Fusion Energy Sciences Program at LLNL

2021 Fusion Power Associates Meeting

Harry S. McLean
Program Leader, Fusion Energy Sciences Program
Associate Division Leader, PLS/Physics

December 15-16, 2021

LLNL-PRES-830677

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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The Fusion Energy Sciences Program (FESP) at LLNL delivers mission science, discovery science, and workforce development

FESP's broad engagement across LLNL provides scientific depth and flexibility in applying resources

- **Fusion Science and Plasma Physics:** core competencies and disciplines essential to LLNL's mission-based science from both NNSA and SC perspectives.
- **S&T for HEDS:** The SKAs underlying Burning Plasmas is central to LLNL's HEDS applications space.
- **Partnering within LLNL:** exploit capabilities within LLNL's Physical Sciences, Computations, and Engineering Directorates
- **Partnering with other DOE Labs, Academia and Industry:** LLNL has experimental and theoretical collaborations with all major DOE FES facilities as well as PI and co-PI roles in multi-institutional fusion centers.

FESP at LLNL is the POC for two DOE Offices: SC/FES and ARPA-E/Fusion

LLNL FES Program and Discipline FY22 Leadership

Harry McLean
FES Program Leader
ADL PLS/PHYS

National Security Applied Plasmas
John Barnard

Pulsed Power Fusion Plasmas
Andrea Schmidt (APL)

Theory & Modeling
Alex Friedman

DIII-D
Steve Allen

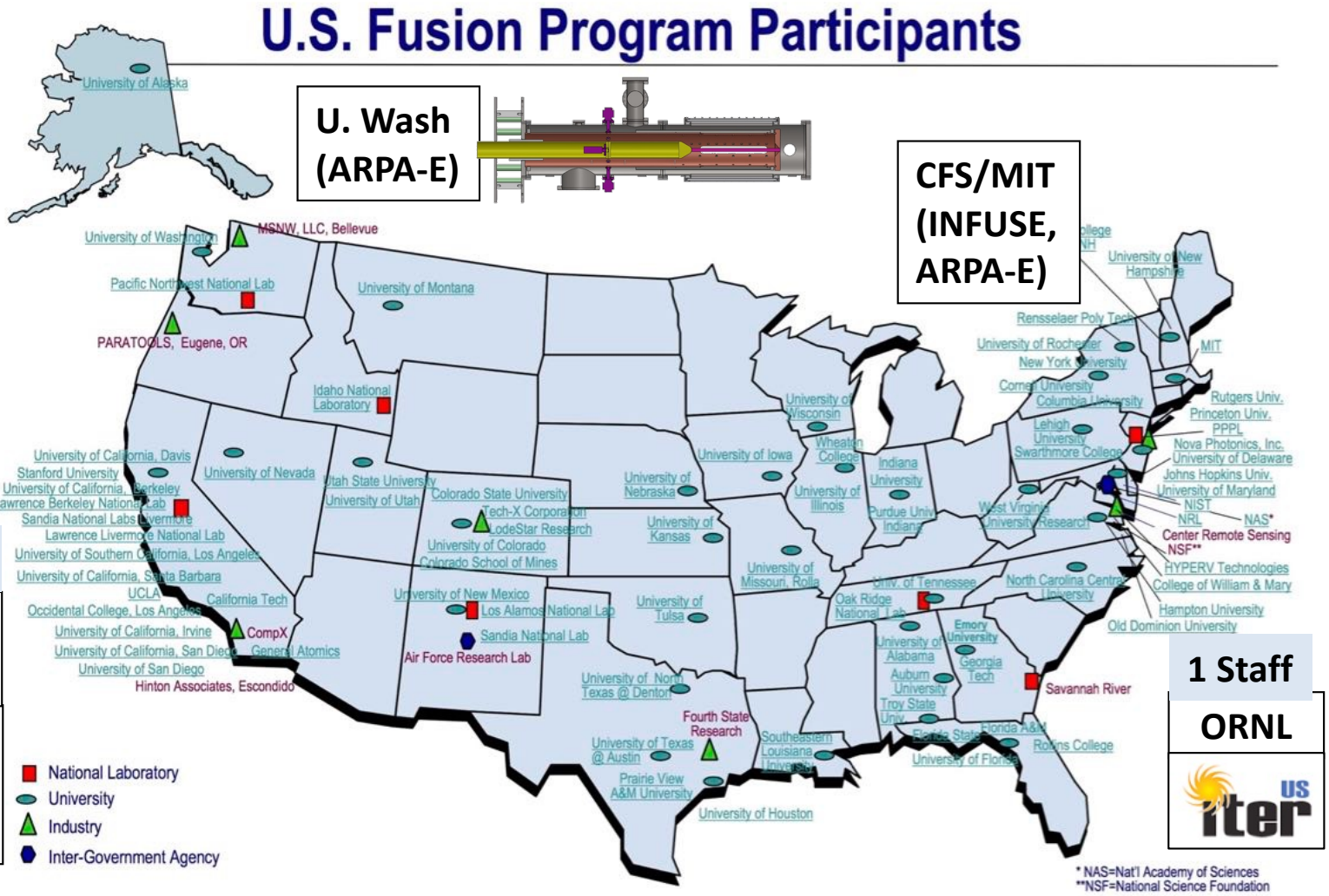
NSTX-U
Vlad Soukhanovskii

Mat'ls & Technology
Tom Rognlien

HEDLP/LaserNetUS
Tammy Ma

ITER Magnets
Nicolai Martovetsky

LLNL/FESP participates at the primary US MFE Facilities



30 Staff

LLNL

10 Staff

General Atomics

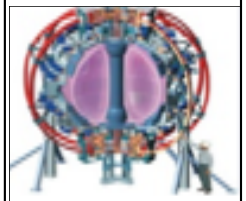
DIII-D

U. Wash (ARPA-E)

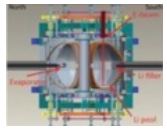
CFS/MIT (INFUSE, ARPA-E)

