

Tokamaks and Tokamak Physics

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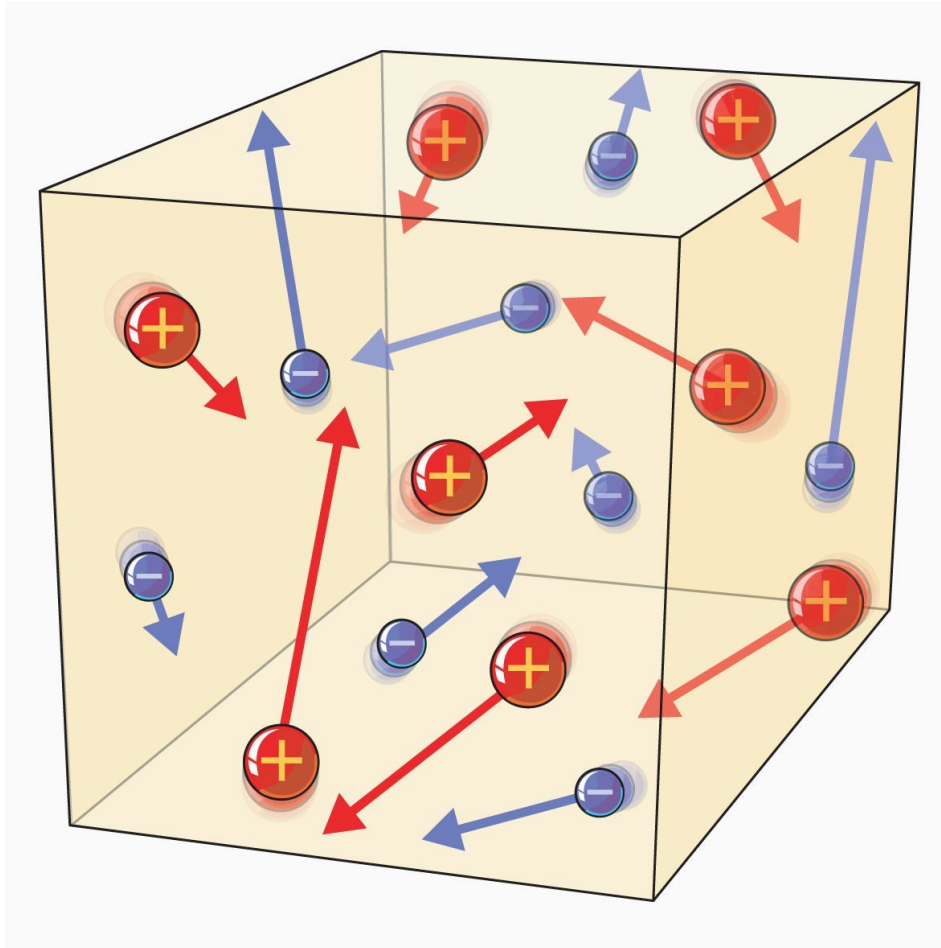
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Learning outcomes

- Describe/recap plasma motion in electromagnetic fields
- Define toroidal and poloidal fields in tokamaks \Rightarrow device setup and plasma geometry
 - Tokamak = Toroidal'naya Kamera s Magnitnymi Katushkami (= Toroidal chamber with magnetic coils)
- Understand tokamak startup and flattop phases: how is a tokamak operated? What does a tokamak plasma look like?
- Be familiar with principal configurations: limiter and diverted configurations

At fusion-relevant temperatures, a plasma of unbounded ions and electrons exists

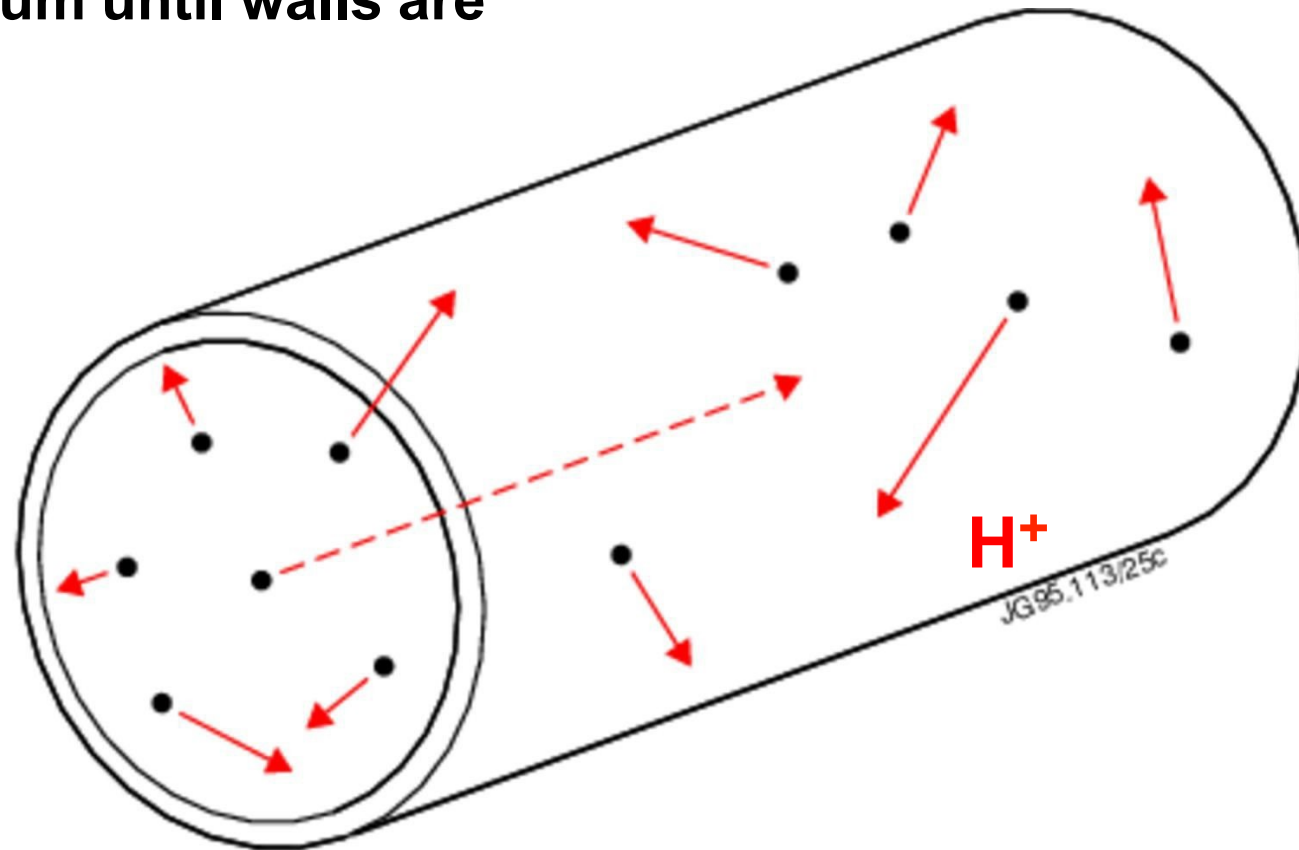
From lecture 2:



- **Outside the Debye sphere, plasmas are electrostatically neutral**
- **Plasmas need to be constrained, or confined to remain hot**
 - **Magnetic fields**
 - **Inertia**
 - **Gravity**

(Also in a cylindrical system) charges particles will eventually leave the confinement system

- Plasma particles expand into vacuum until walls are reached

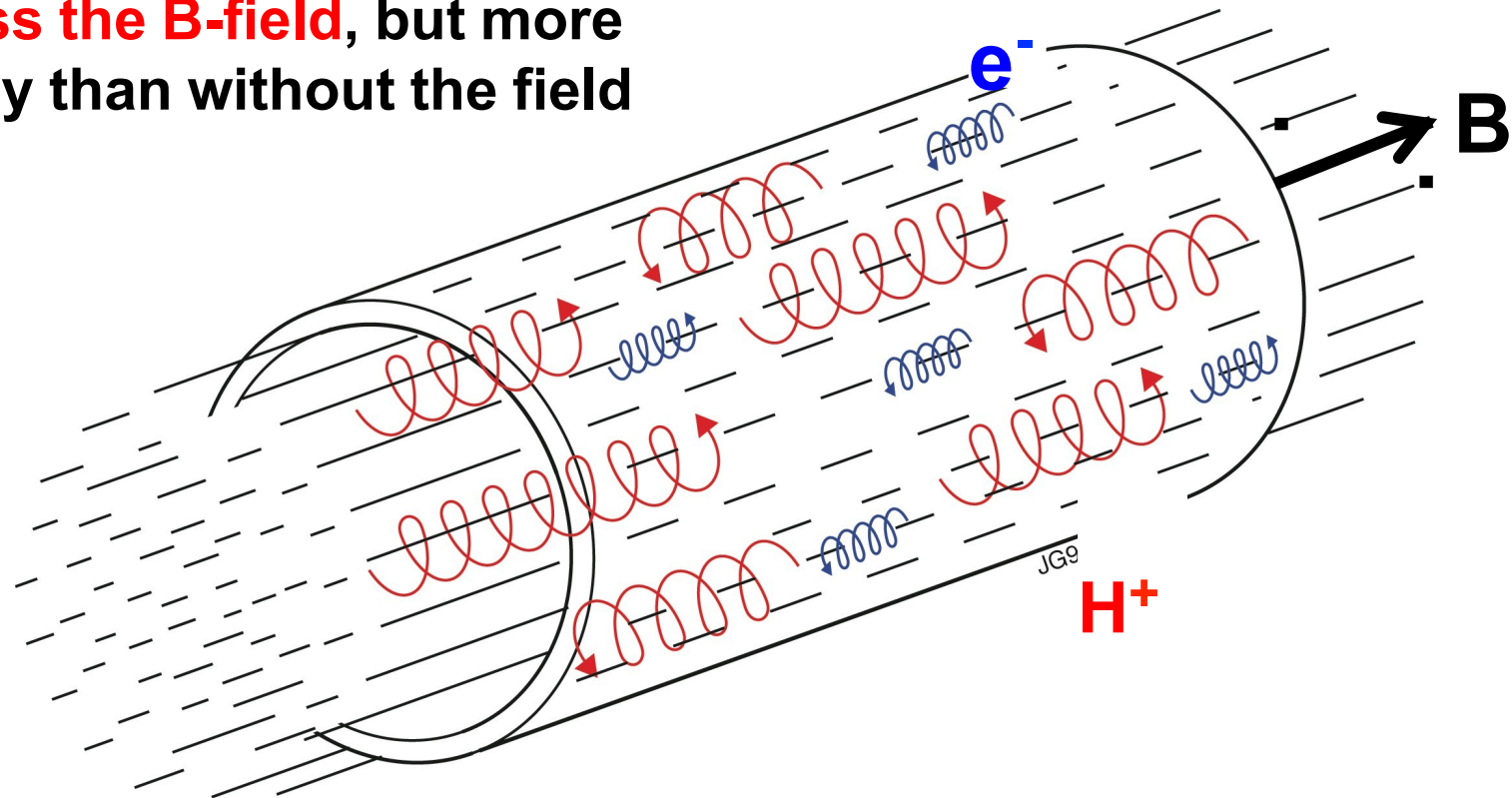


Applying a homogenous and axisymmetric magnetic field confines the particles to field lines

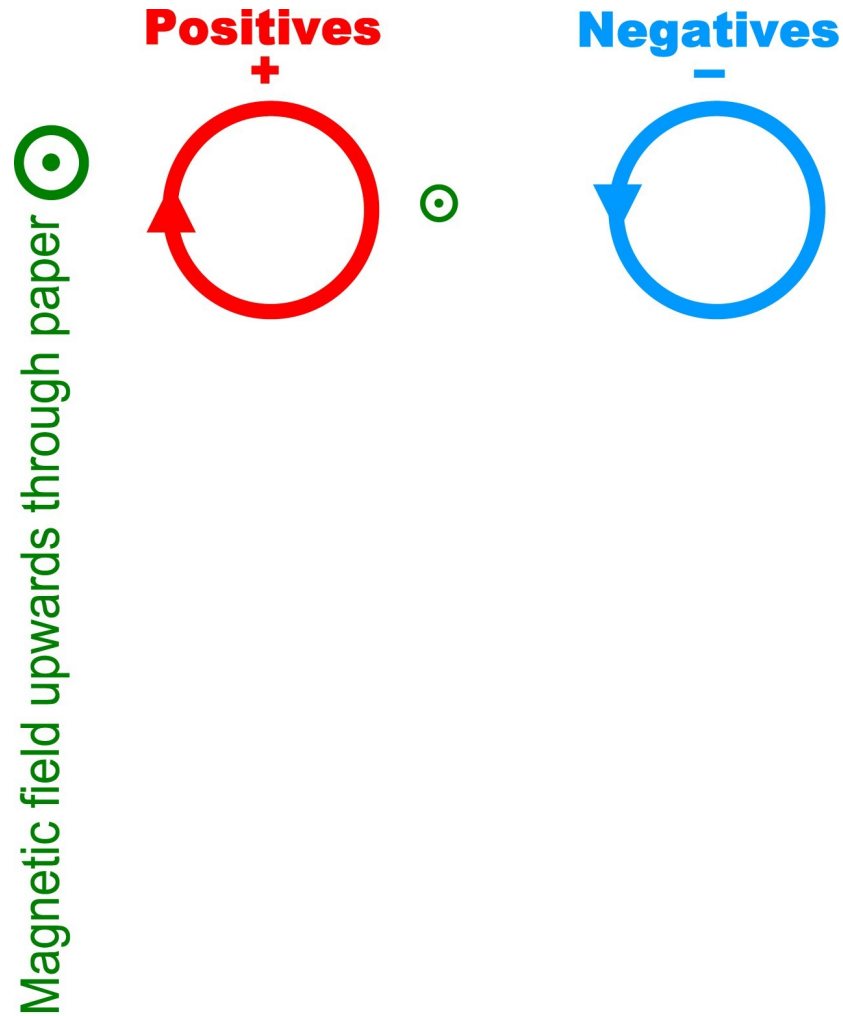
- Particles move along field lines and gyrate around them given by their Larmor radius:

$$r_L = \frac{m v_{\perp}}{eB}$$

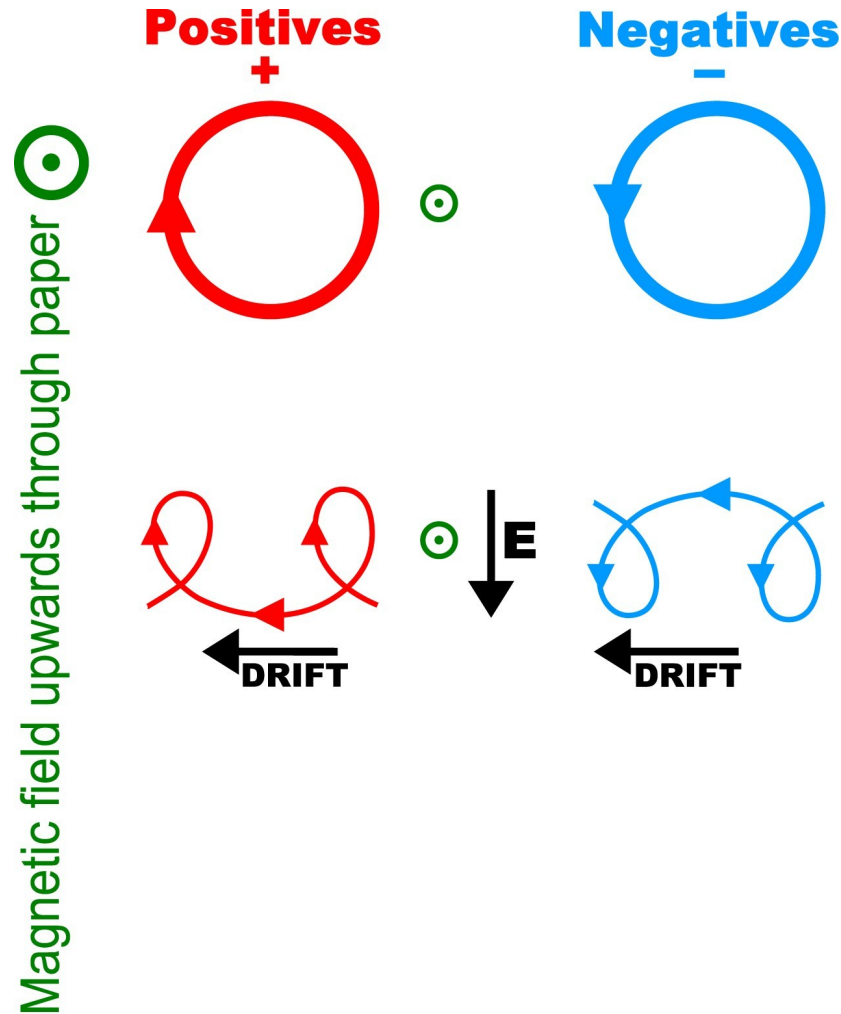
- **Yet, particles still move across the B-field**, but more slowly than without the field



Electric fields and inhomogeneous magnetic fields lead to cross-B field drifts



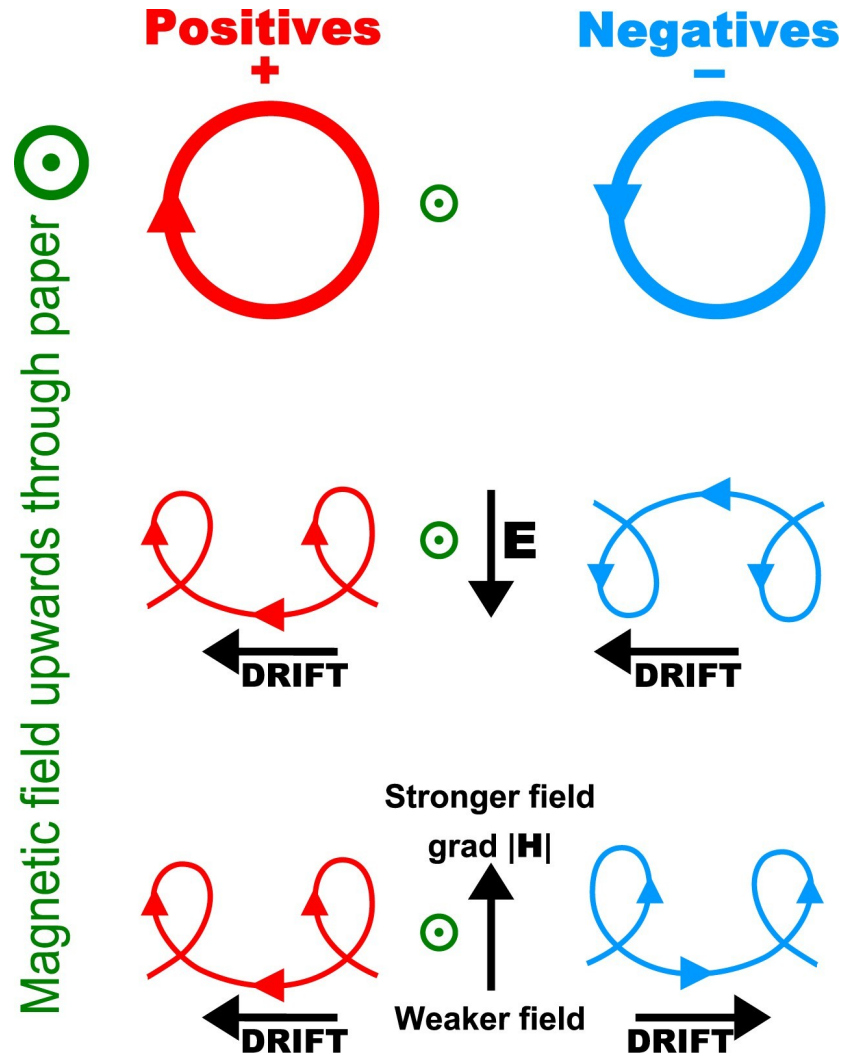
Electric fields and inhomogeneous magnetic fields lead to cross-B field drifts



- **Non-field aligned electric fields (charge-independent!):**

$$\vec{v}_{ExB} = \frac{\vec{E} \times \vec{B}}{B^2}$$

Electric fields and inhomogeneous magnetic fields lead to cross-B field drifts



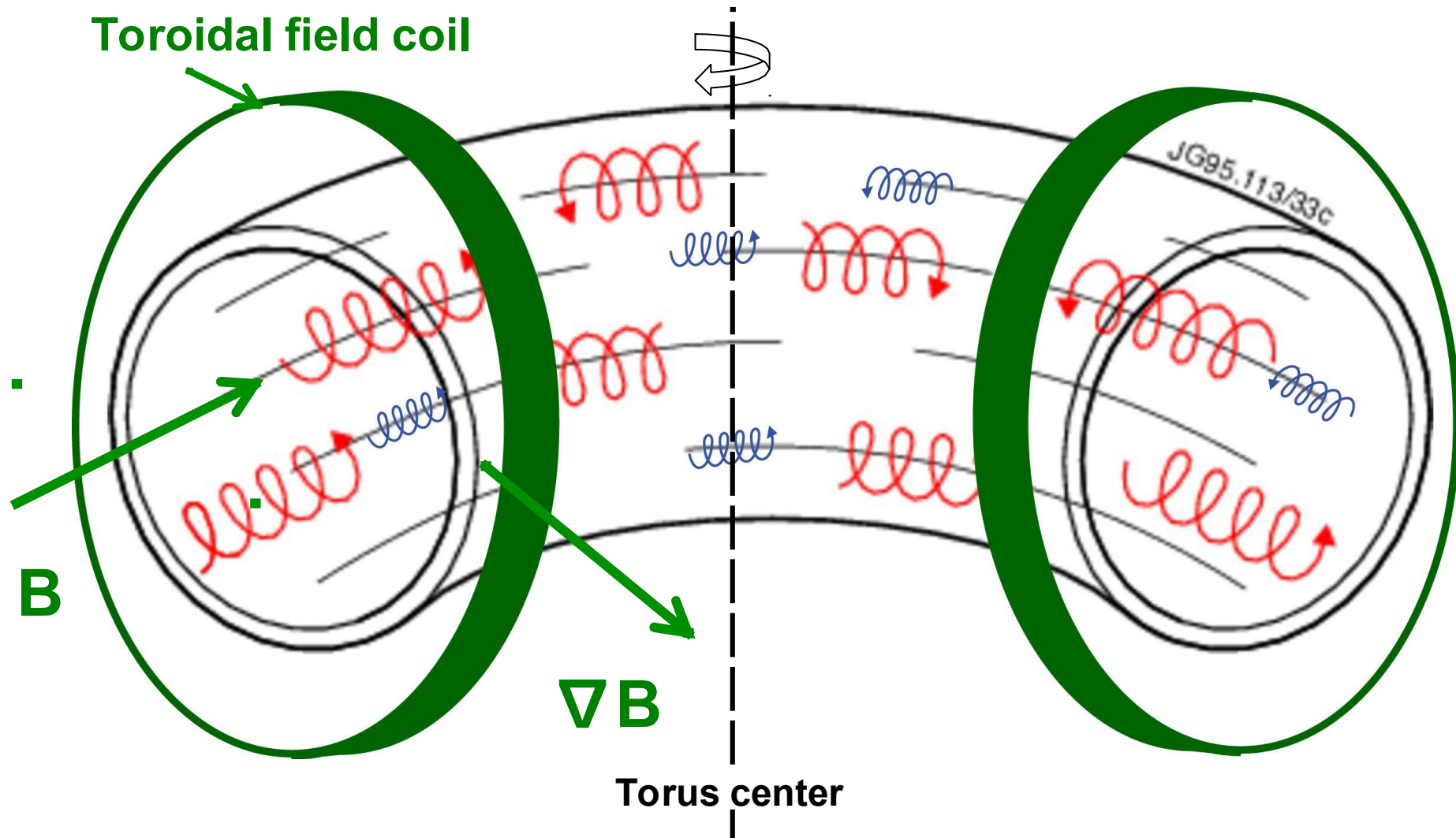
- **Non-field aligned electric fields (charge-independent!):**

$$\vec{v}_{E \times B} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

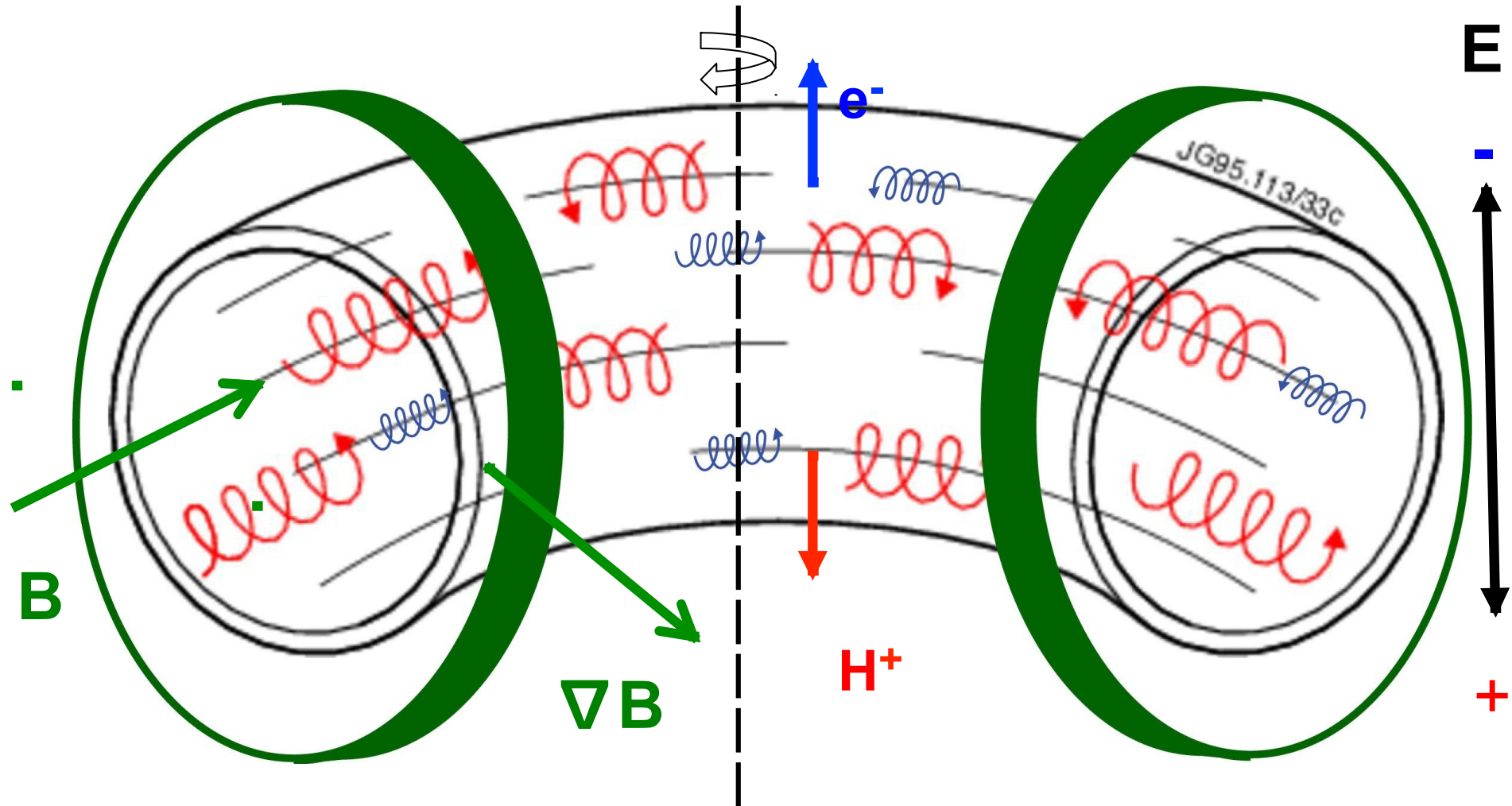
- **Inhomogeneous B-field \Rightarrow ions and electrons drift in opposite directions \Rightarrow charge separation \Rightarrow electric field:**

$$\vec{v}_{\nabla B} = \frac{m_{e,i} v_{\perp}}{2e_{e,i} B} \frac{\mathbf{B} \times \nabla B}{B^2} v_{\perp}$$

