Fusion Energy Sciences Program at LLNL

2022 Fusion Power Associates Meeting

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Associate Division Leader, PLS/Physics

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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

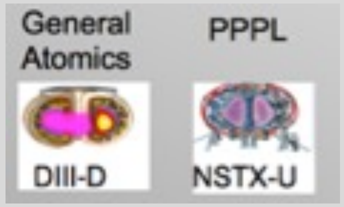
- **Fusion Science and Plasma Physics:** core competencies and disciplines essential to LLNL's mission-based science from both NNSA and SC perspectives.
- **S&T for HEDS:** The SKAs underlying Burning Plasmas is central to LLNL's HEDS applications space.
- **Partnering within LLNL:** exploit capabilities 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's Fusion Energy Sciences Program (FESP) executes in all SC FES research areas

SC FES FY22 (~700 M$)

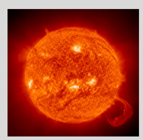
- **Foundations (~300M)**
  - MFE Experiments
  - MFE Theory



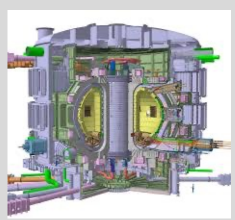
- **Long Pulse (~100M)**
  - Superconducting Tokamaks
  - Stellarator Experiments
  - Materials
  - Technology

EAST (China)

- **Discovery Plasma Sci. (~50M)**
  - General Plasma Science
  - Measurement Innovation
  - HEDLP: Expts at JLF, NIF, SLAC/LCLS, LLE/OMEGA
  - Quantum Information Sci



- **ITER + MEC (~250M)**
  - US-ITER Project Office
  - ITER Organization
  - MEC ~ 11 M

