DOE/FES, ARPA-E, and (mostly) non-NNSA Parts of Fusion Energy Sciences at LLNL:

2019 FPA Meeting

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

December 3-4, 2019

LLNL-PRES-763608
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

Lawrence Livermore National Laboratory

The Fusion Energy Sciences Program at LLNL (FESP) leads MFE, ARPA-E, and many non-NNSA Plasma Physics areas

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

- **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:** shared capabilities with LLNL Engineering on pulse-power driven fusion devices (DPF, "other" areas and sponsors)
- **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.

Fusion delivers mission science, discovery science, and workforce development

LLNL FES Program and Discipline FY19 Organization

Harry McLean
FES Program Leader
ADL PLS/PHYS

National Security Applied Plasmas
John Barnard

Pulsed Power Fusion Plasmas
Andrea Schmidt (APL)

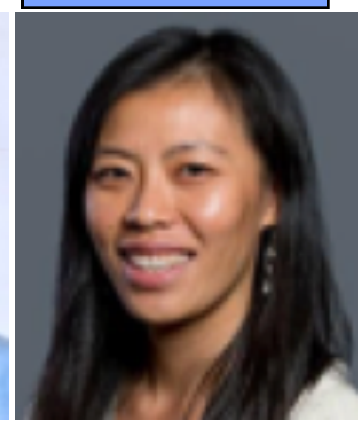
Theory & Modeling
Alex Friedman

DIII-D
Steve Allen

NSTX-U
Vlad Soukhanovskii

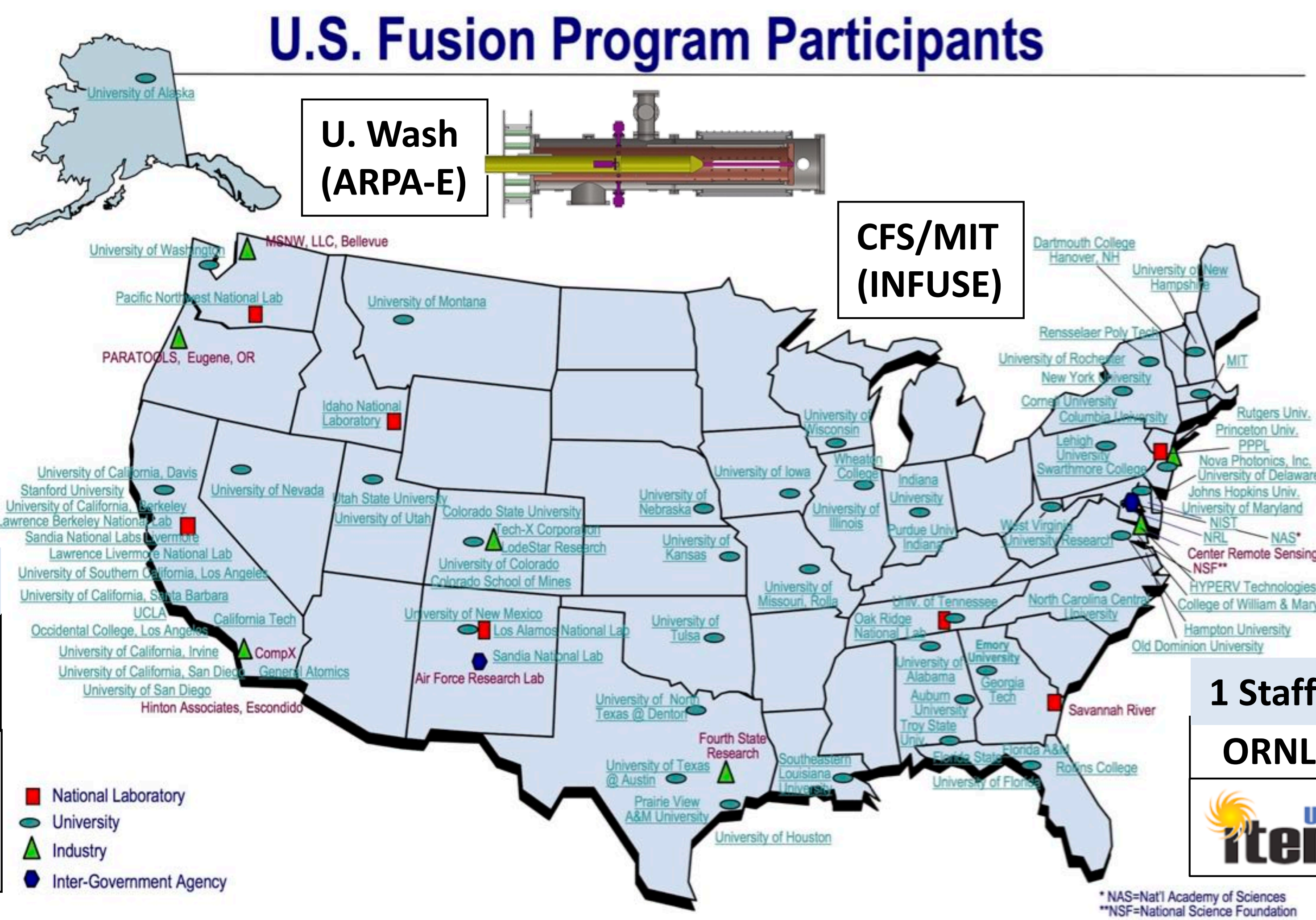
Mat'ls & Technology
Tom Rognlien

HEDLP/LaserNetUS
Tammy Ma



ITER Magnets
Nicolai Martovetsky

LLNL/FESP participates at the primary US MFE Facilities



U. Wash (ARPA-E)

CFS/MIT (INFUSE)

30 Staff

LLNL

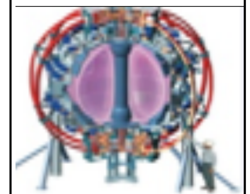
10 Staff

General Atomics

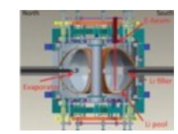
DIII-D

2 Staff

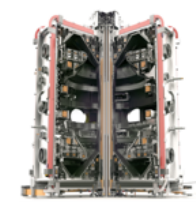
PPPL



NSTX-U



LTX-β



Mast

1 Staff

ORNL

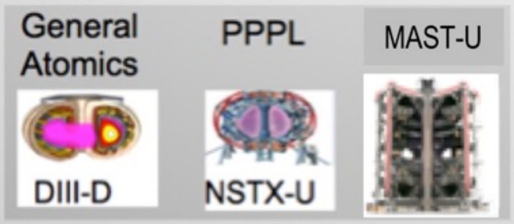
US iter

National presence is boosted by having permanent LLNL staff in residence

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

DOE SC FES

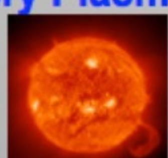
- **Foundations**: Science of plasmas for magnetic fusion

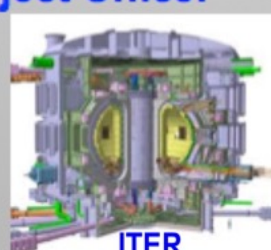


- **Long Pulse**:
  Long pulse tokamaks & stellarators, and fusion materials & technology

EAST (China)
KSTAR (S. Korea)

