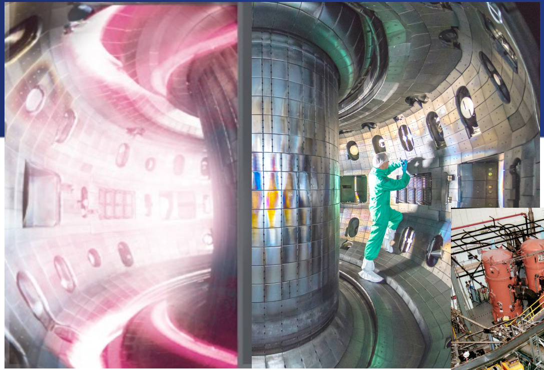
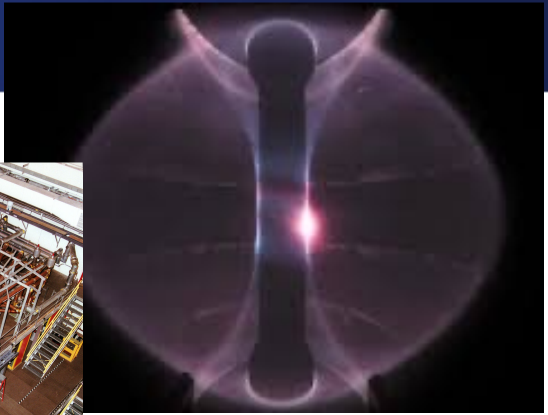
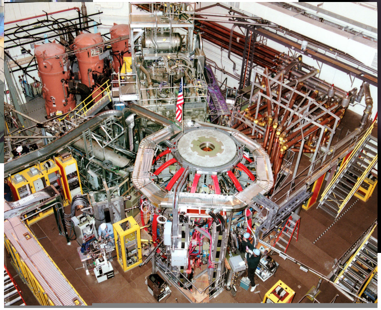
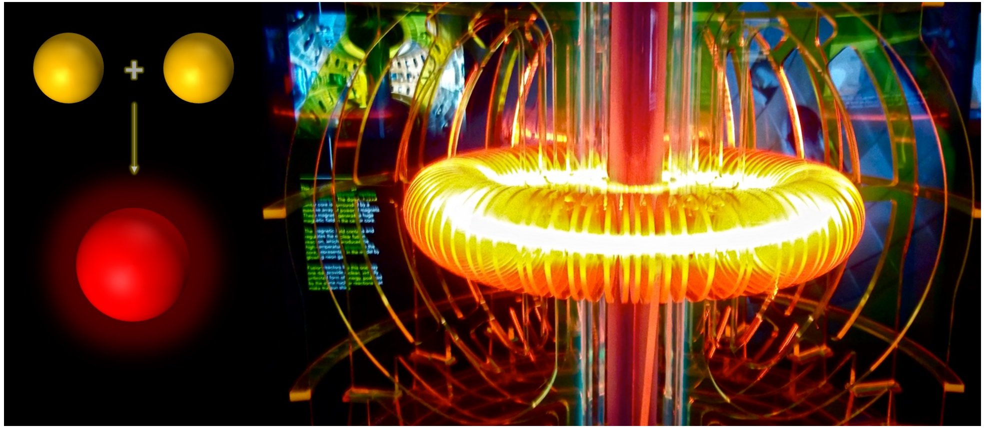
Tokamaks

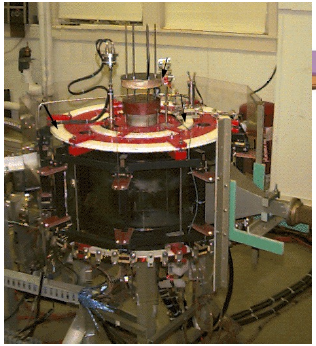


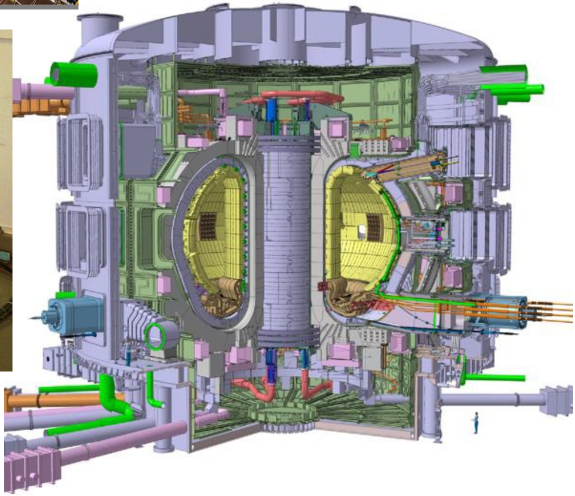




by
Kathreen E. Thome







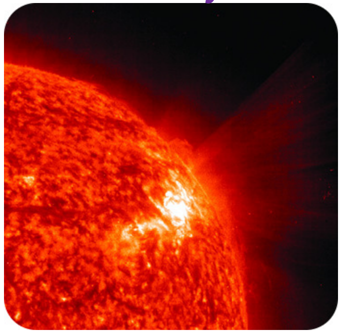
Presented virtually at the
2021 Intro to Fusion Energy and Plasma Physics Course

June 21, 2021

GENERAL ATOMICS

My Fusion Journey So Far!

10^{th} grade
Chemistry class



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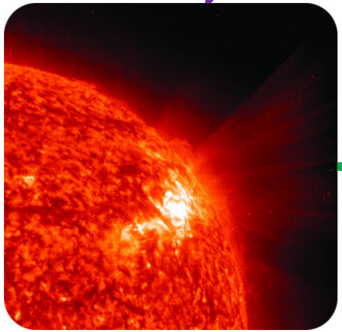

MIT for undergrad to do fusion research!

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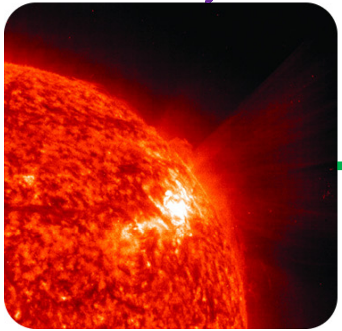

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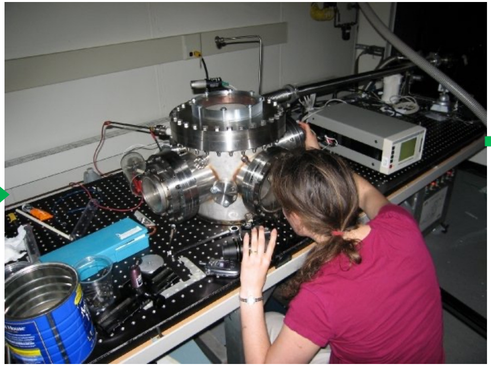

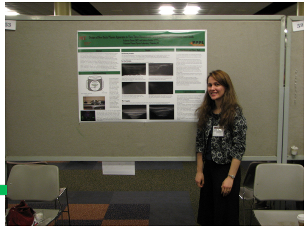

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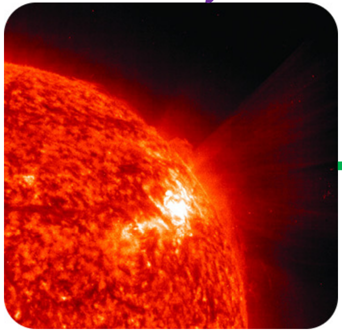

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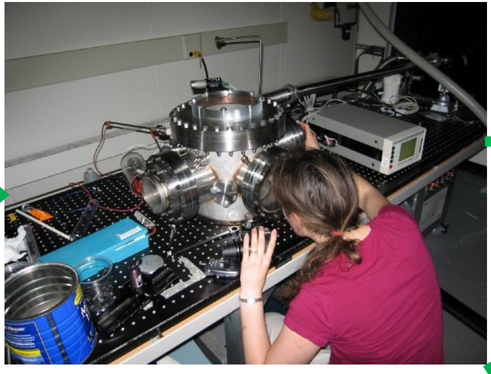
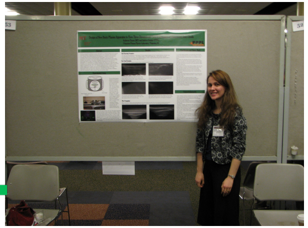
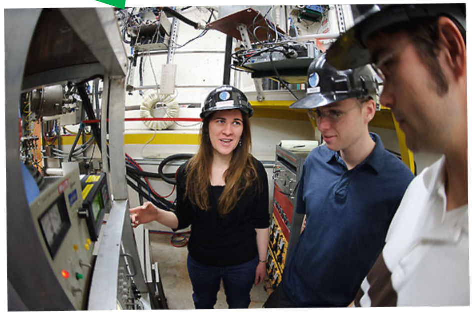




UW-Madison for grad school on Pegasus



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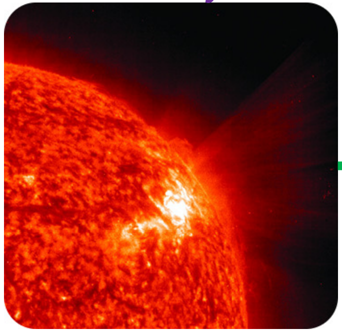

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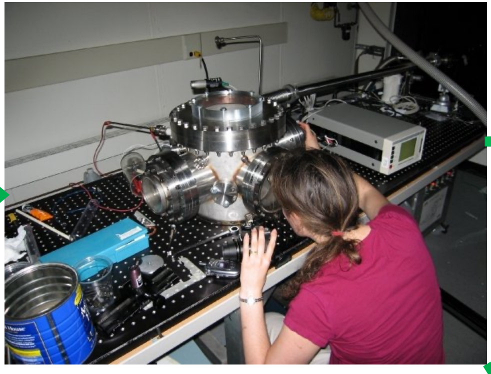

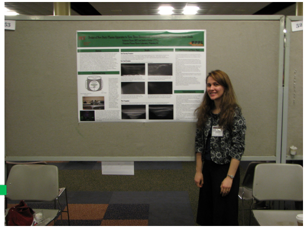

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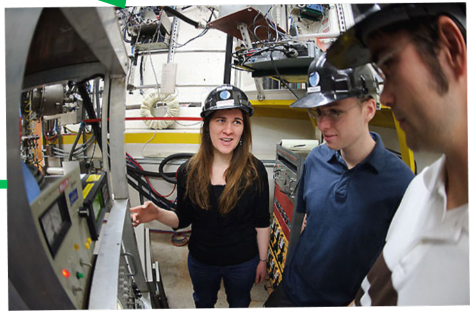

DIII-D for my postdoc

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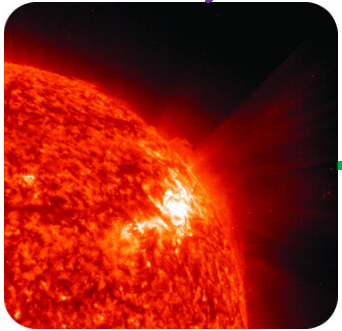

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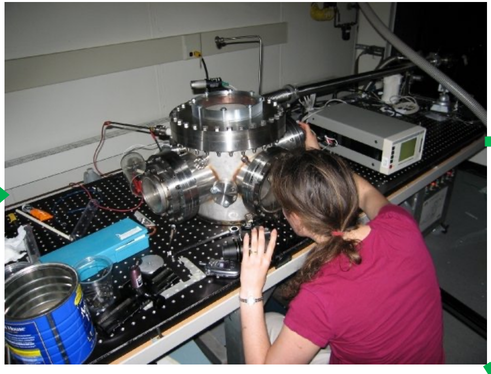

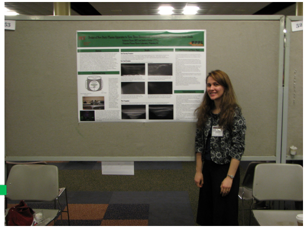

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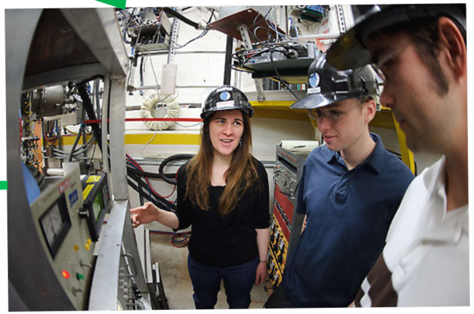

