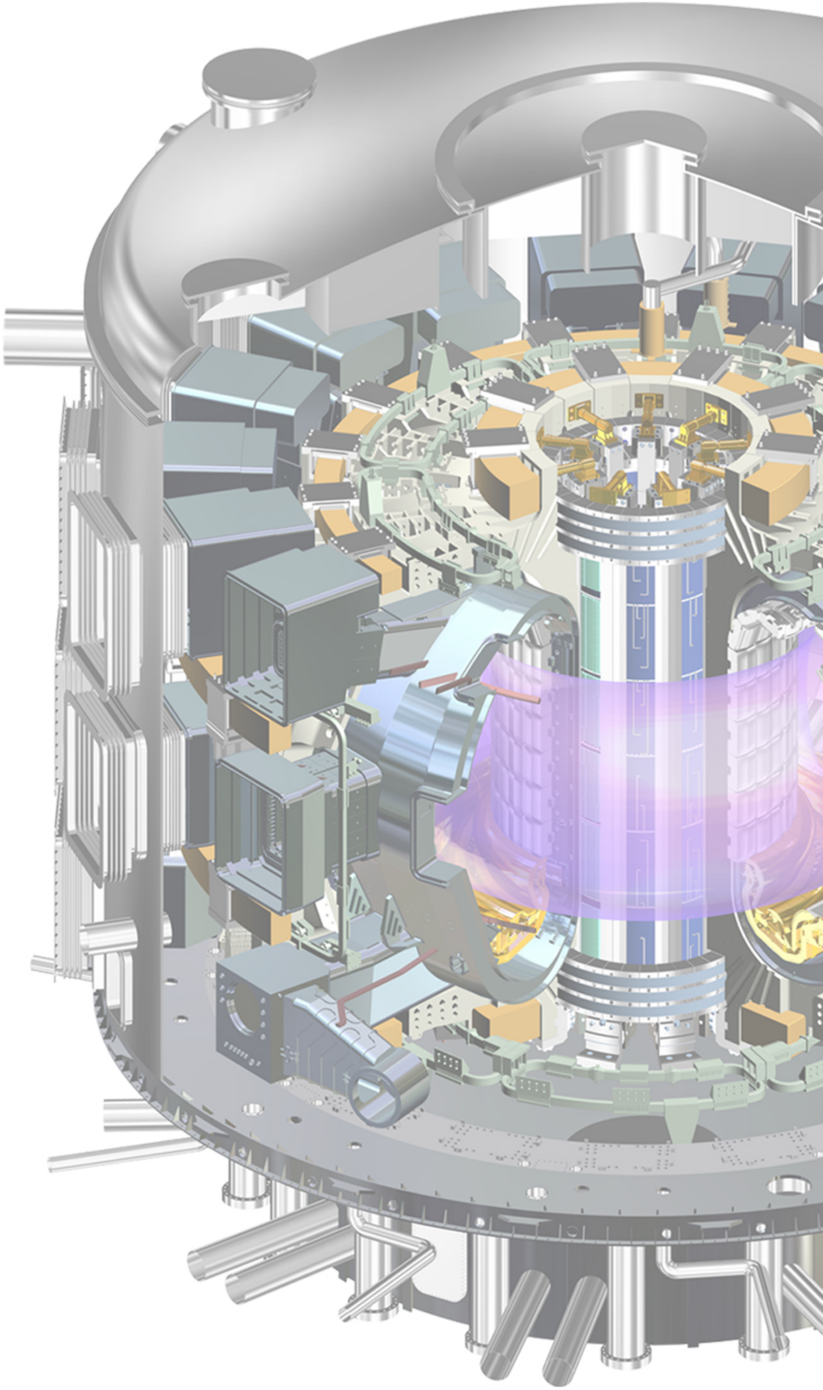
Perspectives from the US ITER Project

Ned R. Sauthoff

Director, US ITER Project Office

NAS Committee for a Strategic Plan for U.S. Burning Plasma Research

August 29, 2017



Outline

- **Developments Since 2004**
  - Negotiations Phase
  - International Construction and Hardware Progress
  - ITER Management Turnaround
  - Hardware Progress in US
  - US Project Management
- **Project Engagements and Impacts**
- **Summary**
- **Further Information**

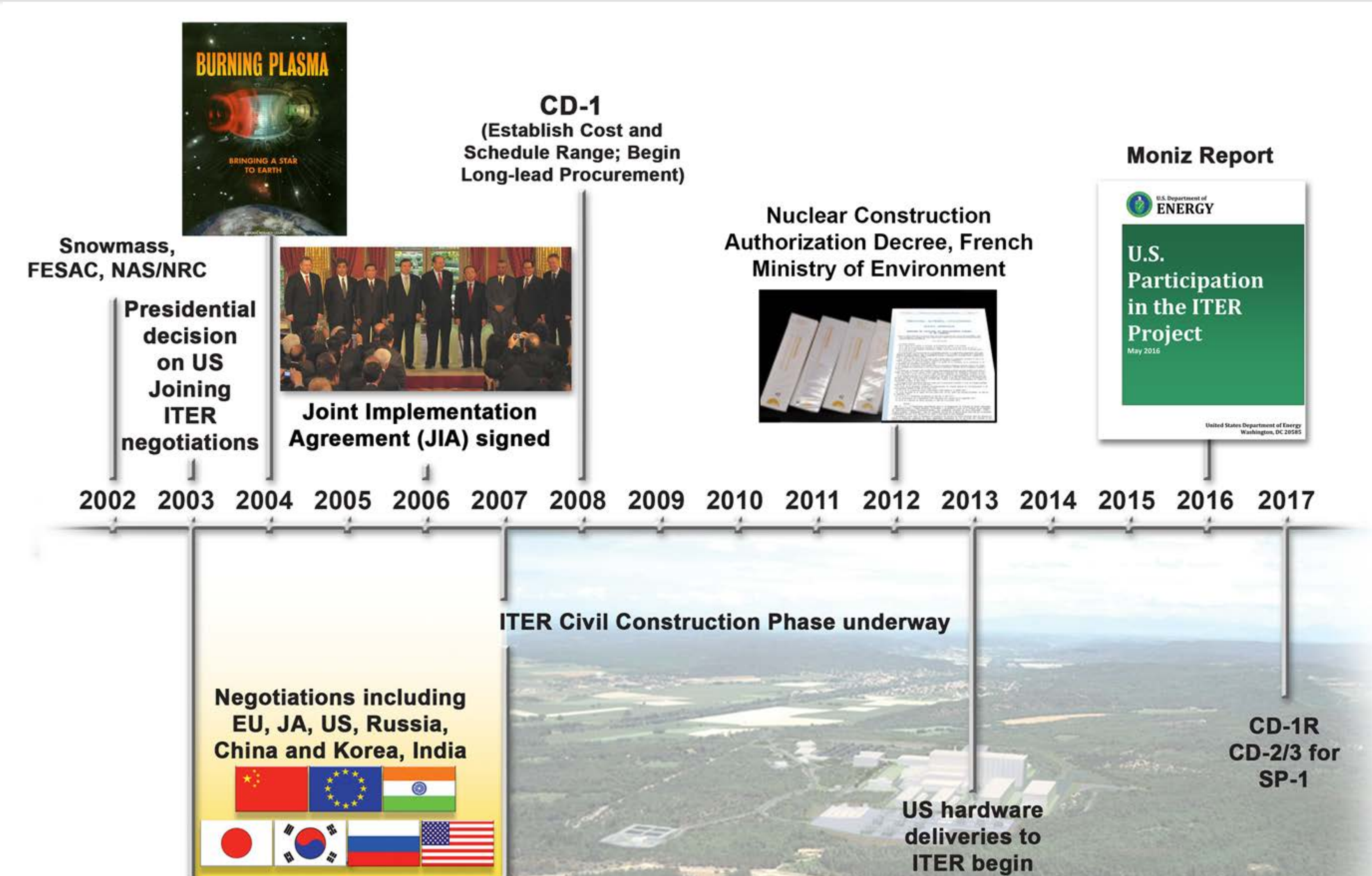
Developments Since 2004

Excerpts from NRC 2004 Recommendations

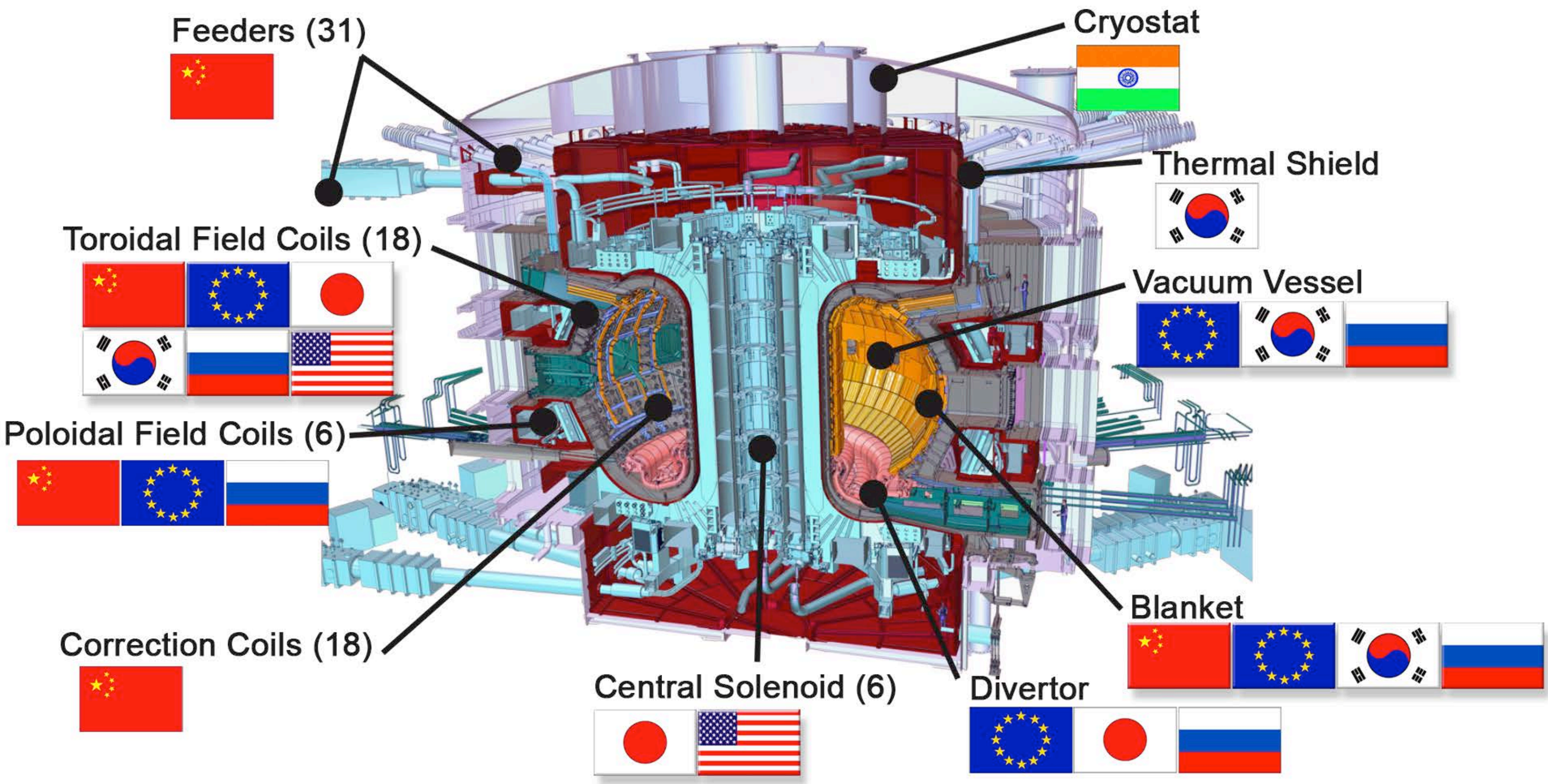
- "The United States should participate in a burning plasma experiment."
- "The United States should participate in the International Thermonuclear Experimental Reactor (ITER) project. If an international agreement to build ITER is reached, fulfilling the U.S. commitment should be the top priority in a balanced U.S. fusion science program."
- "The United States should pursue an appropriate level of involvement in the ITER project, which at a minimum would guarantee access to all data from ITER, the right to propose and carry out experiments, and a role in producing the high-technology components of the facility consistent with the size of the U.S. contribution to the program."
- "A strategically balanced U.S. fusion program should be developed that includes U.S. participation in ITER, a strong domestic fusion science and technology portfolio, an integrated theory and simulation program, and support for plasma science. As the ITER project develops, a substantial augmentation in fusion science program funding will be required in addition to the direct financial commitment to ITER construction."

Source: National Research Council. 2004. *Burning Plasma: Bringing a Star to Earth*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10816, p. 4, 6.

