FESAC International Benchmarking Report on International Collaboration Opportunities, Modes, & Workforce Impacts for Advancement of US Fusion Energy

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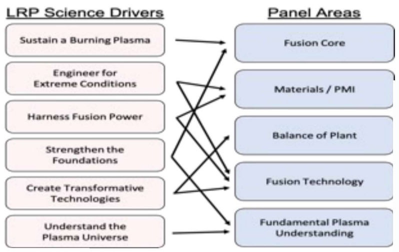
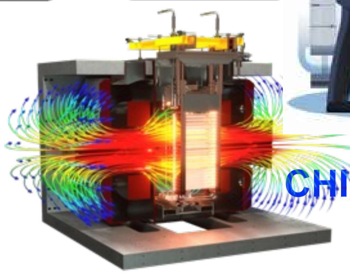
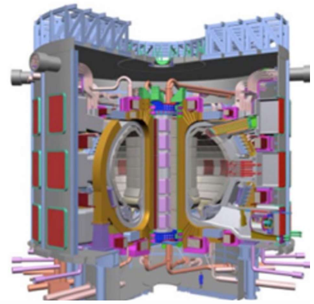
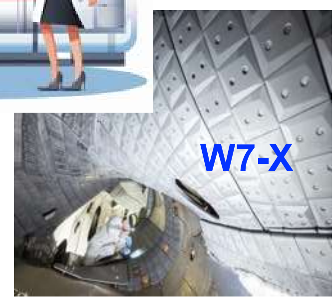
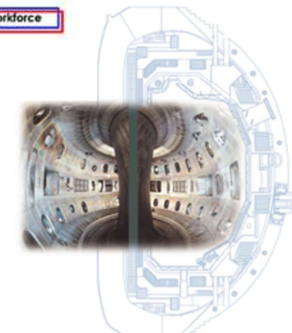


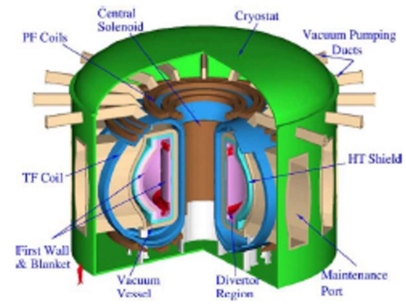






KSTAR





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Summary: FESAC International Benchmarking Identified Opportunities, Best Modes of Collaboration, Leadership Status, and Workforce

- **FESAC was charged in 2022 with updating International Benchmarking from previous 2012 study:**
  - Assess opportunities, status of international collaboration in context of Bold Decadal Vision
  - Five separate charges including collaboration modes, leadership, public-private role, workforce
  - Subcommittee was formed to produce assessment

- **Key high-level observations regarding international collaboration:**
  - Cannot replace need for strong domestic program in general
  - Can provide important complementary resources, and fill gaps in US capabilities
  - Requires dedicated, sustained support and specific practices to maximize impact

- **High-level recommendations:**
  - Specific tokamak, stellarator, alternative MFE, IFE, technology facilities are key to the BDV
  - International public-private collaborations can help to advance US private fusion efforts
  - Several key areas identified that need advancement in US leadership to realize the BDV
  - Large workforce development effort needed to provision US fusion program for coming decade

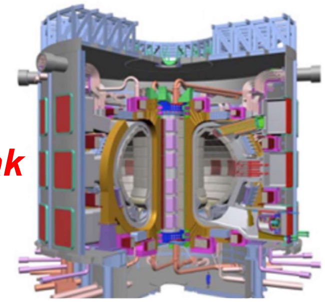
Overview

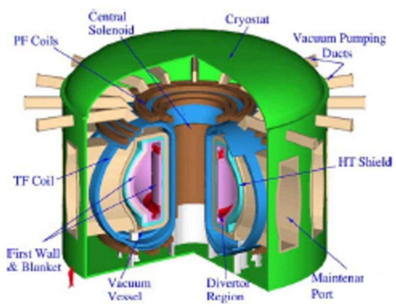
- **Background and Context: Fusion's Bold Decadal Vision**
- **Charges**
- **Subcommittee: Membership, Topical Panels**
- **Opportunities (Charge 1) and Potential for Bold Decadal Vision (Charge 2a)**
- **Cross-cutting charges: Maximizing Collaboration Impact (2b), Public-Private International (3), US Leadership (4), and Workforce Development (5)**
- **Conclusions**

