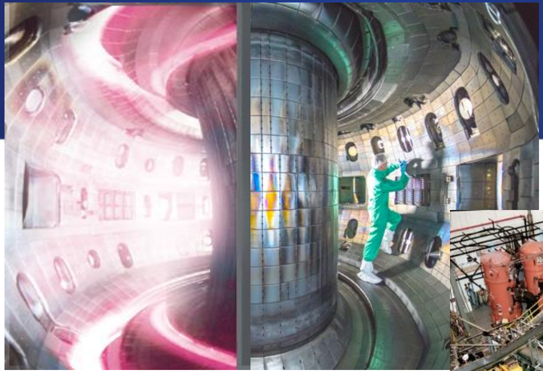
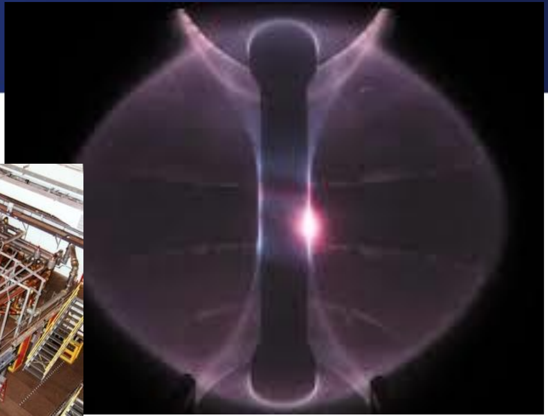
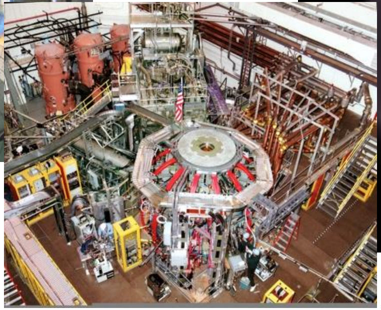
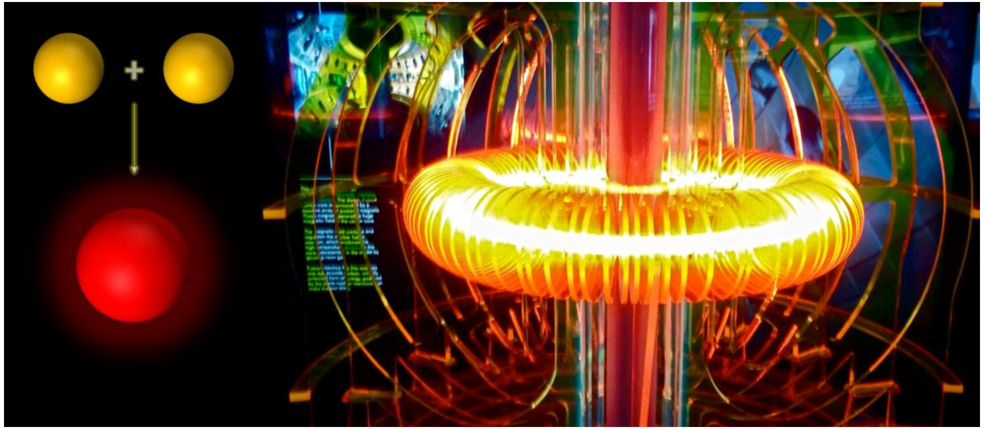
Tokamaks

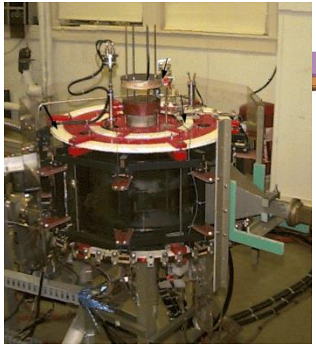


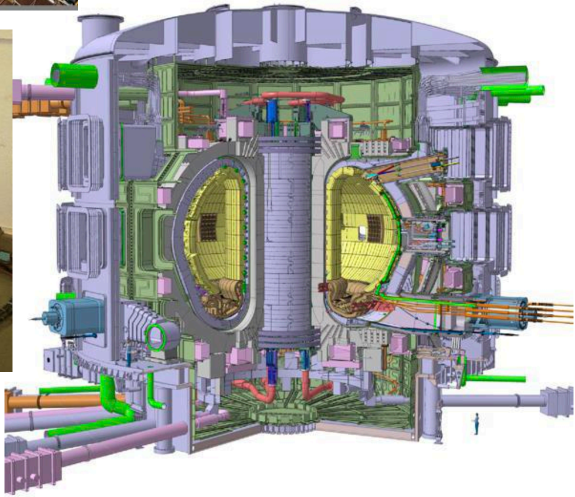


by
Kathreen E. Thome









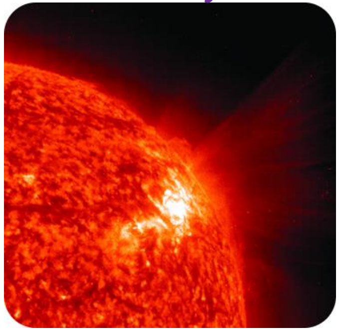
Presented virtually at the
2026 Intro to Fusion Energy and Plasma Physics Course

June 4, 2026

GENERAL ATOMICS

My Fusion Journey So Far!

10^{th} grade Chemistry class



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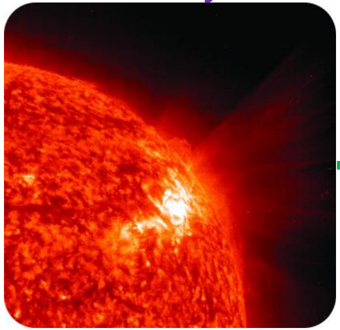

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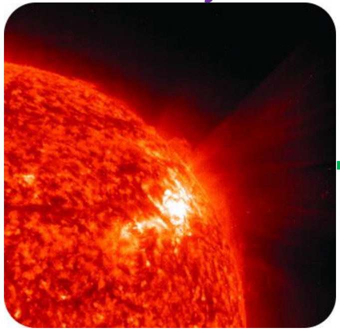

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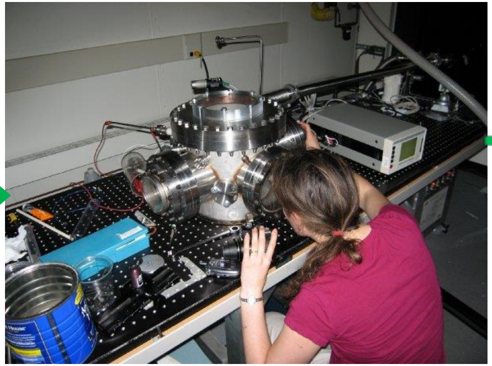

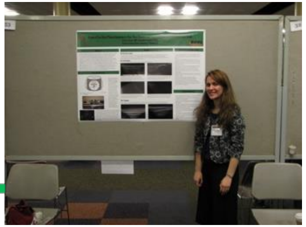

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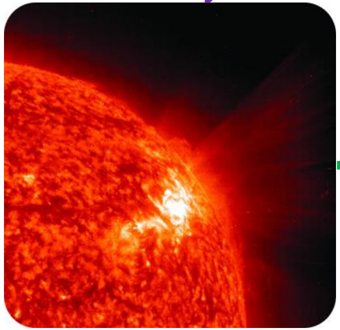

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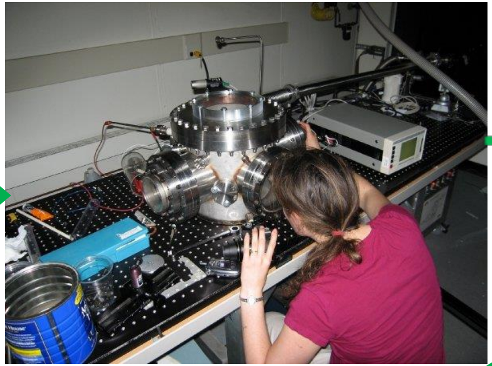

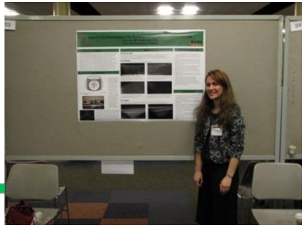

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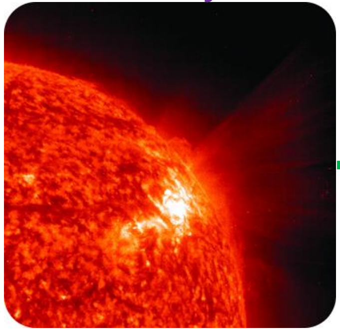

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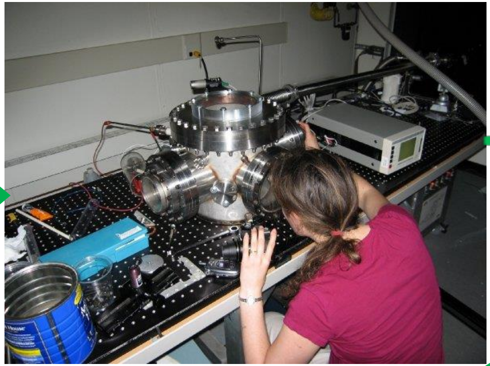

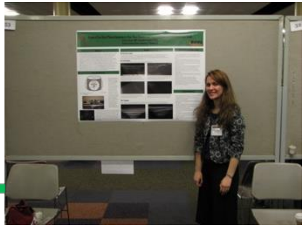

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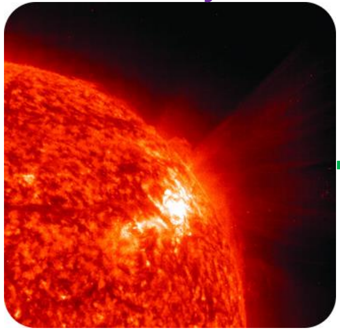

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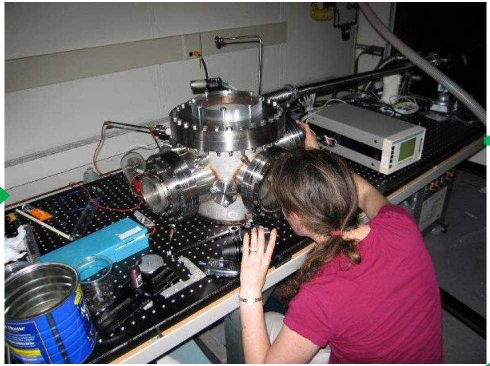

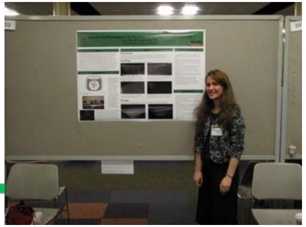

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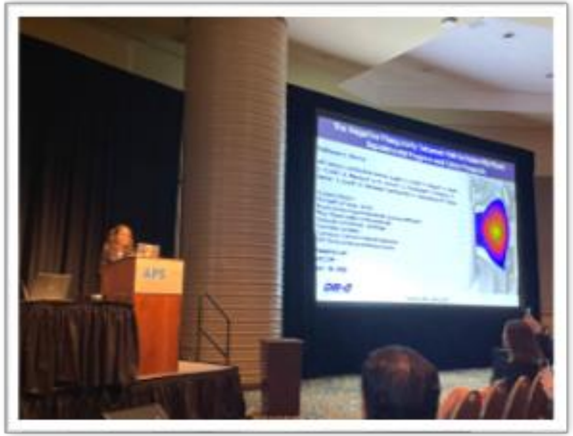
DIII-D for my postdoc

Staff Scientist at General Atomics since 2018!

