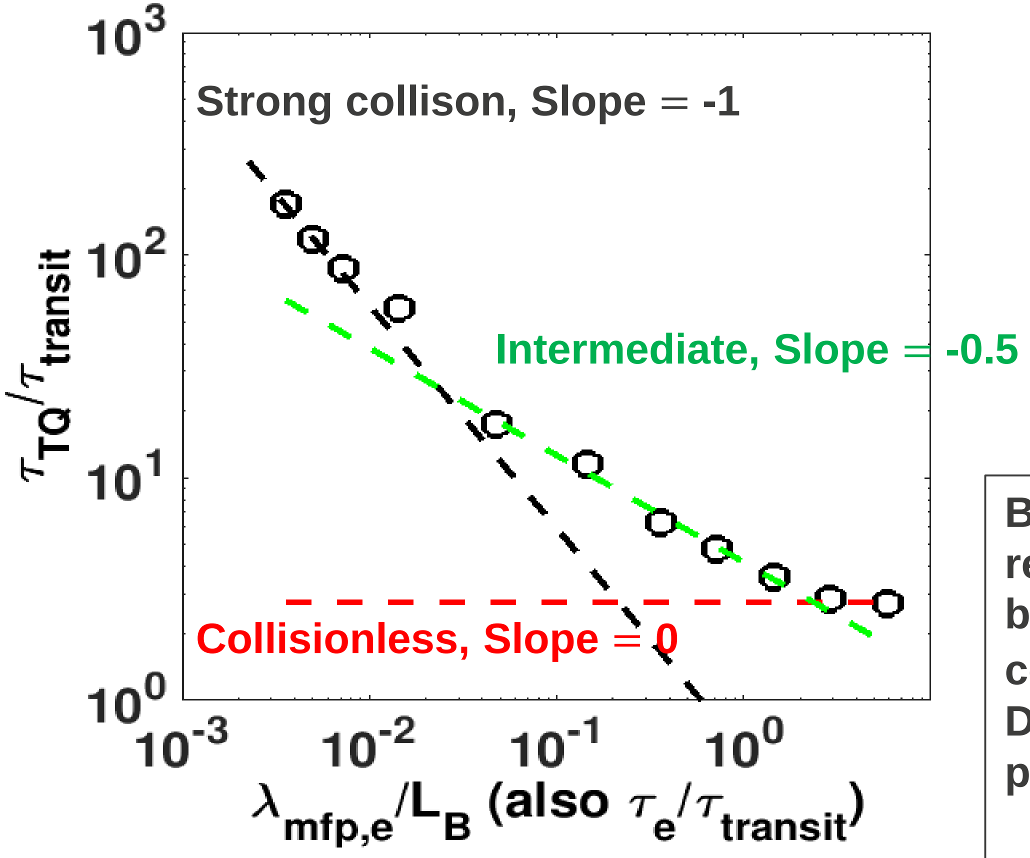




Team: Keramidas, Chacon, Tang

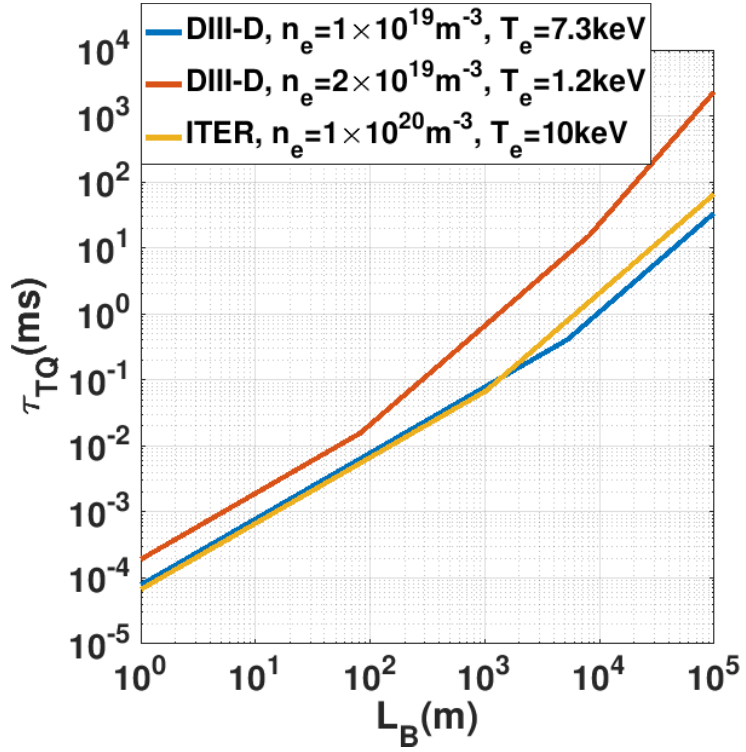
Work supported by OFES fusion theory program and OFES/OASCR Tokamak Disruption Simulation (TDS) SciDAC Project

Fully kinetic VPIC* simulation establishes thermal quench time τ_{TQ} as a function of magnetic connection length L_B in a 3D stochastic magnetic field



In strong collision limit, $\tau_{TQ} \propto \frac{\tau_{transit}^2}{\tau_e}$, agreeing with existing theory; In collisionless limit, τ_{TQ} saturates to a few times of $\tau_{transit}$, $\tau_{TQ} \propto \tau_{transit}$; In the intermediate range, $\tau_{TQ} \propto \frac{\tau_{transit}^{3/2}}{\tau_e^{1/2}}$

Based on these scaling results, we give predictions between τ_{TQ} and magnetic connection length L_B for DIII-D and ITER plasma parameters



Team: Li & Tang

*VPIC capability developed by NNSA ASC program and supported develop by FES

Work supported by OFES fusion theory program and OFES/OASCR Tokamak Disruption Simulation (TDS) SciDAC Project

A 2D-2P runaway-electron simulation capability for realistic magnetic fields and arbitrary plasma temperatures (SCREAM SciDAC)

Scientific Achievement

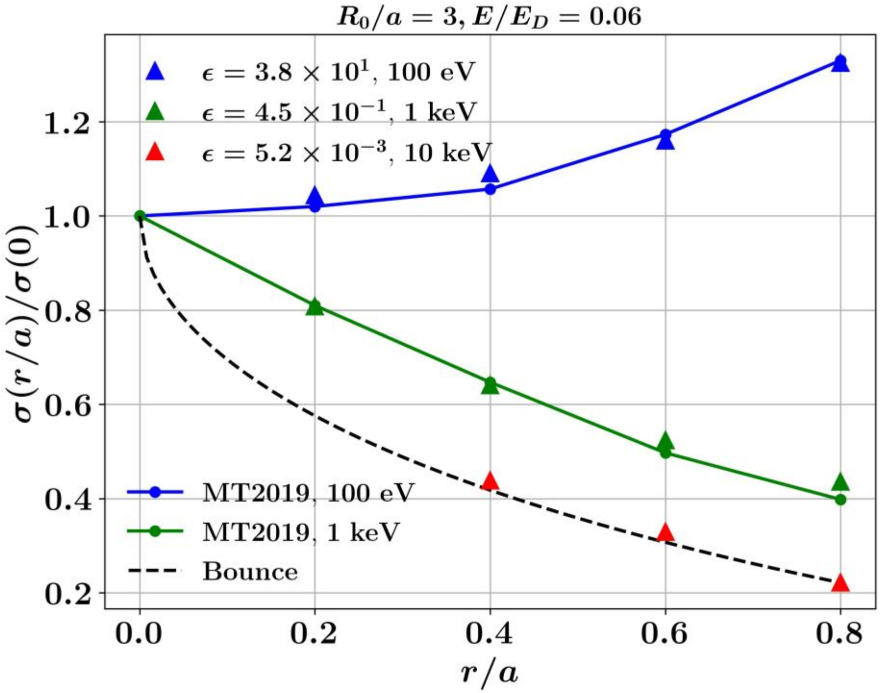
- LANL researchers developed a semi-Lagrangian 2D-2P (two spatial dimensions and two momenta) nonlinear relativistic Vlasov-Fokker-Planck (VFP) simulation tool
- models runaway-electron dynamics in realistic magnetic fields and arbitrary plasma temperatures.

