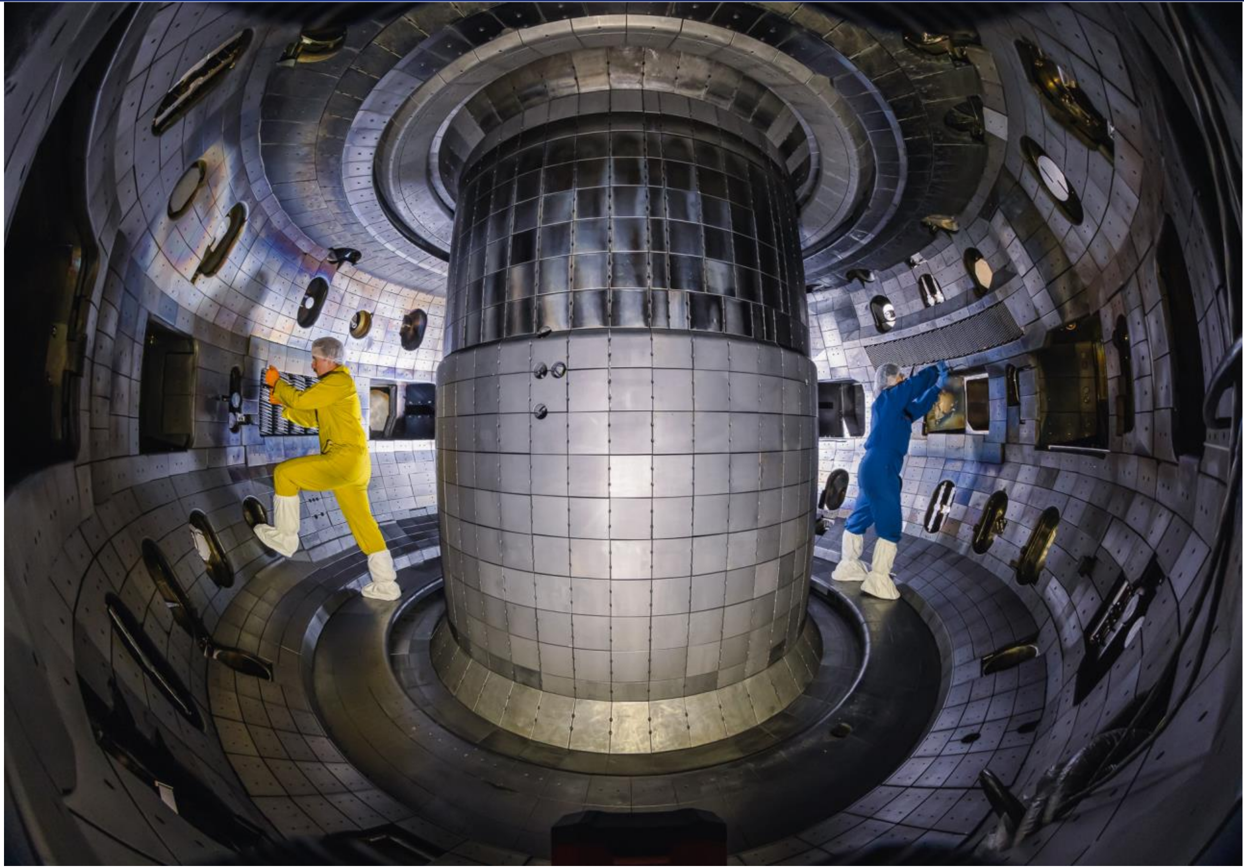
Introduction to tokamaks

Auna Moser



Presented virtually at the 2024 Intro to Plasma and Fusion Course

June 13, 2024

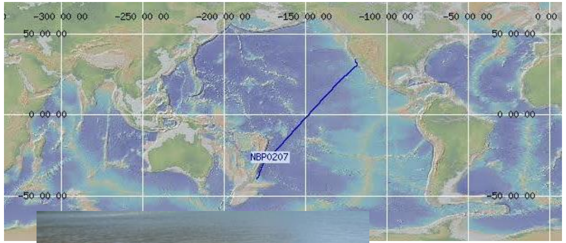
Who am I?

Caltech, BS in Geology, 2002

Who am I?

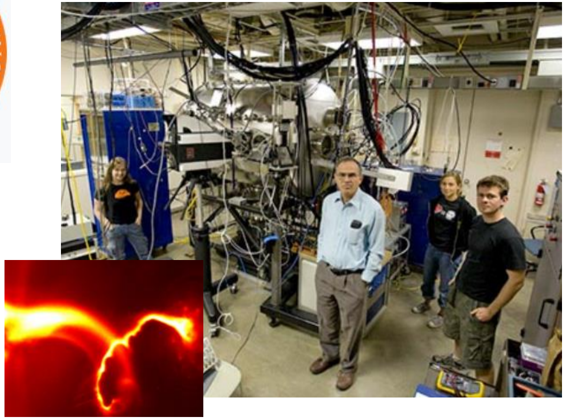
Caltech, BS in Geology, 2002

Two years off from school



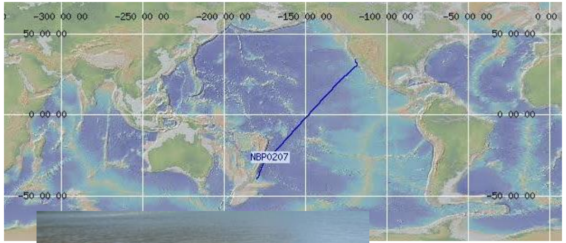
Who am I?

Caltech, PhD in Applied Physics, 2012



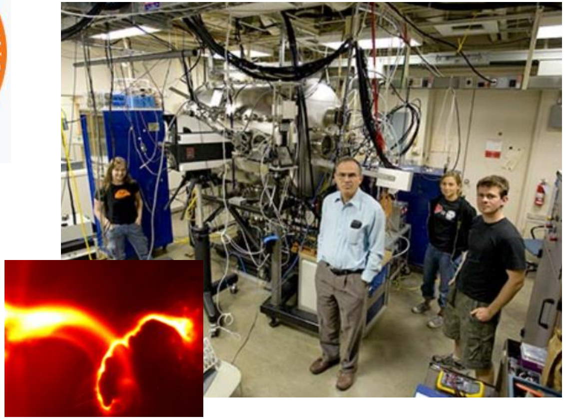
Caltech, BS in Geology, 2002

Two years off from school



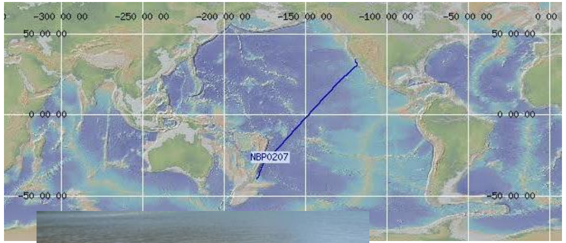
Who am I?

Caltech, PhD in Applied Physics, 2012



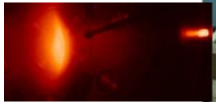
Caltech, BS in Geology, 2002

Two years off from school



LANL, Postdoc, 2012-2014

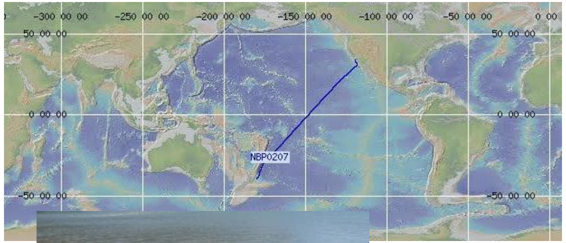
Los Alamos
NATIONAL LABORATORY
EST. 1943



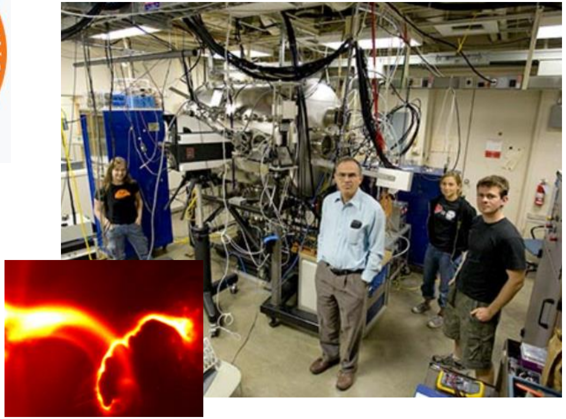
Who am I?

