A (brief) Introduction to Tokamaks

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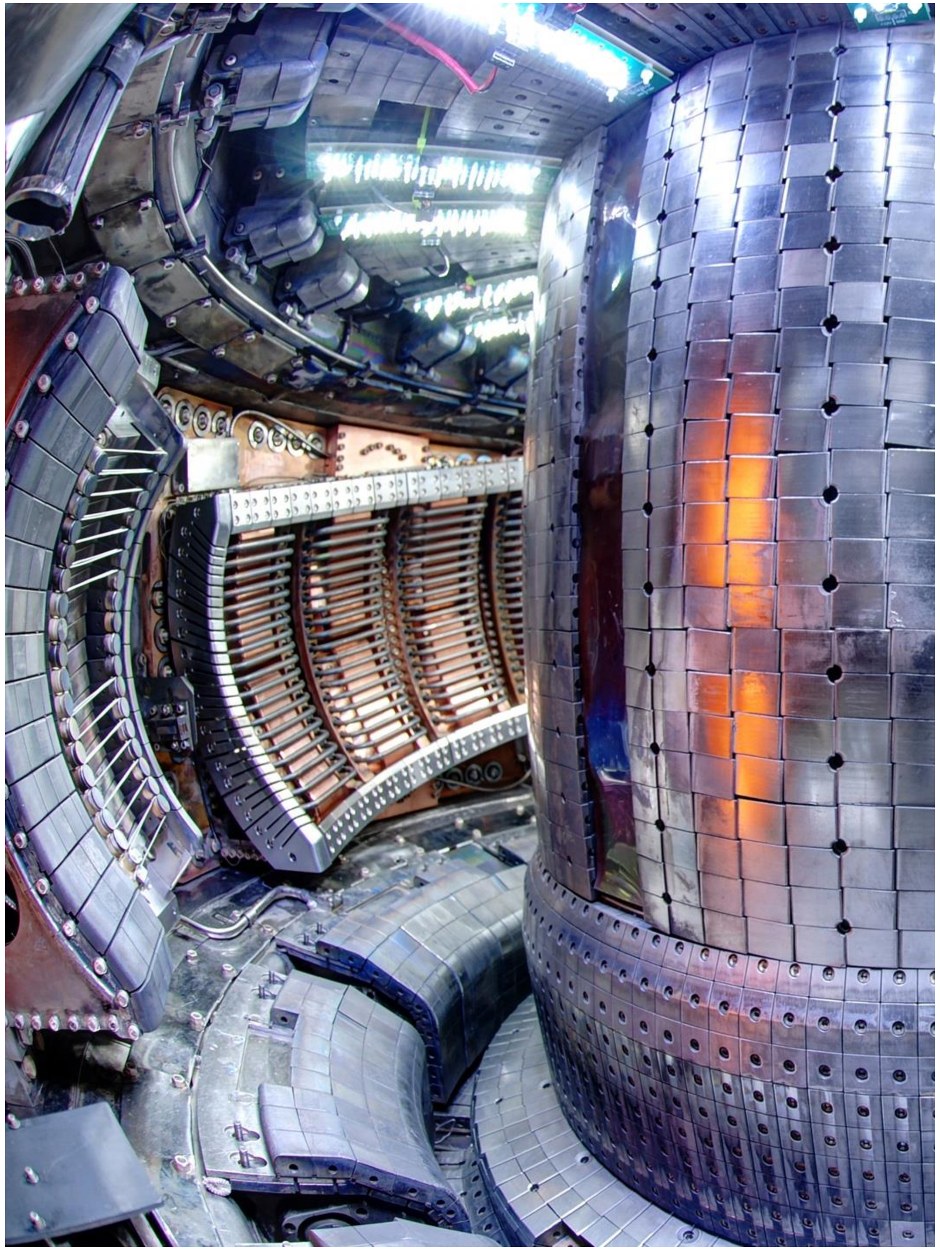
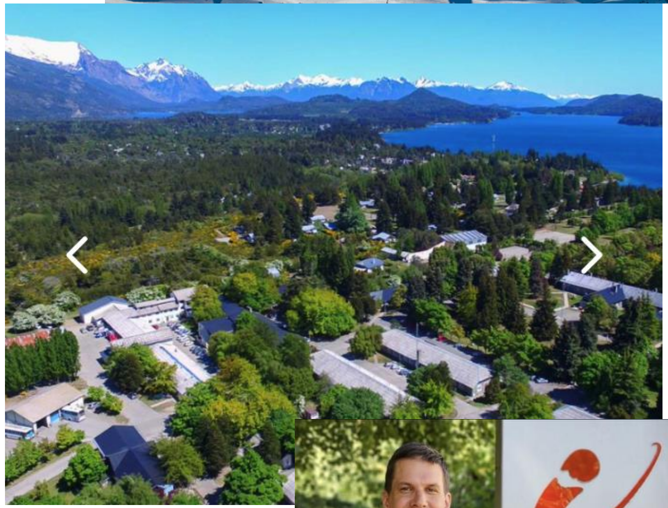


My way in fusion

Studied physics in Argentina

Bariloche Atomic Center & Balseiro Institute



My way in fusion

Plasma Science & Fusion Center

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Had a visiting scholar appointment at UCSD (at DIII-D)

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Huemul Project: The first (but failed) fusion project in the world

My way in fusion

Plasma Science & Fusion Center

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Then moved to Princeton as a postdoc at PPPL

PPPL started as a secret lab after the Huemul Project

My way in fusion

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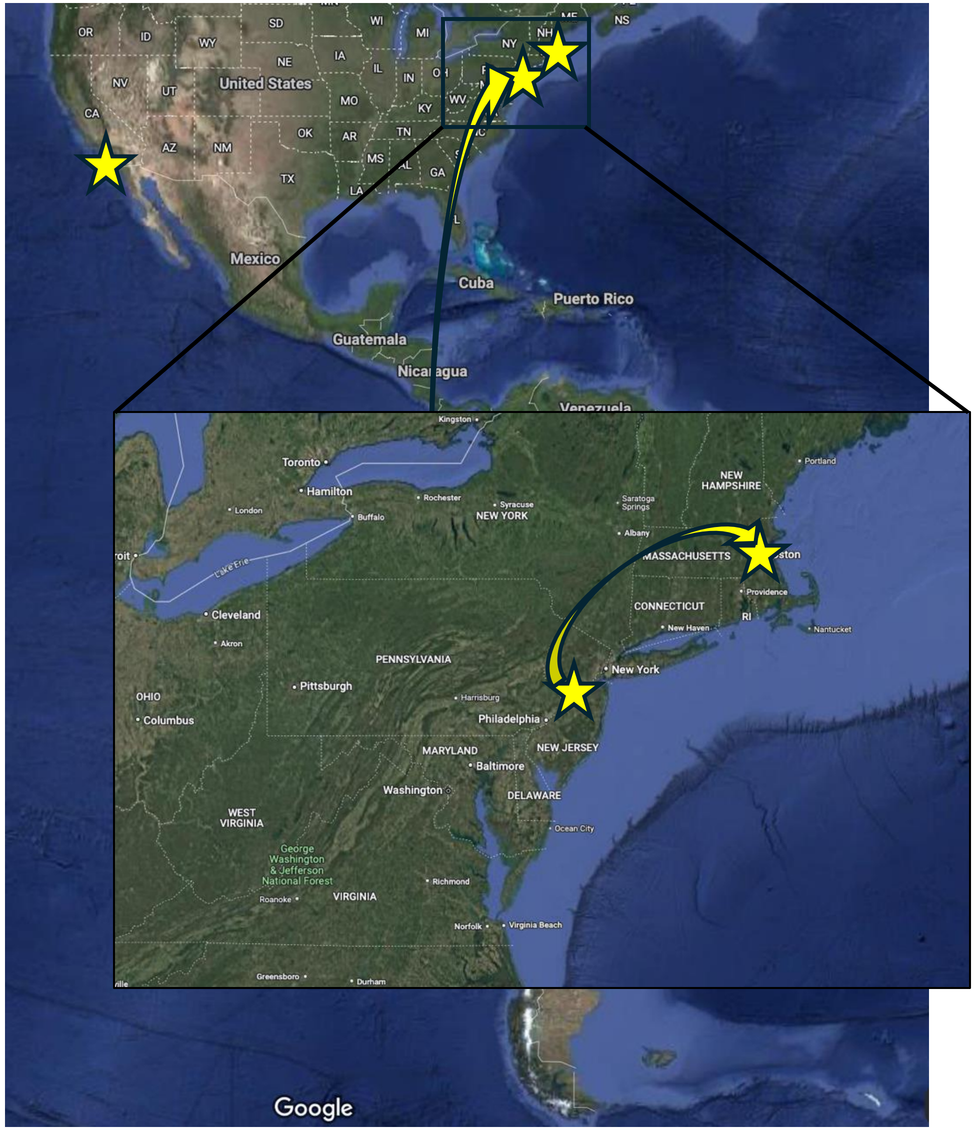

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Then moved to Cambridge MA, as a research scientist at MIT

A (brief) Introduction to Tokamaks

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What will we cover?

