Misura della topologia magnetica

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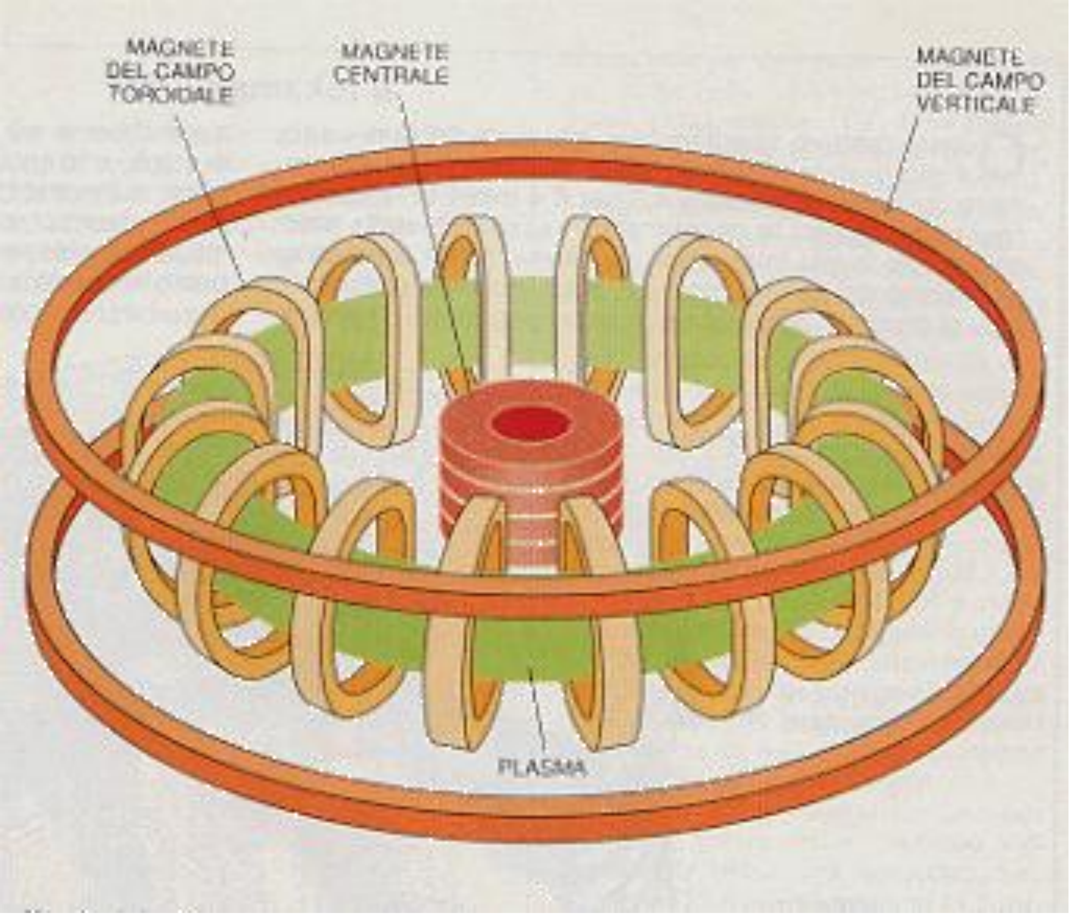
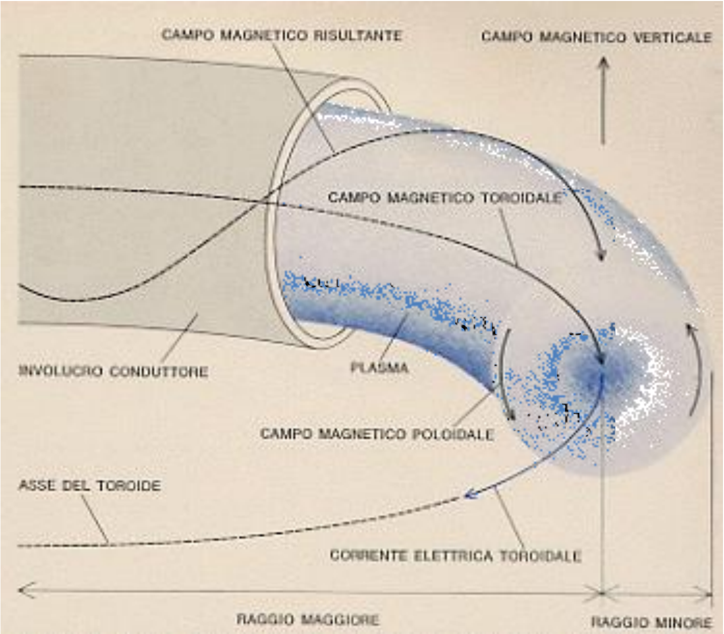
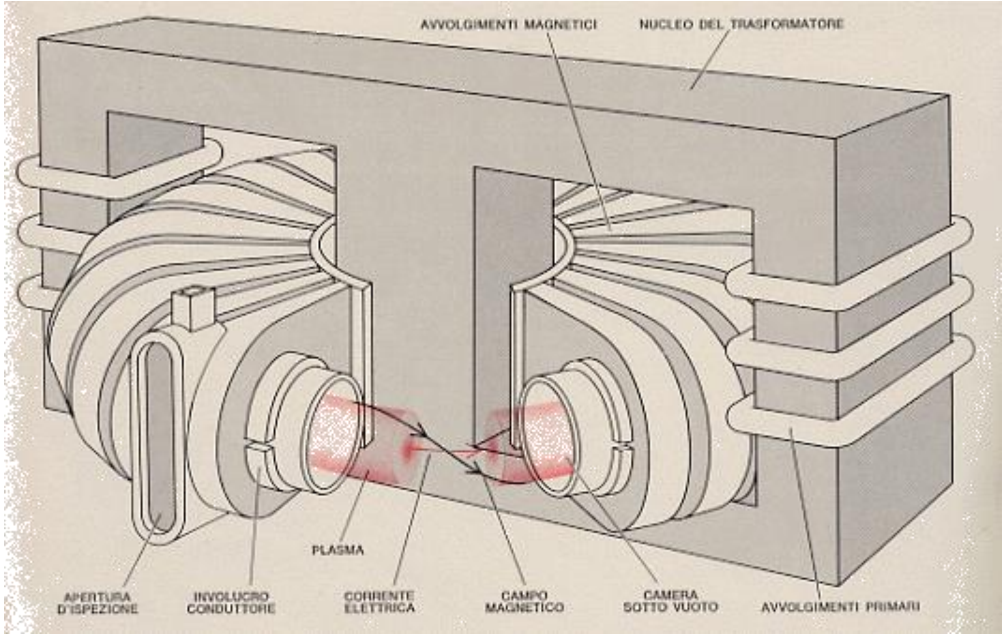
Reattori a Fusione: Tokamak

Il principio del Tokamak si basa su tre gruppi di elettromagneti. Un primo gruppo produce un *campo toroidale*, che funge da "manicotto" e confina il plasma. I *magneti centrali* del trasformatore servono per indurre una corrente elettrica nel plasma, la quale fluisce toroidalmente e riscalda il plasma. I *magneti del campo verticale* agiscono in modo da stabilizzare il plasma e mantenerlo al centro del toro.



Tokamak: confinamento

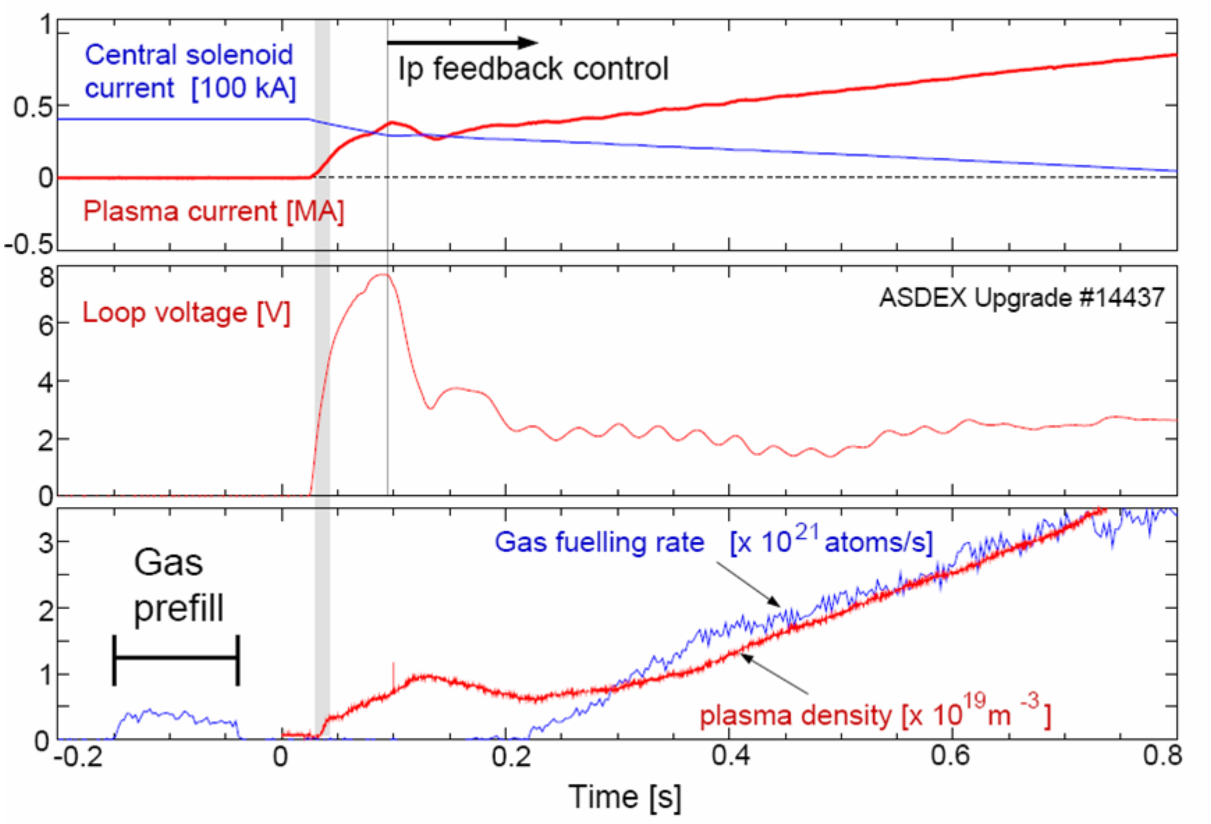




Il campo magnetico elicoidale è il risultante di due campi componenti: uno ***toroidale*** ed uno ***poloidale***.
Una configurazione del plasma di questo tipo, nella quale un plasma a forma di salvagente (toroide) è soggetto ad una forza costrittiva, viene detta *strizione toroidale*.