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



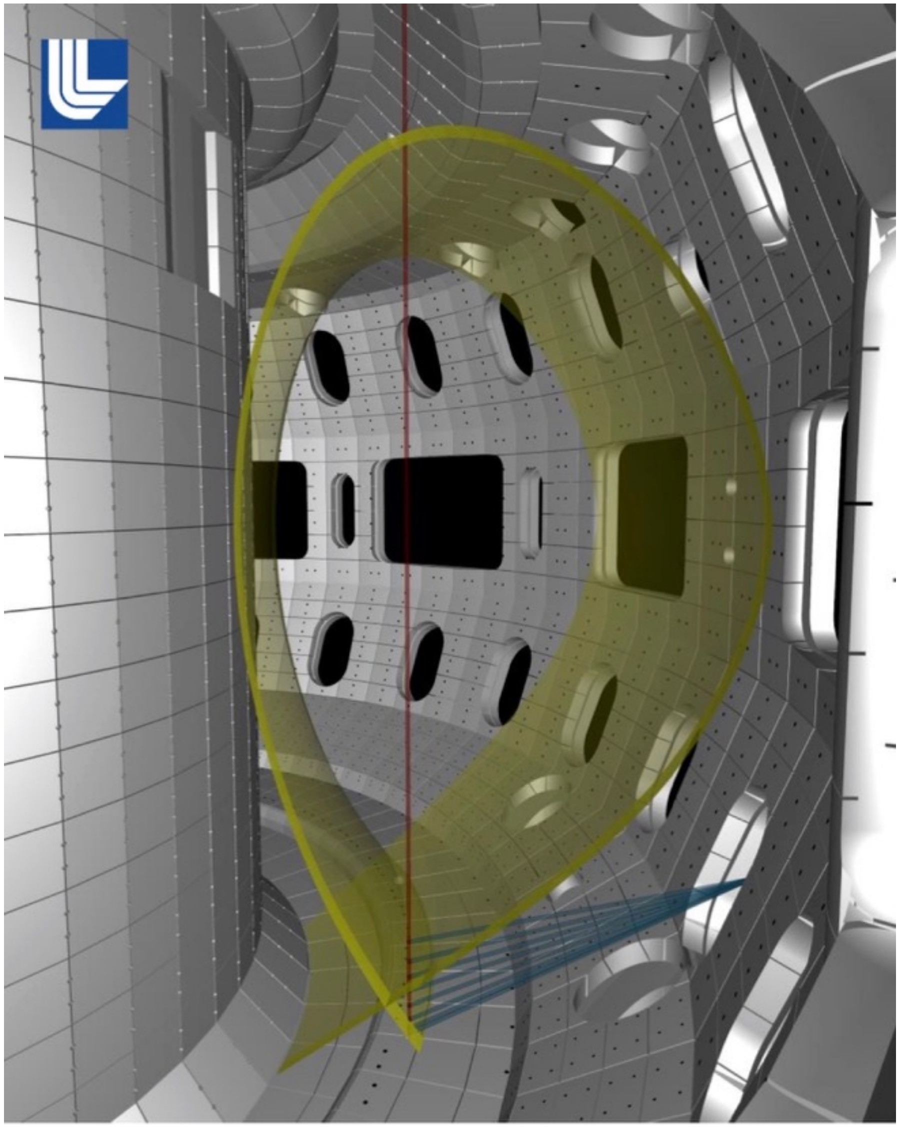


LLNL FES Program (FESP)

- **Foundations:**
  - DIII-D collaboration at GA, 10 LLNL staff in residence
  - PPPL, MAST(UK) collaboration, 2 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
  - HEDLP:
    - Expts at JLF, NIF, SLAC/LCLS, LLE/OMEGA
    - Three (current) HEDS FES Early Career awards
    - LaserNetUS: New initiative, 9-hubs including JLF

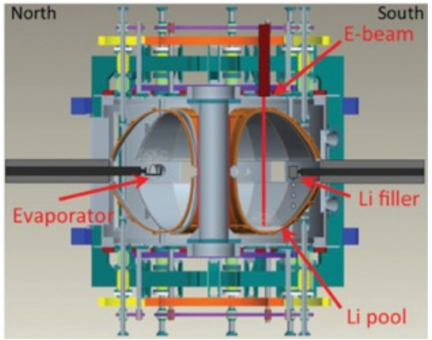
LLNL at DIII-D is active in both Divertor Science and Advanced Tokamak (Steady-state operation) Research

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



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

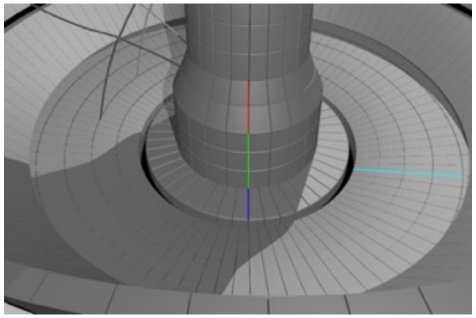
1. **Boundary Physics Research on Spherical Tokamaks**
   - Lithium Tokamak Experiment (LTX)–beta
     - SOL turbulence and plasma-surface interactions with liquid lithium and tin
   - Mega-Ampere Spherical Tokamak Upgrade (MAST-U) in the U.K.
     - Divertor detachment and snowflake divertor studies

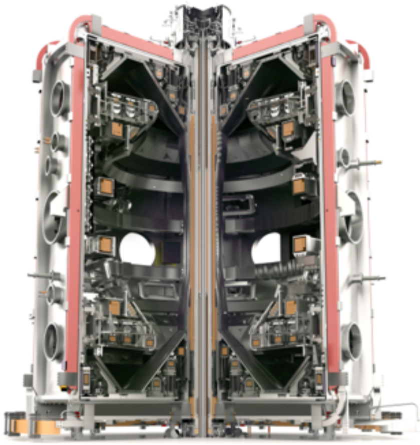


Lithium Tokamak eXperiment Beta in Princeton Plasma Physics Laboratory, Princeton, New Jersey

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

Conceptual view of PFC monitoring system viewing NSTX-U divertor

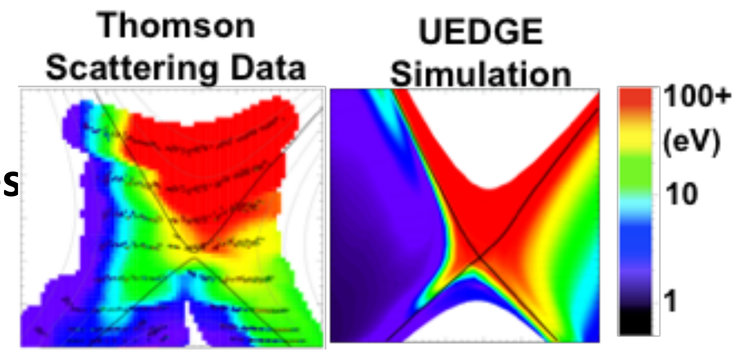




Mega-Ampere Spherical Tokamak Upgrade in Culham Centre for Fusion Energy, Culham, United Kingdom

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
- We also prioritize our 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

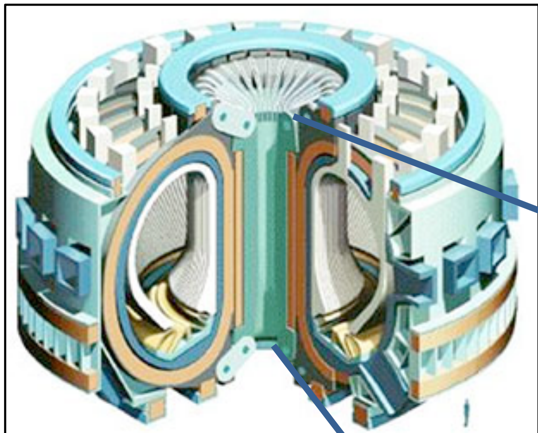
- Whole device modeling
- Advanced Tokamak experiments and remote control

