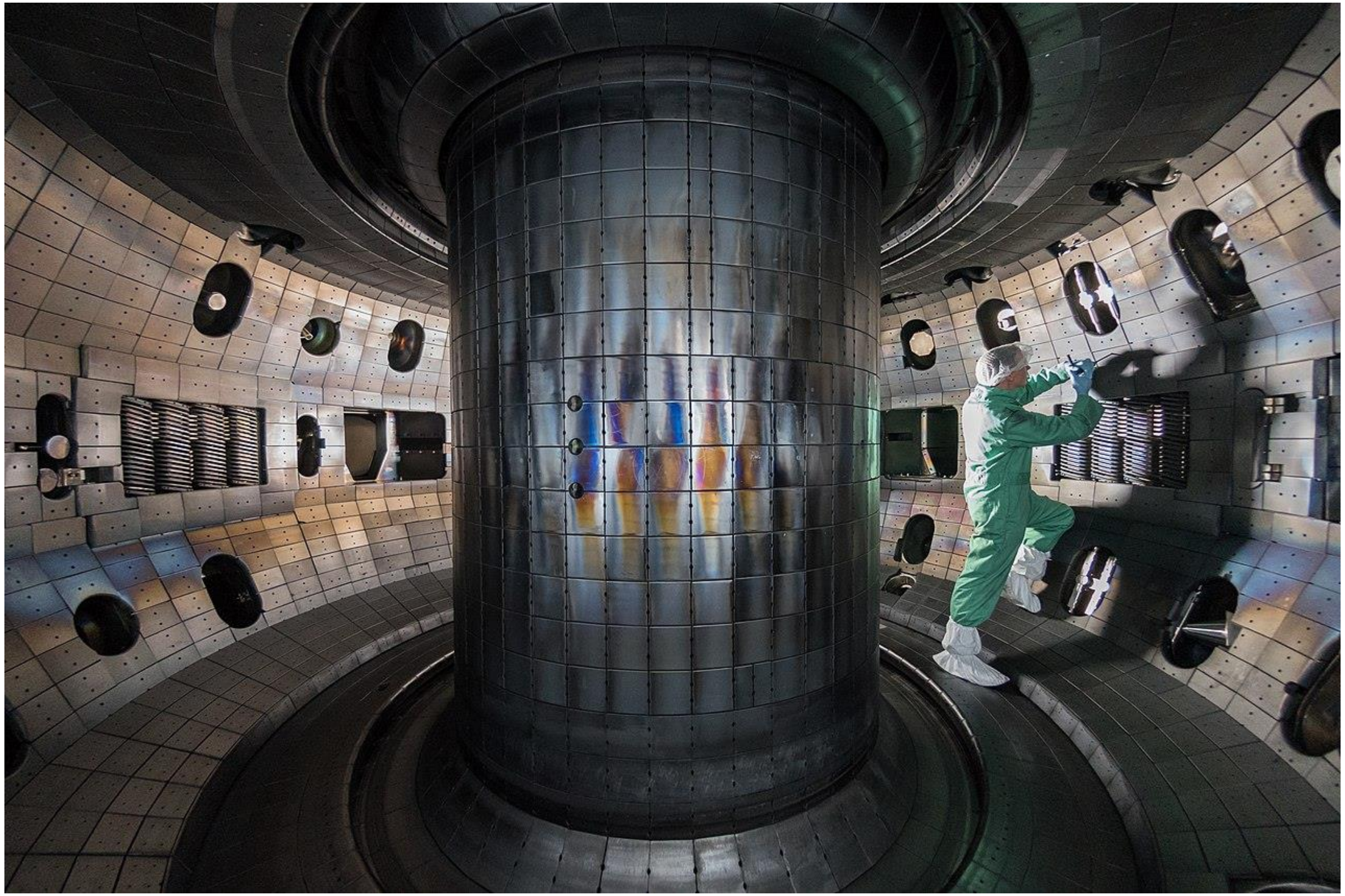
Introduction to Tokamaks

T.M. Wilks

June 15, 2022



Presented virtually to:

2022 SULI Introduction to Fusion Energy and Plasma Physics Course

DIII-D NATIONAL FUSION FACILITY

PSFC

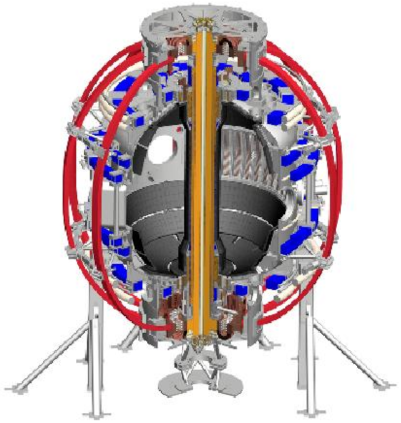
Who am I?

- **B.S. Mechanical and Nuclear Engineering at UC Berkeley**
  - SULI appointment at LBNL researching pulsed solenoid magnetic systems for heavy ion fusion
- **M.S. & Ph.D Nuclear Engineering, Georgia Tech**
  - Research on DIII-D tokamak experiment
  - SGCSR appointment at NSTX-U at PPPL
- **Post-doctoral associate, MIT Plasma Science and Fusion Center (PSFC)**
  - Appointment at DIII-D tokamak
- **Research Scientist, MIT-PSFC**

NDCX-II heavy ion accelerator

Inside DIII-D tokamak

NSTX-U tokamak



What we'll discuss…

- The case for tokamaks
- Tokamak engineering design
- Tokamak physics considerations
- Industry context

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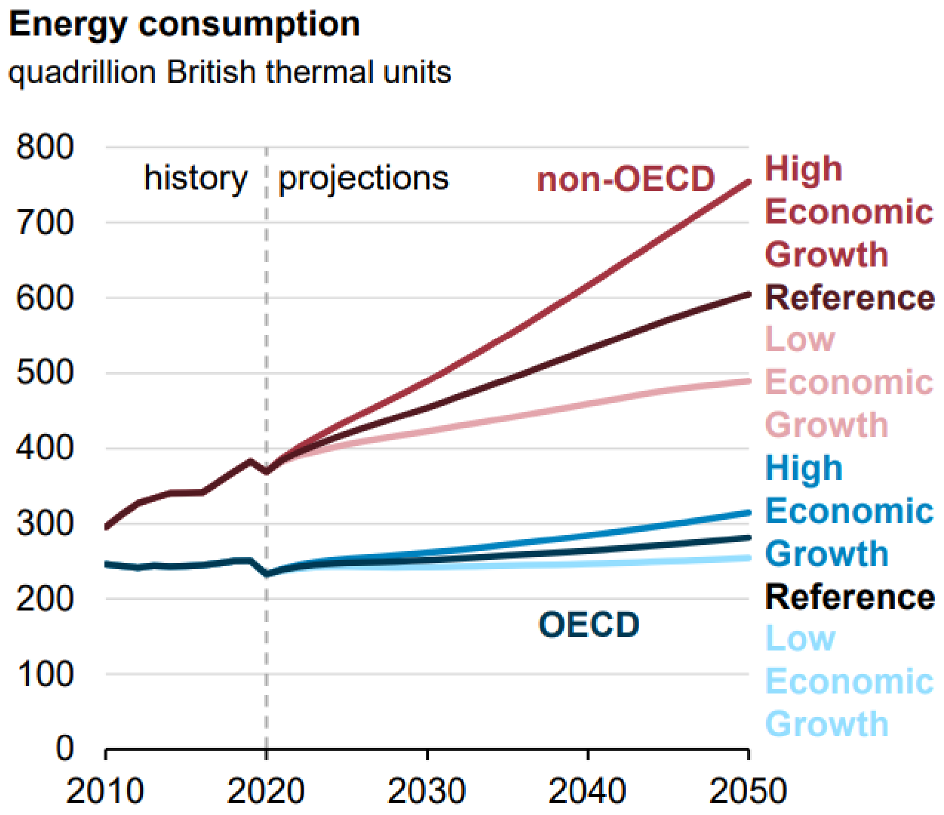
Worldwide energy demand is skyrocketing and we need a carbon free solution

- **Substantial increase in projected energy consumption from 2020 to 2050**

(OECD = Organization for Economic Co-operation and Development)

- **Still need to advance grid and energy production in much of the world – including the US**

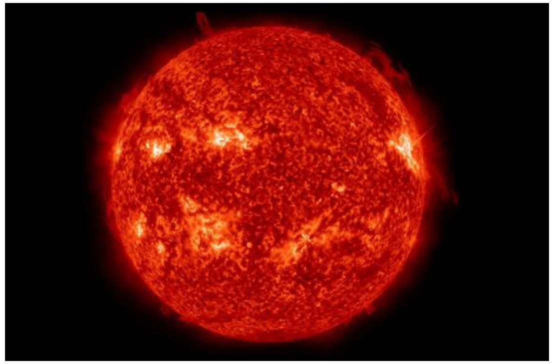
- **Fusion represents an attractive carbon free solution for baseload power generation**
  - Widely available fuel source (water)
  - Highest energy density reaction (~4Mx more than chemical reactions, ~4x more than fission)
  - No CO, no long-lived radioactive spent fuel
  - Limited risk of nuclear proliferation



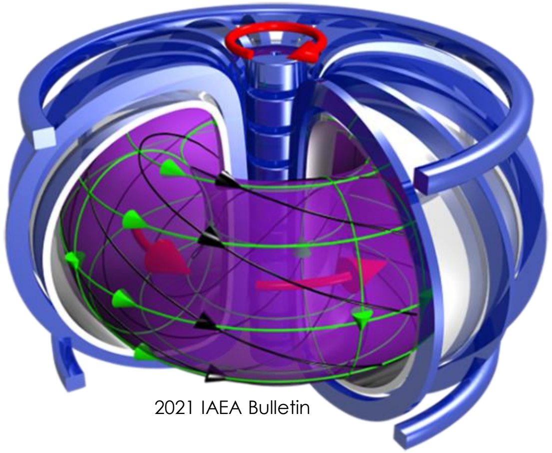
U.S. Energy Information Administration, International Energy Outlook 2019

Triple product is a convenient metric for measuring progress of fusion for different types of confinement devices

Gravitational Confinement

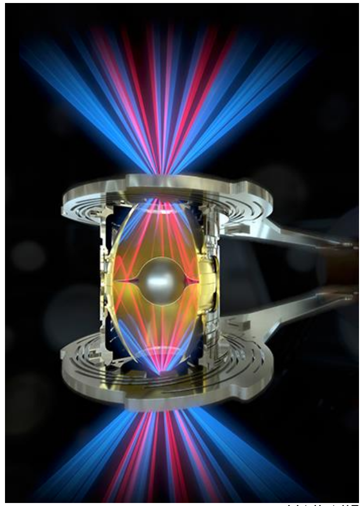


Magnetic Confinement



2021 IAEA Bulletin

Inertial Confinement



LLNL NIF

$$Triple\ Product = n * T * \tau_E$$

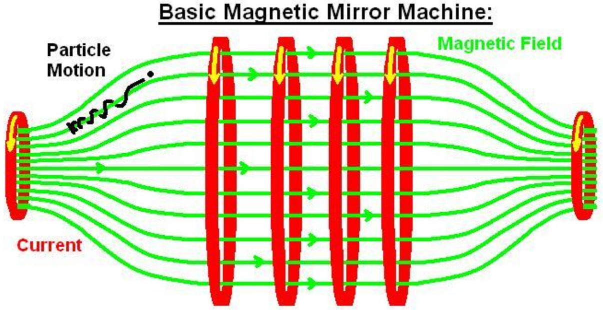
Density · Temperature · Confinement Time