Significance and Impact

- Violent temperature and magnetic-field evolution in a tokamak disruption demands the ability to simulate runaway electrons (RE) in arbitrary magnetic fields and plasma temperatures.
- This research demonstrates an efficient algorithm in toroidal geometry suitable for arbitrary plasma temperatures, which can be readily extended for arbitrary 3D

Research Details

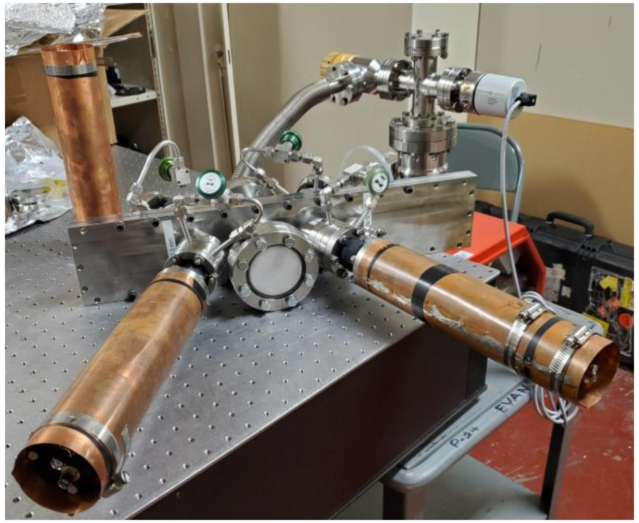
- Fast electron bounce times, infrequent collisions, and relativistic speeds pose a significant challenge for RE modeling in realistic geometry. Researchers at LANL have developed a novel asymptotic-preserving algorithm that is able to accurately capture fast electron motion while following slower collisional time scales.
- Approach employs our recently developed fully nonlinear conservative relativistic Fokker-Planck collision algorithm [1],
- Uses a novel Green's function method to integrate collisional effects along electron orbits that can be readily generalized to arbitrary magnetic fields.



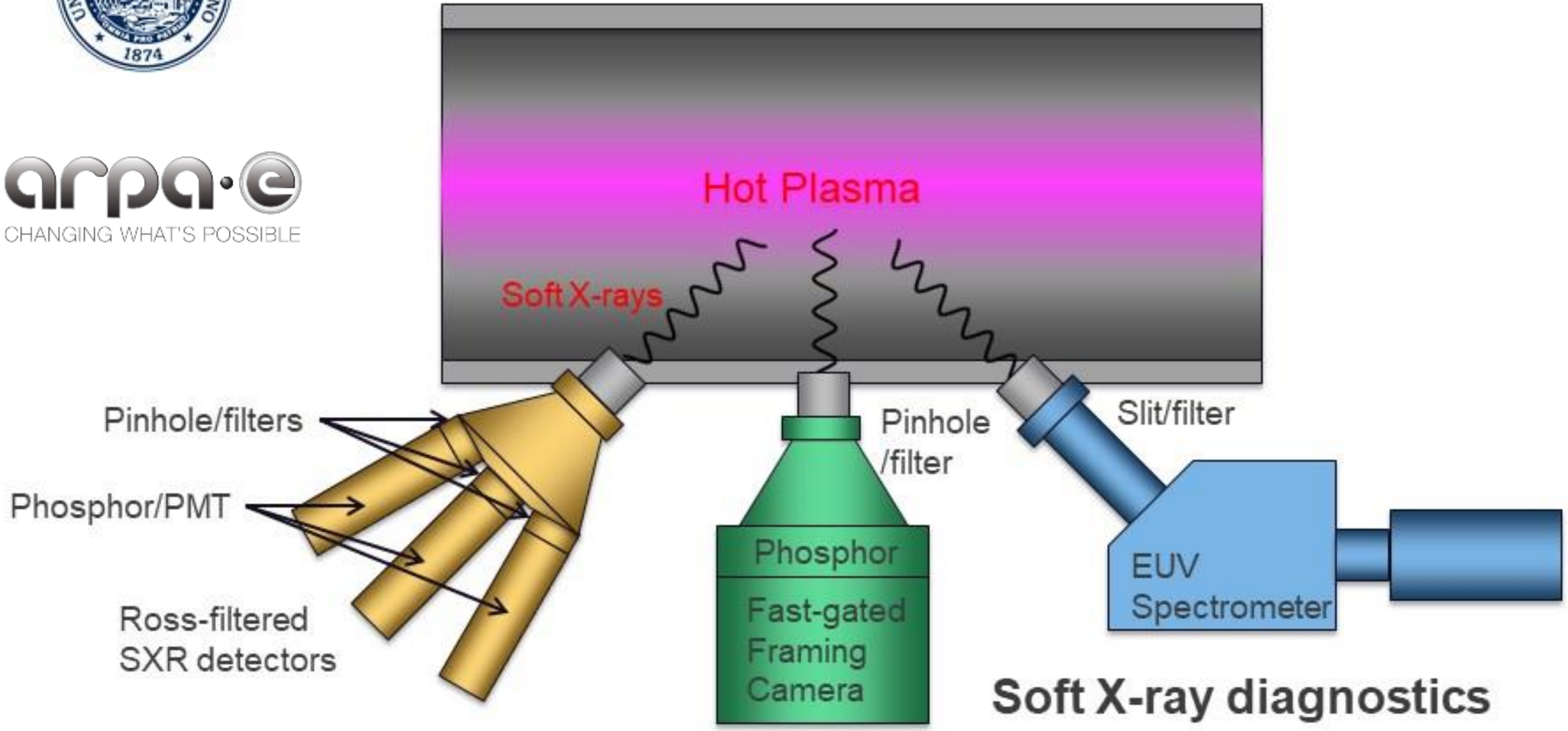
Relative Dreicer RE generation rate vs toroidal radius in a 2D toroidally symmetric magnetic geometry for various plasma temperatures (corresponding to different asymptotic parameters ε). Triangles are the results of our novel algorithm. Dashed line denotes the bounce-averaged solution for hot plasmas. Lines are the solutions found with a particle method in [McDevitt & Tang, EPL, 217 (2019)]. It can be seen that our approach matches results in different regimes perfectly.

1. D. Daniel, W. Taitano, L. Chacón, *Comput. Phys. Comm.*, **254**, 107361 (2020)

Our new BETHE proposal included both optical and particle diagnostics *



LANL and the University of Nevada, Reno will be providing three soft x-ray diagnostics to one or more ARPA-E transformative fusion facilities, starting with FUZE and ZAP at the University of Washington in 2020. They will provide information on electron temperature, hot spots, and impurity radiation.

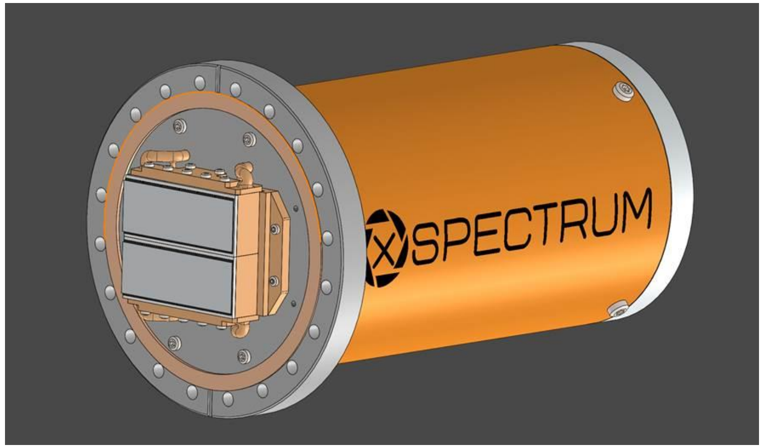


Soft X-ray diagnostics

*Only the optical diagnostics are funded

BETHE Capability Team will be testing a novel high speed solid state camera along with Major tasks

- We will test a new high-speed solid state "adaptive gain integrating pixel detector" (AGPID) x-ray imager from X-Spectrum LLC in Germany, multi-frame soft x-ray imaging of all but the shortest duration plasmas. It is capable of taking 352 frames (128x512 pixels) at a rate of 4.5 million frames/second.
- We will make fiber-optically coupled time-resolved impurity measurements using visible spectra at up to 5 simultaneous spatial locations (Model 218 0.3 meter spectrometer with PiMax gated imager), complemented with several PMT based spectrometers.



Team: Dr. Glen Wurden (LANL PI), Dr. Jeph Wang, Dr. Tom Weber, John Dunn (LANL); Prof. Bruno Bauer (UNR co-PI), Dr. Stephan Fuelling, & Students

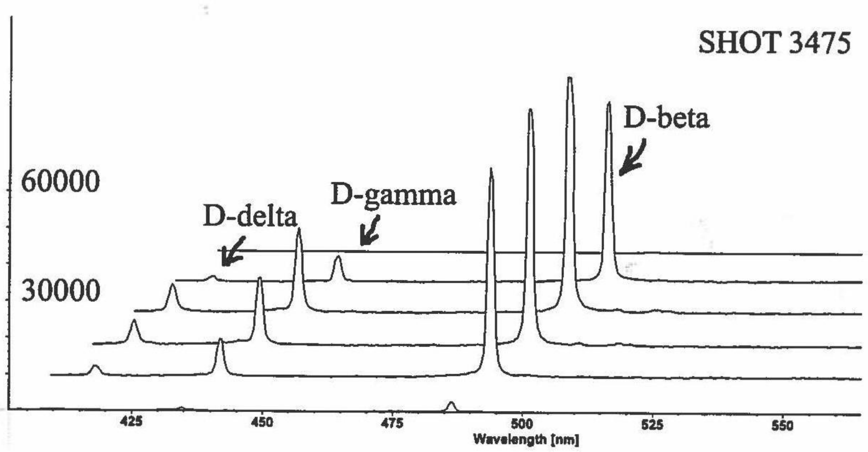


Figure 1: Preionization plasma is clean at early times

CHANGING WHAT'S POSSIBLE

LANL is participating in 2 INFUSE awards

Company: **HelicitySpace**, DUNS: 117087016
Title: Simulation of Plectoneme Formation

LANL providing support through high-performance 3D MHD numerical simulations of the formation process of plectonemes to improve the understanding of the SSX and MOCHI results, and help enable predictive capabilities for the Helicity Drive concept.