2 Staff

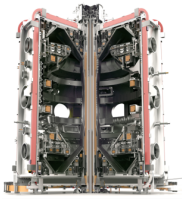
PPPL



NSTX-U



LTX-β



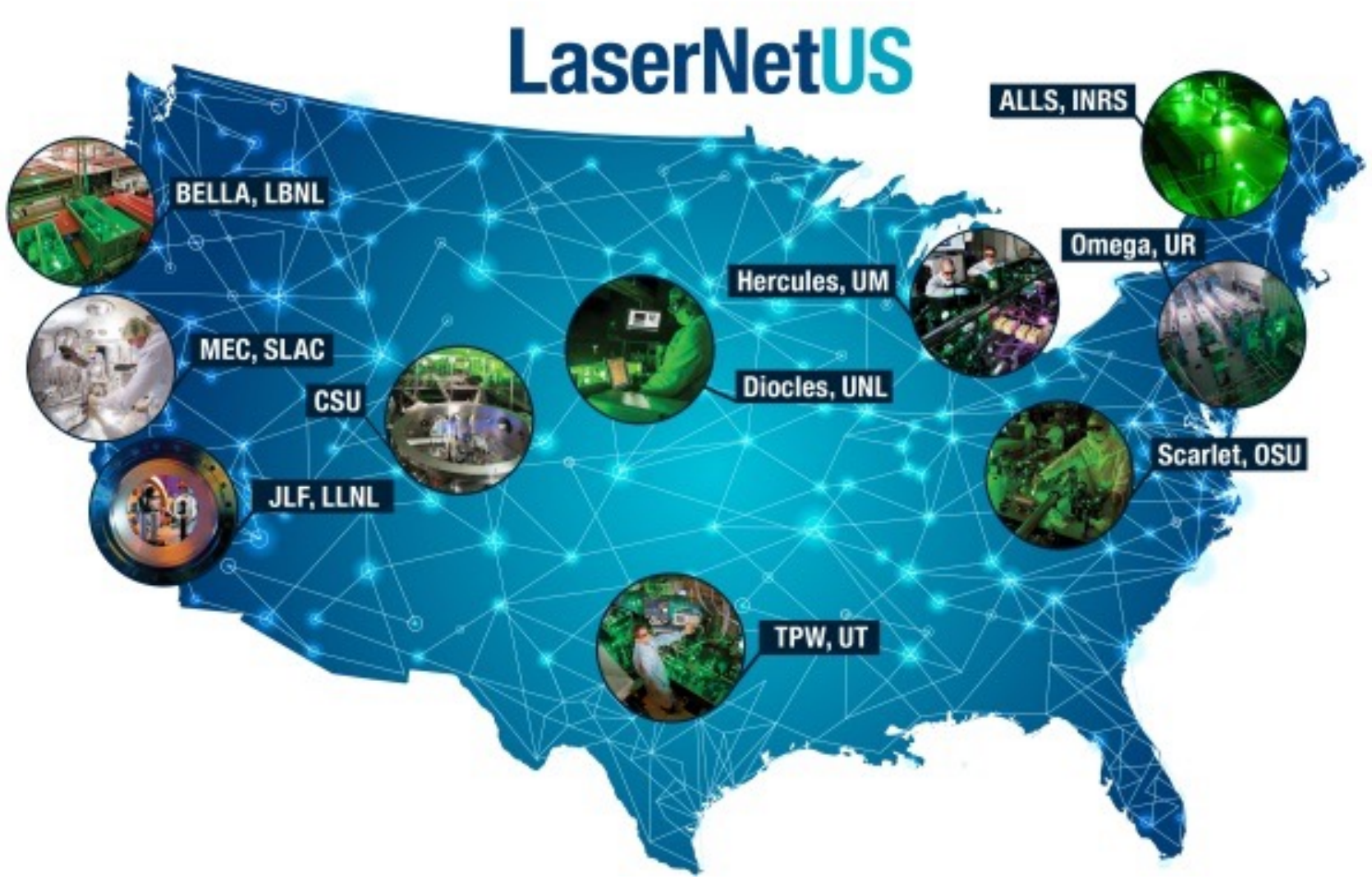
Mast

1 Staff

ORNL

National presence is boosted by having permanent LLNL staff in residence

LLNL/FESP also participates at LaserNetUS and other HEDLP Sites

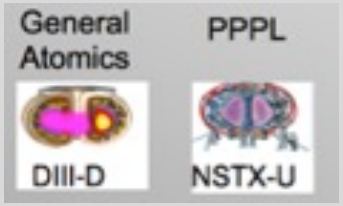


LLNL helps manage procurements and other needs to execute experiments

LLNL's Fusion Energy Sciences Program (FESP) has funded activities in all SC FES research categories

SC FES FY21 (672 M$)

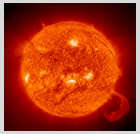
- **Foundations (288M)**
  - MFE Experiments
  - MFE Theory



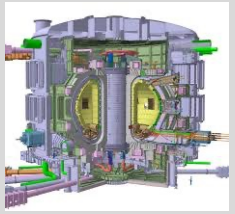
- **Long Pulse (73M)**
  - Superconducting Tokamaks
  - Stellarator Experiments
  - Materials
  - Technology


EAST (China)

- **Discovery Plasma Sci. (54M)**
  - General Plasma Science
  - Measurement Innovation
  - HEDLP: Expts at JLF, NIF, SLAC/LCLS, LLE/OMEGA
  - Quantum Information Sci



- **ITER + MEC (257M)**
  - US-ITER Project Office
  - ITER Organization
  - MEC ~ 15 M