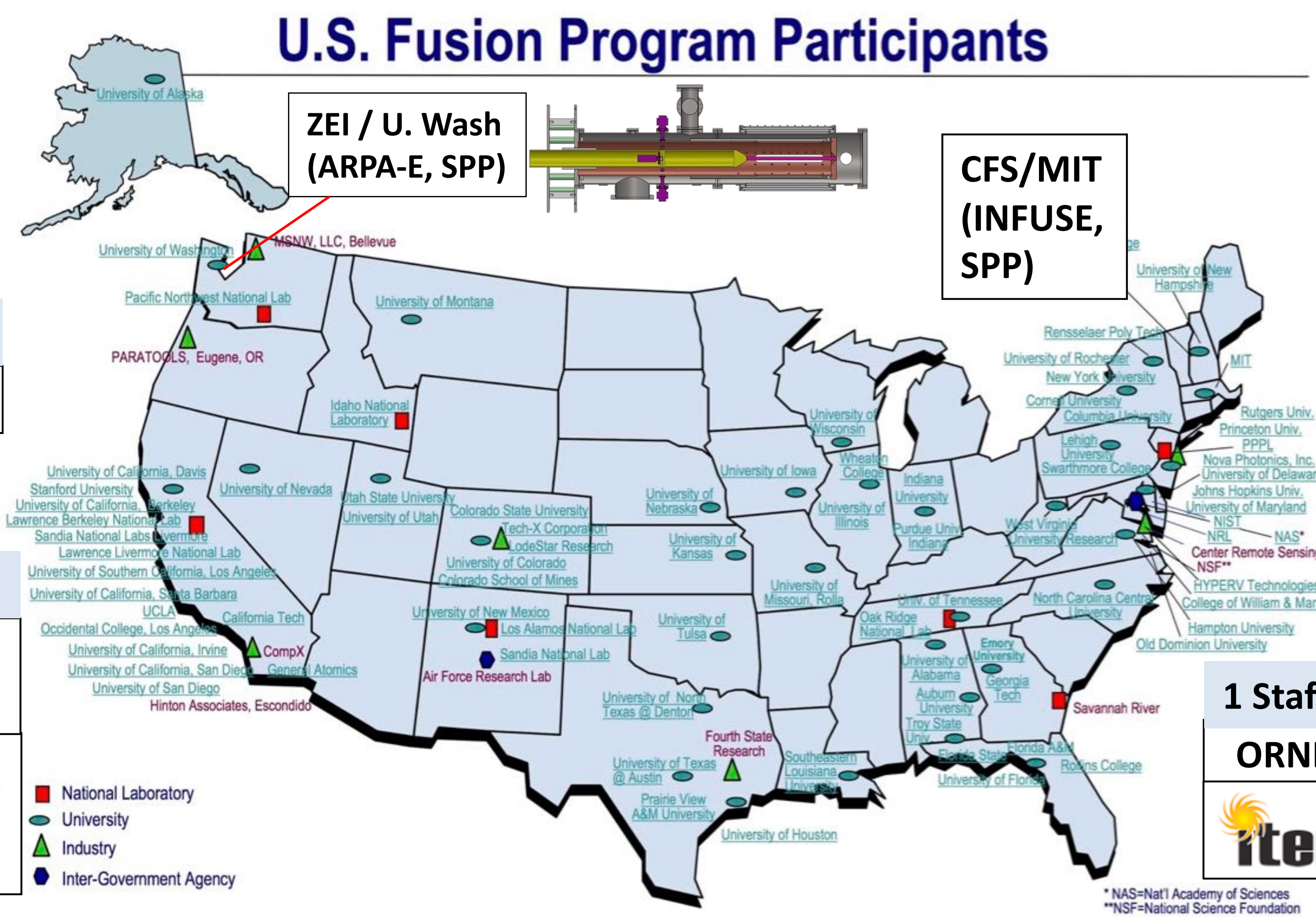


ITER (France)

LLNL FES Program FY22 (~16 M$)

- **Foundations (~10M):**
  - 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 (~2M)**
  - International: EAST (China)
  - Materials and Fusion Nuclear Science
- **Discovery Plasma (~4M)**
  - 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, 4 FY22, 3 FY23)
    - LaserNetUS (experimental support)
  - QIS: Hardware and software (fusion applications)
- **Construction: ITER (1 FTE)**

LLNL/FESP participates at the primary SC-FES MFE Facilities and several private efforts



ZEI / U. Wash (ARPA-E, SPP)

CFS/MIT (INFUSE, SPP)

30 Staff

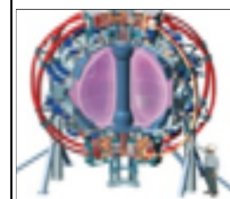
LLNL

10 Staff

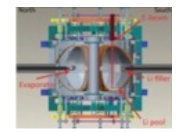
General Atomics

2 Staff

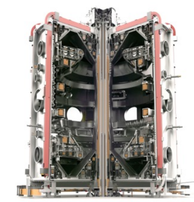
PPPL



NSTX-U



LTX-β



Mast

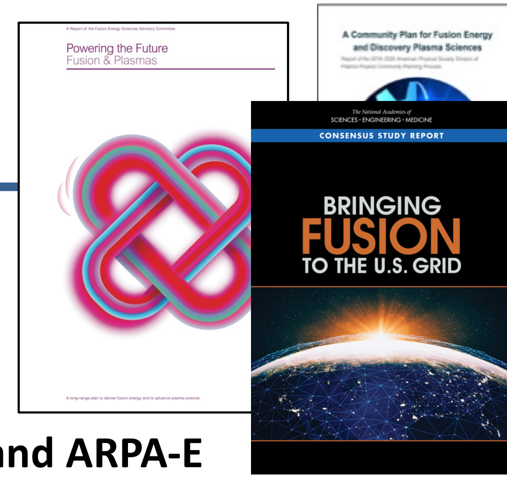
1 Staff

ORNL

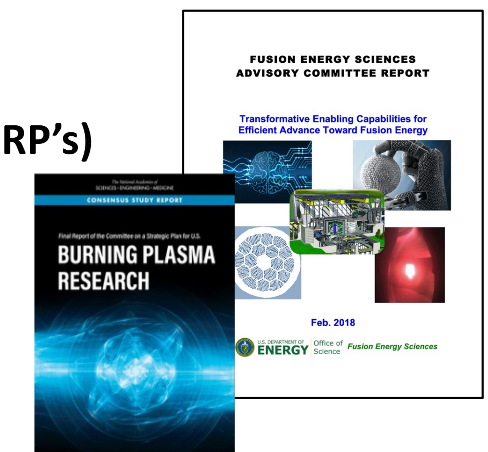
US iter

National presence is boosted by having permanent LLNL staff in residence

LLNL FESP “road ahead” for 2023 and beyond is aligned with the recent community reports



