Establishing fusion reactor control scenarios based on information from a reduced set of nuclear-compatible diagnostics

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IAEA Technical Meeting on Long-Pulse Operation of Fusion Devices

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Outline

- Context to this presentation
- Motivation/Background
- Approach
- Next Steps

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Context

- In early 2022 the US DOE OFES sponsored a Research Needs Workshop to assess the U.S. ITER Research Program
  - Final report available here.
- We submitted a "white paper" to stimulate discussion on the topic of "reduced diagnostic sets for fusion reactor control."
- Research at ORNL on this topic is just beginning and is related to talks (by others) at this IAEA LP Fusion Plasmas workshop.
  - I am here to listen, more than lecture.
- Thank you for your patience and I value any feedback you want to give, as I walk through the thought-process

“Establishing fusion reactor control scenarios based on information from a reduced set of nuclear-compatible diagnostics”

- A successful US fusion pilot plant (FPP) design will need to incorporate knowledge gained from ITER in these areas:
  - 1) nuclear compatible diagnostic designs,
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  - 3) reactor control scenarios that utilize that information to operate robustly and safely in a specific configuration for fusion energy production.

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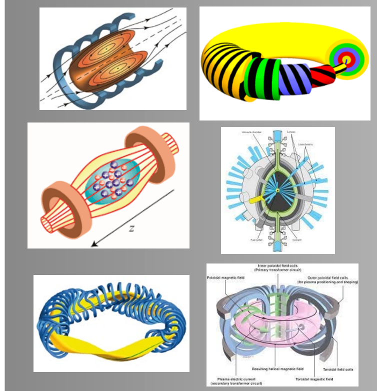
Motivation

R&D

Industry



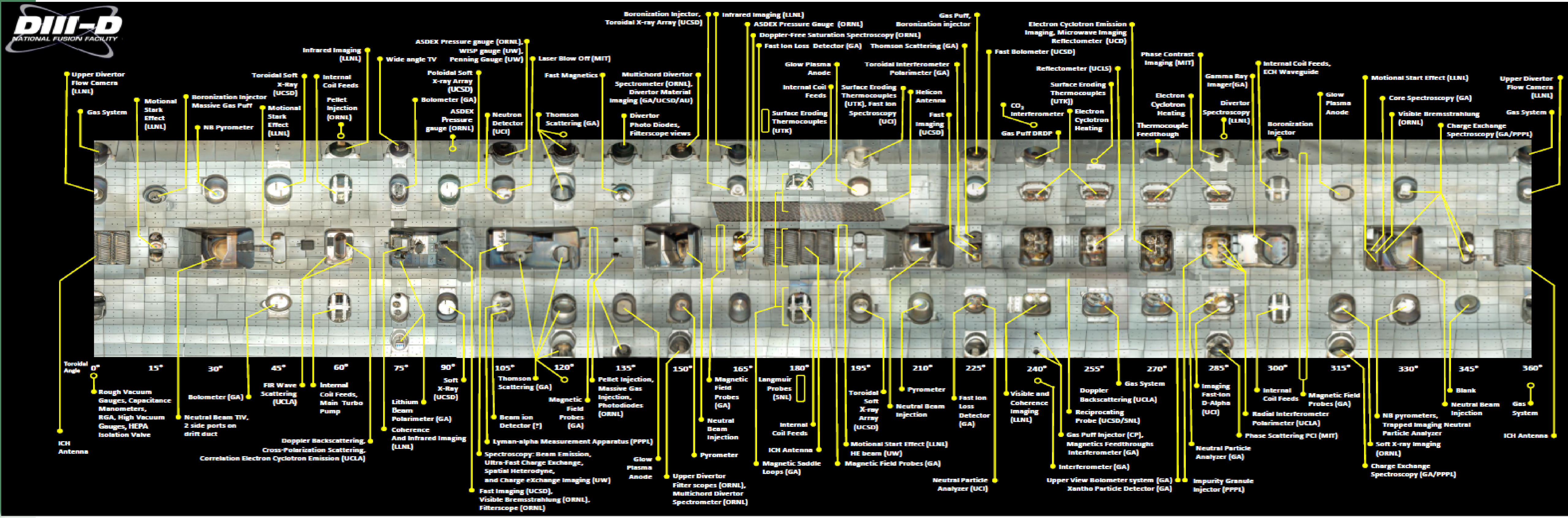
"The Recipe for Fusion"

Diagnostics: TS, OES, BES, CXRS, TALIF, DLPs, MSE, IR imaging, Vis imaging, reflectometry, bolometry, interferometry, neutrons, RGA, etc.

Objective: Develop and exploit diagnostic systems to establish a burning plasma scenario suitable for a fusion reactor.

Today's fusions devices are perhaps at the pinnacle of diagnostic coverage and sophistication, commensurate with their R&D mission.

From S-H Hong, "DIII-D diagnostic development plan towards fusion science and technology.", DIII-D PAC, July 2022



Over 130 participating institutions including universities, national laboratories, and industry, 17 institutions provide over 100 diagnostics

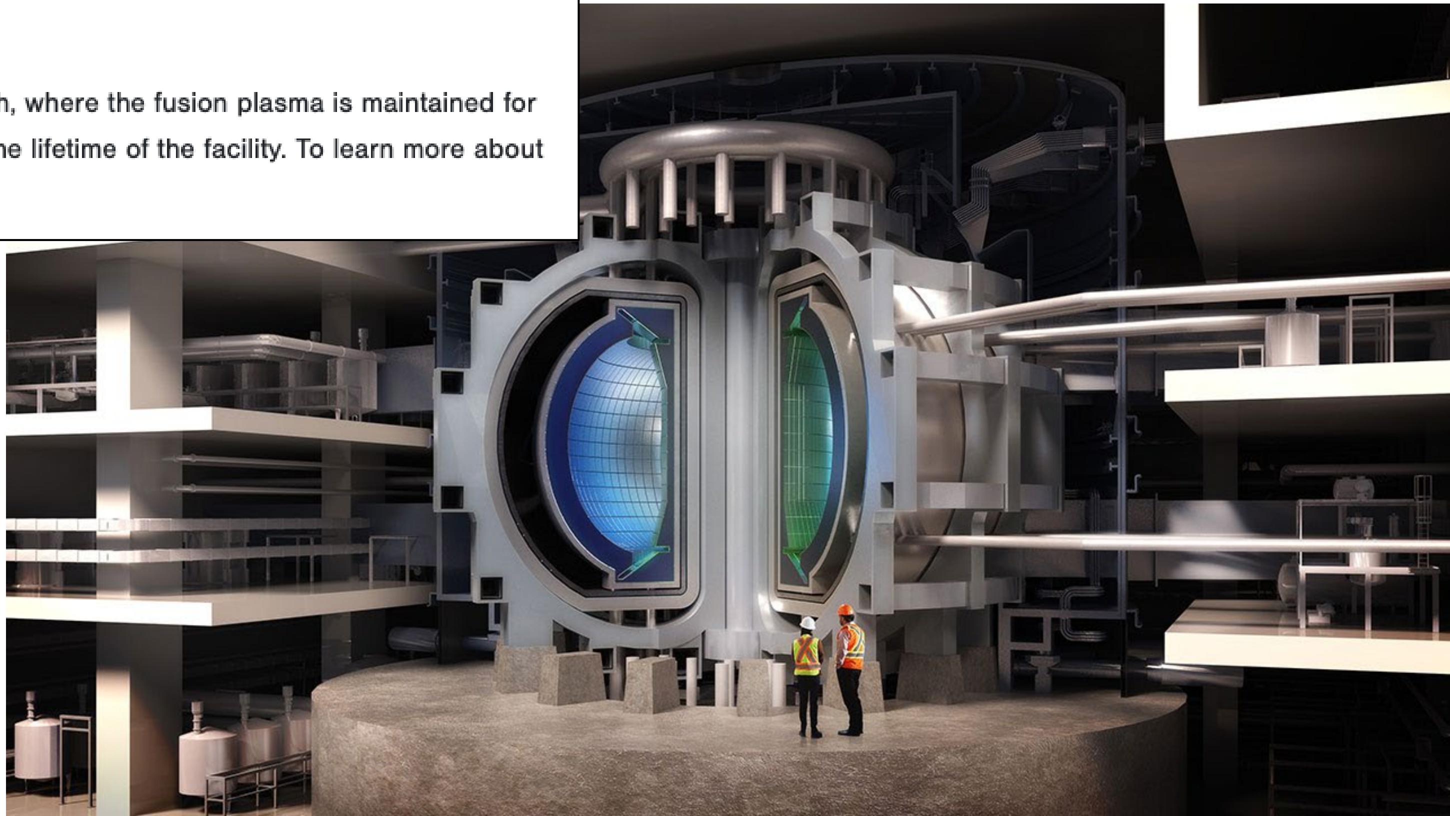
Tomorrow’s fusion pilot plants have a much-reduced diagnostic set, commensurate with their industrial energy production mission.

