Tokamaks and Tokamak Physics

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Learning outcomes

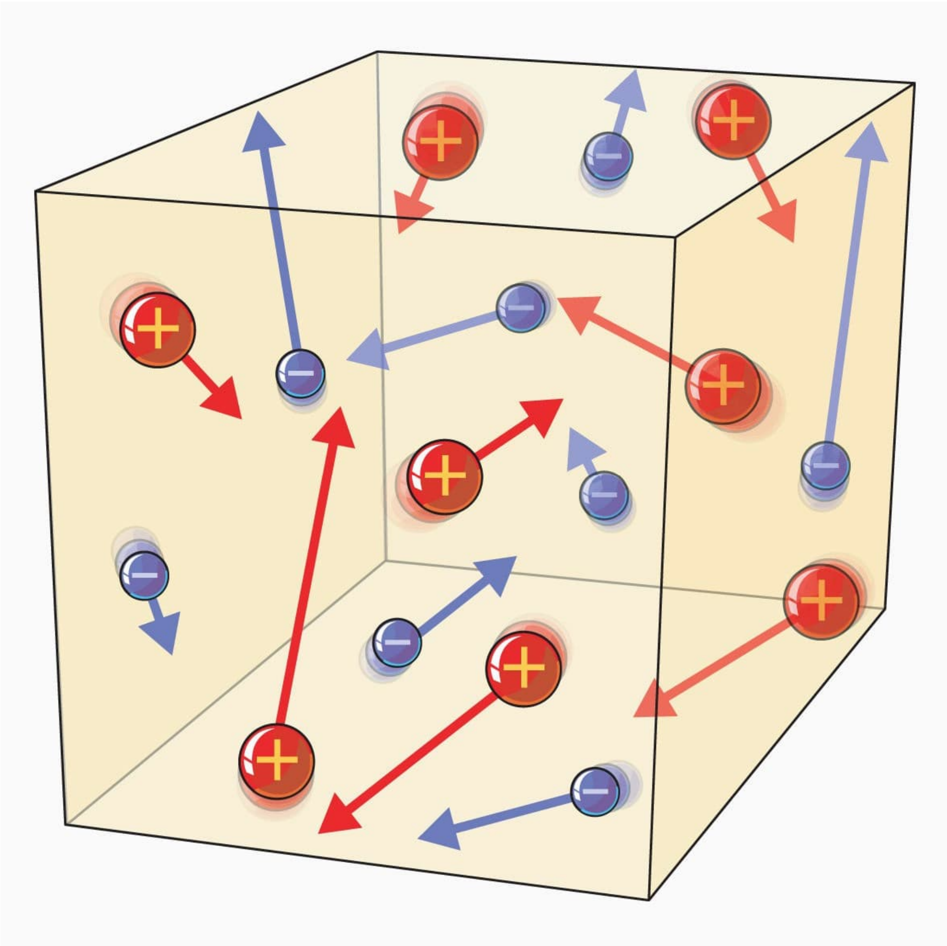
- **Describe/recap plasma motion in electromagnetic fields**
- **Define toroidal and poloidal fields in tokamaks ⇒ device setup and plasma geometry**

  – **Tokamak = To**roidal'naya **Ka**mera **s Ma**gnitnymi **K**atushkami (= Toroidal chamber with mangetic 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

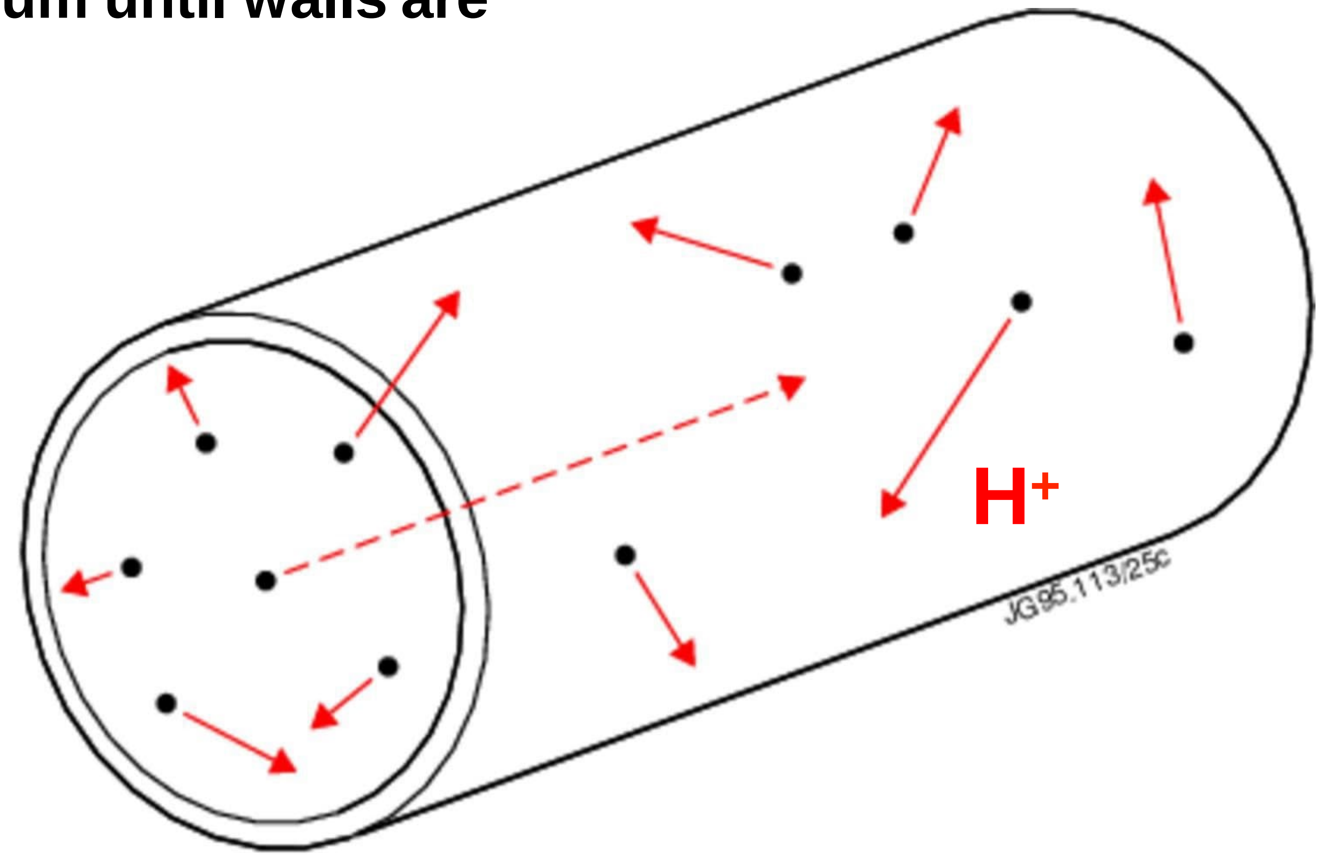
From lecture 2:



- **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**

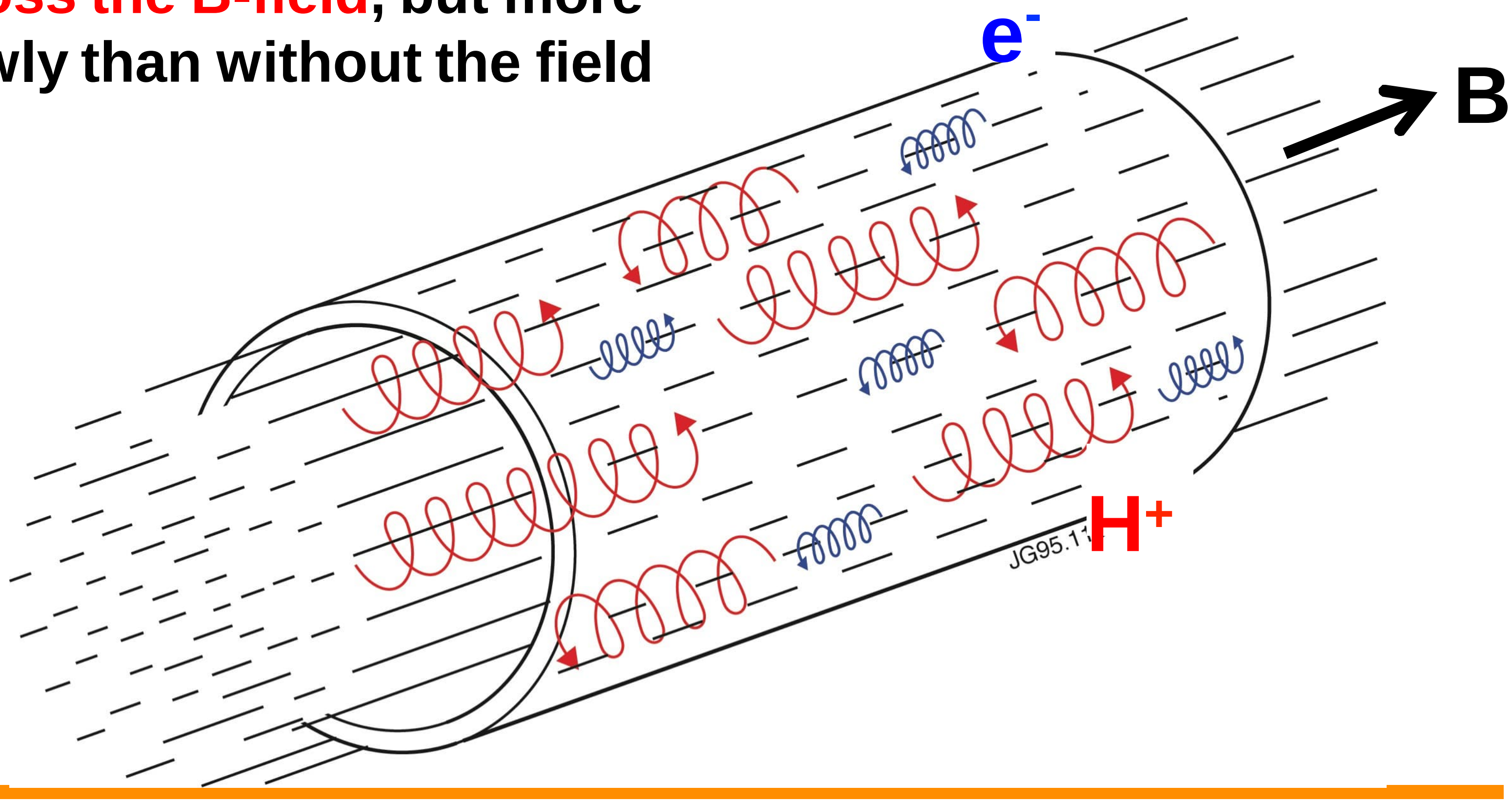


Applying a homogenous and axisymmetric magnetic field confines the particles to field lines

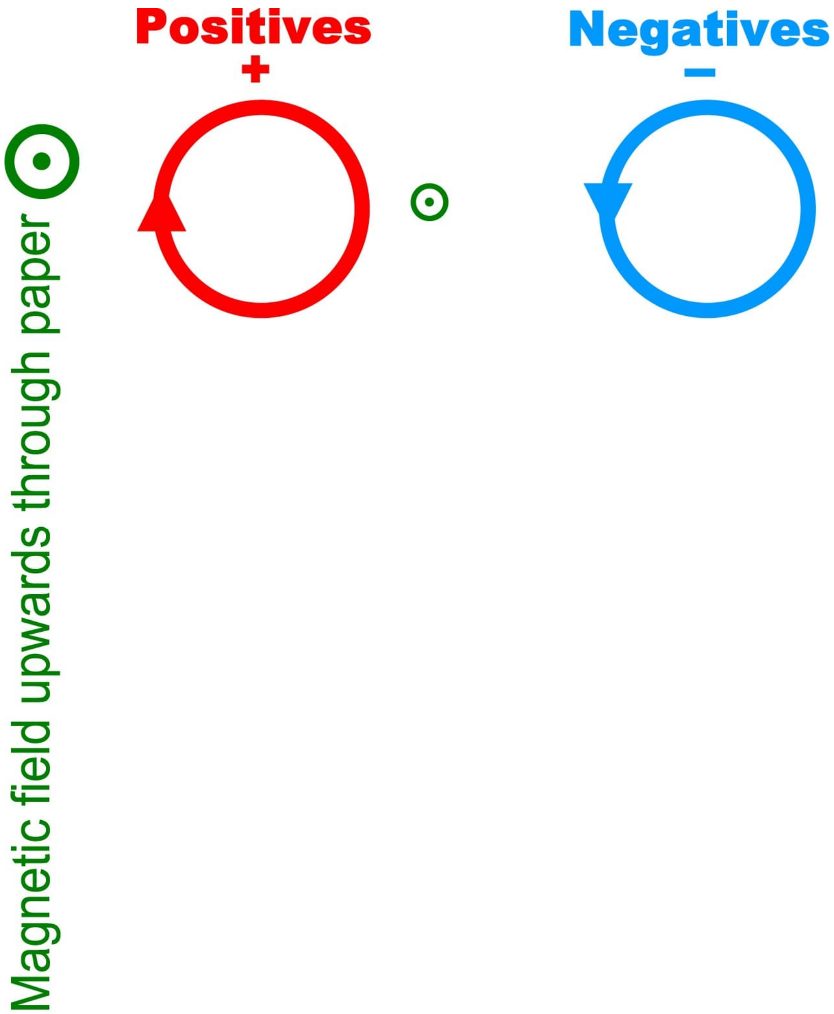
- **Particles move along field lines and gyrate around them given by their Larmor radius:**

