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US – PRC Collaborations in Fusion Energy Sciences

by
Matthew Lanctot
U.S. DOE Office of Science

at
10th US-PRC Magnetic Fusion Collaboration Workshop
March 23-27, 2021

Image: Lower hybrid waves in EAST from TorLH (courtesy MIT)

Purpose and Outline

- **Thank you to the organizers for their persistence in planning this meeting**
  - Acknowledgements: Houyang Guo and Xuru Duan for collecting recent highlights
- **Purpose of this talk**
  - Provide high-level context for this workshop and highlight select recent events in the U.S. program
- **Outline**
  - Brief history of US-PRC collaborations
  - Mutual benefits of ongoing collaborations
  - FES programmatic highlights
  - Upcoming events relevant to US-PRC collaborations

Brief History of US-PRC Collaborations

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PRC and US collaboration on fusion energy R&D occur under both bilateral and multilateral agreements

- **Bilateral** (main focus of this workshop)
  - USG and PRC signed Science and Technology Agreement on January 31, 1979
  - Formal relations between U.S. DOE and PRC State Science and Technology Commission established on May 11, 1983 with focus on Nuclear Physics and Magnetic Fusion Energy
  - Many collaborations take place under a protocol between DOE and ASIPP

- **Multilateral**
  - International Atomic Energy Agency (IAEA)
    - Fusion Energy Conference, various Technical Meetings
  - International Energy Agency (IEA)
    - Fusion Power Coordinating Committee (FPCC), Technology Collaboration Programmes
  - International Tokamak Physics Activity
  - ITER Agreement

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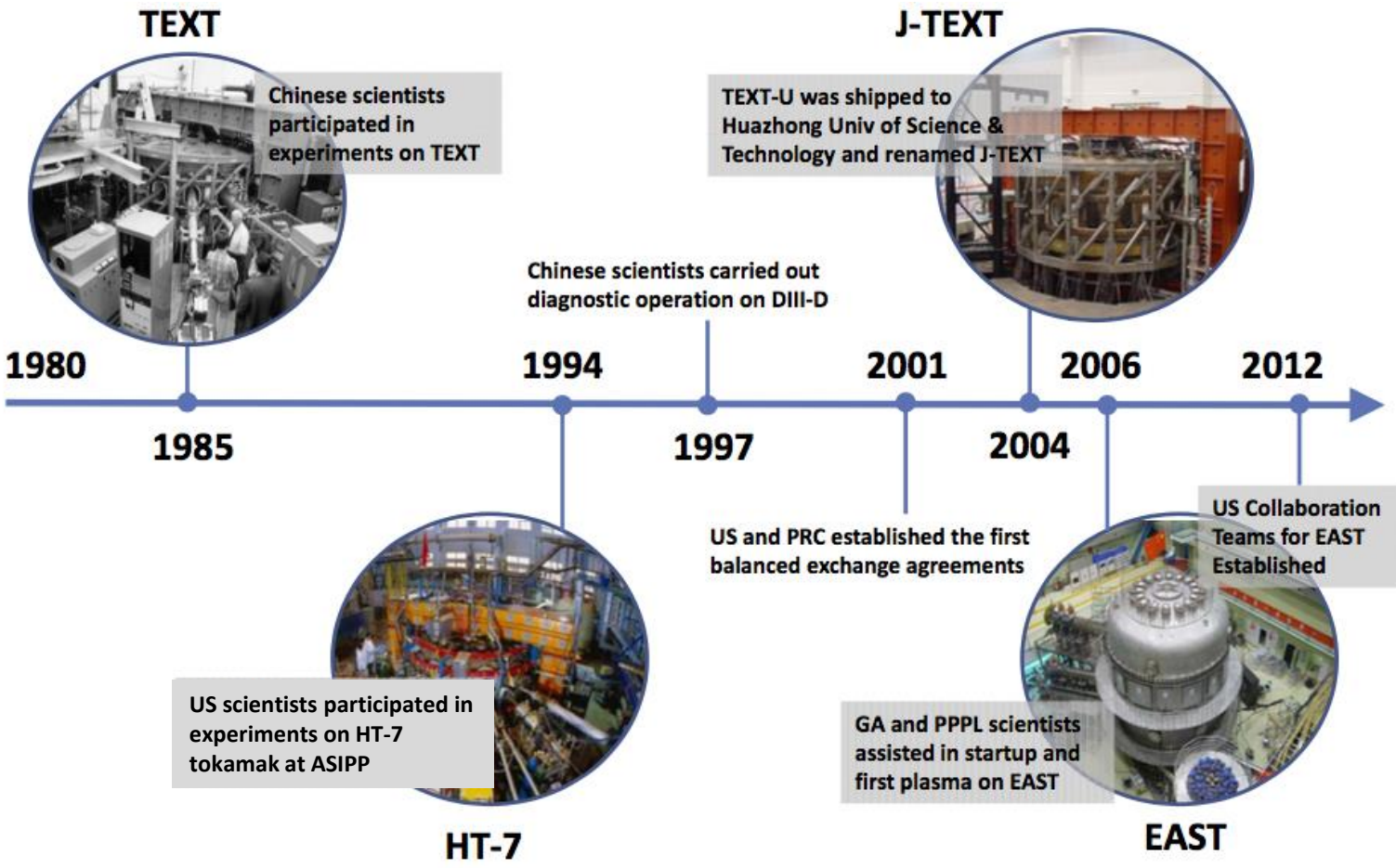
Formal agreements enabled early personnel exchanges that expanded into larger collaborative efforts



team 1 — Control and Extension of ITER and Advanced Scenarios to Long Pulse in EAST and KSTAR

- Extension/optimization of high-performance scenarios
- Long pulse disruption-free control
- Develop diagnostics/actuators for scenario extension
- Scenario simulation and control modeling
- Remote collaboration and third shift operation of EAST

30 scientists (~9 FTE), 70 person-weeks/year on-site at EAST

team 2 — Development of Long-Pulse Heating and Current Drive Actuators and Operational Techniques Compatible with a High-Z Divertor and First Wall

- High-power, long-pulse RF actuators
- Tungsten divertor design
- Impurity control
- Long pulse wall-plasma coupling

2013-2016

team 3 — Control of the plasma-material interface for long pulse optimization in EAST

- Evaluate PFC materials
- Analyze role of Lithium
- Deploy impurity powder dropper

2016-2019

Collaborative teams are supported under the FES Long Pulse Tokamak Program

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Plasma control collaborations on the EAST facility have facilitated cooperation

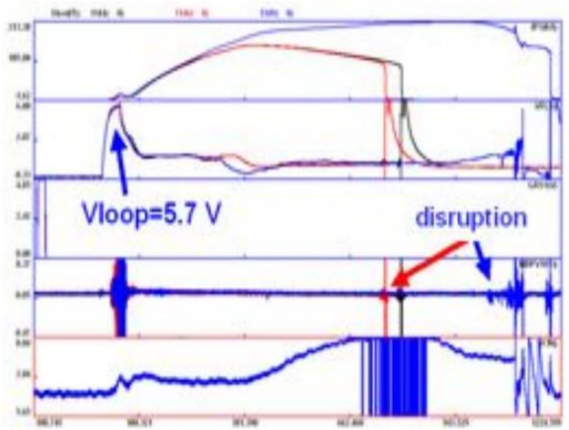
Xiao (ASIPP), Hyatt(GA), Mueller(PPPL) Supporting Shaped Plasma Experiments in EAST Control Room

- **PRC & US collaborated on EAST startup**
- **Shared control architecture allows rapid deployment of new algorithms**
  - RIP and shape control were early examples

S. Dong, 2010 US-PRC Bilateral Meeting

ASIPP

The first Plasma was got on September 26 2006



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Joint collaborations have made significant advances in both fusion science and technology (a few examples here)

PHYSICS OF PLASMAS 23, 062511 (2016)

Progress toward steady-state tokamak operation explo bootstrap current fraction regime

Q. L. Ren,[1,a)] A. M. Garofalo,[2] X. Z. Gong,[1] C. T. Holcomb,[3] L. L. Lao,[2] G. O. Meneghini,[2] G. M. Staebler,[2] B. A. Grierson,[5] J. P. Qian,[1] W. M. Solom A. D. Turnbull,[2] C. Holland,[6] W. F. Guo,[1] S. Y. Ding,[1] C. K. Pan,[1] G. S. Xu,