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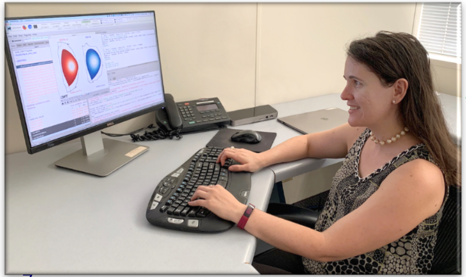
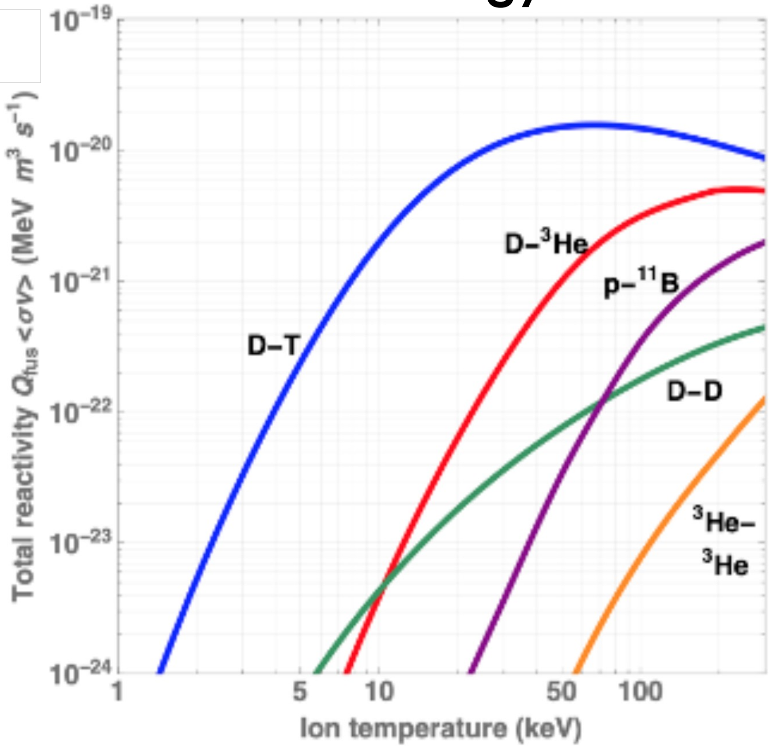
Now a Staff Scientist at General Atomics!



Deuterium-Tritium Fusion Occurs at the Lowest Temperatures

Reaction cross section times total energy released

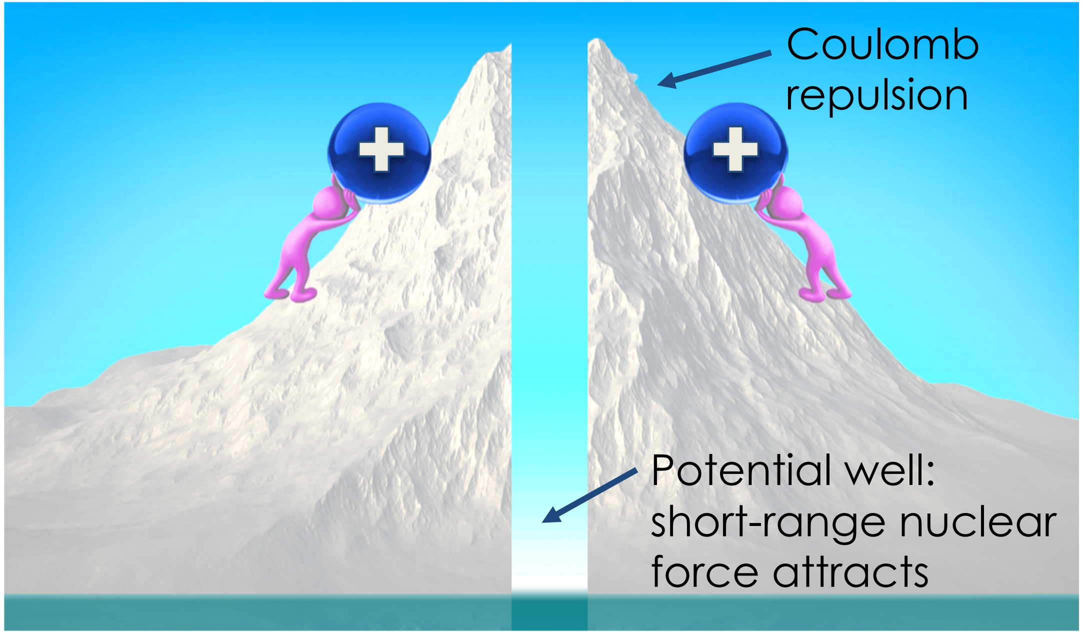


Think back to Collins Day 1

- **D-T is the easiest due to its occurrence at lower temperature and is the planned scenario for a reactor**
  - Reactor will want to be at ~15 keV
- **Usually most tokamak and fusion experiments use deuterium gas**
  - Don't need to worry about tritium, less overall radioactivity

How do we Contain Plasmas?

We want two positive particles to combine



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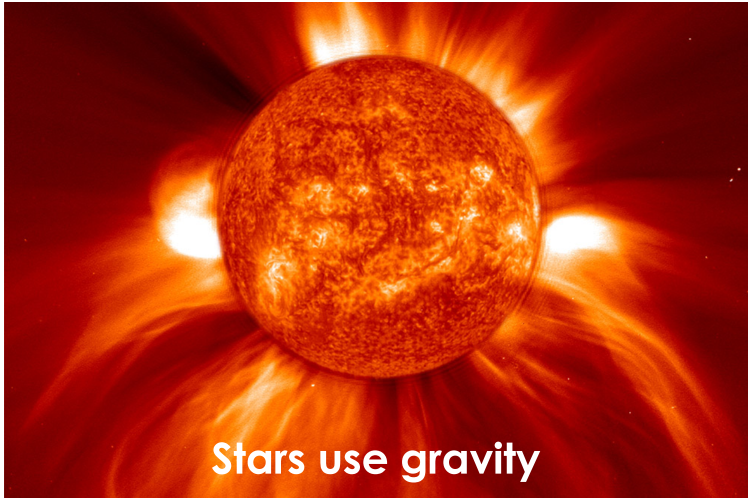

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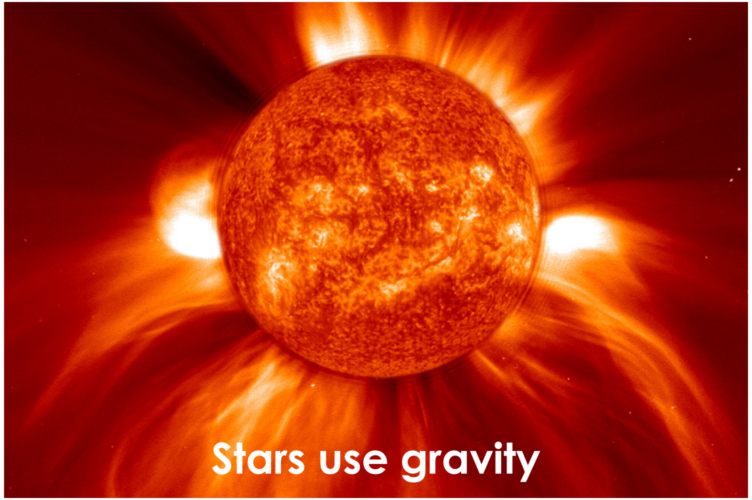
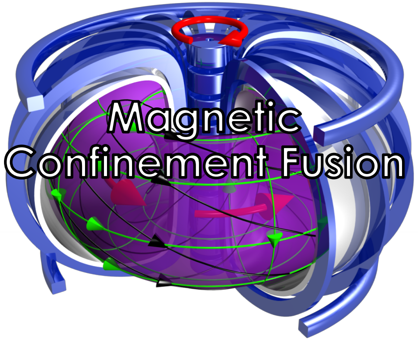
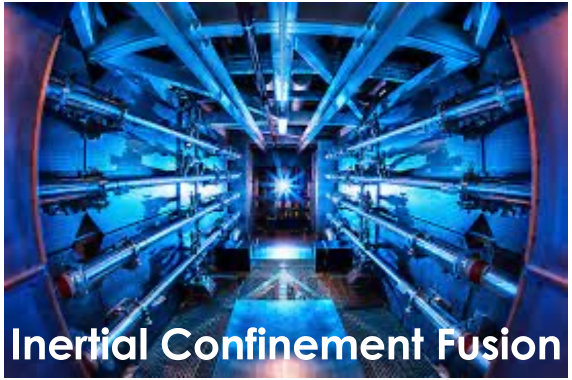


On Earth we use

Magnets



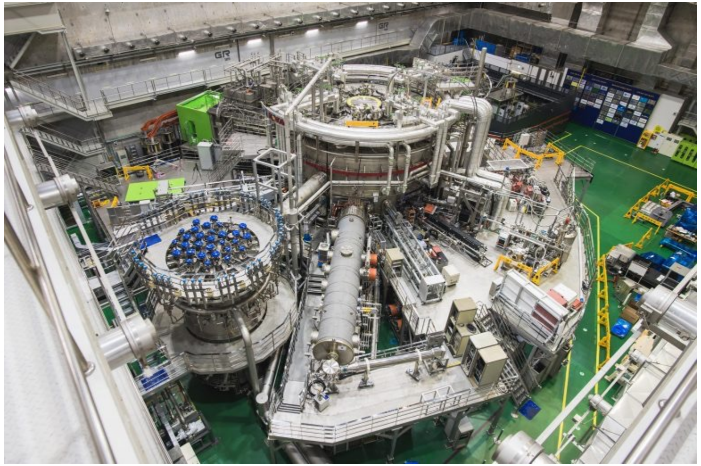
Inertia via compression



Today is Magnetic Confinement Fusion Day!

- **And we’re going to talk about tokamaks**

- **There are other types of magnetic confinement fusion devices and you will learn about them in the following lectures**
  - Stellarators (Paul at 130)
  - Alternative Configurations (Woodruff at 3)



Where did Tokamaks come from? A Brief History

1920s-1930s

Beginning of the nuclear age: Fusion and fission first theoretically proposed, realization that nuclear fusion happens in stars

$E=mc^2$

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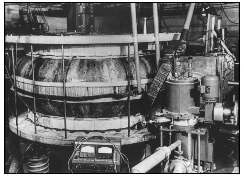

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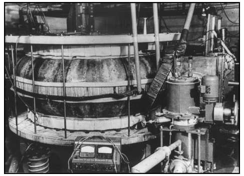

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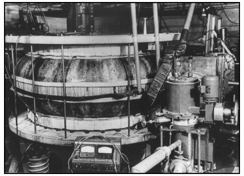

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Fusion is harder than we thought… losing too much energy

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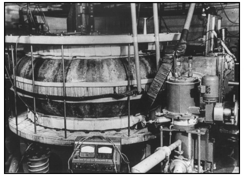

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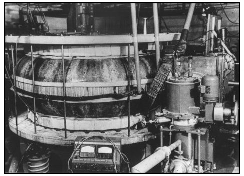

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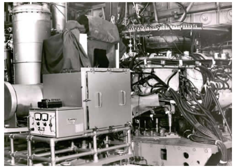

Where did Tokamaks come from? A Brief History

The rest is history… the rest of the world quickly switches to the tokamak concept, even PPPL, over 200 tokamaks have been built!