Caltech, BS in Geology, 2002

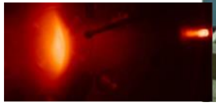
Two years off from school

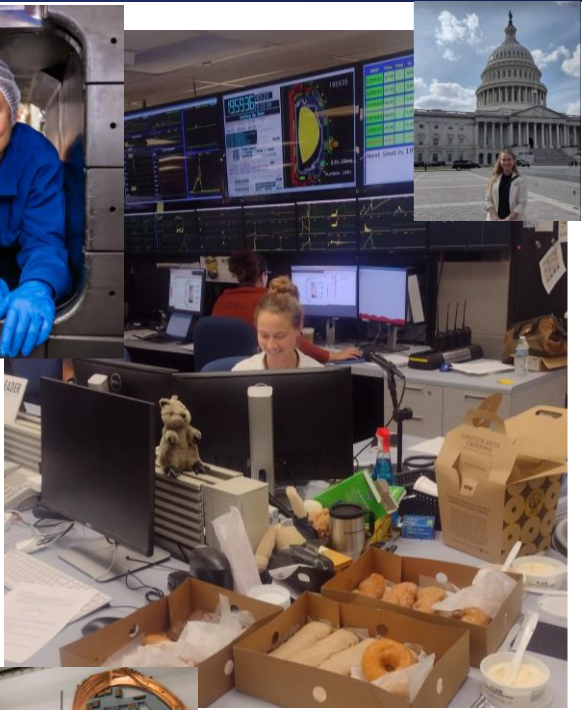


Caltech, PhD in Applied Physics, 2012



LANL, Postdoc, 2012-2014

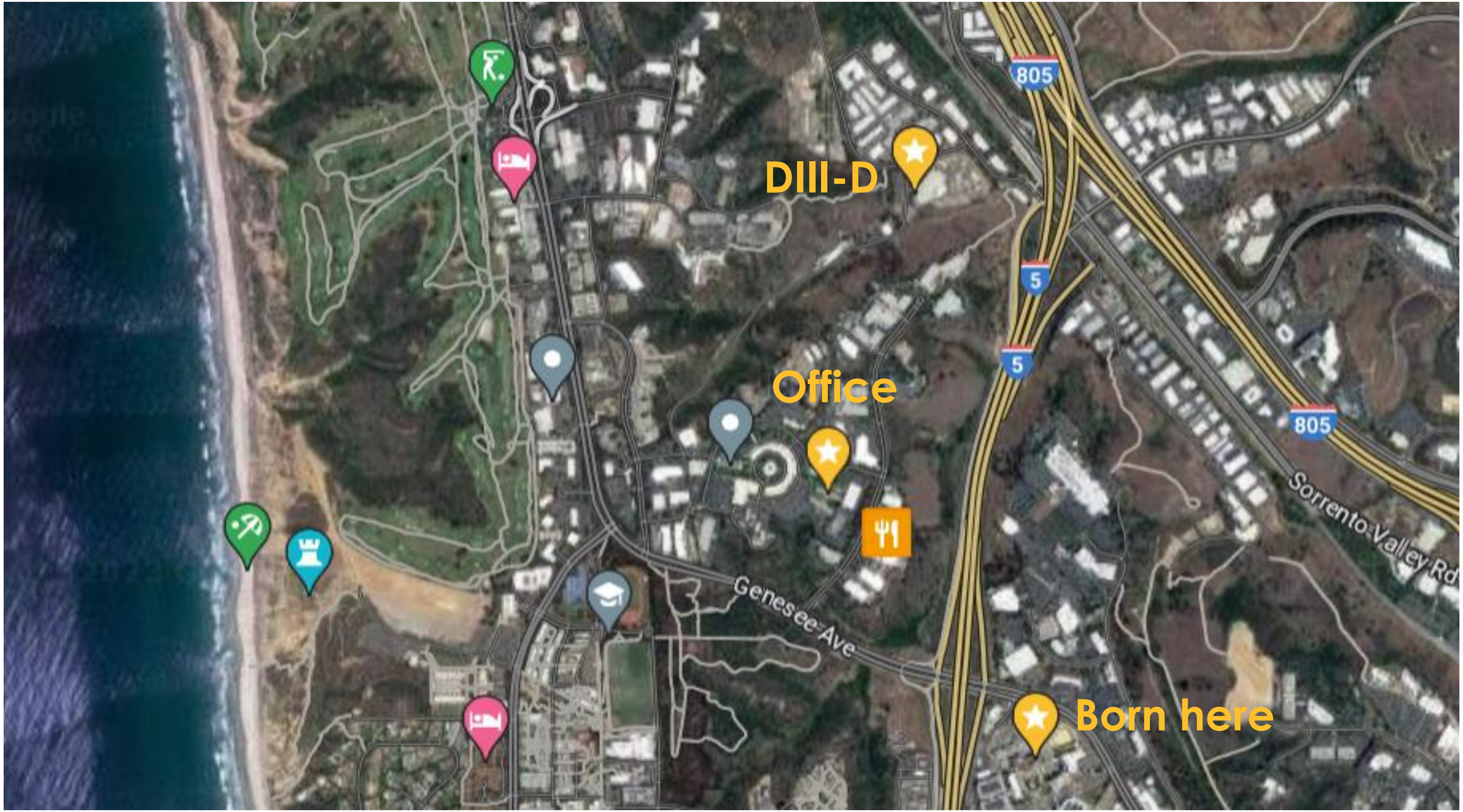




General Atomics,
Staff scientist at DIII-D,
2014-present

DIII-D
NATIONAL FUSION FACILITY

I didn’t get very far!

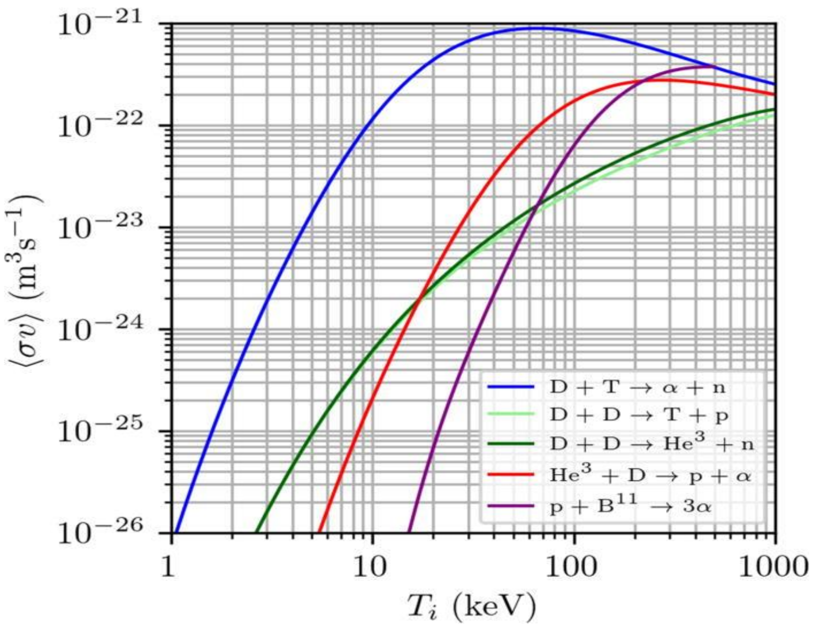


Where are we going?

- **Overview/review of key ideas**
- **How does a tokamak work?**
  - Nested flux surfaces
  - Shaping
  - Heating and current drive
- **Some current research areas**
- **How can you get involved?**

What have you learned so far about fusion?

- **Fusion is a clean, safe type of nuclear power with abundant fuel**
- **"Easiest" reaction is D-T** See *Srinivasan*, 6/10



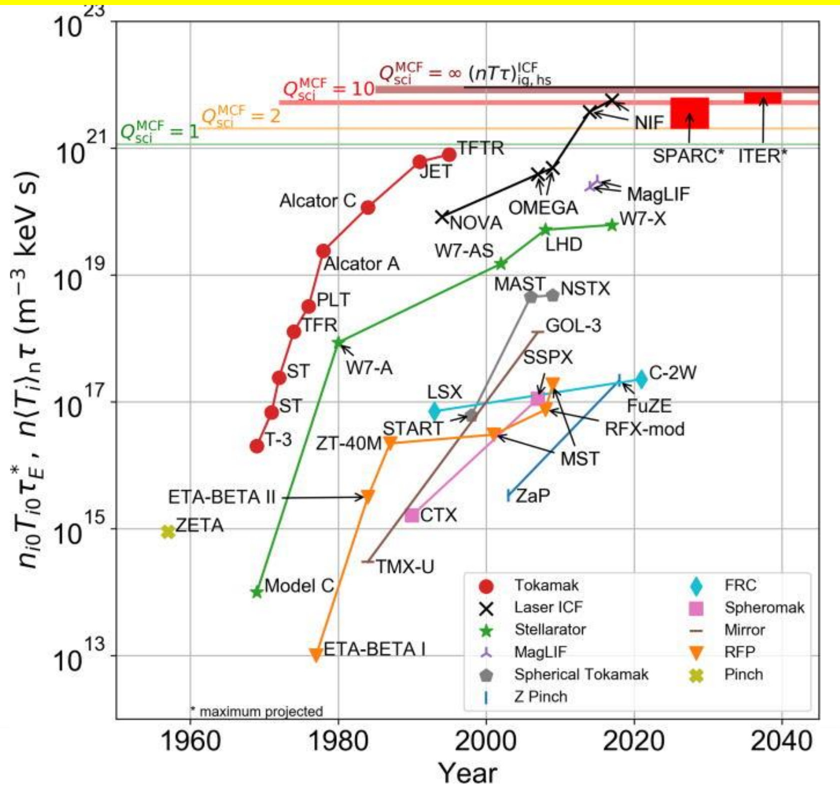
Wurzel et al, PoP 29, 062103 (2022)

What have you learned so far about fusion?

- **Fusion is a clean, safe type of nuclear power with abundant fuel**
- **"Easiest" reaction is D-T**
- **Reaction requires a high enough (Lawson criterion) triple product $nT\tau_\varepsilon$**
  - We have made a ton of progress!

See Wurzel, 6/21

Ignition from 2022 on not shown here! See *Simpson*, 6/14

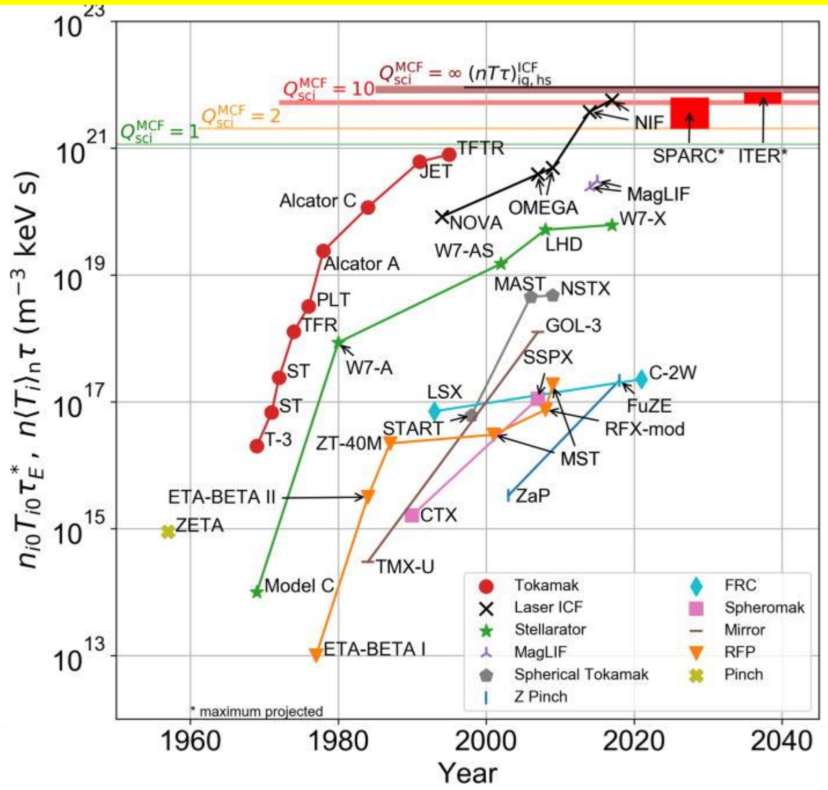


Wurzel et al, PoP 29, 062103 (2022)

What have you learned so far about fusion?

- **Fusion is a clean, safe type of nuclear power with abundant fuel**
- **"Easiest" reaction is D-T**
- **Reaction requires a high enough (Lawson criterion) triple product $nT\tau_\varepsilon$**
  - We have made a ton of progress!
- **There are different ways to confine a plasma to achieve fusion**
  - Gravitational, magnetic, inertial
  - Stellarator — See *Proll*, 6/13 (previous talk)
  - Tokamak — This talk
  - Reversed field pinch, field reversed configuration, magnetic mirror, z-pinch, spheromak... See *Parke*, 6/13 (next talk)

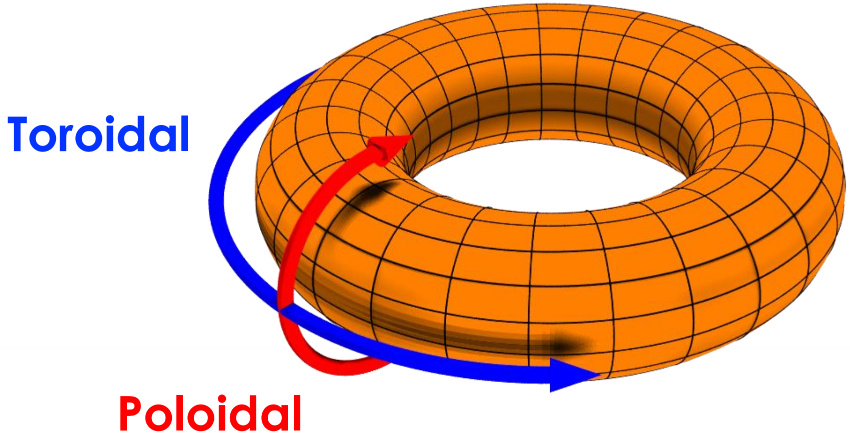
Ignition from 2022 on not shown here! See *Simpson*, 6/14



Wurzel et al, PoP 29, 062103 (2022)

What are the basic ideas behind confinement in a tokamak?