$$r_L = \frac{mv_\perp}{eB}$$

- **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



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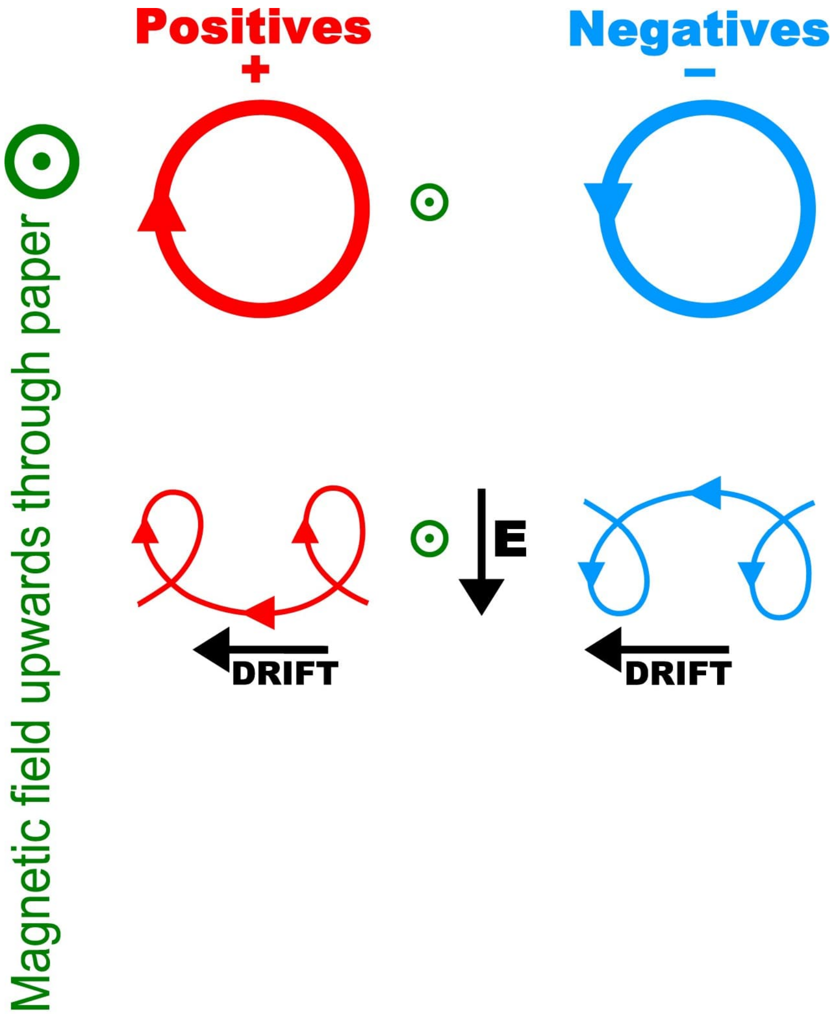
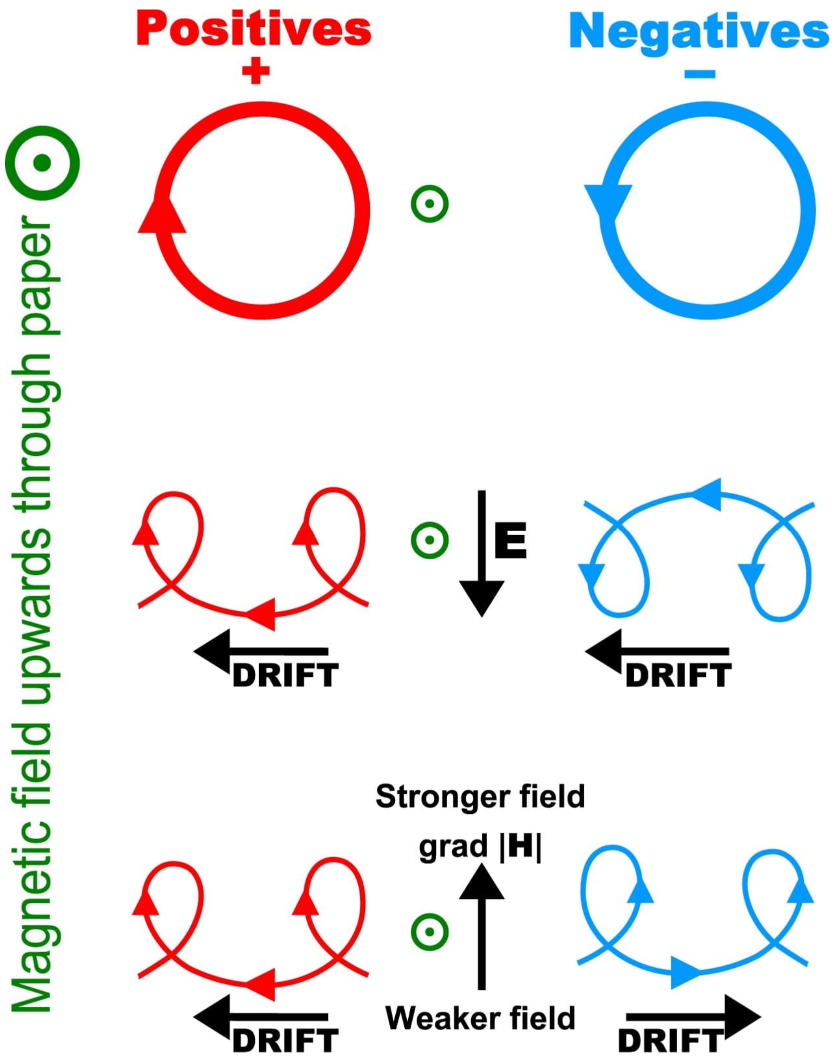


- **Non-field aligned electric fields (charge-independent!):**

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

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



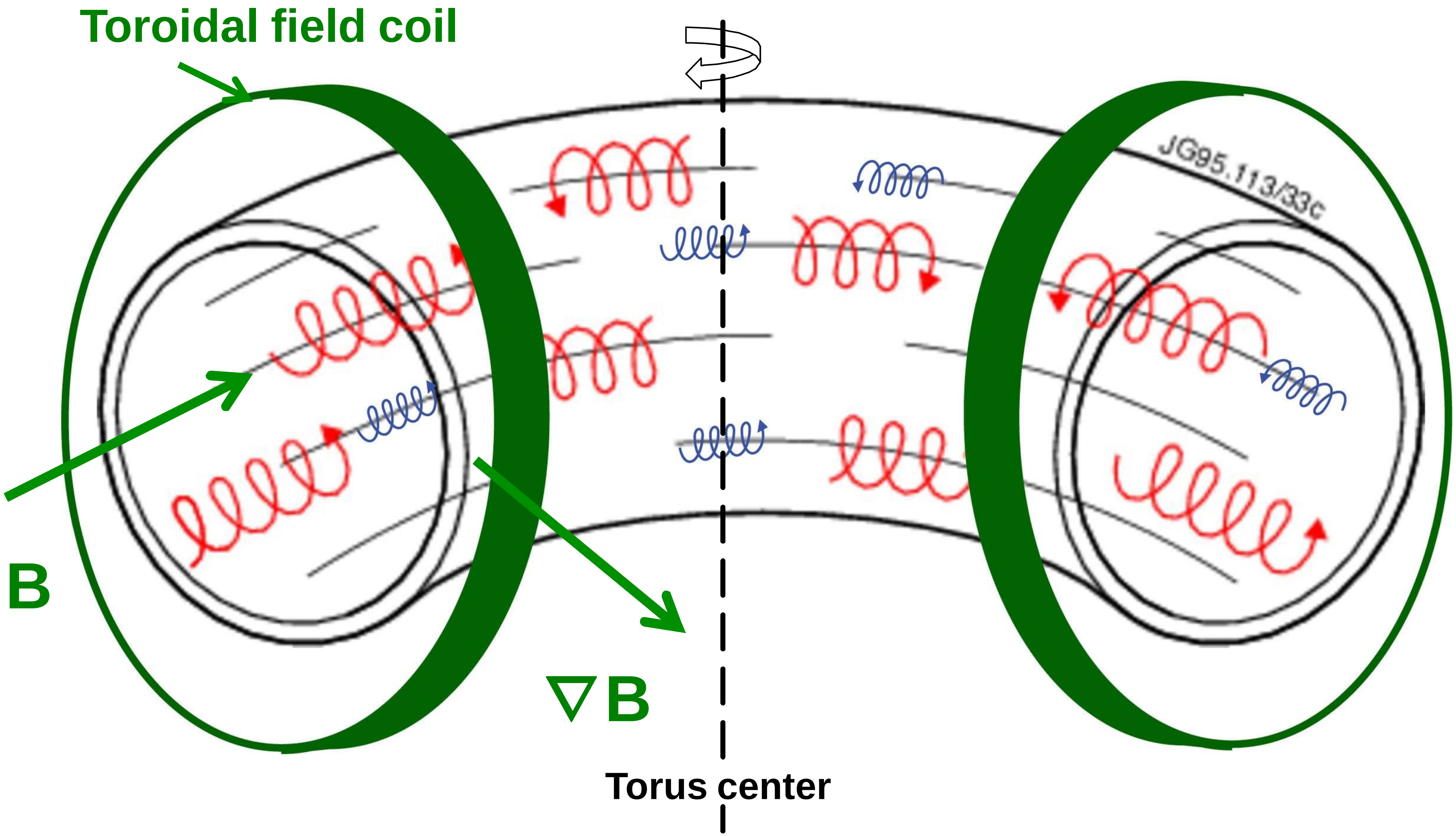
- **Non-field aligned electric fields (charge-independent!):**

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

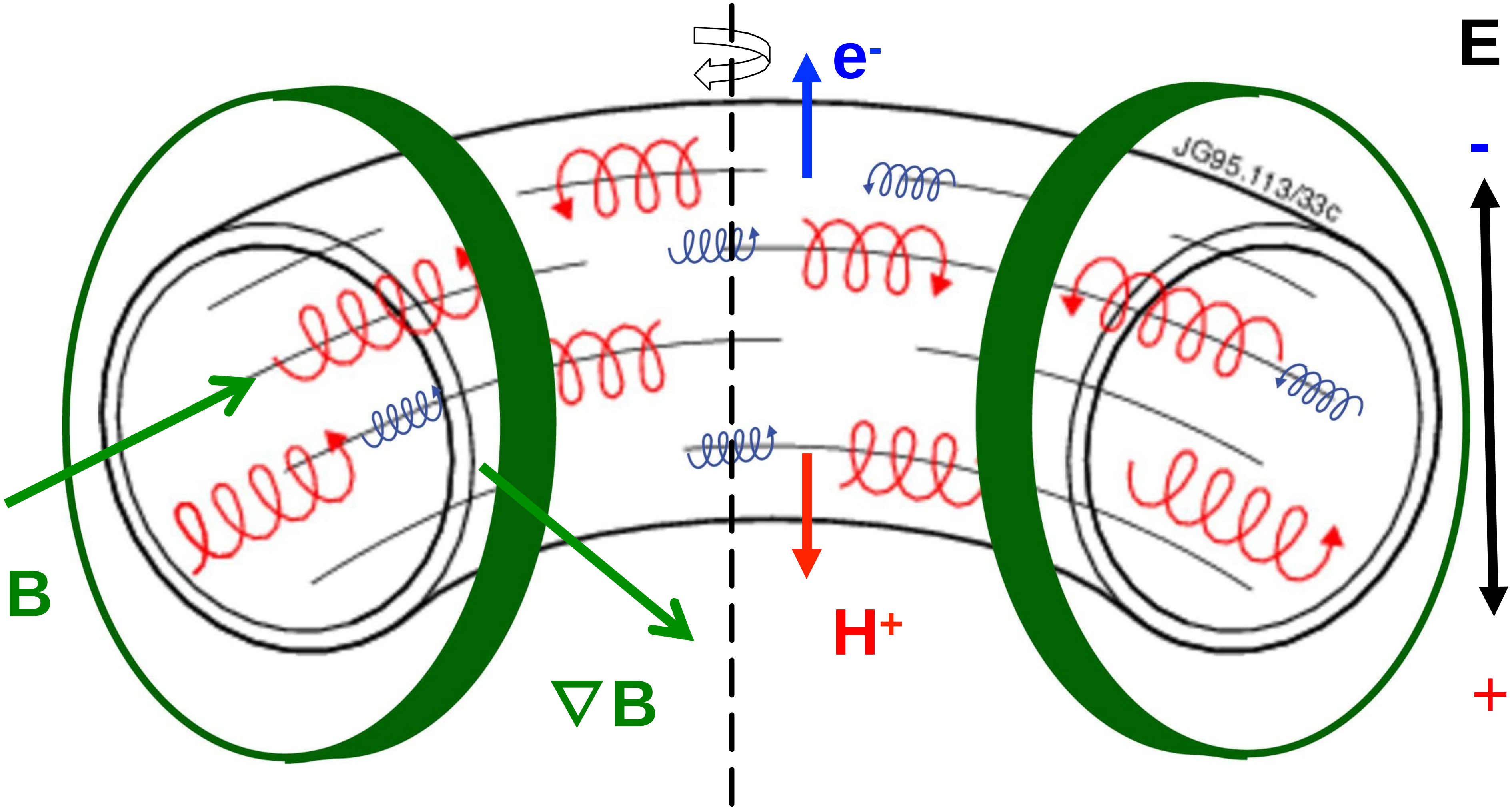
- **Inhomogeneous B-field ⇒ ions and electrons drift in opposite directions ⇒ charge separation ⇒ electric field:**

