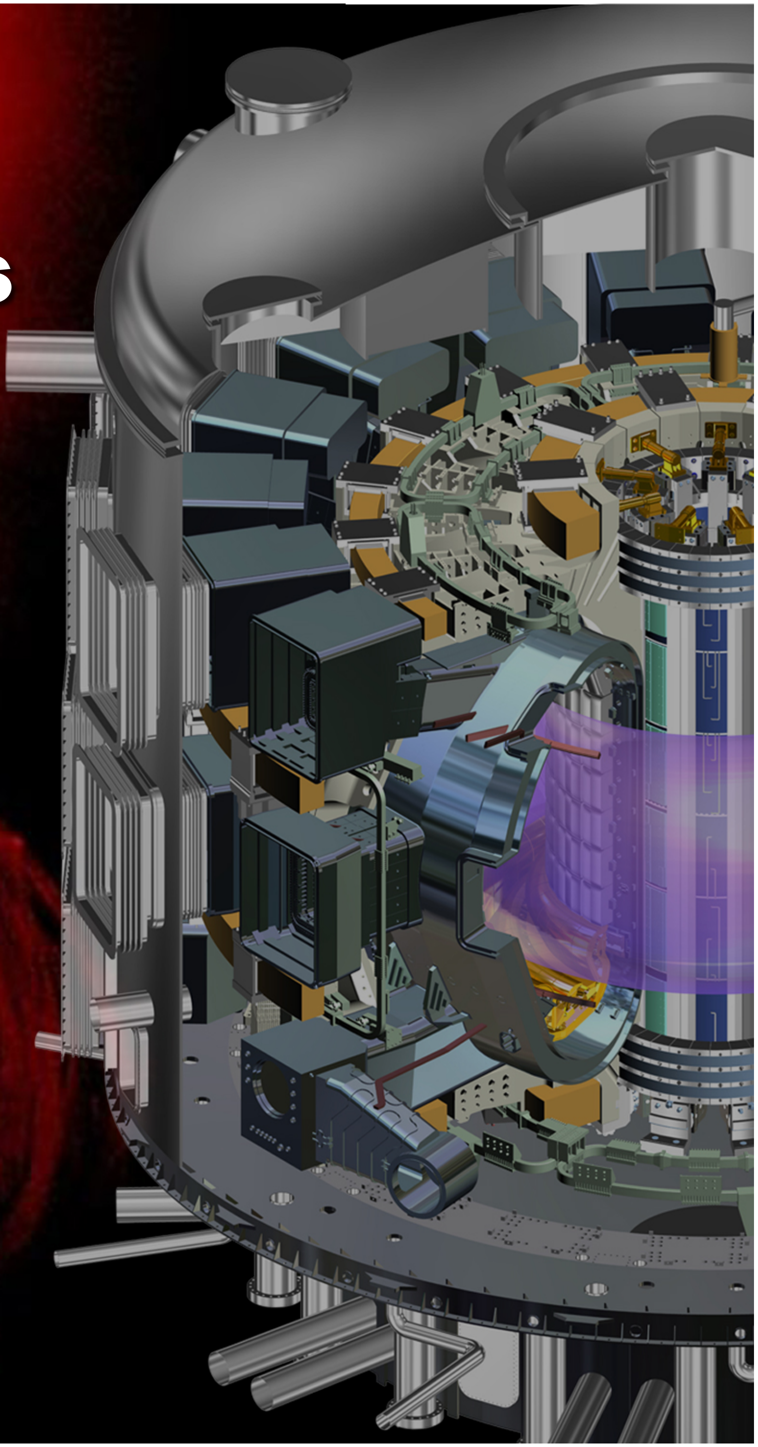
US ITER Project Status

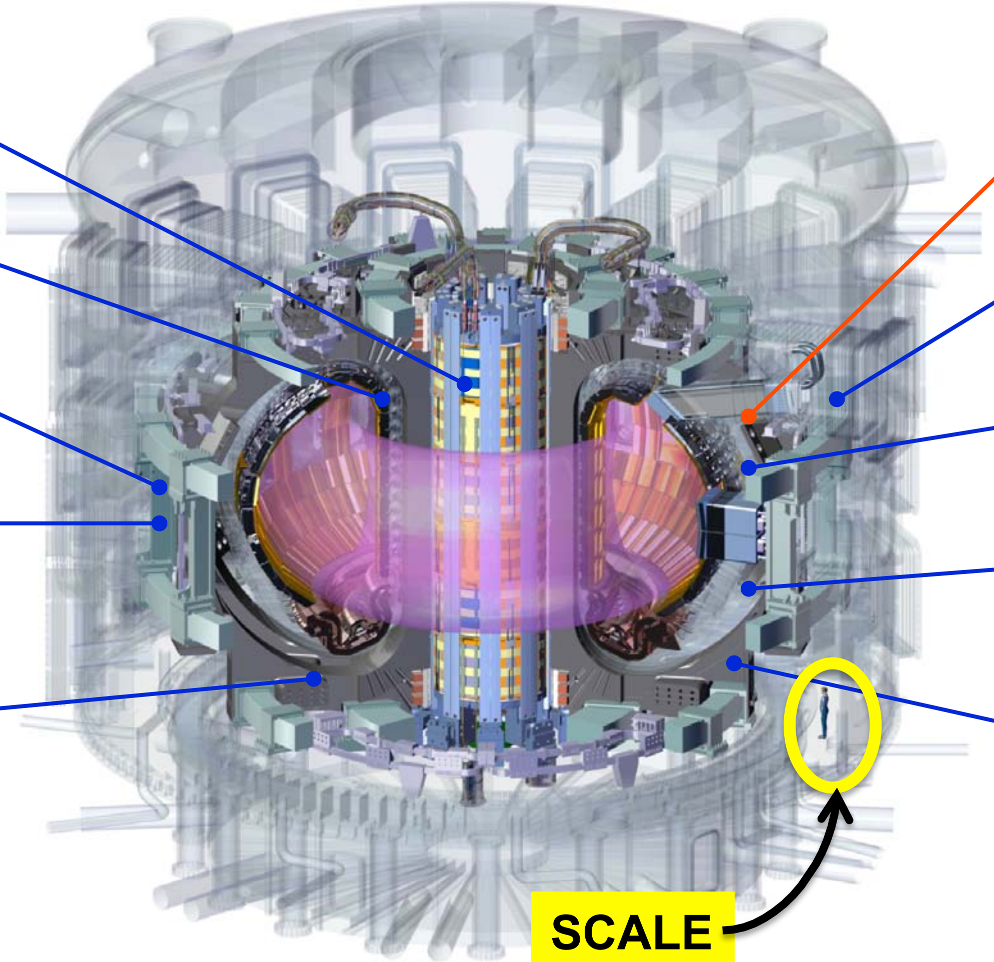
Fusion Power Associates
34th Annual Meeting and Symposium

Ned Sauthoff
Director, US ITER Project Office

December 10, 2013



US Technical Scope



ORNL
100% Central Solenoid
(using JA conductor)

ORNL
8% of Toroidal
Field Conductor

ORNL
100% Pellet Injector

ORNL
100% Disruption
Mitigation
(up to capped value)

ORNL
100% Tokamak Cooling
Water System

PPPL
75% Steady State
Electrical Network

PPPL
14% of Port-based
Diagnostics

ORNL
100% Ion Cyclotron
Transmission Lines

ORNL
100% Electron
Cyclotron
Transmission Lines

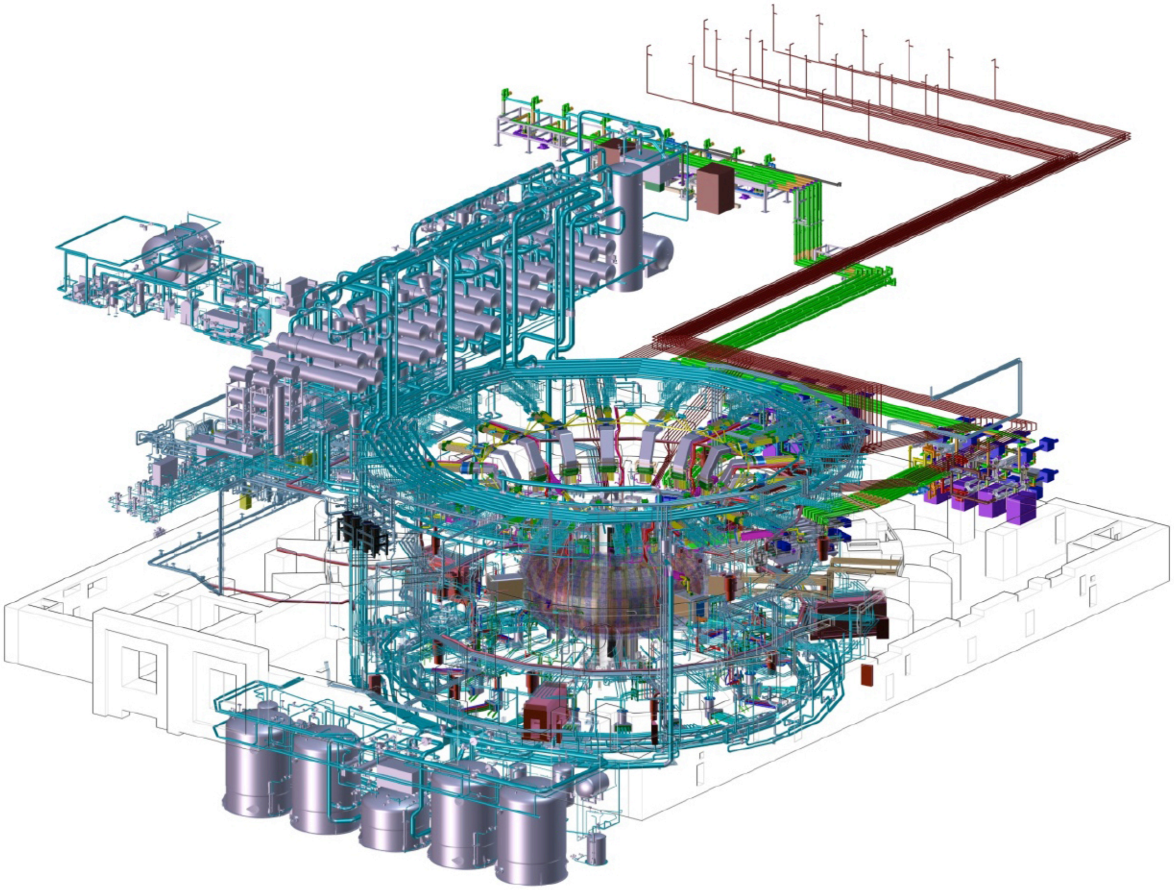
ORNL
Blanket/Shield
(design support)

ORNL
100% Roughing Pumps,
Vacuum Auxiliary System

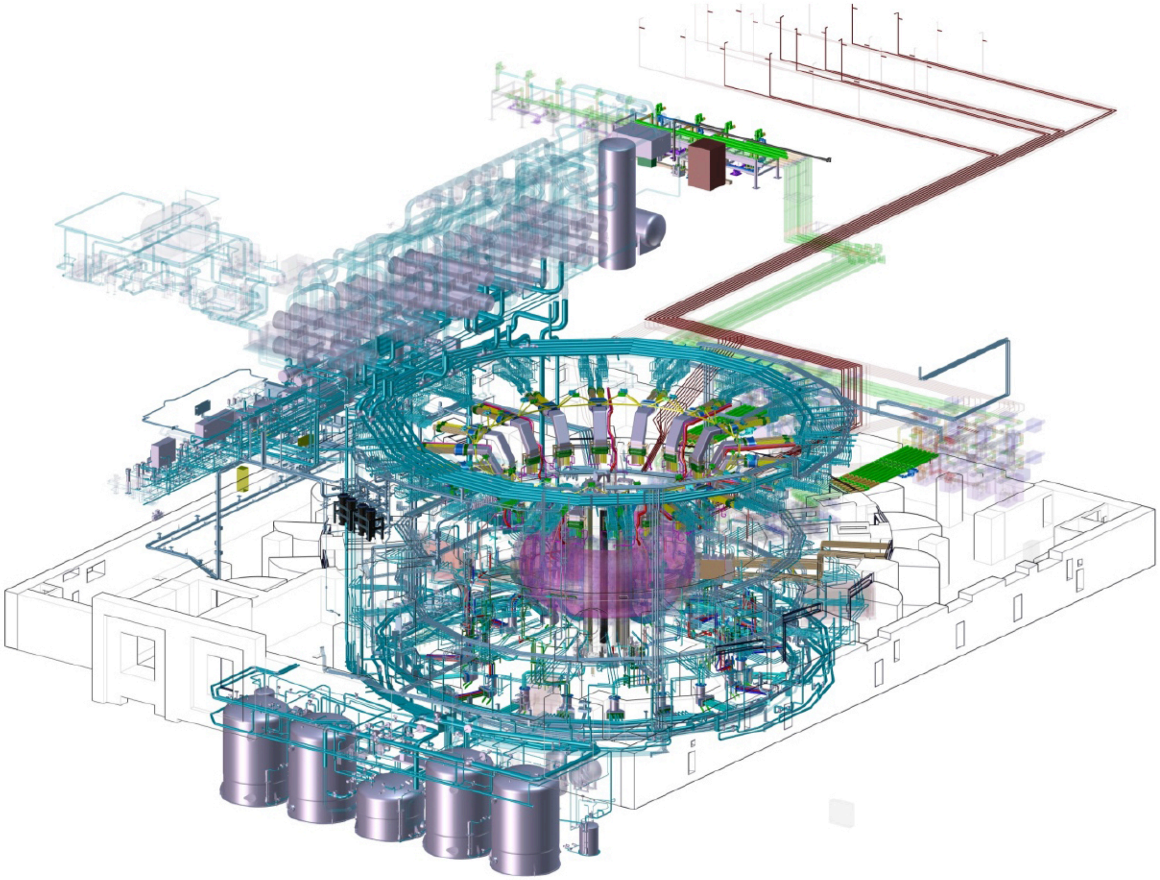
SRNL
100% Tokamak Exhaust
Processing System