[1]*Institute of Plasma Physics, Chinese Academy of Science, Hefei, Anhui 230031, China*
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[6]*Center for Energy Research, University of California San Diego, 9500 Gilman Dr., La Jolla*

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Nucl. Fusion 57 (2017) 076037 (9pp) https://doi.org/10.1088/1741-4

Development of high poloidal beta, steady-state scenario with ITER-like tungsten divertor on EAST

A.M. Garofalo[1], X.Z. Gong[2], J. Qian[2], J. Chen[2], G. Li[2], K. Li[2], M.H. Li[2], X. Zhai[2], P. Bonoli[3], D. Brower[4], L. Cao[2], L. Cui[5], S. Ding[2], W.X. Ding[4], W. Guo[2], C. Holcomb[6], J. Huang[2], A. Hyatt[1], M. Lanctot[1], L.L. Lao[1], H. Liu[2], B. Lyu[2], J. McClenaghan[7], Y. Peysson[8], Q. Ren[2], S. Shiraiwa[3], W. Solomon[1], Q. Zang[2] and B. Wan[2]

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-021-21645-y OPEN

Check for updates

Integration of full divertor detachment with improved core confinement for tokamak fusion plasmas

L. Wang[1], H. Q. Wang[2✉], S. Ding[1,3], A. M. Garofalo[2], X. Z. Gong[1], D. Eldon[2], H. Y. Guo[2], A. W. Leonard[2], A. W. Hyatt[2], J. P. Qian[1], D. B. Weisberg[2], J. McClenaghan[2], M. E. Fenstermacher[4], C. J. Lasnier[4], J. G. Watkins[5], M. W. Shafer[6], G. S. Xu[1], J. Huang[1], Q. L. Ren[1], R. J. Buttery[2], D. A. Humphreys[2], D. M. Thomas[2], B. Zhang[1] & J. B. Liu[1]

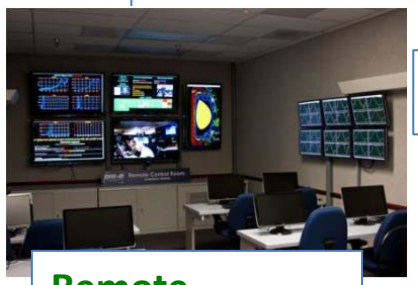
2010

2013

2016

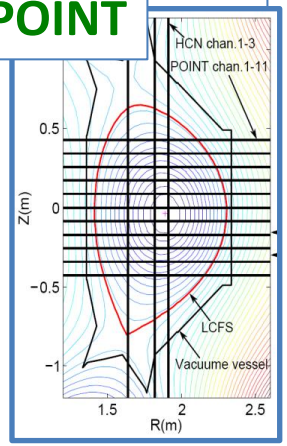
2019

2022

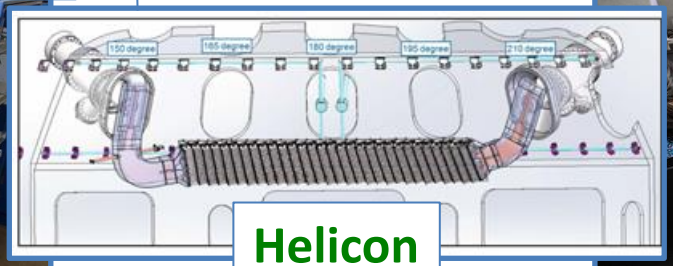


Remote participation prototypes

POINT



Power supplies



Helicon

3rd Shift EAST operation

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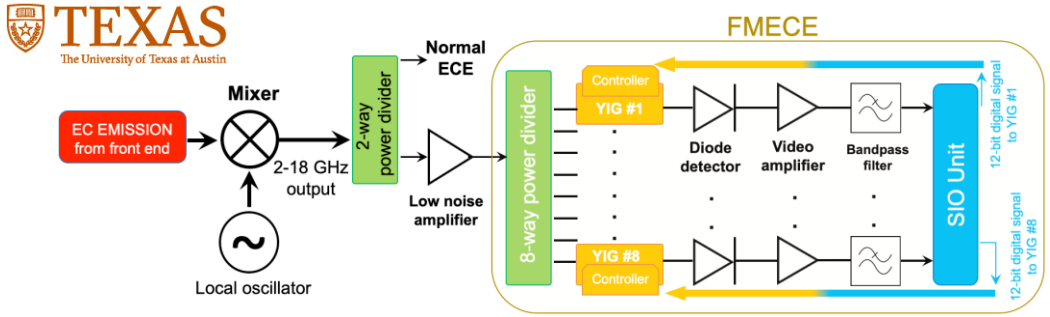
Mutually beneficial collaborations continue in all the areas covered by this workshop

- Diagnostics
- Theory/Simulation & Model Validation
- Plasma control
- Scenarios Development
- Materials and Technology Development
- Remote Operations

Diagnostic collaborations have been instrumental, enabling both the science and technology missions

Major Recent Achievements:

- **ECE/UTX: Variable frequency channels integrated into the EAST's ECE radiometer in 2018; expanded system ready for install in 2021**
  - Supports confinement and tearing mode studies
  - Continues/expands collaboration on TEXT-U and J-TEXT
- **POINT/UCLA: Data used to constrain EFIT and determine q-profile in EAST**
  - Supports current drive studies and integrated data analysis
  - Vertical position control under development
- **ECEI: Simultaneously and co-located ne, Te measurement by ECEI and Microwave Imaging Reflectometer on EAST; Upgrade ECEI on HL-2M**
  - Supports analysis of 3D structures & disruptions
- **BES: 16-channel BES system with SWIP**
  - State-of-the-art system for L-H and turbulence studies



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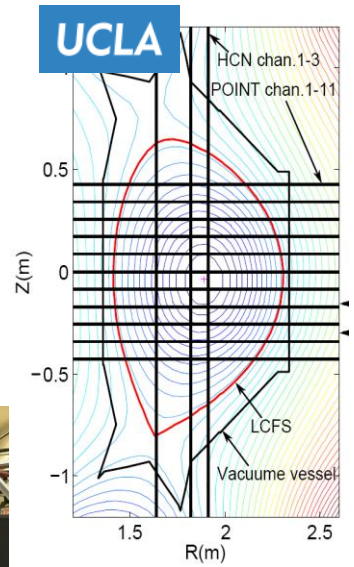
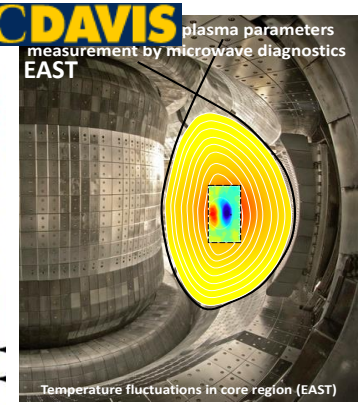
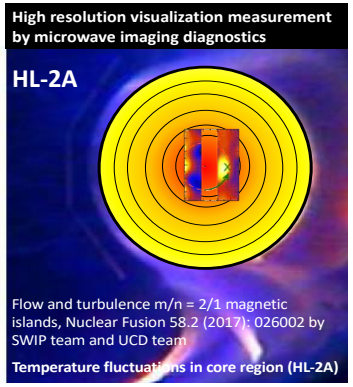
UNIVERSITY OF WISCONSIN-MADISON

UCDAVIS







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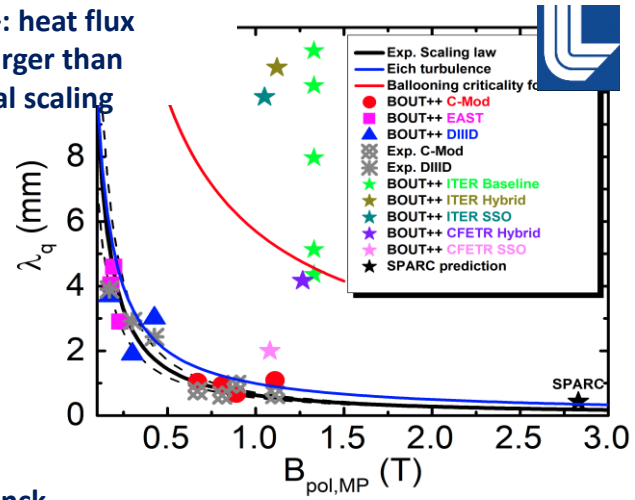
Advanced data analysis, theory, and simulation bring essential understanding for extrapolation to future facilities

