International Collaboration in Fusion Energy Sciences Research Opportunities and Modes During the ITER era

FESAC Panel Report

February 28, 2012

Draft report – Not to be quoted or referenced until issued by FESAC

Outline

- Charges
- Panel and Process
- International Collaboration in Fusion during the ITER Era
- Charge One: Identify “Compelling” research opportunities
    - Scientific Challenges for the ITER Era
    - Capabilities to Address Challenges
    - Recommendations on Collaborative Opportunities
        - Extending High Performance Regimes to Long Pulse
        - Development and Integration of Long Pulse Wall Solutions
        - Burning Plasma Research in Advance of ITER
- Charge Two: Effective Modes of International Collaboration
    - Experience
    - Challenges
    - Recommendations on Modes of Collaboration
        - Structure
        - Implementation
- Concluding remarks

FESAC International Collaboration Panel 2011

- Charge #1: **What areas of research on new international facilities provide compelling scientific opportunities for U.S. researchers over the next 10 – 20 years? Look at opportunities in long-pulse, steady-state research in superconducting advanced tokamaks and stellarators; in steady-state plasma confinement and control science; and in plasma-wall interactions.**

- Charge #2: **What research modes would best facilitate international research collaborations in plasma and fusion sciences? Consider modes already used by these communities as well as those used by other research communities that have significant international collaborations.**

Panel Membership

David Anderson, U. Wis. – Fusion research

Michael Bell, PPPL – Fusion research

Richard Buttery, GA – Fusion research

Jeffrey Harris, ORNL – Fusion research

David Hill, LLNL – Fusion research

Amanda Hubbard MIT – Fusion research

Gerald Navratil, Columbia University – Fusion research

Robert Rosner Univ of Chicago – Astronomy research

George Tynan, UCSD – Fusion research

Frank Wuerthwein, UCSD – High Energy Physics research

Wesley Smith, U. Wis. – High Energy Physics research

Dale Meade, Chair, FIRE – Fusion research

Panel Process

The panel held two in-person meetings

November 17, 2011, APS-DPP Meeting, Salt Lake City, Utah

December 19-21, 2011, General Atomics, La Jolla, CA

The panel held 28 meetings by conference calls using ESNet Collaboration Service Ready Talk with video support.

A presentation was made at the University Fusion Association meeting at the APS-DPP meeting on November 14 with public discussion. A special public input session was organized and held at the APS-DPP meeting on November 16, 2011.

Several requests were made to the fusion community requesting White Papers related to the FESAC Panel charge on International Collaboration. A total of 18 white papers were received from the community, and were posted on a public information web site at http://fire.pppl.gov/fesac_intl_collab_2011.html.

Vision for the US Fusion Program 2021

- The world fusion research community is now embarked on the construction of ITER, the world's largest scientific facility, to demonstrate the scientific and technological feasibility of fusion energy. The US is one of seven international partners (EU, JA, RF, IN, KO, CN and US) who are collaborating in this historic endeavor which is scheduled to begin operation in ~2020.

- At that time, it is a goal of the US Fusion Energy Sciences (FES) program that the **US be a leader in burning plasma science** to obtain the maximum benefit from participation in the ITER research program. It is also the goal of the FES program **for the US to assert itself in long-pulse, 3D magnetic confinement science, and fusion materials science research within the next decade**. In addition to the burning plasma physics and fusion technology experience which will be gained from ITER, a significant effort will be required to develop the materials needed to withstand the intense power densities and neutron irradiation that will be required for the plasma facing components of a fusion power plant. It is envisioned that a Fusion Nuclear Science program will be established in the US **to enable a decision on a Fusion Nuclear Science Facility (FNSF)** by the end of the decade.

Goal of International Collaboration

- During this next decade while ITER is under construction, the US FES program needs to **make effective use of limited resources** to explore critical issues at the frontiers of fusion research with a **balanced program that exploits both the strength of its domestic research program and new unique capabilities** that are becoming available overseas.

- **Recommendation:** Selection of an international collaboration should be made only after careful consideration to both:

(1) our national goal to advance critical fusion energy science issues and

(2) the need to maintain and strengthen a US domestic research infrastructure that supports the US ITER mission, positions the US to benefit from ITER's success, and make an informed decision on the best approach to the design of a Fusion Nuclear Science Facility (FNSF).

Criteria for Selecting Int'l Collaboration Opportunities

I. **Importance of Scientific Issue to be Resolved**

Potential impact of resolving this issue on the feasibility of fusion energy, urgency of resolving the issue and the link to other critical issues in our strategic plan for fusion energy.

II. **Significance and Distinctiveness of US Contributions and Potential for Success**

US contribution would be significant, recognizable and increase the potential for success in resolving the scientific issue.

III. **Positions the US to obtain optimum benefit from ITER participation and builds foundation for potential future US development path in fusion energy.**

Would develop experience and build working relationships that enable the US to engage in desired ITER research activities, and position the US to move forward in developing fusion energy after ITER.

IV. **Strengthen, extend and regenerate the US scientific workforce**

Strengthens and extends the US scientific workforce in areas needed to carry out the US fusion program in the longer term.

V. **Resource requirements and impact**

Is the most cost effective way to address scientific goals rapidly and has a positive synergy with domestic activities and US long term goals.

Fusion Research Themes and Main Issues*

- **Creating Predictable High-Performance Steady State Burning Plasmas .**
  - Integration of high performance steady-state burning plasmas.
  - Control high performance plasmas for long pulse without disruptions or major transients.

IC Panel

- **Taming the Plasma Material Interface**
  - Understand and control of all processes coupling high performance plasma to nearby materials
  - Development of plasma facing components for HP Steady-State

- **Harnessing the Power of Fusion**
  - Materials in Fusion Environment
  - Power Extraction
  - Fusion Fuel Cycle

FNSP Panel

* From "Priorities, Gaps and Opportunities: Toward a Long Range Strategic Plan for Magnetic Fusion Energy" - FESAC 2007

Scientific Challenges for Collaboration

1. Extending High Performance core regimes to Long Pulse

- scenario development
- plasma control - current and pressure profiles
- transient avoidance and mitigation
- diagnostics
- steady-state heating/current drive
- integration with PMI and boundary

2. Development and Integration of Long Pulse Plasma Wall Solutions

- materials development
- particle and power handling
- material migration (erosion, transport, redeposition)
- PFC component lifetime, RF launchers for heating and current drive
- particle and tritium retention at high temperature >500°C
- integration with core plasma

