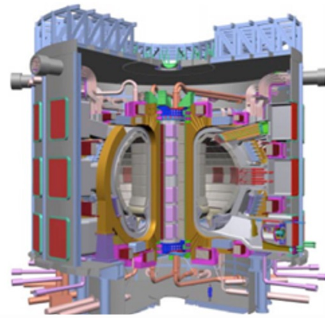
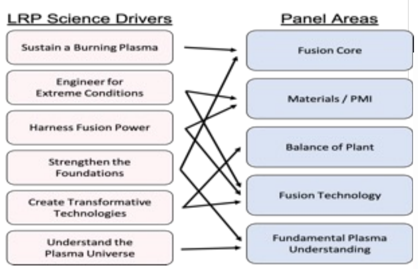
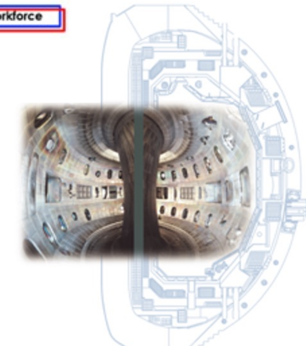
FESAC International Benchmarking Report on International Collaboration Opportunities, Modes, & Workforce Impacts for Advancement of US Fusion Energy

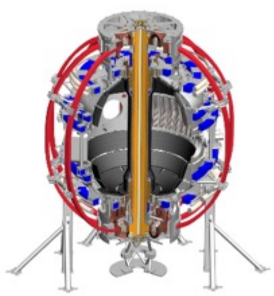
D. Humphreys, P. Bonoli, L. Casali, N. Ferraro, K. Field, A. Gleason, C. Holcomb, P. Humrickhouse, T. Ma, R. Magee, J. Marian, S. Murph, C. Paz-Soldan, M. Walker, A. White (Ex-Officio)

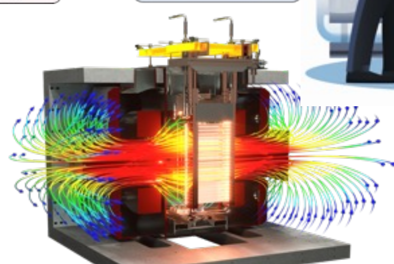




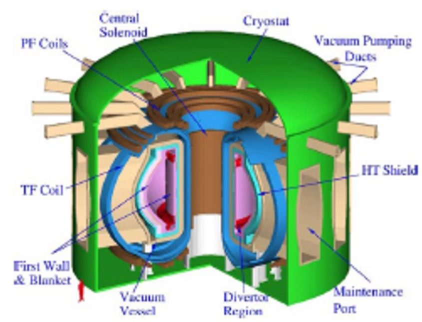
KSTAR







CHIMERA



FESAC Presentation
18 September 2023

Overview

- **Charges and elucidations**
- **Subcommittee Process: Membership, Topical Panels, Information Collection & Assessment**
- **Opportunities (Charge 1) and Potential for Bold Decadal Vision (Charge 2a)**
- **Cross-cutting charges: Maximizing Impact (2b), Public-Private International (3), Leadership (4), and Workforce (5)**
- **Conclusions**

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

- **Charge 1: International collaboration opportunity areas of research and facilities?**
  - Since the last time FESAC assessed the opportunities afforded to U.S. scientists by international fusion facilities with unique capabilities, a number of new facilities have come online, and existing facilities have undergone significant upgrades. **In what areas of research and on which facilities are there compelling opportunities** for U.S. researchers over the next 10 years?

- **Charge 2: Potential for addressing priorities and recommendations of LRP/NASEM reports with international facilities?**
  - What is the **potential of these facilities to help U.S. scientists address priorities and recommendations in the LRP** **(Charge 2a)** and the National Academies report on "Bringing Fusion to the U.S. Grid", contribute to the Administration's bold decadal vision for commercial fusion, and increase the U.S. readiness for ITER operation? In addition, please **assess whether the existing modes of collaboration are adequate for maximizing the impact** **(Charge 2b)** of international collaborations on the U.S. fusion program and objectives.

- **Charge 3: How can we leverage fusion private sector in international engagement?**
  - How can the **U.S.** take advantage of its considerable and growing **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 to FESAC: Update "International Benchmark" with Expanded Scope Relative to Previous 2012 Benchmark

- **Charge 4: Identify areas of US leadership, threatened leadership, non-leadership**
  - Within the Fusion Energy Science-supported research areas and facility capabilities for fusion energy science and discovery plasma science, what are the **areas where the U.S. is leading**, the areas where **U.S. leadership is threatened** in the near- and long-term, and the areas in which **U.S. is not leading** at present but **where investing resources could offer significant opportunities for leadership** that would be beneficial to the U.S. fusion program goals and objectives?

- **Charge 5: Ensuring workforce for fusion including recruitment of talent from underrepresented groups**
  - How can the U.S. ensure the availability of a highly trained and internationally competitive **workforce in fusion science and technology** and related areas, including the recruitment of **talent from traditionally underrepresented groups within the U.S.?**

Subcommittee Membership Includes Broad Representation

Last Name	First Name	Institution	Field	Email
Casali	Livia	U. Tenn.	MFE	lcasali@utk.edu
Bonoli	Paul	MIT. (Vice-Chair)	Theory	bonoli@psfc.mit.edu
Ferraro	Nate	PPPL	Theory	nferraro@pppl.gov
Field	Kevin	U. Mich.	Technology	kgfield@umich.edu
Gleason	Arianna	SLAC	HEDLP	ariannag@stanford.edu
Holcomb	Chris	Lawrence Livermore Nat'l Lab.	MFE	holcomb@fusion.gat.com
Humphreys	Dave	GA. (Chair)	MFE	humphreys@fusion.gat.com
Humrickhouse	Paul	Oak Ridge Nat'l Lab.	Technology	humrickhoupw@ornl.gov
Ma	Tammy	Lawrence Livermore Nat'l Lab.	IFE/ICF	ma8@llnl.gov
Magee	Rich	TAE	Private-MFE	rmagee@tae.com
Marian	Jaime	UCLA	Technology	jmarian@ucla.edu
Murph	Simona	Savannah River Nat'l Lab.	GPS	simona.murph@srnl.doe.gov
Paz-Soldan	Carlos	Columbia U.	MFE	carlos.pazsoldan@columbia.edu
Walker	Mitchell	Georgia Institute of Tech.	GPS	mitchell.walker@ae.gatech.edu
White	Anne	MIT. (Ex Oficio)	MFE	whitea@mit.edu

Panel Leads Vice Chair

Subcommittee Had Demanding Process and Schedule

- **Assessment and report preparation process:**
  - Google Drive for common work and references; framework document to define process…
  - Panels formed mapping LRP/CPP/NASEM topical areas to fusion R&D areas
  - Plenary meetings every 1-2 weeks, panel meetings every 1-2 weeks
  - Early definition of draft report structure and content targets, some adjustment along the way… Section/charge leads identified
  - Metrics for opportunity/facility assessments identified and applied to selection/prioritization process
  - Consultation of ~40 experts in collaboration/topical areas, primarily through panels
  - Extensive panel topical assessments of opportunities/facilities (Charges 1, 2a), implications for Charges 2b-5
  - Collective assessments of Charges 2b-5
  - Report writing…

- **Key Milestones and Schedule:**
  - August 5, 2022: Subcommittee Kickoff
  - Mid-Sep 2022: framework document describing process for IB subcom task and report outline
  - Early-Dec 2022: status and draft report outline presentation to FES
  - End-Jan 2023: Preliminary draft report to FES (very drafty; updated outline, bullets/initial text, identified issues)
  - Mid-Apr 2023: Draft report to FES
  - August 4, 2023: Final report completed and delivered to FES POC
  - Mid-September: Presentation to FESAC