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

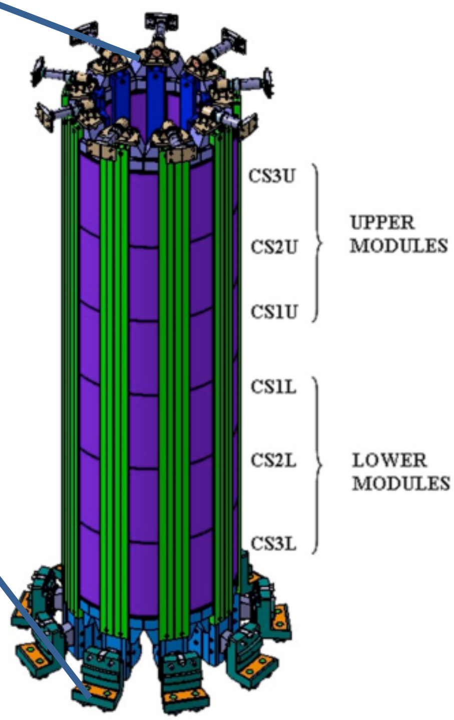
- Plasma-edge physics
- Boundary-turbulence modeling
- Yearly BOUT++ Workshop

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

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

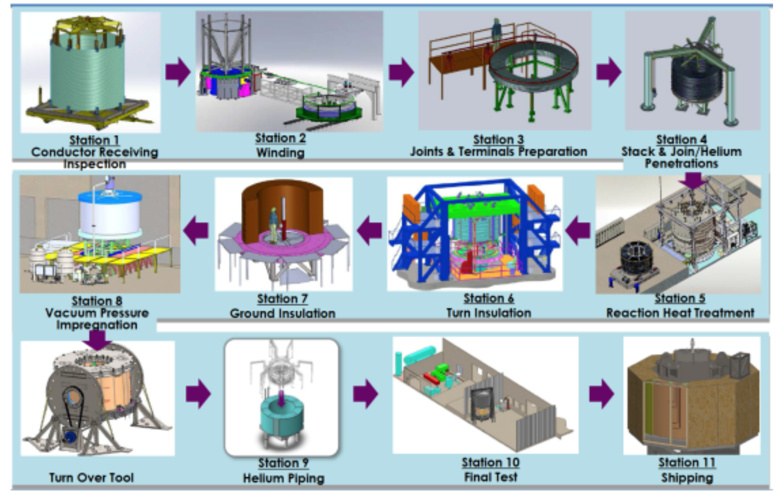


Worlds largest pulsed superconducting magnet



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

Fabrication process developed and qualified



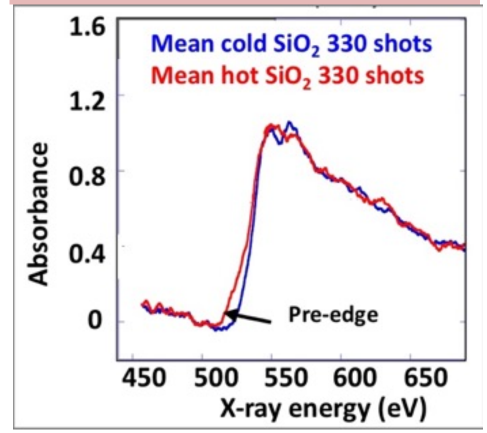
Discovery Science/HEDLP: enhanced by FES-ECRP awards, e.g. Félicie Albert leads laser driven x-ray sources.

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

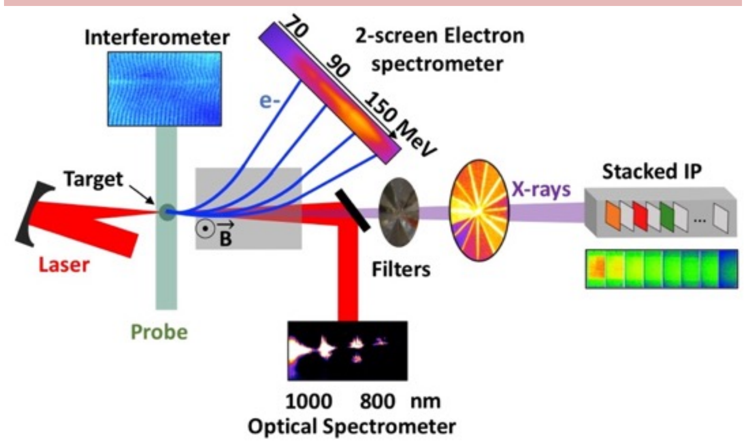
- **Accomplishments in FY18**
  - Continue work on betatron radiation with picosecond lasers with new publications:
    - F. Albert et al, POP (In press, 2018)
    - F. Albert and al., Nuclear Fusion (in press, 2018)
    - N. Lemos et al, PPCF (2018)
    - Publications in preparation: 1 PRL (N. Lemos), 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)

- **Experiments in FY19**
  - LCLS experiments
  - OMEGA-EP experiments
  - JLF/Titan experiments
  - NIF experiments: 1 shot day in FY19

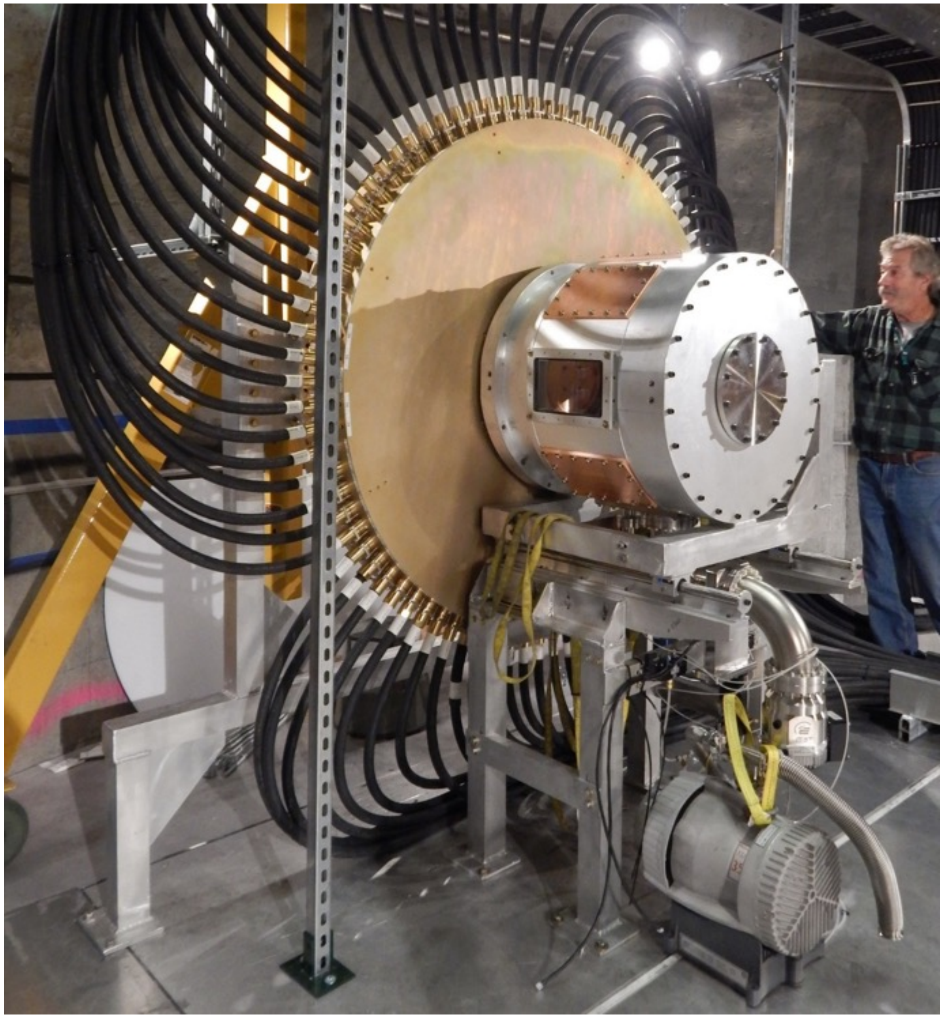
O2 K-edge spectra with LCLS betatron source