Connecting the two ends of a cylinder forms a closed system, i.e., a torus



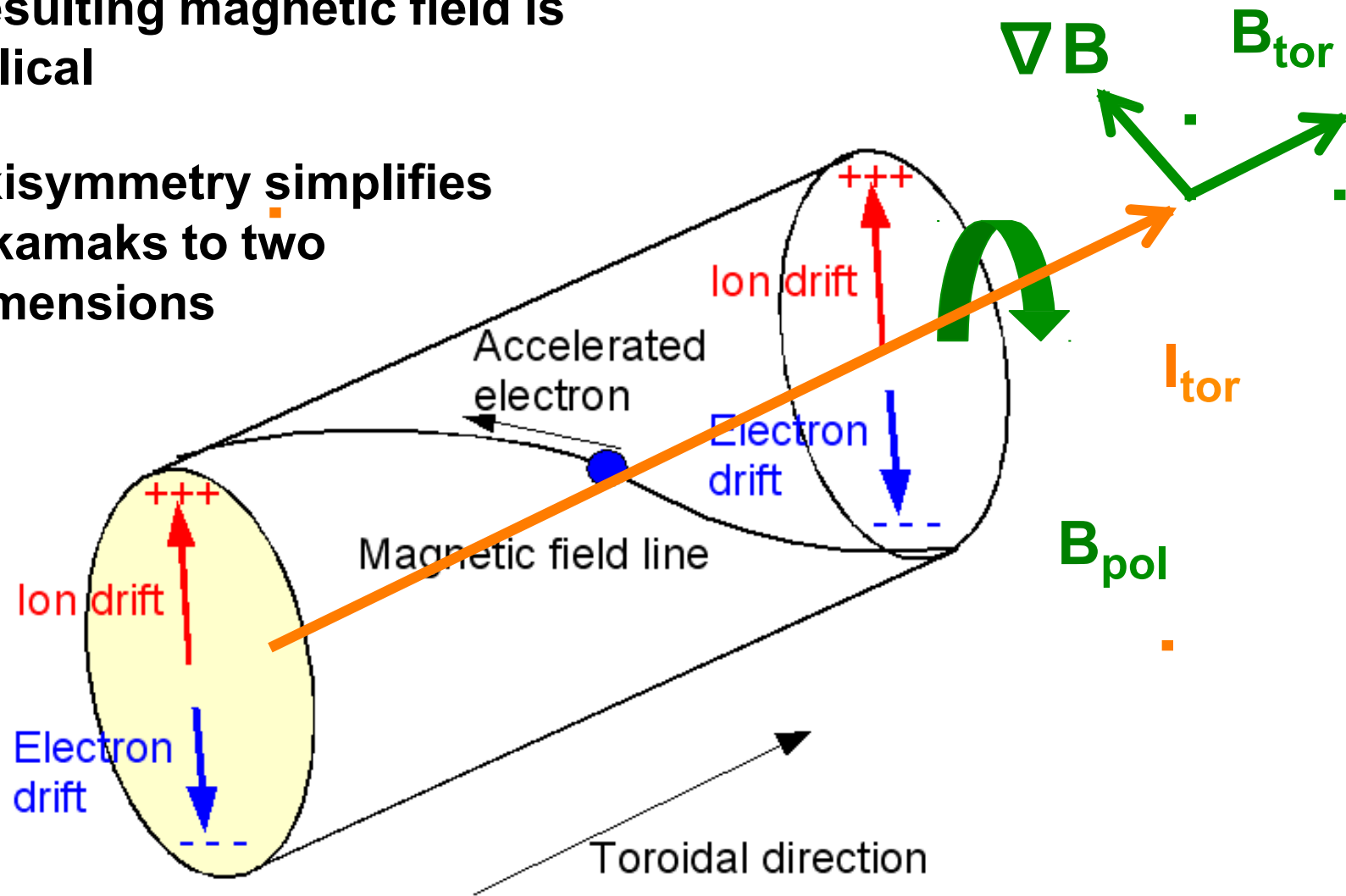
A purely toroidal system will lead to (up-down) charge separation and ∇B radial outward drifts



⇒ Short-circuit of up-down charge separation is required

A poloidal magnetic field produced by an electric current cancels the top-bottom charge separation

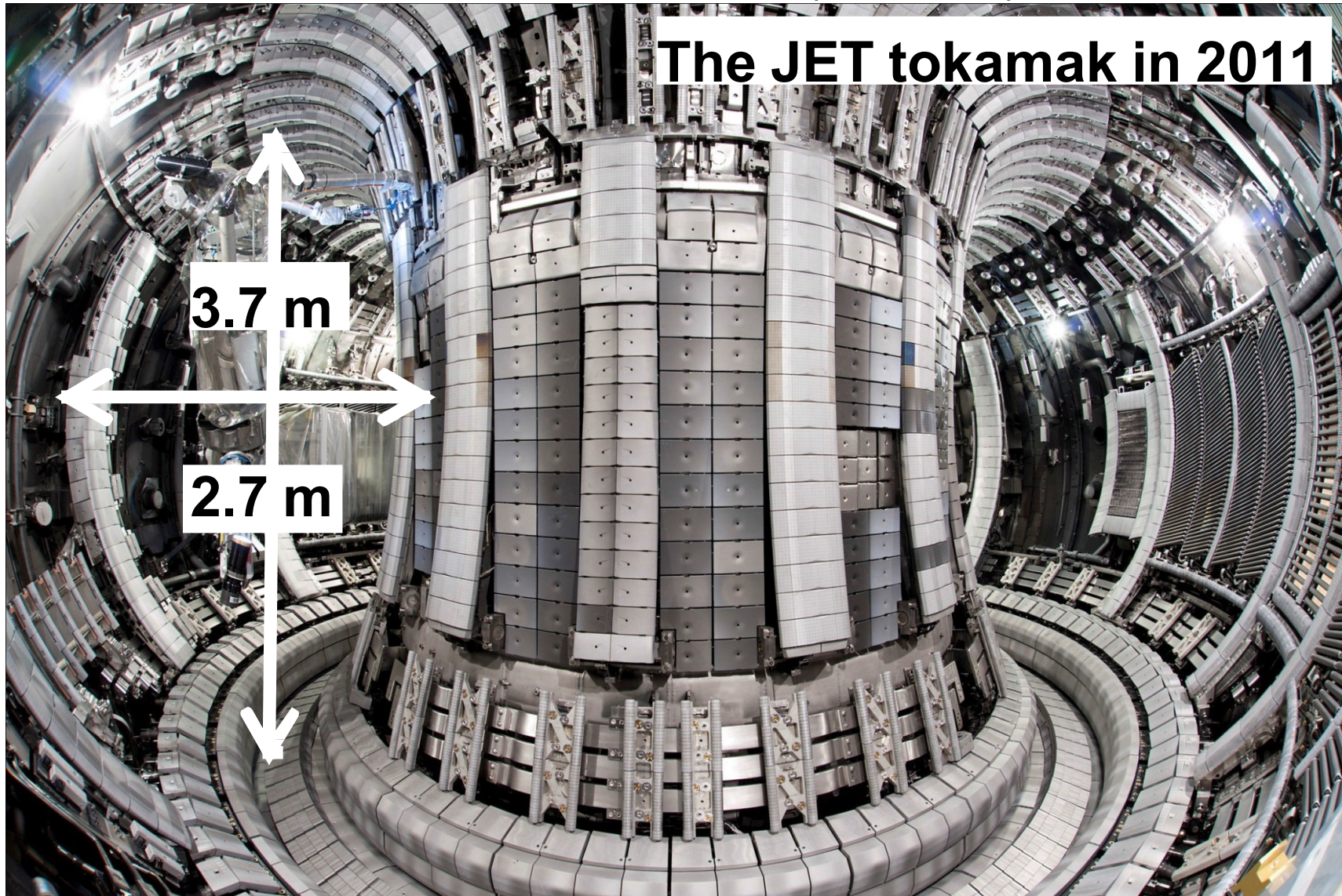
- Resulting magnetic field is helical
- Axisymmetry simplifies tokamaks to two dimensions





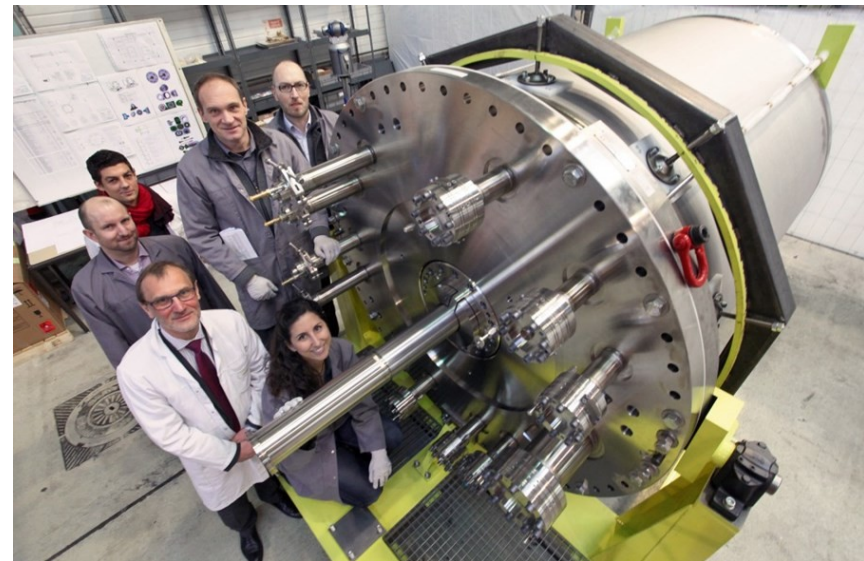
Technical realization

A plasma is created and contained in a vacuum chamber at a base pressure $\approx 10^{-6}$ to 10^{-5} Pa
(10^{-8} – 10^{-7} atm)



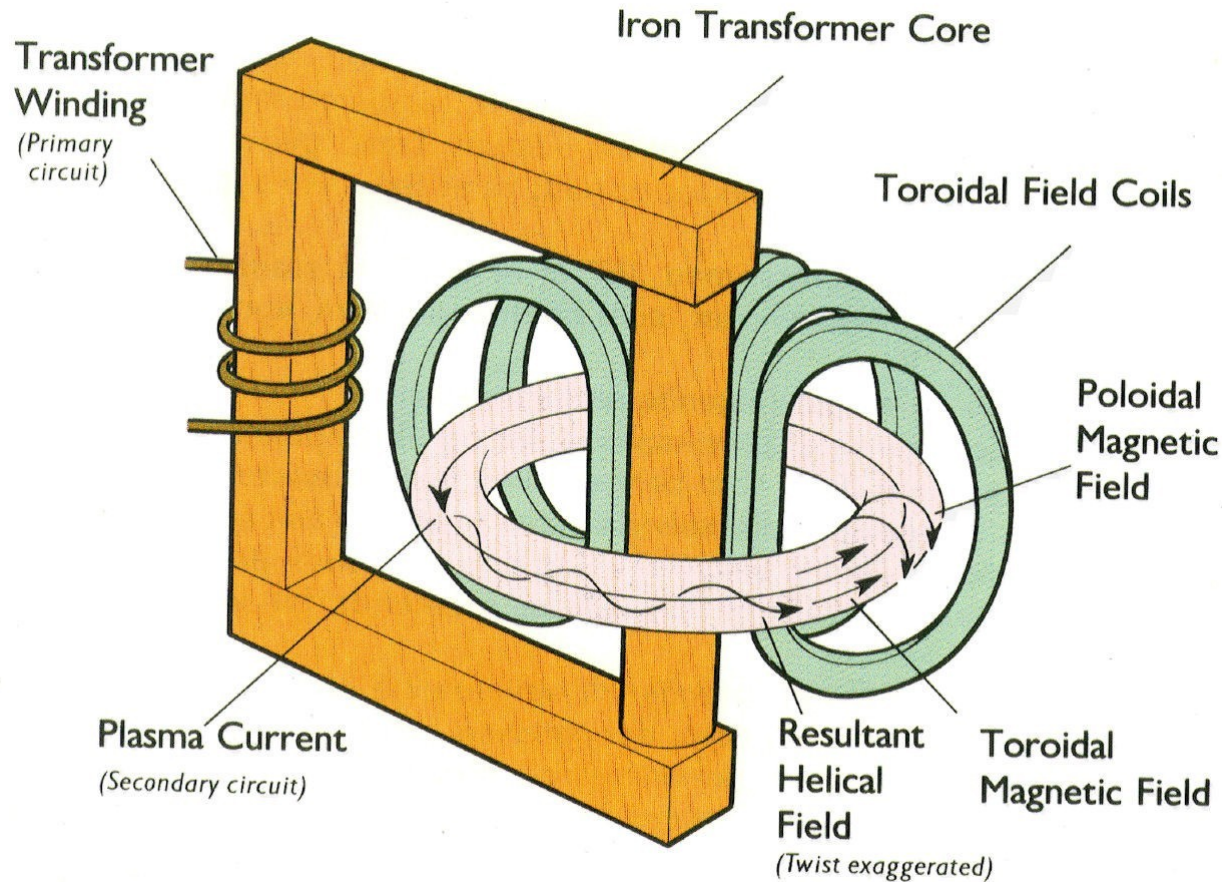
A plasma is created and contained in a vacuum chamber at a base pressure $\approx 10^{-6}$ to 10^{-5} Pa

- Vacuum pumping is required (prior to start) to eliminate all sources of organic molecules
- It is also required to create low density—about one million times lower than the density of air.
- Mechanical/cryogenic pumps evacuate the air out of the vessel and the cryostat
- E.g in ITER, this operation will take 24 to 48 hours.



