Fusion Energy Sciences at LLNL

2018 FPA Meeting

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

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Lawrence Livermore National Laboratory

LLNL's FESP focuses on existing priorities and engages on new opportunities of importance to SC/FES and NNSA:

- MFE experimental and theoretical research, including:
  - National research (DIII-D, NSTX-U, LTX-b)
  - International research (MAST-U, EAST, KSTAR)
  - SciDAC Engagement
  - Preparations for ITER and the burning plasma era
- Exascale computing relevant to 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
- Fusion Materials and Technology
  - PFC model validation
  - Advanced design studies to include liquid walls
  - Predictive modeling of material behavior (LLNL Material Science Division, R. Rudd)
  - Additive manufacturing of tungsten (LLNL Material Science Division, M. Wang)
- Discovery Plasma Science
  - 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 including LLNL Jupiter Laser Facility
  - Steward existing activities and foster new opportunities in LaserNetUS: LCLS (BES), JLF/NIF (NNSA), and BELLA Center (HEP)

FESP (Program + Discipline) leads Magnetic Fusion Energy Science and related Plasma Physics areas within LLNL: We deliver mission science, discovery science, and workforce development

- **LLNL Core Competency:** Fusion Science and Plasma Physics are core competencies and disciplines essential to LLNL's mission-based science from both NNSA and SC perspectives.
- **S&T for HEDS:** The science underlying Burning Plasmas is central to LLNL's HEDS applications space.
- **Partnering with SC 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.

LLNL has many plasma scientists in many program areas. FESP's broad engagement across LLNL is a key benefit to SC-FES both for our scientific depth and our flexibility in adjusting to budget fluctuations

Our primary program customer is Fusion Energy Sciences within the DOE Office of Science (SC-FES)

FESAC
Sam Barish
Sandy Newton

Office of Fusion Energy Sciences
James W. Van Dam, Associate Director (Acting)

- **Gene Nardella** – Chief of Staff
- **Vera Bibbs** – Administrative Specialist
- **Pam Miller** – Budget & Human Resource Liaison

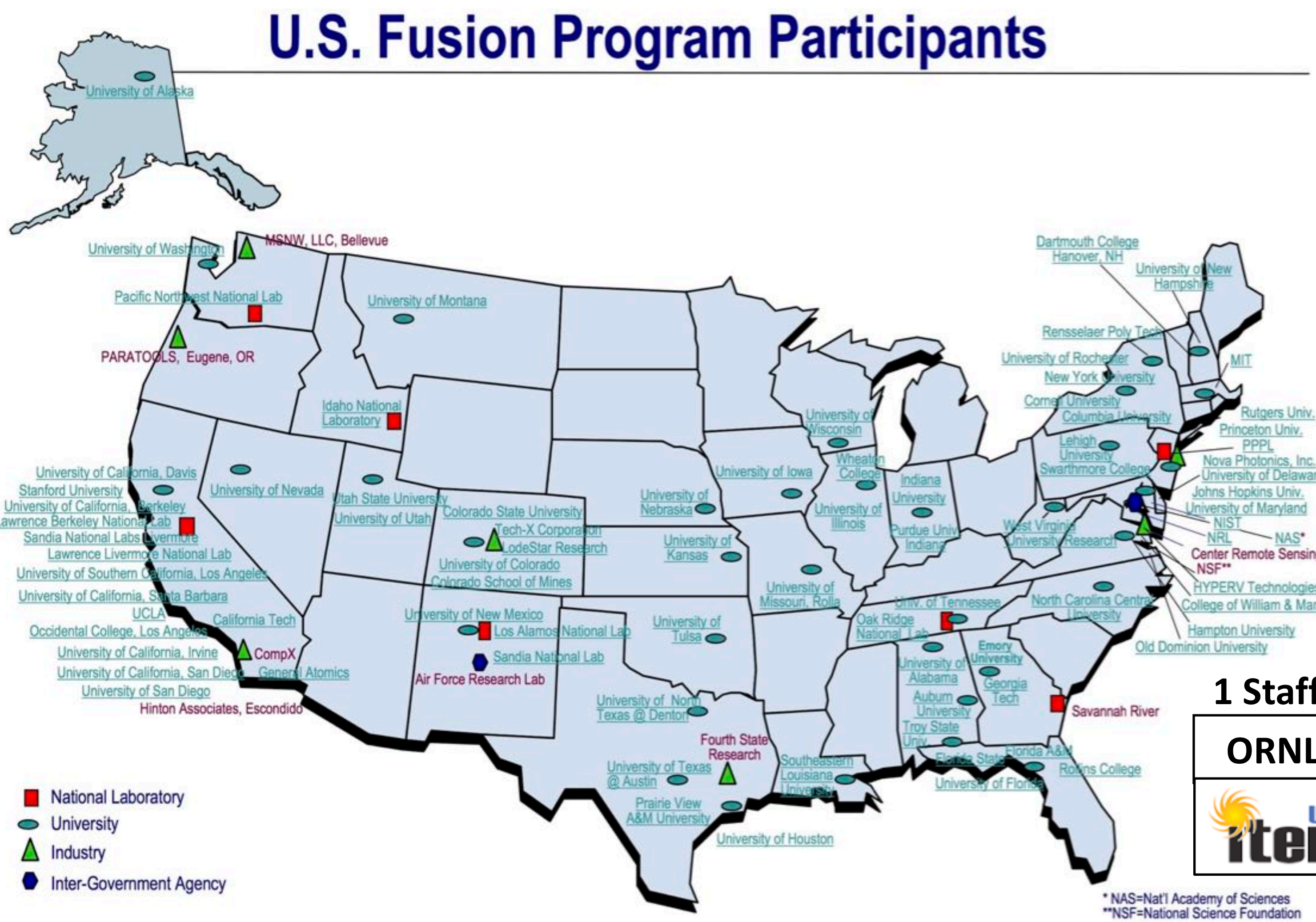
Research Division
John Mandrekas, Director (Acting)

