Fusion Energy Sciences Program at LLNL

10th US-PRC Magnetic Fusion Collaboration Workshop

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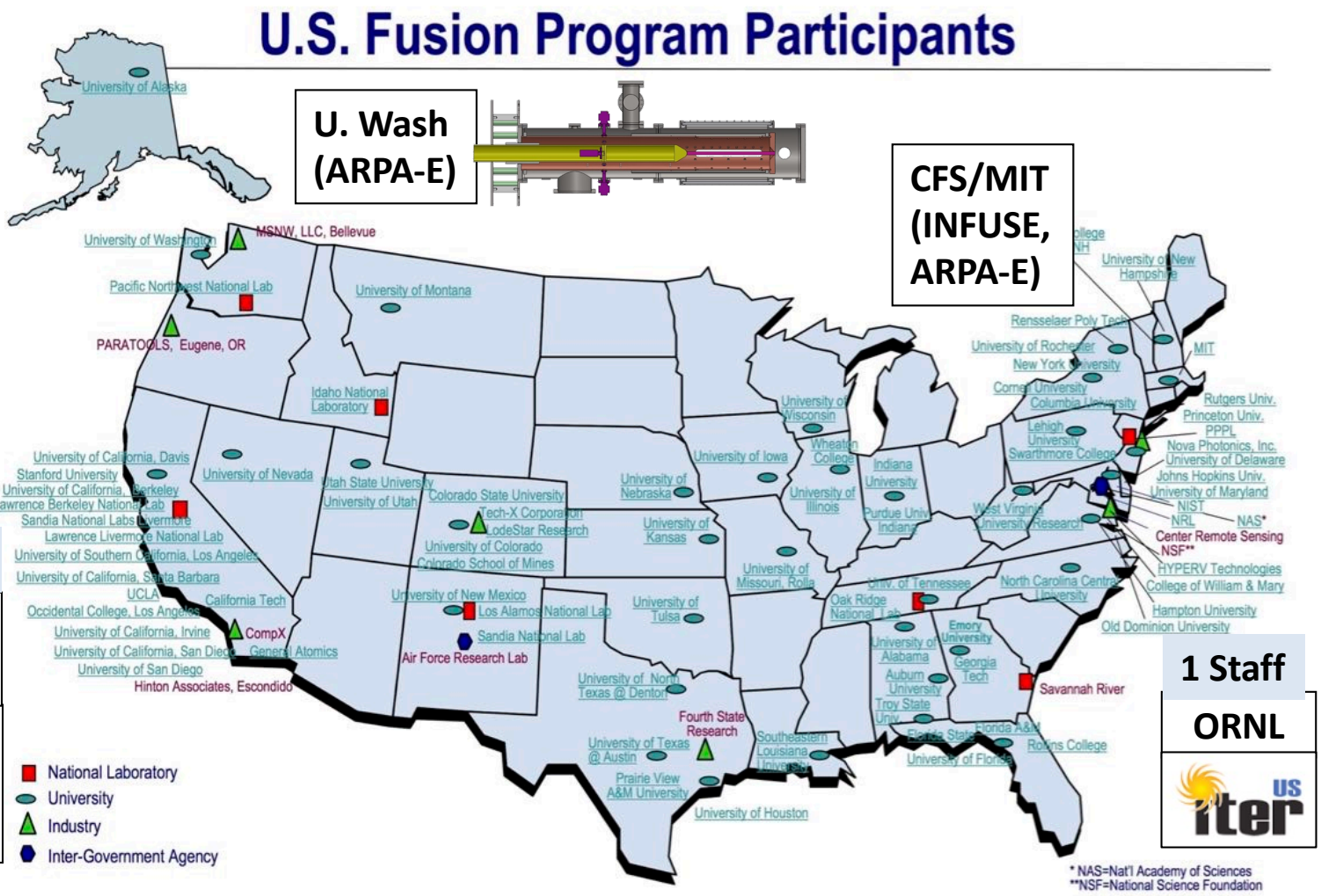
The Fusion Energy Sciences Program (FESP) at LLNL is the POC for two DOE Offices: SC/FES and ARPA-E/Fusion.

- **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 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.