$$\bar{v}_{\nabla B} = \frac{r_L}{2}\frac{B\times\nabla B}{B^2}v_\perp$$

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



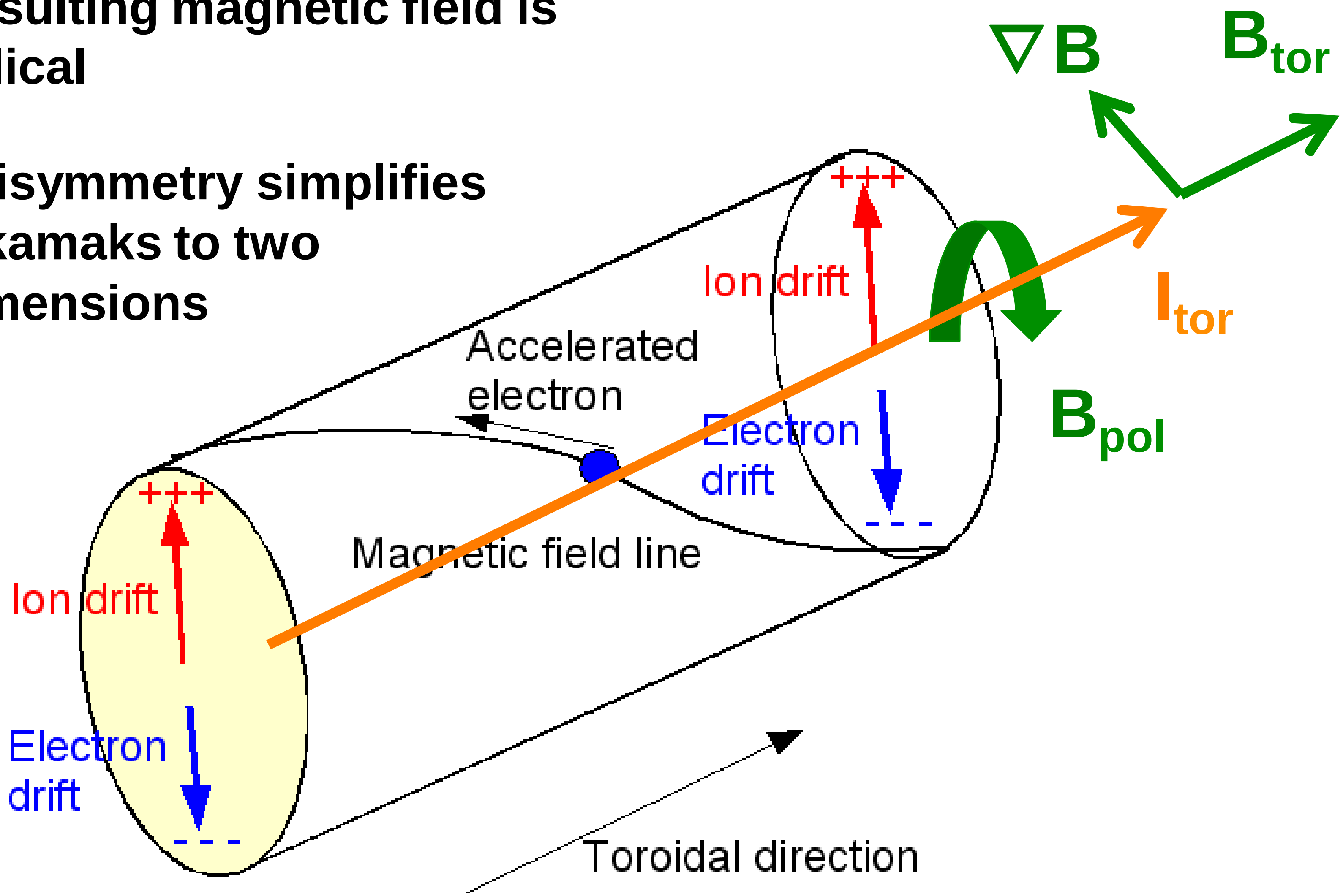
A purely toroidal system will lead to (up-down) charge separation and ∇B radial outward drifts



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

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

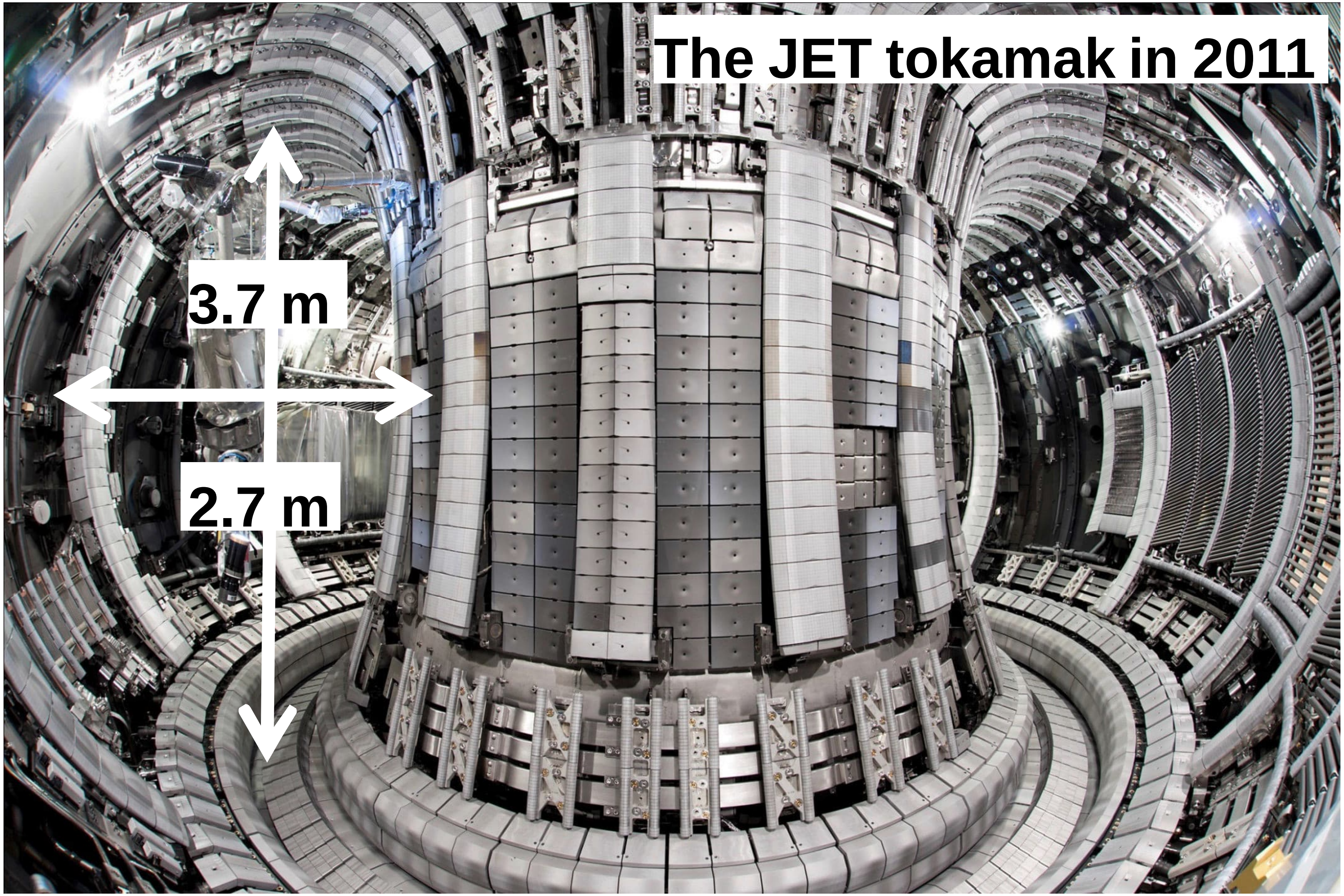
- **Resulting magnetic field is helical**
- **Axisymmetry simplifies tokamaks to two dimensions**



Technical realization

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

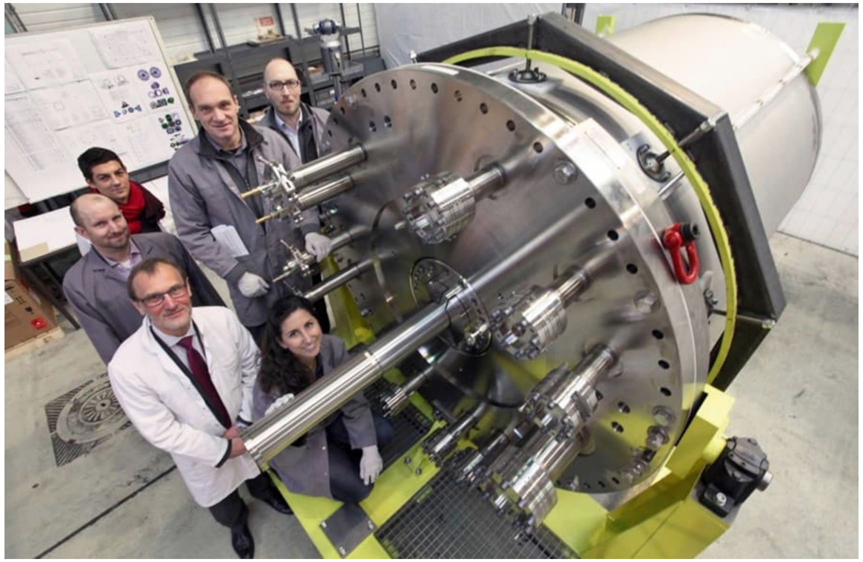
(“base pressure” = pressure before introducing fuel)



A plasma a is created and contained in a vacuum chamber at a base pressure ≈ 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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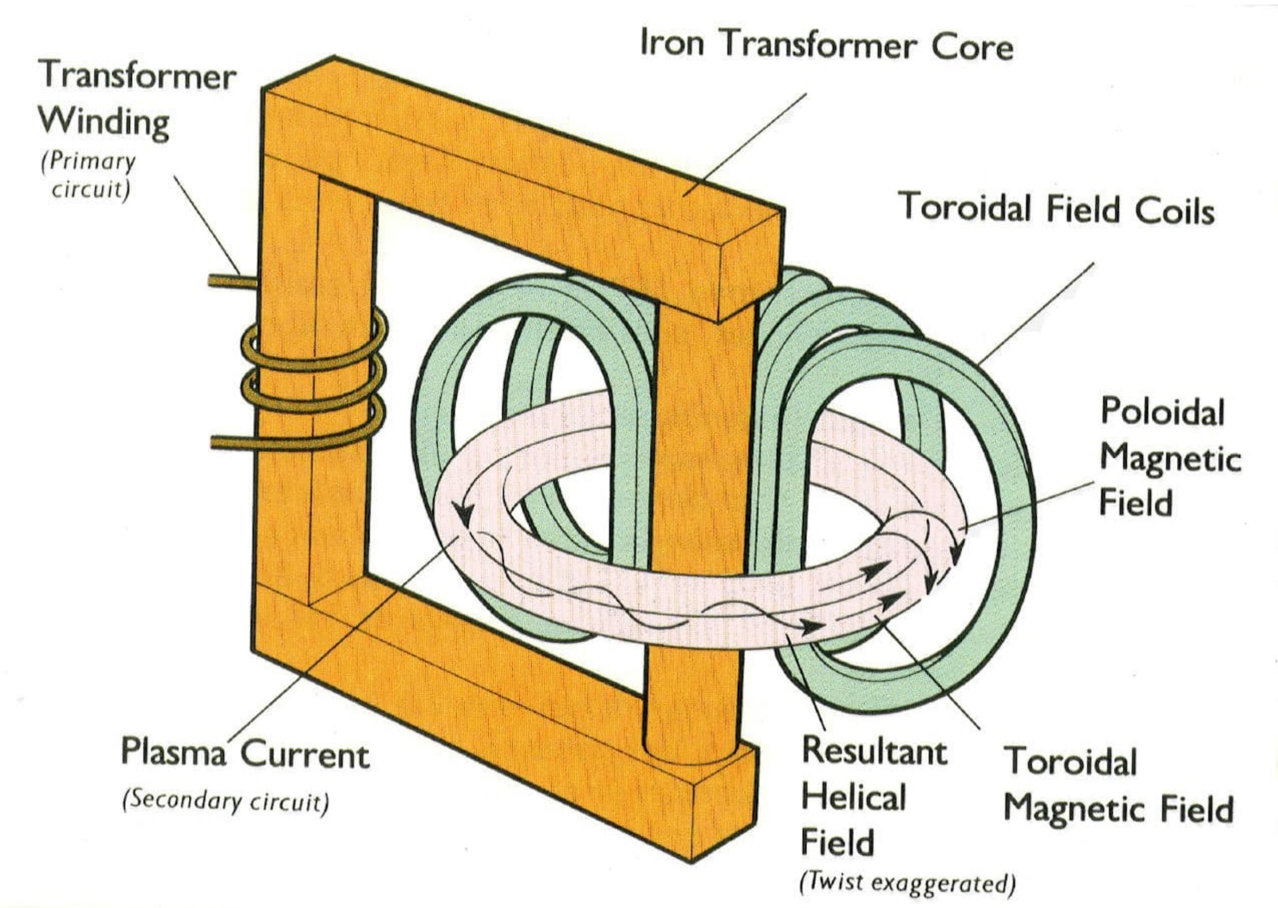
Presemo quiz #1

