Magnetic Diagnostics for Plasmas

bernardo.carvalho@tecnico.ulisboa.pt

APPLAuSE Advanced Program in Plasma Science and Engineering

Outline

Outline

Portuguese Discoveries, XV - XVI Centuries

The Portuguese Heroes

Henry the Navigator 1394-1460

King John II 1455-1495

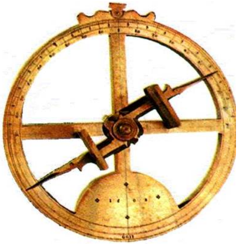
Vasco da Gama 1460-1524

Pedro Alvares Cabral 1467-1520

Ferdinand Magellan 1480 1521

The Instruments

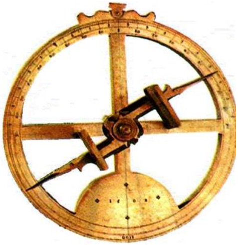
The Caravel



The Astrolabe

The Instruments

The Caravel



The Astrolabe

The Compass

Magnetic Diagnostics: General Principles

Magnetic measurements provide some of the most fundamental and essential information about a fusion plasma:

- I_{plasma}, Internal Inductance ℓ_i, Position and Speed of current centroid, Boundary Shape, Thermal Energy, Currents in the magnet coils, and the strength of the magnetic fields confining the plasma.
- Information about the internal characteristics of the plasma and about asymmetries caused by large-scale MHD instabilities.
- Halo Currents in machine structures.

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General Principles II

- Essential for Equilibrium Reconstructions
  - Post-discharge full equilibrium codes
  - Real-Time Plasma Shape and Position Control
- Magnetic diagnostics are external, passive and ROBUST!
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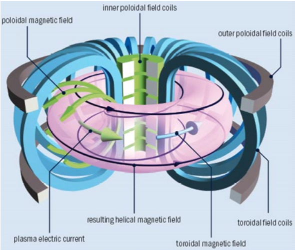
Axisymmetric Configuration of Fusion Devices

Magnetic field

- In a cylindrical coordinate system, (R, Z, ϕ), $\vec{B}$ can be expressed in terms of two scalar functions, F, and Ψ:

$$\vec{B} = (F\hat{\phi} + \nabla\Psi \times \hat{\phi})/R$$

- $\vec{B}$ field can be separated in
  - Toroidal Field: $\vec{B}_\phi = \frac{F}{R}\hat{\phi}$
  - Poloidal Field: $\vec{B}_p = \frac{\nabla\Psi}{R}$



TÉCNICO LISBOA

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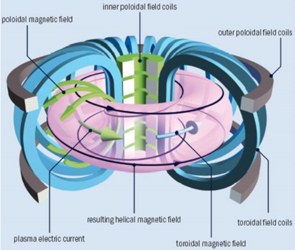


Axisymmetric Configuration

Poloidal Fluxes

Magnetic Flux

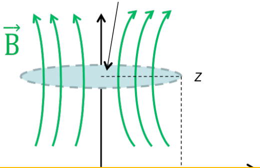
Mag. Poloidal flux (PF), $\Psi(R,Z)$ over one major circle, at (R,Z).

$$\psi(R,Z) = \frac{\Psi(R,Z)}{2\pi}\ \text{, flux per radian}$$
$$\Psi(R,Z) = \iint d\vec{B}\cdot d\vec{S}$$

Current Flux

Poloidal current function, F, crossing the major circle, at (R,Z).

$$F(R,Z) = \mu I_{pol}\Psi(R,Z)/2\pi = R\,B_\phi$$
$$I_{pol}(R,Z) = \iint d\vec{j}_{pol}\cdot d\vec{S}$$



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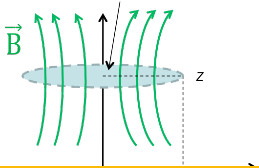
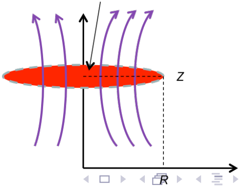
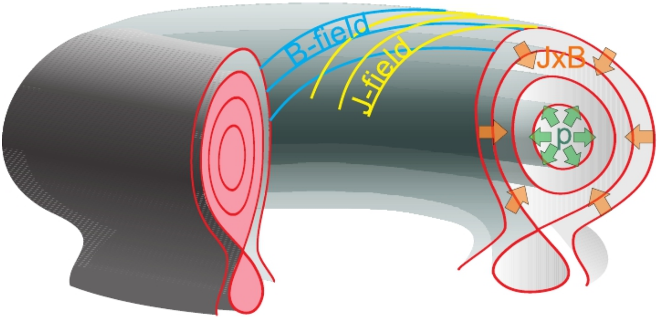




Axisymmetric Configuration

Flux Surfaces

Both Fluxes, (ψ, F) are constant on the `Flux Surfaces`:

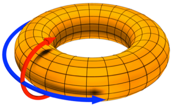


Toroidal Magnetic Field

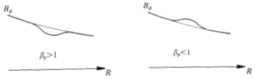
Ampere's Law

$$\nabla \times \vec{B} = \vec{J_{free}}$$
$$\nabla F \times \hat{\phi} = \mu_0 R\, J_{pol} \text{ (poloidal comp.)}$$

- **In vacuum:** $\nabla F = 0$, so $B_\phi(R)$ varies only with $1/R$
  - Result: No information from the plasma taken from external local B_ϕ measurements



$$B_\phi = \frac{F}{R}$$



Diamagnetic Paramagnetic

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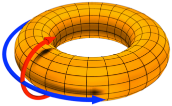

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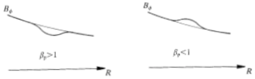

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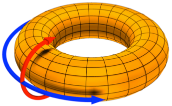
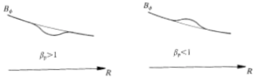
- **Within Plasma:** $B_\phi(R, Z)$ depends on poloidal currents, J_{pol}.
  - **Diamagnetic loop** can measure the surface integral change.