Kraus, Day 3

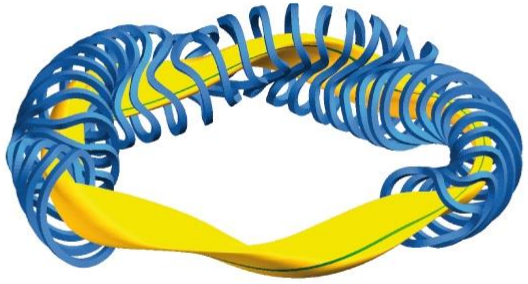
- **Fusion progress measured by triple product → can use density or temperature as a lever (or mixture of both)**
- **Sun uses gravity, magnetic confinement uses high temperature thermalized ions, and inertial confinement uses pulsed implosions**

Multiple methods for containing the sun's fusion reaction in the laboratory: focus here on TOKAMAK magnetic confinement

- **Magnetic mirror seemed promising, but too many losses out of the ends → toroidal geometry closes the loop**



Stellarator

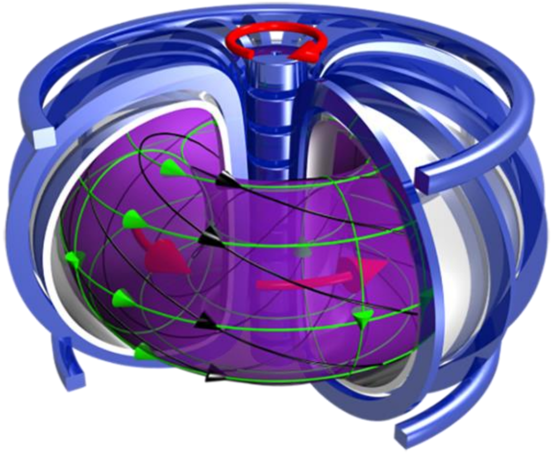


Hammond, Day 1

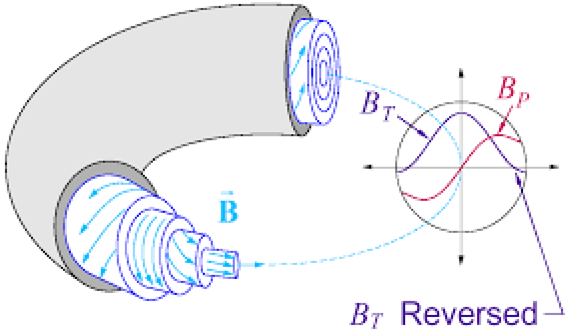
- **TOKAMAK = Russian acronym**

“Toroidal Chamber with Magnetic Coils”

Tokamak



Reverse Field Pinch



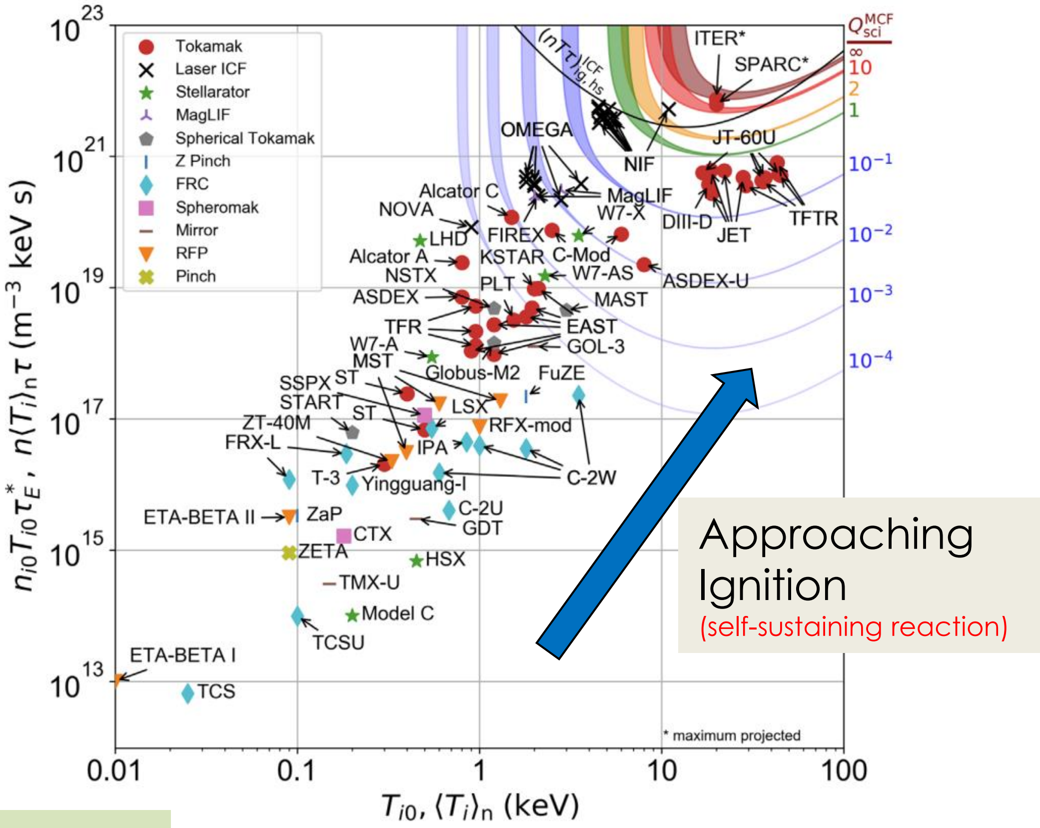
… and more!

Many tokamaks around the world, including both public and private sector investments, are making strides towards ignition

- **Copper magnetic field coils**
  - DIII-D (USA), JET (UK), ASDEX-U (Germany), COMPASS (Czech Republic), WEST (France), TCV (Switzerland)
- **Superconducting magnetic field coils**
  - EAST (China), KSTAR (Korea), JT60-SA (Japan)
- **Low aspect ratio**
  - NSTX-U (USA), MAST-U (UK)
- **Future public sector devices**
  - ITER (France)
  - DEMO class devices: CFETR (China), EU-DEMO (EU), STEP (UK), ARC (US), FPP (US)
- **Many private sector companies entering the market**
  - Commonwealth Fusion Systems (SPARC/ARC, US)
  - Tokamak Energy (ST40, UK)
  - Tri-alpha Energy (Copernicus)

Salazar, Day 5

… and more!



Wurzel et al, PoP 29, 062103 (2022)

Wurzel, Day 5

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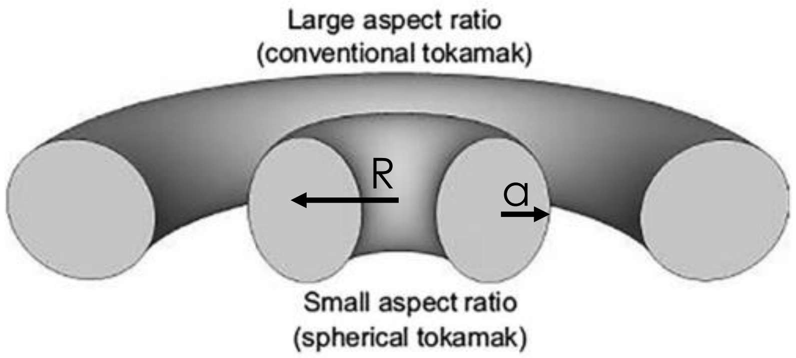
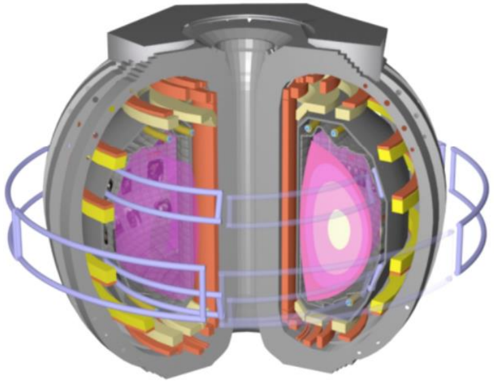
Two major U.S. facilities are DIII-D and NSTX-U, specializing in different aspect ratios

- **U.S. program has two types of tokamaks, which leverage different aspect ratios → plasma behaves differently**
- **“Conventional tokamak”: A > 2.5**
- **“Spherical tokamak”: A ~ 1-2.5**

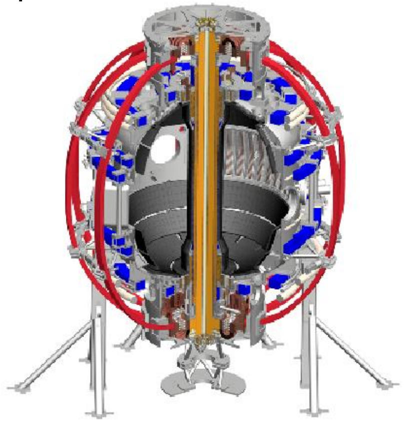
$A = R/a$

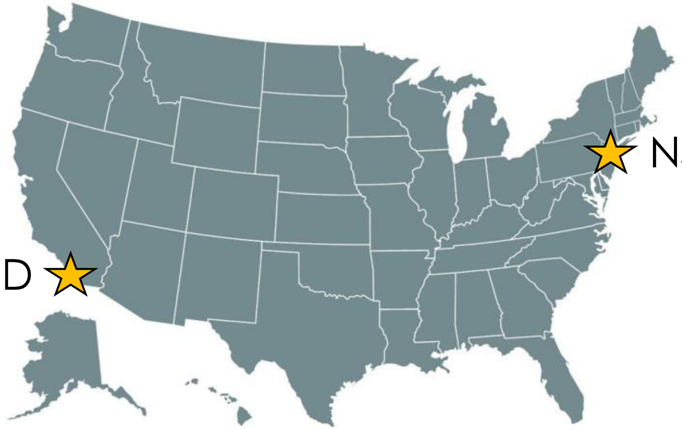


DIII-D
conventional tokamak



NSTX-U
spherical tokamak





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- **Tokamak design considerations**
- Some tokamak physics
- Industry context

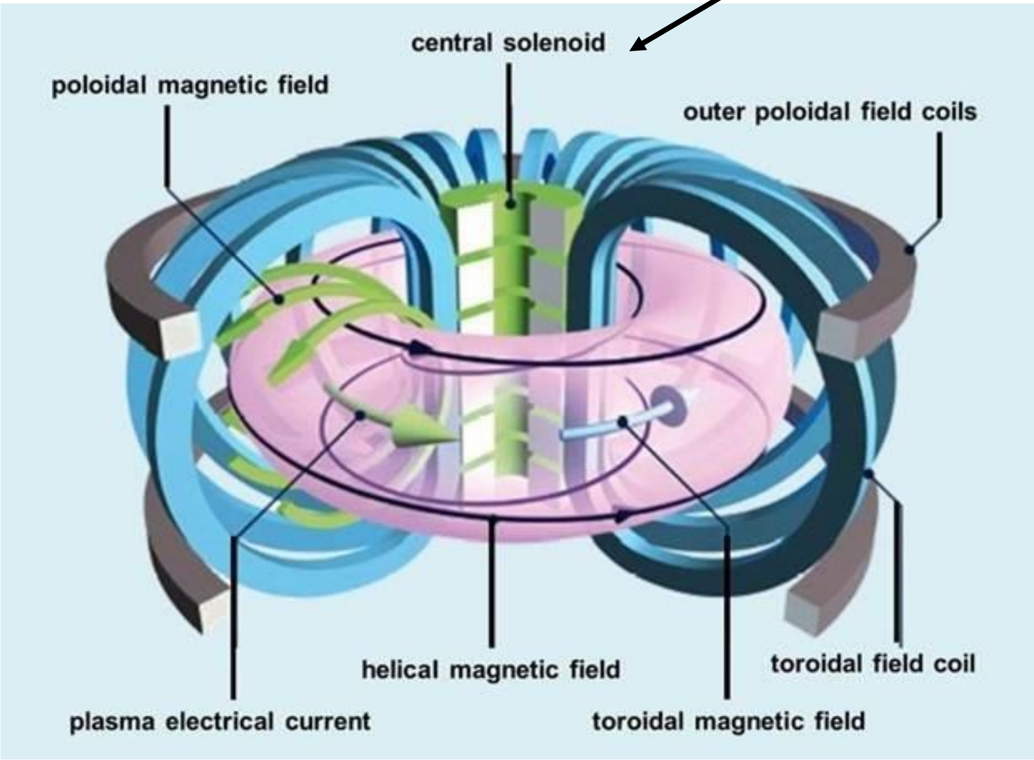
Tokamaks use magnets to confine the plasma inside a vacuum vessel