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In a tokamak, a transformer-induced current in the plasma generates a poloidal field



- **External toroidal field**

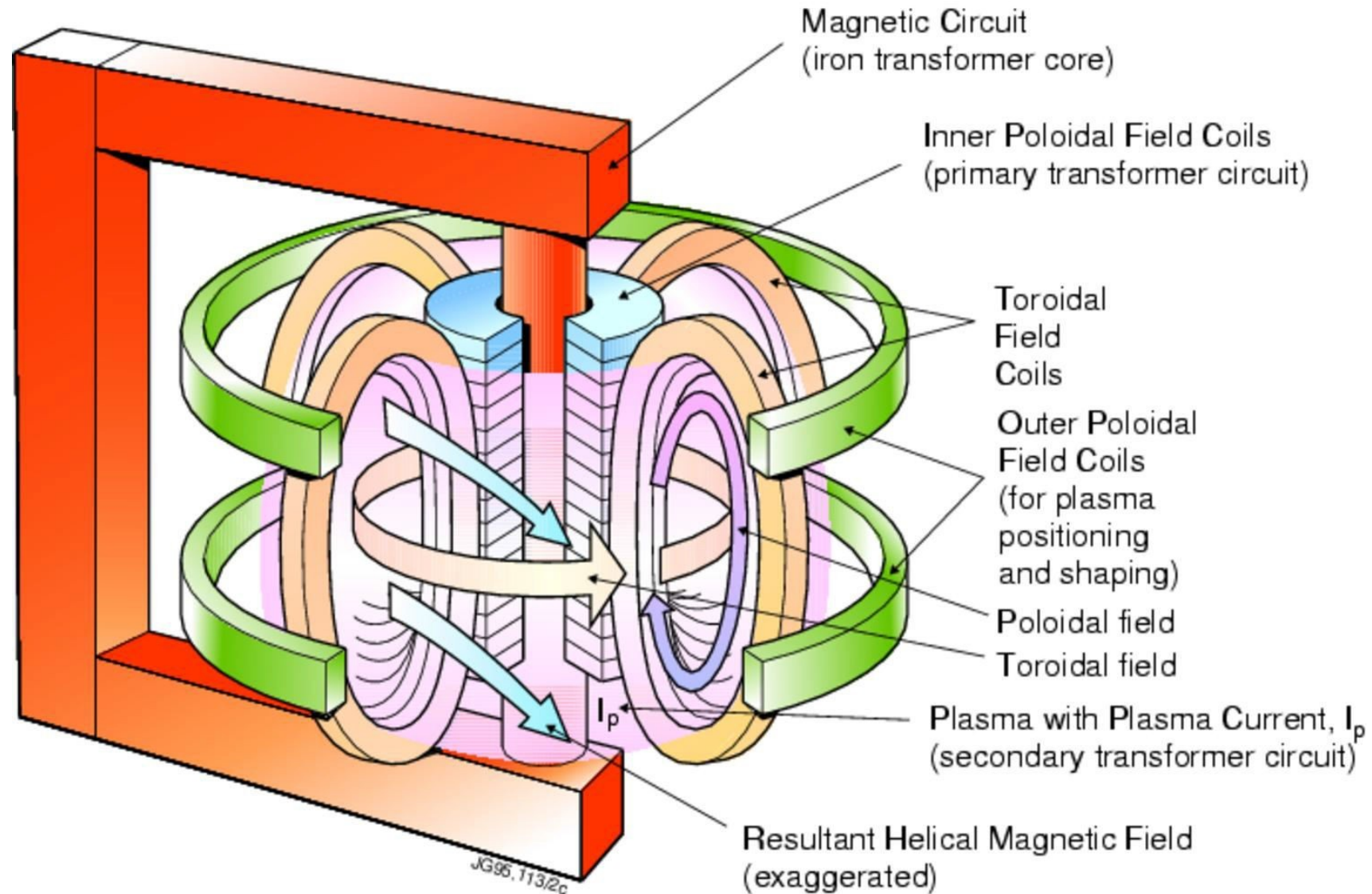
→ **Question: # of coils?**

Transformer winding
⇔ **plasma acts as secondary circuit**

- **Toroidal + poloidal fields ⇒ helical field**

Toroidal'naya Kamera s Magnitnymi Katushkami

An additional set of poloidal field coils are needed to plasma positioning and shaping

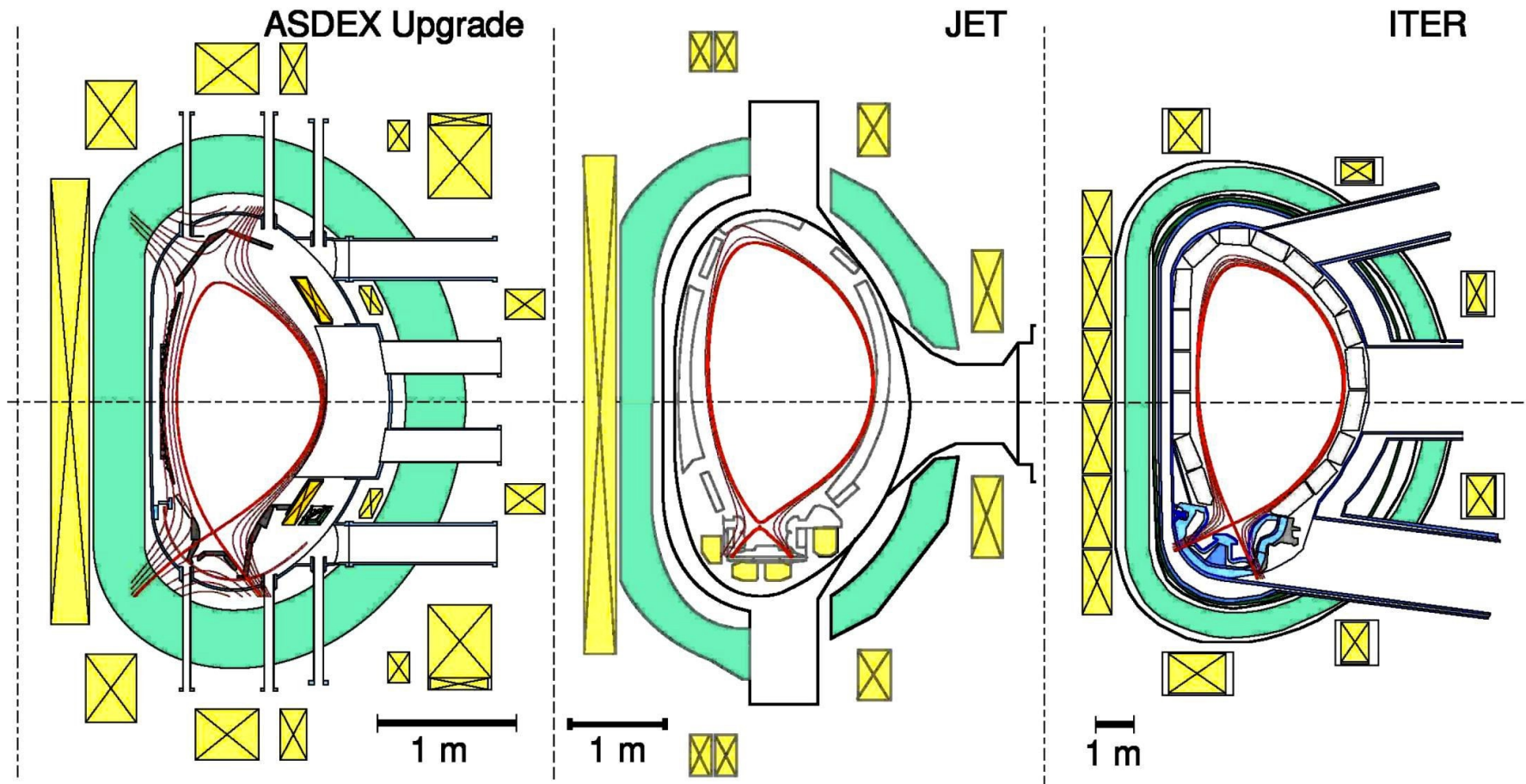


A larger number of toroidal field coils reduces the toroidal field inhomogeneity (toroidal ripple)

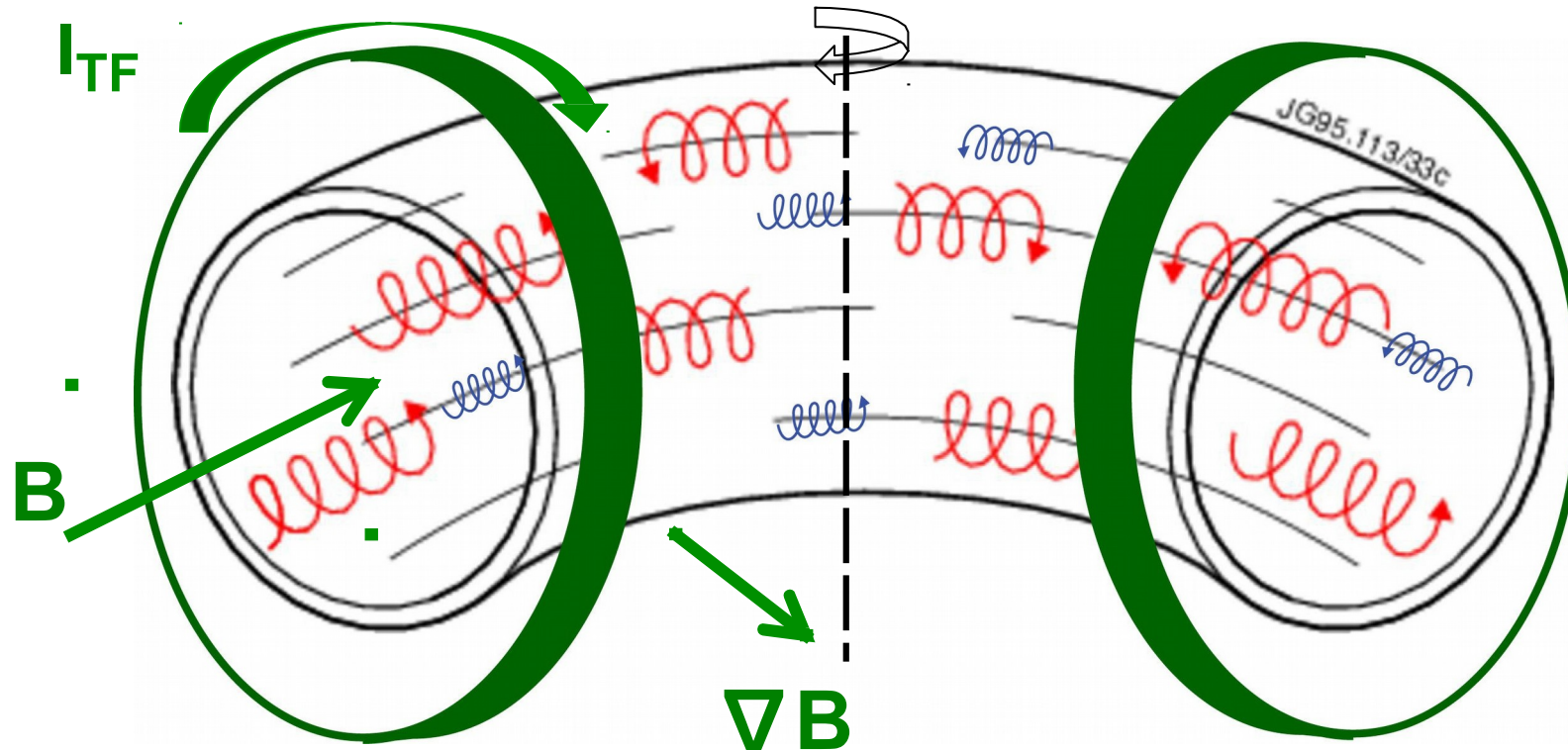
Major Radius **16 / 0.8%**
R = 1.65m

32 / 0.08%
R=3m

18 / 1.0%
R=6.2m



The toroidal field exhibits $1/R$ dependence, which leads to trapping of particles on the low field side



• Toroidal magnetic field strength by Ampere's law:

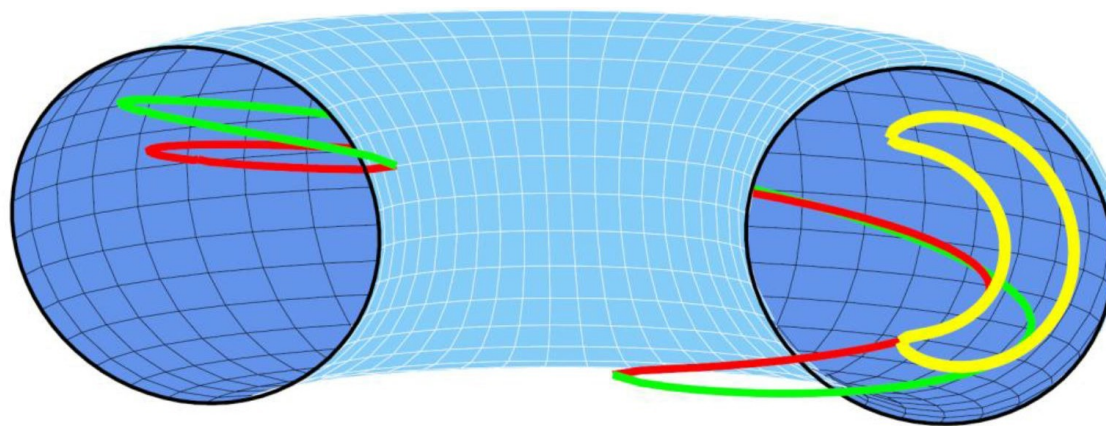
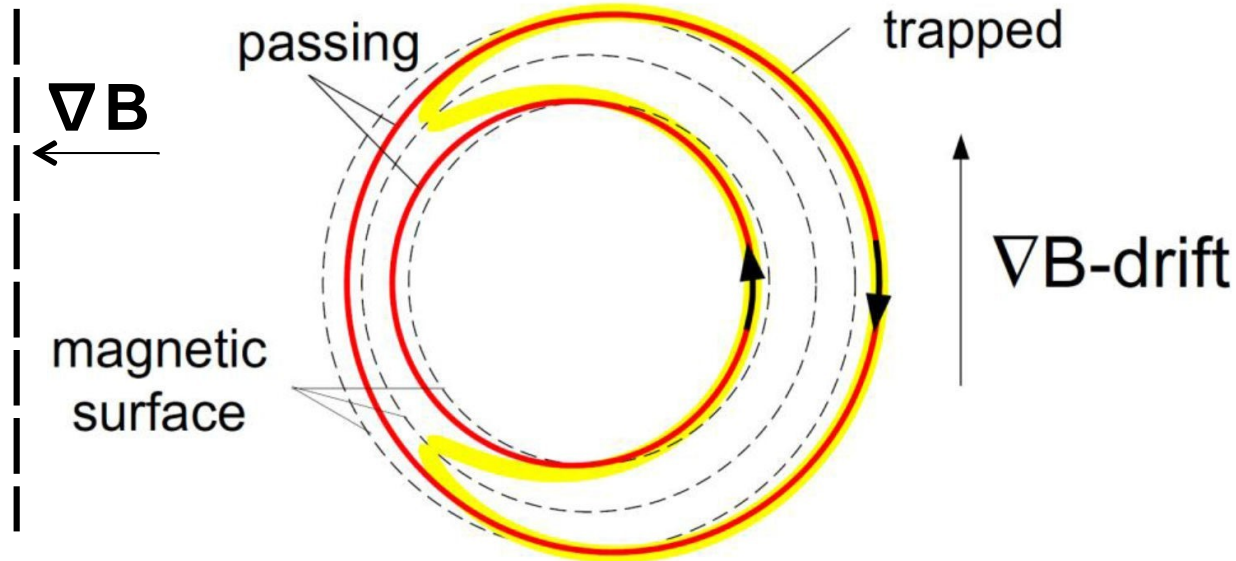
$\Rightarrow B_T$ non-uniform in R :

$$\nabla \times B = \mu_0 I_{TF} \Rightarrow B_T = \frac{\mu_0 I_{TF}}{2\pi R}$$

$$\frac{\Delta B_T}{B_{T,0}} \approx \frac{2R_{\text{minor}}}{R_0} \approx \frac{3}{4}$$

Particles moving into the higher magnetic field can be reflected (mirror effect)

Torus center



- **Trapping, if:**

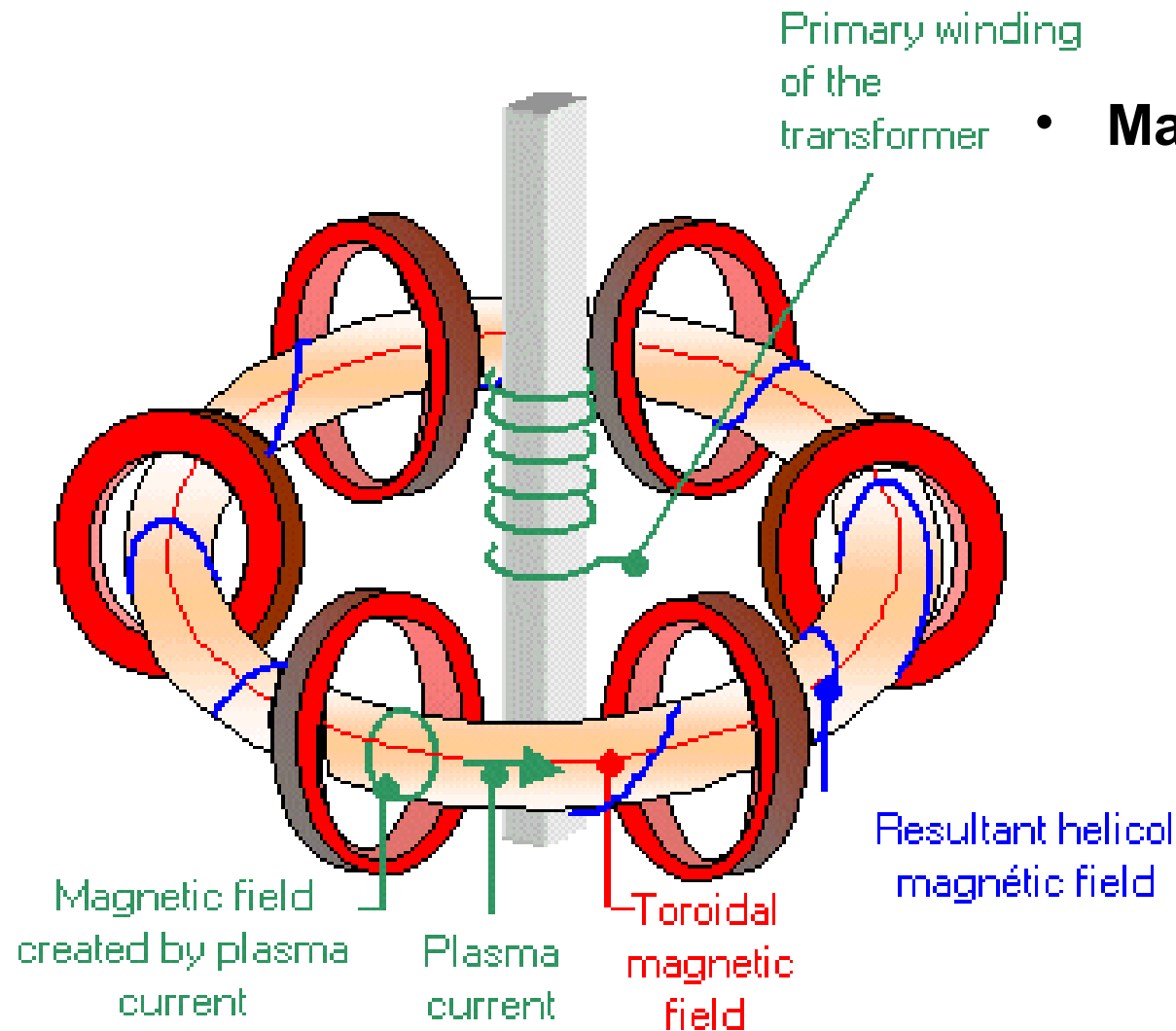
$$\frac{v_{||,0}}{v_{\perp,0}} \leq \sqrt{2 \frac{r}{R_0}}$$

- **Guiding center drifts lead to banana shaped orbits**
- **Orbits are wide compared to “classical” gyro-orbits → neoclassical transport**

Inductive start-up of the plasma

- **In present day tokamaks, the main technique to initiate breakdown and drive a toroidal current is use of a central solenoid that supplies magnetic flux and induces a toroidal electric field.**
- **Typically, before start-up, hydrogen or deuterium gas is injected into the vacuum vessel and the solenoid is precharged with a current in the desired direction of the plasma current.**
- **Start-up phase also heats the plasma (Ohmic heating)**

A time-varying current in the transformer primary induces a toroidal electric field \Rightarrow plasma current



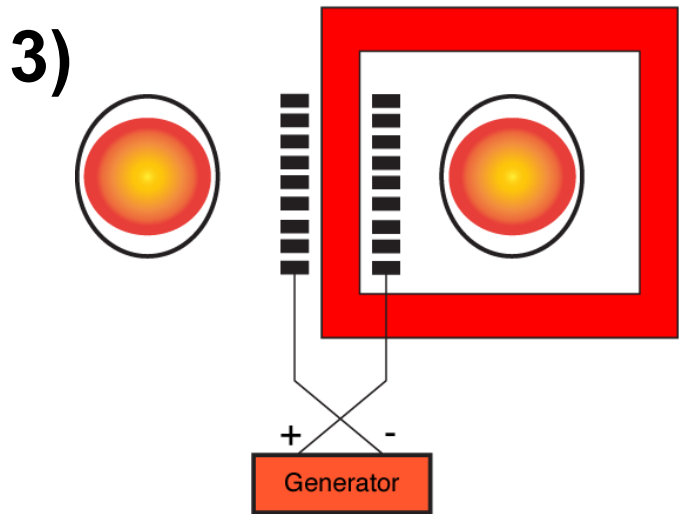
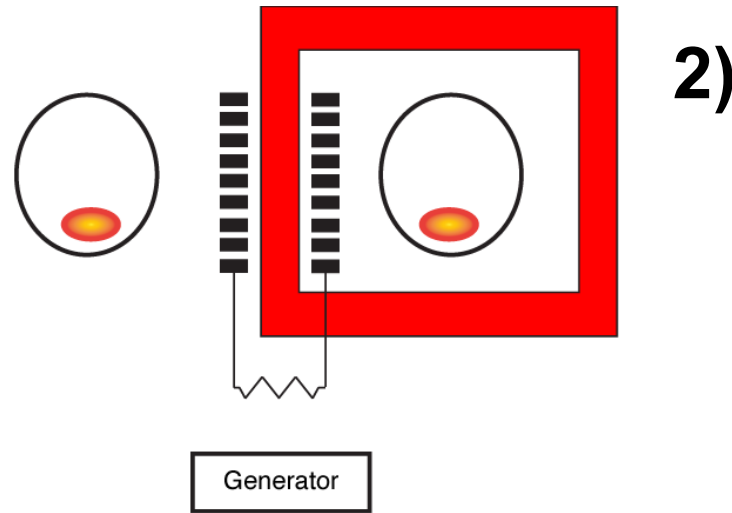
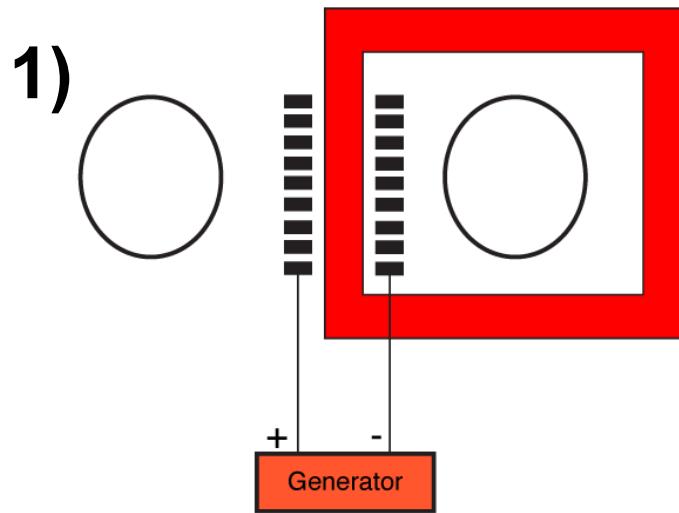
- **Maxwell-Faraday:**

$$-\frac{\partial B}{\partial t} = \nabla \times \vec{E}$$

\Rightarrow **Tokamaks are pulsed devices**

- **Electric field drives plasma ion in one direction, electrons in the opposite \Rightarrow collisions heat plasmas**

The current in primary coils is ramped down, then up, to break down the plasma and to drive the current



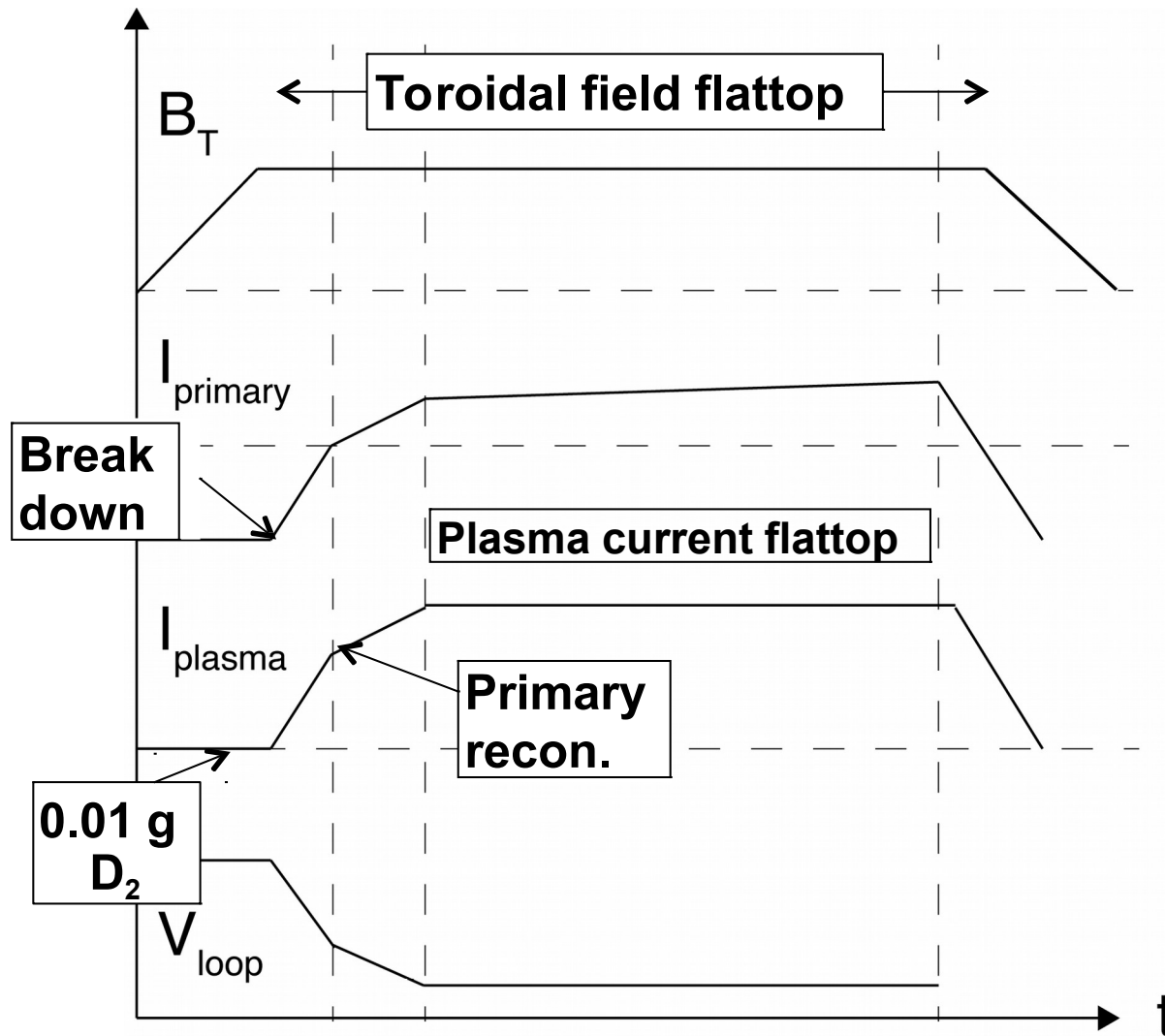
1) Pre-magnetization of primary poloidal field coils

