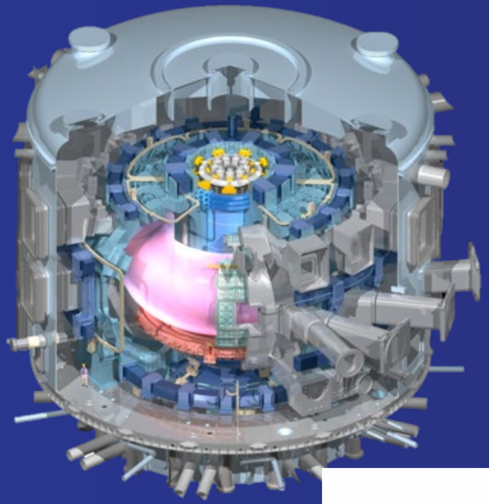
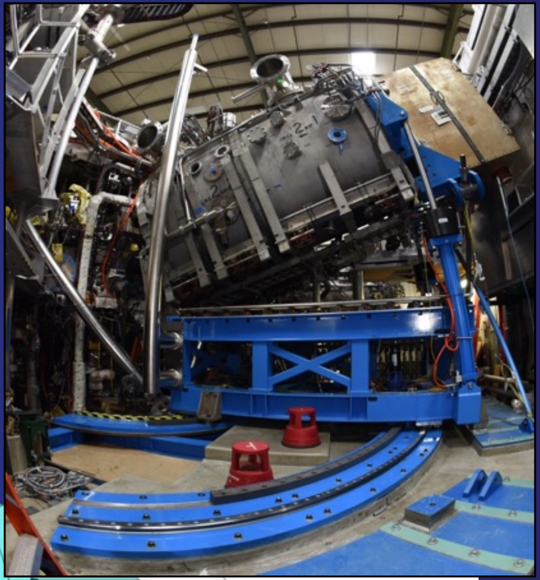
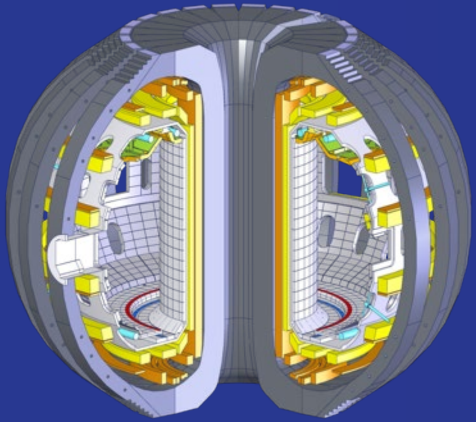
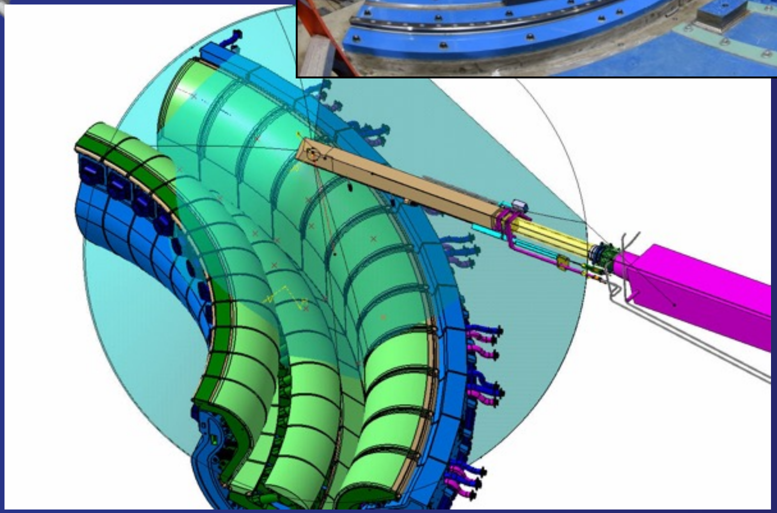
DIII-D and ITER: Latest Experimental Plans and Diagnostic Development









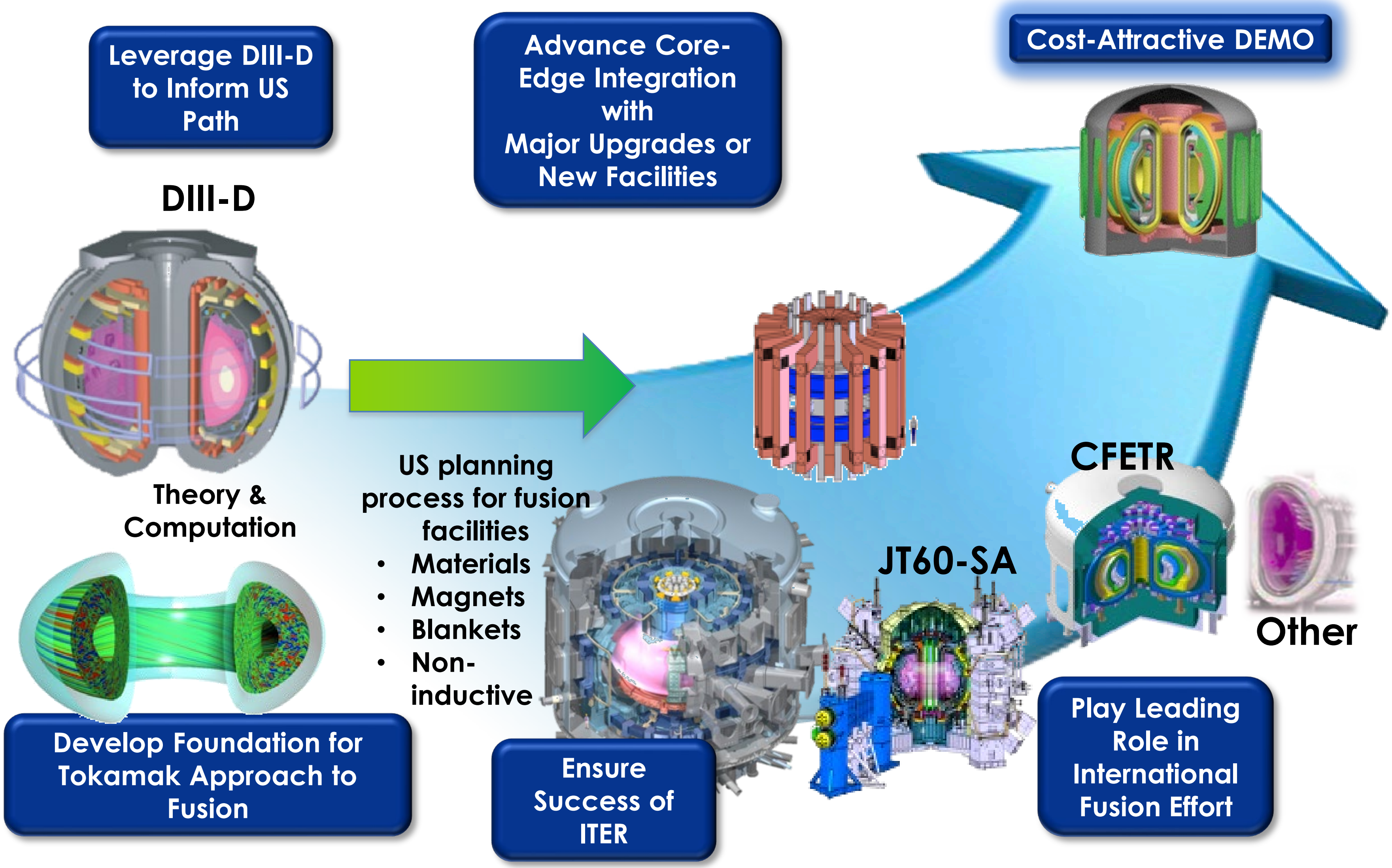
R. Boivin, General Atomics

LLNL, April 25th 2019

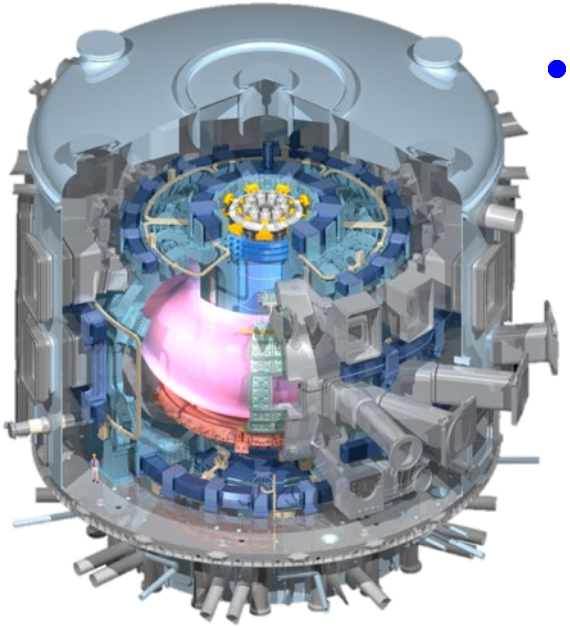
Outline

- Latest plans from DIII-D
- Status of ITER project
- Diagnostic Developments in MFE and connections with ICF diagnostic R&D

DIII-D Program Is Based on Scientific Research and Discovery in Support of an Energy Goal



DIII-D Mission



- **Make ITER better**
  - Prepare for effective operation & scientific exploitation
- **Path to a steady state reactor**
  - Establish physics & technical basis

Common Critical Physics

- *Burning plasma conditions*
- *Transients (stability, ELMs, disruptions)*
- *Self-consistent fully non-inductive*
- *Integrated core-edge solution*

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DIII-D Five-Year Research Plan Focuses On Key Challenges Facing Future Burning-Plasma Experiments

- **<u>Fusion alphas heat electrons, rather than the ions</u>:**
  changing character of turbulent energy transport

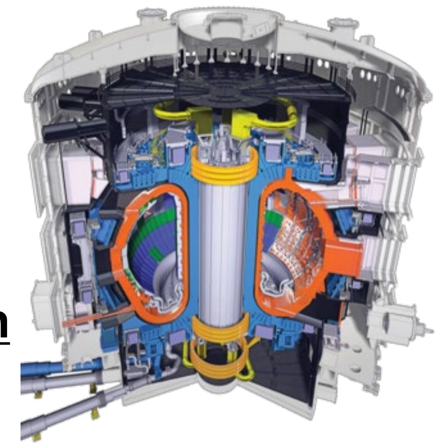
- **<u>High-β Steady-state regimes with broader current profiles</u>:**
  macroscopic stability, 〈 confinement, and turbulent transport

- **<u>High-β, low collisionality core, bounded by sharp transition to cold Scrape-Off-Layer (SOL)</u>:**
  pedestal stability, fueling, and impurity screening

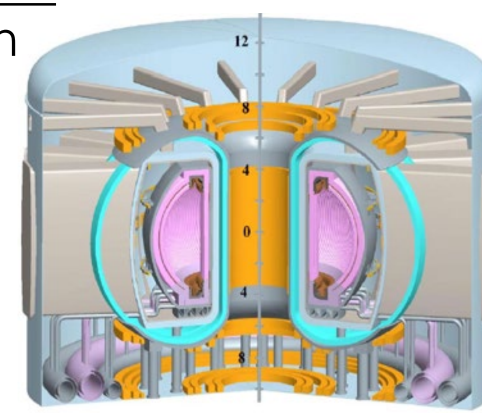
- **<u>Steady-state heat flux SOL connected to material surfaces</u>:**
  heat flux & particle control, material erosion/migration contamination

- **<u>Fusion technology in reactor environments</u>:**
  plasma control, H & CD systems, PFCs and materials

ITER



DEMO



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DIII-D Program Addresses High-Impact Challenges for Fusion Spanning From Core to Divertor and Plasma-Facing Components

Research Program Elements → **Predictive Understanding**

- **Scientific Basis for Burning Plasma Core**
  - Transient Control
  - Enabling ITER Q=10
  - Path to Long Pulse

- **Scientific Basis for Boundary Solutions**
  - Detachment control
  - Divertor optimization
  - Test new wall materials

Core-Pedestal-Boundary Integration

- **Integrated Approach to Physics Interpretation**
  - Innovative diagnostics
  - High-performance computing
  - Experiments targeting model validation

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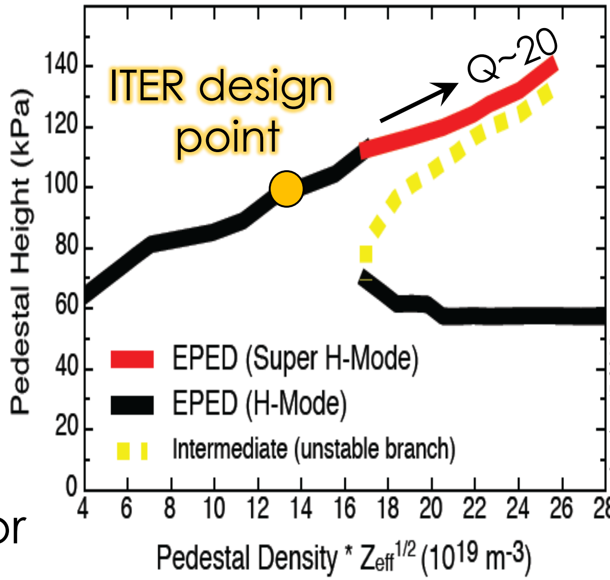
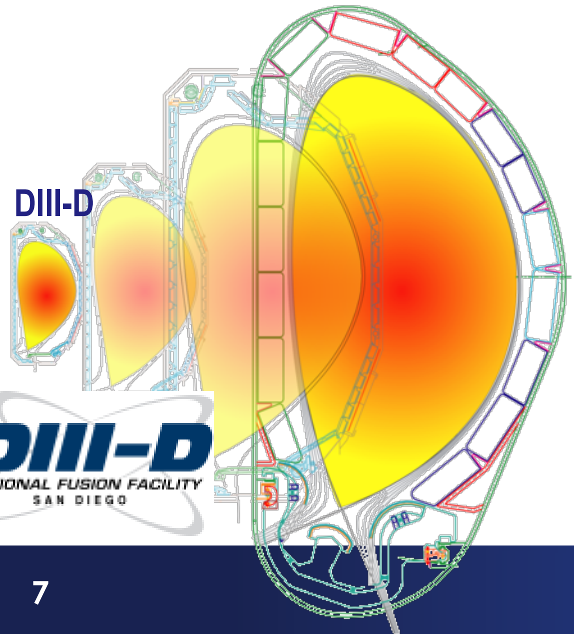
DIII-D Key Goal: To Enable ITER's Success