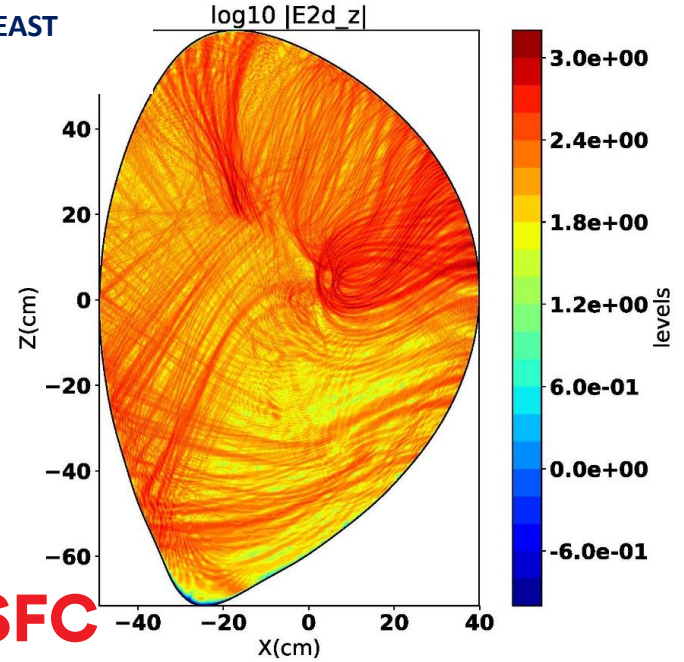
Major Recent Achievements:

- **POINT-constrained EFIT analysis continues to improve**
  - Starting point for all advanced data analysis workflows
- **EFIT:** GPU-based P-EFIT reproduce EFIT at fraction of computational cost
- **OMFIT:** Framework used extensively by DIII-D/EAST Task Force
- **TRANSP: Modeling revealed LH synergy for 30% increase in CD efficiency**
  - Modeling allows optimization of existing scenarios
- **BOUT++:**
  - CFETR & ITER may be in turbulence-dominated regime
  - Drifts increase amplitude and width of divertor heat flux
  - Divertor heat flux width with LHW much larger than NBI-heated case
  - Theory program bolstered through international collaboration
- **RF modeling (TorLH, GENRAY/CQL3D)**
  - LHCD rotation angle (+40 deg.) of perpendicular wave-vector is optimal, possibly due to wave scattering that reproduces expt. profiles

BOUT++: heat flux width larger than empirical scaling



Full-wave/Fokker Planck simulation of EAST LHCD



MIT PSFC

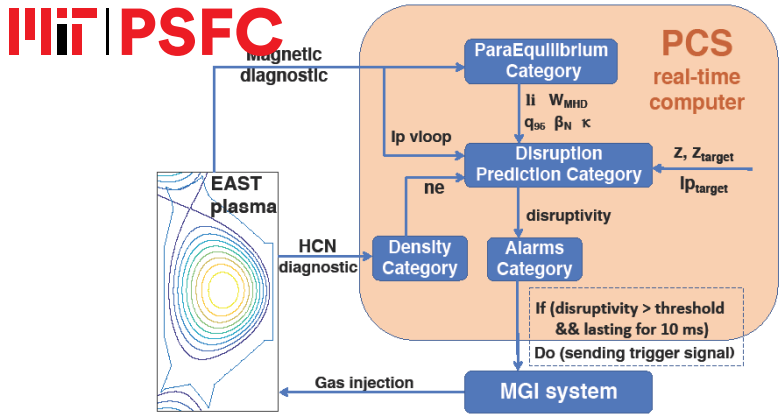
Plasma control algorithms provide essential capabilities for sustaining high performance tokamak scenarios

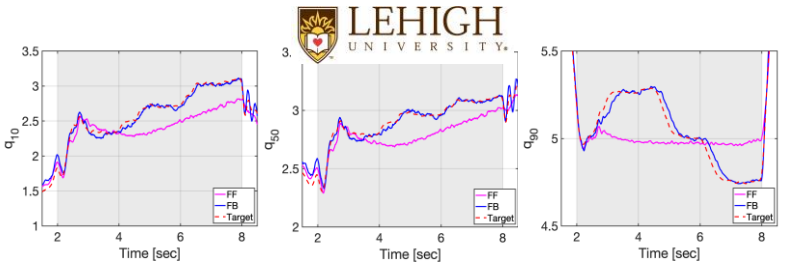
Major Recent Achievements:

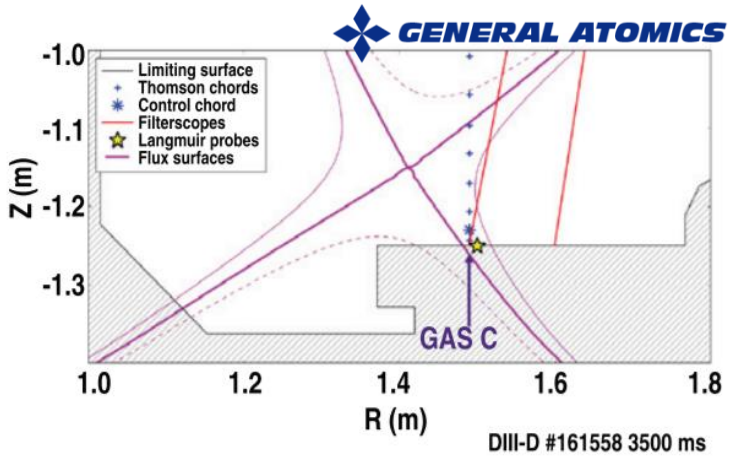
- **Machine learning real-time disruption predictor operating in EAST PCS**
  - MIT algorithms exploit understanding gained on several facilities

- **Integrated model-based plasma control approach leverages diagnostic data and validated physics models to regulate q-profile using LH**
  - Lehigh modeling and control tools are pioneering profile and burn control for the advanced tokamak

- **Detachment control demonstrated on DIII-D and EAST using electron temperature and ion saturation current density**
  - Enhancements allow elaboration of detachment control including “degree of detachment”







Plasma technology development has been accelerated through technology deployment on US & PRC facilities

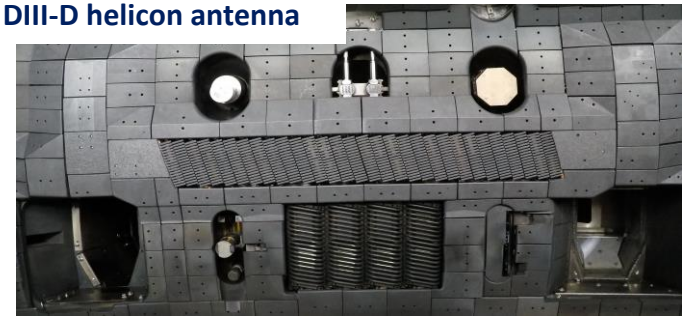
Major Recent Achievements:

- **Helicon antenna in DIII-D installed on schedule with support from ASIPP**
  - System is currently being conditioned on DIII-D

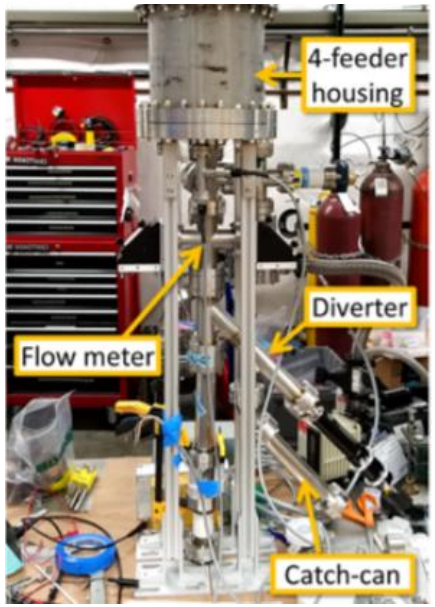
- **Impurity powder dropper deployed on EAST for real-time wall conditioning and edge stability studies**