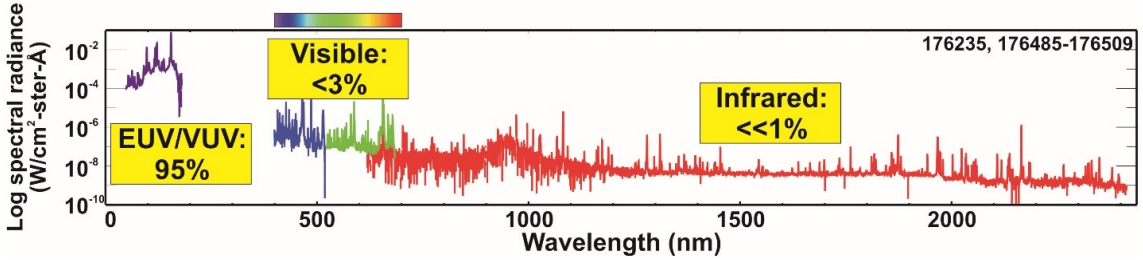

ITER (France)

LLNL FES Program

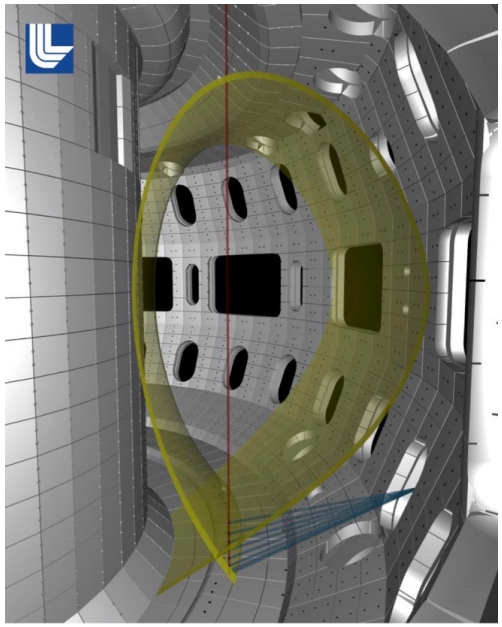
- **Foundations:**
  - DIII-D collaboration at GA, 10 LLNL staff in residence
  - PPPL, MAST (UK) collaboration, 2 staff in residence
  - Theory & Modeling + SciDACS, 16 Staff
  - HED Machine Learning
  - INFUSE
- **Long Pulse**
  - International: EAST (China)
  - Materials and Fusion Nuclear Science
- **Discovery Plasma**
  - Gen. Plasma Sci: Sheath, flux tube physics
  - Measurement Innovation
    - Quantum Calorimetry
    - High-Rep HEDLP Diags
  - HEDLP: Expts at JLF, NIF, SLAC/LCLS, LLE/OMEGA
    - FES Early Career (3 FY19, 4 FY20, 4 FY21)
    - LaserNetUS (experimental support)
  - QIS
- **Construction: ITER (1 FTE)**

LLNL at DIII-D is active in both Divertor Science and Advanced Tokamak (Steady-state operation) Research

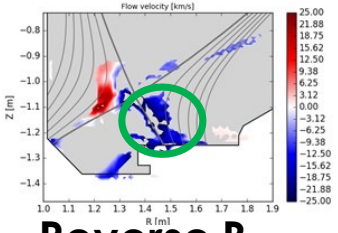
1. **Divertor Science: detachment / model validation / building design tools**
   - EUV spectroscopy, Infrared imaging, divertor T_i
   - UEDGE modeling, including plasma flow effects
   - Snowflake joint project: DIII-D, LLNL Theory, NSTX
2. **Advanced Tokamak program and Scenario Development**
   - Long-pulse Dynamics & Control
   - Core measurements
   - International Collaboration with EAST
3. **Plasma Diagnostics designs and lends operational support:**
   - LLNL leads routine operation of many critical diagnostic systems
   - Example: Building continuous absolutely-calibrated capability from IR to EUV



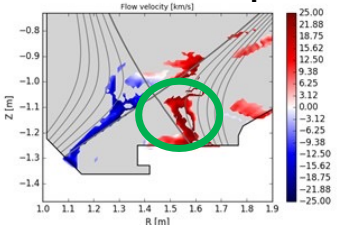
4. **Collaboration with Universities**
   - Tungsten Source Rates
   - Flow vs. B_{Tor} polarity in SOL and divertor via Coherence Imaging diagnostic



Forward B_T

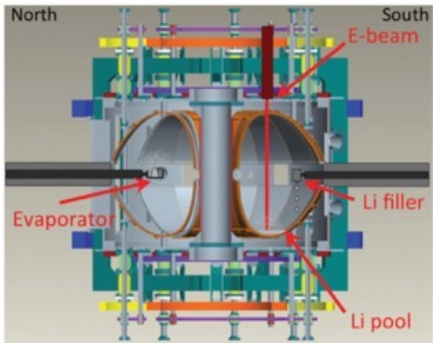


Reverse B_T

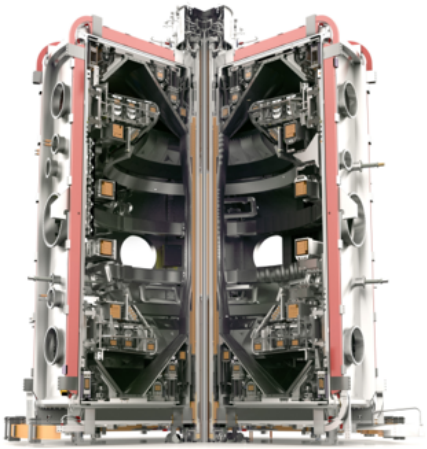


LLNL Experimental Research at PPPL is focused on Spherical Tokamak Program: LTX, MAST-U, and NSTX-U Recovery/Physics Planning