What Do I Do in My Job?

- Run experiments and help others run experiments as a DIII-D physics operator!
- Conduct, lead and present research in negative triangularity!
- Serve as PI for a group of GA scientists conducting research in spherical tokamaks on NSTX-U (PPPL) and MAST-U (UKAEA)




Outline

- **Introduction to MFE**
- Tokamak History
- How Does a Tokamak Work?
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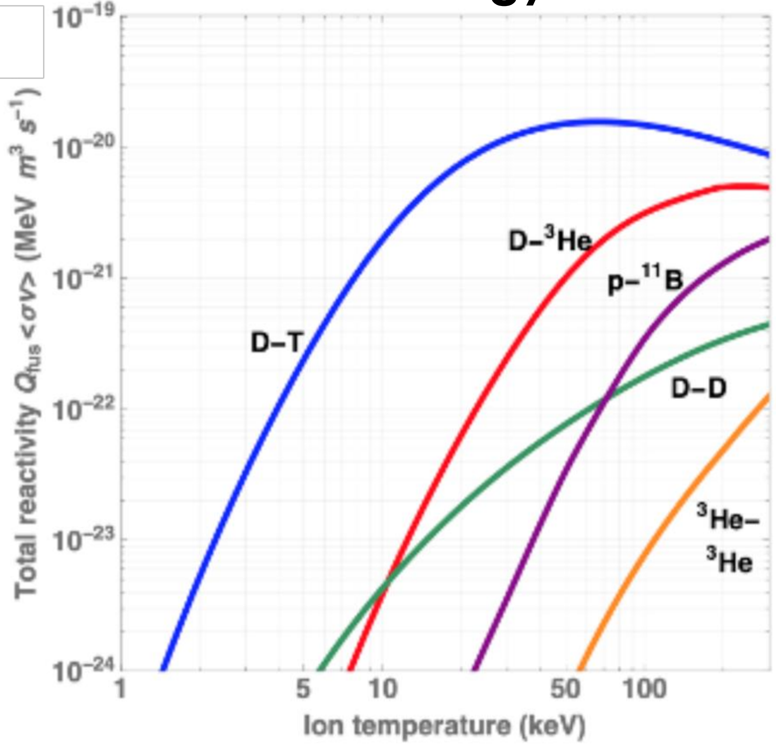
Deuterium-Tritium Fusion Occurs at the Lowest Temperatures

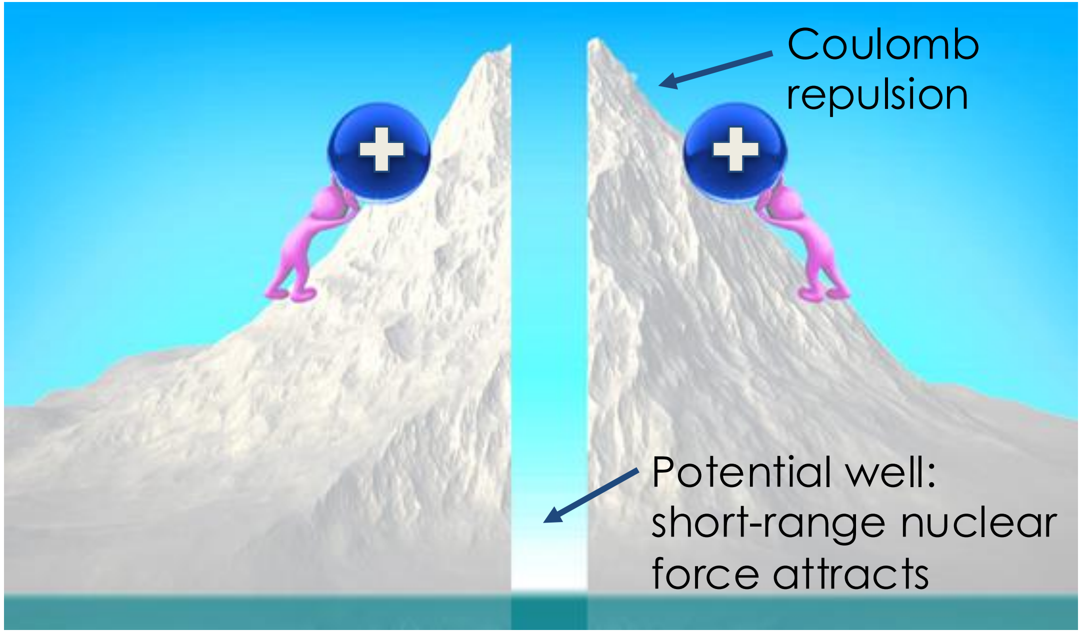
Reaction cross section times total energy released



- **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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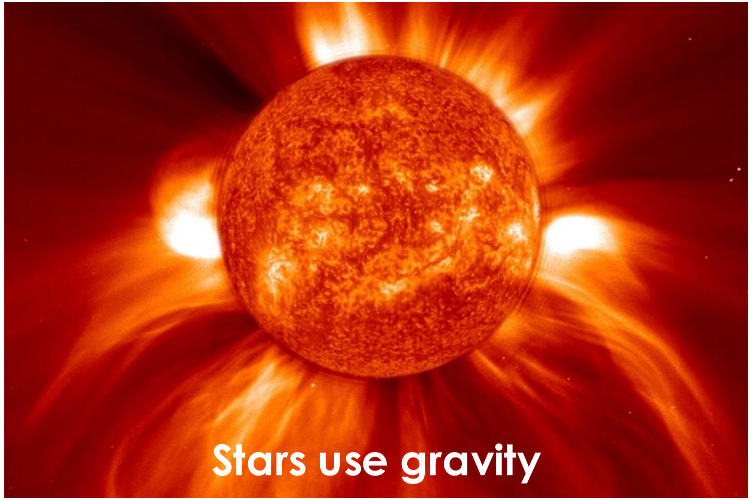

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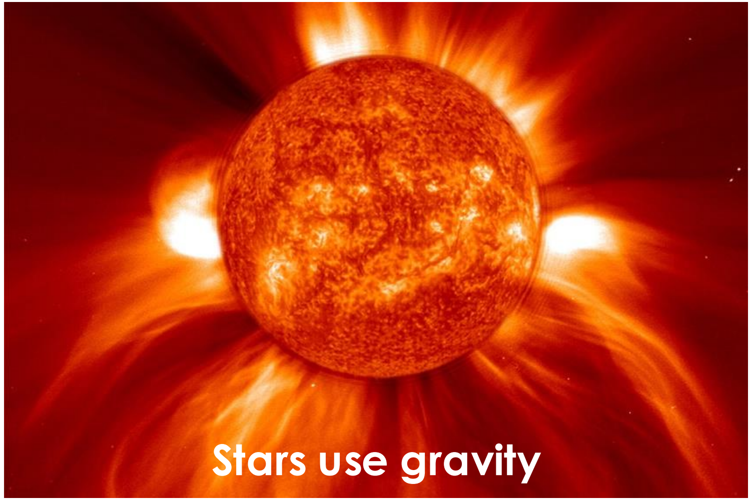
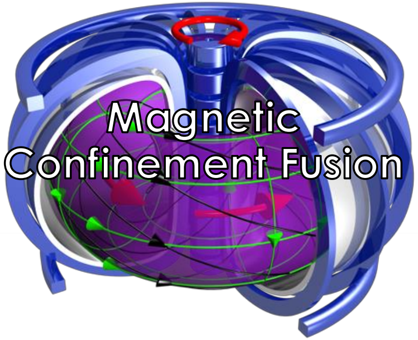
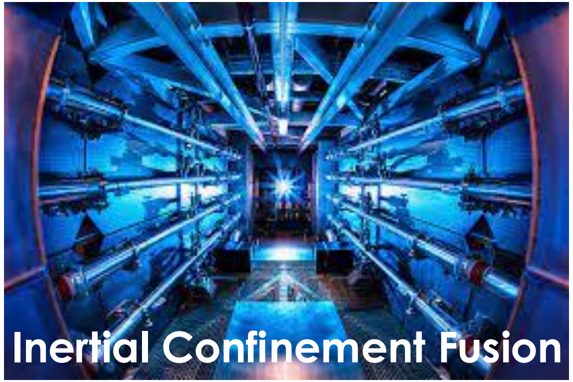


Magnets



Inertia via compression



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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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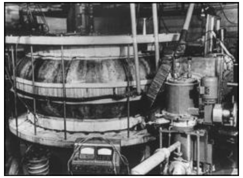

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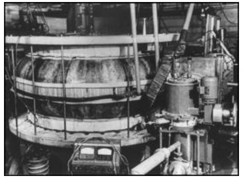

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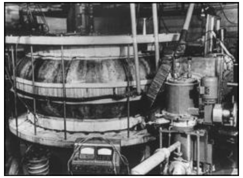

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Fusion is harder than we thought… losing too much energy

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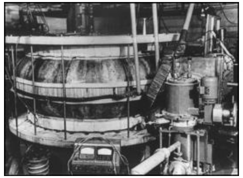

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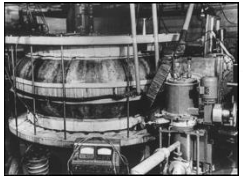

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British confirm 1 keV temperature on T3 using Thomson scatting

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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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W…