- **Central solenoid: wound magnet at the core of the tokamak used to inductively (ohmically) drive current in the plasma**
  - Can only be used in a pulsed manner
  - Plasma current in toroidal direction generates a magnetic field in the poloidal direction → creates a helical field line essential for plasma confinement

- **Toroidal field coils: D-shaped coils generating magnetic field along the axis of the plasma (toroidally)**

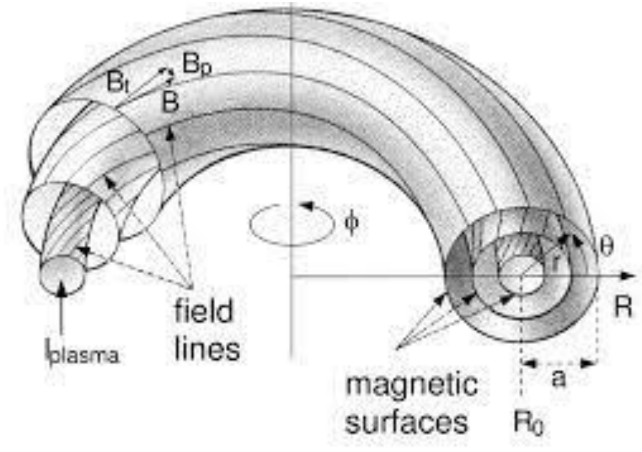
- **Poloidal field coils: circular coils that aid in controlling plasma shape and position within the vacuum vessel**

$$I_p \propto -\frac{d\Phi_{CS}}{dt}$$



Helical field lines lead to a set of nested magnetic surfaces

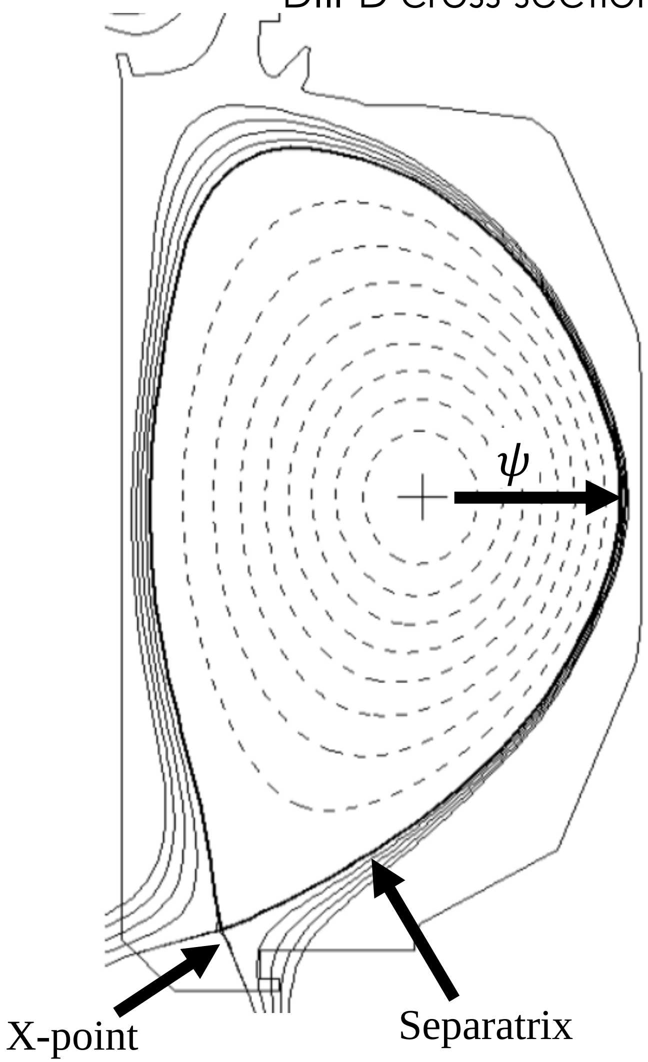
- **Nested magnetic surfaces are called "flux surfaces"**
  - Defined by a surface of constant flux when solving the Grad-Shafranov equation
  - Each surface defined by a safety factor, normalized flux ψ_N
  - Many quantities are conserved on flux surfaces (often used as a quantity to collapse to1D geometry)
- **Poloidal shaping coils can push/pull the plasma to form an x-point, or separatrix (last closed flux surface)**
  - Open field lines outside of the separatrix divertor plasma → scrape off layer
  - Specially designed target plate called divertor used to handle the heat load



$$q = \frac{d\phi}{d\theta} = \frac{toroidal\ transits}{poloidal\ transits}$$

Safety factor

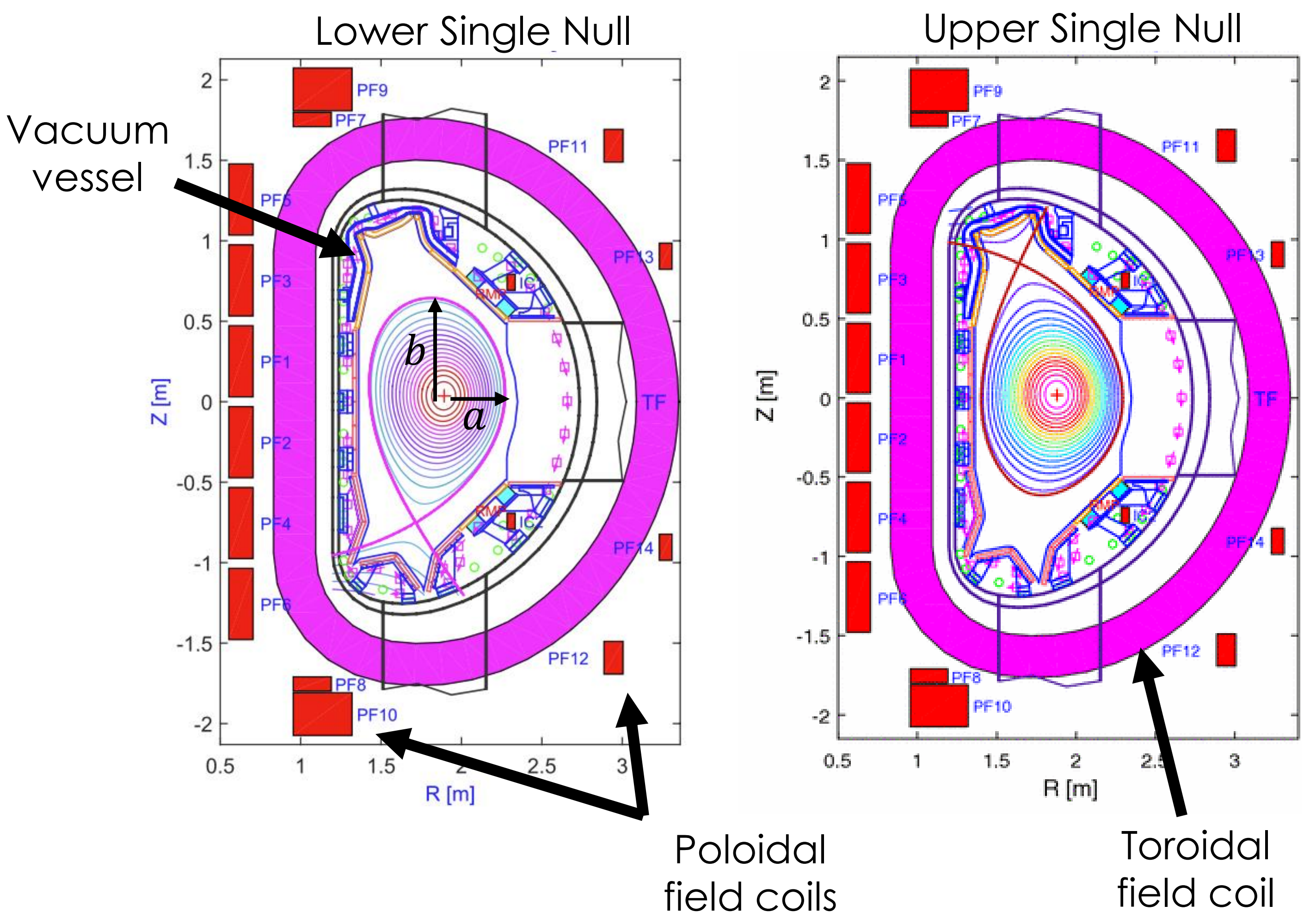
DIII-D cross section



Poloidal field coils are used to control plasma shape

- **Changing currents in poloidal coils change the confining fields that shape the plasma**
  - Plasma is pushing outwards
- **Plasma shape impacts stability**
- **Free parameters for shape control:**
  - Magnetic major (R), minor (a) radius
  - Triangularity, $\delta_{up} = (R_{geo} - R_{up})/a$
  - Elongation, $\kappa = a/b$
  - X-point location
  - Separatrix location

EAST tokamak cross section



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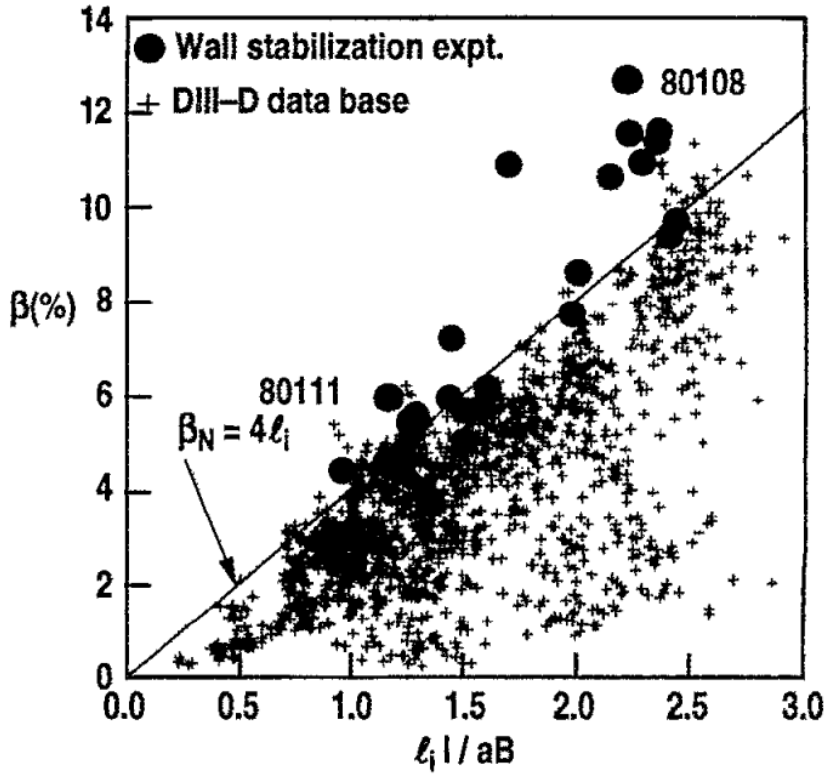
Plasma "efficiency" can be defined by the factor beta