Co. PI: Dr. Setthivoine You
Laboratory: LANL
Lab PI: Dr. Hui Li

Company: **Hyperjet Fusion Corp.**, DUNS: 080736078
Title: 3D MHD Simulations Support for PJMIF

LANL is performing 3D MHD simulations of our proposed target formation approach, assessing relevant merging conditions of the compact toroids that can be created in the near term and to assess the magnetic topology and plasma properties that can be obtained

Co. PI: Dr. Franklin Witherspoon
Laboratory: LANL
Lab PI: Dr. Samuel Langendorf

Dr. Glen Wurden is the LANL INFUSE POC

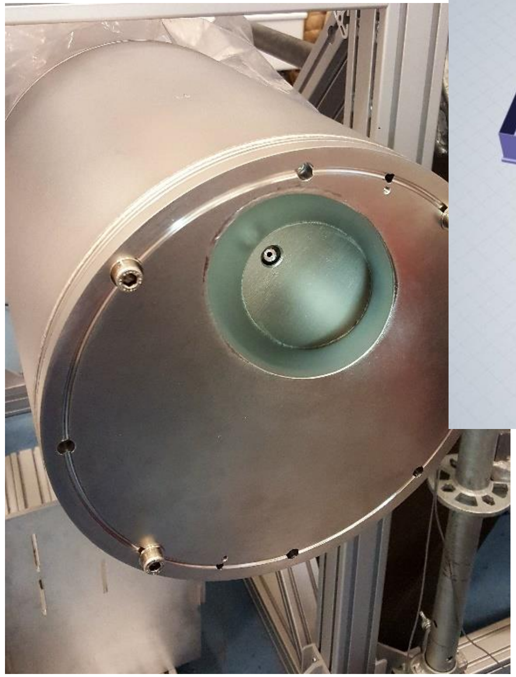
Work supported by OFES INFUSE program

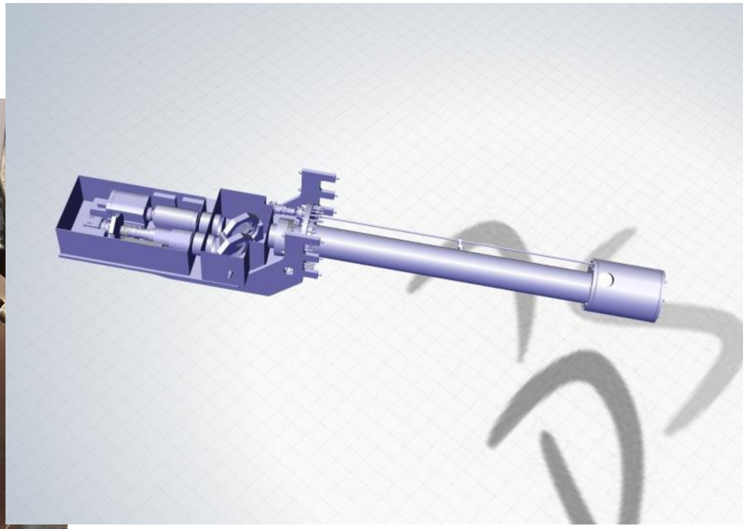
Innovation leading to additional pathways to fusion energy

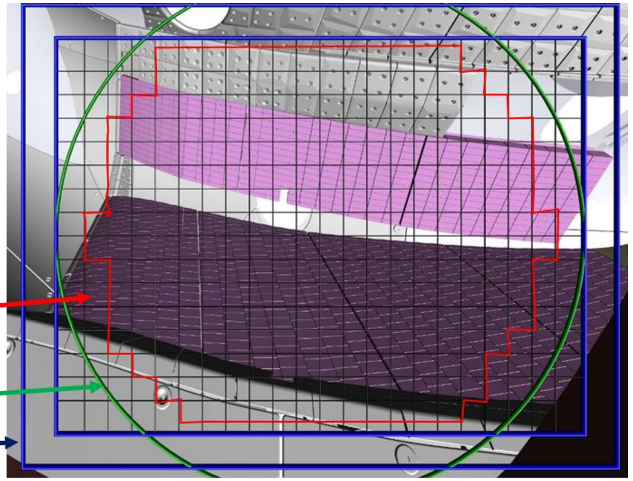
Innovative ideas: The plan embraces the development of innovative ideas that could lead to more commercially attractive fusion systems and address critical gaps with entirely new concepts. The quasi-symmetric stellarator is the leading US approach to develop disruption-free, low-recirculating-power fusion configurations and should be tested experimentally with a new US stellarator facility. Liquid metal plasma facing components have the potential to ameliorate some of the extreme challenges of the plasma-solid interface and may reveal new plasma operating regimes. Inertial fusion energy research can leverage significant investments in the US in order to establish new technologies and approaches toward energy production.

LANL continues to engage in an international collaboration on W7X repurposing hardware used during initial operations for an Infrared Imaging Bolometer

- A prototype IR bolometer diagnostic is a US/Germany/Japan collaboration
- A LANL visible/IR endoscope diagnostic from the last W7X campaign is being fitted with a pinhole camera snout and a thin (2 um thick) platinum foil. The foil becomes the sensing element for plasma radiation originating in the divertor regions.
- Imaging bolometers, first patented by G. Wurden in 1997 (US5861625A) and later by B. Peterson in Japan, have been deployed succesfully at LHD and KSTAR.
- Preparations are delayed due to Covid, but time line matches current W7-X (first plasmas for OP2.1 in 2022).
- Microwave stray radiation loading tests on the foil and baffles were conducted this summer at the IPP Mistral microwave test stand by our German colleagues.
- The diagnostic has to be ready for installation by ~ November 2021







~267 usable bolometer pixels
It will view the divertor in Module 5
IR system FoV
Edge of frame (IRVB FoV)

Wendelstein 7-X

IPP Max-Planck-Institut für Plasmaphysik

Los Alamos NATIONAL LABORATORY EST.1943

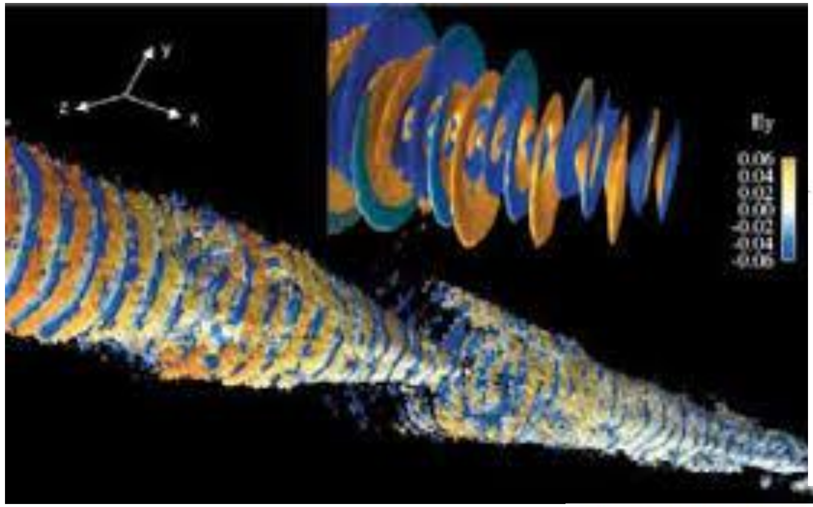
LHD NIFS

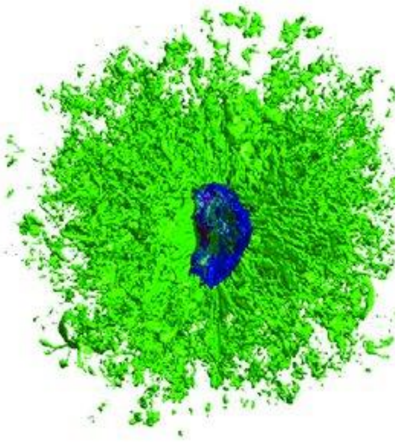
A foil and front pinhole snout will be added to this IR endoscope

