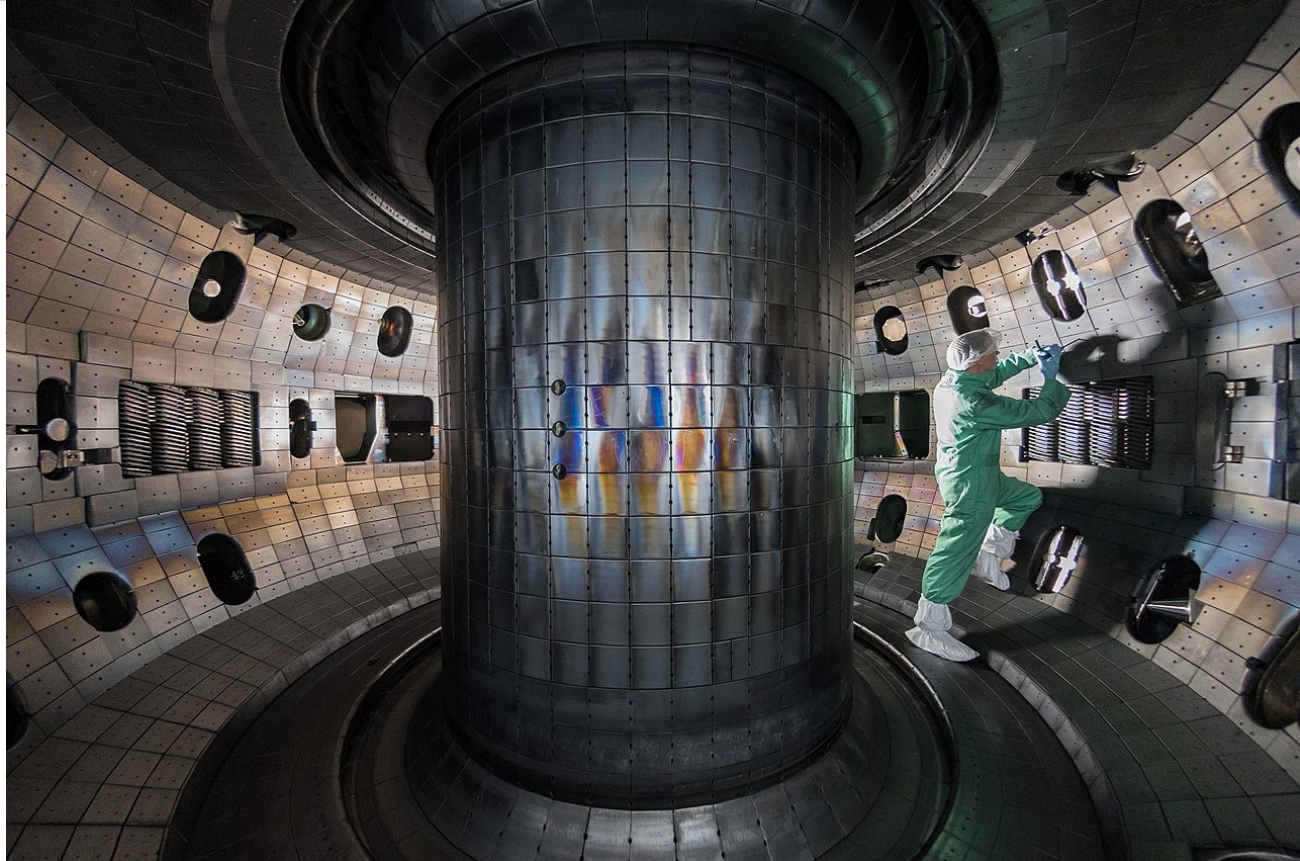


Introduction to tokamaks

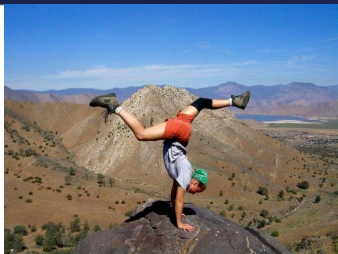
Auna Moser

Presented virtually at the
2023 Intro to Fusion Energy
and Plasma Physics Course

June 12, 2023

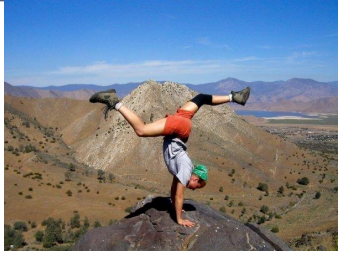


Who am I?



Caltech, BS in Geology, 2002

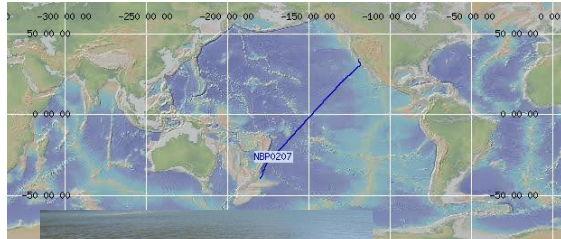
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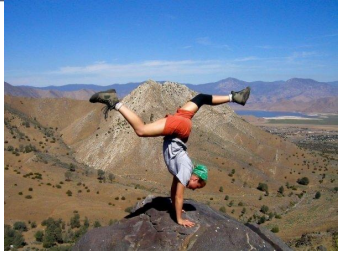
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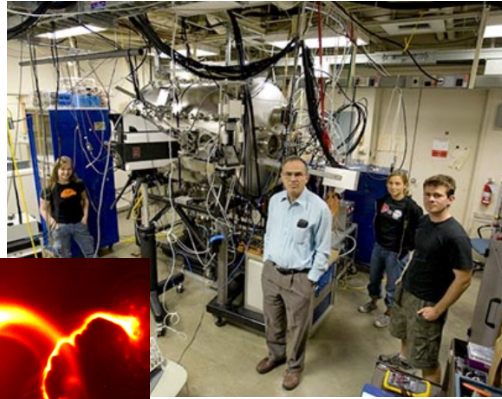
Two years off from school



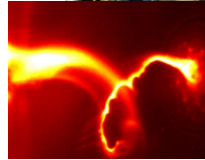
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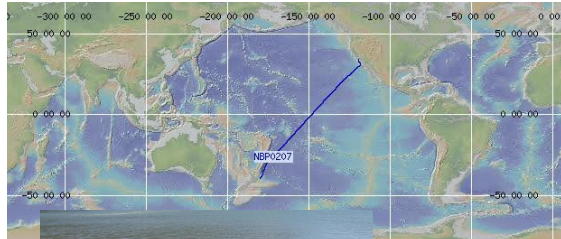
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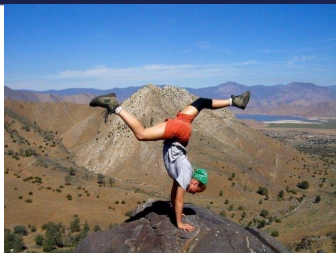
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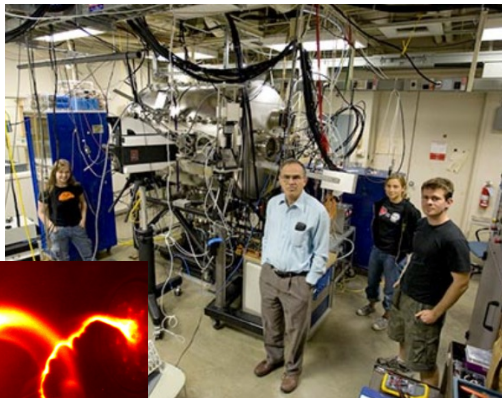
Two years off from school



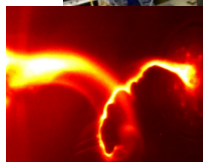
Who am I?



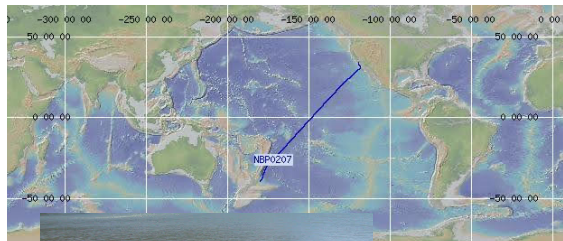
Caltech, PhD in Applied Physics, 2012



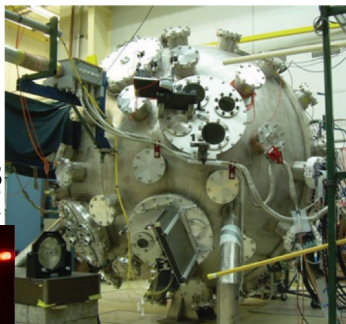
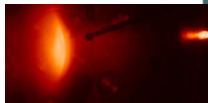
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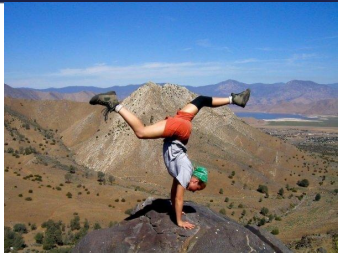
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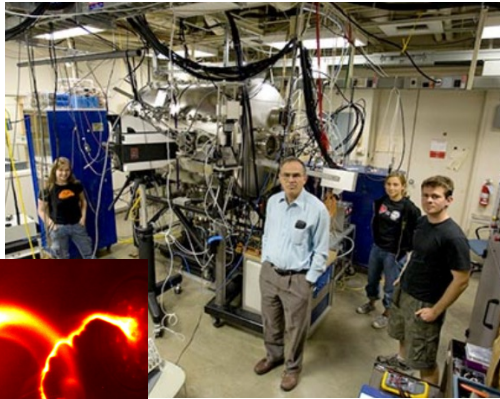
LANL, Postdoc, 2012-2014



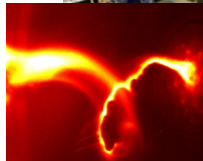
Who am I?