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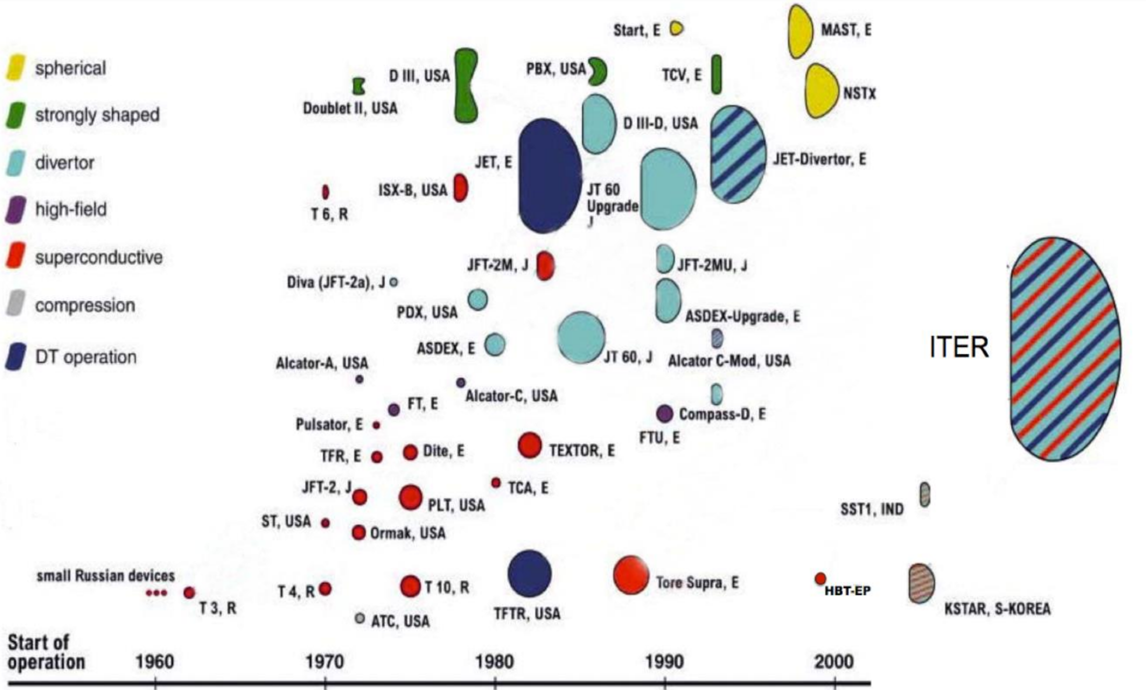

…68

…viets announce they …ve achieved 1 keV …T3 tokamak, 10x …gher than any other …eriment – the world …eptical

…nt…

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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

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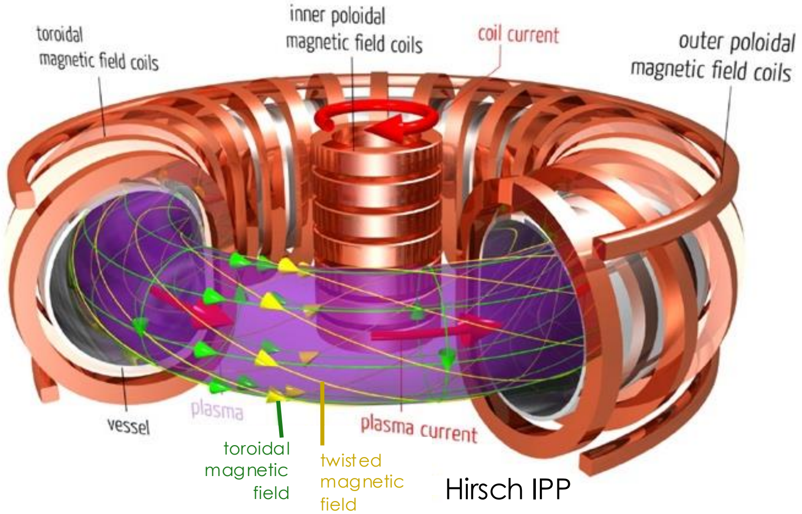
Tokamaks Utilize Both External Coils and Driven Toroidal Current to Produce Magnetic Fields

- **Toroidal coils provide the strong confining field**
  - Plasma current and poloidal coils add the helical twist



Hirsch IPP

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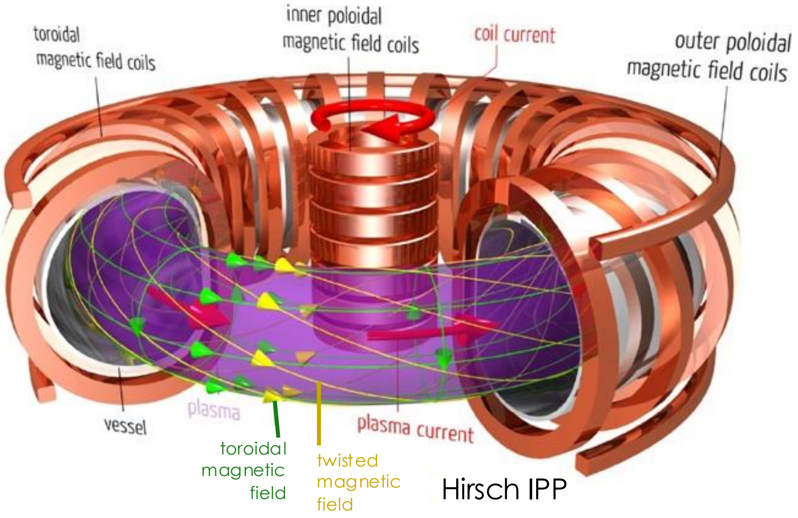
- **Poloidal coils determine cross-sectional shape**
  - Early tokamaks all had nearly circular cross-sections
  - Non-circular cross-sections began to be explored in 1970s-1980s
  - 1980s: MHD modeling predicted advantages for non-circular cross-sections + Dee shape matched optimized magnetic designs



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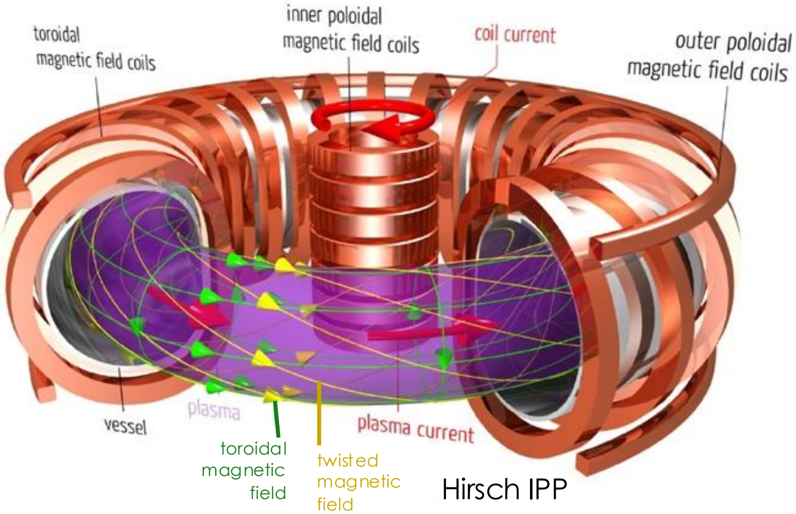

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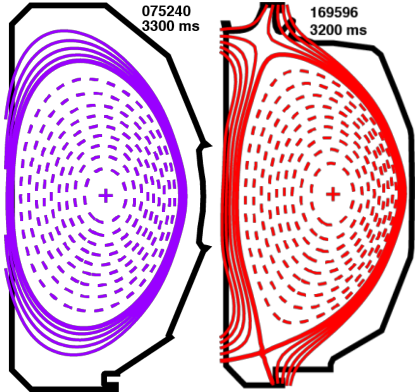
- **Two types of magnetic topologies**
  - **Limited**: last closed flux surface (LCFS) defined by solid surface (limiter)
  - **Diverted:** LCFS defined solely by magnetic field, requires extra coils



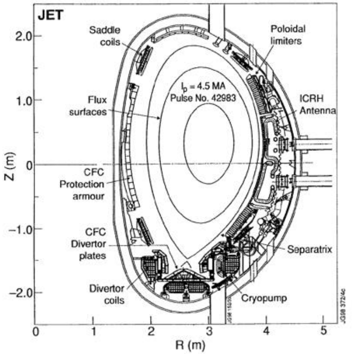
A Fusion Reactor Needs A Sustainable Scenario Not Just High Performance

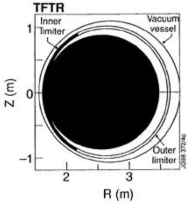
- **Tokamaks have numerous scenarios with different pressure and current profiles**

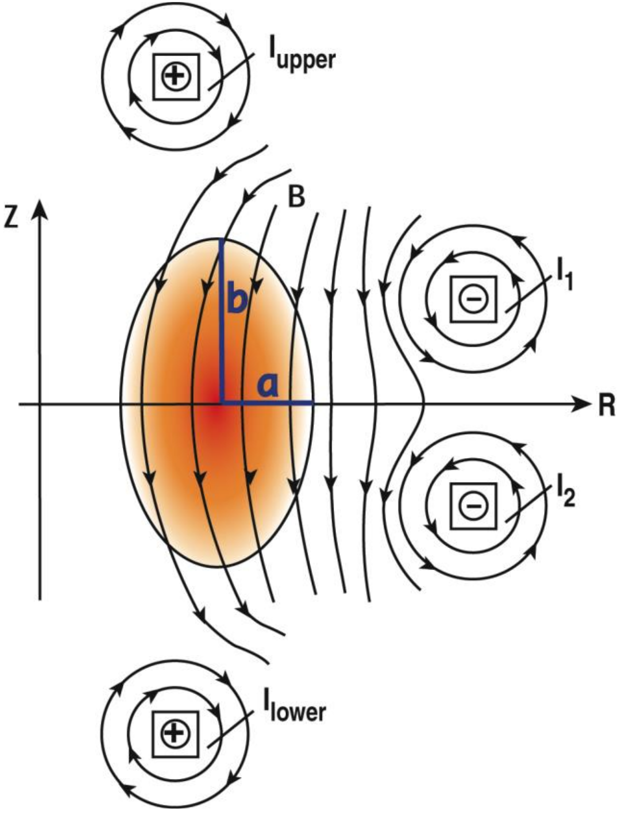
- **Achieving high performance is critical to meeting the Lawson criterion and reducing cost**