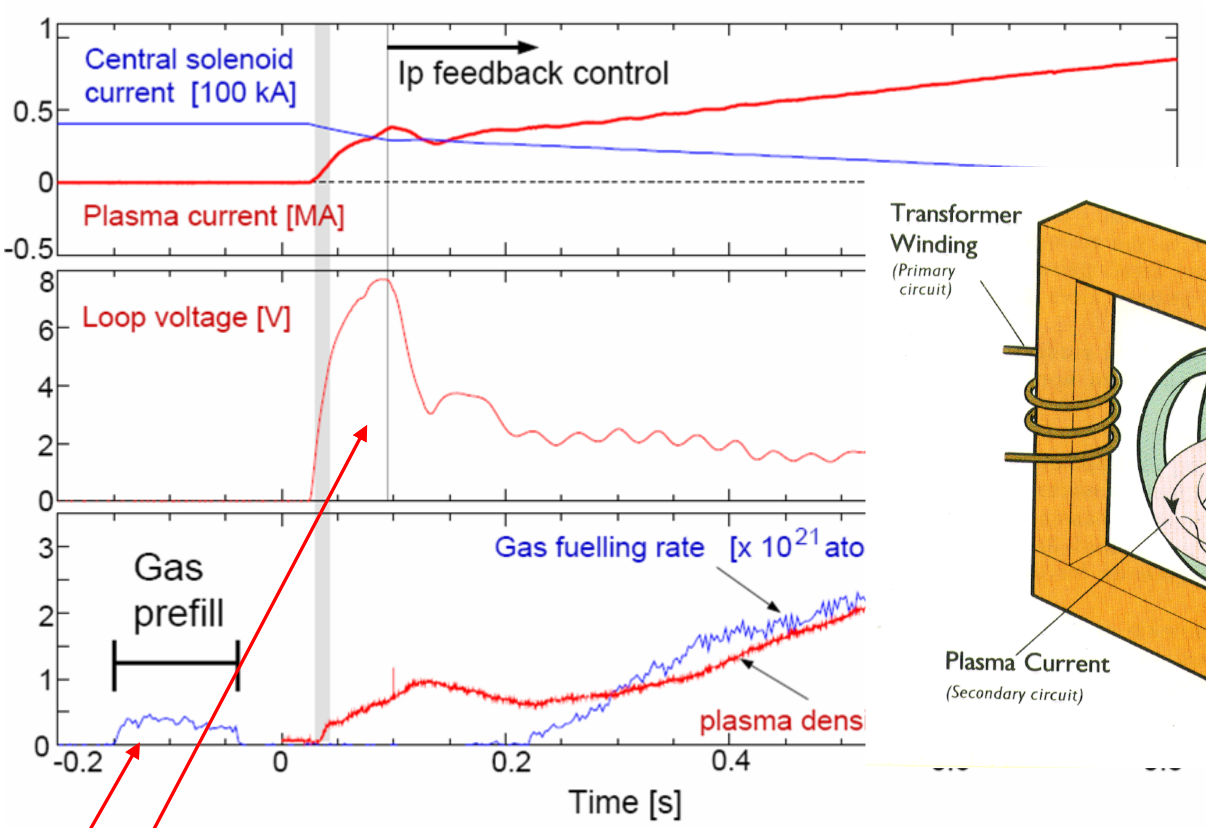
Running a discharge

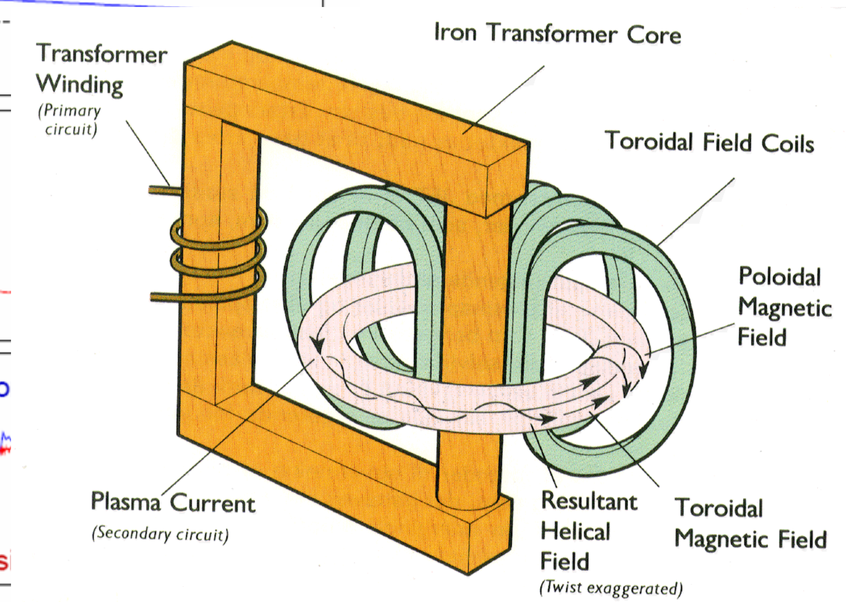
Startup



- Start with pumping the main vessel to obtain a good vacuum
- Then ramp up the toroidal field
- At the start of this picture there is a vacuum with a toroidal magnetic field

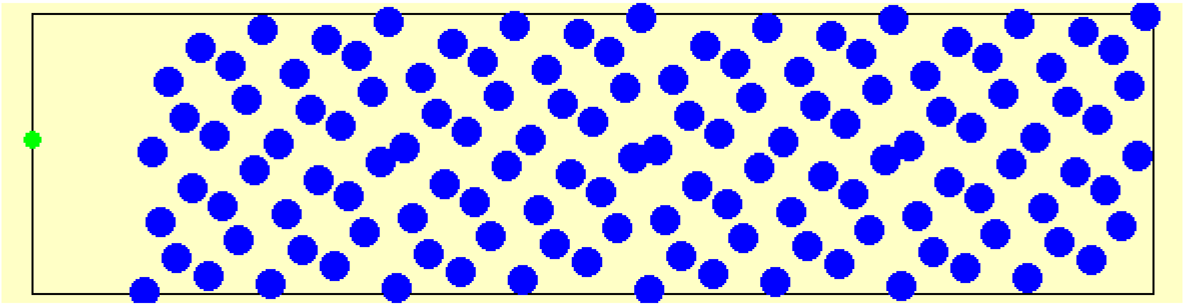
Startup





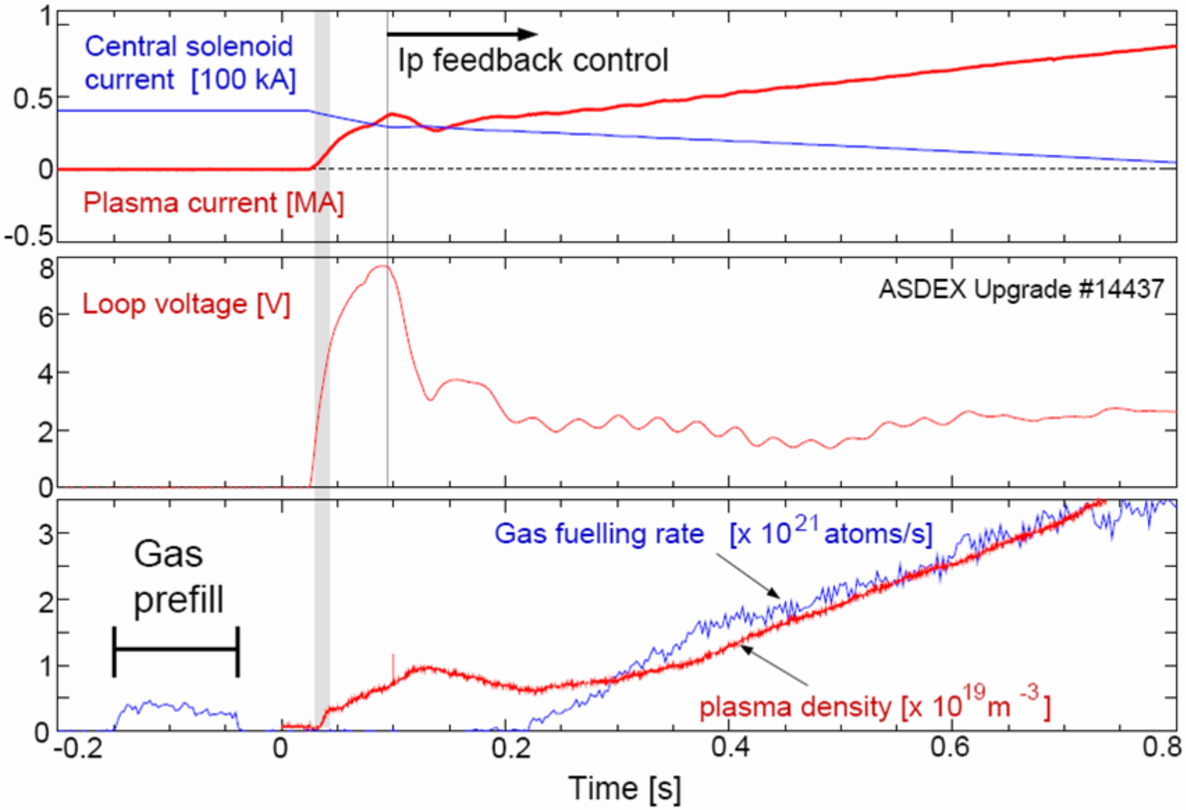
- Give a small puff of gas into the vessel (this neutral gas fills the whole vessel)
- Ramp up the flux in the transformer to obtain a high Electric field (this leads to plasma breakdown