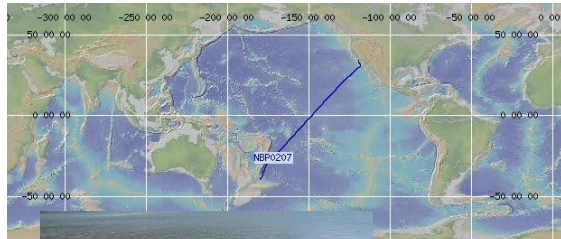
Caltech, PhD in Applied Physics, 2012



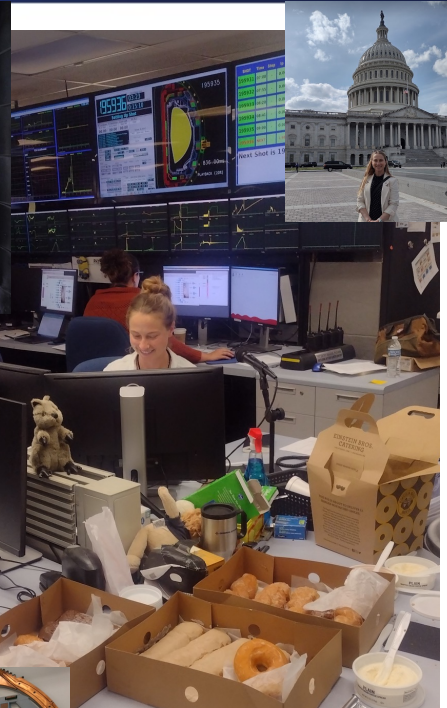
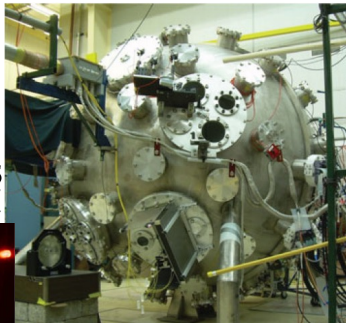
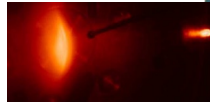
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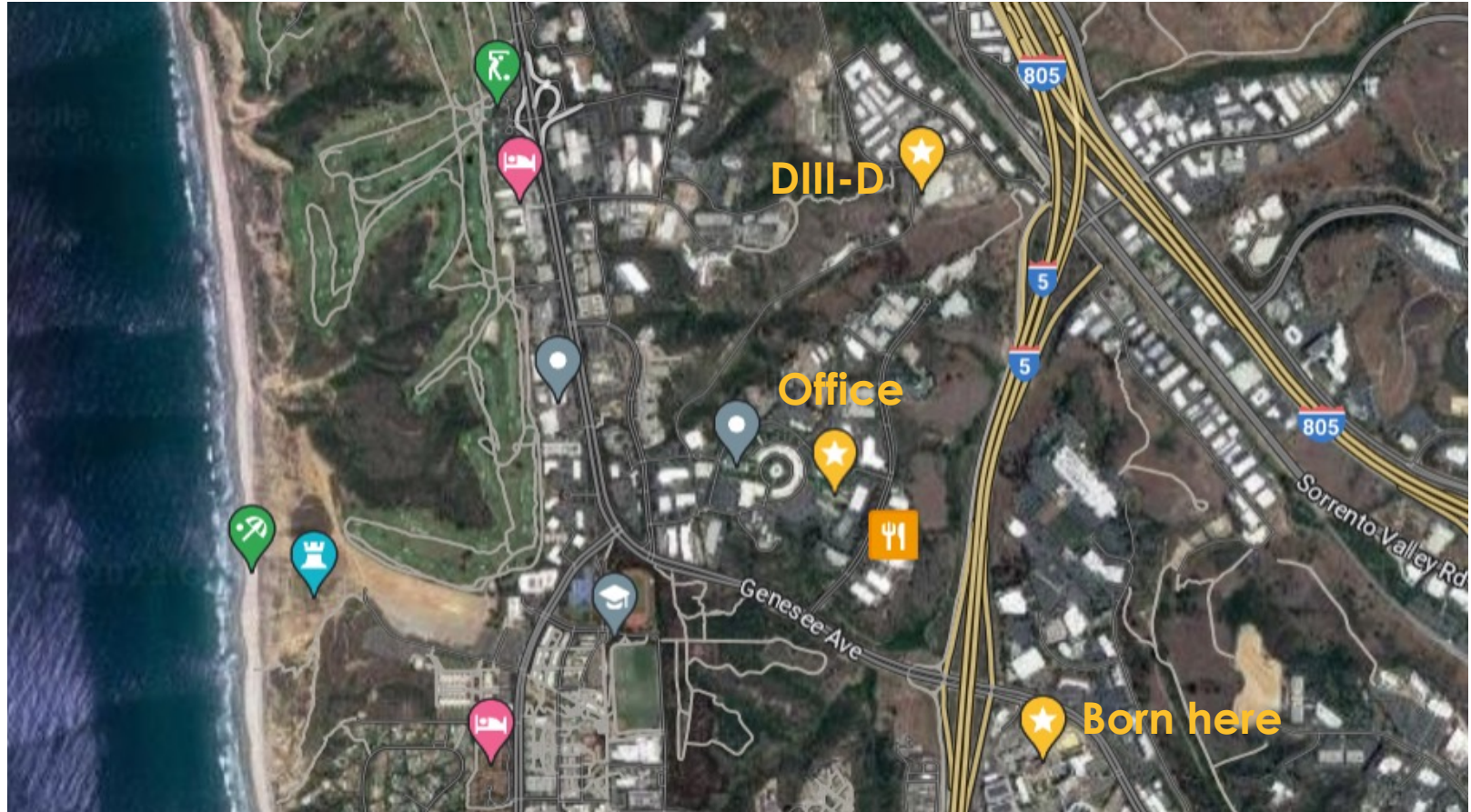
LANL, Postdoc, 2012-2014



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



I didn't get very far!

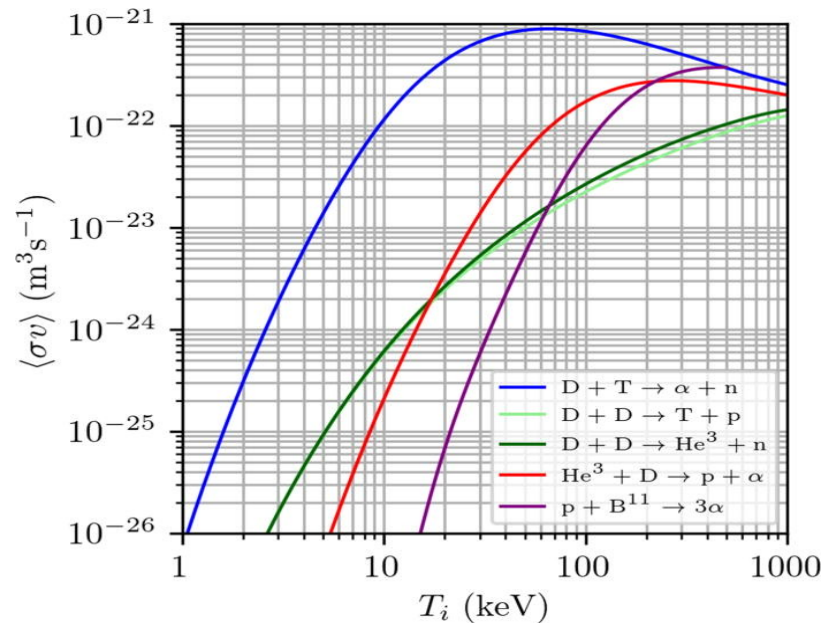


Where are we going?

- **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?

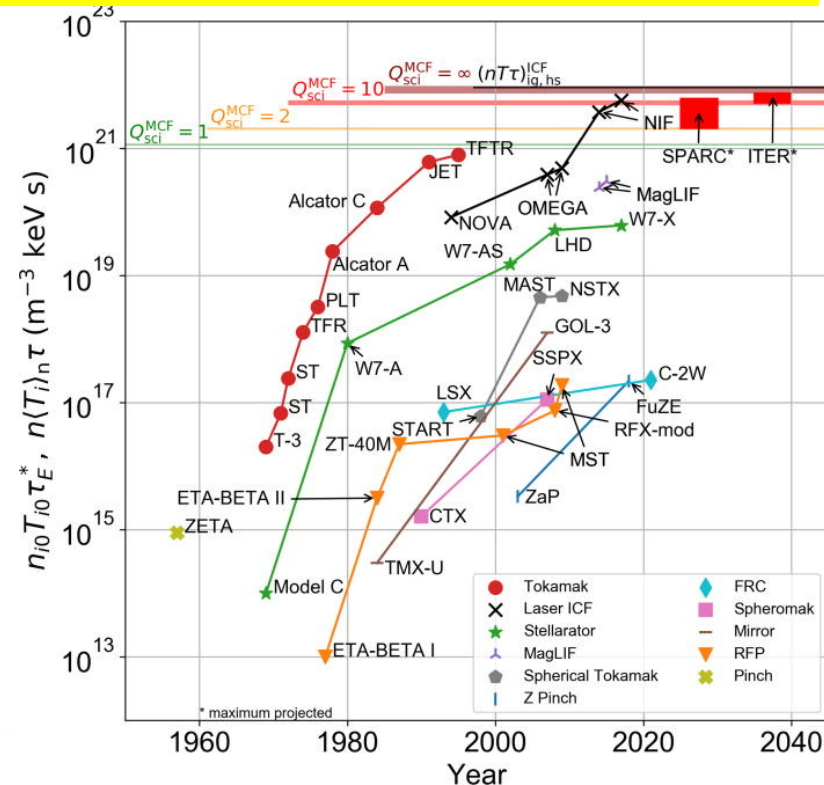
- Fusion is a clean, safe type of nuclear power with abundant fuel
- “Easiest” reaction is D-T See Diaz, 6/5



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 $nT\tau_E$
 - We have made a ton of progress!