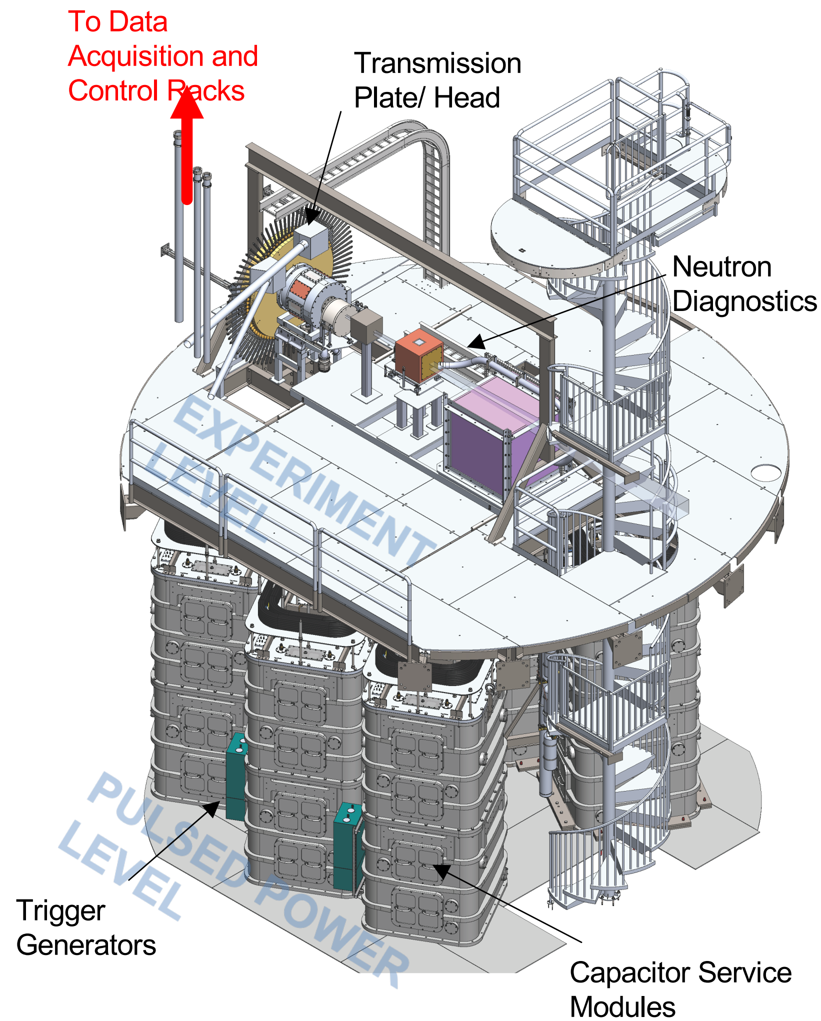


Platform for betatron experiments with picosecond lasers



Pulsed Power Fusion Group has installed a multi-MJ DPF in the NOVA Laser Facility building for National Security Missions



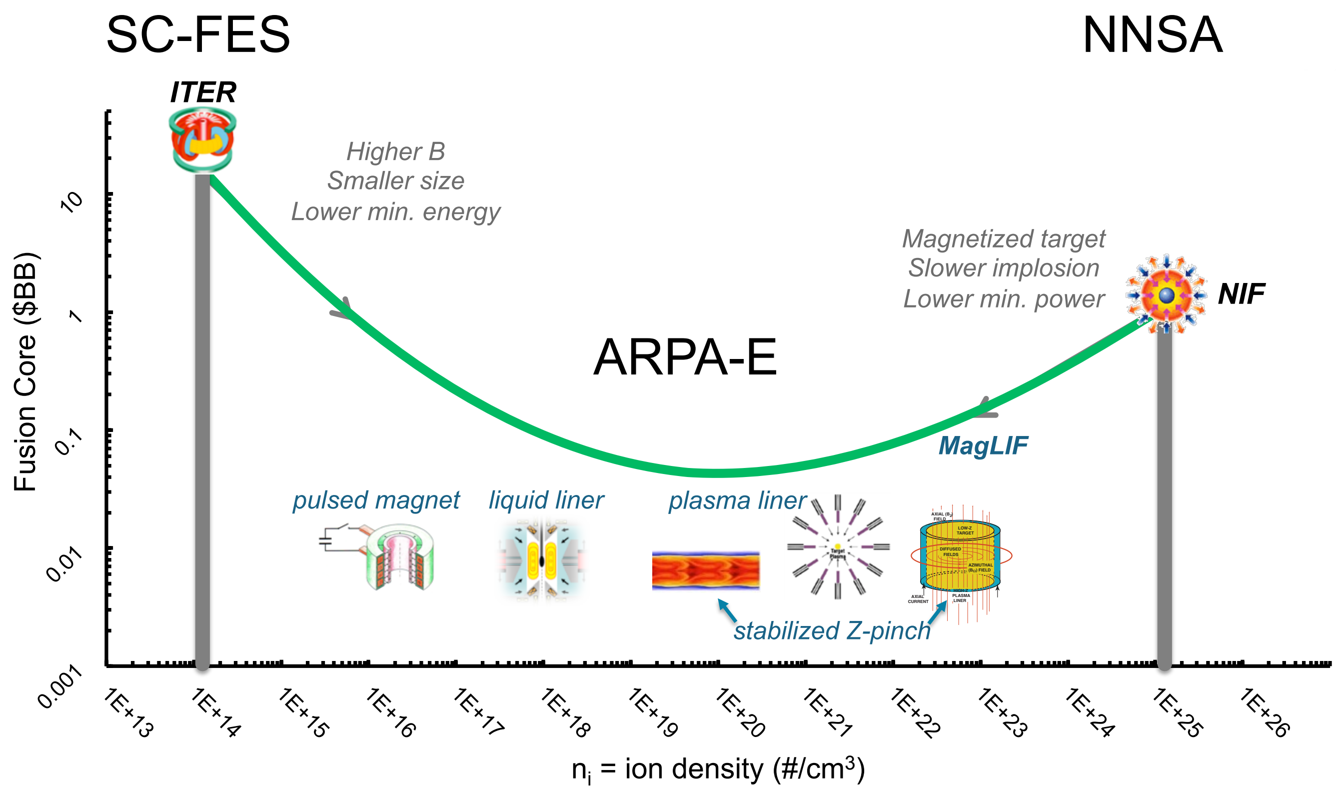


ARPA-E fusion efforts targeted concepts in between the extremes of MFE and ICF

Plotting Cost vs. Plasma Density is a useful way to define the landscape:

$P_{Fusion} \sim T\, n^2\, \tau_{confinement}$

Cost ~ complexity, size^x



MFE = Magnetic Fusion Energy

ICF = Inertial Confinement Fusion

ARPA-E:

Is there an opportunity in the intermediate density regime?

