TRILATERAL EUREGIO CLUSTER

JÜLICH FORSCHUNGSZENTRUM

UNIVERSITEIT GENT

# Diagnostics and control of fusion plasmas

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DPG School “The Physics of ITER”

Bad Honnef, 26.09.2014

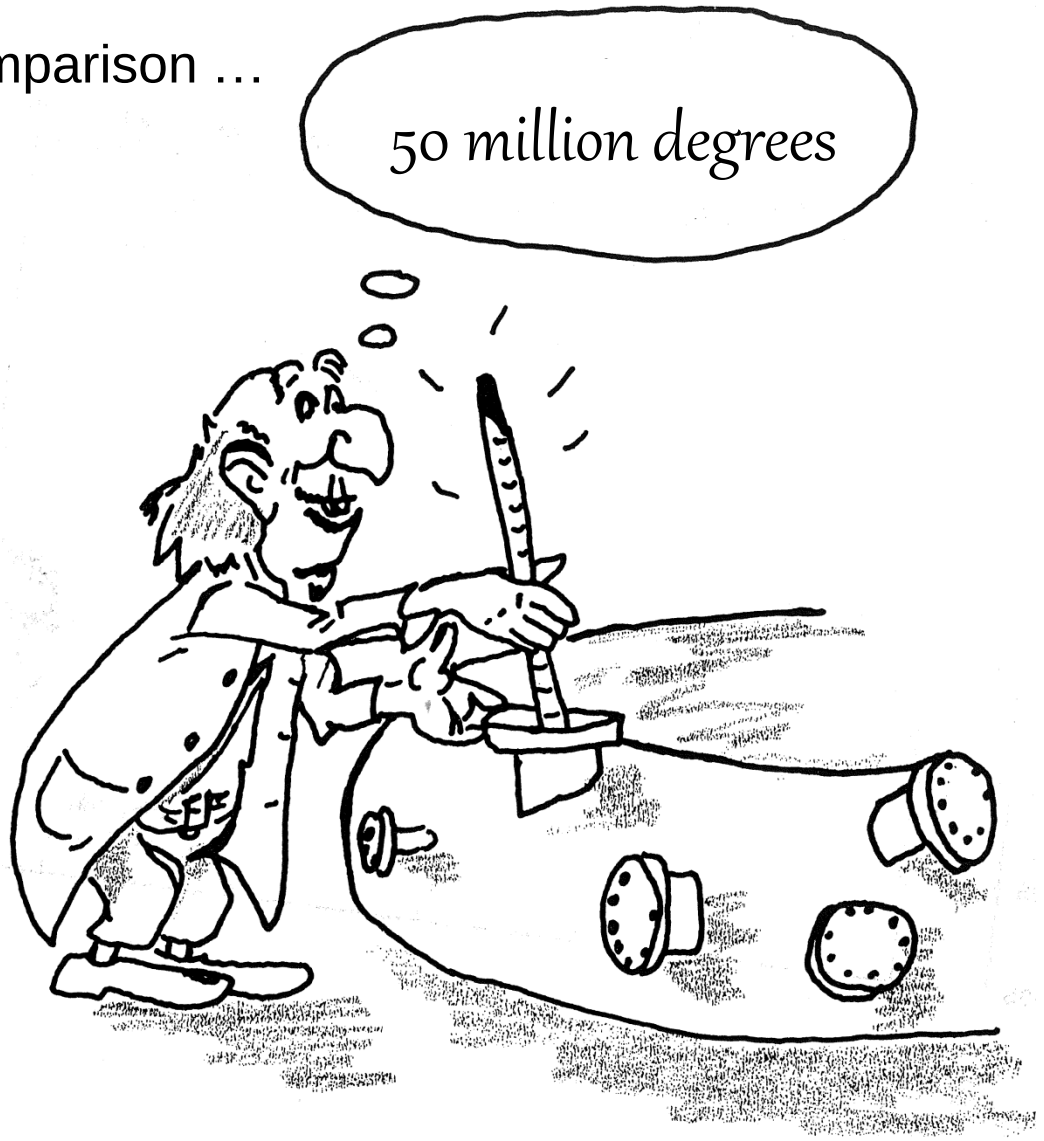
# Plasma diagnostics

Measurement means comparison …

… but how to perform measurements in a hot fusion plasma?