Fusion Approaches Fall Into Two Categories: Magnetic Confinement or Inertial Confinement

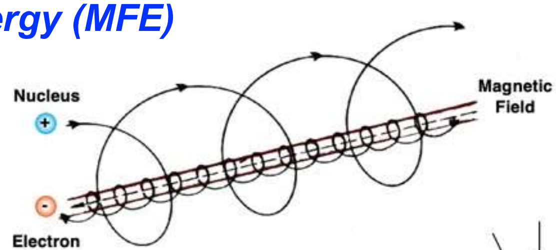
Magnetic Fusion Energy (MFE)

ITER Tokamak

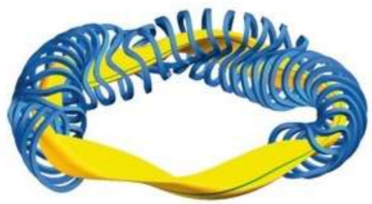


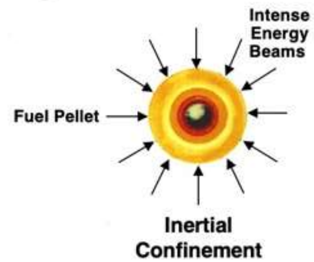


ARIES Tokamak Power Plant Design



W7-X Stellarator – Max-Planck IPP

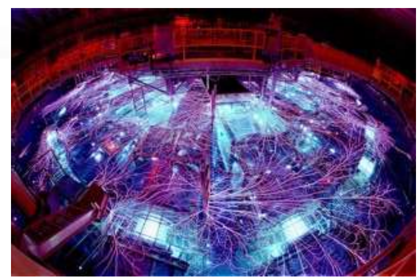




Inertial Fusion Energy (IFE)

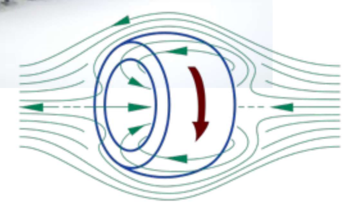
Omega Laser Facility – LLE

National Ignition Facility – LLNL



Z Machine Magnetized Target Fusion - SNL

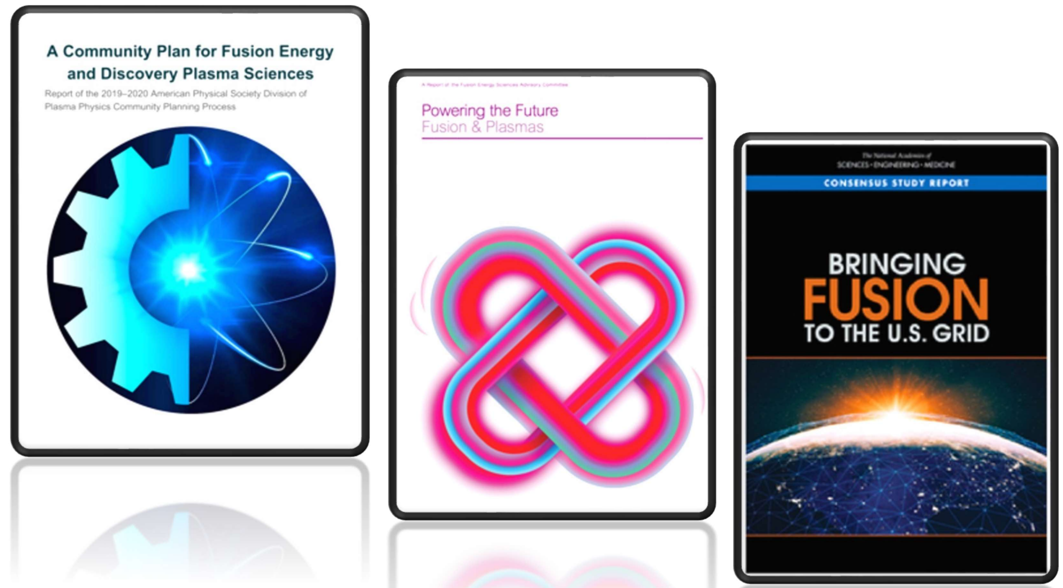
Norman beam-driven FRC - TAE Technologies