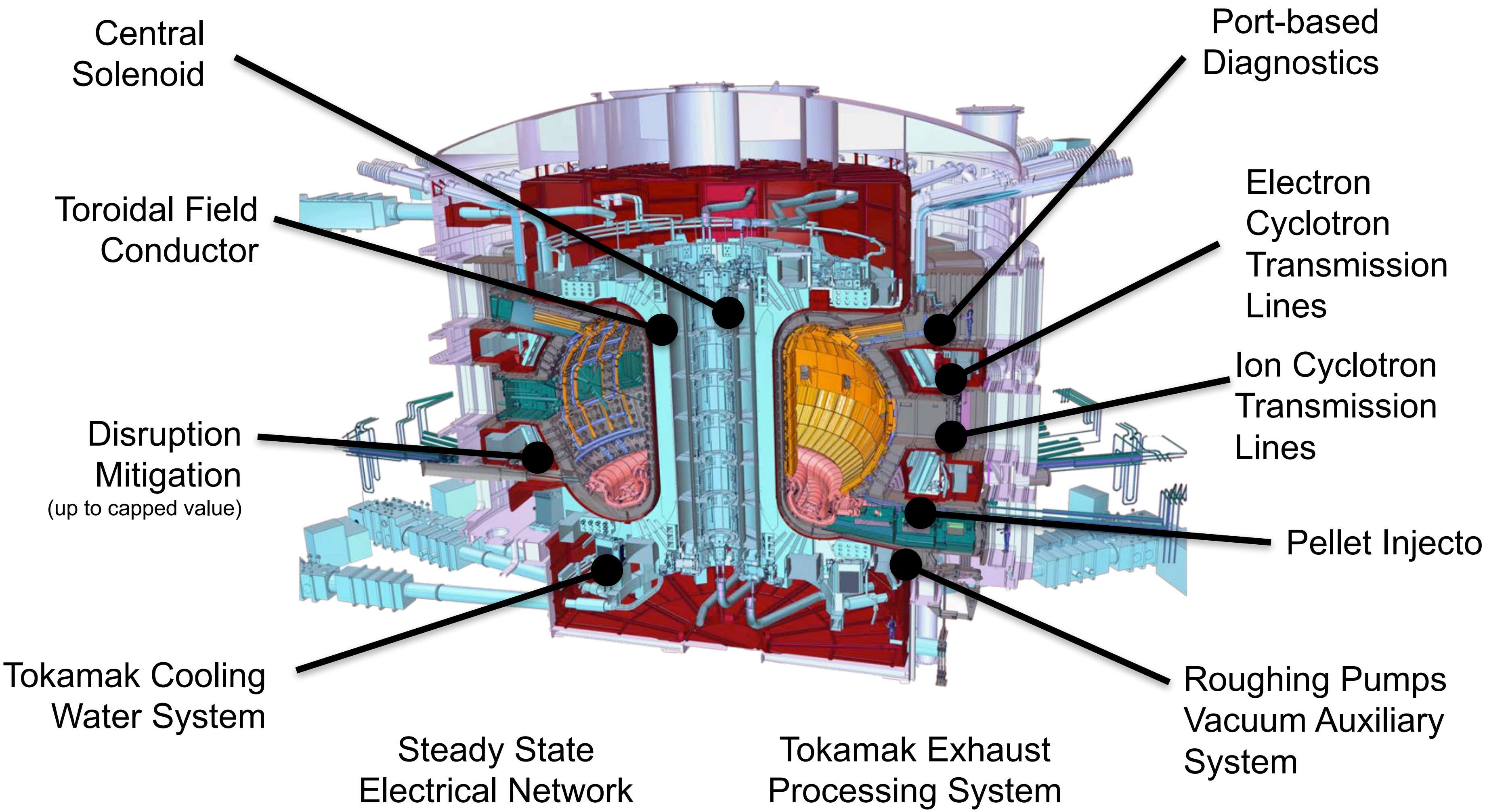
Project History



High Level International Procurement Arrangements



High Level US Procurement Arrangements



International Construction

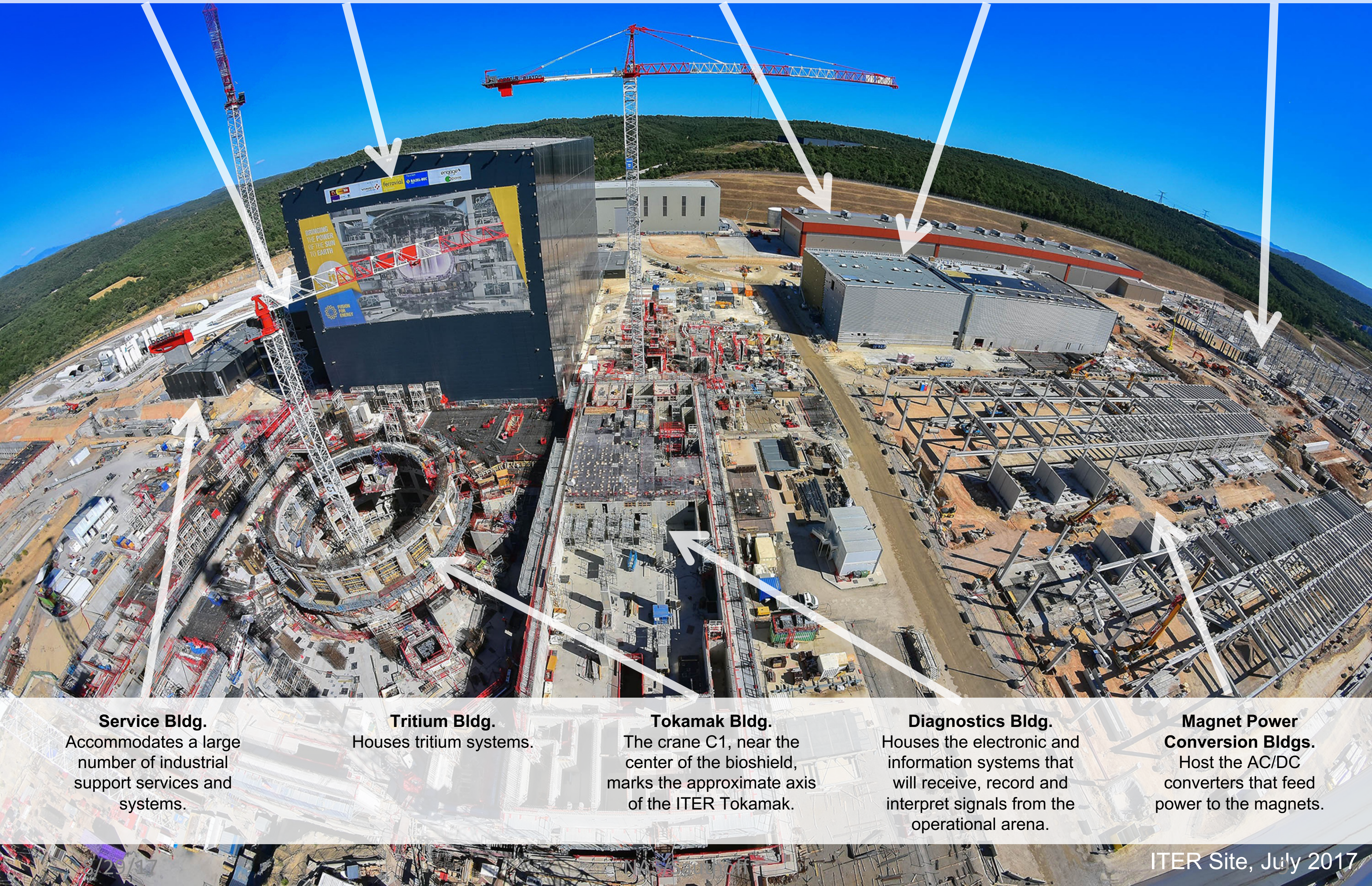
Radio Frequency Bldg.
Hosts the radio wave-generating systems that will contribute to heating the plasma.

Assembly Hall
Components will be pre-assembled in this 6,000-square-meter building, equipped with a double overhead traveling crane and powerful handling tools.

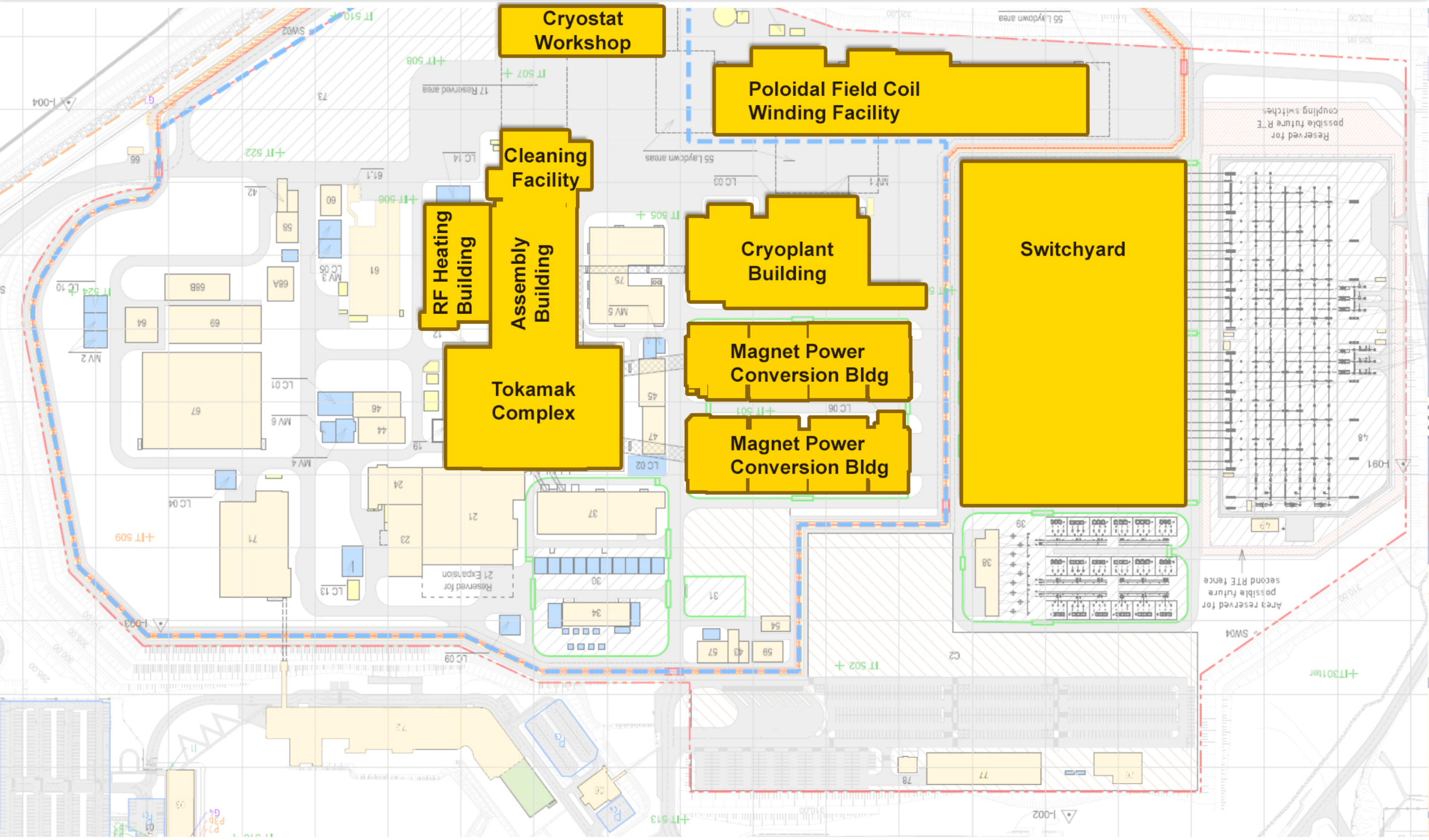
Poloidal Field Coils Winding Facility
Four of the six poloidal field coils will be produced by Europe in this 257-meter long facility.

Cryoplant
Will provide coolant to the Magnet Systems, the cryopumps and the thermal shield.

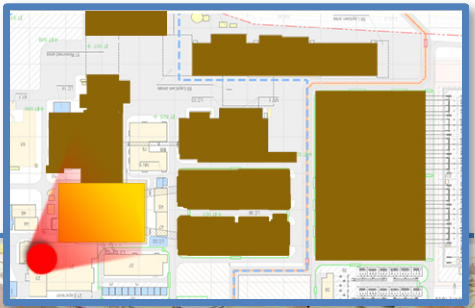
400 kV Switchyard
Connects the site to the grid.