SCALE

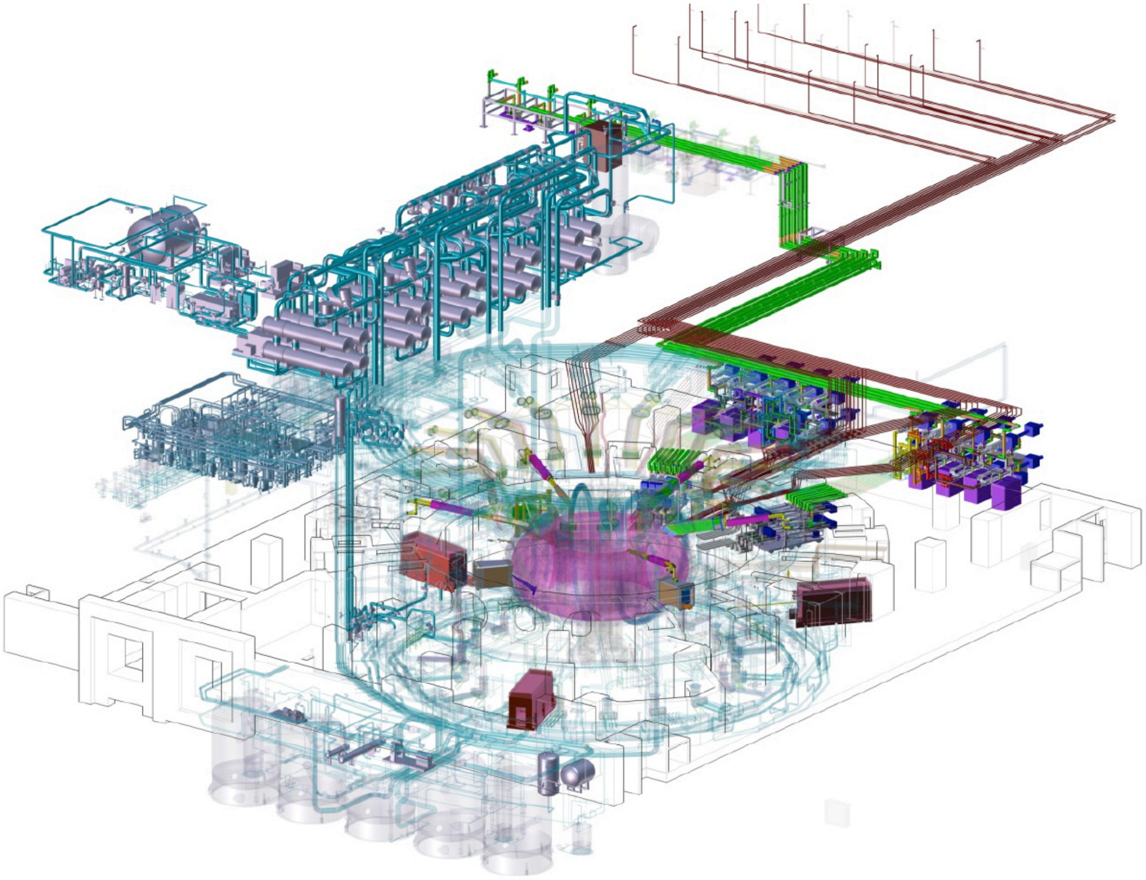
US Hardware – Full Design Scope



US Hardware Scope Provided for 1st Plasma



US Hardware Scope Post -1st Plasma

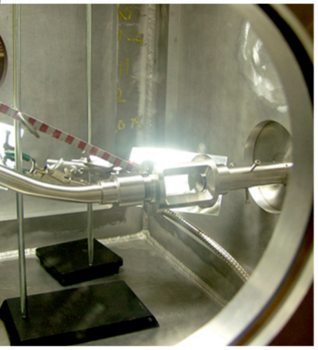


Technology Highlights

A drain tank head undergoes quality control inspection at ODOM Industries in Milford, Ohio.

Gas barrier prototypes Mega Industries.

Initial deliveries for the vacuum auxiliary system have been underway since fall of 2012; small helium leak detectors (pictured at left) were delivered in October 2012.



A shattered pellet flight tube used in massive pellet injection testing at ORNL.

A view of a section of the Ion Cyclotron coaxial transmission line shows thick quartz insulators inserted into the outer conductor.

General Atomic’s central solenoid module fabrication facility in Poway, CA is preparing for tooling stations. The large crates contain dummy conductor for the mock-up module.

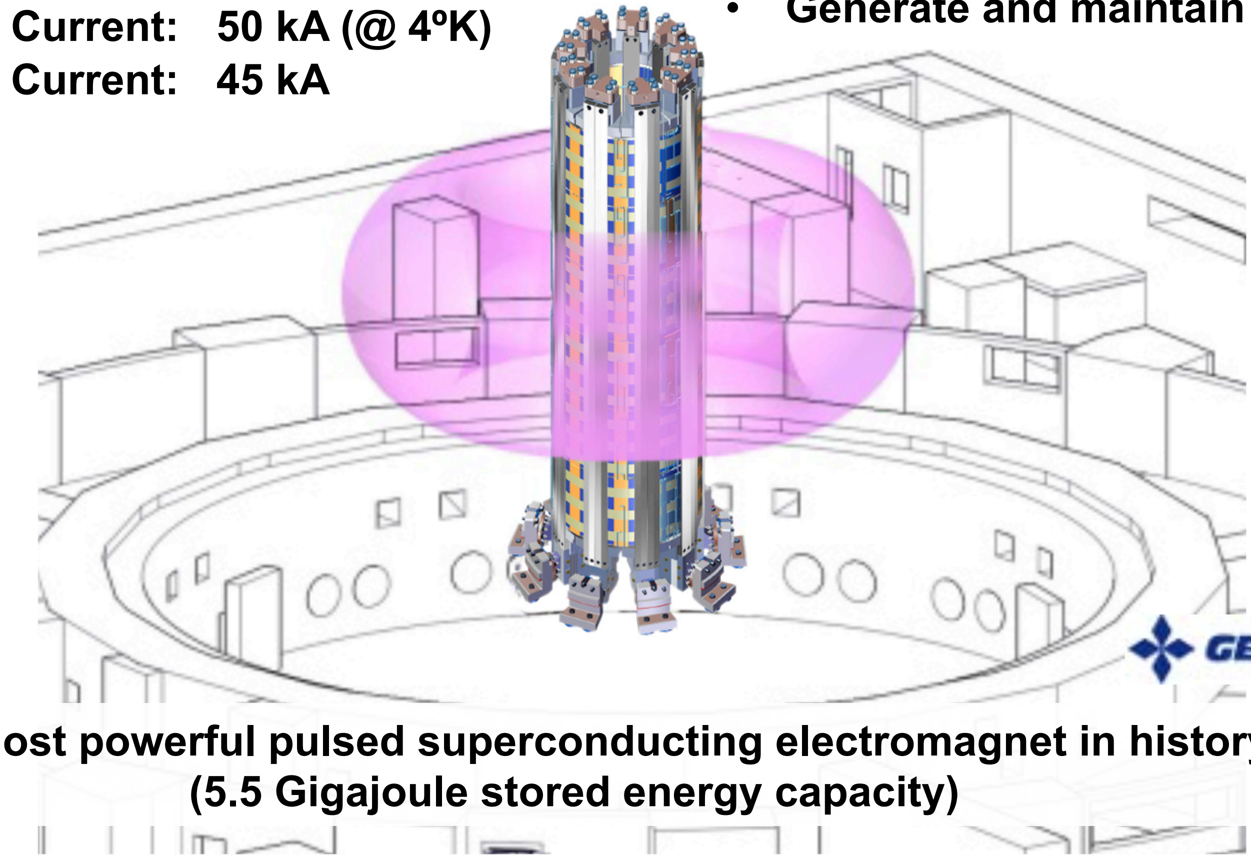
800 m dummy TF conductor at High Performance Magnetics, Tallahassee, Florida.

Central Solenoid –
The Heartbeat of ITER

Coil Packs:	6 + 1 spare
Field Strength:	13 T
Test Voltage:	30 kV
Operating Voltage:	14 kV
Test Current:	50 kA (@ 4ºK)
Operating Current:	45 kA

1,000 tonne magnet induces the majority of magnetic flux charge needed to:

- Initiate plasma
- Generate and maintain plasma current



GENERAL ATOMICS

The most powerful pulsed superconducting electromagnet in history (5.5 Gigajoule stored energy capacity)

Central Solenoid

Specs: 6 independent coil packs of cable-in-conduit conductor (produced in up to 910 m lengths), plus pre-compression structure

- 13 Tesla • 5.5 GJ • 30 kV • 1.2 T/s • 45 kA

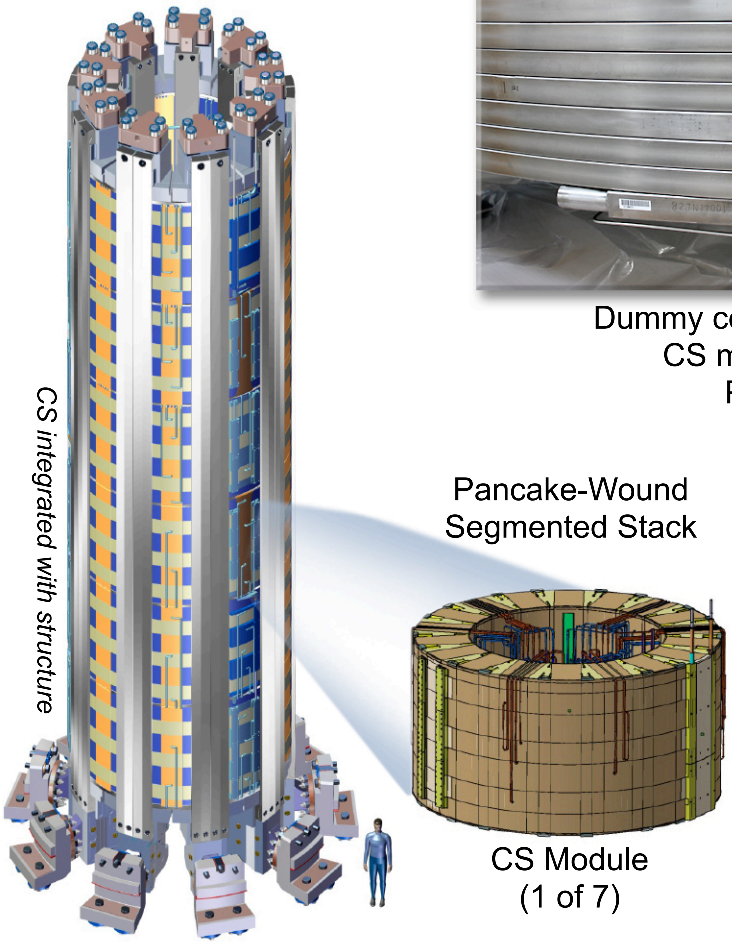
Key Vendors:

- General Atomics (modules) with Tauring, Ridgway, Babcock Noel, Martinez & Turek, Seco Warwick (tooling stations)
- G&G Steel (prototype tie plates)
- Major Tool & Machine, Inc. (prototype tie plates)

Status: Final Design Review Completed in November 2013

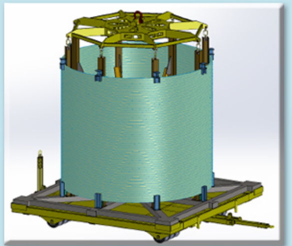
- CS manufacturing building ready
- FDR completed for winding, heat treatment and turn insulation stations
- PDR completed for VPI station
- Conceptual design of 4 K test facility completed
- Tie-plate feasibility studies performed

Dummy conductor for the
CS mock-up module
Photo: US ITER

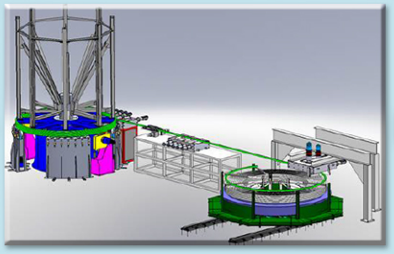


Central Solenoid Module Production Process

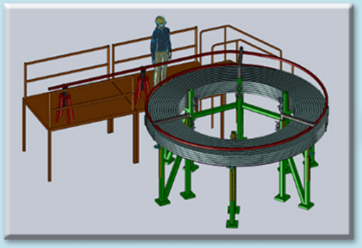
Tooling stations are being procured and assembled by General Atomics



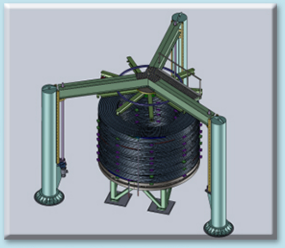
Conductor Receiving Inspection



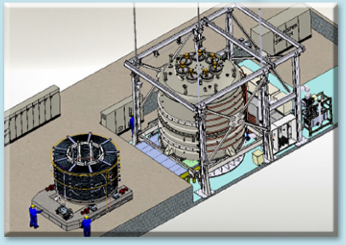
Winding (2)