- **Flowing liquid Li limiter (FLiLi) and Liquid Metal Infused Trenches (LiMIT) exposed to EAST plasma**
  - Follows prior studies on HT-7

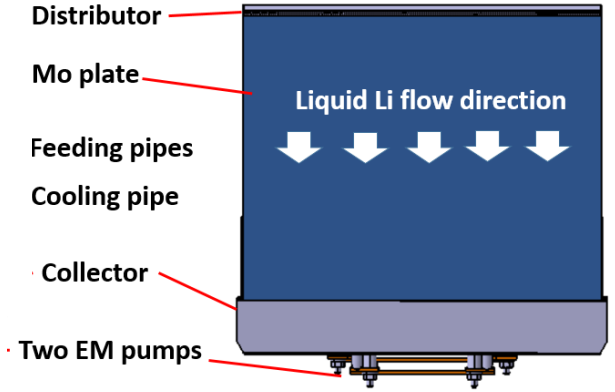
DIII-D helicon antenna

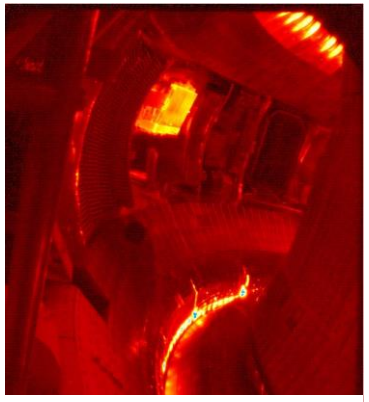


(b) EAST Impurity Powder Dropper



Flowing Li Limiter





LiMIT exposure on EAST

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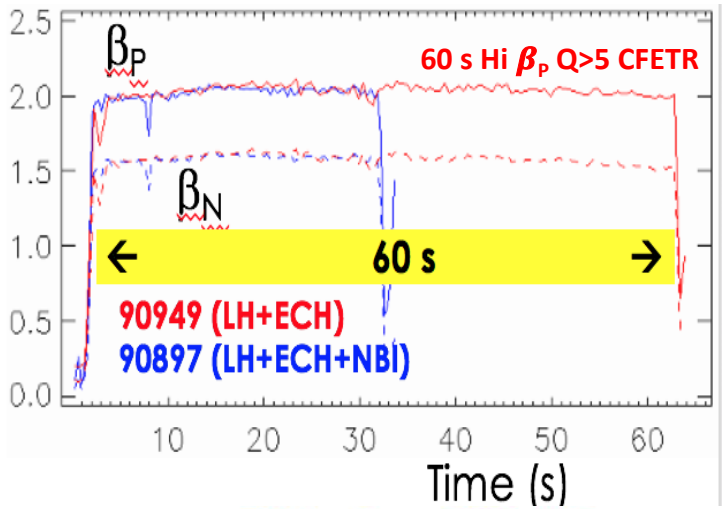
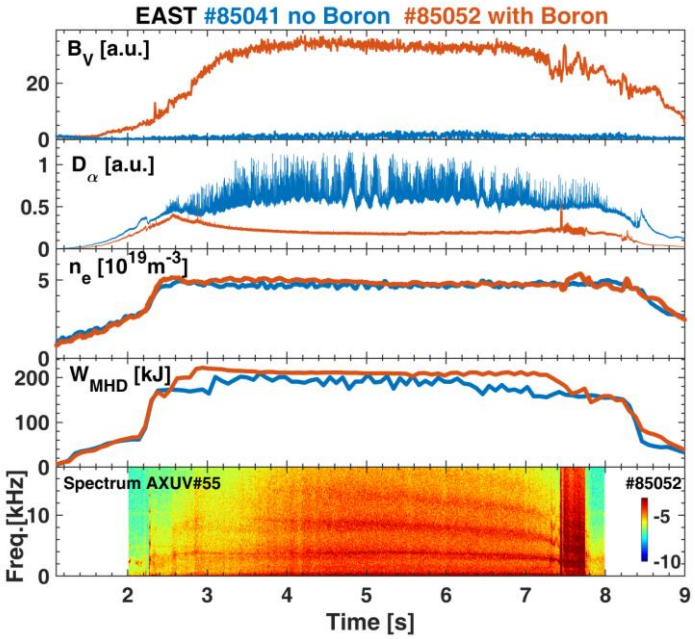
Plasma scenarios integrate existing knowledge and control tools to realize burning plasma regimes

Major Recent Achievements:

- **Key contributions to extension of DIII-D High-βp scenario to 60 sec on EAST projecting to steady-state Q>5 in CFETR**
- **Simultaneous injection of 2.45 GHz and 4.6 GHz lower hybrid wave gives higher current drive efficiency, validating TRANSP predictions**
- **3D fields used to modify q-profile for scenario optimization**
- **Impurity injection used to modify edge stability**
  - Powder dropper suppress ELMs with Lithium or Boron
  - Granule injector increases ELM frequency, reduces size





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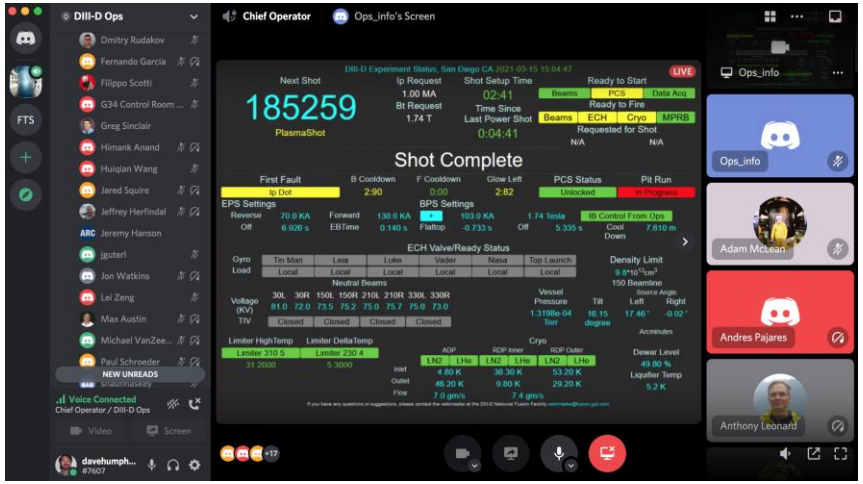
Experience from remote participation on EAST enabled rapid deployment of remote posture on DIII-D during pandemic

Major Recent Achievements:

- **Remote 3rd Shift Experiments in EAST 2019-20 Campaign**
  - Detachment control experiments
  - Extension of DIII-D High-bP scenario to longer pulse in EAST
  - Current profile control experiments
  - Disruption prediction, prevention, avoidance experiments
- **EAST Remote Operation methods helped enable DIII-D to operate with majority of staff off-site**
  - DIII-D remote functions exploit procedures pioneered in EAST remote operation
  - Remote monitoring facilities imported from GA Remote Control Room (machine status, real-time traces, real-time boundary reconstruction, …)
  - Remote Physics Operations (plasma control system access and operation) modeled on EAST remote 3rd shift
  - Discord video gaming software use for EAST 3rd shift enables operations-physics team communication in DIII-D campaign