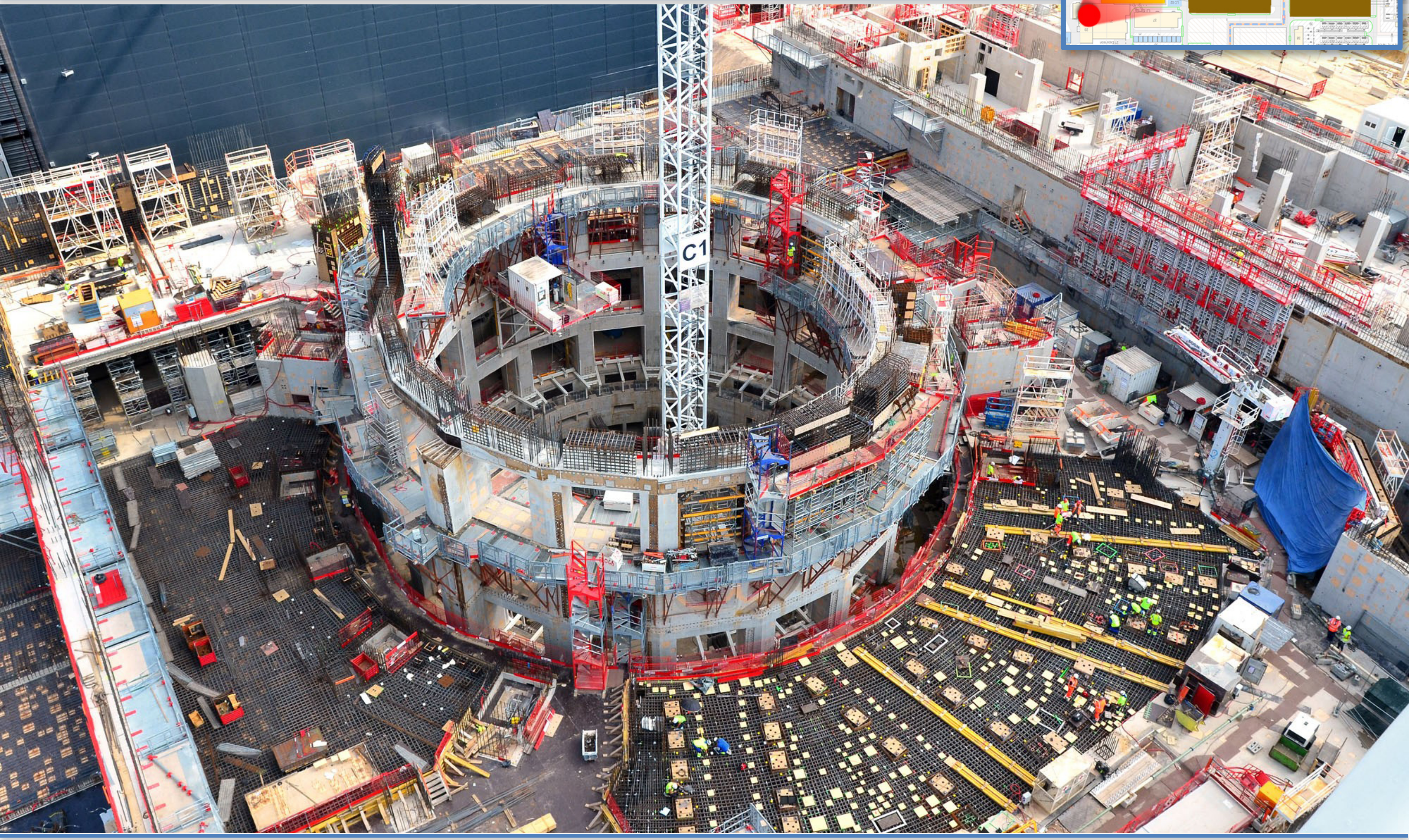


Overview of ITER Site

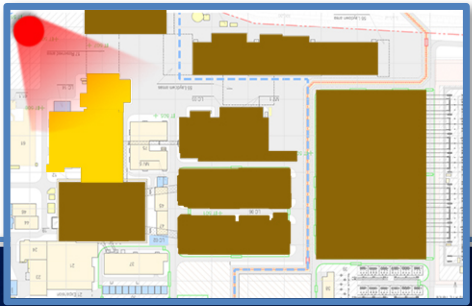


Tokamak Complex



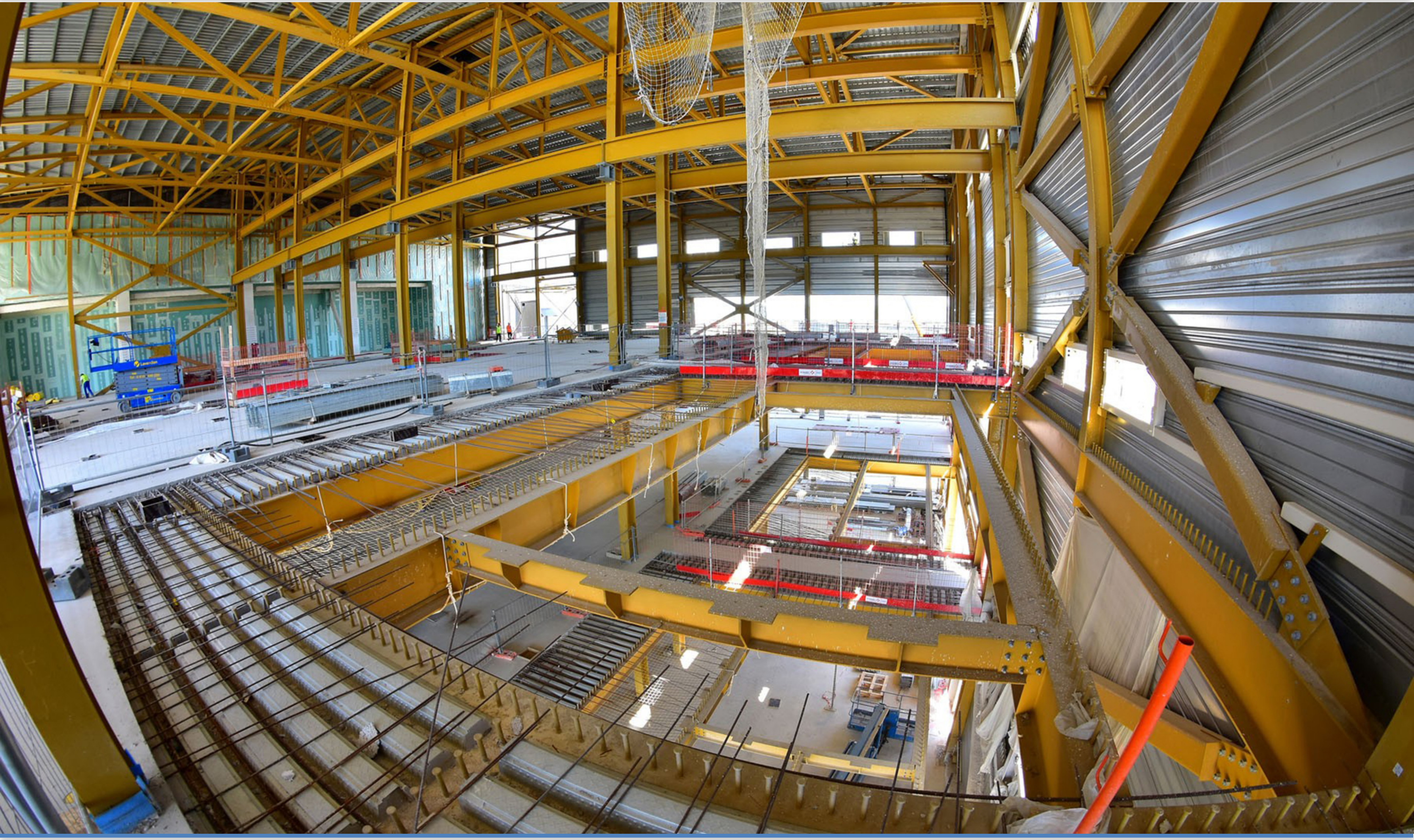


Assembly Building, Cleaning Facility and RF Heating Building

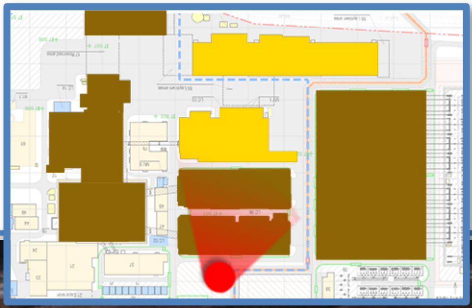


Assembly Building

RF Heating Building



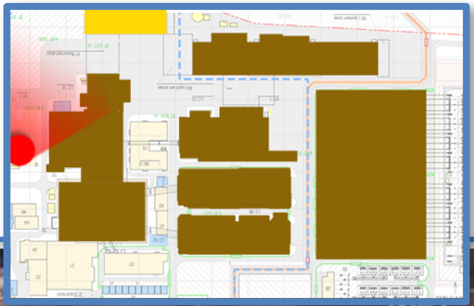
Poloidal Field Coils Winding Facility and Cryoplant



Poloidal Field Coils
Winding Facility

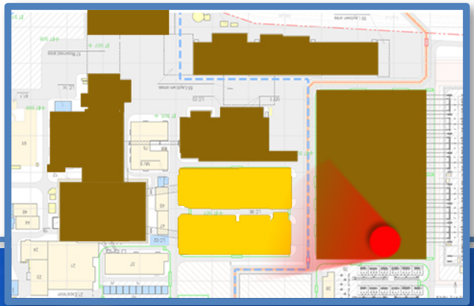
Cryoplant Building

Cryostat Workshop

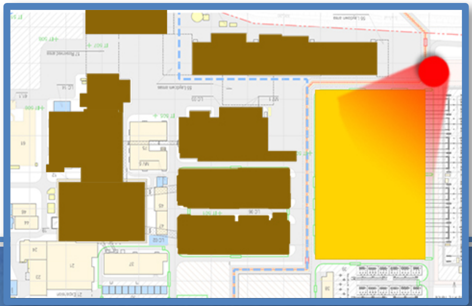


Cryostat Workshop

Magnet Power Conversion Buildings

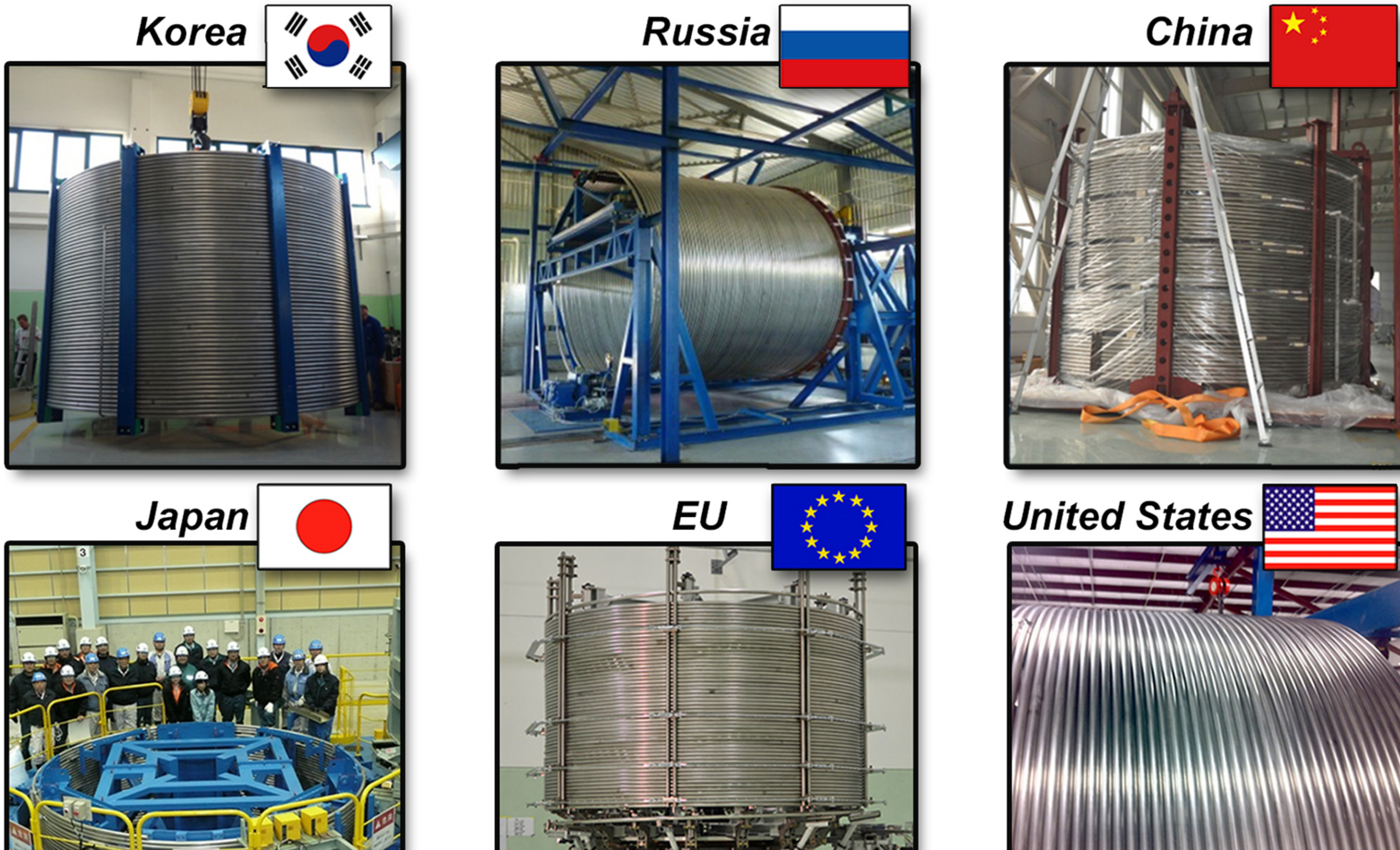


Switchyard



Hardware Progress in Domestic Agencies

Toroidal Field Conductor



All toroidal field conductor has been delivered

EU Progress

A poloidal segment of one vacuum vessel sector is fitted. Four segments, each weighing over 6 tonnes, form the full sector.
Photo: Walter Tosto

Production winding has begun for poloidal field #5. Photo: ITER Organization

Scope: Buildings, Vacuum Vessel, Magnet Systems, Power Systems, Heating & Current Drive Systems, Cryoplant, Divertor, Fuel Cycle, Blanket, Tritium Plant, Diagnostics, Radioactive Materials

Korea Progress

Port stub assembly for Sector 6 of the vacuum vessel.
Photo: ITER Korea

The first fully assembled, 800-tonne vacuum vessel sector sub-assembly tool (SSAT) has been test fitted and is ready to ship to the ITER site. The first batch of elements arrived in June.
Photo: ITER Korea

Scope: Vacuum Vessel, Thermal Shield, Magnet Systems, Assembly Tooling, Power Systems, Blanket, Tritium Plant, Diagnostics

India Progress

The lower cylinder of the cryostat is now being assembled in the Cryostat Workshop at the ITER site. Photo: ITER Organization

Thousands of in-wall shielding plates have been fabricated at Avasarala Technologies Ltd. in Bengaluru, Karnataka. Deliveries to Korea began in 2015. Photo: ITER India

Scope: Vacuum Vessel, Cryostat, Cryogenic Systems, Heating and Current Drive Systems, Cooling Water System, Diagnostics

Russian Federation Progress

This port stub extension component has successfully passed pressure and helium leak tests in accordance with French regulations on pressure equipment (ESPN). Photo: ITER Russia

At the Efremov Institute in Saint Petersburg, equipment for ITER's switching network and fast discharge units has been fabricated and over 70 tonnes of material, including aluminum busbars and busbar components, was shipped in December. Photo: ITER Russia

Scope: Vacuum Vessel, Magnet Systems, Power Systems, Blanket, Divertor, Diagnostics, Heating & Current Drive Systems

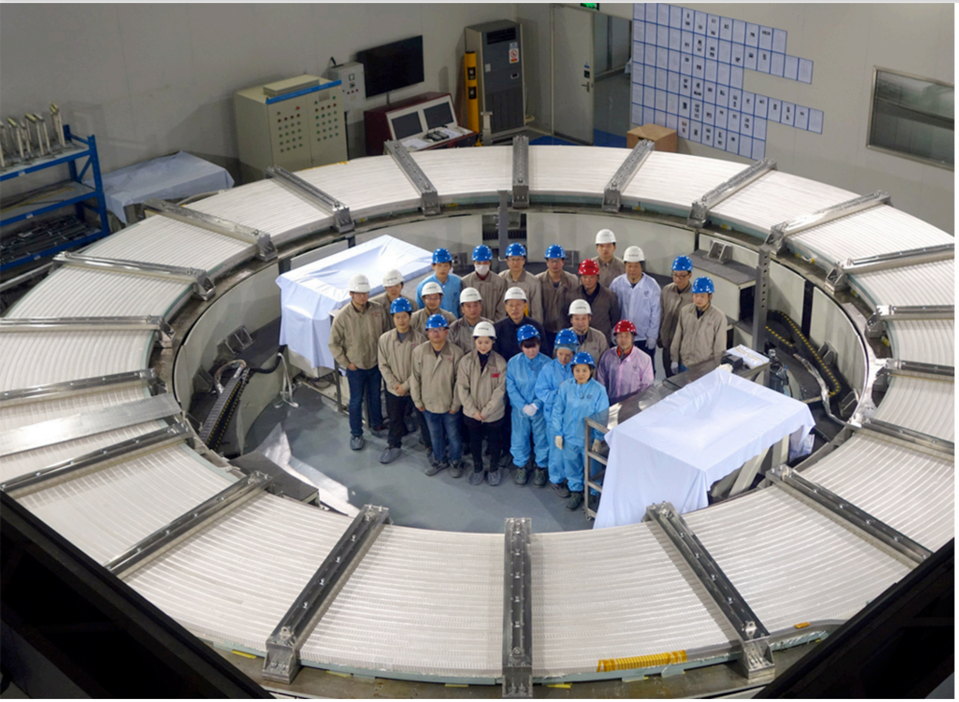
Japan Progress

Japan completed its first toroidal field winding pack in January. Photo: ITER Japan

The 1 MV bushing at Hitachi for the full-scale ITER neutral beam injector. The bushing has since been delivered to the PRIMA neutral beam test facility in Italy for the MITICA (Megavolt ITER Injector and Concept Advancement) test bed. Photo: ITER Japan

Scope: Magnet Systems, Heating & Current Drive Systems, Remote Handling, Divertor, Tritium Plant, Diagnostics

China Progress



Qualification activities for ITER's smallest poloidal field magnet (PF6) are underway at ASIPP in Hefei, China. A dummy double pancake winding was completed in January 2017 and successfully passed a manufacturing readiness review. Photo: ITER China

A prototype side correction coil (SCC) at ASIPP is made of eight layers of niobium-titanium superconductor. Photo: ITER China

Scope: Magnet Systems, Power Systems, Blanket, Fuel Cycle, Diagnostics

ITER Management Turnaround

2015-2017 Timeline

March 2015: Director General Bernard Bigot appointed and action plan approved by ITER Council.

November 2015: Resource-loaded "Overall Project Schedule to 1st Plasma" presented to ITER Council, including 29 milestones for 2016-2017.

April 2016: Independent ITER Council Review Group finds that sequence and duration of resource-loaded schedule are logical, and inventory and integration of schedule activities are complete.

June 2016: Construction-Management-as- Agent contract signed with MOMENTUM joint venture, to manage and coordinate assembly and installation of Tokamak and associated plant systems.

November 2016: ITER Council approves* Overall Project Schedule through 1st Plasma in 2025 and onward to start of Deuterium-Tritium (DT) operation.