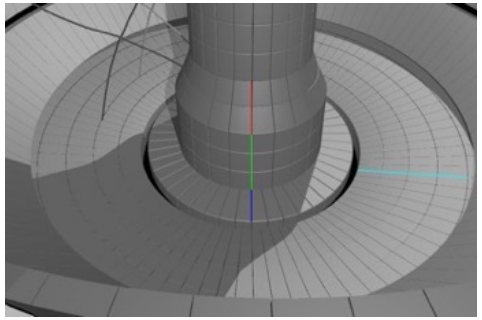
1. **Boundary Physics Research on Spherical Tokamaks**
   - Lithium Tokamak Experiment (LTX)–beta
     - SOL turbulence
     - PFC studies, Lithium sputtering measurements
   - Mega-Ampere Spherical Tokamak Upgrade (MAST-U) in the U.K.
     - Fielding Diagnostics
     - First physics campaign started 5/2021
     - Divertor detachment and snowflake divertor studies
2. **NSTX-U collaboration research**
   - NSTX-U Program activities, Research Objective Leadership
   - Developing preliminary concepts for PFC monitoring system
   - Contributions to machine, PFC and diagnostic design, engineering, and assessment



Lithium Tokamak eXperiment Beta in Princeton Plasma Physics Laboratory, Princeton, New Jersey



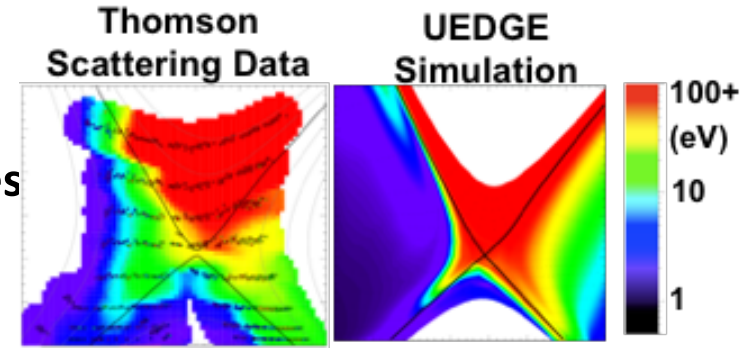
Mega-Ampere Spherical Tokamak Upgrade in Culham Centre for Fusion Energy, Culham, United Kingdom



Conceptual view of PFC monitoring system viewing NSTX-U divertor

LLNL/FESP's Theory, Modeling, SciDAC research focuses on tokamak edge physics and integrated modeling/MHD

- **Mission: Advance theoretical understanding and predictability of fusion plasmas**
  - Two main research focus areas: Edge Physics and Integrated Modeling
- **We pursue innovation in areas such as:**
  - advanced divertor design and operation
  - understanding, control, and mitigation of instabilities
  - predictive and whole device modeling
  - advanced algorithm development
  - advanced computing through SciDAC, exascale, and QIS other initiatives



- **We prioritize research with strong connections to experimental physics:**
  - Provide theoretical support for planning, analysis and modeling of experiments on DIII-D, NSTX-U, MAST, EAST, KSTAR, …, and many others
  - Provide scenario development tools for ITER and CFETR
- **Efforts are strengthened by connections to NNSA and SC computational mathematics:**
  - LLNL Center for Applied Scientific Computing (CASC)
  - LBNL Applied Numerical Algorithms Group (ANAG)

International collaborations with China and South Korea are a part of reciprocal relationships

FESP Staff "go" to China several times a year

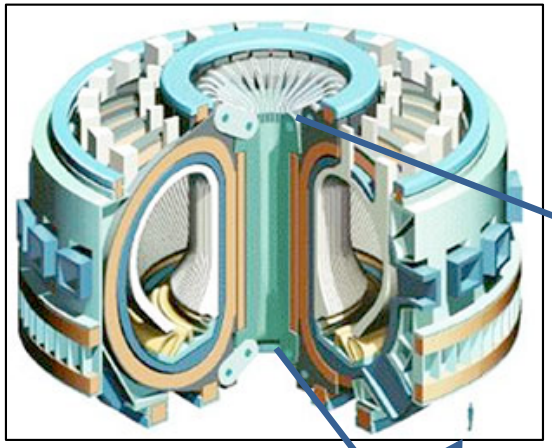
- Whole device modeling
- Advanced Tokamak experiments and remote control

FESP host at LLNL 4-6 Chinese faculty, post-docs, and students

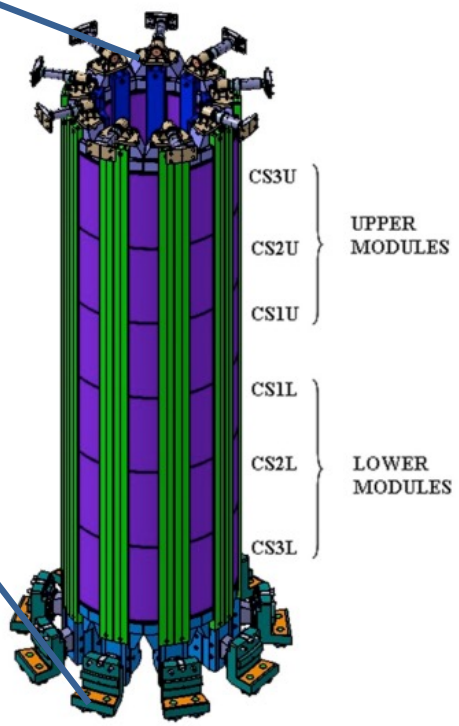
- Plasma-edge physics
- Boundary-turbulence modeling
- Yearly BOUT++ Workshop
- LLNL hosted US-PRC MFE Workshop in Spring 2021

U.S.- and China-based magnetic fusion scientists in the control room of the DIII-D tokamak in San Diego

FESP staff at ORNL: R&D for design, fabrication, and testing of ITER Central Solenoid, now includes HTSC work on SNS-STS and for CFS

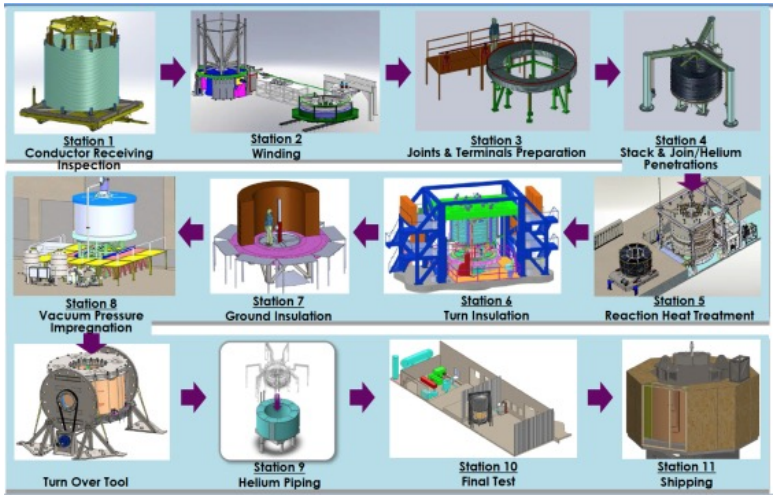


Worlds largest pulsed superconducting magnet



Nicolai Martovetsky:
Chief engineer for US ITER magnet systems, assigned off-site at ITER-US at ORNL.