- **Make ITER work – Make ITER <u>better</u>**
  - Physics to raise performance
  - Stable, ELM controlled regimes
  - Disruption mitigation
- **Validate simulation to design discharges**
  - Gain U.S. leadership on ITER
  - Provide predictive tools for U.S. reactor



Improved pedestal may raise ITER Q



- **Resolve ITER issues when it is running**
  - High flexibility: can be rapidly configured & deployed
- **DIII-D is the U.S.'s ITER simulator**
  - Relevant collisionality, ω, T_e/T_i, β, q_{95}, shape, aspect ratio & control

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A High Level Goal of the DIII-D Research Program is to Ensure the Success of ITER's Q=10 Mission

ITER baseline confinement

- **Key challenge: Maintain high confinement and robust stability at low torque with dominant electron heating, integrated ELM and heat flux control, disruption avoidance**

- **Requires predictive understanding to rapidly advance ITER research and optimize (Q>10)**

- **DIII-D has unique capabilities and flexibility to develop the physics basis and operational know-how for ITER**
  - Low torque, high power (balanced NBI, ECH)
  - Low collisionality
  - Dominant electron heating (ECH, helicon, LH)
  - ELM control techniques (3D, RMP, QH, pellets)

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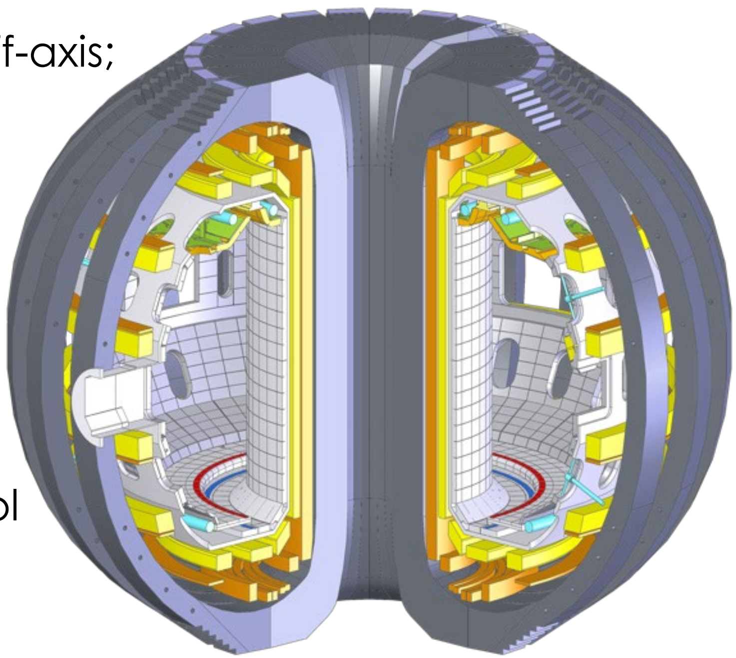
System Capabilities

Heating and Current Drive (injected power/pulse)

- **NB: 8 sources; 16 MW (4 s) / 19 MW (3 s)**
  - 4 co- sources on axis; 2 co- sources 0 -16.4° off-axis;
  - 2 co/counter sources fixed @18.4° off-axis
- **EC: 4 gyrotrons: 2.4 MW (5 s);**
  - 8 steerable outside launchers,
    1 fixed Top launch



Coils

- **18 Poloidal field shaping coils**
- **6 external coils, 12 internal coils**
  - Error field control, RWM feedback, ELM control

Divertor/First Wall

- **Open Lower Divertor - 1 cryopumps; 20,000 ℓ/s**
- **Closed Upper Divertor – 2 cryopump 15-20,000 ℓ/s**
  - Small Angle Slot Divertor in upper divertor (no pumping)
- **ATJ graphite — 90% coverage**

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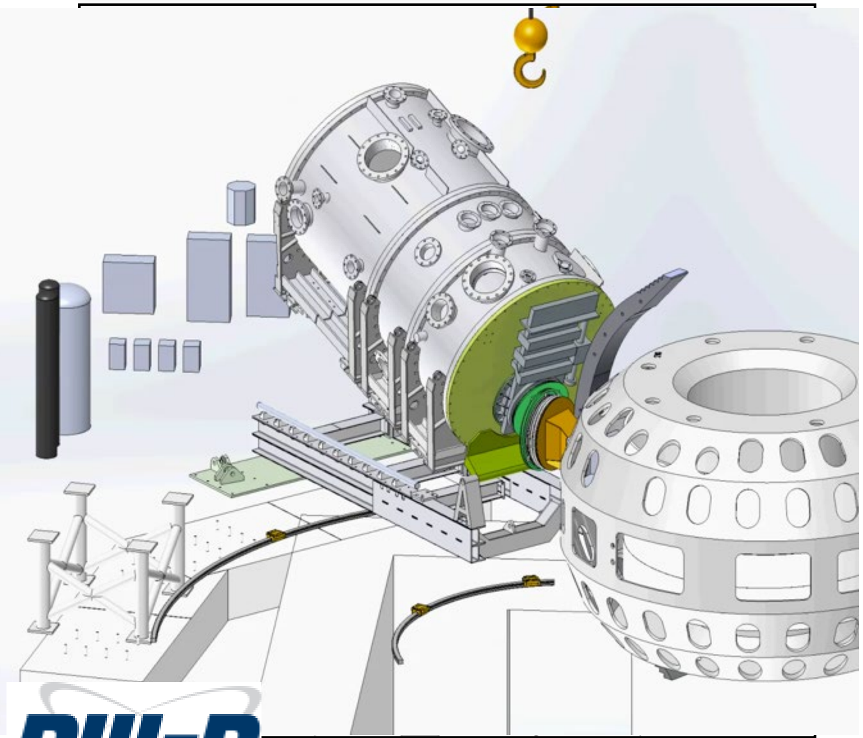
One-year Long Torus Opening Provides Major Capability Improvements

Operations to resume May 2019

210 Co-counter OANB #2:



- Install worlds first co-counter Off-Axis Beam
- Optimize alignment of upper SAS tiles with associated diagnostic upgrades
- New Top-launch ECCD system, new 117GHz gyrotron, replacement tubes
- High Power Helicon CD system ready for operation in January 2020

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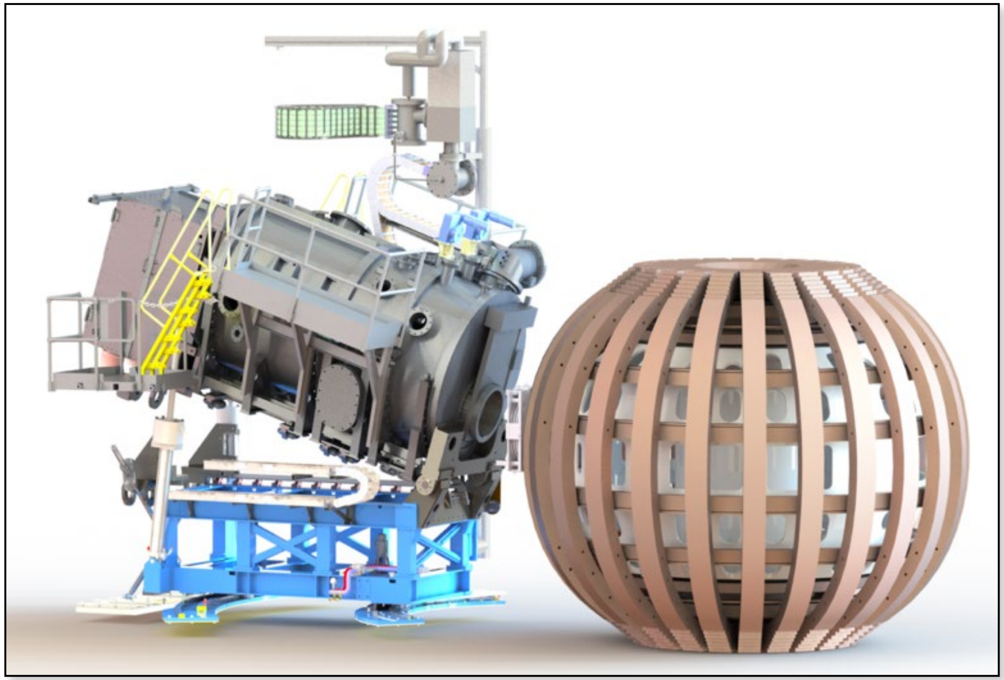
New Co-Counter Off-Axis Beam is Critical for Advancing DIII-D Research Program

- **Better tailor current and pressure profile to maximize beta limits**
- **Explore trade-offs in stability, confinement, energetic particle transport, current drive, and power exhaust**
- **Capability for counter injection retains key flexibility for exploring ITER issues (low torque)**



DIII-D
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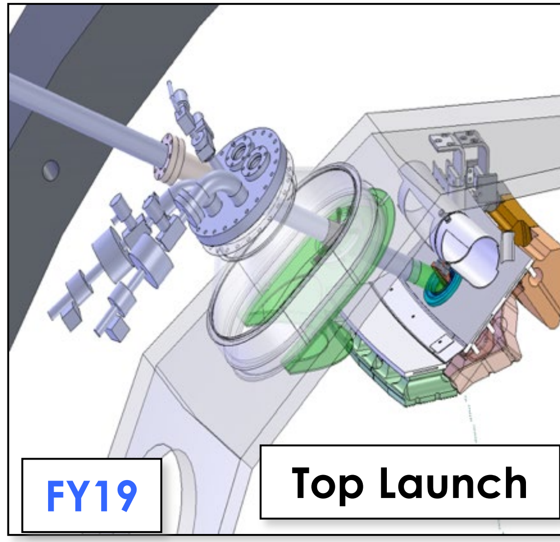
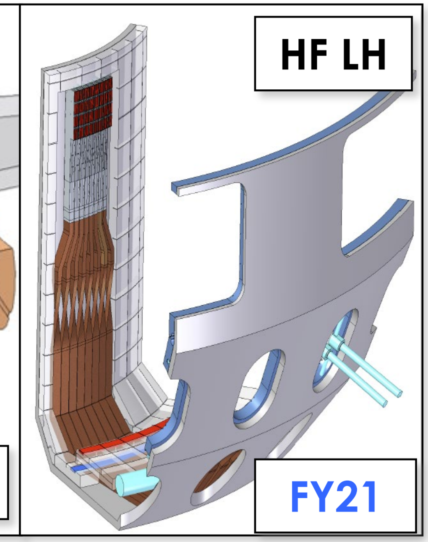
DIII-D Will Test Innovative New Current Drive Solutions that Can Improve Power Plants Efficiency

- **Top Launch ECCD uses large Doppler shift and greater absorption to double efficiency (110GHz)**
  - Compare experimentally
- **Evaluate potential of helicon (476 MHz)**
  - Antenna technology, wave launch and propagation, evolution and damping
- **Improve current drive efficiency with high-field side launch (Lower Hybrid)**





DIII-D Has a Path to Provide Vital Foundation for ITER and Develop Basis to Establish Path to Fusion Energy

2018 2020 2022 2024

ITER remains priority #1

Disruptions, stability ELM control

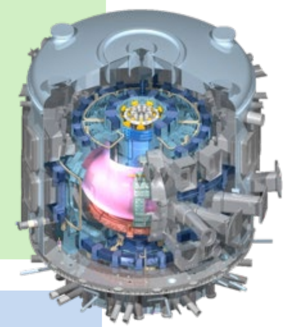
Resolve predictive burning plasma transport models

Know-how to run and exploit ITER

Increasing ECH → 9 MW

3D optimization of the tokamak

ITER detachment control



Steady State Path to Fusion Energy

AT core physics relevant regimes

ECH, LH, helicon → β_N=5 & low Ω burn

NBI: off-axis…

NBI energy & pulse length…

Balanced beams

Core-edge integration → High power

Basis to decide future reactor

Pedestal & neutral diagnostics

Divertor physics

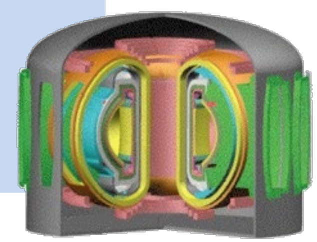
Integrated physics tests

SAS 1 Diagnostics SAS-2 upper

Materials Materials facility

SiC limiters

New wall material



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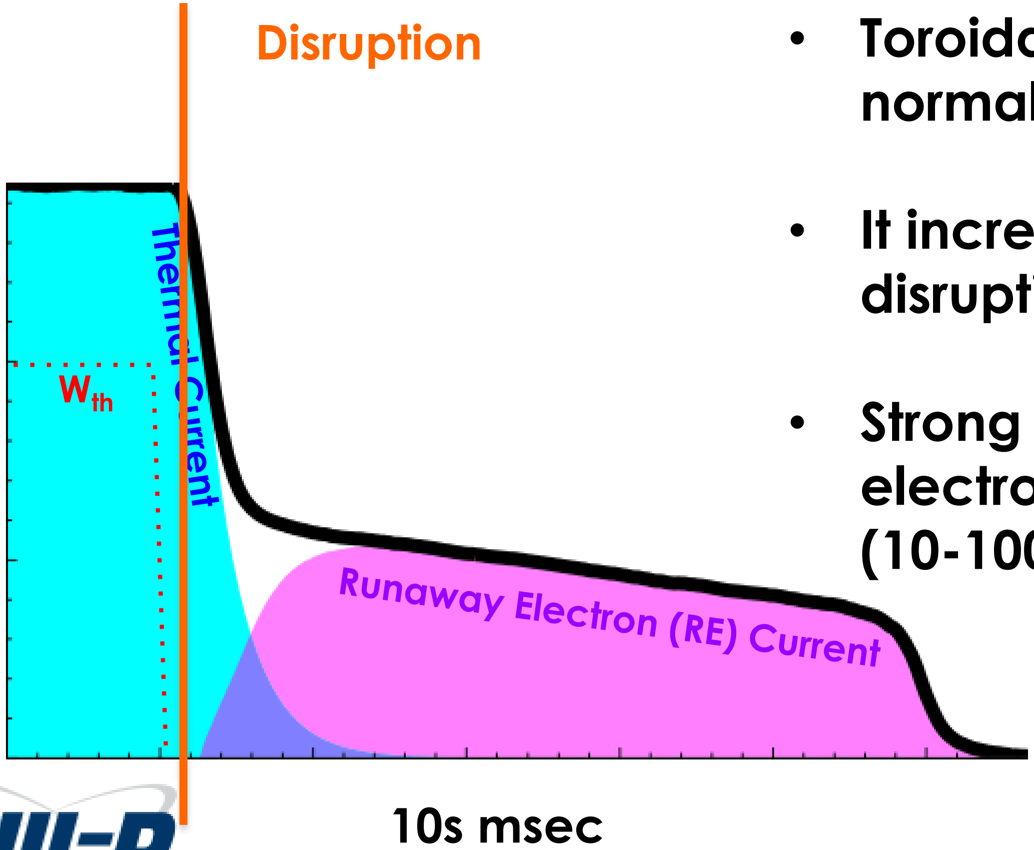
Runaway Electrons Can Be Produced by Strong Electric Field During Disruptions