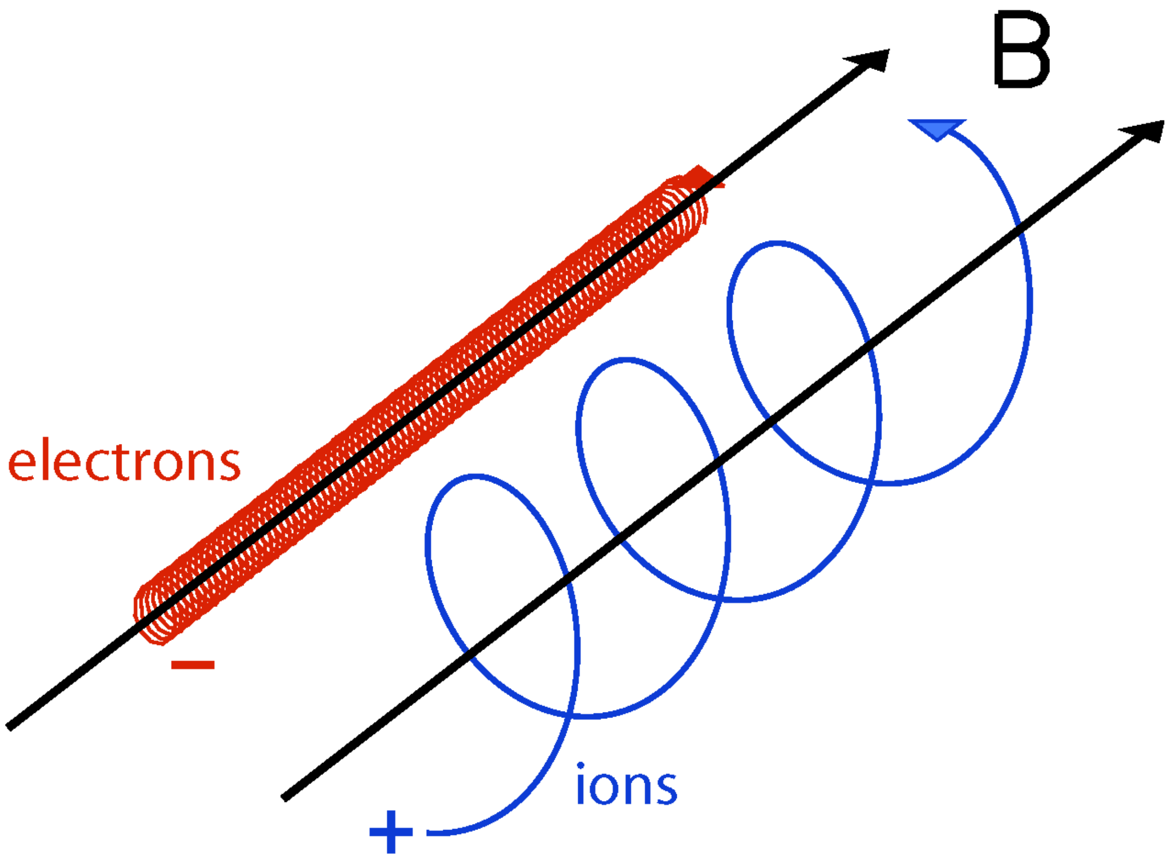
- Tokamak: particle orbit picture
- Tokamak equilibrium: Grad-Shafranov equation
- How a discharge looks like?
- The future of Tokamaks: towards FPPs
- Challenges: Disruptions

Tokamak: particle orbit picture

Plasma Can Be Confined by the Gyration Of Charged Particles in a Magnetic Field

Magnetic Confinement = Thermal Insulation Perpendicular To Field

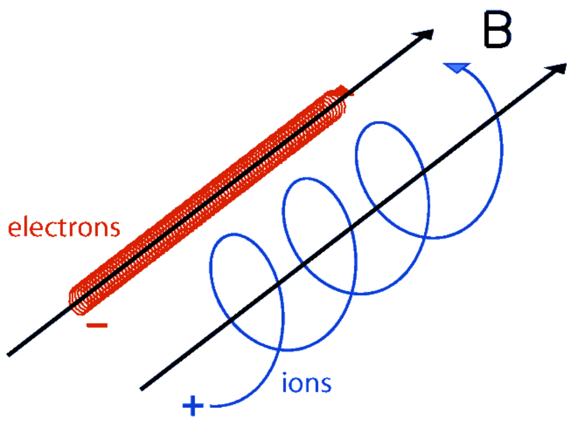
The quality of the magnetic insulation increases with the strength of the magnetic field



At B = 10T, T = 10keV

- ρ_e = 0.033 mm
- ρ_i = 1.5 mm
- We need a device size ~500 - 1,000 x ρ_i
  - i.e. ~ 1 m
  - (Breeding blanket also requires about 1 m)

Tokamak: particle orbit picture

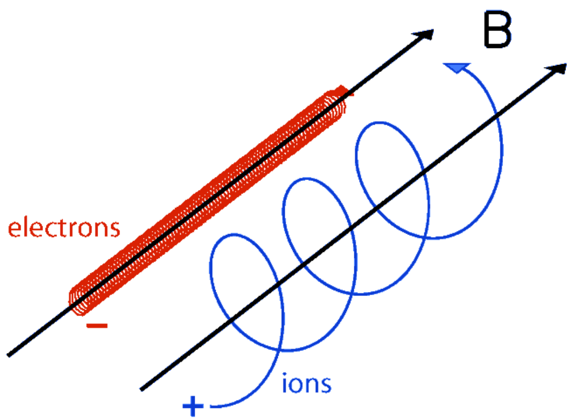


- At the temperatures involved, ions are moving at over 1,000 km/s

- But, the average time for an ion to fuse, even at these temperatures ~ 25 seconds

- So, the end losses must be eliminated somehow

Tokamak: particle orbit picture



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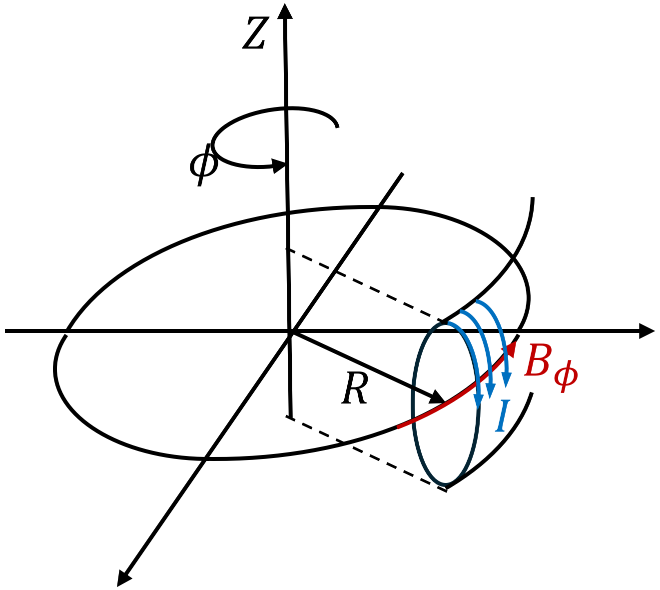
A toroidal configuration would solve this problem!



$$\mathbf{B}_\phi = \frac{\mu_0 N I}{2\pi R}\,\hat{\phi}$$

Tokamak: particle orbit picture

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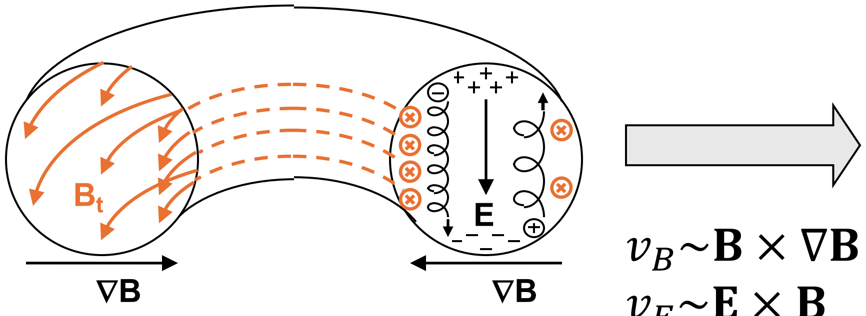
However… there are some side effects



$v_B \sim \mathbf{B} \times \nabla \mathbf{B}$
$v_E \sim \mathbf{E} \times \mathbf{B}$

- Solution 1: Torus solves the end-loss problem
- Issue 2: In a simple toroidal field, particle drifts lead to charge separation and loss of equilibrium.

Tokamak: particle orbit picture

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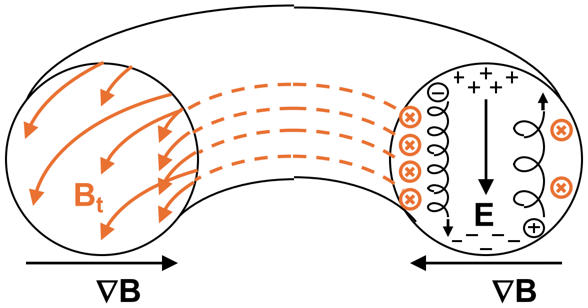

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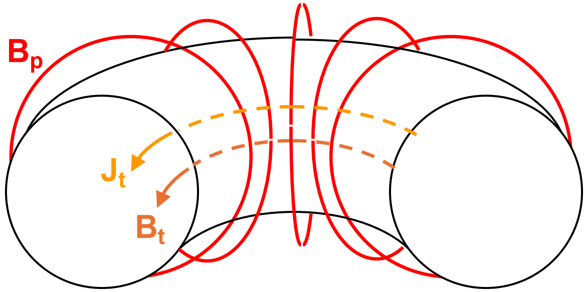

- Solution 1: Torus solves the end-loss problem
- Issue 2: In a simple toroidal field, particle drifts lead to charge separation and loss of equilibrium.
- Solution 2: Add poloidal field (*through a toroidal plasma current*), twist then allows particles to sample regions of inward and outward drift.
- Issue 3: Hoop stress from unequal magnetic and kinetic pressures.