$B_\phi = \frac{F}{R}$

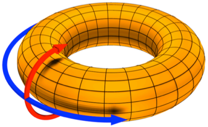


Diamagnetic Paramagnetic

Poloidal Magnetic Field

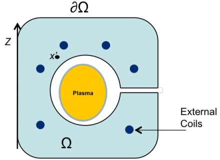
Ampere's Law (toroidal comp.)

$$\Delta^*\Psi \equiv R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial\Psi}{\partial R}\right) + \frac{\partial^2\Psi}{\partial Z^2} = \mu_0 R\, J_\phi$$



$$\begin{aligned}
\Psi(x') &= -\int_\Omega G(x,x')J_\phi^{ext}(x)dx \\
&\quad + \oint_{\partial\Omega} \frac{1}{\mu_0 R}\left(\Psi\frac{\partial G}{\partial n} - G\frac{\partial \Psi}{\partial n}\right) dS \\
x' &= \text{point in } \Omega \\
G(x,x') &= \text{Green function for } \Delta^* \text{ operator.} \\
\frac{\partial}{\partial n} &= \text{normal derivative}
\end{aligned}$$

$$B_p = \frac{\nabla\Psi}{R}$$



Equilibrium reconstruction

Basic restriction for the magnetic diagnostics

Green′s Theorem

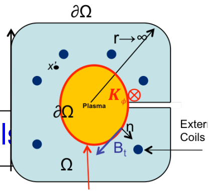
Ω bounded by Plasma and $r \to \infty$.

$$\Psi(x') =$$

$$\boxed{-\int_{\Omega} G(x, x') J_{\phi}^{ext}(x) dx, \text{ Currents in external coils}}$$

$$+ \oint_{\partial\Omega} \frac{1}{\mu_0 R} \Psi \frac{\partial G}{\partial n} dS$$

$$- \oint_{\partial\Omega} \frac{1}{\mu_0 R} G \frac{\partial \Psi}{\partial n} dS$$



$\Psi = C^{nst}$

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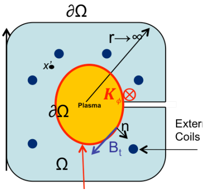
$$\boxed{+\oint_{\partial\Omega}\frac{1}{\mu_0 R}\Psi\frac{\partial G}{\partial n}dS\ ,\ \Psi = C^{nst}\text{ at the boundary}}$$
$$-\oint_{\partial\Omega}\frac{1}{\mu_0 R}G\frac{\partial\Psi}{\partial n}dS$$



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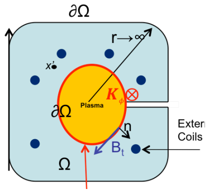
$$\Psi(x') = - \int_\Omega G(x,x') J_\phi(x) dx + \oint_{\partial\Omega} \frac{1}{\mu_0 R} \Psi \frac{\partial G}{\partial n} dS \boxed{- \oint_{\partial\Omega} \frac{1}{\mu_0 R} G \frac{\partial \Psi}{\partial n} dS}$$



$\Psi = C^{nst}$

Term 3 is the only one that depends on internal current, J_ϕ^{plasma}.

Equilibrium reconstruction

Basic restriction for the magnetic diagnostics

BUT solution depends only on B_t distribution on the Plasma boundary. Since many distributions, $J_\phi^{plasma}(r)$, give the SAME B_t.

Reconstruction $\Psi(R, Z)$ in Vacuum ☺

External measurements can determine the $\Psi(R, Z)$ anywhere in Ω and B_t on $\partial\Omega$. ☺

Reconstruction $\Psi(R, Z)$ inside Plasma ☹

External measurements alone CANNOT distinguish different internal current, $J_\phi(r)^{plasma}$ and $\Psi^{plasma}(R, Z)$ INSIDE the plasma! ☹

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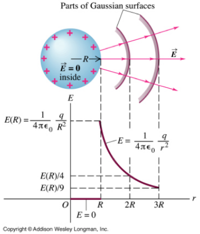
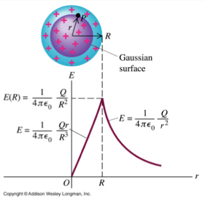
Electrostatics Equivalent Parallel Case

The Electric Field outside the Sphere is the same for a given charge surface density or other (infinite) volume distributions.





Reconstruction inside a sphere

External measurements CANNOT distinguish different Volume charge distributions.

Plasma Equilibrium in Fusion Plamas

Grad-Shafranov Equation

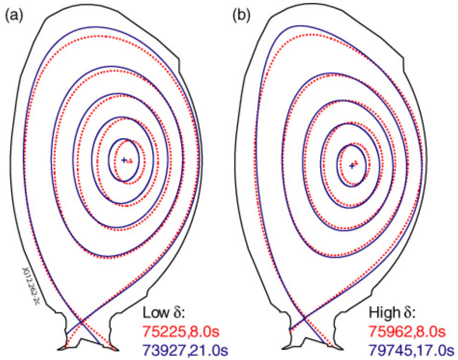
- Combining equation for Ψ with magnetic force balance $\nabla p = \vec{J} \times \vec{B}$ gives G-S equation inside the plasma:

$$\Delta^* \Psi = -\mu_0 R J_\phi = -\mu_0 R^2 \frac{dp}{d\Psi} - \frac{1}{2}\frac{dF^2}{d\Psi}$$

- G-S gives additional constraint on $\vec{B}$ within the plasma but also introduces another unknown scalar functions: the pressure and current
- Need to make some assumptions on $p(\Psi)$ and $F(\Psi)$ to calculate full plasma equilibrium solution.