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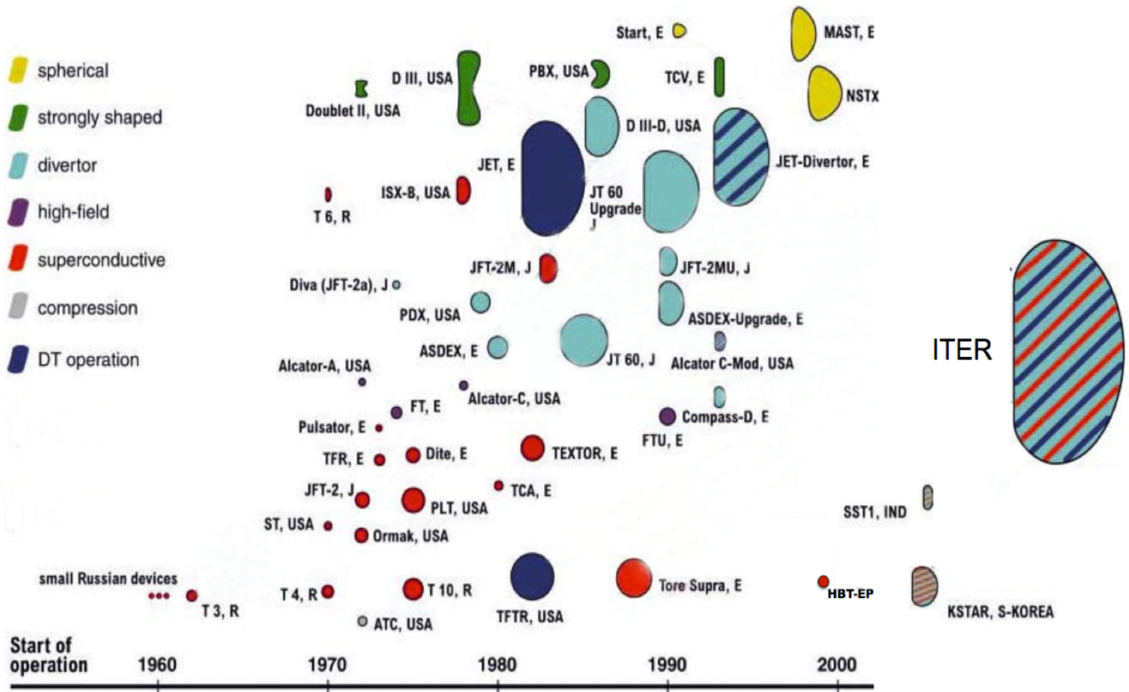

68

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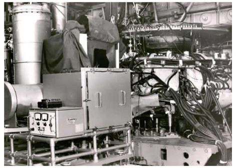


What does Tokamak Mean?

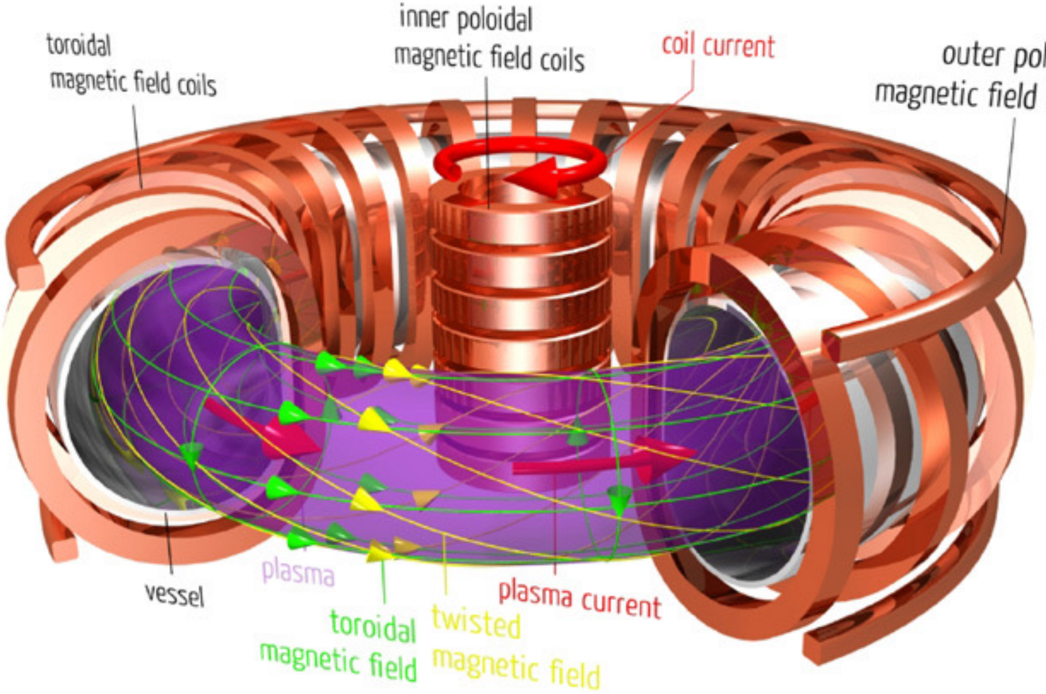
Tokamak is a Russian acronym for “toroidal chamber with magnetic coils”

тороидальная камера с магнитными катушками
Toroidalnaya camera s magnitnymi katushkami

How does a Tokamak Confine Particles?

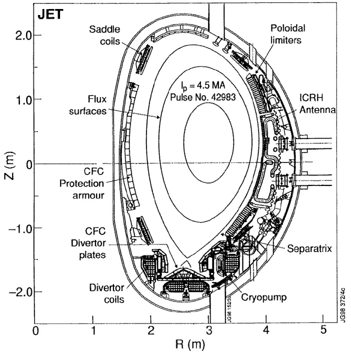
Remember day 2 Hussein's Single Particle Motion talk!

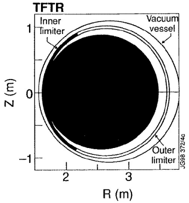
Tokamaks have both external coils to produce fields and a driven toroidal current to produce a poloidal field

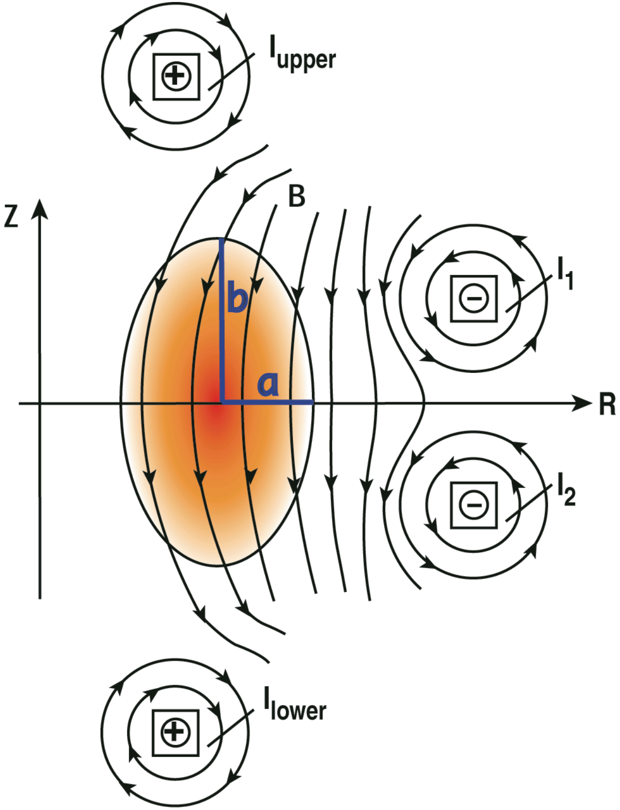


Poloidal Field Coils Provide Stability, Allow Plasma to "Elongate" and Improve Performance

- Originally all tokamak plasmas were circular
- Elongation increases the cross section of the plasma
  - Area ~ pi*a*b
- More room for fusion at the same major radius
- Elongation is *unstable* and requires *active control*







Courtesy M. Walker, GA

Two Types of Tokamaks: Conventional Aspect Ratio and Spherical Tokamaks

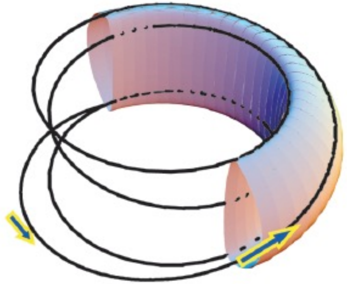
- **Aspect Ratio A=R/a**

- **Most conventional aspect ratio tokamaks A>2.5**

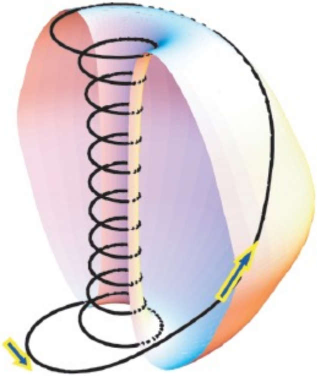
- **Spherical tokamaks aspect ratio A=1-2.5**
  - A lot of conventional aspect ratio assumptions, physics is slightly different at lower aspect ratio

- **NSTX-U and MAST-U biggest spherical tokamaks, also smaller ones like Pegasus!**

$A \geq 4,\ q_\psi \geq 4$

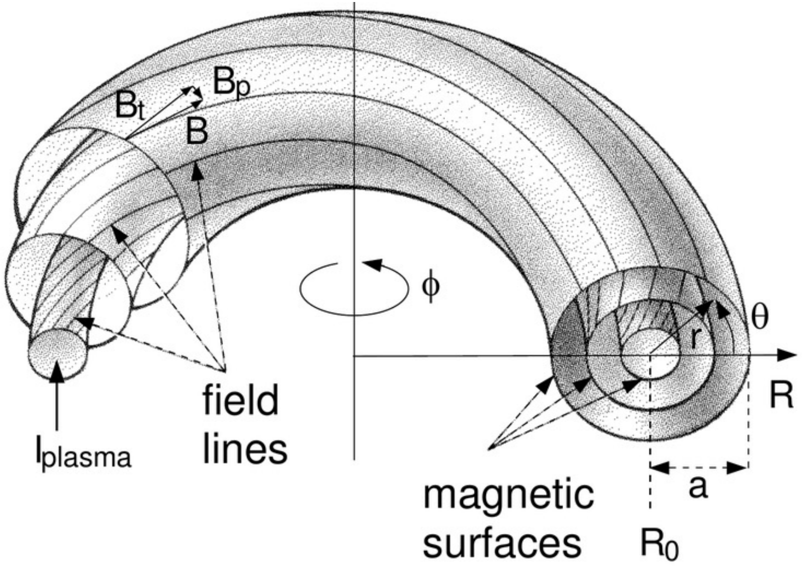


$A \geq 1.25,\ q_\psi \geq 12$



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

Tokamaks have Magnetic Surfaces



- **q= 2π/i safety factor= toroidal transits/poloidal transits**
- ***Often reduce 3D toroidal coordinates (φ, θ, R) to 1 D magnetic surfaces coordinates Ψ when possible***

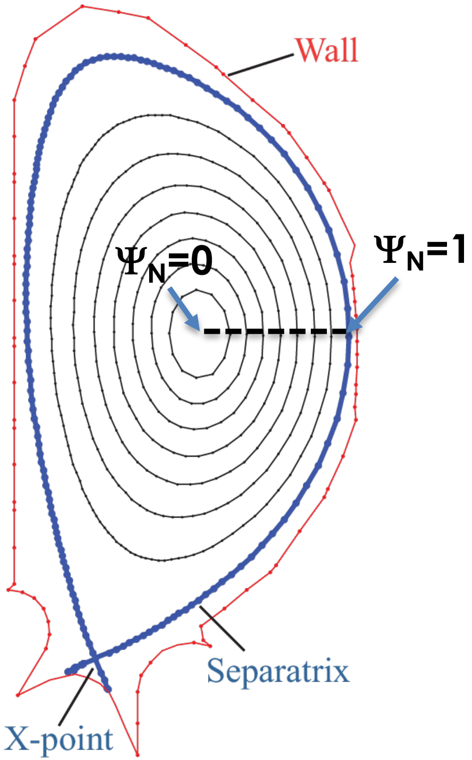
Axisymmetric Toroidal Equilibria are Described by the "Grad Shafranov" Equation[1,2]

Grad Shafranov:

$$\mathbf{J} \times \mathbf{B} = \nabla p$$

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

- **Provides a solution for the Flux (Ψ) as a function of space (R, Z) and Pressure (p) and current (F)**
- **Contours of equal flux are called "*Flux Surfaces*"**
  - Pressure is constant on a flux surface
- **Outermost flux surface is called the "*Separatrix*"**
- **We label radius by "normalized flux"**
  - Core = 0, Separatrix = 1