Tokamak: particle orbit picture

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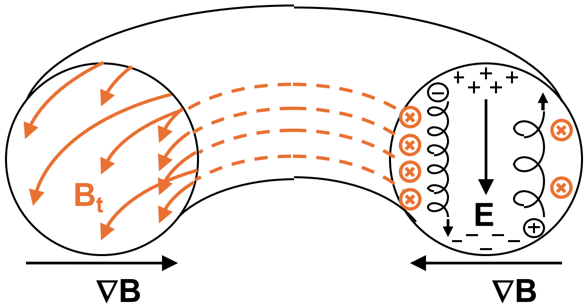

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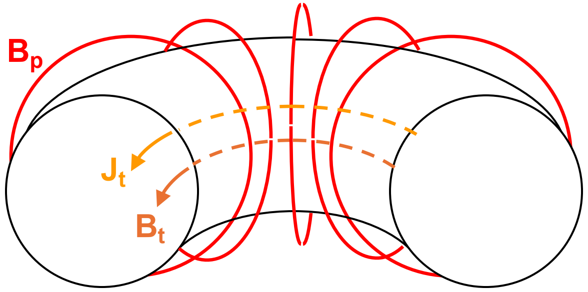

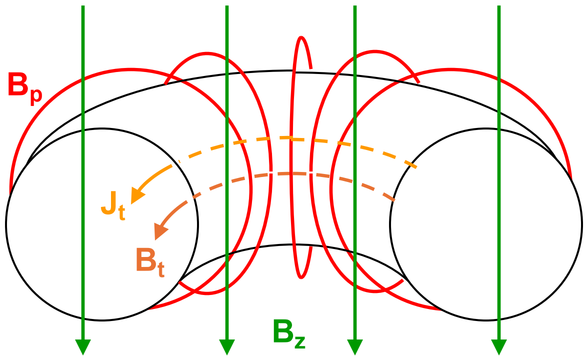

$\mathbf{F} = \mathbf{J}_t \times \mathbf{B}_z$

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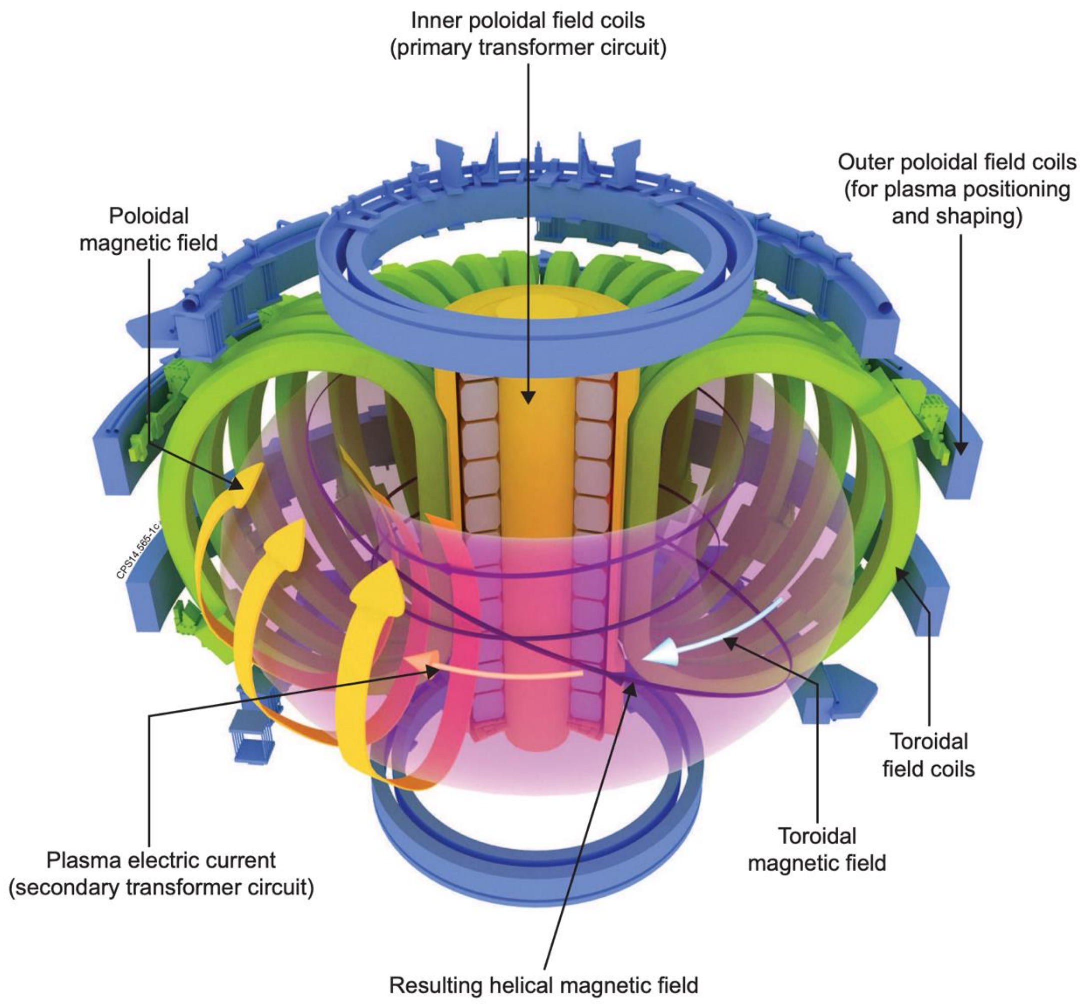
- Solution 2: Add poloidal field (*through a toroidal plasma current*), twist then allows particles to sample regions of inward and outward drift.
- Issue 3: Hoop stress from unequal magnetic and kinetic pressures.
- Solution 3: Add vertical field, to counteract hoop stress.
- Magnetic confinement experiments are variations on this theme.

Putting all these required fields together results in a tokamak



- Formulated in the 1950s by Russian scientists
  First tokamak, T-1, operated in 1958
- Tokamaks confine with an *externally* produced toroidal field and a *plasma current* produced poloidal field
- TOKAMAK is a Russian acronym:
  “Toroidal Chamber with Magnetic Coils”
- Leading magnetic confinement concept in terms of number of facilities and funding

How do tokamaks look like?

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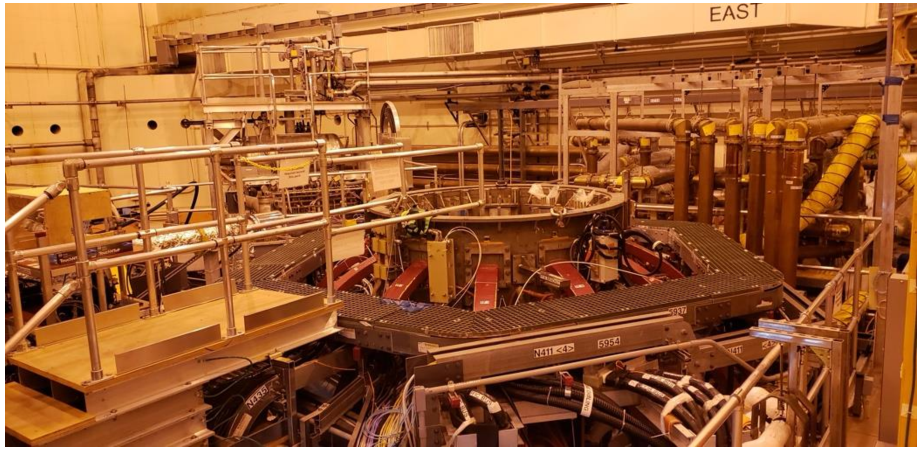
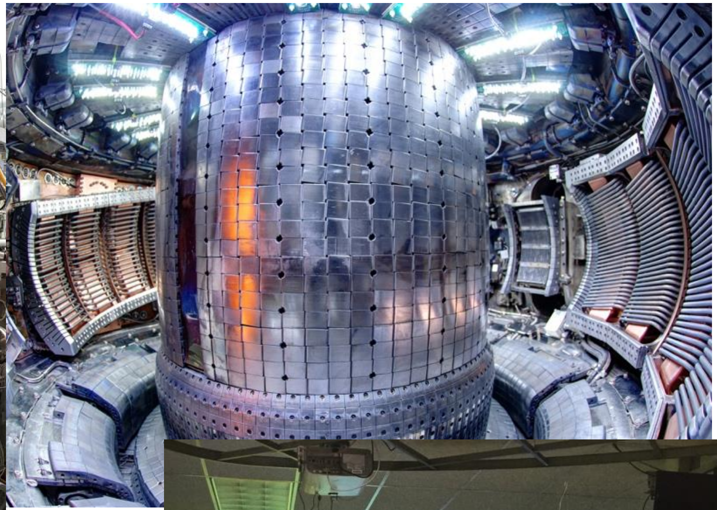
NSTX | PPPL