ARPA-E: Starting Point 2015 with ZAP experiment: Axial plasma flow with velocity shear in the radial direction shown to be stabile for a 1 m long x 1 cm diameter 50 kA z-pinch column for 20-40 usec


Volume 75, Number 18 PHYSICAL REVIEW LETTERS 30 October 1995

Sheared Flow Stabilization of the $m = 1$ Kink Mode in Z Pinches

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Lawrence Livermore National Laboratory, Livermore, California 94550

Volume 87, Number 20 PHYSICAL REVIEW LETTERS 12 November 2001

Evidence of Stabilization in the Z-Pinch

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University of Washington, Aerospace and Energetics Research Program, Seattle, Washington 98195-2250
D. J. Den Hartog*

PHYSICS OF PLASMAS VOLUME 10, NUMBER 5 MAY 2003

Sheared flow stabilization experiments in the ZaP flow Z pinch[a)]

U. Shumlak,[b)] B. A. Nelson, R. P. Golingo, S. L. Jackson, and E. A. Crawford
University of Washington, Aerospace and Energetics Research Program, Seattle, Washington 98195-2250
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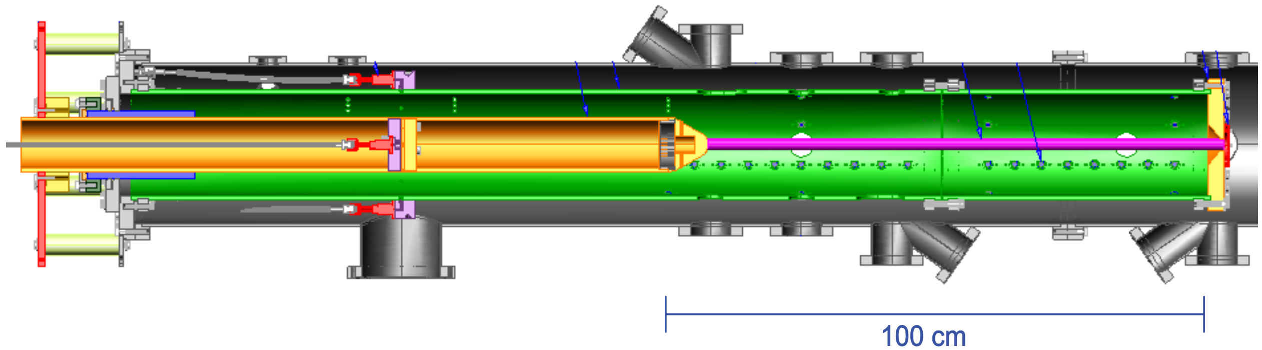
Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706
(Received 7 November 2002; accepted 9 January 2003)

IOP Publishing and International Atomic Energy Agency — Nuclear Fusion
Nucl. Fusion 49 (2009) 075039 (9pp)

Equilibrium, flow shear and stability measurements in the Z-pinch

U. Shumlak, C.S. Adams, J.M. Blakely, B.-J. Chan, R.P. Golingo, S.D. Knecht, B.A. Nelson, R.J. Oberto, M.R. Sybouts and G.V. Vogman
Aerospace and Energetics Research Program, University of Washington, Seattle, WA, USA

Received 24 December 2008, accepted for publication 20 May 2009
Published 6 July 2009



Nucl. Fusion 49 (2009) 075039 U. Shumlak et al

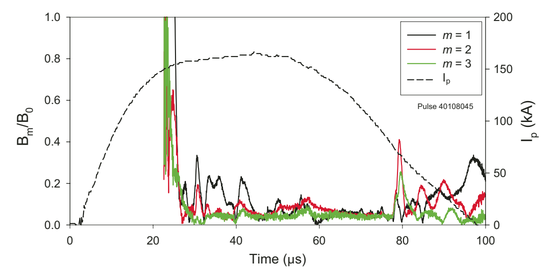


Figure 2. Time evolution of Fourier components of the normalized magnetic field fluctuation at $z = 0$ for the $m = 1, 2, 3$ modes for the original 0.1 m diameter inner electrode. The values are normalized to the average magnetic field value. A quiescent period is evident from 42 to 79 μs which defines the normalized time $\tau = 0$ to 1 for this pulse. The evolution of the total plasma current (dashed curve) is included for reference.

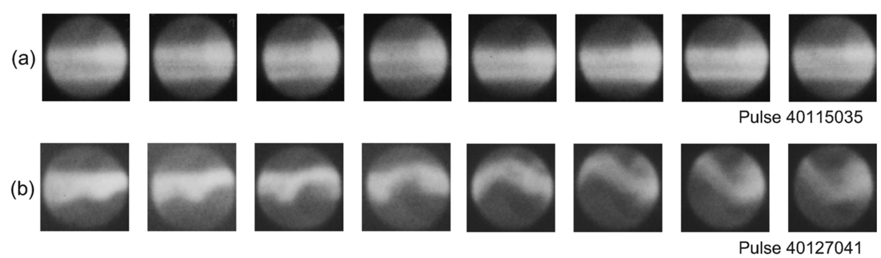


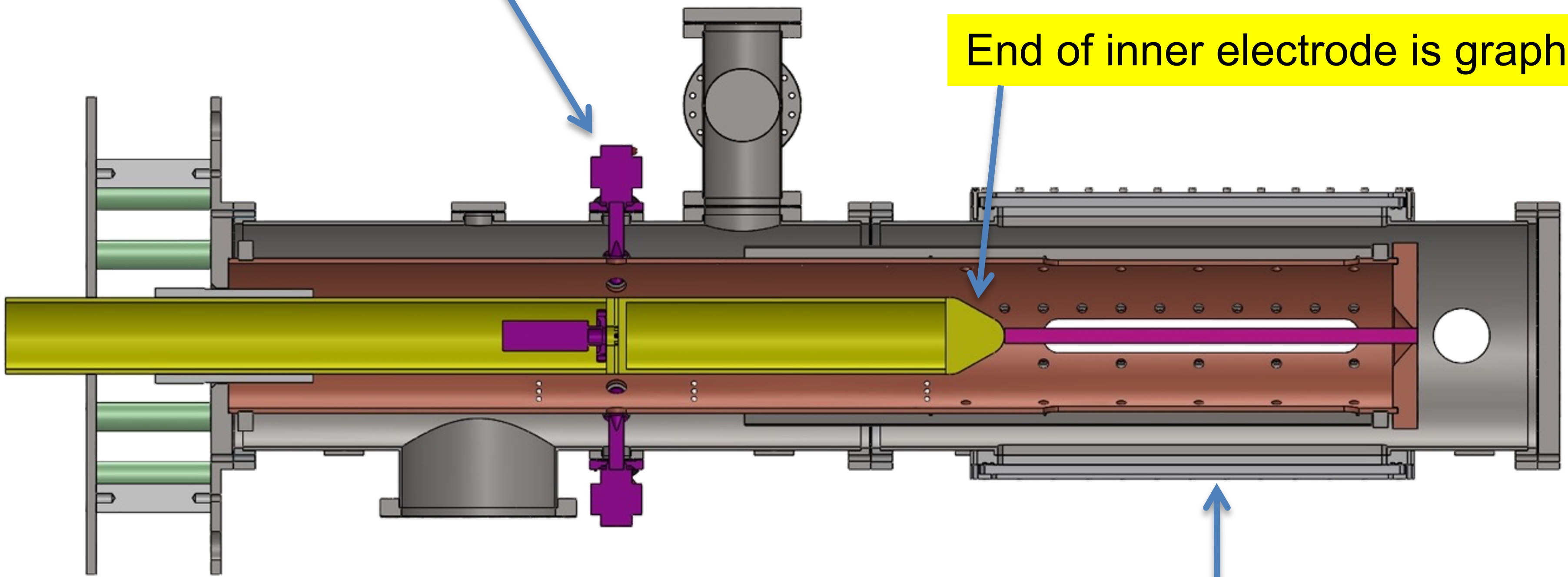
Figure 3. Fast framing camera images of visible light from the plasma viewed through a 5 cm hole at $z = 0$. Images are taken every 200 ns during a single plasma pulse. (a) Images obtained during 47.7–49.1 μs, the middle of the quiescent period. (b) Images obtained during 75.3–76.7 μs, near the end of the quiescent period.