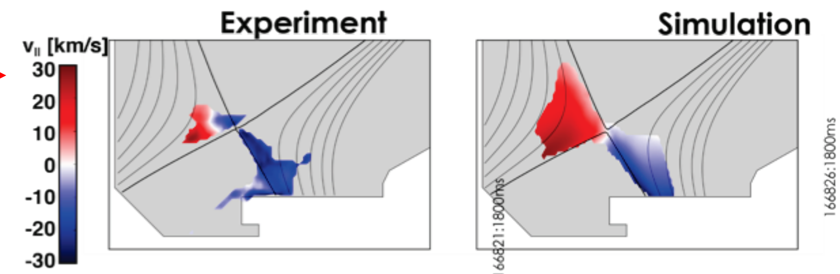
- **Continue MFE experimental and theoretical basic research:**
  - National research (DIII-D, NSTX-U, LTX-β)
  - International research (MAST-U, EAST, KSTAR)
  - Preparations for ITER and the burning plasma era
  - Expand partnerships with Private Industry via FES INFUSE/Milestone and ARPA-E
- **Establish capabilities relevant to FPP divertor design and whole-device modeling**
  - Leverage partnerships within LLNL between FESP (SC-FES) and CASC (SC-ASCR), new LDRD
  - Expand collaborations beyond LLNL e.g. SC-FES and SC-ASCR supported institutions, PPP
  - Exploit our SciDAC Engagement, QIS explorations, AI/machine learning projects
- **Expand efforts to utilize LLNL’s extensive Materials and Technology expertise**
  - PFC model validation, advanced design studies to include liquid metals/liquid walls (FESP)
  - Predictive modeling of material behavior (LLNL Material Science Division, new FES ECRP)
  - 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
  - Steward existing activities and foster new opportunities in LaserNetUS:
    - LCLS (BES/FES), JLF/NIF (NNSA), and BELLA Center (HEP)
    - Respond to FES and user needs
  - Re-initiate appropriate IFE activities as guided by upcoming BRN Report



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

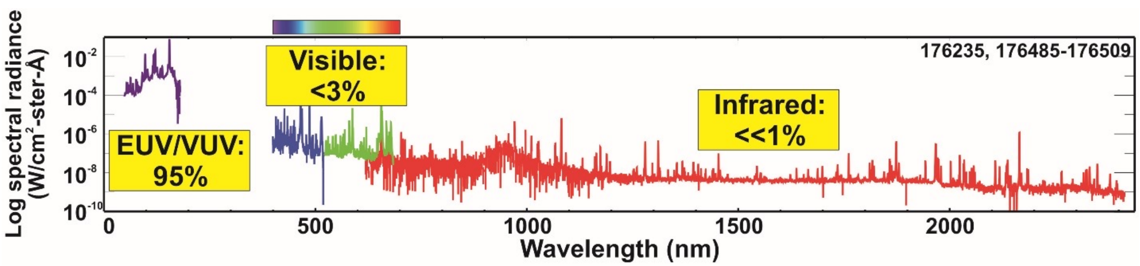
LLNL at DIII-D is focused on Divertor Science and Advanced Tokamak (Steady-state operation) Research

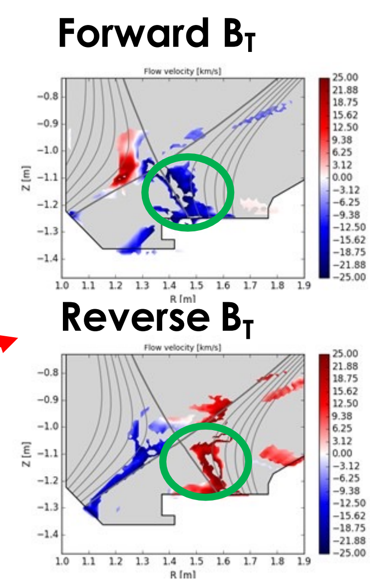
1. **Divertor Science: detachment / model validation / building design tools**
   - EUV spectroscopy, Infrared imaging, divertor T_i
   - UEDGE modeling, including plasma flow effects
   - Snowflake joint project: DIII-D, LLNL Theory, NSTX



2. **Advanced Tokamak program and Scenario Development**
   - Long-pulse scenario optimization, Dynamics & Control
   - Core impurity measurements/ transport
   - International Collaborations with EAST, KSTAR

3. **Staff contributes operational support via Plasma Diagnostics**
   - LLNL leads routine operation of many critical diagnostic systems
   - Example: Building continuous absolutely-calibrated capability from IR to EUV



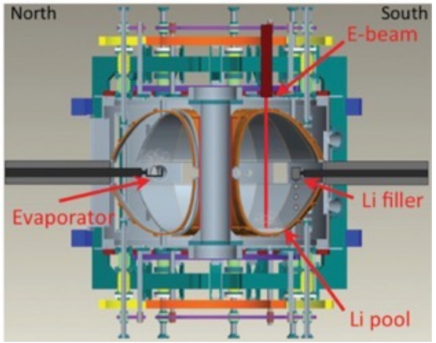


4. **Collaboration with Universities**
   - Coherence Imaging diagnostic (Auburn, ANU, AALTO)
     - Flow vs. B_{Tor} polarity in SOL and divertor directly impacts detachment
   - EUV, SHS Spectrometers, Tungsten Source Rates, (UCSD, UW-Madison)

LLNL staff hold management and technical leadership positions within DIII-D National Program