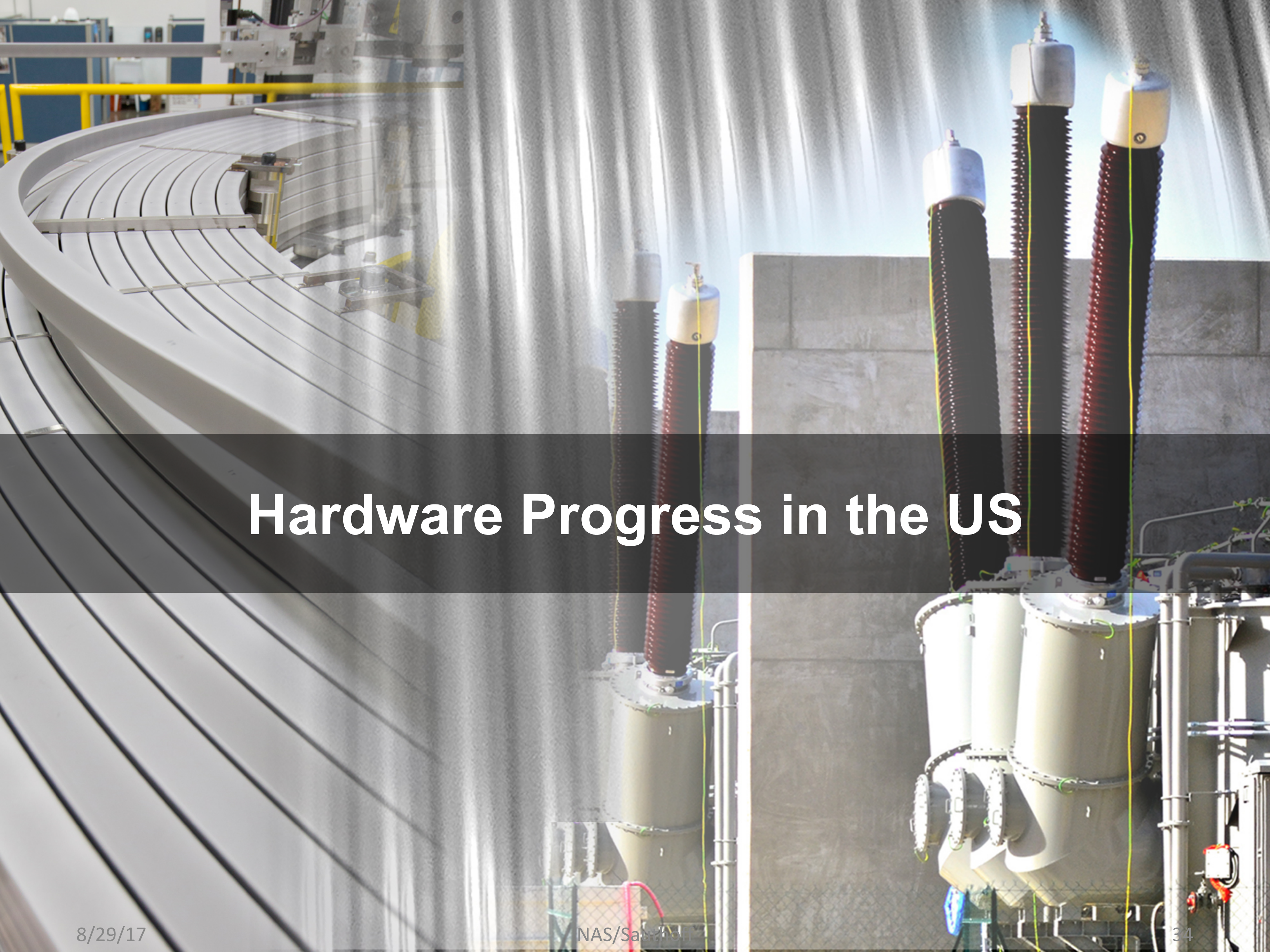
*Subject to Members' internal approval processes.

ITER Management has been Significantly Improved

- **Project decision-making more effective**
  - Executive Project Board
- **Risk/issue management upgraded, and mitigation actions taken**
  - Vacuum Vessel segments transferred from EU to IO to Hyundai Heavy Industry
  - Building services installation scope transfer from EU to IO…
- **Systems engineering and configuration management improved**
  - Central integration and systems engineering: systems, training and utilization
  - Interface resolution and control
- **Project controls upgraded**
  - Greatly improved project management and team-building/ training
  - Milestones established and achieved

All 25 IC Milestones Due by the End of Q2 2017 Achieved

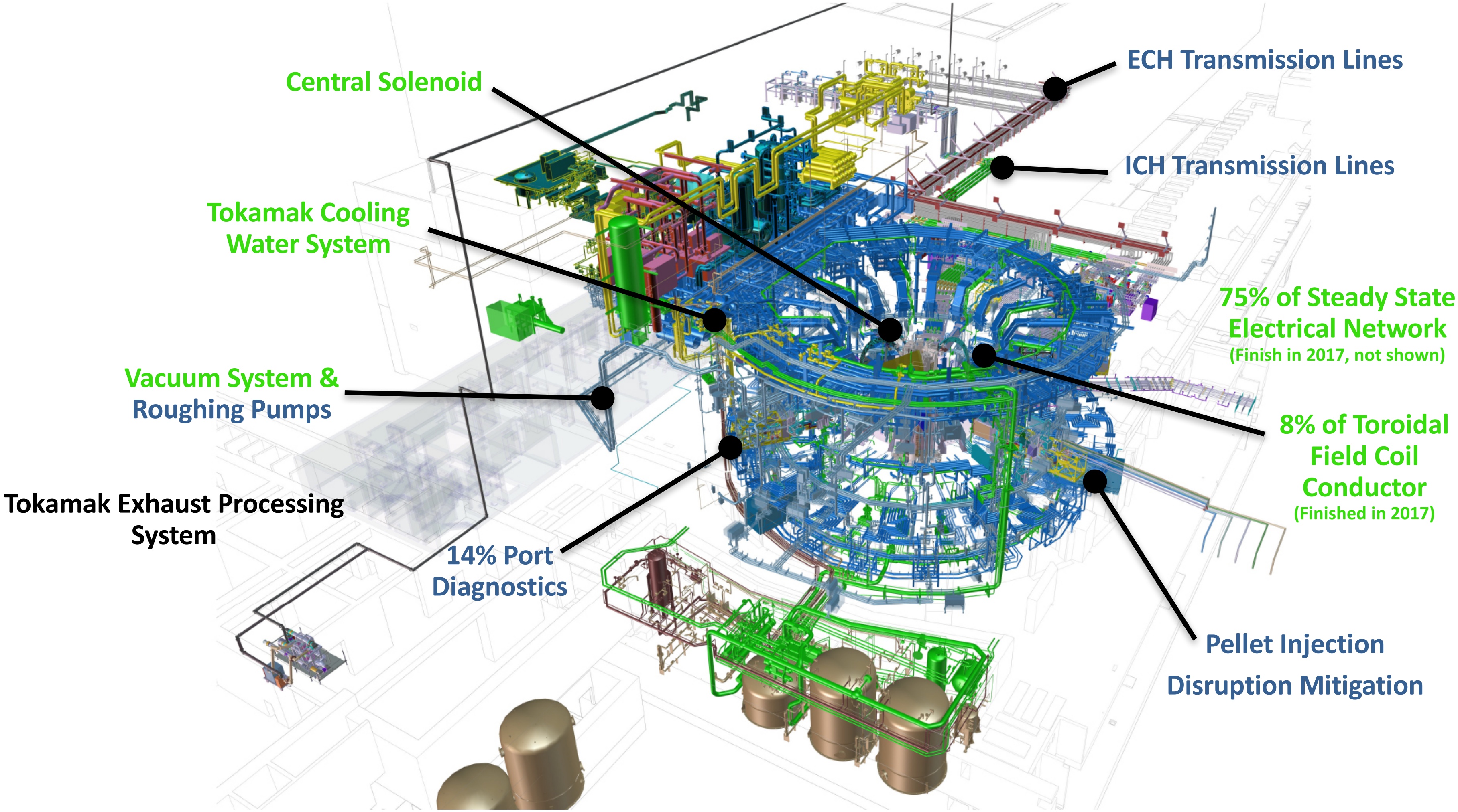
2016Q1: Tier-1 Cryostat Base Section Delivered	2016Q3: CMA Contract Signed
2016Q1: B1 Civil Works Started in Tokamak Bldg.	2016Q3: 4th US TF Conductor Unit Length Completed
2016Q1: Lot-1 Piping Delivered	2016Q3: IC-Agreed Staffing Positions Recruited
2016Q1: IC Independent Reviews Initiated	2016Q4: 1st Vacuum Vessel Sub-segment Completed
2016Q2: Assembly Hall Main Cranes Erected	2016Q4: 1st LN2 Refrigerator FAT Completed
2016Q2: 1st EU TF Winding Pack Completed	2016Q4: SSEN Power Transformers Delivered
2016Q2: TF Conductor Fabrication from RF, CN and JA Completed	2016Q4: LHe Plant Equipment FAT Completed
2016Q2: PF5/2 Conductor Fabrication Completed	2016Q4: VAS Flanges Ready to Ship
2016Q2: Divertor OVT Unit Test Completed	2017Q1: 1st JA TF Winding Pack Completed
2016Q2: WDS Tanks Installed in Tritium Bldg.	2017Q1: 400 kV Switchyard Energized
2016Q2: CS Module 1 Winding Completed	2017Q2: Start of Work Cryoplant Compressor Bldg. 51
2016Q2: 1st Independent Review Report Completed	2017Q2: Completion of RFE 1A (Assembly Hall)
	2017Q2: Receiving Inspection of Sector Sub-Assembly Tool (SSAT)



Hardware Progress in the US

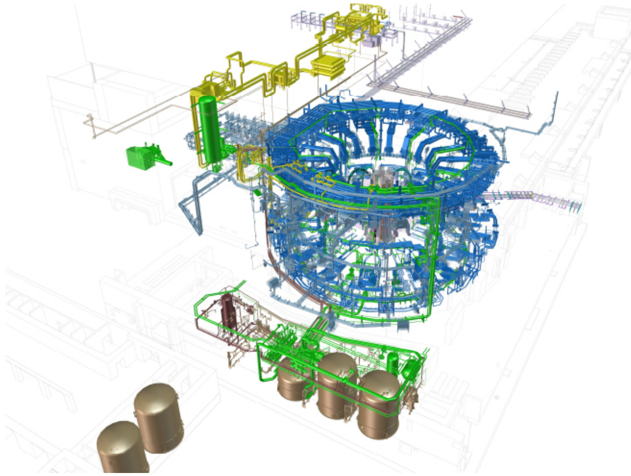
US ITER Hardware Scope

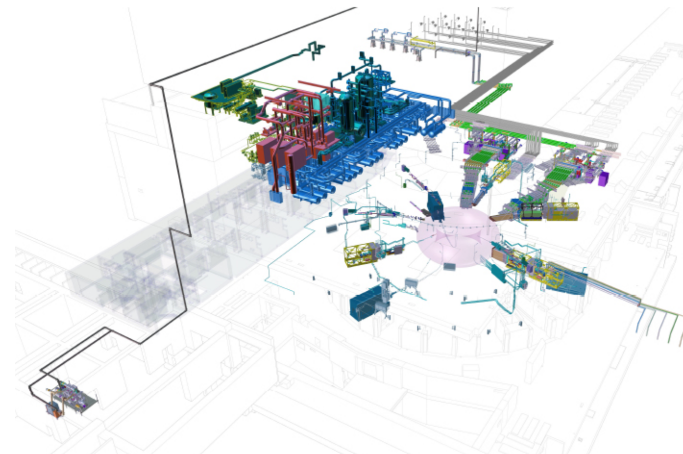
Full Scope



Key: Hardware in fabrication • Prototypes in fabrication • In design

ITER Project has Defined First-Plasma and Post-First-Plasma Hardware





US First Plasma SP-1

US Post-First Plasma SP-2

R&D and Design

Completion for All Hardware

Full Fabrication

- Central Solenoid (in fabrication)
- Toroidal Field Conductor (completed in FY17)
- Steady State Electrical Network (to be completed in FY17)

Partial Fabrication

- Tokamak Cooling Water System (some delivered)
- Roughing Pumps
- Vacuum Auxiliary System (some delivered)
- Pellet Injection
- Ion Cyclotron Heating
- Electron Cyclotron Heating
- Diagnostics
- Instrumentation & Controls

Completion of Fabrication

Full Fabrication

- Tokamak Exhaust Processing
- Disruption Mitigation

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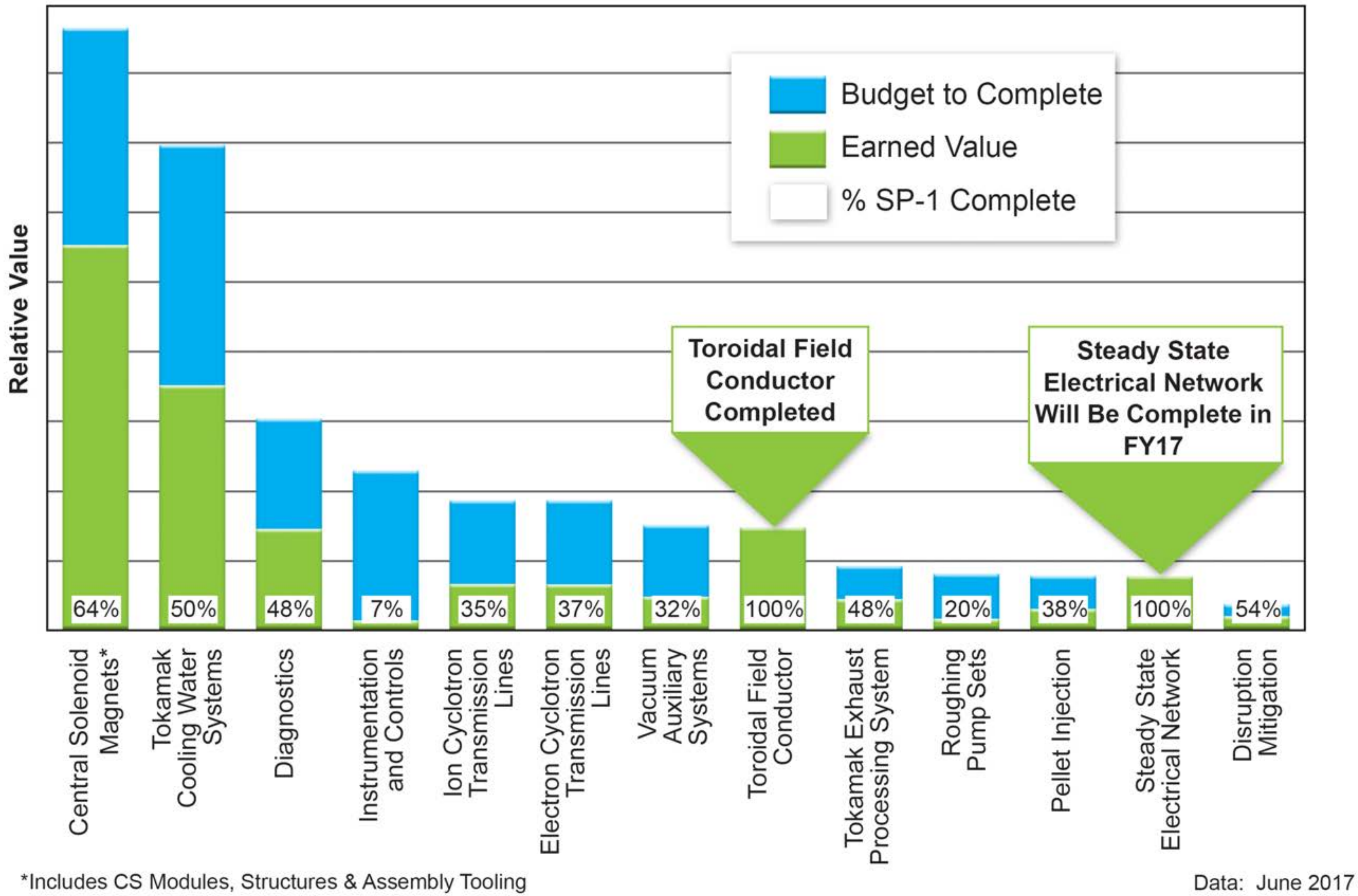
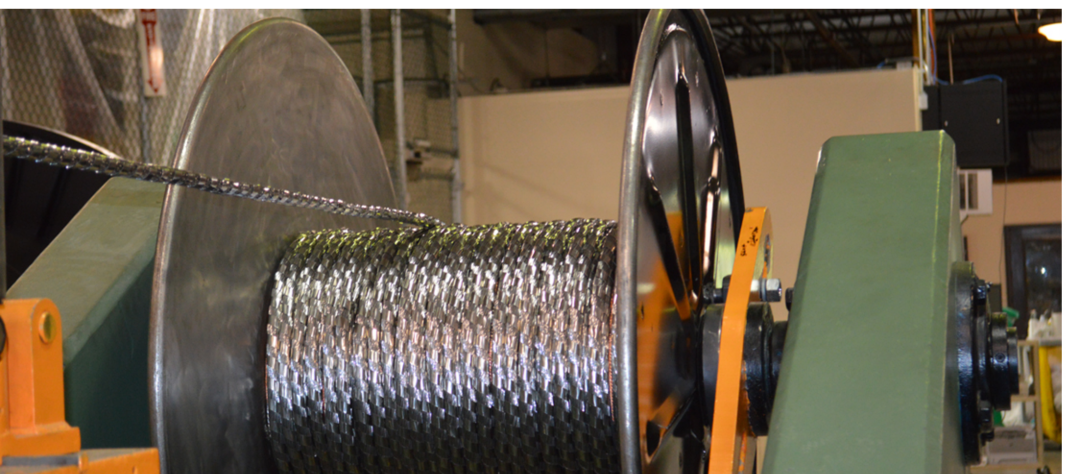
US SP-1 Systems by Value



US Hardware

Toroidal Field Conductor Completed

Strand was produced by Luvata Waterbury, Inc. in Waterbury, CT (above) and Oxford Superconducting Technologies in Carteret, NJ.