Recent Consensus Community Reports and Demand for Clean Energy Have Highlighted Need for Fusion Advances

Addressing Climate Change Requires New Clean Energy Sources

Fusion Community Reports Identify a Fusion Pilot Plant (FPP) as Primary Objective of the Bold Decadal Vision for Fusion



Collaborations providing access to international resources are critical to fusion energy advances

Charge to FESAC: Update "International Benchmark" with Expanded Scope Relative to Previous 2012 Benchmark

- **Charge 1:** What research areas/facilities provide key **opportunities** for US researchers?
- **Charge 2a:** Identify facilities' **potential** to contribute to the Bold Decadal Vision for commercial fusion and plasma science, and increase readiness for ITER operation
- **Charge 2b:** What modes of international collaboration **maximize research impact**?
- **Charge 3:** How can the U.S. leverage **fusion private sector** in international engagements, and how can we cooperate with overseas public-private partnership programs that focus on accelerating the development of commercial fusion?
- **Charge 4:** Within FES research areas, what are the areas where the **US is leading**, leadership is threatened, or US is not leading at present?
- **Charge 5:** How can U.S. ensure an internationally competitive **workforce for fusion**, including recruitment from traditionally underrepresented groups within the U.S.?

Subcommittee Distributed Broadly Across Institutions and Panels to Assess Charges by Topical Research Area

Last Name	First Name	Institution	Panel 1: Fusion Core	Panel 2: Materials/PWI	Panel 3: Balance of Plant	Panel 4: Technologies	Panel 5: Fundamental Plasma Science
Bonoli	Paul	MIT					
Casali	Livia	U. Tenn.					
Ferraro	Nate	PPPL					
Field	Kevin	U. Mich.					
Gleason	Arianna	SLAC					
Holcomb	Chris	LLNL					
Humphreys	Dave	GA					
Humrickhouse	Paul	ORNL					
Ma	Tammy	LLNL					
Magee	Rich	TAE					
Marian	Jaime	UCLA					
Murph	Simona	SRNL					
Paz-Soldan	Carlos	Columbia U.					
Walker	Mitchell	Georgia Tech.					

Key: Green = Panel Lead, Yellow = Panel Member

Charges 1 and 2a: International Opportunities and Facilities

Charge 1: What research areas/facilities provide key opportunities for US researchers?

Charge 2a: Identify facilities' potential to contribute to the Bold Decadal Vision for commercial fusion and plasma science, and increase readiness for ITER operation

Charge 1 Response: Many International Research Facilities Offer Opportunities to Advance US Fusion in Several Topical Areas

- **Tokamak, ST, stellarator, alternate MFE, ICF/IFE research:**
  - Optimize design/operation of divertors, scenarios, disruption avoidance/mitigation in conditions not present in US
  - Long pulse with high beta, higher B-field, metal walls, different divertor geometries at high heat flux
  - KSTAR, EAST, JT-60SA, DTT, MAST-U, ST80-HTS (STX)
  - US leadership in stellarator physics requires enhanced collaboration with international programs, especially W7-X
  - US leads in IFE but should augment domestic efforts with international community in materials, full system modeling
- **Materials: Plasma-Facing and Bulk Structural**
  - Solid and liquid metal walls: primarily EAST
  - Fast spectrum reactors or spallation sources for high-energy neutrons; triple-ion beam facilities for multi-species effects
- **Balance of Plant: Tritium Handling and Breeding Blankets, Waste, Safety, RAMI, Power Conversion**
  - CHIMERA blanket component testing, H3AT for tritium processing
- **Technology :**
  - ICRH in all-metal environment (e.g. WEST); high energy CW neutral beams (IPP-Garching, Nat'l Inst for QST/JA)
  - HTS magnet manufacturing capability (e.g. Tohoku Univ., Robinson Inst.); high frequency CW gyrotrons (KIT, Kyoto Fusioneering…)
- **Fundamental plasma science:**
  - Opportunities in high rep-rate lasers, ignition science, QED, laser-plasma interaction; ELI Beamlines/NP, ExFEL, Apollon, LMJ, LULI, CORELS, EPAC