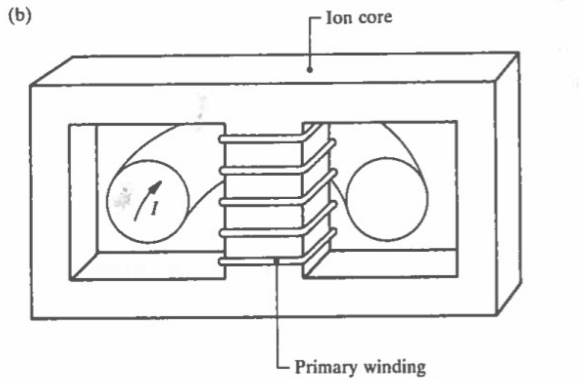


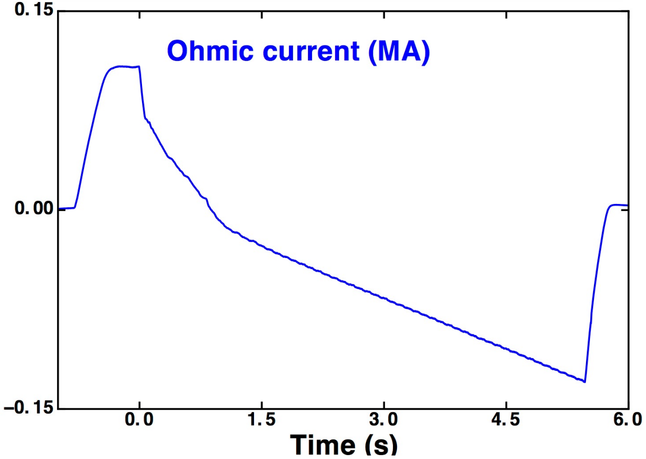
ITER Equilibrium

1. *Proceedings of the Second United Nations Conference on the Peaceful Uses of Atomic Energy*, Vol. 31, p.190
2. *Sov. Phys. JETP* **6**, 545 (1958)

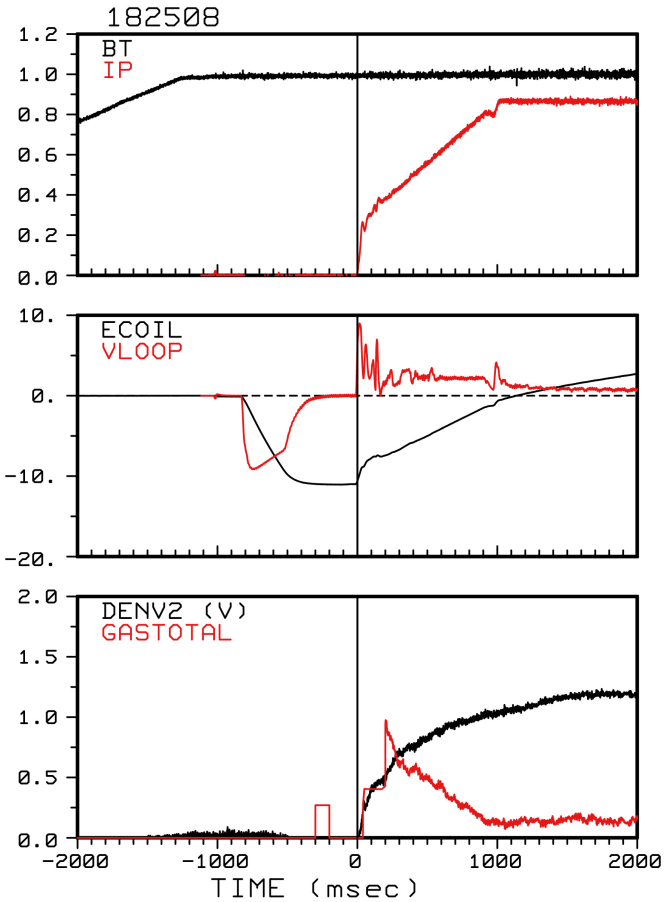
Toroidal Current must be Sustained in a Tokamak

- **Initially induce current using a central solenoid (called Ohmic heating, inductive drive)**
  - Change of flux through solenoid induces a toroidal electric field
  - Cannot sustain current steady-state
  - Can be used to startup a plasma

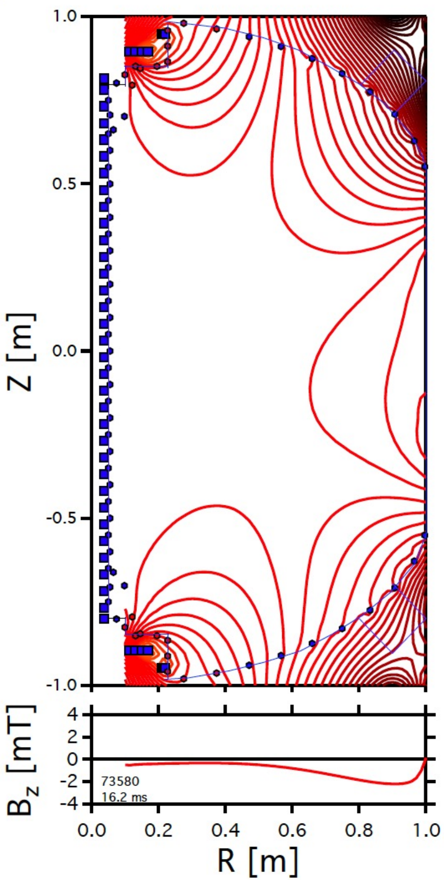




How do you Ohmically Startup a Tokamak?



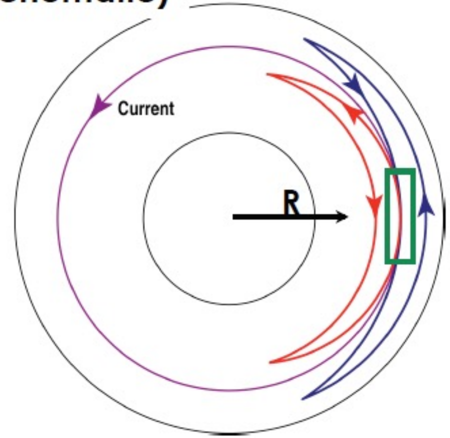
- Maximize volume of poloidal field null
- Gas puffing ('prefill')
- Reverse bias on ohmic primary
- Paschen minimum
- Create closed flux surfaces, grow the plasma



Need Both Current Drive and Heating in a Tokamak

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

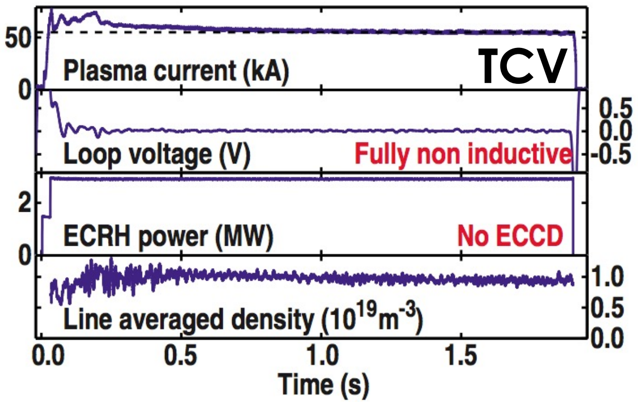
Tokamak Top View with Ion Orbits (Schematic)



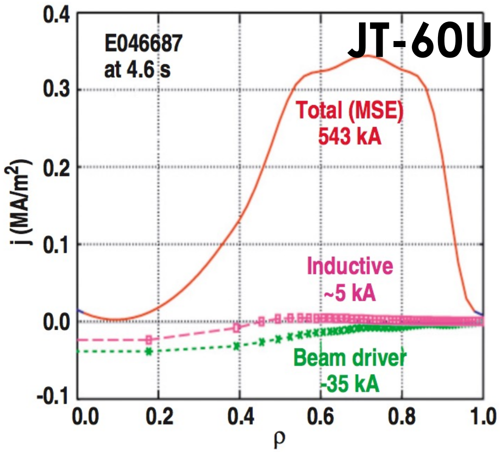
Luce et al PoP **18** 030501 (2011)

Wait Can't We Just Use Bootstrap Current?

- **Full current drive by bootstrap current has been demonstrated but NOT in parameter regimes suitable for fusion energy**

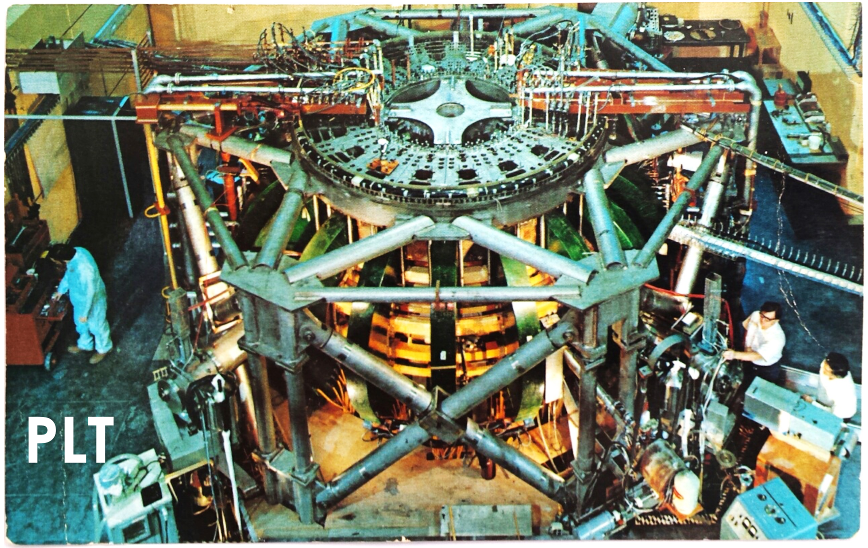


- **ITER Physics Basis: "Steady state operation of the tokamak requires that at least 20% of the plasma current is provided by an external source"**



We Need More Power – Neutral Beam Injection (NBI) Big Success

- **Ohmic heating not sufficient, auxiliary heating and current drive first developed around 1971**



With 2.4 MW of D^0 injection into an H^+ plasma, we have achieved ion temperatures up to 6.6 keV recorded by an analysis of charge-exchange neutrals as shown in Fig. 1. A supportive diagnostic for this ion-temperature measurement is Doppler broadening of Fe XXIV. At this power level, ion temperature and central density $[n_e(0) = 5\times 10^{13}$ $cm^{-3}]$, Fe XXIV is strongly heated by the beam ions and can be raised to temperatures well above the thermal H^+ plasma. We calculate, for this case, that the temperature of Fe XXIV should exceed that of the thermal protons by 1700 eV. The