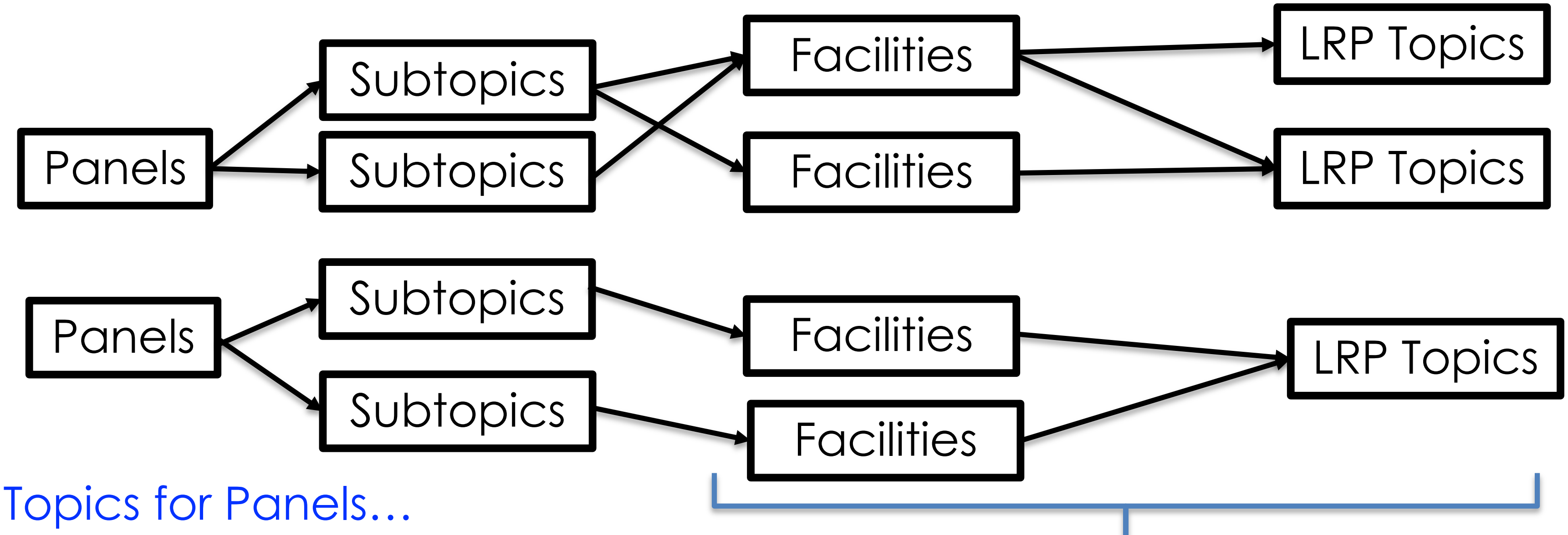
Subcommittee Distributed Broadly Across Panels and Topics

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	Savannah River Natl Lab					
Paz-Soldan	Carlos	Columbia U.					
Walker	Mitchell	Georgia Tech.					

Key: Green = Panel Lead; Yellow = Panel Member

Process for Opportunities/Facilities Assessment for Charges 1-2a Was Driven by Topical Panels

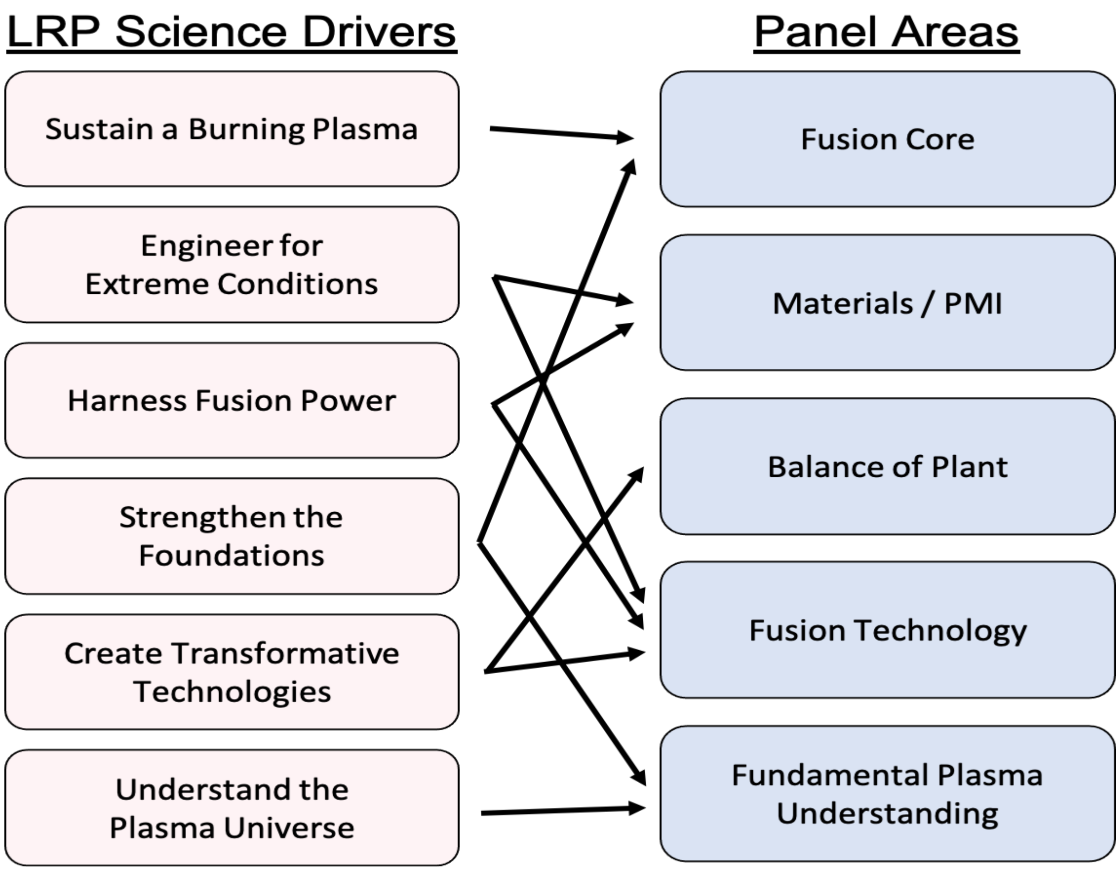
Charge 1-2a: Facilities-Topics (metrics)



Topics for Panels…
Subtopics for Facilities ID…
Metrics
Experts
Assessments

Charge 2b: How Best to Collaborate (procedures)
Charge 3: Leadership (metrics)
Charge 4: Public-Private (metrics)
Charge 5: Workforce (metrics)

CPP/LRP Topics Were Mapped to Panel Topics and Subtopics



- **Panel areas more directly map to opportunities and facilities:**
  - MFE experiments
  - Materials development/test stands
  - Blanket test facilities
  - Technology development labs
  - Fundamental science facilities
- **Panel areas span the space of the LRP science drivers**
  - LRP/NASEM/BDV vision well-represented by panels
- **Panel areas enable better focus on key gap topics**
  - "Orthogonalization" of topics and facilities

Charges 1 and 2a: International Opportunities and Facilities

Charge 1: In what areas of research and on which facilities are there compelling opportunities for US researchers?

Charge 2a: What is the potential of these facilities to help US scientists address priorities and recommendations in the LRP/NASEM reports, contribute to the Bold Decadal Vision for commercial fusion, and increase readiness for ITER operation?