GA Remote Control Room Supports EAST 3rd Shift Experimental Operations

Discord Software for Remote Operations in 2020-21 DIII-D Campaign

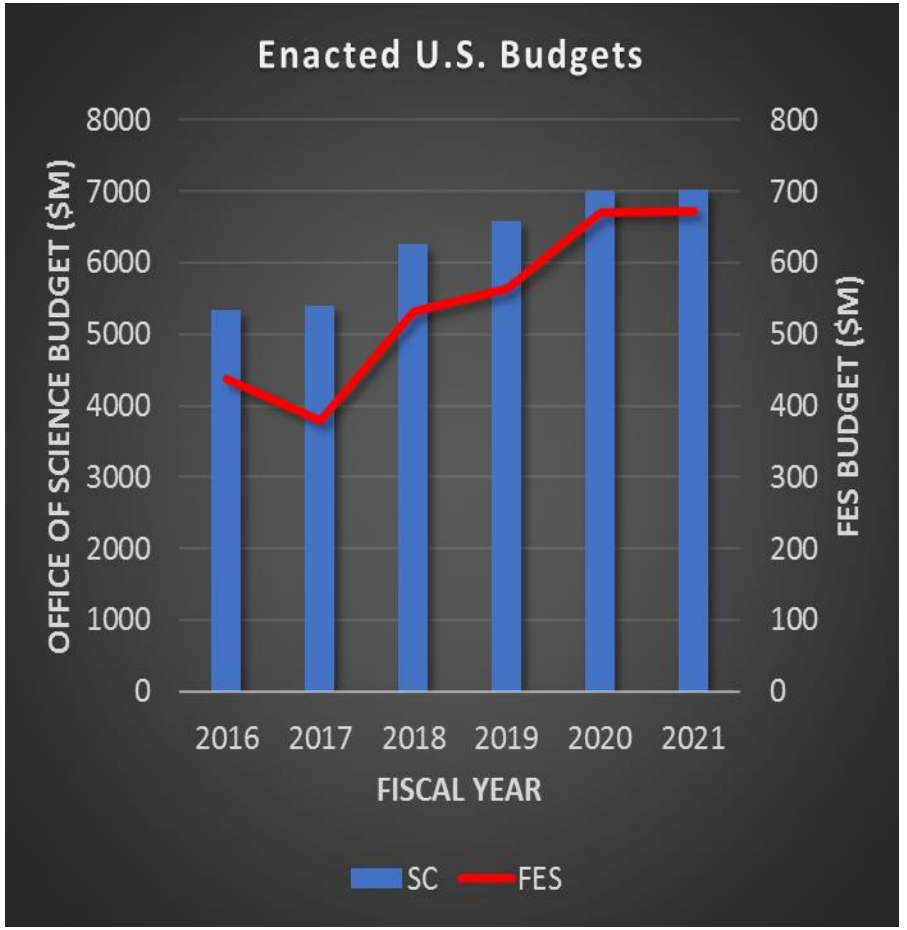


FES Programmatic Updates

Budget status

- **FY 2021 Enacted Budget**:
  - $672M total for FES
    - $242M for ITER
      - $60M of the total for cash

- **FY 2022 Budget Request**:
  - The FY 2022 budget process has been delayed due to the Administration transition



Recent enacted budgets have enabled accelerated progress throughout the program

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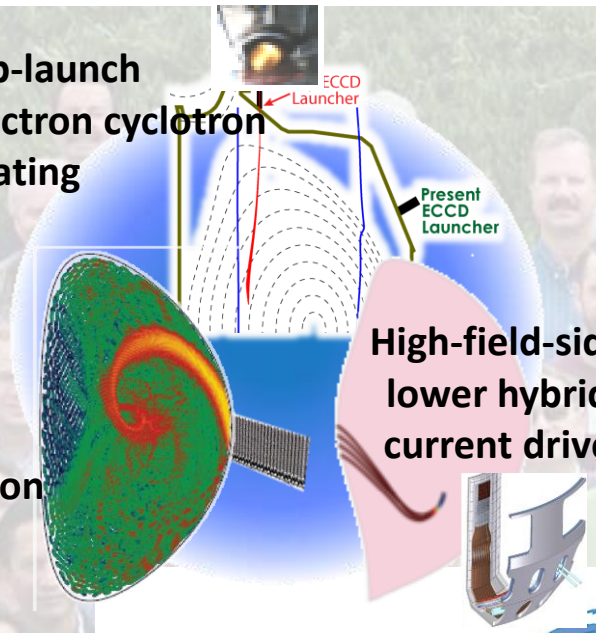
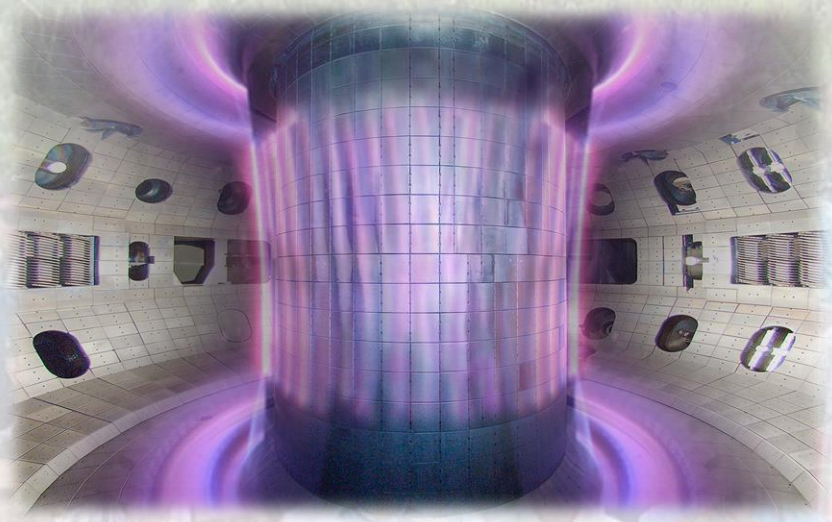
The DIII-D program continues to make significant contributions to magnetic fusion research

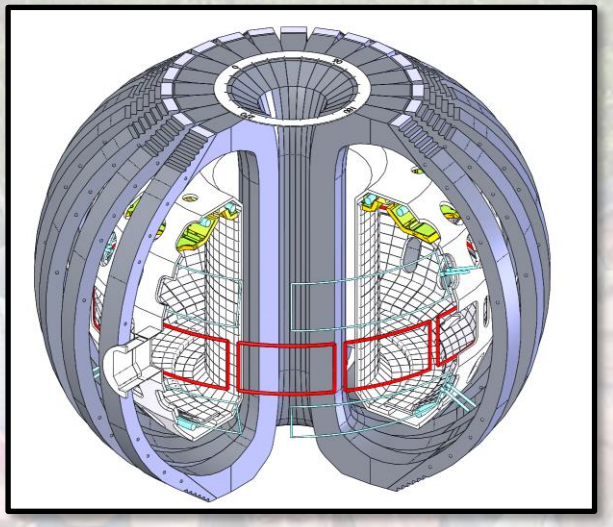
Top-launch electron cyclotron heating

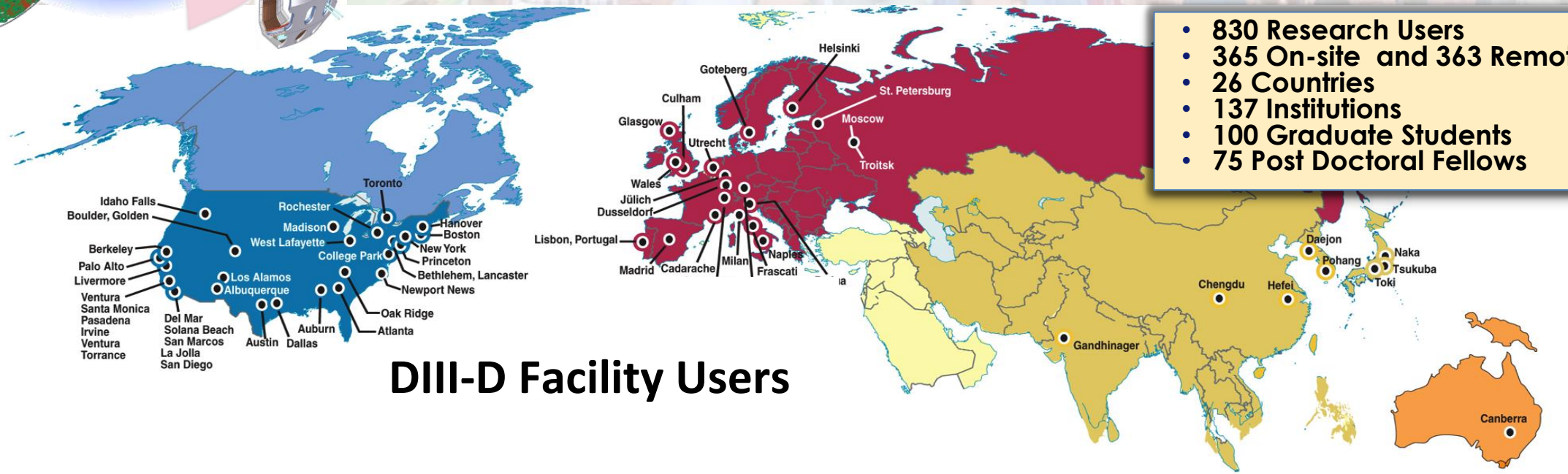


High-field-side lower hybrid current drive

Helicon







- 830 Research Users
- 365 On-site and 363 Remote
- 26 Countries
- 137 Institutions
- 100 Graduate Students
- 75 Post Doctoral Fellows