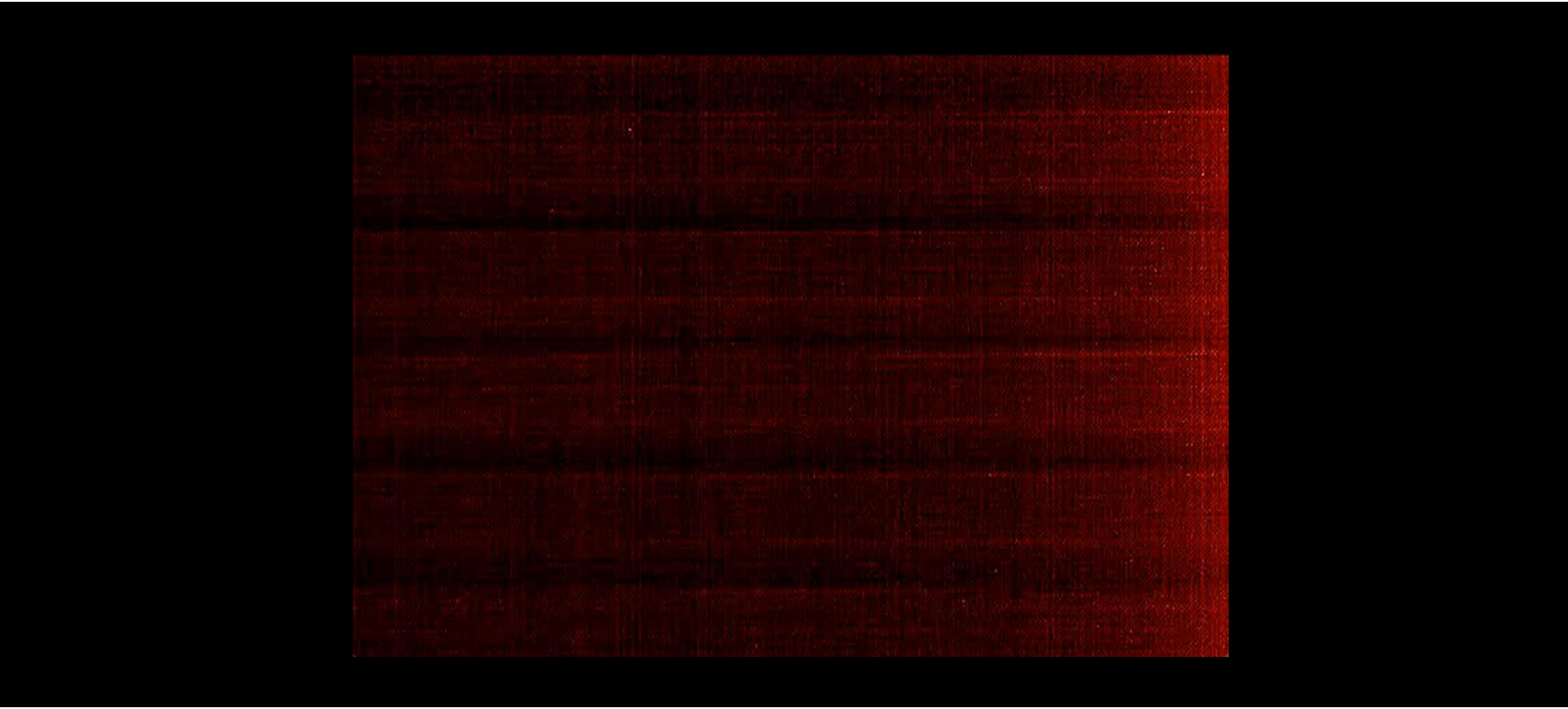


DIII-D | General Atomics

C-Mod | MIT



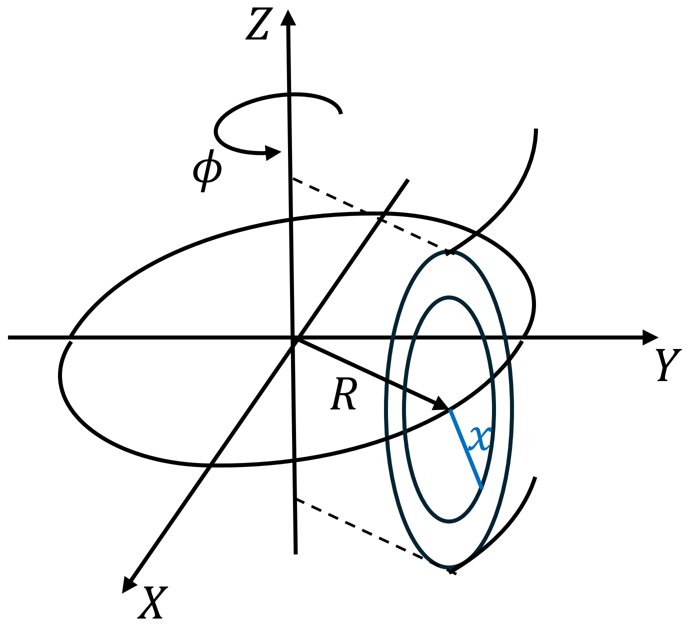
How does a discharge look like?



Tokamak equilibrium

A useful way to reconstruct a discharge is by obtaining its equilibrium at different times

$\nabla p = \mathbf{J} \times \mathbf{B}$ $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$ $\nabla \cdot \mathbf{B} = \mathbf{0}$ $(\rightarrow \mathbf{B} = \nabla \times \mathbf{A})$



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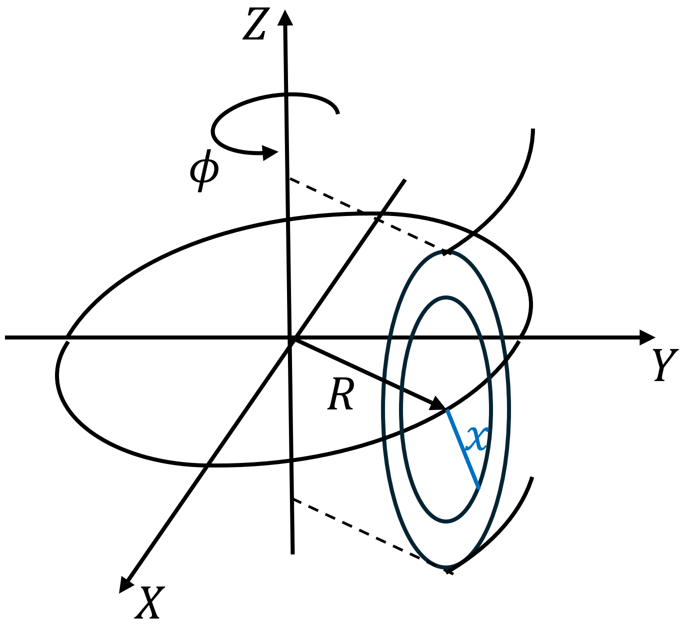
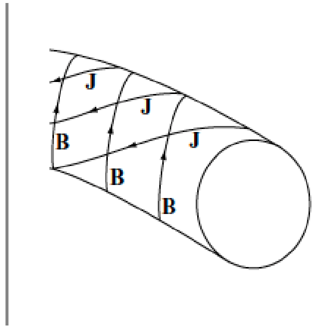
Some basic properties

$\mathbf{B} \cdot \nabla p = \mathbf{0}$ Magnetic field lines lie in surface of p=const.

$\mathbf{J} \cdot \nabla p = \mathbf{0}$ Current density lines also lie in surface of p=const.





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Plasma Science & Fusion Center

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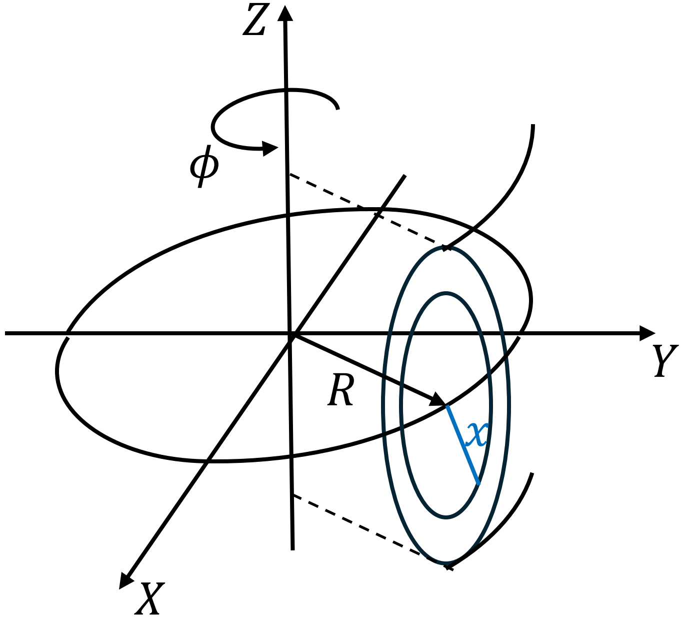
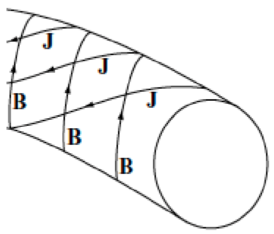
Assuming axi-symmetry, $\partial_\phi \equiv 0$, it is possible to solve for a 'radial' force balance equation (Grad-Shafranov)

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

$\mathbf{B} = \frac{1}{R}\hat{\phi} \times \nabla\psi + \frac{F}{R}\hat{\phi}$ $\quad F = F(\psi)$ $\quad p = p(\psi)$