- **Plasma pressure pushes outwards and is balanced by magnetic pressure**
  - β_N is "bang for your magnetic buck"

$$\beta_N = \frac{plasma\ pressure\ (fusion\ output)}{magnetic\ pressure\ (economic\ cost)} \propto \frac{<p>}{B^2}$$

- **Maximum plasma pressure and current allowable for each magnetic configuration**
  - β limit (coupled w/ current limits) sets tokamak operating space

$$P_{fusion} \propto \beta^2 B^4 \left(\frac{< \sigma V >}{T^2}\right)$$



Taylor et al, PoP 2, 2390 (1995)

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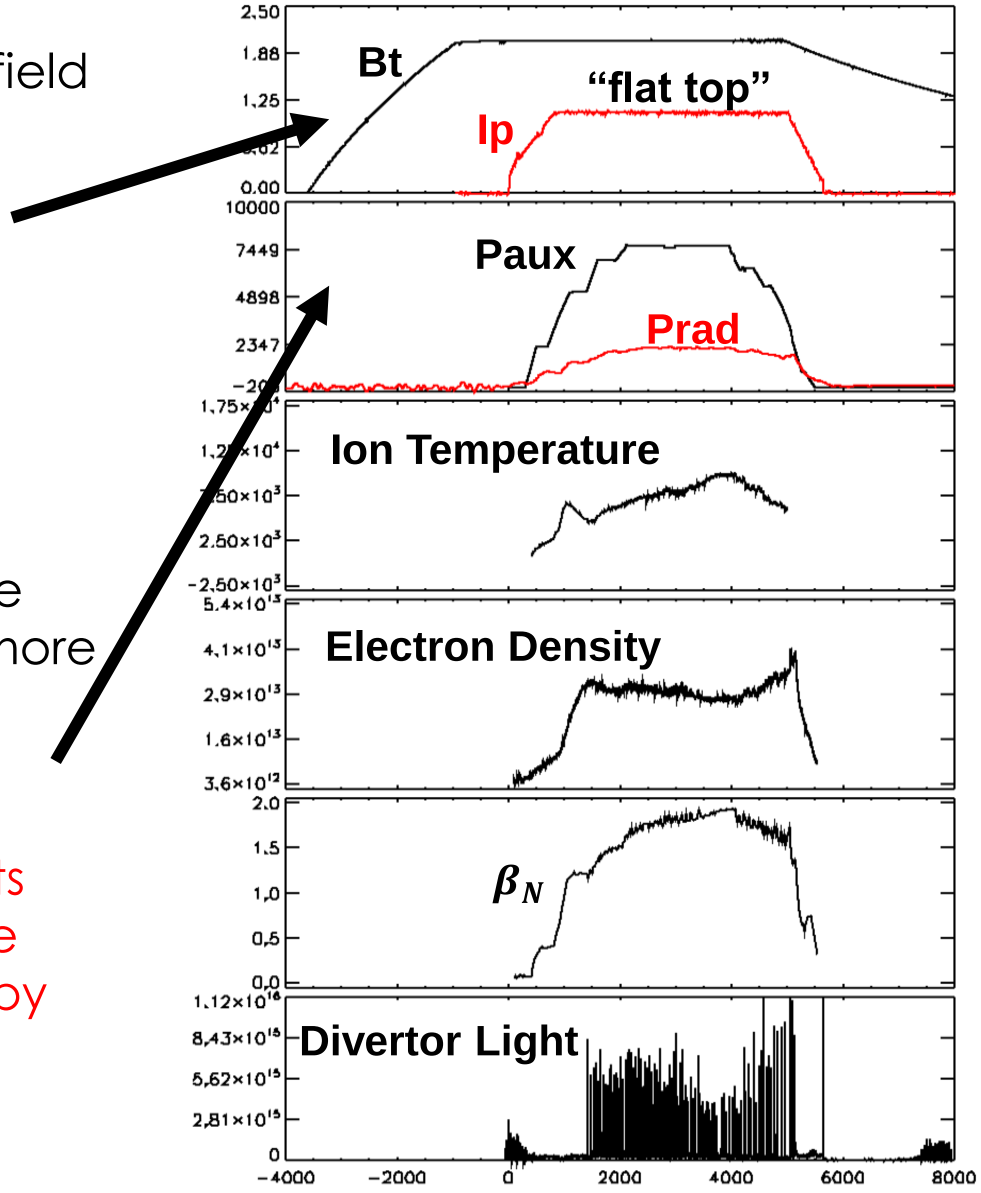
Example of a DIII-D plasma discharge

- Toroidal magnetic field ramps up first
- Central solenoid ohmically induces plasma current
- Auxiliary systems required to heat the plasma and drive more current
- Radiated power measures represents energy loss from the system (measured by bolometers)



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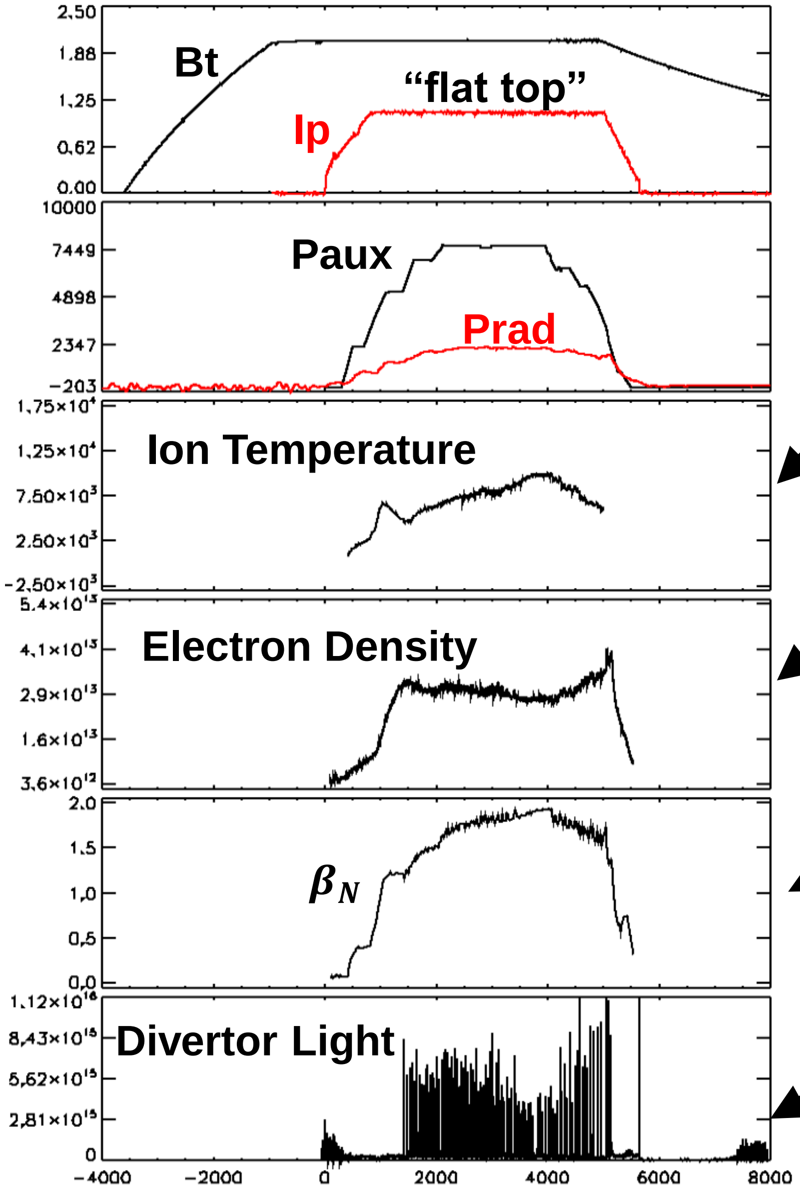

- Ion temperature measured by Charge Exchange Recombination Spectroscopy
- Electron Density measured by interferometers
- Normalized β calculated from "real time EFIT" → equilibrium solver
- Divertor light measured by filterscopes represent typical plasma instabilities

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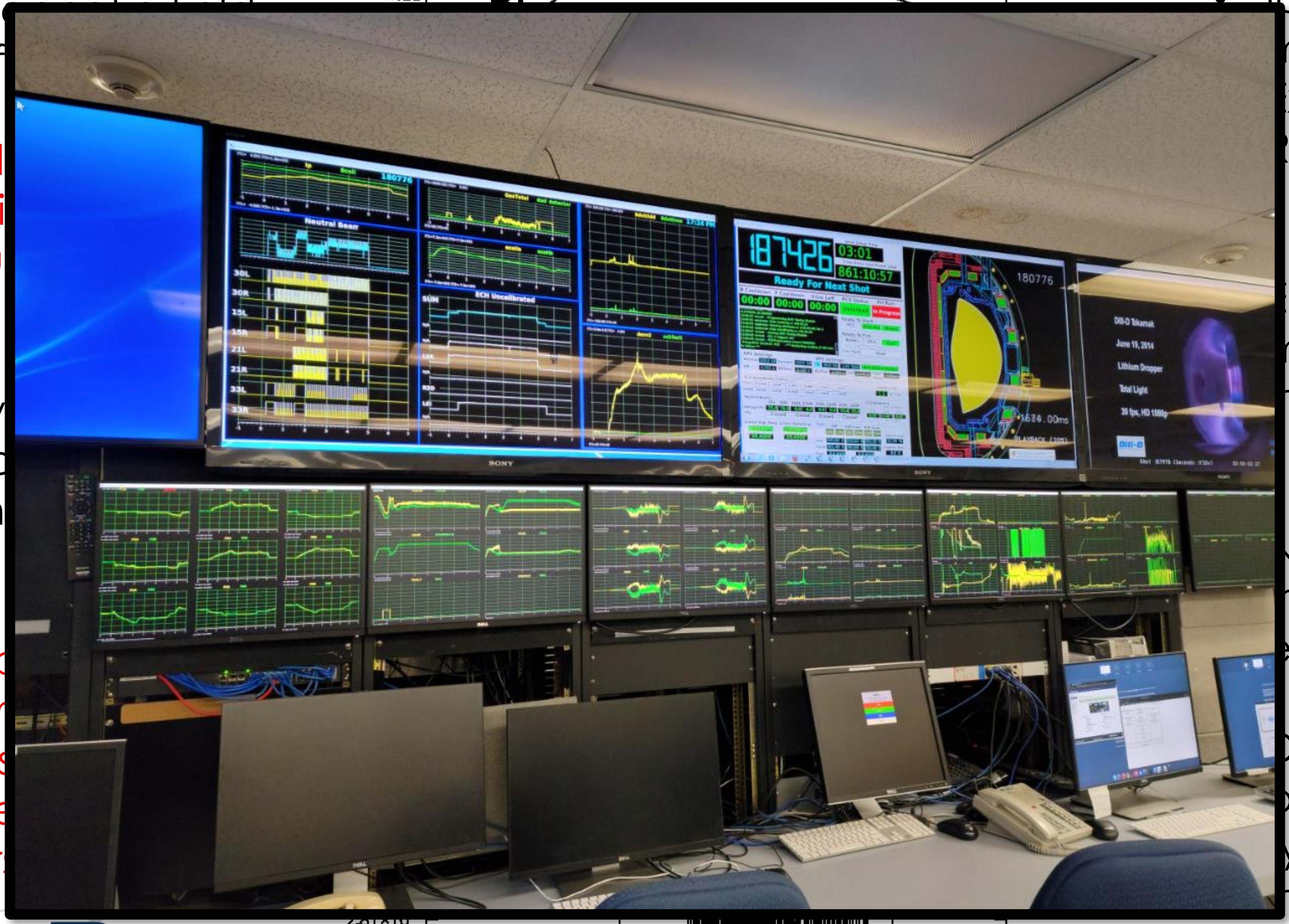
Example of a DIII-D plasma discharge