3. Understanding the dynamics and stability of the burning plasma state.

- create a dominantly self-heated plasma
- alpha physics

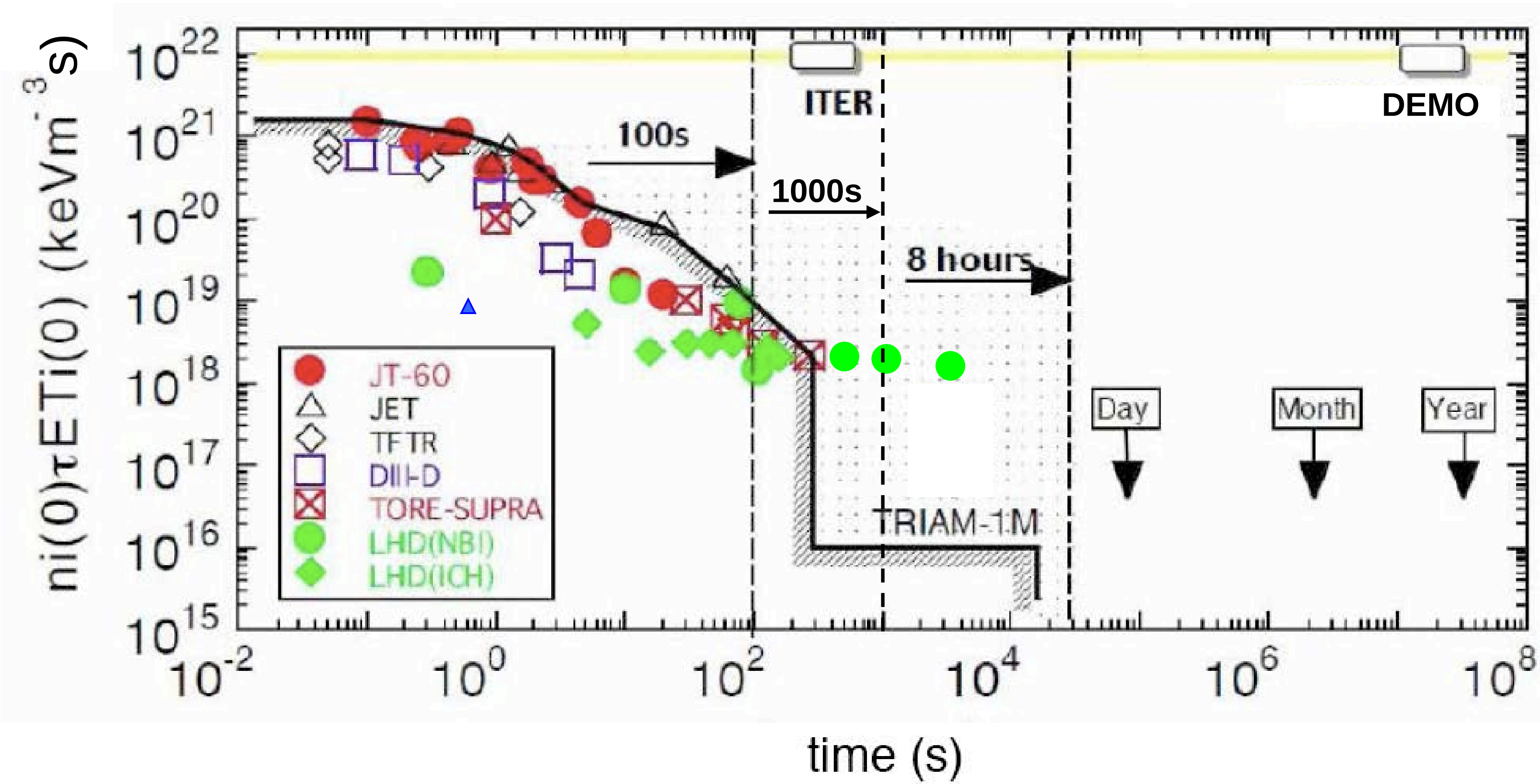
Time Scales Required to Address Issues

For medium-size plasmas C-Mod, DIII-D, EAST, KSTAR)	Range
1. Confinement and Transport (energy confinement time τ_E)	0.1 – 0.5 s
2. Stability Control	0.1 – 10 s
3. Current profile relaxation(τ_{CR})	1 – 5 s
4. Plasma Material Interaction (particle inventory)	1 – 100 s
5. Plasma Facing Component (thermal equilibration)	5 – 100 s
6. Wall Material Migration (cumulative operating time)	10^4 – 10^5 s
Plasma Facing Component Operating Temperature	100 – 500 °C
Plasma Exhaust Power Density (Power/ Plasma Surface Area)	~1 MWm^{-2}

- The core plasma issues(1,2,3) for medium size plasmas can be addressed with plasma durations of less than ~10s. This can be best done using copper coil magnets with lower cost and greater flexibility.

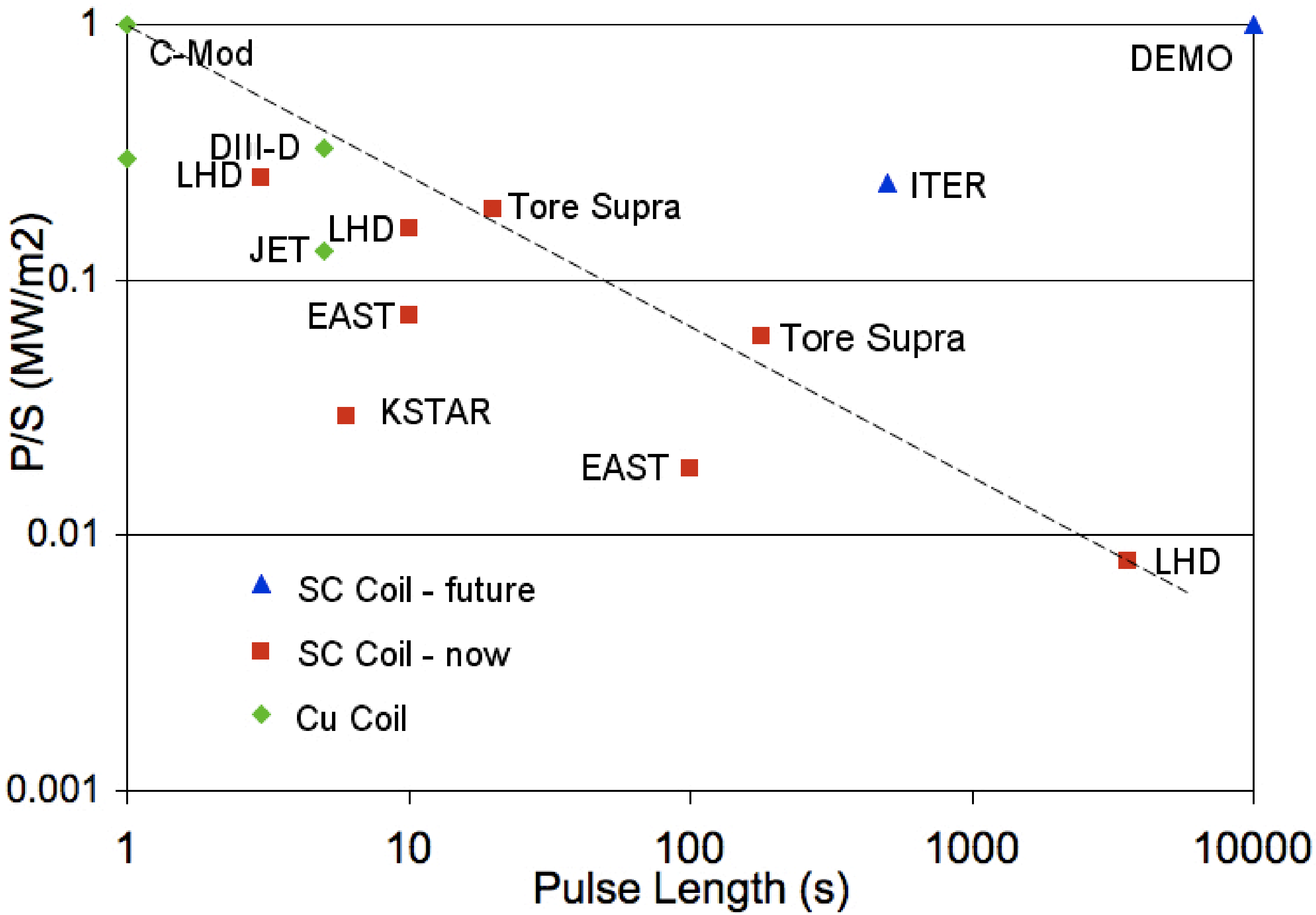
- Extending stability control (3) to long pulse, and plasma material interaction (PMI) issues(4,5,6) require plasma durations of ~100s and beyond. This is best done using superconducting coil magnets.