https://presemo.aalto.fi/fet/

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



Toroidal'naya **Ka**mera **s** **Ma**gnitnymi **K**atushkami

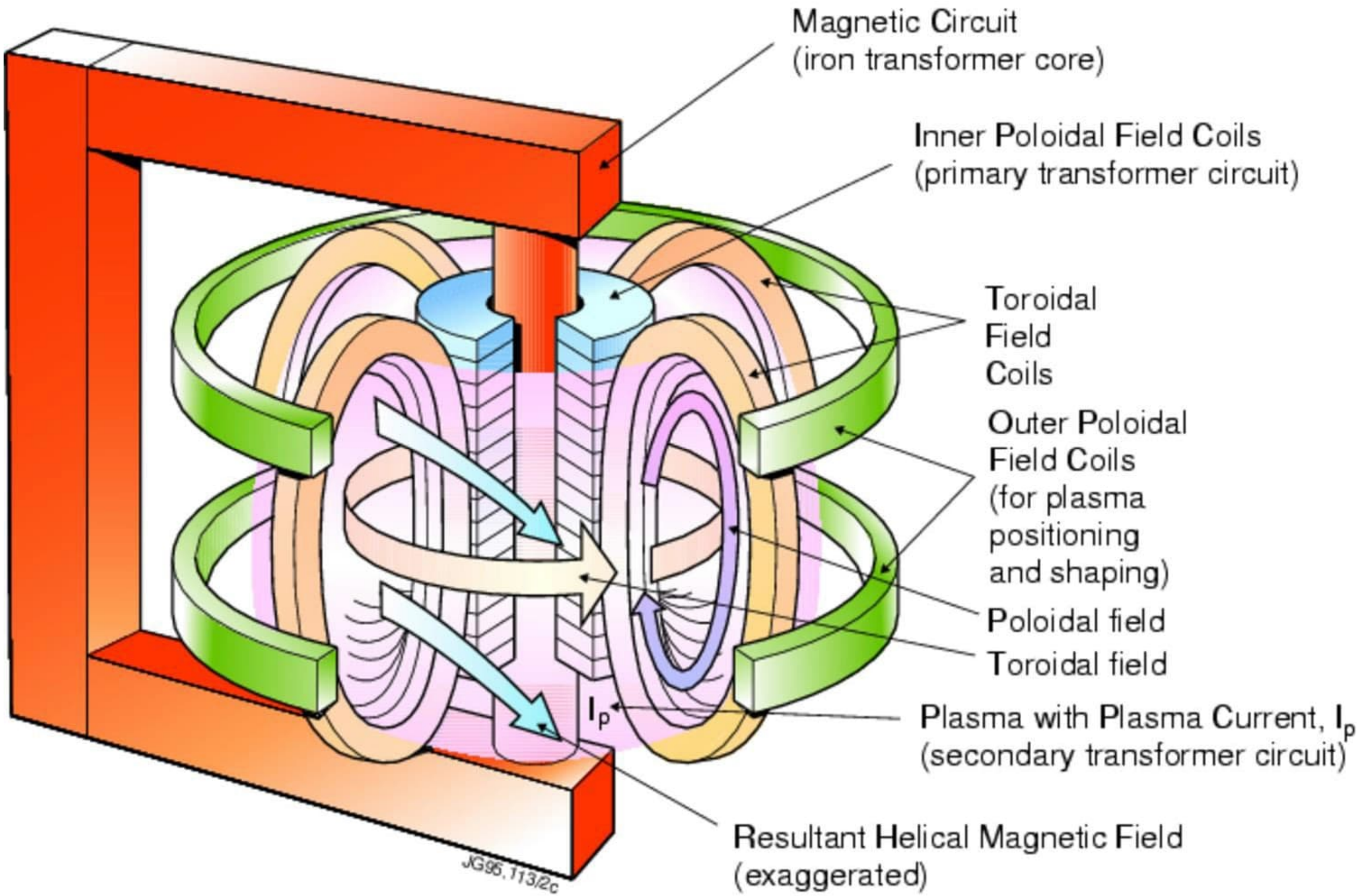
- **External toroidal field**

→ Question: # of coils?

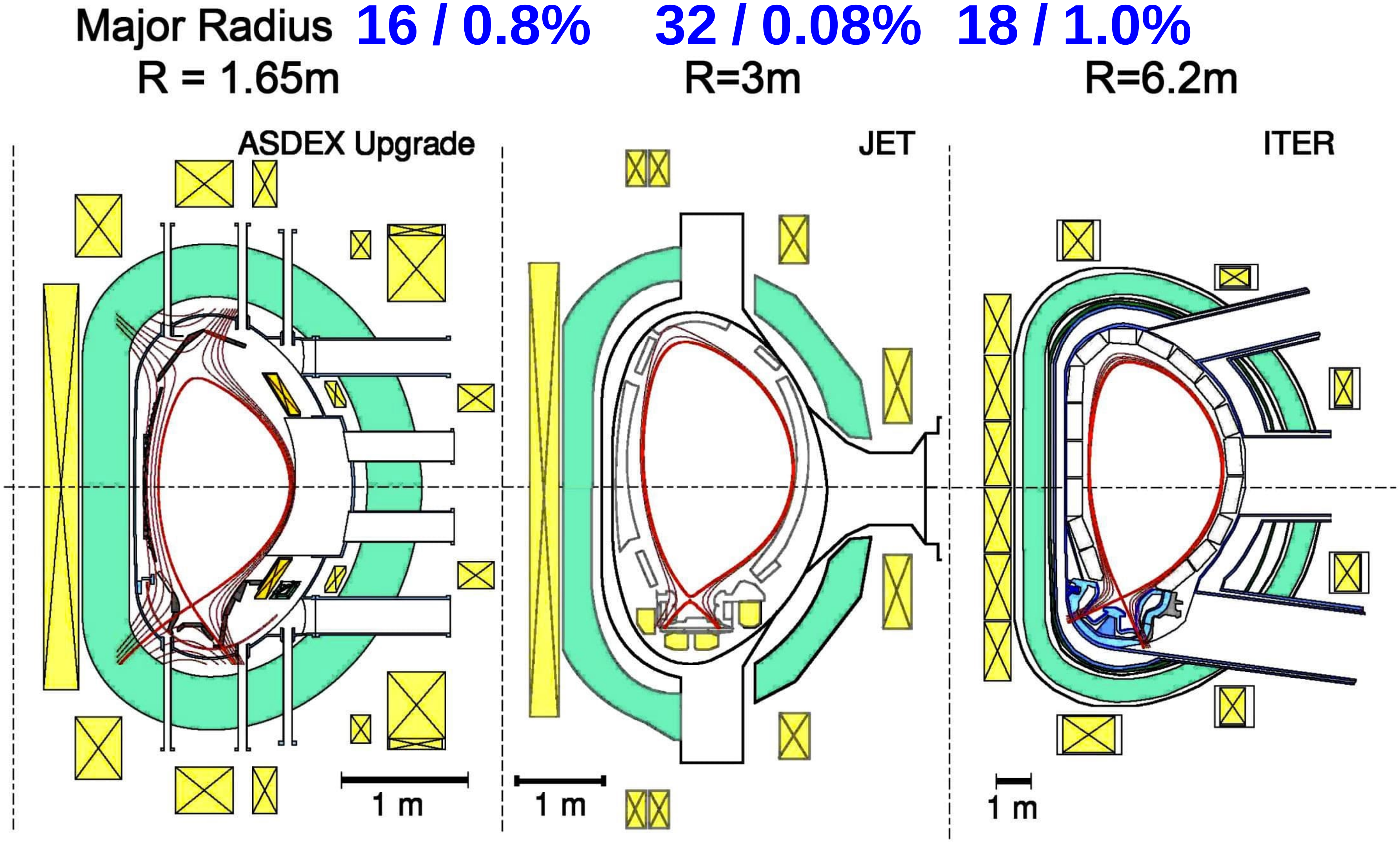
Transformer winding ⇔ plasma acts as secondary circuit

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

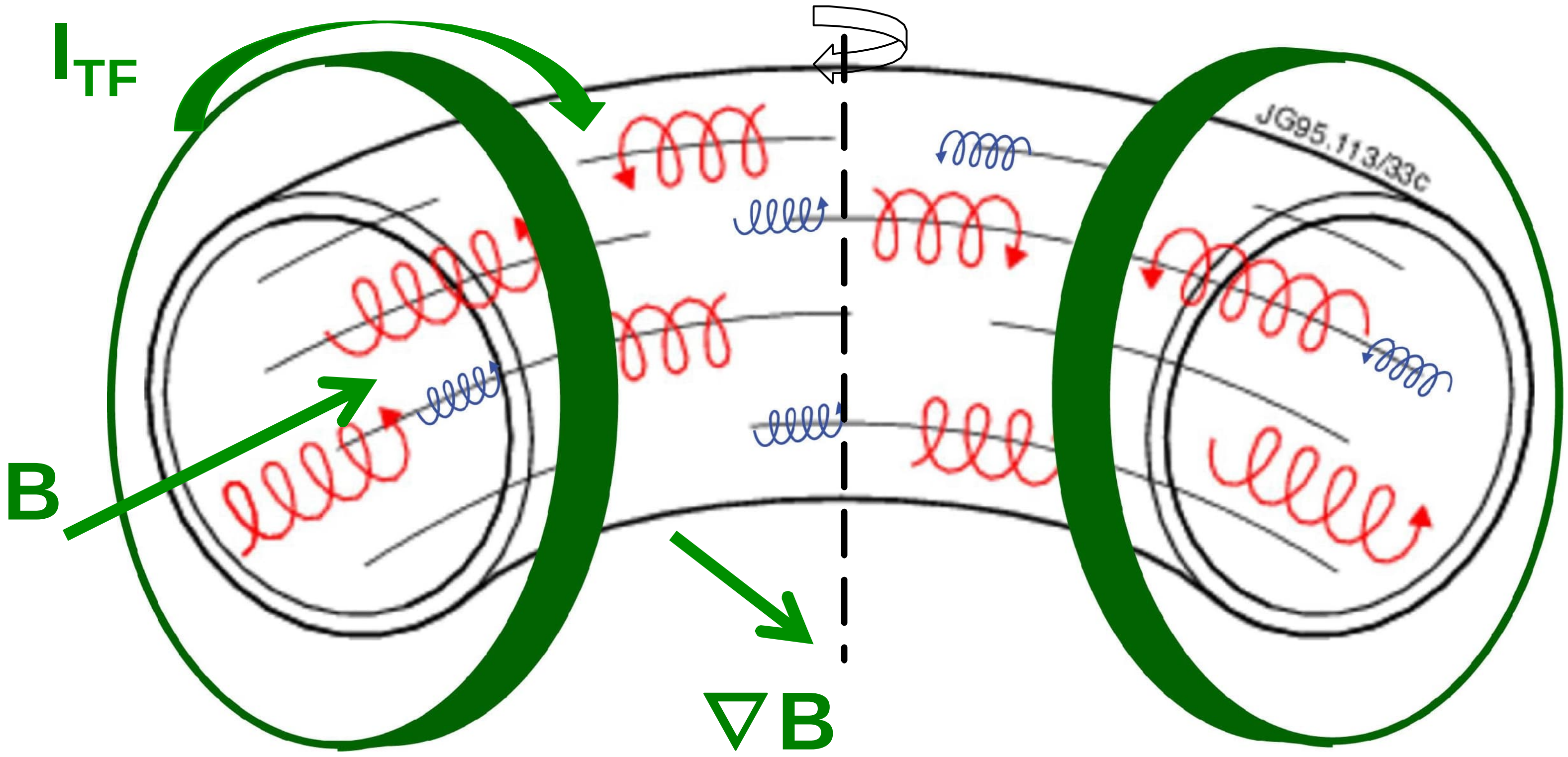
An additional set of poloidal field coils are needed to plasma positioning and shaping