Response Summary for Charge 1: International collaboration opportunity areas of research and facilities

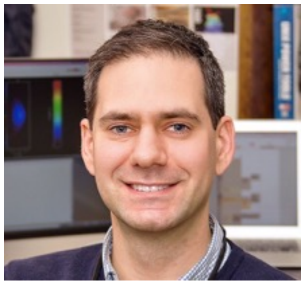
- **Compelling opportunities for tokamak, ST, stellarator, alternate MFE, ICF/IFE research:**
  - Optimize design/operation of divertors, scenarios, disruption avoidance/mitigation in conditions not present in US
  - Long pulse with high beta, higher B-field, metal walls, different divertor geometries 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 ICF but should augment domestic efforts with international community in IFE materials, full system modeling, waste
- **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:**
  - Ignition science, QED, laser-plasma interaction; ELI Beamlines/NP, ExFEL, Apollon, LMJ, LULI, CORELS, EPAC

Response Summary for Charge 2a: Potential of international facilities to help US scientists address priorities of LRP/BDV

- **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
  - Engagement with ITPA amplifies US theory/simulation/computational physics impact
  - Potential to increase US readiness for ITER operation, increase likelihood of ITER success

Panel 1: Fusion Core

Panel Members:



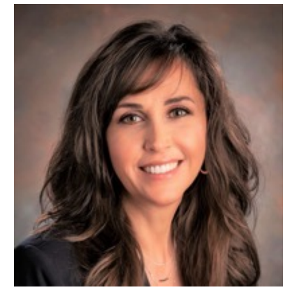
Nate Ferraro
PPPL
(Panel Lead)

Chris Holcomb
LLNL

Tammy Ma
LLNL

Rich Magee
TAE

Jaime Marion
UCLA



Simona Murph
SRNL

Panel Subtopics:

- **Tokamaks:**
  - Burning plasma physics
  - Divertor solutions
  - FPP scenarios
  - Disruptions
  - Tokamak PFC issues
- **Stellarators:**
  - Optimized geometry
  - Quasisymmetry
  - Core physics
  - Divertor solutions
- **IFE:**
  - Core physics
  - Drivers
- **Alternates:**
  - Alternate MFE
  - Core physics

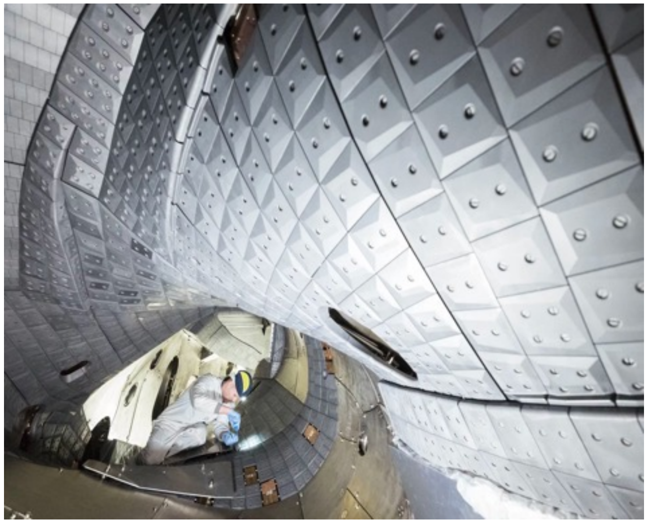
Panel 1: Fusion Core - Selected Findings and Recommendations

Findings

- **F1-1:** JET has large database of value to US
- **F2a-1:** Range of divertor geometries on MAST-U, TCV, and ASDEX-U, can help the US in FPP designs
- **F2a-2:** KSTAR and EAST offer opportunities for control solutions, ITER operations preparation, detached W-divertor, stationary long pulses in low-to-medium PB/R
- **F2a-5:** W7-X likely only existing optimized stellarator in the near future; steady-state high-power, model validation, divertor ✓
- **F1-15:** Resources in alternative concepts abroad can be leveraged by US, public and private; mitigate risk with diversity
- **F1-18/2a-7:** US is undisputed leader in ICF/IFE physics; gaps in high rep-rate

Recommendations

- **R2a-1:** Prioritize collaborations with KSTAR, EAST, MAST-U, JT-60SA, DTT, JET, ST80-HTS; scenarios, divertors, disruptions; key burning plasma gaps, ITER preparation
- **R1-2:** Expand collaboration with W7-X, HELIAS, FFHR for stellarator core physics, model validation ✓
- **R1-3:** Support international collaboration on alternative MCF concepts where complementary
- **R1-4:** Leverage US leadership in ICF in international collaborations on complementary facilities
- **R2a-3:** Pursue collaborative research on international high rep-rate lasers



Wendelstein W7-X

Panel 2: Materials/PMI

Panel Members:

Jaime Marion
UCLA
(Panel Lead)

Livia Casali
U. Tenn.

Kevin Field
U. Mich.

Carlos Paz-Soldan
U. Columbia

Panel Subtopics:

- **Bulk materials neutron testing:**
  - Fusion prototypic neutron sources (FPNS) & neutron irradiation test facilities
  - Handling & post testing of irradiated materials
- **Plasma-facing materials**
  - Interaction of fusion plasmas with solid metal PFC's
  - Assessment of liquid metal PFC's
- **Computational modeling:**
  - Model testing & validation
  - HPC requirements

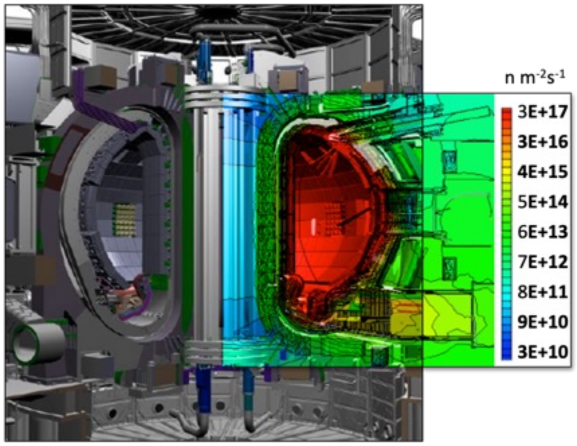
Panel 2: Materials/PMI - Selected Findings and Recommendations

Findings

- **F1-20**: In the absence of a FPNS, the US currently lacks operational fast neutron spectrum test reactors.
- **F2a-8:** MPEX timeline (operational 2028) will be too late to impact many private industry FPP design choices.
- **F1-21:** No suitable high flux PMI test stand for liquid metal PFCs exists domestically or internationally. ✓
- **F1-22:** International tokamak programs strongly emphasize solid metal PFC development for ITER (W, Be).
- **F1-23:** The current methods for international collaboration for irradiated materials are time consuming and inefficient.

Recommendations

- **R1-5:** Strengthen ties with IFMIF-DONES to enable US researchers to access prototypical fusion neutrons; consider international triple-ion beam irradiation facilities as a bridge to FPNS.
- **R2a-4:** Collaborate on Magnum-PSI to test materials at high heat flux until MPEX is ready.
- **R1-6:** Leverage EAST, COMPASS-U, and DTT liquid metal PFC's to advance US expertise and experience with liquid metal PFC's until NSTX-U installs a liquid metal divertor. ✓
- **R1-7:** Leverage international collaboration with existing solid metal wall tokamaks such as AUG, WEST, EAST.
- **R1-8:** Work with international partners with critical irradiation testing facilities and develop more efficient protocols for irradiated material transport.



Expected neutron load in the different ITER chamber and structural components.