Challenge I - High Performance Plasma Regime for Long Pulse



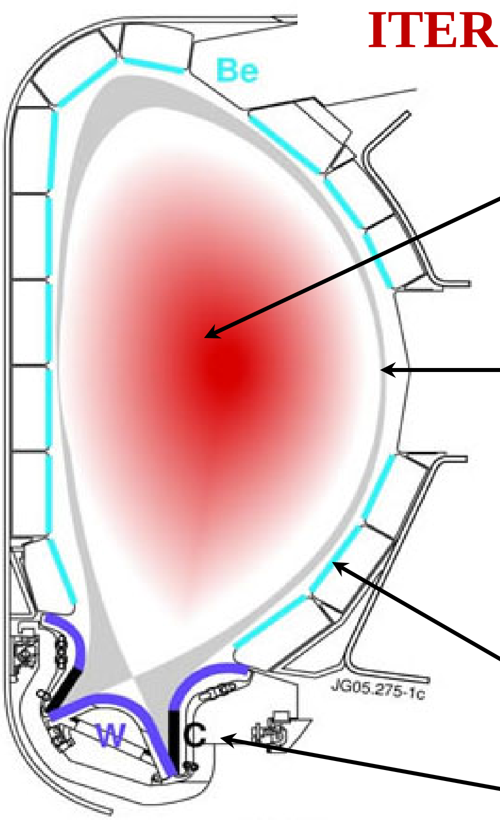
- at core plasma time scale – within a factor of 10 of ITER needs
- at plasma wall time scale – about a factor of 10,000 needed

Challenge II - Integration of Long Pulse Plasma Wall Solutions



- P/S = Power exhausted/ plasma surface area - is one measure of the Plasma Material Interaction
- Challenge: mitigate plasma power exhaust while maintaining performance with fusion relevant materials.

The Plasma Core and PMI are Strongly Coupled



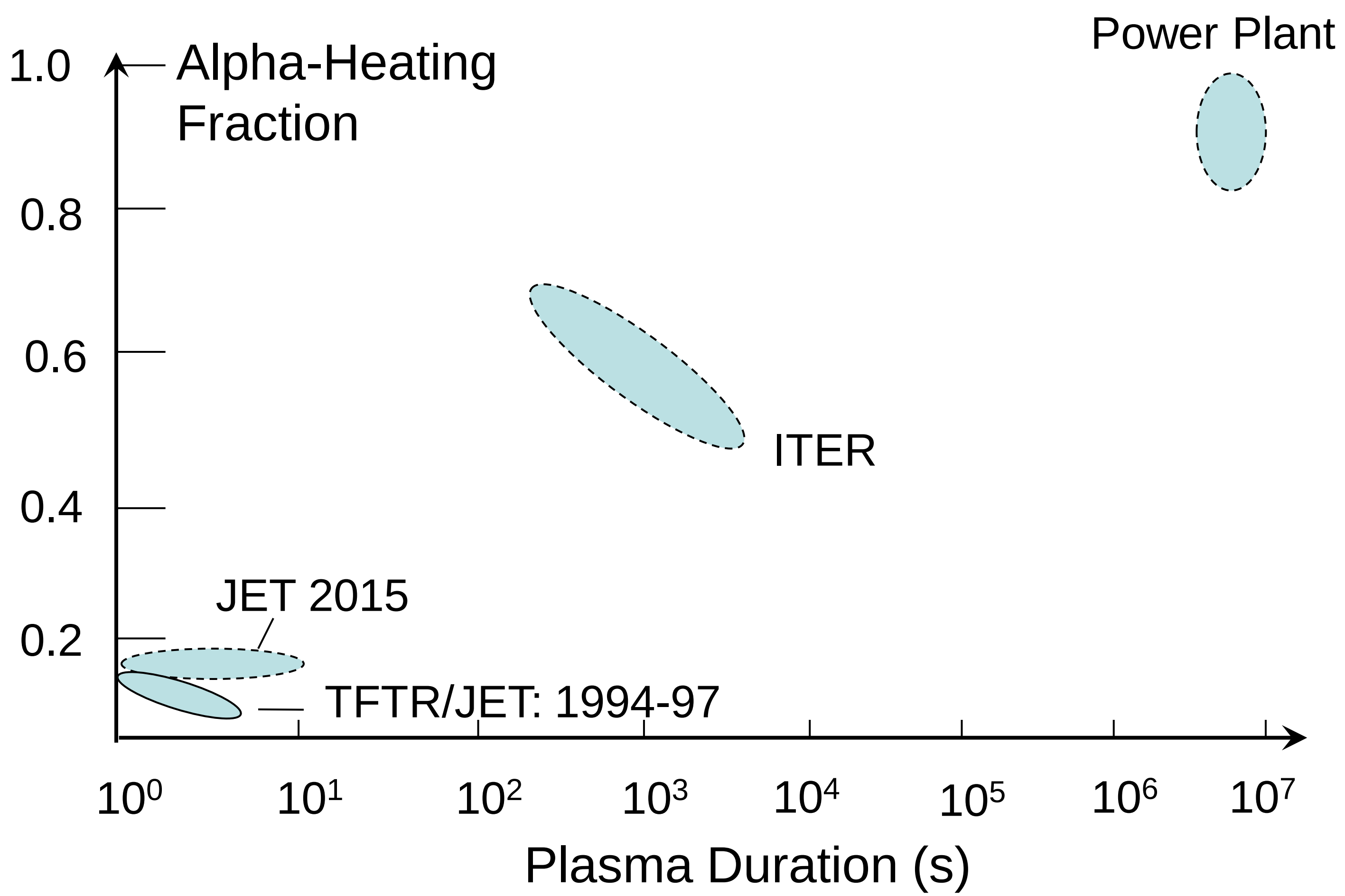
High Performance Steady-State
Burning Plasma Core

Boundary Plasma

Today
Divertor = C, First Wall = C, 150 °C
Mo (C-Mod), W coated C (AUG)
W/Be (JET)
ITER
Divertor = W, First Wall = Be, 150 °C