DIII-D Facility Users

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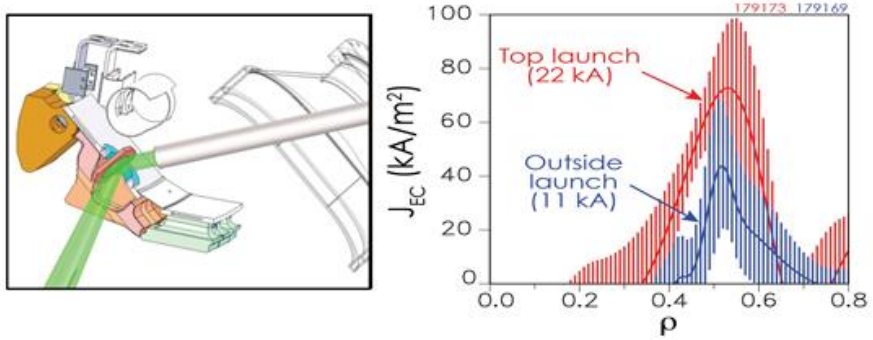
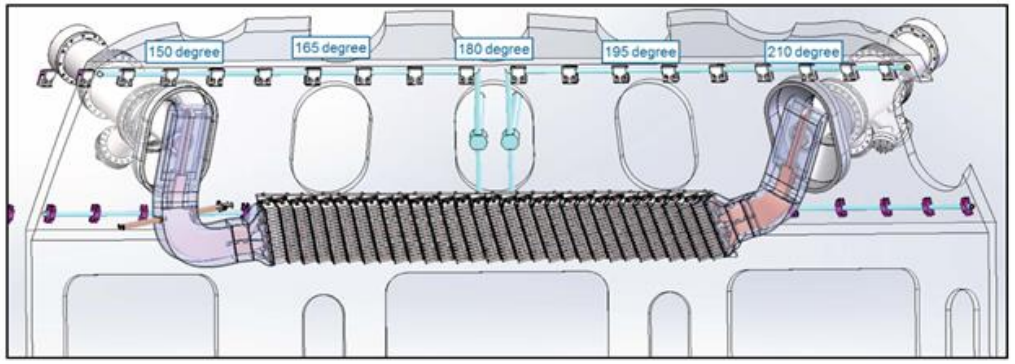
DIII-D is testing three current drive technologies offering high efficiency and improved access for higher-density scenarios

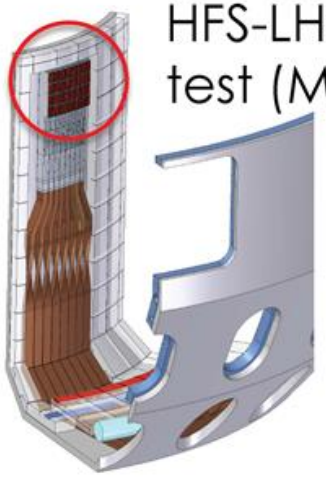
1. **Top launch ECCD doubles efficiency as expected**
   - PAC rated priority #1,
   - Successful demonstration in 2020



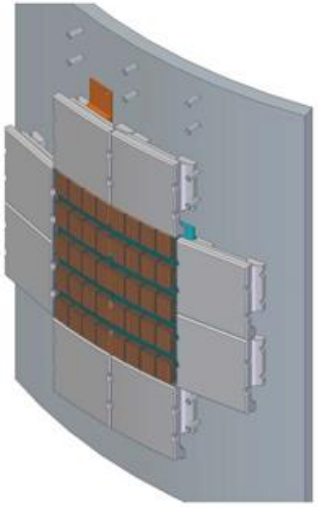


2. **Helicon currently being commissioned**
   - 1MW launcher installed during LT03
   - Klystron from SLAC (with NFRI/KSTAR)

3. **HFS LHCD in development**
   - AT plasmas found compatible with low inner gaps →
   - HFS test tile in FY18, completion during summer 2021 vent



HFS-LHCD test (MIT)



Replica Launcher test April 2018

DIII-D NATIONAL FUSION FACILITY

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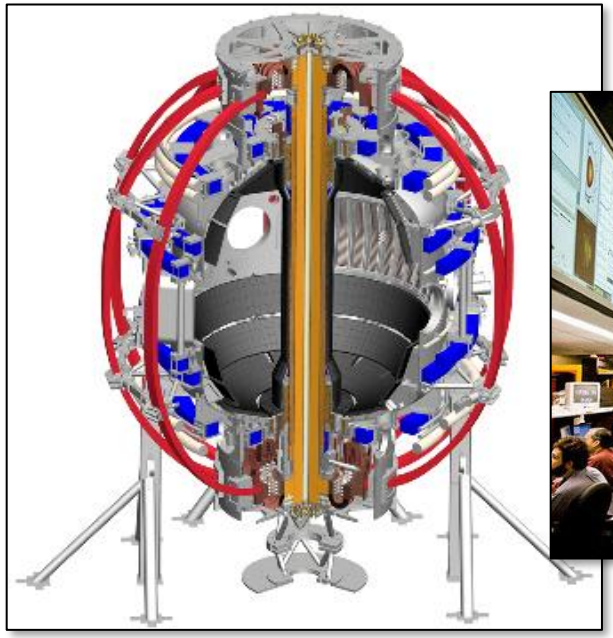
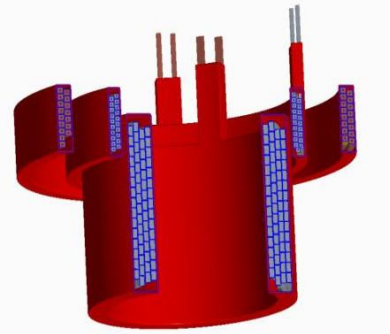
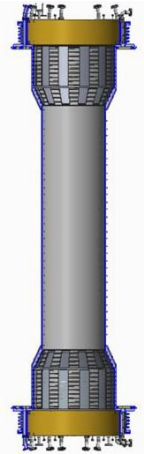
National Spherical Torus Experiment-Upgrade



- Project impacted by COVID-19
- Limited staff on-site; vendor delays

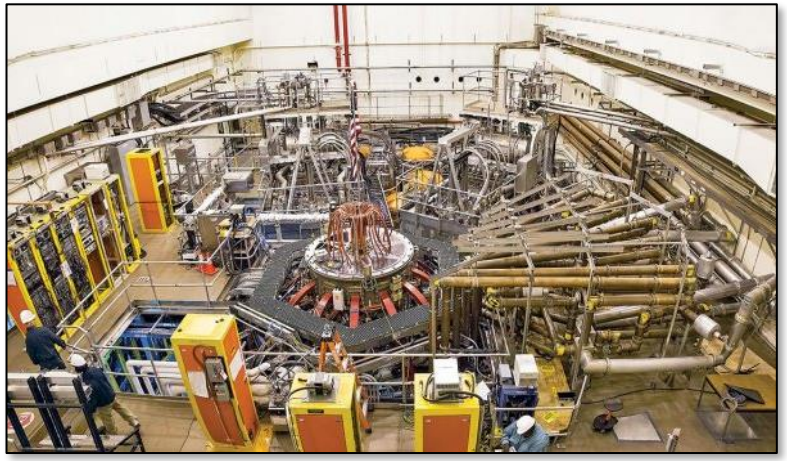


Six new inner-PF coils
(PF-1a, b, and c, upper and lower)



New CS casing

National Spherical Torus Experiment-Upgrade @ PPPL



NSTX-U is currently in Recovery/repair phase

- Six replacement poloidal field coils (plus three spares) have been delivered to PPPL.
- Work continues on center stack casing, new tiles, passive plates, and additional diagnostics.