- Particles (mostly) stay along field lines *See Duarte, Dominguez, 6/11*
- Close those field lines into a torus to confine them
- Add twists to keep particles from drifting out *See Dominguez, 6/11*
- Confine plasma with toroidal and poloidal magnetic fields



What is a tokamak?

- **Tokamaks confine with an *externally* produced toroidal field and a *plasma current* produced poloidal field**

- **TOKAMAK is a Russian acronym: (тороидальная камера с магнитными катушками) "Toroidal Chamber with Magnetic Coils"**

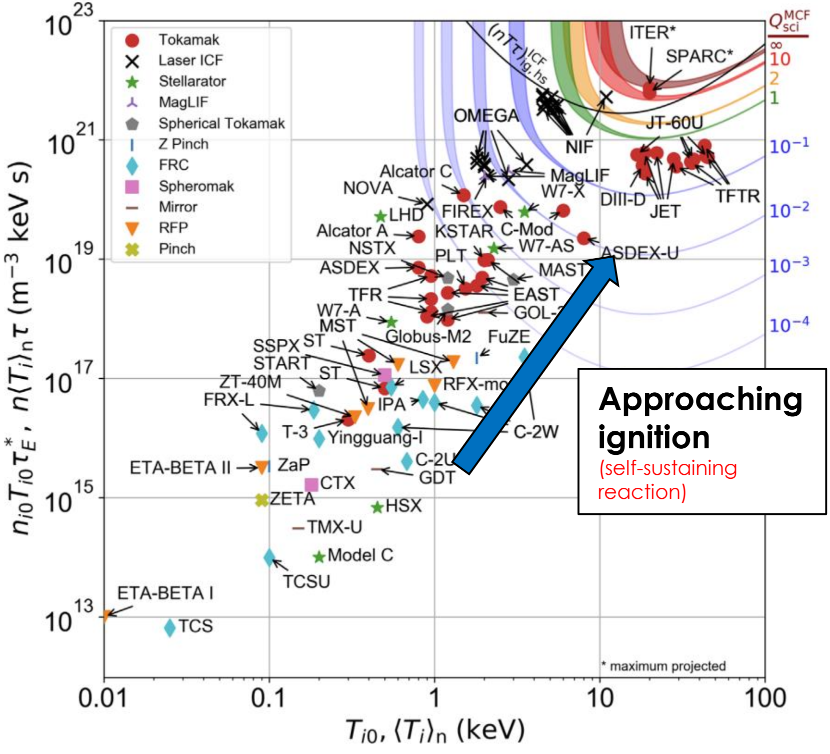
- **Leading magnetic confinement concept in terms of number of facilities and funding**

- **Caveat!: I only have personal experience with DIII-D, so what I present today will be heavily biased towards DIII-D**

Many tokamaks around the world are making strides towards ignition

Ignition from 2022 on not shown here! See *Simpson*, 6/14

- **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), FPP (US)
- **Many private sector companies entering the market**
  - Commonwealth Fusion Systems (SPARC/ARC, US)
  - Tokamak Energy (ST40, UK)
  - DOE awarded grant to eight companies advancing designs and research and development for fusion power plants
  - And more!

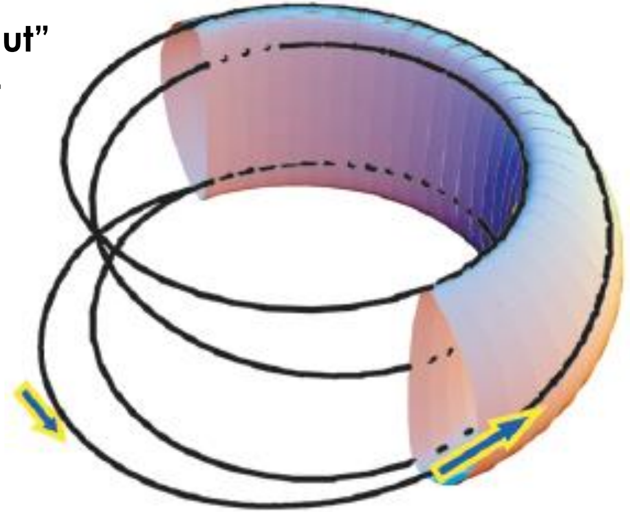


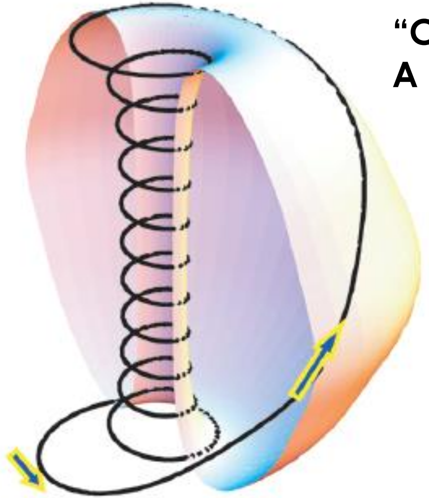
[Wurzel et al, PoP 29, 062103 (2022)](https://doi.org/)

https://www.fusionenergybase.com

https://www.energy.gov/articles/doe-announces-46-million-commercial-fusion-energy-development

Two types of tokamaks: Conventional aspect ratio and spherical tokamaks





Conventional tokamaks

Usually A>2.5

Ex: ITER, ASDEX, JET, DIII-D, EAST, SPARC…

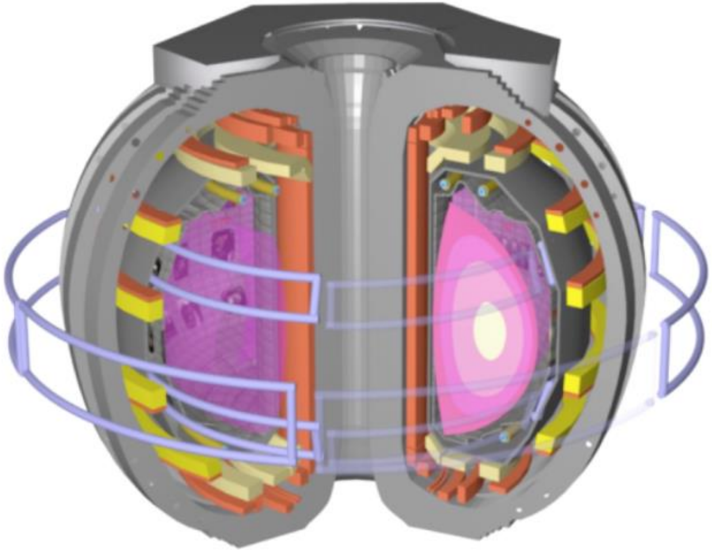
Spherical tokamaks

A=1-2.5

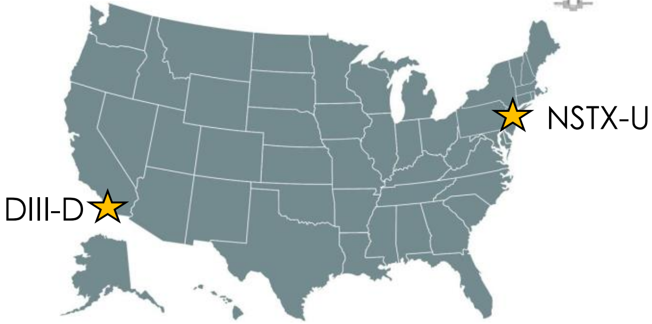
Ex: MAST, NSTX-U…

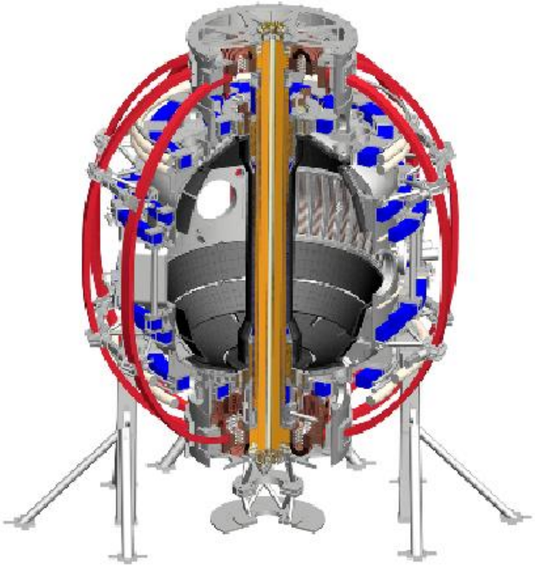
Peng, Phys. Plasmas, **7**, 1681 (2000).