Fusion Power (e.g., FNSF)
Divertor = W, First Wall = W, 600 °C

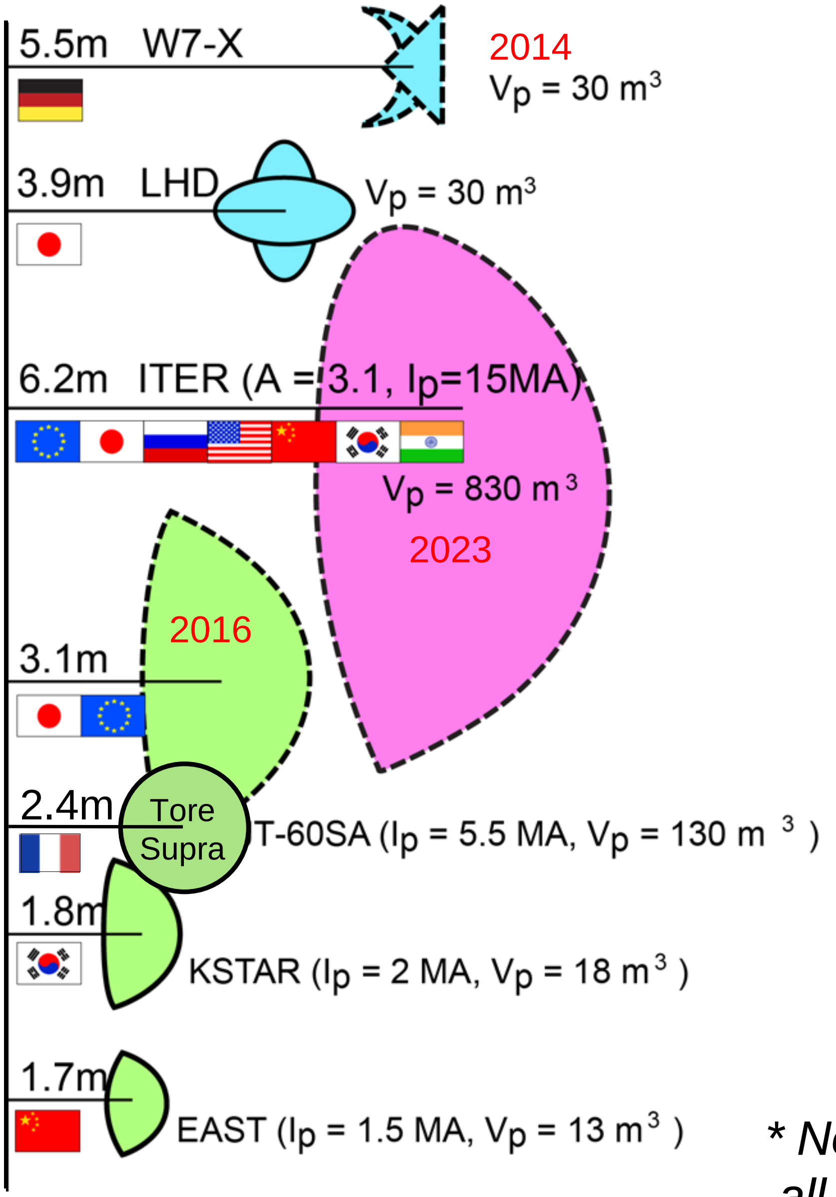
Challenge III - Dynamics and Stability of the Burning Plasma State



- An area of US strength in theory, diagnostics and experiments: initial DT experiments confirmed alpha dynamics including alpha heating.

- Development of diagnostics, tests of alpha physics on JET in preparation for ITER

Capabilities for Addressing High-Performance Long-Pulse



- Major fusion devices with superconducting coils have been operating for over a decade
  - Tore Supra* - tokamak, France 1988
  - LHD - helical, Japan 1998
- In Asia, two SC tokamaks have begun operations, and a third is under construction.
  - EAST - tokamak, China 2006
  - KSTAR - tokamak, Korea 2008
  - JT-60SA - tokamak, Japan 2016
- In Europe, a SC stellarator is under construction
  - W7-X stellarator, Germany 2014

** Note: All have SC TF coils, all have SC PF coils except Tore Supra*

Major International Magnetic Fusion Facilities

	EAST	KSTAR	JT-60SA	ITER	LHD	W7-X	JET-IW	Tor Sup	DIII-D	C-Mod
Location	**CH**	**ROK**	**JA**	**FR**	**JA**	**Ger**	**UK-EU**	**Fr**	**US**	**US**
Status (1st Plasma)	2006	2008	2016	2019	Mature	2014	2011/M	Mature	Mature	Mature
Configration	AT	AT	AT	AT	Stell	Stell	AT	Cir T	AT	AT
fuel	H, D	H, D	H, D	**DT**	H, He	H, D	**DT**	**H,D**	H, D	H, D
Major Radius (m)	1.85	1.8	2.96	6.2	3.9	5.5	3	2.4	1.67	0.67
Minor radius (m)	0.45	0.5	1.18	2	0.65	0.5	1.2	0.75	0.67	0.22
Plasma Vol(m3)	13	16	130	837	32	30	140	27	27	1
Plasma Surf (m2)	44	48	180	638	100	110	180	72	60	7
B(T)	4	3.5	2.25	5.6	3	3	4	4.2	2	5
Ip (MA)	1.5	2	5.5	15	~0	~0	5	2	2	1.5
B<a> (T-m)	2.1	2.3	3.7	13.1	2.0	1.5	6.3	3.2	1.8	1.1
Coil Technology	SC	SC	SC	SC	SC	SC	Cu	SC-TF	Cu	LN-Cu
Pulse Length (s)	1000	300	100	2,500	3,600	1,800	20	180	5	5
Paux(total)(MW)	30	28	41	150	36	20	35	25	25	7
Divertor	DN,SN	DN,SN	DN	SN	HD	Island	SN	Limiter	DN,SN	DN,SN
Cooling	H2O,He	H20	H20	H2O	H20	H20	H20	H20	inertial	inertial
Plasma Facing Mat'l	C=>W	CFC>w	CFC	Be/W	C	C=>W	W/Be	C	CFC	Mo>W
P/S(MW/m2)	0.68	0.58	0.23	0.24	0.36	0.18	0.19	0.35	0.42	1.00
P/R(MW/m)	16	16	14	24	9	4	12	10	15	10

Operating Plans for the “Emerging” Asian S/C Tokamaks

Device	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
EAST	Goal: Advanced Tokamak β_N <3, $I_{bs}/I_p \approx$ 50%									
	PFC - SiC H_20 Cool			W/Cu H_20 Cool			W > 400 °C He Cool			
	~ 1MW => 10 MW				20 MW			30 MW		
	10 - 100s				400s				1000s	
KSTAR	Goal: Advanced Tokamak β_N <5, $I_{bs}/I_p \approx$ 70%									
	PFC - C H_2O Cool				W-SN div/Cwall H_20 Cool					
	~ 1 MW => 8 MW				10 MW			20 MW		30 MW
	~ 10 s				50 s			300 s		
JT-60SA						Large Size (~8xVol of EAST/KSTAR)				
						Goal: Adv Tok β_N < 5.5, $I_{bs}/I_p \approx$ 70%				
						PFC -C H_20 Cool				
						23 MW		33 MW		37 MW
										100s