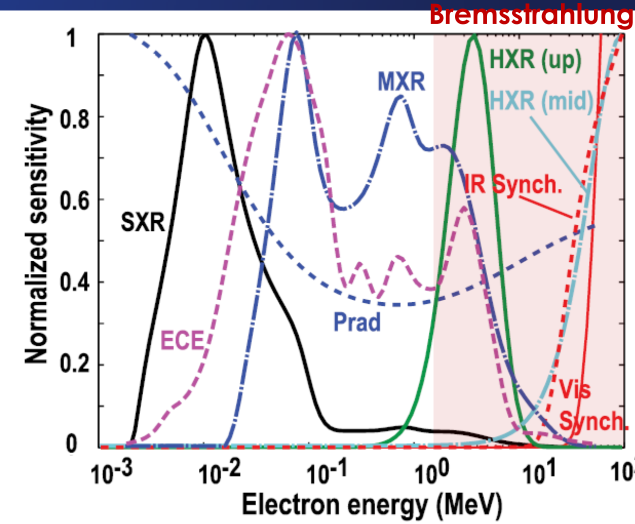
Ensuring Effective Disruption Mitigation Remains Major Challenge for tokamaks



- Toroidal electric field is small during normal discharges (~0.1 V/m)
- It increases by x100 in tokamak disruptions
- Strong electric field can accelerate electrons up to relativistic energies (10-100 MeV)

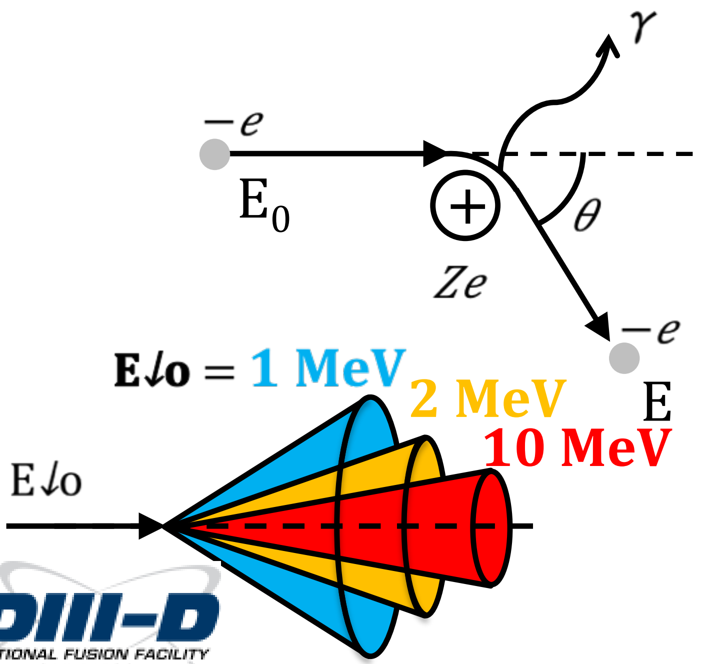
REs are Observed by their Emission of Radiation

Electrons are observed by their emission of
- **Cyclotron radiation (mm waves, antennas)**
- **Synchrotron radiation (infrared waves, CCD cameras)**
- **Bremsstrahlung radiation (gamma rays, scintillators)**



Hollmann et al. PoP 2015

Relative sensitivities of DIII-D diagnostics to RE energy



- **γ rays are emitted in cones based on RE energy**
- **$f_e(E_\parallel, E_\perp)$ produces unique bremsstrahlung spectrum**
- **Measurement of bremsstrahlung radiation can provide information on RE distribution, RE energy, and energy evolution**

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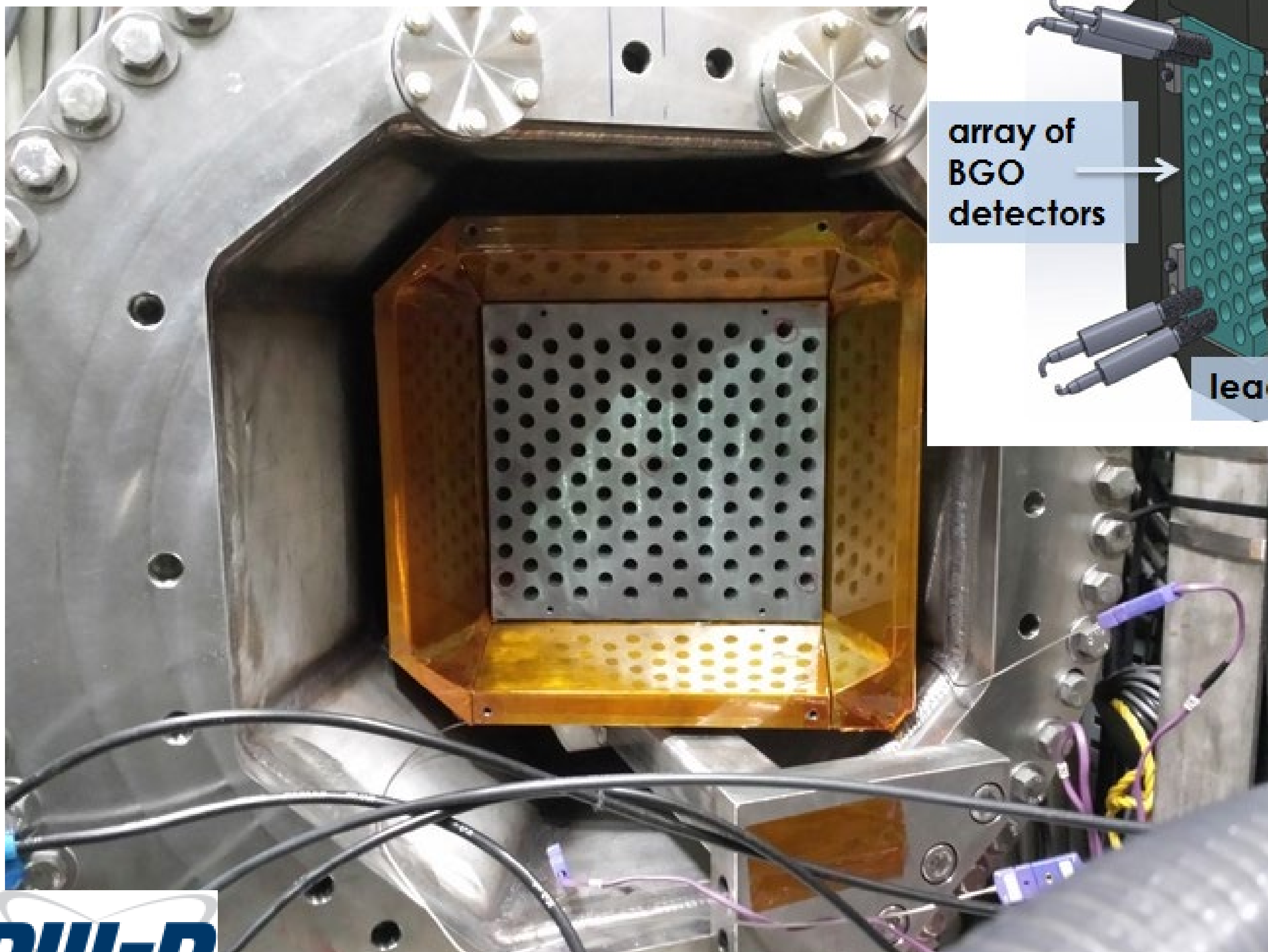
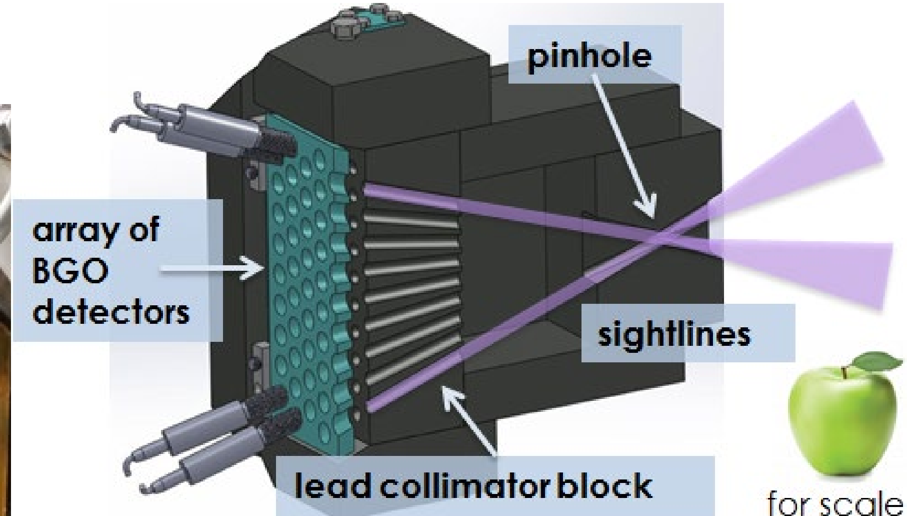
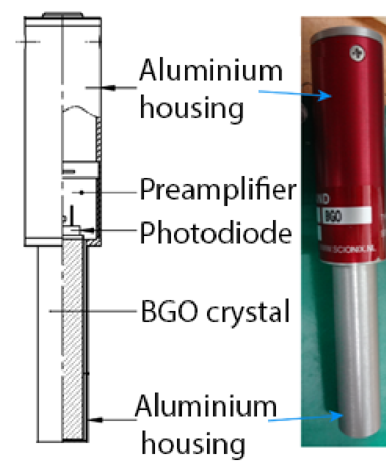
Detecting Gammas Require a Very Good Collimator





BGO detector



Upgraded detectors: LYSO ($Lu_{1.8}Y_{0.2}SiO_5$:Ce)

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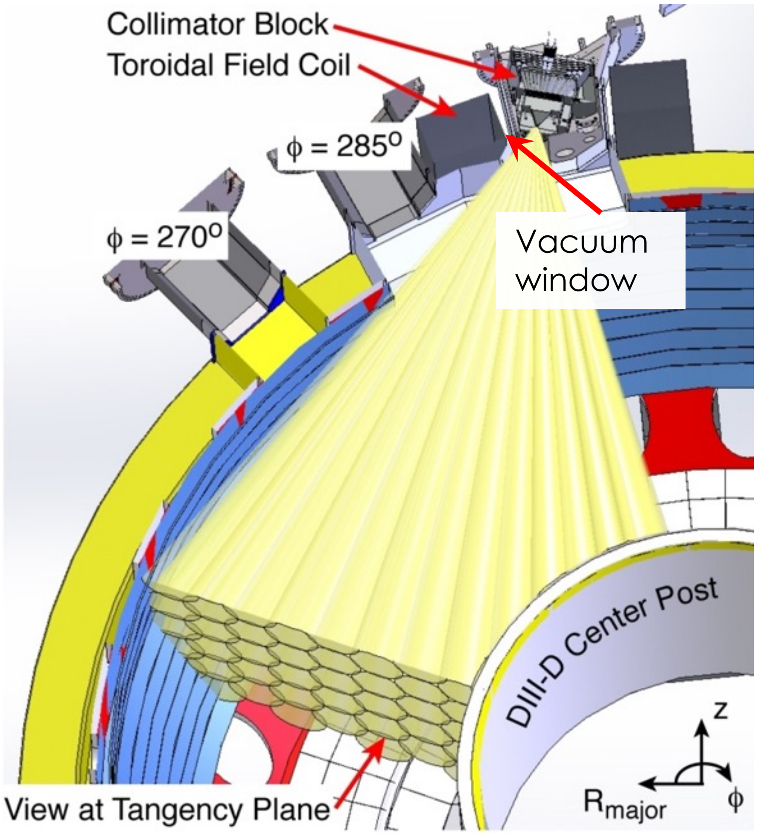
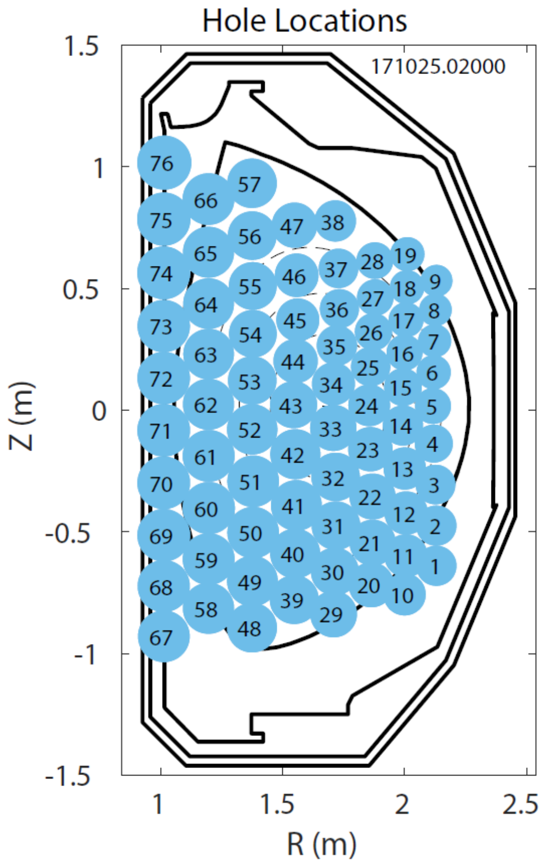
DIII-D Gamma Ray Imager Spans Entire Plasma Poloidal Cross-section