General Atomics Announces Plans for Fusion Pilot Plant

Innovative concept leverages decades of expertise in fusion research and development

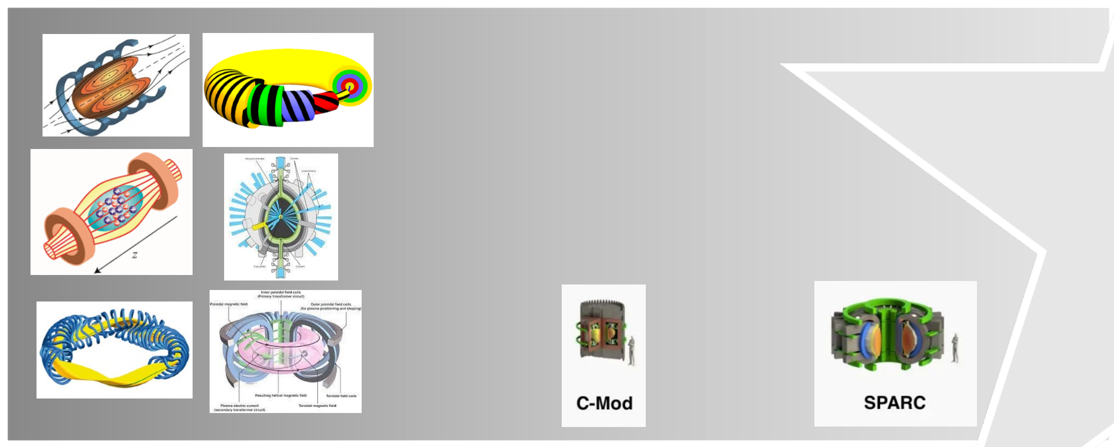
San Diego, Oct. 20 – Today, General Atomics (GA) announced a new concept for a fusion pilot plant (FPP) to deliver clean, safe, and economically viable fusion energy.

GA’s FPP concept utilizes a steady-state, compact advanced tokamak design approach, where the fusion plasma is maintained for long periods of time to maximize efficiency, reduce maintenance costs, and increase the lifetime of the facility. To learn more about the concept, please visit: www.ga.com/fusion-pilot-plant.



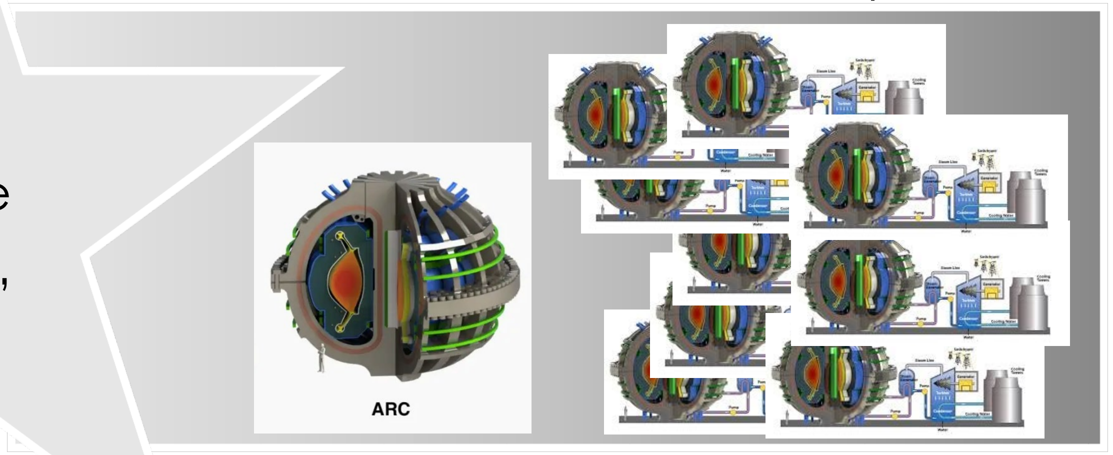
Motivation

R&D



"The Recipe for Fusion"

Industry



Diagnostics: TS, OES, BES, CXRS, TALIF, DLPs, MSE, IR imaging, Vis imaging, reflectometry, bolometry, interferometry, neutrons, RGA, etc.

Diagnostics: one neutron detector

Objective: Develop and exploit diagnostic systems to establish a burning plasma scenario suitable for a fusion reactor.

Objective: Establish fusion reactor control scenarios based on a reduced set of nuclear-compatible diagnostics.

Question: What is the least/critical amount of information that industrial fusion reactors will need to operate robustly and safely?