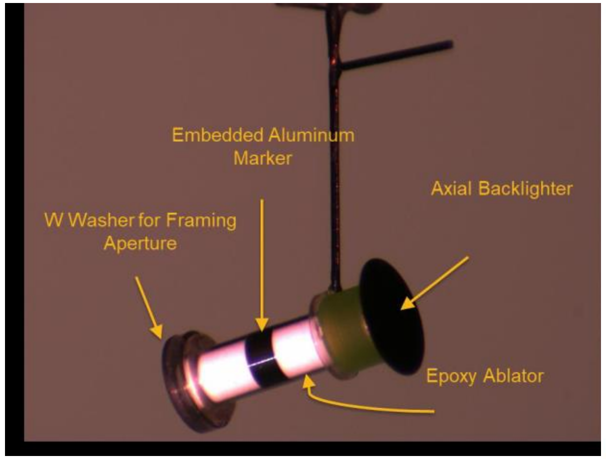
Work supported by OFES

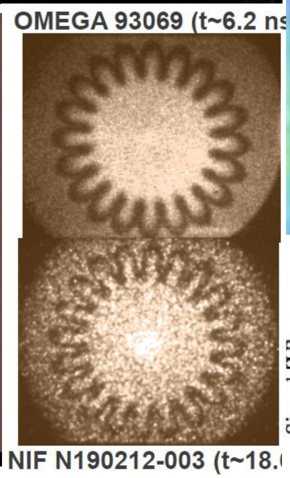
Two critical scientific areas in which technical readiness level must be improved is laser plasma and hydrodynamic instabilities, core LANL strengths

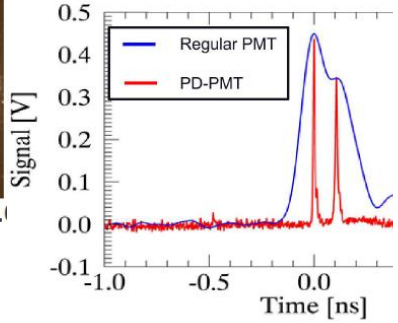
- **Major ICF design lab with computing resources and experimental capabilities**
- **ICF Target engineering**
- **Strong Laser Plasma/Matter Interactions research capabilities for 3D modeling**
  - Exascale computing potential with multi-scale integrations
  - Implicit PIC codes
- **Unique computation capabilities for integrated 3D target simulations**
  - xRage Eulerian code
- **Prompt gamma history diagnostics with 10 ps resolution to diagnose IFE implosions**





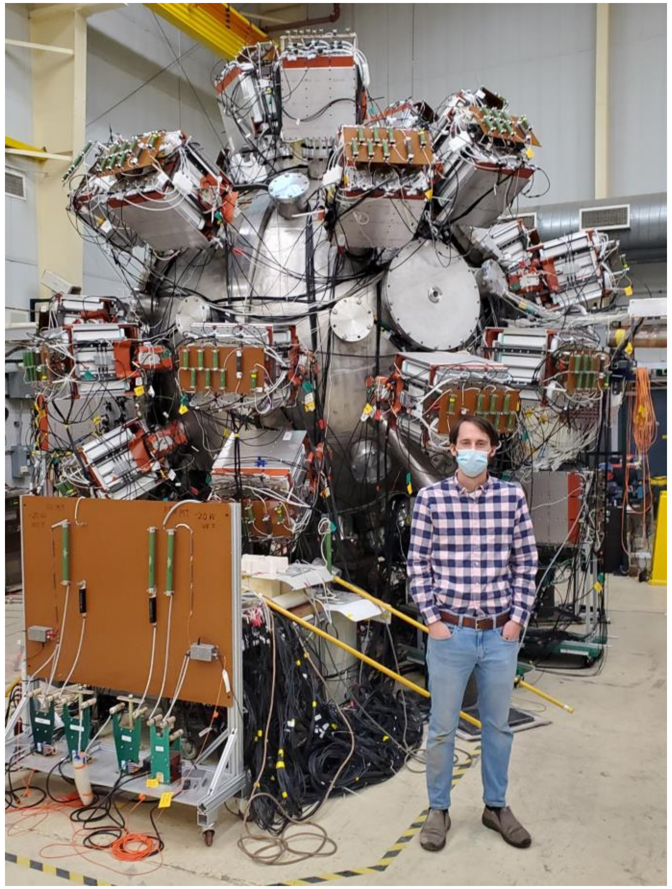






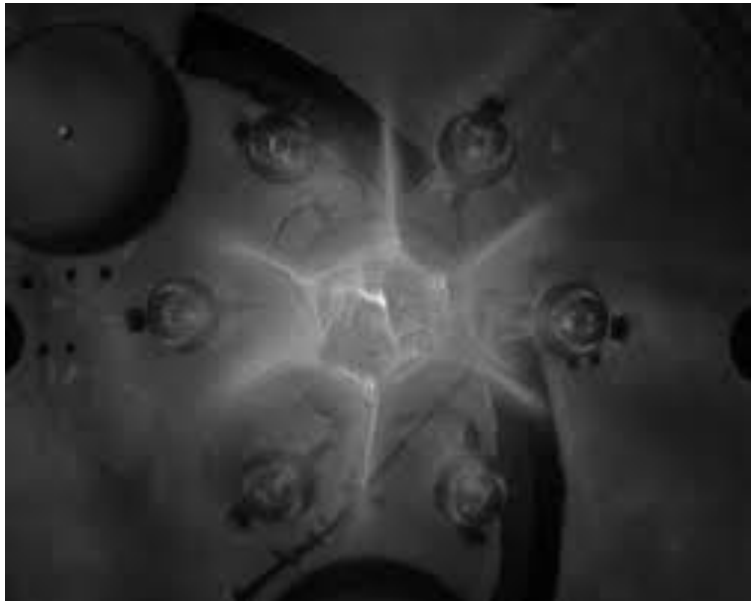
LANL continues to make progress developing Plasma Liner Experiment (PLX) to investigate the efficacy of plasma jet driven magnetized target fusion

PLX with all guns



Schematic for PLX

Plasma Image from multi-jet experiment



Team: S. Langendorf, Feng Chu, T. Byvank* (*now in XTD)

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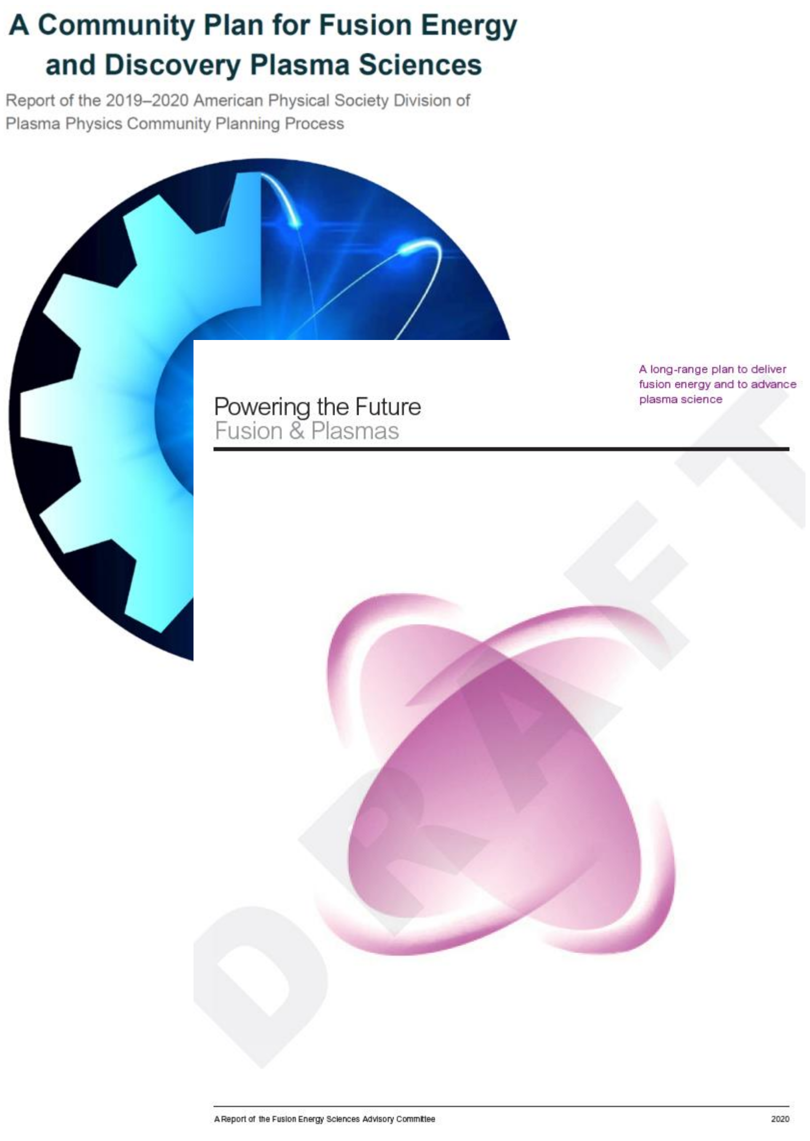