- **Yvette Walker** – Administrative Specialist
- **Marty Carlin** – Procurements
- **Kramer Akli** – High Energy Density Laboratory Plasma,
- **Josh King** – Spherical Tokamak
- **Sam Barish** – Long Pulse: Stellarator
- **Matthew Lanctot** – Long Pulse: Tokamak Advanced Tokamak
- **Curt Bolton** – Measurement Innovation SBIR/STTR
- **John Mandrekas** – Theory & Simulation
- **Daniel Clark** – Materials & Fusion Nuclear Science
- **Nirmol Podder** – General Plasma Science, Exploratory Magnetized Plasma

Facilities, Operations, and Projects Division
Joseph J. May, Director

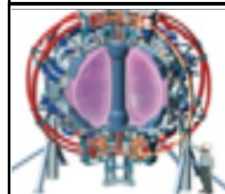
- **Sandy Newton** – Program Support Specialist
- **Shahida Afzal** – International Agreements
- **Barry Sullivan** – Enabling R&D, Fusion Nuclear Science NSTX-U, ES&H
- **Mark Foster** – Advanced Tokamak
- **Tom Vanek** – ITER, International Agreements Program
- **(Vacant)** – U.S. ITER Program Manager *Joseph May, Acting*

LLNL/FESP fields permanent staff at the primary US MFE Facilities

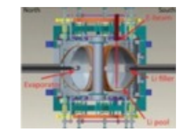


3 Staff

PPPL



NSTX-U



LTX-β

9 Staff

General Atomics

DIII-D

1 Staff

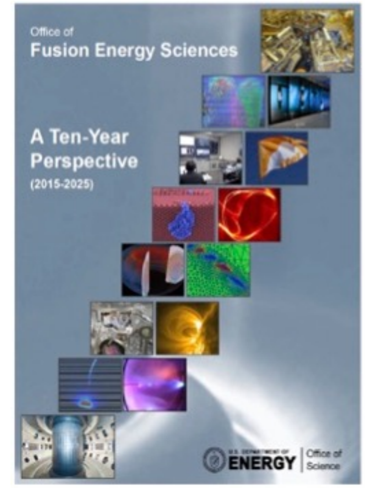
ORNL

US iter

National presence is boosted by having permanent staff in residence

SC Office of Fusion Energy Sciences Ten-Year Perspective

"... five areas of critical importance for the U.S. FES enterprise over the next decade"



1) "Massively parallel computing with the goal of validated whole-fusion-device modeling will enable a transformation in predictive power, which is required to minimize risk in future fusion energy development steps."

2) "Materials science as it relates to plasma and fusion sciences will provide the scientific foundations for greatly improved plasma confinement and heat exhaust."

3) "Research in the prediction and control of transient events that can be deleterious to toroidal fusion plasma confinement will provide greater confidence in machine designs and operation with stable plasmas."

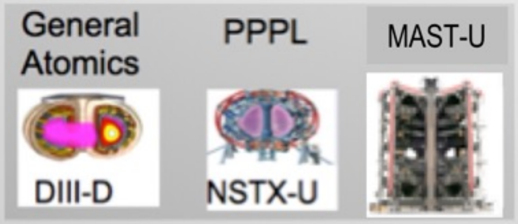
4) "Continued stewardship of discovery in plasma science that is not expressly driven by the energy goal will address frontier science issues underpinning great mysteries of the visible universe and help attract and retain a new generation of plasma/fusion science leaders."

5) "FES user facilities will be kept world-leading through robust operations support and regular upgrades."

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

DOE SC FES

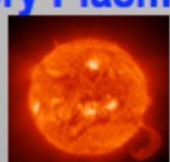
- **Foundations**: Science of plasmas for magnetic fusion

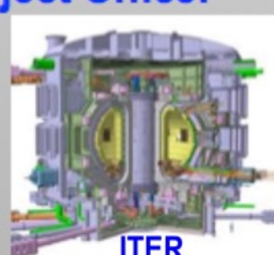


- **Long Pulse**:
  Long pulse tokamaks & stellarators, and fusion materials & technology

EAST (China)
KSTAR (S. Korea)

- **High Power-US ITER Project Office:**
- **Discovery Plasmas**:



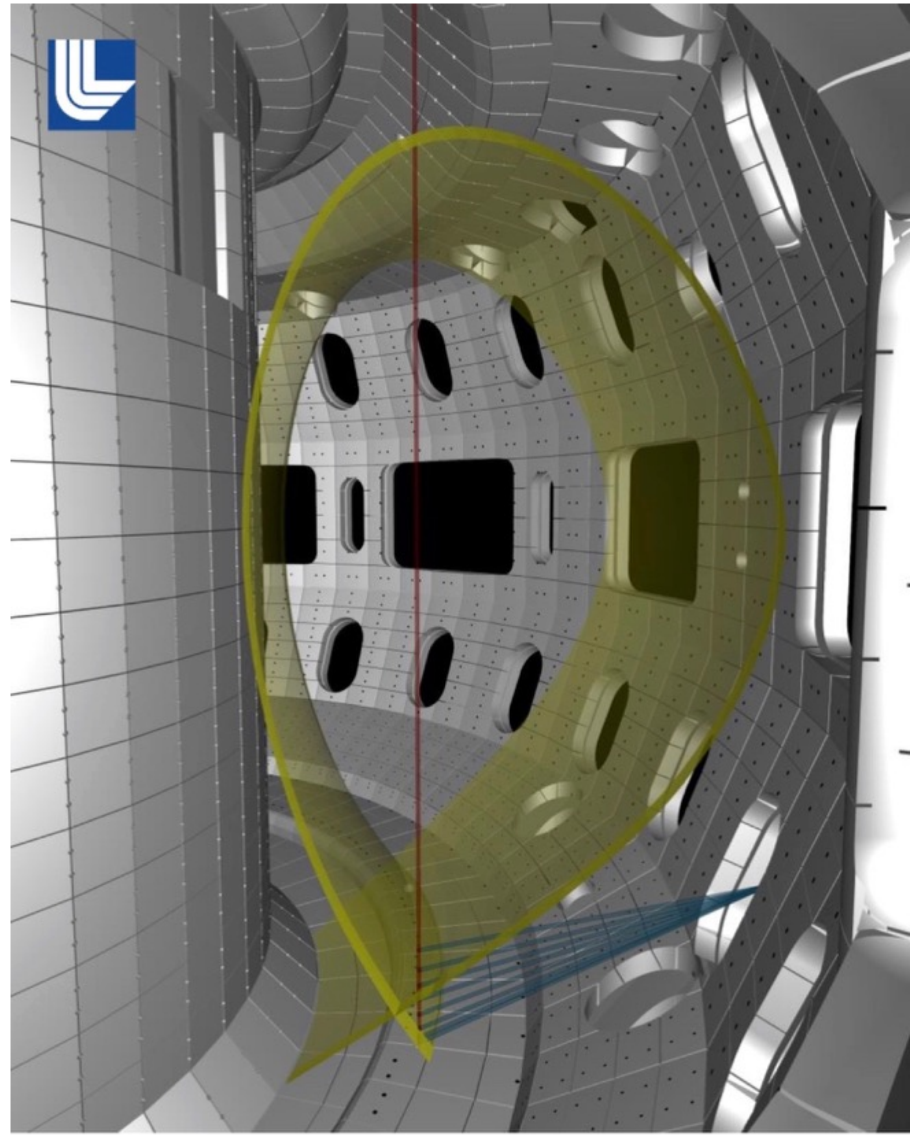


LLNL FES Program (FESP)

- **Foundations:**
  - DIII-D collaboration at GA, 9 LLNL staff in residence
  - PPPL, MAST(UK) collaboration, 3 staff in residence
  - Theory & Modeling + SciDACS, broad program
- **Long Pulse:**
  - International: EAST (China) and KSTAR (S. Korea)
  - Materials and Fusion Nuclear Science
- **High Power (ITER):**
  - SPP (WFO) from US ITER for ITER magnets
  - SPP (WFO) from GA for ITER diagnostics
- **Discovery Plasma:**
  - Basic Plasma Physics Sheath Physics
    - Sheath physics, Diagnostics
  - <u>HEDLP:</u>
    - Expts at JLF, NIF, SLAC/LCLS, LLE/OMEGA
    - Three (current) HEDS FES Early Career awards
    - LaserNetUS: New initiative, 9-hubs including JLF

Foundations: FESP at DIII-D is active in both Divertor and Advanced Tokamak (Steady-state operation) Research

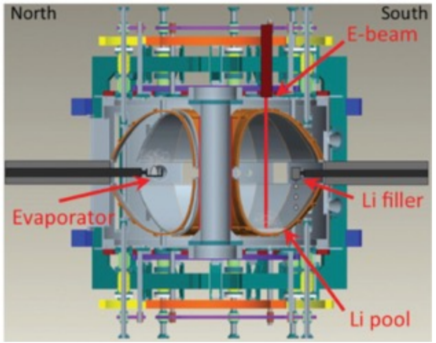
1. **Divertor Research: new measurements / modeling**
   - EUV spectroscopy, Infrared imaging, divertor T_i
   - UEDGE modeling, including plasma flow effects
   - Snowflake joint project: DIII-D, LLNL Theory, NSTX
2. **Advanced Tokamak program and Scenario Development**
   - Long-pulse Dynamics & Control
   - Core measurements
   - International Collaboration with EAST
3. **EUV spectrometer- Tungsten campaign**
   - Joint with LLNL/PLS/Physics
   - Similar to instrument fielded by FESP on NSTX
4. **Collaboration with Universities**
   - Tungsten Source Rates
   - Flow measurements via Coherence Imaging diagnostic
   - Diagnostic development on Auburn device



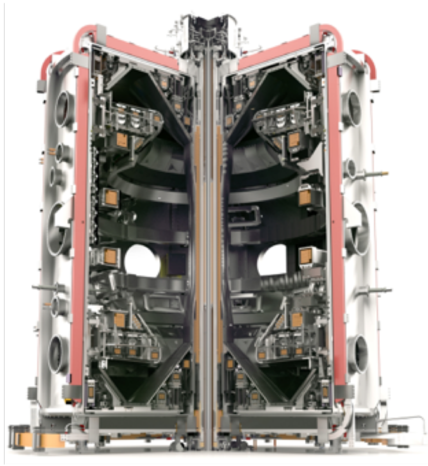
<u>Foundations</u>: LLNL Experimental Research at PPPL is focused on Spherical Tokamak Program: LTX, MAST-U, and some NSTX-U Recovery

1. **Boundary Physics Research on Spherical Tokamaks**
   - **Lithium Tokamak Experiment (LTX)–beta**
     - **SOL turbulence and plasma-surface interactions with liquid lithium and tin**
   - **Mega-Ampere Spherical Tokamak Upgrade (MAST-U) in the U.K.**
     - **Divertor detachment and snowflake divertor studies**

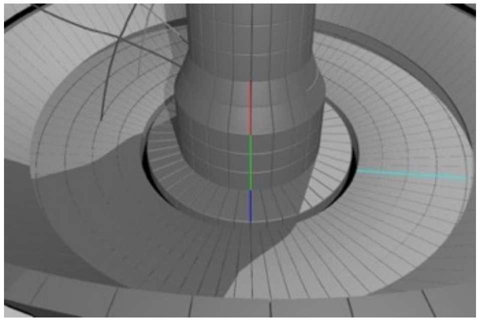
2. **NSTX-U collaboration research**
   - **Contribute to NSTX-U Program activities (e.g., PAC, JRT)**
   - **Develop preliminary concepts for PFC monitoring system**
   - **Contributions to machine, PFC and diagnostic design, engineering, and assessment**



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



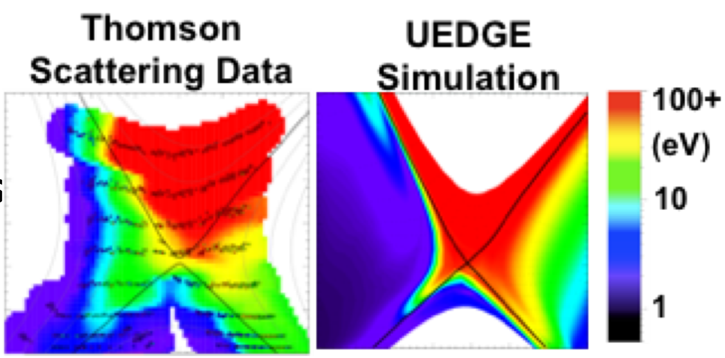
Mega-Ampere Spherical Tokamak Upgrade in Culham Centre for Fusion Energy, Culham, United Kingdom