Plasma Equilibrium

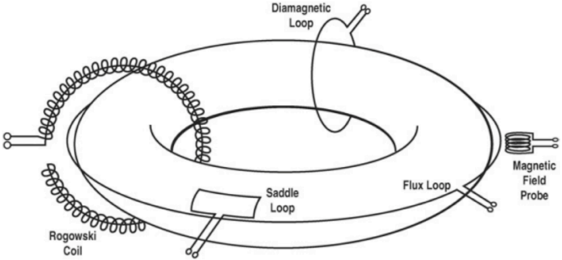
Example: JET Reconstruction



Magnetic configuration of the (a) low- and (b) high-triangularity plasmas for the hybrid (red) and baseline H-mode (blue) plasmas.

Magnetic Inductive Sensors

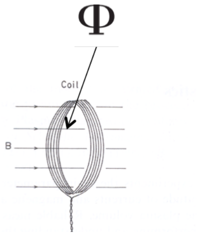
Basic Types



Schematic figure of a toroidal plasma, showing the basic types of inductive sensors.

Magnetic Inductive Sensors

Signal is a time derivative



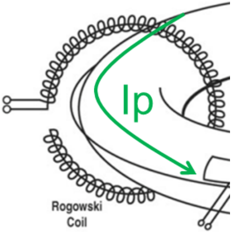
Mag. Flux on the Sensor Loops

$$
\begin{aligned}
V_{sensor}(t) &= \oint \vec{E} \cdot \vec{ds} = -\frac{\partial \Phi(t)}{\partial t} = NA\dot{B} \text{ , Faraday Law} \\
\Phi(t) &= \int_{t_0}^{t} V(t')dt'
\end{aligned}
$$

Magnetic Inductive Sensors

Rogowski Coil

- Measures total electric current flowing through the enclosed surface,
  - e.g. plasma, plasma + vessel, external coils, passive conductors, Halo Currents, etc.
- If $|\Delta B|/B \ll n$ (n is turns / m), total flux is:
  $\Phi = n \oint_\ell \int_A \vec{B} \cdot \vec{d\ell} dA = nA\mu_0 I_p$
- Signal is proportional to current time derivative:
  $V(t) = \dot{\Phi} = nA\mu_0 \dot{I}_p$

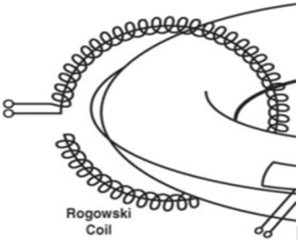


Conducting path from one end must return along the axis to the other end

Magnetic Inductive Sensors

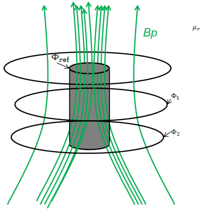
Sinus-cosinus Coil

- A variation of Rogowski Coil but winding density, $n(\theta)$, varies with $\sin(\theta)$ or $\cos(\theta)$
- Used to measure Plasma Displacements



Magnetic Inductive Sensors
Poloidal Flux Loops

- Measures $\Psi(R,Z)$ on a given (R,Z)
- On Iron Core Tokamaks with ohmic heating, most of the poloidal flux is on the core itself: $B = \mu_r\mu_0 H,\ \mu_r(iron) \approx 4000$
- To improve the sensivity, a smaller loop is chosen as reference and subtracted from others: $\Psi_i = \Psi(R,Z) - \Psi_{ref}$



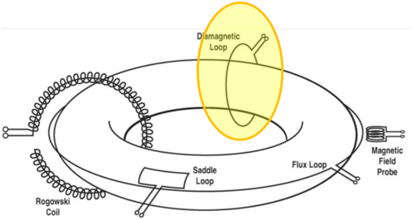
Loop Voltage

Voltage signal from a flux loop is the local one-turn V_{loop}, which drives I_p

Magnetic Inductive Sensors

Diamagnetic Loop

- Measure the toroidal magnetic flux for the purpose of estimating the thermal energy of the plasma $\langle p \rangle \propto W$.
- Normally located in a poloidal plane to minimize coupling to the B_{pol}.
- At low beta, the change in the total toroidal flux is small. $\beta = 2\mu_0 \langle p \rangle / B^2 \ll 1$



A reference signal coupled to $B_{\phi,vacuum}$ is usually subtracted: $\Delta\Phi_{Diag} = \Phi_{total} - \Phi_{vacuum}$

Basic Magnetic Inductive Sensors

Integral quantities

- Total **Plasma Current** , I_ϕ (Rogow.)
- **Ohmic Power** (Rogow+ V. Loop)

$$P \equiv \int_{Vol} \vec{E} \cdot \vec{j}\, d^3x = V_\phi I_\phi - \frac{\partial}{\partial t}(\frac{1}{2} L I_\phi^2)$$