2) Plasma break-down at $I_{\text{primary}} = 0$

3) Reconnection and re-direction of

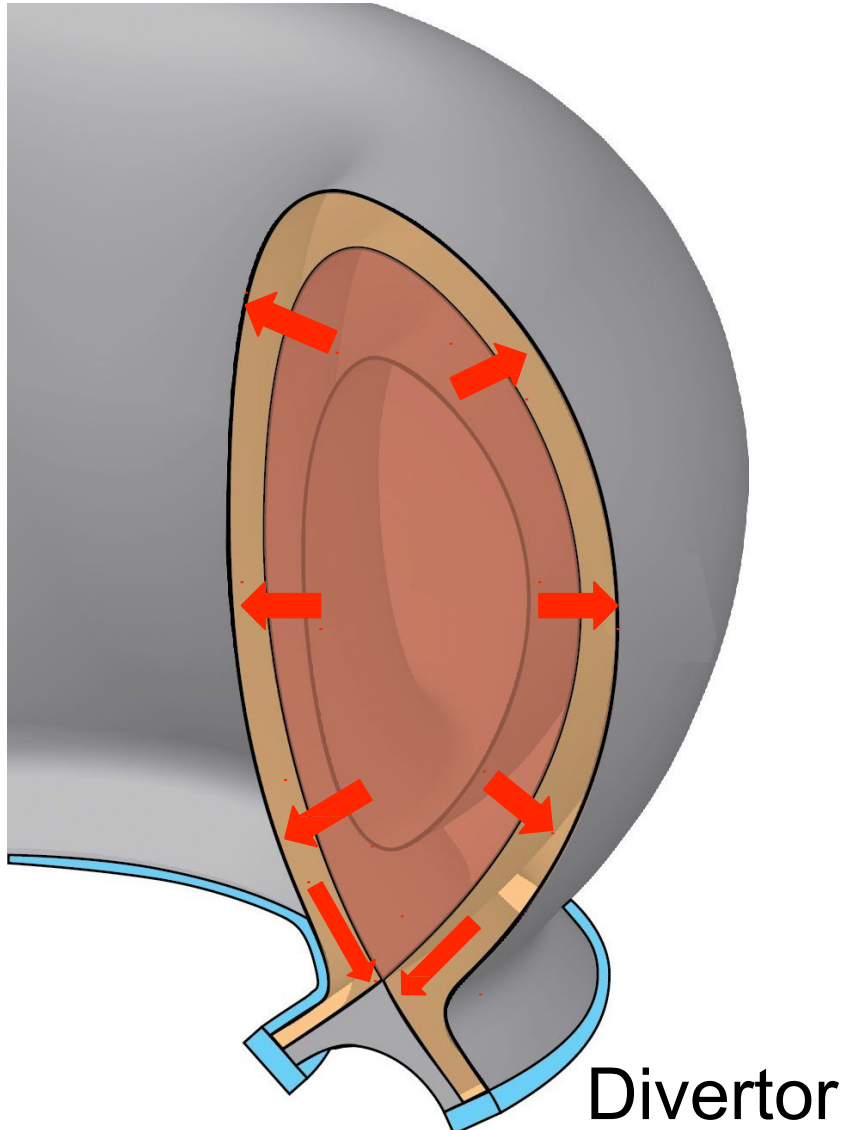
I_{primary}

The current in primary coils is ramped down, then up, to break down the plasma and to drive the current

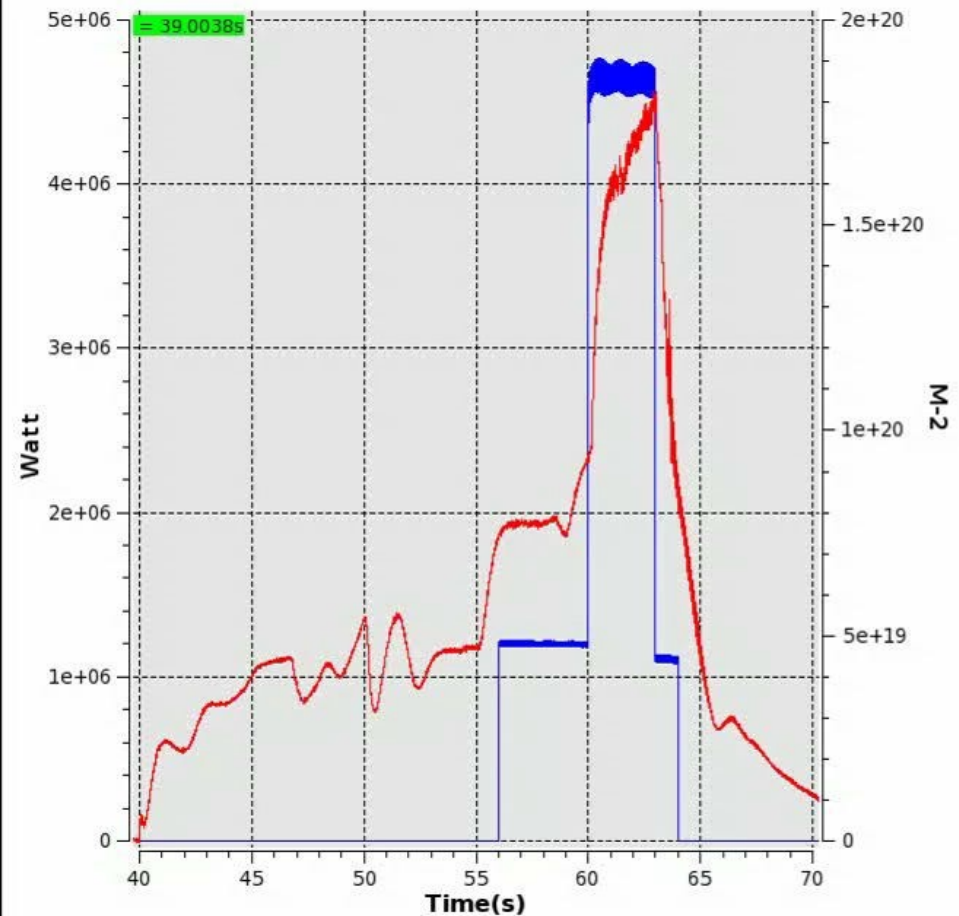


- Tokamaks are pulsed devices
- Change in I_{primary} determines I_{plasma}
- Resistivity ($\sim T^{-3/2}$) of the plasma limits I_{plasma} flattop phase

In diverted configurations, the main plasma-wall interaction is at the bottom \Rightarrow hydrogen emission



Typically, the interaction of the plasma with the wall is imaged \Rightarrow excitation of hydrogen atoms

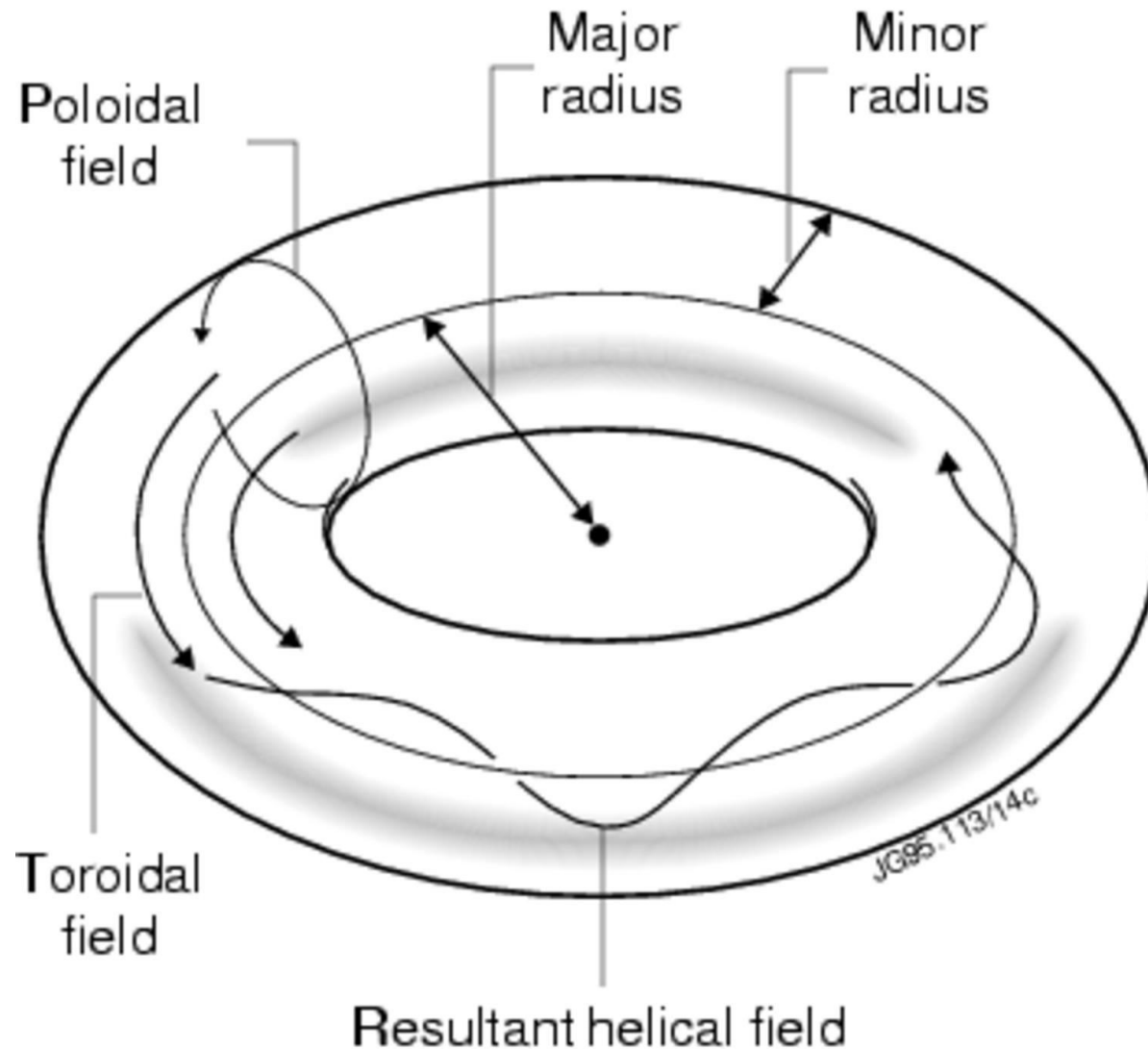


Plasma in JET: <https://www.youtube.com/watch?v=IS9YBmgcHX4>



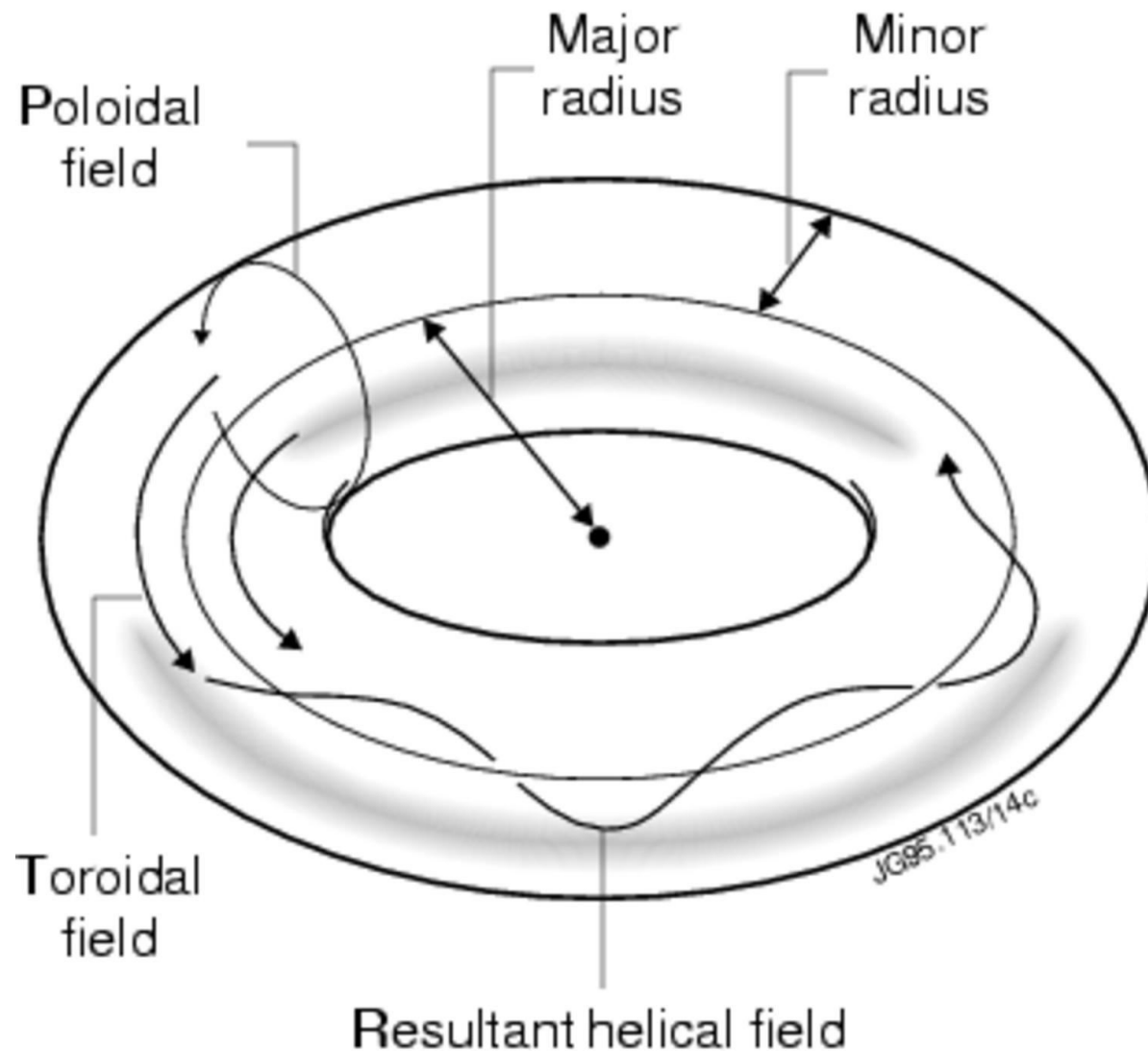
Tokamak fields, dimensions, currents and plasma configurations