Charge 2a Response: Many International Facilities Have High Potential to Help US Address Priorities of Bold Decadal Vision

- **KSTAR, EAST, MAST-U have high potential to help close gaps in tokamak/ST physics**
  - Boost ITER success, contribute to FPP design on BDV timescale
  - Before 2030: JT-60SA, DTT, ST80-HTS
- **Bulk materials and plasma facing components can benefit from international collaboration:**
  - IFMIF-DONES and Magnum-PSI high potential for irradiation and high heat flux studies; EAST for solid/liquid metal walls
  - High importance before US MPEX and FPNS realized
- **Balance of Plant can be advanced by H3AT and CHIMERA collaboration if no US facilities:**
  - Blanket Test Facility and tritium processing plant essential to inform FPP design on BDV timescale
- **Technology collaborations have high potential to resolve key FPP design issues for BDV:**
  - ICRH; high energy CW neutral beams; HTS magnet manufacturing; high frequency CW gyrotrons
- **Theory and Computational Physics collaborations accelerate and expand design capabilities:**
  - Strong potential for acceleration of BDV goals: CEA/IRFM, Max-Planck IPP, CCFE, CREATE, DIFFER, EPFL/SPC
  - Continued engagement with ITPA amplifies US theory/simulation/computational physics impact
  - Potential to increase US readiness for ITER operation and likelihood of ITER success

Charge 2b: What modes of international collaboration maximize research impact?

Charge 2b Response: Collaborations Maximize Impact by Creating Clear Goals, Defined Roles, Good Cyber Access

- **General Practices for Impactful Collaborations:**
  - Strong frameworks, definition of collaboration goals/roles
  - Run collaborations like true projects: schedule, goals, deliverables, project controls
  - Experiments: close communication for device scheduling
  - Technology: focus on user procedures, safety coordination
  - Theory/Foundational Science: strong dependence on cyber access, high bandwidth/low latency data communication, data standards, modern software management

- **Recommendations:**
  - Require strong collaborative frameworks/definitions in proposals
  - Require specification of key tools/mechanisms to maximize impact, e.g. project management tools, coordination software and methods, common data standards, etc…
  - Provide strong international agreement frameworks, science networks, support for travel, onboarding and on-site location of participants
  - Support remote operation and/or participation where they can provide good value

Remote Control Rooms Enable Effective Remote Collaboration in Experiments and Operations

- **Charge 3: How can the U.S. leverage fusion private sector in international engagements, and how can we cooperate with overseas public-private partnership programs that focus on accelerating the development of commercial fusion?**

Charge 3 Response: Supporting Fusion Private Sector Engagements in International Collaboration Can Help Accelerate Development

- **Alternate concept facilities abroad offer valuable opportunities to private sector:**
  - Tokamaks and stellarators constitute a minority of concepts in US private sector, approximately 30%
  - Multiple IFE companies have been recently established, and are either internationally-based (roughly half of IFE startups to date) or have both a US and international presence (balance of startups)

- **Recommendations:**
  - A public-private partnerships program should be created to facilitate the collaboration of domestic private companies and international resources
  - Collaborations supported should:
    - ➢ Be limited in scope with well-defined deliverables
    - ➢ Strike a clear balance between openness and IP protection
    - ➢ Be modeled after successful agreements such as INFUSE and CRADA

- **Private sector is best leveraged with focused goal-oriented collaborations:**
  - Private sector can provide unique opportunities for connections with international facilities that are especially mission-driven and potentially more focused and flexible than public research collaborations.