Conceptual view of PFC monitoring system viewing NSTX-U divertor

Foundations: 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
- We also prioritize our connections to computational mathematics:
  - LLNL Center for Applied Scientific Computing (CASC)
  - LBNL Applied Numerical Algorithms Group (ANAG)

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

FESP Staff go to China several times a year

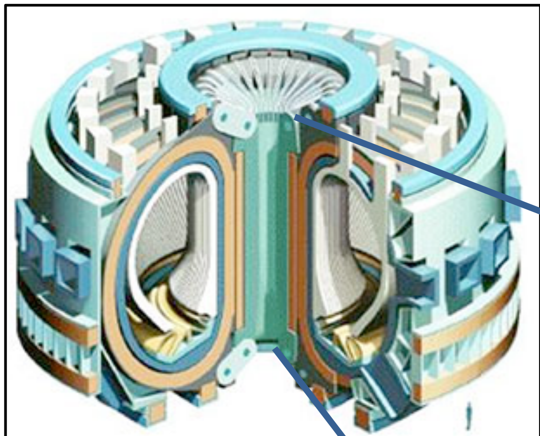
- Whole device modeling
- Advanced Tokamak experiments and remote control

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

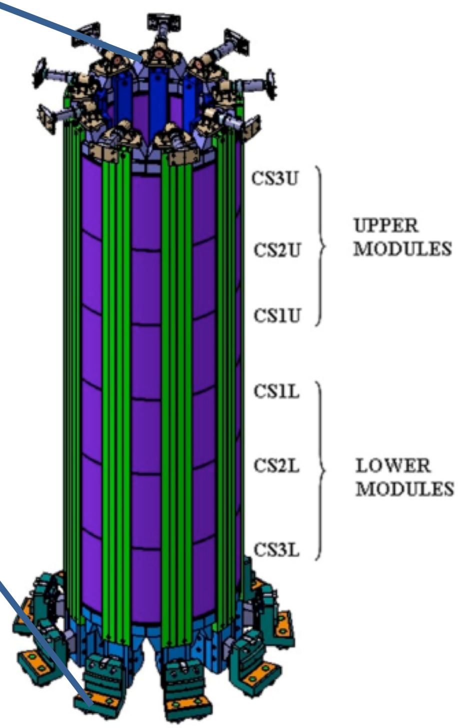
- Plasma-edge physics
- Boundary-turbulence modeling
- Yearly BOUT++ Workshop

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

High-Power: FESP staff performs R&D for design, fabrication, and testing of ITER Central Solenoid



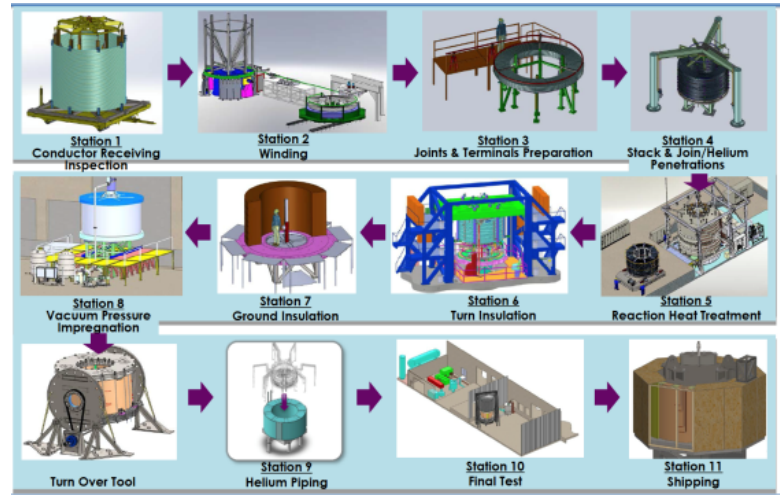
Worlds largest pulsed superconducting magnet



Nicolai Martovetsky:

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

Fabrication process developed and qualified



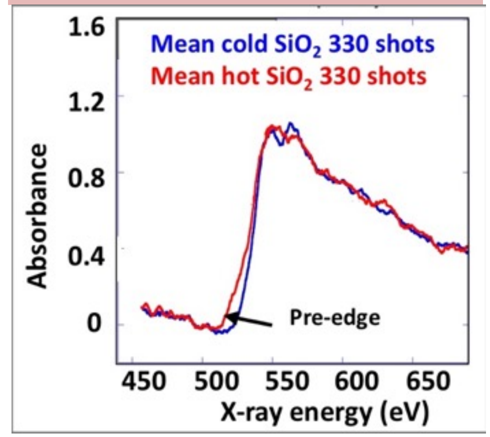
Discovery Science/HEDLP: enhanced by FES-ECRP awards, e.g. Félicie Albert leads laser driven x-ray sources.

- Goal: Use x-rays from laser-plasma accelerators to probe high energy density science experiments using spectroscopy and imaging techniques