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***





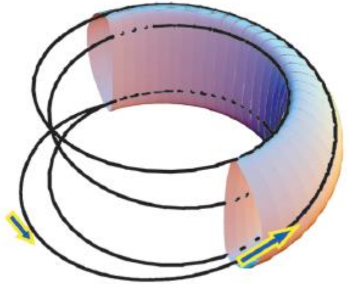


Courtesy M. Walker, GA

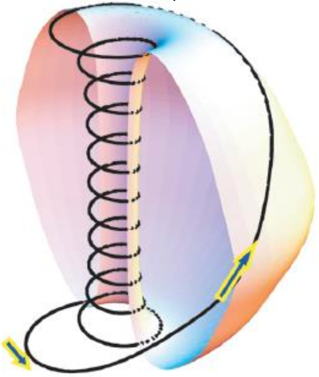
Two Types of Tokamaks: Conventional Aspect Ratio and Spherical Tokamaks

- **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!**

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



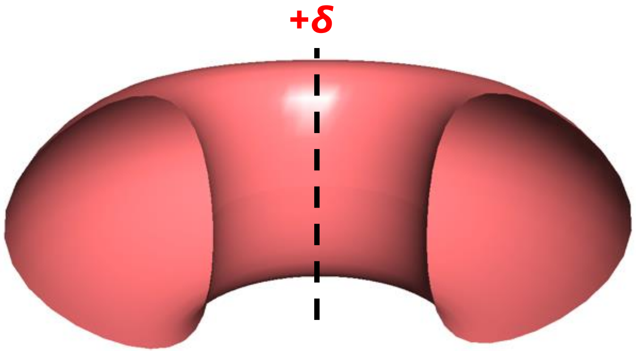
$A \geq 1.25,\ q_\psi \geq 12$



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

PT (+δ) is the Conventional Tokamak Poloidal Cross Section

- δ is used to define poloidal cross-section triangularity



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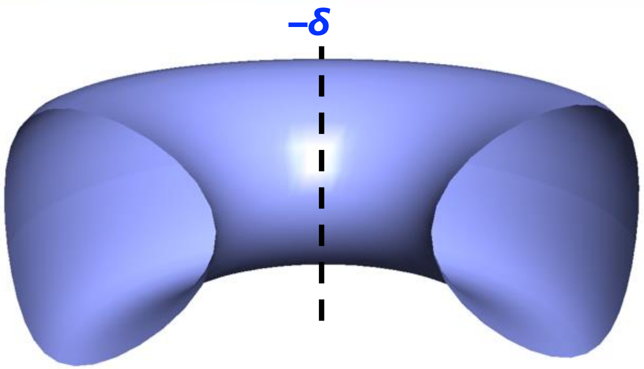
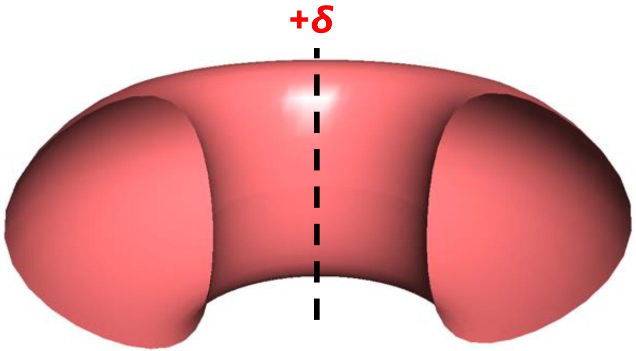
- *δ* is used to define poloidal cross-section triangularity

- **Negative triangularity (NT) (–*δ*)** is a plasma shape where the highest elongation is on the large R_{maj} side of the magnetic axis, making an inverted-D





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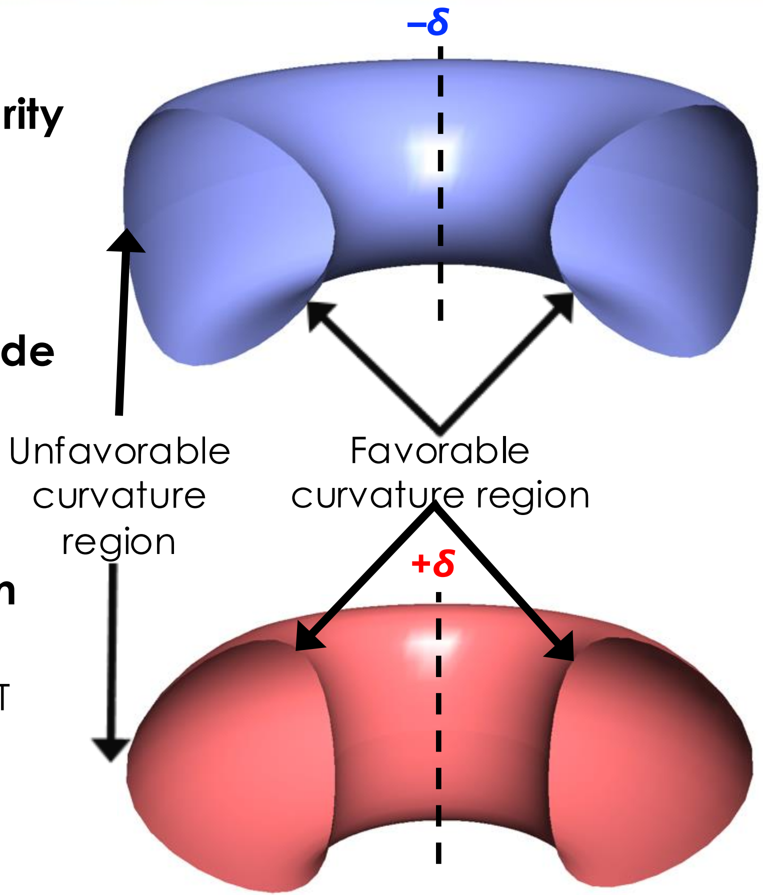
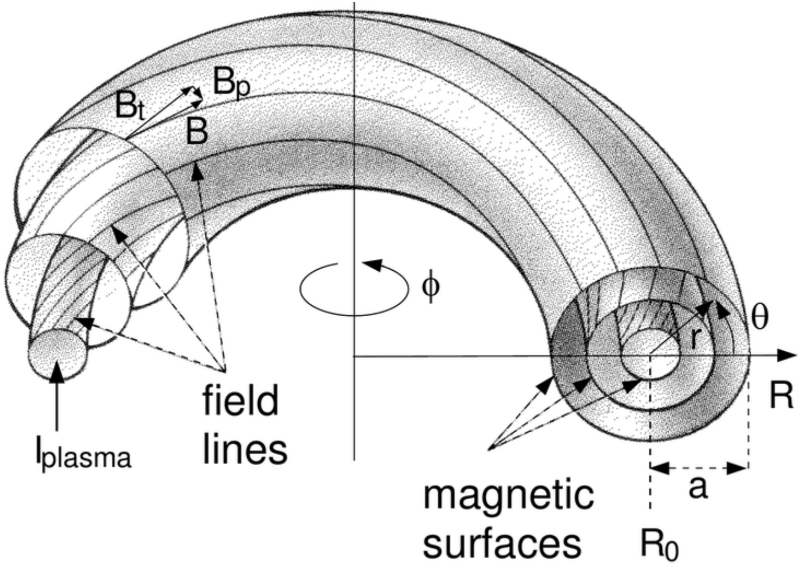
- **δ is used to define poloidal cross-section triangularity**
- **Negative triangularity (NT) (–δ) is a plasma shape where the highest elongation is on the large R_{maj} side of the magnetic axis, making an inverted-D**
- **The inner surfaces is the favorable curvature region and the outer surfaces the unfavorable region**
  - NT has more particles in the unfavorable region than PT



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***

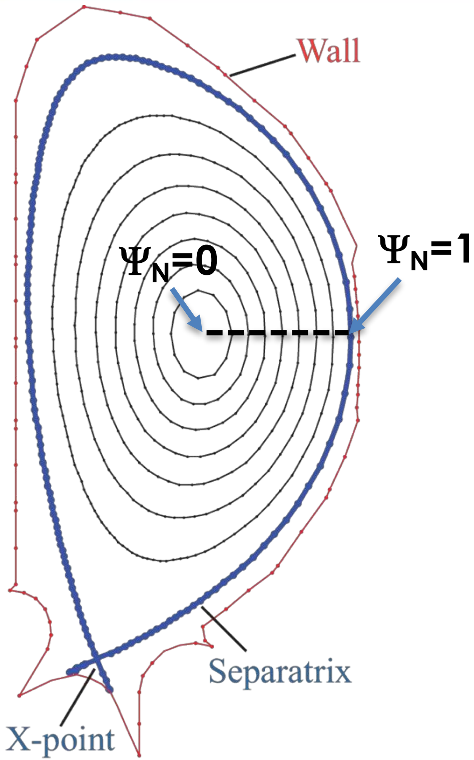
Axisymmetric Toroidal Equilibria are Described by the "Grad Shafranov" Equation[1,2]

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

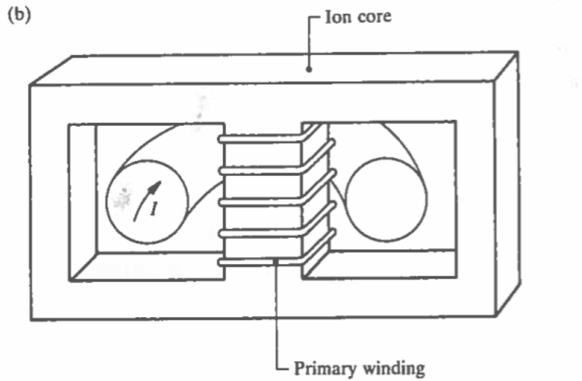


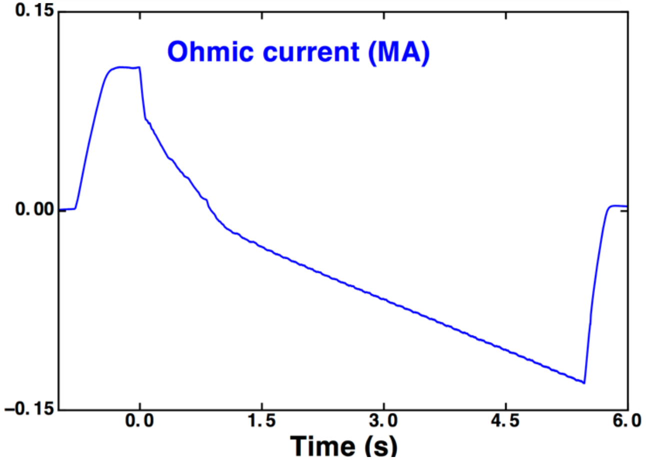
ITER Equilibrium

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)