$(\psi = -RA_\phi)$





Tokamak equilibrium

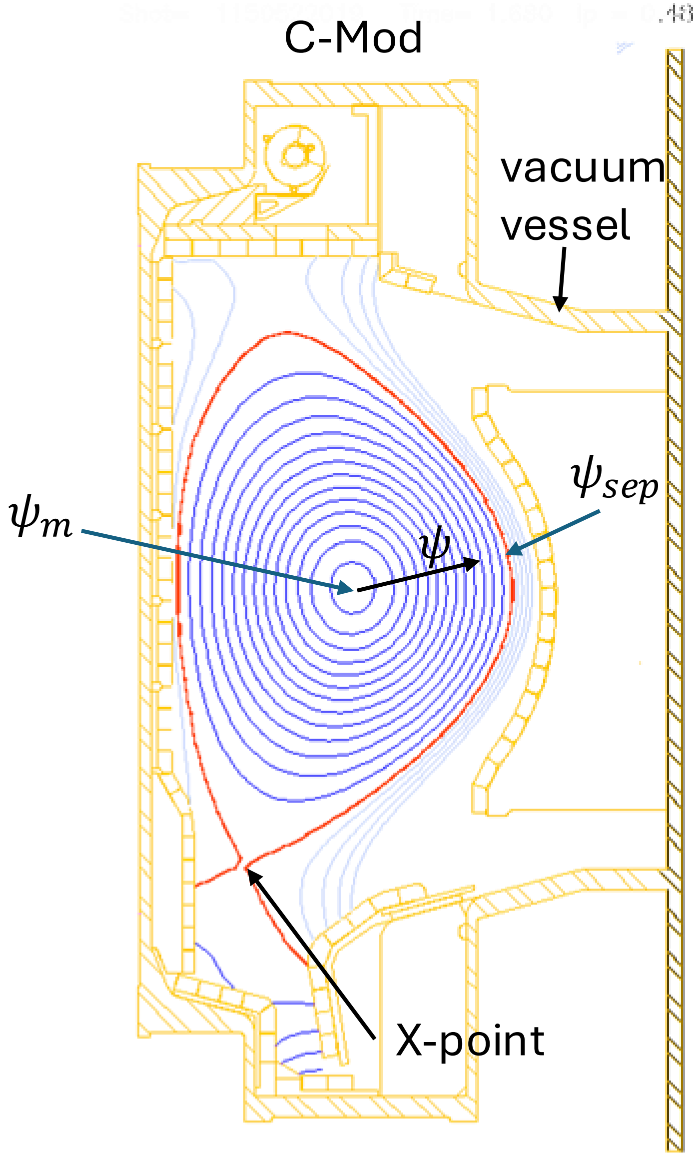
G-S equation relates poloidal flux function (ψ), pressure (p), and current flux function (F)

Finding the equilibrium consists of solving the G-S equation for ψ (which is also our 'radial' coordinate)

Equilibrium is axisymmetric so, we only show a ***poloidal cross-section***

Surfaces of constant ψ are called 'magnetic surfaces'

- magnetic field and current density lie in those surfaces
- pressure and F are constant on magnetic surfaces
- The *separatrix* separates the *confined region* from the *open field line region*



How does a discharge look like?

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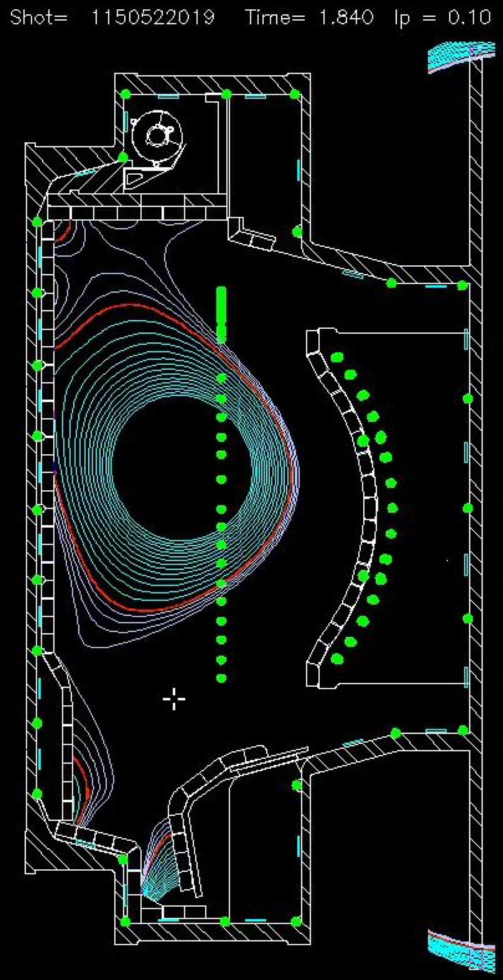

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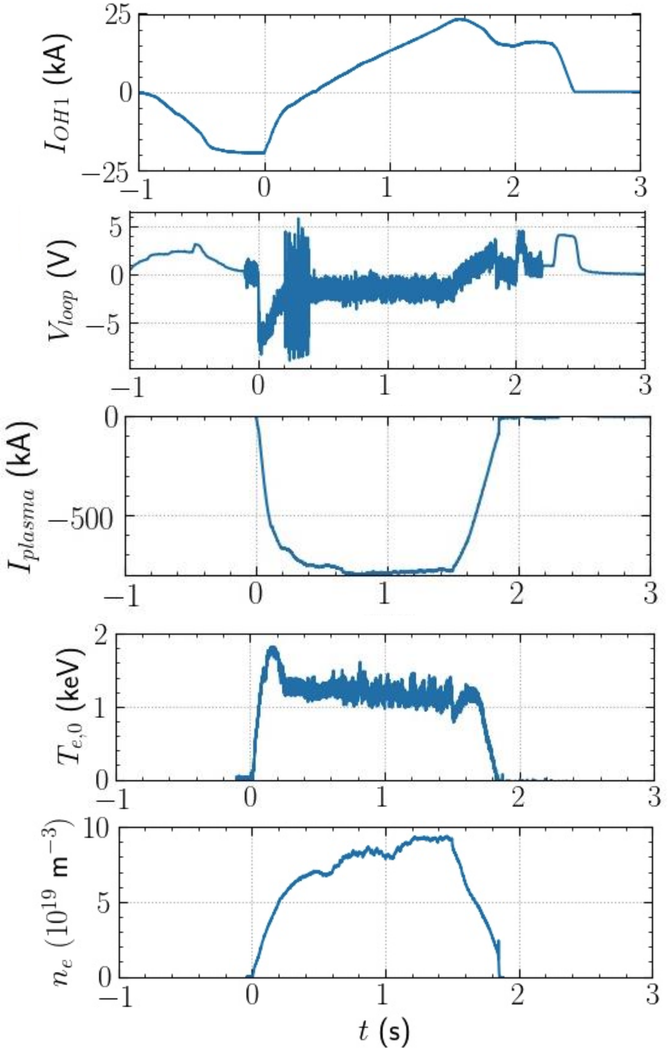
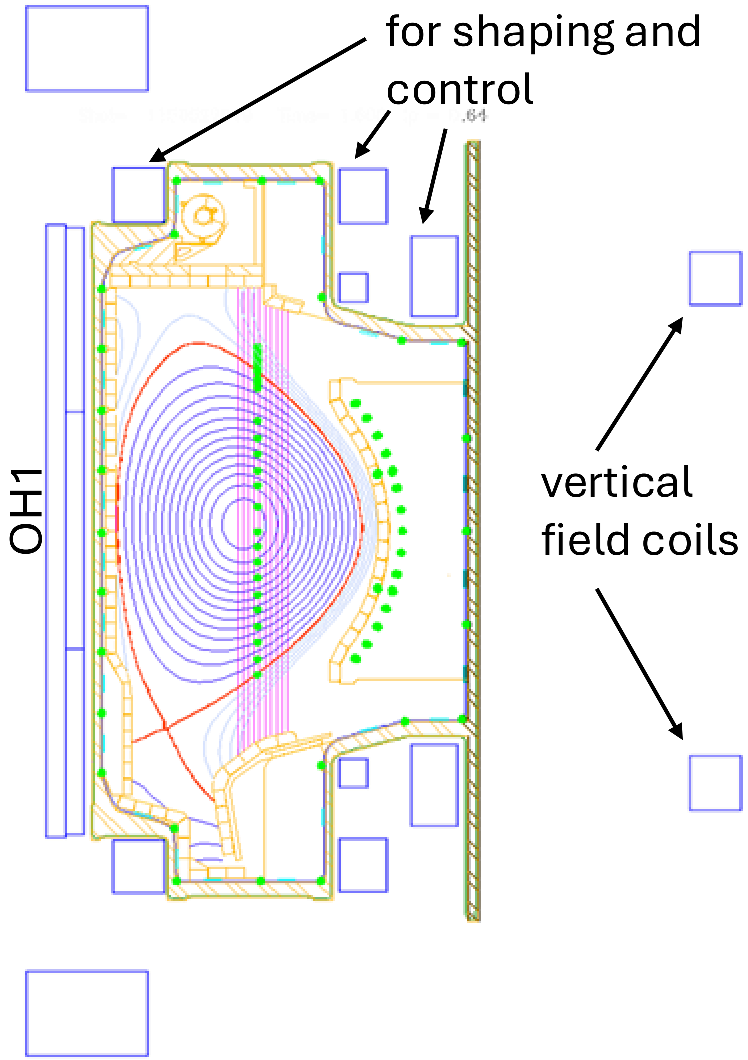
Magnetic sensors and diagnostics allow the reconstruction



- central solenoid (OH1) ‘pre-charges’
- quick change in OH1 current generates a loop voltage
- plasma current is driven
- Thomson Scattering for electron temperature
- TCI for electron density



How does a discharge look like?