Stable for:
$T_{quiescent}$ ~ 40 uS
I_{pinch} ~ 50 kA

ARPA-E: The new device, FUZE is about the same dimensions handles much higher discharge current, higher heat loads, and features modular capacitor bank along with flexible gas injection capability with a total of 9 fast-puff gas valves.

Gas valves are external at 8 locations plus one inside the inner electrode on axis
Nozzles extend through vacuum envelope to the outer electrode

End of inner electrode is graphite



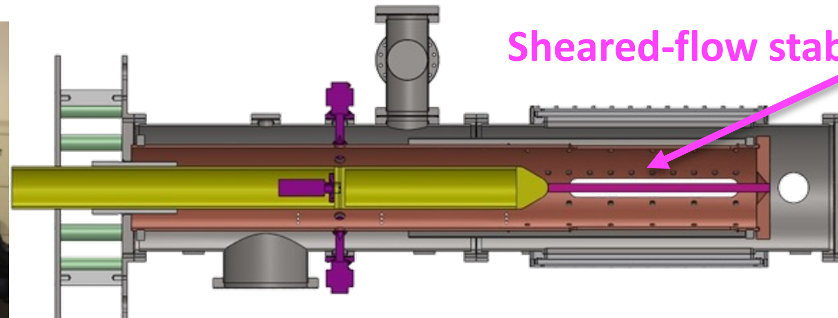
Plasma gun region gun is very similar

Larger vacuum pumping ports at multiple locations

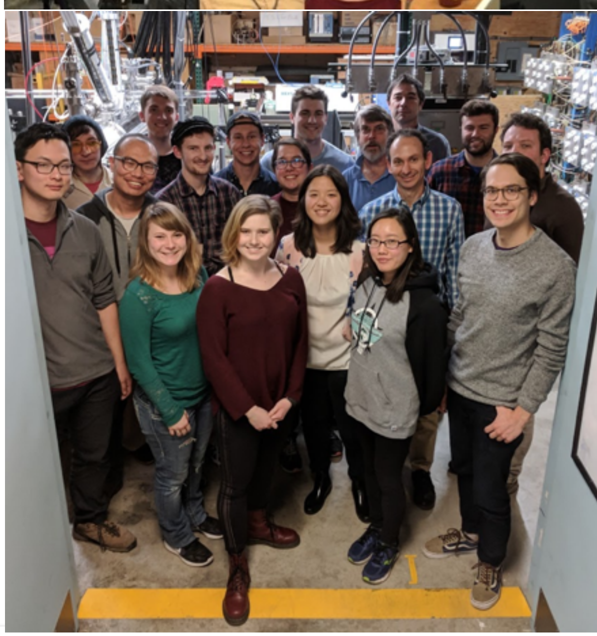
Pinch region is shorter, but can be easily changed

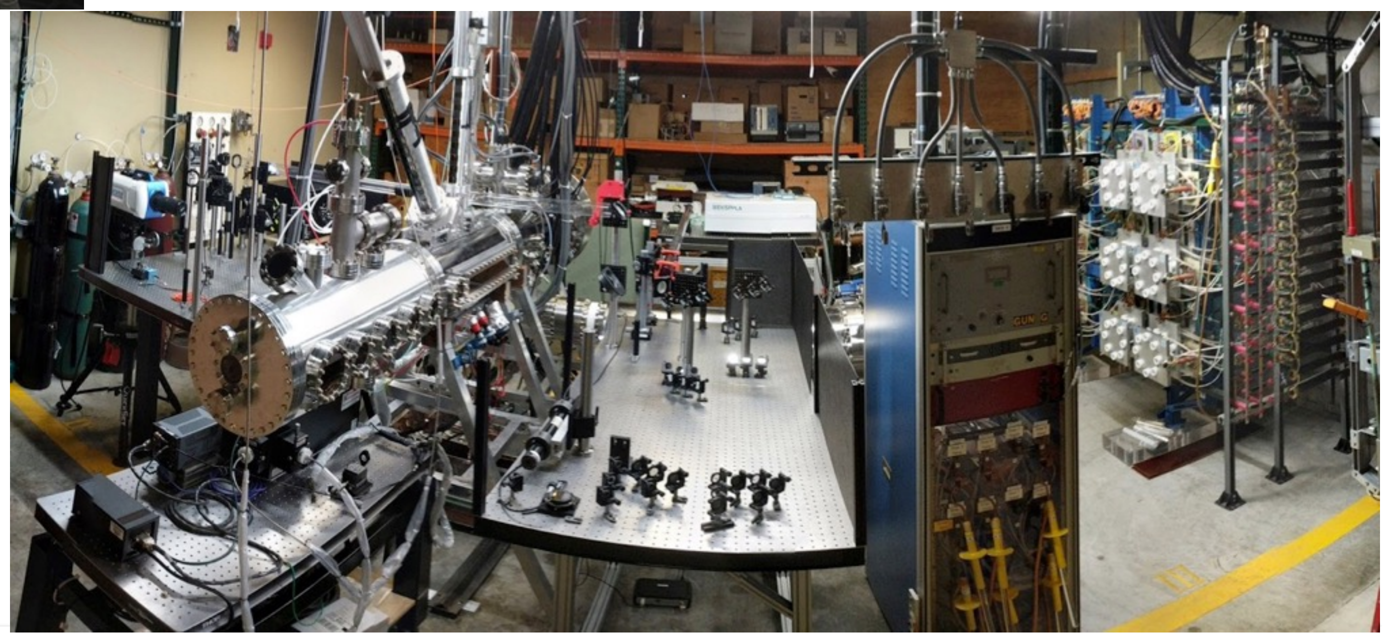
ARPA-E: Experimental and computational efforts seek to answer key questions on whether the sheared-flow stabilized Z-pinch concept has the potential to scale to a fusion power reactor

- University of Washington / LLNL partnership initiated 2015 (ALPHA)
- New diagnostic projects in 2019: Neutron Production/Spectroscopy and Portable Thomson Scattering
- Expansion planned in 2020 with proposals to “Capability Teams” for pulse power, modeling. (BETHE)