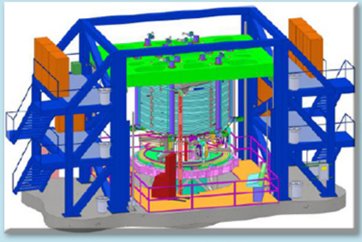
Joints & Terminals Preparation



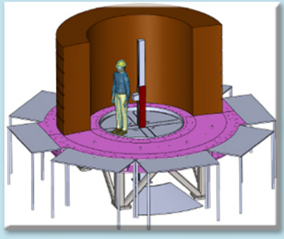
Stack & Join/Helium Penetrations



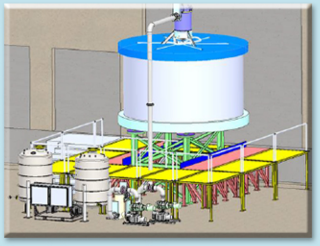
Reaction Heat Treatment



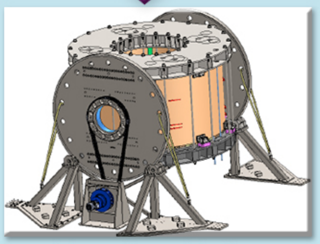
Turn Insulation



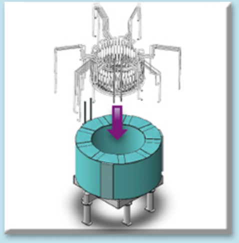
Ground Insulation



Vacuum Pressure Impregnation

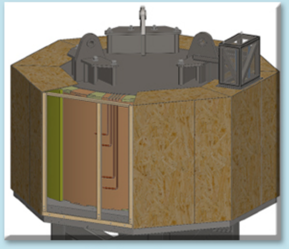


Turn-Over Tool



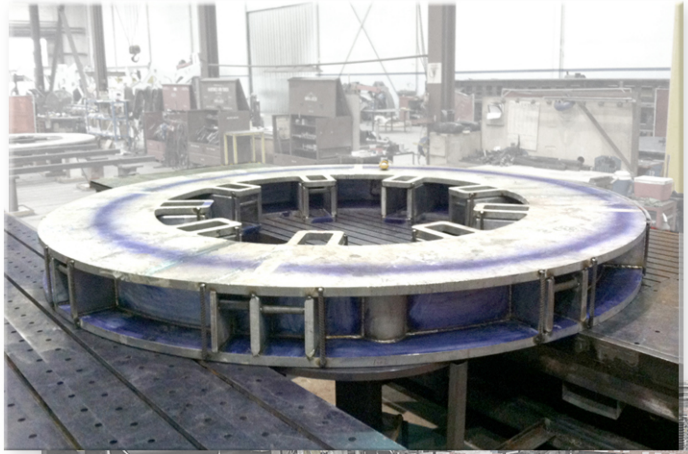
Helium Piping & Measurement

Final Test

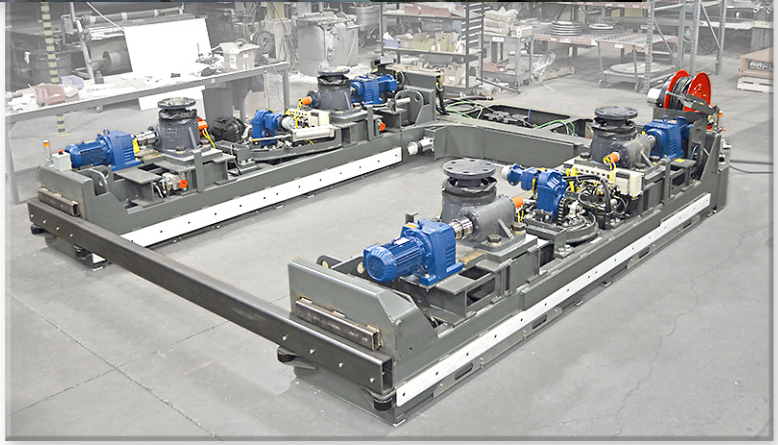


Shipping

Central Solenoid Tooling Stations



Coil support frame for stack & join, heat treatment and turn installation stations
Photo: Martinez & Turek, Inc. (Rialto, CA)



Coil transport tool ready to begin pre-commissioning at Airfloat (Decatur, IL)
Photo: General Atomics (San Diego, CA)

Prototype automated wrapping head Ridgway Machines (Leicester, UK)
Photo: General Atomics (San Diego, CA)

Machine wrapping of conductor bars by Ridgway Machines (Leicester, UK)
Photo: General Atomics (San Diego, CA)
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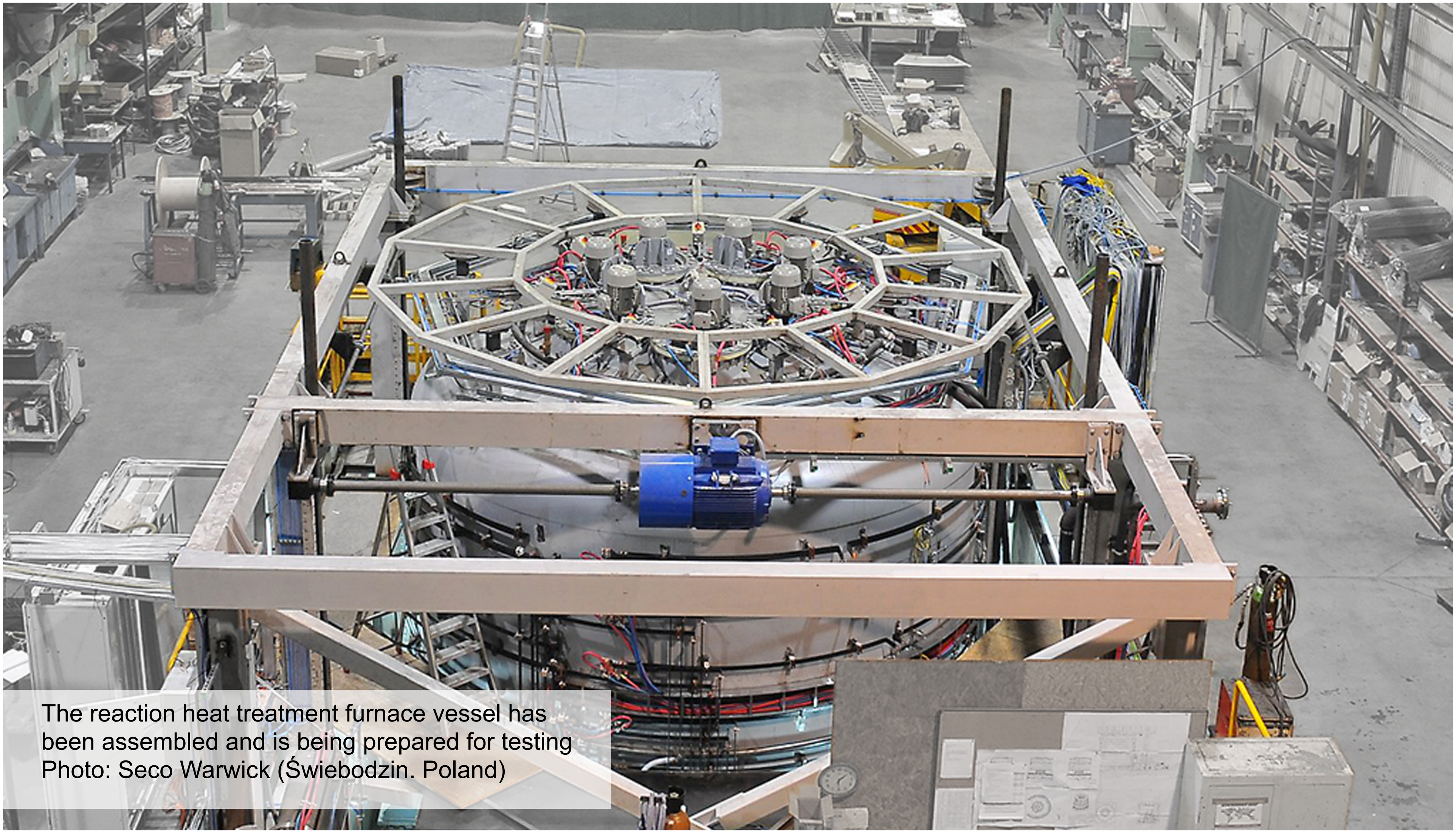
Central Solenoid Tooling Stations



The reaction heat treatment furnace vessel has been assembled and is being prepared for testing
Photo: Seco Warwick (Świebodzin. Poland)

Toroidal Field Conductor

Specs: 18 toroidal field coils are designed to have

- Total magnetic energy of 41 gigajoules
- Maximum magnetic field of 11.8 tesla

Key Vendors:

- Luvata Waterbury, Inc., Waterbury, CT (strand)
- Oxford Superconducting Technologies, Carteret, NJ (strand)
- New England Wire Technologies Lisbon, NH (cabling)
- High Performance Magnetics, Tallahassee, FL (jacketing and integration)

Status: In Fabrication

Strand

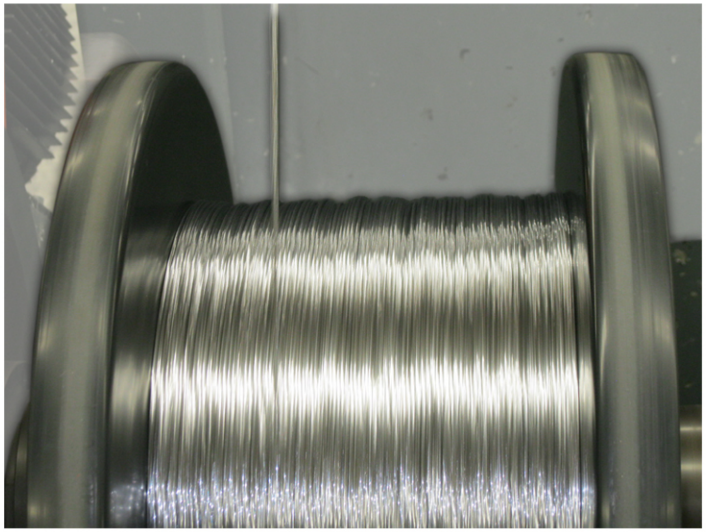
- Production completed

Cabling

- Dummy cable completed
- Production cable is well underway

Jacketing

- 800 m dummy conductor completed
- Preparation for shipment has begun



Production cable at New England Wire Technologies (Lisbon, NH)

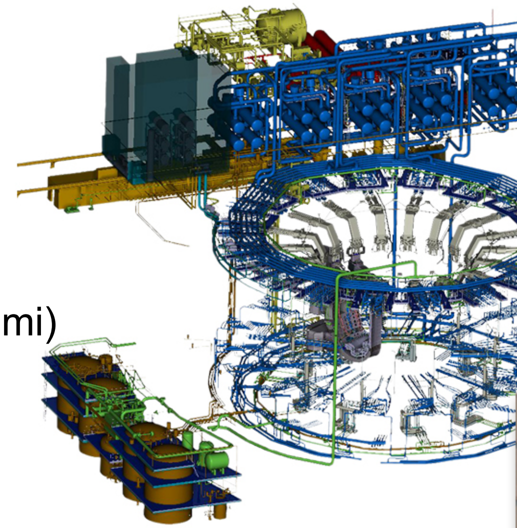
800 m dummy conductor at High Performance Magnetics (Tallahassee, FL)

Tokamak Cooling Water System (TCWS)

Requirements:

- Remove ~1 GW of heat,
- Drain and dry,
- Control water chemistry
- instrumentation / control

Configuration: 36 km (22 mi) of piping, ~230 pieces of equipment, classified as safety important for the confinement of radioactivity



Key Vendors:

AREVA Federal Services, Charlotte, NC (design, Title III for drain tanks) with Joseph Oat Corporation and ODOM Industries (drain tank manufacture)

Status:

In Fabrication: Drain tank fabrication / inspections

In Design: 59% of preliminary/final design completed; completed conceptual design

Drain tank heads from Odom Industries (Milford, OH) delivered to JOC for tank fabrication

Drain tank rolling is underway at Joseph Oat, Corp. (Camden, NJ)

TCWS Drain Tank Fabrication – Progress

- All tank shell, formed heads and nozzle material on site at Joseph Oat Corporation for fabrication
- Welding, grinding, and Non-destructive Examination (NDE) processes in progress
- Plate rolling underway for the first normal drain tank
- Fabrication scheduled for completion October 2014
- Delivery scheduled to ITER site December 2014

Drain tank head positioned for welding at Joseph Oat Corp. in Camden, NJ
Photo: US ITER

Ion Cyclotron Transmission Lines

Specs:

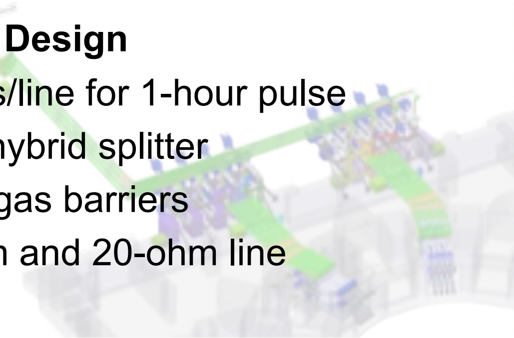
- Deliver up to 6 MW per transmission line from transmitters to two ICH Launchers
- Load-tolerant tuning over 40-55 MHz

Key Vendors:

Mega Industries, LLC, Goreham, ME (coaxial components, gas barriers)
Dielectric Communications, Raymond, ME (coaxial components, gas barriers)
Comet, San Jose, CA (tunable capacitors)
General Atomics, San Diego, CA (RF matching components)
National Instruments, Austin, TX (data acquisition systems)
Cincinnati Fan, Mason, OH (cooling gas circulation blowers)

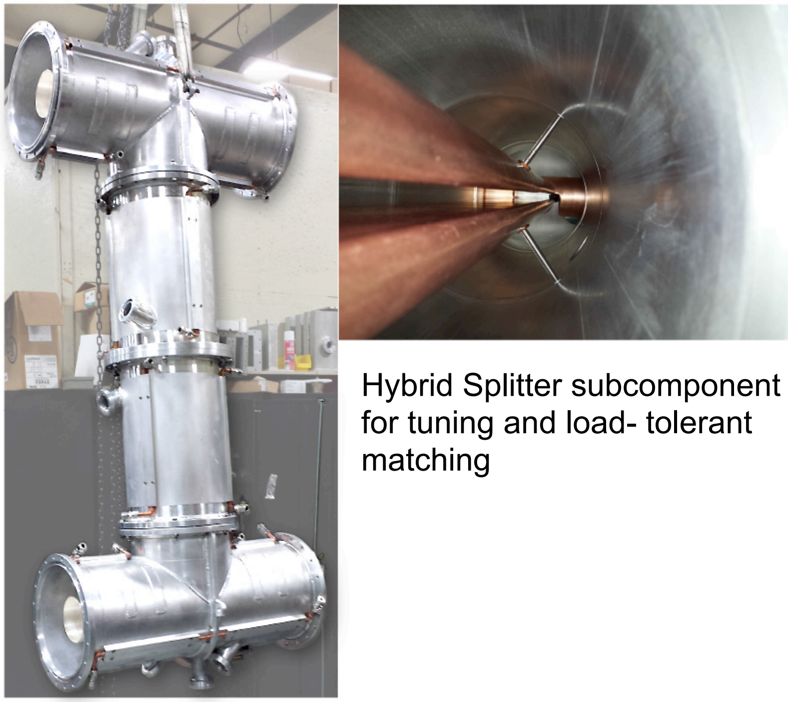
Status: In Preliminary Design

- Demonstrated 6 MWs/line for 1-hour pulse
- Fabrication of 50/50 hybrid splitter
- Fabrication of in-line gas barriers
- Fabrication of 50-ohm and 20-ohm line components