Panel 3: Balance of Plant

Panel Members:

Paul Humrickhouse
ORNL
(Panel Lead)

Kevin Field
LLNL

Dave Humphreys
GA

Simona Murph
SRNL

Panel Subtopics:

- **Tritium breeding:**
  - Blanket design
  - Blanket testing
- **Tritium handling:**
  - Fuel cycle
  - Tritium processing
- **Balance of plant:**
  - Brayton cycle
  - Heat exchange
  - Fusion power conversion
- **RAMI and Safety:**
  - Reliability
  - Availability
  - Maintenance
  - Inspectibility
  - Remote handling

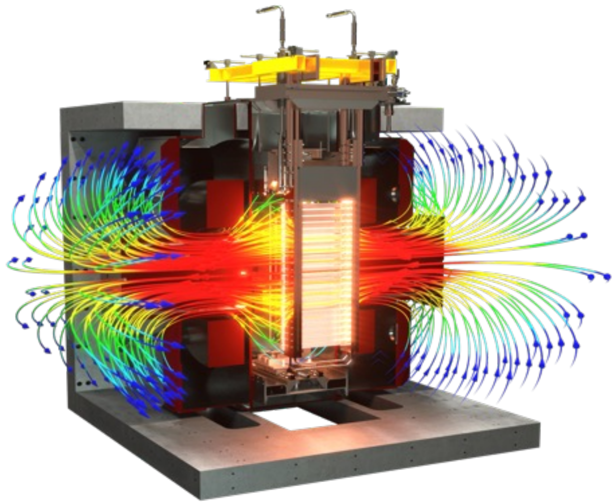
Panel 3: Balance of Plant - Selected Findings and Recommendations

Findings

- **F1-24:** US programs no longer world-leading in breeding blankets, fuel cycle, balance of plant technology
- **F2a-9:** FPP depends critically on breeding blanket, fuel cycle, and other balance of plant technologies; requires both strong domestic effort and leveraged international collaboration
- **F1-25:** 2020 US-EU technical workshop identified critical priorities in balance of plant ✓
- **F2a-10:** LRP/CPP identified need for Blanket Test Facility for integrated, non-nuclear testing & development of blanket prototypes

Recommendations

- **R1-9:** Target international collaboration on tritium breeding blanket, fuel cycle, and balance of plant technologies
- **R1-10:** Pursue collaborations in safety assessment, nuclear design integration, tritium permeation and handling, MHD flow in blankets, and waste management (2020 US-EU Technical Workshop) ✓
- **R2a-5:** Evaluate CHIMERA and H3AT in the UK to test US blanket concepts and ancillary systems. Pursue collaboration if evaluation is favorable and no domestic facility available in a decade

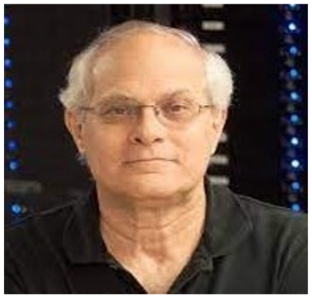


CHIMERA Facility (UK) will test meter-scale blanket components in fusion-relevant (non-nuclear) environments

Panel 4: Technology

Panel Members:

Mitchell Walker
Georgia Tech
(Panel Lead)



Paul Bonoli
MIT

Arianna Gleason
SLAC

Rich Magee
TAE

Panel Subtopics:

- **Neutral Beam Injection (NBI) Actuators:**
  - NNBI source development and testing
  - Long pulse capability
- **Radio-frequency (RF) Actuators:**
  - Source development and testing
  - PMI & nuclear resilience
- **Magnets**
  - HTS technology
  - Manufacturing capability
- **Lasers:**
  - High performance drivers
  - High repetition rate

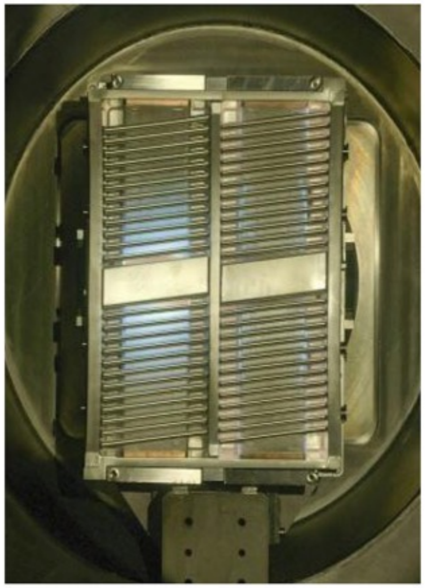
Panel 4: Technology - Selected Findings and Recommendations

Findings

- **F1-26:** Experimental data on ICRF antenna performance in all-metal environments is very limited.
- **F2a-11:** CW, high-energy, negative ion NB technology needed.
- **F1-27:** The US lacks at-scale manufacturing capability and commensurate magnet test facilities for ReBCO tapes. ✓
- **F1-28:** There is a need for higher source frequencies and tube efficiencies, greater source reliability in ECRF.
- **F1-30:** Currently no solution for neutron-capable RF launchers
- **F1-31:** The US currently at forefront of laser science and technology innovation; leveraging this to build local laser capabilities & facilities is lacking

Recommendations

- **R1-11:** Collaborate with CEA/WEST on ICRF impurity generation and mitigation; collaborate on CEA ICRF test stand facility (TITAN) to study more reactor relevant RF launchers.
- **R2a-6:** Support collaborations with IPP-Garching and QST to develop long pulse, high energy neutral beam technology.
- **R2a-7:** Collaborate with HFLSM, the Robinson Institute, and Sultan to advance at-scale domestic manufacturing capabilities for REBCO tape. ✓
- **R2a-8:** Support collaboration on the development of high-frequency (> 200 GHz) gyrotron.
- **R1-12:**,Use reliable international suppliers of gyrotrons to overcome the limited capacity of the domestic market.
- **R1-13:** Enable US scientists and engineers to access key international laser facilities, e.g., ELI, to exercise high rep rate laser technologies.



WEST ICRF Antenna

Panel 5: Fundamental Understanding of Plasmas

Panel Members:

Arianna Gleason
SLAC
(Panel Lead)

Dave Humphreys
GA

Tammy Ma
LLNL

Simona Murph
SRNL

Mitchell Walker
Georgia Tech

Panel Subtopics:

- **Plasma states:**
  - Dusty
  - Warm Dense Matter
- **Laser-Plasma Interaction:**
  - Interaction science
  - Ignition Science
  - Driver science
- **Foundational materials:**
  - Experimental science
  - Computational
- **Basic applications:**
  - Space propulsion
  - Agricultural plasma
  - Plasma medicine

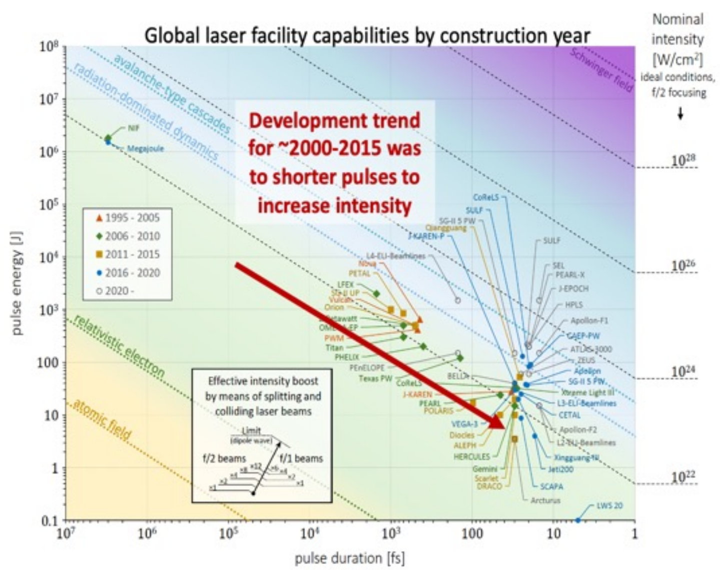
Panel 5: Fundamental Understanding of Plasmas – Selected Findings and Recommendations

Findings

- **F1-32:** US currently in leadership role for laser technology development in science areas; but domestic experimental facilities limited, requiring access to international resources, particularly for high rep rate capabilities
- **F1-34:** Domestically and internationally, experimental and modeling communities in fundamental plasma science are not effectively connected
- **F1-35:** Materials and plasma properties data are needed across wide range of conditions, time, and length-scales for fundamental studies. Enhanced international collaborations with e.g. ELI, LULI, DiPole, can help to build needed databases and workflows

Recommendations

- **R1-14:** Establish collaborations at key international laser facilities: ELI Beamlines/NP, DiPOLE, Fair, Apollo CORELS for high-rep-rate science
- **R1-15:** Support and exploit US-international networks (similar to LaserNetUS, X-lites) to expand connections in fundamental research



Laser capabilities for discovery plasma and HED science are expanding across the globe