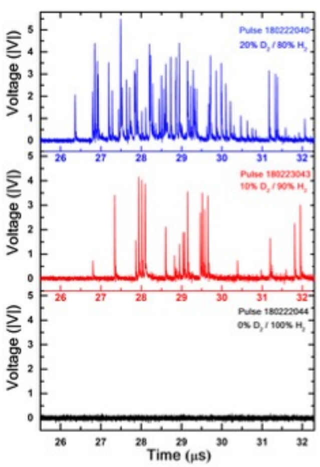


Sheared-flow stabilized Z-pinch Plasma

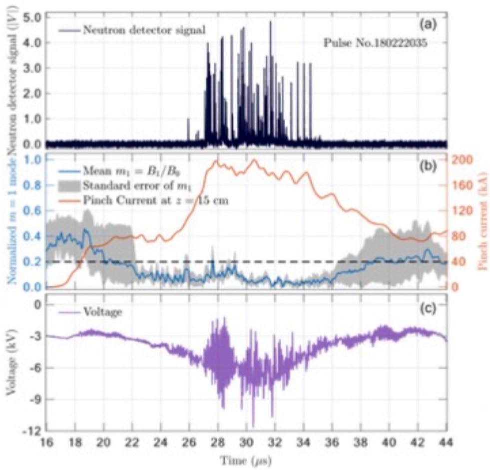




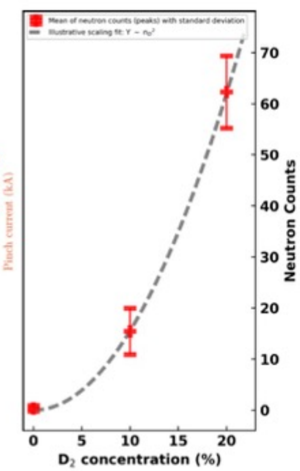
ARPA-E: The FuZE project has essentially met all technical milestones, is producing DD fusion neutrons, and extending performance to higher current.



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



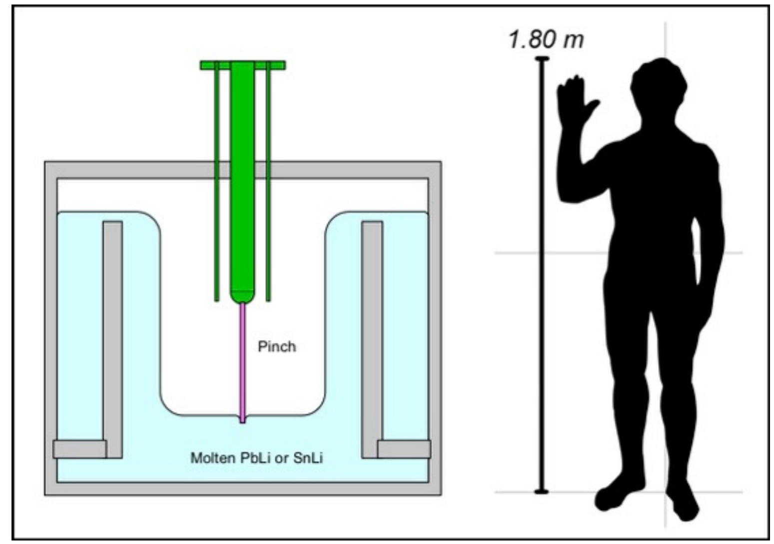
Neutron emission occurs over a 5 μs period; greater than 5000 instability growth times



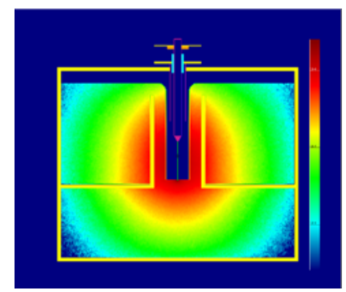
Neutron counts proportional to n_D^2

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**



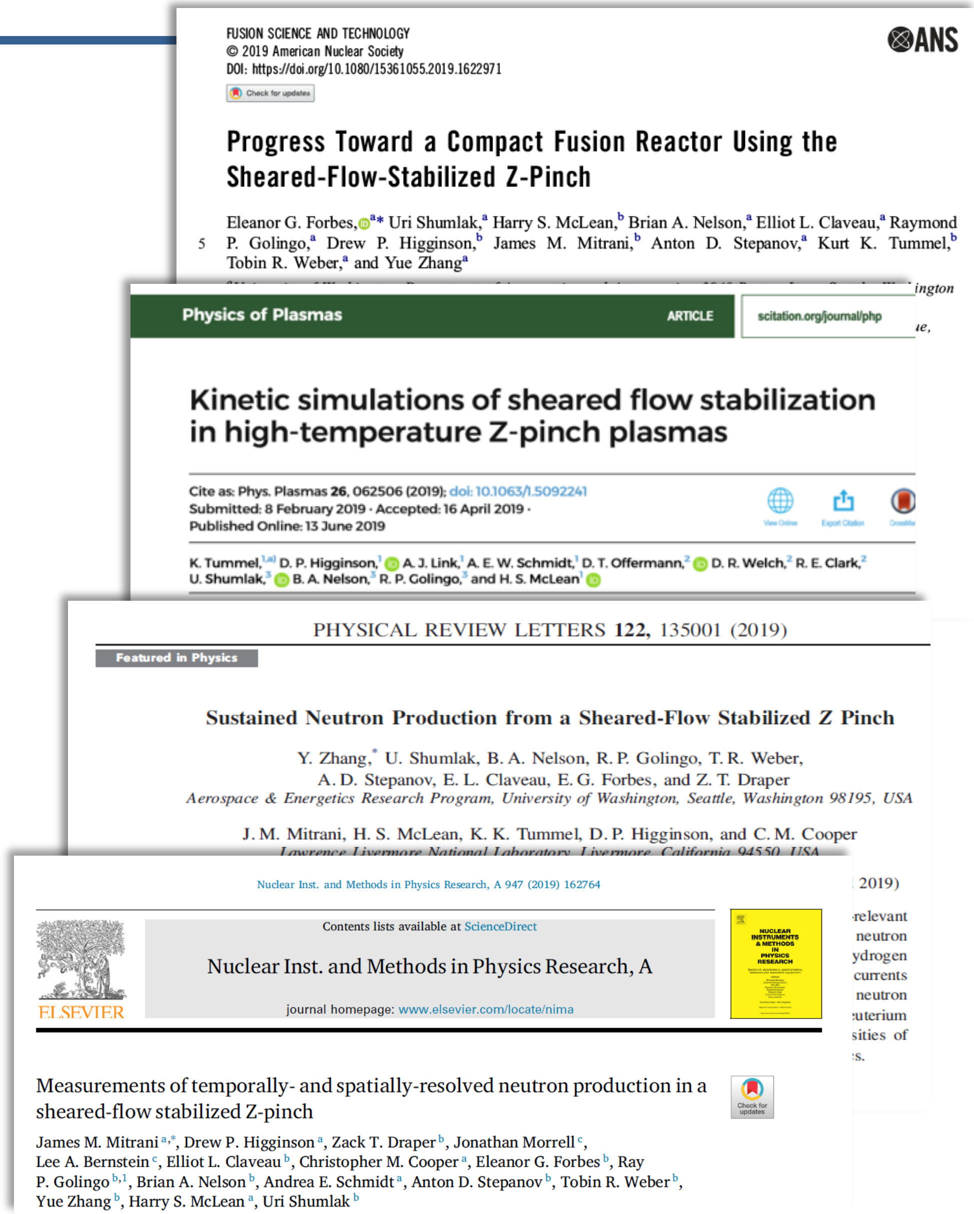
MCNP calculation of local tritium breeding ratio. Total TBR ~1.1