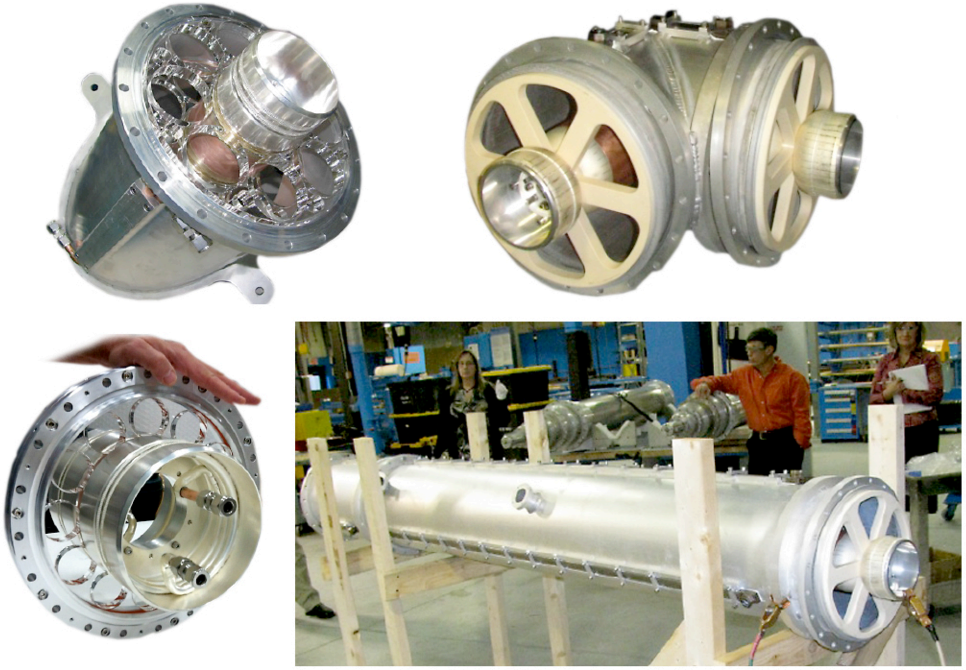


Ion Cyclotron resonant loop test stand at ORNL

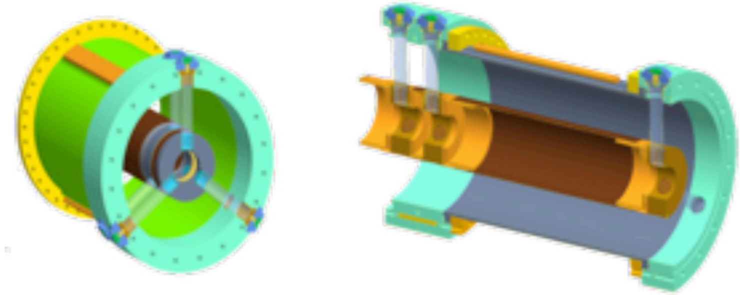
ICH Transmission Line and Matching System Fabrication/Assembly and Power Testing



Hybrid Splitter subcomponent for tuning and load- tolerant matching



Line and elbow sections with quartz and alumina insulators



Issues identified during test assembly of lines and elbows have led to new designs of insulators/supports

Electron Cyclotron Transmission Lines

Specs:

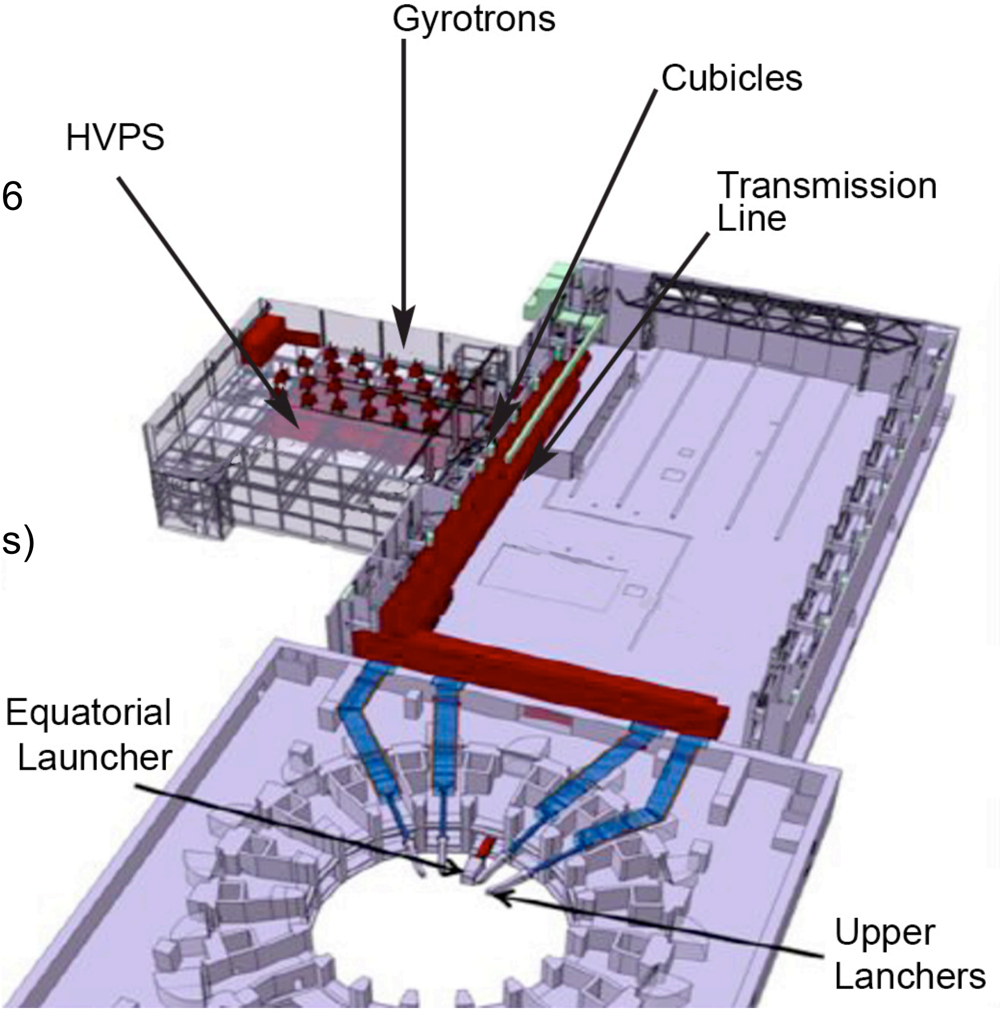
- Provide efficient power transfer from 170 GHz gyrotron sources to 20 MW launchers
- Minimize power losses to < 10%
- 4 km of transmission line, with 24 sources to 56 feeds

Key Vendors:

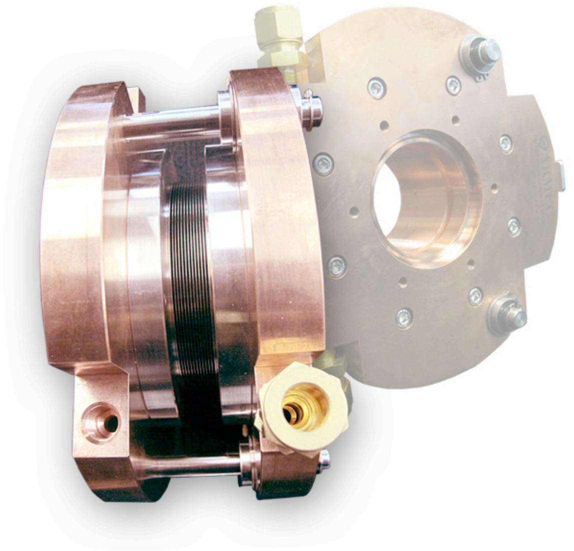
- General Atomics, San Diego, CA (waveguide components)
- Dymenso, San Francisco, CA (power loads)
- Calabazas Creek, San Mateo, CA (power loads)
- ARMEC, Knoxville, TN (metrology services)

Status: In Final Design

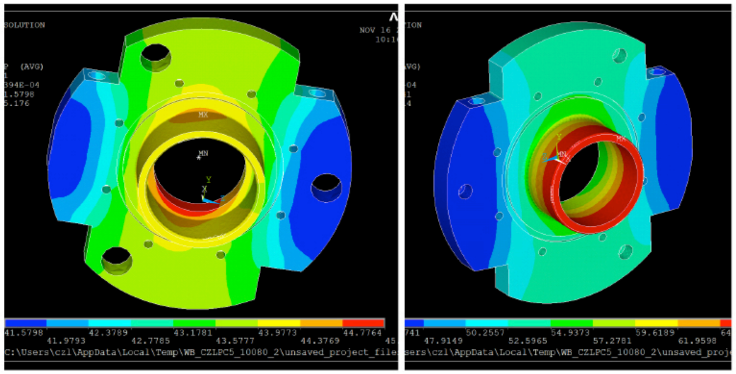
- Cooling performance analysis underway
- Mode conversion loss reduction studies
- Support structure design
- Alignment metrology and assembly studies



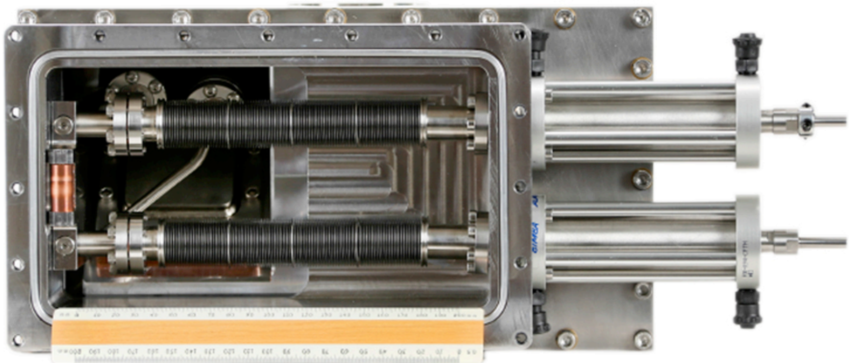
Modeling, Manufacturing Studies and Tests Address High Power Long Pulse Challenges



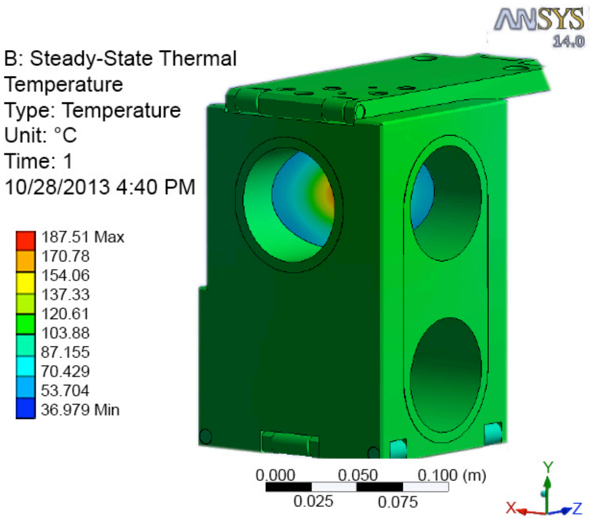
Waveguide expansion unit allows expansion and contraction to maintain alignment during thermal and mechanical cycles



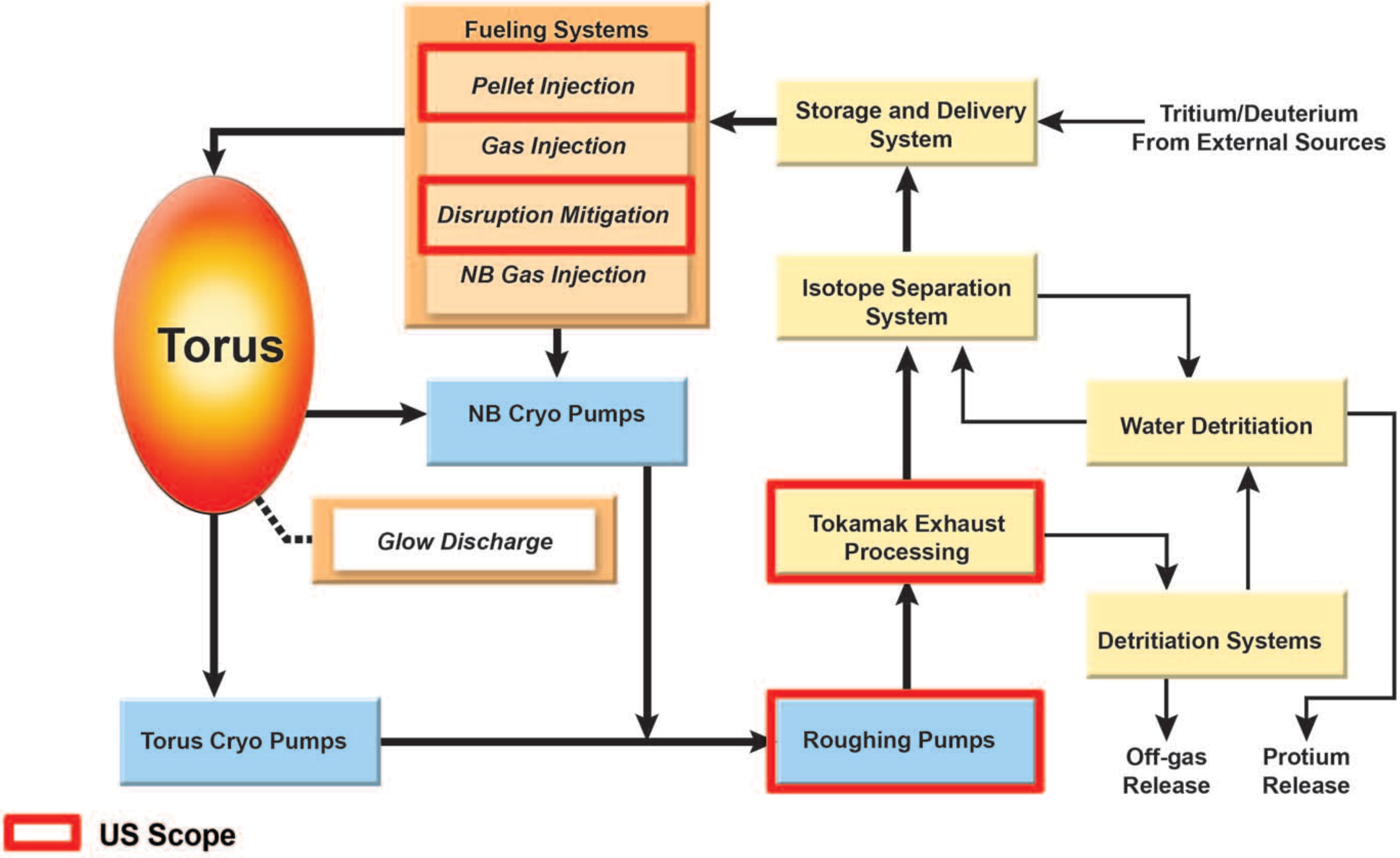
Waveguide gap expansion unit studies show effective cooling under high heat loads