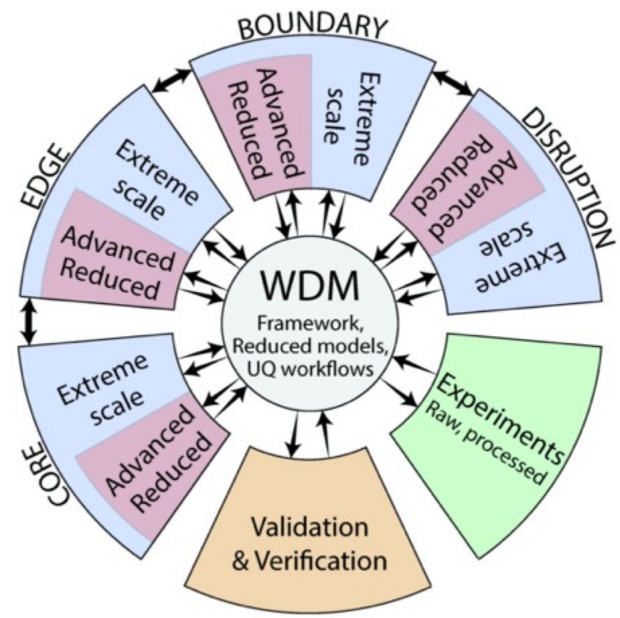
Cross-Cutting Topics: Theory, Algorithms, Computation - Selected Findings and Recommendations

Findings

- **F2a-12:** International collaborations in theory, algorithms, modeling, computational physics, design, have strong potential for advancing BDV goals
- **F2a-13:** International collaborations in ML/AI and control mathematics have strong potential for advancing BDV goals ✓
- **F1-36:** ITPA is a very effective framework for international collaboration, focused on ITER needs but also enabling broader burning plasma research progress
- **F1-37:** Rise of high rep rate lasers increases data quantities, requires ML methods to automate analysis; improved standardization from international facilities, ML/AI resources to access

Recommendations

- **R2a-9:** Pursue collaborations with CEA/IRFM, Max-Planck IPP, CCFE for development of models, and UKAEA, EuroFusion, KFE, QST for fusion device design
- **R2a-10:** Pursue collaborations in control and ML/AI with CREATE, DIFFER, and EPFL/SPC to accelerate US capabilities and help prepare for ITER operations ✓
- **R1-16:** Expand US participation in ITPA joint experiments, theory, computational physics, control; support US members beyond voluntary efforts to enhance accessibility
- **R1-17:** Facilitate collaboration on ML/AI linked to laser facilities, and develop common metadata standards



Computational models require many multi-physics modules. International collaboration provides modules, cross-code verification and validation

Charge 2b: Maximizing Impact of International Collaboration

Charge 2b: Assess whether the existing modes of collaboration are adequate for maximizing the impact of international collaborations

Charge 2b: Maximizing Impact – Context and Observations

- **General Practices for Impactful Collaborations:**
  - Strong frameworks, definition of collaboration essential
  - Impact maximized by running collaborations like true projects: schedule, goals, deliverables, project controls
- **Experiments**
  - Device schedules are fluid, requiring close communication
  - Dynamic re-assignment frequently needed
  - On-site and remote experiments have different needs
- **Technology**
  - Development different from testing collaborations
  - Technology collaboration often requires scheduling, user procedures, safety coordination like experiments
- **Theory and Foundational science:**
  - Dependence on cyber access, high bandwidth, low latency
  - Use of data standards, modern software management
  - Reliance on international agreements, networks, ease of onboarding and on-site location of participants

Remote Control Rooms Enable Remote Collaboration in Experiments and Operations

Response Summary for Charge 2b: Maximizing Impact of International Collaboration

- **Existing modes of collaboration incorporate a wide range of practices:**
  - Varying effectiveness and impact on US fusion program
  - Subcommittee felt best approach was to identify best practices in general (rather than assess specific collaborations)

- **Practices that maximize impact have certain key characteristics:**
  - Strong collaborative frameworks with clear definition of roles and goals
  - Mechanisms for communication and coordination of project

- **Experimental collaborations have unique demands due to shared use of devices and facilities:**
  - Clear understanding of experimental device/facility use, operational and safety procedures
  - Timely and effective communication to manage schedules and responsibilities

- **Theory and Computational Science collaborations are dominated by data-intensive workflows:**
  - Low administrative barriers to cyber access, data, and computer resources
  - Ease of software sharing with management and protection of intellectual property and assets

- **Remote operation and participation can enables effective collaboration when travel is difficult:**
  - On-site: safety, direct contact with experiments…
  - Remote off-site: effective operations and experiments, no travel costs, mitigation of time zone and jet lag impacts

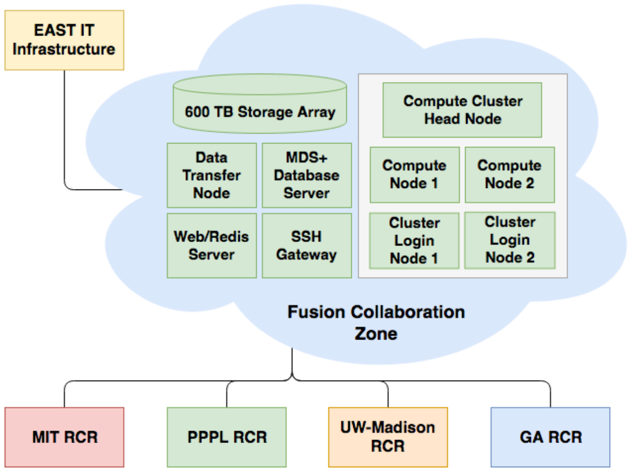
Charge 2b: Maximizing Impact - Selected Findings and Recommendations

Findings

- **F2b-1:** Most useful guidance for Charge 2b is to identify means of maximizing impact
- **F2b-2:** Need strong frameworks for function/communication of team
- **F2b-3:** Experimental collab: need specific means of scheduling, coordination, mix of on-site/remote, participation of collaborators in domestic research if possible
- **F2b-4:** Technology development different from testing; IP handling ✓
- **F2b-5:** Theory/data-intensive collaborations rely on cyber access
- **F2b-6:** Small-scale (e.g. person-to-person) collaborations have been very impactful in the past…
- **F2b-7:** Discovery science can benefit greatly from international networks, unique approaches

Recommendations

- **R2b-1:** Construct strong collab frameworks: document goals, team/roles, mechanisms for communication
- **R2b-2:** Experimental collab: coordination with host institution; mix of on-site/ remote participation; invite participation in complementary domestic studies
- **R2b-3:** Technology collab: explicit handling of IP and invention provenance; specific training for safety and user procedures ✓
- **R2b-4:** Theory/computational: low barriers to cyber access, high performance data access; modern software management
- **R2b-5:** Broaden support for small-scale, short-timescale, smaller-scope collab beyond present large-scale teams
- **R2b-6:** Establish international networks, agreements for collaborations on discovery science, model of LaserNetUS



Efficient transfer of scientific data is critical to successful remote experimental collaboration

Charge 3: Fusion Private Sector

Charge 3: How can the U.S. take advantage of its 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: Fusion Private Sector – Context and Observations

- **Magnetic Fusion Energy in the Private Sector:**
  - Tokamaks and stellarators constitute a minority of concepts, approximately 30%.
  - If alternate concept facilities exist abroad it is in the interest of Federal government to facilitate public-private collaborations with them.

- **Inertial Fusion Energy in the Private Sector**
  - 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)

- **Scope and Constraints**
  - Private companies often have their limited experimental resources focused on their primary research channel, thus they need access to other facilities to test components or major subsystems.
  - Private companies often seek to answer technical questions with a binary outcome, usually well-defined, short-term, and limited in scope, making them ideal projects for collaboration.

- **Leveraging the private sector**
  - Private sector can provide unique opportunities for connections with international facilities that are especially mission-driven and potentially more focused and effective than public research collaborations.