- **2015 50-100 kA, 1e16/cc, 100 eV**
- **2018 200-250 kA routine operation, 1e17/cc, 1 keV**
- **2020 Extension goal is to achieve routine operation at 300-400kA, 1e18/cc, >2 keV**
  - **Installed higher voltage cap bank modules (6 modules, 25 kV, 6 x 37.5 uF).**
  - **Optimizing input parameters (current drive waveform, gas injection, gas species, timing)**
  - **Modeling to guide experiments and understand physics**

Power reactor requires 1.5 MA in the pinch

ARPA-E: program includes significant science output

- **Publications:**
  - **FS&T (2019), Forbes *et al*.**
  - **PoP (2019) Tummel *et al*.**
  - **PRL (2019) Zhang *et al*.**
  - **NIMA (2019), Mitrani *et al*.**
- **Manuscripts in preparation**
  - **PoP, Stepanov *et al.***
  - **PoP, Claveau *et al.***
  - **PoP, Mitrani *et al*.**
  - **JoAP, "Perspective: Z-Pinch Fusion", Shumlak *et al.***
- **Invited Talks:**
  - **Tummel, APS DPP 2018**
  - **Forbes, TOFE 2018**
  - **Stepanov, APS DPP 2019**
- **Plenary Talk:**
  - **Shumlak, IEEE PPPS 2019**



FUSION SCIENCE AND TECHNOLOGY
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Progress Toward a Compact Fusion Reactor Using the Sheared-Flow-Stabilized Z-Pinch

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Physics of Plasmas ARTICLE scitation.org/journal/php

Kinetic simulations of sheared flow stabilization in high-temperature Z-pinch plasmas

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PHYSICAL REVIEW LETTERS 122, 135001 (2019)

Featured in Physics

Sustained Neutron Production from a Sheared-Flow Stabilized Z Pinch

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Measurements of temporally- and spatially-resolved neutron production in a sheared-flow stabilized Z-pinch

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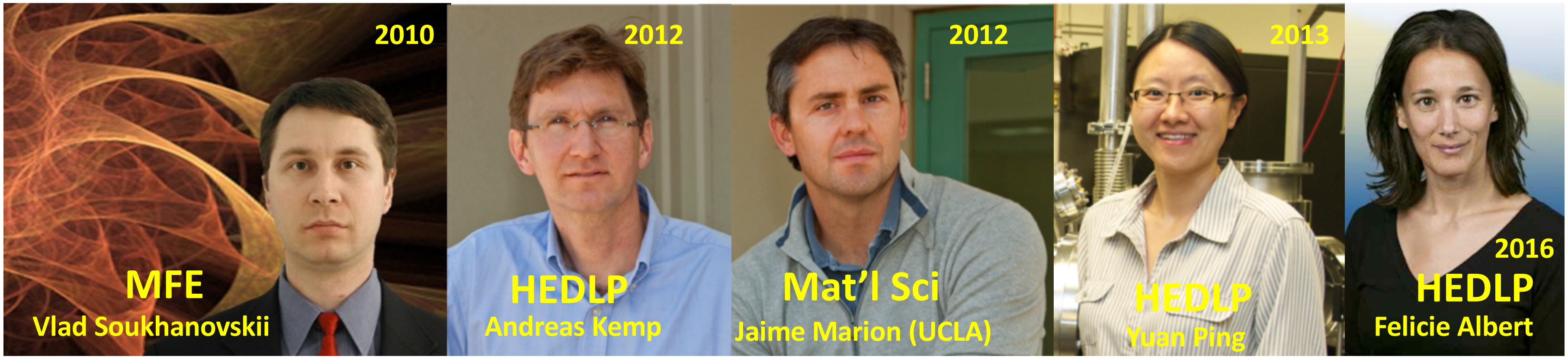
Overall LLNL FESP Outlook for 2020's for all sponsors

- **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

Additional planning activities, reports, and studies…

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

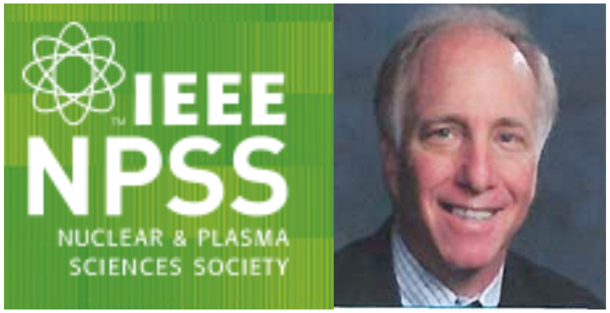


U.S. DEPARTMENT OF
ENERGY

Office of Science
Early Career
Research Program

Awards and Recognition

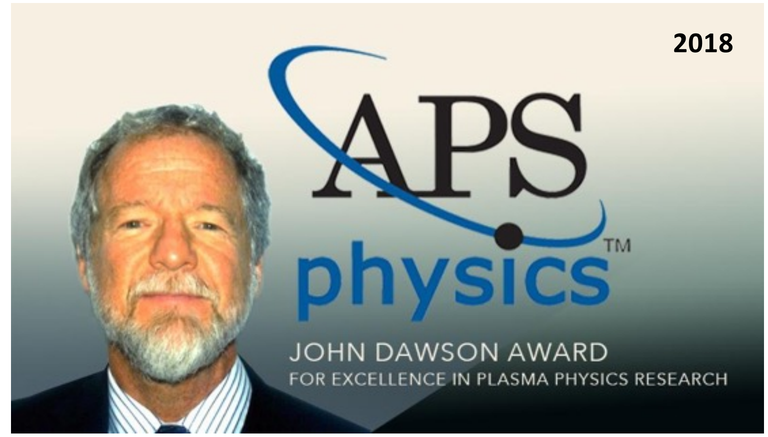
Alex Friedman



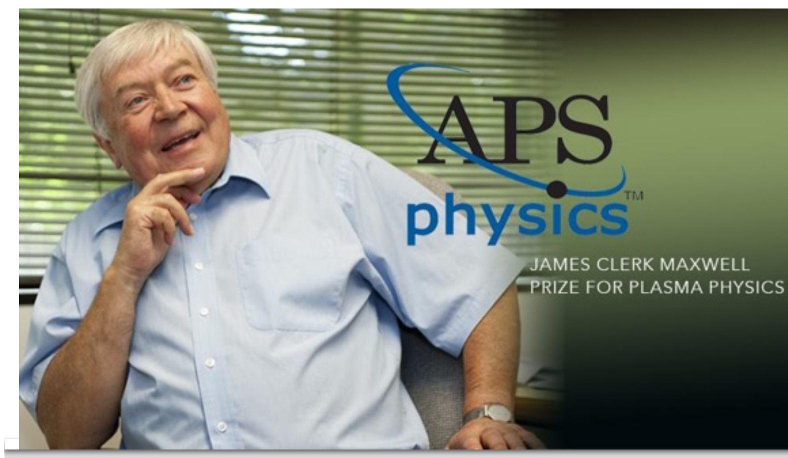
Charles K. Birdsall Award for Contributions to Computational Nuclear and Plasma Sciences

Chris Holcomb

Max Fenstermacher



Dmitri Ryutov



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