- Toroidal m… ramps up f…
- Central sol… ohmically i… plasma cu…
- Auxiliary sy… required to… plasma an… current
- Radiated p… measures r… energy loss… system (me… bolometer…



- Ion temperature …easured by Charge …xchange …ecombination …pectroscopy
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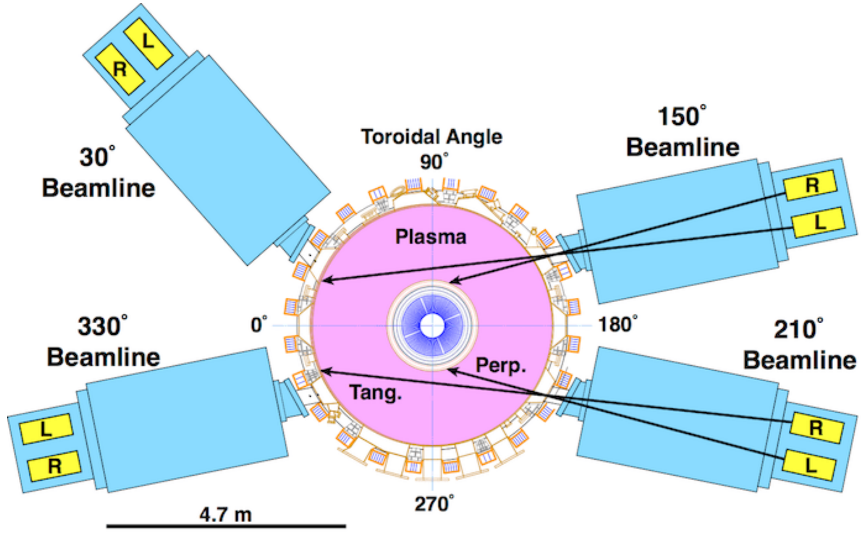
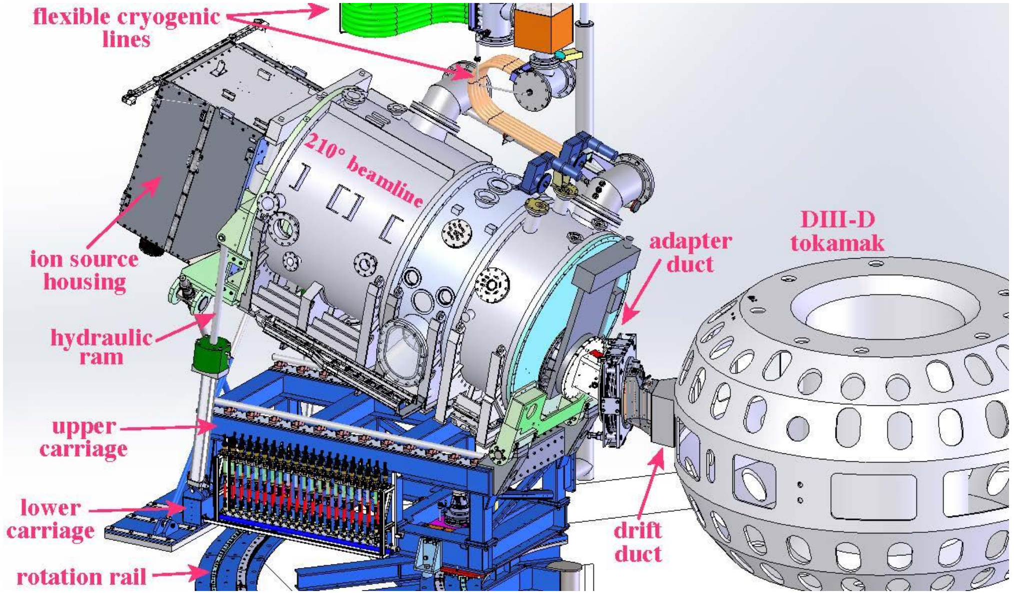
- …ormalized β calculated …om "real time EFIT" → …quilibrium solver
- …ivertor light measured …y filterscopes represent …ypical plasma …nstabilities

Neutral Beam Injection (NBI) is a primary heating and current drive systems in present-day tokamaks

- **Most tokamaks require external systems to drive toroidal current**
  - Some self-driven current, called “bootstrap current”
- **On DIII-D, each beamline has 2 ion sources and can deliver ~2MW**
  - 2 of the beams can tilt, and one can rotate!
- **Beamlines accelerate ions to high energies, then neutralize with electrons before injecting into the plasma**
  - Injected neutrals re-ionize in the plasma and deposit particles, momentum, and energy (big lever for experimental studies)





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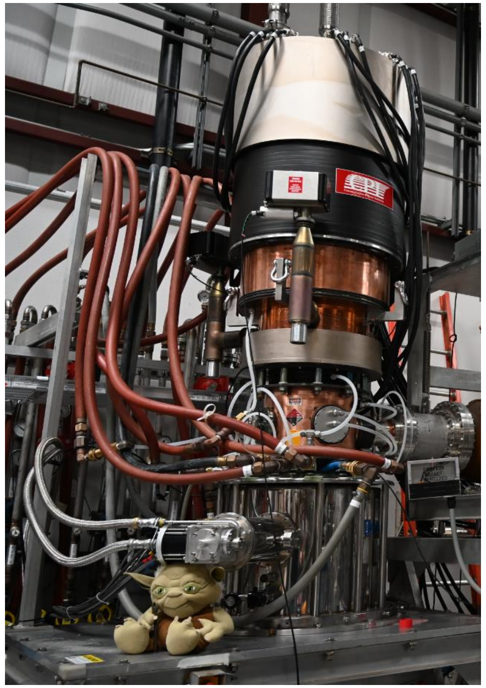
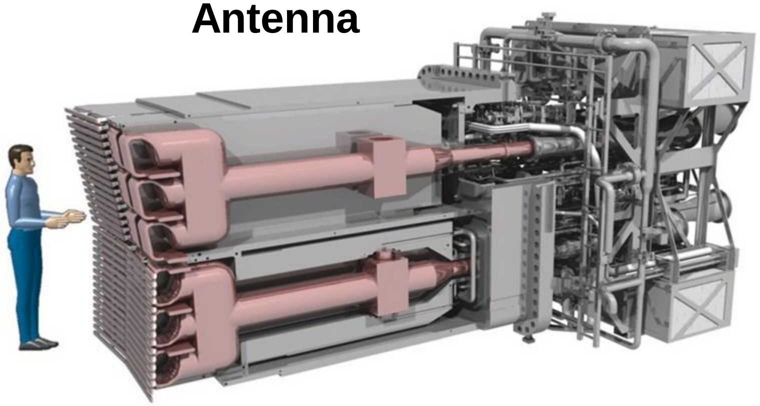
Radio Frequency (RF) is another primary heating and current drive systems in tokamaks

Diem, Day 2

DIII-D Gyrotron "Yoda"



ITER's Ion Cyclotron Antenna



WEST Klystrons

Delpech et al, EPJ Web of Conferences 157, 03009 (2017)

- **Several different types of RF power and current drive**
  - Electron cyclotron → wave guides deliver ~10-300GHz waves from a *gyrotron*
  - Ion cyclotron → antenna structure couples ~0.5-10GHz waves from *tetrode* to plasma
  - Lower hybrid → phased wave guides couple ~20-200MHz waves from a *klystron* or *helicon*

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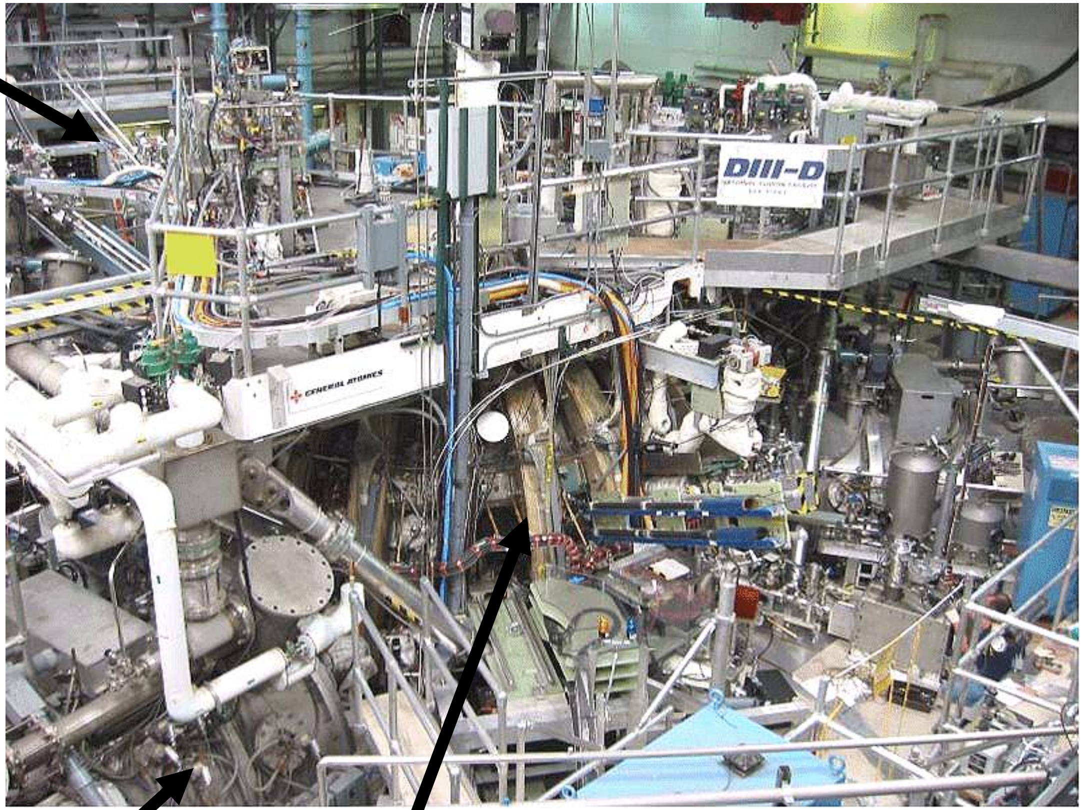
"The Pit" is where the DIII-D Tokamak is housed, along with MANY other systems



- 160+ ports in vacuum vessel → filled with diagnostics, fuel injectors, heating systems
- Motor-generator used to deliver power from the grid for a plasma discharge
- Many auxiliary systems: vacuum, high voltage, water, air, gas, cryo systems, computer and data acquisition