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



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



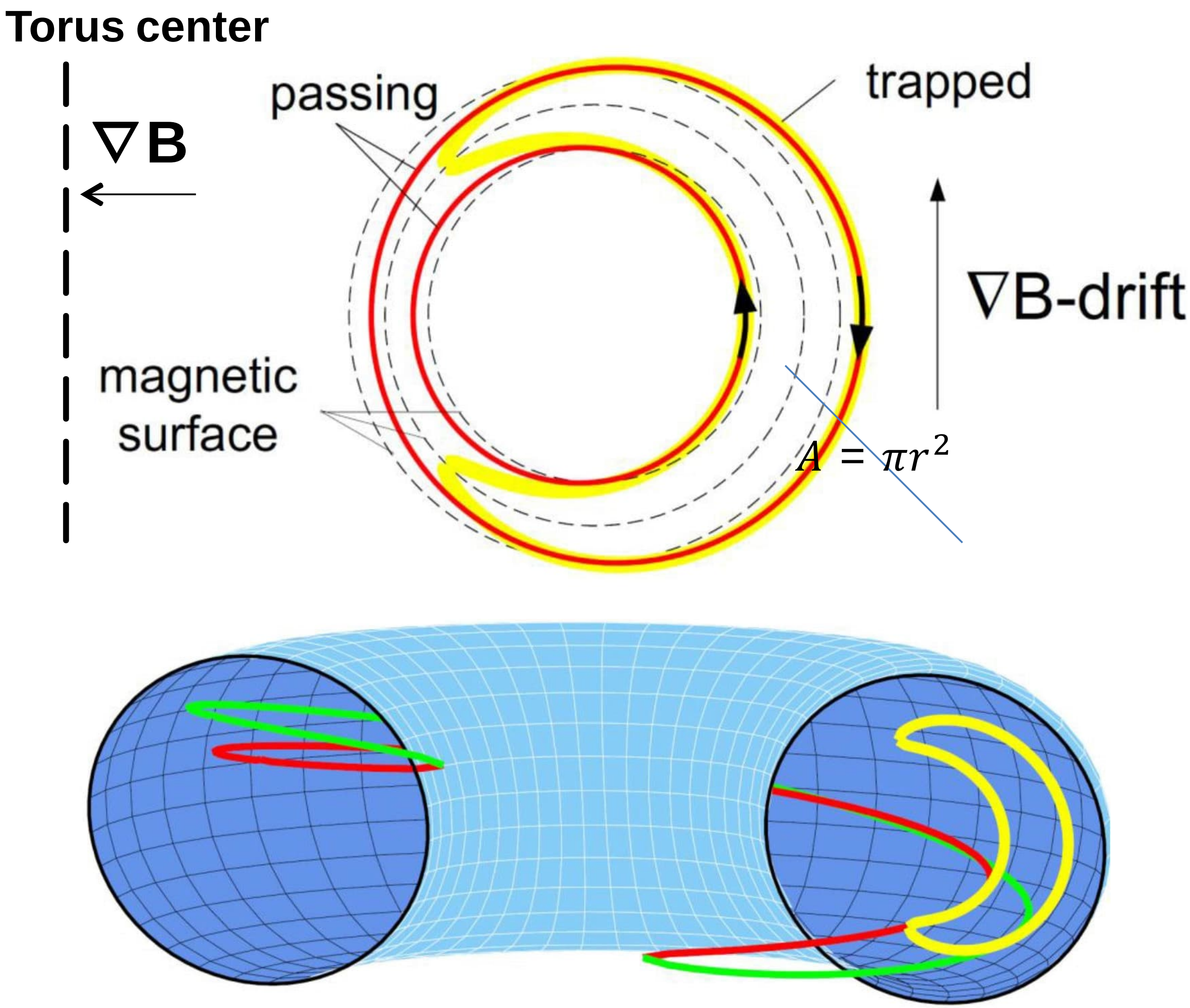
Toroidal magnetic field strength by Ampere's law:

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

⇒ B_T non-uniform in R:

$$\frac{\Delta B_T}{B_{T0}} = \frac{2R_{minor}}{R_0} \approx \frac{3}{4}$$

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



- **Trapping, if:**

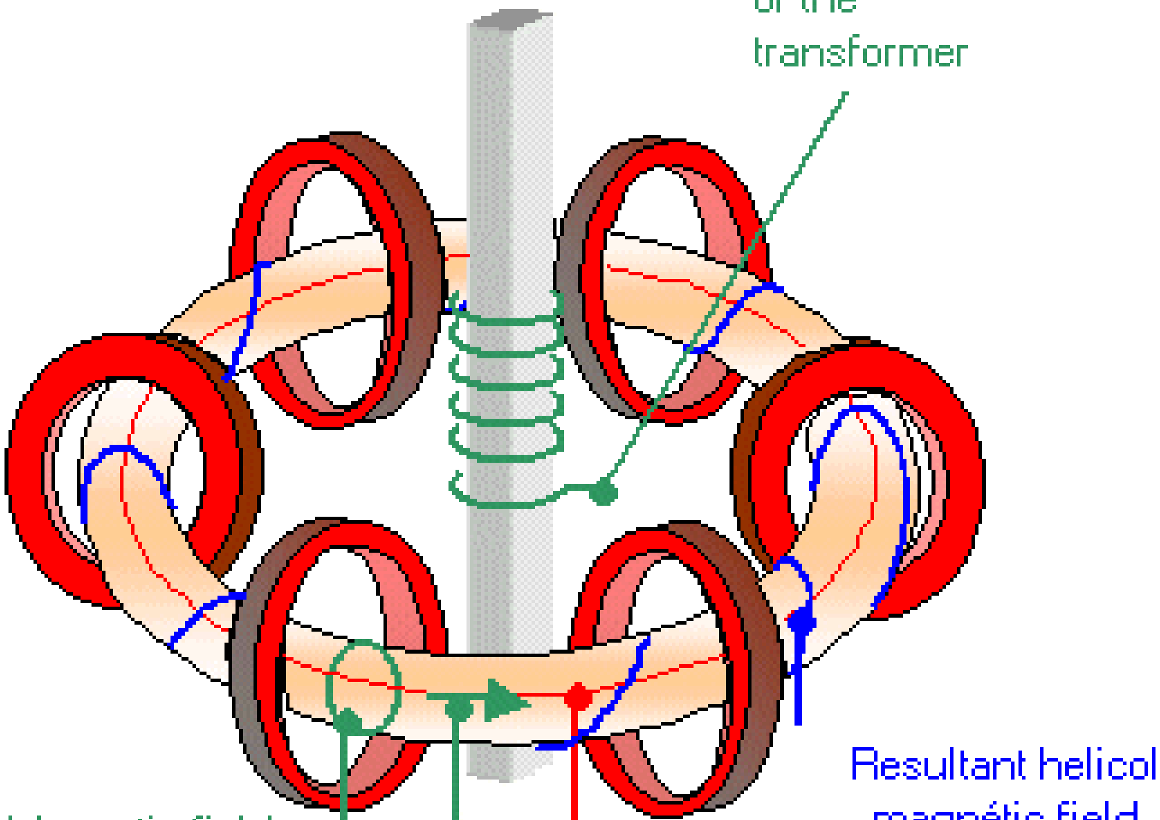
$$\frac{v_{\parallel,0}}{v_{\perp,0}} \leq \sqrt{\frac{2r}{R}}$$

- **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 ⇒ plasma current



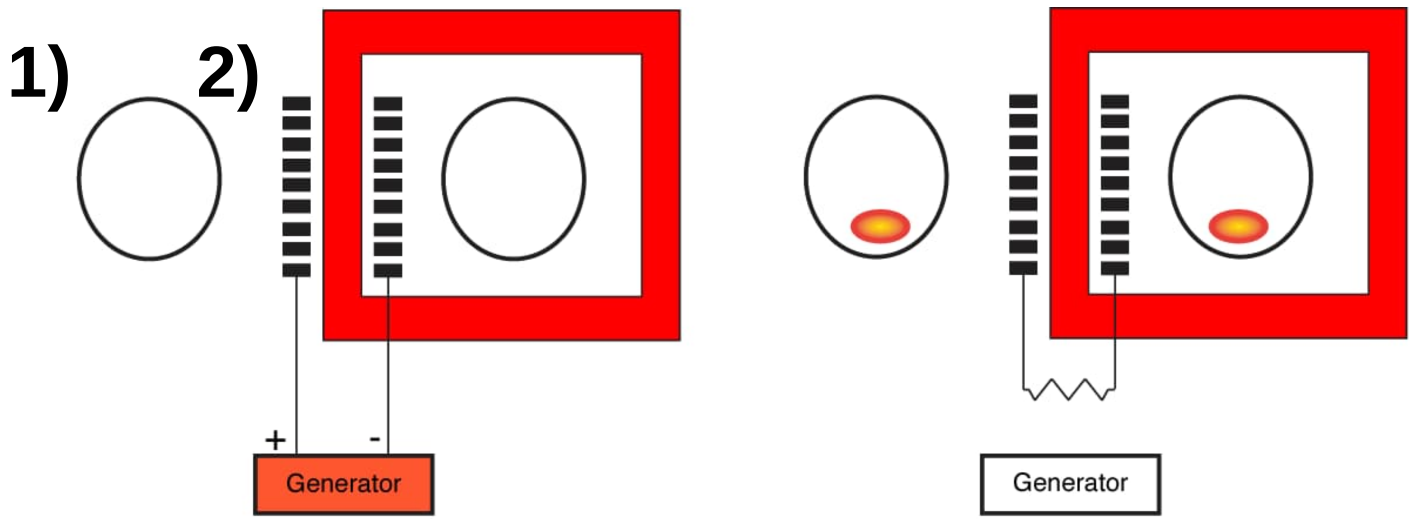
- **Maxwell-Faraday:**

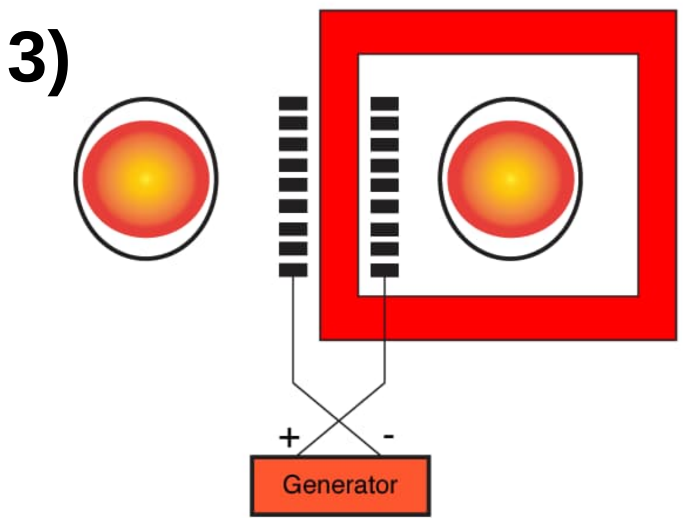
$$-\frac{\partial B}{\partial t} = \nabla \times \vec{E}$$

⇒ **Tokamaks are pulsed devices**

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

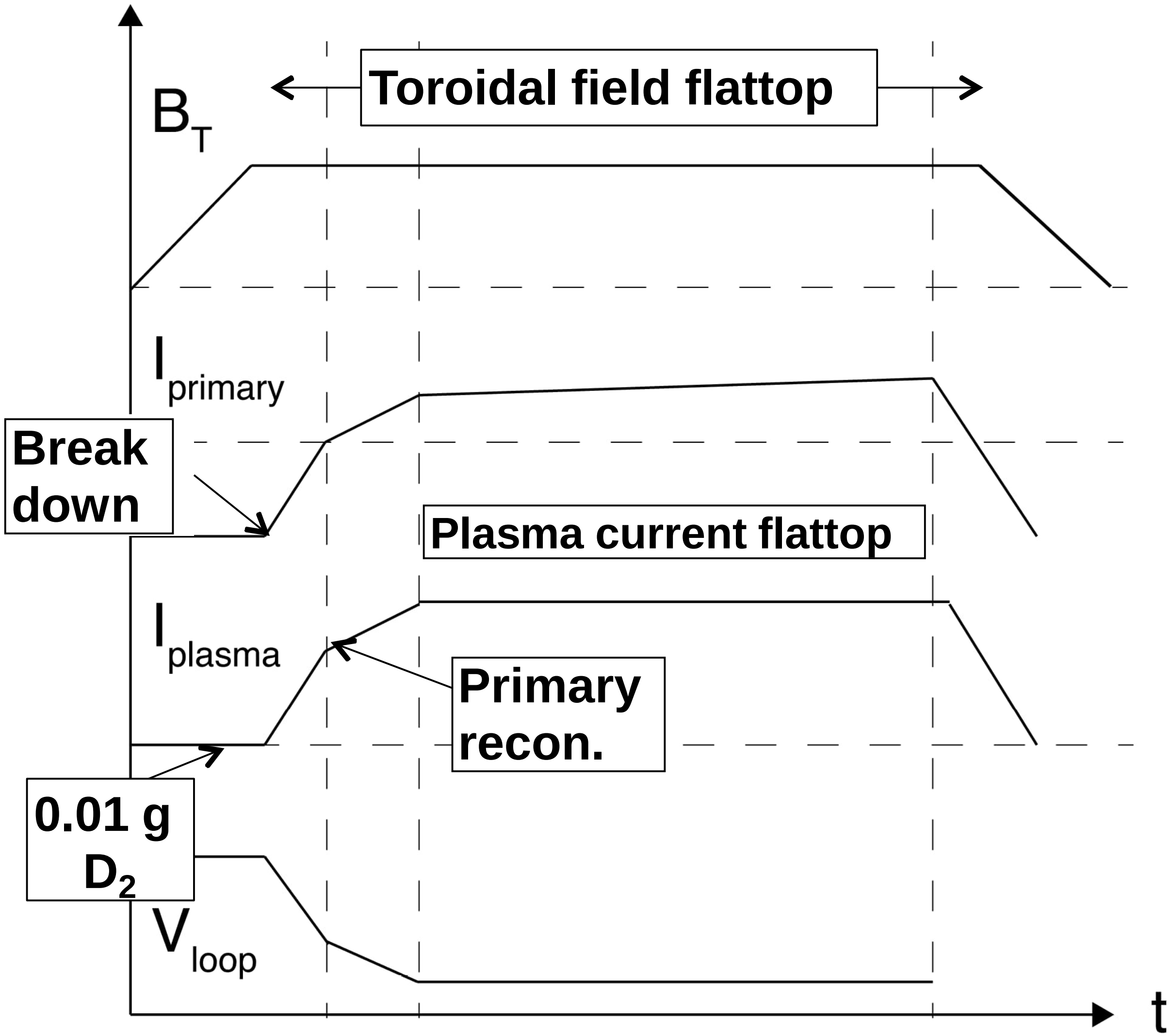
The current in primary coils is ramped down, then up, to break down the plasma and to drive the current