Tokamaks are defined by their fields and currents, and their sizes



- **Toroidal fields (B_T) up to 5 T**
- **Plasma currents (I_p) up to 7 MA**
- **Poloidal fields (B_P of conventional tokamaks) $\approx 1/10 B_T$**

Tokamaks are defined by their fields and currents, and their sizes



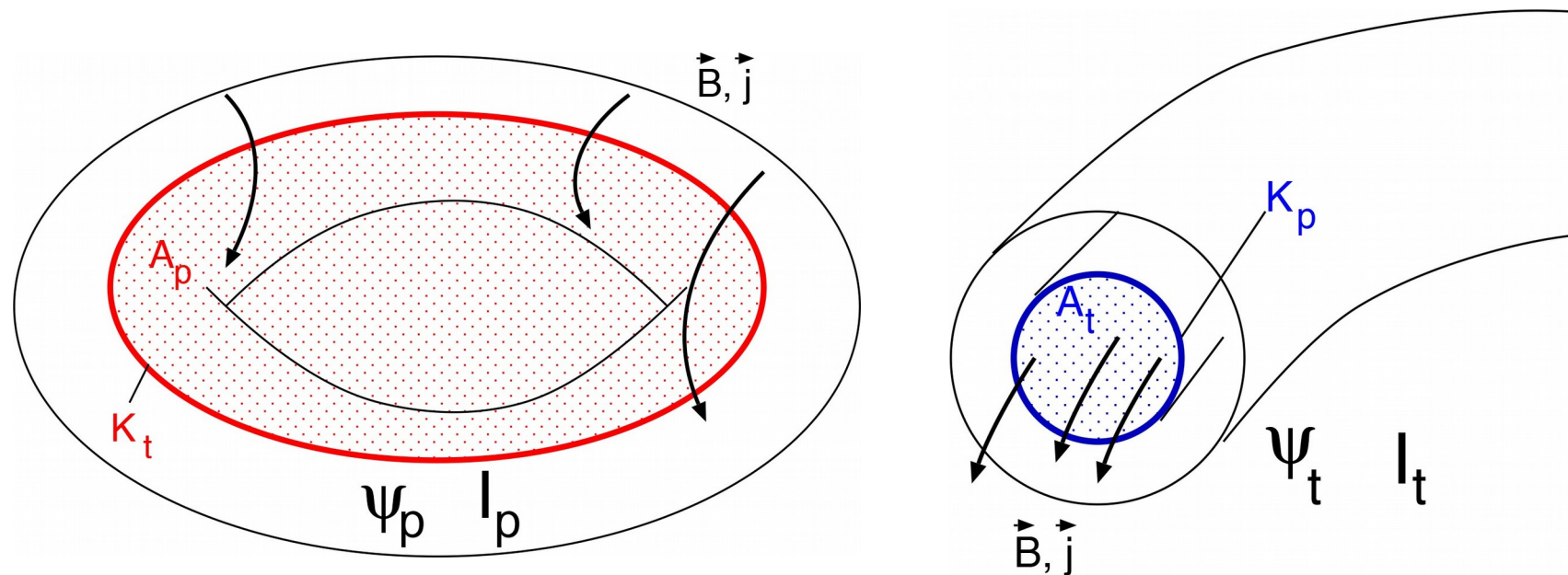
- **Major and minor radius up to 3 m and 1.5 m, respectively (6.2m and 2m for ITER)**

- **Aspect ratio:**

$$A \equiv \frac{R_{\text{major}}}{R_{\text{minor}}}$$

- **Conventional tokamaks: $A \approx 3$, spherical tokamaks $A \rightarrow 1$**

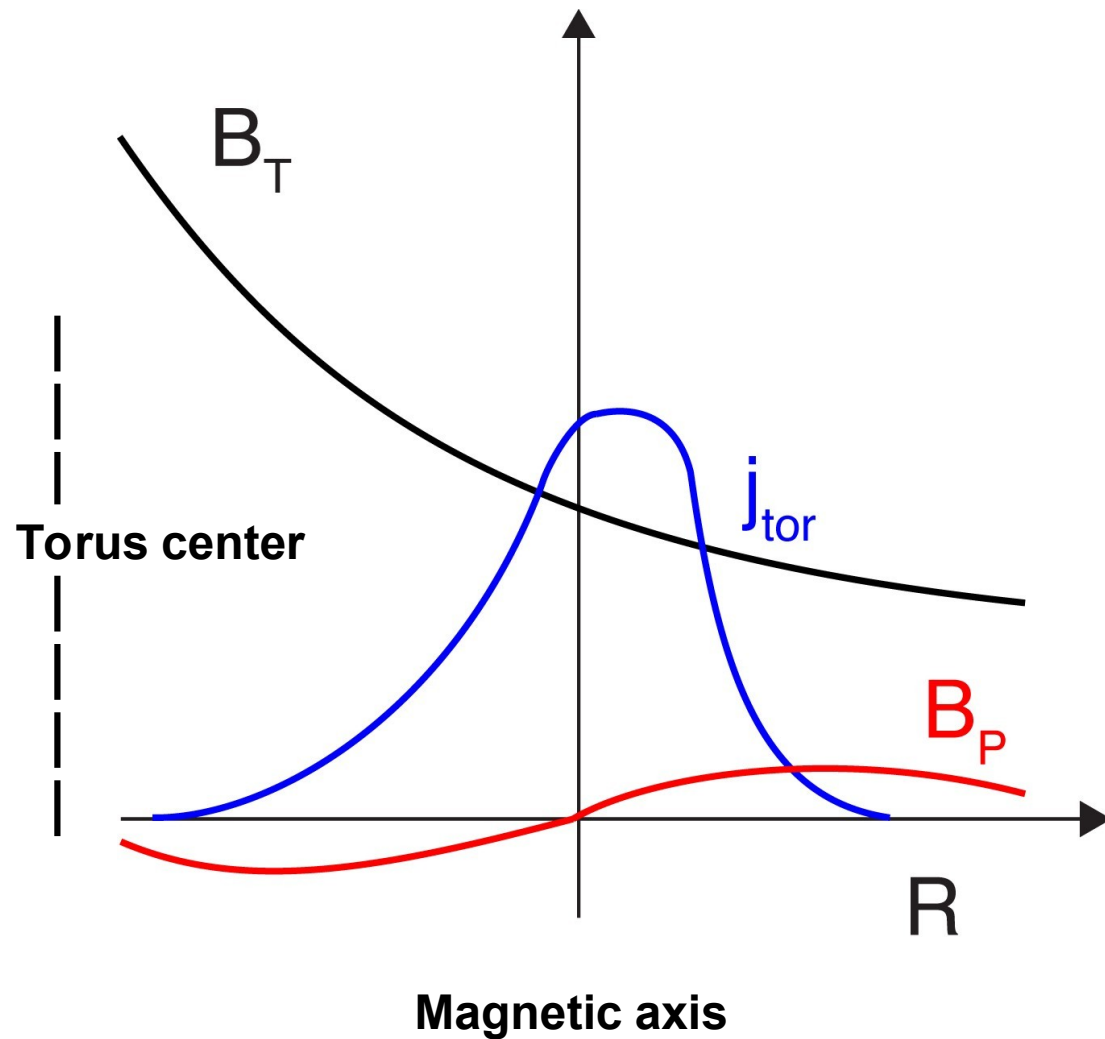
Magnetic surfaces can also be described by poloidal and toroidal fluxes



- Ψ_p through surface with normal A_p and boundary K_t
- Ψ_t through surface with normal A_t and boundary K_p

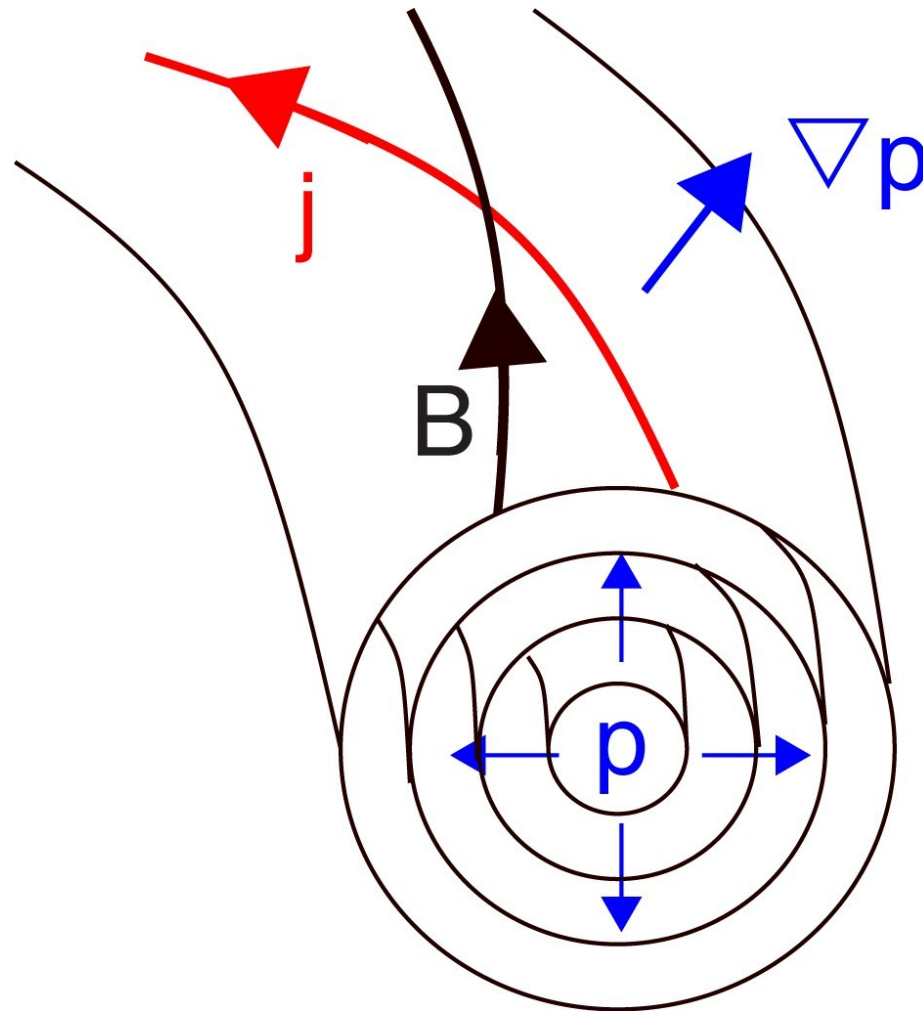
\Rightarrow Describe equilibrium by $(\Psi_p, I_p) \Rightarrow$ Grad-Shafranov equation

Tokamaks are defined by their fields and currents, and their sizes



- Toroidal magnetic field (B_T) peaks at the torus center and falls off radially ($1/R$)
- **Poloidal field (B_P)** is zero on the magnetic axis $\Rightarrow B_P/B_T \approx 1/10$
- **Plasma current density (j_{tor})**, up to MA/m² peaks on the magnetic axis \Rightarrow plasma current of the order MA's