Plasma breakdown



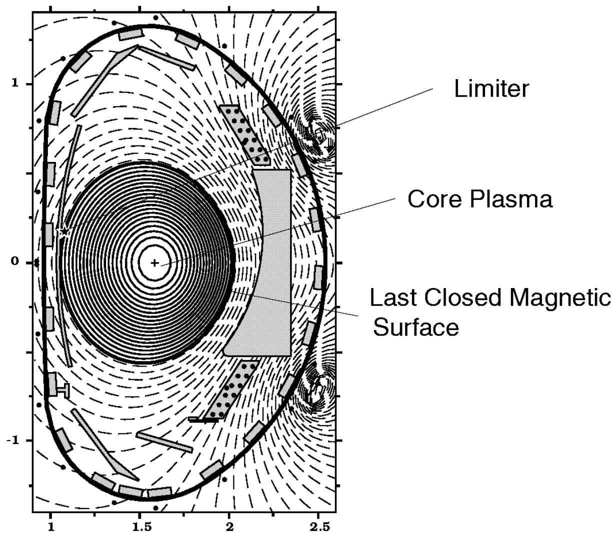
- Gas mostly neutral. But always one of the electrons is free
- The electric field accelerates this electron which gains in energy
- When the fast electron hits one of the atoms it can ionize it and generate an additional electron
- The avalanche leads to the break down
- Works well for low density (long mean free path) and high electric field
- Conditions mostly empirically determined

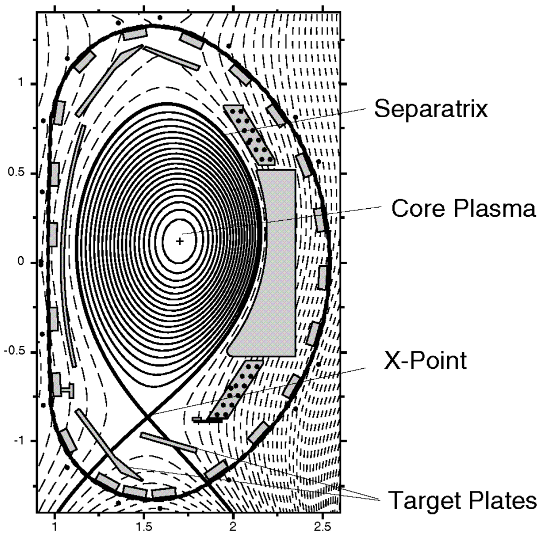
Startup



- Short time after the plasma breakdown one starts the feed back control of the plasma current
- It is slowly ramped to a stationary value required by the discharge

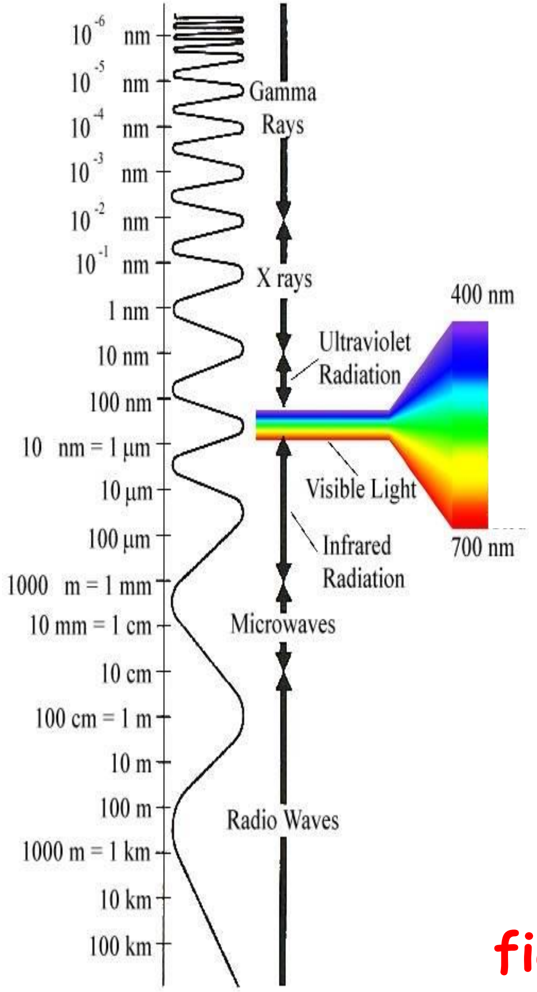
Breakdown also at non controlled position

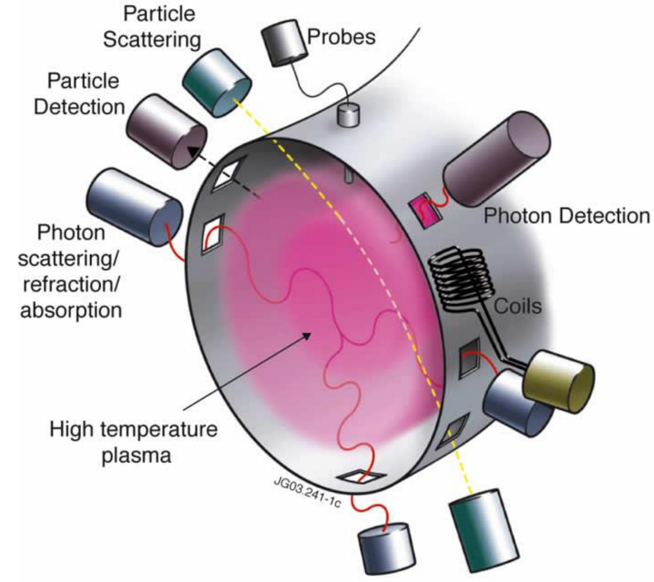




- Left possible position of the plasma at breakdown
- Right what one wants to achieve

Electromagnetic spectrum





Coil systems

$$V = -\frac{d\phi}{dt}$$

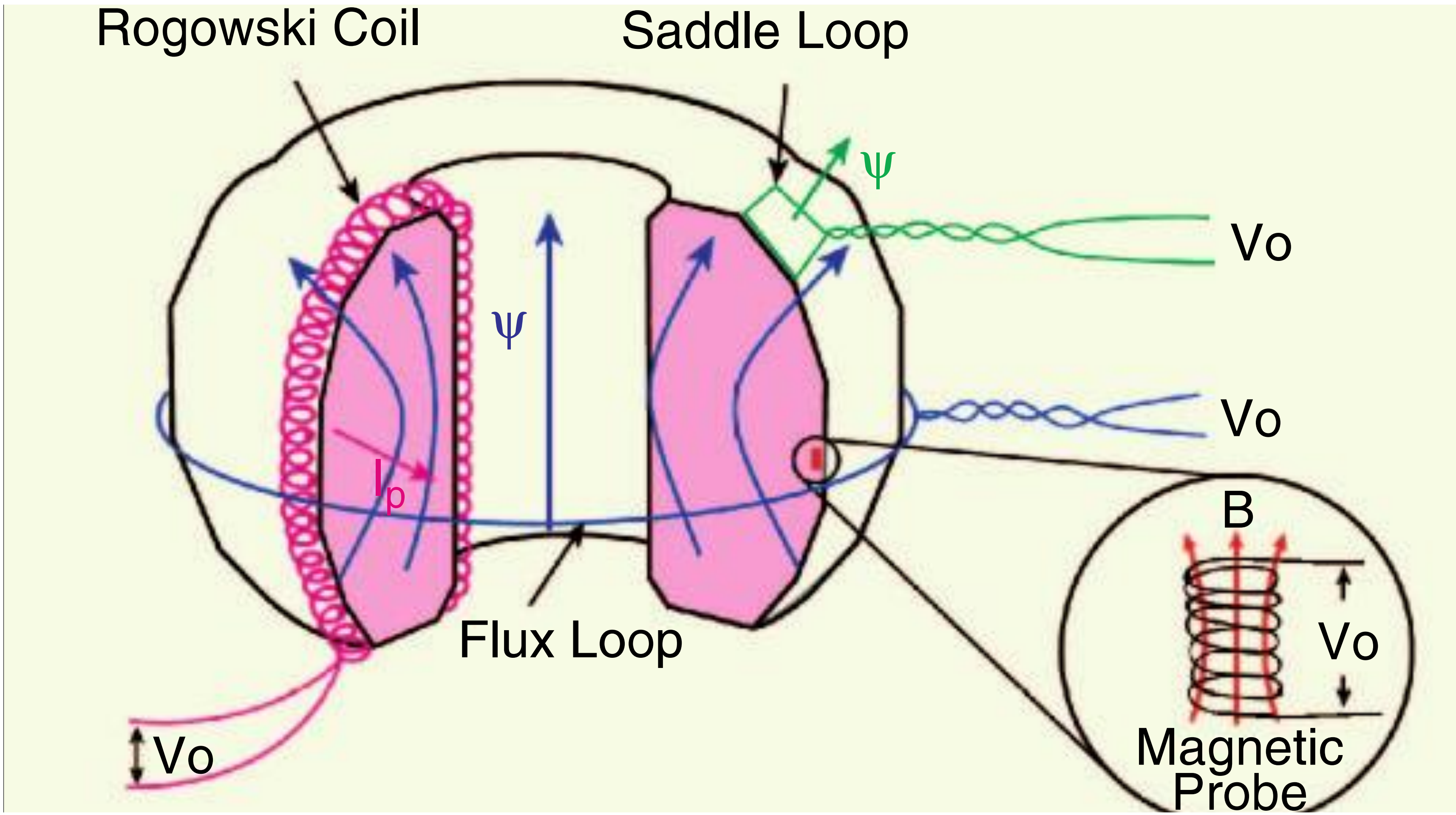
The traditional measurements of the magnetic fields outside the plasma are performed with coils and are based on induction.