- **Poloidal beta** , β_p, (Rogow+ Diag. Lop)
  $\beta_p \equiv 2\mu_0 \langle p \rangle / B_{p,a}^2 (\ll 1)$, $B_{p,a} = \mu_0\, I_\phi / \Gamma$, Γ is length of a poloidal plasma contour.
  - Circular Plasma $\beta_p = 1 - \frac{8\pi B_{\phi,vacuum}}{(\mu_0 I_\phi)^2} \Delta\Phi_{Diag}$
  - Non-Circular Plasma

$$\beta_p \approx 1 - \frac{1+\kappa^2}{2\kappa} \frac{8\pi B_{\phi,vacuum}}{(\mu_0 I_\phi)^2} \Delta\Phi_{Diag}$$

κ is the vertical elongation of plasma

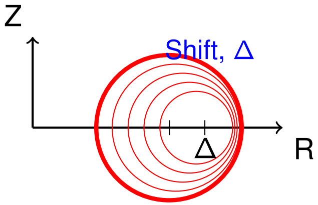
Basic Magnetic Inductive Sensors

Integral quantities II

- Total **Shafranov shift** , Δ. (From Rogow. + Vertical Field Current)

At Large Aspect Ration approximation:

$$\Delta' = \frac{r}{R}\Lambda, \quad \Lambda = \beta_{pol} + \ell_i/2$$



Basic Magnetic Inductive Sensors

Integral quantities III

- **Plasma conductivity** , σ (Rogow+ V. Loop)

$$\hat{\sigma} = \frac{2\pi R}{\pi a^2} \frac{I_\phi^2}{P}, (\text{ if } \frac{\partial}{\partial t} = 0)$$

- **Electron Temperature** , T_e

$$\sigma = 1.9 \times 10^4 \left(\frac{T_e^{3/2}}{Z_\sigma \ln \Lambda} \right)$$

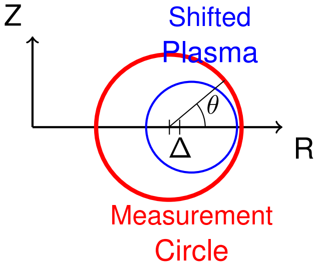
  - Z_σ, resistance anomaly determined by ion charge
  - $\ln \Lambda$, Coulomb logarithm:

$$\ln \Lambda \approx 31 - \ln(n_e^{1/2} / T_e)$$

Magnetic Inductive Sensors

Plasma Displacement

- Cylindrical Approximation $R \gg a$. Plasma Displaced by $\Delta \ll a$



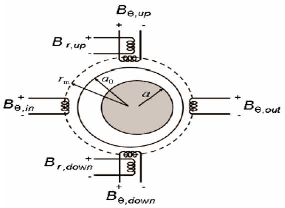
- Measured poloidal field is:

$$B_\theta(\theta) = \frac{\mu_0 I}{2\pi a}\frac{1}{\left[\sin^2\theta + (\cos\theta - \Delta/a)^2\right]^{1/2}} = \frac{\mu_0 I}{2\pi a}\left(1 + \frac{\Delta}{a}\cos\theta\right)$$

- Displacement can extracted from the Sinus-cosinus Coils.

Magnetic Probes

- Probes measure components of the local magnetic field strength.
- Usually solenoidal, with dimensions small compared to the gradient scale length of the magnetic field.

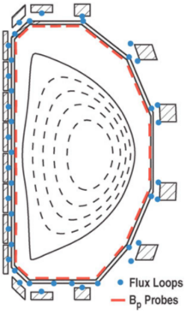


$$\Phi_{probe} = N\,A\,B_{\parallel}$$

Magnetic Local Probes

Shielding

- Probes should be located on the plasma-facing side of the vacuum vessel wall.
- Should be oriented to measure the field tangential to the wall; otherwise, eddy currents in the wall will attenuate the high-frequency part of the signal.

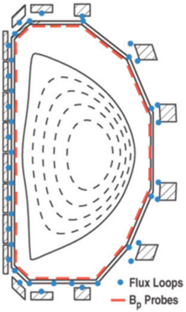


Magnetic Local Probes
Shielding

- Shielding of the tangential field by the conductive wall.

$$\frac{B(inside)}{B_0} = \frac{1+2i\omega\tau_w}{1+i\omega\tau_w}$$
$$\frac{B(outside)}{B_0} = \frac{1}{1+i\omega\tau_w}$$

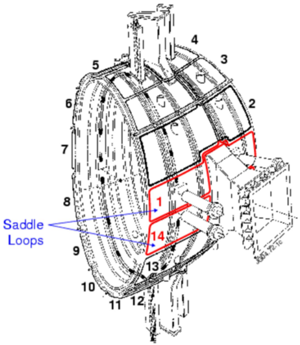
τ_w is the characteristic time for the magnetic flux to diffuse through the wall



Saddle Loops

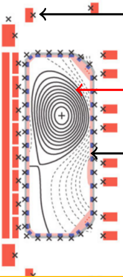
Can be viewed as

- A large-scale magnetic probe for the magnetic field normal to the surface. $\Phi(saddle) = N\,A\langle B_\perp\rangle$
- or as probes measuring Flux Difference: .
  $\Phi(saddle) = N\,\Delta_\phi\,\Delta_\psi$



Determination of Plasma Shape

1. Taking measurements of the $\Psi(R, Z)$ and poloidal B_{pol} near the Wall, plus the currents in external Coils allows local Ψ extrapolation.
2. Plot the contours of $\Psi(R, Z) = C^{nst}$. Find the Last Closed Flux Surface LCFS, or Separatrix in Divertor tokamaks