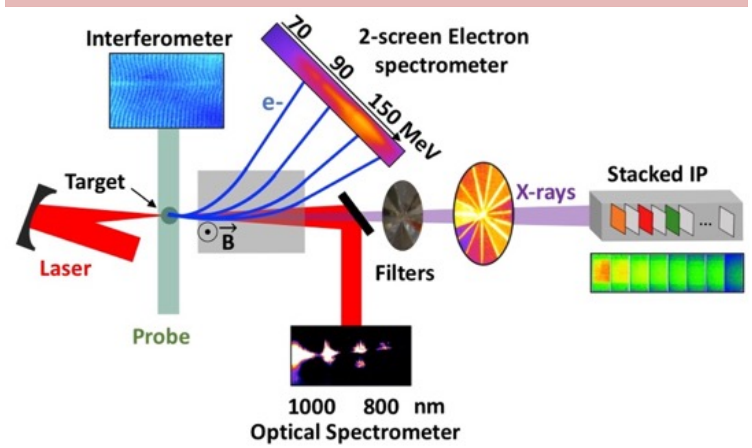
- **Accomplishments in FY18**
  - Continue work on betatron radiation with picosecond lasers with new publications:
    - F. Albert et al, POP (In press, 2018)
    - F. Albert and al., Nuclear Fusion (in press, 2018)
    - N. Lemos et al, PPCF (2018)
    - Publications in preparation: 1 PRL (N. Lemos), 1 RSI and 1 POP (P. King)
  - Continue work on developing and using betatron radiation at LCLS (data analysis of previous experiments, publication in preparation)
  - Invited talks related to the project:
    - APS/DPP 2017 (Katherine Weimer Award), IFSA 2017 (Fabre Prize), IPAC 2018, CLEO 2018, AAC 2018, ICPP 2018, SPIE-OPIC 2018, Nuclear Photonics 2018, PQE 2018, CHILI 2017, ICEL 2017, EAAC 2017.
  - Experiments at large facilities (Titan summer 2018, 2 months)
  - Awarded 2 shot days through NIF discovery science (FY19-20)
  - Hired new LLNL graduate scholar working full time on the project (P. King)

- **Experimental plans for FY19**
  - LCLS experiments: applied for run 17 (results expected in May 2018)
  - OMEGA-EP experiments (applied through LBS, results expected June 2018)
  - JLF/Titan experiments (will apply in Fall)
  - NIF experiments: 1 shot day in FY19

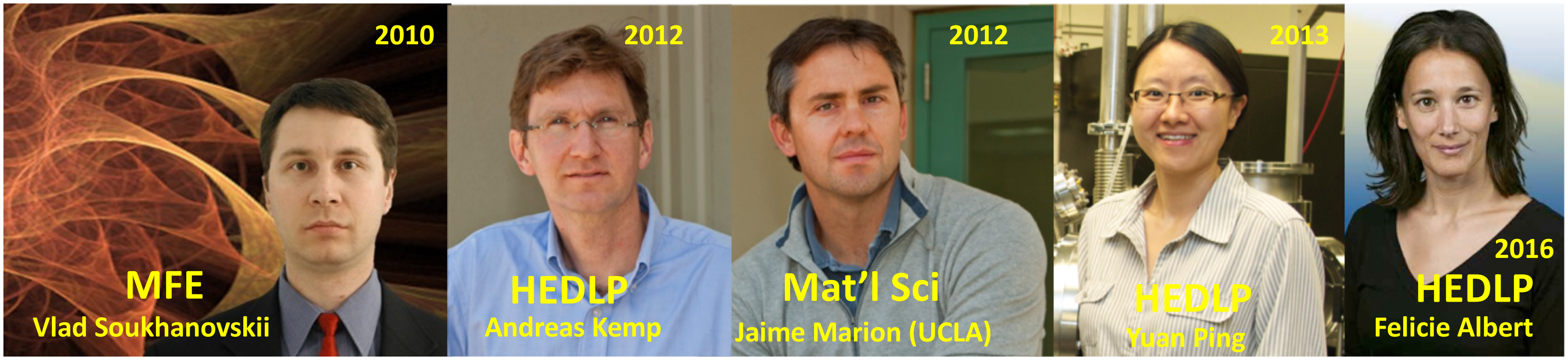
O2 K-edge spectra with LCLS betatron source



Platform for betatron experiments with picosecond lasers



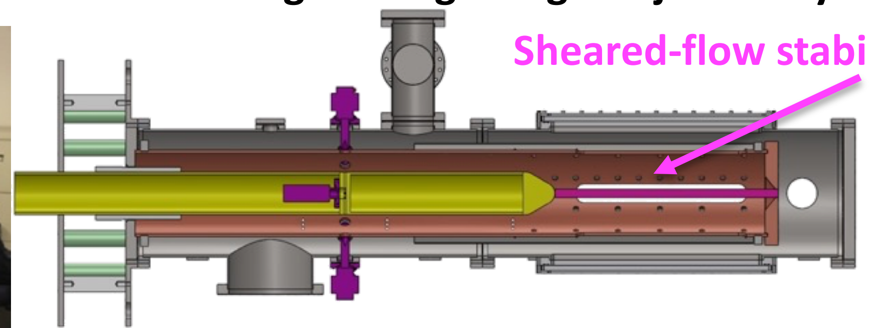
LLNL Researchers have earned 7 DOE Office of Science Early Career Research Program Awards through FESP



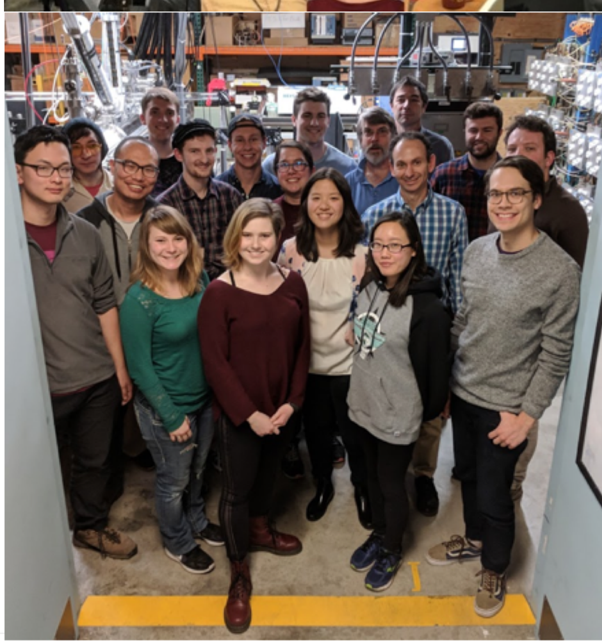
U.S. DEPARTMENT OF
ENERGY
Office of Science
Early Career
Research Program