Ignition from 12/22 not shown here! See Kritcher, 6/8

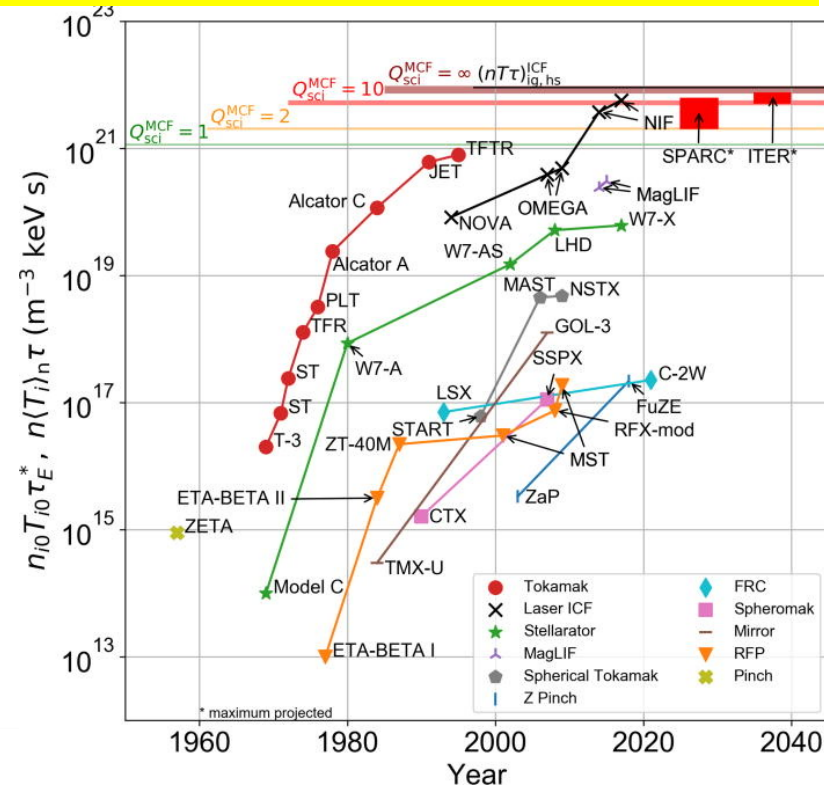


[Wurzel et al, PoP 29, 062103 \(2022\)](#)

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 $nT\tau_E$
 - We have made a ton of progress!
- There are different ways to confine a plasma to achieve fusion
 - Gravitational, magnetic, inertial
 - Stellarator See Paul, previous talk
 - Tokamak This talk
 - Reversed field pinch, field reversed configuration, magnetic mirror, z-pinch, spheromak... See Sutherland, next talk

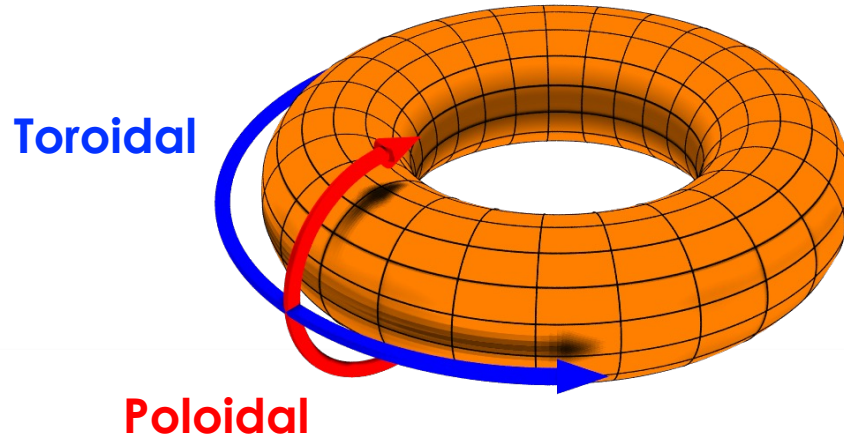
Ignition from 12/22 not shown here! See Kritcher, 6/8



[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, Sinha, 6/6
- Close those field lines into a torus to confine them
- Add twists to keep particles from drifting out See Sinha, 6/6
- 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:
*TO*roidal'naya *K*Amera s *MA*gnitnymi *KA*tushkami
“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

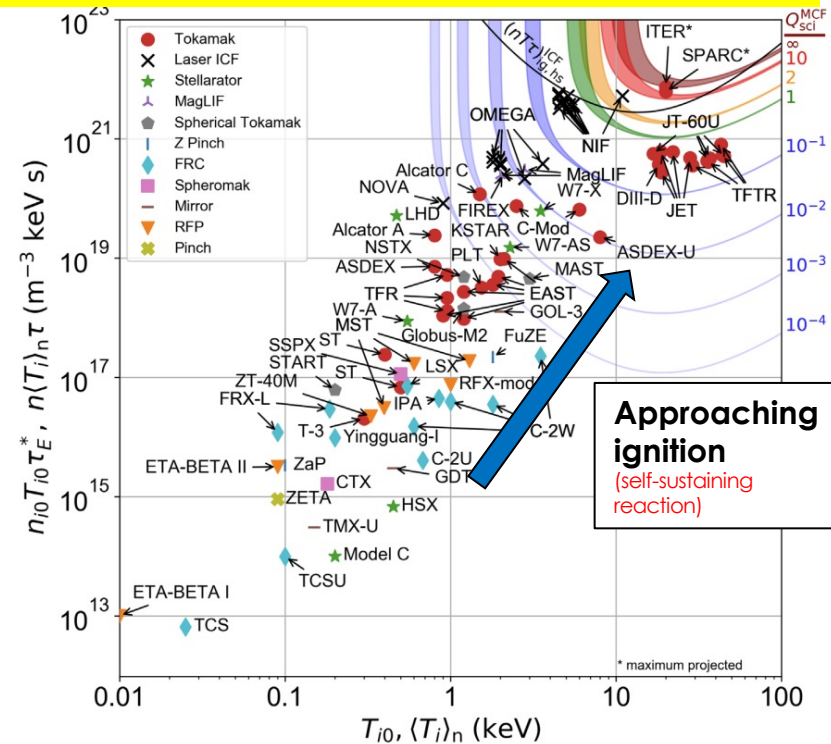


Many tokamaks around the world are making strides towards ignition

- **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)

... and more!

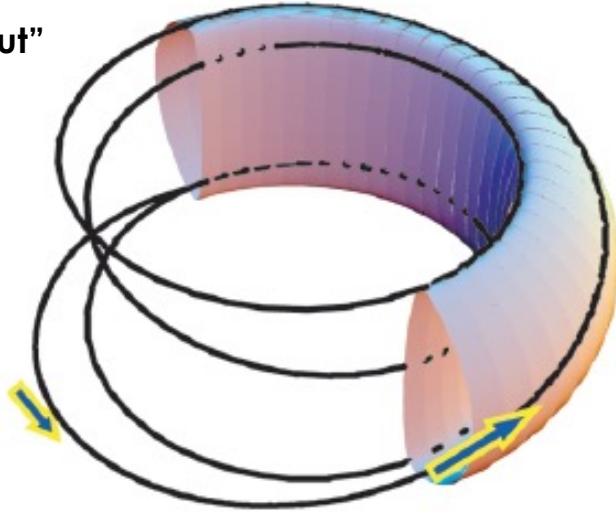
Ignition from 12/22 not shown here! See Kritcher, 6/8



Wurzel et al, PoP 29, 062103 (2022)