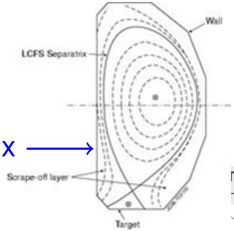


Flux Loops $\Psi(R, Z)$

LCFS

Magnetic Probes $B(R, Z)$

Separatrix



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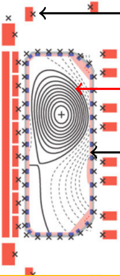

Flux Loops $\Psi(R, Z)$

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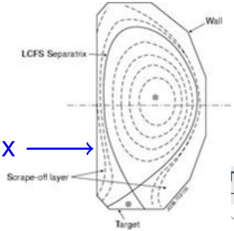


Outline

Integration of signals from Mag. Sensors

Analog Integration

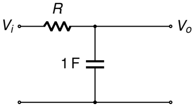
- To obtain the fluxes and magnetic field values from inductive sensors we must integrate the signal in time: $V_{out}(t) = -\frac{1}{\tau}\int_0^t V_{in}(t')dt' = \Phi(t)/\tau$

$$V_{in} \longrightarrow \boxed{\frac{1}{\tau}\int_0^t dt'} \longrightarrow V_{out}$$

- Typical loop flux values vary from few $mV.s$ to $V.s$ (e.g. Iron core), so integrator circuits are used with $1\ ms < \tau < 1\ s$.

Integration of signals

Analog Passive Integrator



- Simple Passive Integrator (RC Low Pass Filter, 1^{rst} Order , $-20dB/dec.$), $\tau = RC$

$$V_{out}(\omega) = -\frac{1}{1 + i\omega\tau} V_{in}(\omega) \Rightarrow V_{out}(t) \approx -\frac{1}{\tau}\int_{t_0}^{t} V_{in}(t')dt'$$

RC Limitation!

The approximation fails for timescales $t \geq RC$.

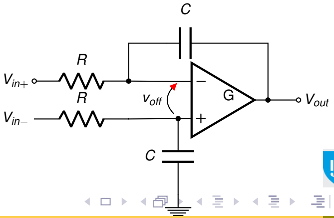
Integration of signals

Analog Active (Op-Amp) Integrator

- Gain is similar to passive integrator, $1/RC$, but timescale is increased from $\sim RC \rightarrow \sim G \cdot RC$ (1 ms to 10 s).

NEW problem: Integrator Drift by OpAmp Input V_{off}

Example: for $RC = 10\,ms$ a $V_{off} = 100\,\mu V$ integrates to a $0.1\,V$ after $10s$



Integration of signals
Analog Active (Op-Amp) Integrator

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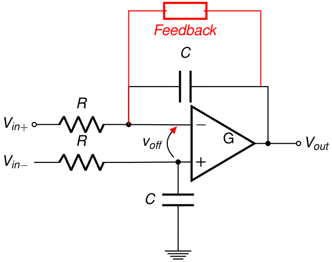


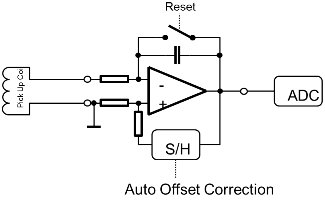
Solution

Basic compensation circuit

Analog Integrators

Advanced Designs

- Automatic drift-compensation: Measurement of drift before integration, store and compensate offset during integration.
- Drift can be reduced down to several $0.1\,mVs@1000s$
- But worse values if signal is applied during drift compensation!



Tore Supra

Drift achieved: $< 135\mu Vs@1000\,s$

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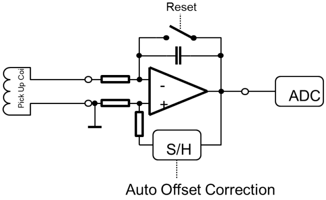

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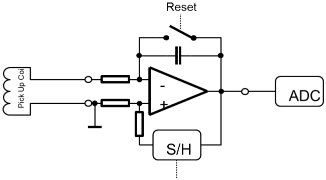

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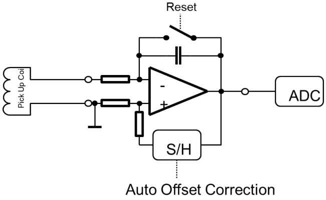

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Drift achieved:
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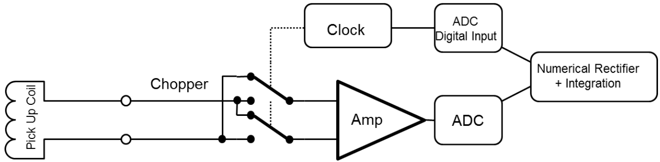
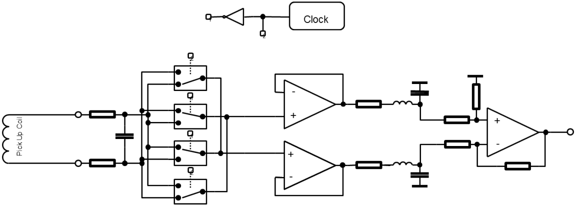
Digital Integrators
Chopper Input

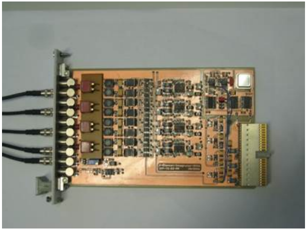


- Dynamic range limited by input stage
- Not affected by input stage semiconductors
- Complex offset correction algorithms feasible