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

Response Summary for Charge 3: Leveraging fusion private sector in international collaboration

- **A public-private partnerships program should be created to facilitate the collaboration of domestic private companies and international resources:**
  - Extensive and sometimes unique resources exist outside of the United States that could accelerate the technological development of fusion if opened to the private sector.

- **Collaborations supported through this program should:**
  - Be limited in scope but bear well-defined deliverables
  - Strike a clear balance between openness and IP protection
  - Be modeled after successful agreements such as INFUSE and CRADA

- **This type of program would benefit DOE goals by accelerating the development of fusion technology and eventual commercialization.**

Charge 3: Fusion Private Sector – Selected Findings and Recommendations

Findings

- **F3-2:** Private companies primarily have an interest in limited scope collaboration on topics such as the development of supporting technology (e.g., neutral beams, RF, magnets) and diagnostics and simulation benchmarking.
- **F3-3:** While the private sector typically seeks to minimize disclosure requirements and maximize IP protection when entering into partnerships, the public sector seeks to maximize the contribution to public knowledge and the federal program. ✓
- **F3-4:** There also exist counter-streaming opportunities, in which international private companies seek to utilize resources from the federal program, especially in inertial fusion energy.
- **F3-5:** There exists a burgeoning international private sector effort pursuing the development of supporting technology (e.g., blankets, balance-of-plant, materials, etc.).

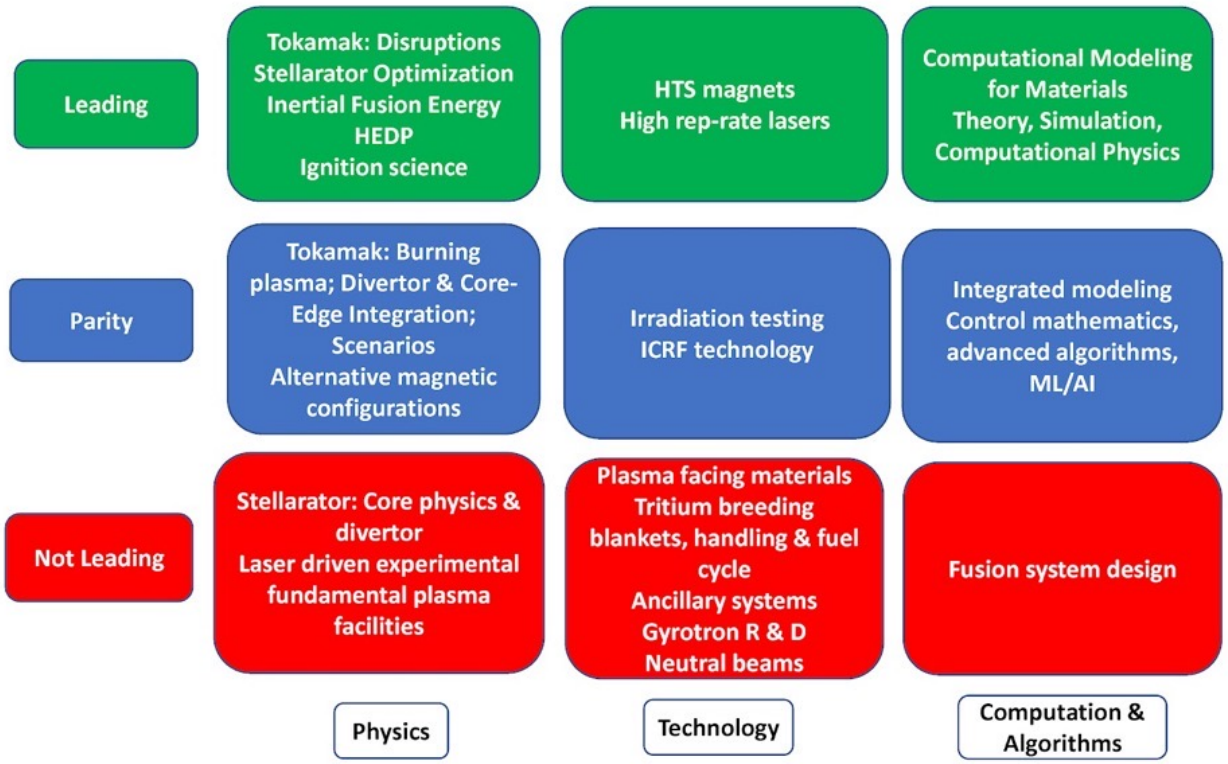
Recommendations

- **R3-1:** Create a program that facilitates targeted collaboration between domestic private companies and international institutions engaged in fusion development which strikes a balance between openness and IP protection.
- **R3-2**: Create opportunities for private companies from abroad to collaborate in the US, while ensuring all activities stay consistent with DOE/government regulations for protecting assets as necessary. ✓
- **R3-3:** Encourage US fusion community engagement with international companies primarily focused on fusion reactor goals, and also with international plasma science and technology companies with supporting technology goals.

Charge 4: Leadership

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: Leadership – Context and Observations



- **US occupies a strong leadership position in worldwide fusion program despite historical program size relative to e.g EU**
- **Nevertheless, several key areas need specific advancement in leadership status in order to realize the BDV**

Summary of topical areas grouped horizontally by color in which the US is leading (green); the US is competitive, at approximate parity with international parties (blue); and the US is not leading (red). Topical areas are further grouped into columns by discipline corresponding to Physics, Technology, and Computation & Algorithms.

Response Summary for Charge 4: Areas of US leadership, threatened leadership, non-leadership

- **US leads in many aspects of tokamak physics, including demo of high-performance scenarios in short pulse, disruption avoidance & mitigation physics/control, and core-edge integration**
  - Leadership in these areas is not significantly threatened at present

- **The US lacks a sufficient number of large facilities to maintain overall leadership in the operation of large fusion facilities:**
  - The US only has access to superconducting tokamaks through international collaborations to study long pulse performance, and burning plasma experiments have been led by JET.
  - The US should leverage international collaborations on large-scale fusion facilities to develop and maintain the necessary skill-set in building, operating, and executing fusion research at scale.

- **As demonstrated by the recent ignition achievement, the US is the international leader in ICF now:**
  - In order for the US to grow and maintain its leadership in ICF/IFE, it is important to keep science open as much as possible for international collaboration while still retaining and protecting US intellectual property.

- **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 4: Leadership - Selected Findings and Recommendations

Findings

- **F4-1:** In areas where US presently leads, leadership is not significantly threatened. Need to gain in areas where lacking leadership. Important to identify and satisfy US national leadership goals in international collaborations. ✓
- **F4-2:** Laser technology development is an area where the US has ported its most valuable capabilities overseas (in ELI) and creates an opportunity to collaborate with ELI to train our scientists, engineers and future workforce on their rep-rated laser infrastructure.
- **F4-3:** Long-term public and private leadership status and goals are important considerations to usefully inform public grants/investments.
- **F4-4:** The US lacks a sufficient number of large facilities to maintain leadership in operation of large fusion facilities.

Recommendations

- **R4-1:** Clearly identify the anticipated roles in international collaborations in satisfying US national goals as part of a national strategy for technical advancement and leadership ✓
- **R4-2:** Keep the scientific process in ICF/IFE programs open as much as possible for international collaboration, and pursue collaboration with ELI to grow US rep-rated laser expertise for ICF/IFE applications.
- **R4-3:** Review best practices in other industries and apply them to obtain the best return on public investment when supporting public-private partnerships and international collaborations for maintaining or establishing leadership.
- **R4-4:** Leverage international collaborations to facilitate access to large-scale fusion facilities to develop and maintain leadership in construction and operation, as well as to obtain good scientific output from such facilities.