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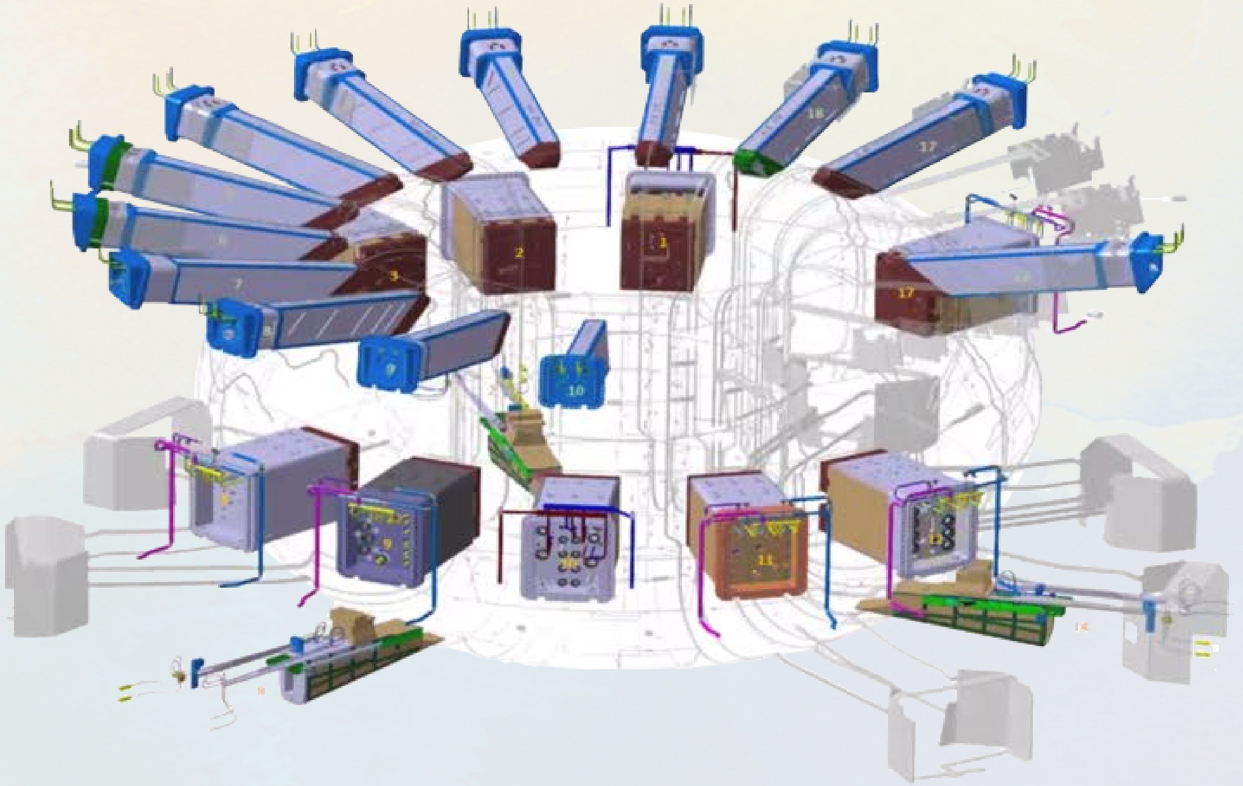
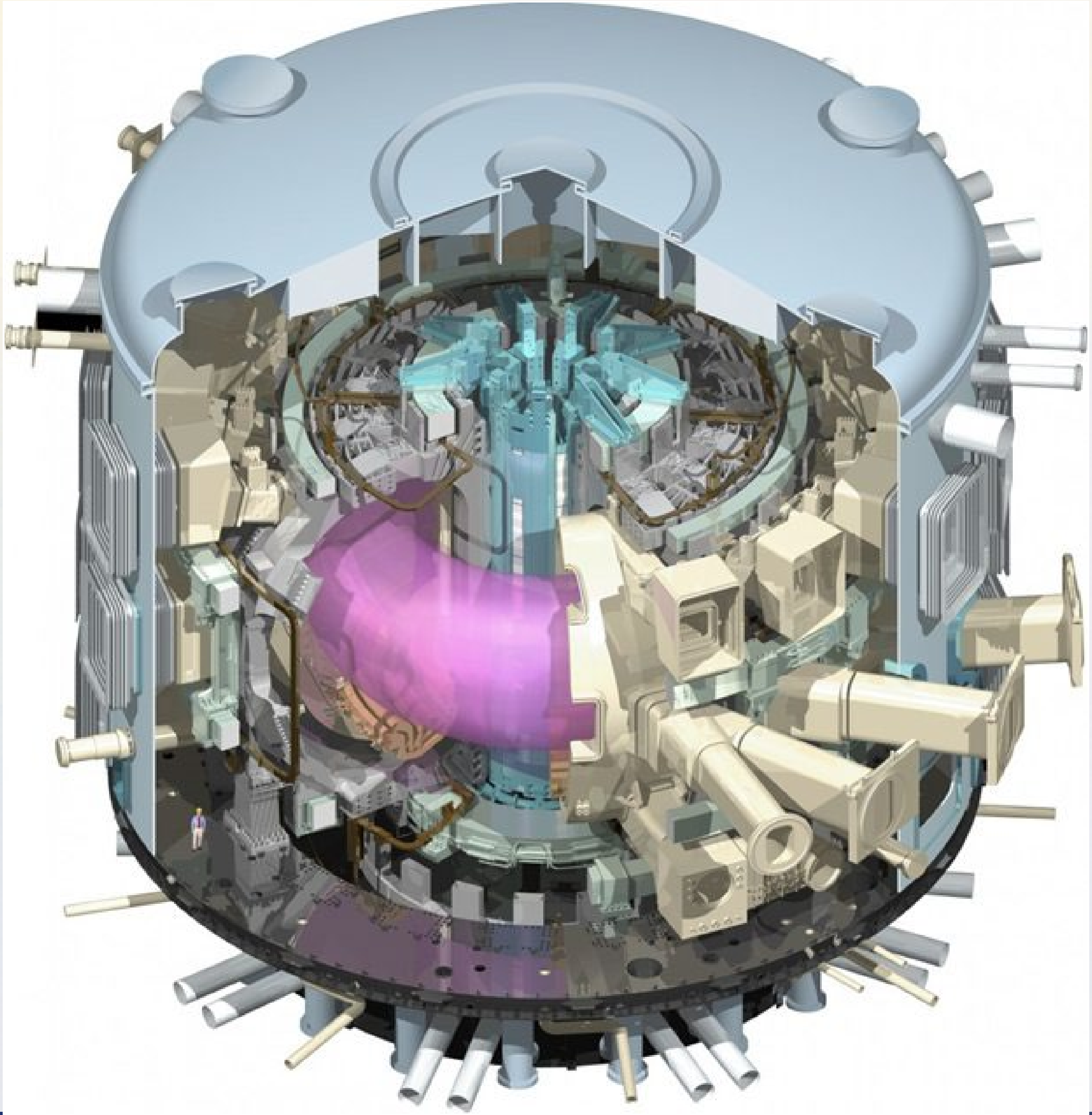
From D. Rasmussen, US ITER, “Fusion 101”

ITER Diagnostics

Diagnostics: ~60 instruments measuring ~100 parameters





Diagnostic information will likely be limited in a fusion plant

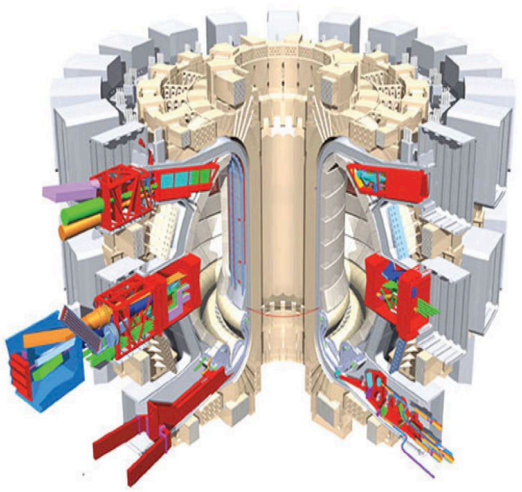


Figure 1. ITER port plugs (red) showing "front-end" diagnostic components.

From "Research Needs for Magnetic Fusion Energy Sciences" report, 2009

GROUP 1A MEASUREMENTS FOR MACHINE PROTECTION AND BASIC CONTROL	GROUP 1B MEASUREMENTS FOR ADVANCED CONTROL	GROUP 2 PERFORMANCE EVALUATION AND PHYSICS
Plasma shape and position, separatrix-wall gaps, gap between separatrices	Neutron and a-source profile	Confined a-particles
Plasma current, $q(a)$, $q(95\%)$	Helium density profile (core)	TAE modes, fishbones*
Loop voltage	Plasma rotation (toroidal and poloidal)*	T_e profile (edge)
Fusion power	Current density profile (q-profile)*	n_e, T_e profiles (X-point)
$\beta_N = \beta_{tor}(aB/I)$	Electron temperature profile (core)*	T_i in divertor
Line-averaged electron density*	Electron density profile (core and edge)*	Plasma flow (divertor)
Impurity and D, T influx (divertor*, & main plasma)	Ion temperature profile (core)*	$n_T/n_D/n_H$ (edge)
Surface temperature (divertor & upper plates)*	Radiation power profile (core, X-point & divertor)	$n_T/n_D/n_H$ (divertor)
Surface temperature (first wall)	Z_{eff} profile	T_e fluctuations
Runaway electrons	Helium density (divertor)*	n_e fluctuations*
Halo currents	Heat deposition profile (divertor)*	Radial electric field and field fluctuations
Radiated power (main plasma, X-pt & divertor)	Ionization front position in divertor	Edge turbulence
Divertor detachment indicator	Impurity density profiles*	MHD activity in plasma core
(J_{sat}, n_e, T_e at divertor plate)	Neutral density between plasma and first wall	
Disruption precursors (locked modes, m=2)	n_e of divertor plasma*	
H/L mode indicator*	T_e of divertor plasma	
Z_{eff} (line-averaged)	a-particle loss	
n_T/n_D in plasma core	Low m/n MHD activity	
ELMs	Sawteeth	
Gas pressure (divertor & duct)	Net erosion (divertor plate)	
Gas composition (divertor & duct)*	Neutron fluence	
Dust		