Digital Integrators

W7-X / IST ADC chopper module

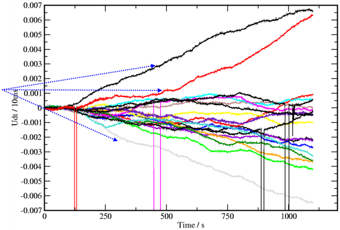


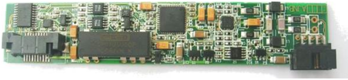


Digital Integrators

IST prototype

- 100s drift compensation
- 1000s run Cold Integrator



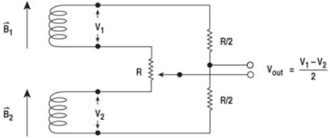


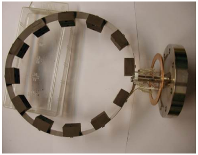
Outline

Non-Integrated Signal

Inductive probes

- Usally as linear combinations of flux Loop and/or field probes (analog adders)
- Direct information on Plasma Speed: $V(t) \propto Vel_{R,Z}(t)$
  - Used as controllable variables for active control

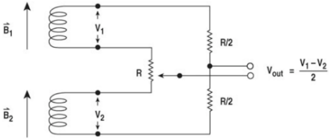


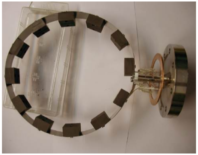


Non-Integrated Signal

Inductive probes

- High Frequency MHD plasma instabilities detection and control
  $V(t) \propto \dot{B}(t) \sim \omega B(t)$
  - Mirnov coils, poloidal or toroidal arrays oriented to measure $\dot{B}_{pol}(t)$

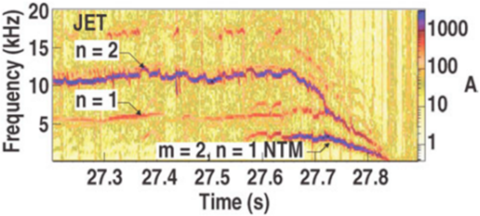




Non-Integrated Signal

MHD Instabilities Diagnostics

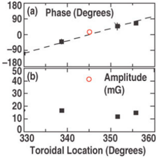
- Analyses Techniques: Spectrogram (Fourier analysis of successive short-time windows).
- Other techniques:
  - Wavelet analysis.
  - Hilbert transform.
  - Singular Value Decomposition (SVD).



Non-Integrated Signal

MHD Instabilities mode number detection

- Usual MHD perturbation: $\delta B(t) \propto \delta B(r) \cos(m\theta + n\phi - \omega t)$
- Mode numbers m, n are determined by the phase shift between equally separated Mirnov coils, by Fourier Analysis.



Identification of the toroidal mode number $n = 7$ of a compressional Alfven eigenmode in NSTX.

Non-Integrated Signal

Auto and Cross Correlation between two signals

Defining a dot product between 2 functions

$$< f, g >= \int_{-\infty}^{\infty} f^*(t)g(t)dt$$

Cross-correlation :

$$\begin{cases} (f * g)(\tau) = \int_{-\infty}^{\infty} f^*(t)f(t+\tau)dt & \text{Continuous,} \\ (f * g)[n] = \sum_{m=-\infty}^{\infty} f^*[n]g[n+m] & \text{Discrete.} \end{cases}$$

Auto-correlation :

$$\begin{cases} (f * f)(\tau) = \int_{-\infty}^{\infty} f^*(t)f(t+\tau)dt & \text{Continuous,} \\ (f * f)[n] = \sum_{m=-\infty}^{\infty} f^*[n]f[n+m] & \text{Discrete.} \end{cases}$$

Non-Integrated Signal

Auto and Cross Correlation between two signals

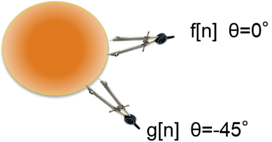
Cross-correlation of real life finite sampled signals

- Real life signals have only limited number of samples
- Cross-correlation easier to interpret when bounded in [-1,1]
- Lag vector (index-n) also finite
- MATLAB/Octave Funtion *r= xcorr(x , y)*

$$(f * g)[n] = \begin{cases} \dfrac{\sum_{m=1}^{N-|n|}(f[m+|n|]-\bar{f})(g[n]-\bar{g})}{\sqrt{\sum_{m=1}^{N}(f[m]-\bar{f})^2}\sqrt{\sum_{m=1}^{N}(g[m]-\bar{g})^2}} & \text{if } n < 0, \\[2ex] \dfrac{\sum_{m=1}^{N-n}(f[m]-\bar{f})(g[n+m]-\bar{g})}{\sqrt{\sum_{m=1}^{N}(f[m]-\bar{f})^2}\sqrt{\sum_{m=1}^{N}(g[m]-\bar{g})^2}} & \text{if } n \geq 0. \end{cases}$$

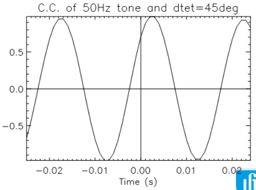
Non-Integrated Signal

Cross Correlation as wavenumber *m, n* estimator



$$
\begin{aligned}
f[n] &= \cos(w_1 t[n] - k\theta_1) \\
g[n] &= \cos(w_1 t[n] - k\theta_2)
\end{aligned}
$$

$$
\begin{aligned}
w_1 t[n + lag_{max}] - k\theta_2 &= w_1 t[n] - k\theta_1 \\
\tilde{}\; w_1 (t[n + lag_{max}] - t[n]) &= k(\theta_2 - \theta_1) \\
k &= \frac{w_1 \cdot t[lag_{max}]}{\theta_2 - \theta_1}
\end{aligned}
$$