Operating Plans for Large S/C Stellarators

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
LHD	Heliotron (3T, $V_p = 30m^3$)									
	PFC-$H_2$0 Cool C=>W on C									
	25 MW/ 3s				33 MW/ 3s					
	16 MW/10s				21 MW/1,800s					
	0.8 MW/3,600s				5 MW/1,800s					
W7-X	Optimized Stellarator (3T, $V_p = 30m^3$)									
				PFC	C unCooled		Install PFC Cooling		C H_2O Cool	
					8 MW/ 10s				18 MW/10s	
					1 MW/ 50s				10 MW/1,800s	

Three “Compelling” Areas of Research have been Identified

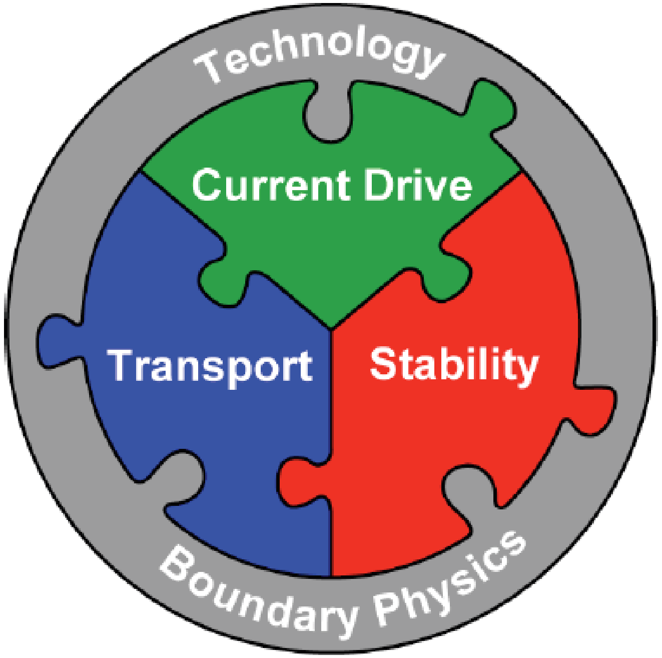
1. Extending High Performance Regimes to Long Pulse

2. Development and Integration of Plasma Wall Solutions for Fusion

3. Burning Plasma Research in Advance of ITER

Topic 1: **Extending High Performance Regimes to "Steady-State"**

- **Transport, stability & current drive are interdependent**
  - Flexibility needed to determine regime solution & resolve physics
  - *Requires powerful tools to access, optimize & control the regime*



- **Solution must be compatible with plasma facing components**
  - Test in relevant environment
  - Mitigate plasma exhaust (transients & time averaged)

- **Steady state is an area of US world leading capability**
  - Many of the best tools*, unique access, powerful diagnostics
  - ***Where are the gaps?***

[Luce, APS 2010]

*Eg. NSTX, DIII-D and C-Mod just tooled up with off axis current drive systems

Timescale is Key Distinguishing Feature of S/C Facilities

		Ratio to target:	
Characteristic Timescale or Other Parameter	Target	**US facilities**	**Super/C Facilities**
Confinement & transport	$\tau_E \sim 0.1$s	~100 ✓	~10000 ✓
Stability Control	~0.3s	~50 ✓	~5000 ✓
Steady State Profile Evolution	$\tau_R \sim 2$-5s	~5 ✓	~100 ✓
Wall equilibrium and recycling	~5-100s	~0.1-1 ≈	10-100 ✓
PFC Thermal Equilibrium	$\sim 10^2$s	~0.1 ✗	1-10 ✓
Material Migration (Total discharge time per year)	$\sim 10^5$s	~0.1 ✗	~5 ✓
PFC Temperature	>500 °C	1 ✓	1 ✓
Heat Flux Challenge, P/S:MW/m²	~1	~1 ✓	~1 ✓

US strengths
Integrated core solution & control schemes

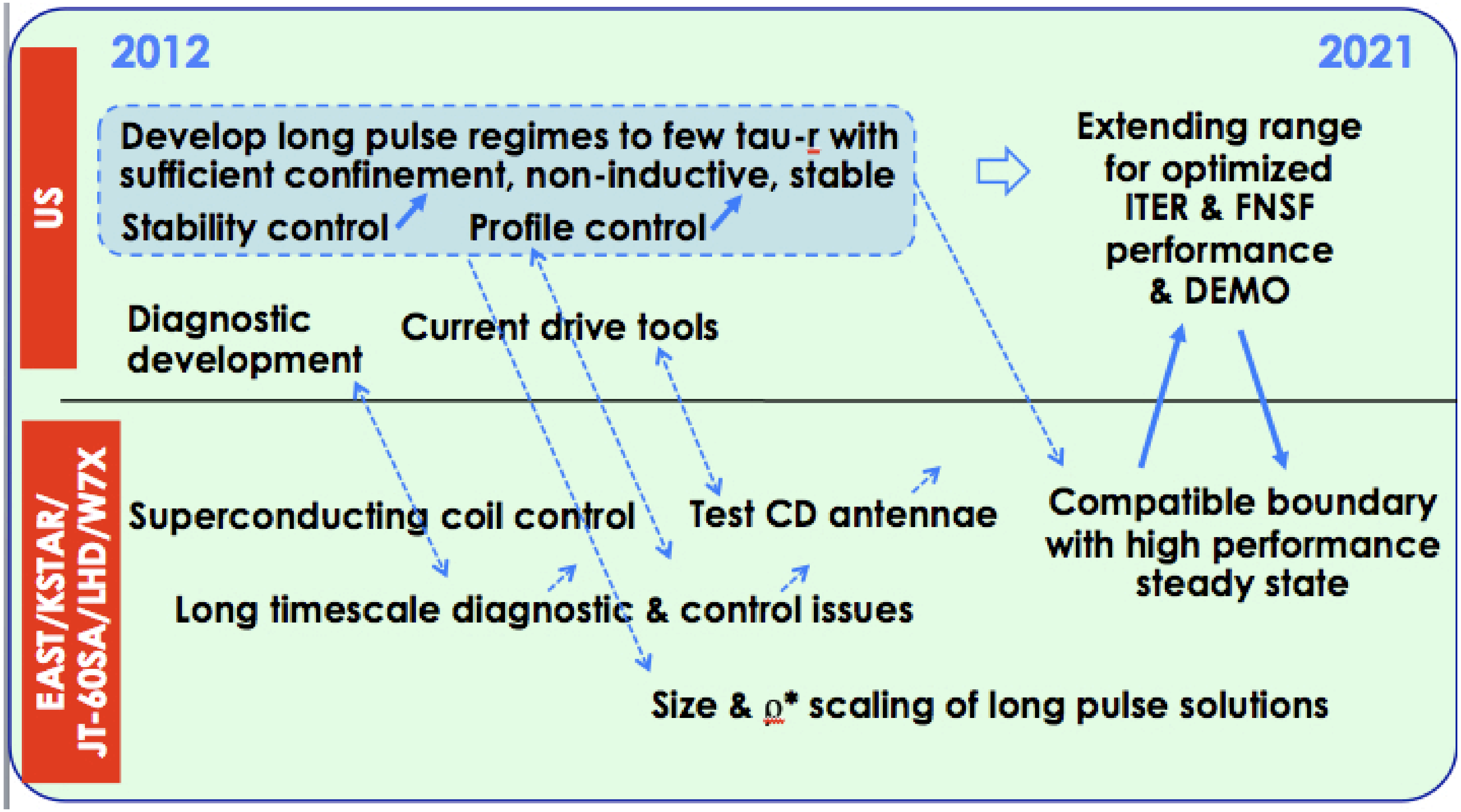
US gaps
PFC issues & control on extended timescales

Size (ρ*) range also needed to extrapolate to regimes future devices

- **Complementary capabilities provide opportunity for collaboration & mutual benefit**

Collaboration on "Steady-State" Offers Strong Mutual Benefit

- **US facilities required to establish physics & develop solutions**
  - Exploit high flexibility, diagnostics, forgiving PFCs
- **Key 'gap' tests & optimizations collaboratively**



Levers US program. Ensures leadership & influence. Meets strategic goals.