Role of the magnetic measurements

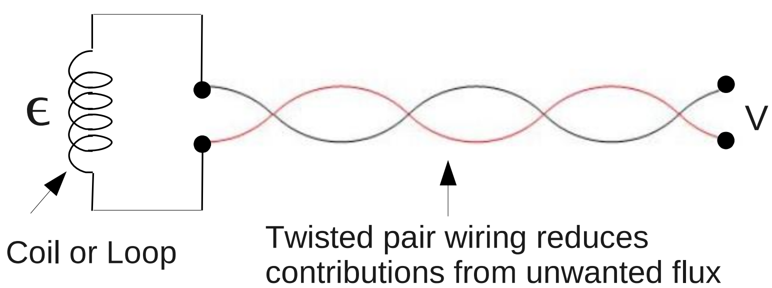
- **REAL TIME OPERATIONS**
  - **Protection System**: Some MHD activity can cause damage to reactor structure. Keep them under control is of fundamental importance.
  - **Plasma position and shape control** : Plasma distance from material components must be controlled
  - **Measurement:** Plasma current, Halo currents, magnetic field coils currents and currents in the machine conducting structures.

- **OFFLINE ANALYSIS**
  - **Magnetic reconstruction:** plasma boundaries and flux surfaces. Good knowledge of plasma magnetic geometry is **crucial to correctly locate and interpret information coming from many other diagnostics**, such as local temperatures, local densities, etc.
  - **MHD Analysis**: study of high frequency activity is indeed very important to gain insight into the physics of a broad range of plasma phenomena.

Sensori induttivi



Principio di funzionamento



ϵ = induced electromotive force
N = number of turns
A = coil's cross section
NA = effective coil's area ($\rightarrow$ S)
C = contour of S ($\rightarrow$ wires of the coil)
Φ = magnetic field flux linked to S

$$\Phi = \int_S \vec{B} \cdot \vec{ds} = \langle B \rangle S$$

mean component of $\vec{B}$ normal to A

$$\oint_C \vec{E} \cdot \vec{dl} = -\int_S \frac{\partial \vec{B}}{\partial t} \cdot \vec{ds}$$

Faraday's Law: induced electromotive force is proportional to the time derivative of the magnetic field flux

$$\epsilon = -\frac{d\Phi(\vec{B})}{dt}$$

$\epsilon \approx V \longleftarrow$ Assume high impedance electronics

$$\Rightarrow \boxed{V = -NA\langle \dot{B} \rangle}$$

By measuring V we measure the time derivative of B

$$\Rightarrow \boxed{\Phi = NA\langle B \rangle = -\int V dt + const.}$$

The time integral of the measured signal V is the linked flux and is proportional to the mean magnetic field on the coil's axis.

Magnetic field measurement

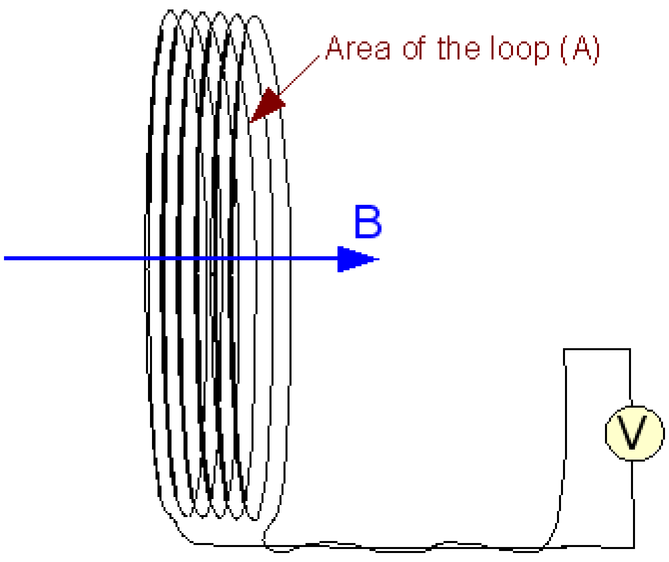
- Magnetic field is measured with small coils at many different positions

$$V = N\frac{\partial \psi}{\partial t} = NA\frac{\partial B_\perp}{\partial t}$$

Voltage Number of windings Area Magnetic field

$$B_\perp = \frac{1}{NA}\int_{-\infty}^{t} V(t)\mathrm{d}t$$

- Easy to construct diagnostic. Only disadvantage related to a possible drift due to spurious voltage



Schematic drawing of the coil with which the magnetic field is measured

Current measurement

- Plasma current is measured by a Rogowski coil

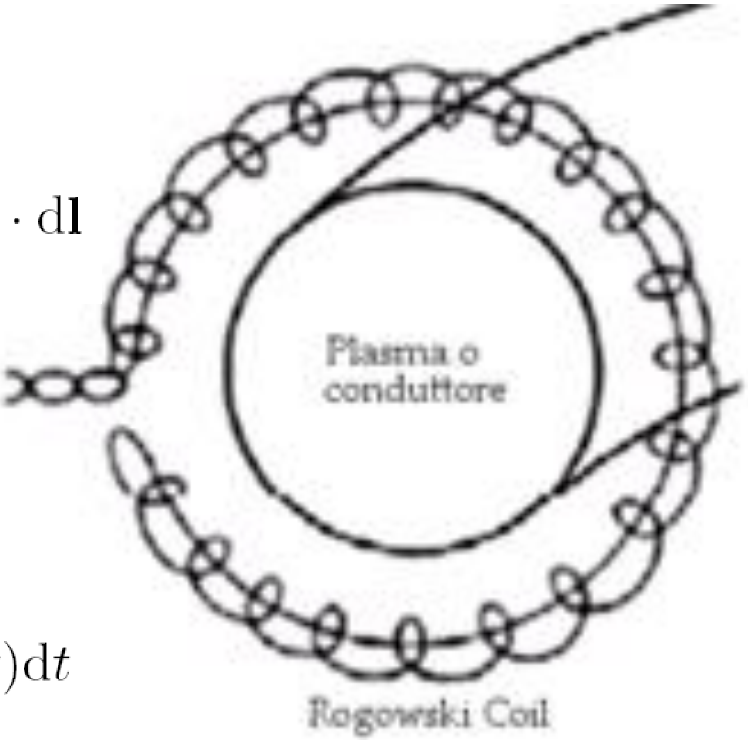
$$V = A \sum_i \frac{\partial B_{\perp i}}{\partial t} \approx \frac{A}{\Delta l} \frac{\partial}{\partial t} \oint \mathbf{B} \cdot \mathrm{d}\mathbf{l}$$

Sum over the windings

Distance between the windings

- Enclose current directly follows from

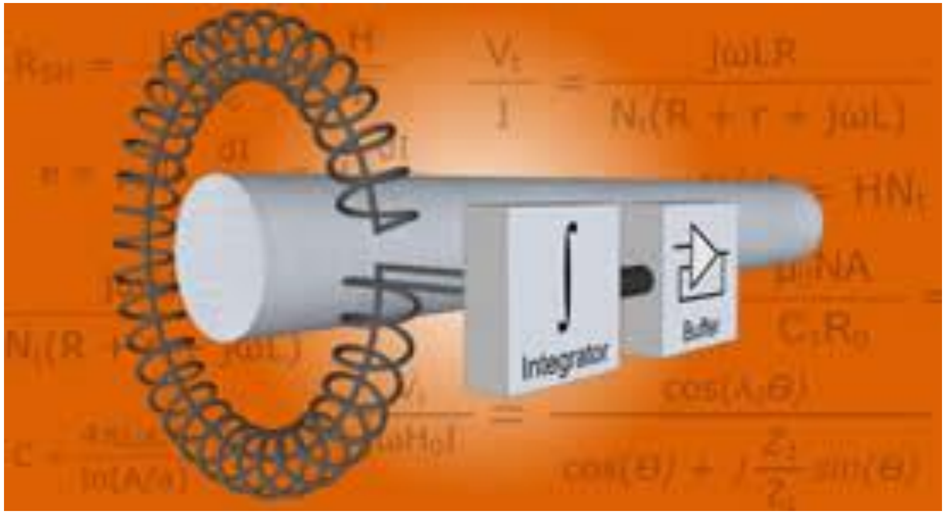
$$\mu_0 I = \oint \mathbf{B} \cdot \mathrm{d}\mathbf{l} = \frac{\Delta l}{A} \int_{-\infty}^{t} V(t) \mathrm{d}t$$