Cabling of the strand was performed by New England Wire Technologies in Lisbon, NH.

The conductor was jacketed and integrated at High Performance Magnetics in Tallahassee, FL and Criotec in Chivasso, Italy (above).

US Hardware

Steady State Electrical Network Nearly Complete (will finish in FY17)

The final shipments of power transformers were delivered in December 2016.

The first lots of reactive power compensators were shipped in April 2017; the remainder will be shipped by September.

Reactive power compensators in final assembly testing before shipment.

HV transformers were delivered and installed on site in 2015.

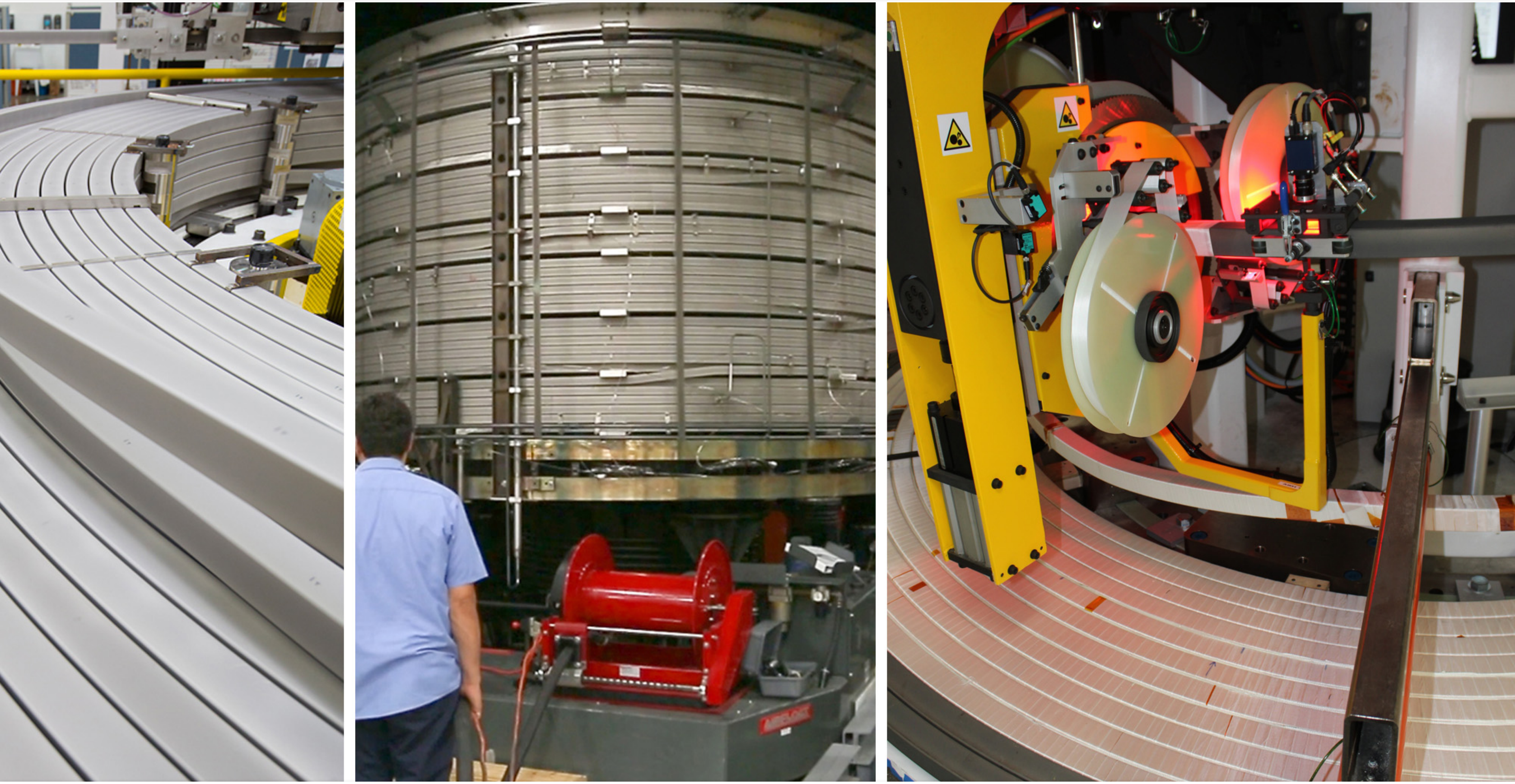
US Hardware

Central Solenoid Module Fabrication Progressing

General Atomics developed a 64,000 ft^2 Magnet Technologies Production facility with 10 work stations

US Hardware

Central Solenoid Module Fabrication Progressing



Left: Winding of Modules #1 and #2 is complete; #3 is underway. Middle: Heat treatment of the Module #1 is complete.
Right: Module #1 is now in the turn insulation station. Photos: GA

US Hardware

Tokamak Cooling Water System

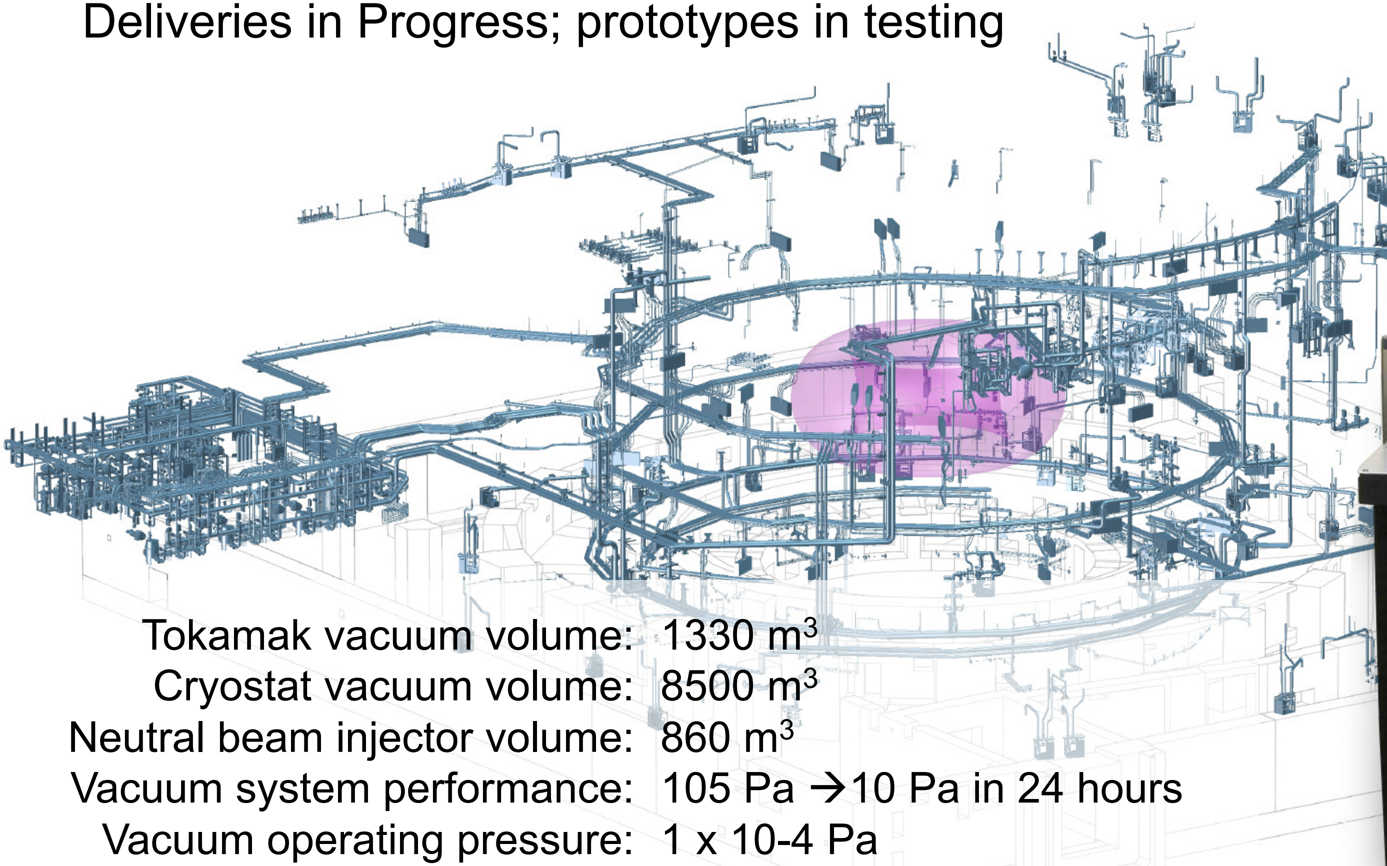
Initial deliveries complete; piping fabrication underway
Final Design Review for First Plasma hardware planned for November 2017

Drain tanks fabricated in the US were the first nuclear-certified components delivered to the ITER site (September 2015).

Pipe fabrication is underway at the Schulz Xtruded Products facility in Robinsonville, MS.

US Hardware
Vacuum Auxiliary System

Deliveries in Progress; prototypes in testing



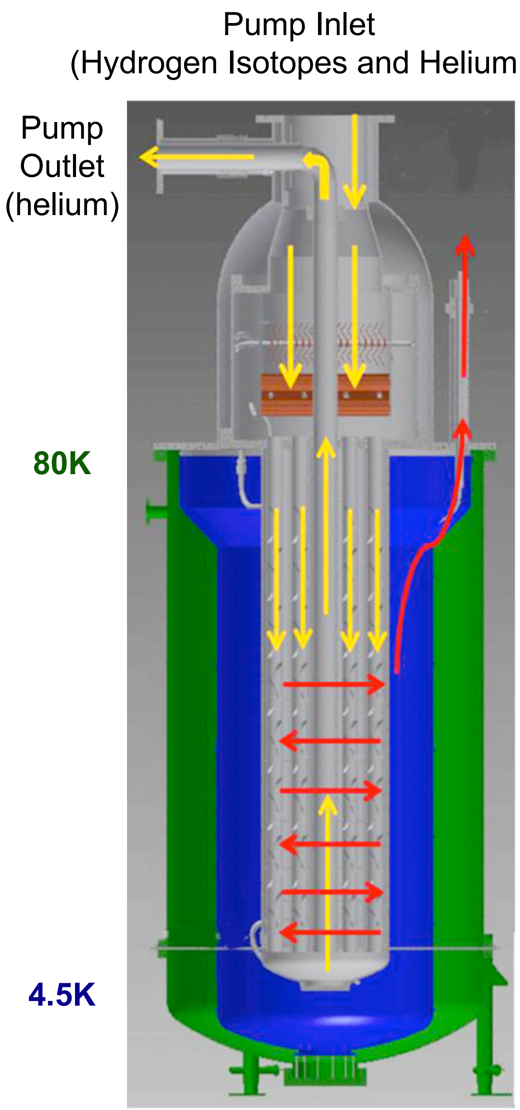
Tokamak vacuum volume:	1330 m^3
Cryostat vacuum volume:	8500 m^3
Neutral beam injector volume:	860 m^3
Vacuum system performance:	105 Pa → 10 Pa in 24 hours
Vacuum operating pressure:	1 x 10-4 Pa
Roughing pumps:	400+ vacuum pumps (10 different technologies)
Service vacuum system:	>1500 clients
Vacuum piping:	6 km

Hydrogen Isotope
Selective Pumping Unit (HISPU)

US Hardware

Vacuum Roughing Pumps

- Novel second stage pumps regenerated hydrogen isotopes fuel and helium from first stage cryo-sorbtion pumps.
- Hydrogen isotopes pumped by cryo-condensation and helium pumped by the flow of hydrogen isotopes and mechanical pumps
- Separates fuel and helium created in the fusion process.



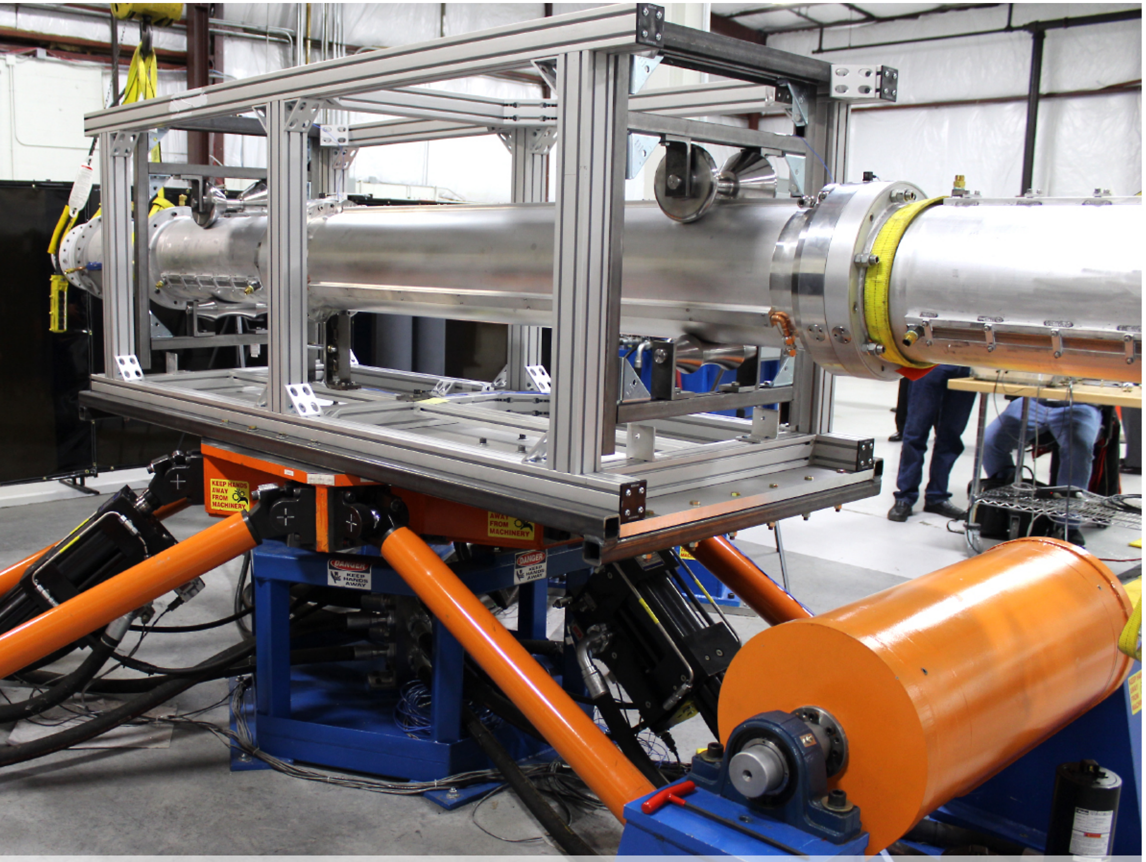
The full-sized cryoviscous compressor prototype was tested at ORNL's Spallation Neutron Source Cryogenic Facility before shipment to ITER for further testing.