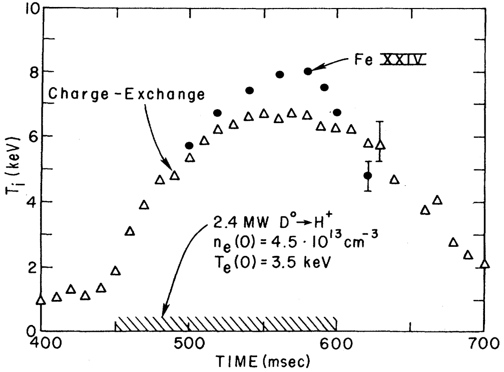
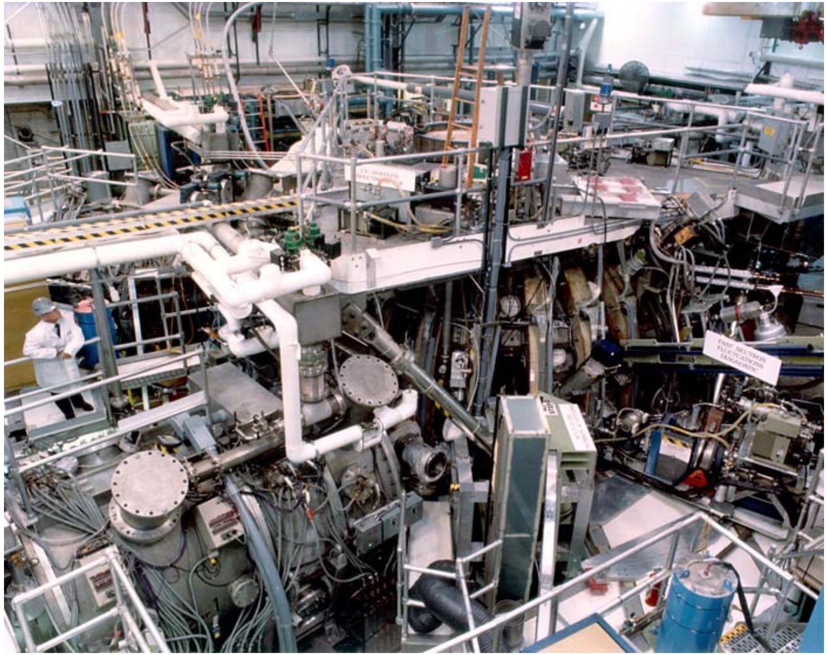
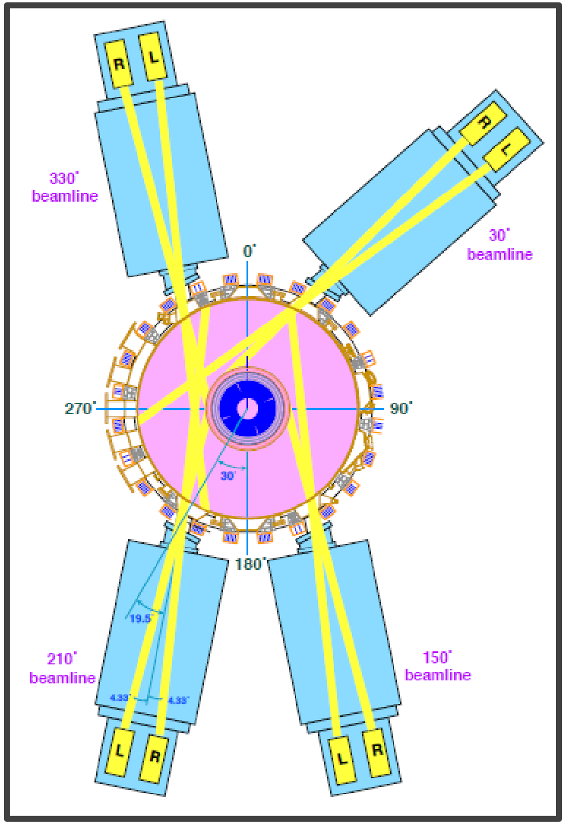


FIG. 1. Ion temperature (H^+) vs time as measured by analysis of charge-exchange neutrals and Doppler broadening of Fe XXIV for 2.4-MW D^0 injection into a H^+ plasma. Calculations indicate that the maximum temperature of Fe XXIV should exceed that of H^+ by 1700 eV.

Neutral Beams are Huge!!!! Often Bigger than Tokamak

- **Example: plan view of DIII-D with 4 beamlines**

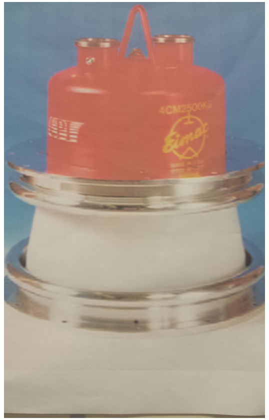




Advantages and Disadvantages: Neutral Beams

- 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, operation up to 0.5 MeV demonstrated in Japan
  - Need to demonstrate higher voltages and current densities
- Larger aperture required, removing blanket and shielding
  - Reduces tritium breeding capability and protection from neutrons
- Large addition to volume of plant exposed to tritium
- Could drive fast-ion instabilities

Waves are the Main Alternative Heating/Current Drive Method: There are Many Types!



Ion Cyclotron RF
f<200 MHz
(FWCD/HHFW also ICCD)
Tetrodes

Lower Hybrid RF
f<0.5-10 GHz
LH, whistlers/helicon
Klystrons

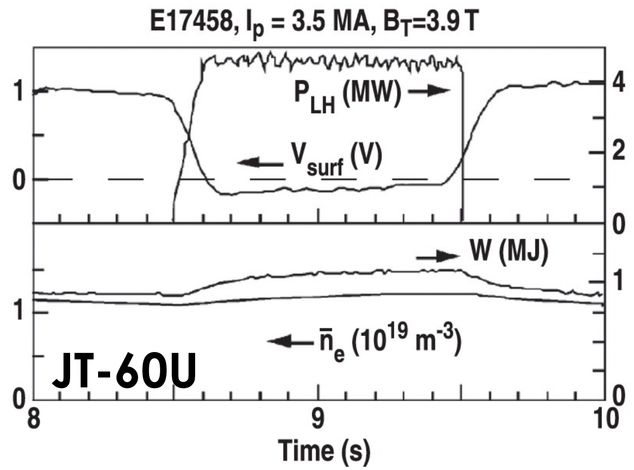
Electron Cyclotron RF
f<10-300 GHz
Gyrotrons

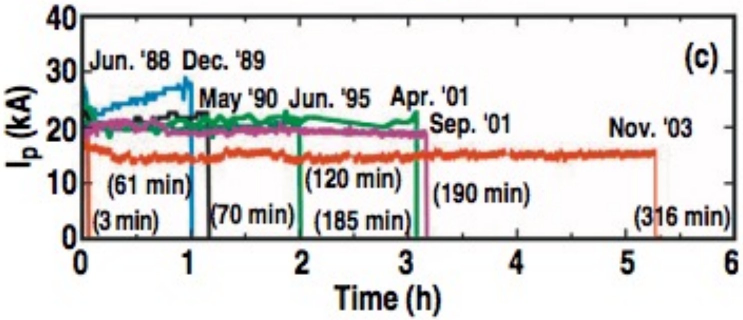
Lower Hybrid Current Drive the Most Successful Wave Current Drive to Date

- **Performance**
  - Current record: JT-60U fully non-inductive up to 3MA for one second
  - Energy record: Tore Supra 6 minutes 6 GJ

- **Pulse length**
  - TRIAM-1M at 1e18 m^{-3}, 6 T, 5 hours 16 minutes

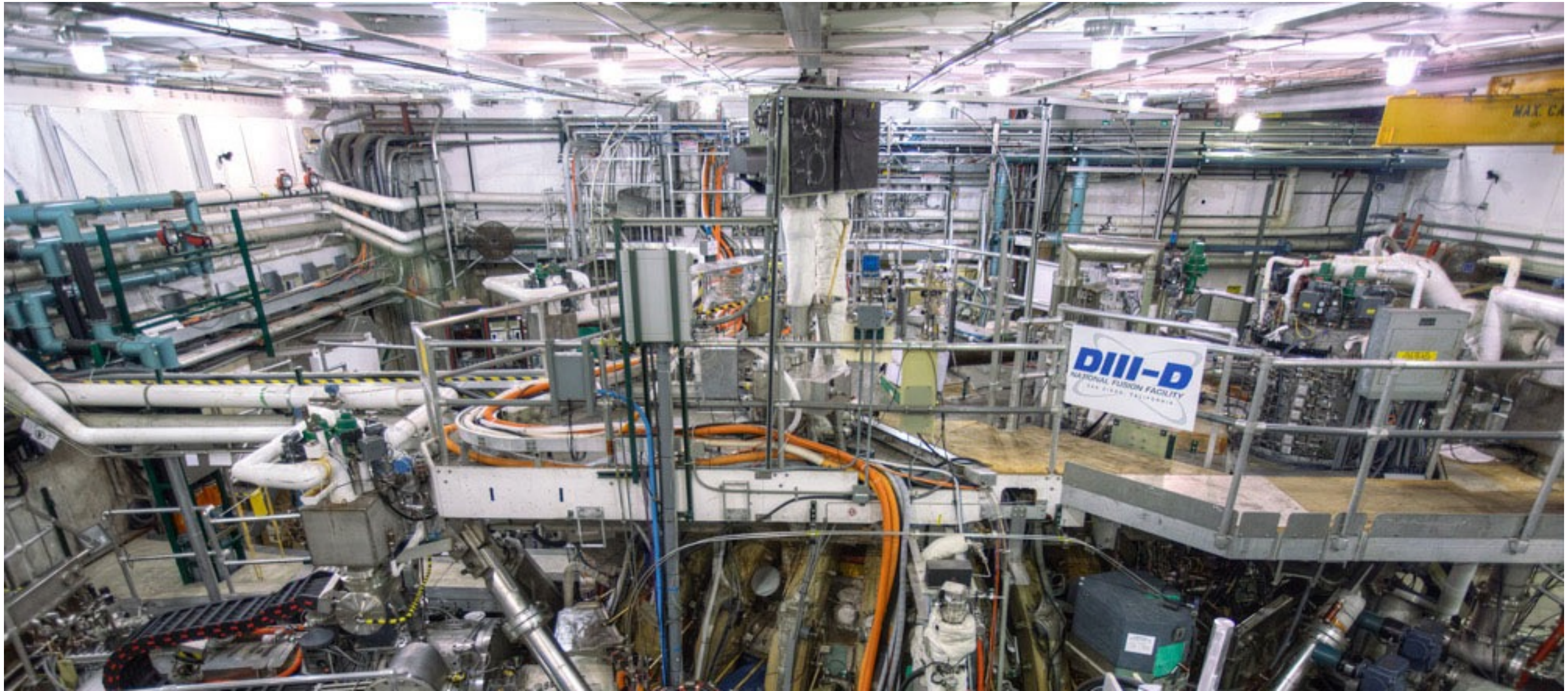
- **Plan is to use negative neutral beam injection, electron cyclotron, lower hybrid and ion cyclotron heating and current drive on an upcoming demonstration tokamak**



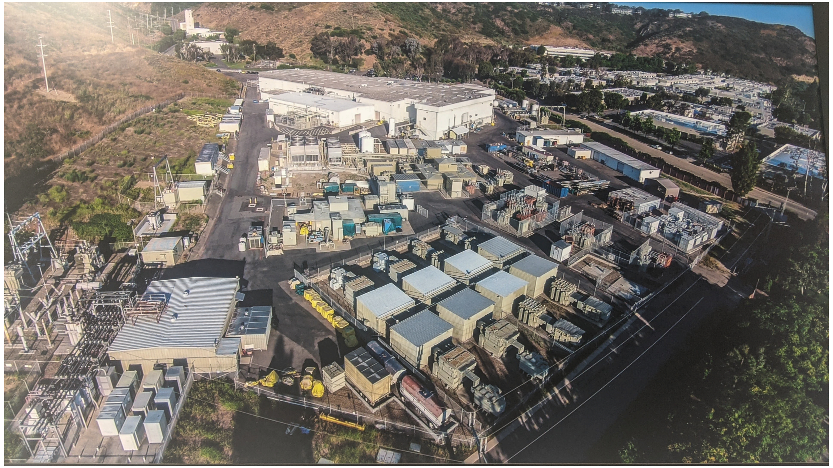


Tokamak is Only One Part of the Machine Hall!

Need: Diagnostics, Vacuum, Power Supplies, HV Power Supplies, Heating Systems, Gas Systems, Water Cooling, Computer Systems…etc. Requires a big team with many different skills (physicists, engineers, technicians, computer programmers, etc.)