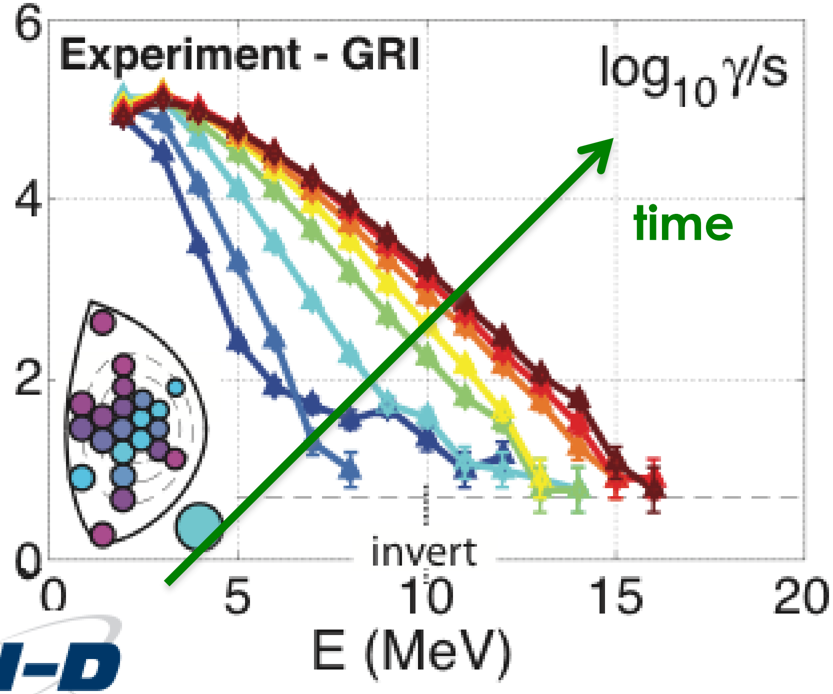
DIII-D toroidal cross-section

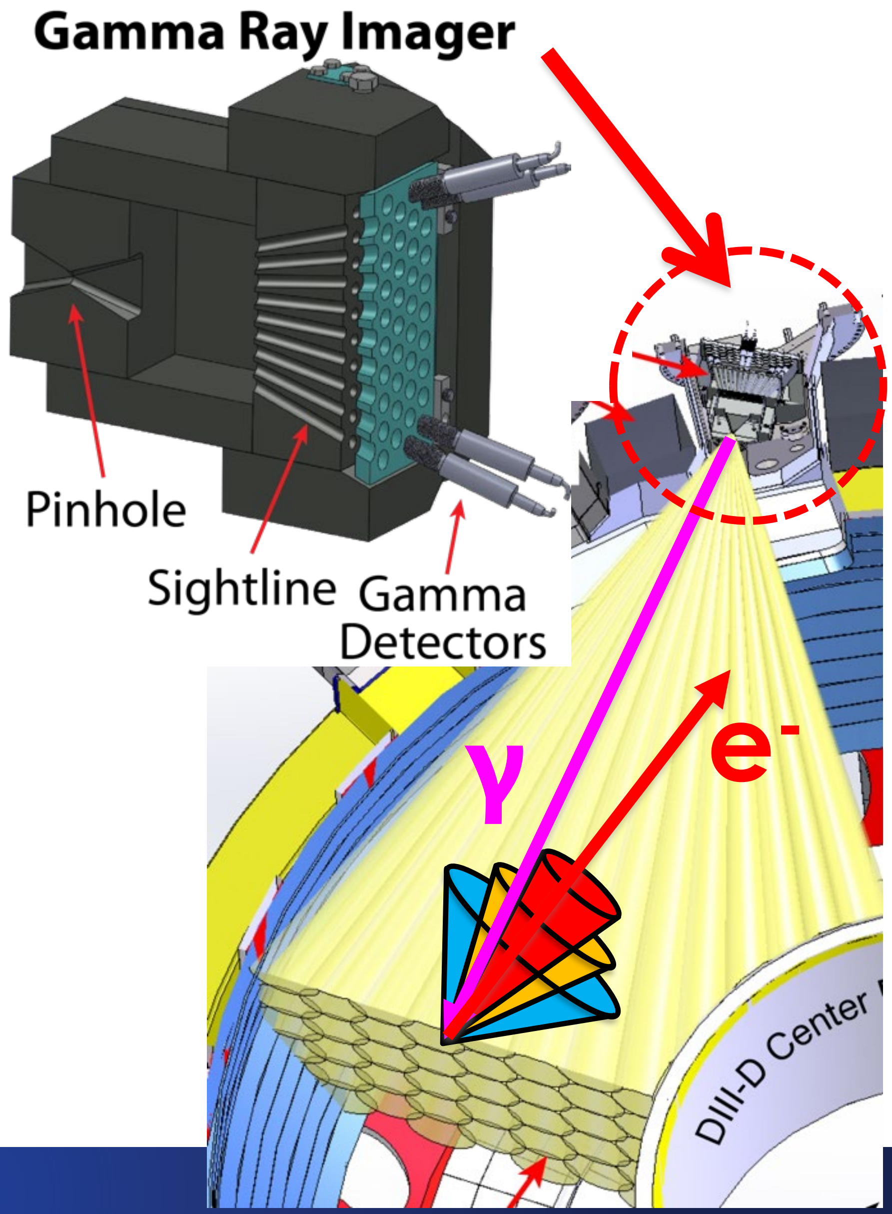


DIII-D poloidal cross-section

Gamma Ray Imager (GRI) Measures Emission from Main Part of RE distribution

- **Pinhole camera made of lead digitizes individual HXR pulses**
- **Binning in time demonstrates energization of HXR population:**





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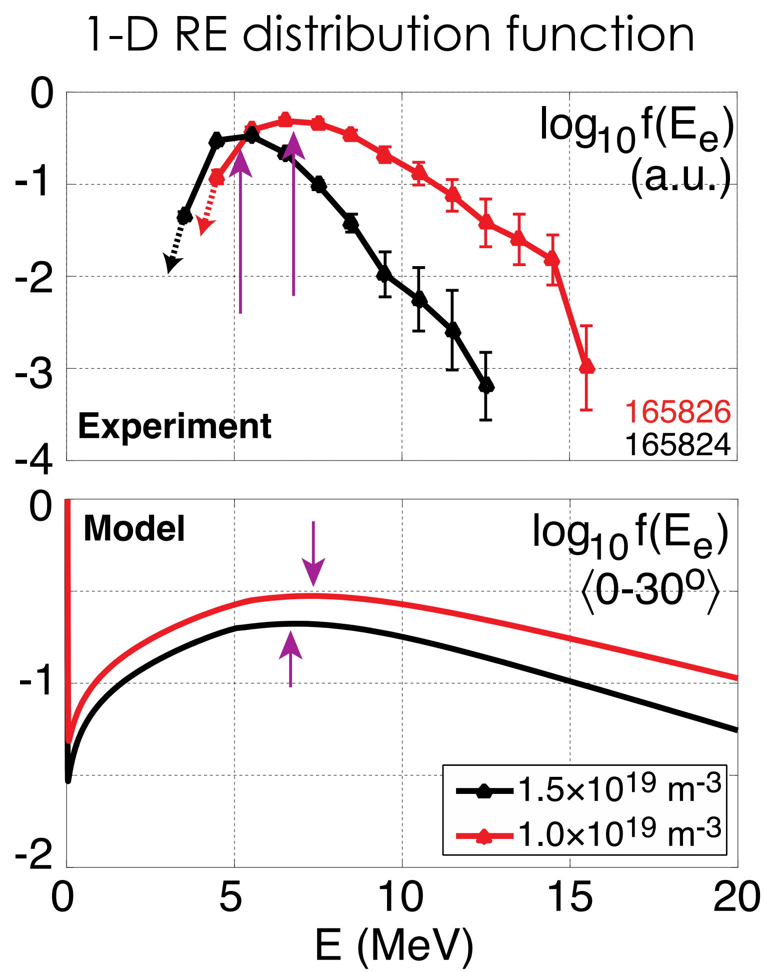
Comparison of Experimental and Theoretical Distribution Function Reveals Partial Agreement

- **Modeled and experimental distributions both peak at similar energies (~ 7 MeV)**
  - No free parameters in model
- **RE spectrum is narrower in experiment than in model**
- **Increasing collisions reduces RE energy and reduces energy of peak by 1-2 MeV**



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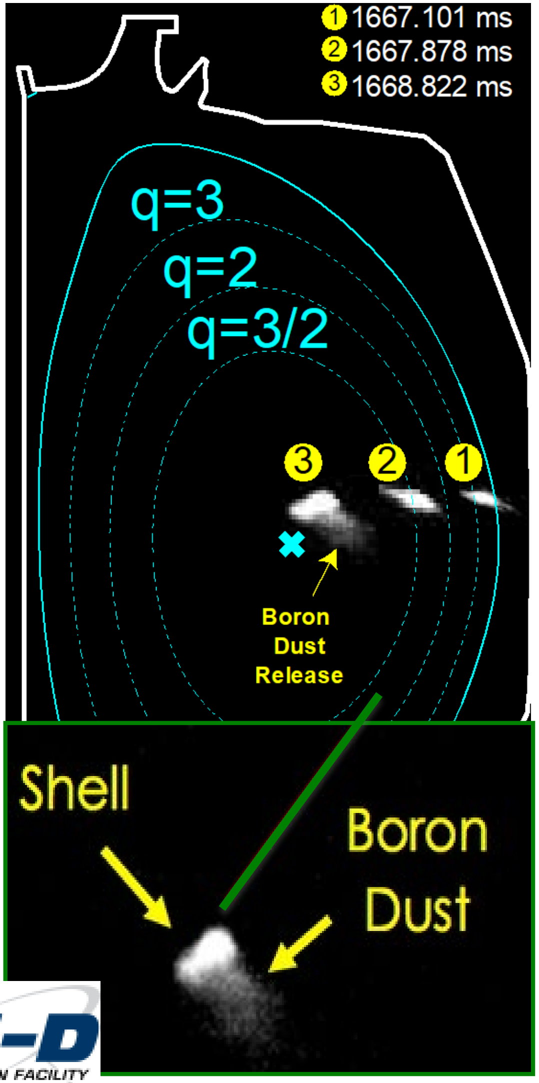
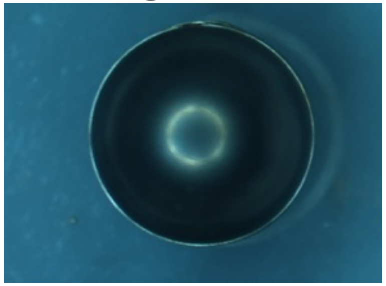
Boron Filled Shell Pellets Injected in H-mode Plasma Can Be Used for Disruption Mitigation



- Impurities transported to core inside shell

- Core ablation releases impurity payload and
  induces "inside-out" Thermal Quench
- Advantages for Thermal Quench, Current Quench and Runaway seed suppression