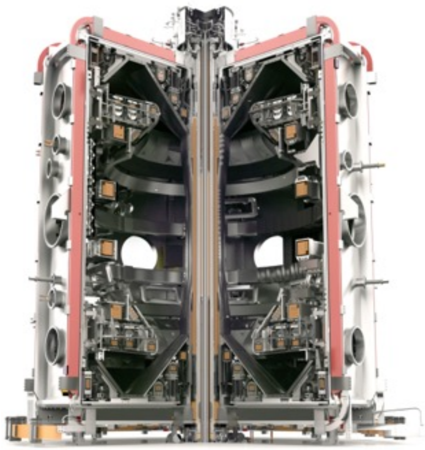
LLNL Experimental Research at PPPL is focused on Spherical Tokamak Program: LTX, MAST-U, and NSTX-U Recovery/Physics Planning

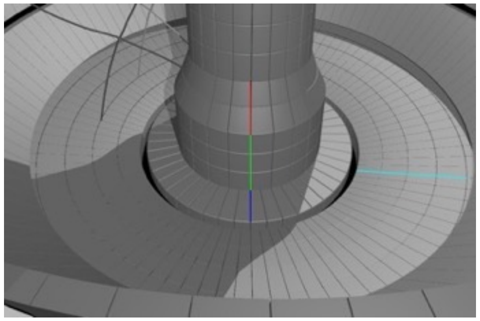
1. **Boundary Physics Research on Spherical Tokamaks**
   - Lithium Tokamak Experiment (LTX)–beta
     - SOL turbulence
     - PFC studies, Lithium sputtering measurements
   - Mega-Ampere Spherical Tokamak Upgrade (MAST-U) in the U.K.
     - Fielding Diagnostics
     - Divertor detachment and snowflake divertor studies



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

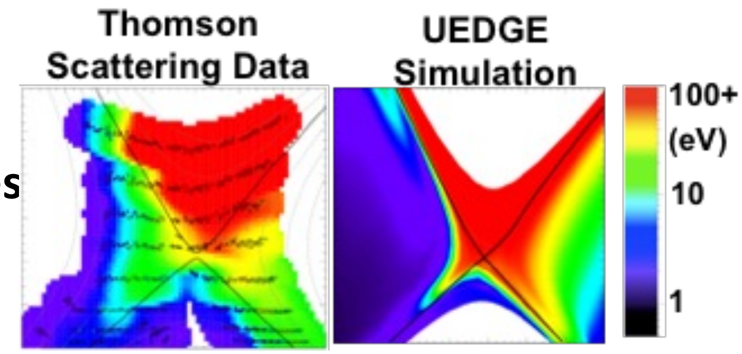
2. **NSTX-U collaboration research**
   - NSTX-U Program activities, Research Objective Leadership
   - Developing preliminary concepts for PFC monitoring system
   - Contributions to machine, PFC and diagnostic design, engineering, and assessment


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

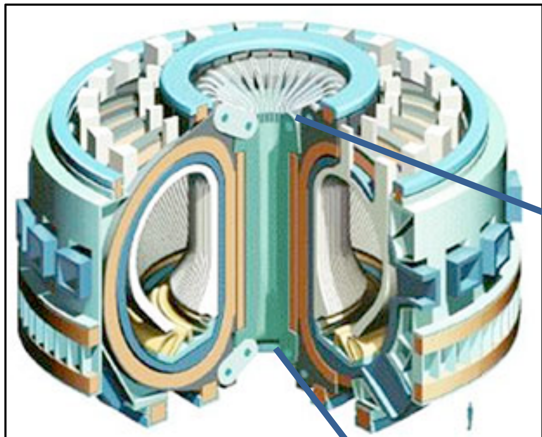
- Whole device modeling
- Advanced Tokamak experiments and remote control

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

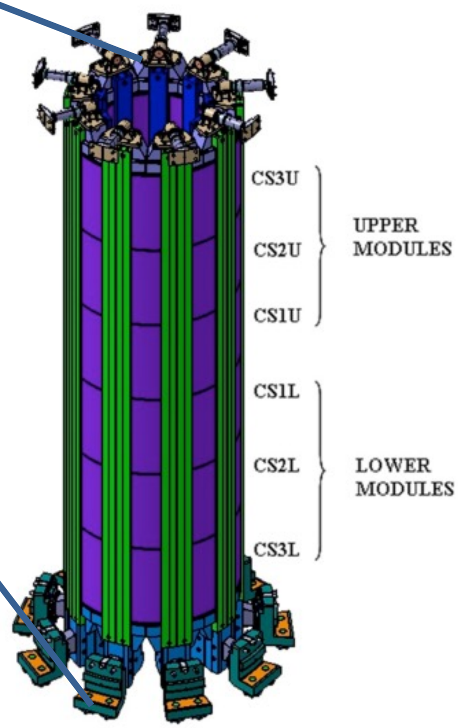
- Plasma-edge physics
- Boundary-turbulence modeling
- Yearly BOUT++ Workshop
- LLNL hosted US-PRC MFE Workshop in Spring 2021