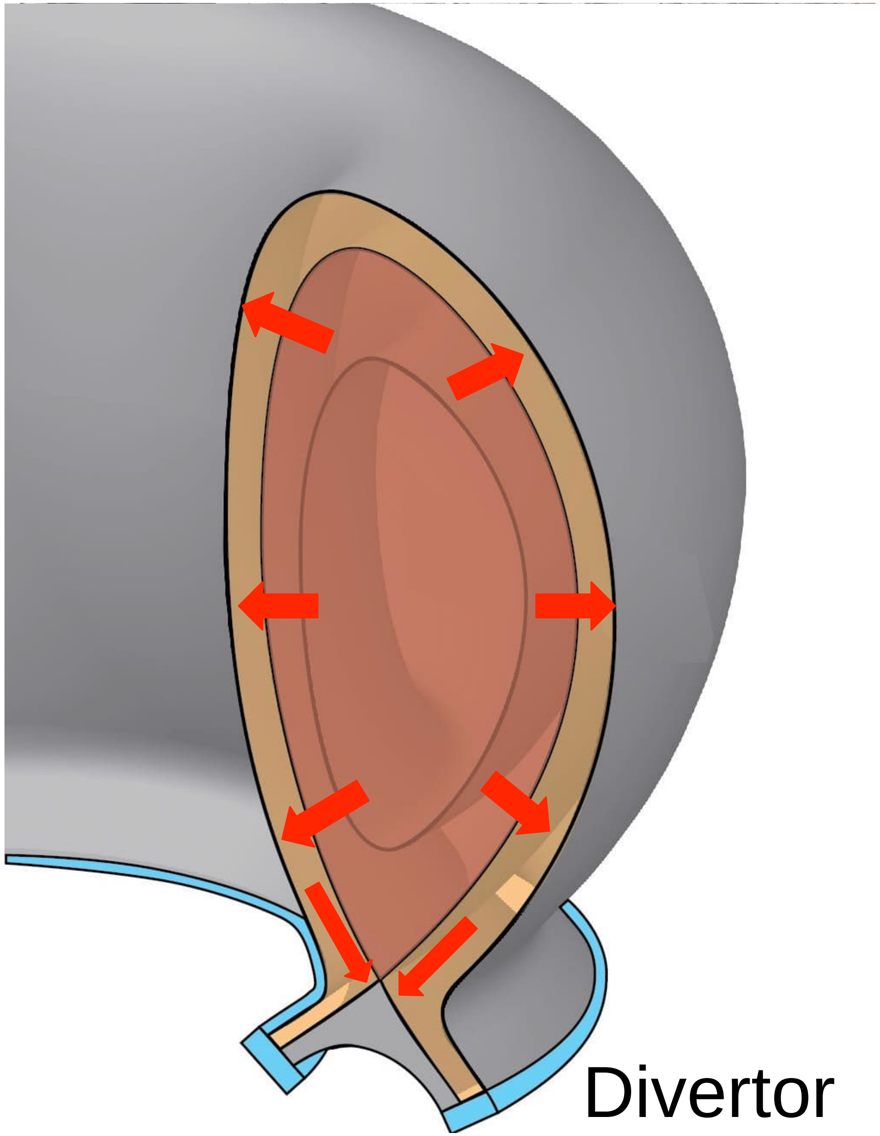
1) **Pre-magnetization of primary poloidal field coils**
2) **Plasma break-down when $I_{primary}$ starts changing in time**
3) **Reconnection and re-direction of $I_{primary}$**

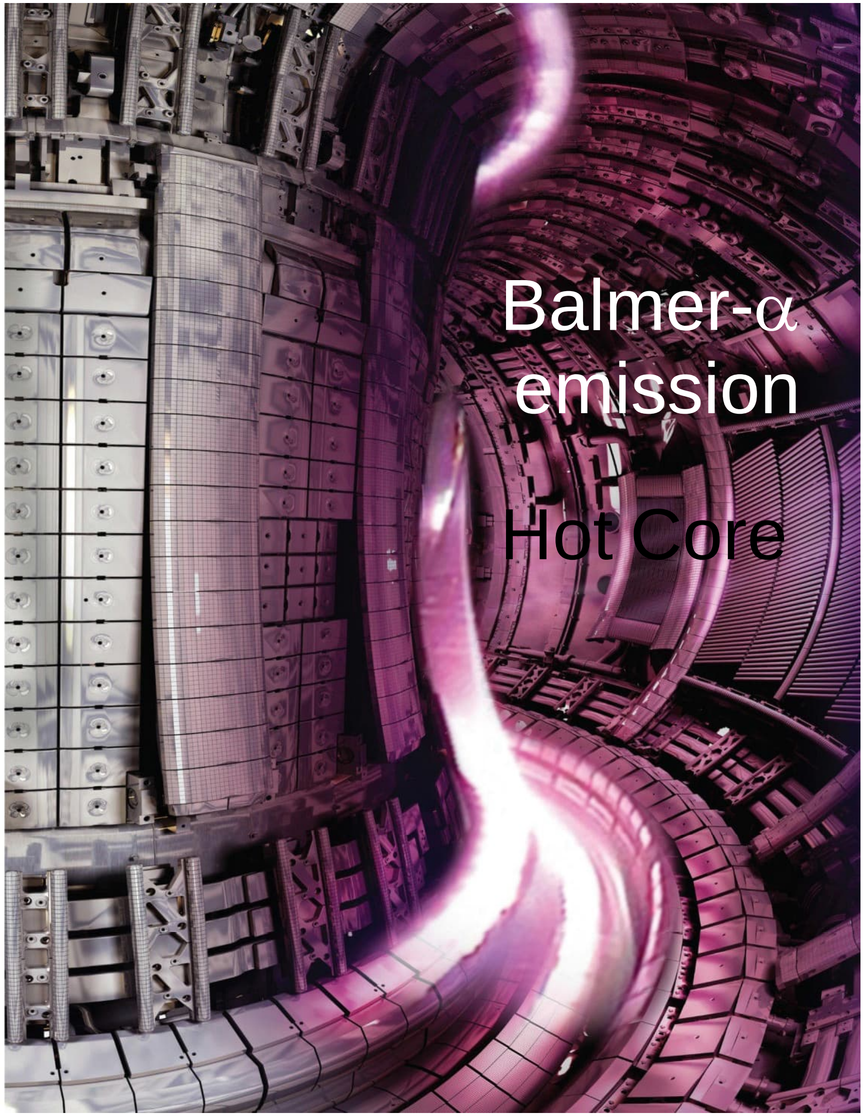
The current in primary coils is ramped down, then up, to break down the plasma and to drive the current



- **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 ⇒ hydrogen emission





Video: Fusion plasma control in ST25/ST40

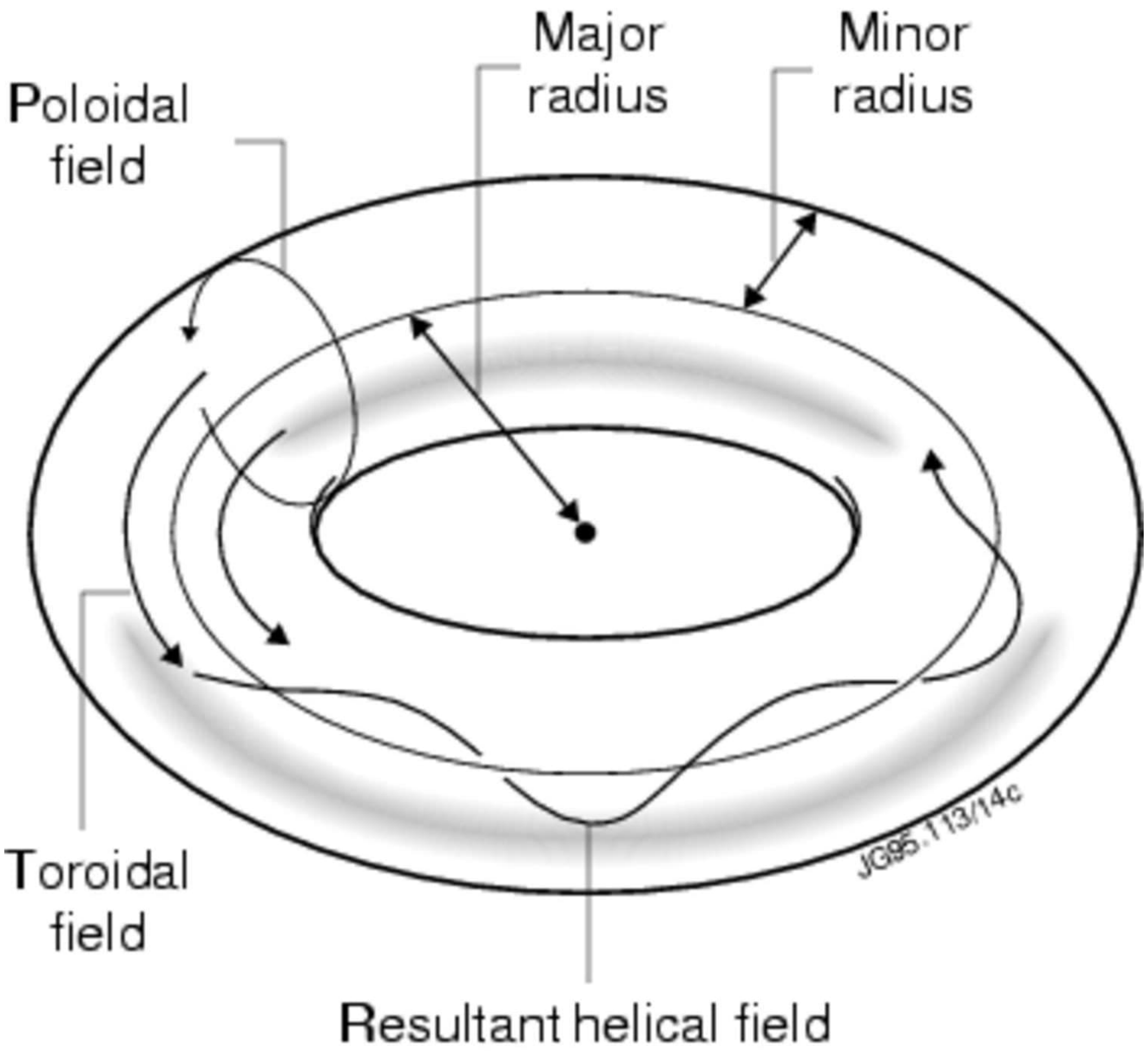
- **Plasma in Tokamak Energy Ltd (video 2:16):**

  https://www.youtube.com/watch?v=0c9XepeVvzc

- **Motivation for the video:**
  a) **To show the real tokamak plasma discharge**
  b) **To show example of private company developing fusion devices**
  c) **To show example of careers of our students**

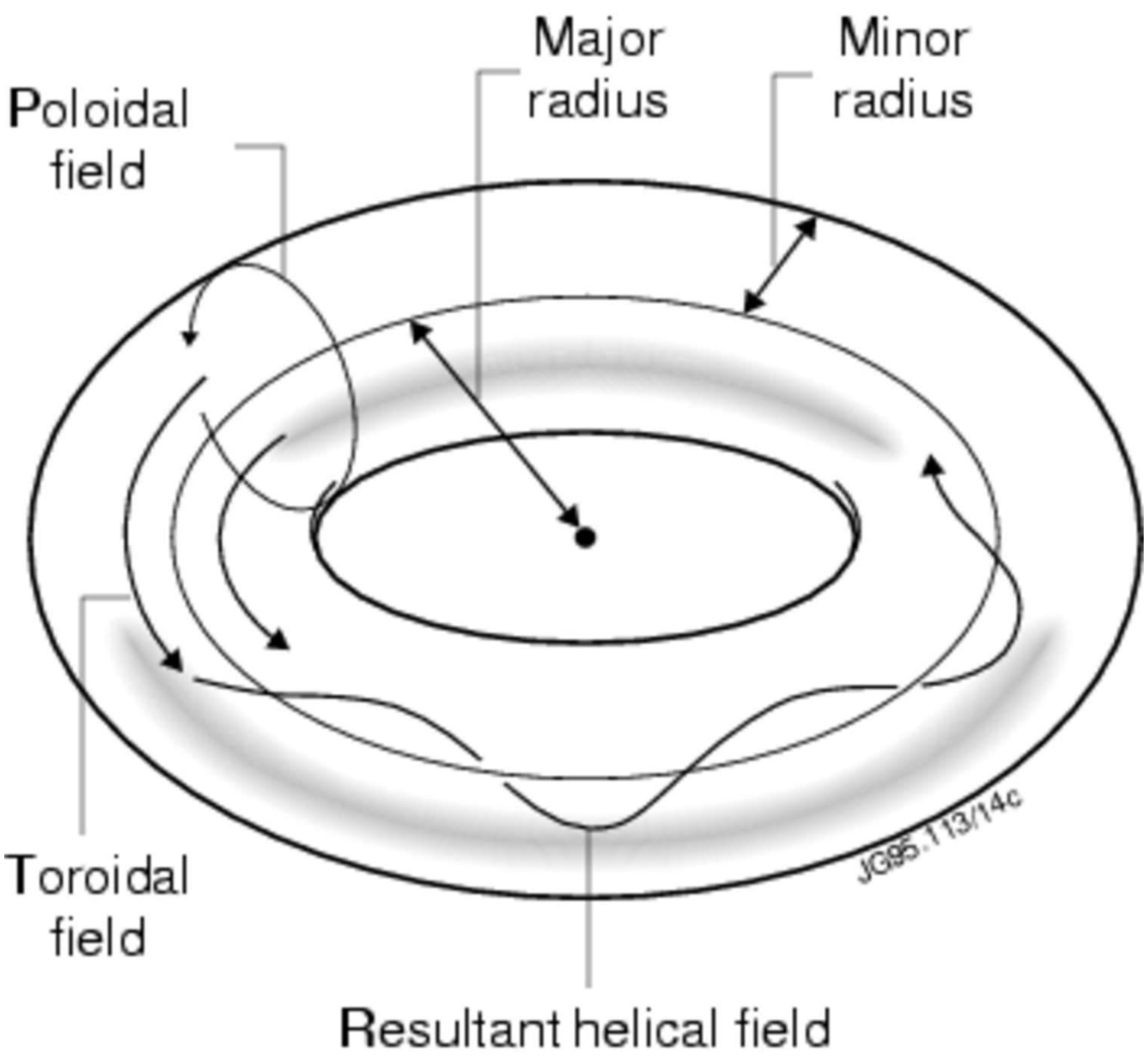
Tokamak fields, dimensions, currents and plasma configurations