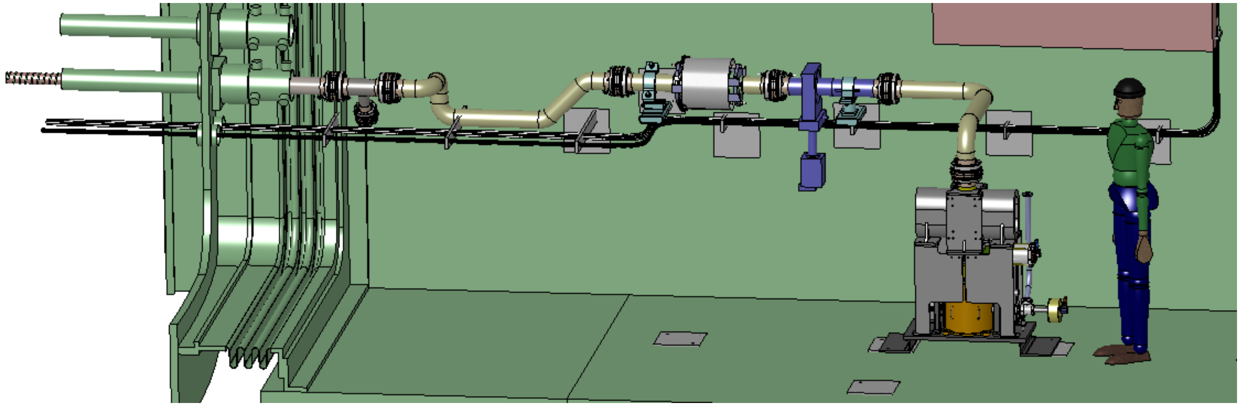
Color coding: Expect performance to meet measurement requirements; maybe/maybe not; expect not to meet requirements.
Indicates at least one primary technique at risk due to mirror degradation.
** Indicates measurement for which US ITER Project has responsibility to provide a primary diagnostic.*

Table 1. ITER measurements categorized by role, performance expectation, mirror risk, and US ITER Project involvement.

Measurement Requirements of the DRGA Systems

- DRGA measurements **<u>during pulse</u>**
  - Group 1a2 measurements needed for basic machine control.
  - <u>Goal</u>: measure fuel ratios, He (ash), and impurity concentrations
  - 1-100 amu range, with 0.5 amu or better
  - Time response: <1 s in divertor, <10 s at midplane

- Nuclear-qualified environment drives the design
  - Particularly challenging to be robust against "off-normal" loads, conditions, and events.



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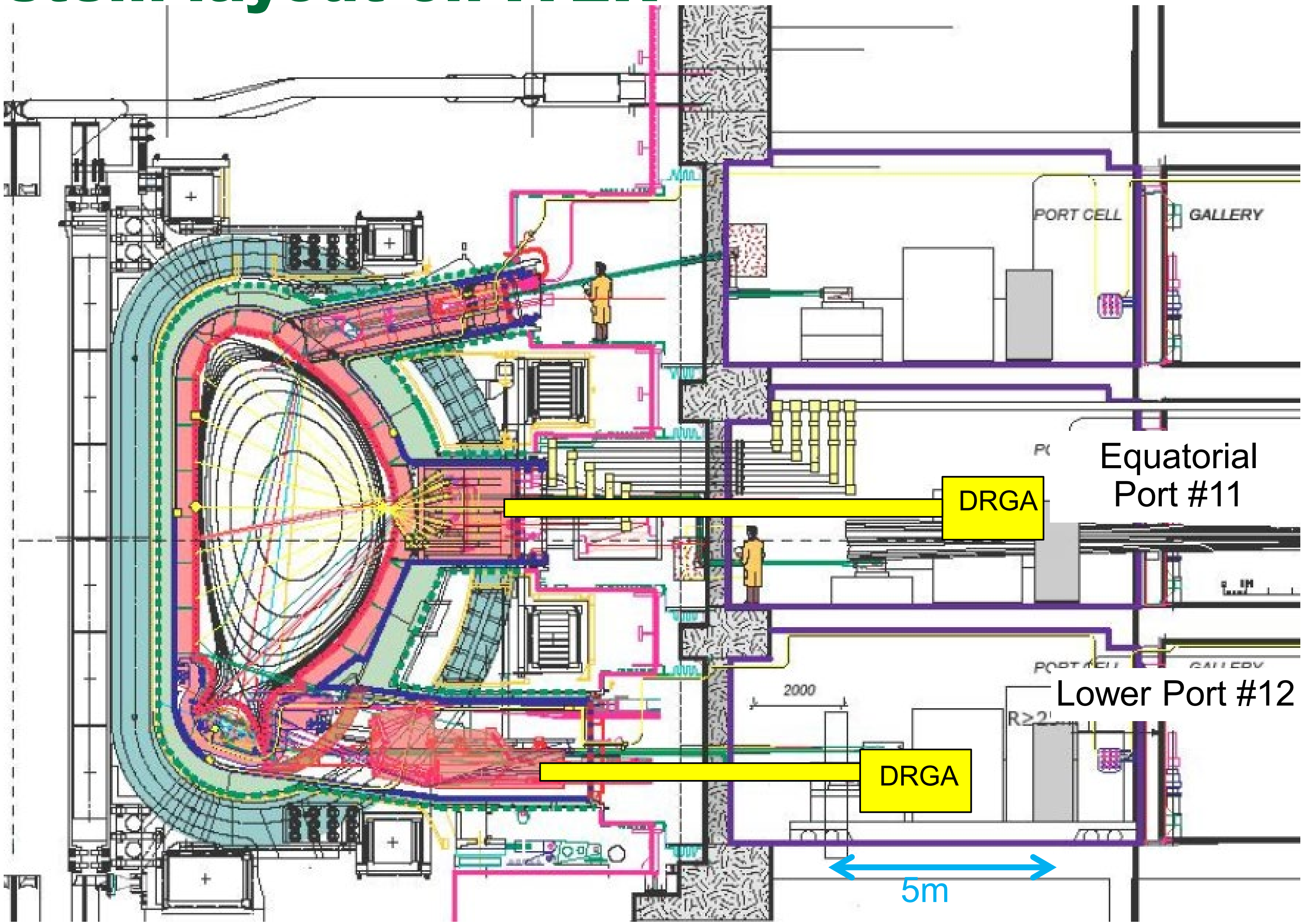
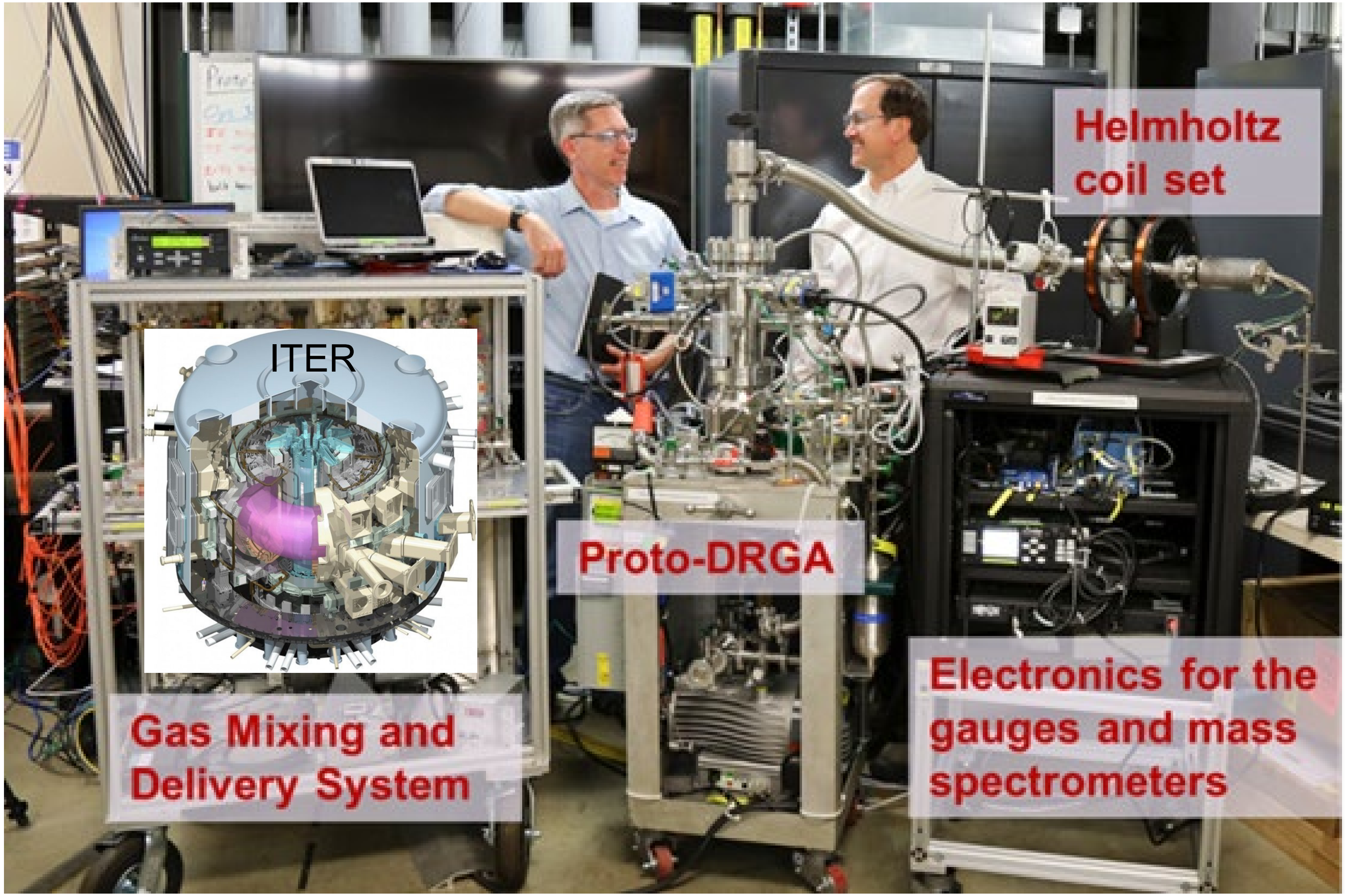
DRGA system layout on ITER