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



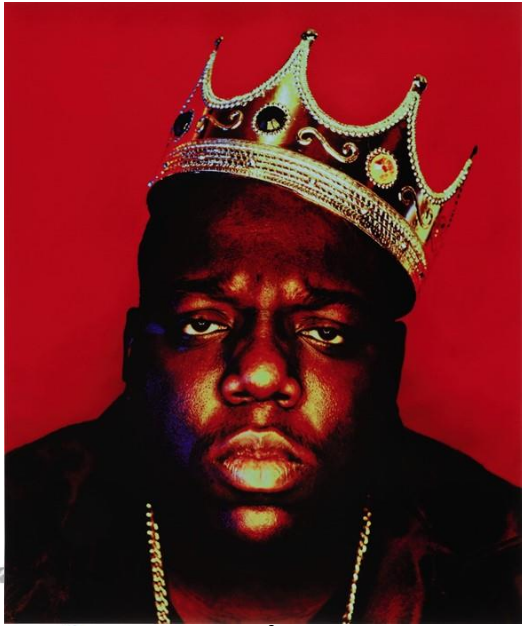
DIII-D,
Conventional tokamak
A=2.7





NSTX-U
Spherical tokamak
A=1.3

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



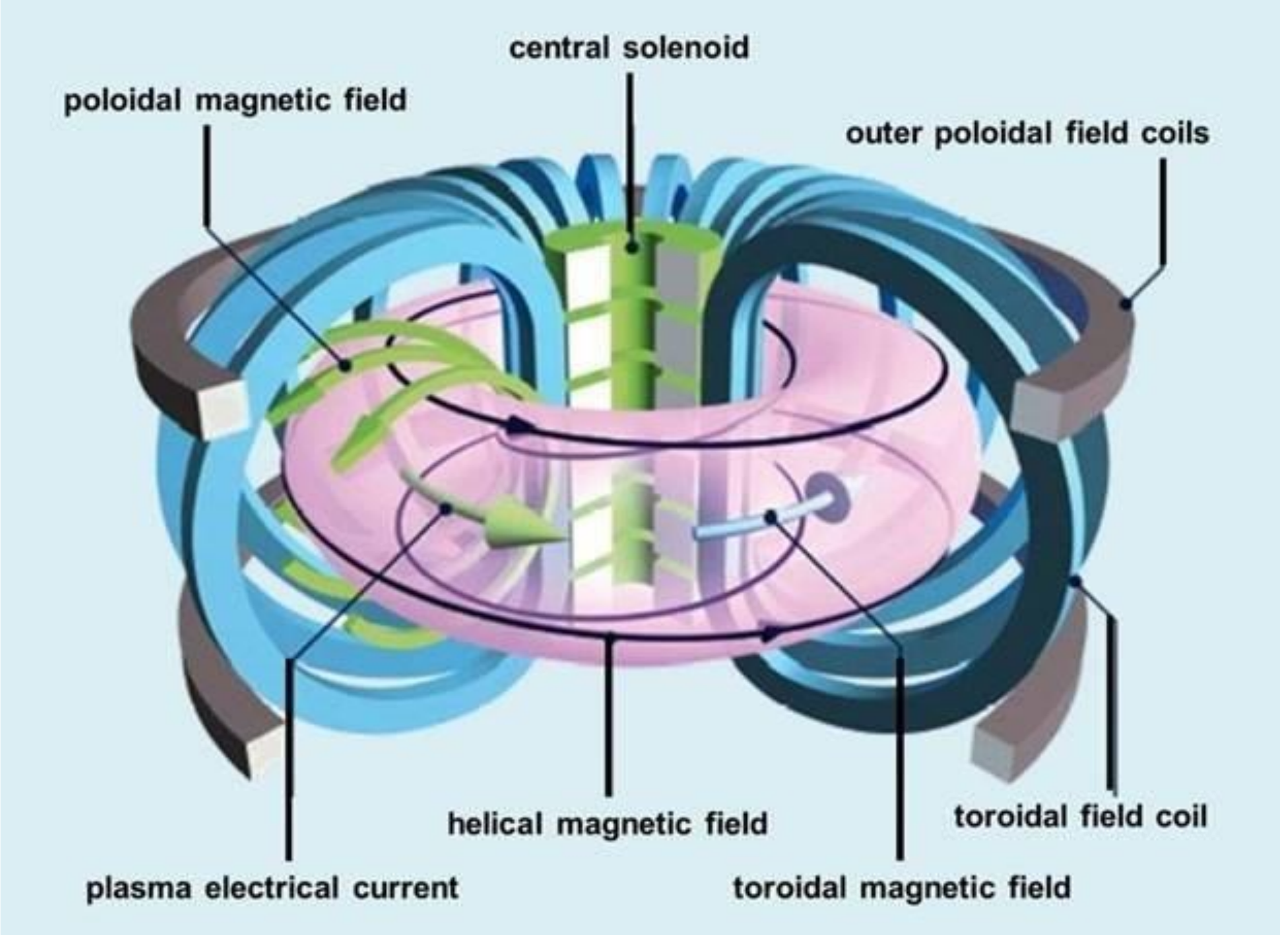
DIII-D,
Conventional tokamak
A=2.7

NSTX-U
Spherical tokamak
A=1.3

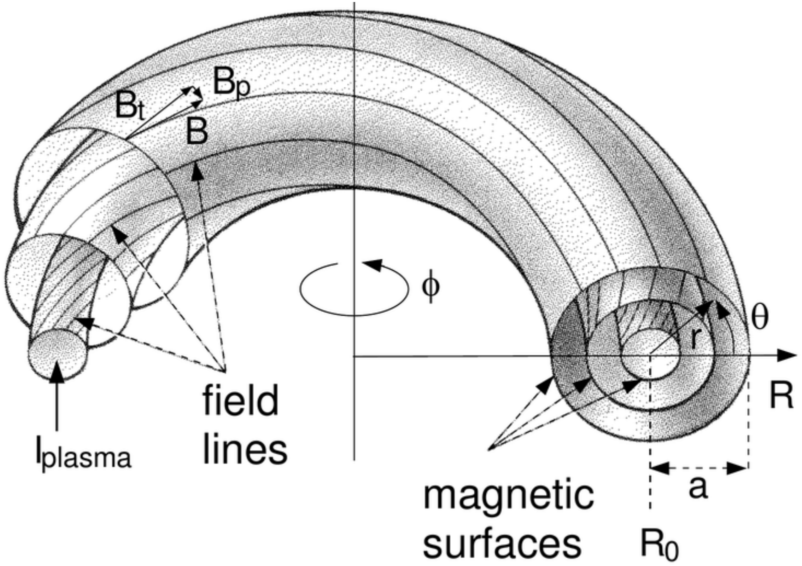
Where are we going?

- Overview/review of key ideas
- **How does a tokamak work?**
  - Nested flux surfaces
  - Shaping
  - Heating and current drive
- Some current research areas
- How can you get involved?

Tokamaks use magnetic fields to confine a plasma in a toroidal vacuum vessel



Tokamaks have nested magnetic surfaces



Two very important concepts:

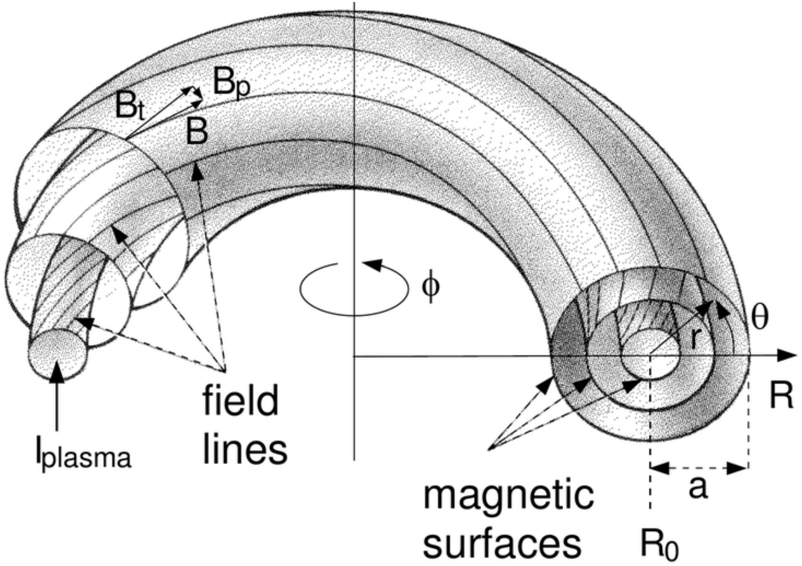
(1) **Magnetic field lines lie on nested surfaces of constant magnetic flux, Ψ**

(2) **Safety factor:**

$$q = \frac{toroidal\ transits}{poloidal\ transits} = \frac{d\phi}{d\theta} \text{ or "pitch"}$$

Tokamaks often use q_{95} which is just inside the last closed flux surface

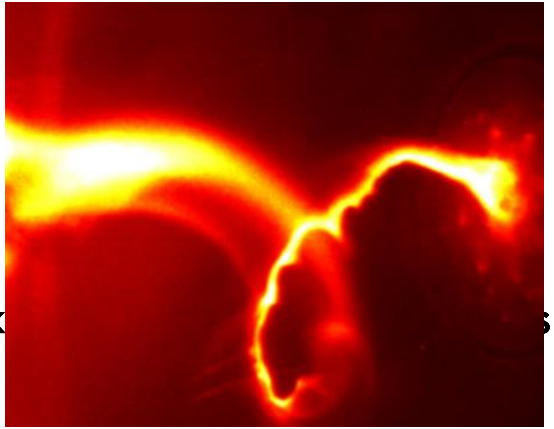
Tokamaks have nested magnetic surfaces



Two very important concepts:

(1) Magnetic field lines lie on nested surfaces of constant magnetic flux, Ψ

(2) Safety factor:



Tok ... just inside the

Surfaces described using ideal magnetohydrodynamics (Ideal MHD)

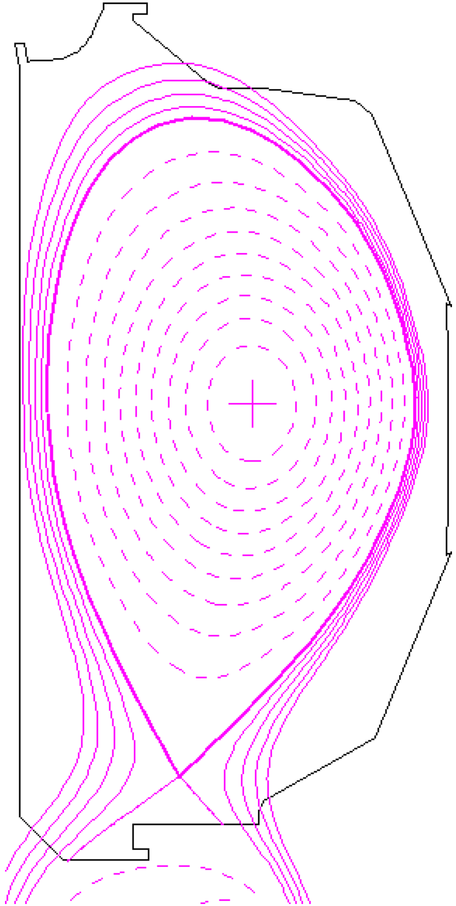
See Parsons, 6/11

MHD equilibrium in toroidally symmetric geometry:

Grad–Shafranov:

$$R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial\Psi}{\partial R}\right)+\frac{\partial^2\Psi}{\partial Z^2}=-\mu_0 R^2\frac{dp}{d\Psi}-F\frac{dF}{d\Psi}$$

Equilibrium equation relates poloidal flux function (Ψ)
Pressure (p) and current flux function (F)



Surfaces described using ideal magnetohydrodynamics (Ideal MHD)