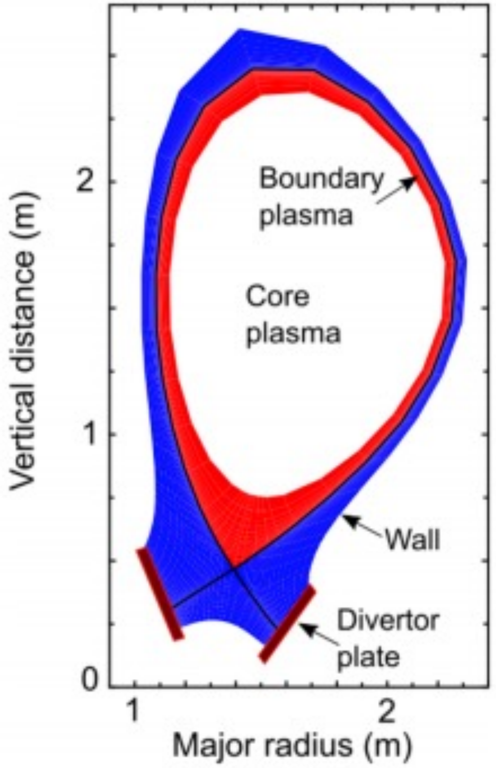
A Tokamak Site is Huge. There are a Bunch of Other Rooms too!



What are Some Active Areas of Research in Tokamaks?

- **Research somewhat broken up by location in plasma**
  - Core plasma
  - Black line is called the separatrix as well as last closed flux surface
  - **Boundary plasma inside of separatrix-called edge**
  - **Boundary plasma outside of separatrix-called SOL**

- **Many topics, some mentioned here, some described in other talks**

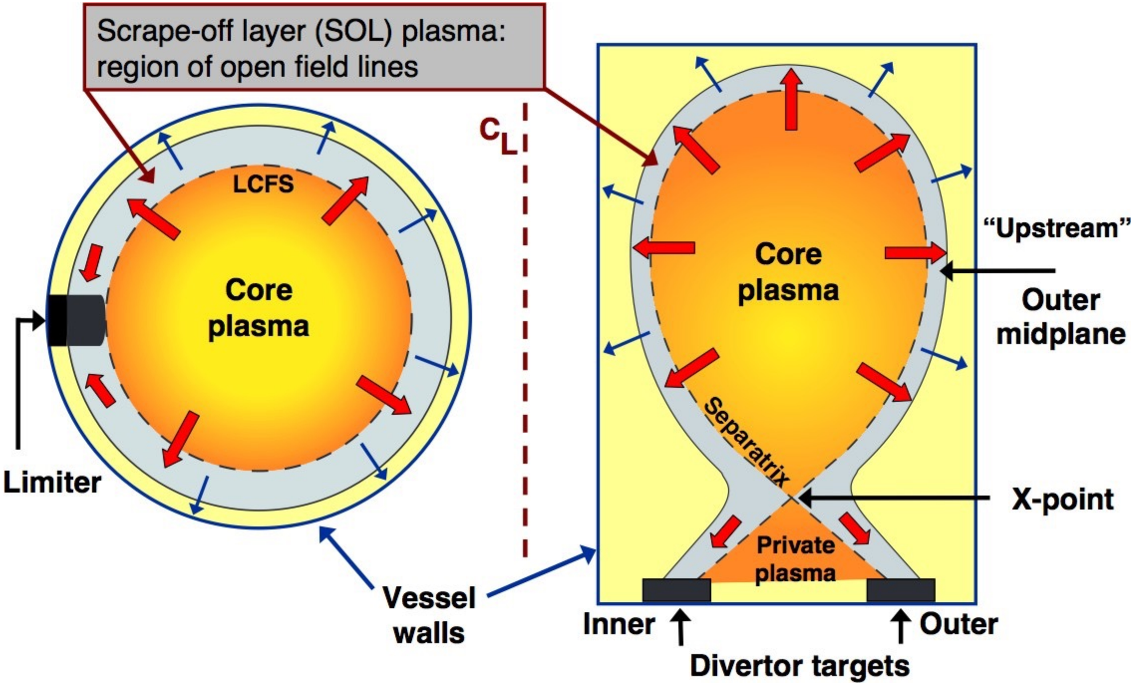


Two General Types of Magnetic Topologies

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

Divertor: magnetic structure is created to localize exhaust

- **Originally magnetic confinement experiments had limiters**
  - Better results with divertors!
  - Most experiments have divertors today
  - Particle control very important for performance

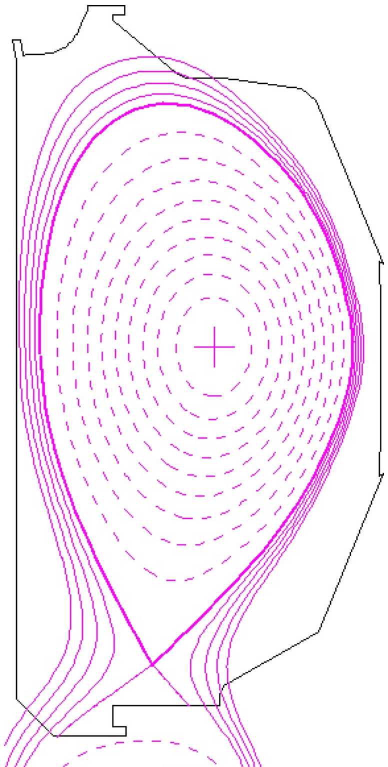


R. A. Pitts, "Tokamak edge physics and plasma surface interactions" 2007
crppwww.epfl.ch/~pitts/pitts/pitts_varenna_27_09_2007.pdf

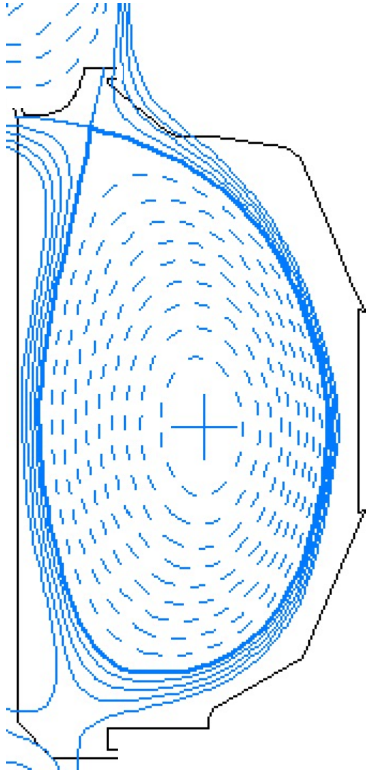
Many Types of Divertor Topologies

- **Originally magnetic confinement experiments had limiters**
  - Better results with divertors!
  - Most experiments have divertors today
  - Particle control very important for performance
- **Use external coils to create poloidal field nulls**
  - Single Null
  - Double Null
  - More complicated: Snowflake, Super-X etc

Lower single null



Upper single null

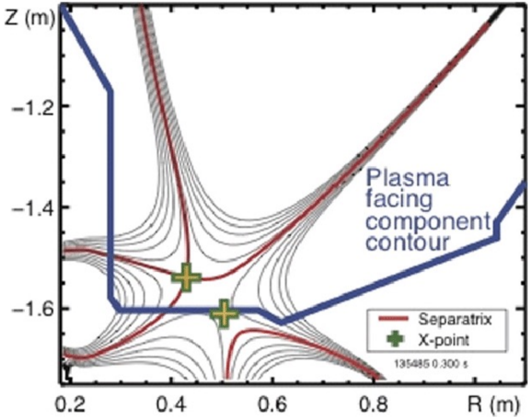


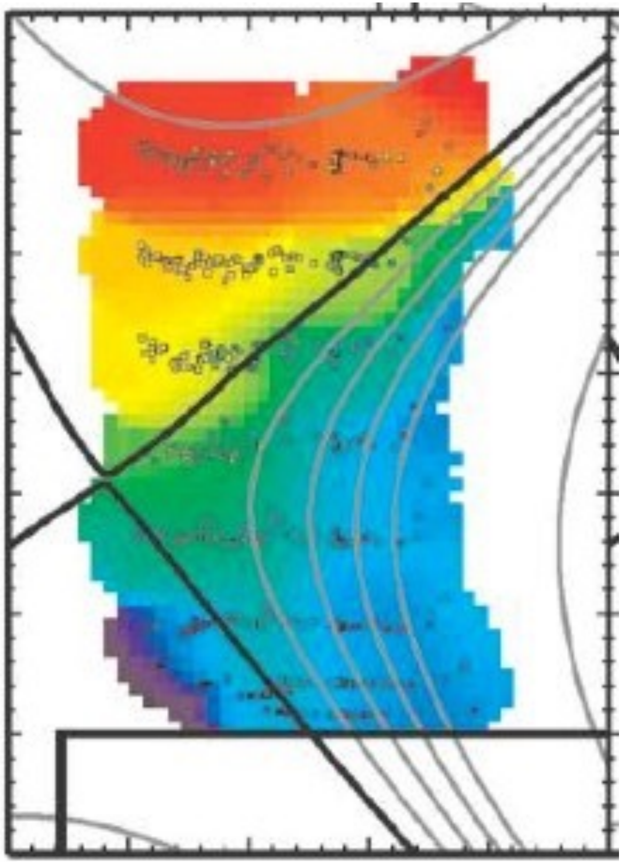
Narrow Heat and Particle Width Can Damage Divertor Plates

- **Many strategies to reduce divertor heat flux**
  - Detachment-raise density
  - Expand magnetic flux using snowflake and super-X configurations
  - Add impurities to increase radiation in SOL
  - Shaping the divertor baffle

- **Figuring out what materials to use for the divertor and other parts of the vessel is an active area of research**

Find out more tomorrow!





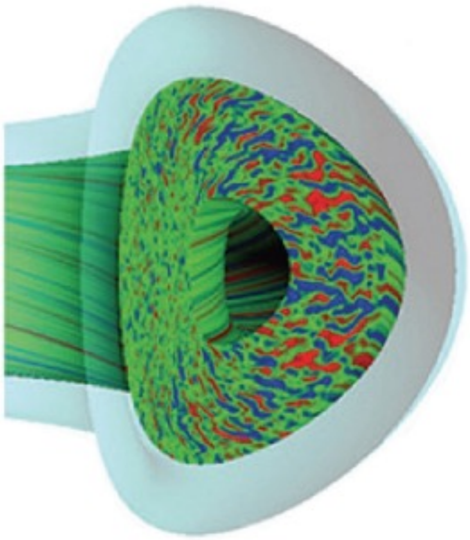
Transport: Need to Confine the Heat Put into the Tokamak

- **Heat you put in the plasma gets transported out!**
- **Study core, pedestal and SOL transport**
  - Confinement and transport are the same thing
  - Fluctuations likely responsible for transport are aligned with magnetic field
  - Want to minimize transport and turbulence
  - Different plasma regimes are governed by different transport
- **Transport of density, momentum and temperature are observed and they all depend upon each other**

$$Q_{th} = \frac{P_{fus}}{P_{heat}} = \frac{P^2 V}{PV/\tau} \propto < Pressure > I \left(\tau/_{I}\right)$$

Energy Confinement Time

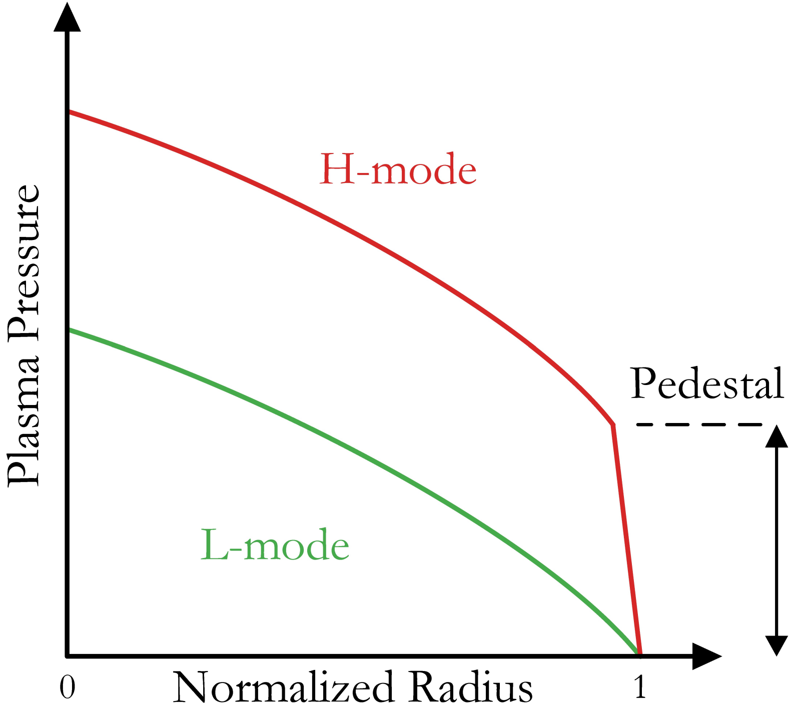
τ = Thermal Energy / P_{heat} $\propto I$ ← empirical