Two types of tokamaks: Conventional aspect ratio and spherical tokamaks

“Donut”
 $A \geq 4$

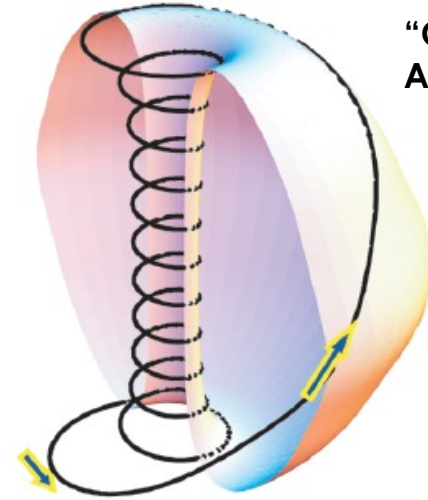


Conventional tokamaks

Usually $A > 2.5$

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

“Cored apple”
 $A \geq 1.25$

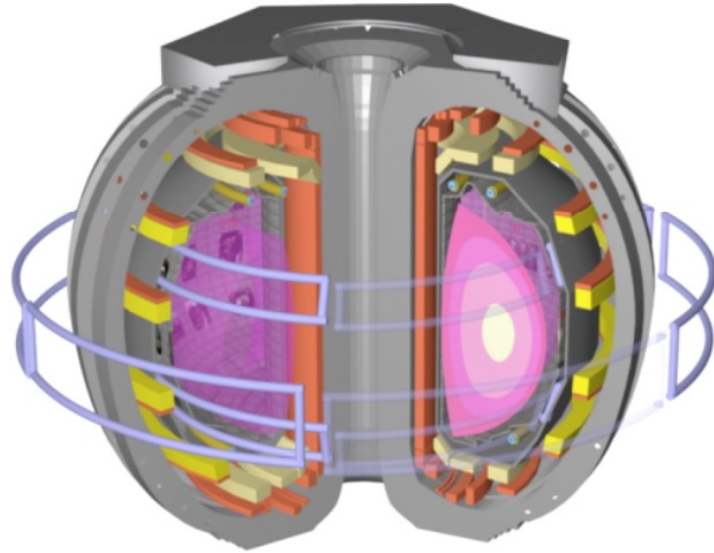


Spherical tokamaks

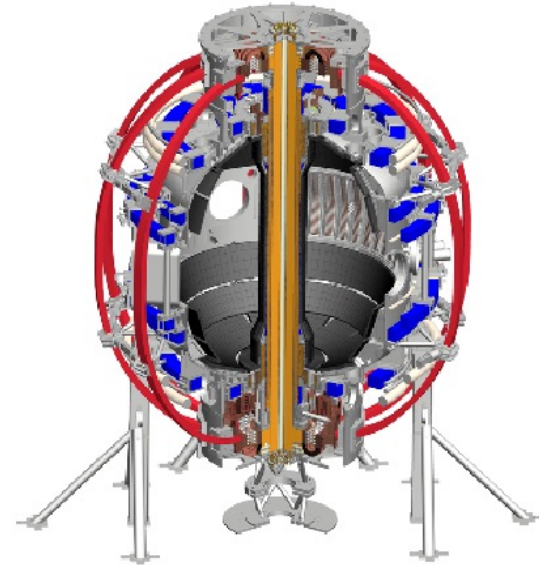
$A = 1 - 2.5$

Ex: MAST, NSTX-U...

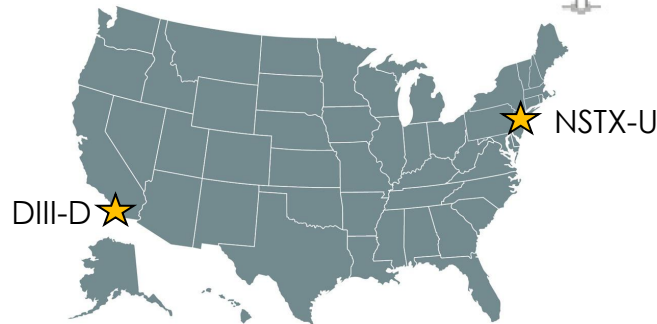
Two major U.S. facilities are DIII-D and NSTX-U, specializing in different aspect ratios



DIII-D,
Conventional tokamak
 $A=2.7$



NSTX-U
Spherical tokamak
 $A=1.3$



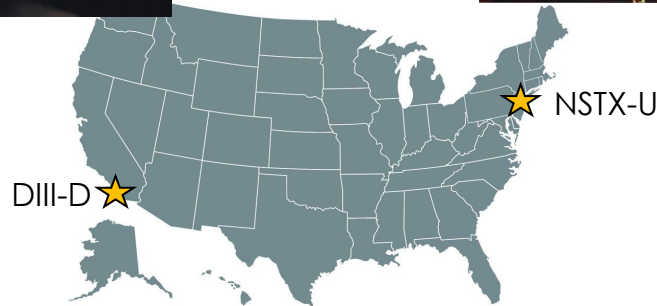
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DIII-D,
Conventional tokamak
 $A=2.7$



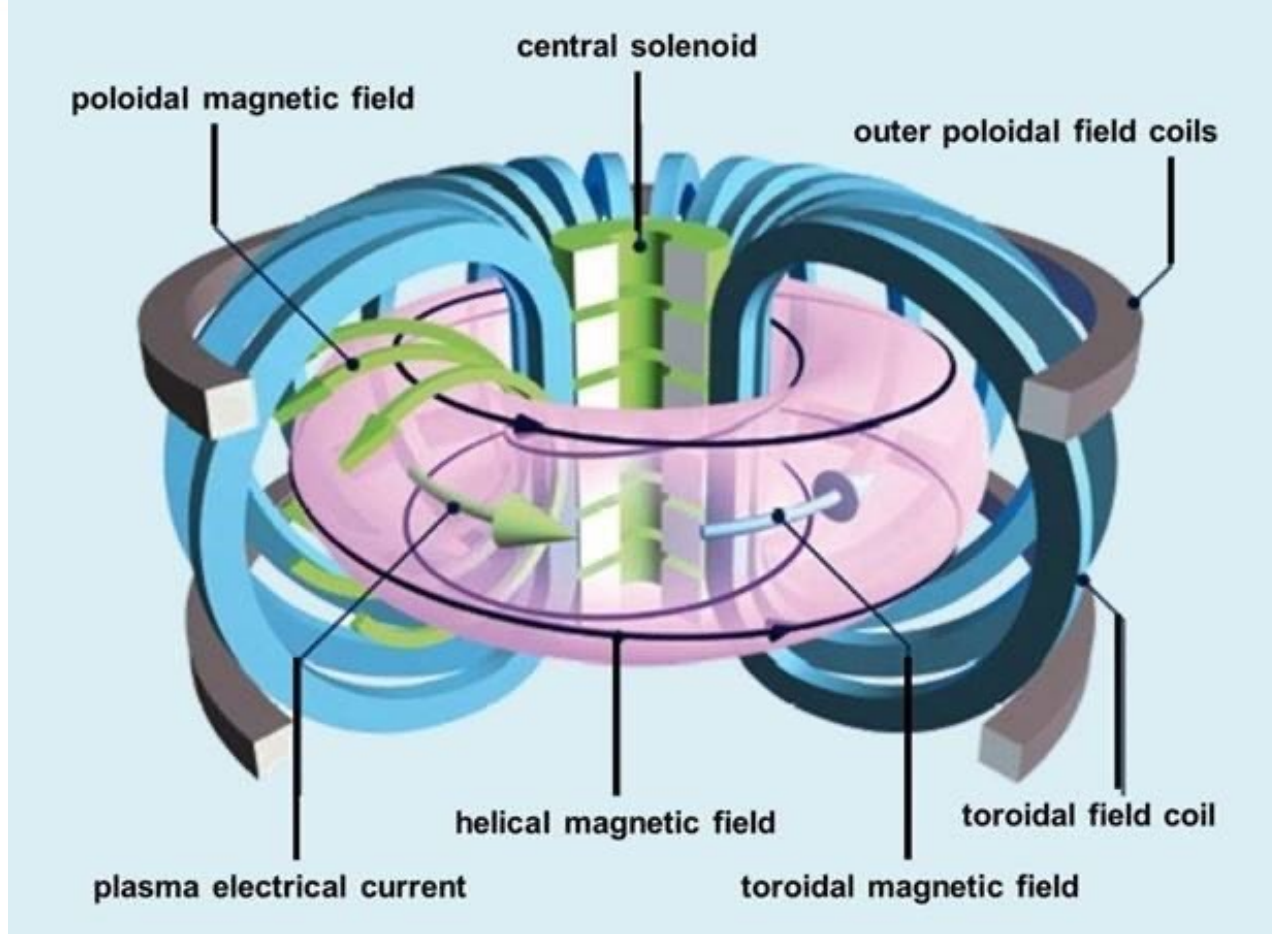
NSTX-U
Spherical tokamak
 $A=1.3$



Where are we going?

- Overview/review of key ideas
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 - Nested flux surfaces
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Tokamaks use magnetic fields to confine a plasma in a toroidal vacuum vessel



Tokamaks have nested magnetic surfaces

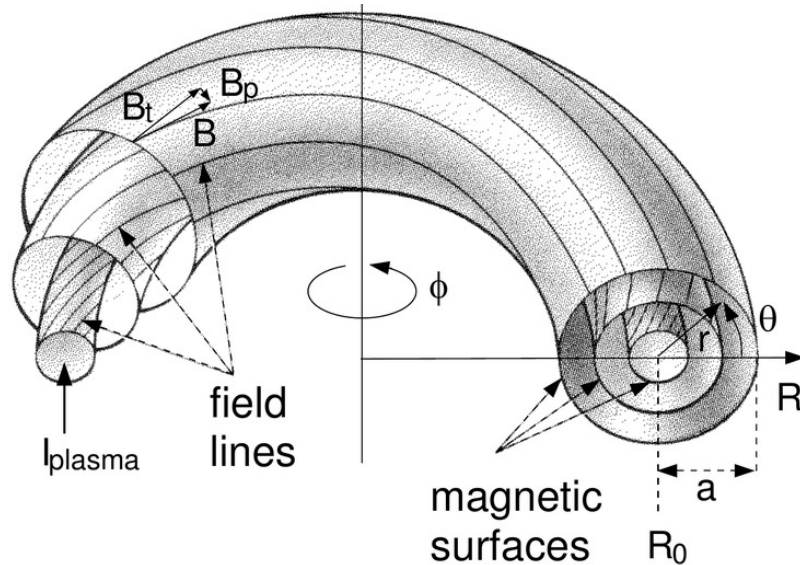
Two very important concepts:

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

(2) Safety factor:

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

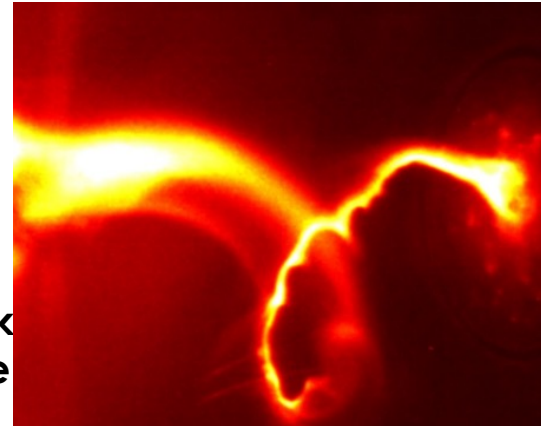
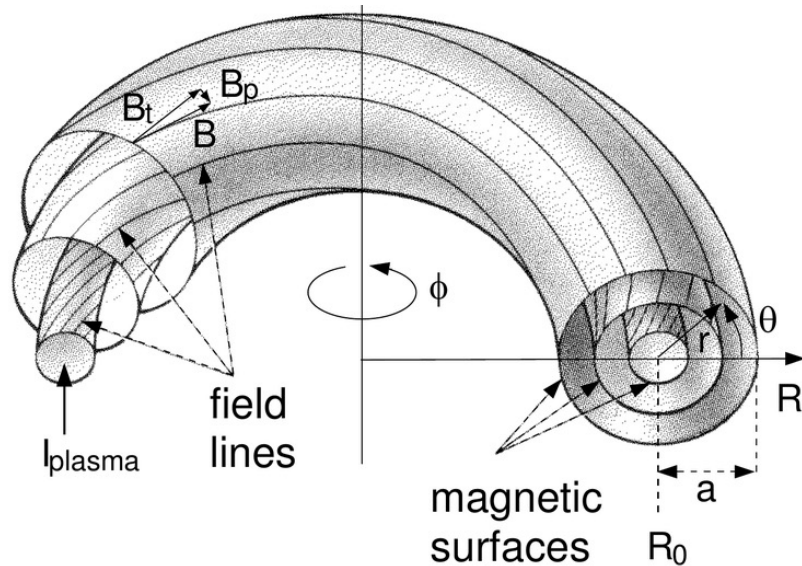
Tokamaks often use q_{95} which is just inside the last closed flux surface



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:



Tokamak plasma just inside the

Surfaces described using ideal magnetohydrodynamics (Ideal MHD)

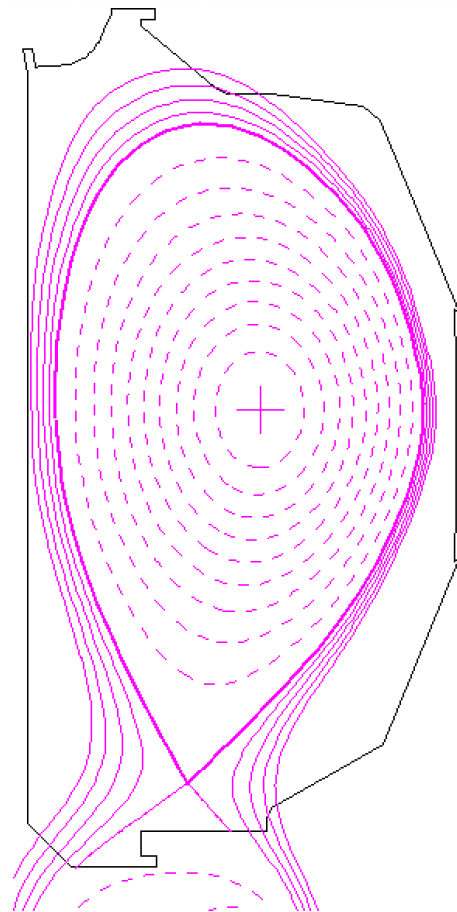
See Thakur, 6/6

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 Thakur, Tue 6/6

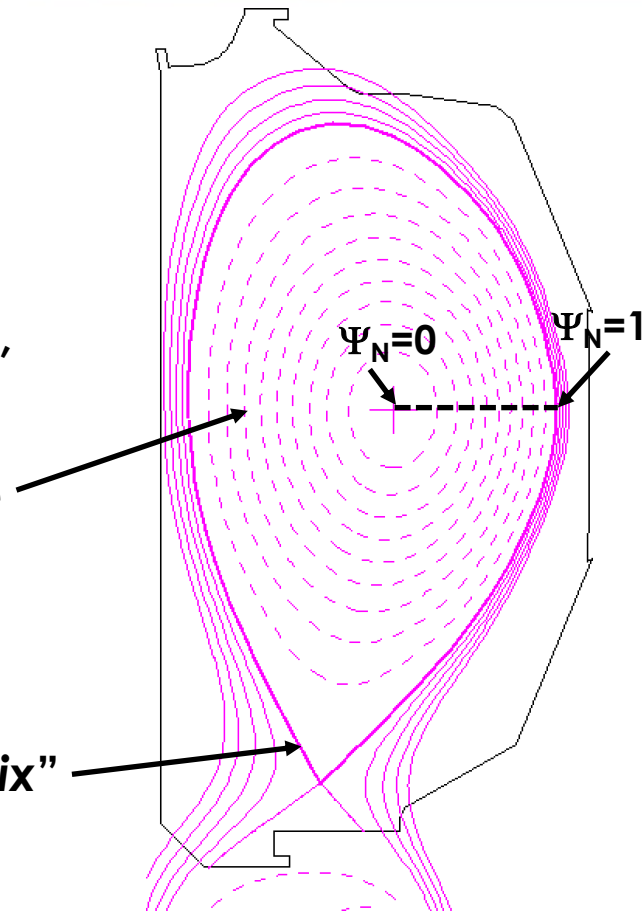
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Equilibrium equation relates poloidal flux function (Ψ), pressure (p), and current flux function (F)

- 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

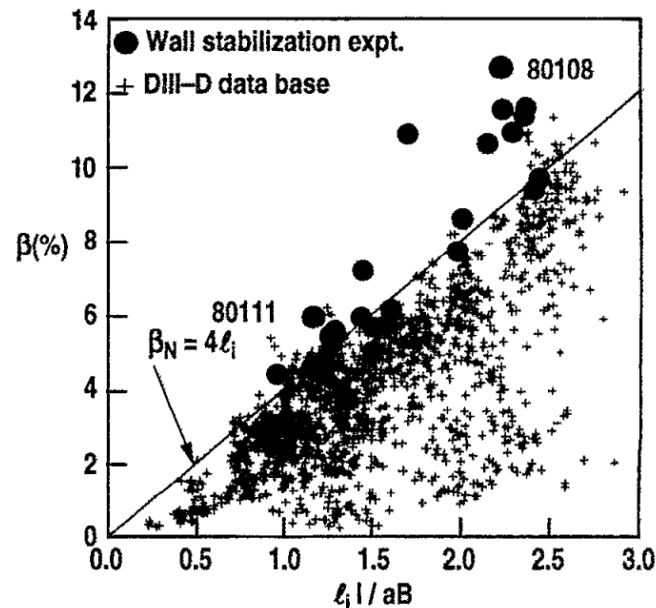
$$\beta = \frac{nkT}{B^2/2\mu_0}$$

- Plasma pressure (fusion output) pushes outwards and is balanced by magnetic pressure (economic cost)

- $\beta \propto \text{output/cost}$
- “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

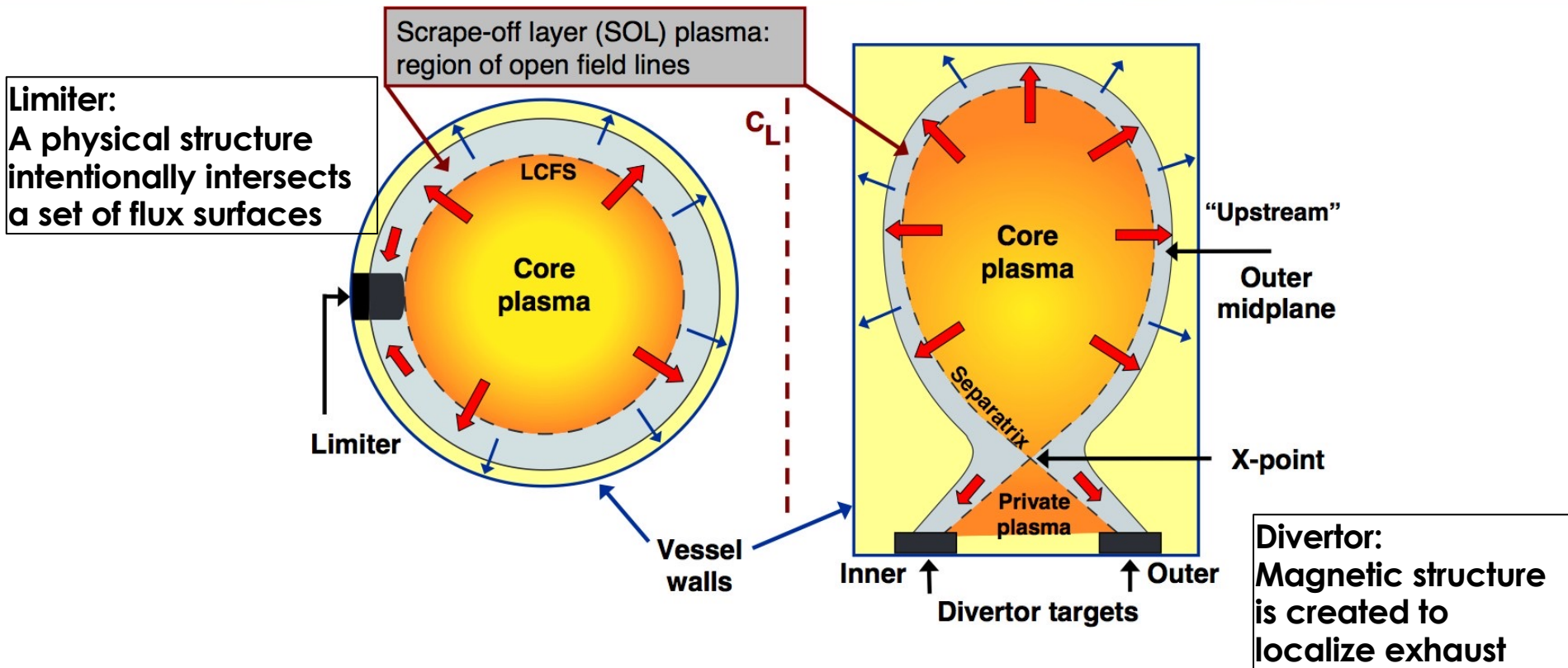


[Taylor et al, PoP 2, 2390 \(1995\)](#)