Fabrication process developed and qualified

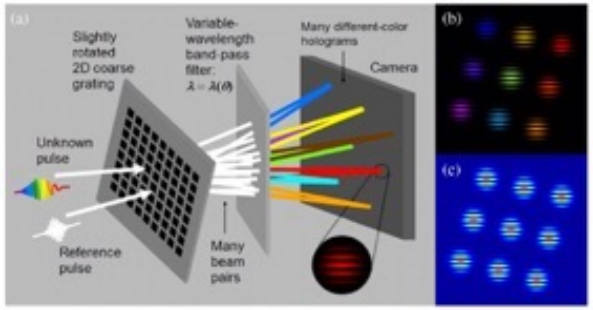


Discovery Science/HEDLP: enhanced by FES-ECRP awards

ECRP 1 (Ma): Multi-ps Short-Pulse Laser-Driven Particle Acceleration for Novel HED & ICF Applications

Goal: Explore the scaling physics of electron, proton, and light ion generation in multi-ps short pulse laser parameter space using an integrated experimental and modeling approach

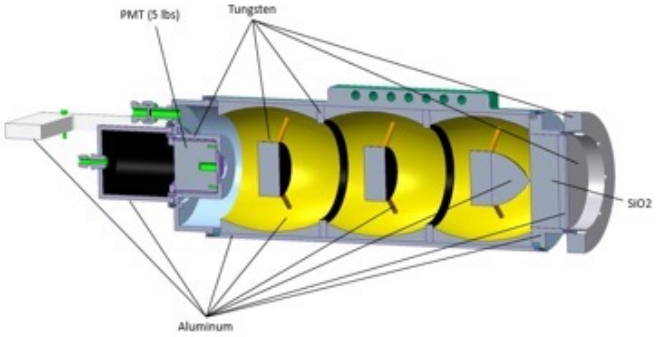
STRIPED FISH diagnostic for complete spatiotemporal single-shot measurement of high-intensity lasers.



ECRP 2 (Zylstra): Studying nuclear astrophysics with inertial fusion implosions

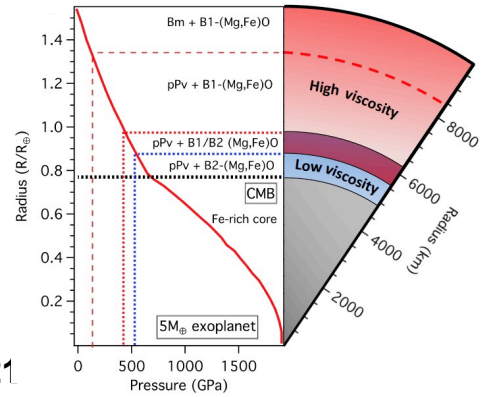
Goal: Improve our understanding of how the elements were produced by nucleosynthesis processes in the universe by studying nuclear reactions in analogous laboratory plasmas.

New Cherenkov detector designed and fabricated for nuclear astrophysics measurements at OMEGA



ECRP 3 (Coppari): Expanding Capabilities to Unlock the Mysteries of Complex Warm Dense Matter

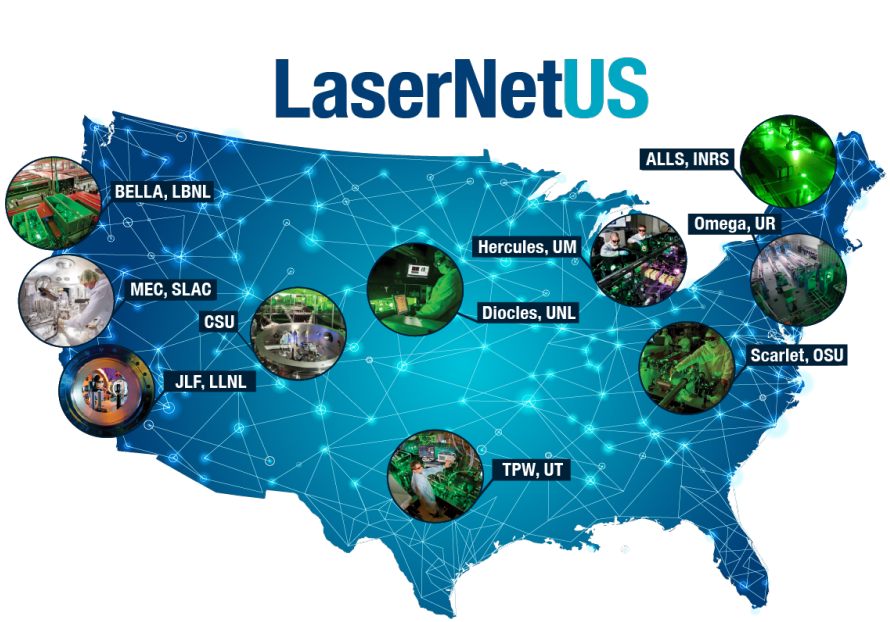
Goal: Characterize the properties of complex warm dense matter at the atomic level elucidating mixing and pathways to phase transitions to improve models describing planetary interiors