See Parsons, 6/11

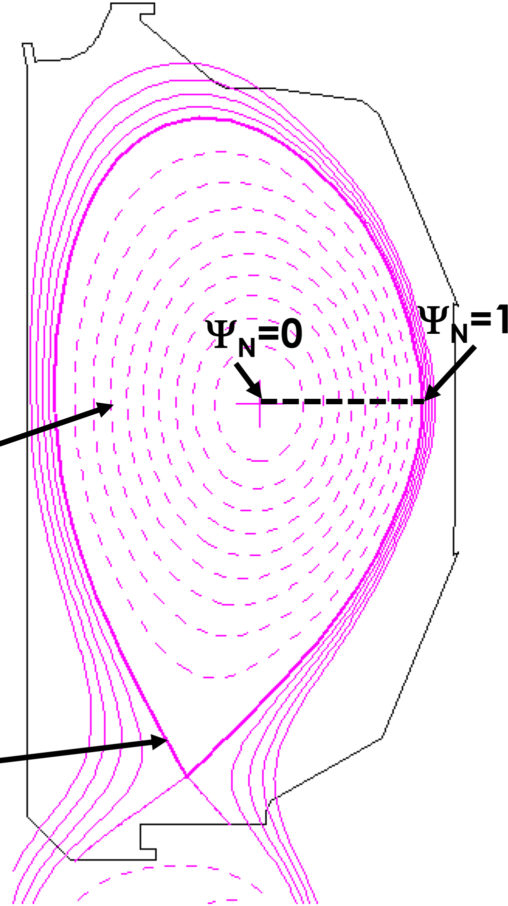
MHD equilibrium in toroidally symmetric geometry:

Grad–Shafranov:

$$R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial \Psi}{\partial R}\right)+\frac{\partial^2\Psi}{\partial Z^2}=-\mu_0 R^2\frac{dp}{d\Psi}-F\frac{dF}{d\Psi}$$

Equilibrium equation relates poloidal flux function (Ψ), pressure (p), and current flux function (F)

- **Nested magnetic surfaces of constant flux are called "*flux surfaces*"**
  - **Pressure, current, q constant on a flux surface**
- **We use flux coordinates to collapse to a 1D system, plotted vs. "normalized flux" Ψ_N**
- **Last *closed* flux surface is called the "*separatrix*"**



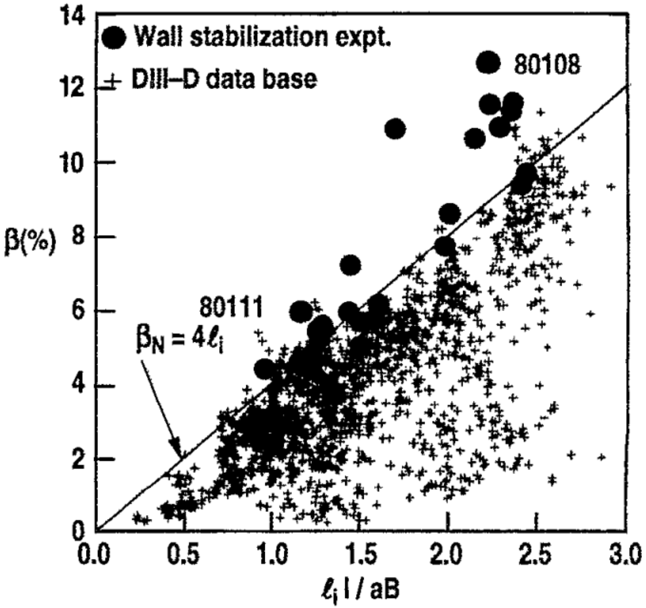
Pressure limit: Plasma "efficiency" can be defined by the parameter β

- **Ratio of thermal pressure to magnetic pressure**

$$\beta = \frac{nkT}{B^2/2\mu_0}$$

- **Plasma pressure (fusion output) pushes outwards and is balanced by magnetic pressure (economic cost)**
  - $\beta \propto$ output/cost
  - "bang for your magnetic buck"

- ***β* limit (coupled with current limit) sets tokamak operating space**
  - Maximum plasma pressure and current allowable for given magnetic configuration

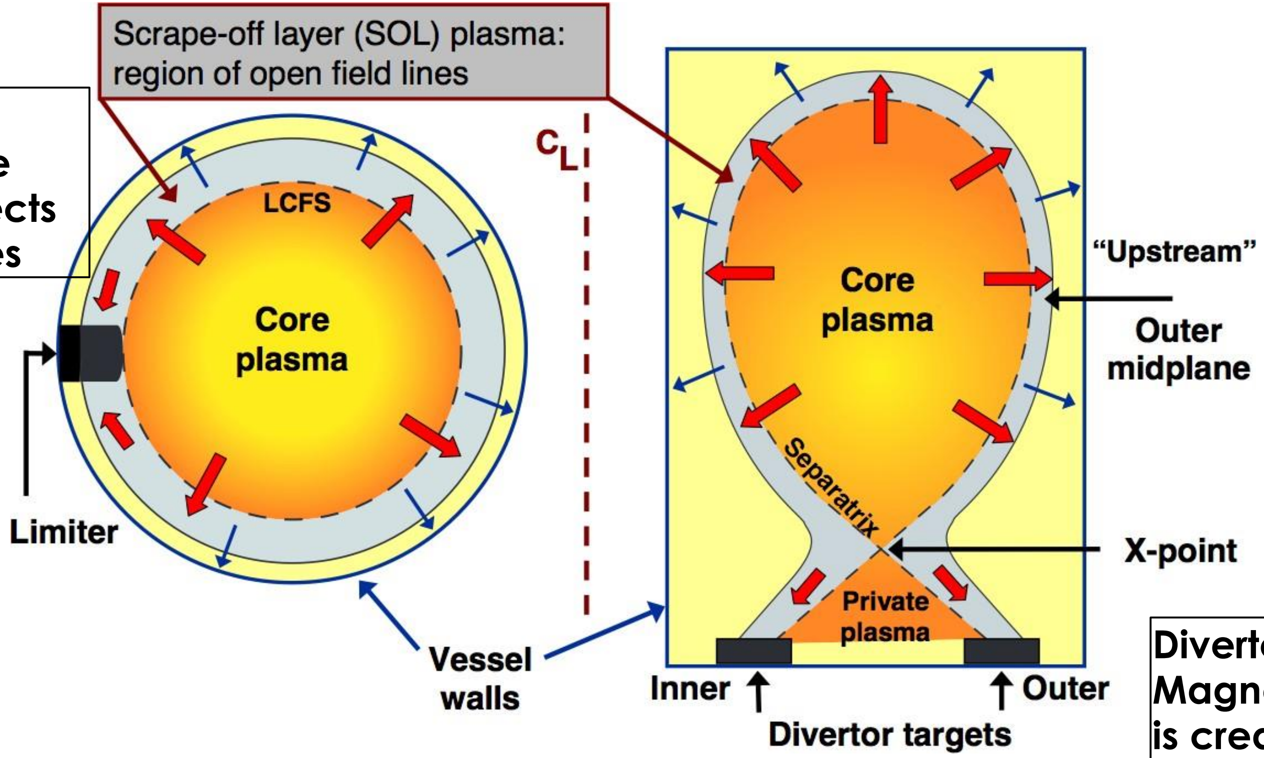


Taylor et al, PoP 2, 2390 (1995)

Tokamaks normalize to an empirical current limit: $\beta_N = \beta \frac{aB_T}{I_p}$

Two general types of tokamak magnetic topologies

Limiter:
A physical structure intentionally intersects a set of flux surfaces



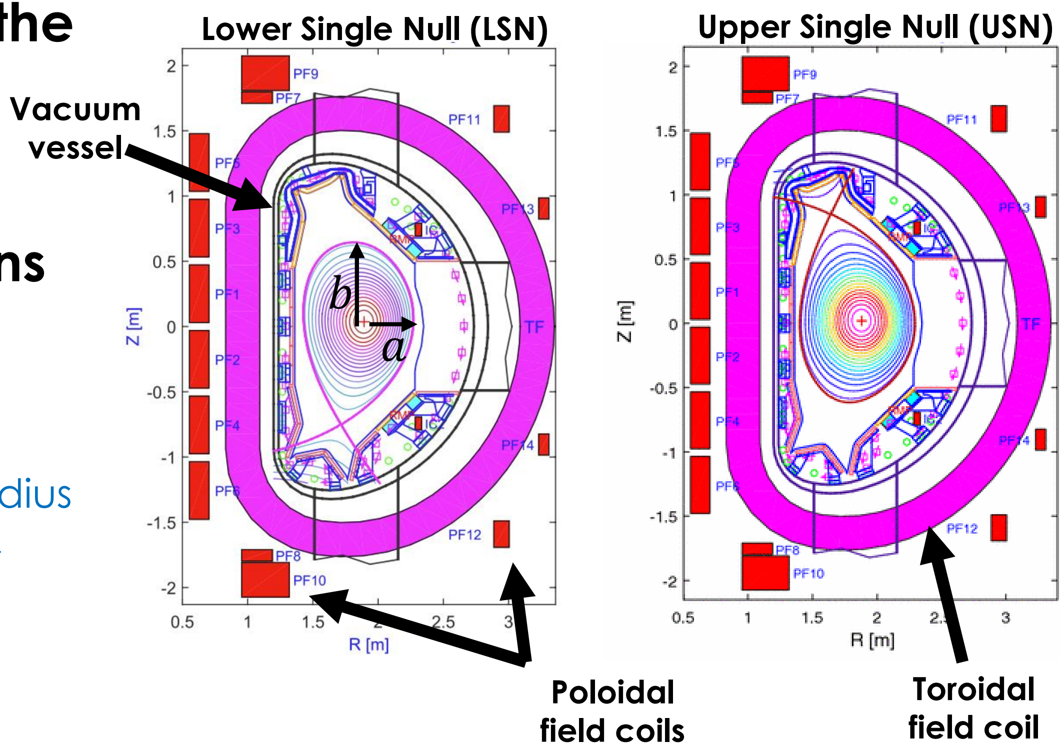
Divertor:
Magnetic structure is created to localize exhaust