- High priority for FY19-20 experiments



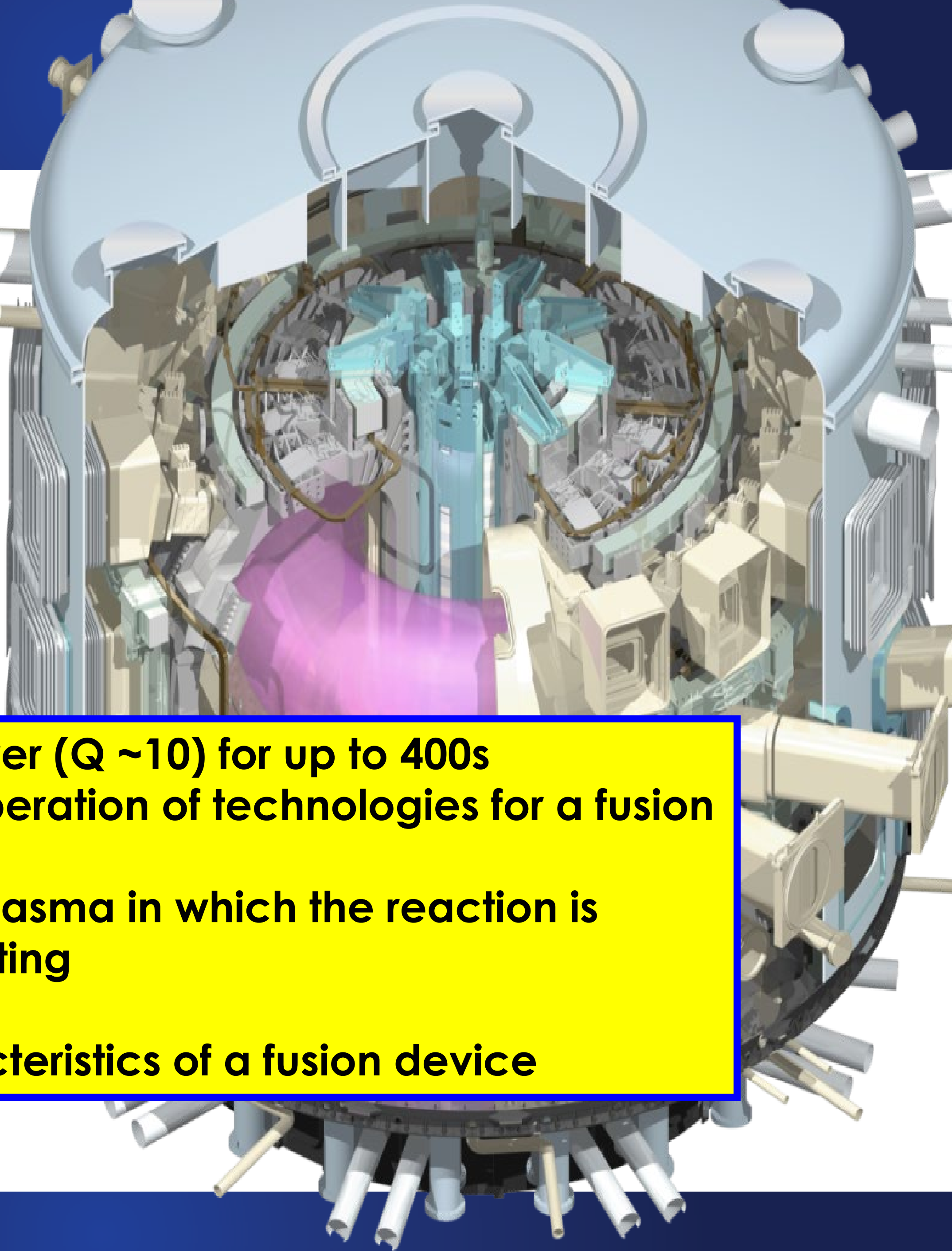
3.6 mm

X-ray image of boron-filled 40 μm thick diamond shell

ITER mission

To demonstrate the scientific and technological feasibility of fusion power

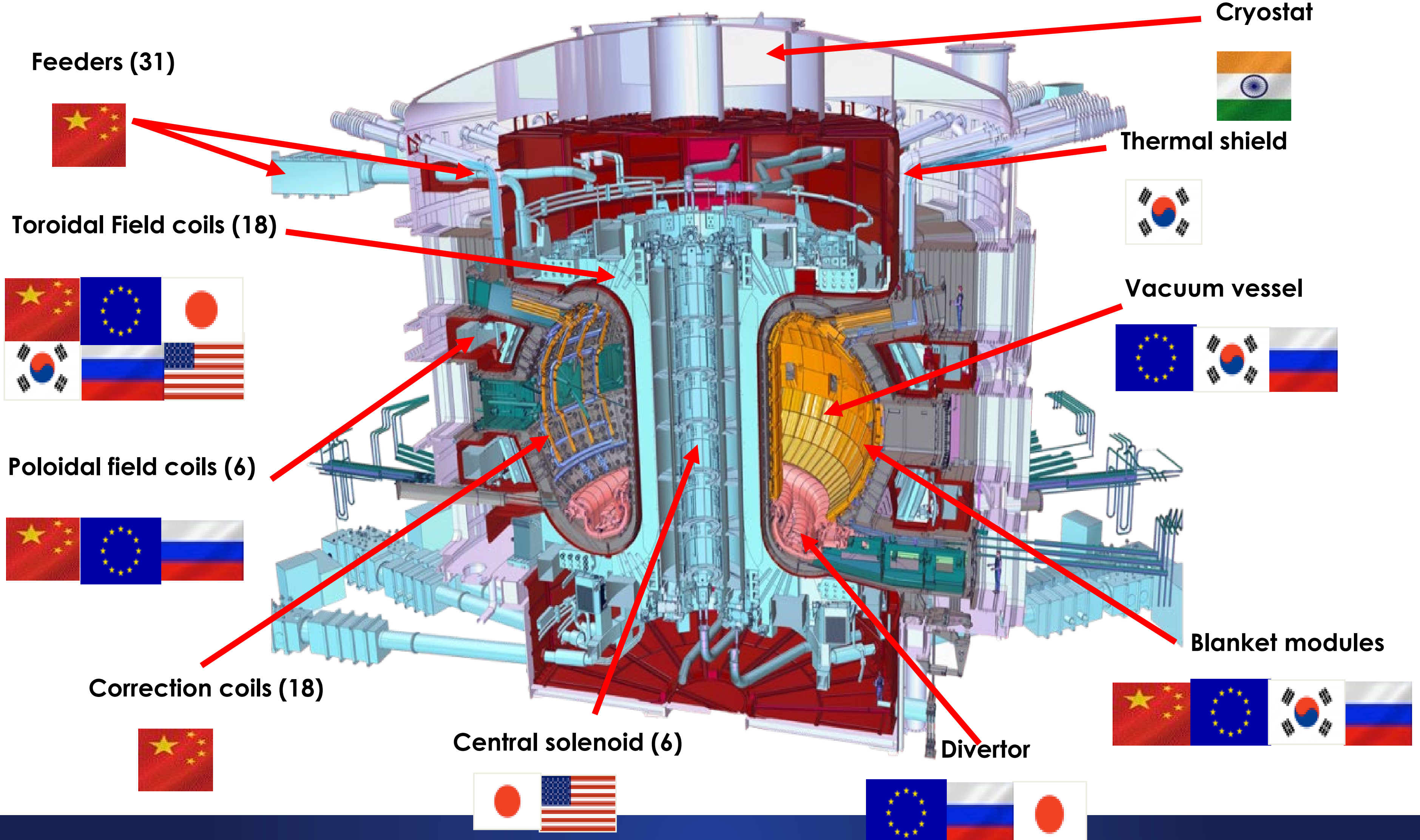
ITER is the only magnetic fusion device under construction aimed to produce a burning plasma.



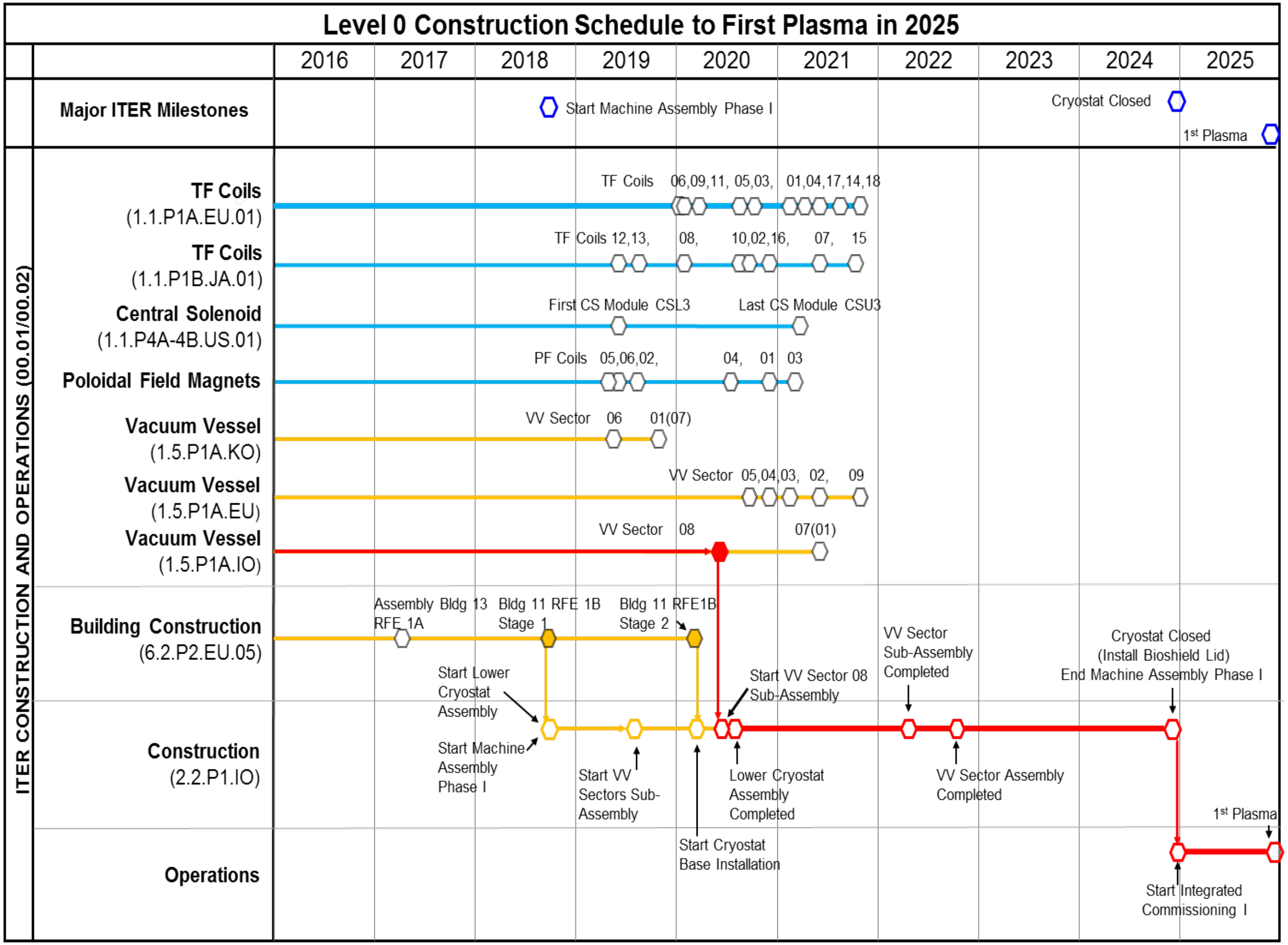
1) Produce 500 MW of fusion power (Q ~10) for up to 400s
2) Demonstrate the integrated operation of technologies for a fusion power plant
3) Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating
4) Test tritium breeding
5) Demonstrate the safety characteristics of a fusion device

The ITER Members Share The Tasks of Constructing Components

Nearly 80% of the components represent procurement in kind

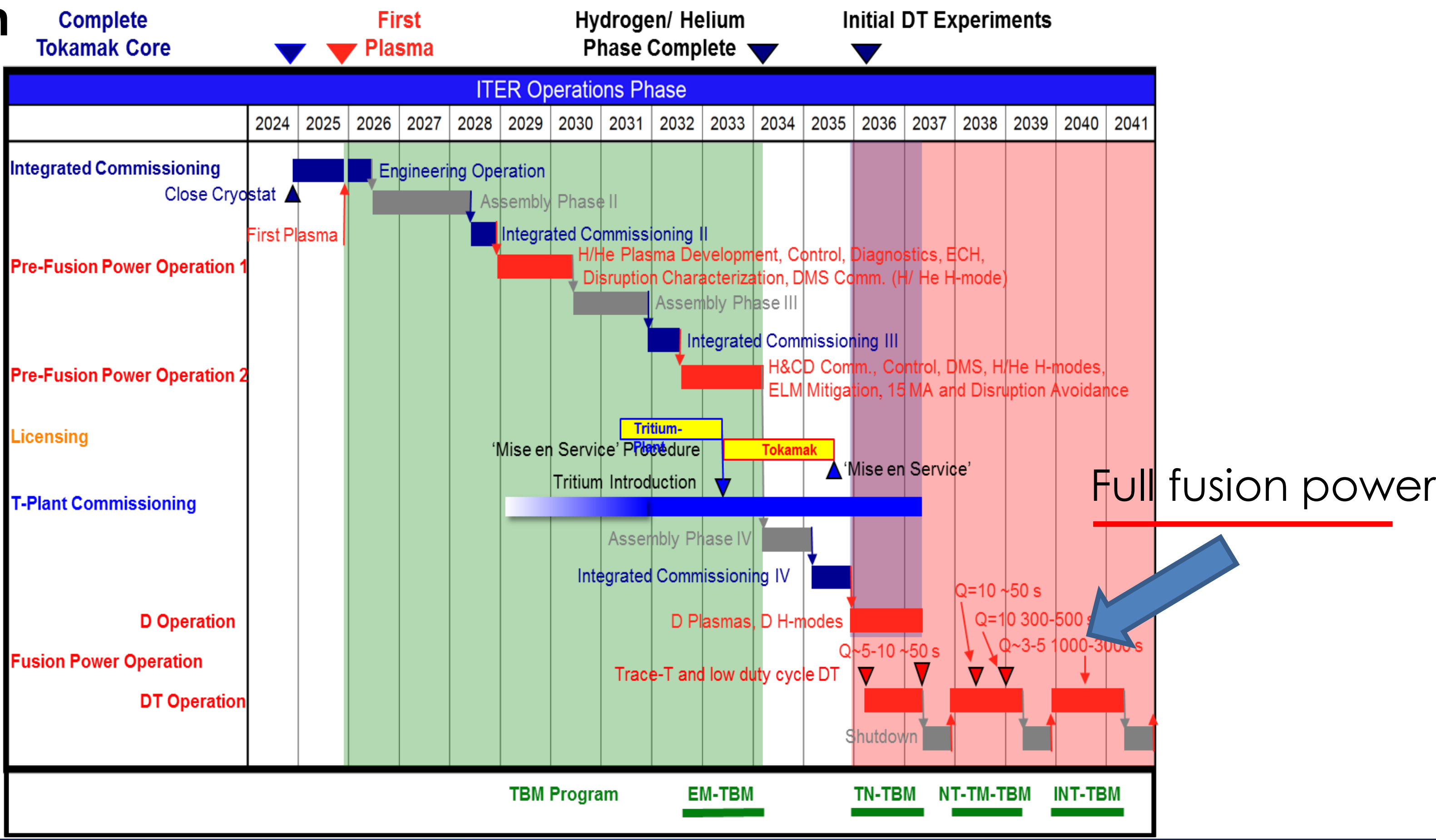


Major assembly milestones



ITER Research Plan (IRP) within Staged Approach

- **IRP developed from First Plasma through to achievement of Project's goals: Q = 10 (300-500 s), Q = 5 (1000 s) & Q = 5 steady-state**
- **R&D supported by available systems in each phase of Staged Approach**



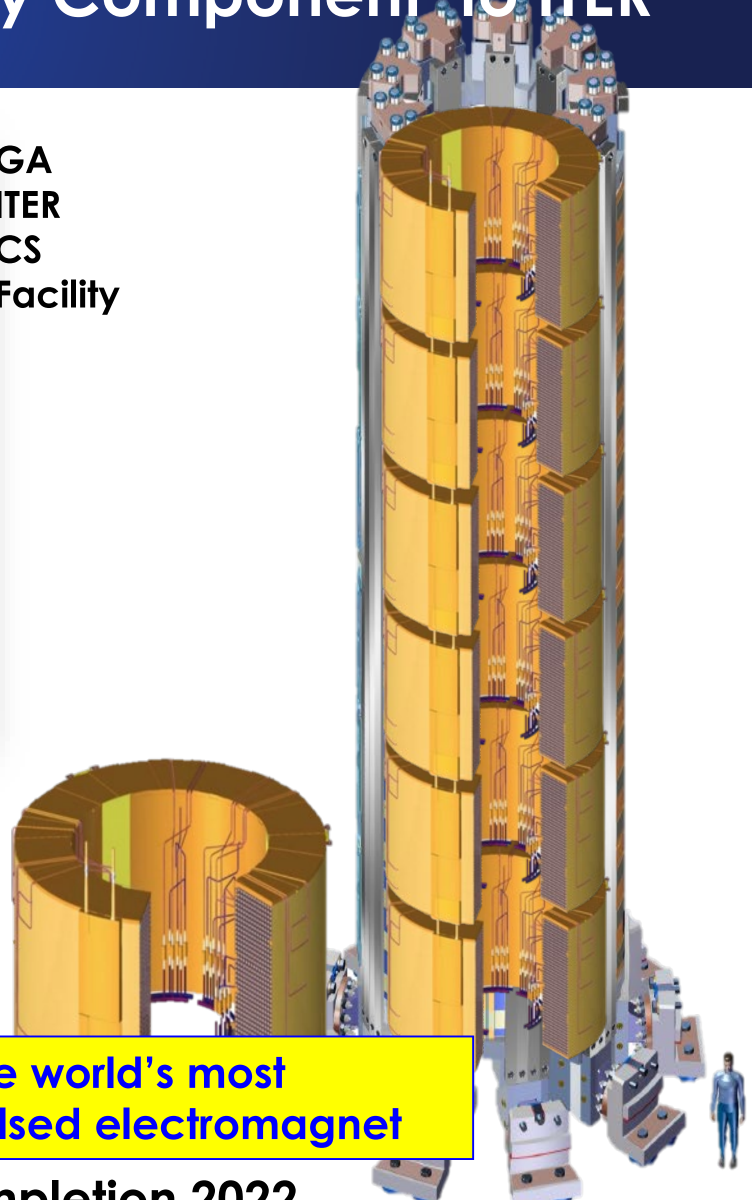
ITER Research Plan (IRP) within Staged Approach