Coppari *et al*, Nature Geoscience 14, 121 (2021

Discovery Science/HEDLP: LaserNetUS User Support

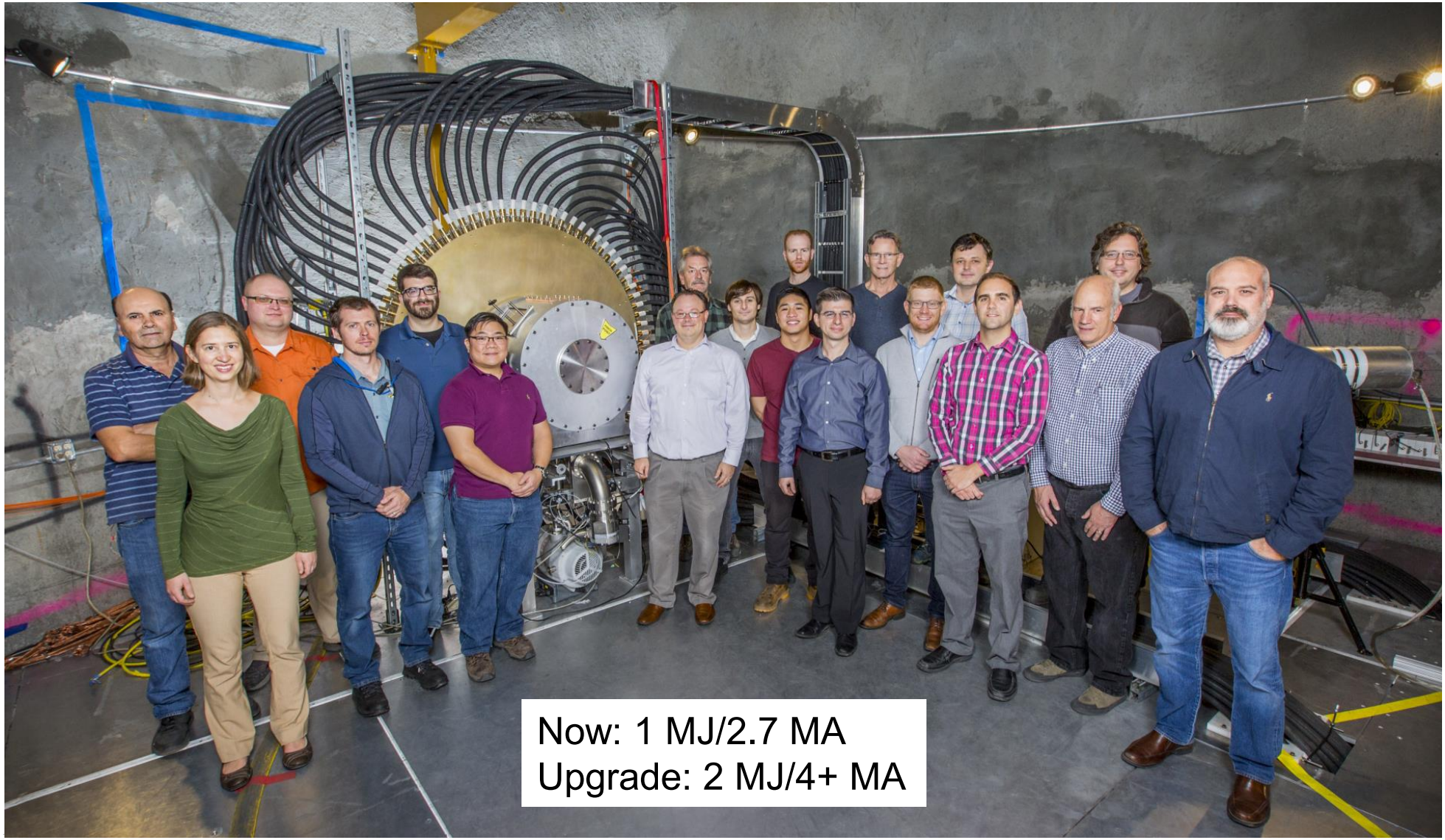
Objective: Support sub-awards to users allocated beam time through the proposal review panel (PRP). Funding is applied toward travel and procured materials/supplies/services as approved by the FES Program Manager



By the Numbers:

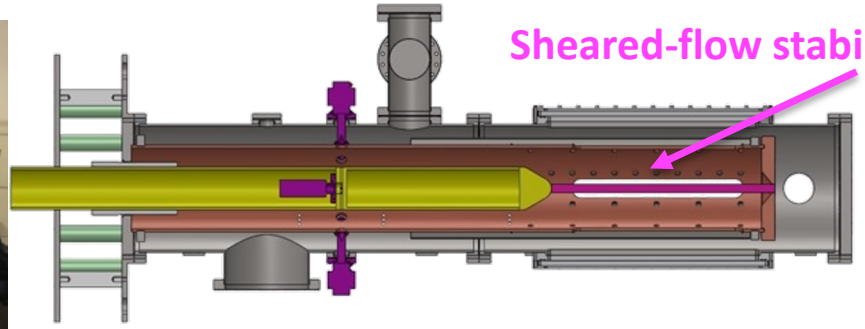
- Number of experiments supported: 29 of the 81 awarded proposals over 3 cycles (in progress; expect ~8 more to request support)
- Travel for teams: 11
- Target builds: 20 experiments
- Capability enhancement for facilities: BELLA, OSU, TPW, CSU
  - –Long focal length beamline (CSU & OSU)
  - –Engineering & parts to increase shot rate (TPW, CSU)
  - –Betatron source (BELLA)