Principal Steady State Collaboration Opportunities Abroad

Test key elements of US developed technology & approach abroad:

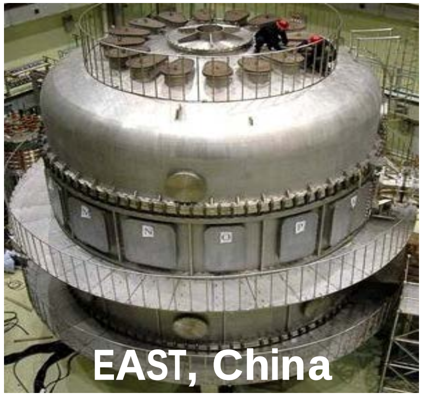
- **Size / ρ* scaling to extrapolate regimes**
- **Extend control to long pulse**
  - Test US developed control with superconducting coils
  - Extended evolution event response & performance recovery
  - Long pulse compatibility of current drive systems
- **Prove diagnostic techniques in long pulse conditions**
  - Long time scale & high fluence plasma environment
  - Robustness to nuclear radiation environment
- **Boost US theory & modeling through stellarator path**
  - Underlying transport & transient physics with 3D geometry
  - Apply to tokamaks. Lever role on W7X → stellarator power plant

Should pursue balanced collaborations – genuine two way engagement:
Joint development paths. Test aspects in US. US inward investment.

Not simply an effort to export US intellectual property and leadership wherever collaboration possible.

Principal Facilities for Steady-State Collaboration

- **Size scaling through JET and later JT-60SA**



- **Earliest opportunity for long pulse: EAST**

- Good power levels by 2014
- 400s operation, tungsten PFCs, SND & DND
- Aggressive development path
    - *Should increase focus on this opportunity*

- **Longer term KSTAR & JT-60SA remain interesting**

- KSTAR higher β emphasis and novel 3D coils
- JT60SA strong ITER focus, future possibilities towards DEMO
    - *Should retain a linkage with these programs*

- **Stellarator primary focus must be around W7X role**

- (US hardware role on boundary interactions & fuelling)
- Lever wider performance and transport issues through theory, preparing through tests on LHD

Topic 2: **Development and Integration of Long Pulse Plasma Wall Solutions**

- Issue long recognized as **critical** for fusion energy
- Power flux and particle & heat fluence increase with device size and will become extreme in reactor-scale systems
- PFC/First Wall materials must:
  - Withstand high thermal power fluxes,
  - Retain a small fraction of incident fuel particles
  - Maintain high-temperature (>500 °C for efficient reactors) thermo-mechanical properties under intense neutron irradiation.
- Reactor-scale surface-averaged heat fluxes:
  - Attained on C-Mod for ~second.
  - In current large tokamaks and stellarators, ITER-like power densities are tolerable only for < 5s.
- Existing materials not suitable for fusion nuclear environment involving tritium fuel and intense neutron irradiation
- Research needed to gain understanding required to then create fusion-energy relevant solution

Research Program Goal & Science Challenges Identified

- **Goal:** provide the scientific basis for PFCs that have required lifetime, with validated performance predictions, in the severe plasma and nuclear PMI environment of an FNSF/DEMO.
- **Science Challenges** Clear:
  - Understand the steady-state boundary and core plasma and PFC response to the high operational materials temperatures that will occur in a FNSF device
  - Understand, predict and manage the long-term material migration that will occur in a long pulse FNSF/DEMO due to plasma-material interaction
  - Optimize the configurations for magnetic divertors to spread the heat load over a sufficient area for steady state removal, while maintaining high performance steady state
  - Resolve the physics and engineering challenges of launching waves required for heating and current drive.

The Science Requires an Integrated Approach

- **Off-line single effect, linear plasma device simulators and irradiation facilities**
  - Erosion, redeposition & co-deposition studies
  - D/T/He retention, diffusion & permeation at prototypical particle/Heat fluxes; Impact of Neutron/Ion-beam irradiation
  - Develop understanding leading to model development
- **Existing short pulse confinement experiments**
  - SOL heat flux physics, plasma flows
  - Erosion & redeposition studies for migration evaluation
  - RF effects on PMI
  - Development of real-time in-situ diagnostics
  - Novel divertor concepts
  - Model refinement & testing in confinement systems
  - Tests of hot (>600 °C) W PFCs and effects on integrated scenarios
- **New Collaborations on Emerging Facilities in Asia & Europe**
  - Could address critical ITER-relevant, Long-pulse and 3-D physics issues

International Collaboration Opportunities

- **JET ITER-like Wall Experiment:**
  - Provides first operational experience with these materials and experimental basis for the tritium inventory estimates required for ITER licensing
  - The US could contribute additional PWI expertise and diagnostics
  - *Benefit*: *US gains experience valuable to future participation on this topical area on ITER.*
- **EAST:**
  - **US should participate in EAST High Temperature tungsten wall & PFCs upgrade**
  - **Uniquely addresses** PFC/PMI Fusion Nuclear Science challenges & integrates with long pulse high performance core plasmas
  - **US could provide experience** from hot divertor program on C-Mod, novel real-time PMI diagnostics, and PMI expertise
  - ***Benefit:*** *US gains the understanding needed to validate models for the design and operation of FSNF/DEMO*

International Collaboration Opportunities (cont'd)

- **W7-X and LHD:**
  - Develop and assess 3-D divertor configurations for long pulse, high performance stellarators.
  - US has a significant collaboration in place on W7-X and is responsible for key high heat flux elements, 3D analysis codes and diagnostics
  - LHD could provide an additional opportunity
  - *Benefit: Strengthens US capability to pursue the stellarator as a potential path to fusion energy should tokamak encounter show-stopping issues*
- **K-STAR**
  - Longer term (~5-10 year) opportunity for Long Pulse actively cooled PMI/PFCs
  - Current plan is for Carbon PFCs at low temperature
  - An upgrade to hot C walls could provide a solid wall backup pathway should W prove unworkable
  - K-STAR considering W PFCs (water cooled) for lower divertor in 2015
- **JT60-SA:** Longer term possibility; Watchful waiting

Topic 3: **Understanding the Dynamics and Stability of the Burning Plasma State**