Los Alamos

NATIONAL LABORATORY

EST. 1943

NNSA
National Nuclear Security Administration
Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

LANL is engaged and positioned to meet the scientific and technology priorities of the FES fusion community.†

Materials: **a pivot toward research and development of fusion materials** and other needed technology. Emphasis is needed on fusion materials science, **plasma facing components**, tritium-breeding blanket technology and the tritium fuel cycle. A number of key experimental facilities are recommended. **The Fusion Prototypic Neutron Source (FPNS)** will provide unique material irradiation capabilities …

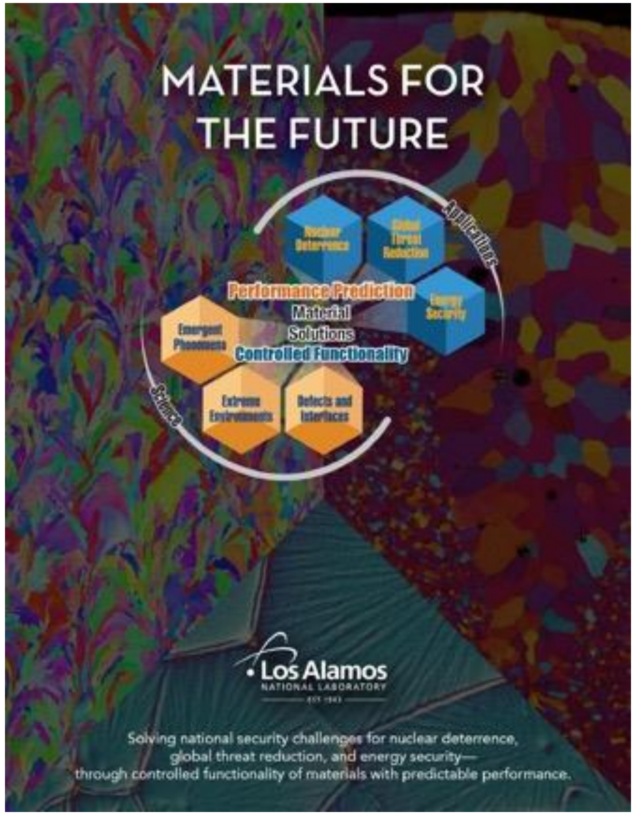
Tritium Processing: Closure of the fusion fuel cycle via successful breeding and extraction of tritium will be critical for the sustained operation of an FPP. … understand fundamental tritium transport properties and phenomena in solid and liquid breeder materials, and associated modeling and model validation efforts. Tritium technologies related to fueling and exhaust from the plasma, and subsequent processing,

Public/Private Partnerships: Public-private partnership should be used as a tool to engage and stimulate industry involvement. DOE Fusion Energy Sciences has already established successful PPP programs, notably the Innovation Network for Fusion Energy (INFUSE). These activities should be expanded …

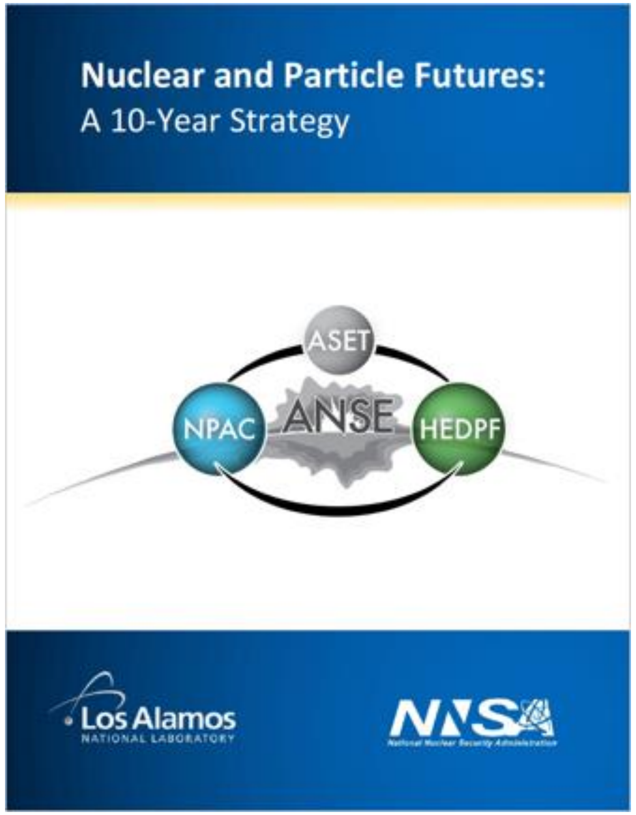
Theory/Diagnostics: This includes the expansion of theory and modeling efforts that support advancing technology readiness levels (TRLs), accelerating development of diagnostics and measurement systems that will function in fusion nuclear (irradiation-hardened) environments, and rapid maturation of enabling technologies.

IFE: Inertial fusion energy (IFE) utilizes advances in lasers, pulsed power technology, and other innovative drivers to achieve fusion at high fuel density. The enormous progress made with indirect drive at the National Ignition Facility, direct drive, magnetic drive Inertial Confinement Fusion (ICF), and heavy ion fusion underpin the promise of IFE. An IFE program that leverages US leadership and current investments should be targeted.

LANL strategies and core competencies offer excellent synergies and leverage for FES activities.

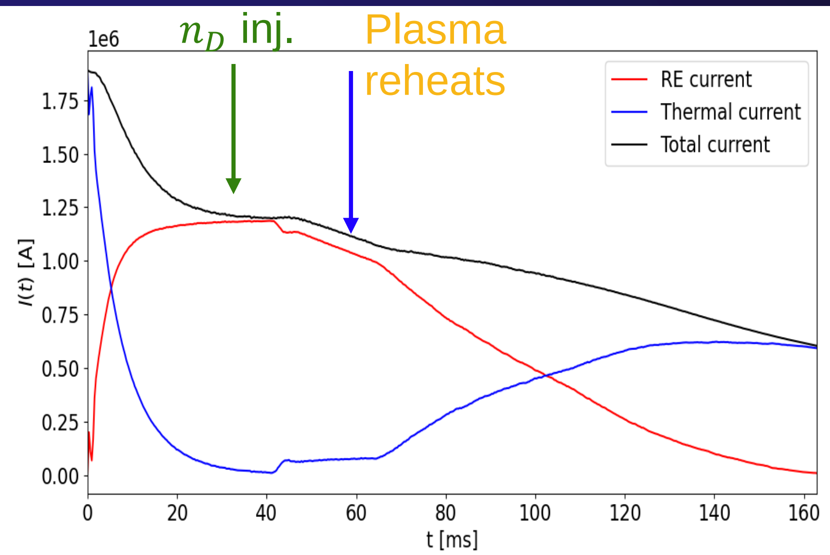


- The Laboratory's National Security mission requires a multidisciplinary approach to solve some of the nation's toughest challenges.
- We believe that the greatest science breakthroughs will come as we approach difficult problems in revolutionary ways drawing from a large pool of disciplines
- ***LANL has six pillars it uses as a framework for working together applying skills across the traditional boundaries of their disciplines.***
- **Materials for the future**
    - Materials in extreme environment
- **Nuclear and Particle Futures:**
    - High energy density, plasmas, and fluids



Control CQ duration and runaway density and energy

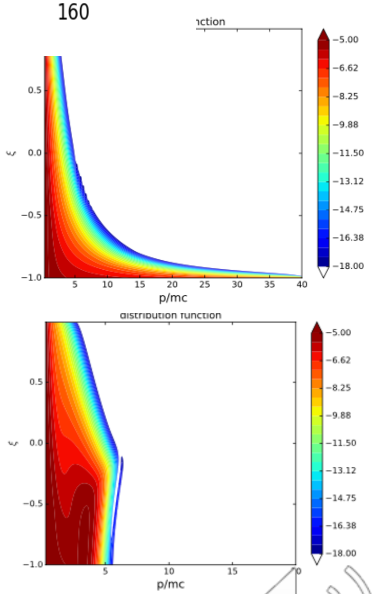
- **CQ and runaway control via material injection**
  - Ohmic-to-runaway current conversion simulation allows examination of critical physics that set runaway peak current
  - Runaway-to-Ohmic current conversion simulation allows investigation of critical energy balance issues that underlines a benign termination of runaway current
- **CQ duration and runaway energy control via externally injected waves**
  - Target low energy runaways via the normal Doppler-shifted cyclotron resonance → limit the runaways to much lower energy by design
    - Waves counter-propagate in runaway direction
  - Static error field approach by Rax et al necessarily push the resonance to much higher runaway energy
  - TDS is also looking at resonant and non-resonant runaway interaction with a range of lower frequency waves (e.g. CAE)