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

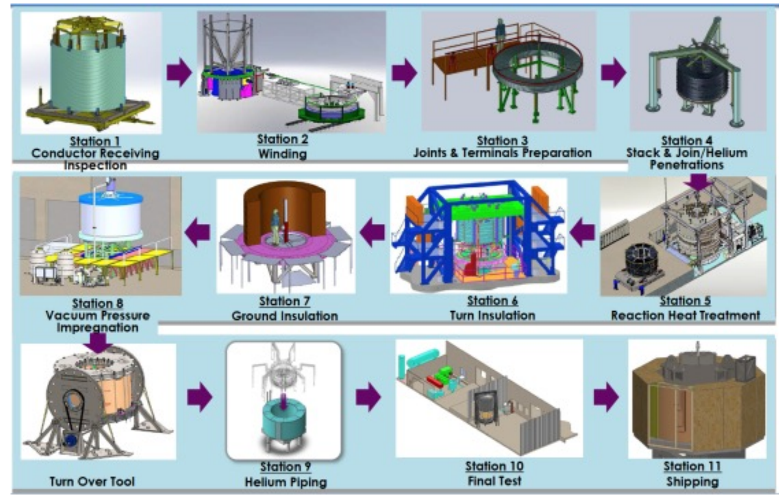


Worlds largest pulsed superconducting magnet



Nicolai Martovetsky:
LLNL Scientist/Engineer for US ITER magnet systems, assigned at ITER-US at ORNL (now retired-Thank you!)

Fabrication process developed and qualified

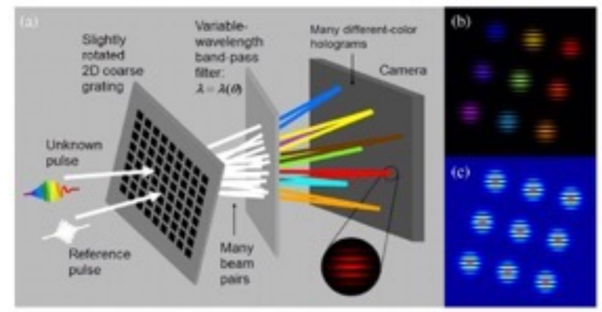


Discovery Science/HEDLP: enhanced by FES-ECRP awards

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

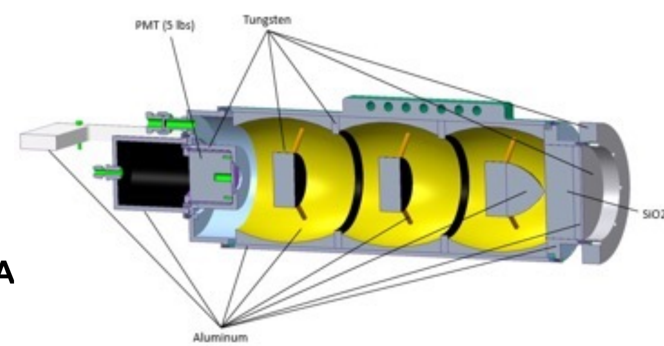
STRIPED FISH diagnostic for complete spatiotemporal single-shot measurement of high-intensity lasers.



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

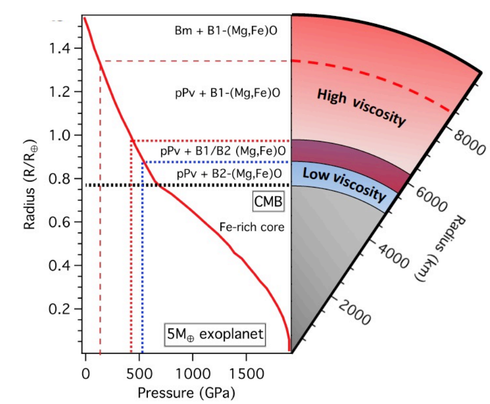
Goal: Improve our understanding of how the elements were produced by nucleosynthesis processes in the universe by studying nuclear reactions in analogous laboratory plasmas.