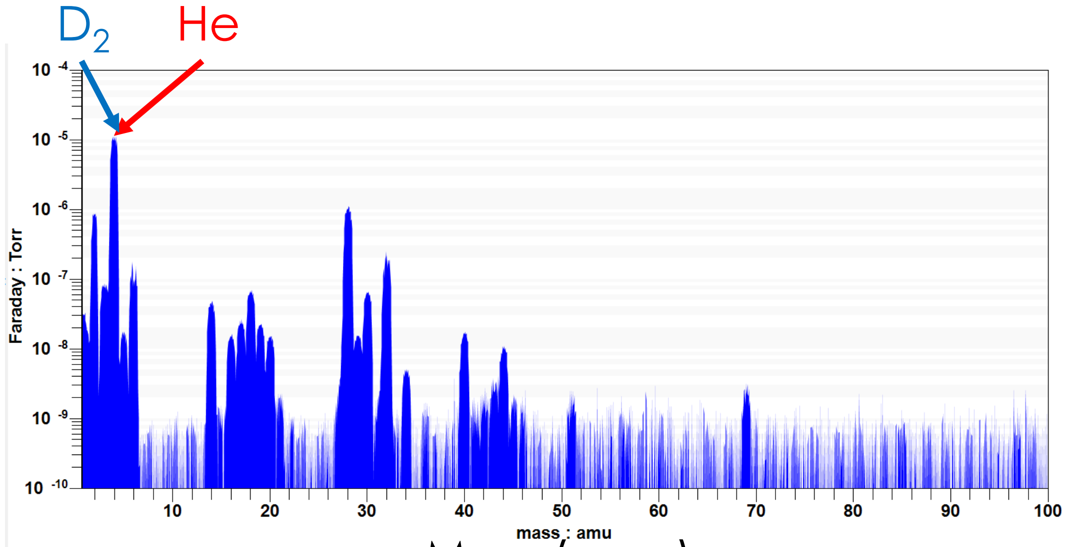
ORNL DRGA development for US ITER, credited by ITER IO



DRGA: unique composition of multiple techniques

Mass Spectroscopy

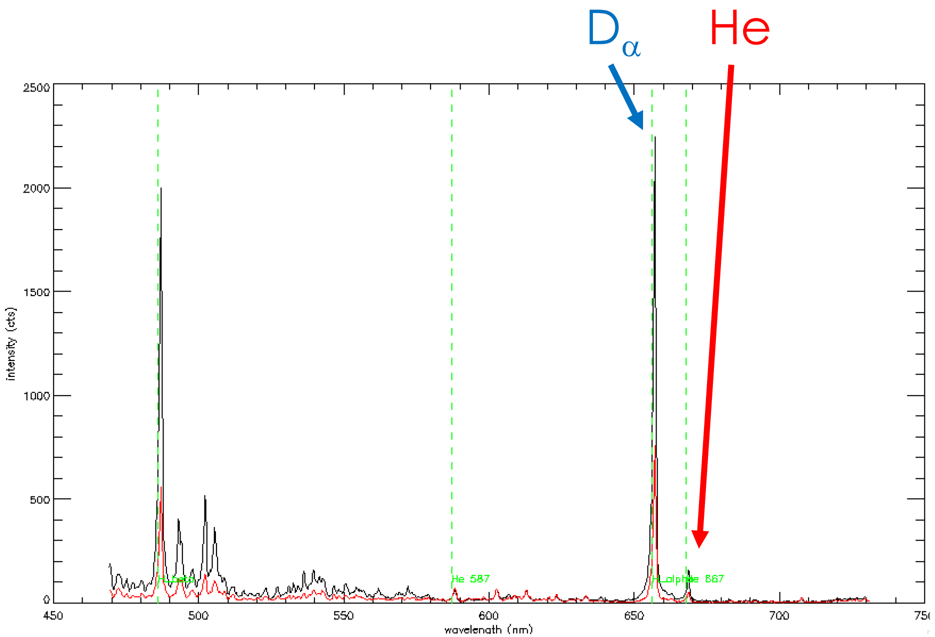
- 1-100 amu range
- Time response limited by QMS
  - ~ gas conductance time scale
- D_2 and He (mass 4) very difficult to resolve



Mass (amu)

Light Spectroscopy

- D and He are relatively easily resolved
- Time response much higher than gas conductance time scale



wavelength (nm)