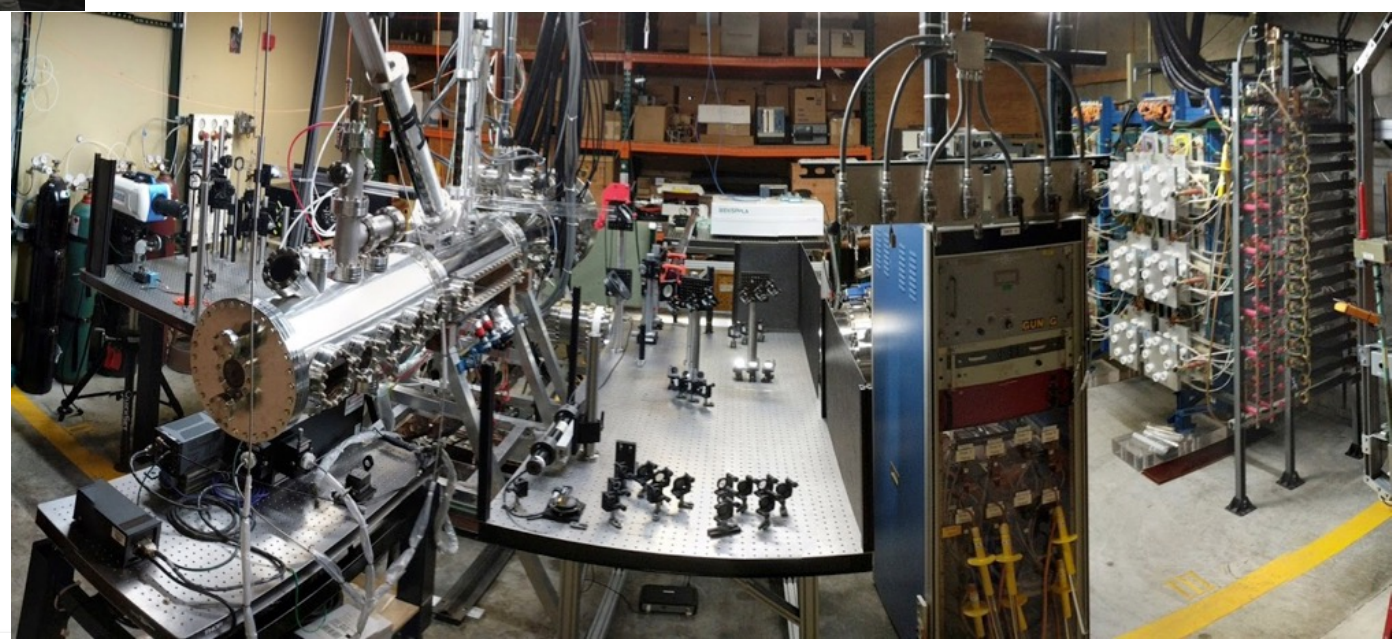
Univ. of Washington / LLNL team awarded $5.6M (3 years) from ARPA-E's Accelerating Low-cost Plasma Heating and Assembly (ALPHA) Program.

- Experimental and computational efforts to answer key questions on whether the sheared-flow stabilized Z-pinch[1] concept has the potential for scaling to a fusion power reactor.
- Based on successful low-power device, the new device at UW handles much higher discharge currents, higher heat loads, and has flexible high voltage an gas injection systems

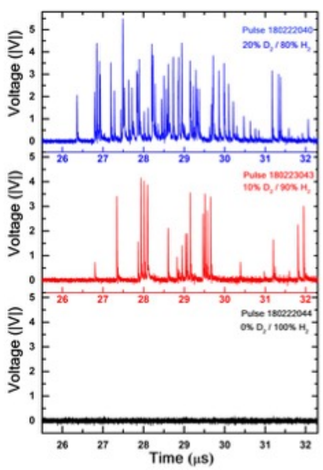


Funded by ARPA-E
$5.8M 3 yrs FY16-18
(2.8 LLNL / 3.0 UW)

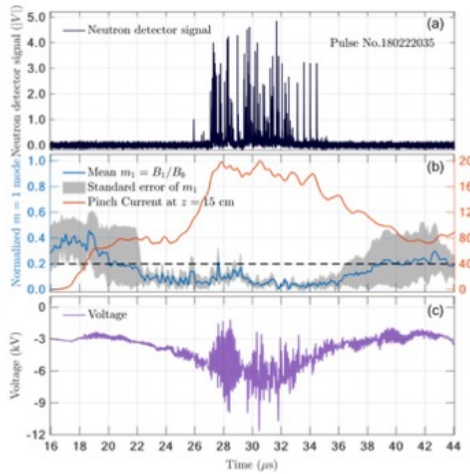




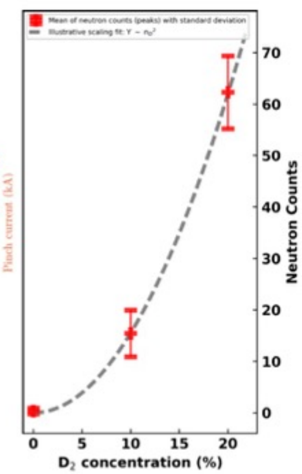
ARPA-E: The 3-year FuZE project has essentially met all technical milestones, is producing DD fusion neutrons, and extending performance to higher current.



Neutron emission depends on D_2 fraction (0%, 10%, 20%)



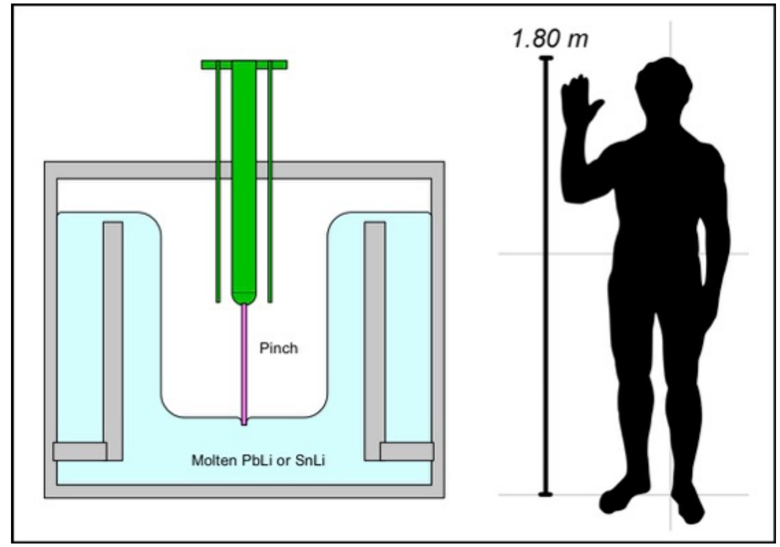
Neutron emission occurs over a 5 μs period; greater than 5000 instability growth times