Transport: High Confinement (H-mode) Has Higher Plasma Pressure than Low Confinement (L-mode) Operating Regime

- **Low confinement (L-mode) is the baseline tokamak operating regime**
  - Linear T_e, n_e profiles
  - High levels of microturbulence
  - Not a viable regime for fusion reactors

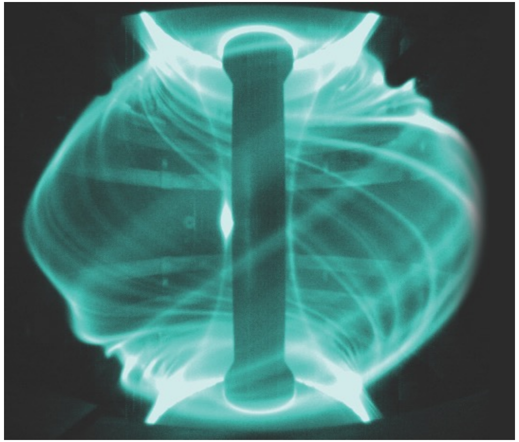
- **High confinement (H-mode) is reactor compatible**
  - Significant improvement in particle and energy confinement compared to L-mode
  - Formation of edge transport barrier



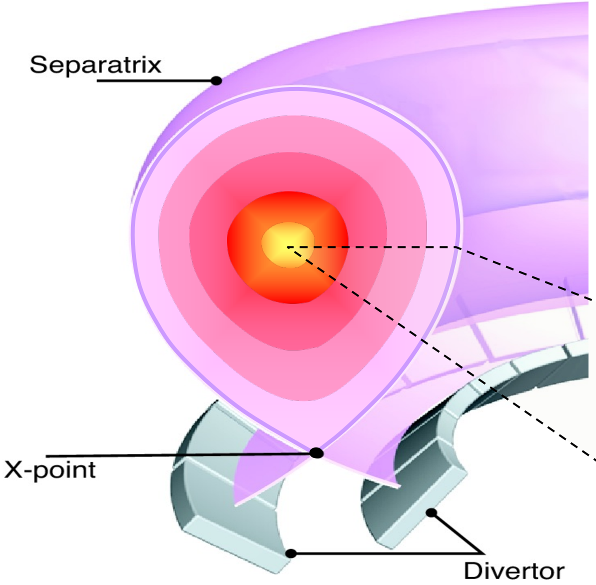
[1] M. W. Bongard, PhD Dissertation, UW–Madison, 2011.

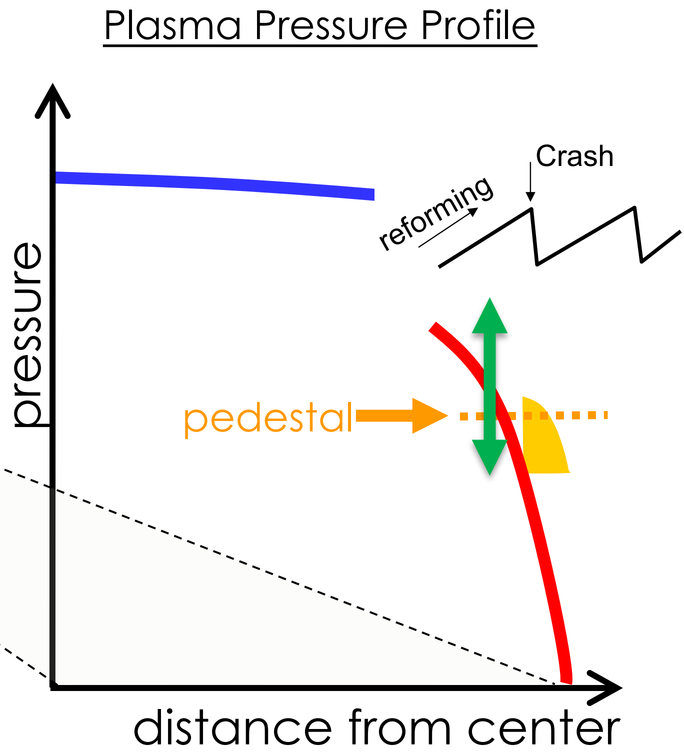
Pedestal: The Tokamak “Pedestal” Can be Locally MHD Unstable … Yielding an “Edge Localized Mode” (ELM)

Why are ELMs bad?
Because they dump energy too quickly and melt stuff
ELMs in a reactor would be a disaster



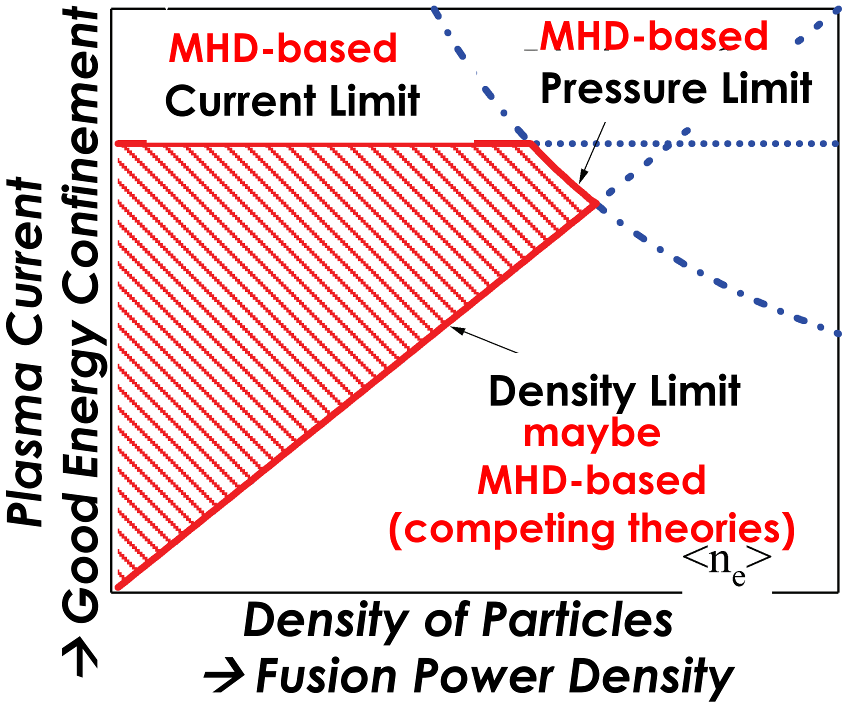
Courtesy: MAST / CCFE





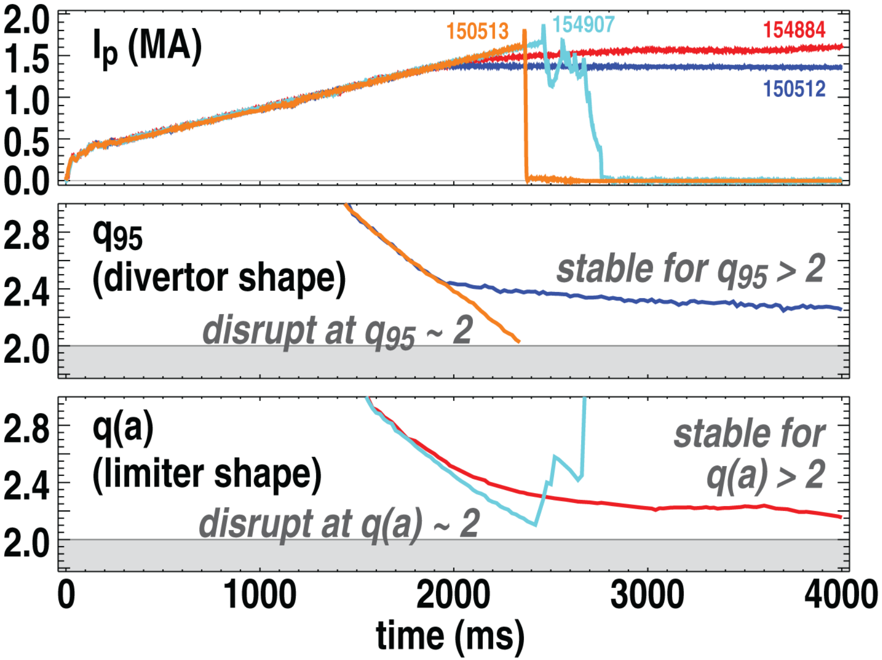
Stability: Want as Much Bang for our Buck but Need Stable Plasmas

Key Variables:
Magnetic Field, Pressure, Current

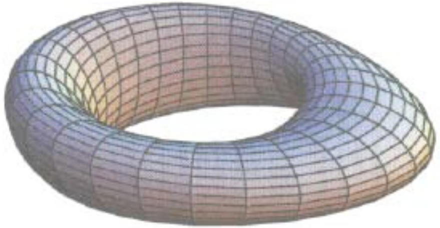


Stability: Current Limit is Set by Kink Instabilities

- Limit on magnetic field twist (q_{95}, q_{min})
- Can be overcome somewhat by active control

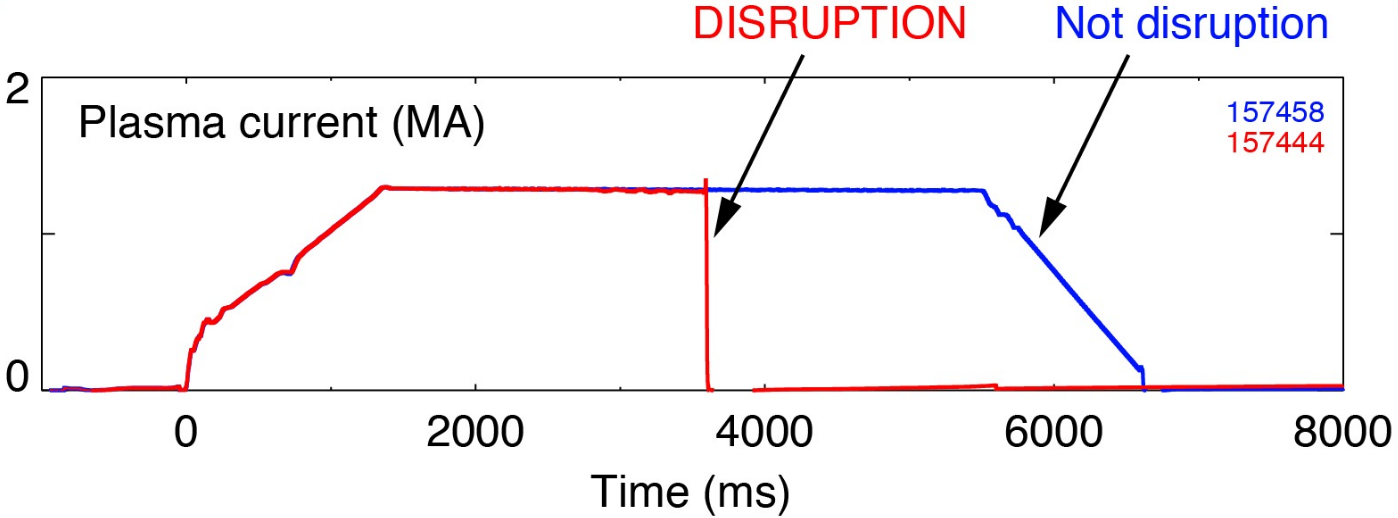


J. Hanson, APS-DPP 2013



"Disruption"

Stability: Disruptions are a Rapid and Complete Loss of Current and Energy



- **Three threats for a tokamak-possible disaster for a reactor**
  - Thermal Load: high heat flux to divertor
  - Electromagnetic forces
  - Runaway electrons