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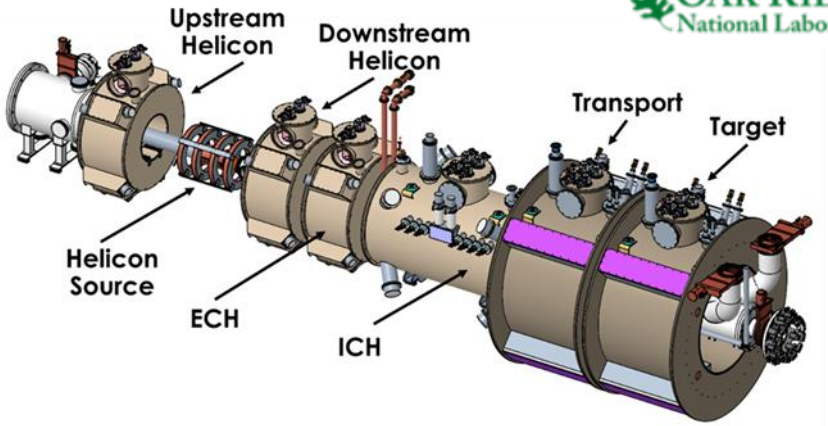
Construction projects for new world-leading facilities

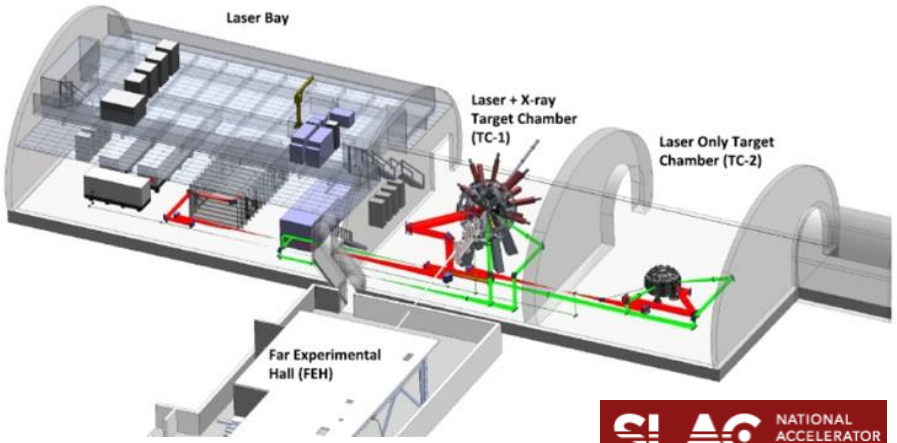
- **FES has initiated a new Major Item of Equipment project for a linear divertor simulator**
  - Critical Decision-3A, Approve Long-Lead Procurements was obtained October 2020
  - The Material Plasma Exposure eXperiment (MPEX) will address need for expanded materials science capabilities
  - MPEX is a high-priority recommendation in the FESAC Long Range Plan (2020)

MPEX

OAK RIDGE National Laboratory



- **FES is exploring a petawatt laser facility upgrade at the Matter in Extreme Conditions (MEC) end station at LCLS**
  - Addresses recommendation in the 2017 NASEM report *Opportunities in Intense Ultrafast Lasers*
  - PLF will study properties of matter in extreme conditions of densities and temperatures, relativistic plasmas, planetary science and laboratory astrophysics, plasma photonics and nonlinear optics, and strong field quantum electrodynamics
    - High energy long pulse: 1 kJ @ 10ns
    - High rep-rate short pulse: 150 J, 150 fs, 1 PW, 10 Hz, upgradable up to 2 PW or operate as High rep-rate long pulse: 200 J @ 2ω @ 10ns; 10 Hz



SLAC NATIONAL ACCELERATOR LABORATORY

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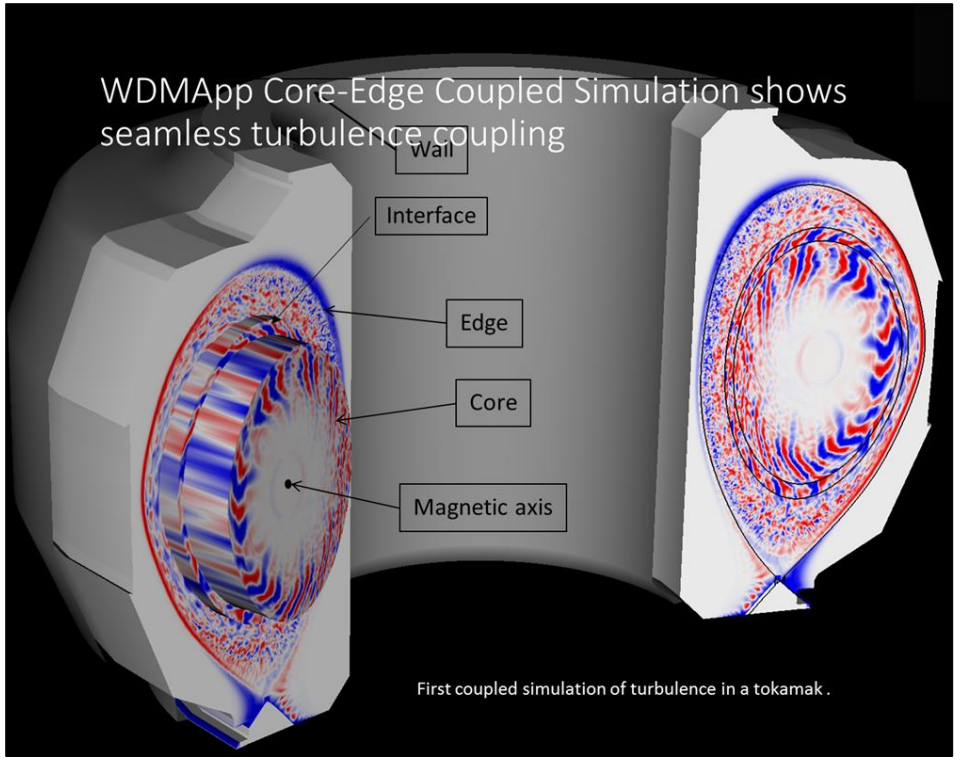
FES high-performance computing research

- **SciDAC**:
  - The nine FES multi-institutional SciDAC projects are making progress toward integration and Whole-Device Modeling

- **Exascale**:
  - The PPPL-led WDMApp project in the SC Exascale Computing Project (ECP) portfolio is developing core-edge coupling technology with continuum and particle codes
  - FES scientists are preparing for use of the first Exascale computing systems (Frontier at ORNL and Aurora at ANL)

NERSC @ LBNL



SUMMIT @ ORNL

FRONTIER Exascale Computer @ ORNL (due in 2021-2022)

AURORA Exascale Computer @ ANL (due in 2022-2023)

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Long-range strategic planning activities for FES completed Phase 2