Charge 5: Workforce

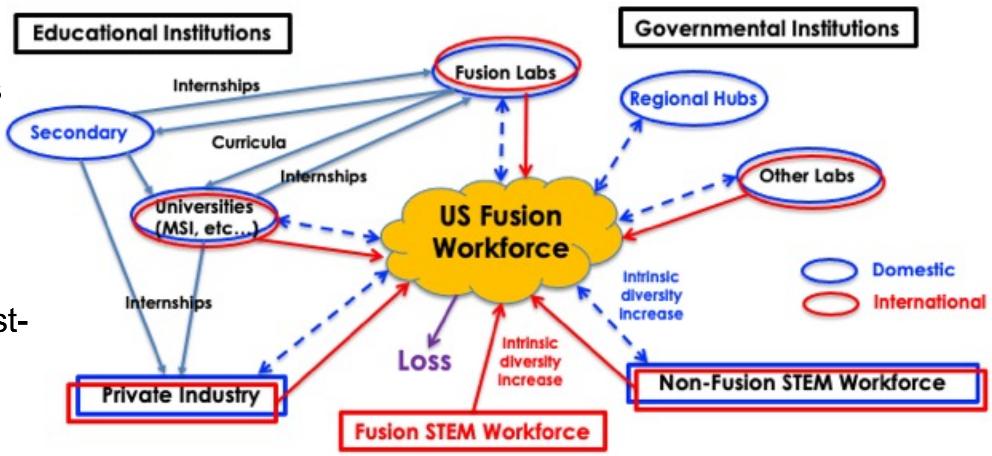
Charge 5: How can the U.S. ensure an internationally competitive workforce for fusion, including the recruitment of talent from traditionally underrepresented groups within the U.S

Charge 5: Workforce – Context and Observations

- **General Observations:**
  - Large challenge for fusion power commercialization
  - Need includes work categories beyond plasma physics: materials science, all engineering disciplines, mathematics, computer/data scientists, system engineers, project managers, CAD design, technicians
  - Many thousands of new personnel needed…

- **Domestic Workforce Expansion:**
  - Dedicated domestic efforts will be required
  - Support for all educational levels: undergrad, grad, post-grad; scholarships/internships/fellowships/curricula
  - Focused effort on Minority Service Institutions and underrepresented communities

- **Workforce Expansion through International Collaboration:**
  - Long an effective source for US workforce growth
  - Must build in funding/planning for use of collaborations to grow workforce: student training, conduit for international personnel to the US



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

Response Summary for Charge 5: Ensuring workforce for fusion including recruitment of talent from underrepresented groups

- **Fusion workforce expansion is essential to success of BDV:**
  - Potentially thousands of new, trained personnel needed
  - Essential to recruit effectively from underrepresented groups, MSI's, HBCU's, diverse communities

- **Dedicated, targeted, well-funded efforts needed to reach both domestic and international sources:**
  - Specific training and educational funding mechanisms to attract secondary, undergraduate, graduate students, post-docs, and international experts (in-field and out-of-field)
  - Exploit fundamental, discovery science and technology programs with strong educational components

- **Resourcing new personnel from key diverse communities naturally increases US diversity:**
  - Non-fusion STEM fields in US and internationally
  - International fusion communities

- **Make use of ongoing research programs to augment workforce:**
  - Explicitly include student development and international experts into research opportunities
  - Improving efficiency and availability of long-term visas and permanent resident status can help increase rate of acquisition and retention of international experts

Charge 5: Workforce - Selected Findings and Recommendations

Findings

- **F5-1:** Domestic workforce expansion in STEM areas is critically needed to support the BDV
- **F5-2:** Present student pipeline is inadequate
- **F5-3:** Discovery science is useful vehicle for general pipeline growth
- **F5-4:** Domestic/international public-private partnerships include discovery/applied science and technology development, often in diverse academic communities
- **F5-5:** Domestic workforce needs expansion in manufacturing, engineering, and technician work to fulfill the BDV ✓
- **F5-6:** DOE funded research could offer opportunities for student and fusion professional development. Efficiency of visa/green card acquisition is important.

Recommendations

- **R5-1:** Expand domestic support for students; all levels; engineering, science, mathematics, computer science, increase by many thousands in 10 yrs; increase in fusion undergrad interns (e.g. SULI), grad research (e.g. SCGSRs), FES post-docs
- **R5-2:** Increase research capacities at MSI's & women-only institutions; international fellowships to MSIs; US-led community networks that expand diversity
- **R5-3:** Invest in undergrad curricula, practica, lab infrastructure; faculty professional development at targeted institutions including MSIs. Hold topical summer schools
- **R5-4:** Enhance educational opportunities in discovery science programs in academia & nat'l labs; faculty/student exchange programs (labs, universities, MSIs)
- **R5-5/5-6:** Support engagement of US students & early career with domestic & international private industry; tradesmanship/apprenticeships in manufacturing, ✓ engineering, technician training including non-advanced degrees
- **R5-7:** Incorporate undergrad/grad/out-of-field/post-grad/international experts into all research opportunities for explicit workforce development. Maximize efficiency of long-term visas and permanent residency for international workers.

Summary and Conclusions

- **FESAC 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 MCF, 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

Much Appreciation!!!

- **Thanks to Sam Barish for all of his extensive help throughout the process!!!**
  - Close engagement, critical clarifications, key guidance – every step of the way…
- **Thanks to Anne White for her constant support and key inputs:**
  - Resolution of difficult issues and key strategic guidance at critical points
- **Thanks to all the OFES contributors along the way:**
  - Timely comments and edits for all major checkpoints in process
  - Several critical course tweaks
- **Thank you for the opportunity to contribute to International Benchmarking 2022-23!**
  - Subcommittee members all feel this was an important, high-impact, and rare opportunity
- **Personal thanks to the subcommittee members for their hard work and dedication!!! Special thanks to Paul Bonoli for his huge support as vice chair, and essential work from beginning to end**

Backup Slides for FESAC Presentation

Panel Topics Derived from LRP/CPP Topical Areas

- **Panel 1: Fusion Core**
  - Tokamak/stellarator plasmas, IFE plasmas
  - Stability, transport…
- **Panel 2: Materials and PMI**
  - Divertors, PFC's, PMI
  - Materials development
- **Panel 3: Balance of Plant**
  - Tritium breeding and handling
  - Power conversion, RAMI, safety, licencing, remote handling
- **Panel 4: Technologies**
  - RF actuators, magnets, lasers, transformative potential technologies
- **Panel 5: Fundamental Plasma Understanding & Experiments in New Regimes**
  - HED, rep-rated lasers, space-astrophysical plasmas, exotic matter and new regimes
  - Transformative technologies for plasma understanding

High-Level Metrics for Opportunity Assessment

- **Metrics and decision criteria for facilities and collaborative institutions [critical to interpret these as QUANTITATIVE: 1 to 5; 1=lowest goodness, 5=highest goodness; "goodness" has various qualia, e.g. potential/impact/ability/…**

- **Metrics more toward Energy/Bold Decadal Vision mission (charges 1-2a):**
  - TRL advancement potential. [potential for impact on our problems]
  - Potential for impact on Bold Decadal Vision/FPP
  - Relevance to US technology drivers/preferences/focus…

- **Metrics more toward other charges (3-5; largely cross-cutting):**
  - Potential to contribute to US leadership
  - Ability to help and/or leverage private sector (advance US private, leverage US and international private…).
  - Ability to help grow/develop US workforce

- **Panel 5 (Fundamental Understanding of Plasmas) requires more/different metrics…**
  - Potential to advance understanding in fundamental plasma science…

Detailed Panel Process, Metrics

- **Process for each panel:**
  - Identify subtopics in their scope
  - Identify metrics for selecting/prioritizing international collaborations (discuss in combined meetings; share among panels)
  - Identify experts to call/solicit in panel scope (coordinate for combined meeting presentations)
  - Create spreadsheet to capture facilities/institutions/teams for key collaborations (or use Topics-2-Facilities)
  - Identify charge impacts: leadership, best collaboration practices, public-private, workforce…
  - Prioritize collaborations from metrics and iteration
  - Cross-cut with other panels… collect and combine charge impacts… coordinate experts…
  - Write subsection(s)…

- **Panels to determine their own best metrics, but integrate where appropriate:**
  - TRL advancement appropriate for technologies, less for for science understanding
  - Possibly different approaches to US leadership metrics in different areas
  - Private sector issues potentially vary among topical areas
  - Workforce development likely spans all areas similarly…

Charge 2b: Considerations and Reasoning for Approach to Response

- **Charge statement implies assessment of (specific) present approaches to collaboration:**
  - "Assess whether existing modes of collaboration…"
  - "…adequate for maximizing impact…"

- **Subcommittee felt strongly that strict and limited response would not be informative or useful:**
  - Result would be set of discrete evaluations of specific existing collaboration approaches: Adequate, Somewhat-Adequate, Insufficiently-Adequate…
  - Many problems with this approach: lack of completeness (these aren't adequate, and these are okay, but how do we really do it best?), conflation of intrinsic challenges with approaches (e.g. different collaboration types need very different approaches), poor guidance for improvement (how do we use these piecemeal assessments to improve or provide actionable guidelines to excellence?)