Tokamaks normalize to an empirical current limit:

$$\beta_N = \beta \frac{aB_T}{I_p}$$

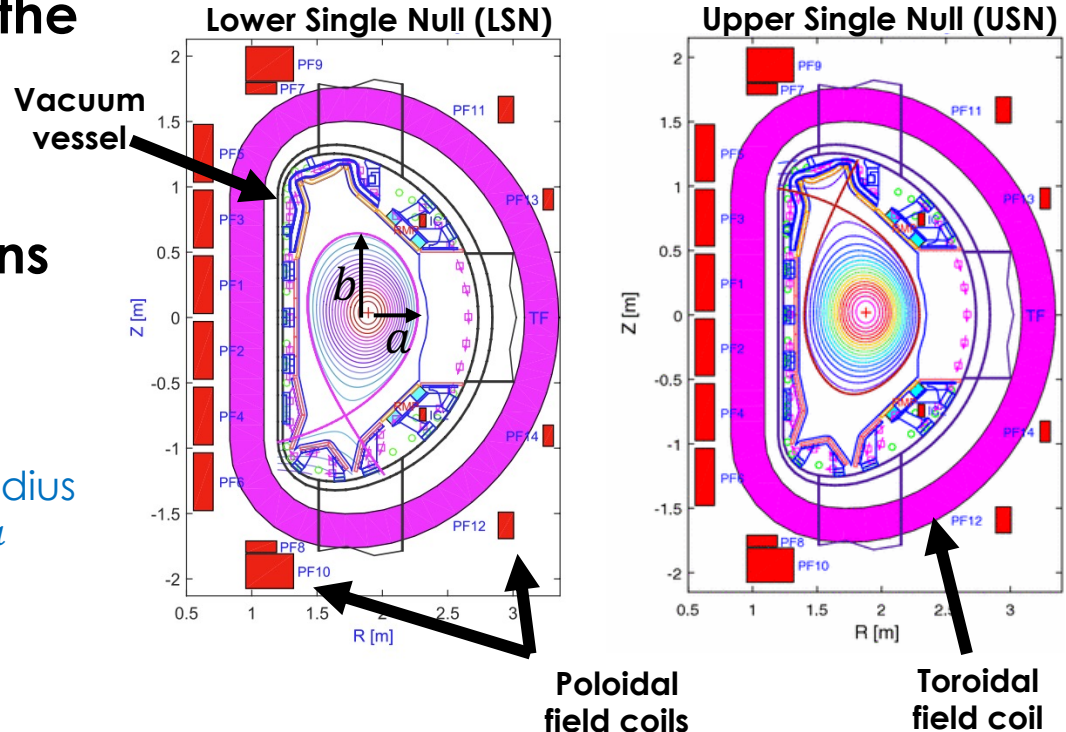
Two general types of tokamak magnetic topologies



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

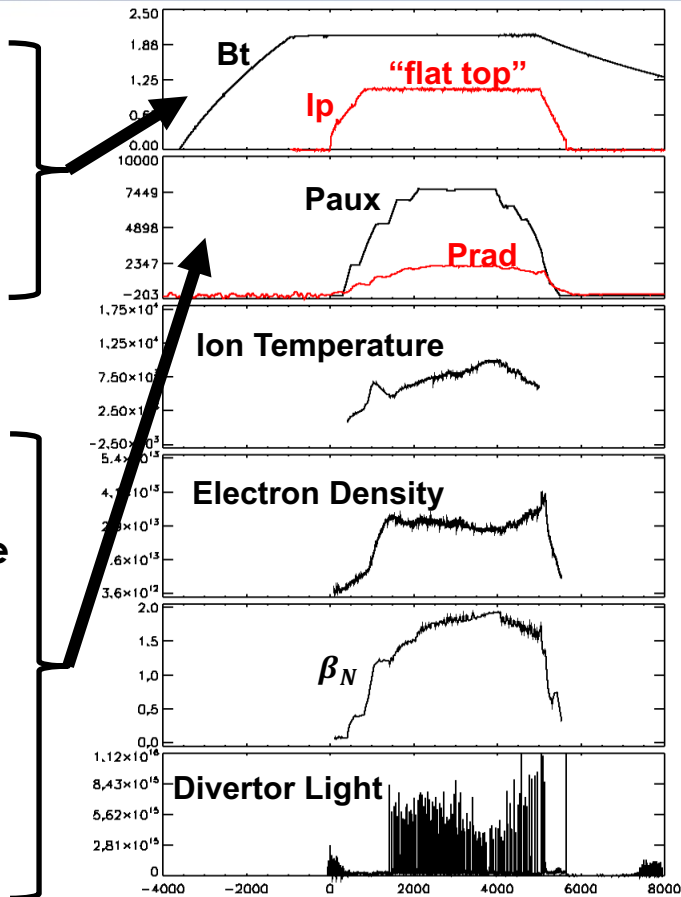




<https://www.youtube.com/watch?v=Yu9C5TEhAdQ>

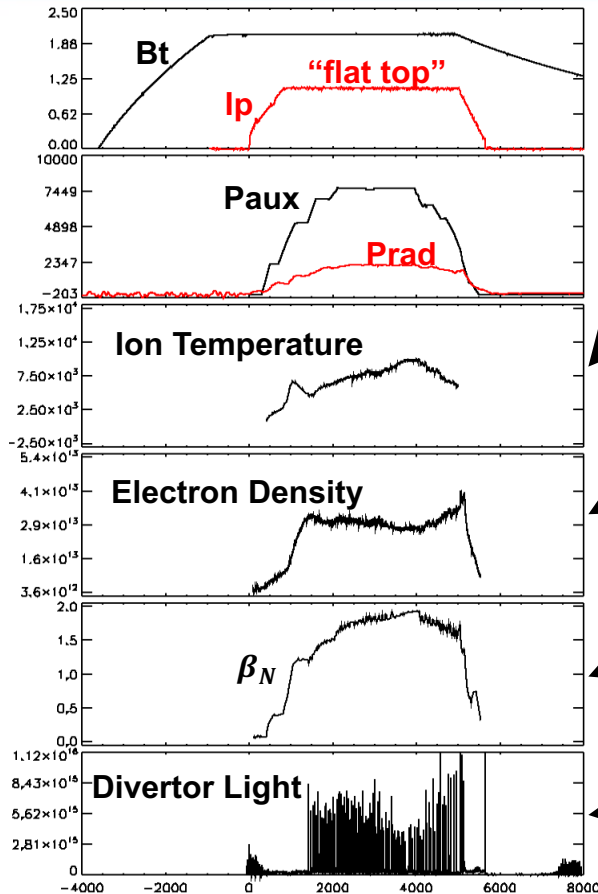
Example of a DIII-D plasma discharge

- 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 energy loss from the system (measured by bolometers)



Example of a DIII-D plasma discharge

- Toroidal magnetic field ramps up first
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- Radiated power measures 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 magnetic field ramps up first
- Central solenoid ramps up ohmically in parallel with plasma current
- Auxiliary systems required to maintain plasma and current
- Radiated power measures radiated energy loss system (multicolor bolometers)



Ion temperature
measured by Charge
exchange
Recombination
spectroscopy

Electron Density
measured by
interferometers

Normalized β calculated
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Divertor light measured
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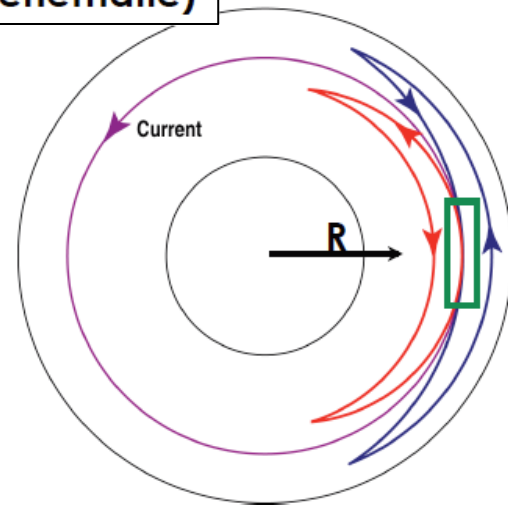
See Delgado-Aparicio, 6/15



Need both current drive and heating in a tokamak

- Heating is required in a reactor to ~ 15 keV
- Non-inductive current drive is required for steady-state operation
- Tokamaks naturally generate toroidal current (called bootstrap current) thanks to trapped particles
 - Profile gradients mean more trapped particles moving in the current driving direction at any one location
 - Trapped particles cannot carry current but transfer current to passing particles via collisions
- Physics of heating and current drive is very similar
 - If there is current drive, there is also heating