- **First Plasma Operation : nominally 100 kA / 100 ms**
  - plasma current of ~ 1 MA / 3s
  - complete engineering tests including full SC Magnet Systems
- **Pre-Fusion Power Operation 1 (H/He): up to 7.5MA/20MW EC/2.65T**
  - L-mode Operation with full tokamak plasma, [Explore H-mode Ops]
  - Investment protection and plasma control
  - Diverted and shaped plasma
- **Pre-Fusion Power Operation 2 (H/He): up to 7.5MA/53MW/2.65T (He) H-mode Operation and 15MA/53MW/5.3T (H)**
  - Auxiliary system commissioning for nuclear phase [Full H&CD and Diagnostics]
- **Fusion Power Operation (nuclear DD/DT): 15 MA DD/DT-operation,**
  - All systems required for nuclear operation and tritium handling with full remote-handling

Worksite progress

US and GA are Providing a Key Component to ITER

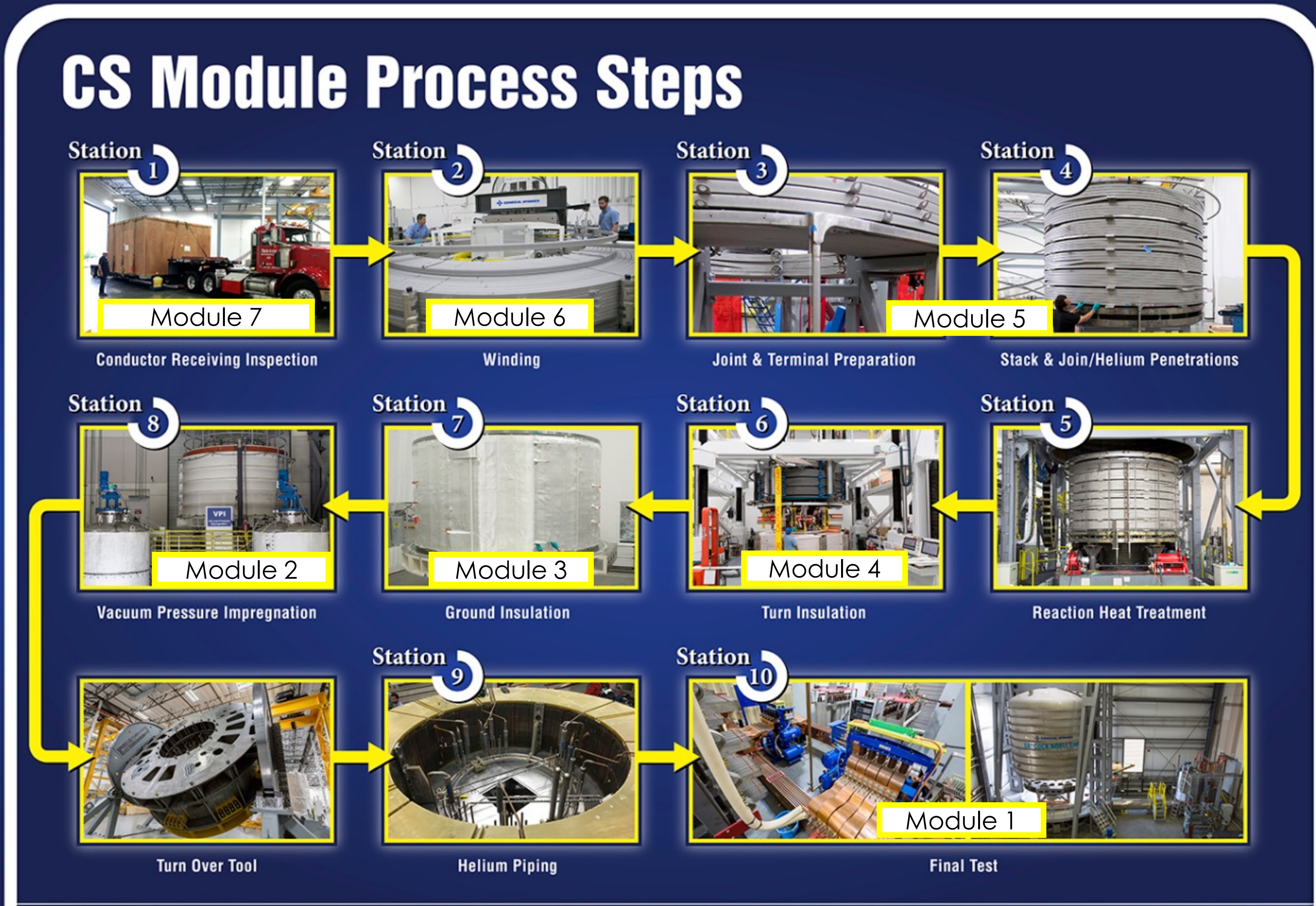
GA
ITER
CS
Facility



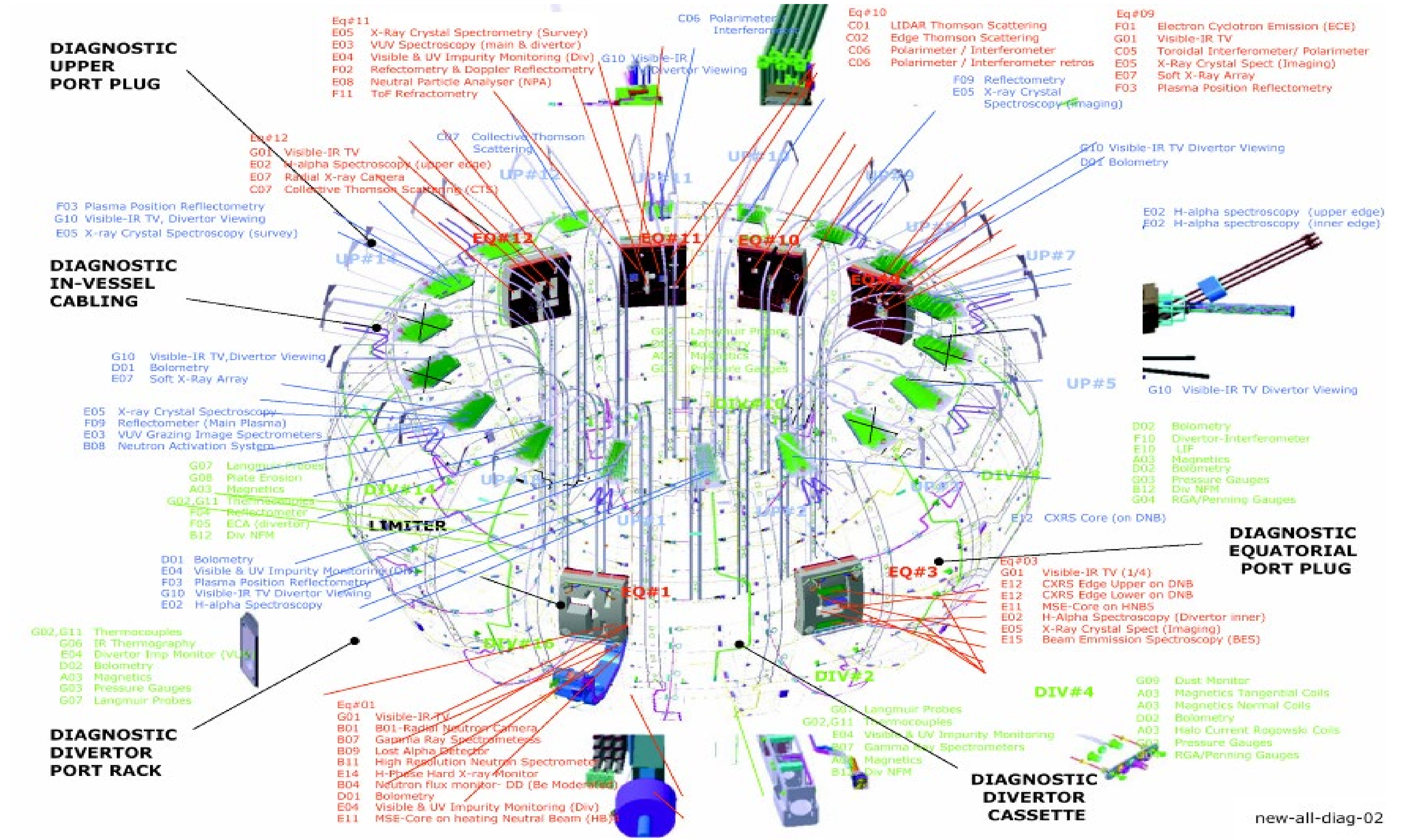
CS Coil – The world's most powerful pulsed electromagnet

GA is building the ITER Central Solenoid; completion 2022

Construction of the CS Modules is Far Along

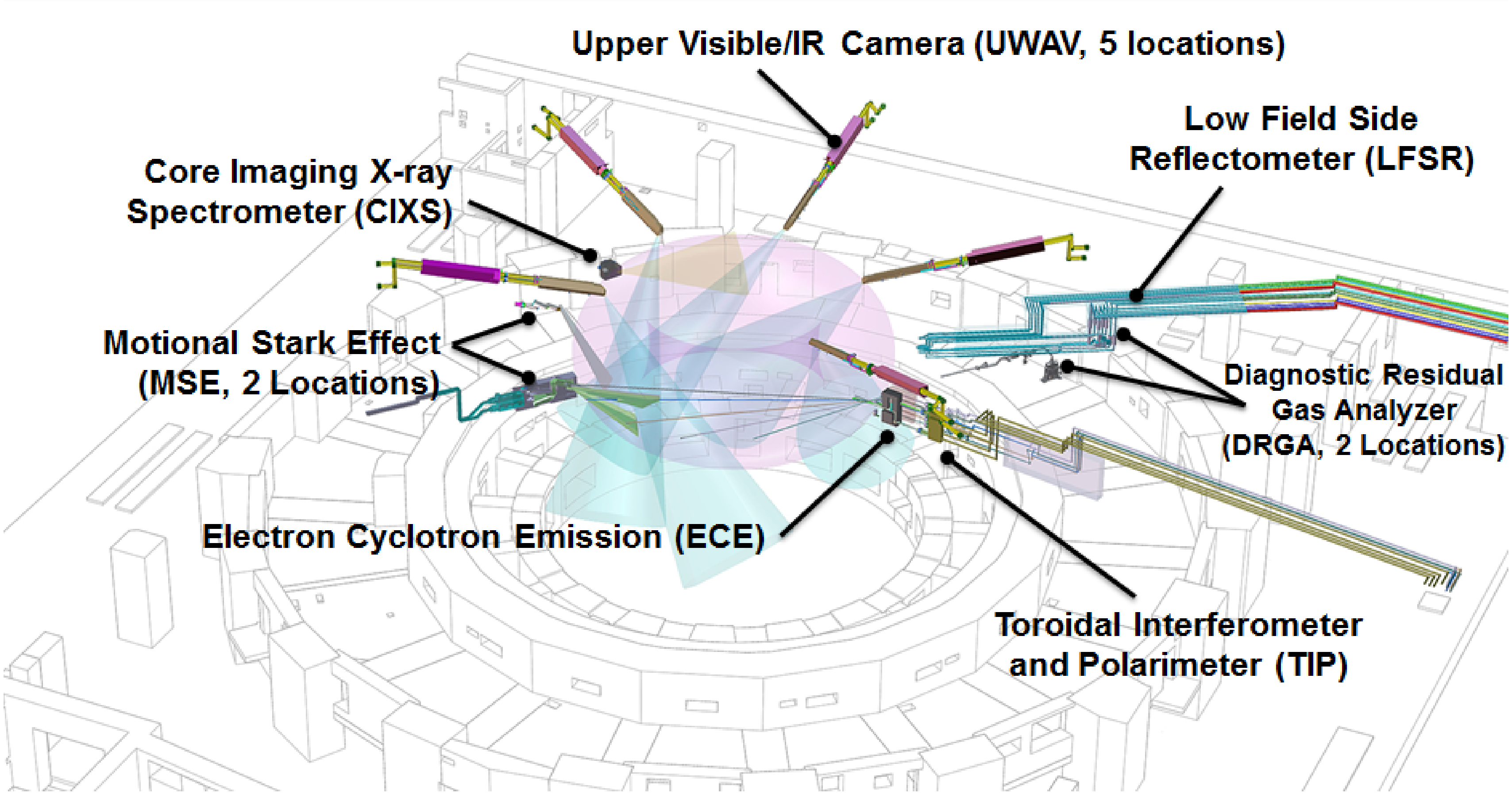


ITER Project Includes a Comprehensive Set of Diagnostics



Seven Diagnostics Provided by US-ITER Project Office

Machine protection, plasma control and the physics experimental program



- **The diagnostics are distributed in <u>13 different installations</u> in <u>11 different port plugs.</u>**

Seven Diagnostics Provided by US-ITER Project Office

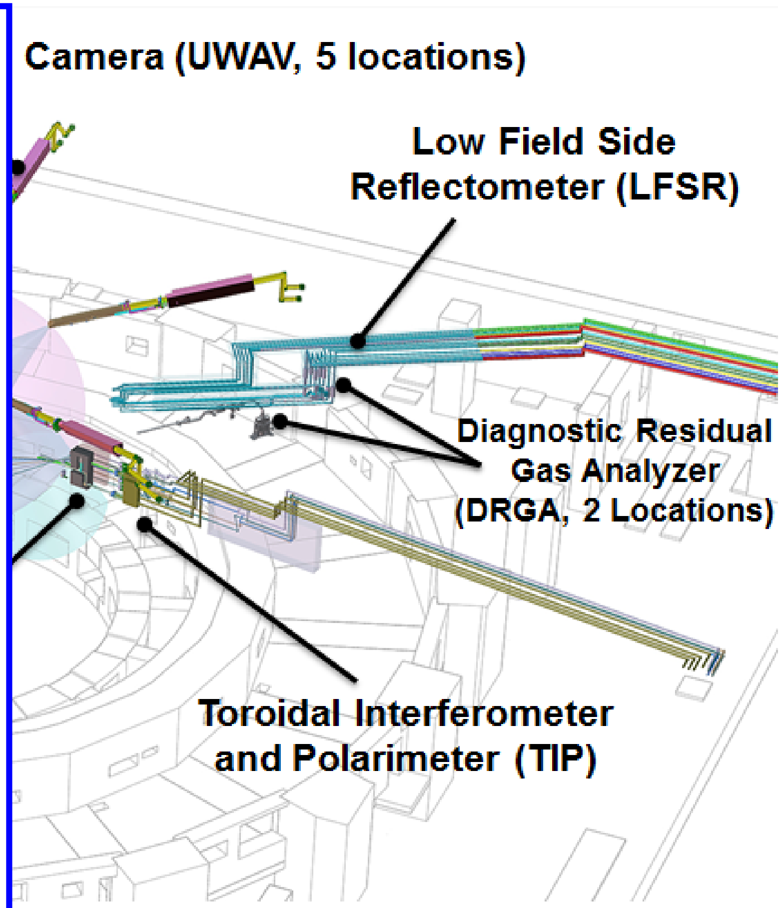
Machine protection, plasma control and the physics experimental program