- Key frontier of fusion research: ***the next major step for MFE***
  - Produce, control, characterize plasmas with dominant self-heating: **Q > 5**
- **This is the role of ITER: *instrinsically international collaboration***
- New regimes for physics will become accessible
  - Large $R\nabla\beta_\alpha$ of energetic ($v_\alpha/v_{Alfvén}$>>1) alphas to drive Alfvén instabilities
  - Large a/ρ_α allows many overlapping modes affecting alpha-confinement
- Plasma control and operation will be significant challenges
  - Exothermic, potentially thermally unstable plasma
  - Non-linear couplings between local heating rate and
    - energy and momentum confinement
    - self-generated plasma current
    - MHD stability
- For success in ITER, we must explore this physics in most relevant conditions available and develop strategies appplicable to ITER

Good Progress in Advancing Towards Burning Plasmas

- DT experiments in 90s in JET, TFTR began exploration
  - First indications of alpha-heating: $\Delta T_e/T_e$ ~ 10% at Q = 0.3 - 0.6
  - Measured energetic alpha population and He ash
  - Confirmed classical confinement of alphas in quiescent plasmas, *but*
  - Anomalies in DT reactivity and alpha confinement in “advanced” modes
  - Expected alpha-driven Alfvén instabilities damped by sub-Alfvénic NBI
- Since then, physics of energetic particle instabilities has advanced
  - Use NB-injected and RF-accelerated ions as surrogates for alphas
  - Developed innovative mode diagnostics, active MHD-spectroscopy
  - **Very productive coupling between theory, modeling and experiment**
- Confidence in confinement needed for ITER baseline mode increased
  - Remains to be demonstrated with ITER-like PFCs at high power
- Understanding and control of advanced modes needed for ITER steady-state mission has developed greatly
  - Now need to confirm compatibility with alpha confinement and heating

Opportunity 3.1:
Alpha Particle Confinement, Heating and Instabilities

- Need: understanding and predictive capabilities to plan for ITER
- JET planning DT experiments in 2015: nearest in scale to ITER
  - Upgraded heating (35MW, 20s NBI) for thermalized alphas at Q = 0.6
  - Improved diagnostics for detecting alpha confinement, modes, heating
- Opportunities for US involvement
  - Support for US-supplied lost-alpha detector and AE diagnostics
  - Model JET alpha confinement and instabilities with US suite of codes
    - Predictive modeling in advance provides stringent tests
  - Apply US-developed experiment analysis codes to alpha heating data
    - Needs access to full data set through cooperative arrangement
- Complementary domestic research
  - Continue productive theory/experiment code development, fast particle and mode diagnostic development, and validation
- Benefits
  - Strengthen US capabilities for application to and participation in ITER

Opportunity 3.2:
Exploration and Optimization of ITER Operating Modes

- Need: develop predictable scenarios & prepare for ITER operation
  - Must match best normalized performance achieved in smaller tokamaks
    - Challenges of size, low shot rate, need to avoid transients, regulation
- JET now operating with ITER-Like Wall, including DT phase in 2015
  - Examine issues of impurities, T-retention, transients, damage tolerance
  - Crucial size scaling and effects of isotopic composition
- Opportunities for US involvement
  - Active participation of US experts in design, performance of experiments
    - Need suitable cooperative arrangements
  - Involve US experts in T-retention, material migration, dust formation
- Complementary domestic research
  - Predictive application of theory/modeling for core and edge confinement
- Benefits
  - Strengthen US capabilities for major role in ITER operation, experiments

Discussion on Modes of Collaboration

Charge 2: *What research modes would best facilitate international research collaborations in plasma and fusion sciences?* Consider modes already used by these communities as well as those used by other research communities that have significant international collaborations.

In considering this charge, the panel

- **Surveyed the present status and modes of collaboration in use in FES.**
- **Examined experience of other fields, notably HEP and astronomy.**
- **Used our criteria to determine key considerations, including workforce issues, and positioning the FES program for ITER and beyond.**
- **Made a number of recommendations to modes which best meet these criteria, and means of implementing them.**

Current of Modes of Collaboration

Existing collaborations in magnetic fusion energy:

- **Result from case by case opportunities or initiatives**. Not centrally coordinated.
- **May be focused on science topics or hardware tasks.**
- **Span a wide spectrum of scales and modes, as appropriate, ranging from:**
  1. **Individual Scientific Exchanges**
     e.g. ITPA joint experiments.
  2. **Group or Institutional Collaborations**
     e.g. GA/DIII-D collaboration with EAST, KSTAR.
  3. **National Teams**
     e.g. Stellarator collaboration with W7-X
  4. **International Teams**
     e.g. ITER TBM Error Field Simulator.

Each of these modes can be effective and has advantages for certain types of collaborations.

Experience from High Energy Physics

- The US HEP program now relies on international collaborations at the Large Hadron Collider (LHC) at CERN, in the Energy frontier. It maintains strong domestic efforts at the Intensity and Cosmic frontiers.
- Science at the LHC is done by two competing experiments, ATLAS and CMS, each operated by an international collaboration of roughly 2000 physicists from close to 200 institutions across 40 countries. The US LHC community accounts for roughly one-third of the total.
  - About 25% of the US LHC personnel are stationed at CERN for one year or longer.
  - They are supported by the balance (75%) of US LHC personnel based at domestic universities and laboratories.
- The HEP community identifies four crucial elements for successfully maintaining future competitiveness when the only Energy Frontier facility is overseas:
  - **Maintain centers of excellence in the US.**
  - **Establish a culture of remote participation.**
  - **Maintain the ability to station personnel overseas for extended periods.**
  - **Establish cohesive US-ATLAS and US-CMS projects and collaborations.**

Experience from Astronomy

- The International Collaborations in Space Science carried out by NASA are the largest (in dollar value) international science collaborations carried out by the US.
- They range from “hardware” (e.g., rockets and other launch vehicles, satellites, and launch facilities) to “operations” and to science and engineering programs.
- Since the late 1970s, virtually all NASA missions have had some component of international collaboration; many missions carry onboard a mix of instruments built in the US or abroad. US scientists also contribute instruments to missions led by other nations.
- There is a long tradition of sharing of mission databases, sometimes after a short period of limited access.
- NASA collaboration rules which seem particularly relevant to fusion include:
  - **Cooperation is undertaken on a project-by-project basis, not on an on-going basis for a specific discipline, general effort, etc.**
  - **Each cooperative project must be both mutually beneficial and scientifically valid.**
  - **Scientific/technical agreement must precede political commitment.**

Findings derived from prior collaboration experiences:

- **The US-HEP collaboration with LHC is an example of a successful structure** for carrying out an effective collaboration on a complex megaproject located overseas.
  - Significant overseas presence is required to acquire positions of leadership
  - Collaboration is supported by strong capabilities in U.S. (~75% of the budget)
  - The US team approach for LHC can provide a model for ITER participation. However, it may not provide a model for smaller collaborations.

- The formation of **national and international research teams organized by scientific topic** can be an effective research structure for international collaboration.

- **The cost per researcher sited overseas is significantly higher than for research sited at a home laboratory.**
  - Opportunities must be carefully selected to focus on critical issues that cannot be addressed in the US and provide clear benefit to the US program.
  - Their scale must be no larger than is necessary.