US Hardware

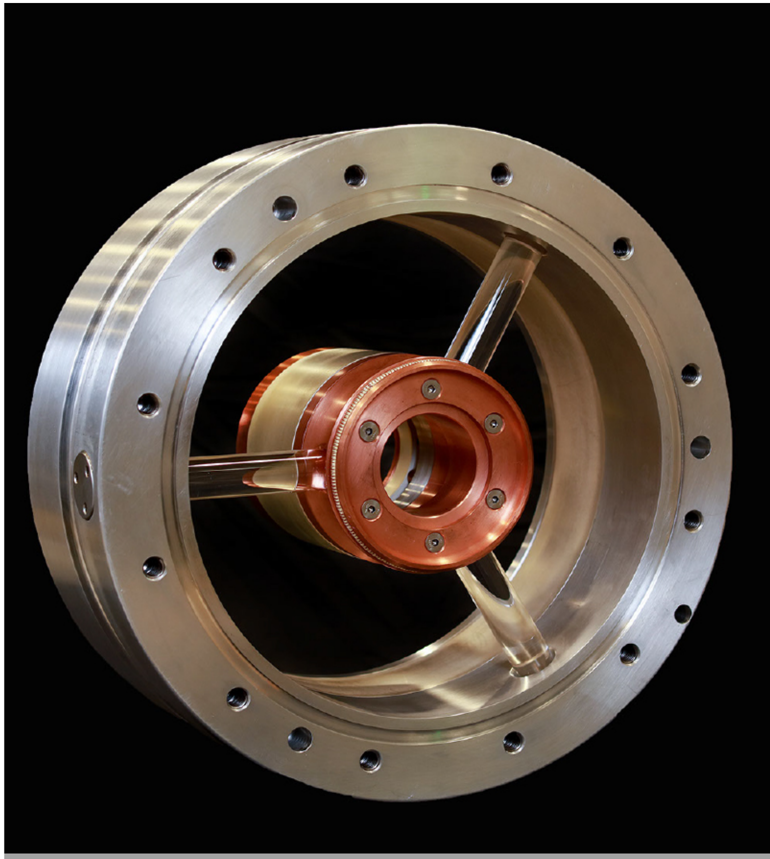
Ion Cyclotron Transmission Lines

Prototypes in fabrication and testing; production unit fabrication started

- 20 megawatts total power transfer to the plasma
- Up to 6 megawatts per line



Tri-axial vibrational test stand



Insulator flange with 3-spoke quartz pin supports

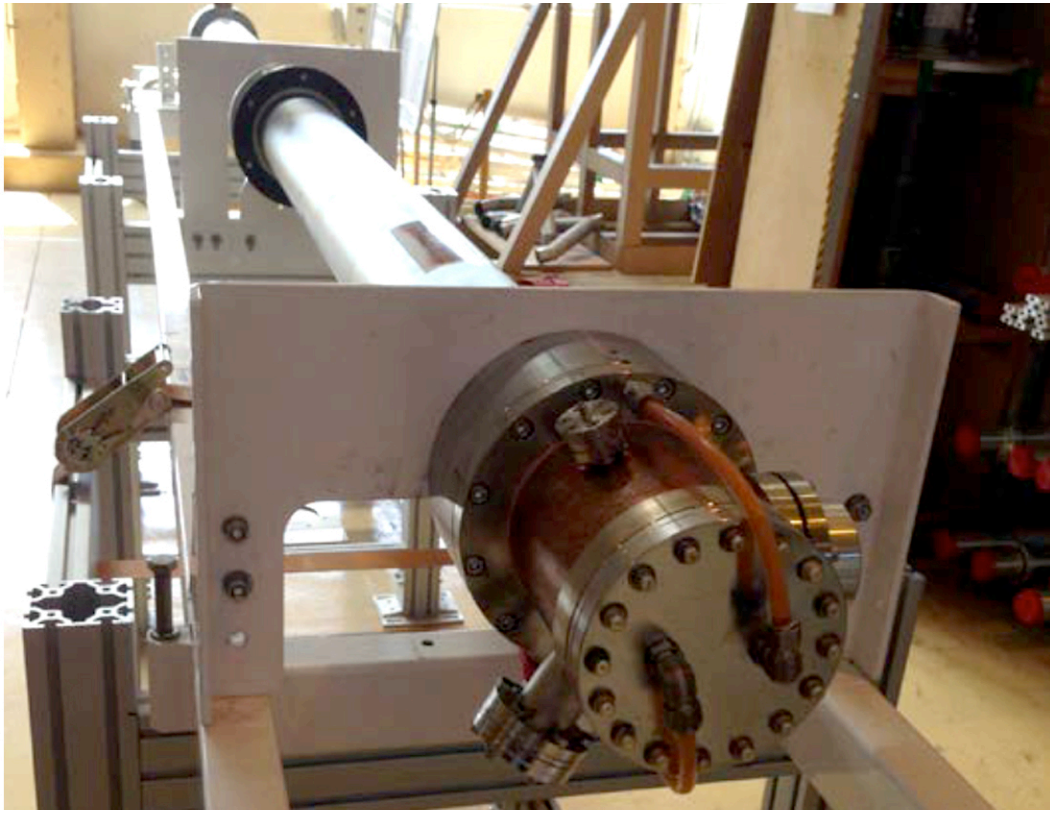
US Hardware

Electron Cyclotron Transmission Lines

Prototypes in fabrication and testing; contracts for manufacturing processes awarded

- 20 megawatt total power transfer to the plasma
- 1.2 megawatts per line

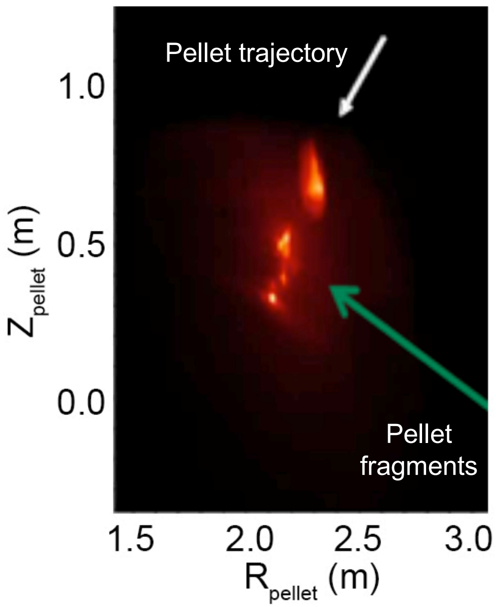
A laser-based wave guide inspection system was developed



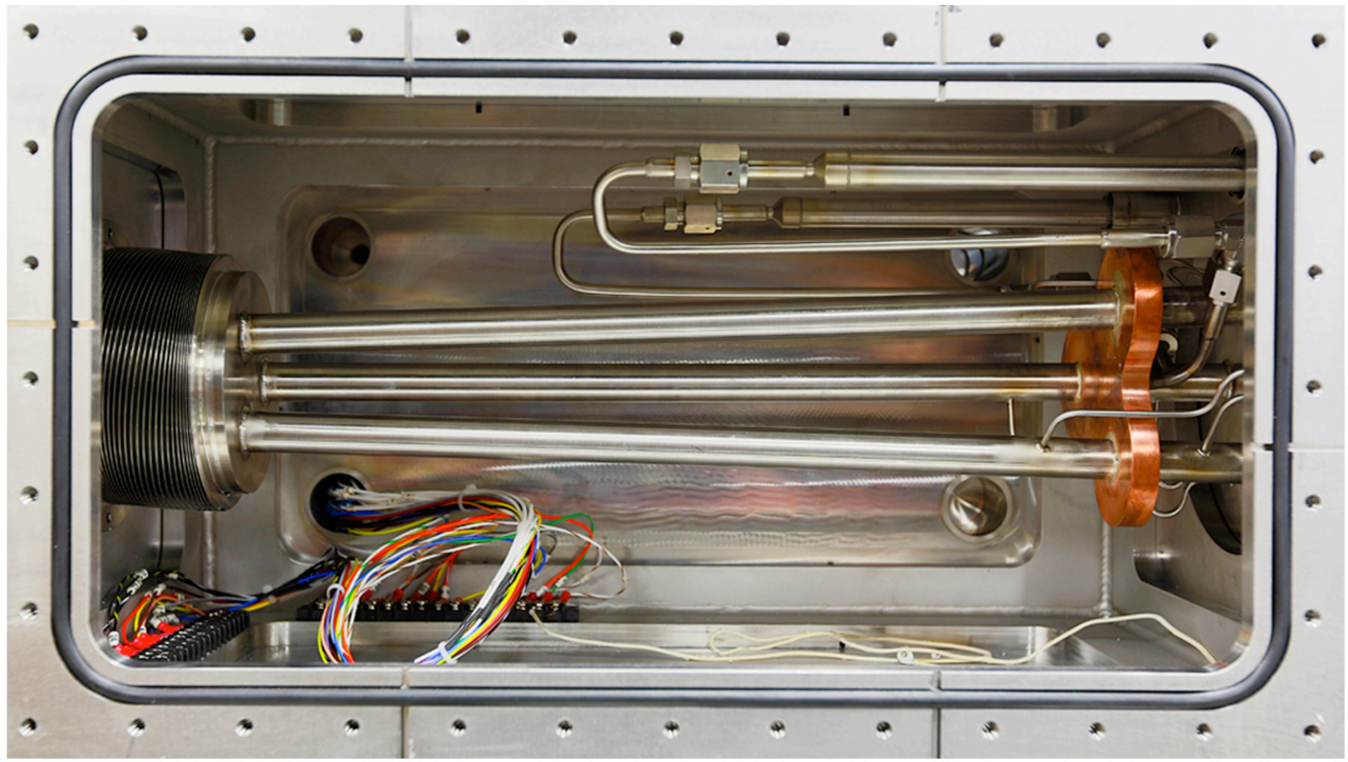
1.5 MW power load test stand

Pellet Injection and Disruption Mitigation Systems

- Prototypes are in fabrication and testing; testing on current tokamaks continues
- Cryogenic pellet plasma fueling in development to perform at 300 m/s at 16 Hz



A shattered 7 mm neon pellet in DIII-D tokamak plasma

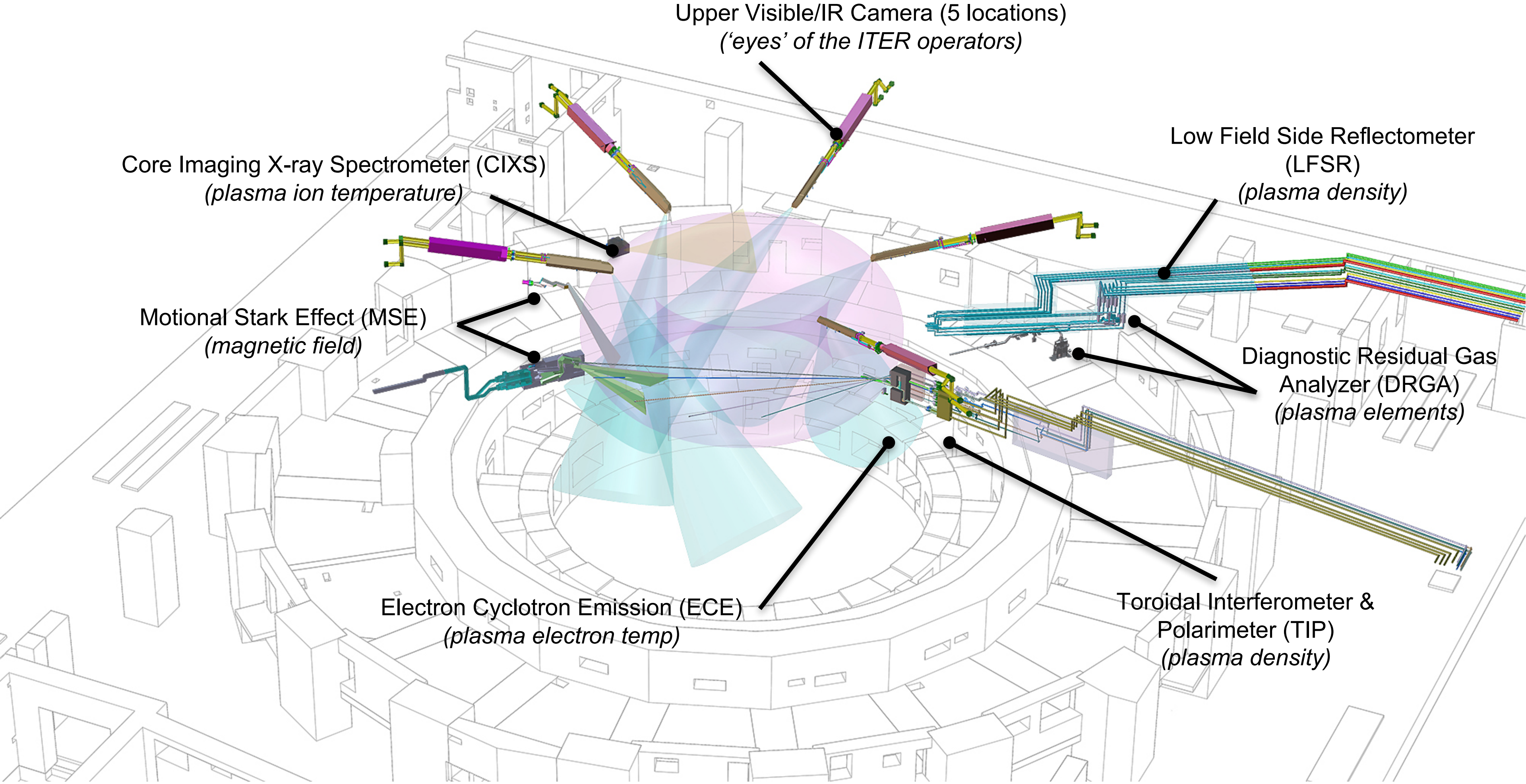


A three-barrel prototype for shattered pellet injection (SPI). SPI components will be installed on JET for further testing.