Fusion delivers mission science, discovery science, and workforce development

LLNL/FESP participates at the primary US MFE Facilities



30 Staff

LLNL

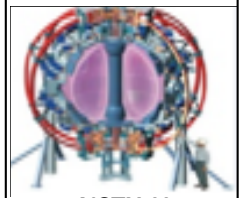
10 Staff

General Atomics

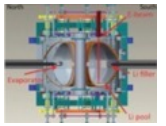
DIII-D

2 Staff

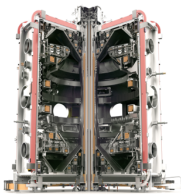
PPPL



NSTX-U



LTX-β



Mast

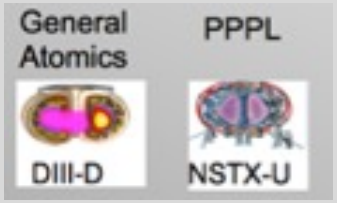
1 Staff

ORNL

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

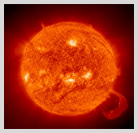
SC FES Program



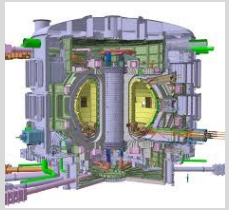
- **Foundations**
  - MFE Experiments
  - MFE Theory
- **Long Pulse**
  - Superconducting Tokamaks
  - Stellarator Experiments
  - Materials
  - Technology

EAST (China)

- **Discovery Plasma Sci.**
  - General Plasma Science
  - Measurement Innovation
  - HEDLP: Expts at JLF, NIF, SLAC/LCLS, LLE/OMEGA



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



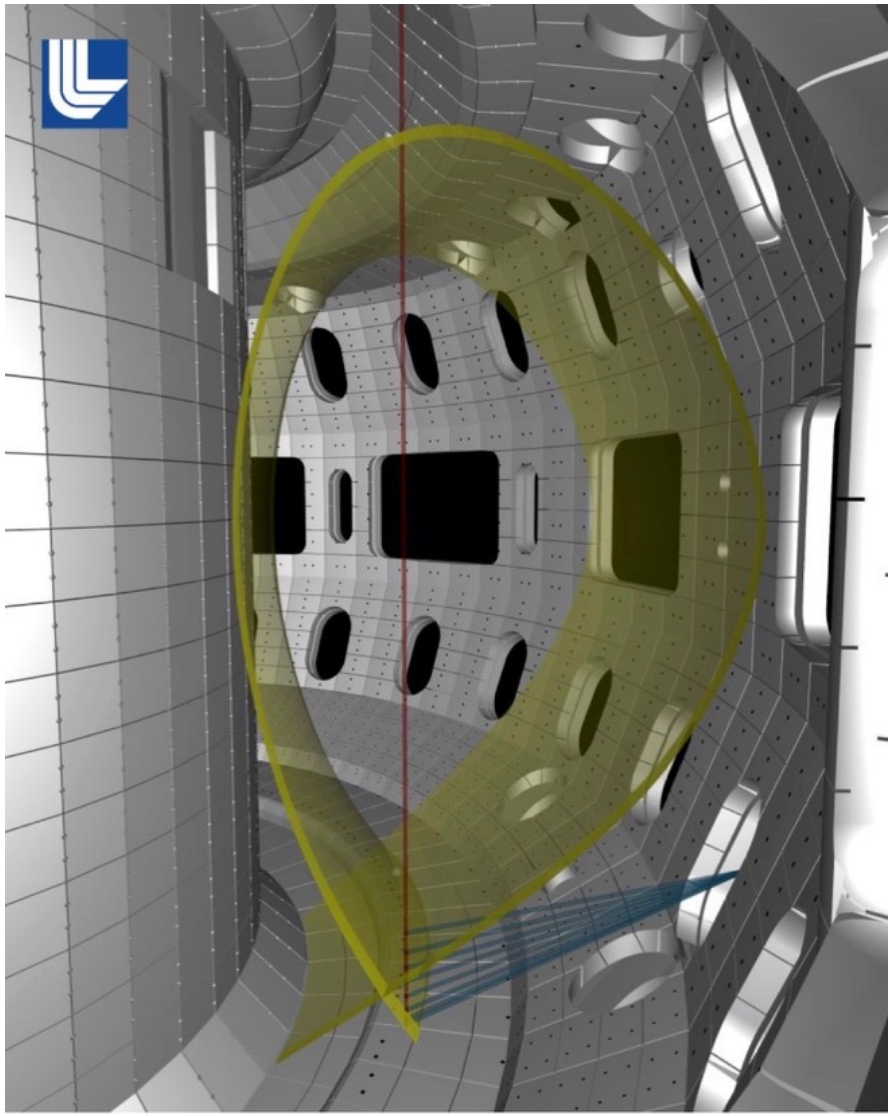
ITER (France)