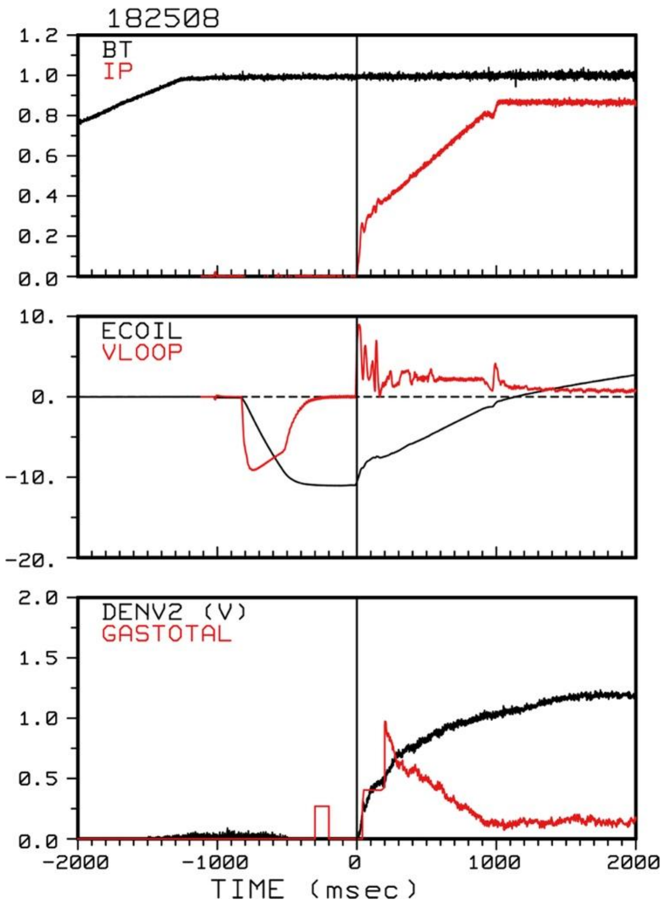
Toroidal Current must be Sustained in a Tokamak

- **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

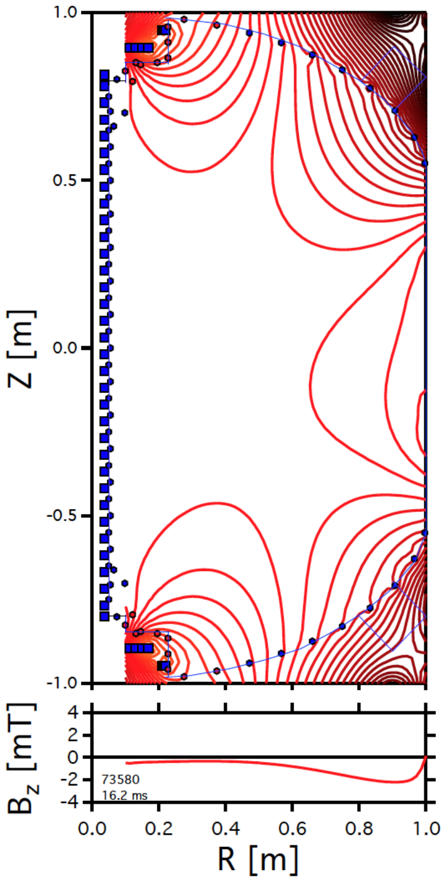




How do you Ohmically Startup a Tokamak?



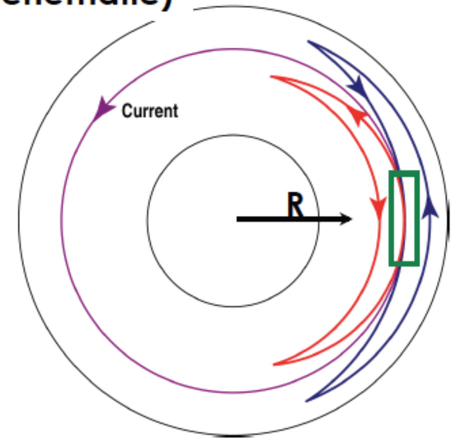
- **Maximize volume of poloidal field null**
- **Gas puffing ('prefill')**
- **Reverse bias on ohmic primary**
- **Paschen minimum**
- **Create closed flux surfaces, grow the plasma**



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)

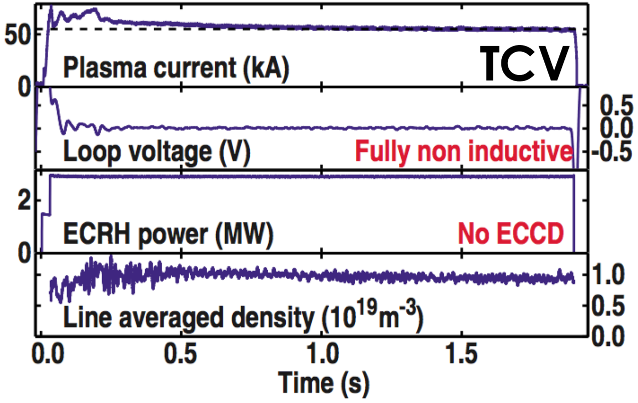


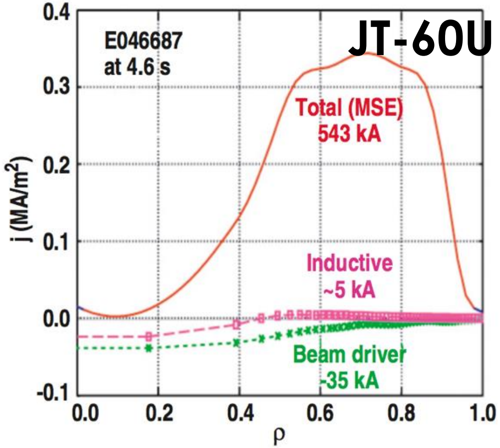
Luce et al PoP **18** 030501 (2011)

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

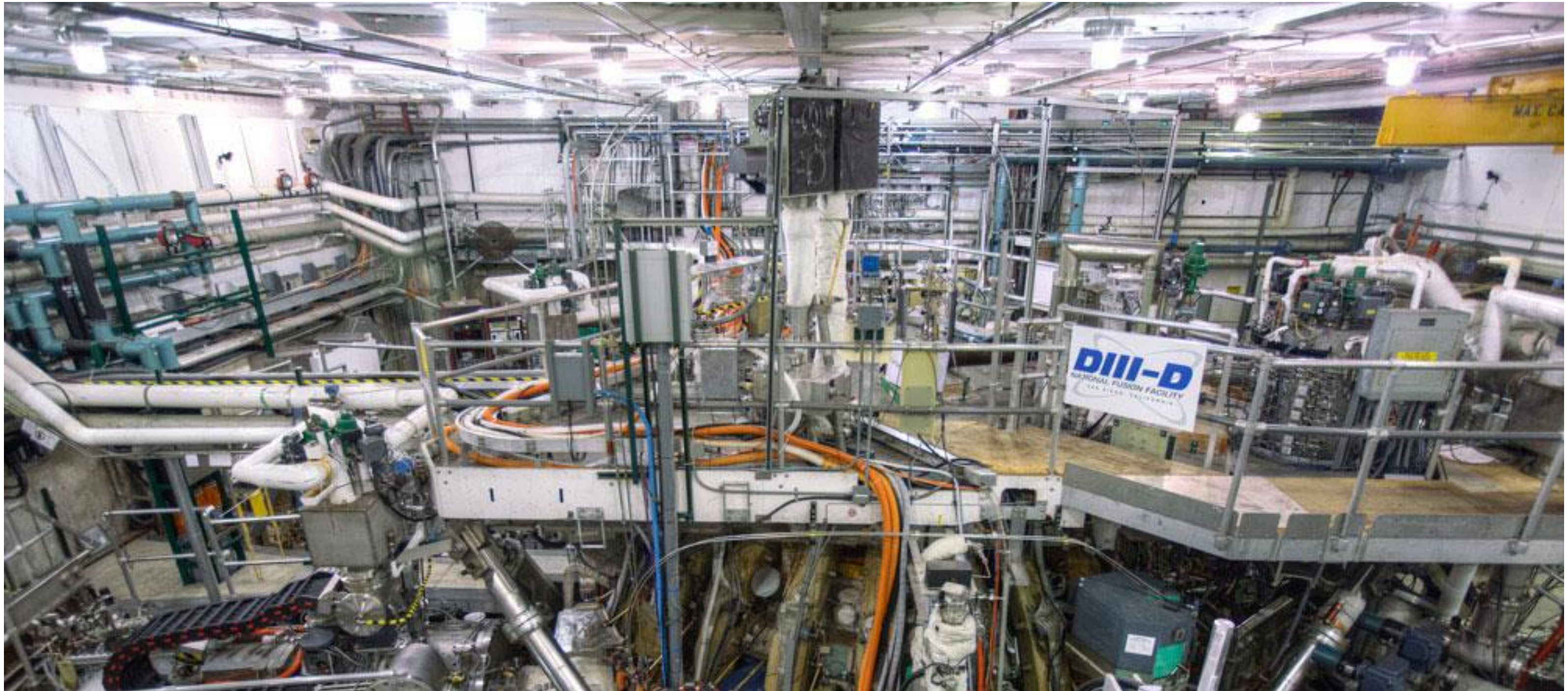
- ITER Physics Basis: "Steady state operation of the tokamak requires that at least 20% of the plasma current is provided by an external source"
  - Learn more tomorrow!