Waveguide switch to direct microwave power to either upper or equatorial launchers



Fuel Cycle


Fueling Systems
Pellet Injection
Gas Injection
Disruption Mitigation
NB Gas Injection
Storage and Delivery System
Tritium/Deuterium From External Sources
Torus
Isotope Separation System
NB Cryo Pumps
Water Detritiation
Glow Discharge
Tokamak Exhaust Processing
Detritiation Systems
Torus Cryo Pumps
Roughing Pumps
Off-gas Release
Protium Release
🟥 US Scope

Vacuum Auxiliary and Roughing Pump Systems

Specs: Service vacuum for ~5000 clients (VAS) and continuous H, D, T and He gas pumping (RP)

Key Vendors:

- Inficon, Inc., E. Syracuse, NY (test equipment)
- Pfeiffer, Nashua, NH (prototype roots pump)
- Major Tool and Manufacturing, Indianapolis, IN (prototype full-scale CVC pump)

Status: Shipping and **In Preliminary/ Final Design**

Delivered VAS test equipment

Fabrication of:

- CVC cryogenic valve box
- Prototype tritium compatible vacuum roots pump
- Tritium compatible vacuum screw pump
- Prototype roughing pump test stand components
- Full size prototype cryogenic viscous compressor (CVC) vacuum pump

Small helium leak detector delivered as part of VAS test component shipment

Development of Roughing Pumps for Helium, Deuterium and Tritium

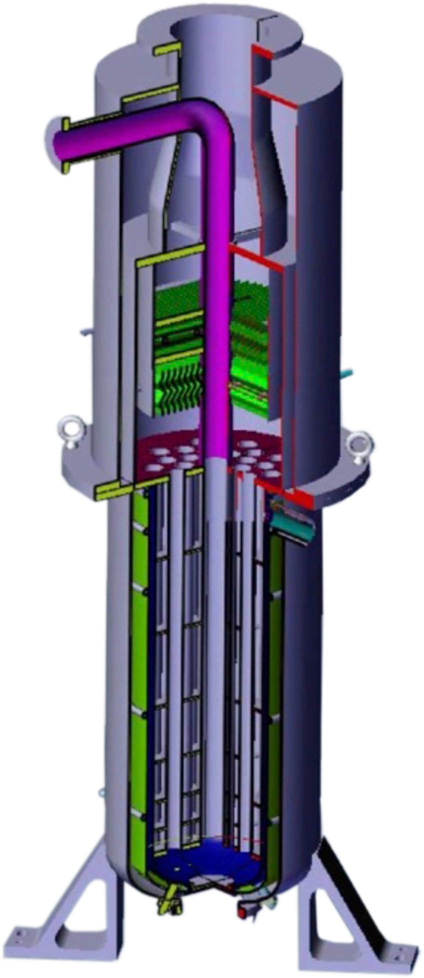
CVC cryogenic valve box
Photo: US ITER

Cryogenic viscous compressor (CVC) vacuum pump concept for 1st stage rough pumping.

Separates He and D/T pump streams cryogenically.

Pre-prototype single tube unit has been successfully tested.

Prototype unit being fabricated for full scale tests.



CVC pump design

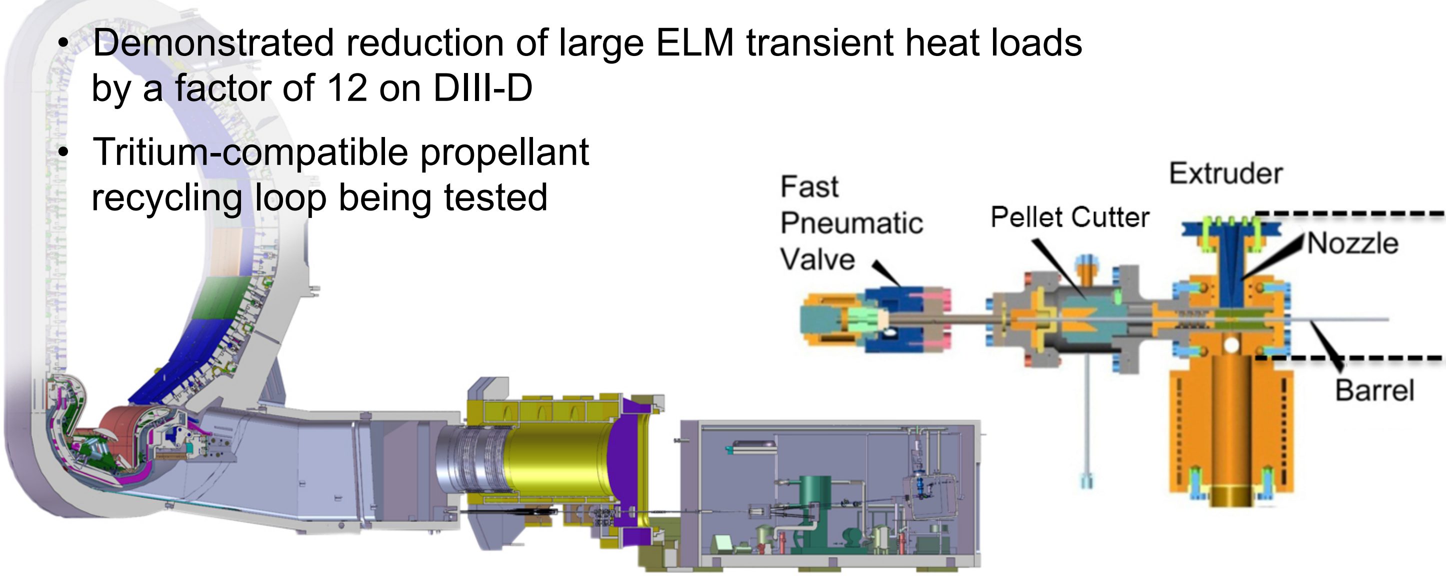
Pellet Injection System

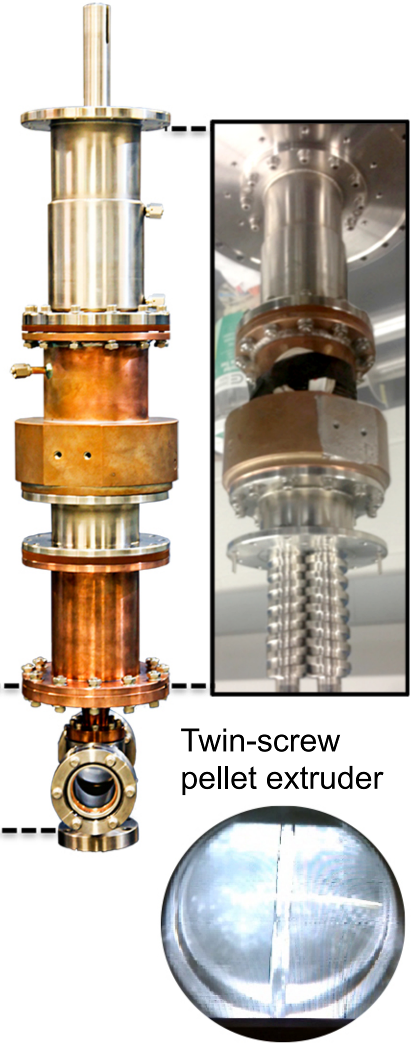
Specs:

- Continuous and reliable H/D/T fueling and ELM control
- Pellets accelerated by high pressure gas
- Extruder nozzle produces adjustable length pellets for fueling or ELM triggering

Status: In Preliminary Design

- Supercritical He cooling to increase mass flow and delivery period by a factor of 1000
- Pellet and injection technology extended to > 20 Hz
- Demonstrated reduction of large ELM transient heat loads by a factor of 12 on DIII-D
- Tritium-compatible propellant recycling loop being tested

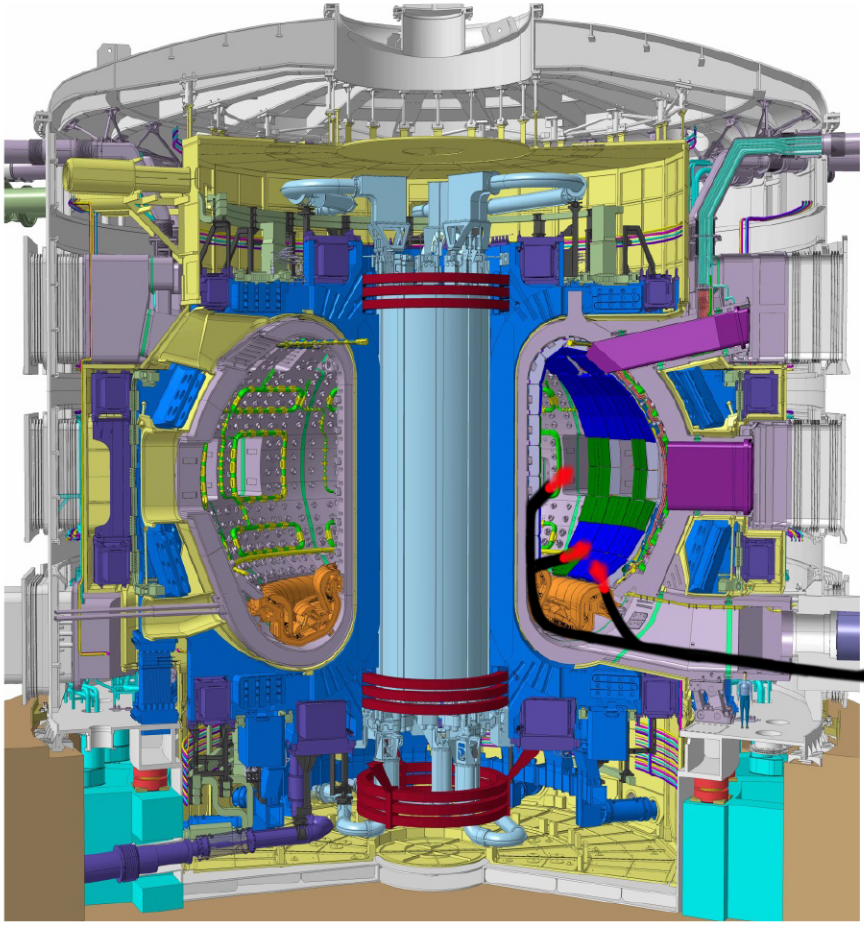




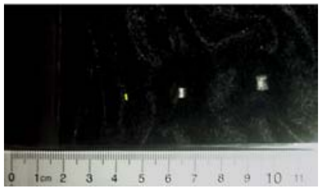
Pellet Fueling and Pellet ELM Mitigation are Functions of the ITER Pellet Injection System

Up to 6 injectors deliver H, D, or DT pellets to

- Provide a steady supply of deuterium and tritium fuel via HFS injection (~5mm DT pellets at 4 Hz)
- Mitigate the impact of ELMs via LFS or HFS (~3mm D_2 pellets at 45 Hz)
- Pellet speed = 300 m/s to survive the curved guide tubes

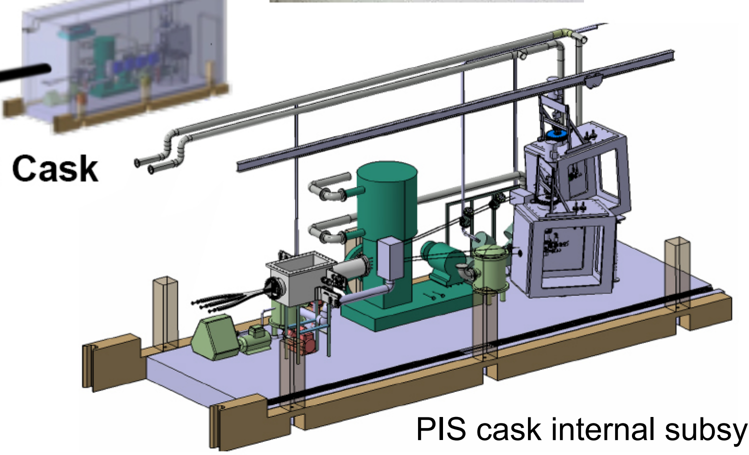


6 HFS & 3 LFS Pellet Guide Tubes



Pellet Path

PIS Cask



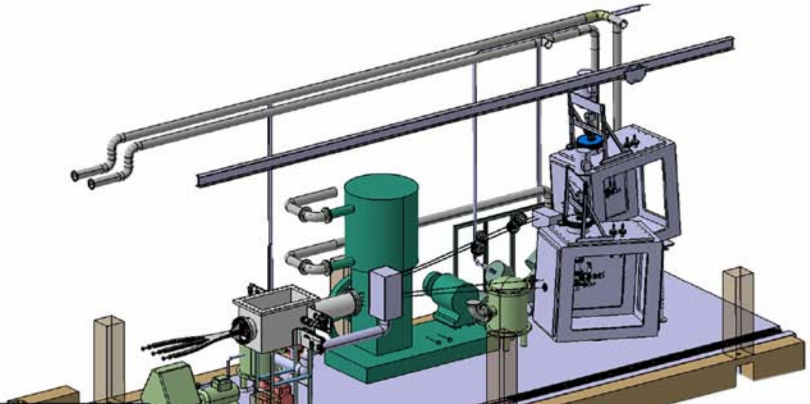
PIS cask internal subsystems

Pellet Injection
Piston Pump Testing in Progress

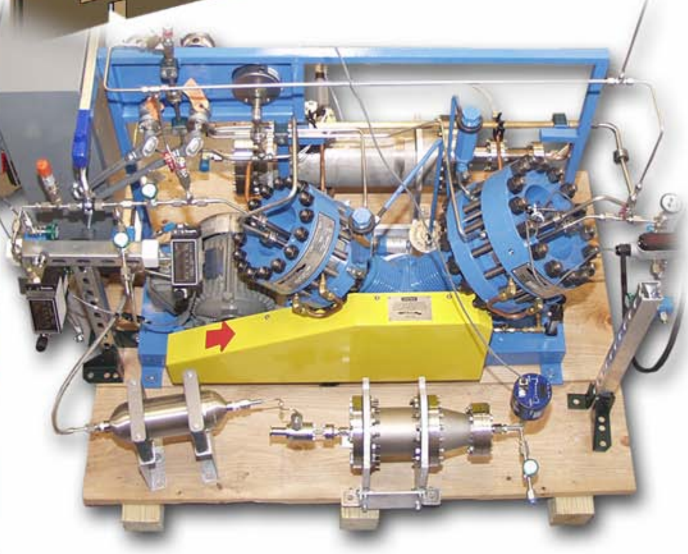
Fuel and propellant loops require:

- Tritium-compatible compressors
- Tritium-compatible vacuum piston pump
- Long-term reliability tests (underway)

Subsystems are being tested in the laboratory

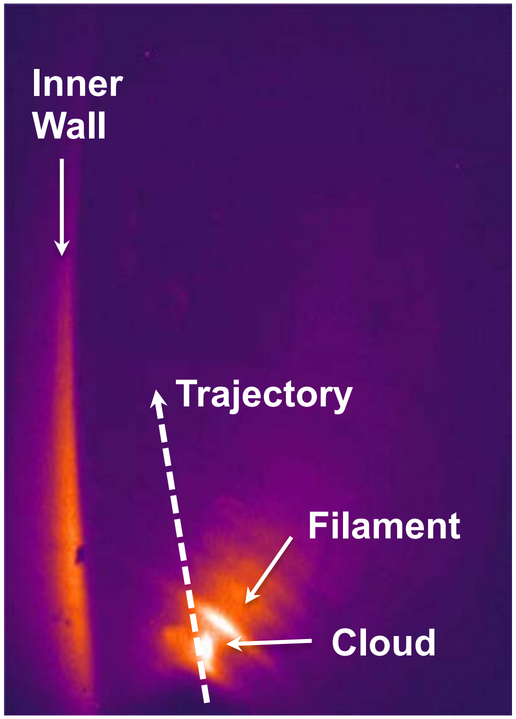


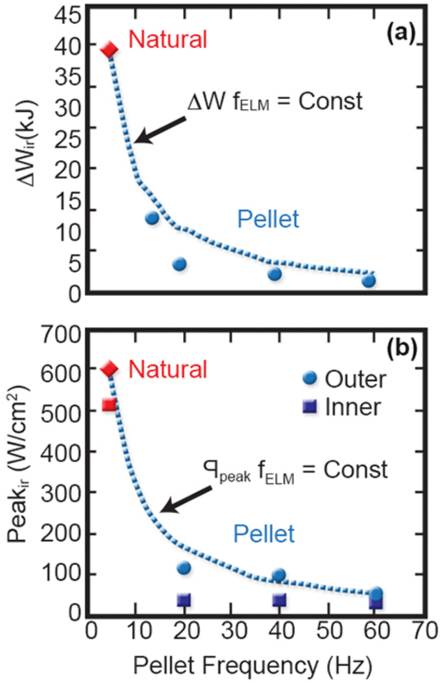
Tritium-compatible vacuum piston pump



Propellant recycling system

Pellet ELM Pacing Mitigation Using Lower Port Injection on DIII-D





- Pellet ELM pacing on DIII-D using ITER relevant hardware and lower port geometry
- Excites a filament just in front of the pellet ablation cloud
- Subsequently triggers an ELM

- Pellet pacing rate varied in DIII-D experiments
- ELM frequency increase of up to 12x natural rate
- Achieved > 12x reduction in divertor ELM energy and peak heat flux

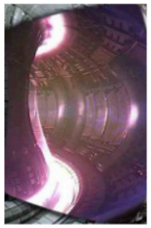
Mitigation of Disruptions is a Challenge for ITER

To mitigate thermal and current quench,

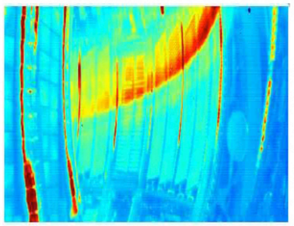
- Use large shattered pellets composed of neon with a deuterium shell

To suppress & dissipate runaway electrons,

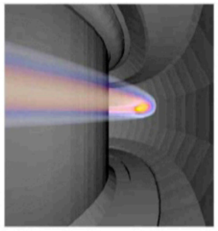
- Use massive gas or shattered pellet injection



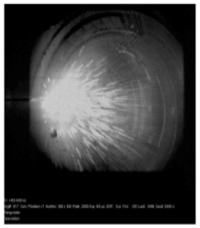
Burning Plasma



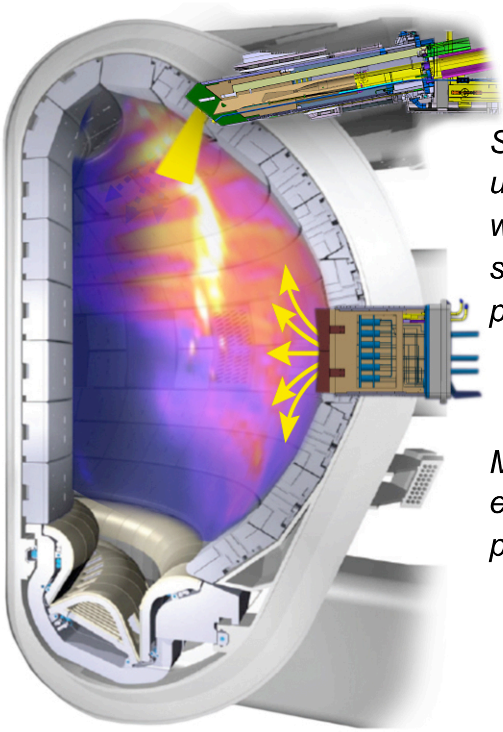
Disruption Precursor Thermal Quench



Current Quench

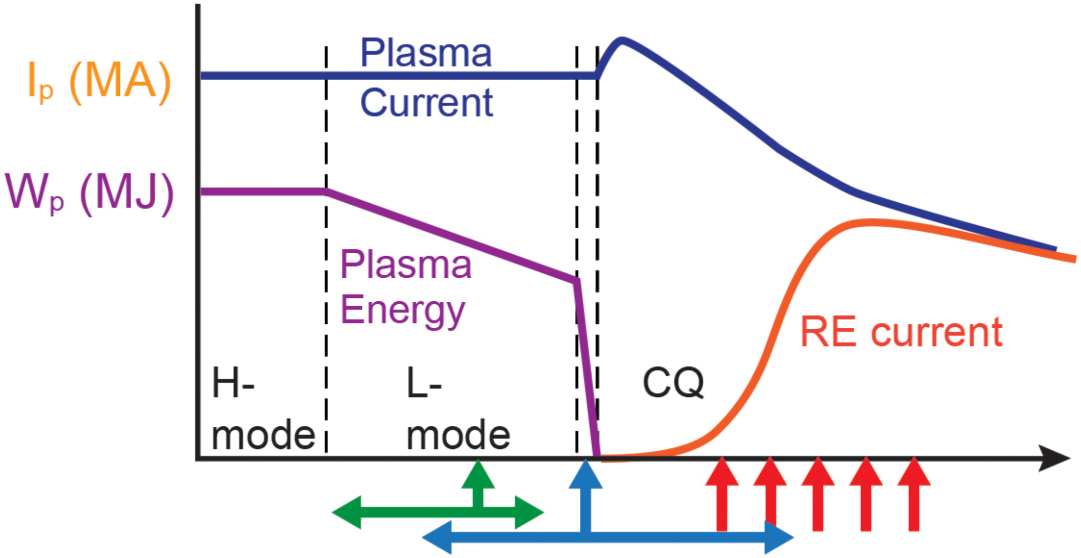


Runaway Electrons



SPI located in upper port plugs with pellet shattered near plasma edge

MGI located in equatorial port plugs



Preventive SPI and MGI of material for **Thermal Quench** and **Current Quench**

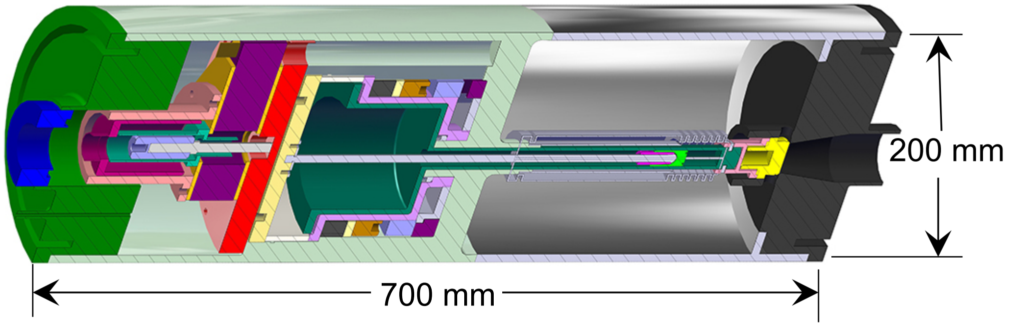
MGI and SPI **RE suppression or dissipation**

Disruption Mitigation

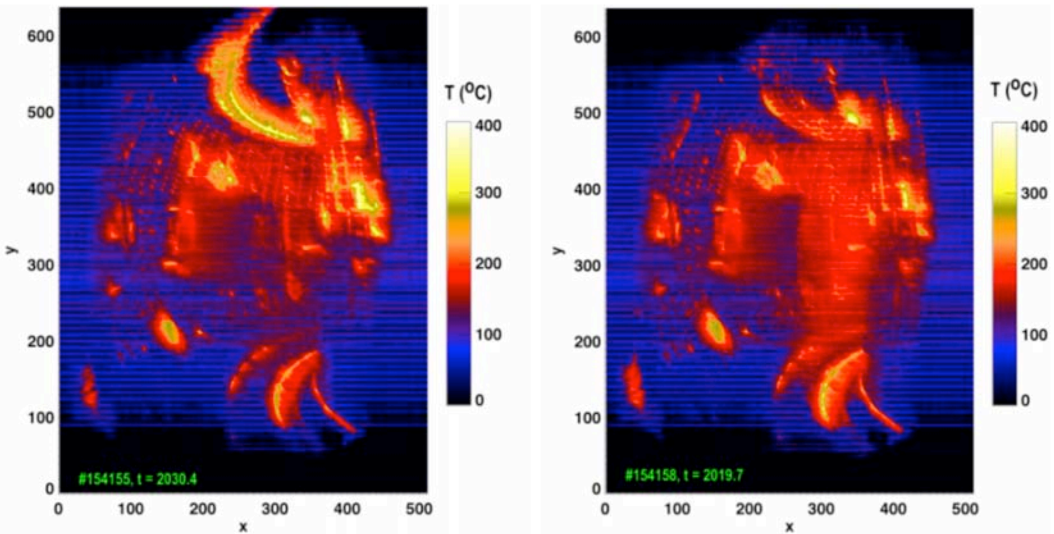
Specs: Massive gas injection and shattered pellet injection will be used to limit impacts of plasma current disruptions and suppress the formation and deleterious effects of high-energy runaway electrons.

Status: In Preliminary Design

- Massive gas injection developed and tested on ASDEX-U, C-Mod, DIII-D and JET
- Radiation asymmetry characterized
- Large valve developed for JET being redesigned for ITER use
- Shattered pellet injection tested on DIII-D
- Multiple barrel design being developed for ITER use
- ITER environment, delivery distance and required reliability and response time is a design challenge



No residual heat in upper divertor makes mitigation effect clearer: reduction in upper strike point T and increased main chamber T



Unmitigated upward VDE

Upward VDE mitigated 10 ms before VDE TQ time with upper MGI

Tokamak Exhaust Processing

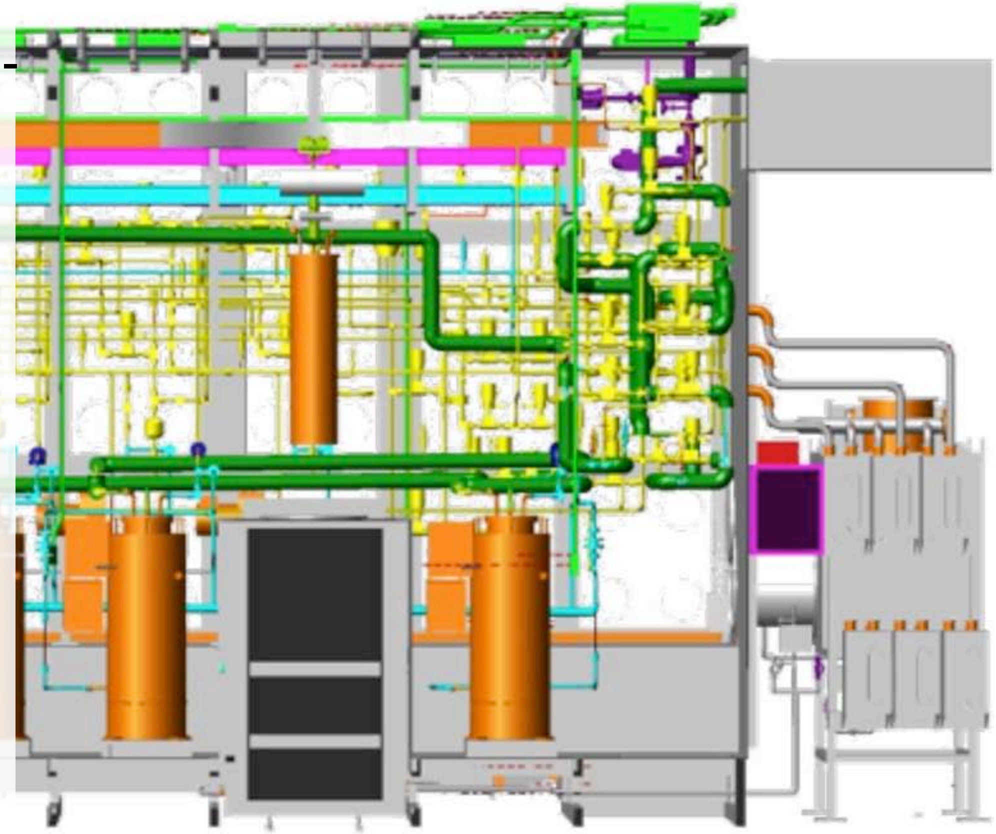
Specs:

- Separates hydrogen isotopes from non-hydrogen in the gas exhaust system
- Delivers hydrogen isotopes to EU's hydrogen isotope separation system

Key Contributor: SRNL

Status: In Preliminary Design

- IO task agreement for the preliminary design support signed by USIPO



Steady State Electrical Network

Scope: 75% of equipment

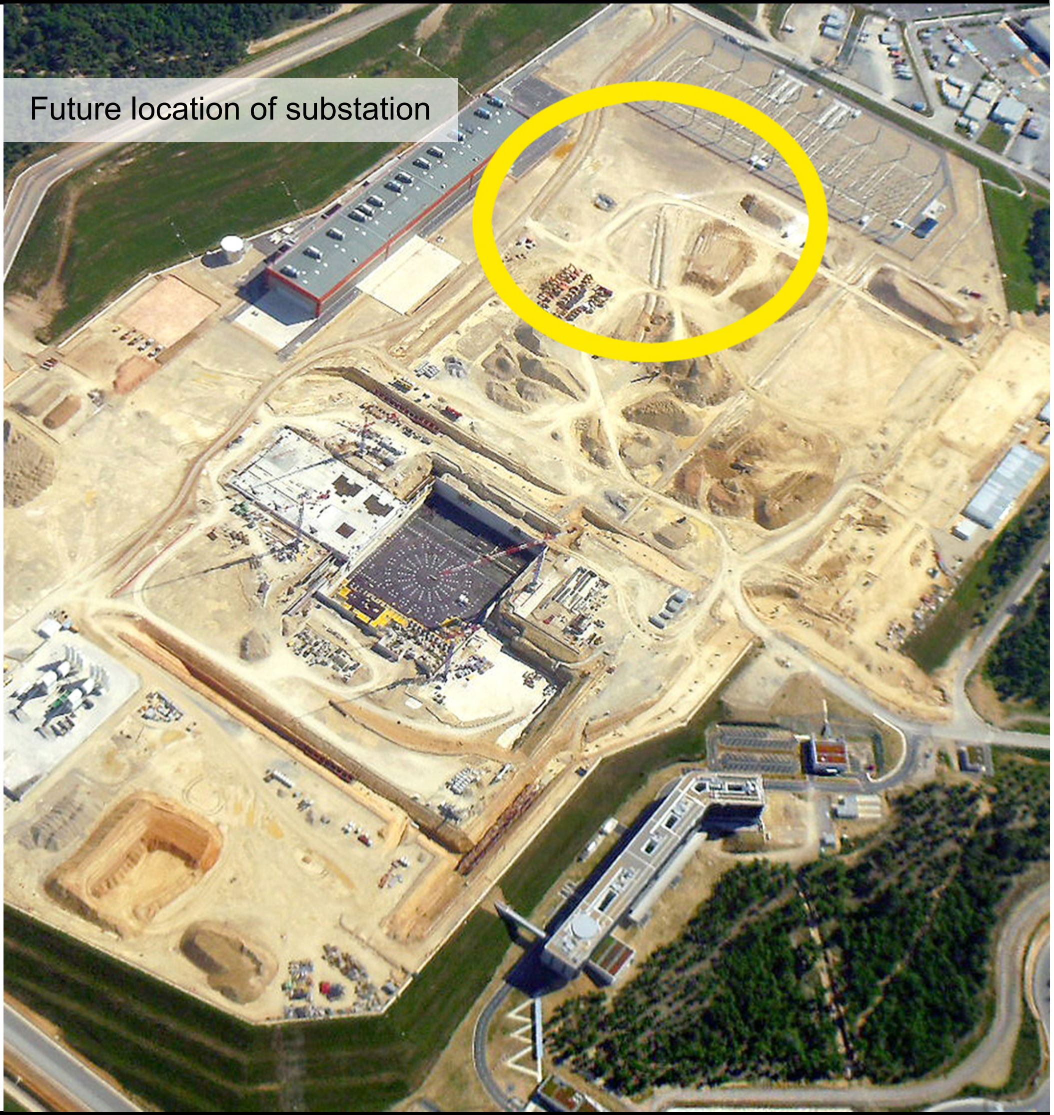
Specs:

- Supplies electrical power to all conventional loads in ITER facility

Key Contributor: PPPL

Status: In Fabrication

- Contracts awarded for:
  - HV switches
  - 22kV switchgear
  - HV current transformers
  - HV circuit breakers
  - HV potential transformers
  - HV surge arresters
  - HV substation hardware
  - HV substation transformers



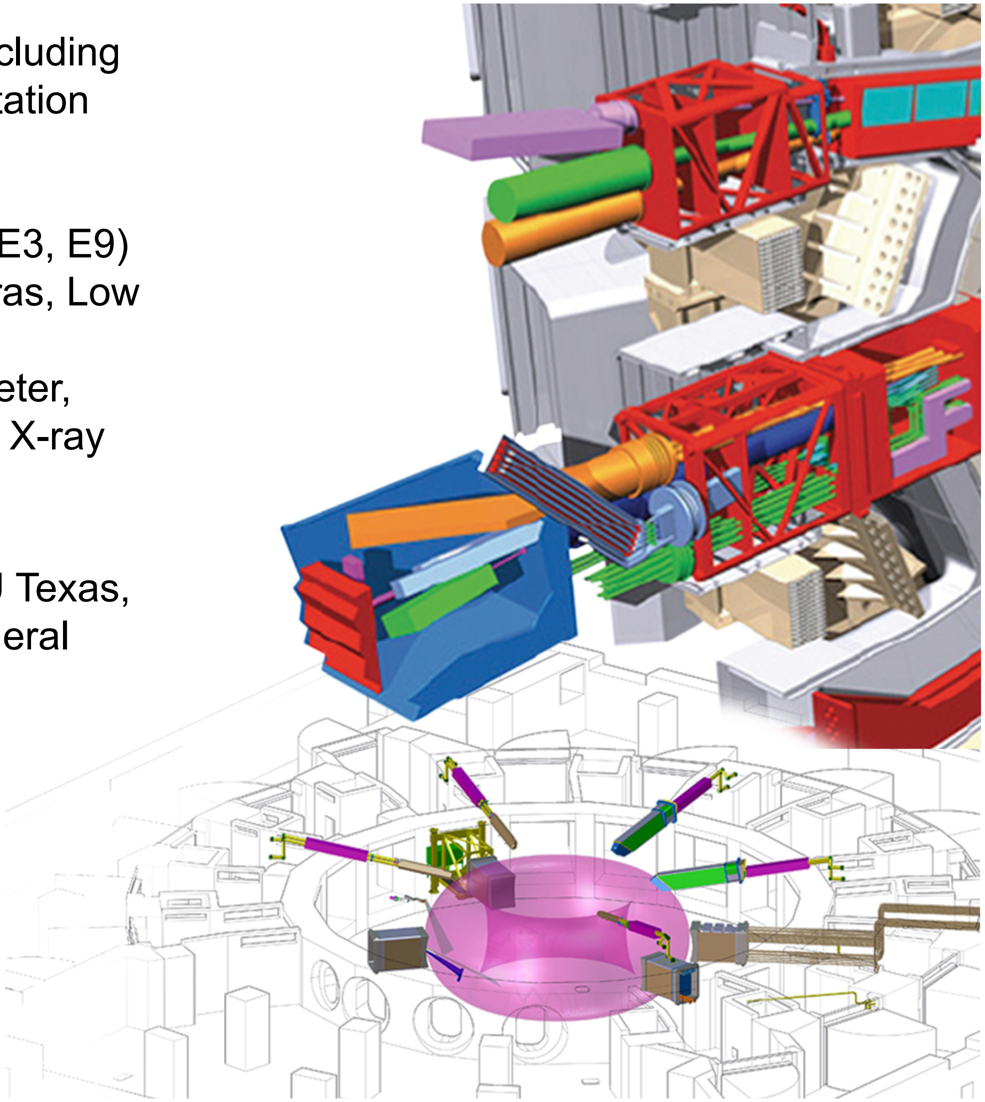
Diagnostics

Scope: 14% of port-based diagnostic systems, including integration of 4 diagnostic ports, plus 7 instrumentation systems

Specs: Ports: Upper (U11, U14) and Equatorial (E3, E9) Instrumentation Systems: Upper IR/Visible Cameras, Low Field Side Reflectometer, Motional Stark Effect Polarimeter, Electron Cyclotron Emission Radiometer, Toroidal Interferometer/Polarimeter, Core Imaging X-ray Spectrometer, and Residual Gas Analyzer

Key Contributors: PPPL, ORNL, LLNL, UCLA, U Texas, U Maryland, MIT, UC Davis, Nova Photonics, General Atomics, TNO

Status: In Preliminary Design, R&D Phase
Residual Gas Analyzer: PDR completed
All others: CDR completed
4 of 6 Procurement Arrangements signed
4 of 6 planned PPPL Procurements in process



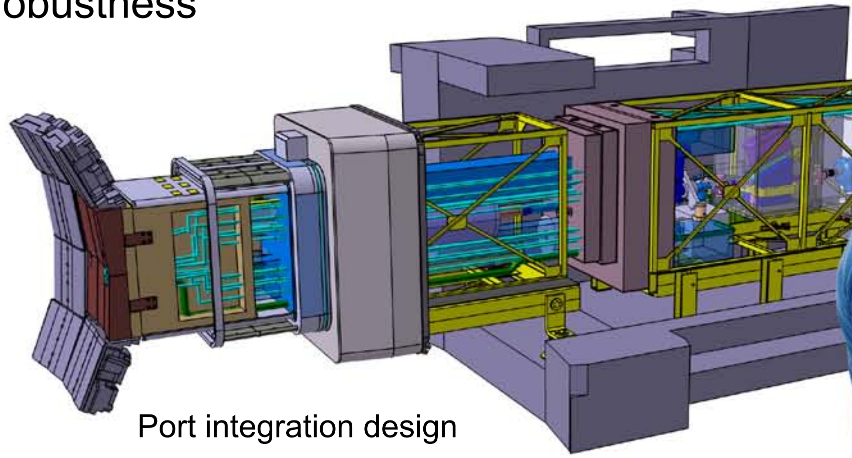
Diagnostic Port Plugs

Challenge

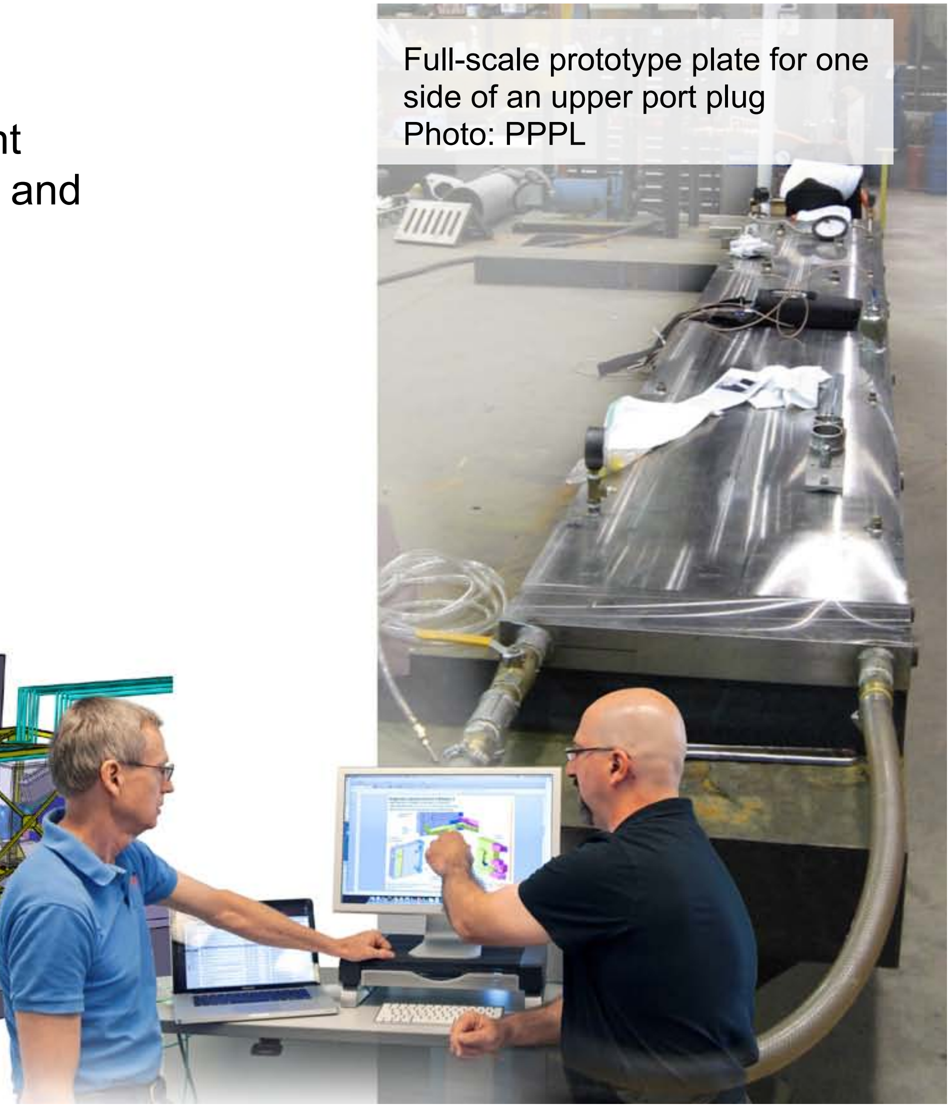
- Preserve diagnostic access and measurement capability while providing adequate shielding and enabling robotic maintenance

Solution:

- Standard diagnostic shield modules with detachable first wall panels
- Perform R&D to demonstrate scalability and robustness



Port integration design



Full-scale prototype plate for one side of an upper port plug
Photo: PPPL

Diagnostics
Low Field-Side Refectometer

Purpose:

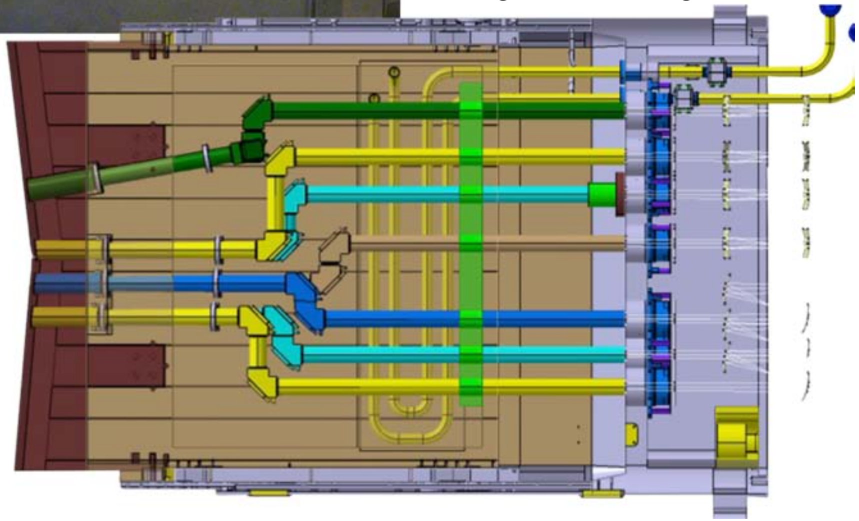
- Measuring edge electron density profile
- Monitoring small-scale turbulence, large-scale MHD modes and ELMs

Progress:

- Monostatic configuration demonstrated on DIII-D
- Antennae used for both launch and receive at different microwave frequency ranges
- Profile data obtained with high temporal and spatial resolution

View from plasma, the picture shows a monostatic antenna that sweeps over the frequency range within the Q-band and another that sweeps over the V-band range

Monostatic configuration design



US ITER Progress Summary

Procurement

- 83% (by value) of IO Procurement Arrangements signed
- 40% of major contracts awarded, totaling $369M (>35% of planned contracts value).