- Challenges
  - High neutron flux and fluence
  - Nuclear Heating

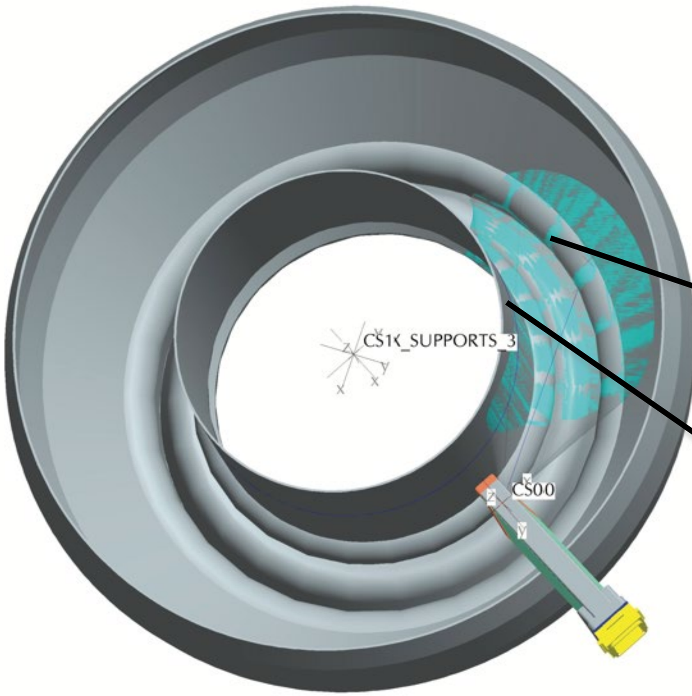
  - Particle flux (erosion/deposition on mirrors)
  - Immune to transients (e.g. disruption, steam events,…)
  - Reduced access
  - Remote handling

  - Alignment feedback required
  - In-situ calibration

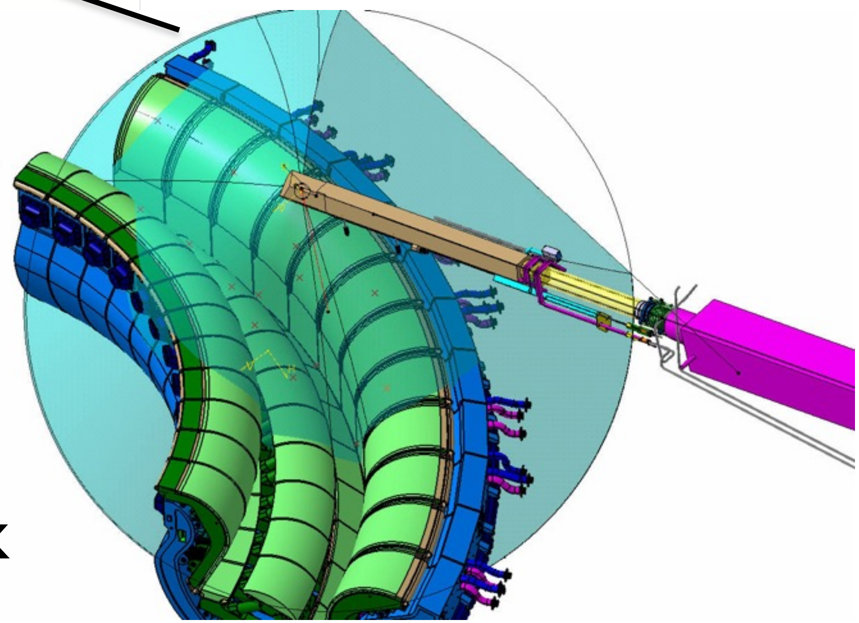
  - High reliability



Upper Wide Angle Viewing System (UWAVS) Monitors the Lower Divertor

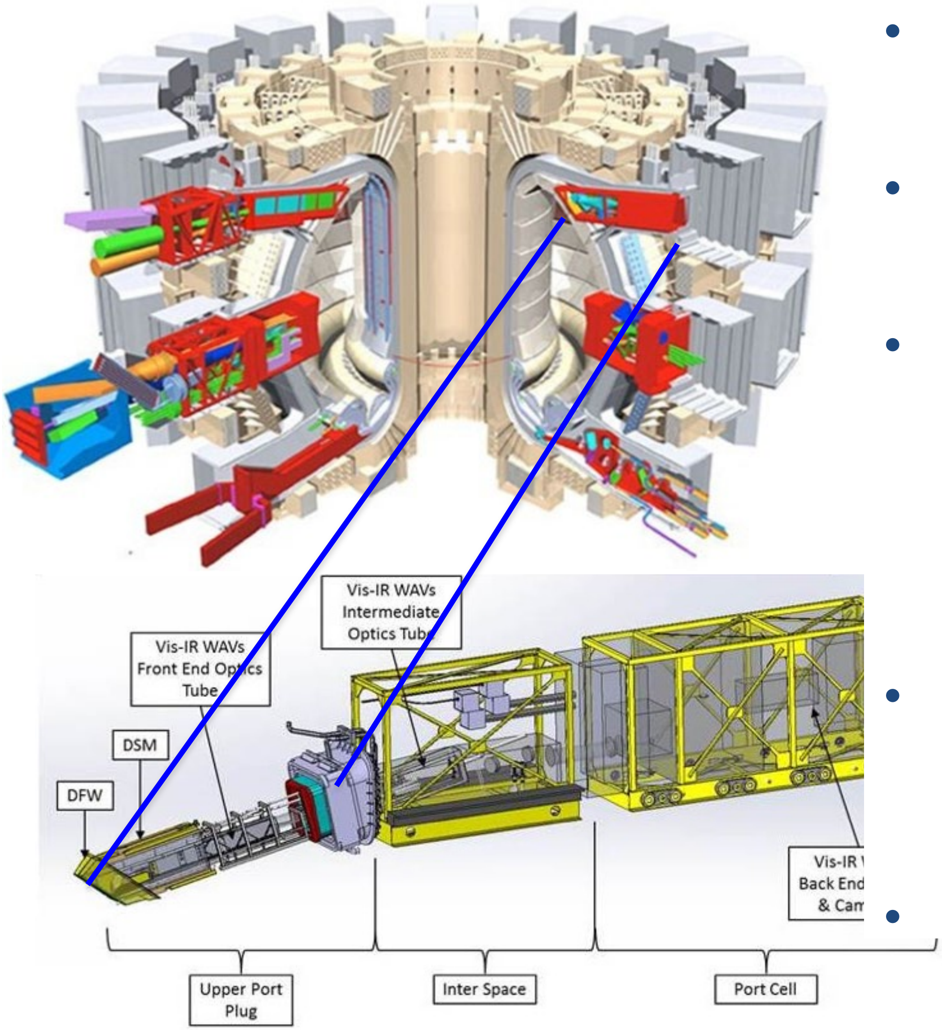


A tilted viewing angle shows more of the divertor. Five UWAVS systems are required to view as much as possible of the ITER divertor



UWAVS monitors divertor temperature and provides operators with visual feedback on health of the divertor

A Comprehensive Set of Cameras Support the Viewing System

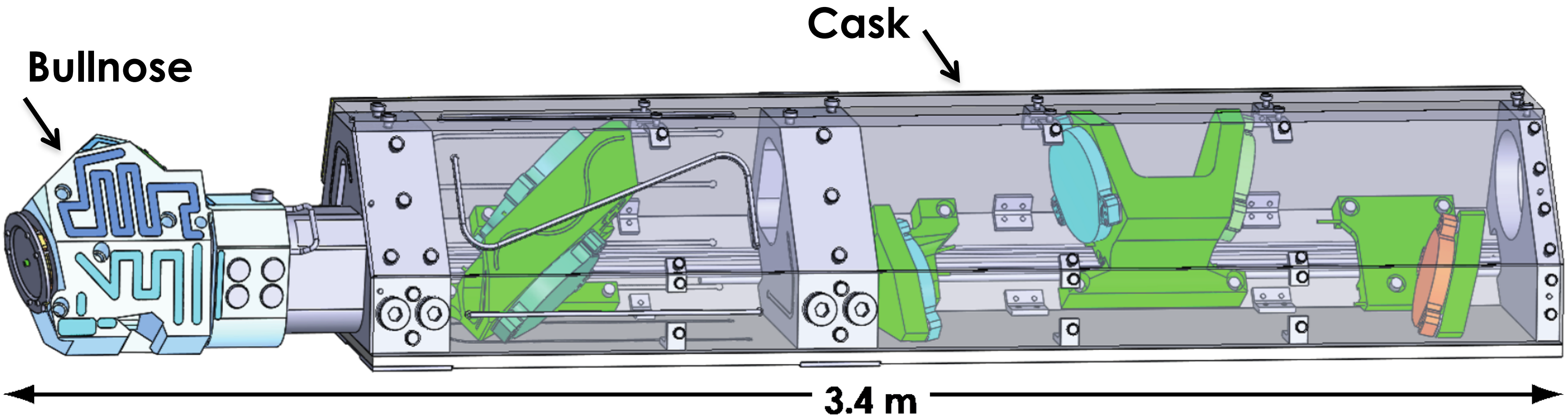


- **The light beam is split into visible and IR spectra**
- **Visible light is fed to one camera per UWAVS port**
- **IR is split into two color bands**
  - A two-color IR system will mitigate the effect of varying emissivity of the tungsten divertor
- **IR is split spatially between two IR cameras per color band, for a total of 4 IR cameras per port**
- **Spatial split allows smaller-sized IR detectors to be used**

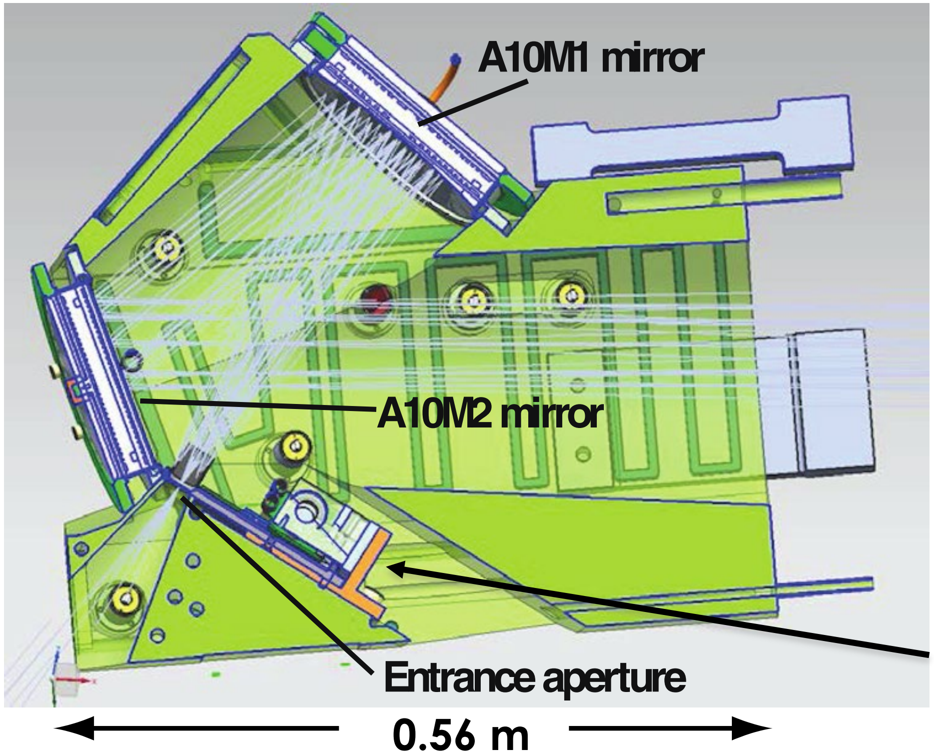
- **Team: GA, LLNL, TNO (Netherlands) under a PPPL contract**

Front End Optics Tube

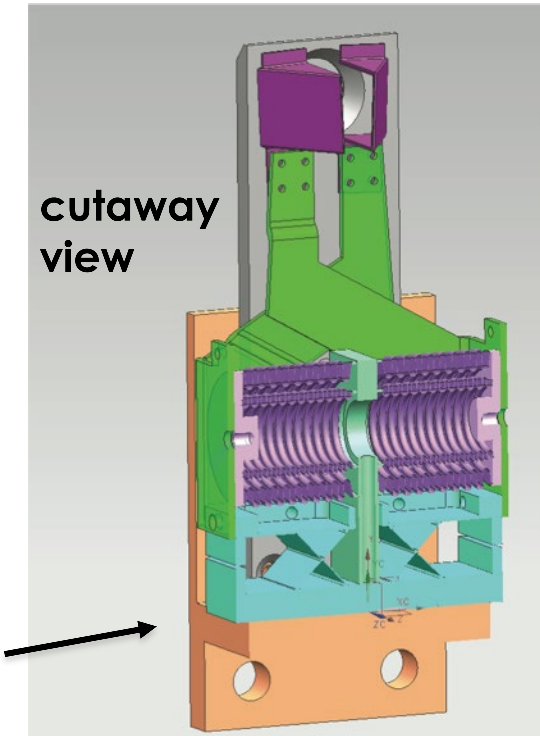
- Designed to withstand specified gravity, electromagnetic, shock, and vibration loads
- Designed to withstand nuclear heating from radiation, and thermal cycling to 240°C for baking
- A bolted and pinned mounting scheme is used to maintain structural integrity and alignment
- The bullnose contains the components most susceptible to damage and is designed for maintenance via remote handling



Bullnose Assembly



Shutter Mechanism



- Entrance Aperture
- Shutter
- First two mirrors
- RF Discharge Mirror Cleaning

- Located at entrance aperture
- Pressure-driven by two double bellows actuators with flexure
- Flexure mechanism is more reliable than a pivot in tokamak vacuum