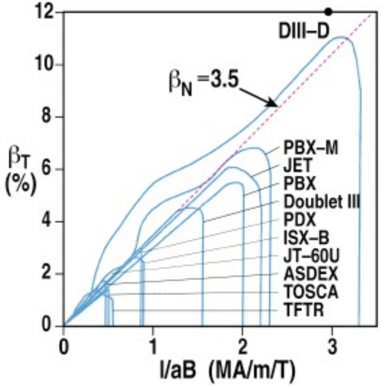
- **Need to avoid, backup plan mitigate disruption**

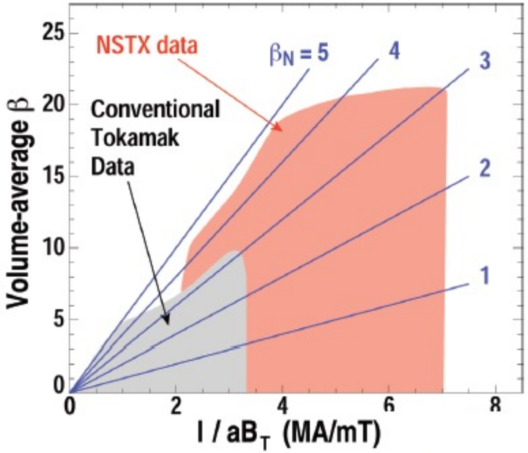
Stability: Tokamak Pressure Limits Follow Normalized Beta

- **Conceptually the plasma beta is as follows:**

$$\beta = \frac{\text{plasma pressure}}{\text{magnetic pressure}}$$

- **Typical values of β are only few %**
- **Low beta is more MHD stable**
  - … but lower pressure (less fusion) at constant magnetic field
- **Tokamak pressure often limited by long-wavelength kink modes**
  - Ideal MHD often limits max β_N to 3.5 on a conventional tokamak, higher on spherical tokamak!
  - Techniques to go above: optimized shape, optimized current profile, optimized pressure profile, wall stabilization
- **Developing accurate and quick (realtime) stability prediction models is needed**





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

Scenario: What Scenario will a Reactor Operate in?

- **Each tokamak has its own set of operating scenarios**
  - On DIII-D there are at least 8
  - Each scenario helps us understand the underlying physics a bit better

I-mode

EP H-mode

RMP ELM-Suppressed

Super H-mode

QH-mode

L-mode

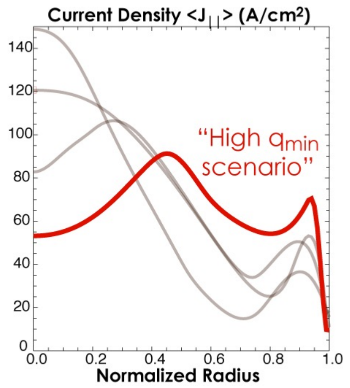
H-mode

Type I ELMs H-mode

EDA H-mode

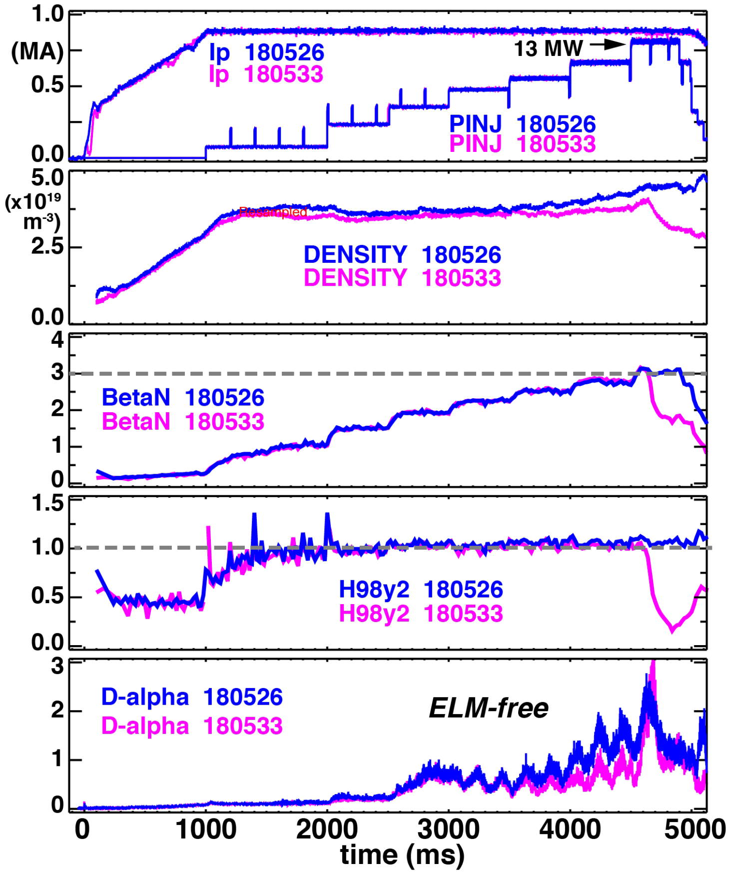
Type III ELMs H-mode

ELM-free H-mode

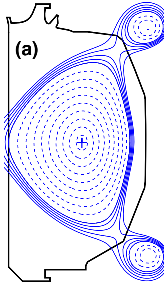


Scenario: Negative Triangularity Innovative Regime that might be Suitable for a Reactor

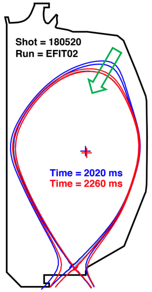
- **Negative triangularity predicted to not have good MHD stability in the late 80s**
  - TCV and DIII-D tokamaks have recently explored it and found better than predicted stability and other characteristics
- **Typically in L-mode with H-mode's good qualities**
- **NegD campaign summer 2022 with armor!**



Inner Wall Limited



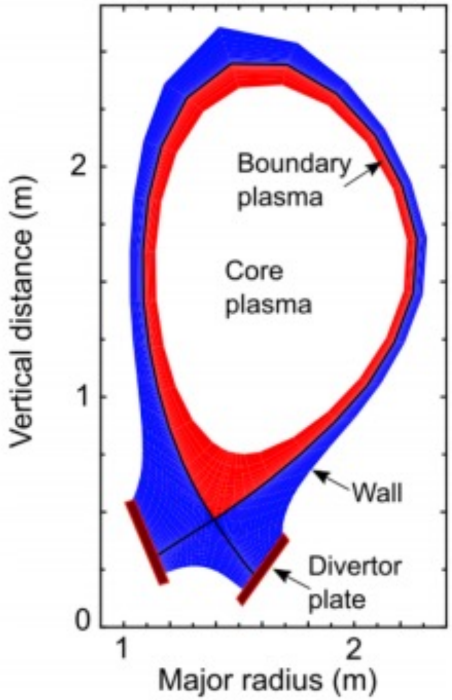
Diverted



See Austin **122** PRL 2019 115001, Marinoni **26** PoP 2019 042515

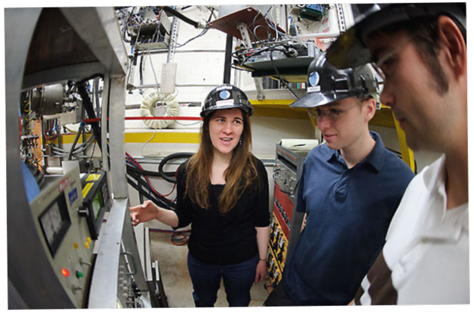
Core-Edge Integration Crucial for a Reactor

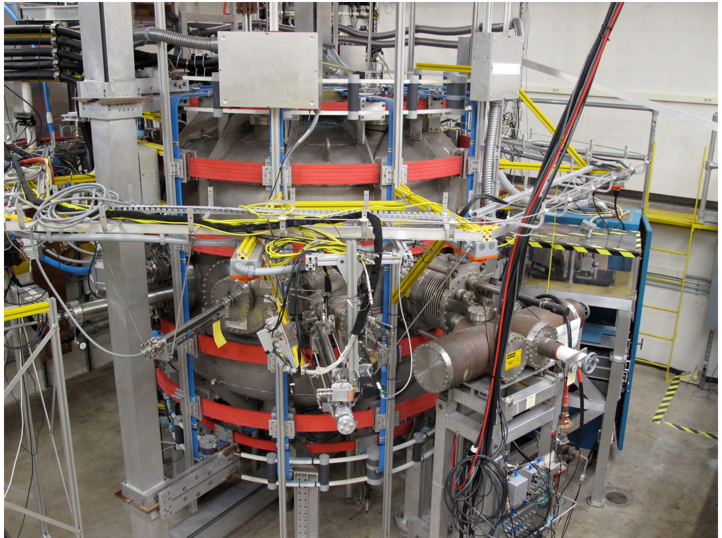
- **Competing requirements on core, pedestal and boundary plasma!**
  - Need to mitigate high boundary heat flux but also maintain confinement
  - Often mitigation ruins confinement
  - One technique is a high pedestal height
  - Also need ELM control!
    - ELM control can also damage confinement
    - Sometimes not compatible with high-performance cores



There are Many Tokamaks in the U.S. that You Could Work On!

- **Currently two bigger facilities: Princeton Plasma Physics Laboratory (Princeton, NJ) and DIII-D National Fusion Facility (San Diego, CA)**
  - At PPPL LTX and NSTX-U
  - A few universities have tokamaks: Pegasus III (University of Wisconsin-Madison), HBT-EP (Columbia University)
  - Many universities have collaborations with PPPL and DIII-D and have on-site grad students
    - Click through the list of schools [here]() and ask around



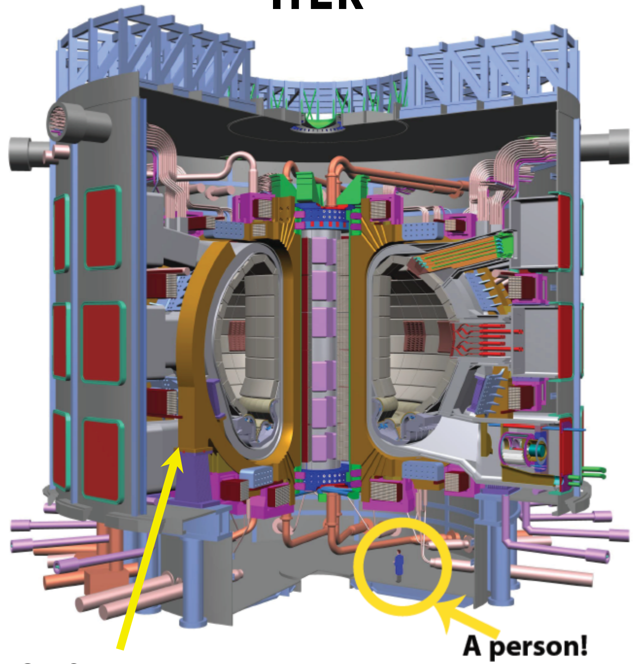


The Biggest Tokamak Ever is Being Built Right Now in France

- **ITER: “the way” in Latin**
  - Huge international partnership
  - Different countries are building different parts of the machine
  - First plasma in 2025!

- **ITER’s mission is to demonstrate fusion energy at an industrial scale**
  - Q = 10, 10x power out than put in
  - 500s pulses!
  - Find out more at iter.org

“ITER”



-270°C
magnets

150 million °C
plasma

Partnership between U.S., EU, Japan, Russia, China, Korea and India

The Biggest Tokamak Ever is Being Built Right Now in France

Largest scientific experiment ever built

Construction towards 1st plasma is 73% complete

It's an Exciting Time for Fusion in the U.S.!

- **Two new tokamaks have been proposed!**
  - SPARC from Commonwealth Fusion in Massachusetts, in collaboration with MIT will have 12T magnets! Magnets currently under construction
  - EXCITE (EXhaust and Confinement Integration Tokamak Experiment) recommended by National Academies and Community Planning Report to close the ITER gap

Powering the Future
Fusion & Plasmas
A long-range plan to deliver fusion energy and to advance plasma science

Conclusion: Tokamaks are the Leading the Charge for Magnetic Confinement Fusion Energy

- Tokamaks have a helical magnetic field from external coils and a driven toroidal current

- There are many active areas of study in a tokamak from the core to the divertor

- It's an exciting time to be doing tokamak research with ITER coming online soon and two new tokamaks proposed in the U.S.