McDevitt & Tang

$$\omega - k_{\parallel} v_{\parallel} = \frac{\Omega}{\gamma};\ k_{\parallel} v_{\parallel} < 0$$

$$k_{\parallel} v_{\parallel} = \Omega/\gamma$$



Guo, McDevitt, Tang

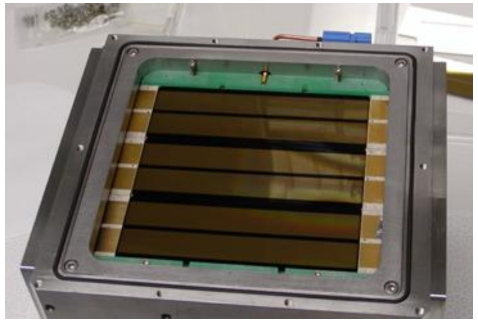
$$\omega - k_{\parallel} v_{\parallel} - k_{\perp} v_{\perp} = 0$$

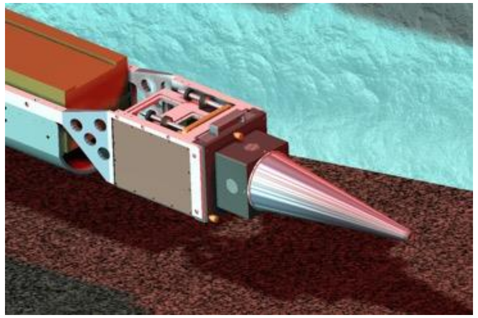
Work supported by OFES fusion theory program and OFES/OASCR Tokamak Disruption Simulation (TDS) SciDAC Project

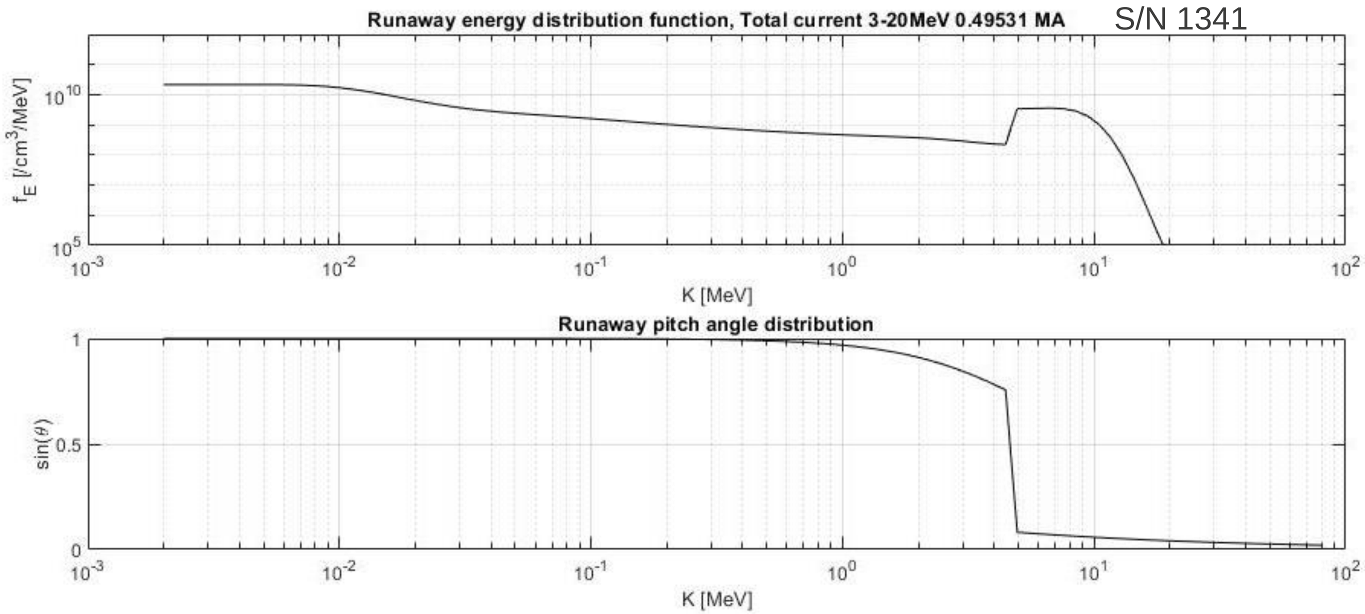
LANL is developing a novel approach to measuring runaway currents using inverse Compton scattering taking advantage of HEDP diagnostic capabilities

Tokamak Diagnostics: Design study for runaway electron laser inverse Compton scattering measurement on DIII-D is nearing completion.

We should be able to measure "bump-on-the-tail" runaway currents from 50-1000 kA on DIII-D with a 7 Joule short-pulse (80 picosecond) laser and soft x-ray Large Format Camera (LFC) developed for ICF, according to our synthetic model (S/N 1341).







Synergies with ICF and NNSA may provide improved detectors in the future.

Work supported by OFES

To get to a demonstration fusion power plant requires developing materials that last under harsh DT reaction environments

FPNS needs compared with applications

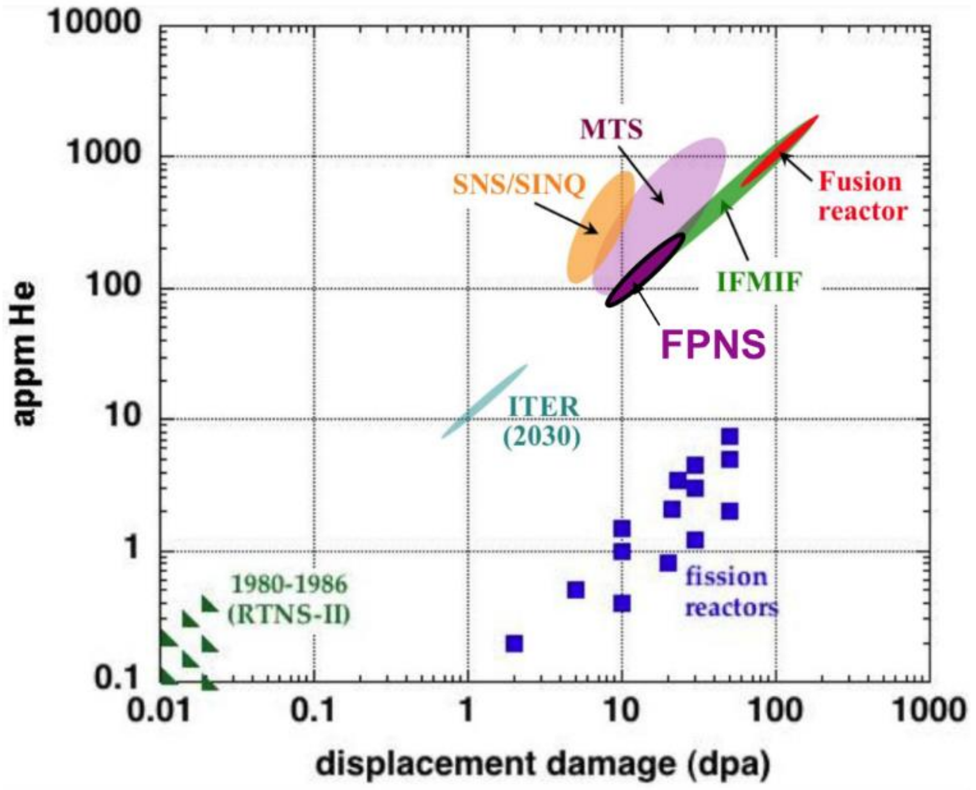
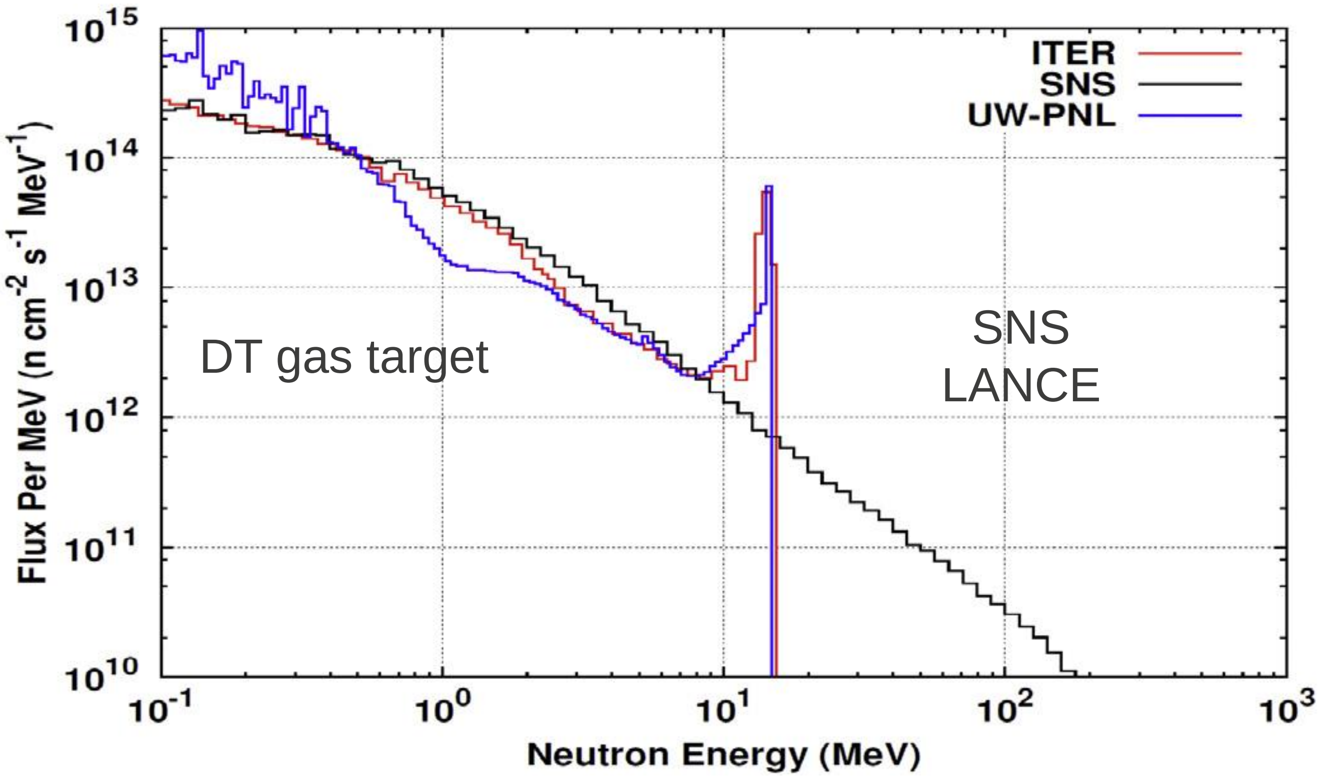