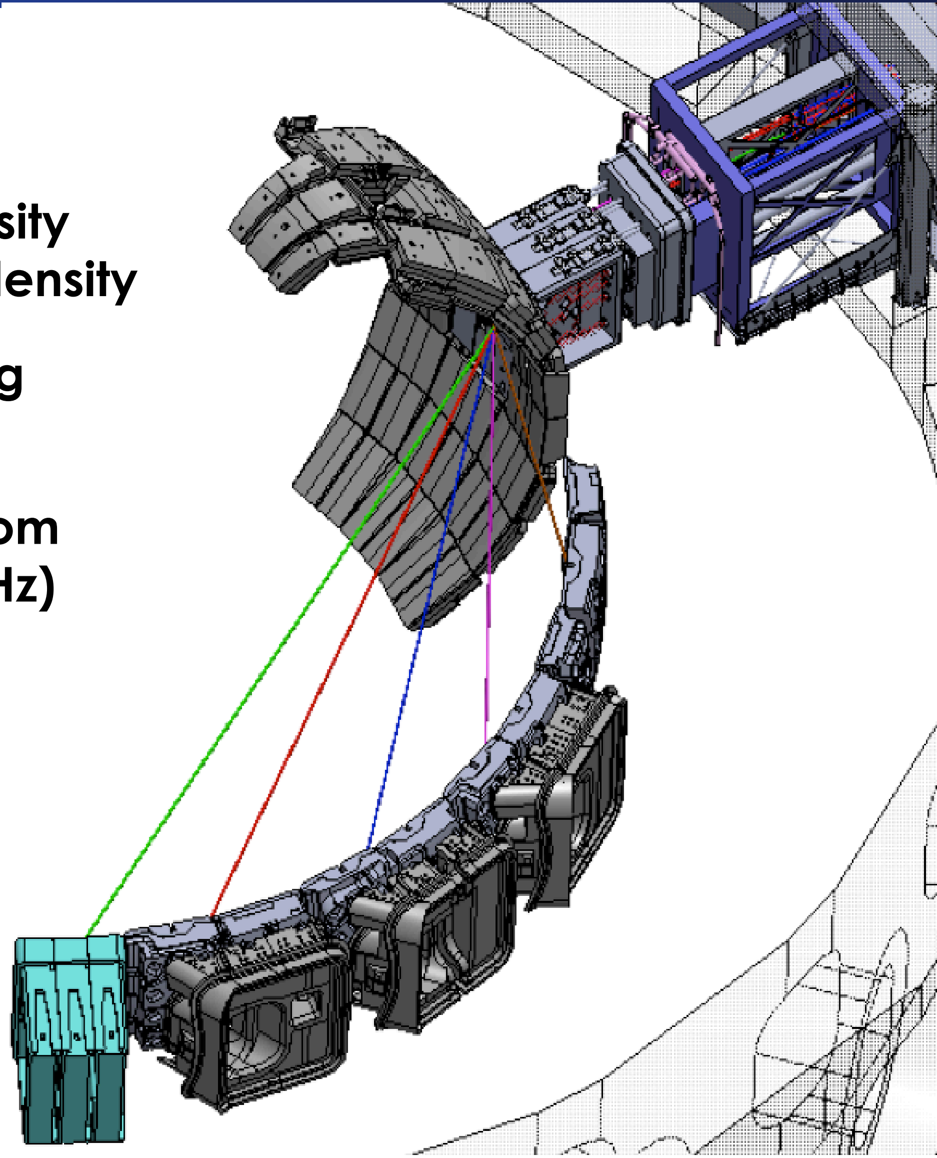
Tororidal Inferometer and Polarimeter (TIP) is One of the Primary Density Diagnostics on ITER

Tip provides:

- "Real-Time" (1 kHz) line-integrated density measurements for feedback control of density
- Global constraints to Thomson scattering density profiles
- Measurements of density fluctuations from turbulence and coherent modes (0-1 MHz)

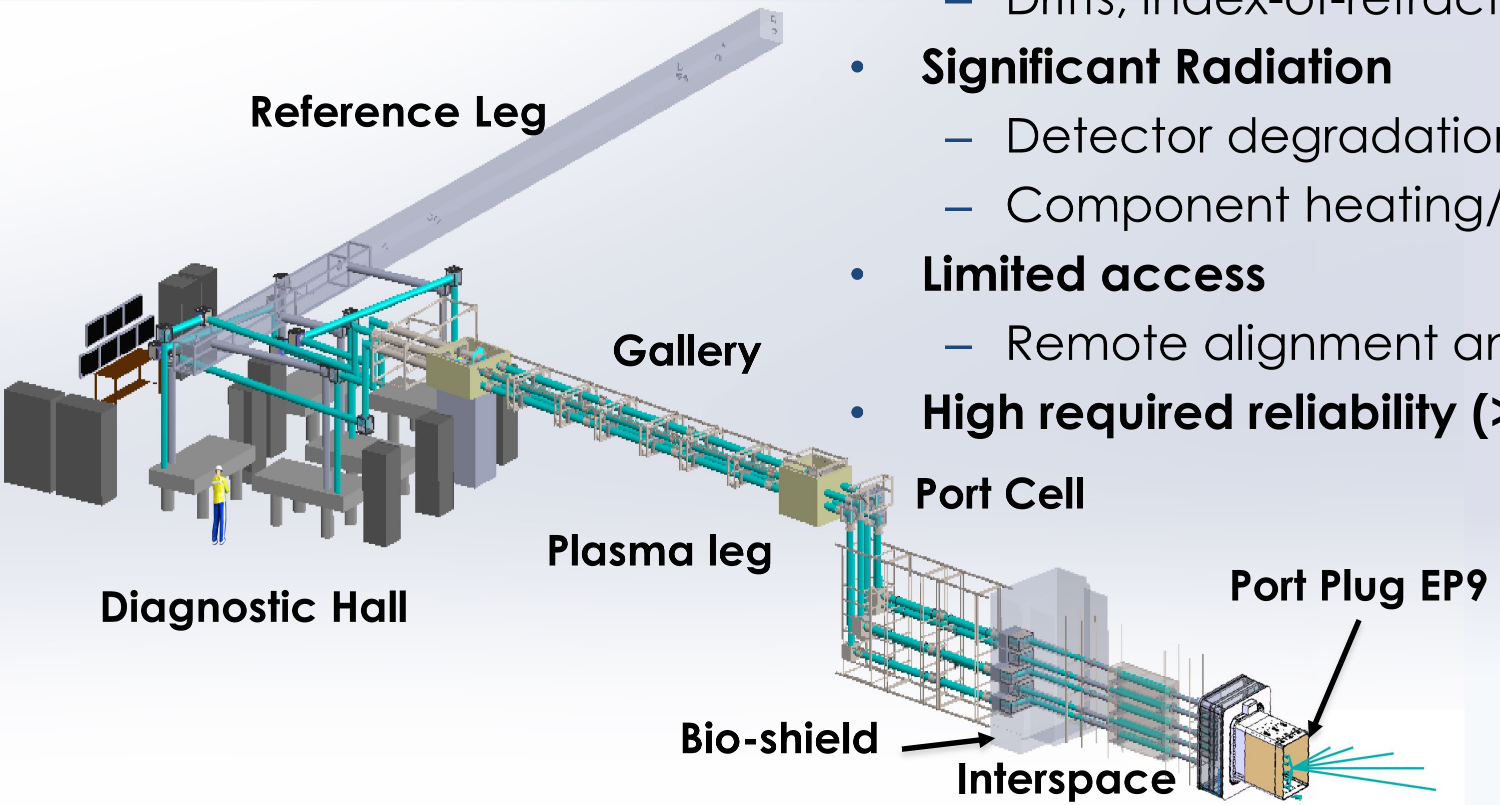
Main Features:

- 5 chords
- Primary: CO_2 at 10 microns
- Bandwidth: >1MHz
- Full automatic feedback system
- Beamline: ~120m (lab to ITER)



Although Many Key Elements Have Been Demonstrated, TIP Faces Several Unique Challenges

ITER TIP Layout



- **Long ~120 m beam path with many optical components**
  - Feedback alignment required
- **Long discharges (1000 s)**
  - Drifts, index-of-refraction changes
- **Significant Radiation**
  - Detector degradation
  - Component heating/expansion
- **Limited access**
  - Remote alignment and maintenance
- **High required reliability (>99%)**

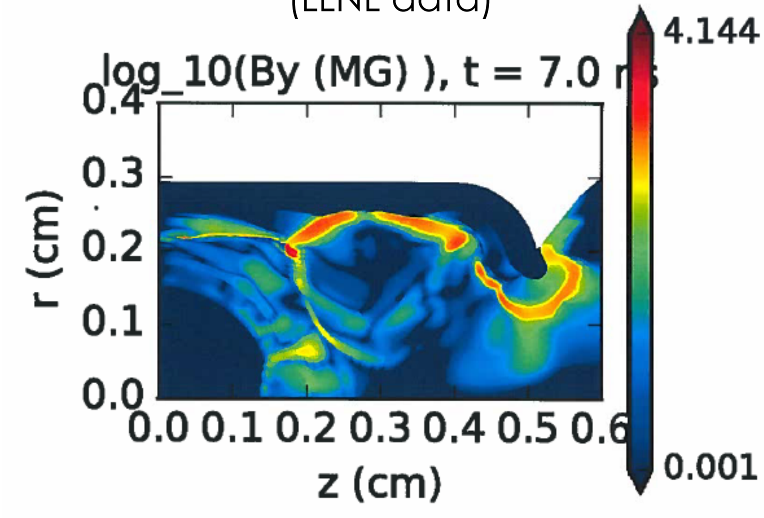
Polarimetry Imaging in NIF Plasma

- **Magnetic field components and electron density can be probed by measuring the state of polarization of a laser beam traversing a plasma**
    - Rotation of the plane of polarization (Faraday rotation): $\alpha_{FR} \propto \lambda_o^2 \int n_e \boldsymbol{B}_{\parallel} dl$
    - Change in the degree of circular polarization (Cotton-Mouton effect): $\alpha_{CM} \propto \lambda_o^3 \int n_e \boldsymbol{B}_{\perp} dl$

- **We are examining the feasibility of polarimetry imaging in NIF plasmas**
    - Imaging of Faraday rotation can be considered under magnetized gas pipes
    - Measurement of the Cotton-Mouton rotation could reveal high azimuthal magnetic field fluctuations that are predicted to exist in localized regions near the critical density surfaces.

Simulated Azimuthal Magnetic Field

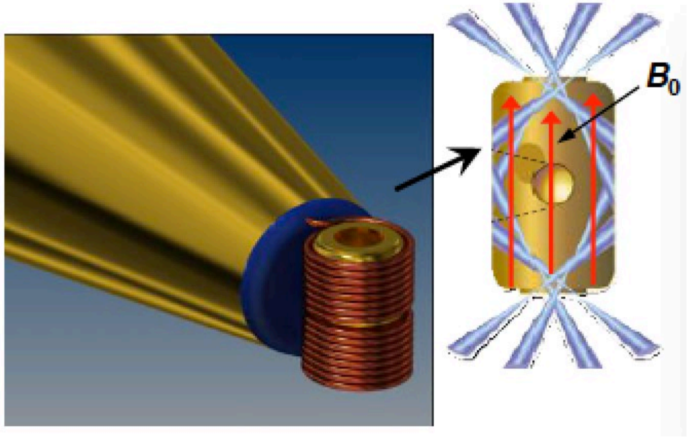
(LLNL data)



Parameter Estimates	
λ_o (nm)	250
n_e (cm^{-3})	$10^{20} - 10^{23}$
$B_{\parallel}$ (T)	30
$B_{\perp}$ (T)	100
L (m)	0.01
α_{FR} [deg.]	> 10
α_{CM} [deg.]	> 0.1

Interferometry / Polarimetry Imaging Outlook

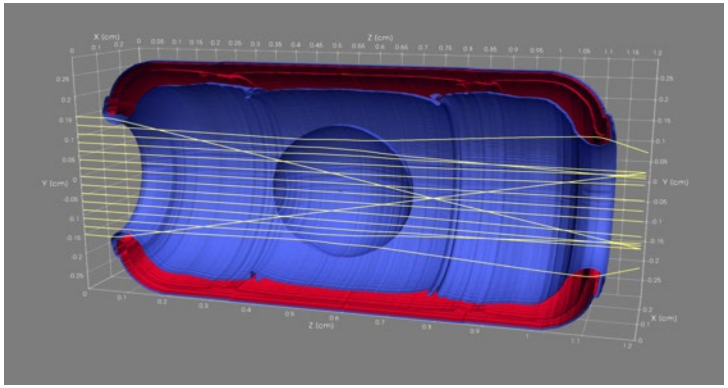
- **Interferometry and Polarimetry imaging diagnostics are complementary**
- **Interferometry provides a quantitative measurements of the plasma electron density**
- **Polarimetry imaging apparatus could be piggybacked to the development of the future NIF interferometric imager**
  - Use of the same 5ω beamline
  - Use of the same telescope module
  - Will require additional cameras / detectors
- **Combined Interferometry and Polarimetry imaging diagnostics could allow for new experiments in NIF magnetized gas pipes (MAGNIF)**
  - Unique magnetic field / electron density imaging data
  - Few measurements capable of probing 2D structures of magnetic field in plasma
  - Useful to validation of NIF modeling codes



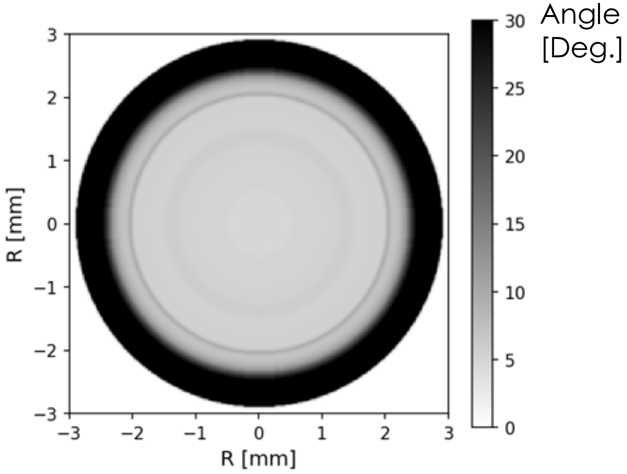
Simulation of Interferometry/Polarimetry Imaging Diagnostics in NIF Hohlraum Plasmas

- **Key elements required to simulate laser measurements of NIF hohlraum plasmas have been developed**
  - Laser beam ray-tracing algorithm
  - 2D interferograms
  - Finite detector resolution
- **Goals:**
  - Assess experimental errors, SNR, density limits, etc.
  - Optimize the experimental apparatus (laser source, detectors, etc) and measurement approach
- **Tools developed to simulate:**
  - Expected Faraday rotation
  - Cotton-Mouton effect
  - Refraction
  - Various detector types & resolution
  - Quantify the typical sources of noise

Laser Ray-tracing through Reconstructed Hohlraum Plasma



Faraday Rotation with B_z = 1T
(beam deflection omitted)



Summary

- DIID-D Program is embarking on a new 5yr plan (2019) which will lead to the scientific basis for next step devices (ITER and DEMO) design and exploitation
- ITER construction is well under way (>60%), with US participation in many components
- Diagnostic development remains at the fore-front of the research in support of fusion: More common features and approach are emerging from MFE and ICF research

Future Is Looking Bright