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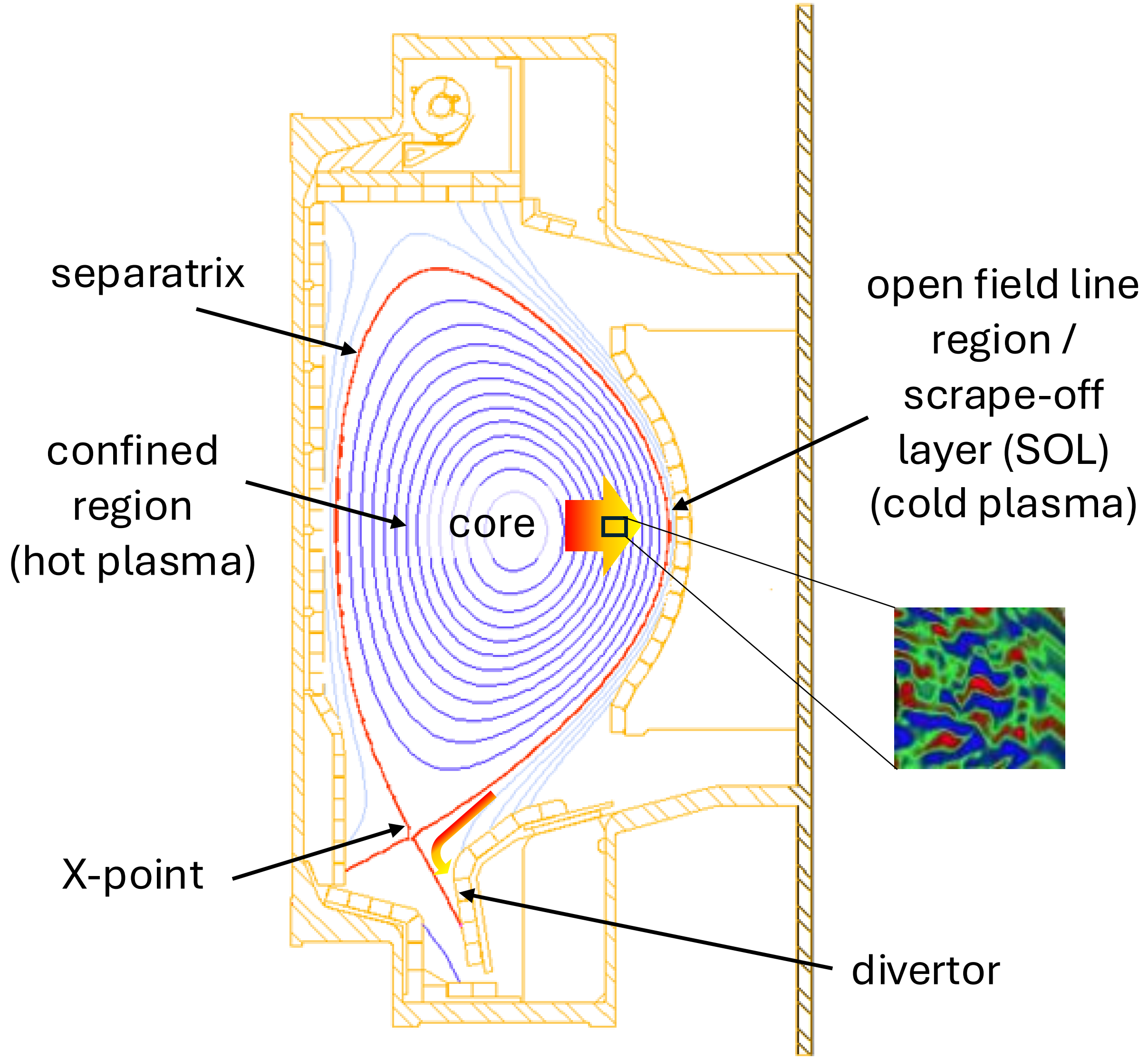
During a discharge, there is a balance of input and loss of thermal energy



- The **confined region** ‘isolates’ our hot plasma from the outer world
- However, radial transport still occurs *Microturbulence* dominates radial transport in tokamaks
- Thermal energy flows from the **core** to the thin **scrape-off layer (SOL)** and gets lost
- (almost) All the heat loss is conducted to the **divertor**

The future of tokamaks…
towards fusion pilot plants (FPPs)

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Some key metrics in fusion

“fusion triple product”

$nT\tau_E \propto R^{1.3}B_T^3$ ($> 3 \times 10^{21}\ \mathrm{m^{-3} keV\ s}$ → Breakeven)

fusion power

$P_{fus} \propto R^3 B_T^4$

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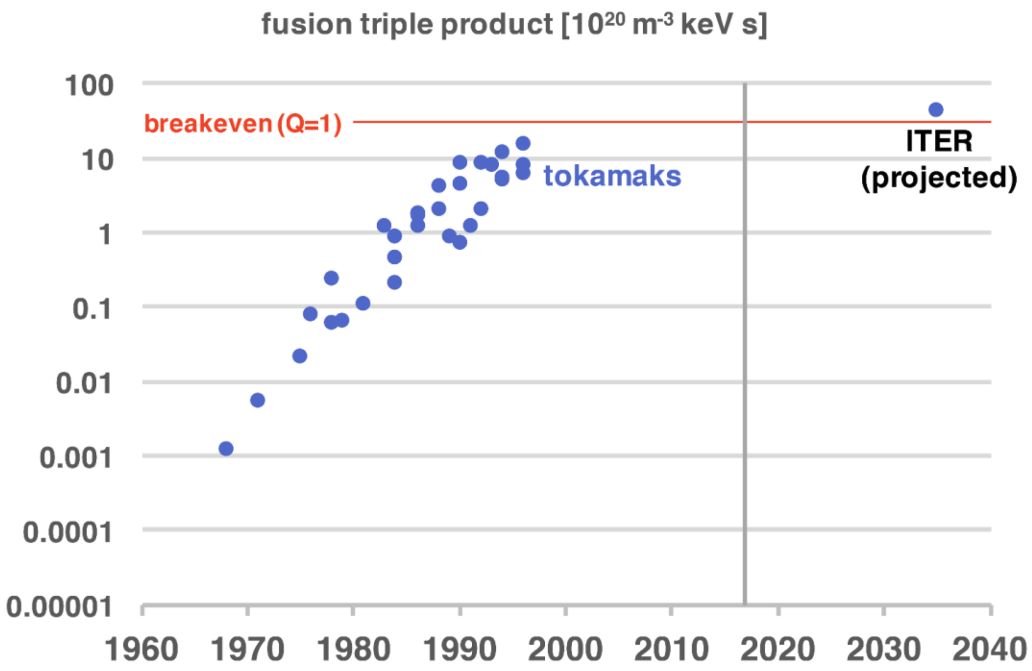
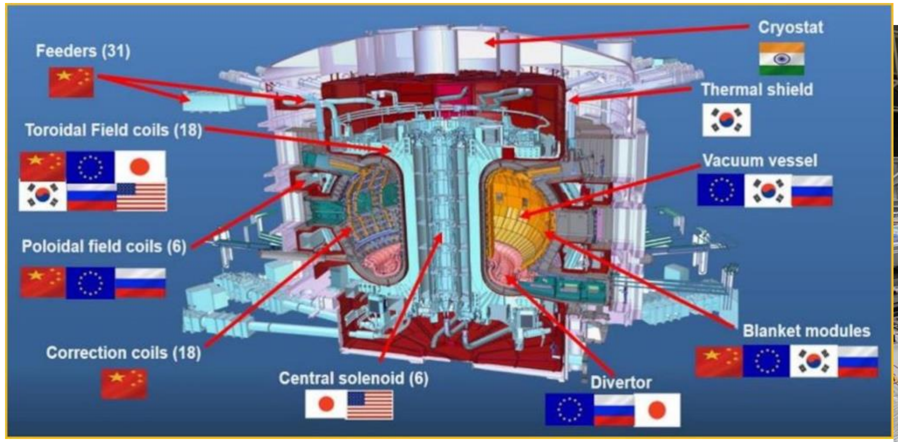
The has been a lot of progress in tokamak performance over their first decades

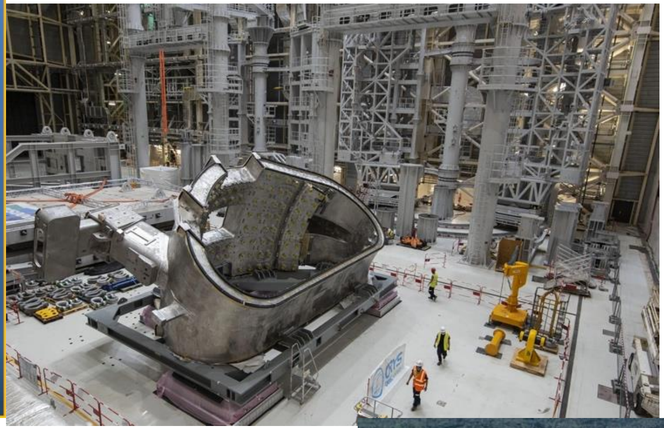
Since late '90, the stagnation was mostly due to size & cost (technology), not saturation due to physics



The future of tokamaks… towards fusion pilot plants (FPPs)

ITER is one of the biggest project of humankind

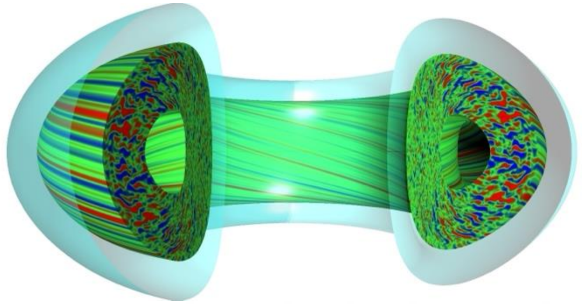


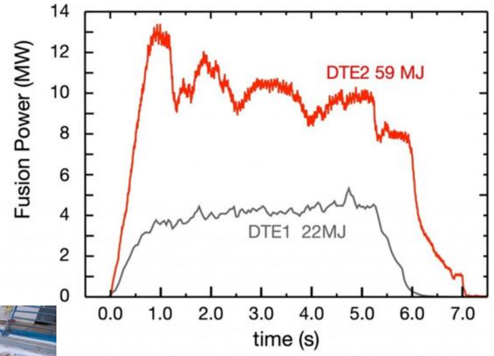


The future of tokamaks…
towards fusion pilot plants (FPPs)