Phase-1

Community awareness

Subfields community self-organization

FESAC charge issued

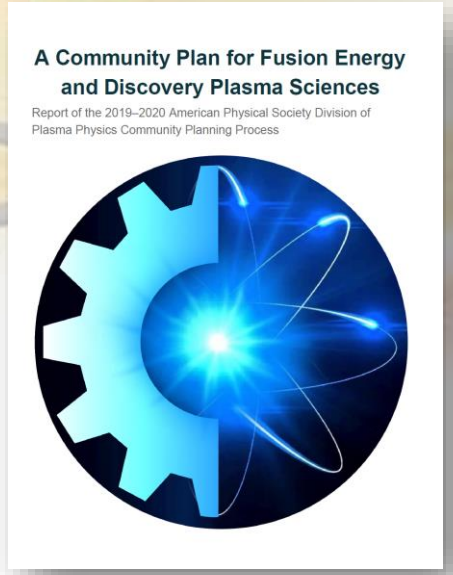
APS DPP town hall meetings

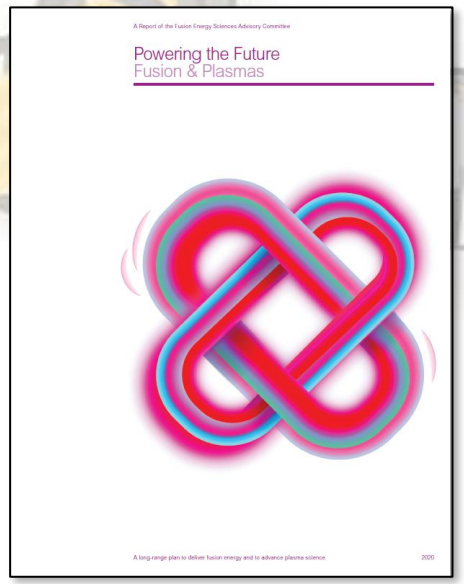
Final CPP workshop (Houston)

Phase-2

- Phase 2, led by FESAC/FESAC Subcommittee, took input from Phase 1 (CPP) to develop the final long-range plan
- Long-range plan was approved at FESAC meeting (December 7, 8, and 10, 2020)

- FES requested APS-DPP to organize CPP program committee and sponsor CPP workshops and travel
- The CPP activities involved broad engagement from the entire U.S. fusion and plasma physics community
- Frequent town halls, webinars, hundreds of small group discussions among subject matter experts, dedicated workshops, and focus group discussions were held.
- Hundreds of white papers and initiative proposals were submitted by the community throughout the process.





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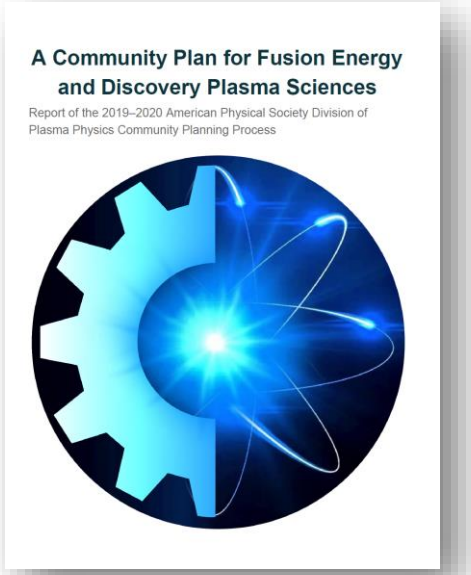
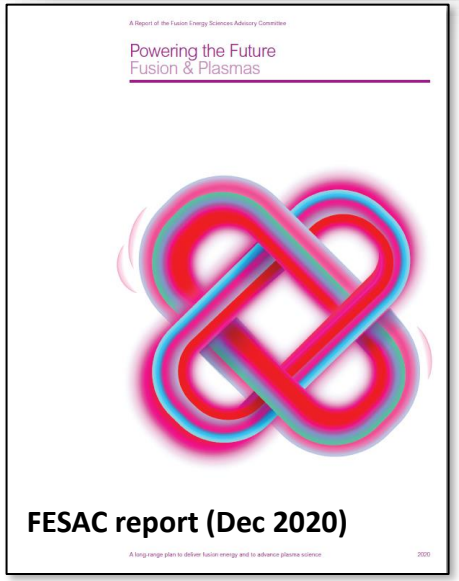
Community/FESAC long-range strategic planning: specific recommendations





FESAC report (Dec 2020)

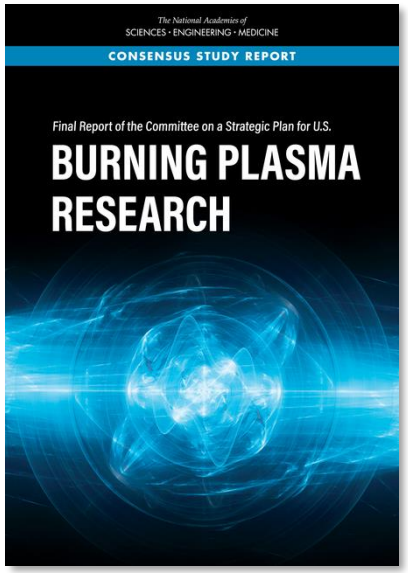
- **Fusion science and technology**: ***Focus on establishing the scientific and technical basis for a fusion pilot plant by the 2040s***
  - Expand fusion materials and technology R&D
  - Pursue Fusion Prototypic Neutron Source
  - Complete MPEX and other high-heat-flux test facilities
  - Expand blanket and tritium R&D
  - Use DIII-D, NSTX-U, and international collaborations to address gaps
  - Form a U.S. ITER Research Team
  - Pursue EXCITE facility to address integrated core performance and plasma exhaust gap
  - Strengthen innovation (e.g., stellarators, liquid metal walls, IFE, alternate concepts)

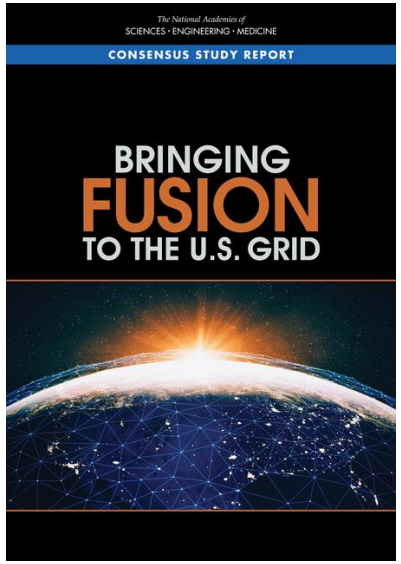
- **Plasma science and technology**: ***Focus on new opportunities to advance fundamental understanding, and in turn translate these advances into technologies that benefit society***
  - Provide steady support for fundamental plasma science to enable innovation and talent development
  - Complete the design and construction of MEC-Upgrade
  - Establish a plasma-based technology research program for translating scientific findings into societally beneficial applications
  - Coordinate a High-Intensity-Laser Research Initiative with relevant DOE offices and other federal agencies
  - Pursue a multi-petawatt laser facility and a high-repetition-rate high-intensity laser facility in the US, in partnership with other federal agencies where possible
  - Support networks to coordinate research and broaden access to state-of-the-art facilities, diagnostics, and computational tools
  - Strengthen support of laboratory-based research relevant to astrophysical and space plasmas

- **These recommendation were prioritized within 3 budget scenarios**

https://science.osti.gov/-/media/fes/fesac/pdf/2020/202012/FESAC_Report_2020_Powering_the_Future.pdf

Recent National Academy advisory reports for FES





Strategic Plan for U.S. Burning Plasma Research (2019)

- **The U.S. should remain an ITER partner** as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant.
- The U.S. should start a national program of accompanying research and technology leading to the **construction of a compact pilot plant** which produces electricity from fusion at the lowest-possible capital cost.

Bringing Fusion to the U.S. Grid: Key Goals and Innovations for a U.S. Fusion Pilot Plant (2021)

- To make an impact on the transition to a low-carbon emission electrical system by 2050, the **Department of Energy and the private sector should produce net electricity in a fusion pilot plant in the United States** in the 2035—2040 timeframe.
- DOE should move forward now to foster the creation of **national teams**, including public-private partnerships, **that will develop conceptual pilot plant designs** and technology roadmaps that will lead to an engineering design of a pilot plant that will bring fusion to commercial viability.
- The participants in the development of the pilot plant should execute the recommendation of the Community Planning Process to “Embrace diversity, equity, and inclusion, and develop the multidisciplinary workforce required to solve the challenges in fusion and plasma science.”

Upcoming Events

- **Following two-year strategic planning activity, FES is considering next steps in light of FESAC recommendations and priorities of the new administration**
  - New Secretary of Energy Jennifer Granholm confirmed February 25, 2021
  - J. Stephen Binkley is Acting Director of the Office of Science

- **International activities supported under the Long Pulse Tokamak program are in the third year of three-year program**
  - Prior solicitations held 2013, 2016, and 2019
  - Any future solicitation will emphasize topics that address high-priority recommendations of the long-range strategic plan