What we'll discuss…

- The case for tokamaks
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- **Some tokamak physics**
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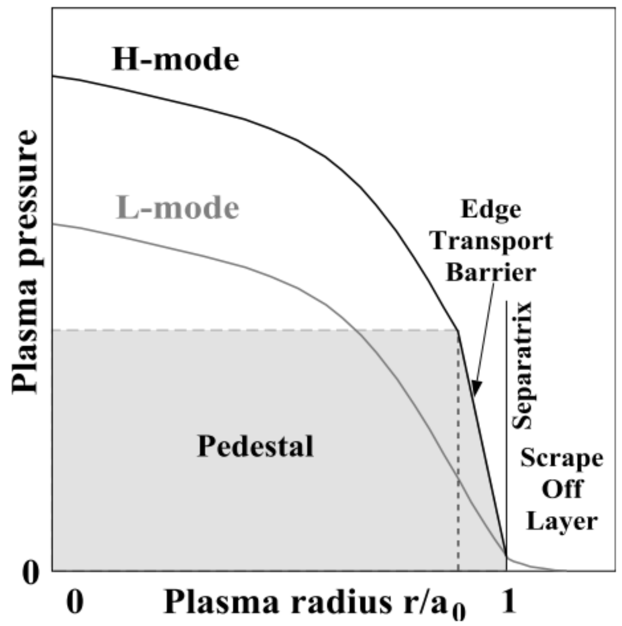
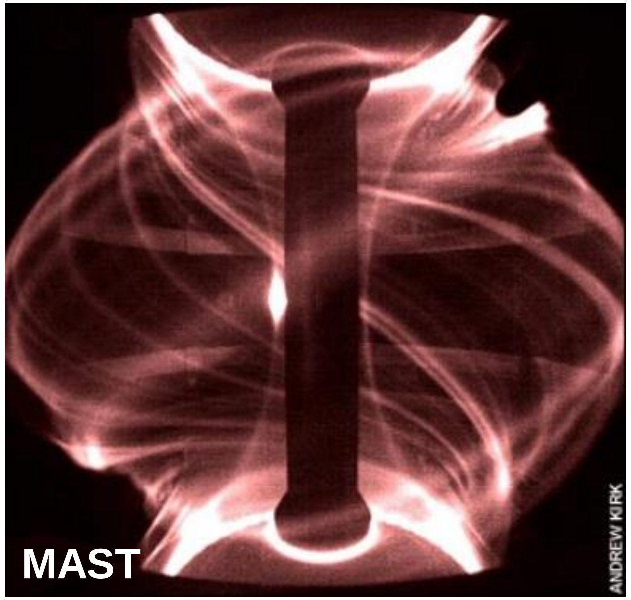
Varied levels of confinement of particles, momentum, and energy depending on the plasma regime

- **Two common plasma modes of operation**
  - L-mode = “low” energy confinement
  - H-mode = “high” energy confinement, often associated w/ plasma instability called Edge Localized Mode (ELM)

- **H-mode extrapolates well to future devices because of energy confinement (due to enhanced pressure from pedestal)**



Lang et al, NF 53, 043004 (2013)



Evans et al, Nonlinear Dynamics Ch 3 (image A. Kirk, Culham)

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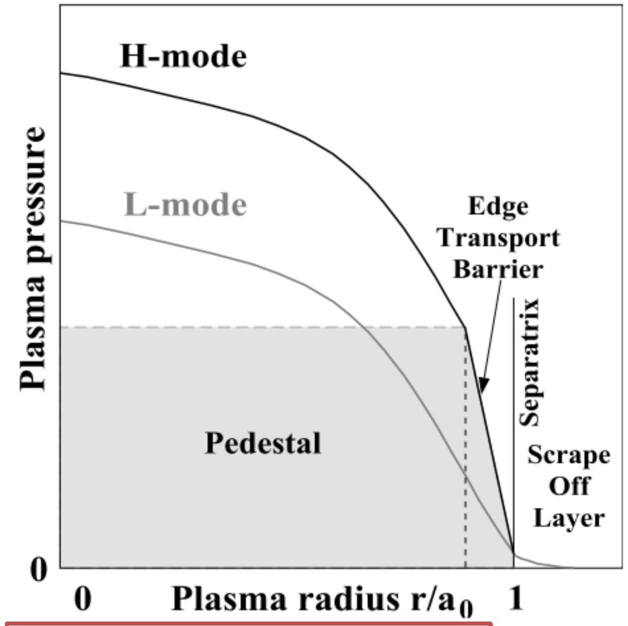
- **H-mode extrapolates well to future devices because of energy confinement (due to enhanced pressure from pedestal)**

- **ELMs deliver large transient heat fluxes to plasma facing components**

- **Other types of modes are an active area of research → e.g. H-modes w/o ELMs or regimes w/ different confinement scalings**



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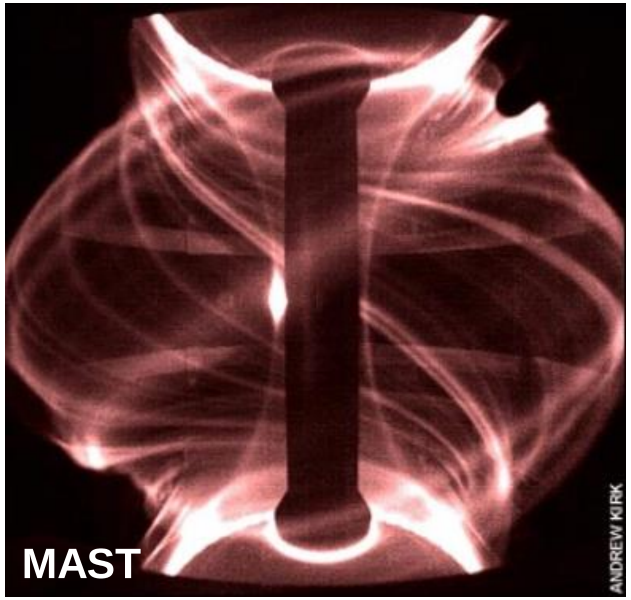

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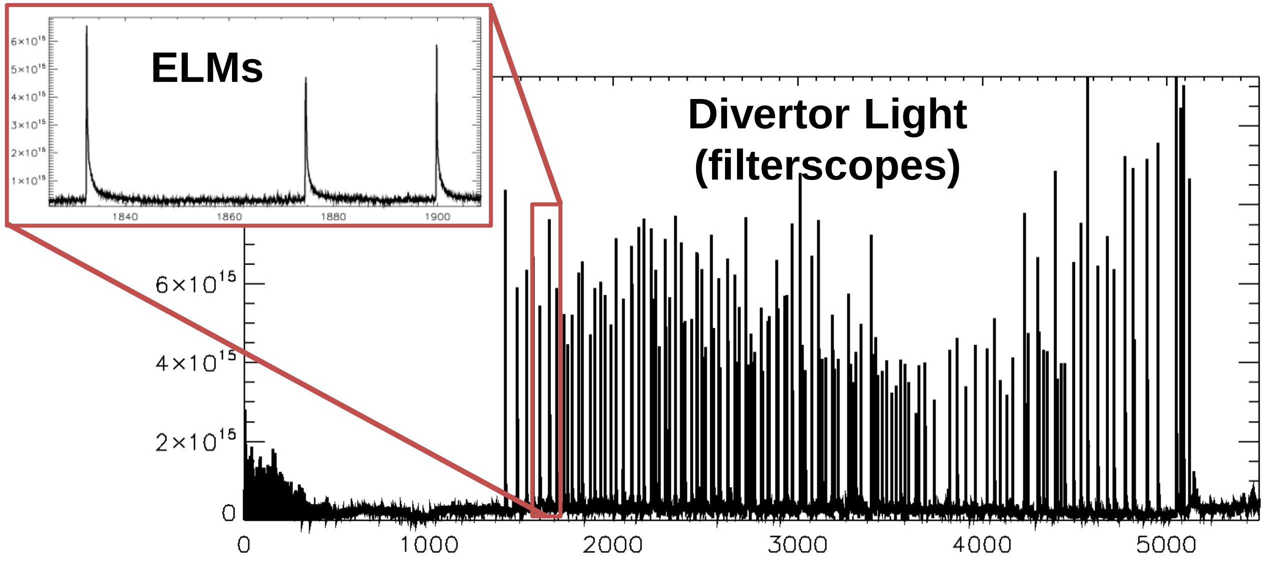
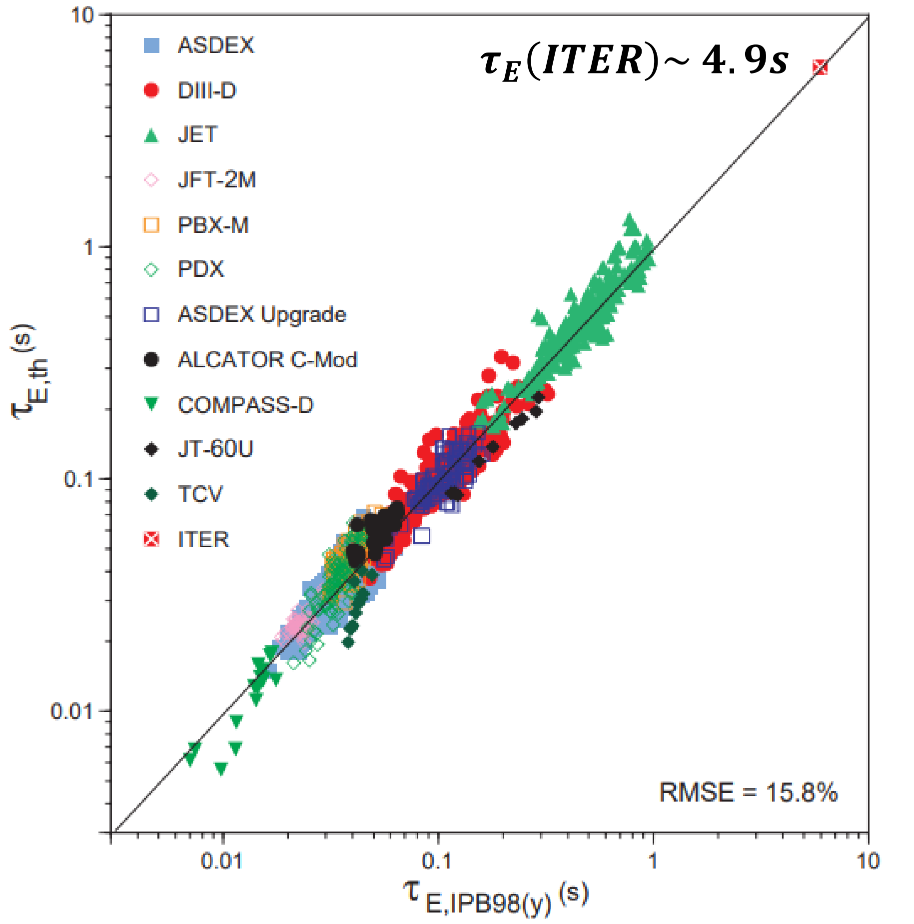


International Tokamak Physics Activity (ITPA) derived energy confinement scalings (and more!) from multi-machine databases

$$\tau_E\ [IPB98(y,2)] = 0.0562\ P_{loss}^{-0.69}\ B_0^{0.15}\ I_p^{0.93}\ \kappa_a^{0.78}\ n_e^{0.41}\ a^{0.58}\ R_{geo}^{1.39}\ M^{0.19}$$

- **Based on ELMy H-mode plasmas**
- **Engineering scaling based on geometric factors of the tokamak (size, shape) and plasma operating point (power, density)**
- **Dimensionless scaling useful because it recasts into relevant physics parameters (ion gyroradius, beta, collisionality, and safety factor)**

$$\tau_E\ (dimensionless) \propto \rho_*^{-2.7}\ \beta^{-0.9}\ \nu_C^{0.08}\ q_{95}^{-3}$$