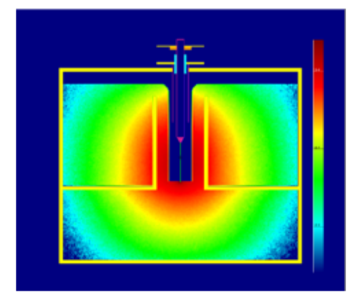
Neutron counts proportional to n_D^2

Present Yield: 10^5 neutrons / pulse for 20% D_2, I_p = 200 kA $n=10^{17}$ cm^{-3}, Ti=1-2 keV
Yield Goal: 10^8 neutrons / pulse for 100% D_2, I_p = 300 kA, $n=10^{18}$ cm^{-3}, Ti>2 keV

100 MWth Reactor embodiment is very compact



Liquid metal:
- **Electrode**
- **Coolant**
- **Tritium breeding**



MCNP calculation of local tritium breeding ratio. Total TBR ~1.1

- **4^{TH} YEAR Extension goal is to achieve routine operation at 300kA and establish capability to push toward 400kA.**
  - **New ignitron bank (6 modules, 20 kV, 6 x 37.5 uF).**
  - **Optimize input parameters (cap-bank volts, gas injection, gas species, timing)**
  - **Modeling to guide experiments and understand physics**

Power reactor requires 1.5 MA in the pinch

Discovery Science/HEDLP:
JLF/Titan Upgrade: 3-year project $2.5M (SC-FES)

FY18-20 JLF Upgrades

- **LLNL's Jupiter Laser Facility short-pulse laser Titan presently operates at maximum 250 J with a minimum pulse length of 700 fs.**
- **A set of improvements will bring the Titan capability to one Petawatt, - 400 J in 400 fs with enhanced shot rate, operational reliability, and beam characterization**

Upgrade requests are guided by community input gathered at the annual NIF/JLF Users Group Mtg

Jupiter Laser Facility User Group Report

By Luke Fletcher and Carolyn Kuranz

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The Jupiter Laser Facility (JLF), operated at the Lawrence Livermore National Laboratory (LLNL), is a unique intermediate-scale multi-platform user facility that has become a critical tool for expanding the frontiers of high energy density (HED) laboratory plasma science. The primary mission of the JLF is to support HED physics at LLNL in several science programs including fusion energy sciences (FES), diagnostic development, plasma physics, and high-pressure physics. The ongoing research at JLF explores an extensive range of topics, from the equation of state of planetary interiors to astrophysical collisionless shocks. Additionally, one of JLF's main objectives is to support, collaborate with, and expand the broader HED physics community in order to train and recruit a future scientific workforce for the National Nuclear Security Administration (NNSA) and Office of Science laboratories.

In FY16 JLF served approximately 200 of the 500 registered users from the academic, national laboratory, and international community. Experimental time for these users' projects was allotted through a peer-reviewed proposal process where over 50% of the proposals were turned down. In the past 10 years since JLF converted to an open Office-of-Science style user facility (beginning in FY08), 93 students have received PhDs where work at JLF was an important component of their thesis research and 94% stayed in HED science labs or universities. In addition to being a training ground for graduate students and postdoctoral scholars, the JLF is a highly productive scientific user facility. There are approximately 8-9 experiments in each target area performed yearly. In the past 10 years, on average, users published results from over 20 refereed journal articles per year, a metric that has consistently remained stable over the years even as the JLF budget has been funded at, or near, the same level since FY08. Furthermore, every year 1 in every 4 of the refereed articles is published in high-impact journals as defined by the Department of Energy (DOE). In keeping with the multidisciplinary nature of the facility, JLF publications reflect the wide range of fields represented by the HED user community: laser-plasma instabilities, materials science, plasma physics, and collisionless shock properties. In addition to publications, in the last year 1 of the 49 DOE early career awards allocated was granted for research that has been and will be performed at the JLF.

While JLF's resources have contracted in recent years, the growing demand for high quality HED experiments has simultaneously increased. In order to meet the demand for a growing and diverse user consortium, the necessary investment of resources from the broader HED and FES community will be required. The user group has identified a series of recommendations that cover a broad range of operational improvements with a general focus on improving laser stability and characterization for the Janus and Titan beamlines. A contract between the user community and the facility should establish a set of baseline standards in terms of deliverable laser specifications that should always be met. The most reiterated recommendation by the user group was the stabilization of the JLF lasers including: shot-to-shot repeatability, reliability, and a way to measure such laser parameters. Such measurements are crucial for improving experimental quality as well as evidence of specifications that are met or exceeded by the facility. An effort needs to be made to characterize each component of the laser in a systematic way that avoids combining elements of the system into an inefficient design. Permanent beamline diagnostics to measure laser performance, that are maintained and operated by the facility, will be a necessary addition to ensure operational quality. The user group, in collaboration with LLNL management, have conducted a thorough assessment of community needs and realistic deliverables. This report will help the facility identify a specific set of additions and refurbishments that can be completed for optimal laser and diagnostic performance. The review, and possible implementation of improvements, will be available in the next fiscal year.

"The user group has identified a series of recommendations that cover a broad range of operational improvements with a general focus on improving laser stability and characterization for the Janus and Titan beamlines."