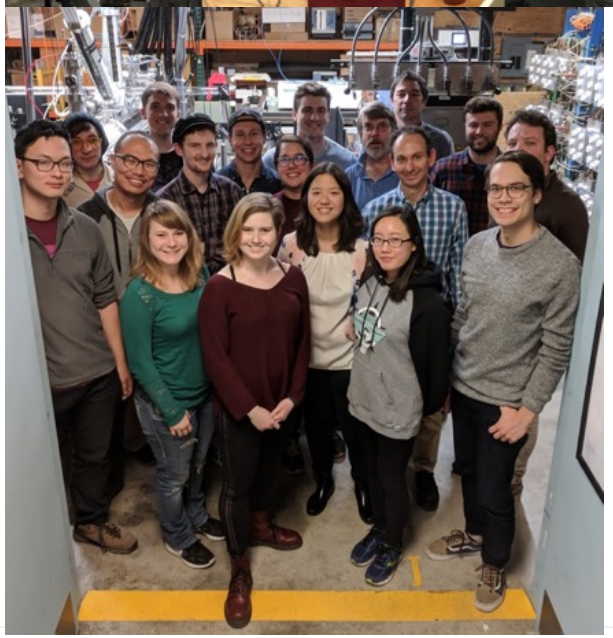
Pulsed Power Fusion Group operates Mjolnir, a multi-MJ DPF in the NOVA Laser Facility building for National Security Missions

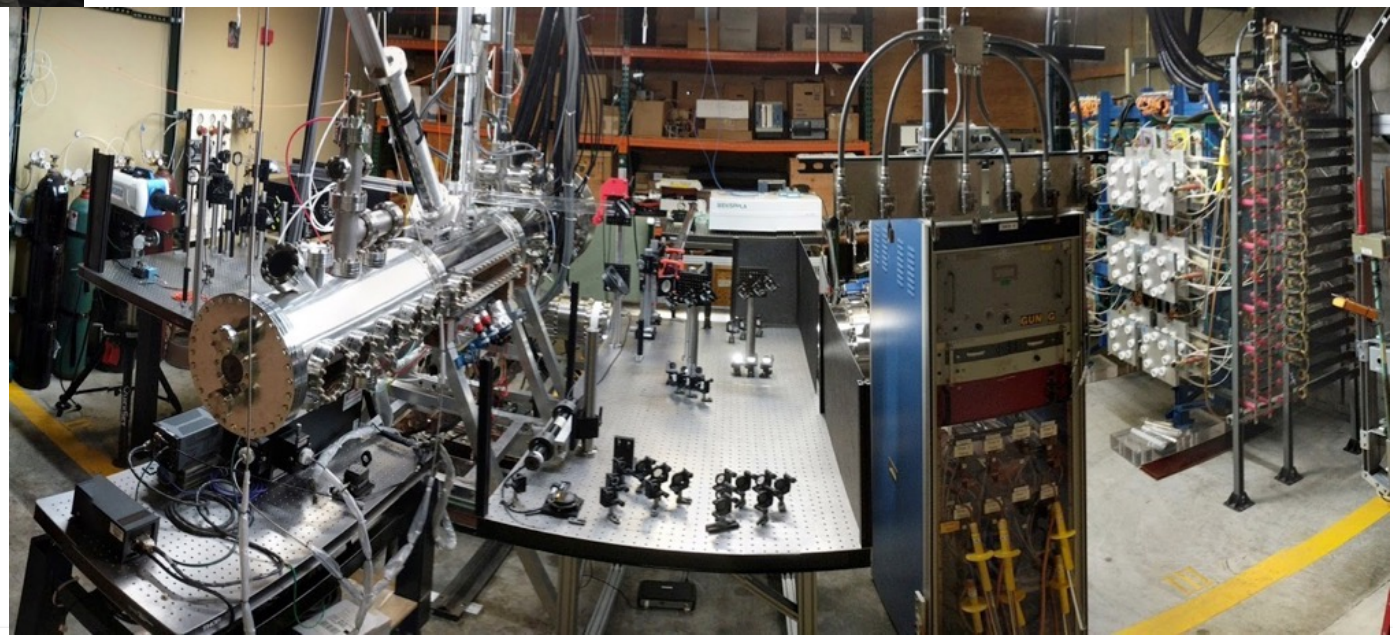


ARPA-E: Experimental, diagnostic, and computational efforts have grown beyond FuZE sheared-flow stabilized Z-pinch concept to include multiple projects

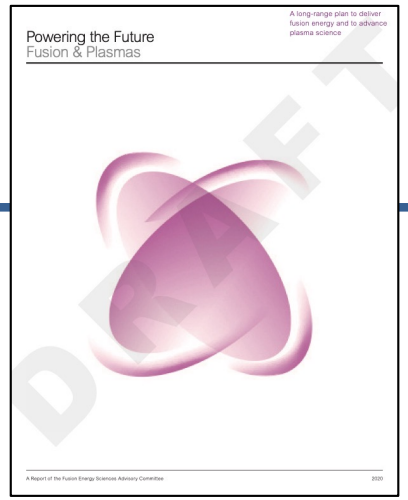
- 2015 University of Washington / LLNL partnership initiated for FuZE Project (ALPHA)
- 2019: Neutron Production/Spectroscopy and Portable Thomson Scattering (Fusion Diagnostics)
- 2020 HTSC CS for CFS, Tungsten Additive Manufacturing, (BETHE, GAMOW/FES)







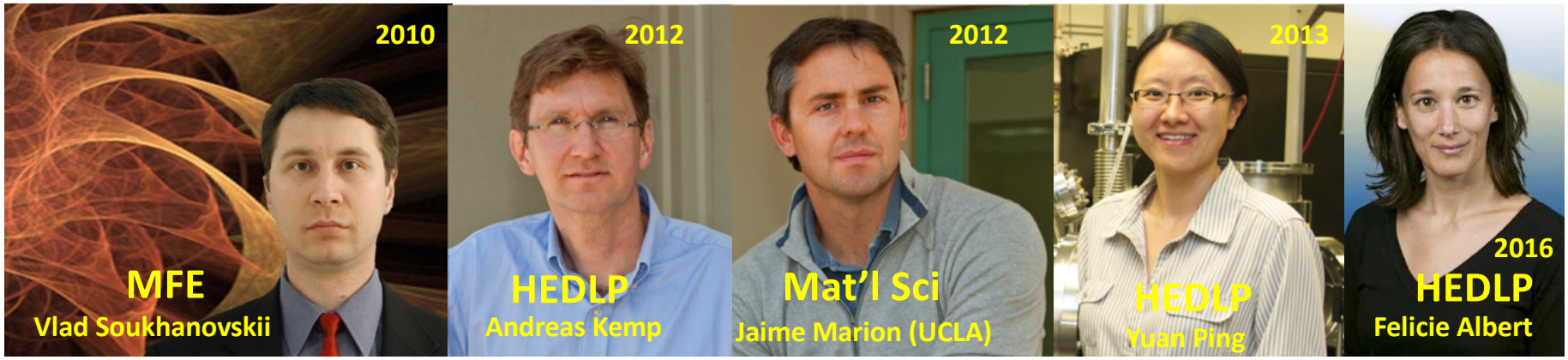
Overall LLNL FESP Outlook for 2022 and beyond for all sponsors is being guided by the new FESAC Report