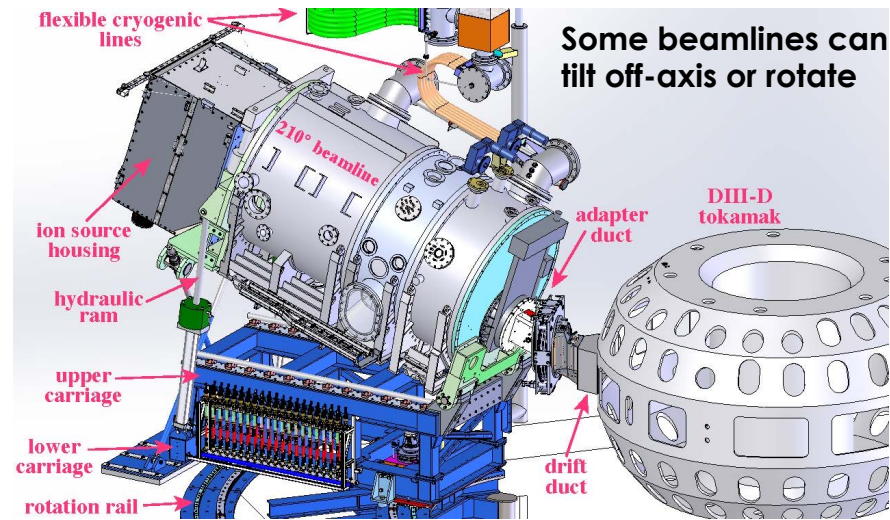
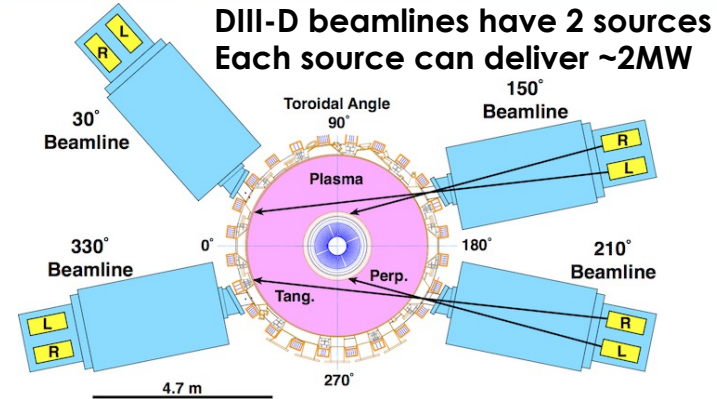
Tokamak Top View with Ion Orbits (Schematic)



Luce et al PoP **18** 030501 (2011)

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

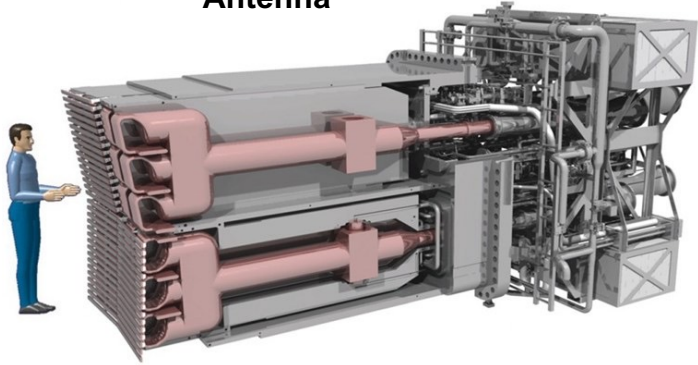
- Beamlines accelerate ions to high energies, then neutralize with electrons before injecting into the plasma
- **Advantage: Drives current in the core of burning plasmas**
 - Neutral beam energy must be high > 1 MeV to reach center of the plasma in a reactor
- **Disadvantages:**
 - Larger aperture required, removing blanket and shielding
 - Large addition to volume of plant exposed to tritium
 - Could drive fast-ion instabilities



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

Several different types of RF power and current drive:

ITER's Ion Cyclotron
Antenna



Ion Cyclotron RF

$f < 200$ MHz

Tetrodes to antenna

WEST Klystrons



[Delnech et al. EPJ Web of Conferences 157, 03009 \(2017\)](#)

Lower Hybrid RF

$f < 0.5-10$ GHz

LH, whistlers/helicon

Klystrons via waveguide

DIII-D Gyrotron "Yoda"

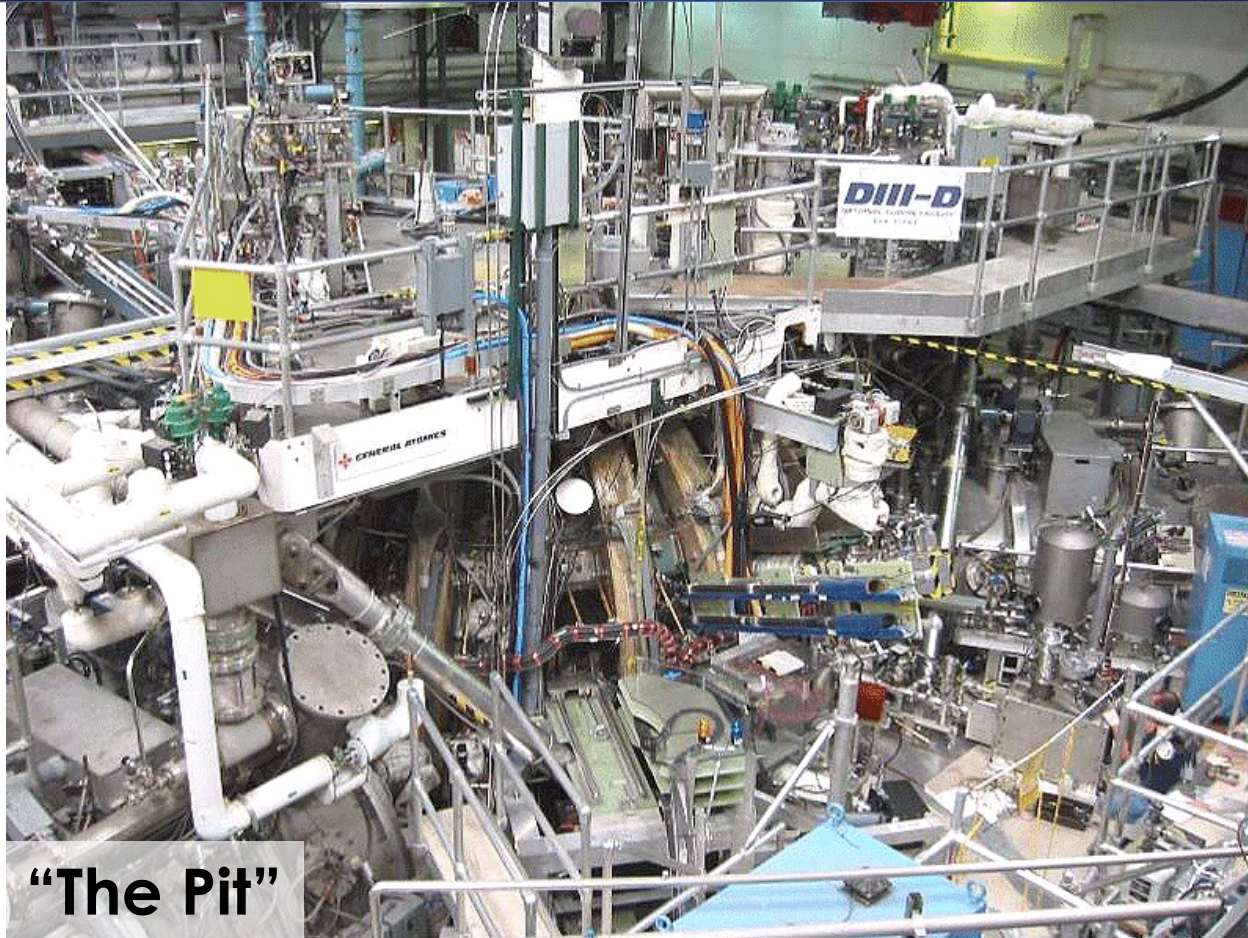


Electron Cyclotron RF

$f < 10-300$ GHz

Gyrotrons via
waveguide

Tokamak is only one part of the machine hall



"The Pit"

Iter will be the biggest tokamak yet

See Loarte, 6/15



Iter site, 3/2023

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

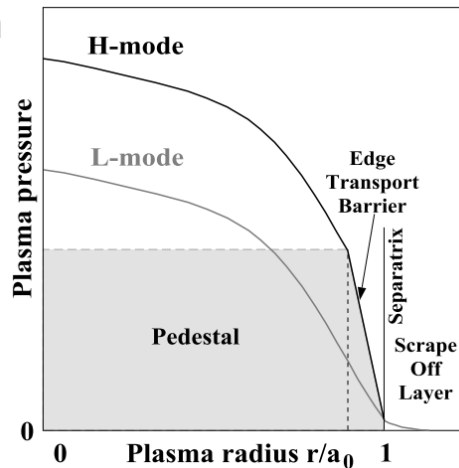
- **Tokamaks confine plasmas with toroidal and poloidal magnetic fields**
- **Tokamaks have nested flux surfaces, important quantities are conserved on a flux surface**
 - Normalized flux coordinate ψ_N , safety factor q , pressure ratio β
- **External coils shape and control the plasma**
 - Separatrix,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

Where are we going?