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) ≈ 1/10 B_T**

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

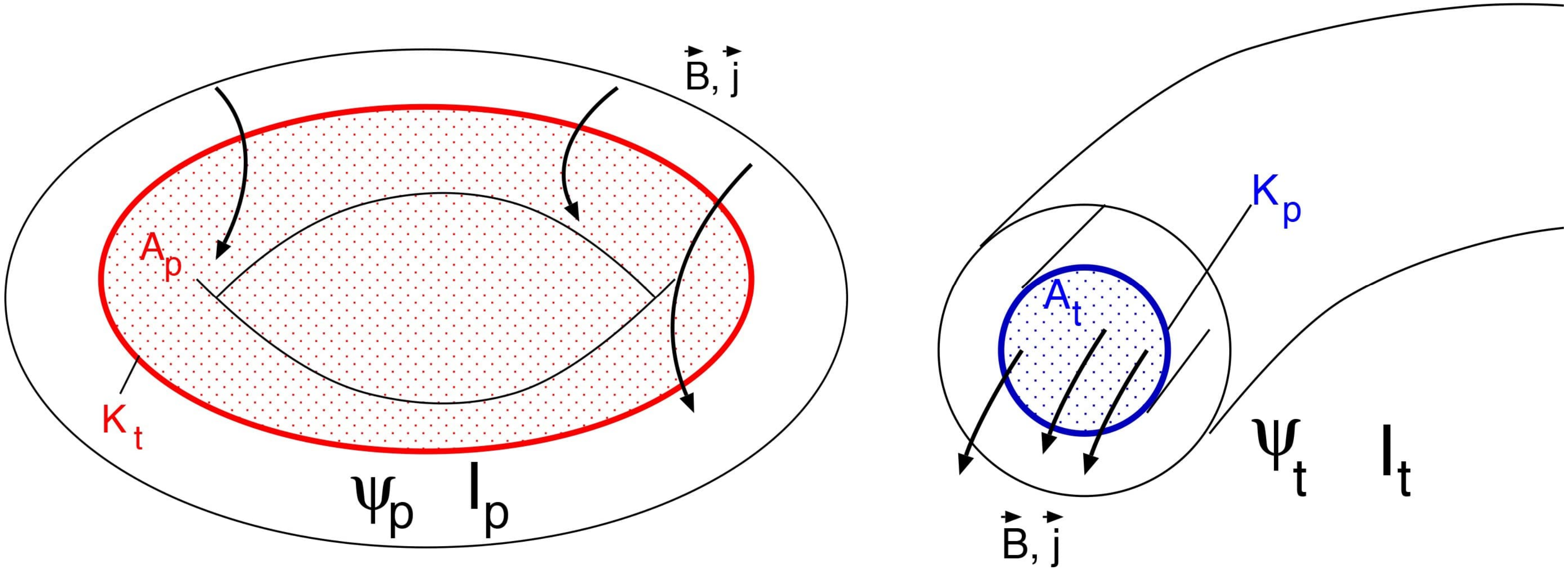


- **Major and minor radius up to 3 m and 1.5 m, respectively (6.2m and 2m for ITER)**
- **Aspect ratio:**

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

- **Conventional tokamaks: A ≈ 3, spherical tokamaks A → 1**

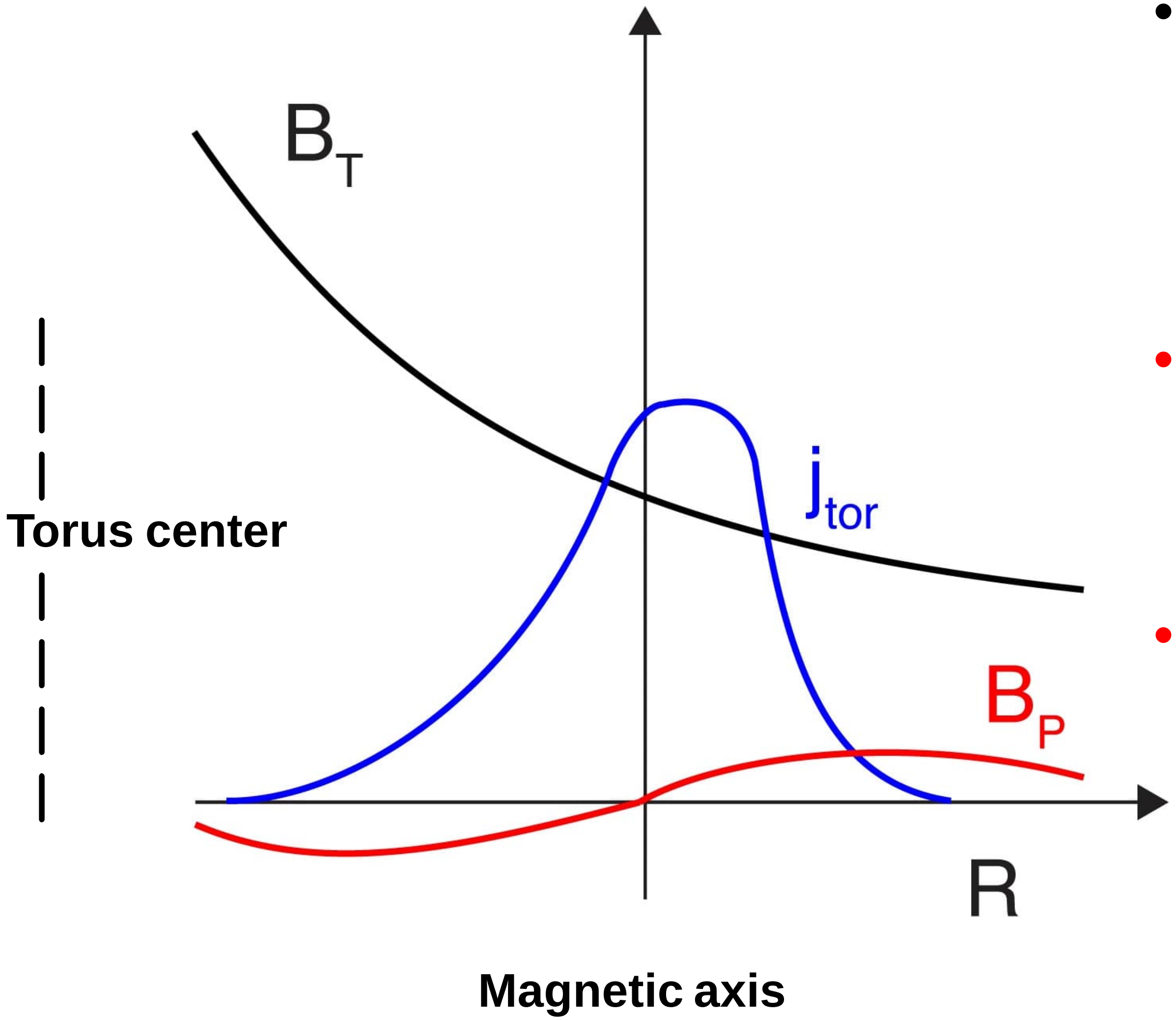
Magnetic surfaces can also be described by poloidal and toroidal fluxes



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

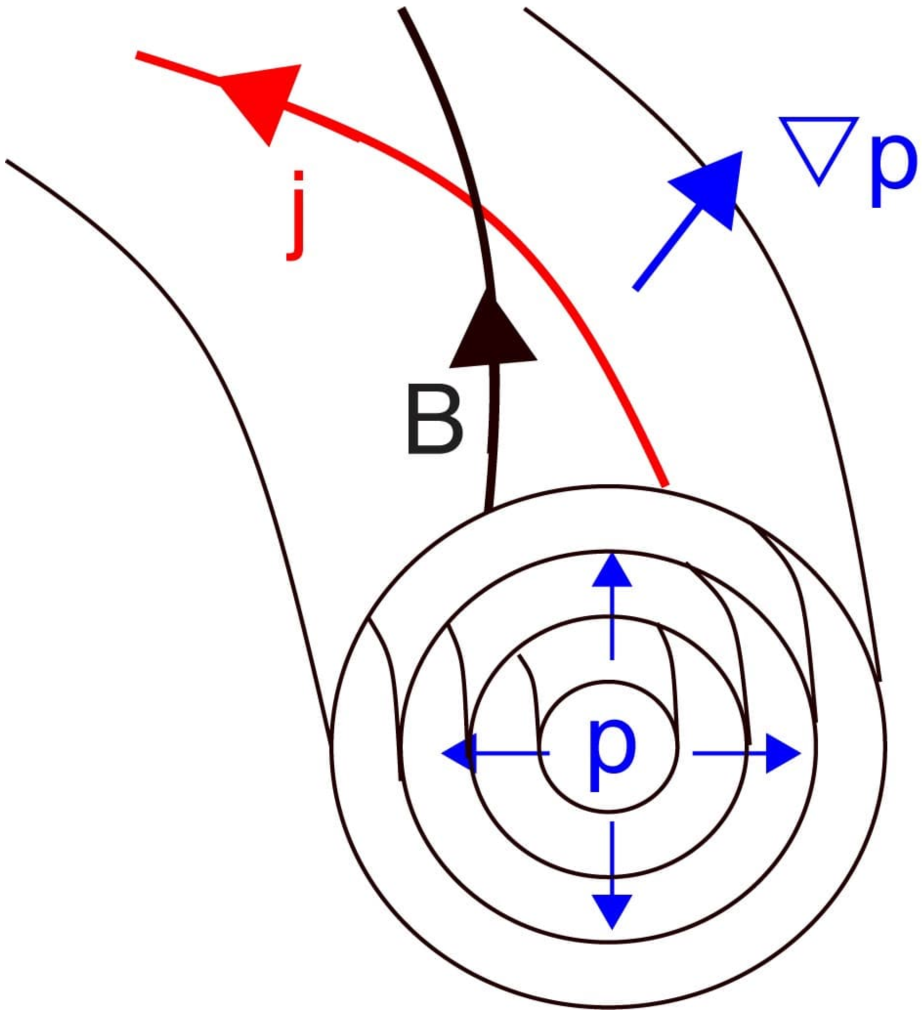
⇒ Describe equilibrium by (Ψ_p,I_p) ⇒ Grad-Shafranov equation

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



- **Toroidal magnetic field (B_T) peaks near the torus center and, inside coils, falls off radially (1/R)**
- **Poloidal field (B_P) is zero on the magnetic axis ⇒ $B_P/B_T \approx 1/10$**
- **Plasma current density (j_{tor}, up to MA/m^2) peaks on the magnetic axis ⇒ plasma current of the order MA's**