Partnerships between the public and private sectors can accelerate the development of fusion energy

- **Charge 4: Within FES research areas, what are the areas where the US is leading, leadership is threatened, or US is not leading at present?**

Charge 4 Response: US Occupies Strong Leadership Worldwide in Many Fusion Areas, But Needs Advancement in Specific Areas for BDV

	Physics	Technology	Computation & Algorithms
Leading	Tokamak: Disruptions Stellarator Optimization Inertial Fusion Energy HEDP Ignition science	HTS magnets High rep-rate lasers	Computational Modeling for Materials Theory, Simulation, Computational Physics
Parity	Tokamak: Burning plasma; Divertor & Core-Edge Integration; Scenarios Alternative magnetic configurations	Irradiation testing ICRF technology	Integrated modeling Control mathematics, advanced algorithms, ML/AI
Not Leading	Stellarator: Core physics & divertor Laser driven experimental fundamental plasma facilities	Plasma facing materials Tritium breeding blankets, handling & fuel cycle Ancillary systems Gyrotron R & D Neutral beams	Fusion system design

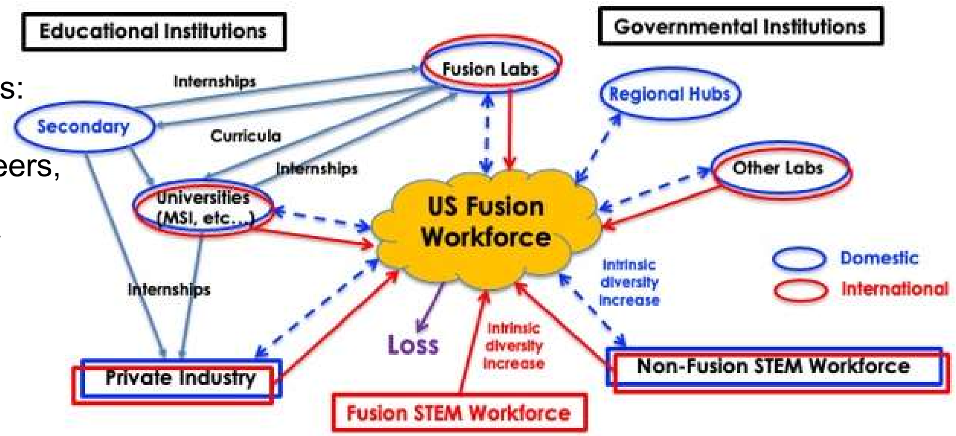
- **US leads in much of tokamak physics: short pulse demo of high-performance scenarios, disruption avoidance & mitigation physics/control, and core-edge integration**
- **The US does not lead in the operation of large fusion facilities due to insufficient number domestically**
- **As demonstrated by the recent ignition achievement, the US is the international leader in IFE now, but should keep science as open as possible to maintain**

- **Two key technology areas in which the US is not leading and could benefit from international collaborations are gyrotron source development and testing/diagnostics development for high-repetition rate lasers**

- **Charge 5: How can U.S. ensure an internationally competitive workforce for fusion, including recruitment from traditionally underrepresented groups within the U.S?**

Charge 5 Response: Dedicated Efforts Will Be Required Both Domestically and in Collaborations to Develop Fusion Workforce

- **Providing Needed Workforce is Large Challenge:**
  - Many thousands of new personnel needed…
  - Dedicated domestic efforts will be required
  - Need includes work categories beyond plasma physics: materials science, all engineering disciplines, mathematics, computer/data scientists, system engineers, project managers, CAD design, technicians
  - International collaborations can help build workforce if mission is built into funding opportunities



Workforce expansion accomplished through domestic and international sources: universities, government labs, private industry, non-fusion STEM

- **Recommendations:**
  - Provide support to pipeline at all educational levels: undergrad, grad, post-grad; scholarships/internships/fellowships/curricula
  - Focus on Minority Serving Institutions/underrepresented communities: research funding, coupling to regional hubs
  - Build in specific funding/planning for use of international collaborations to grow workforce: student training, provide conduit for international personnel to the US
  - Improve efficiency and availability of long-term visas and permanent resident status

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