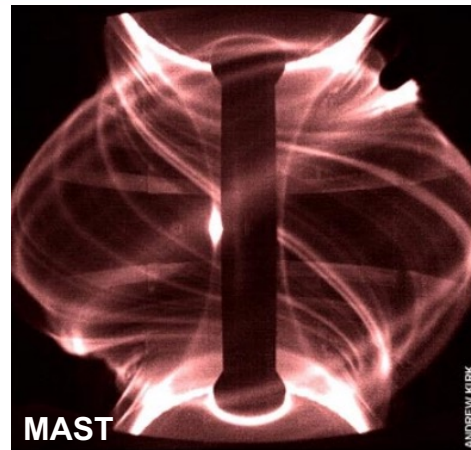
- Overview/review of key ideas
- How does a tokamak work?
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 - Heating and current drive
- **Some current research areas**
- How can you get involved?

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)**



[Lai 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

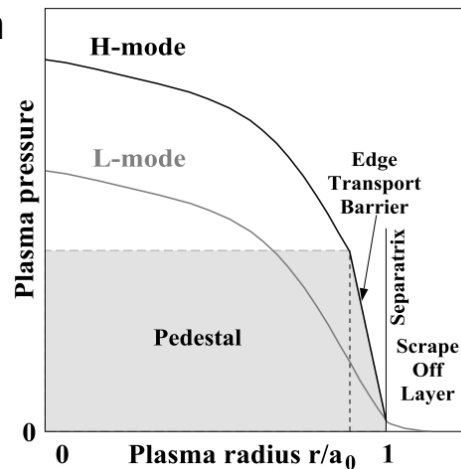
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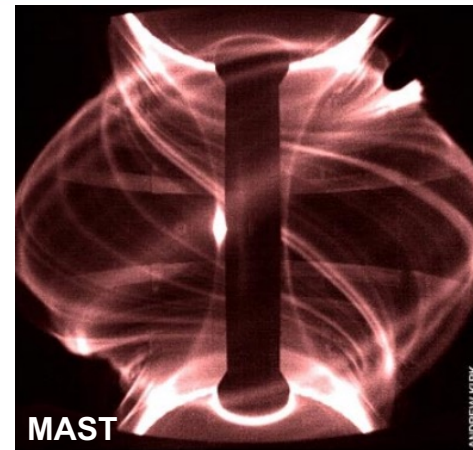
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- ELMs deliver large transient heat fluxes to plasma facing components

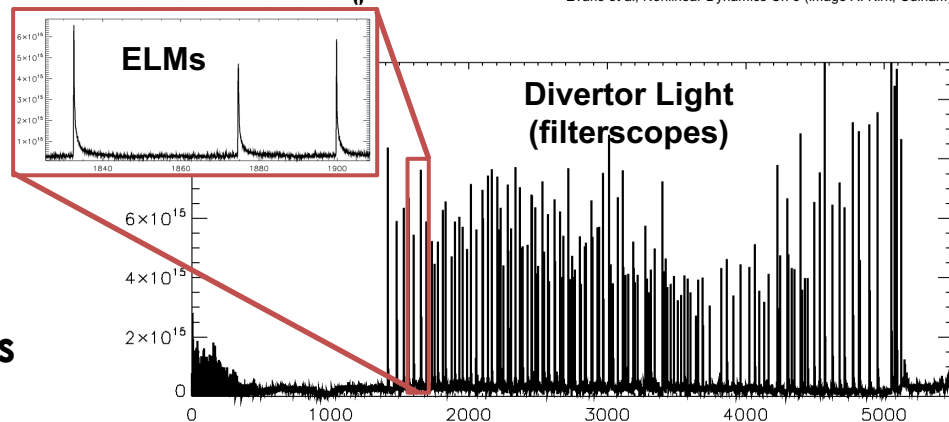
- Other types of modes are an active area of research → e.g. H-modes w/o ELMs or regimes w/ different confinement scalings



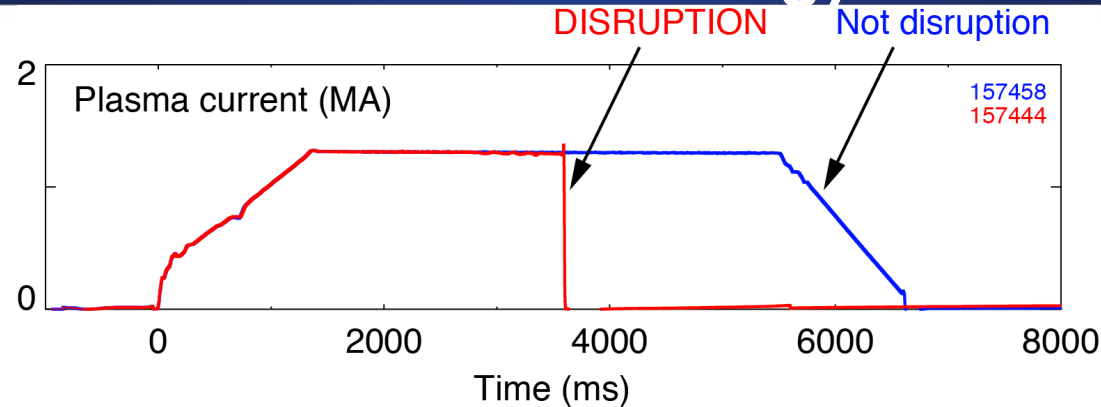
Land et al. NF 53, 043004 (2013)



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



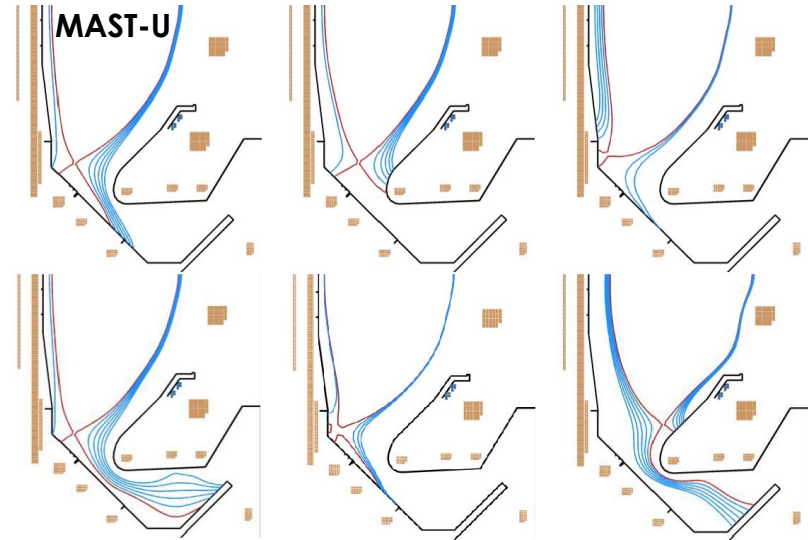
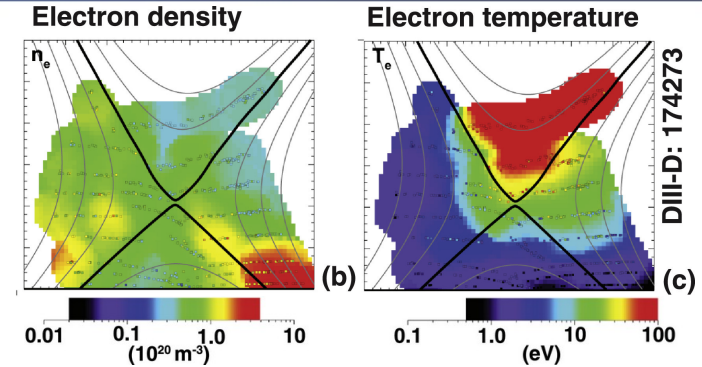
Disruptions are a rapid and complete loss of current and energy



- **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 See Rea, 6/15
- **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 Dennett, 6/13



Where are we going?

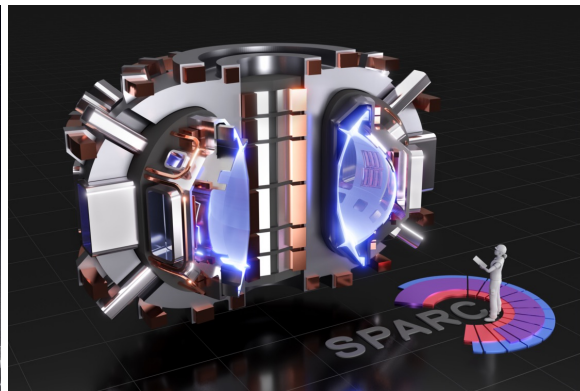
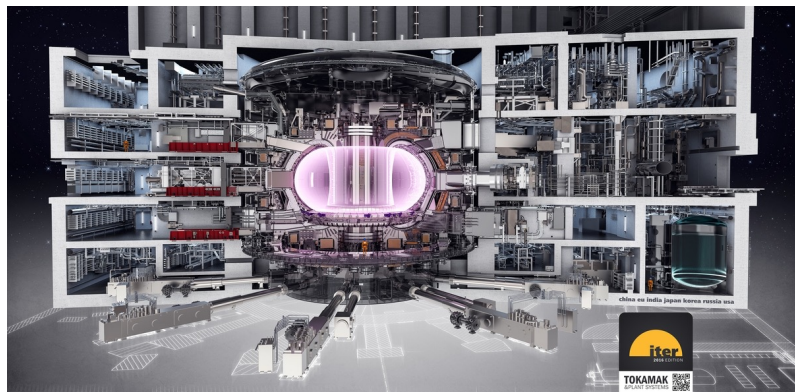
- Overview/review of key ideas
- How does a tokamak work?
 - Nested flux surfaces
 - Shaping
 - Heating and current drive
- Some current research areas
- How can you get involved?

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 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)



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 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!