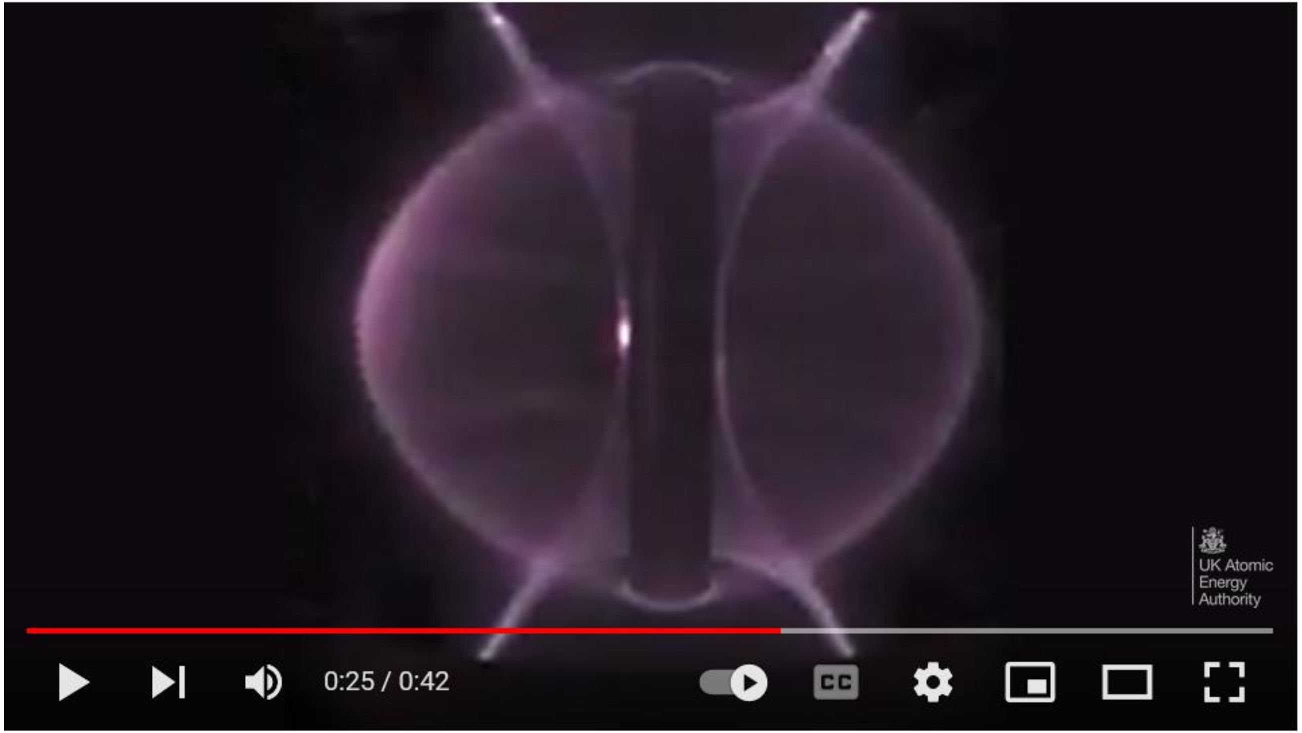
R. A. Pitts, "Tokamak edge physics and plasma surface interactions" 2007
https://crppwww.epfl.ch/~pitts/pitts/pitts_varenna_27_09_2007.pdf

Poloidal field coils control plasma shape

- **Poloidal coils generate the confining fields that shape the plasma**
- **Plasma shape impacts stability and wall interactions**
- **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

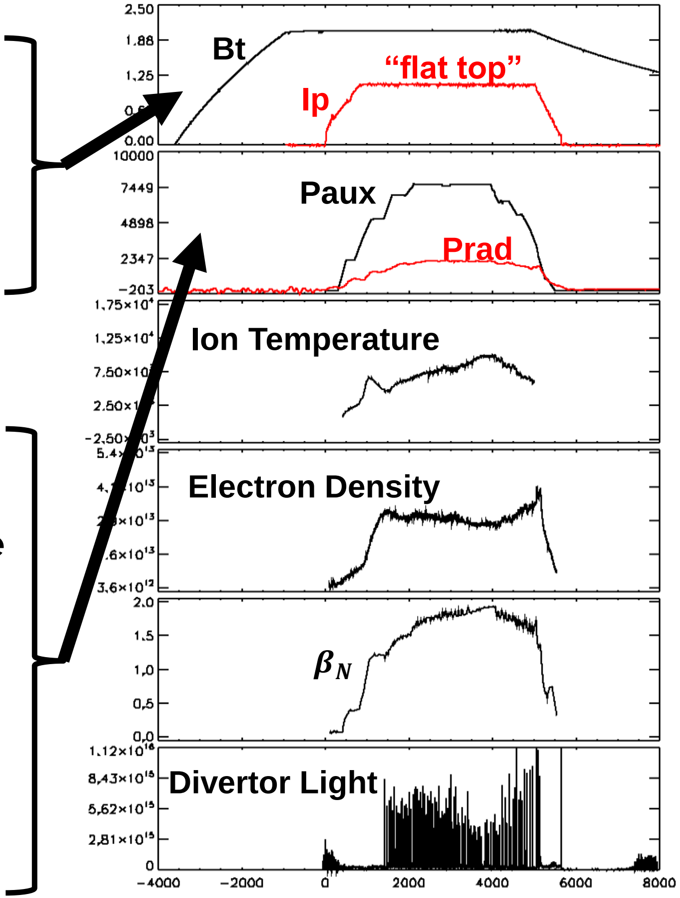




https://www.youtube.com/watch?v=Yu9C5TEhAdQ

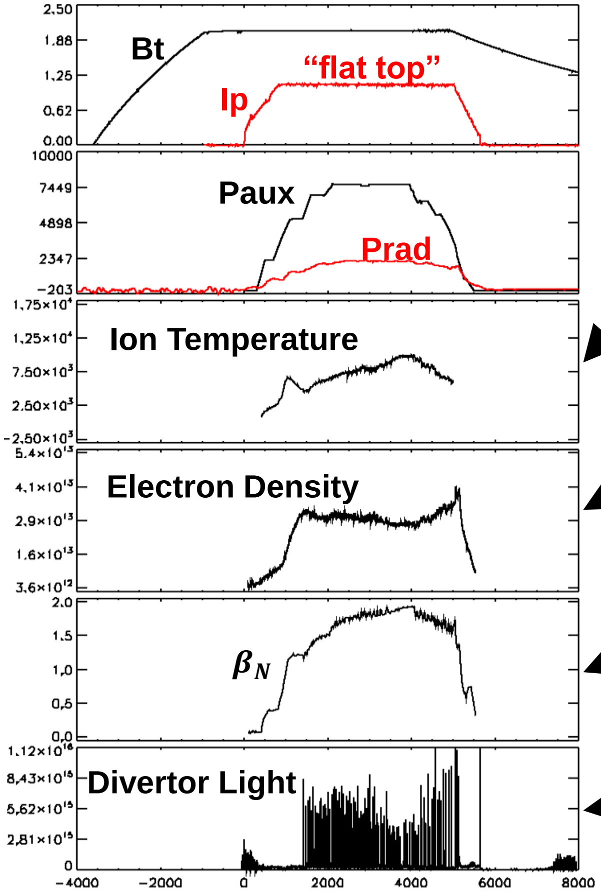
Example of a DIII-D plasma discharge

- 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)



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 represents energy loss from the system (measured by bolometers)



- 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

Example of a DIII-D plasma discharge

- Toroidal ma
  ramps up fir
- Central sole
  ohmically in
  plasma curr
- Auxiliary sy
  required to
  plasma and
  current
- Radiated po
  measures re
  energy loss
  system (me
  bolometers)

on temperature
measured by Charge
Exchange
Recombination
Spectroscopy

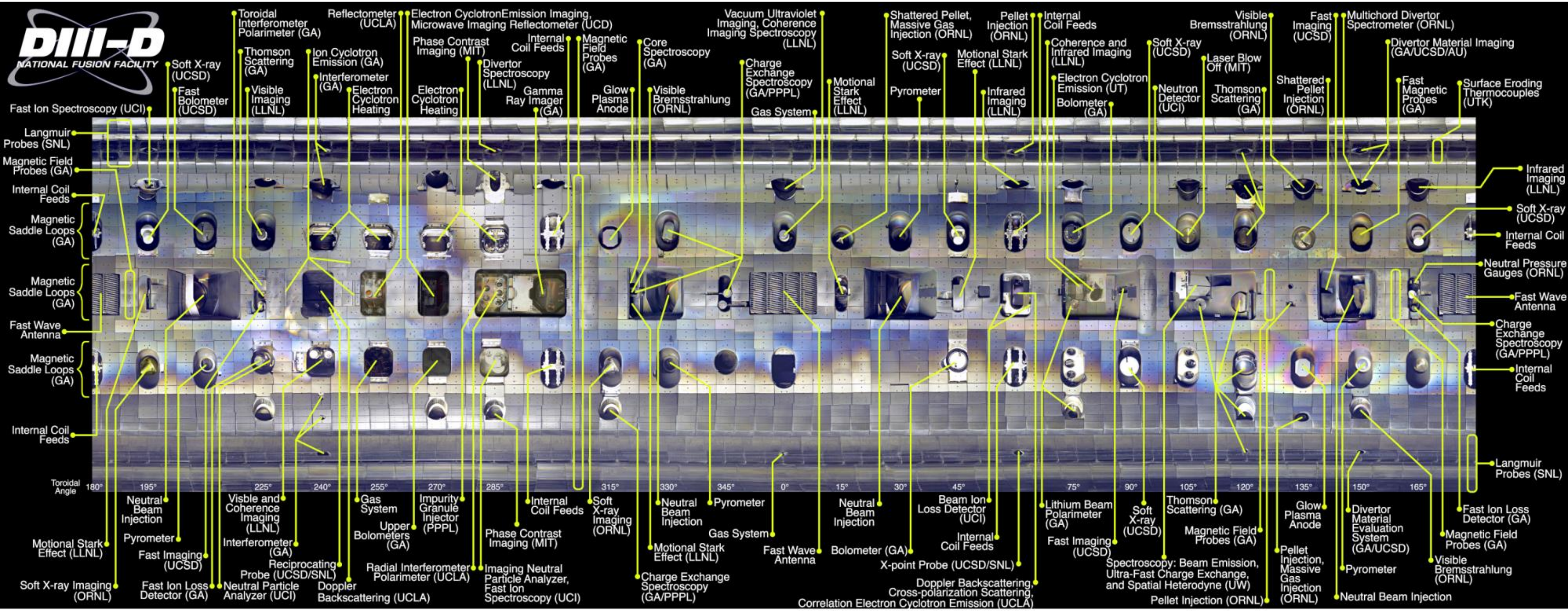
Electron Density
measured by
nterferometers

Normalized β calculated
rom "real time EFIT"
equilibrium solver

Divertor light measured
by filterscopes represent
ypical plasma
instabilities

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

See Delgado-Aparicio, 6/21



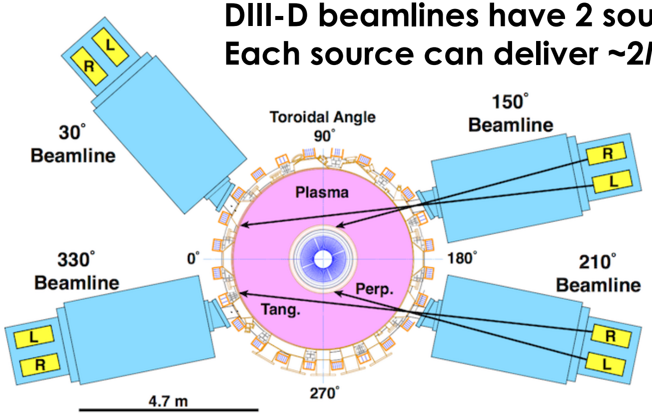
Need both current drive and heating in a tokamak

See Diem, 6/21

- **Heating is required in a reactor to ~15 keV**
- **Non-inductive current drive is required for steady-state operation**
- **Physics of heating and current drive is very similar**
  - If there is current drive, there is also heating