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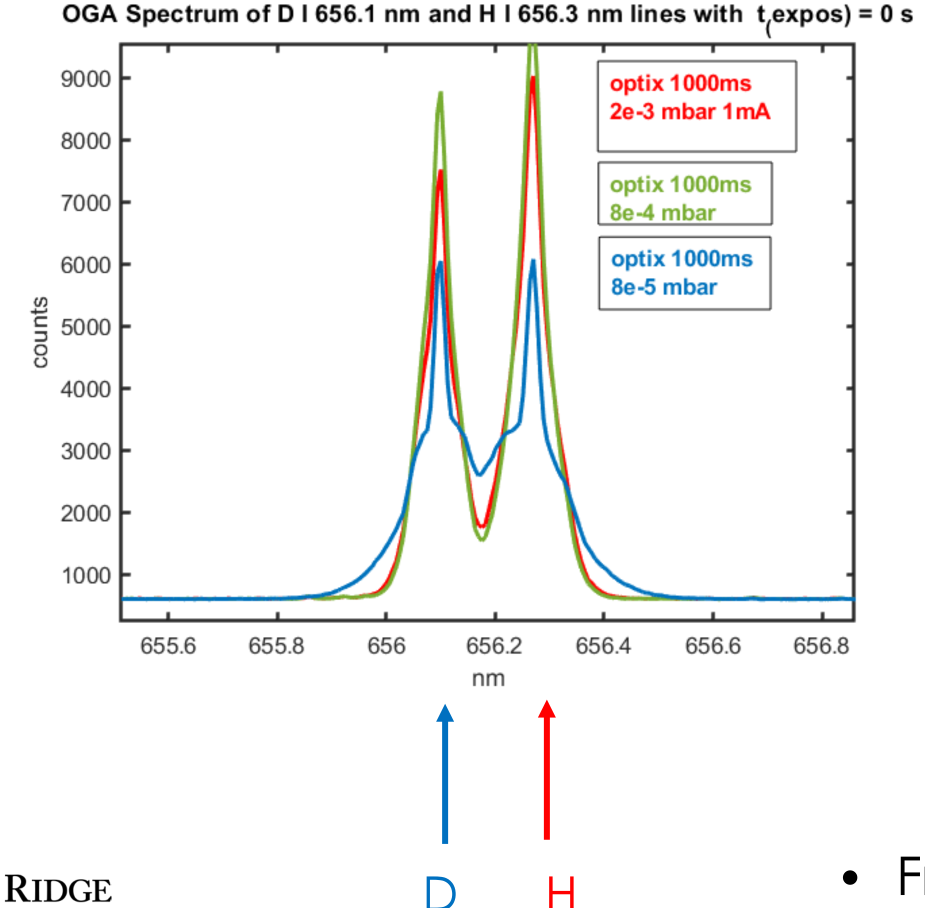
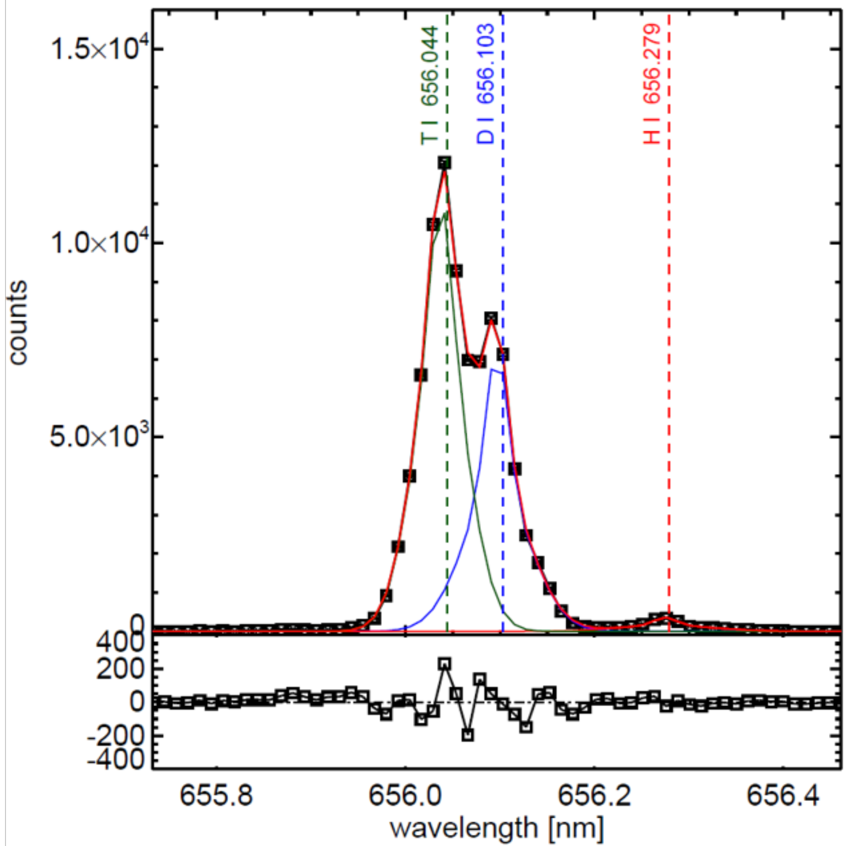
Gas sampled from divertor pumping duct provides information on concentrations of gasses

Laboratory testing at ORNL



JET data (#99627) from DTE2



- From C.C. Klepper, et al, IEEE-TPS (accepted Nov. 2022)

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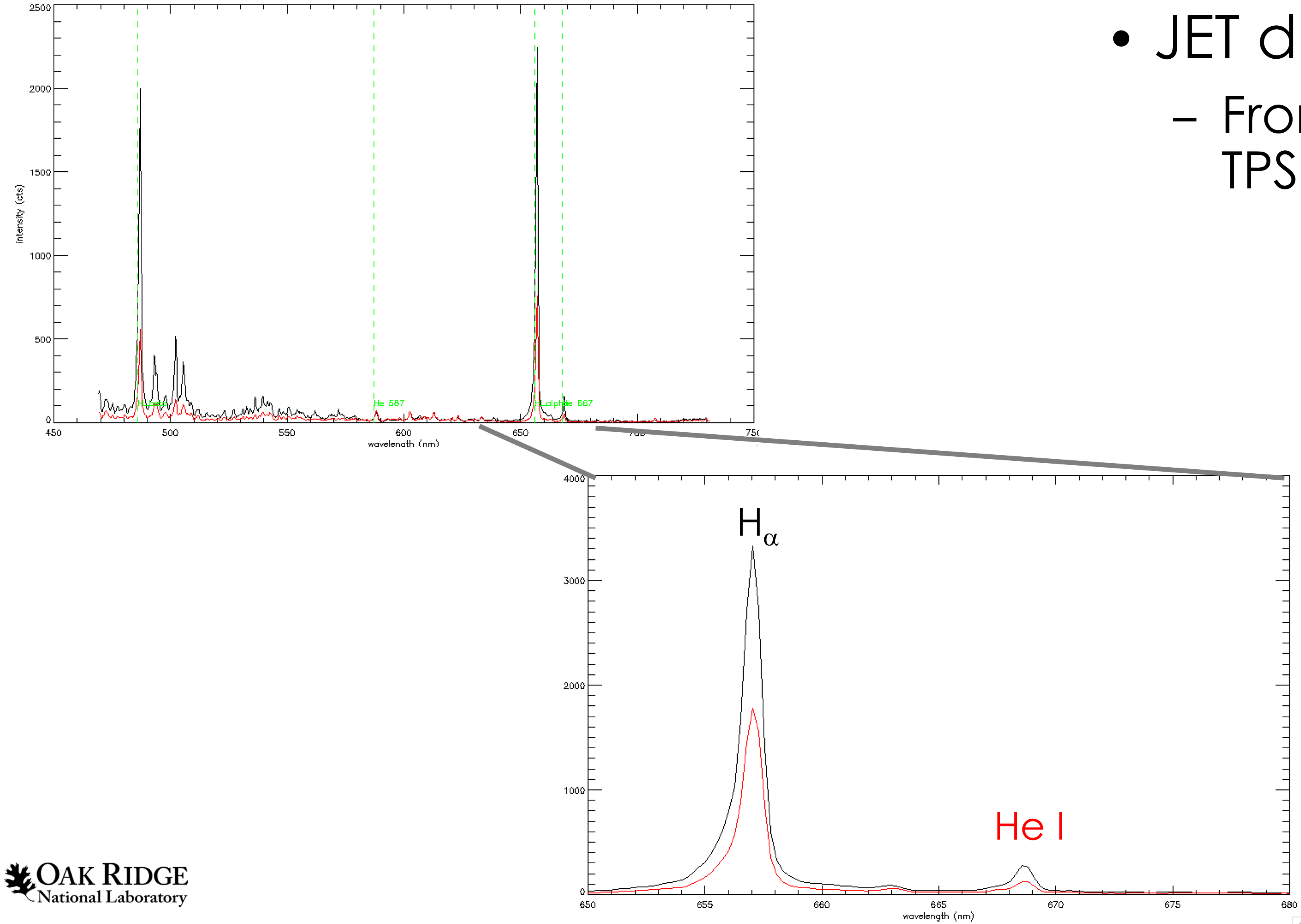
High-dynamic range of the instrument, enables simultaneous measured of D and He light