Design

- 49% (by value) complete
- 66% (by value) in final design phase
- 5,880 (of ~10,000) design documents in work, drafted, checked or complete (60%)
- $213 million in cost savings realized through value engineering

R&D

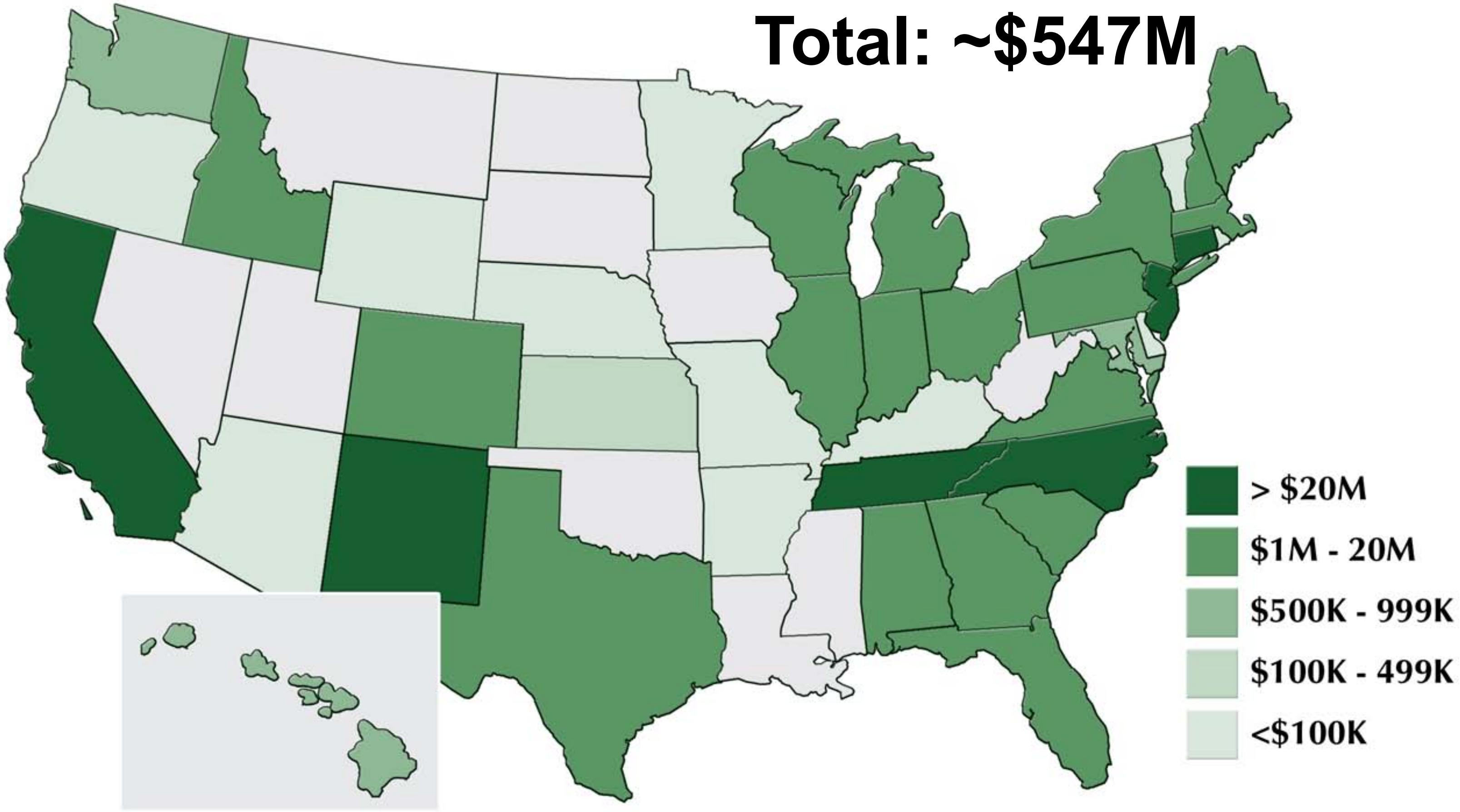
- 85% (by value) complete
- > 80 prototypes in development
  - Tritium-compatible roots and screw vacuum pumps
  - Cryo-viscous compressor vacuum pump/cold box
  - Massive pellet injection (MPI) gun in operation at D-IIID with shattered guide tube
  - MPI 3-barrel gun fabricated
  - Quartz and ceramic gas barriers for high power RF transmission fabricated
  - Water-cooled waveguide joints, switches, miter bends, expansion sections for high power microwave transmission fabricated

Fabrication

- Toroidal field strand production complete
- 12 (of 16) shipments of vacuum test equipment to ITER
- 5 cooling water drain tanks in production
- Central solenoid fabrication building occupancy-ready with 70% tooling contracts awarded

Over 80% of Project Funding will be Spent in the US

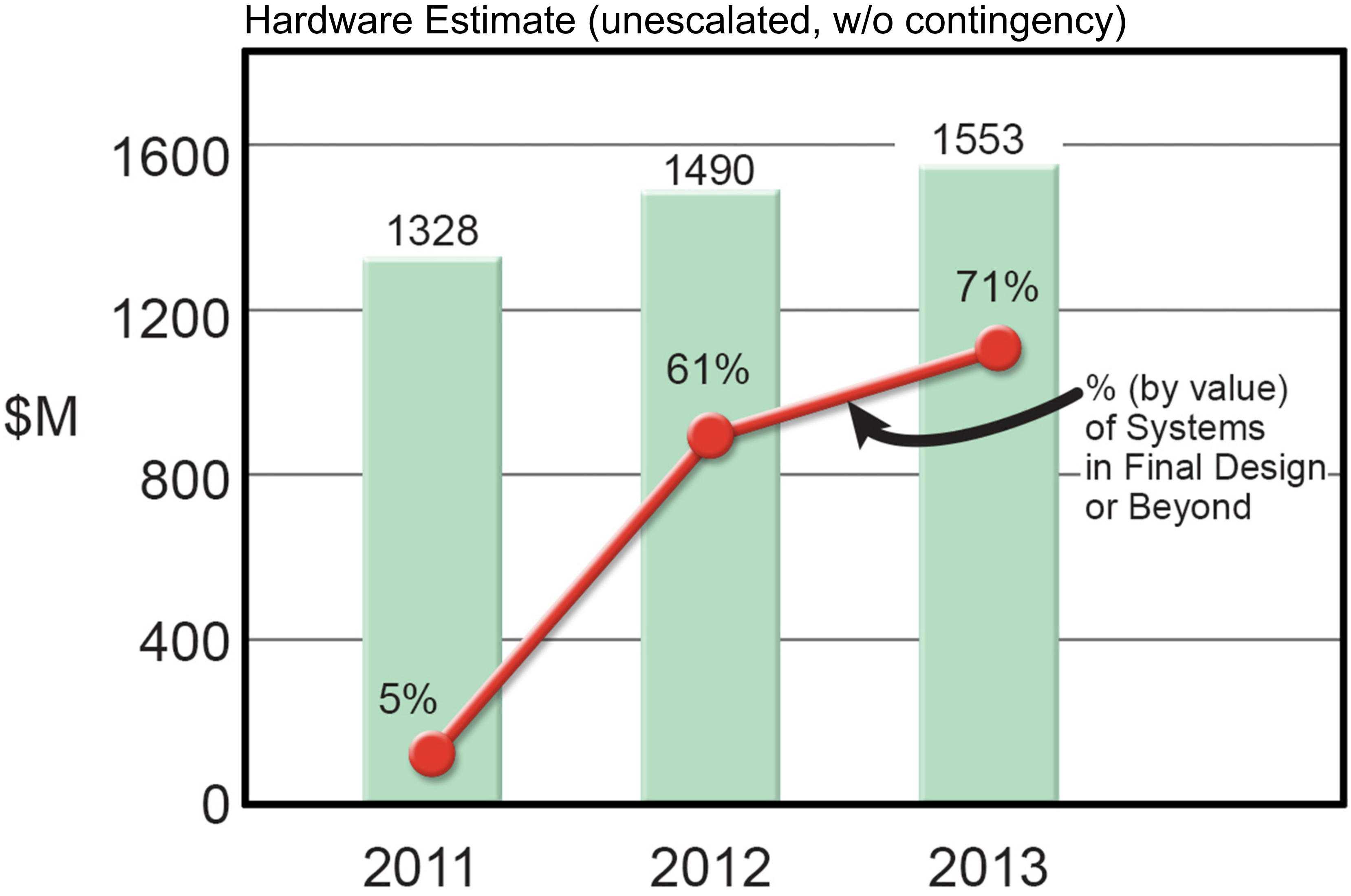
As of September 2013, over $547M has been awarded to US industry, universities and obligated to DOE national laboratories in 39 states plus the District of Columbia.



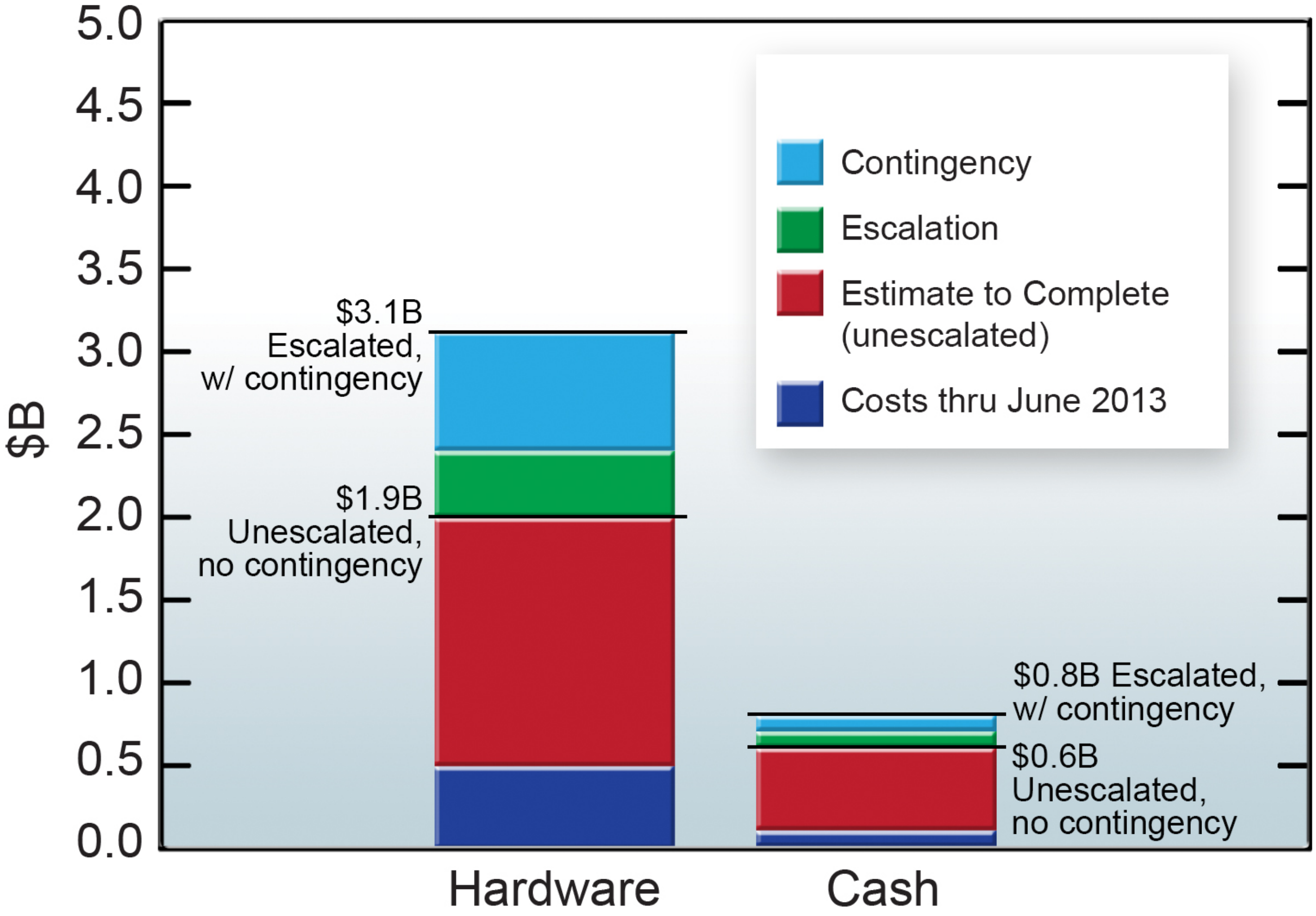
Total: ~$547M

This data does not reflect contracts awarded to US Industry by the EU (>$55M) or Korea (>$23M).

Unescalated Hardware Estimates Have Increased Modestly with Design Maturity



Cost Elements



Cost Elements