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



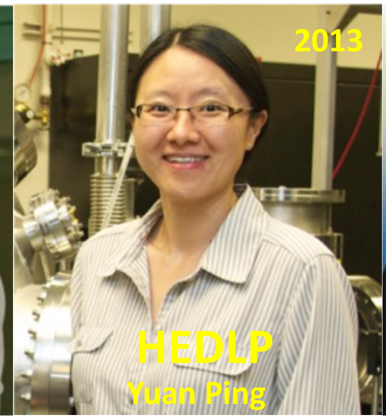
ECRP 3 (Coppari): Expanding Capabilities to Unlock the Mysteries of Complex Warm Dense Matter

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)

LLNL Researchers have earned 10 DOE Office of Science Early Career Research Program Awards through FES



U.S. DEPARTMENT OF ENERGY

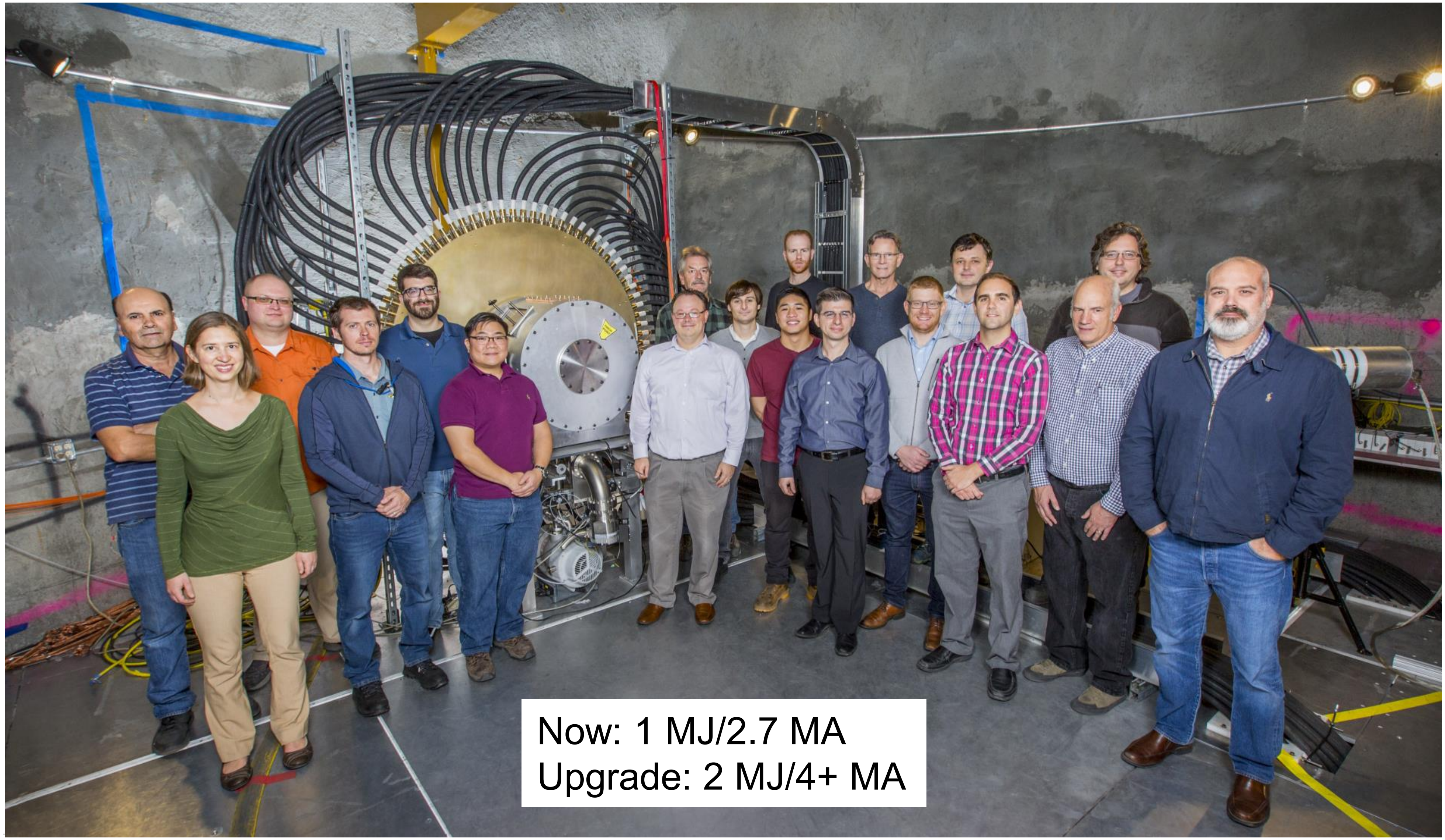
Office of Science

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 $21.8M*

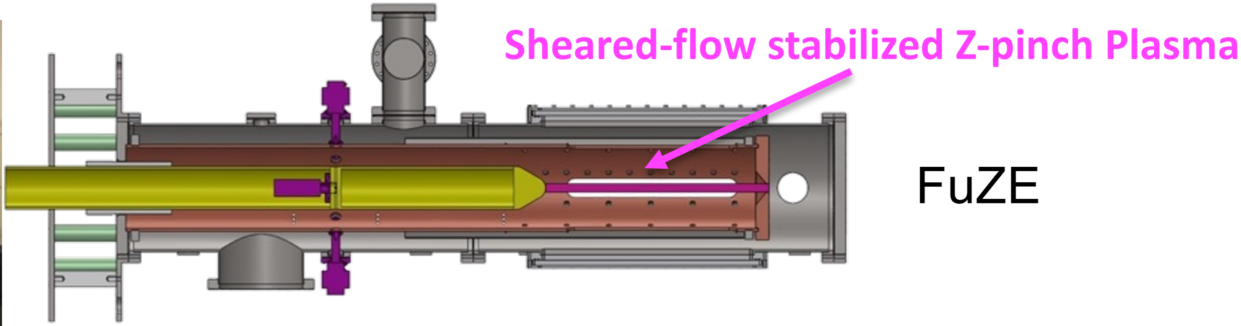
Pulsed Power Fusion Group operates Mjolnir, a multi-MJ DPF in the previous NOVA Laser Facility building for National Security Missions