Figure adapted from FESAC Report DOE/SC-0149, February 2012.

Predicted neutron energy spectrum



B. Egle, et al. “Fusion Prototypic Neutron Source for near-term fusion material testing”, APS-DPP Nov 9th 2020

Hydrogen Storage for Fusion Applications

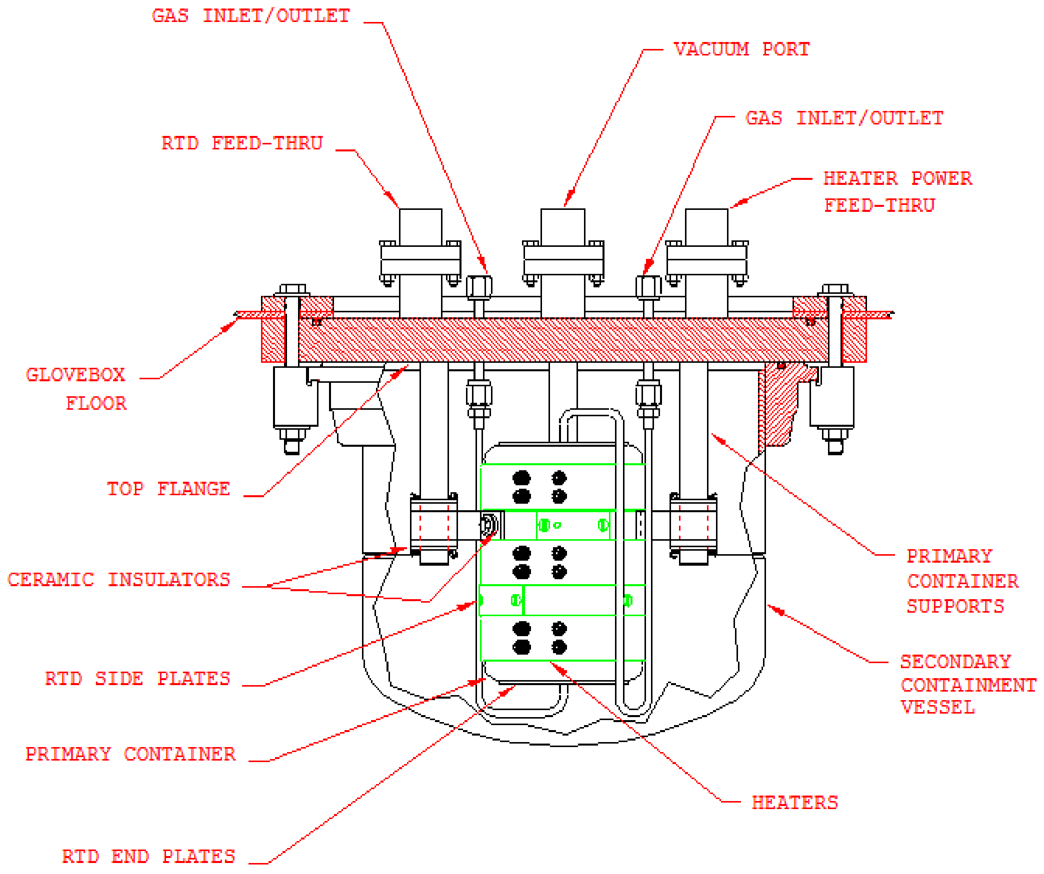
Self-Assaying Tritium Accountancy and Storage for ITER - **STACI**

- **Parametric studies to design ITER fuel cycle**
- **Experimental campaign to determine operating schedules, parameters**
- **Vessel kept under vacuum/inert**
- **Gas flowed in to uranium-containing vessel to react**
- **Gas flows out naturally upon heating**

Previous results: Operation of prototypical-scale depleted uranium storage bed (90 – 100 g T_2 capacity versus 70 g T_2 limit for ITER)

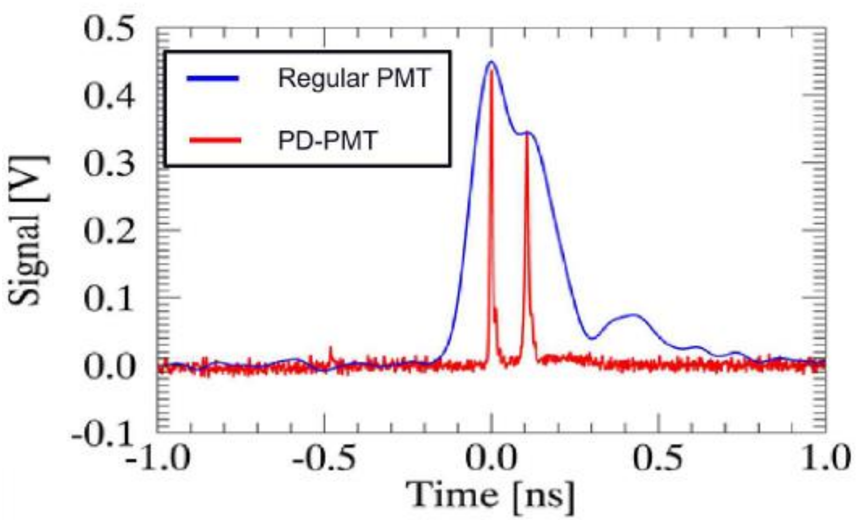
Objectives:

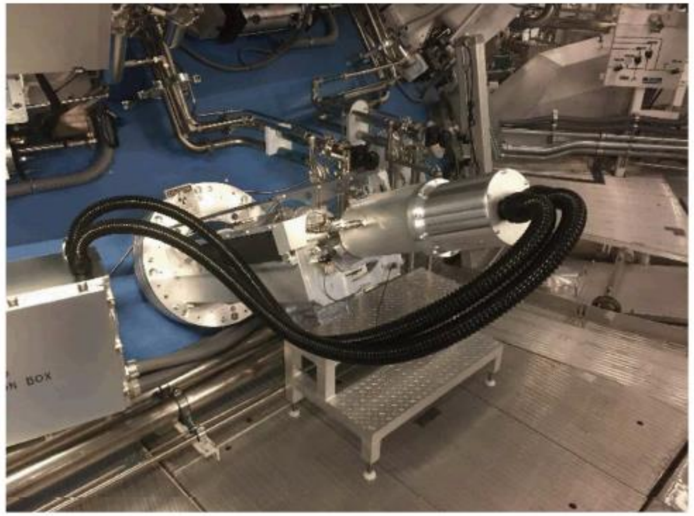
- Use experimental data to confirm that reported hydriding mechanism is plausible
- Develop a model for design and operations of uranium storage beds