Rogowski coil

$$d\Phi = A\langle B\rangle dN \approx ABndl$$

$$\Rightarrow \Phi = nA\oint_C \vec{B}\cdot d\vec{l} = nA\mu_o I_p$$



A = solenoid's cross section, assumed constant

B = local magnetic field component normal to A
(assume B to be uniform on A)

n = number of turns per unit length

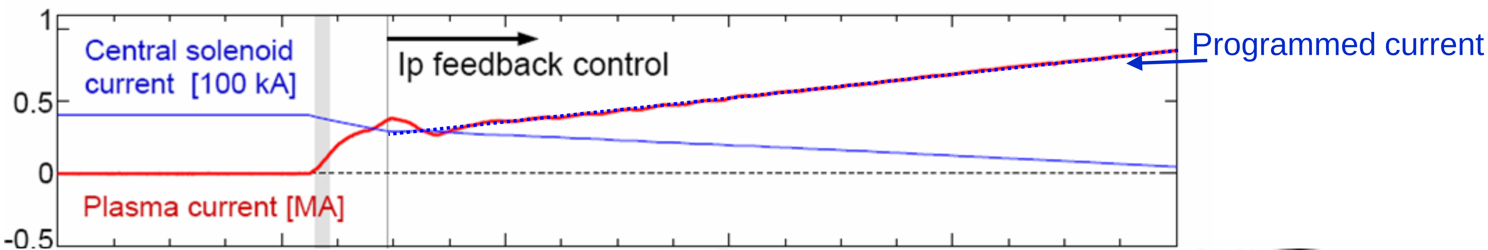
$\oint_C \vec{B}\cdot\vec{dl} = \mu_0 I_p$ ← Ampere's law

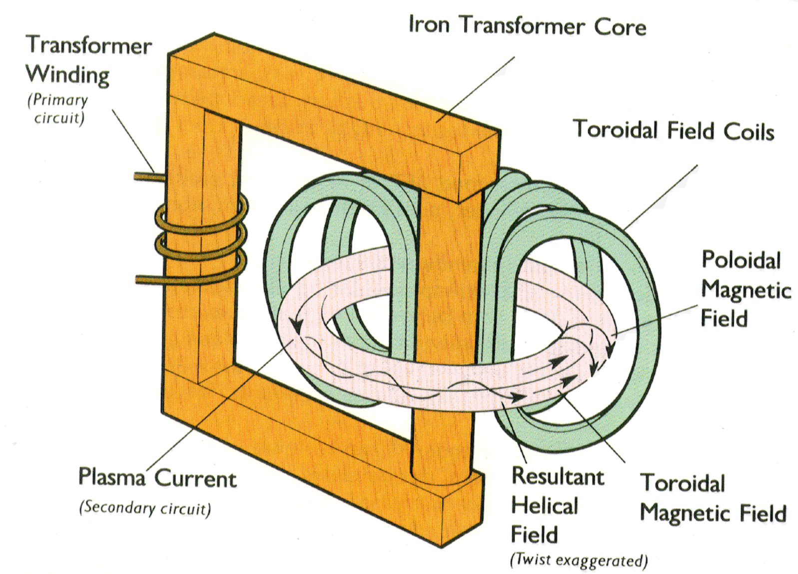
$$\boxed{\Phi = \mu_0 nAI_P = -\int Vdt + const.}$$

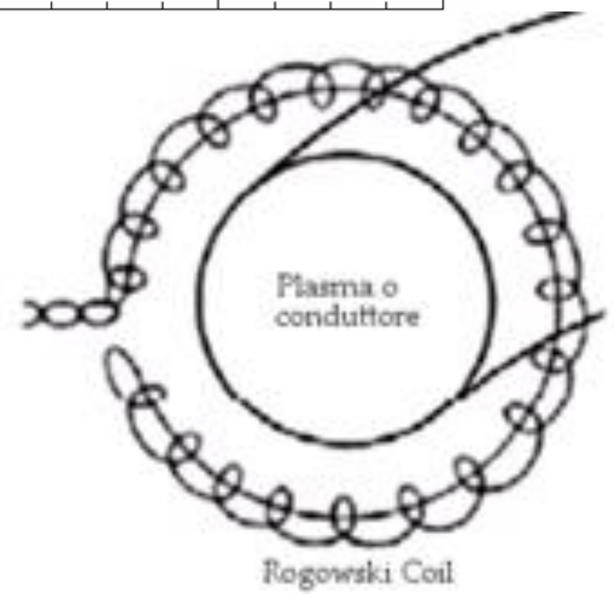
Rogowski coil

- The current measurements do not depend on the rogowski shape, nor on the current distribution inside the plasma
- Wire path must return along the axis to the other end.
- Rogowski coil can be substituted by a set of tangent coils

Startup



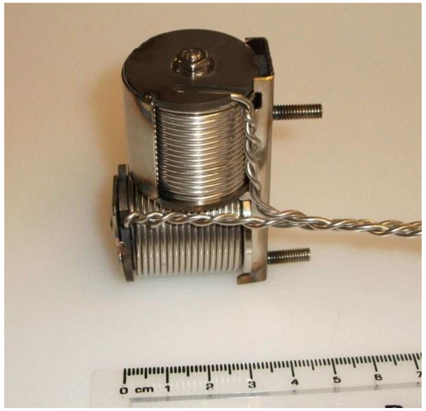




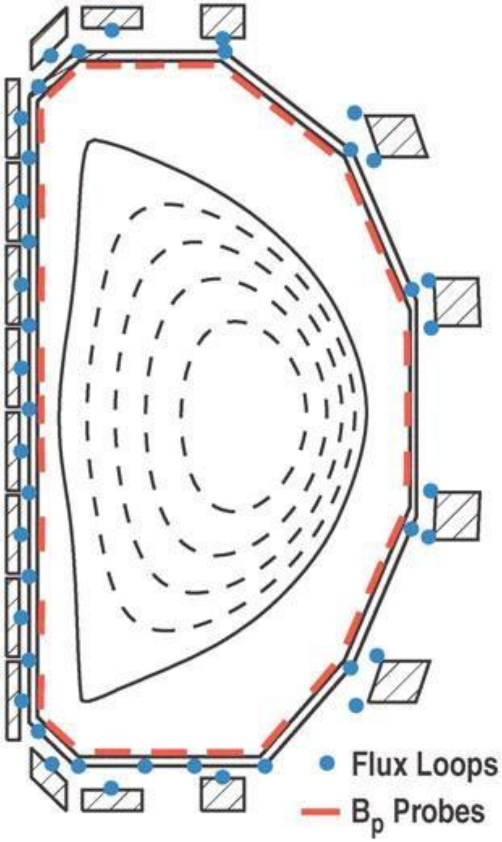
- Plasma current is measured by the Rogowski coil
- If the value is lower than desired one ramps the current in the solenoid a little faster

Pick-up coils

- Small size compared to the gradient scale length.
- Local B measurements
- Direction sensitive



JET coils



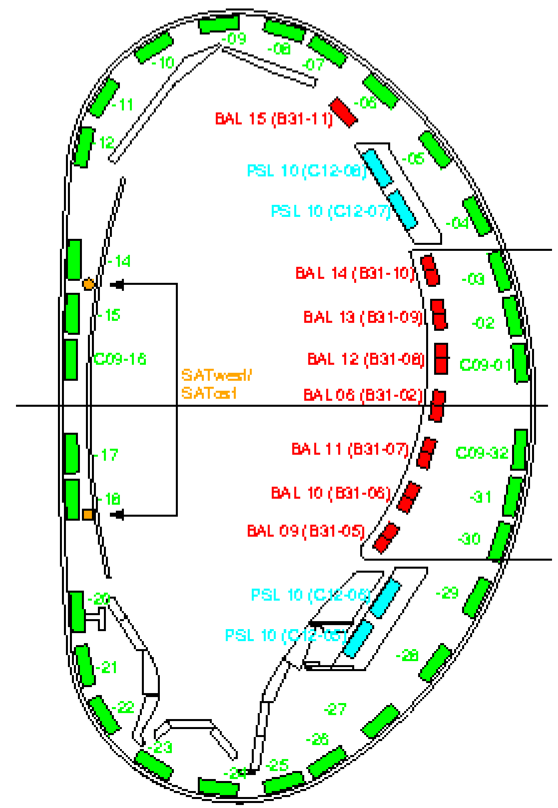
DIII-D

Mainly used for:

- Plasma control and equilibrium reconstruction
  - Low frequency (< 1 kHz)
  - Integrated signal
- Detection of MHD instabilities
  - High frequency (1-100 kHz)
  - Un-integrated

Set of coils measure the magnetic field

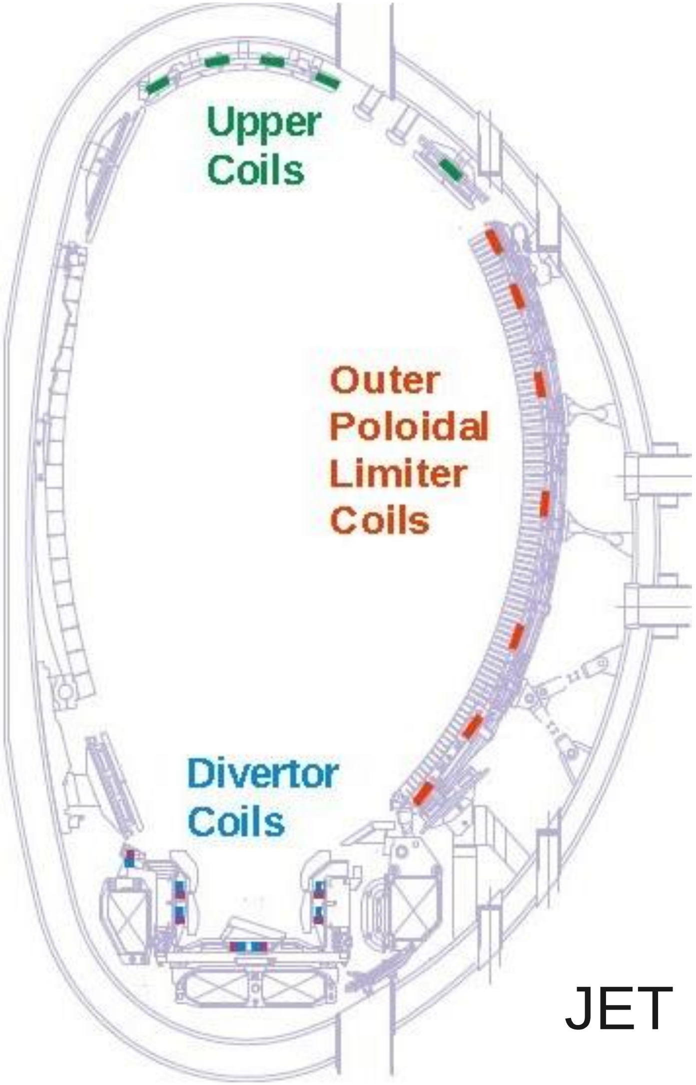
- Magnetic field is measured at the boundary
- Green – Poloidal field
- Red – Radial field
- Blue – poloidal flux
- The plasma position and shape can be reconstructed from these measurements
- Control system then changes the current in the vertical field coils to shape the plasma