- **Most effective and impactful response to charge concluded to be:**
  - Formally assess across the range of present collaborations, many are adequate, many less…
  - Identify explicit best practices to produce highly effective collaborations for each field and type of collaboration: clear applicable guidance for creating and executing collaborations

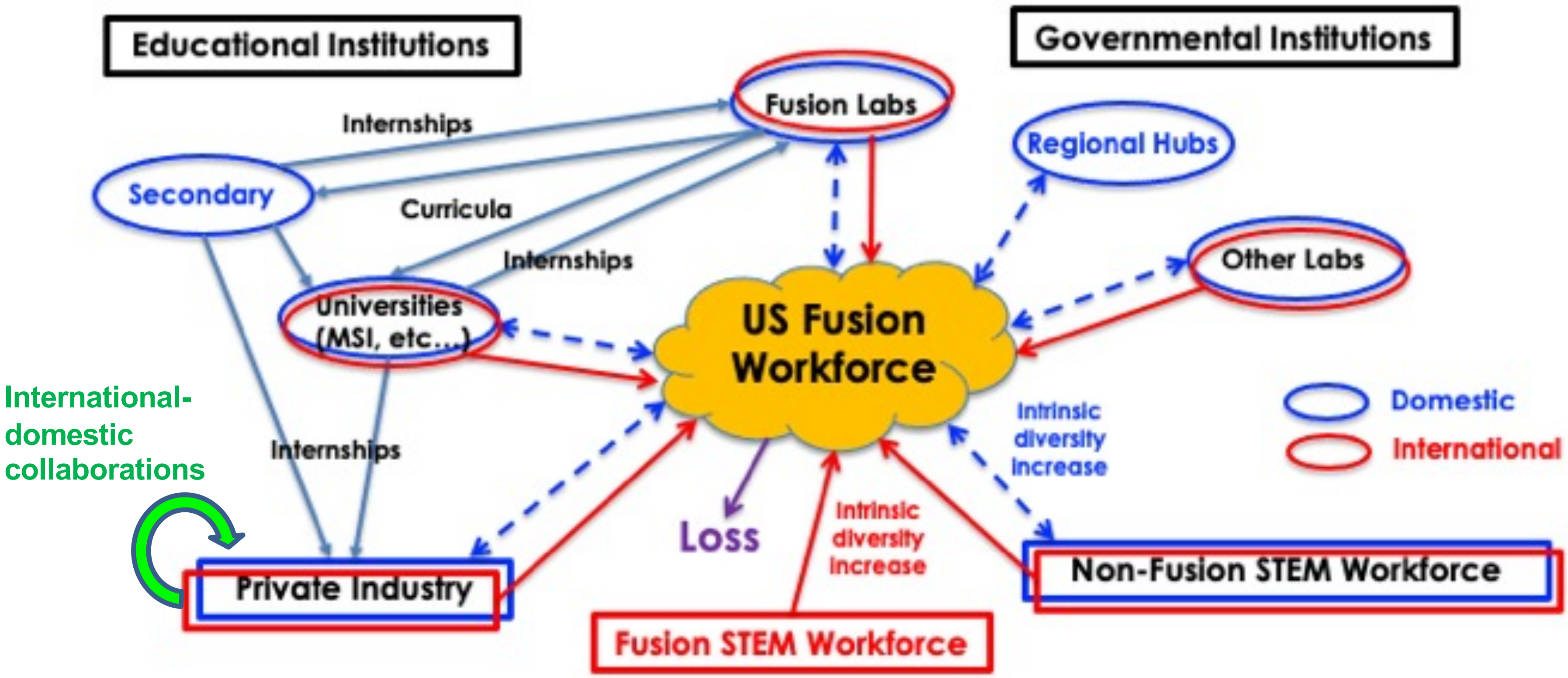
Charge 3: Public-Private Engagement for International Collaboration

- **Charge statement focuses on leveraging BOTH domestic and international private sectors:**
  - …in international "engagements"
  - "how can we cooperate with overseas public-private partnership programs… for commercial fusion". [so this part includes international PPP programs specifically…]

- **Potential questions and answers:**
  - R3-1 focused on need for a PROGRAM to support engagement between US private sector and international institutions: a dedicated program has highest potential for leveraging both for fusion advancement
  - EXPLICITLY called out need to ensure balance between open research and IP protection
  - Key role of private sector in workforce development is called out in Findings for Charge 3, but explicitly in Recommendations for Charge 5…

- **On balance subcommittee recognized principles in making Public-Private recommendations:**
  - Assessments and recommendations should remain relatively high-level, avoid specificity by field, sector, companies, etc…
  - Focus on maximizing impact on US fusion advancement potential with program-level recommendations…

Charge 3: Private Sector needs support in domestic-international collaboration for maximum leverage to advance fusion



Charge 4: Leadership National Strategy Needed

- **Charge 4 asks to identify areas of leadership, threatened leadership, and non-leadership:**
  - …where resource investment would bring significant opportunities and be beneficial…
  - Our response identified leadership, parity, non-leadership areas…
  - Formally assessed that none of the present leadership areas were threatened significantly…

- **Response also discussed need for strategic planning to enhance US leadership:**
  - Subcommittee felt most useful response included recommendations for establishing/maintaining appropriate leadership level in necessary fields…
  - Steps identified in accomplishing this…
  - Key step = establishment of national strategy for leadership priorities in fusion
  - National strategy should include domestic efforts and specific roles for international collaboration, drawn from gap areas identified in present report

- **Creation of national leadership strategy in fusion capabilities is important to realizing BDV:**
  - However, this implies a very large, complex, whole-community, programmatic-level effort… far beyond scope of this subcommittee… Should also include strong private sector participation…

Topical Area/Panel 5 : Fundamental Plasma Understanding

- **Fundamental Plasma Science called out as major driver in LRP/NASEM/BDV:**
  - Advancements in understanding are key to successful realization of BDV
  - Complex relationship and interaction with applied/directed R&D needs
  - Optimal portfolio for R&D and innovation long recognized to include proper fraction of basic research [e.g. "How Innovation Really Works", A.M. Knott, McGraw-Hill, New York 2017]

- **Response focused on high-impact fundamental plasma research areas:**
  - Many research areas considered and metricized: e.g. agricultural plasmas, plasma medicine, dusty/cold lab plasmas, etc…
  - Areas of high metric weight in advancing NASEM/BDV IMPACTFUL fundamental science were identified…
  - Some facility/opportunity specificity for laser-plasma interactions, High Energy Density, high rep-rate experimental facilities, high impact network and data workflow development
  - Similarly to Charge 3, targeted high-level programmatic recommendations to maximize impact on goals for maximizing US fusion understanding
  - Theory/computational elements related to fundamental plasma science captured in integration Sec. IV.6: e.g. high rep-rate lasers, ML/AI for basic science, interoperable metadata standards…