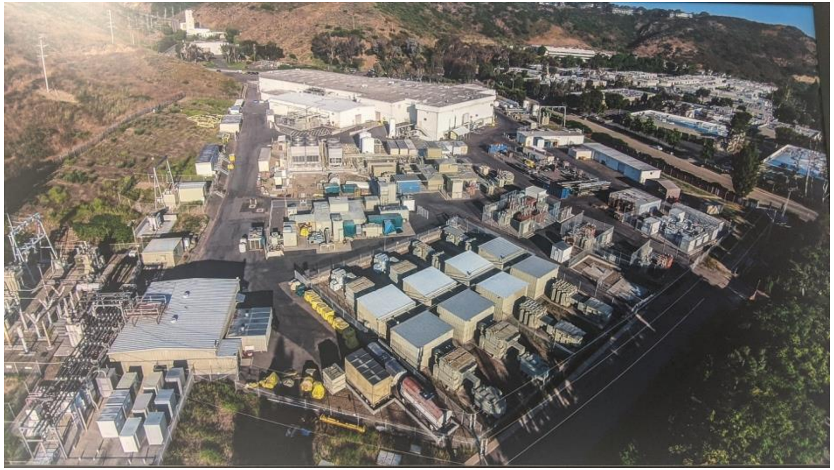


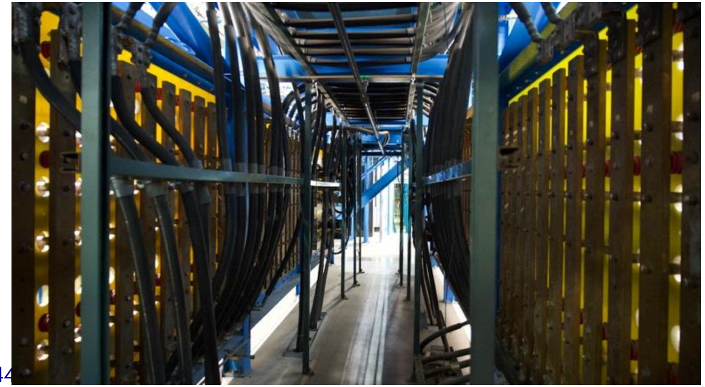
Tokamak is Only One Part of the Machine Hall!

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!





How do you Make a Tokamak Plasma and Conduct an Experiment?

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At the same time, try to not break anything….
Power supplies, computers, diagnostics, heating systems, vacuum, etc

Outline

- Introduction to MFE
- Tokamak History
- How Does a Tokamak Work?
- **Sustainable Tokamak Reactor Scenario**
- What Tokamaks are There?
- Conclusions

A Fusion Reactor Needs A Sustainable Scenario Not Just High Performance

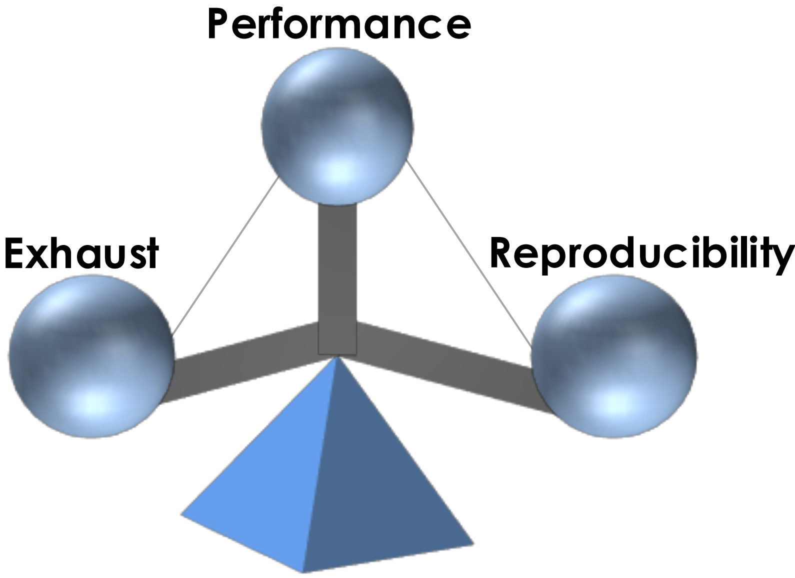
- **Tokamaks have numerous scenarios with different pressure and current profiles**

- **Achieving high performance is critical to meeting the Lawson criterion and reducing cost**

- **However, a reactor must also achieve, simultaneously:**
  - **Exhaust**: Appropriate particle and heat exhaust fluxes within material limits
  - **Reproducibility**: A reproducible, reliable plasma sustained for a sufficiently long time that is easily accessible

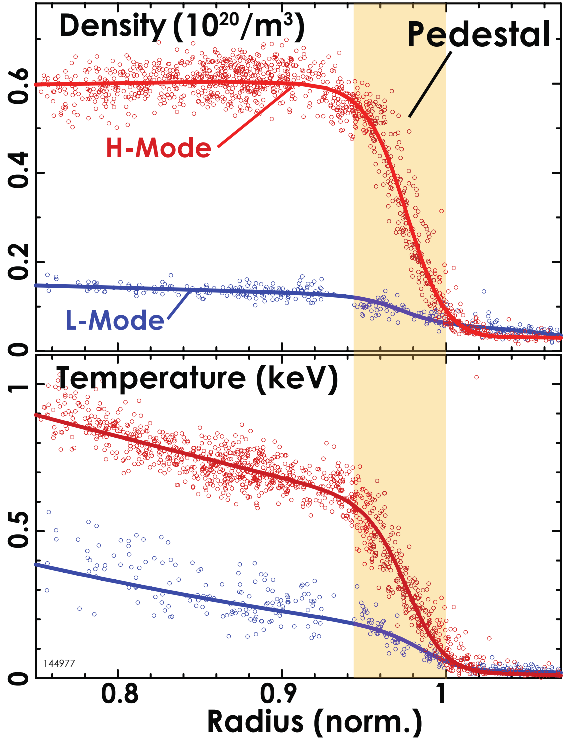
- **Existing tokamak scenarios have made substantial progress toward these goals, but a fully reactor-compatible regime has not yet been achieved**

Sustainable Reactor Scenario



Two General Types of Performance Regimes in Tokamaks

- **Low confinement (L-mode) is the baseline operating regime with linear profiles and high levels of microturbulence**
- **In PT, High confinement (H-mode) occurs when sufficient power is applied above a power threshold**
  - Discovered in 1982 on ASDEX[1]
  - Usually achieved in a diverted configuration
  - Edge transport barrier ("pedestal") forms that allows significant improvement in particle and energy confinement compared to L-mode (usually **2x**)
  - Many different types of H-mode scenarios
- **Last 40+ years of tokamak research have focused on H-mode and it is the planned regime for most tokamak fusion reactors**



[1]Wagner PRL 1982

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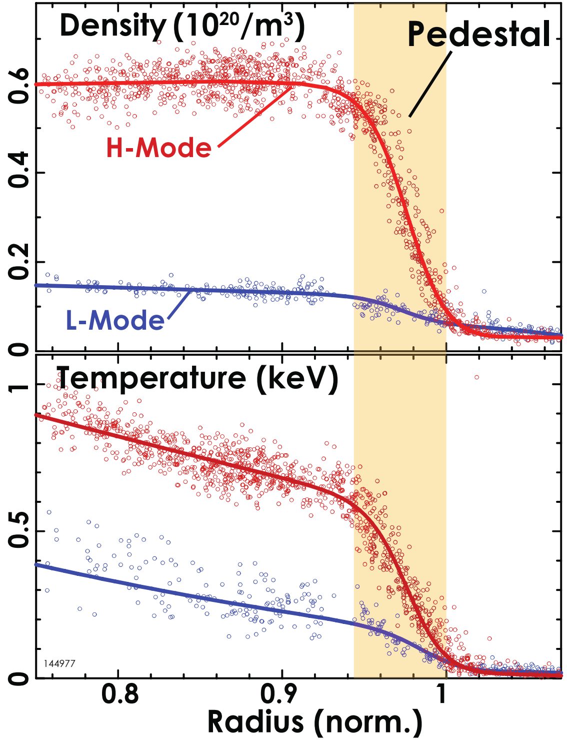
- **Last 40+ years of tokamak research have focused on H-mode and it is the planned regime for most tokamak fusion reactors**
- **Two common performance metrics:**
  - Normalized beta β_N: $\beta_N = 1.5 – 3+$, 1.8 on ITER
  - Energy confinement normalization factor H_{98}: $H_{98} = 1$ H-mode from multi-machine scalings



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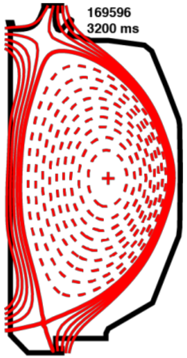
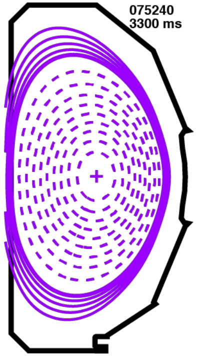
Fusion Reactor Requirements Dictate H-mode-like Performance

Typical DIII-D
H-mode
diverted plasma



Typical DIII-D
L-mode limited
plasma



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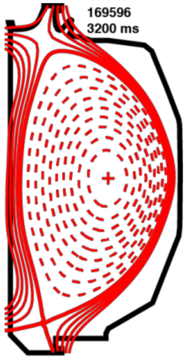
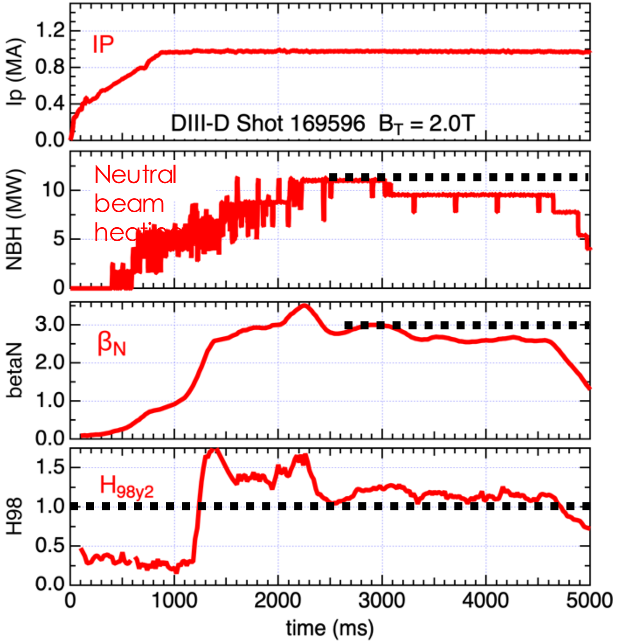
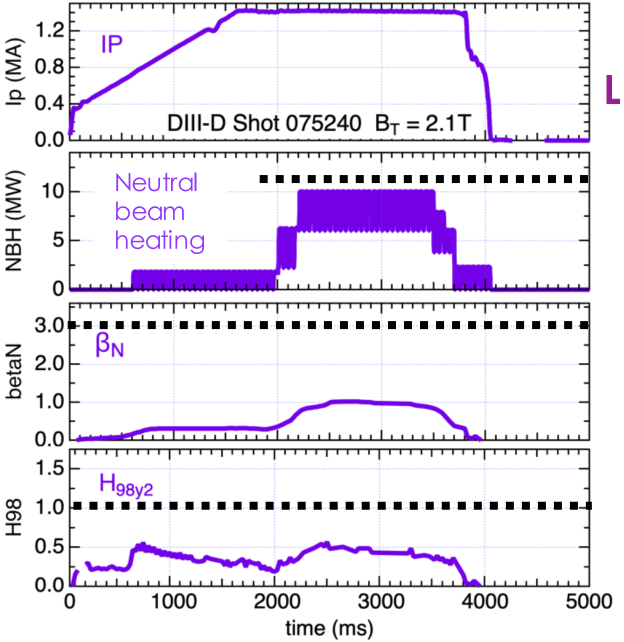
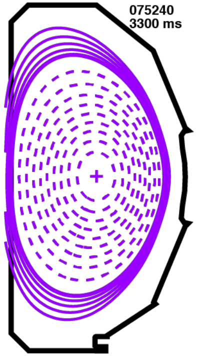