Mirnov coils

When used for MHD activity are called Mirnov coils
Always inside the vessel

JET upper coils



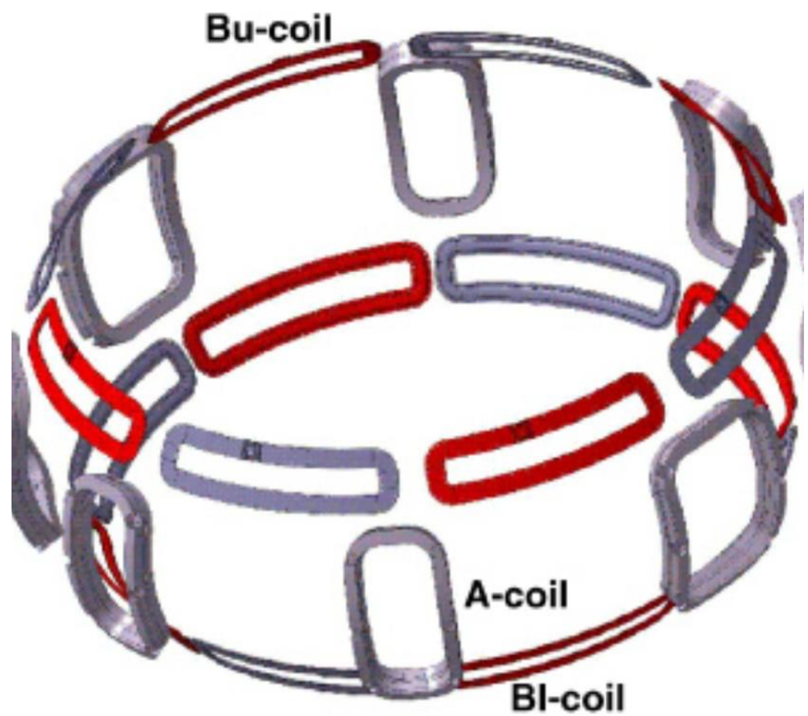
JET

Saddle coils

Saddle coils are extended coils mounted on vacuum vessel which measures the flux of perpendicular field.

$$\Phi = NA \langle B_{\perp} \rangle$$

- Used for equilibrium reconstruction
- A complete set can be used for poloidal flux measurements



ASDEX

Voltage loop

It's a single wire encircling the toroidal direction voltage induced by the transformer (V_ϕ)

Plasma resistance:

$$R_p = \frac{V_\phi}{I_p}$$

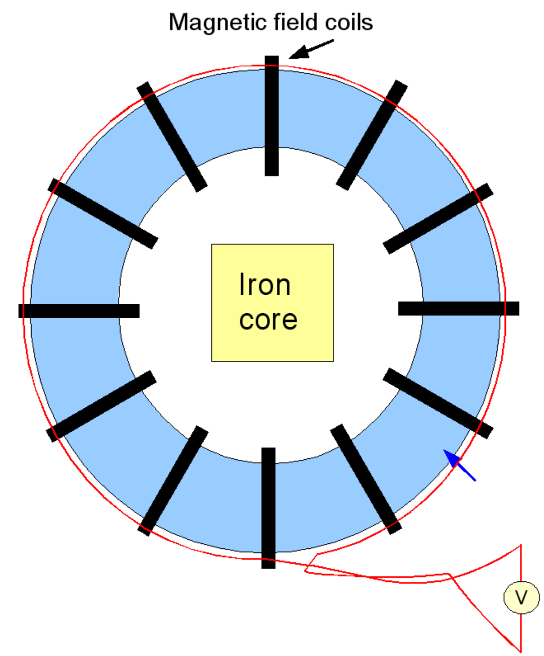
In stationary phase

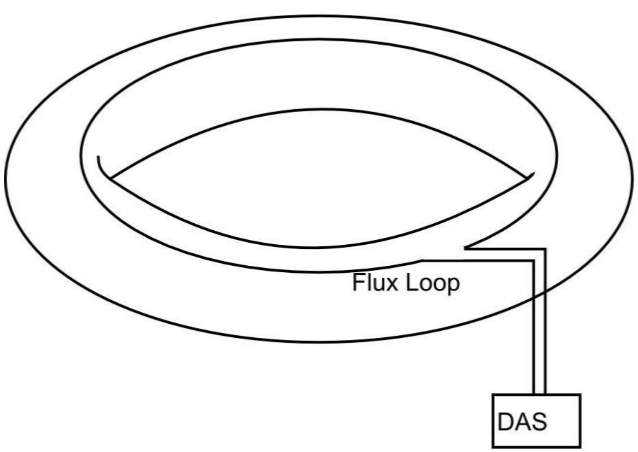
Ohmic input power:

$$P = \int_V \left(j_\phi^2 / \sigma \right) dV = I_p^2 R_p$$

Plasma resistivity:

$$\bar{\sigma} = \frac{1}{\bar{\rho}} = \left(\frac{2\pi R}{\pi a^2}\right)\frac{1}{R_P} \qquad \bar{\sigma} \propto \frac{T_e^{3/2}}{Z_\sigma \ln\Lambda} \approx \frac{T_e^{3/2}}{Z}$$





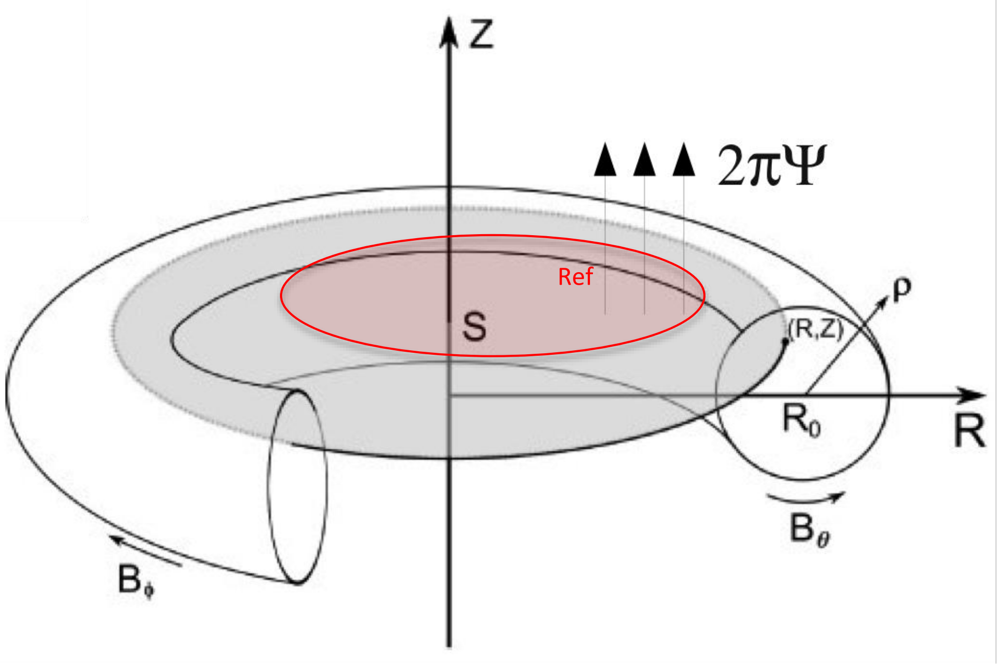
Loop for poloidal flux measurements

The integrated signal measures the poloidal flux for use in plasma control and **equilibrium reconstruction**

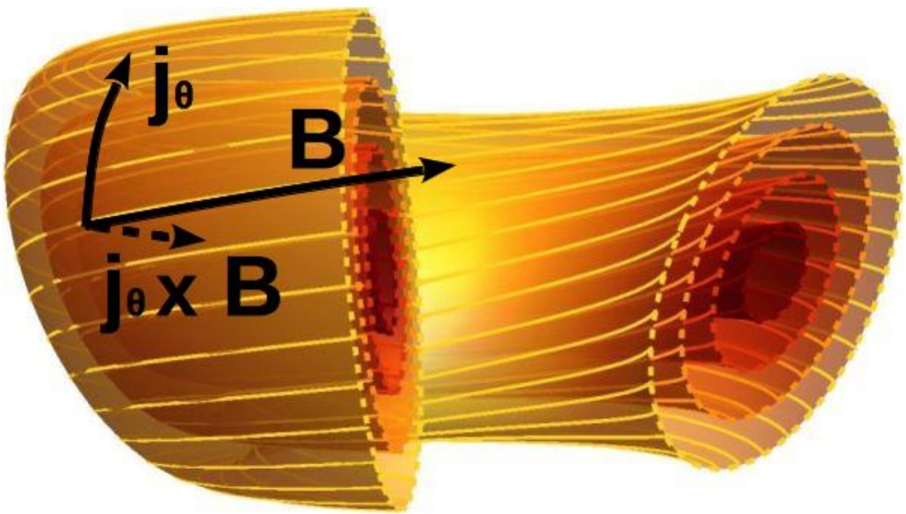
$$\Phi = 2\pi\Psi = -\int V dt$$

In order to subtract the contribution of the transformer, a reference loop is subtracted:

$$\Delta\Phi = 2\pi\left(\Psi - \Psi_{ref}\right)$$



Effetto diamagnetico



From equilibrium

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

Equilibrium develops poloidal currents that reduce toroidal field : diamagnetism

$$\frac{(\nabla \times B) \times B}{\mu_o} = \nabla p$$

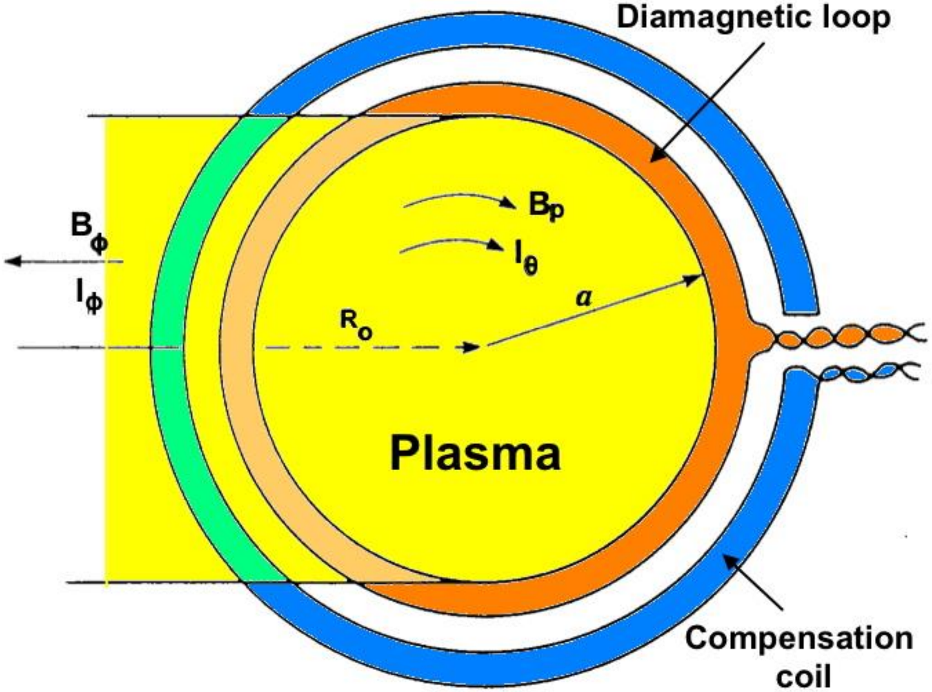
$$\nabla\left(p + \frac{B^2}{2\mu_0}\right) = (\mathbf{B} \bullet \nabla)\frac{\mathbf{B}}{\mu_0}$$

$$\frac{\partial}{\partial r}\left(p + \frac{B_z^2 + B_\theta^2}{2\mu_0}\right) = -\frac{B_\theta^2}{r\mu_0}$$

$$\left(p + \frac{B_z^2 + B_\theta^2}{2\mu_0}\right)_{r=a} = \frac{1}{\pi a^2}\int_0^a \left(p + \frac{B_z^2}{2\mu_0}\right) 2\pi r dr$$

$$2\mu_0 \langle p \rangle = B_{\theta a}^2 + B_{\phi a}^2 - \langle B_\phi^2 \rangle$$

Loop diamagnetico



- Diamagnetic loops measure the plasma energy from the toroidal flux

$$\Phi \propto \langle B_\phi \rangle$$

- Difficult measurement because diamagnetic effect is small
- Alignment is critical for these coils. A small contribution of poloidal field would make a large flux change
- Compensation coil reduces spurious pick-up (sensible only to vacuum field change)

$$\beta_\theta = \frac{2\mu_0 \langle p \rangle}{B_{\theta a}^2} \approx 1 + \frac{2B_{\phi a}\left(B_{\phi a} - \langle B_\phi \rangle\right)}{B_{\theta a}^2}$$

(from P. E. Stott, Varenna School on Plasma Diagnostics, 1982)

Summary

measured quantity	*Technique*				
	Flux loop	pick-up coils	Saddle loop	Diamagnetic Loop	Rogowski coils
Plasma current		S			P
Plasma Position	P	P	S		
Plasma Shape	P	P	S		
Plasma Energy	P	P	S	P	
Toroidal efm	P				
Toroidal magnetic field		P			S
Coils current					P
Halo current		S			P
High f mode (Tearing mode, fishbones, TAE)		P			
Low f mode (RWM, Locked)		P	P		

Magnetic Measurements in the 14 MeV field

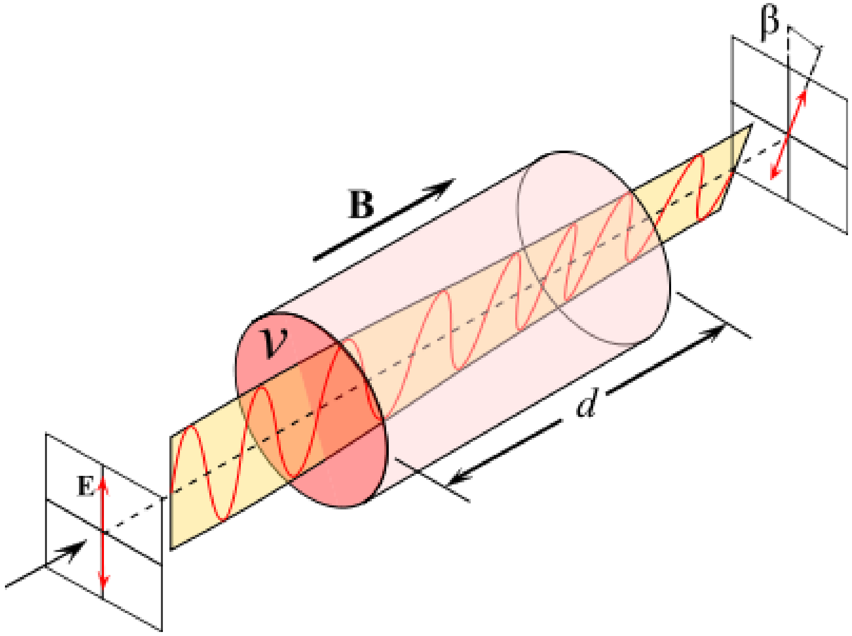
– All the magnetic measurements based on induction (Faraday law) are affected by spurious voltages generated in the cables by the 14MeV neutrons. Testing of the ITER Fiber

– Alternative are measurements based on polarized light and absolute sensors (Hall sensors)

– Optic Current Sensor for plasma current measurements: is based on the Faraday effect, the rotation of the plane of polarization of a laser beam.