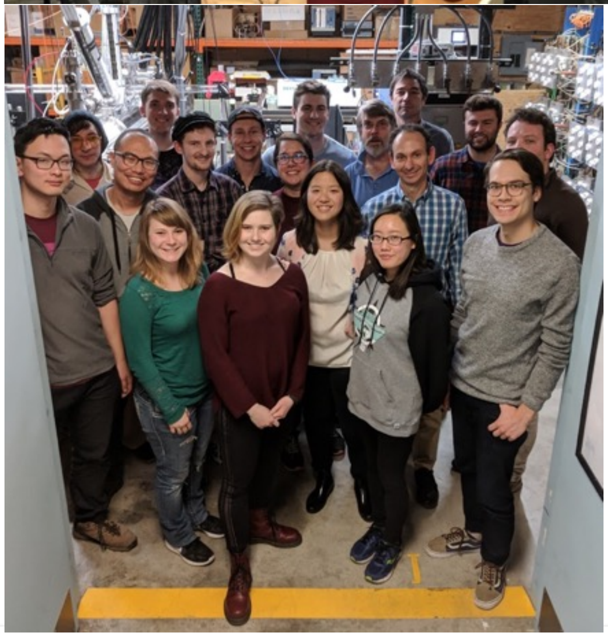


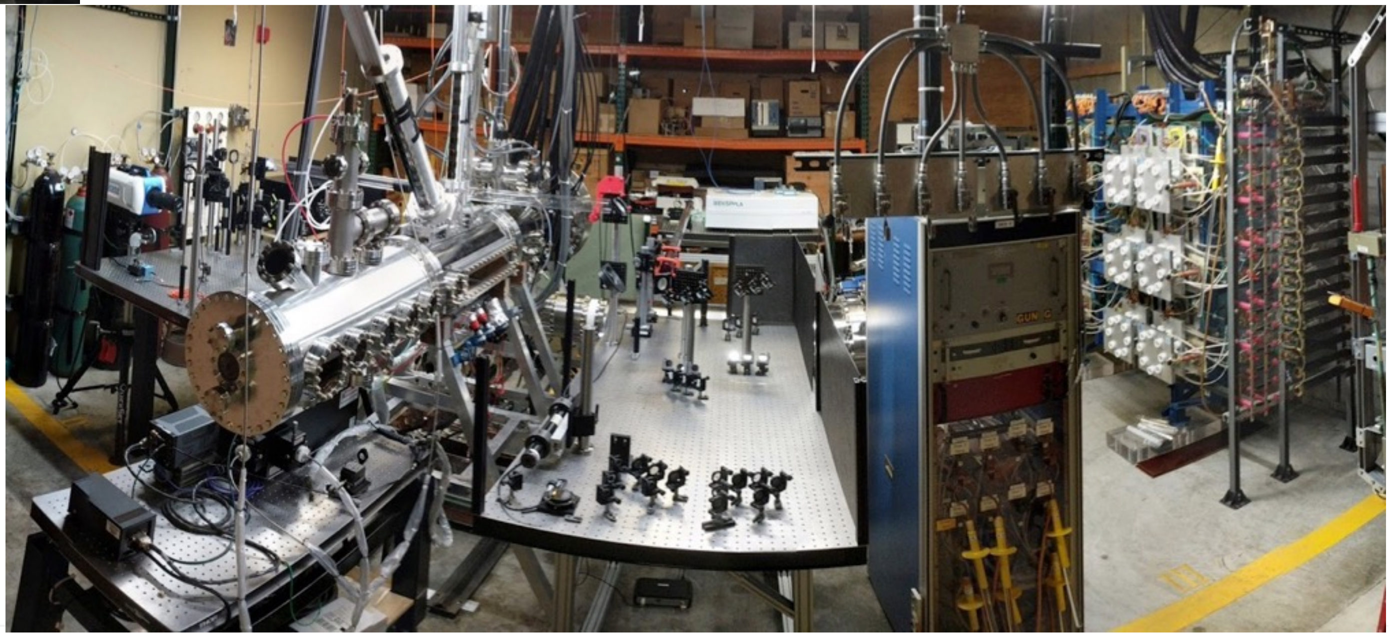
Now: 1 MJ/2.7 MA
Upgrade: 2 MJ/4+ MA

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

- **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)**





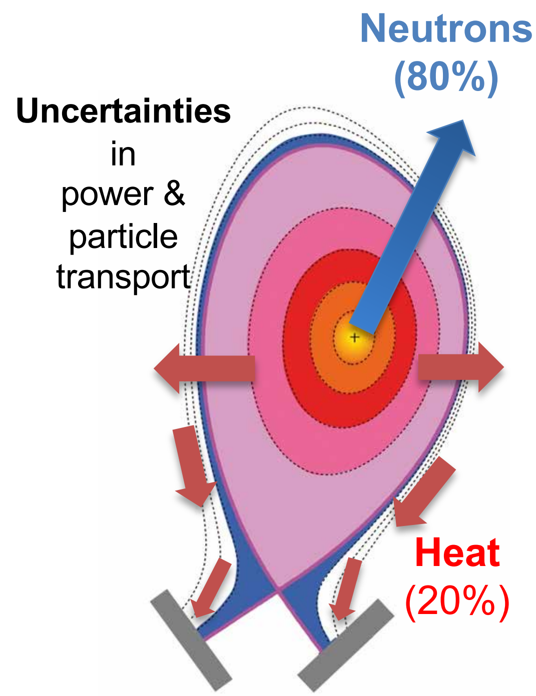


Recent LLNL initiatives support activities to establish capabilities relevant to FPP divertor design and whole-device modeling

- **LLNL is a leader in tokamak divertor science but needs to adapt that science into practical and efficient design tools with quantified confidence/risk**
  - **New Institutional LDRD ($1.8M) : Develop an integrated divertor design optimization capability, combining advanced simulation, data-driven, and ML methods.**
  - **Partnering with LLNL Computations and Adv. Scientific Computing**
  - **Making existing tools (e.g. UEDGE) more robust and less-dependent on human interaction**