Typical DIII-D L-mode limited plasma



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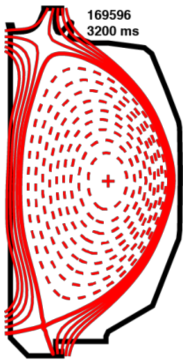

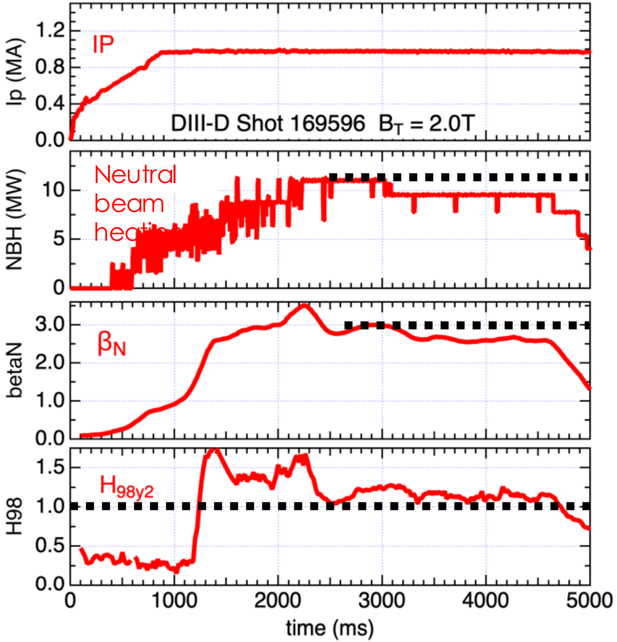

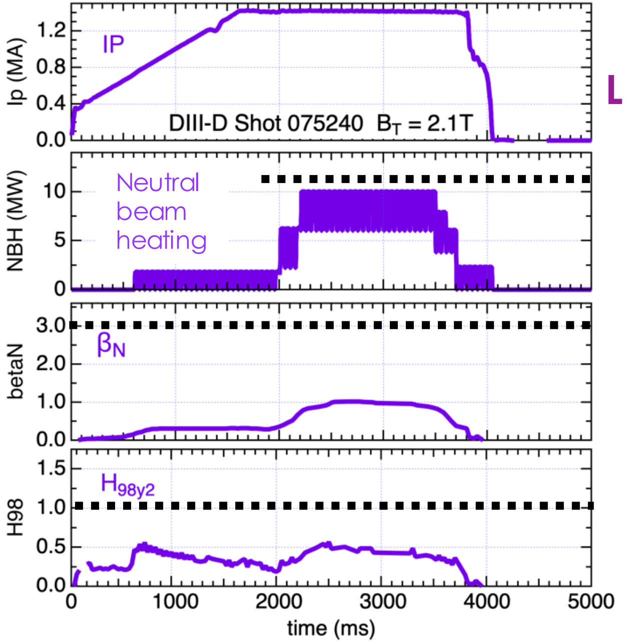

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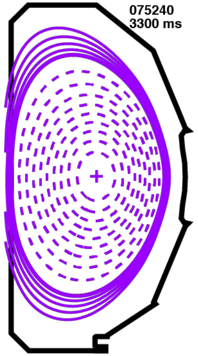
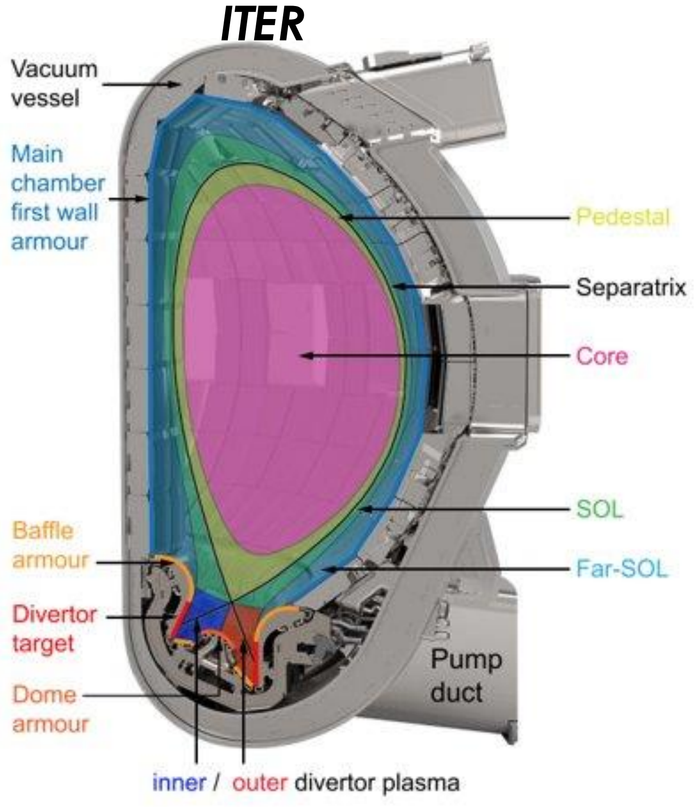


meaningful β_N & H_{98} are generally only achieved in PT in H-mode discharges

Controlling the Heat and Particle Exhaust is a Central Challenge

- **Diverted configurations planned for reactor**
- **Power leaving the plasma core (10-20 MW currently, >100 MW in a reactor) flows through narrow 1-10 mm scrape-off layer towards X-point and divertor targets**
  - Materials can only tolerate few MW/m^2 before melting
  - Must dissipate power before reaching material surfaces (via radiation) to reduce heat flux and minimize sputtering
  - Radiative divertor conditions must be maintained with minimal core degradation
- **Must also exhaust particles, particularly impurities**
  - Helium ash, tritium, intrinsic and extrinsic impurities
  - Low-Z impurities dilutes main fuel → reducing fusion reactions
  - High-Z impurities can cause significant radiation losses
- **Both steady-state and transient fluxes occur**



Krieger NF 2025

Reproducible, Reliable Plasmas Essential for Power Generation at Lower Costs

- **High capacity factor (actual energy output/maximum possible output) important for economic viability**
  - Fission currently 90% (increased with time and experience)
  - Maintenance and unexpected shutdowns decrease capacity factor and increase cost and complexity
  - Plasma performance should not further limit uptime

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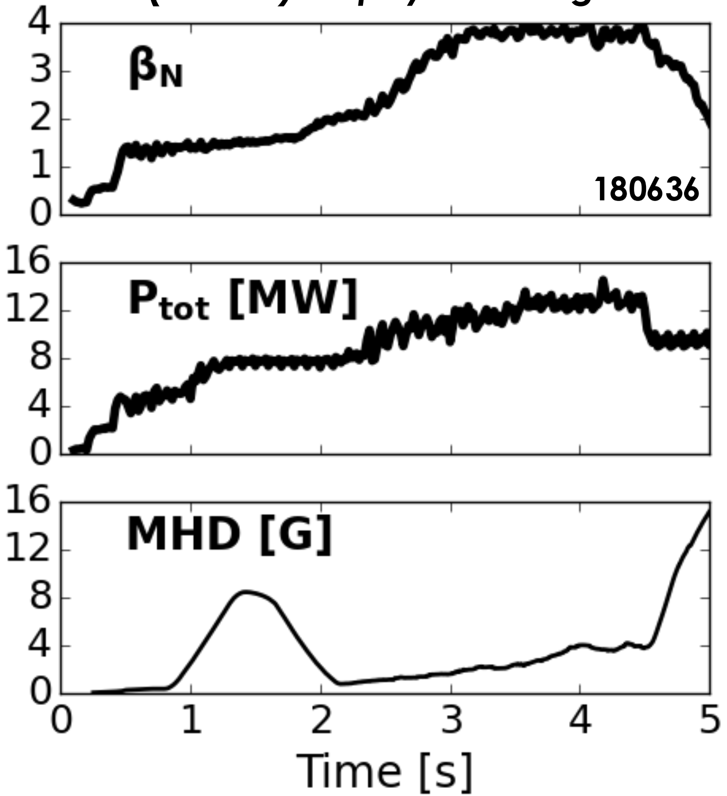
Example DIII-D PT H-mode (Thome) Trophy Discharge



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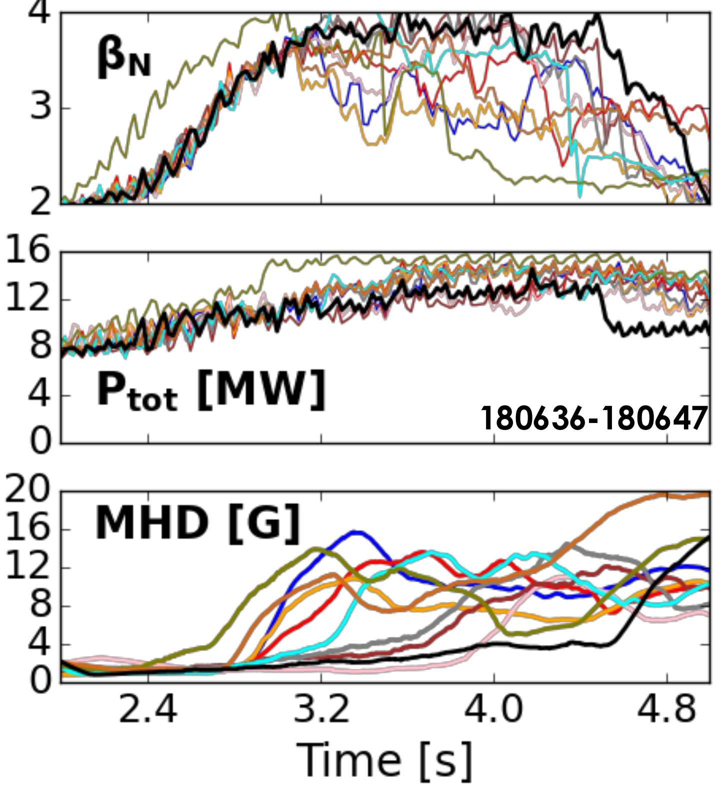
- **Many of the highest performance plasma discharges are "trophy shots" that can be transient and difficult to reproduce**
  - Marginal stability against MHD or edge instabilities makes sustained operation at high performance unreliable
  - Need easy accessibility, ideally over large operating space