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 (4 FY20, 3 FY21)
    - LaserNetUS (experimental support)
  - QIS
- **Construction: ITER (1 FTE)**

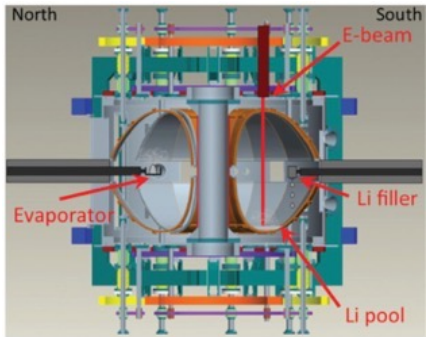
LLNL at DIII-D is active in both Divertor Science and Advanced Tokamak (Steady-state operation) Research

1. **Divertor 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 instruments fielded by FESP on NSTX
4. **Collaboration with Universities**
   - Tungsten Source Rates
   - Flow measurements via Coherence Imaging diagnostic
   - Diagnostic development on Auburn device



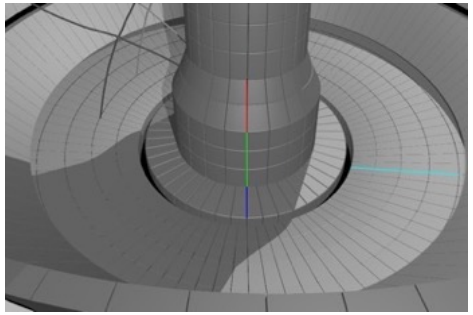
LLNL Experimental Research at PPPL is focused on Spherical Tokamak Program: LTX, MAST-U, and some NSTX-U Recovery/Physics Planning

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
     - Fielding Diagnostics
     - First plasma achieved 29 Oct 2020

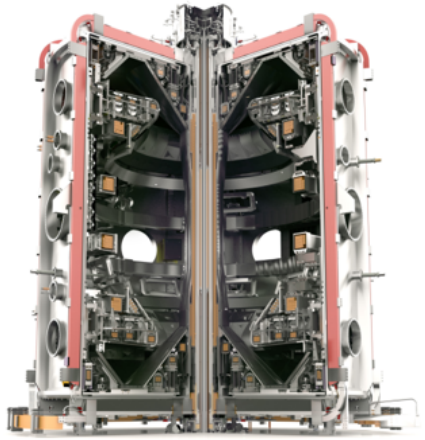


Lithium Tokamak eXperiment Beta in Princeton Plasma Physics Laboratory, Princeton, New Jersey

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



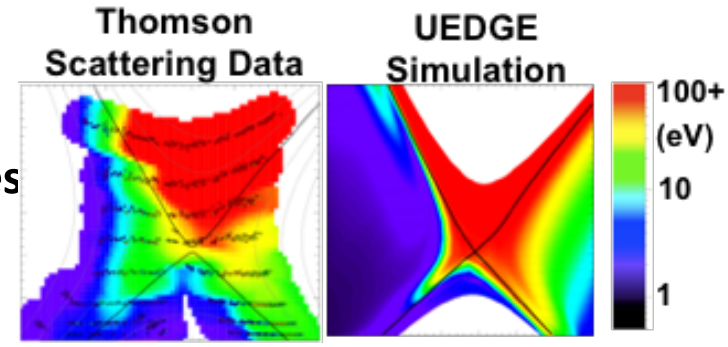
Conceptual view of PFC monitoring system viewing NSTX-U divertor



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

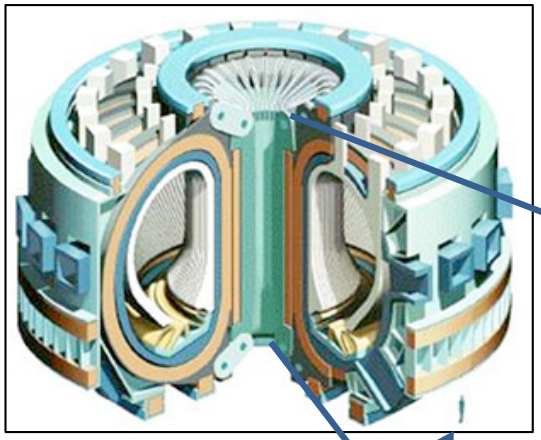
LLNL/FESP's Theory, Modeling, SciDAC research focuses on tokamak edge physics and integrated modeling/MHD