US Hardware

Diagnostics

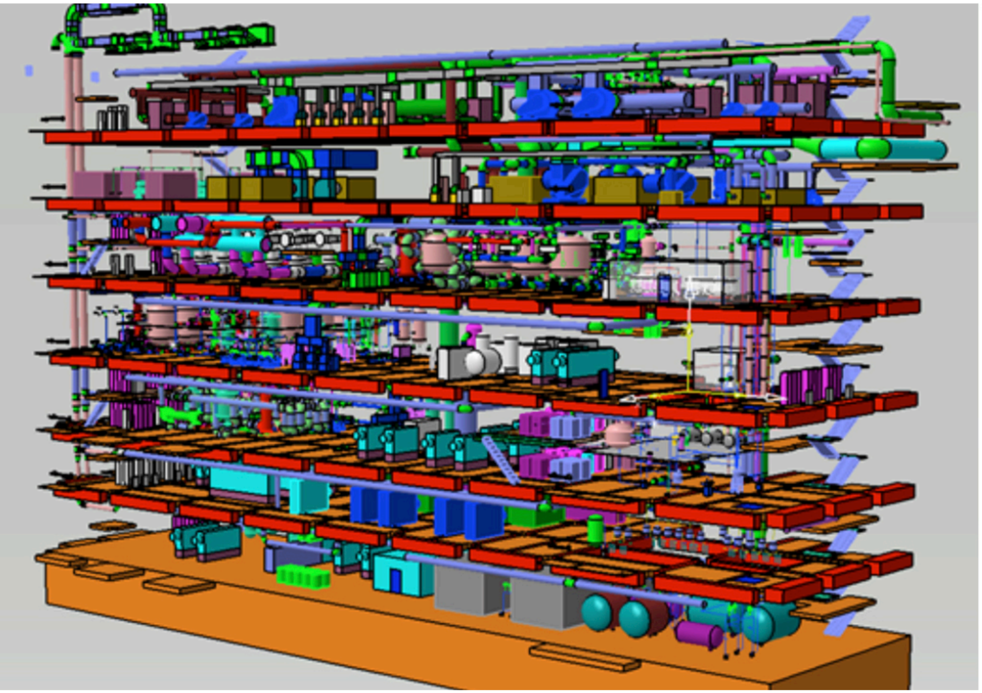
State of the art distributed plasma diagnostics are in design, with prototypes in fabrication and testing



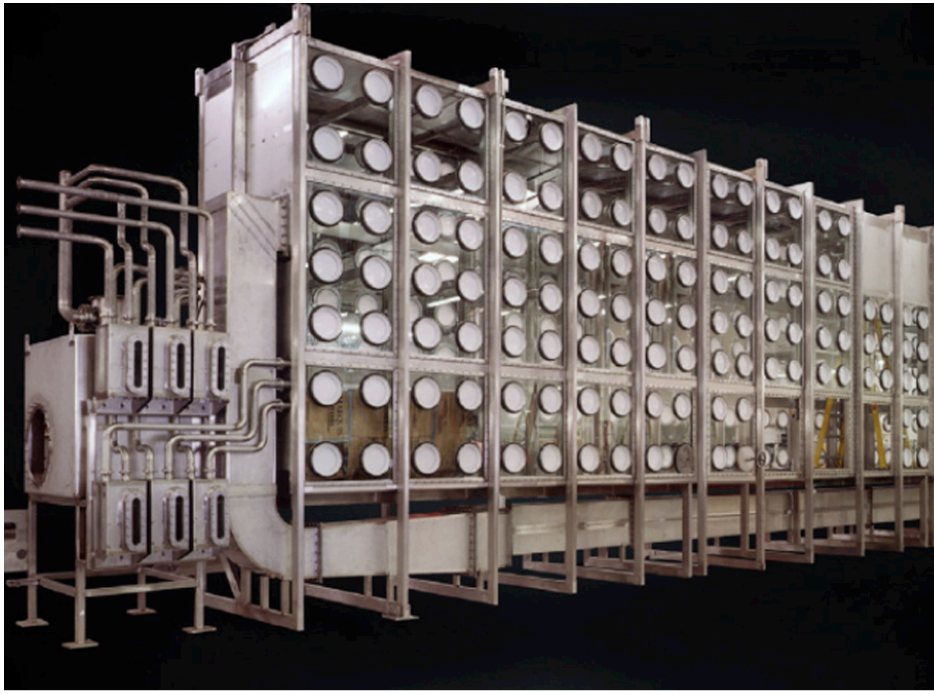
Tokamak Exhaust Processing

Design activities continue

- High-throughput (240 Pa*m^3/sec) tritium processing system is in design.
- Palladium membrane separates hydrogen isotopes from methane-steam reforming reaction



High density of equipment in Tritium Building



Typical glovebox

U.S. Project Management

Assessment of US Performance

June 2014, GAO:

- *US ITER Project's schedule "fully reflects the characteristics of high-quality, reliable schedule estimates"*
- *US ITER's cost estimate "substantially met best practices for comprehensive, well documented, and accurate estimates"*

April 2015, DOE audit of US ITER QA Program:

- *"…. Rigorous process controls for integration of quality principles in all aspects of procurement, design, fabrication and inspection/acceptance testing"*

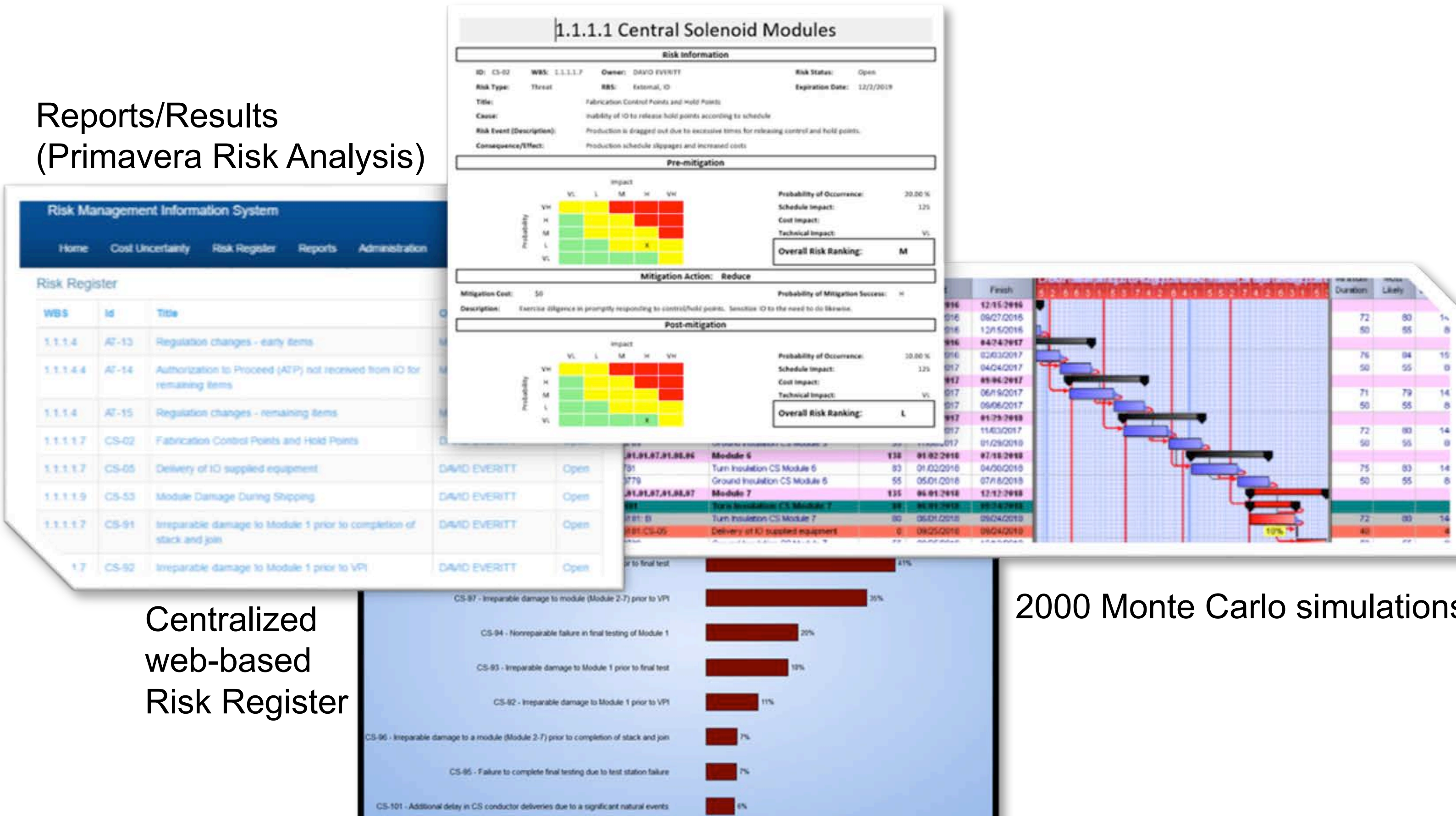
April 2015, DOE Office of Project Assessment

- *"capable management team, and the processes and tools are in place to deliver on the near-term scope"*

Robust Risk Management System Utilized Since 2006

June 2013, DOE Independent External Review Committee:
“The review team found that the US ITER project has developed a relevant and comprehensive risk analysis with a state-of-the-practice process for developing contingency as well as a reasonable and comprehensive approach to risk identification."

Reports/Results
(Primavera Risk Analysis)



Centralized web-based Risk Register

2000 Monte Carlo simulations

DOE Deputy Secretary Approved First Plasma Performance Baseline and Total Project Range on January 13, 2017

DOE-approved Package (Jan 2017)

First Plasma Project Baseline (CD-2/3):

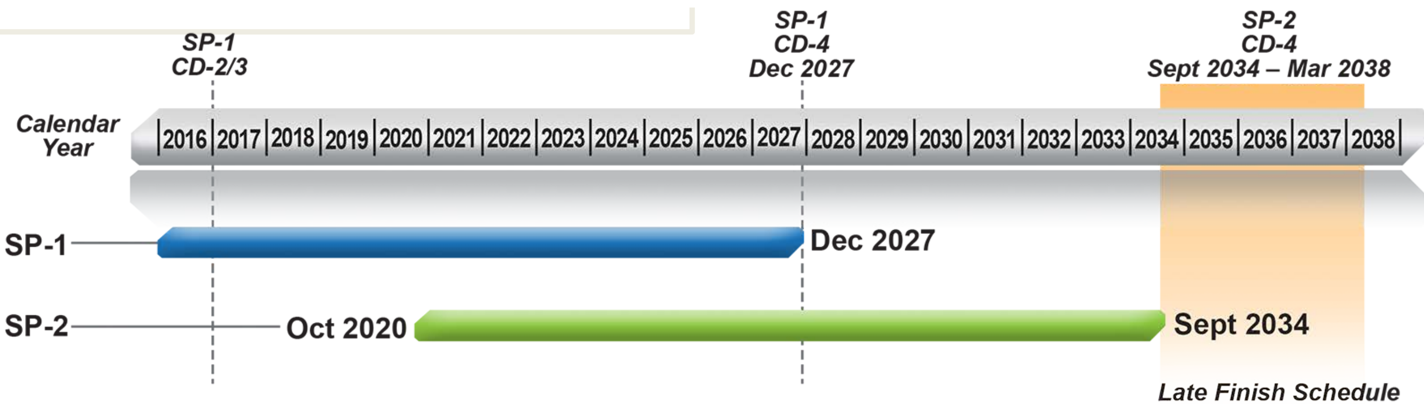
- Total project cost (TPC): $2.5B
- CD-4: December 2027

Total US ITER Project Range (CD-1R):

- Cost range: $4.7B−$6.5B
- CD-4: 2034−2038

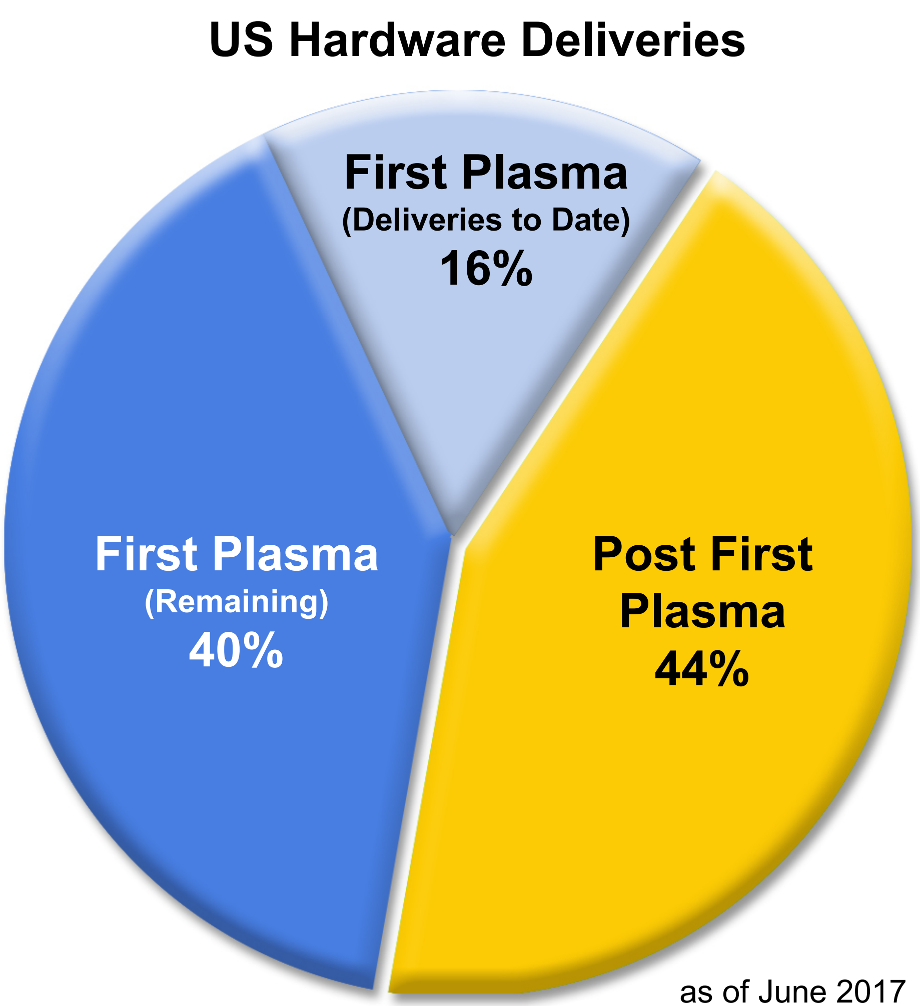
driven by budgetary constraints—not technical

September 2034 – March 2038



16% of All US Hardware Has Been Delivered

- Deliveries by the US of early-need hardware began in 2013
- Deliveries have continued on-pace with the evolving international schedule



Project Engagements and Impacts

Industries are Engaged

Industry	Area of Contribution
General Atomics, San Diego, CA	Central Solenoid modules
AREVA Federal Services, LLC, Charlotte, NC	Tokamak Cooling Water System design and drain tank fabrication
Luvata Waterbury, Inc., Waterbury, CT	Toroidal Field conductor strand
Precision Custom Components, York, PA	Central Solenoid lower structures and tie plates
Transproject, Houston, TX	Shipping
Oxford Superconducting Technology, Carteret, NJ	Toroidal Field conductor strand
High Performance Magnetics, Tallahassee, FL	Toroidal Field conductor integration/jacketing
Schneider Electric, Palatine, IL	Steady State Electrical Network components
Robatel Technologies, Roanoke, VA	Central Solenoid assembly tooling
Petersen, Inc., Ogden, UT	Central Solenoid structures
Superbolt, Carnegie, PA	Central Solenoid tensioning components
Hyundai Corporation, Houston, TX	Steady State Electrical Network HV transformers
New England Wire Technologies, Lisbon, NH	Toroidal Field cabling
Robatel Technologies LLC, Roanoke, VA	Central Solenoid assembly tooling
Hamill Manufacturing, Traford, PA	Central Solenoid upper structures
Major Tool & Machine, Inc., Indianapolis, IN	Central Solenoid structure R&D
Mega Industries, LLC, Gorham, ME	Ion Cyclotron heating
Dielectric Communications, Raymond, ME	Ion Cyclotron heating
Siemen's Industry, Inc., Wendall, NC	Steady State Electrical Network control & protection
Eaton Corporation, Cleveland, OH	Steady State Electrical Network switchgear
G&G Steel, Russellville, AL	Central Solenoid structure tie plate prototype
ABB, Raleigh NC	Steady State Electrical Network transformers

Universities are Engaged

University	Area of Contribution
Columbia University	Project support
Florida State University	Analysis for toroidal field strand and conductor, central solenoid conductor and tie plates
Indiana University	Core imaging x-ray spectrometer R&D
Massachusetts Institute of Technology	Electron cyclotron R&D, central solenoid analysis, quench detection
University of California Los Angeles	Computational fluids dynamic analysis, ITER team training
University of California San Diego	Magnet design review support
University of Michigan	ITER stainless steel
University of Tennessee	ITER stainless steel, central solenoid and toroidal field conductor R&D, central solenoid module R&D, radiation modeling
University of Texas at Austin	Electron cyclotron emission diagnostic R&D
University of Wisconsin at Madison	Global neutronics
Washington State University	Pellet injector experimental support