LLNL Infrastructure Investments: In addition to 2.5M FES-funded capability enhancements, LLNL will address key needs and restore world-class capabilities to the Jupiter Laser Facility with a 8.5M infrastructure refurbishment

- The refurbishment is the first reinvestment in JLF in a decade
- It will correct numerous hardware and optics issues that have accumulated, replace 40-to-50-year-old capacitors, modernize components, install laser system diagnostics, return the systems to original or improved specs, enhance target area user diagnostics, and purchase critical spare parts
- The full investment is \$8.5M (LLNL) + \$2.5M (FES) over ~3 years:
  - FY2018: half the year on procurements and installation; half on user operations and accumulating performance data
  - FY2019: major procurements; half the year on installation and half on user operations
  - FY2020: major components installation; expand Laser Bay; no user operations
  - FY2021: normal user ops; final target area diagnostics installed
- With these measures, JLF will provide world-class capabilities to HED users until some time beyond 2030 including the newly-formed LaserNetUS

Outlook for 2020's

- 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
  - Explore partnerships with ARPA-E and Private Industry
- Pursue Exascale computing relevant to 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
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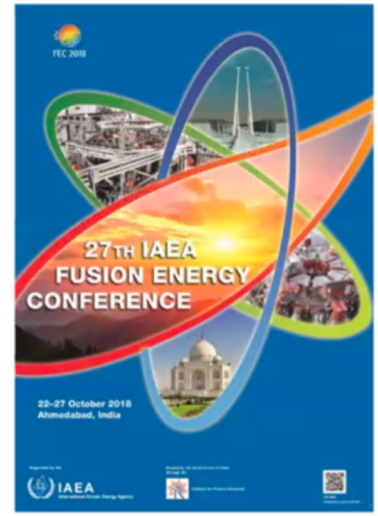
Additional planning activities, reports, and studies…

FESP Significant Recognition FY18-19

- **APS DPP 2018 Meeting features 6 invited talks: 4 FESP plus 2 ECRP-related**
  - **Adam McLean: DIII-D,** Validating divertor power exhaust models with VUV Spectroscopy measurements
  - **Kurt Tummel: ARPA-E,** Stability conditions for sheared-flow-stabilized Z-Pinch via fully kinetic PIC
  - **Drew Higginson: Basic Plasma Physics,** Applications for kinetic-Ion Particle-in-Cell Modeling
  - **Sheng Jiang: Particles and Beams,** Electrode polarity effects in the DPF
  - **Nuno Lemos (Felicie Albert's ECRP),** Hard x-rays via self-modulated LWA
  - **Derek Mariscal (Tammy Ma's ECRP),** Demonstration of ARC-accelerated Proto Beams at NIF
- **APS-DPP John Dawson Excellence in Plasma Physics Award**
  - **Max Fenstermacher, DIII-D Elm Stabilization (with R. Moyer and T. Evans)**
- **Six FESP papers (including one oral) were selected for biennial IAEA Fusion Energy Conference 2018.**



- **FESP researcher received award at the 2017 Fusion Power Associates meeting:**
  - **Excellence in Fusion Engineering Award for Chris Holcomb**

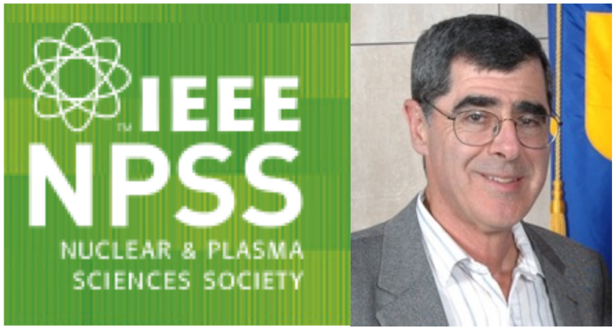
Fusion Power Associates

- **Two additional Early Career Research Program Awards brings total to seven for LLNL FESP**
  - **Tammy Ma**: **"Multi-ps Short-Pulse Laser-Driven Particle Acceleration for Novel HED Applications"**
  - **Alex Zylstra**: **"Studying Nuclear Astrophysics with Inertial Fusion Implosions"**

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

Awards and Recognition

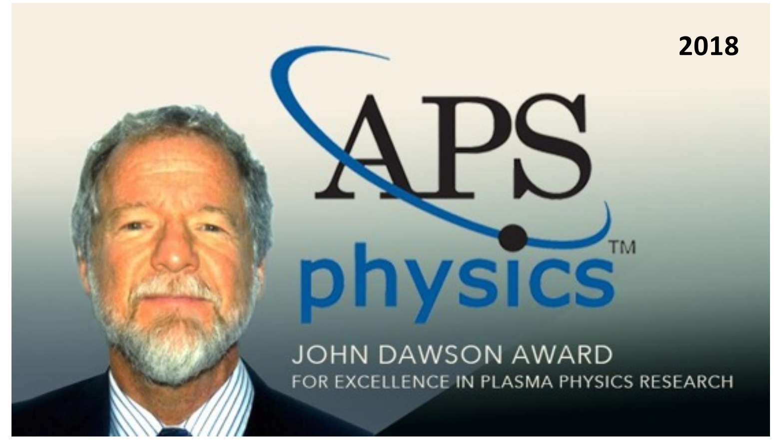
Bruce Cohen



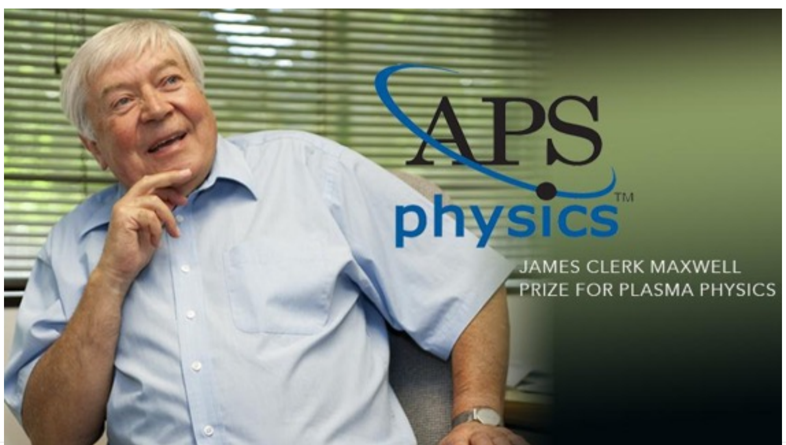
Charles K. Birdsall Award for Contributions to Computational Nuclear and Plasma Sciences

Chris Holcomb

Max Fenstermacher



Dmitri Ryutov



Felicie Albert

Lawrence Livermore National Laboratory