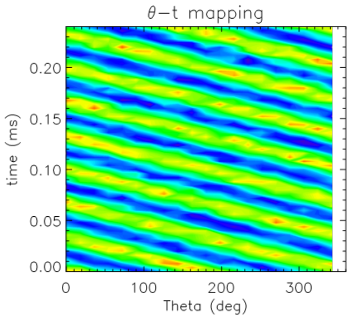
TÉCNICO LISBOA

Non-Integrated Signal

$\theta - t$ space visual analysis

Example

- Magnetic coils :$i = 1 \ldots 12$ eq. spaced in poloidal plane
- $s_i(t) = \cos(\pi f t + m\theta_i) + noise(\mu = 0, \sigma = 0.2)$

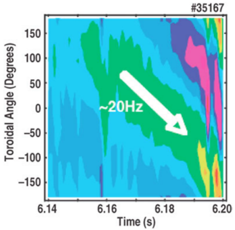


- Wave front propagates clockwise
- Two periods for fixed t (m=2)
- Period $\approx$ $0.03ms$ f $30kHz$

Non-Integrated Signal

MHD Nonrotating Modes

- Nonrotating modes are most commonly detected with toroidal arrays of **saddle coils**
- At low frequencies involved the field perturbation penetrates the vacuum vessel.

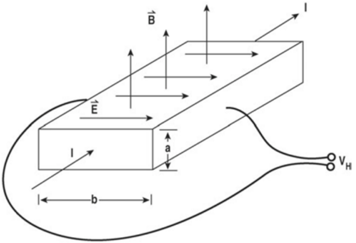


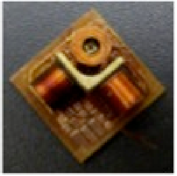
Time evolution of an RWM in JT-60U measured with an array of eight saddle coils.

Outline

Non Inductive Sensors

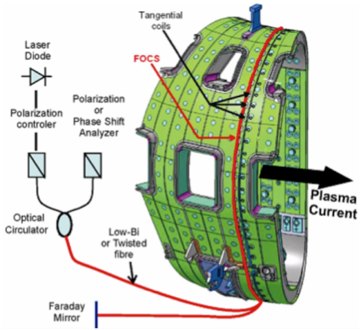
- Signal has direct Value: $v(t) \propto B(t)$.
- Hall Probes are relatively simple and inexpensive. $V_H = \frac{1}{qn}\frac{I_H B}{a}$, $\frac{1}{qn}$ is **Hall coefficient**, is a property of each material.
- low frequency, low sensivity, very sensible to radiation!





Non Inductive Sensors II

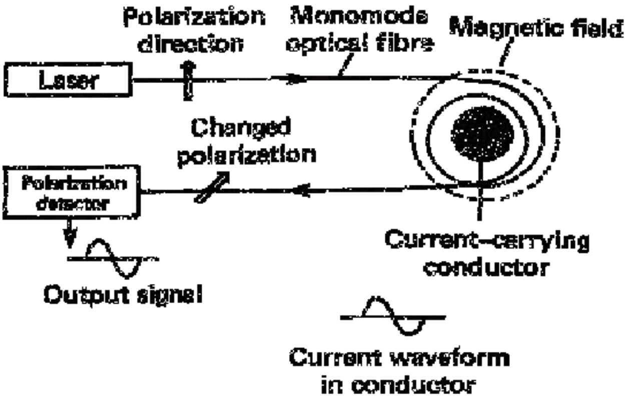
- Resistive Shunts:
  - Measuring halo currents flowing between the plasma and plasma-facing components
- Faraday rotation current measurements:



Schematic overview of a fiber-optic Faraday rotation measurement device.

Non Inductive Sensors III

Faraday effect



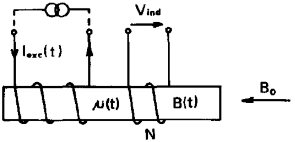
Scheme of the Faraday effect measurement.

Non Inductive Sensors IV

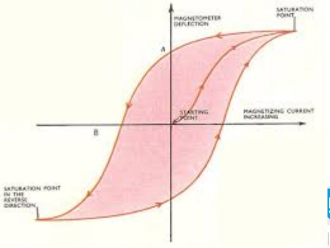
Fluxgate Magnetometer

Basic sensor configuration.

- The core is excited by an AC current I_{exc}.
- The signal induced in the sense coil V_{ind} at the second harmonic of I_{exc} proportional to the external field B_o.



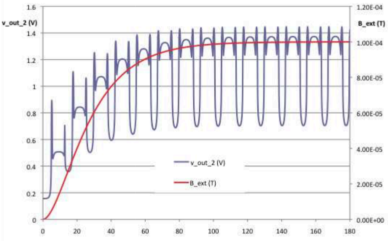
Fluxgate Magnetometer.



Non Inductive Sensors IV

Fluxgate Magnetometer

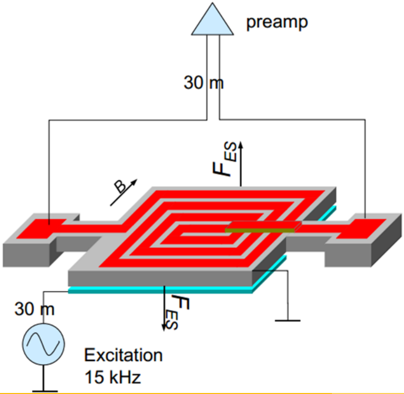
- Capable of measuring low frequency DC/ AC fields in the range $10^{-10} - 10^{-4}T$
- The signal induced in the sense coil V_{ind} at the second harmonic of I_{exc} proportional to the external field B_o.
- Usually double core is adopted



Waveform of sensor signal with variable external magnetic (Red curve .