Challenges for attracting and retaining fusion scientists

- Perhaps the greatest strength of the current US fusion energy sciences program is its experienced and capable scientific and engineering workforce.
- Retaining and renewing this workforce is crucial to fielding strong teams on ITER.
  - 2004 FESAC panel on workforce noted 1/3 were nearing retirement, estimated US needs to train 40 Ph.D.s per year until ITER.
- International collaborations pose significant challenges that must be addressed. **Challenges common to all types and scales of institution include:**
- **Extended overseas assignments challenge families**
  - Most US researchers are in 2 career families; relocation may not be feasible. May impact workforce demographics.
  - Education of children is a concern.
  - Language and cultural barriers are likely to be greater in Asia than in Europe.
- **Extended overseas assignments can impede career advancement.**
  - Maintaining strong connections to home laboratory is important both for researchers, and for retaining the knowledge gained by collaboration.

- **Recommendation:** Developing a **team approach that allows for flexibility and the use of remote communication tools** can mitigate these challenges, as they have in HEP.

Additional challenges for university programs

- **Extended assignments reduce program visibility at home institution.**
  – This can affecting faculty hiring and tenure decisions; retiring faculty may not be replaced by fusion experts.
  – Student recruitment may decline.
  – Likely to be bigger issues for collaborations at smaller facilities, as compared to LHC or ITER.
- **Overseas assignments challenge PhD graduate education programs.**
  – Sequence of coursework and research needs to be modified.
  – Need to maintain good supervision by home department. Difficult for faculty to travel while teaching. In HEP, DOE often 'buys out' teaching commitments.

- **Recommendation:** Given the important role played by universities in supporting faculty working on fusion research, providing fusion research with a broad connection to the larger scientific community, and the recruitment and education of future fusion researchers for ITER and beyond, **universities must be included in the international collaboration program.**
  – Solicitations should be planned accordingly.
  – Experience in fusion and in in HEP, has shown **it is important to support a linked on-campus research program.**

Preparing for effective collaboration on ITER

The modes of collaboration we develop now need to prepare US well for participation on ITER (Panel Criterion # 3).

- Details of US (and international) ITER research organization are not yet defined, though it would be timely to start this discussion.
- From US perspective, ideally should include:
  - Multi-institutional national teams, with national laboratory, university and industry researchers.
  - Teams focused on science issues, enabling US to lead experiments, publish results, NOT just supplying US-obligated hardware items.

Favors having our major near and medium term collaborations follow the ITER model now.

- Multi-institutional national teams, focused on key issues.
- Could carry out research on *multiple* facilities, domestic and international.
- Would result in good integration, 2-way flow of ideas and information, naturally prepare teams which work well together, ready for ITER.
- Should be relatively flexible, efficient and attractive to our research workforce.

These considerations for ITER influenced our recommended modes of collaboration.

Recommendations on Modes of Collaboration (1)

1. ***DOE should seek issue-based, goal-driven international collaborations that are aligned with national priorities, supported by task-based work where appropriate.***
   - Topics for collaboration should focus on activities that address key gaps in US capability to meet US strategic goals
   - Though topical in nature, it may be best to form international collaborations with single overseas facilities

2. ***Mutually beneficial international partnerships should be arranged which strengthen US capabilities in fusion science.***
   - Partnerships or collaborations with common goals are advantageous over unilateral action or "exchanges" since they model likely ITER operation
   - The support and contributions provided by the international partners should be clear from the outset.

3. ***Portfolio of international collaborations should include a range of appropriately scaled and structured collaborations that provide opportunities for new participants on a regular basis.***

Recommendations on Modes of Collaboration (2)

4. ***For large-scale collaborations, an integrated team with a flexible mix of full time, on-site researchers and shorter-term visitors should be employed, structured according to scientific roles, with support flowing directly from DOE to relevant team member institutions wherever possible.***
   - General experience suggests that some consistent presence of on-site personnel is necessary for an effective collaboration and recognized leadership
   - Solicitations should encourage proposals which include a combination of longer and shorter term visits, supported by remote participation tools.

5. ***The structure of these international collaborations should be viewed as an opportunity to develop U.S. fusion program collaboration modalities that prepare for effective participation in ITER***
   - International collaborations involving university programs will be an essential element in attracting the best and brightest young scientists
   - The US should be proactive in recommending to the ITER organization future modes of participation in ITER experiments

Recommendations on Implementation (1)

1. **While solicitations should seek issue-based collaborations, it should be recognized in the selection and award process that it may be most effective to establish separate collaborations with each overseas facility utilizing a DOE-FES umbrella collaboration agreement with the host facility as needed.**
   - Organizing collaborations on a facility-by-facility basis makes it easier to obtain reciprocal agreements or partnerships which result in significant tangible benefits to the U.S. fusion program

2. **The solicitation and selection process should allow a range of modalities, partnerships, and opportunities in order to best utilize expertise in the U.S. fusion program, and it should be clearly defined on the national level with open calls to establish new international collaborations or to renew existing collaborations.**
   - Use something like the selection criteria recommended in this report
   - Proposals should recognize increased costs of supporting overseas assignments
   - Renewals offer opportunities to adjust the mix, goals, tasks, and participation
   - A balance must be maintained between the need for stability and the need for flexibility, allowing for new participants and ideas

Recommendations on Implementation (2)

3. **The division and funding of collaborations should be structured according to scientific roles, with support flowing directly from DOE to relevant team member institutions wherever possible.**
   – U.S. teams should seek appropriate full program integration
   – Clearly defined arrangements between partners should include scientific responsibilities and governance structures

4. **DOE-FES should have a plan in place to assist collaborating institutions navigate the complex Intellectual Property, and Export Control issues, and ensure safety of their personnel.**
   – Each US and overseas institution has its own IP policy, often contradictory; coordinated policy negotiation could be helpful
   – Export Control regulations are complex and could impact some collaborations.
   – Personnel must have a working environment which is as safe as in the U.S.

5. **Capabilities for effective remote collaboration from a number of locations should be provided and expanded as remote communication technology advances.**
   – Infrastructure investment needed to allow routine communication and effective work to be conducted from many US institutions
   – Adequate and open high speed internet to overseas sites must be ensured

Summary: Charge 2

International collaborations bring a number of challenges and opportunities. The manner in which they are carried out can maximize their effectiveness. Key principles include:

- Creating compelling opportunities at the leading edge of fusion research which will provide researchers the needed motivation to participate.
- Setting up teams with a flexible mix of on-site presence, shorter visits and remote participation.
- Enabling all types of institutions to participate, at a range of scales of effort.
- Maintaining strong, closely linked, programs at US institutions, so that expertise is transferred and retained.

If well implemented, collaborations can help prepare the US for effective participation in ITER, and in moving forward with a fusion energy program beyond ITER.

Concluding Remarks

- The Panel has identified a number of “compelling” scientific opportunities using emerging capabilities overseas that could address key scientific issues, strengthen US capabilities, position the US to exploit ITER and move beyond ITER with a strong US domestic fusion program.

- The Panel has also identified and assessed modes of collaboration that could be used to effectively carryout a range of collaborations.

- The US needs to approach these opportunities realistically, proceed step by step with detailed discussions and assessments in regard to expectations and commitments on the part of both parties. Assessment criteria similar to those described in this report should be used.

- For a larger collaboration, an integrated national team approach offers the potential for maximizing benefit to the US, and preparing the US for participation in ITER.

- A plan for international collaborations should be established and integrated into the overall strategic plan for the US Fusion Energy Sciences program.