- **Continue MFE experimental and theoretical research:**
  - National research (DIII-D, NSTX-U, LTX-β)
  - International research (MAST-U, EAST, KSTAR)
  - Preparations for ITER and the burning plasma era
  - Expand partnerships with ARPA-E and Private Industry
- **Pursue advanced computing relevant to predictive whole-fusion-device modeling**
  - Leverage partnerships within LLNL between FESP (SC-FES) and CASC (SC-ASCR)
  - Expand collaborations beyond LLNL with other SC-FES and SC-ASCR supported institutions
  - SciDAC Engagement, QIS explorations, machine learning
- **Expand Fusion Materials and Technology Efforts**
  - PFC model validation, advanced design studies to include liquid metals/liquid walls
  - Predictive modeling of material behavior (LLNL Material Science Division)
  - Additive manufacturing of tungsten (LLNL Material Science Division)
- **Foster Discovery Plasma Science, HEDLP, IFE**
  - Leverage NNSA facilities for SC-FES HEDLP experiments and modeling (ECRP's)
  - Astrophysical plasmas and Basic Plasma Science
  - Respond to user-needs on mid-scale facilities
  - Steward existing activities and foster new opportunities in LaserNetUS: LCLS (BES), JLF/NIF (NNSA), and BELLA Center (HEP)
  - Re-initiate appropriate IFE activities as guided by 2020 FESAC Report and upcoming BRN

Our Focus: Executing FES Programs and connecting FES to other LLNL Capabilities

Impact: LLNL Researchers have earned 9 DOE Office of Science Early Career Research Program Awards through FES



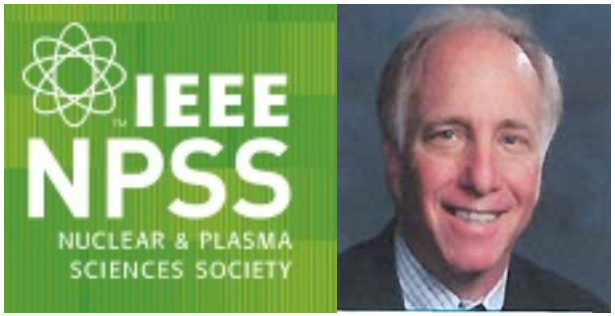
U.S. DEPARTMENT OF ENERGY
Office of Science
Early Career Research Program

*J. Marion left LLNL for UCLA in 2014, reducing his last 2 yrs to 150k/yr

Each ECRP provides $500k/yr x 5 Years. FES investment total of $19.3M*

Recent Awards and Recognition

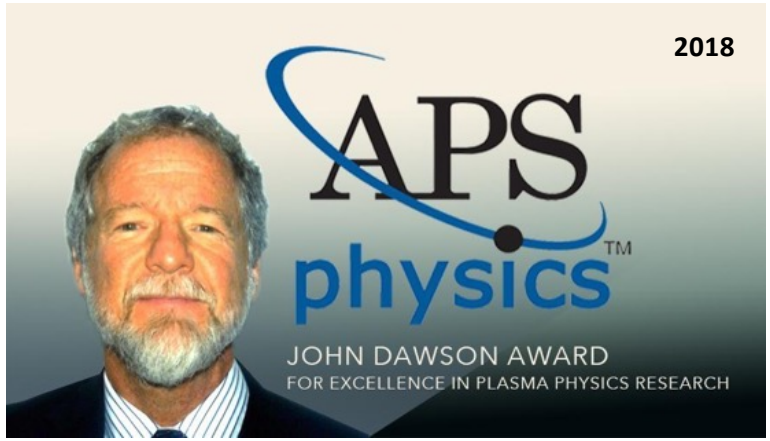
Alex Friedman



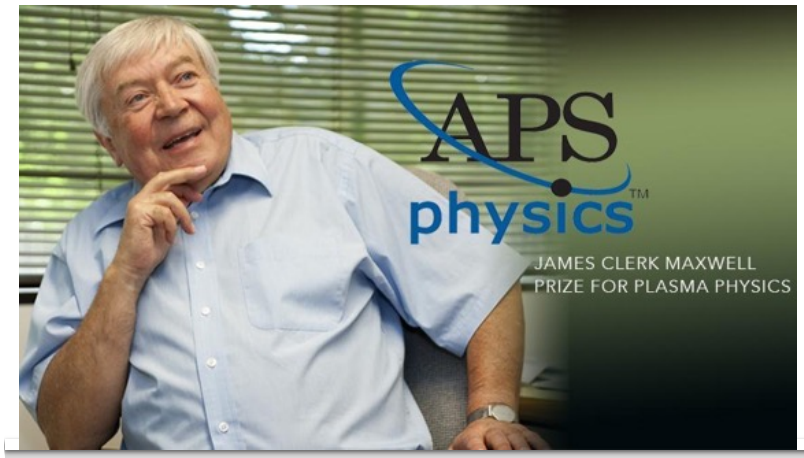
Charles K. Birdsall Award for Contributions to Computational Nuclear and Plasma Sciences

Chris Holcomb

Max Fenstermacher



Dmitri Ryutov



Felicie Albert

Lawrence Livermore
National Laboratory