- **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

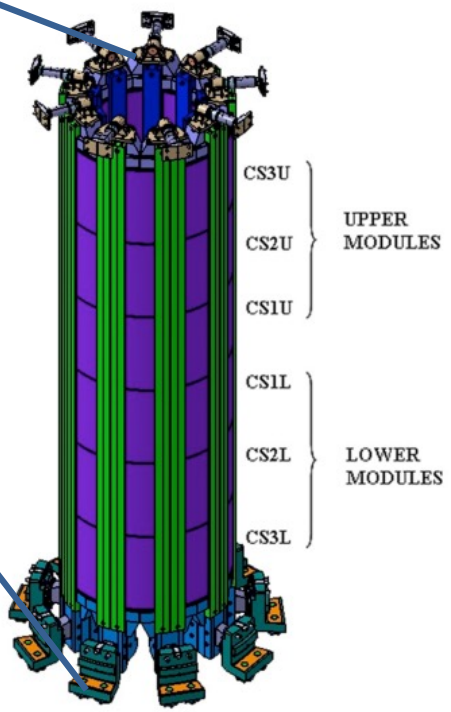


- **We prioritize research with strong connections to experimental physics:**
  - Provide theoretical support for planning, analysis and modeling of experiments on DIII-D, NSTX-U, MAST, EAST, …, and others
  - Provide scenario development tools for ITER and CFETR
- **Efforts are strengthened by connections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

FESP staff: R&D for design, fabrication, and testing of ITER Central Solenoid, will expand to include HTSC work in FY21 (SNS-STS, CFS)

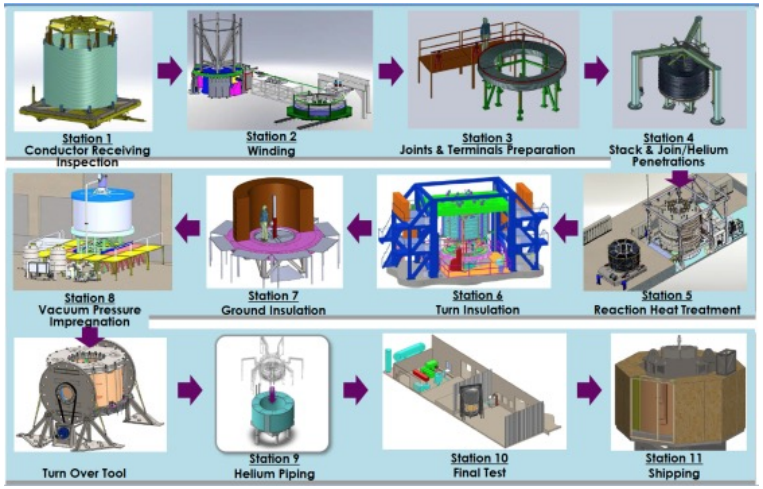


Worlds largest pulsed superconducting magnet



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

Fabrication process developed and qualified



International collaborations with China 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 Hosting 2020 MFE Workshop (Spring 2021)