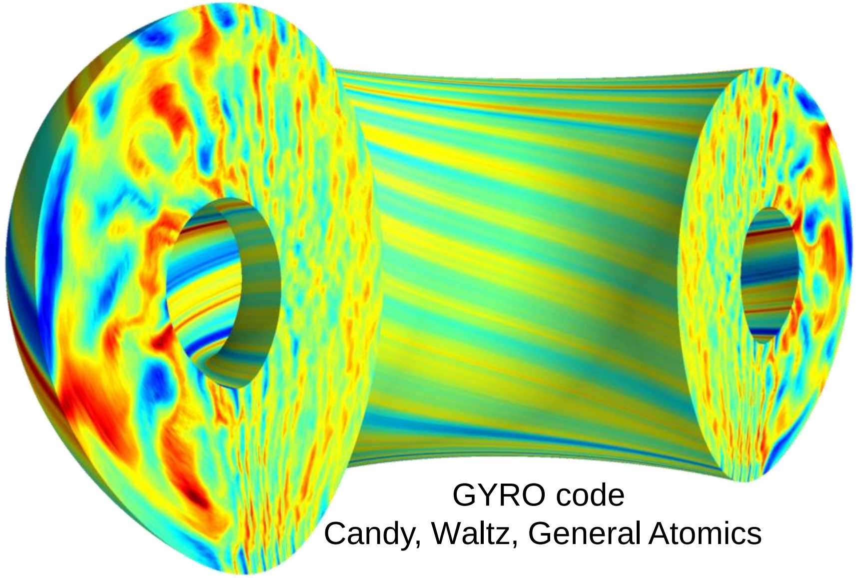


Plasma turbulence often dictates energy confinement times

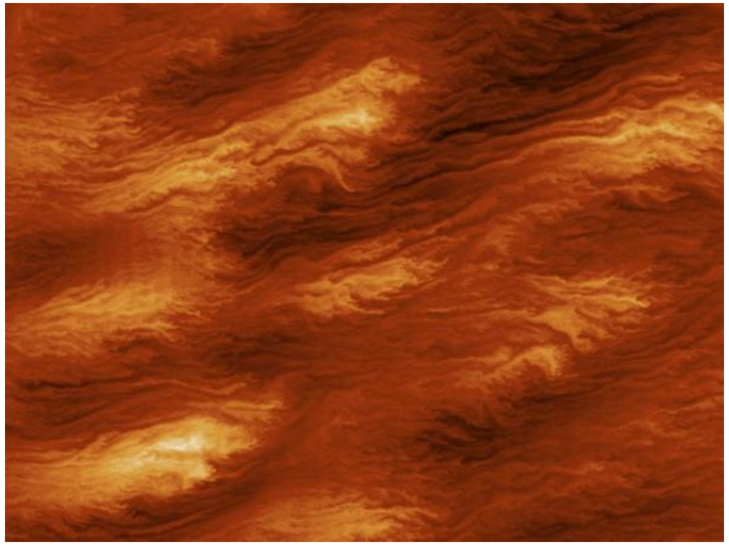
- **High Performance Computing (HPC) advances enable high fidelity and multi-scale plasma simulations**

- **Heat added to the plasma (by alpha particles or auxiliary power) will be transported either out of the plasma or to another particle**

- **Transport of particles, momentum, and energy is different in different locations of the plasma (core vs edge pedestal – often called “transport barrier”)**



GYRO code
Candy, Waltz, General Atomics



CGYRO code
Howard (MIT), Holland (UCSD), Candy (GA)

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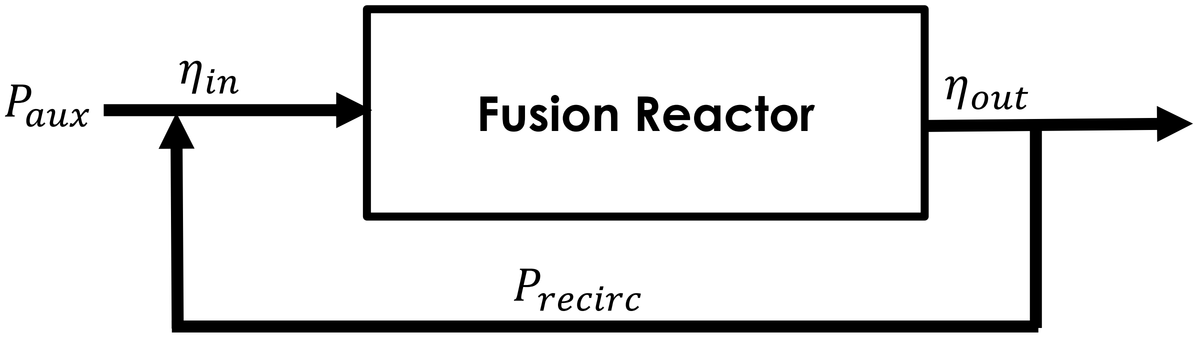
- **Industry context**

Plasma gain and efficiencies are important for balance of plant



$$P_{net} = P_{out} - P_{recirc}$$

$$= \eta_{out}(P_{fusion} + P_{aux}) - \frac{P_{aux}}{\eta_{in}}$$

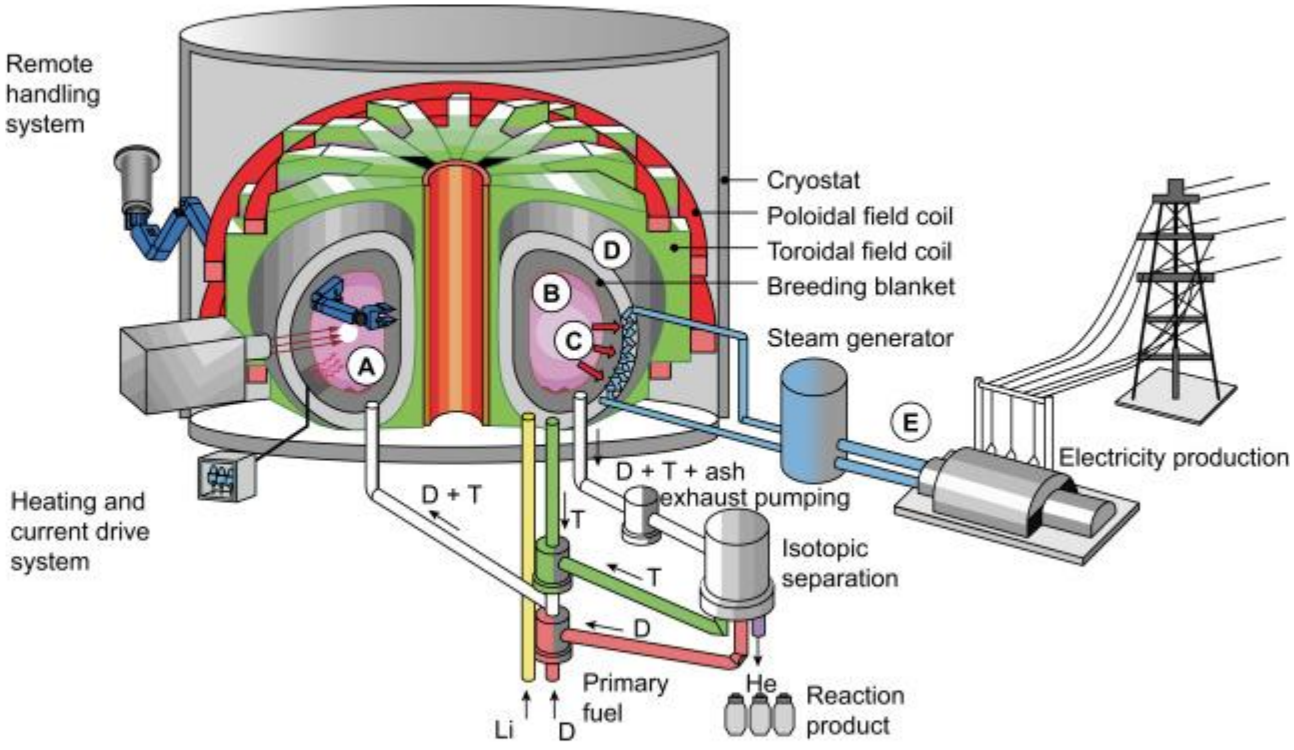
$$= \eta_{out}P_{fusion} + \left(\frac{\eta_{out}\eta_{in} - 1}{\eta_{in}}\right)P_{aux}$$

$$Q_{eng} = \frac{P_{out}}{P_{in}}$$

- **Plasma gain is critical for economic viability of fusion → impacted by confinement**
- **Engineering gain several dictates how much energy makes it to the grid after efficiency losses**

A fusion power plant will require more systems than present devices designed for research

- **Tritium Processing Plant**
  - Need to keep tritium inventory for fueling and radiation safety
  - Technology for pumping/separation
- **Lithium “blanket” surrounding the vacuum vessel**
  - Heat Removal
  - Neutron capture and tritium breeding
- **Generator/turbine and grid connection**
  - Standard for other power plants



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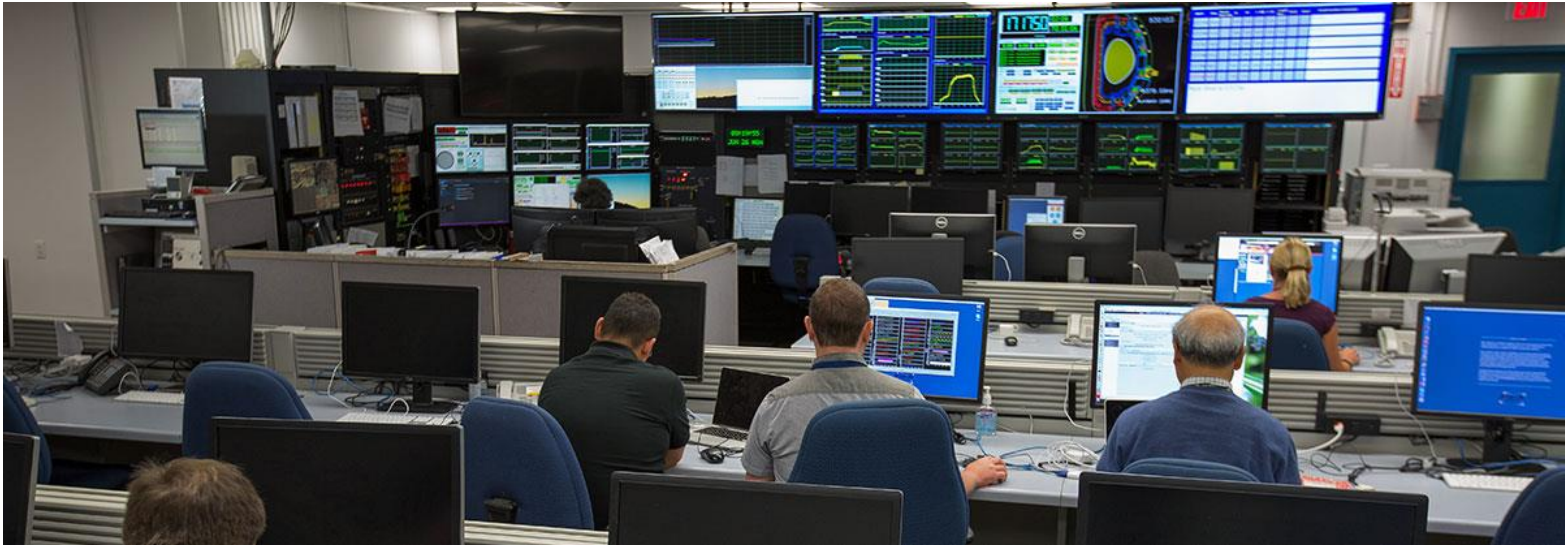
Control Room: where physicists, engineers, diagnosticians, programmers (…etc) perform experiments