The combination of toroidal and poloidal fields produces nested surfaces



- **Stationary equilibrium** determined by balance between **plasma pressure** and **magnetic force** (Grad- Shafranov equation):

$$j \times B = \nabla p$$

- **Efficiency of magnetic confinement** measured by

$$\beta \equiv \frac{p}{B^2 / 2\mu_0}$$

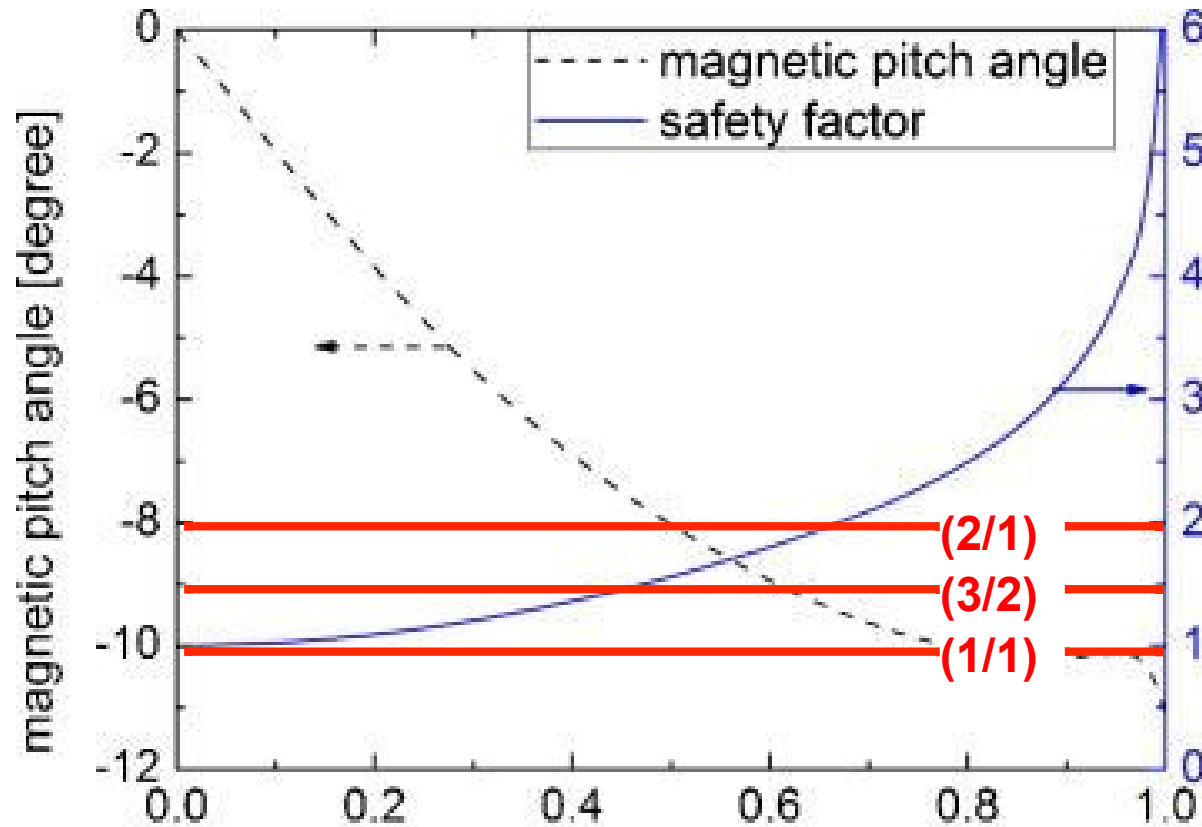
Plasma instabilities, or modes, are often localized on rational values of the safety factor (q)

- **Safety factor:**

$$q(r) \equiv \frac{rB_T(r)}{R_{major}B_P(r)}$$

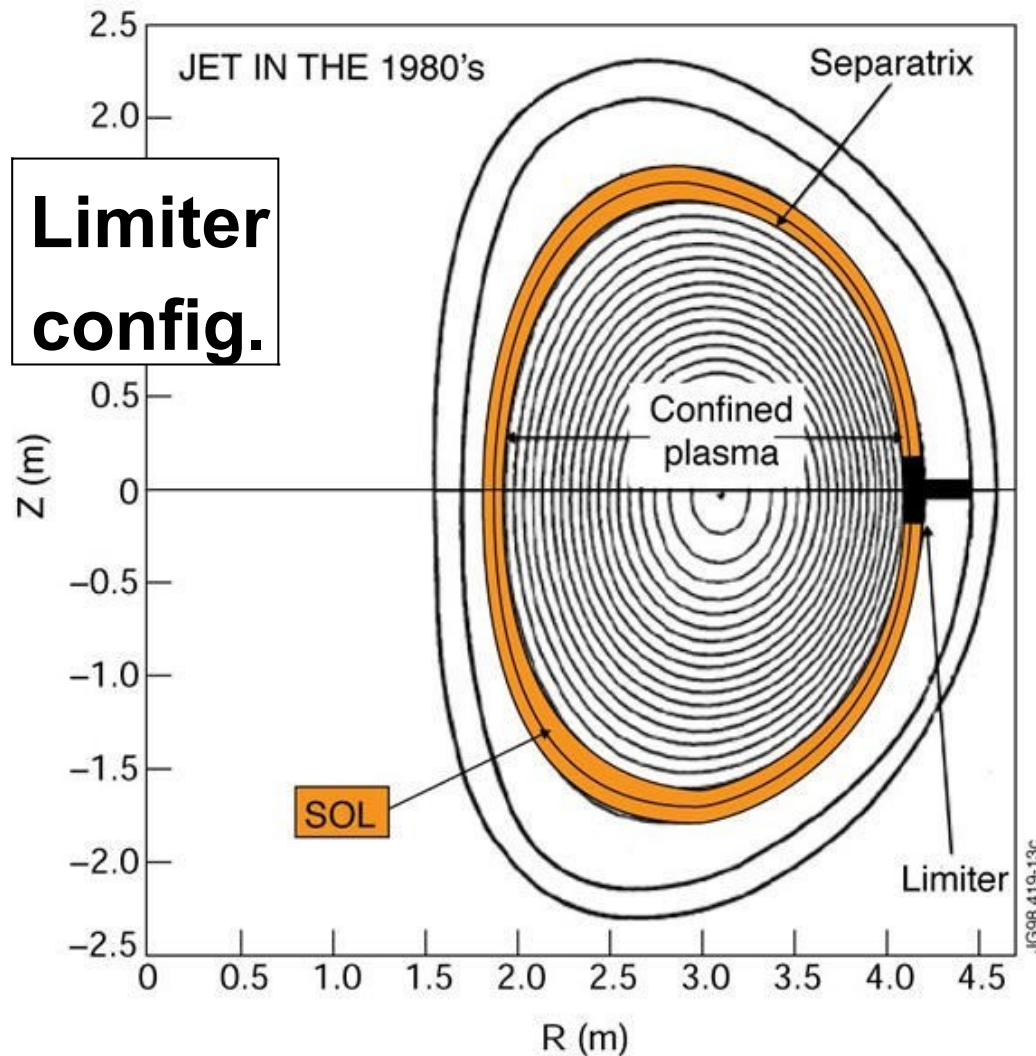
- Typically, $q(r)$ monotonically increase toward edge

- Instabilities grow on rational q values
 \Rightarrow toroidal and poloidal mode numbers n and m



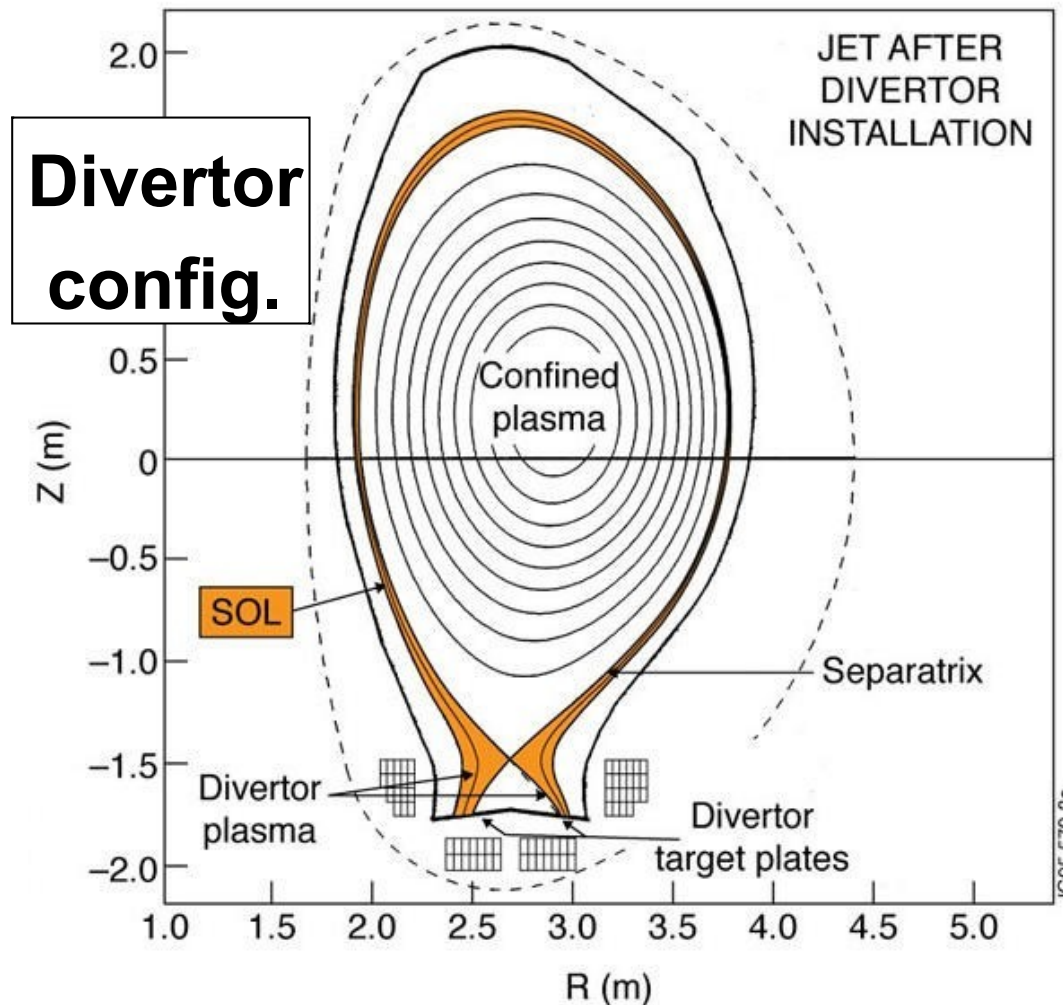
$$\rho \equiv r / R_{\text{minor}}$$

The most basic magnetic configuration is an axisymmetric limiter configuration



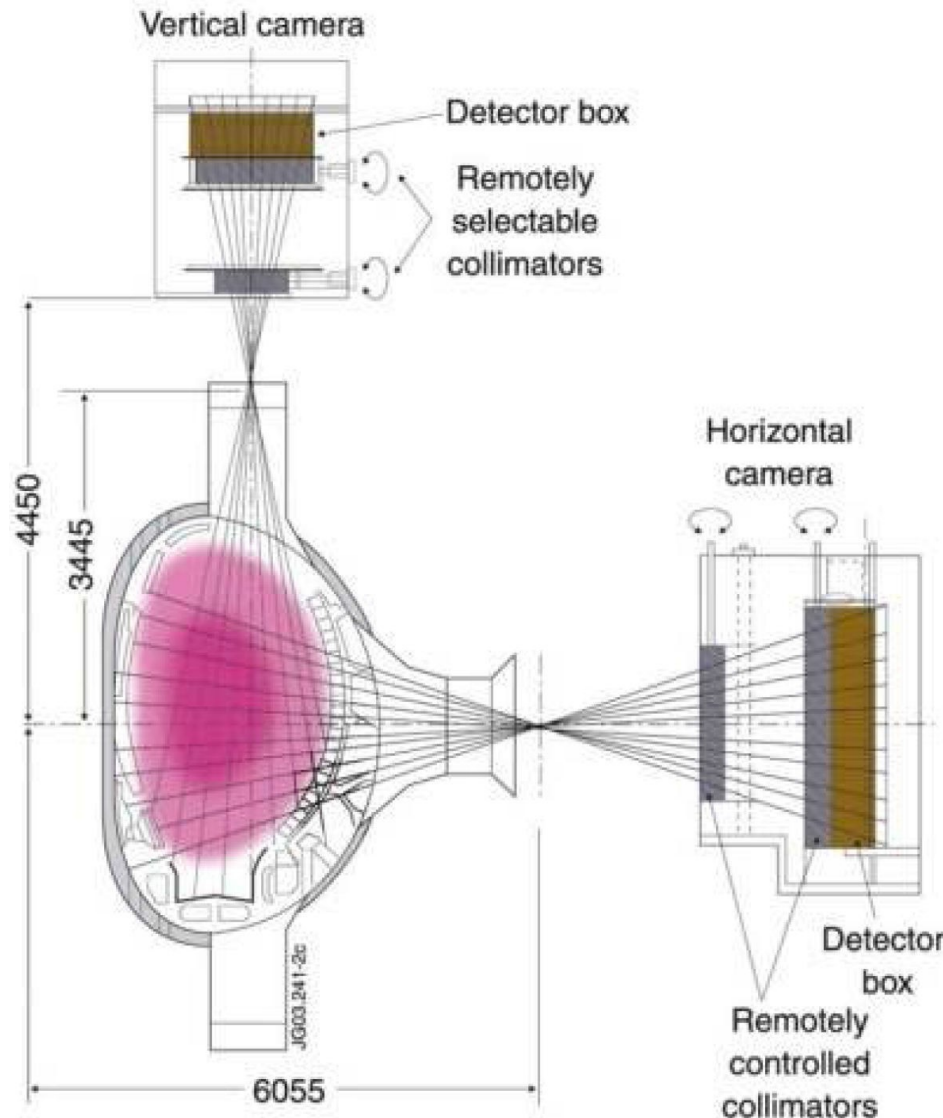
- Plasma typically vertically elongated (D-shaped) to improve its stability
- Plasma fills vacuum chamber
- A protruding material surface (limiter) defines the confined plasma and the **scrape-off layer (SOL)**

Adding coils at the bottom end of the device produces a diverted configuration



- **Magnetic null separating the confined plasma from divertor plasma**
- + **Main interaction zone of plasma with divertor targets**
- **Loss of magn. volume**
- + **Better control of plasma density and impurity content**
- ⇒ **Improvement of confinement by 2x**

Fusion of hydrogen ions occurs in the center of the plasma, where $T \approx 10$ keV



- **JET neutron from D-T and neutral beams at 100 keV**
- **Two orthogonal neutron cameras (res. ~ 10 cm)**
- **Detectors include**
 - NE213 liquid scintillators for 2.5 MeV (D-D) and 14 MeV (D-T)
 - Plastic Bicron 418 scintillators (14 MeV)
 - CsI (TI) photodiodes (hard x-rays and γ emission: $2 < E_\gamma < 6$ MeV)

Summary

- **A tokamak is a toroidal confinement device with magnetic field coils**
- **Plasma generated in vacuum chamber by transformer action driving a plasma current \Leftrightarrow c.f., stellarators**
- **Strong toroidal field for stability, weaker poloidal field for plasma confinement**
- **Nested flux surfaces of balanced force between plasma pressure and electromagnetic force: $\mathbf{j} \times \mathbf{B} = \nabla p$**
- **Principal tokamak configurations are the limiter and divertor configurations**
- **Lectures concerning ITER, SOL, PWI etc still to come!**