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

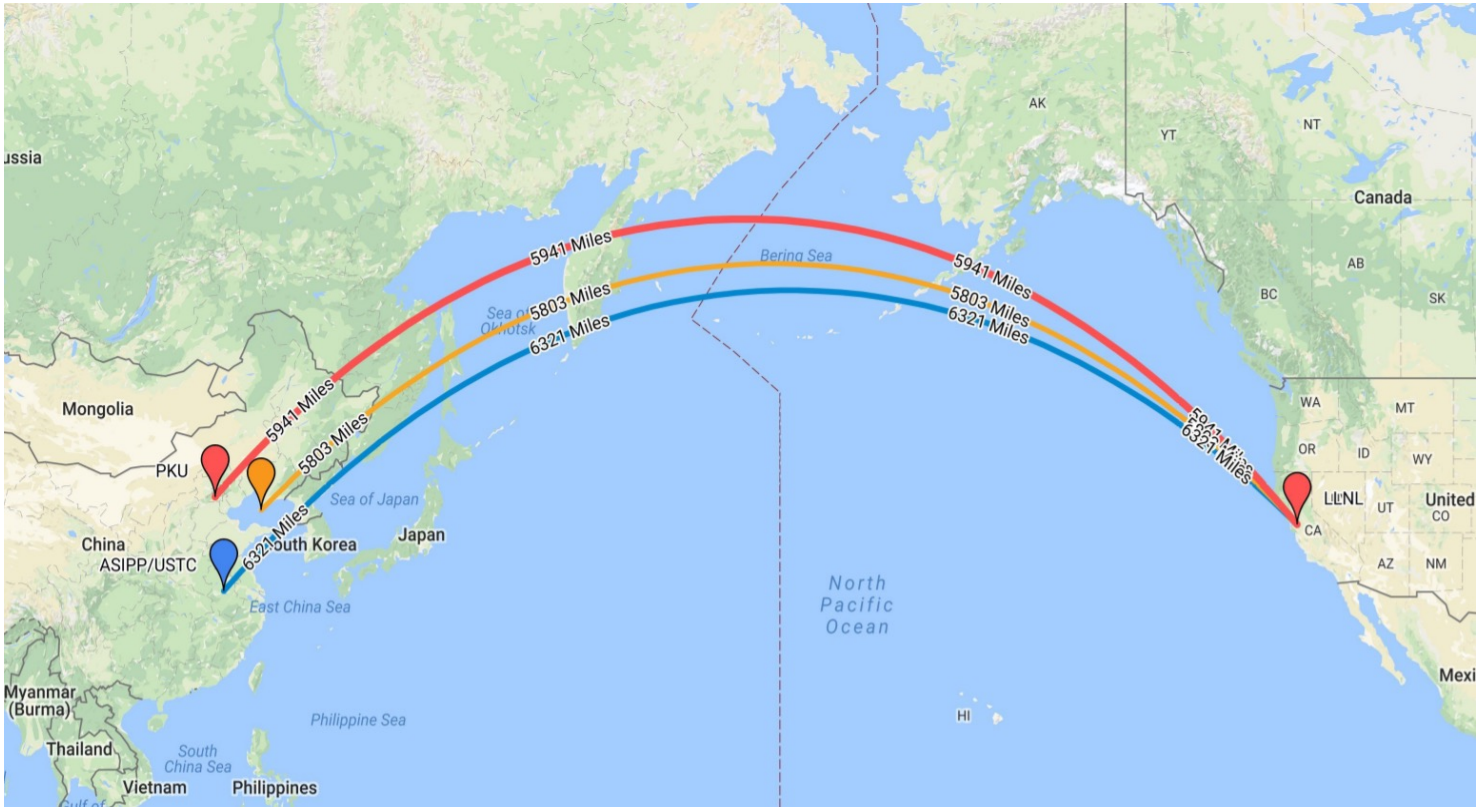
LLNL-China Collaboration has produced 13 PhDs, with an additional 6 in training

Total: **19**
Graduated PhD: **13**
Current PhD Candidates: **6**

Peking University
Pengwei Xi (Graduated)
Chenhao Ma (Graduated)
Jianguo Chen (Graduated)
Chuankui Sun (Graduated)
Zeyu Li (Graduated)
Libo Wang (Graduated)
Xueyun Wang(Graduated)
Pengfei Li (Current)
Kaixuan Fan(Current)
Yi Zhang (Current)
Yong Lang (Current)
Weisheng Lin (Current)

ASIPP/USTC
Bin Chen (Graduated)
Zixi Liu (Graduated)
Guozhong Deng (Graduated)

DLUT
Nami Li (Graduated)
Tengfei Tang (Graduated)
Zhuang Liu (Graduated)
Xiaoxue He (Current)



LLNL-China Collaboration has also been highly successful, as evidenced by the publication record