In parallel, progress has continued steady in many areas

- **Theory / simulations**
  - microturbulence and transport from fundamental physics
  - Extended MHD models including conducting structures (whole device modeling)
- **Data / ML**
  - Tokamaks produce huge amount of data
    Machine Learning is now almost everywhere in fusion
- **Experiments**
  - New records in fusion energy (JET: 69 MJ)
  - New records in pulse duration (EAST: 22 mins)
- **Technology**
  - High-Temperature superconducting magnets





The future of tokamaks… towards fusion pilot plants (FPPs)

With all these advancement, private sector started envisioning a faster approach to fusion energy

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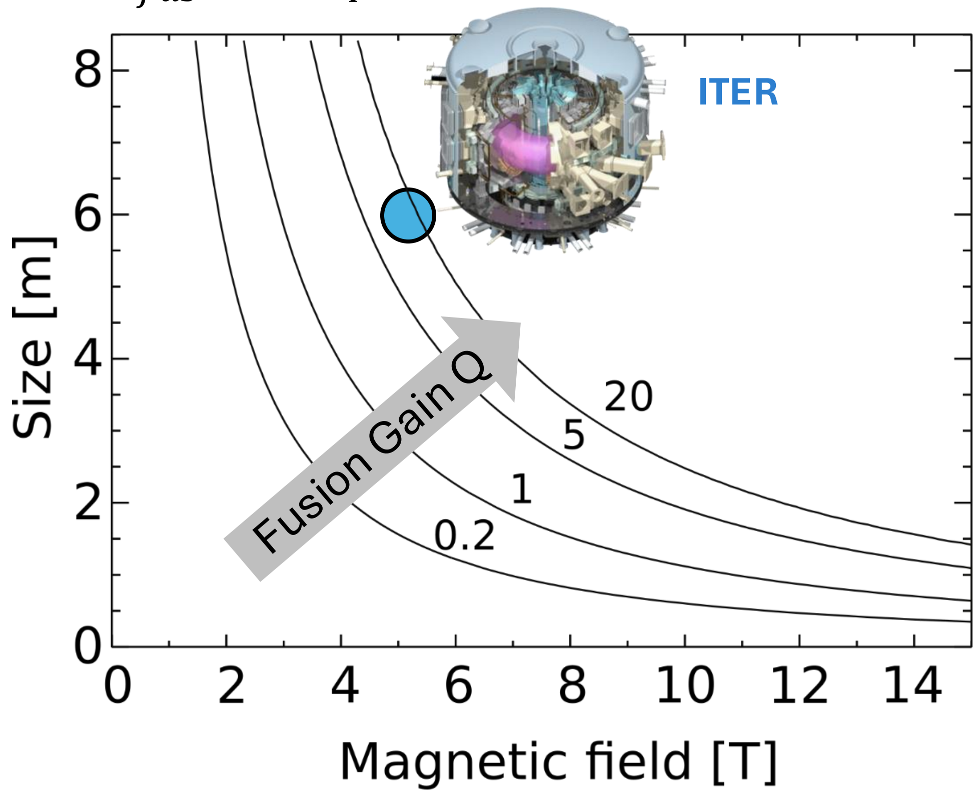

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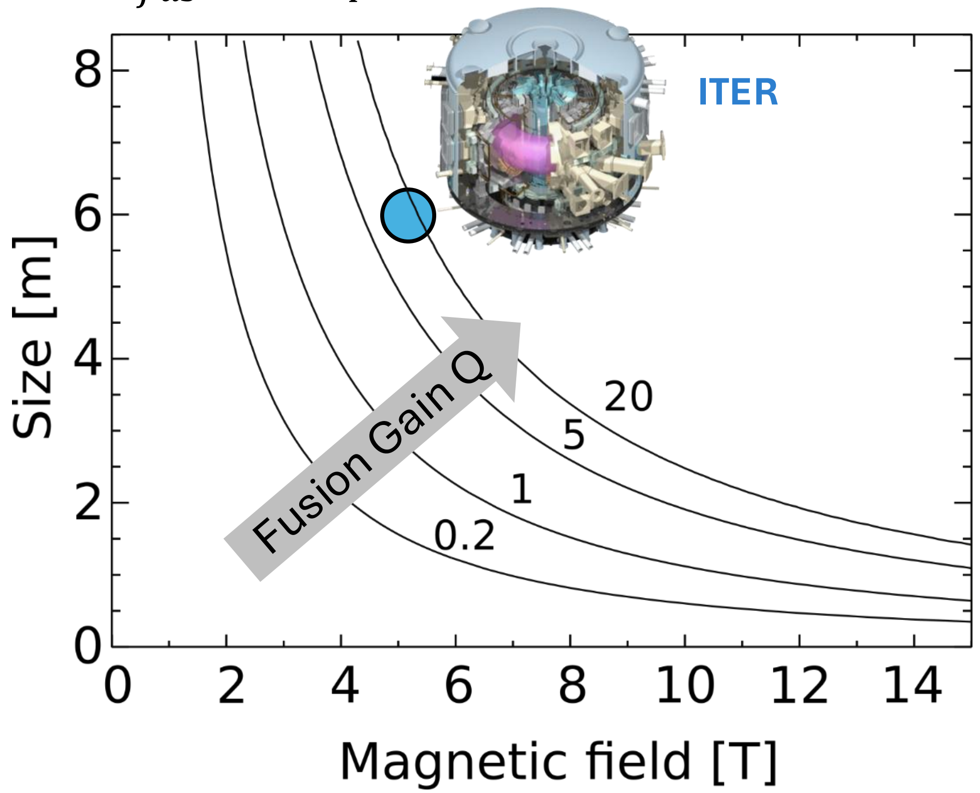

Commonwealth Fusion Systems

In 2021, CFS and MIT demonstrated 20 T Magnetic field

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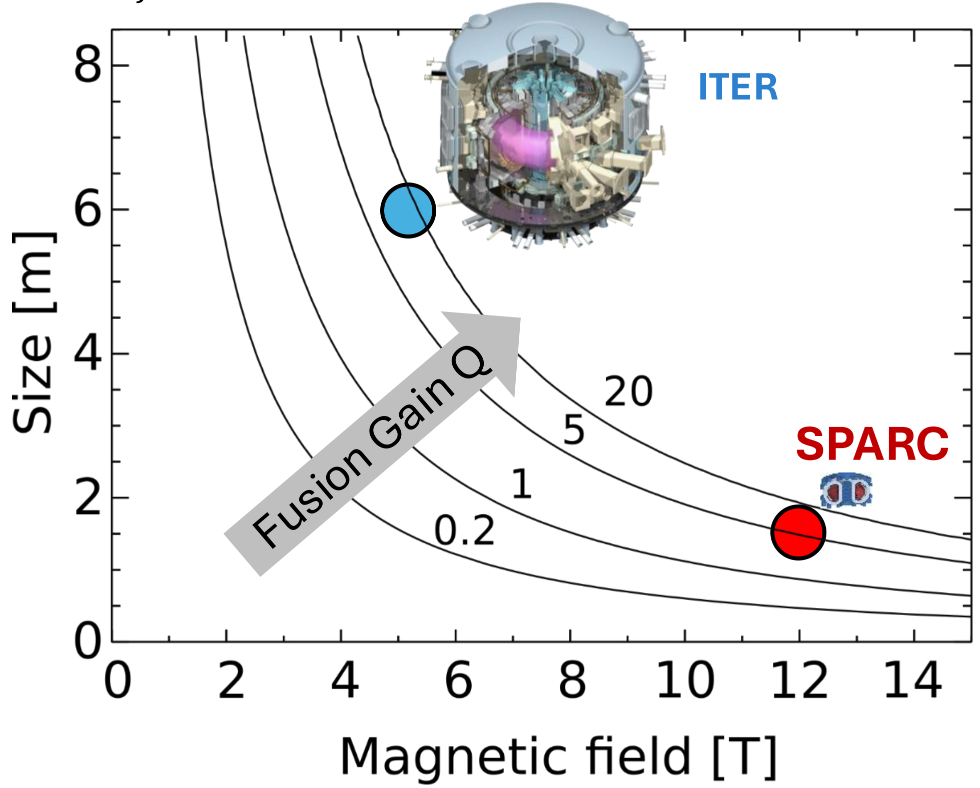

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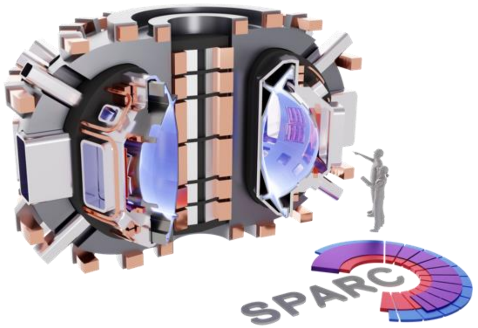
In 2021, CFS and MIT demonstrated 20 T Magnetic field