LANL's fusion diagnostics expertise provides central capabilities needed for Inertial Fusion Energy

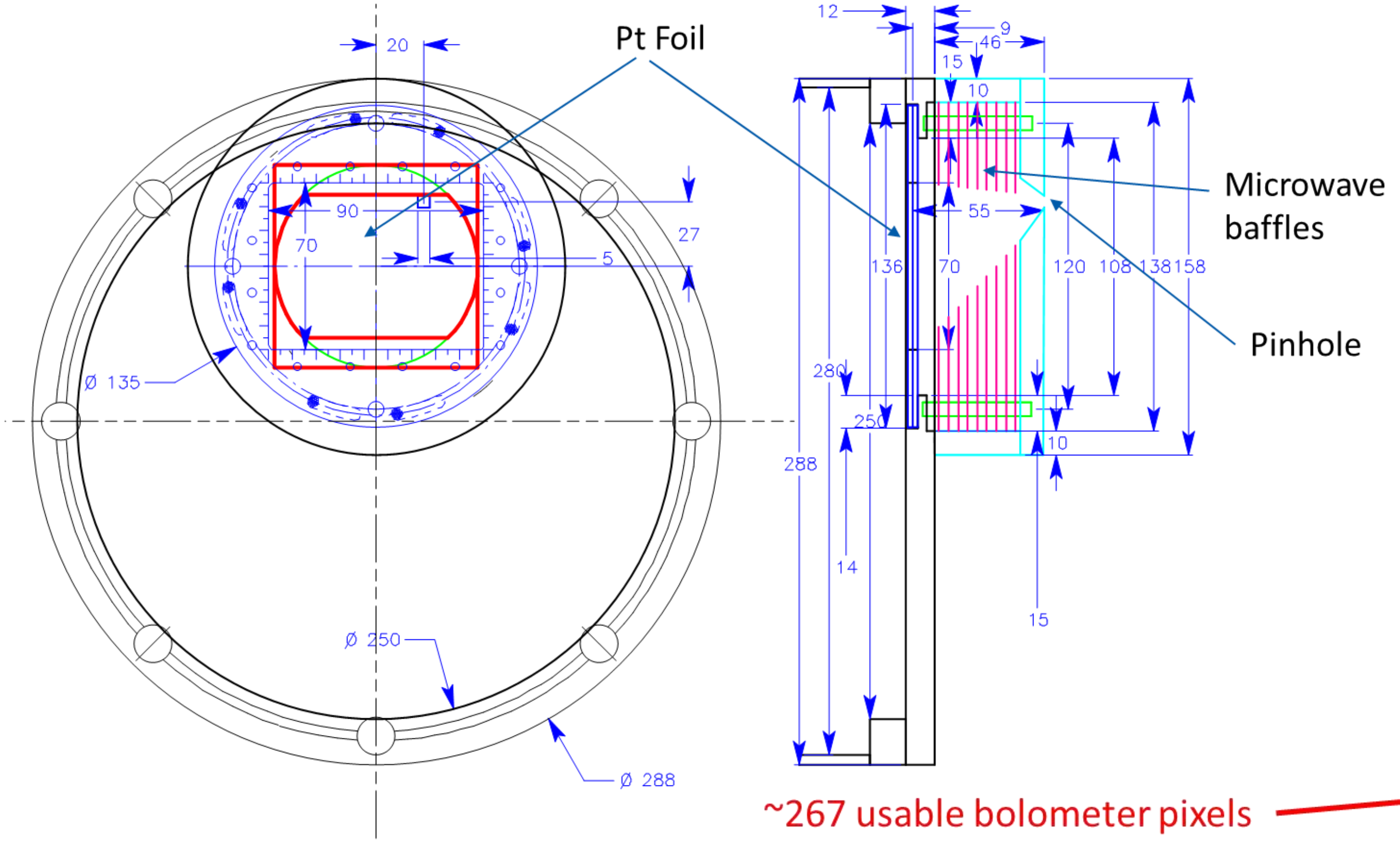
- Any IFE reactor will need prompt diagnostics to monitor implosions during operation
- Gamma Reaction History provides ps time scale measurements with a high TRL
- The reaction history provides key information with regards to thermo-nuclear burn
- Other gamma spectral information can provide additional details
- Prompt gamma spectroscopy needs more development having a much lower TRL





Foil/Pinhole Snout will be added to LANL IR Endoscope

Wendelstein 7-X
IPP
Max-Planck-Institut für Plasmaphysik
Los Alamos NATIONAL LABORATORY EST. 1943
LHD NIFS

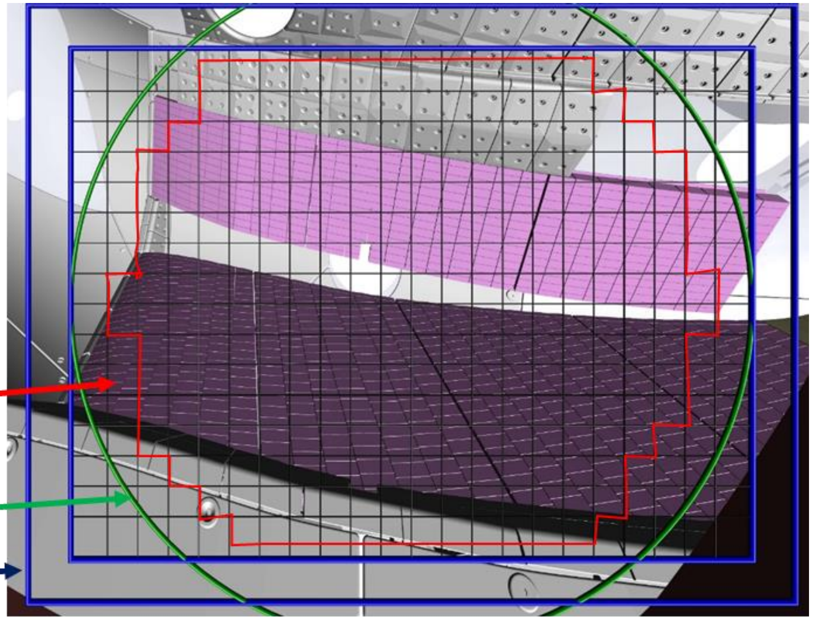


~267 usable bolometer pixels

It will view the divertor in Module 5

IR system FoV

Edge of frame (IRVB FoV)



Edge of frame (IRVB FoV)

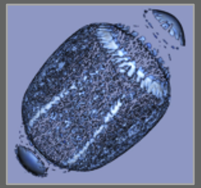
LANL utilizes capability pillars to define key areas of science, technology & engineering important for the lab’s missions

Materials for the Future

- Defects and Interfaces
- Extreme Environments
- Emergent Phenomena

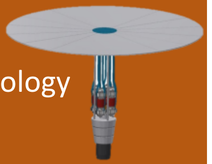
Science of Signatures

- Nuclear Detonation
- Nuclear Processing, Movement, Weaponization
- Natural and Anthropogenic Phenomena



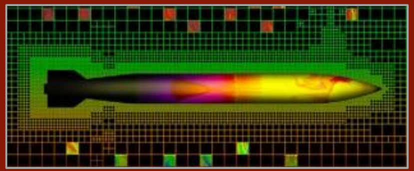
Nuclear and Particle Futures

- High Energy Density Physics & Fluid Dynamics
- Nuclear & Particle Physics, Astrophysics & Cosmology
- Applied Nuclear Science & Engineering
- Accelerator Science & Technology



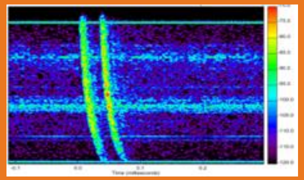
Weapons Systems

- Design
- Manufacturing
- Analysis



Integrating Information, Science, and Technology for Prediction

- Complex Networks
- Computational Co-Design
- Data Science at Scale



Complex Natural and Engineered Systems

- Human–Natural System Interactions: Nuclear
- Engineered Systems
- Human–Natural System Interactions: Non-Nuclear

Self-Assaying Tritium Accountancy and Containment Unit for ITER - STACI

- **Original experimental campaign**
  - 2015-2016
  - 1 conditioning run; heating to ~260ºC only
  - 12 hydriding/dehydriding cycles
    - Half flowed only H_2, others 5-50% H_2 in Ar
- **Regular experimental conditions**
  - Hydriding
    - 250-320 ºC
    - Gas pressures in bed range from vacuum -1500 torr
    - Inlet flow rates up to 50 SL/min
  - Dehydriding
    - Bed temp up to 500ºC
    - Outlet pressures varied with temperature: as high as ~650 torr