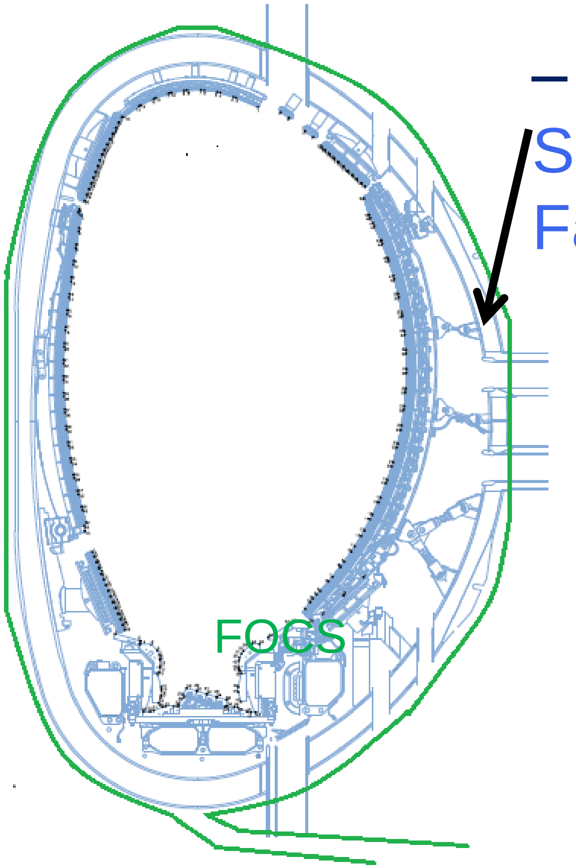
$$\beta = \mathcal{V} B d$$

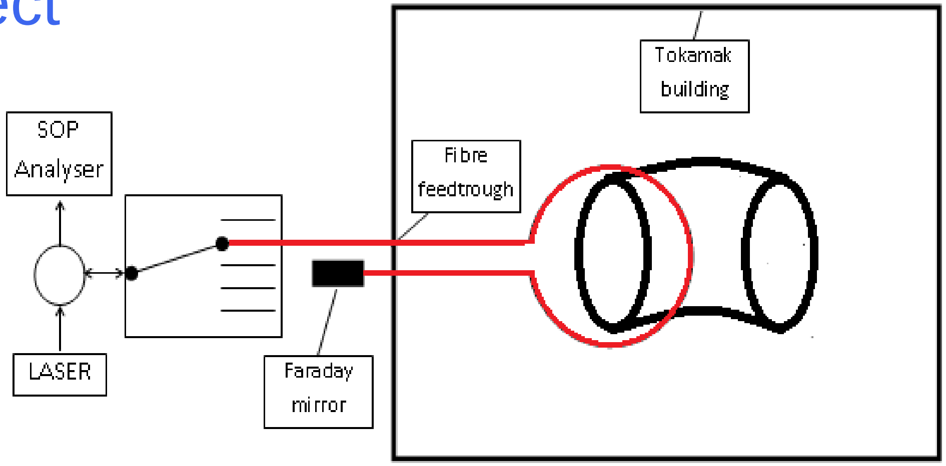
$\mathcal{V}$: Verdet constant



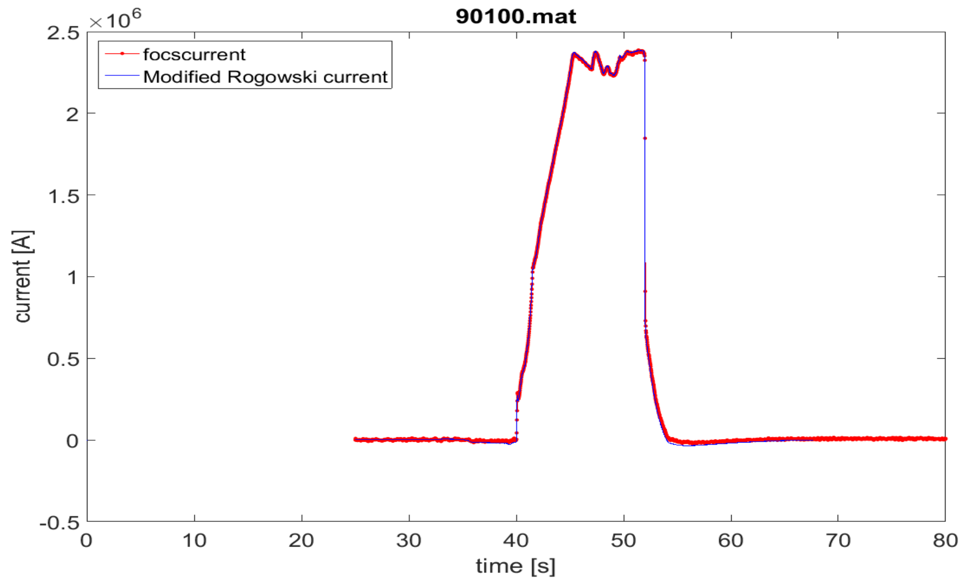
JET3 – Technological exploitation of DT operation

- Testing of the ITER Fiber Optics Current Sensor for plasma current measurements: Faraday effect



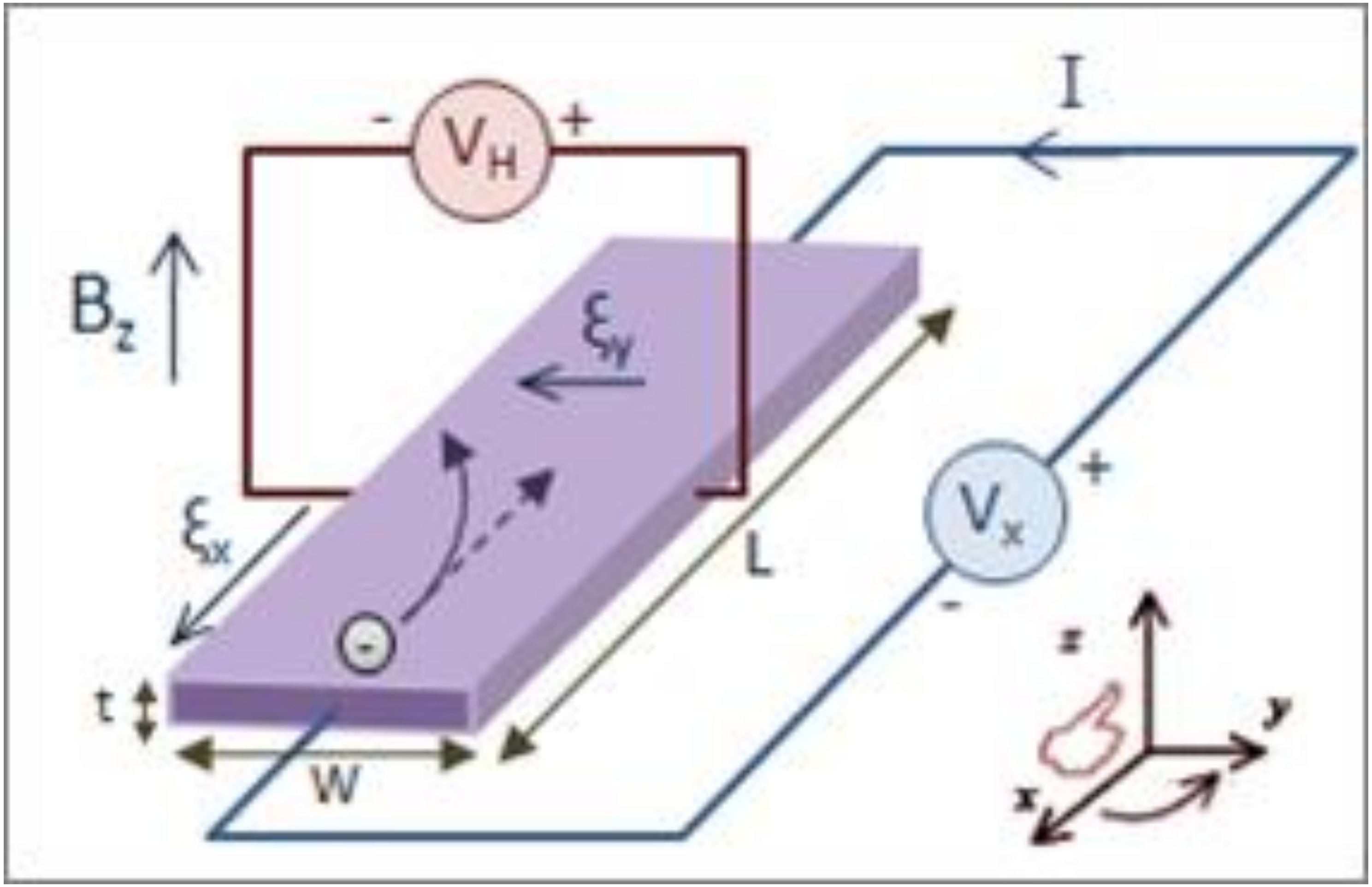


- Experimental measurements in agreement with traditional current measurements

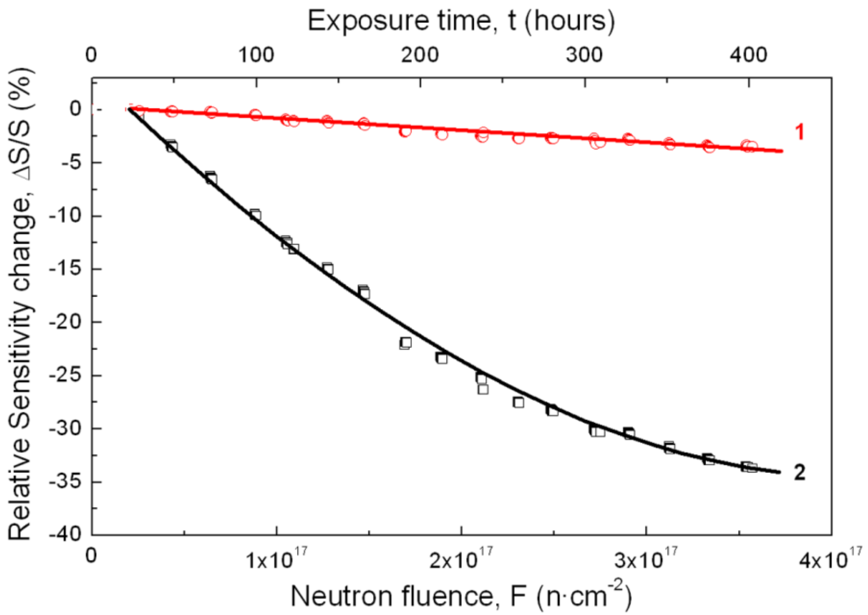


Hall sensors

– Hall sensors measure directly the magnetic field (and not its derivative).



Hall sensors resistance in radiation environment of neutron irradiation



Sensors sensitivity change vs. neutron fluence:

1 – radiation-resistant sensor;

2 – conventional sensor

InSb-based sensors are operable up to neutron fluences $F = 5 \cdot 10^{18}$ cm^{-2}, which exceed maximum fluence in ex-vessel sensor locations at ITER

$F = 10^{15}$ cm^{-2} → $\Delta S/S = 0.04\%$ | $F = 10^{17}$ cm^{-2} → $\Delta S/S = 5\%$

$F = 10^{16}$ cm^{-2} → $\Delta S/S = 0.08\%$ | $F = 10^{18}$ cm^{-2} → $\Delta S/S = 10\%$

Nuclear reactors

Sensor testing in ITER-relevant neutron fluxes

IBR-2
Joint Institute of Nuclear Research, Dubna, Russia

WWR-M
Petersburg Nuclear Physics Institute, Russia

WWR-Ts
Institute of Physical Chemistry, Obninsk, Russia

LVR-15
Nuclear Research Institute, Řež, Czech Republic

TOR VERGATA
UNIVERSITY OF ROME

Neutrons

Fast

Thermal

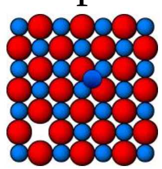
Semiconductor

Mutual compensation

Radiation defects

Nuclear doping

Acceptors



Minimal sensor parameter drift

(subject to correction with dedicated electronic methods)

Donors

$$^{115}In(n,\gamma)^{116}In \xrightarrow[54\,\mathrm{min}]{\beta} {}^{116}Sn$$

(97,5% of possible reactions)

Methods for stabilizing the semiconductor sensor parameters:

- Chemical doping of semiconductor materials (InSb, InAs) with the complex of doping impurities (donor, isovalent, rare-earth ones) up to optimal initial concentration of free charge carriers.
- Radiation modification – preliminary introduction of certain number of radiation defects.

JET: Radiation-hard ex-vessel Hall Probe location

6 Hall Probes with
18 Hall Sensors and
18 microsolenoids → in Octants 5 & 8, Sector D, Ports

Prompt effects to be assessed in D-T

#79206.