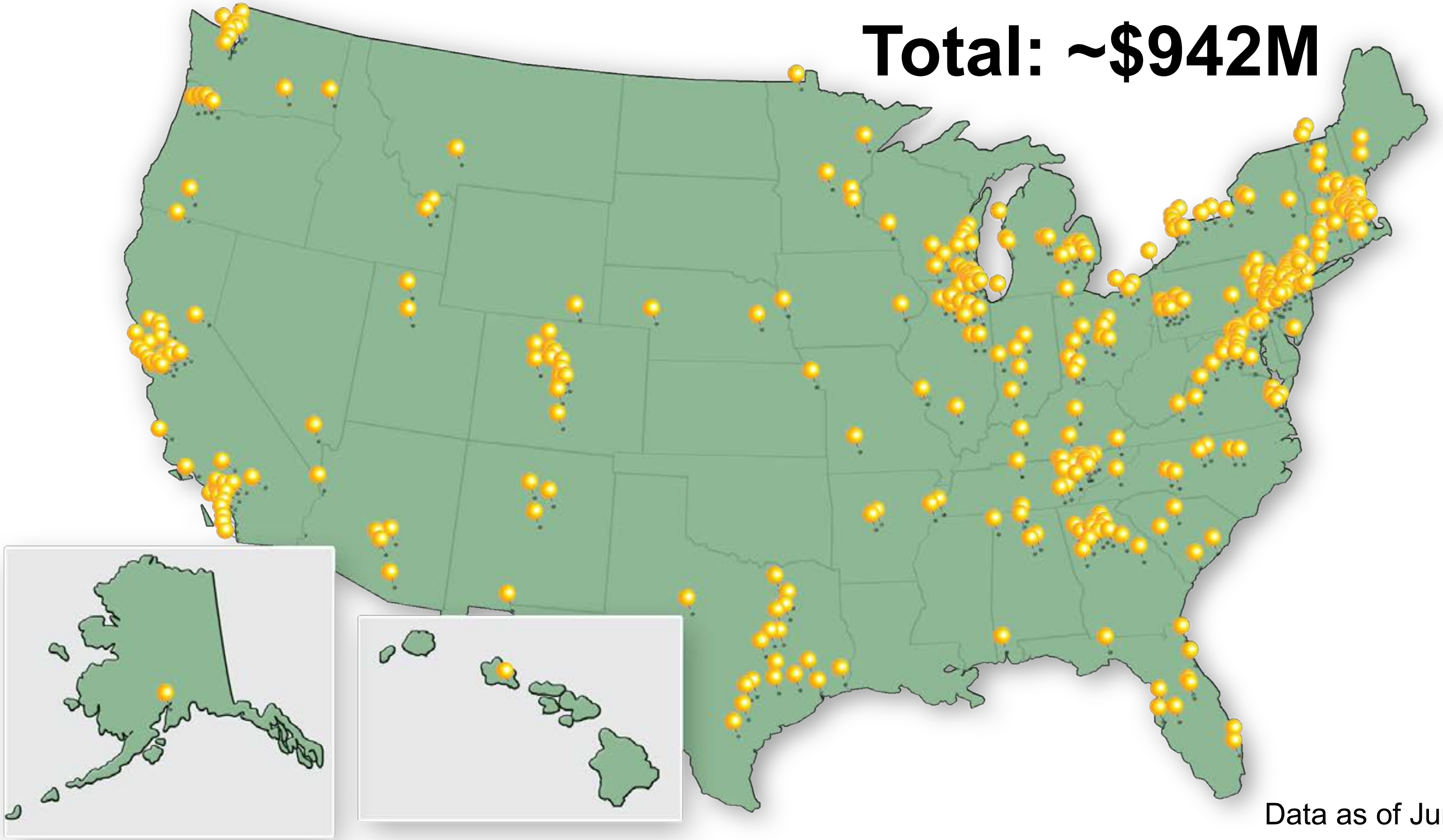
National Laboratories are Engaged

National Laboratory	Area of Contribution
Oak Ridge National Laboratory	Overall U.S. project management, systems engineering, fuel pellet injection technology, and high-performance computing for theoretical models
Princeton Plasma Physics Laboratory	Advanced microwave, laser, x-ray and optical diagnostic instruments, and theoretical models
Savannah River National Laboratory	Exhaust gas processing and tritium recovery
Argonne National Laboratory	Neutronics analysis
Fermi National Accelerator Laboratory	Solenoid cold testing and toroidal field strand testing
Idaho National Laboratory	Beryllium dust characteristics, codes and standards
Lawrence Berkeley National Laboratory	Solenoid support structure design
Lawrence Livermore National Laboratory	Magnet systems design and analysis
Los Alamos National Laboratory	Tritium plant R&D and massive gas injection
Sandia National Laboratory	Blanket and shield R&D and design

Over 80% of Awards and Obligations Remain in the US

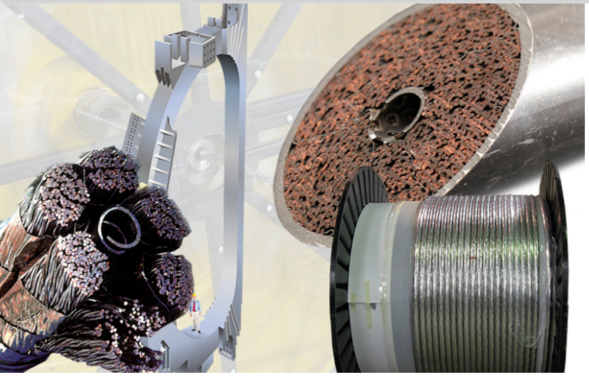
600+ contracts awarded to US industry and universities, and obligated to DOE national laboratories in 44 states

500+ direct jobs and 1100+ indirect jobs created or maintained per year.

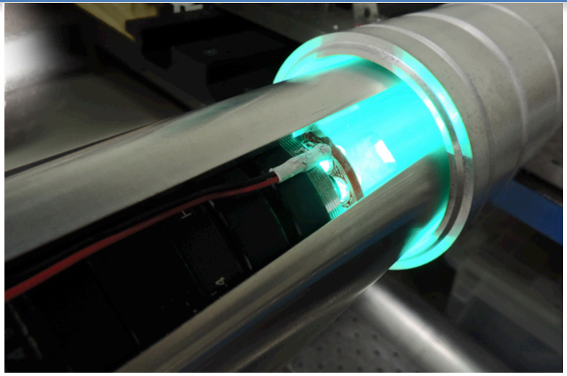


Data as of June 30, 2017

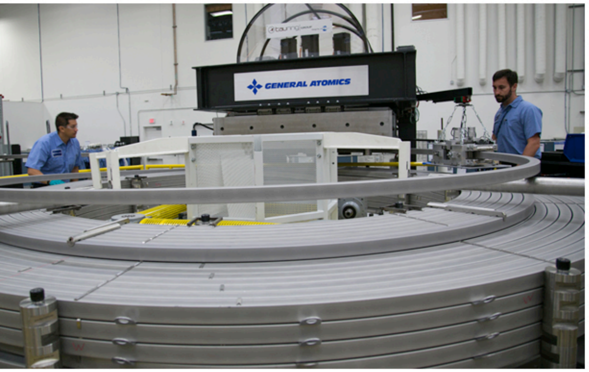
ITER Technologies Advance Domestic Capabilities and Capacities



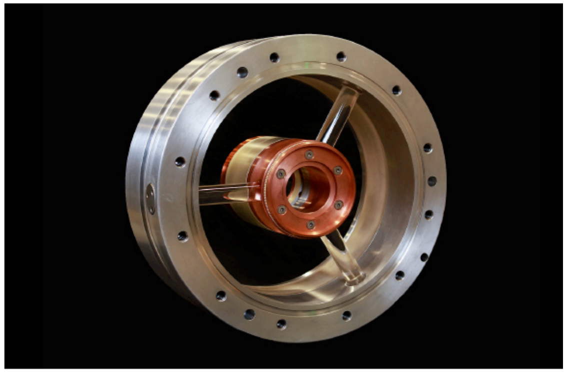
High Power Superconducting Cable-in-Conduit
7 kV @ 68kA



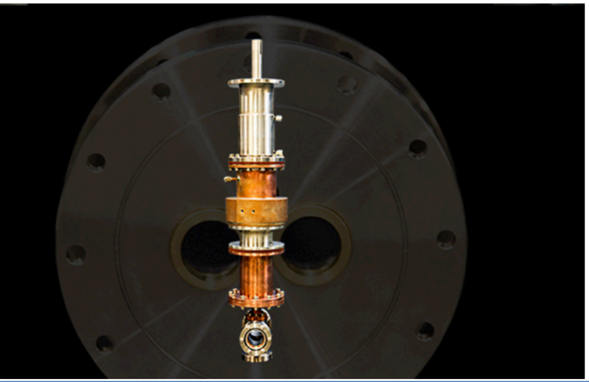
High Power, High Purity Microwave Power Transmission
20 MW transfer capacity,
1.2 MW/line
> 90% mode purity



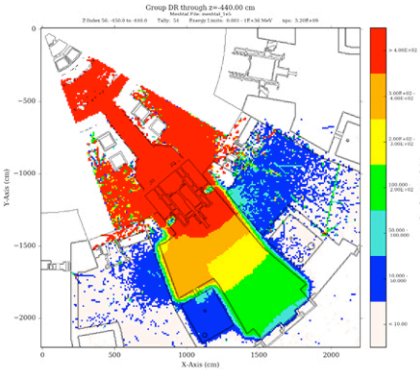
High Field, High Storage Superconducting Magnets
5.5 GJ storage capacity
13.1 T field



High Power, Low Loss Radiofrequency Power Transmission
20 MW transfer capacity,
6 MW/line

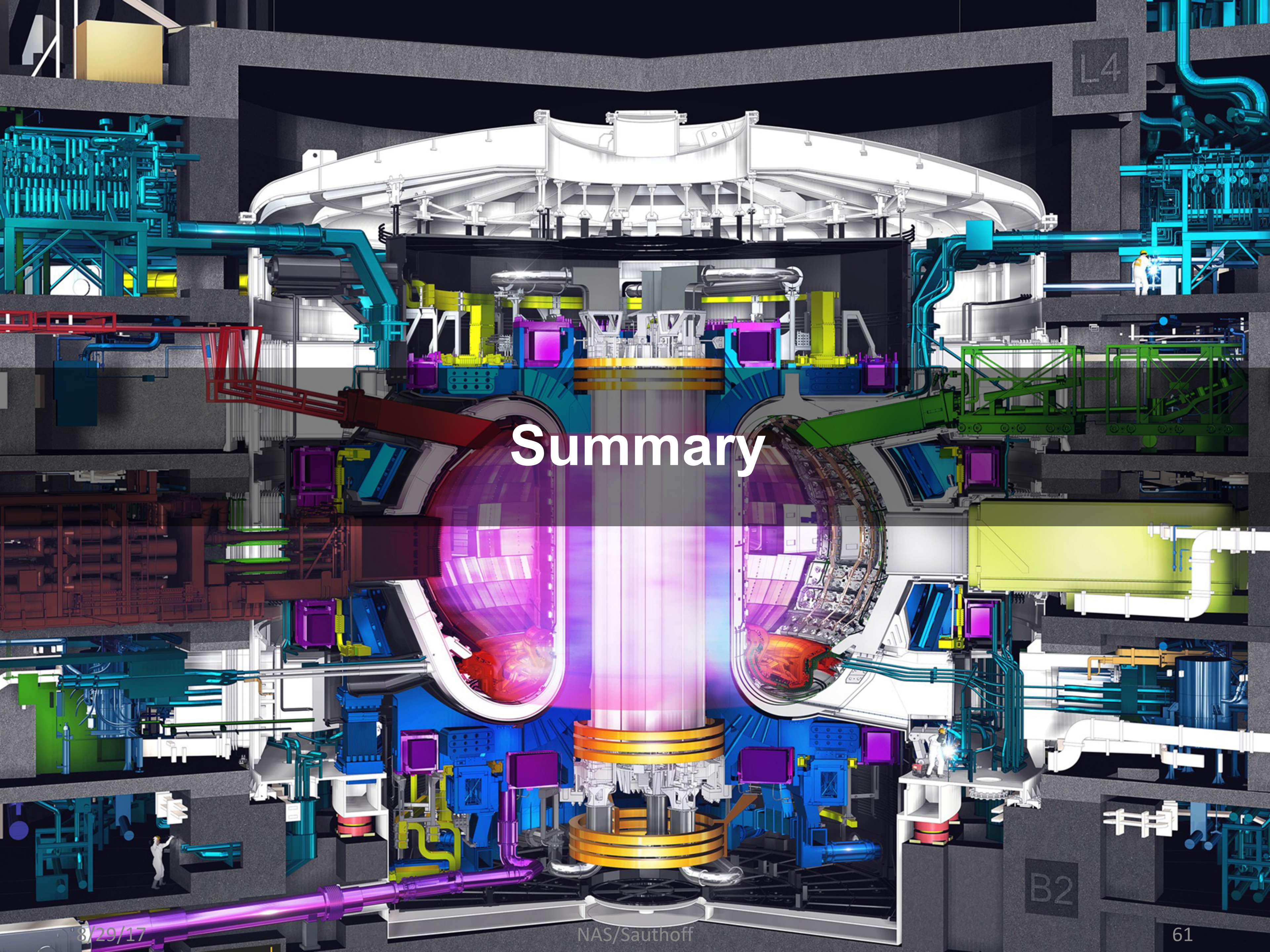


High Velocity, High Rate Cryo-Pellet Injection
300 m/s second
16 Hz



Neutronics Modeling
75 million spatial tally cells
10,000X reduction in computational time

Summary



ITER status summary

- ITER negotiations led to international agreement and ITER construction
- The ITER Organization is now well-managed and is integrating the project
- Construction and fabrication are well underway on
  – Buildings and plant infrastructure at the ITER site
  – Hardware components in all Domestic Agencies
- The US ITER Project has been baselined and has performed well
- US universities, industries and government institutions are engaged

"the importance of U.S. research supporting ITER to the development of fusion energy"

- U.S. burning plasma research is already underway with existing facilities and modelling/simulation, positioning the U.S. to be among the BP-research leaders before and on ITER
  - Guides the design (e.g., disruptions and other transients)
  - Supports operations (e.g., plasma instrumentation and control, predictive models and analysis tools)
  - Enables leading research (e.g., advancing burning plasma understanding and creating related tools such as predictive models for designing BP experiments and interpreting BP data)
- ITER physics and hardware design, the ITPA, and Joint Experiments have
  - Achieved **global convergence** on priorities for advancing tokamak-based fusion science and fusion technology, focusing on issues for a real device
  - Been highly effective as a **forcing function** for progress in fusion science and technology

“the scientific and technical developments since the 2004 report of the NAS Burning Plasma Assessment Committee”

- Physics developments have supported ITER design and research planning
  - Cf. Tony Taylor’s presentation
- Technology developments have enabled the design of ITER’s high-tech systems
  - Cf. Phil Ferguson’s presentation
- Research since 2004 has strengthened our confidence in ITER performance

Possible statements for the Committee

- Tokamaks remain the only concept mature enough to now serve as the basis for a near-term burning plasma experiment.
- The ITER Project, the International Tokamak Physics Activity, and Joint Experiments have
  - Achieved **global convergence** on priorities for advancing tokamak-based fusion science and fusion technology, focusing on issues for a real device; and
  - Been highly effective as a **forcing function** for progress in fusion science and technology.
- Research since the NAS Burning Plasma Report (2004) has strengthened our confidence in ITER performance.

Further Information

[2016 ITER Organization Annual Report]