This created a viable path for compact devices



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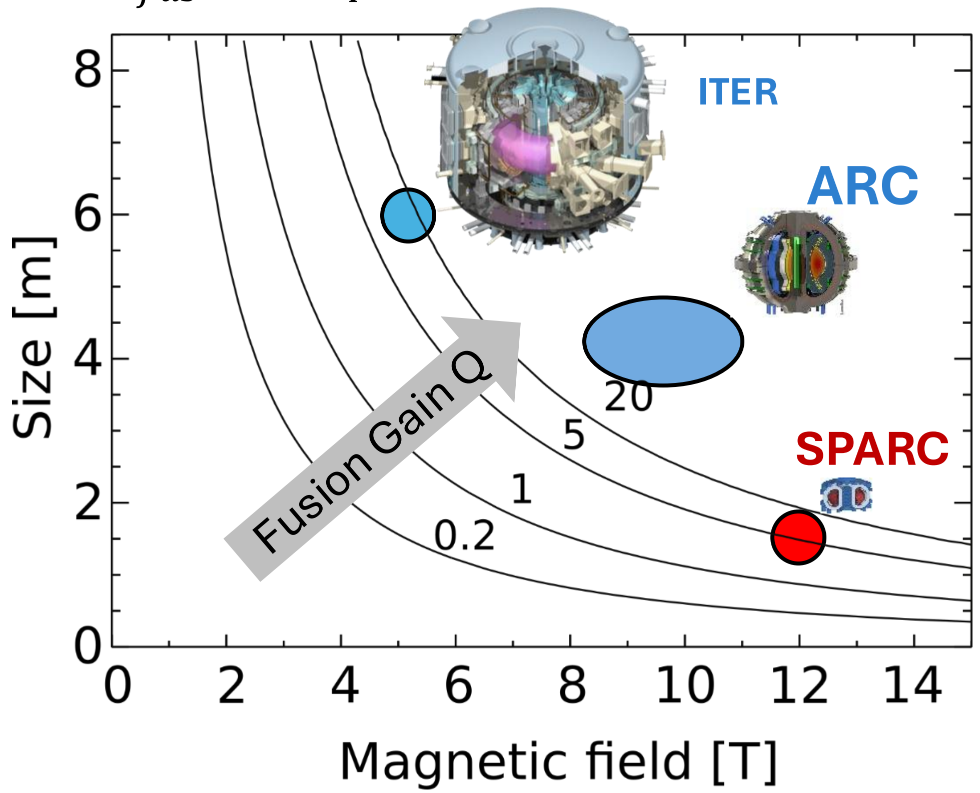

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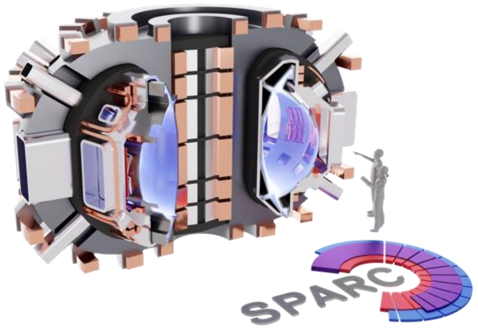

CFS (and partners) are also currently planning ARC: a fusion pilot plant

The future of tokamaks…
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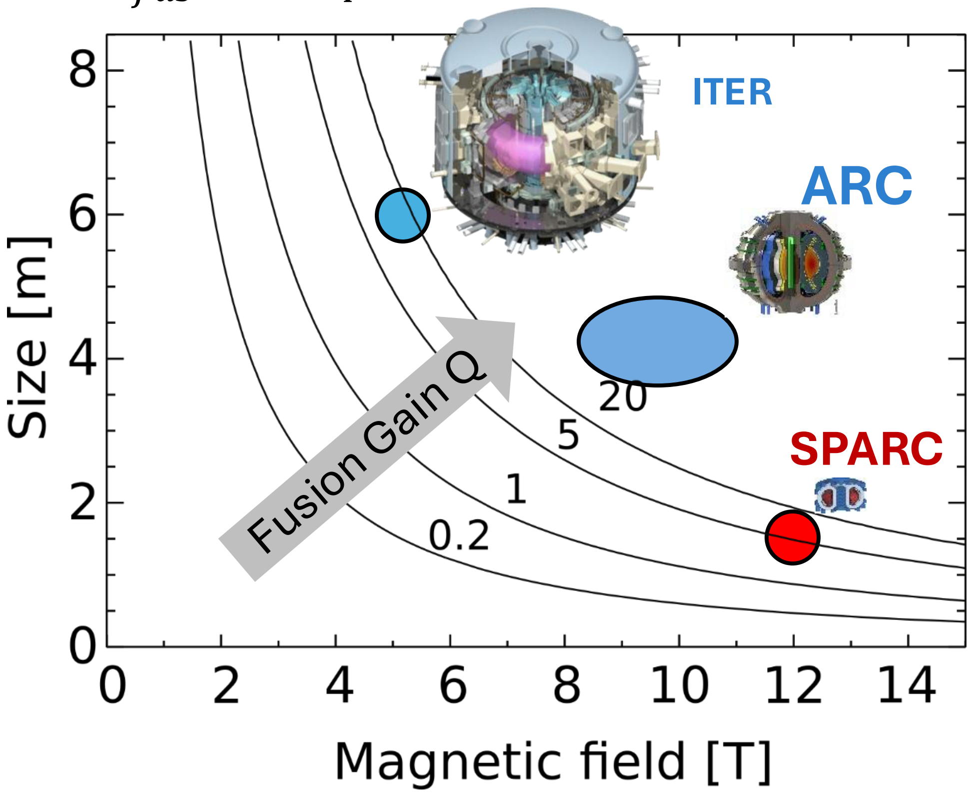

Comparison of ITER, SPARC and ARC

	ITER	SPARC	ARC V2B
B_0 [T]	5.3	12.2	10.8
Ip [MA]	15	8.7	11.2
R0 [m]	6.2	1.85	4.25
a [m]	2	0.57	1.17
P_{fusion} [MW]	500	50 – 140	1000
Q	10	2 – 10	50
$P_{electric}$ [MW]	--	--	400

* V2B target parameters [J. Hillesheim APS-DPP 24]

The future of tokamaks… towards fusion pilot plants (FPPs)

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SPARC is now under construction

SPARC

Devens MA

Tokamak hall

Magnet factory

What are some challenges that tokamaks need to overcome?

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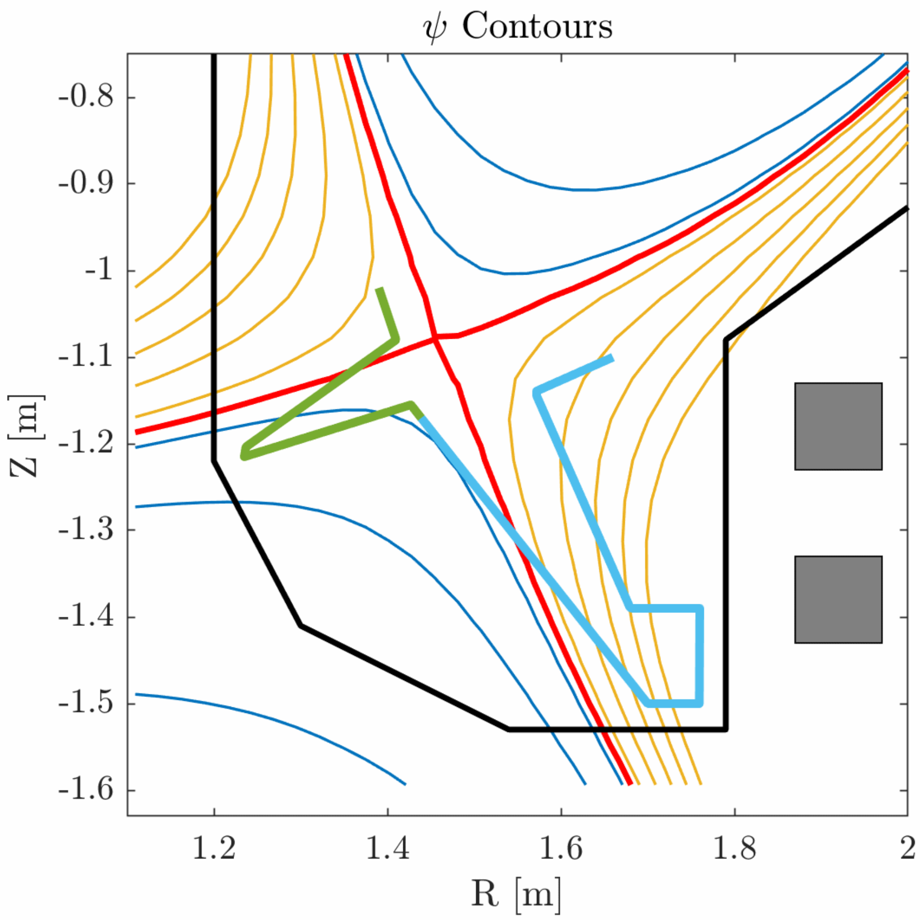
Compact and future FPPs will require advance divertor solutions



What are some challenges that tokamaks need to overcome?

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Another C-Mod Discharge

What are some challenges that tokamaks need to overcome?

Another C-Mod Discharge

Disruptions are abrupt discharge termination due to loss of confinement

Could be caused due to

- internal factors (plasma instabilities)
- external factors (failure in a component)

Plasma energy is released in the ms time-scale with potential damage to the device

What are some challenges that tokamaks need to overcome?

If it helps, let's think in terms of TNT kilograms…

C-Mod:

Plasma energy $\lesssim 1$ MJ (~0.2 kg TNT) released in < 1-2 ms

SPARC:

Plasma energy ~ 100 MJ (~20 kg TNT) released in < 3-10 ms

ITER:

Plasma energy > 500 MJ (~100 kg TNT) released in < 1 – 100 ms

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Disruption physics focuses on

- **prediction / avoidance:** ML has a strong role here
- **Mitigation:** Massive gas injection or pellet injection to radiate as much energy as possible
- **consequences:** Thermal and electromagnetic loads
    - Vertical displacement events, runaway electrons, thermal and fast particle flux

Summary and final remarks...

Plasma Science & Fusion Center

So far, we briefly covered...

- what tokamaks are and why the have the shape they have
- how a discharge and the plasma equilibrium look like
- the path towards fusion pilot plants based on the tokamak approach.
- Disruptions in Tokamaks

Many open areas of research (my very limited list):

- **Integrated modeling**
- **MHD, control and disruption physics**
- **Core and edge Turbulent transport**
- **Boundary physics and plasma-wall interaction**

Reach out at www.psfc.mit.edu!

Thanks!