For most recent period, CY20-21

1) N.M. Li, X.Q. Xu, R.J. Goldston, J.Z. Sun, and D.Z. Wang, **Impact of plasma density/collisionality on divertor heat flux width,** *Nucl. Fusion* **61**, 026005 (2021). 10.1088/1741-4326/abc839
2) Z. Li, Y. Zhu, G. Xu, V.S. Chan, X. Xu, J. Chen, R. Ding, T. Xia, X. Jian, Y. Zou, C. Xiao, X. Wang, and CFETR physics team, **Edge localized mode characteristics and divertor heat flux during stationary and transient phase for CFETR hybrid scenario,** *Plasma Phys. Control. Fusion* **63**, 035006 (2021). 10.1088/1361-6587/abd25d
3) Y.-R. Zhu, Z.-Y. Li, V.S. Chan, J.-L. Chen, X. Jian, B.D. Dudson, A.M. Garofalo, P.B. Snyder, P.B. Snyder, Xue-Qiao Xu, G. Zhuang, **Achieving a robust grassy-ELM operation regime in CFETR,** *Nucl. Fusion* **60**, 046014 (2020). 10.1088/1741-4326/ab72c0
4) L. Wang, X.Q. Xu, B. Zhu, C. Ma, Y.-a. Lei, **Deep learning surrogate model for kinetic Landau-fluid closure with collision,** *AIP Advances* **10**, 075108 (2020). https://doi.org/10.1063/5.0010917
5) H. Ren, X.Q. Xu, **Excitation of zonal flow by nonlinear geodesic acoustic mode,** *Phys. Plasmas* **27**, 034501 (2020). 10.1063/1.5126872
6) Z. Zhu, J. Li, B. Xiao, X. Xu, F. Yang, Y. Guo, **Identification of Plasma Current Center by Neural Network Inference in EAST,** *IEEE Transactions on Plasma Science* **48**, 54 (2020)
7) H. Ren, L. Wei, D. Zhang, X.Q. Xu, **Global geodesic acoustic mode in an ideal magnetohydrodynamic tokamak plasma,** *Physics of Plasmas* **27**, 042504 (2020),
8) Z. Liu, X. Xiao, X. Xu, N. Li, T. Tang, D. Wang, **Modelling of nanometer scale dust grains in tokamak,** *Contrib. Plasma Phys.*, e201900136 (2020)
9) Y.Q. Huang, T.Y. Xia, X.Q. Xu, D.F. Kong, Y.M. Wang, Y. Ye, Z.H. Qian, Q. Zang, M.P. Wu, Y.Q. Chu, H.Q. Liu, B. Gui, X.T. Xiao, D.Z. Zhang, **Nonlinear simulation and energy analysis of the EAST coherent mode,** *Nucl. Fusion* **60**, 026014 (2020)
10) G.Z. Deng, X.Q. Xu, N.M. Li, X.J. Liu, X. Liu, J.C. Xu, W. Feng, J.B. Liu, S.L. Gao, S.C. Liu, T.Y. Xia, L. Wang, **Simulation of divertor heat flux width on EAST by BOUT++transport code,** *Nuclear Fusion* **60**, 082007 (2020)
11) N.M. Li, X.Q. Xu, J.W. Hughes, J.L. Terry, J.Z. Sun, and D.Z. Wang, **Simulations of divertor heat flux width using transport code with cross-field drifts under the BOUT++ framework**, *AIP Advances* **10**, 015222 (2020)
12) .R. Zhang, Y.P. Chen, X.Q. Xu, T.Y. Xia, S.C. Liu, and EAST team, **Simulation of EAST edge plasma using SOLPS-ITER/BOUT++ coupling,** *Nucl. Fusion* **60**, 106015 (2020)
13) J. Huang, X. Gong, A.M. Garofalo, J. Qian, J. Chen, M. Wu, M. Li, Q. Yuan, L. Wang, C. Pan, X. Lin, Q. Yang, A. Ekedahl, R. Maingi, C.T. Holcomb, E. Li, L. Zeng, B. Zhang, J.F. Chang, X.J. Zhang, M. Goniche, Y. Peysson, X. Zhu, Y. Sun, G. Xu, Q. Zang, L. Zhang, H. Liu, B. Lyu, R. Ding, Q. Ren, B. Ding, W. Guo, S. Ding, N. Xiang, Y. Liang, F. Liu, Y. Zhao, B. Xiao, J. Hu, C. Hu, L. Hu, X. Gao, P. Fu, Y. Song, X.D. Zhang, V. Chan, J. Li, B. Wan, and the EAST team, **Progress of physics understanding for long pulse high-performance plasmas on EAST towards the steady-state operation of ITER and CFETR**, *Nucl. Fusion* **62**, 014019 (2019)

Summary of the LLNL International Collaboration with China

- The goals of our LLNL international collaboration are to leverage the available resources in China, and to coordinate the joint-venture collaboration program on experiments at EAST and fusion simulation code development, e.g. BOUT++.
- These collaborations provide access to international magnetic fusion capacities not available in the U.S. for validation of physics models relevant to ITER and future fusion pilot plants.
- These include topics in long-pulse, steady-state research in advanced superconducting tokamaks; in steady-state plasma confinement and control science; in plasma-wall interactions; and in the engineering design of the China Fusion Engineering Test Reactor (CFETR).

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