Non Inductive Sensors V

MEMS magnetic field sensors

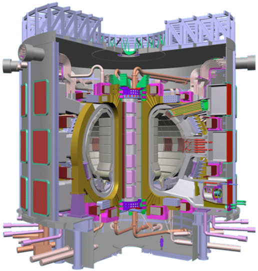


Outline

Burning plasma experiments

ITER

- ITER will be the first burning plasma experiment
- Relative to existing machines (e.g. JET), ITER diagnostic components will be subjected to:
  - High *n* and γ fluxes.
  - *n* Heating (now essentially zero).
  - High fluxes of energetic neutral particles.
  - Long pulse lengths.



ITER diagnostics

Functional requirements

Provide accurate measurements of plasma behavior and performance.

- 3 categories of measurement parameters.

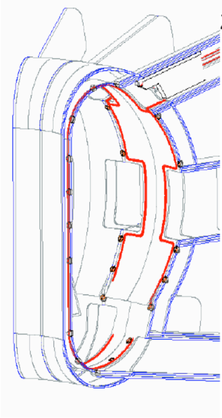
Group	Description	Machine operation?
1	Machine protection and Basic machine control	*Advanced* operation unable without this
1b	advanced plasma control	Unable without
2	Evaluation and physics studies	Able without

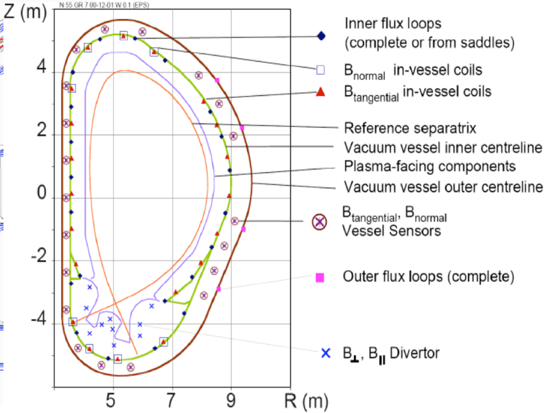
ITER diagnostics
Magnetic Set

Total $\tilde{1}$700 sensors, 19 types, $>$ 300 *km* of cable

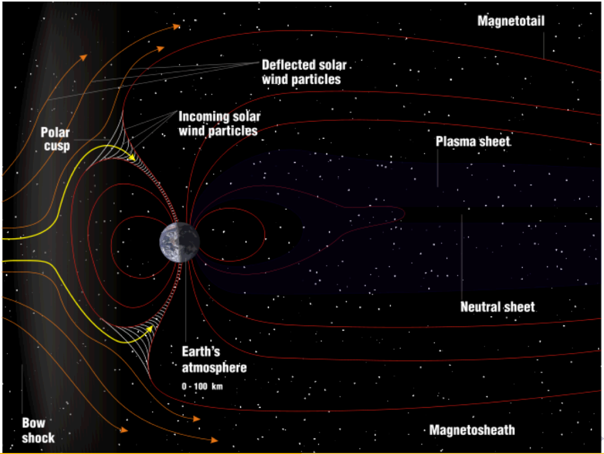
Location	Radiation/Dose (cm^{-2} s^{-1}) / MGy		Type	Number
	n	γ		
In-vessel sensors: Behind blanket modules, fixed on VV inner skin	3. 10^{12} 500	1. 10^{12} 340	Pick-up coils	186
			Rogowski (halo current)	360
			Flux loops	220
	1. 10^{13} 1700	3. 10^{12} 1000	High freq coils	>300
Divertor	1. 10^{13} 1700	3. 10^{12} 1000	Pick-up coils	72
			Rogowski (halo current)	48
Ex-vessel sensors Fixed on VV outer skin	1.5 10^{10} 2.5	1. 10^{10} 3.4	Pick-up coils	360
			Steady state sensors	120
			Flux loops	5
			Optic fibre	12
Inside TFC case (T=4K)	1. 10^{10} 1.7	2. 10^{9} 0.7	Rogowski (I plasma)	≥ 3

ITER diagnostics
Poloidal Magnetic Set

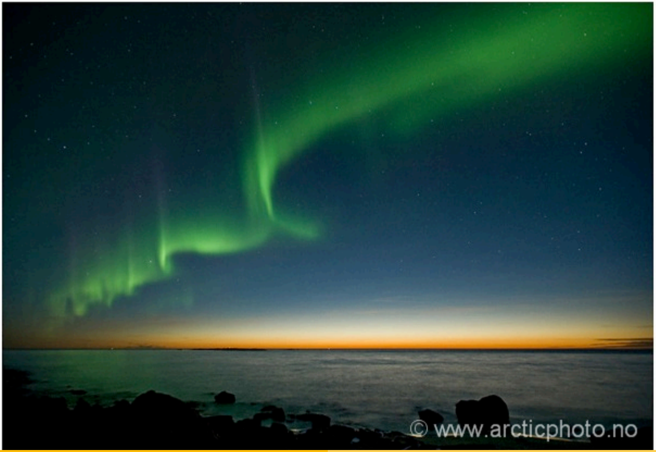




Structure of Magnetosphere
Earth Fields



Magnetosphere
Plasma Diagnostic



Further Reading I

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Magnetic Fields and Magnetic Diagnostics for Tokamak Plasmas, 2008, `web2.ph.utexas.edu/~iheds/magneticfieldsinatokamak.pdf`