The combination of toroidal and poloidal fields produces nested surfaces



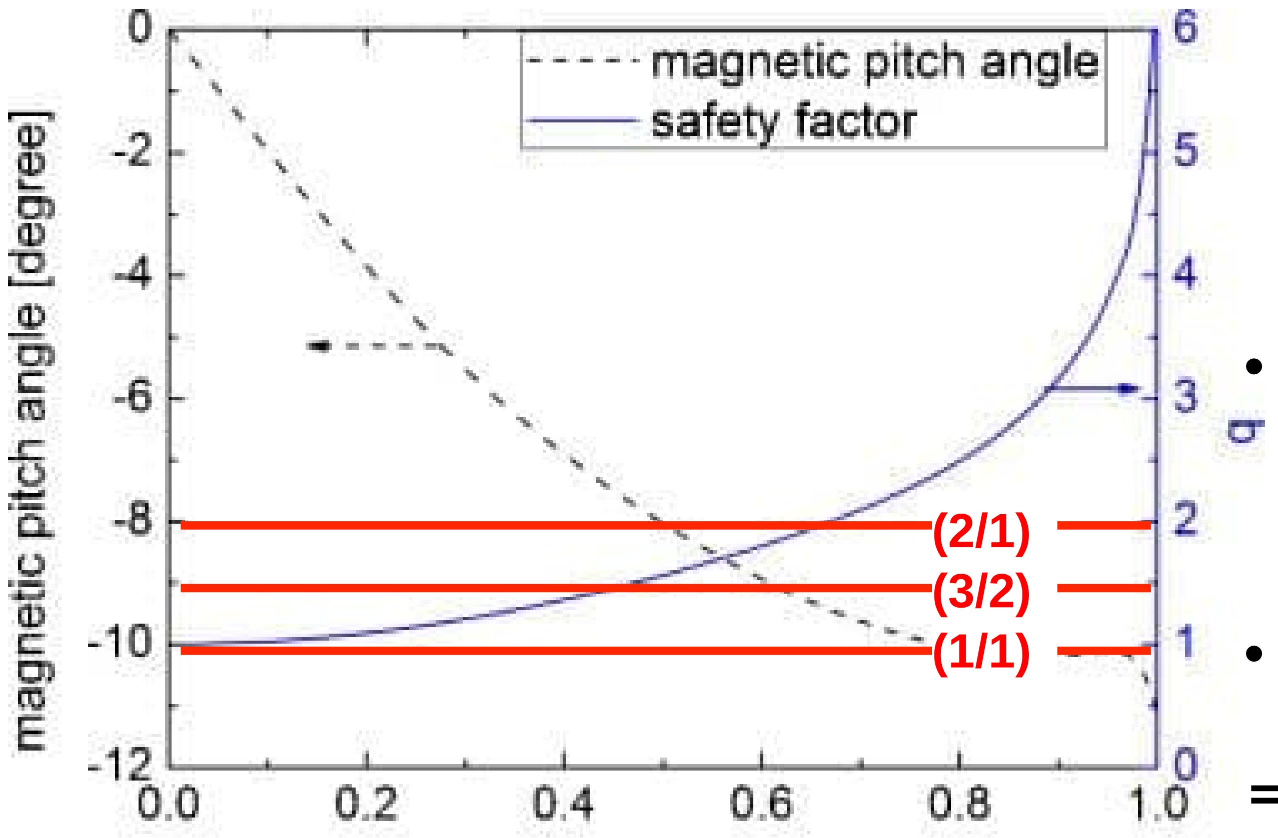
- **Stationary equilibrium determined by balance between plasma pressure and magnetic force (Grad- Shafranov equation):**

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

- **Efficiency of magnetic confinement measured by**

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

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



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

- **Safety factor:**

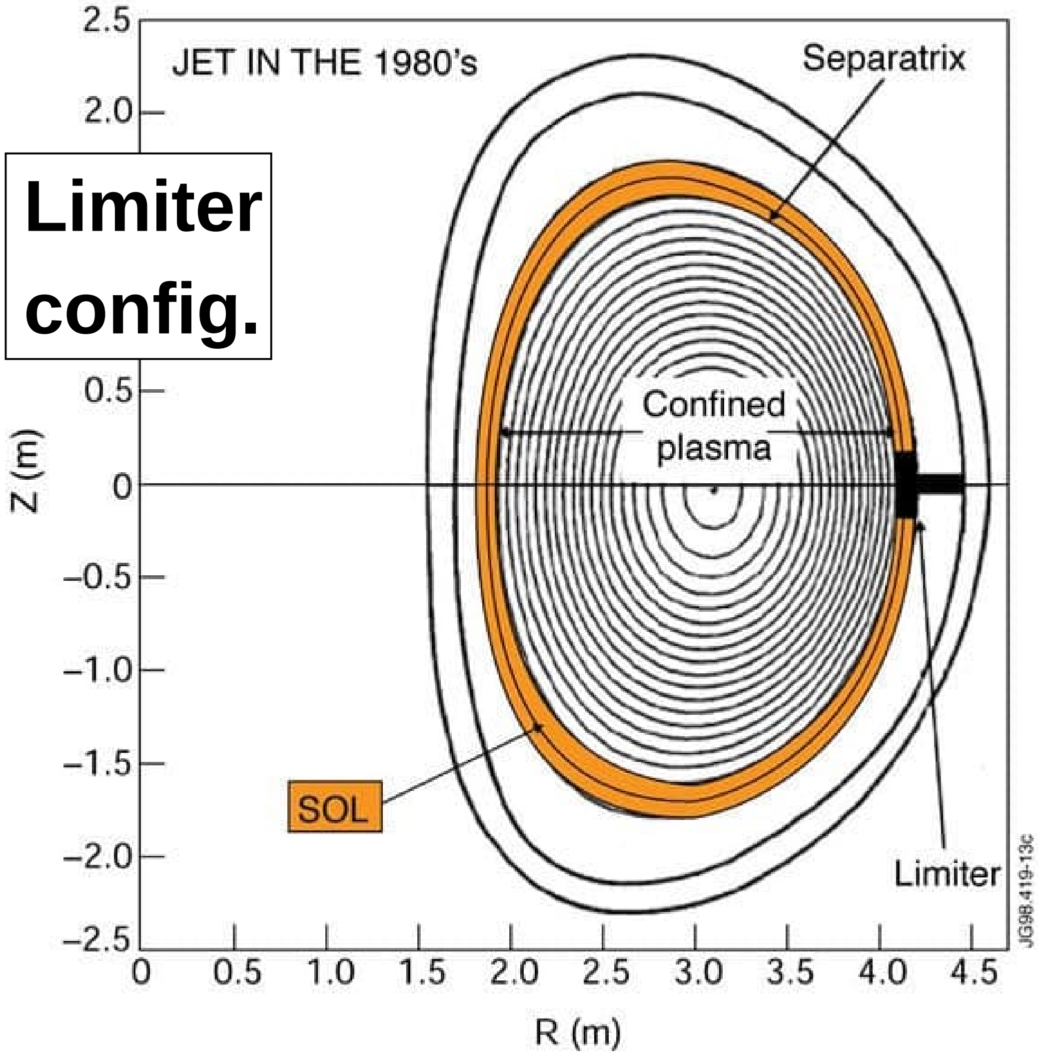
$$q(r) \equiv \frac{r B_T(r)}{R_{major} \, B_P(r)}$$

- **Typically, q(r) monotonically increase towd. edge**

- **Instabilities grow on rational q values**

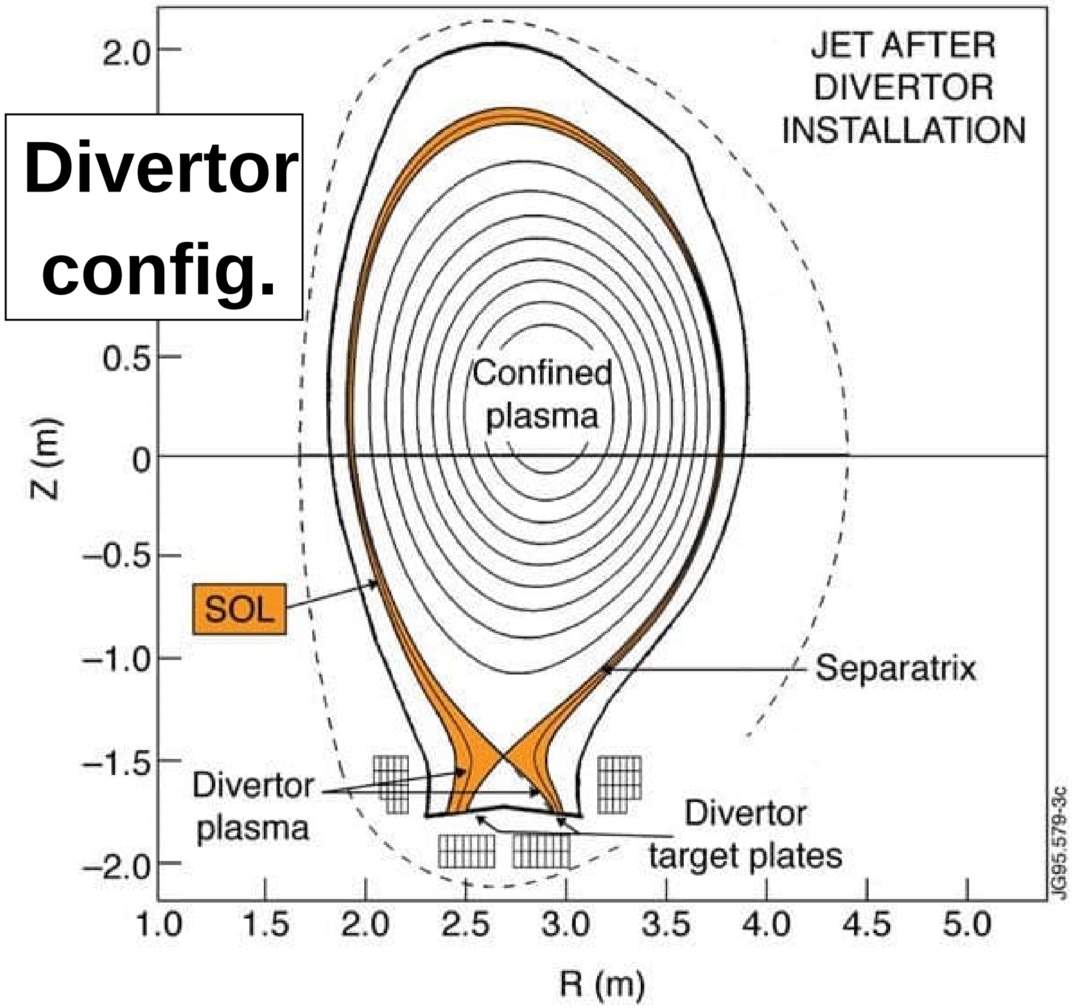
⇒ toroidal and poloidal mode numbers n and m

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**

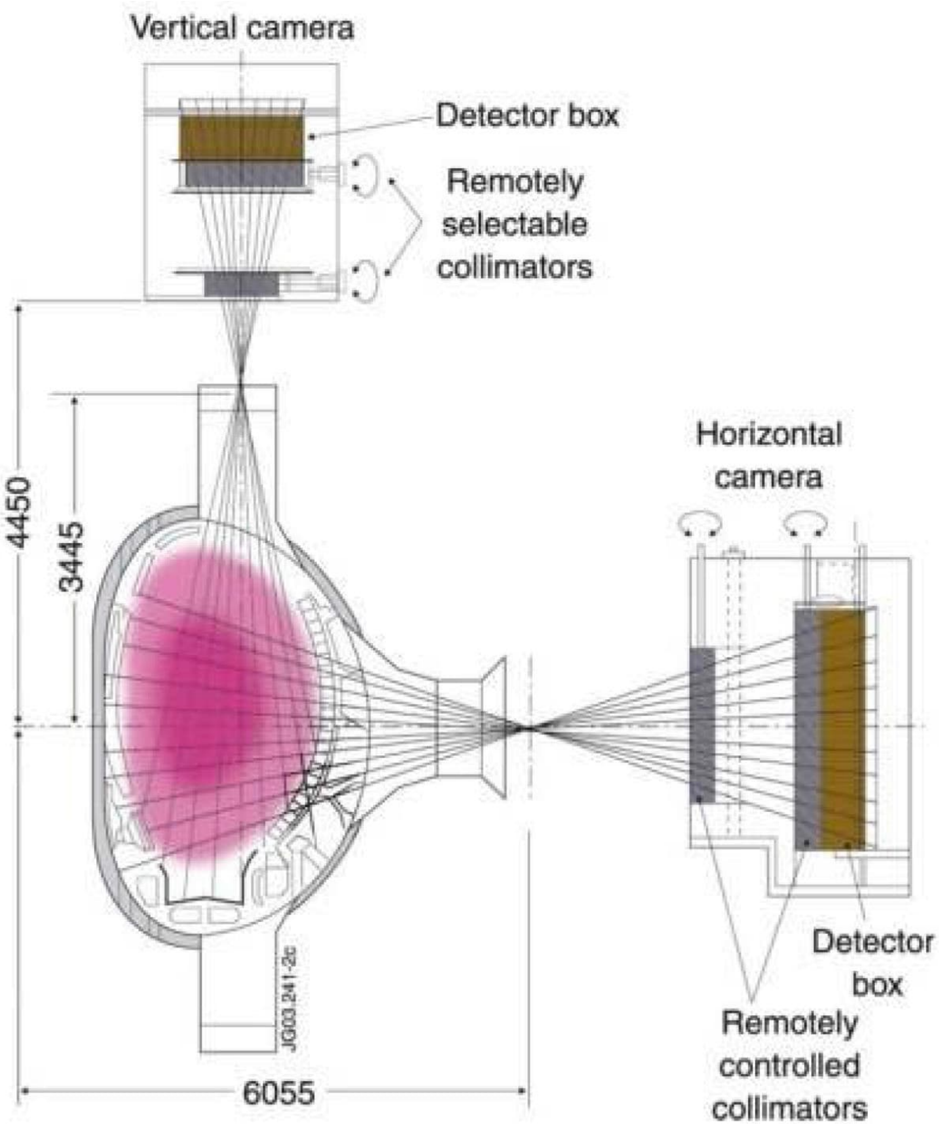
+ **Main interaction zone of plasma with divertor targets**

- **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 ≈ 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)

Presemo quiz #2

https://presemo.aalto.fi/fet/

Summary

- **A tokamak is a toroidal confinement device with magnetic field coils**

- **Plasma generated in vacuum chamber by transformer action driving a plasma current ⇔ 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!**