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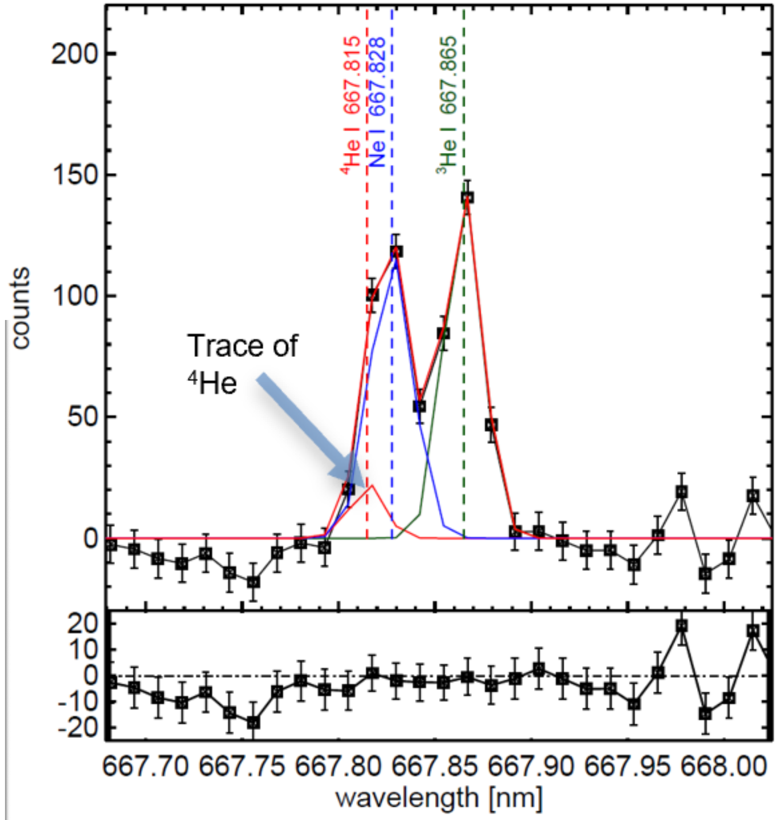

DRGA seems to be one diagnostic technique that can scale to fusion pilot plants (and will be tested on ITER)

- Measures neutral gas concentrations at multiple locations
- Produces signals proportional to:
  - fueling gasses
  - fusion byproducts
  - Core-edge integration relevant: radiative divertor gasses
- Relevant time scales?
  - ~1 Hz (due to gas conductance time)
- To be done: Explore the utility of other diagnostic systems

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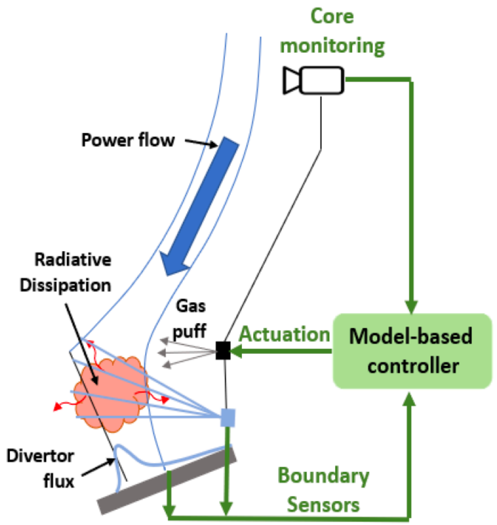
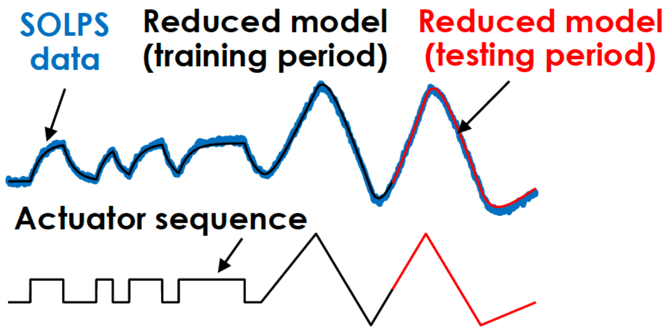
J. Lore, et al: "Model predictive control of boundary plasmas using reduced models derived from SOLPS-ITER"

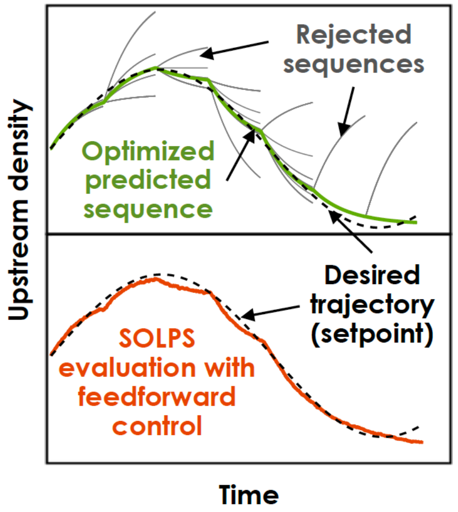
Model based control development to protect fusion reactor plasma facing components

High fidelity plasma model framework → Data-driven system identification → Proof-of-principle model-based controller





Reduced model 1000x faster than high fidelity simulation



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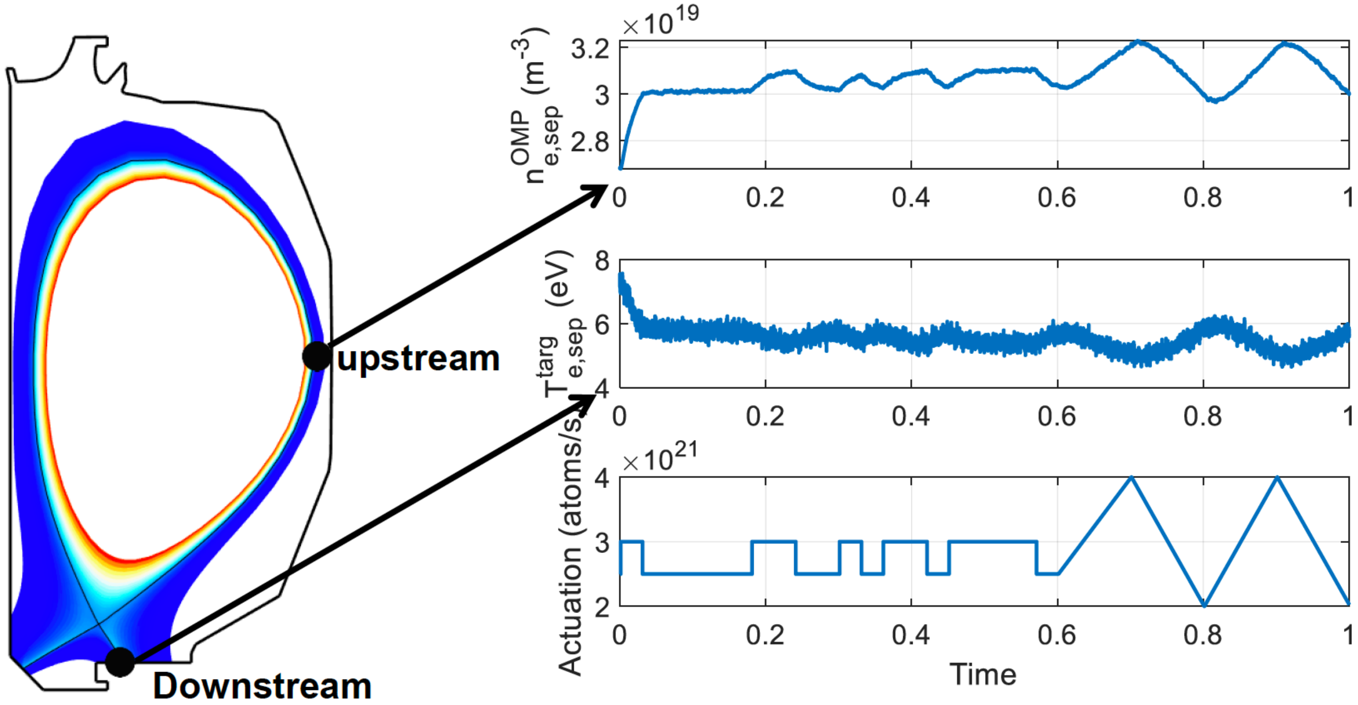
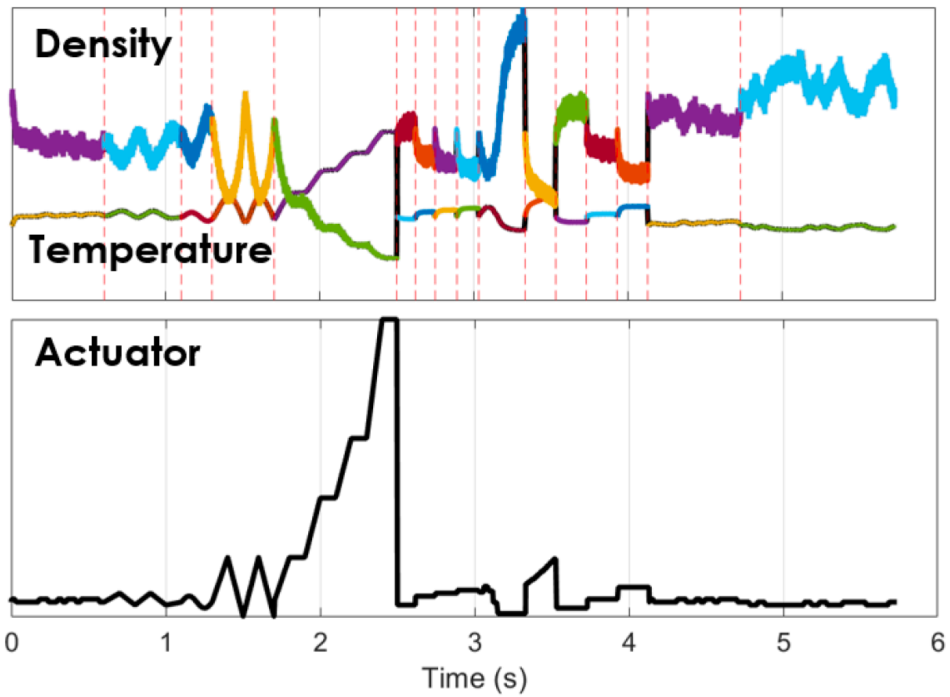
Developing a high-fidelity response to actuator