Example DIII-D PT H-mode (Thome) Trophy Discharge



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  - With effective size increase from current tokamaks, Q >1 possible
  - Research ongoing to further increase performance, lowering cost

$$P_{fus} \propto \beta^2 \cdot B_T^4 \cdot a_{minor}^3$$

Assuming 5-15 keV temperatures

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- **Exhaust: H-mode exacerbates exhaust challenges**
  - Power crossing separatrix must be higher than H-mode power threshold (increases power that needs to be exhausted)

$P_{LH} \sim n_e^{0.717} \cdot B_T^{0.803} \cdot S^{0.941}$

S is plasma boundary surface area

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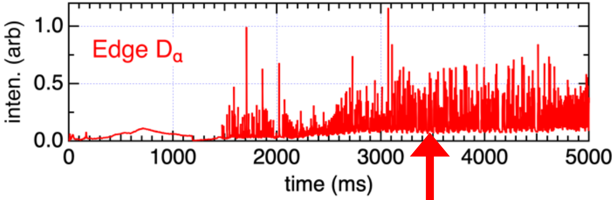

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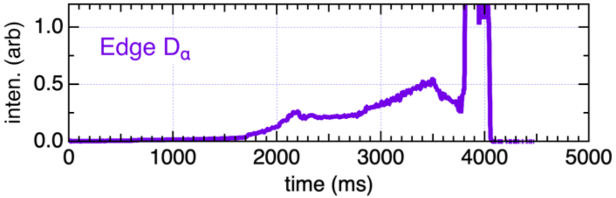
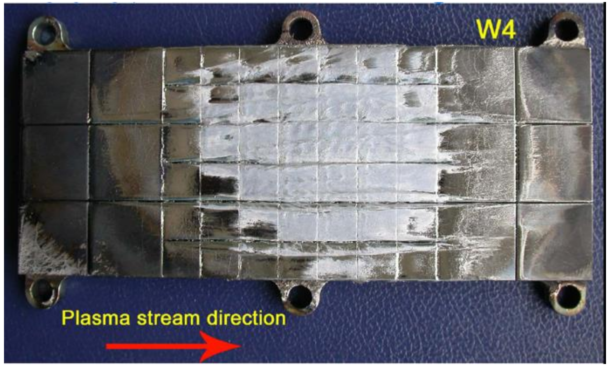


- Power crossing separatrix must be higher than H-mode power threshold (increases heat loads)
- **Edge localized mode (ELM) instability** transiently expels heat and particles
  - Need ELM free or mitigated ELM regimes[1], often affect performance, active area of research

Russian ELM simulator, showing damage to Tungsten surface with ITER ELM-like plasma bombardment



Zhitlukhin JNM 2007

[1]Evans JNM 2013, Paz-Soldan PPCF 2021, Viezzer NME 2023

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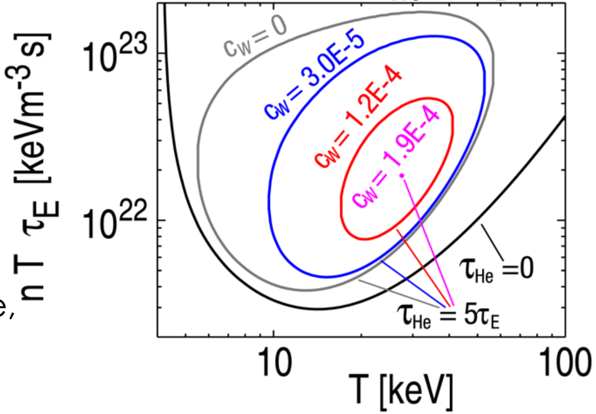
Ignition curves with different W concentrations and assuming τ_{He}= $5\tau_E$



Pütterich NF 2010

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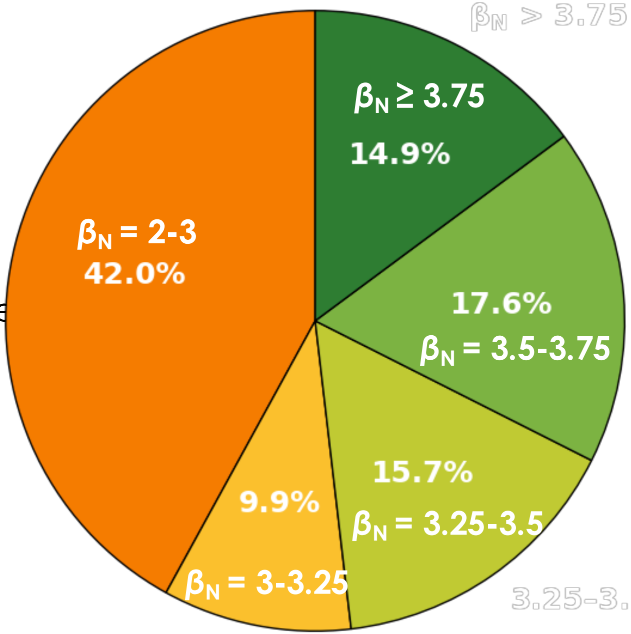
- **Reproducibility: The highest-performance plasmas can be challenging to sustain and reproduce**
  - Need also wide accessibility

PT H-mode High q_{min} DIII-D exp. (Thome), % time at various β_N at high power during I_p flattop



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

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  - At PPPL LTX and NSTX-U
  - A few universities have tokamaks: Pegasus III (University of Wisconsin-Madison), HBT-EP (Columbia University)
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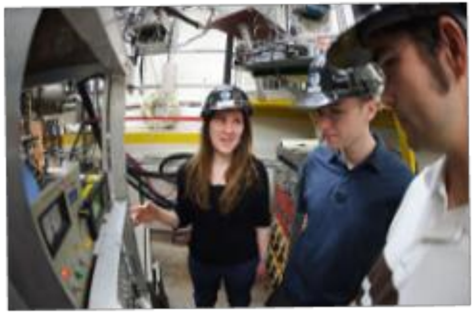

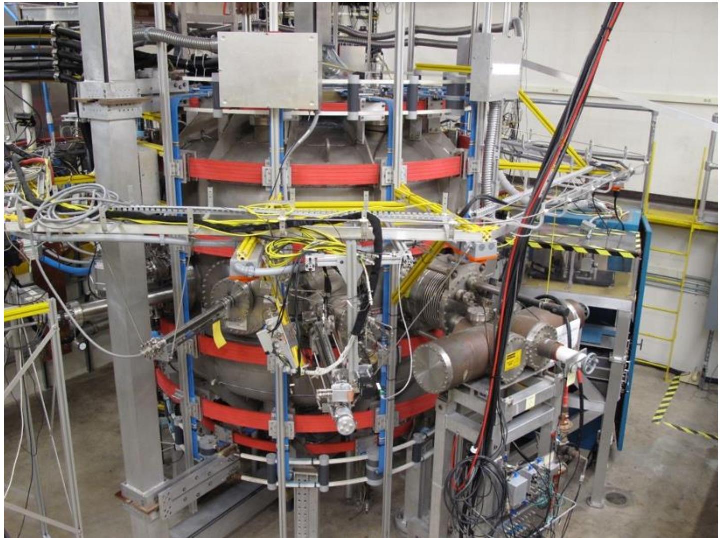

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- **SPARC tokamak at Commonwealth Fusion Systems under construction**

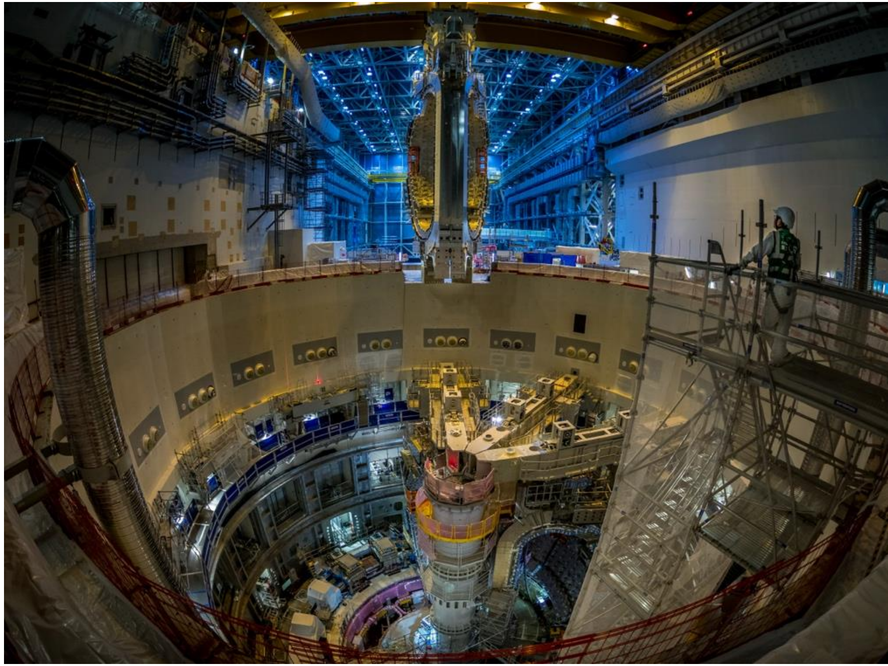
There are Many Tokamaks in the World that You Could Work On!

- **Many public tokamaks around the world currently operating!**
  - Europe: MAST-U, TCV, AUG, WEST
  - Asia: KSTAR, EAST, JT60SA

- **Many more under construction or planned both public and private**
  - Biggest tokamak ever being built in France ITER

- **Countries and companies designing their fusion pilot plants**
  - ARC by CFS
  - STEP by UK
  - DEMOs (EU, Korea, Japan)
  - CFETR by China

"ITER"



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

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 to achieve a sustainable scenario**

- **It's an exciting time to be doing tokamak research with new tokamaks coming on soon around the world!**