Neutral Beam Injection

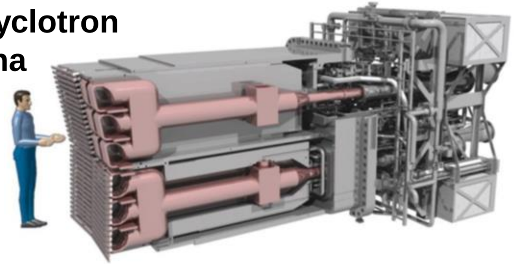
DIII-D beamlines have 2 sources
Each source can deliver ~2MW



Wave heating

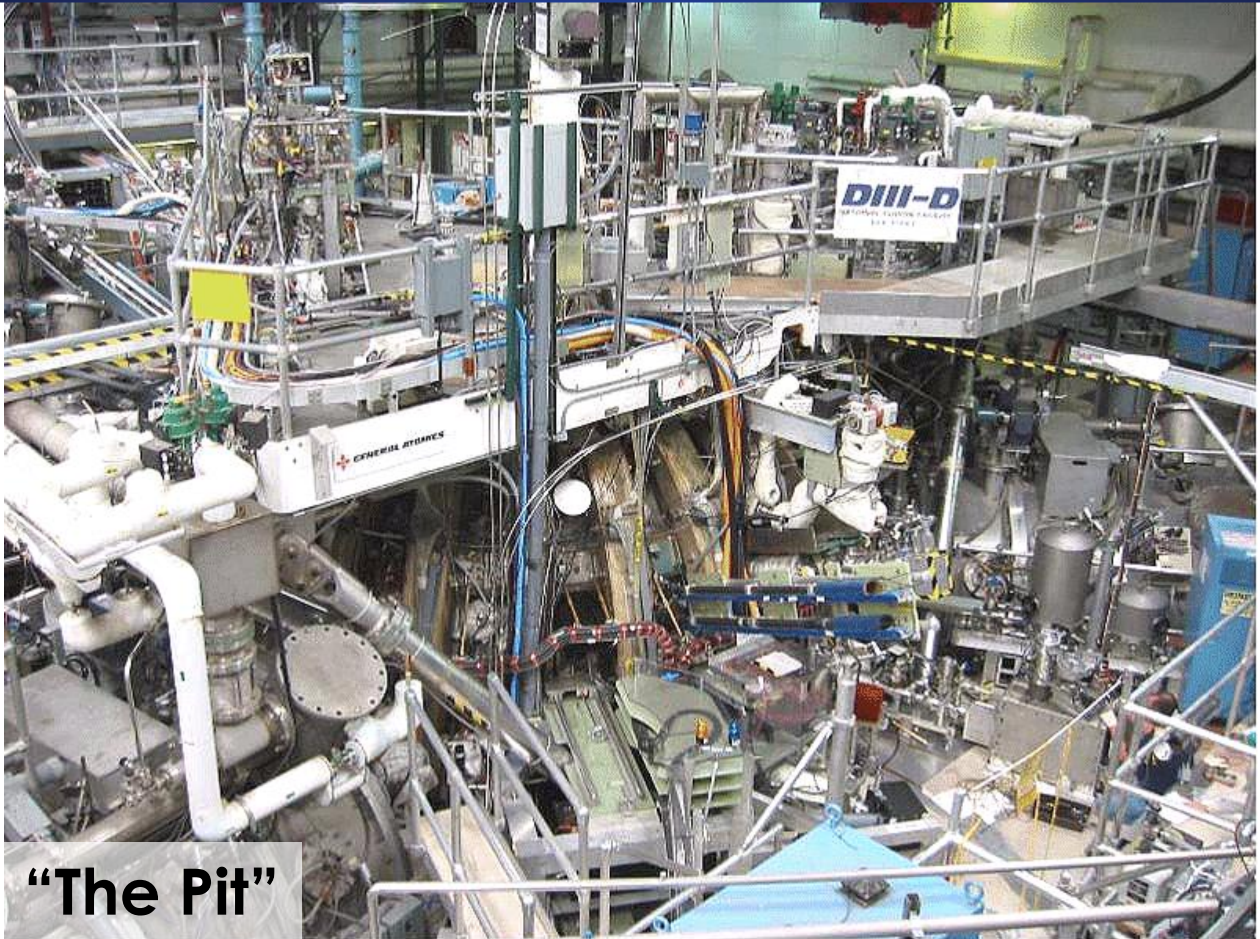
WEST Klystrons (lower hybrid)

ITER's ion cyclotron antenna



DIII-D Gyrotron "Yoda" (electon cyclotron)

Tokamak is only one part of the machine hall

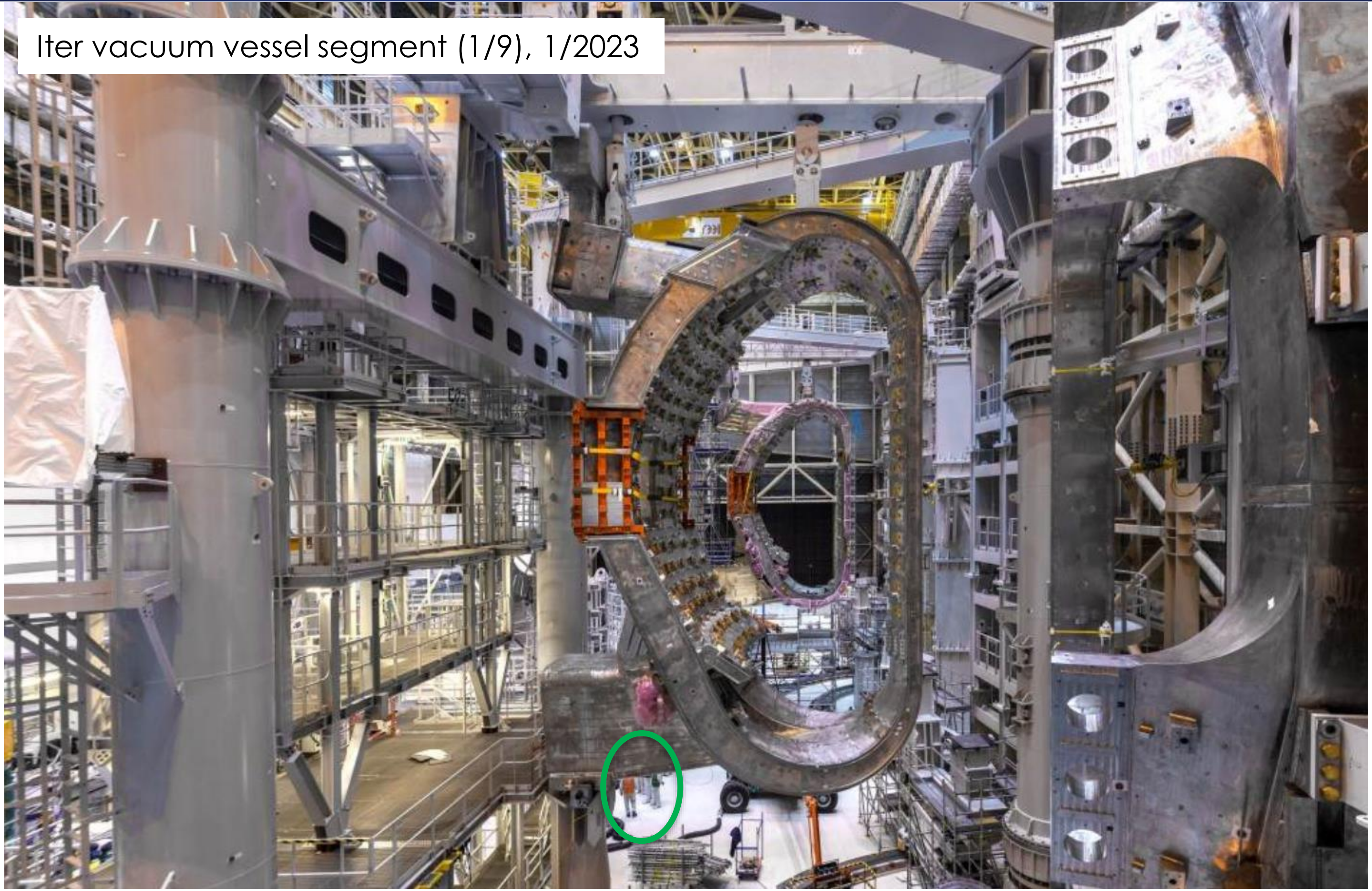


Iter will be the biggest tokamak yet

Iter machine hall, 9/2023

Iter site, 9/2023

Iter will be the biggest tokamak yet



What are some of the key ideas we've covered so far?

- **Tokamaks confine plasmas with toroidal and poloidal magnetic fields**
- **Tokamaks have nested flux surfaces, important quantities are conserved on a flux surface**
  - Normalized flux coordinate ψ_N, safety factor q, pressure ratio β
- **External coils shape and control the plasma**
  - Separatrix, x-point, SOL, divertor
- **Tokamaks are complex, integrated facilities**
  - Heating and current drive, diagnostics
  - Collaborative teams with diverse areas of expertise

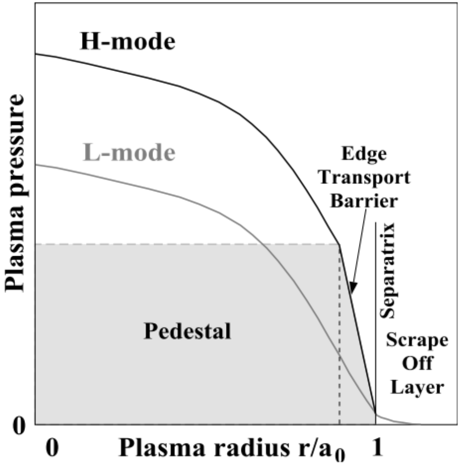
Where are we going?

- Overview/review of key ideas
- How does a tokamak work?
  - Nested flux surfaces
  - Shaping
  - Heating and current drive
- **Some current research areas**
- How can you get involved?