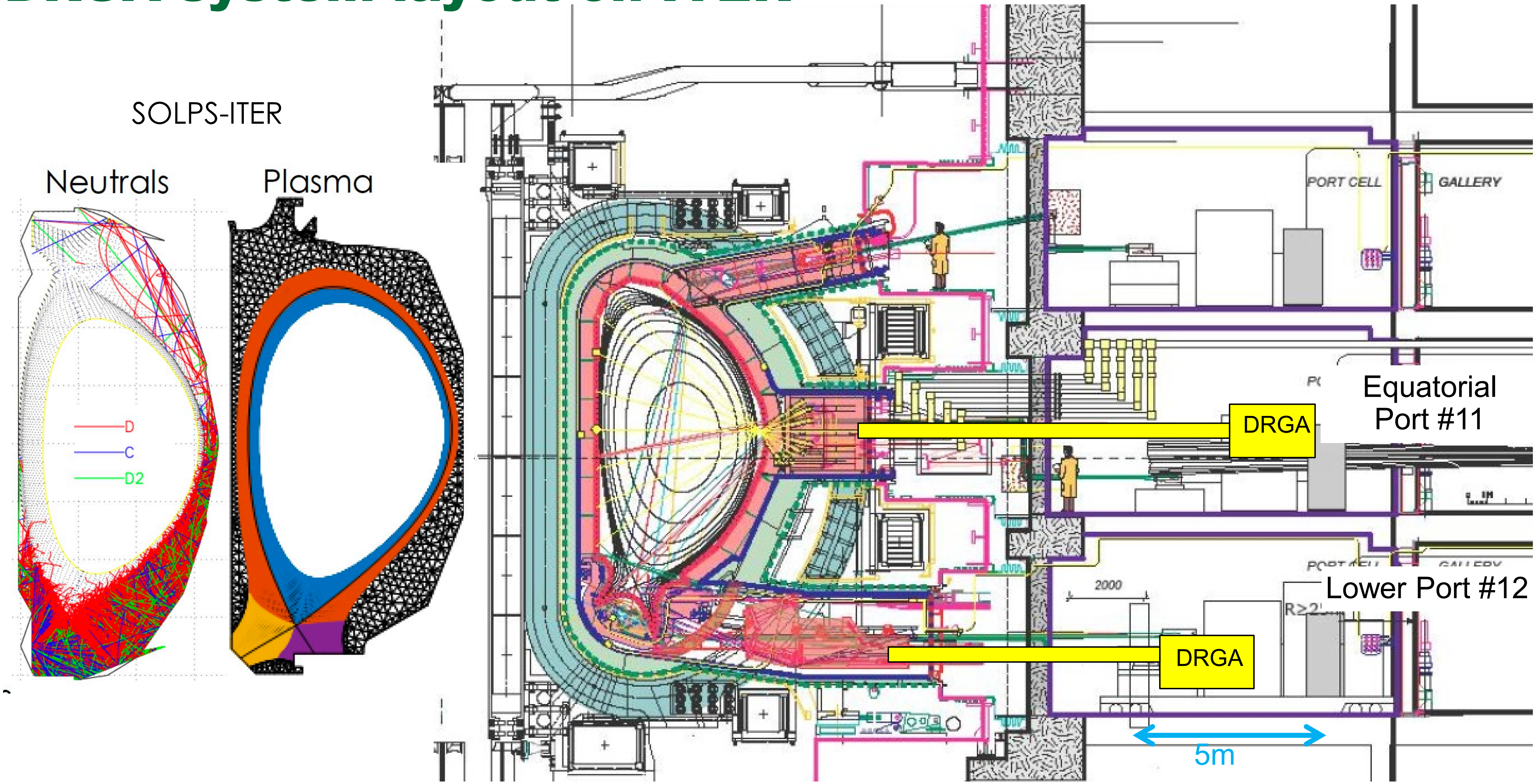
J.D. Lore, APS DPP, 2021

- Implement and test time-dependent SOLPS
  - Set up code to produce physical dynamics
  - Determine computationally tractable simulation setup
- Kinetic neutral transport simulations more tractable than anticipated, do not yet impede data generation
  - Proceeding with kinetic simulations to **demonstrate start-to-finish proof of concept**
- Series of simulations performed to generate dynamics with varying levels of nonlinearity





DRGA system layout on ITER



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T.M. Biewer, et al., IAEA Tech. Mtg. on Long-Pulse Operation of Fusion Devices, Nov. 16th, 2022

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Plasma control systems are not currently part of ORNL's realm of expertise

- MPEX is a linear device under construction at ORNL
  - "Divertor simulator" with 10^6 s discharges
  - I&C personnel are currently authoring the control system software and hardware
  - Steady State diagnostic systems have been designed
    - E.g. including DRGA systems
- Opportunity to collaborate with community experts in this area

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Next Steps

- As given in the context at the beginning, this avenue of research is just beginning at ORNL.
- Some aspects can be investigated on
  - JET, W7X, DIII-D
  - ITER
- TBD: What time response is necessary?
  - Plasma shape and stability in a FPP could be in feed-forward control
  - Radiative detachment may require feed-back control on actuators
- TBD: What fidelity of data + modeling is needed?
- Initial testing on ITER to investigate scaling to FPP

ITER as a platform to test fusion reactor diagnostic sets

- ITER research program straddles "the recipe for fusion" event in the notional timeline
- ITER will have a more comprehensive set of diagnostics than follow-on fusion pilot plant device(s)
  - E.g. including DRGA
- ITER could be used to explore operation with reduced diagnostic information
  - Once fully-diagnosed operations are established

Discussion