  - **Characterize critical uncertainties in divertor performance using modern UQ design tools**
  - **Perform sensitivity analyses to identify key parameters**
  - **Validation through appropriate leveraging of DIII-D and other DOE program data and analysis.**

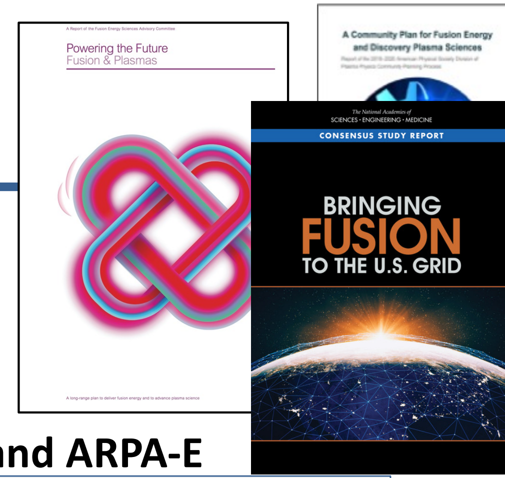
- **Exploiting LLNL's extensive Materials and Technology expertise**
  - **New FES ECRP Predictive modeling of material behavior (LLNL Material Science Division,)**
  - **Additive manufacturing of tungsten (LLNL Material Science Division)**

Divertor shape optimization



Challenging heat fluxes (~ GW/m^2)

LLNL FESP “road ahead” for 2023 and beyond is to initiate/execute community report guidance



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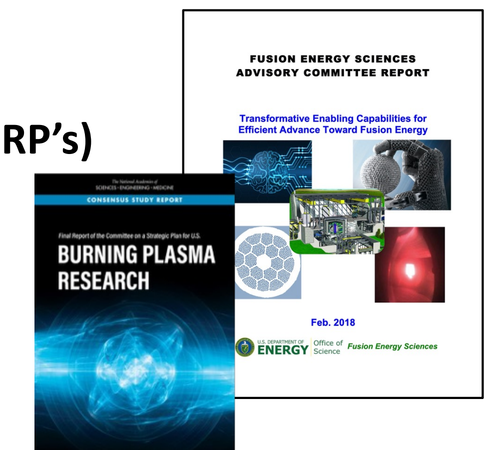

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