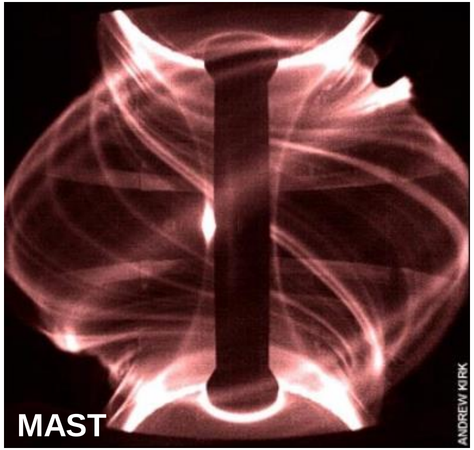
Varied levels of confinement of particles, momentum, and energy depending on the plasma regime

- **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)**



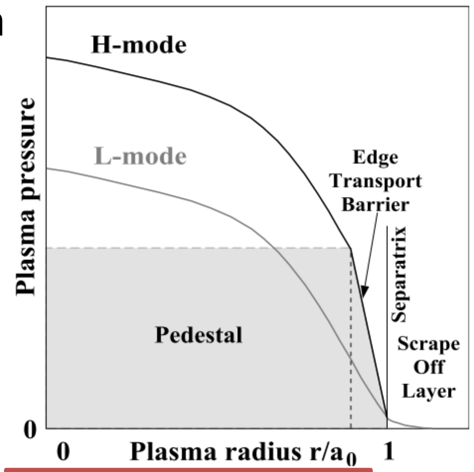
Lang et al. NF 53, 043004 (2013)



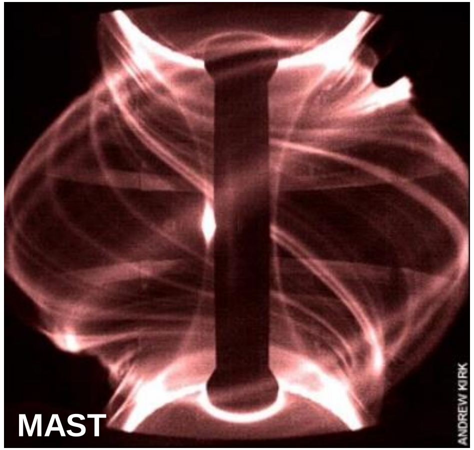
Evans et al, Nonlinear Dynamics Ch 3 (image A. Kirk, Culham)

Varied levels of confinement of particles, momentum, and energy depending on the plasma regime

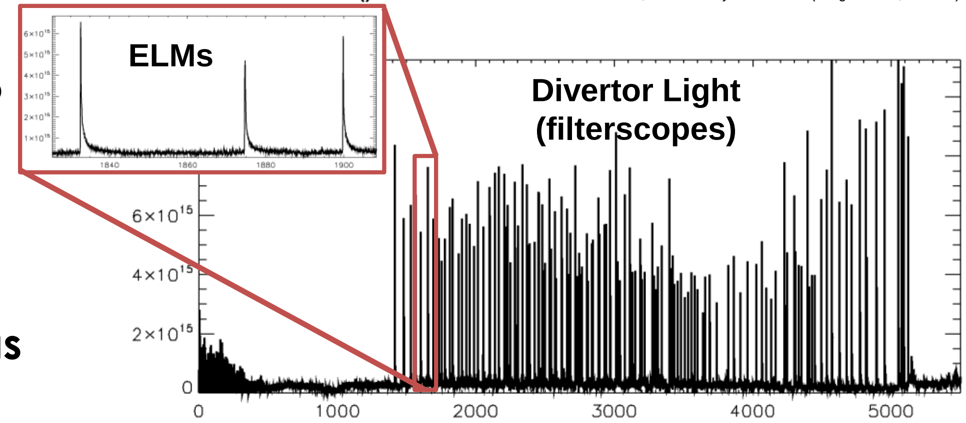
- **Two common plasma modes of operation**
  - L-mode = "low" energy confinement
  - H-mode = "high" energy confinement, often associated w/ plasma instability called Edge Localized Mode (ELM)
- **H-mode extrapolates well to future devices because of energy confinement (due to enhanced pressure from pedestal)**
- **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**



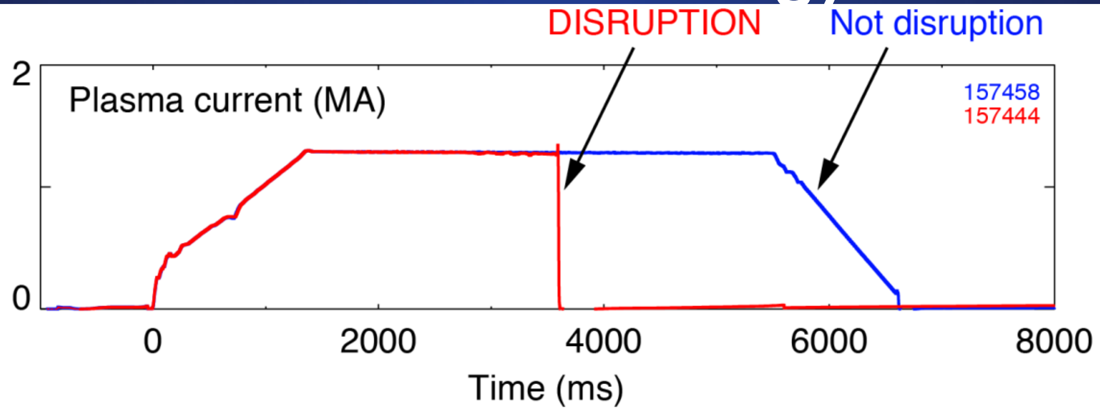
Lang et al. NF 53, 043004 (2013)



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



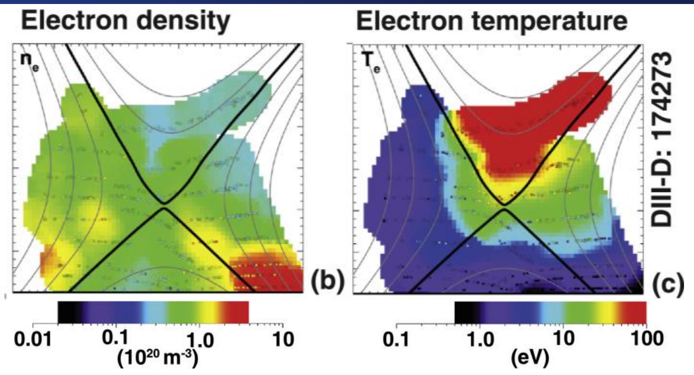
Disruptions are a rapid and complete loss of current and energy



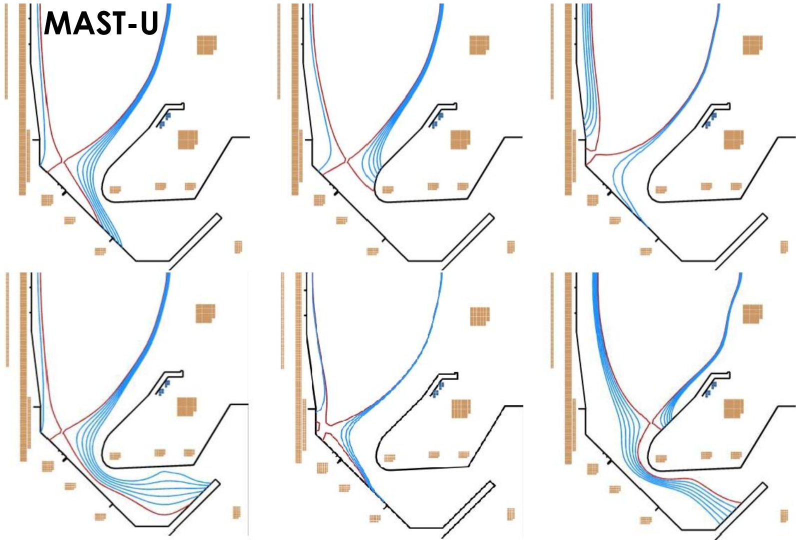
- **Threat for a tokamak, possible disaster for a reactor**
  - High heat flux, large thermal load to divertor
  - Large electromagnetic forces
  - Runaway electrons
- **Disruption avoidance**
  - Prediction, active control to avoid
- **Disruption mitigation**
  - Shattered pellet injection, massive gas injection

High heat flux and narrow profile can damage divertor plates

- **Many strategies to reduce divertor heat flux**
  - Add impurities to increase radiation in SOL
  - Shaping the divertor baffle
  - Expand magnetic flux using snowflake and super-X configurations
- **Core–edge integration is grand challenge**
  - Have to mitigate heat flux without harming confinement
- **Plasma facing materials in the divertor and main chamber wall** See Schamis, 6/18



Jaervinen et al NME **19** (2019)



Morris et al IEEET rans. Plasma Sci. **46** (2018)

Where are we going?

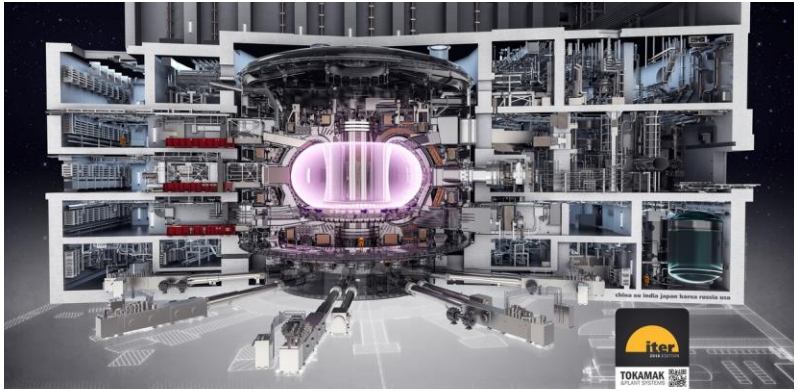
- **Overview/review of key ideas**
- **How does a tokamak work?**
  - Nested flux surfaces
  - Shaping
  - Heating and current drive
- **Some current research areas**
- **How can you get involved?**

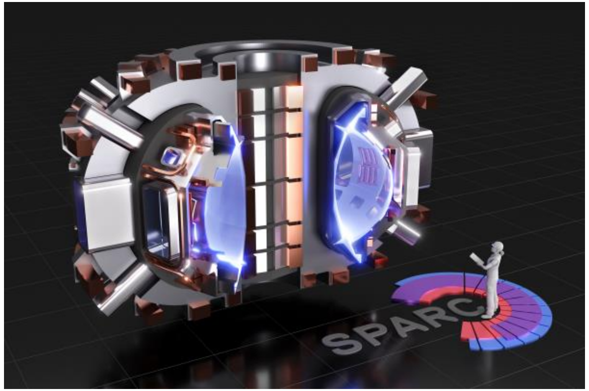
There are many tokamaks in the world you could work on!

- **Currently two big tokamak facilities in the US**
  - NSTX-U and LTX at Princeton Plasma Physics Laboratory (Princeton, NJ)
  - DIII-D National Fusion Facility (San Diego, CA)
  - Universities have collaborations with PPPL and DIII-D and have on-site grad students
- **Some US university tokamaks: Pegasus III (University of Wisconsin-Madison), HBT-EP (Columbia University)**
- **International facilities**
  - Iter (France), JET (UK), ASDEX-U (Germany), COMPASS (Czech Republic), WEST (France), TCV (Switzerland), EAST (China), KSTAR (Korea), JT60-SA (Japan), MAST-U (UK)

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
- Recent community plan aligned goals and prioritized research objectives (Final report here: https://arxiv.org/abs/2011.04806)
- Exciting new opportunities for engagement (ITER, SPARC, EXCITE proposed by NAS and CPP reports, milestone based DOE grants to 8 private companies, including 2 tokamak companies…)





Tokamaks represent a key path towards achieving fusion energy

- Tokamaks are toroidal devices that use toroidal and poloidal magnetic fields to confine the plasma
- Tokamaks can meet the energy challenge
- 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

Thank you and good luck with your research!