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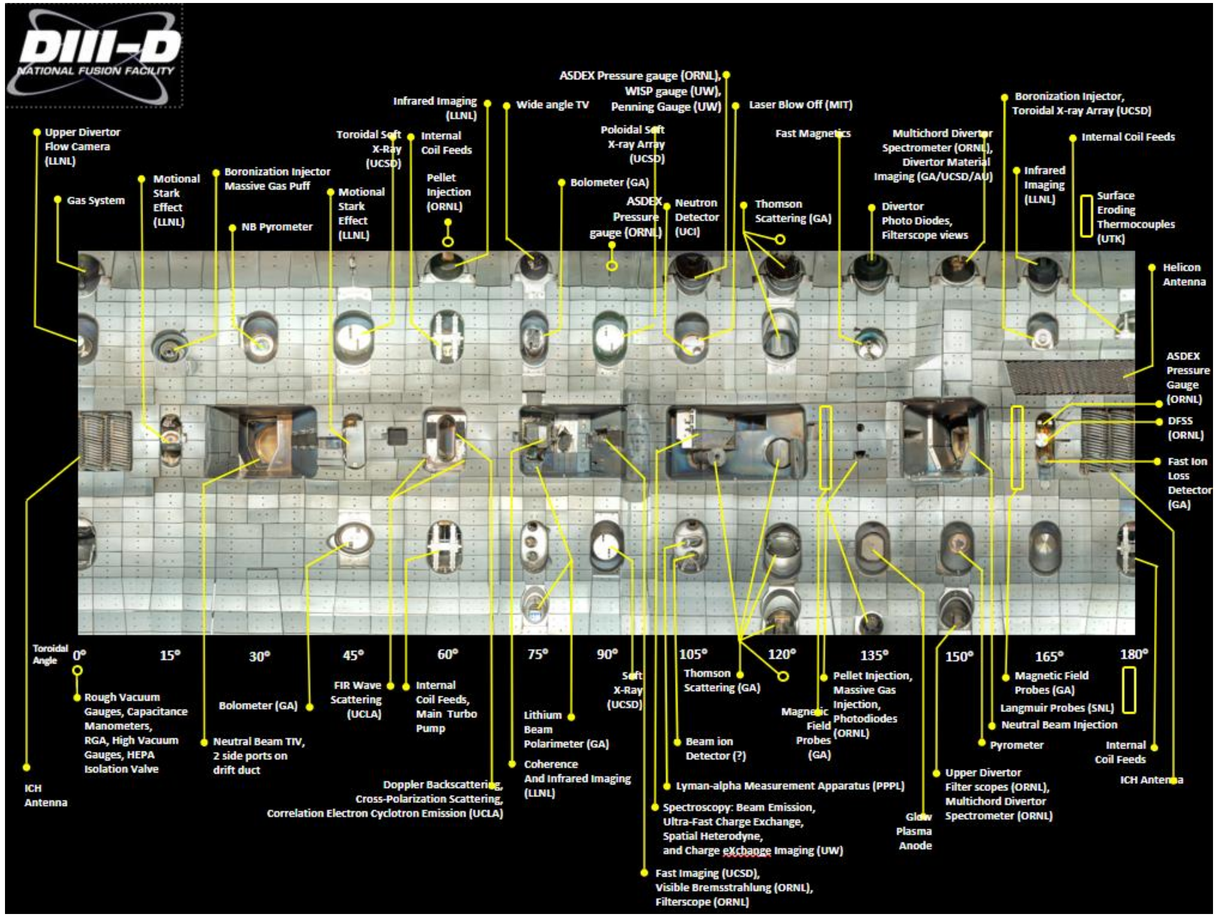
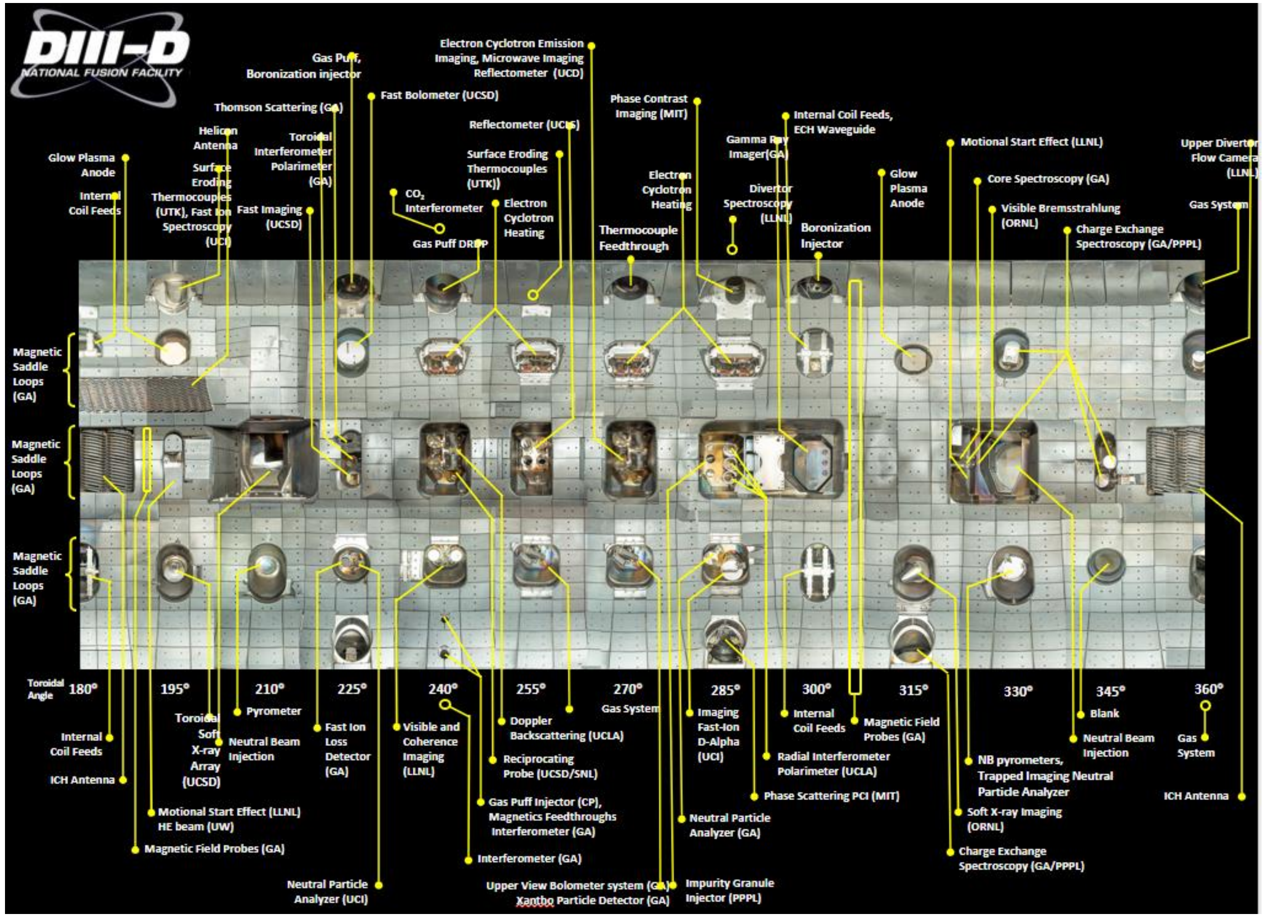
Diagnostics are a key part of tokamak research → how do you diagnose something that is so hot and in vacuum?





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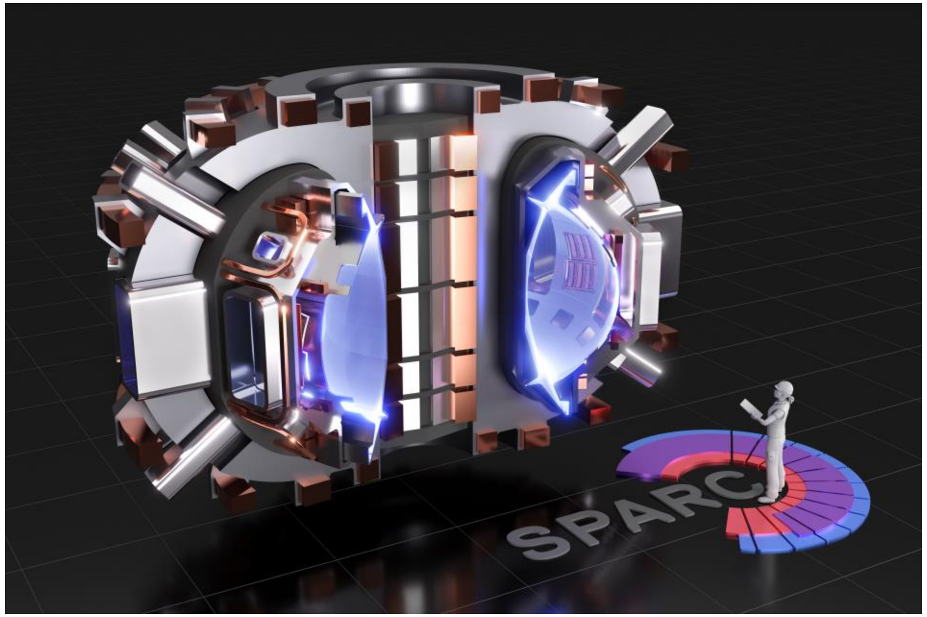
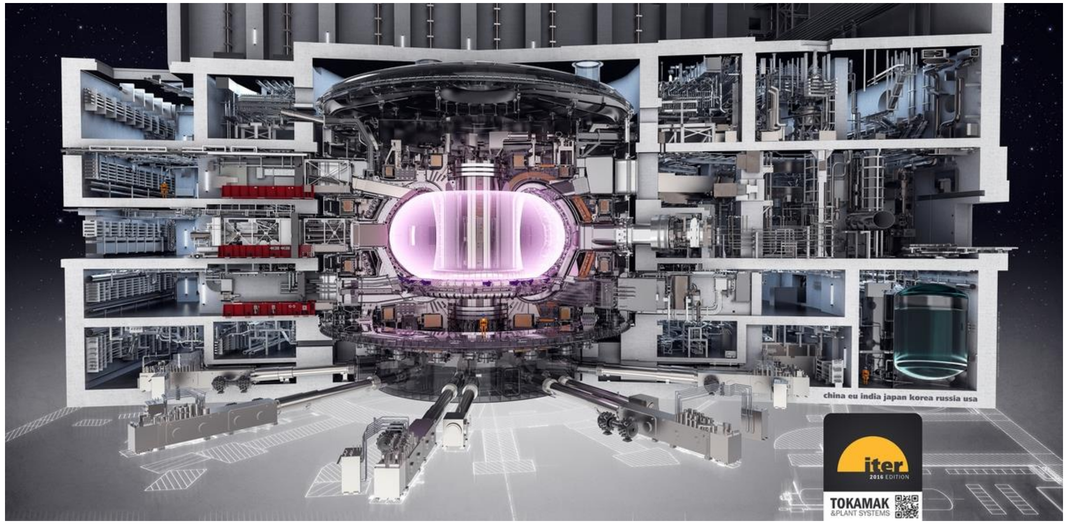
Major topical areas of open research → you can be part of the team to meet these challenges!

- **Many open questions and challenges to address to put fusion on the grid**
- **Recently, made a community plan aligning goals and prioritizing research objectives**
- **Exciting new opportunities for engagement (SPARC, ITER, next public tokamak?)**





Powering the Future
Fusion & Plasmas

A long-range plan to deliver fusion energy and to advance plasma science

TOKAMAKS represent a key path towards achieving fusion energy

- Tokamaks can meet the energy challenge

- Tokamaks are toroidal devices that use magnetic fields to confine the plasma

- Two tokamaks in the US (NSTX-U and DIII-D) used to study and model plasma physics for extrapolation to a fusion pilot plant

- Complex environments with many integrated teams and exciting science

DIII-D NATIONAL FUSION FACILITY