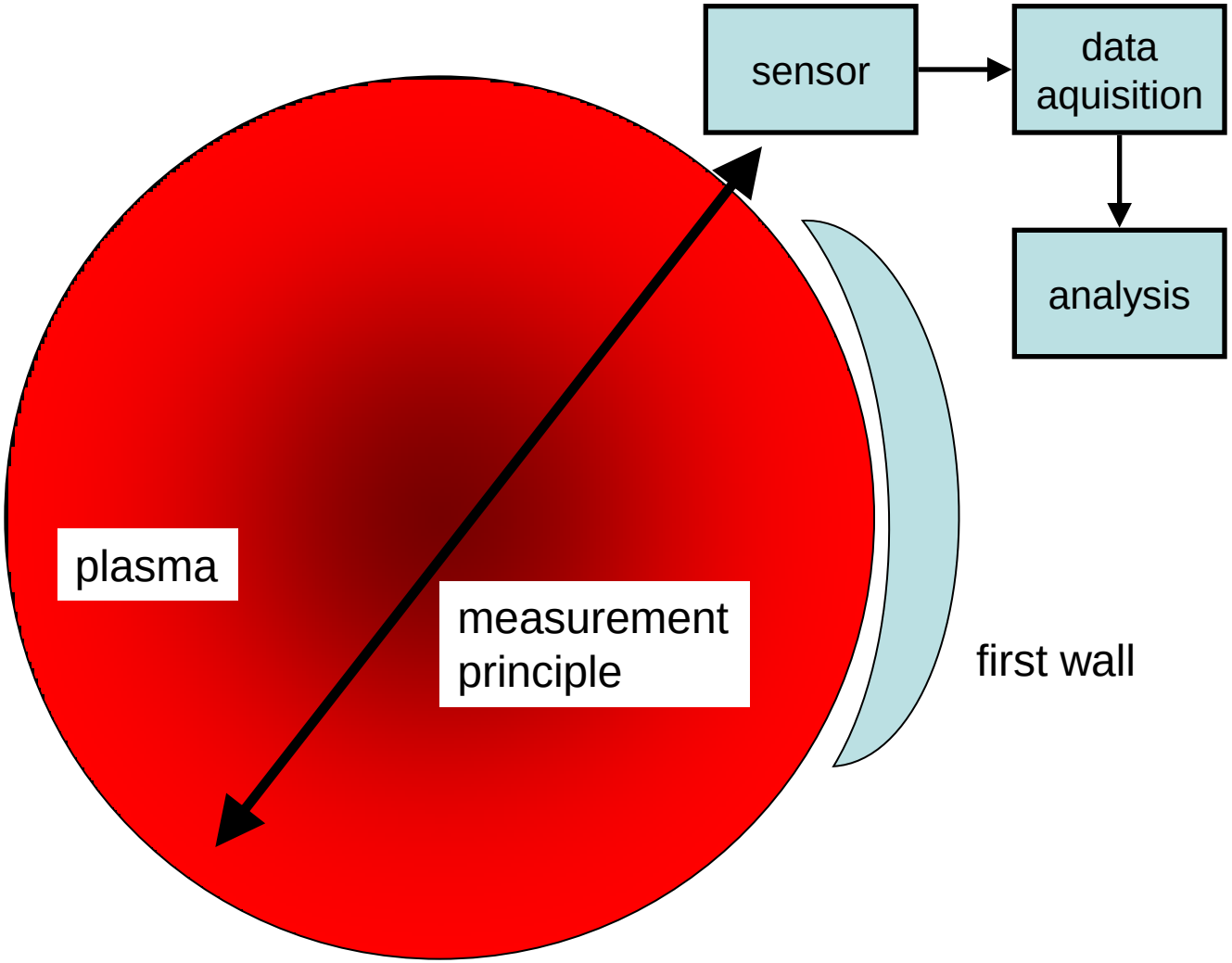
# Plasma diagnostics

Measurement means comparison …



# Measurements in a fusion plasma

… are generally performed in an indirect way …



# Today‘s fusion experiments are amply equipped with diagnostic systems …

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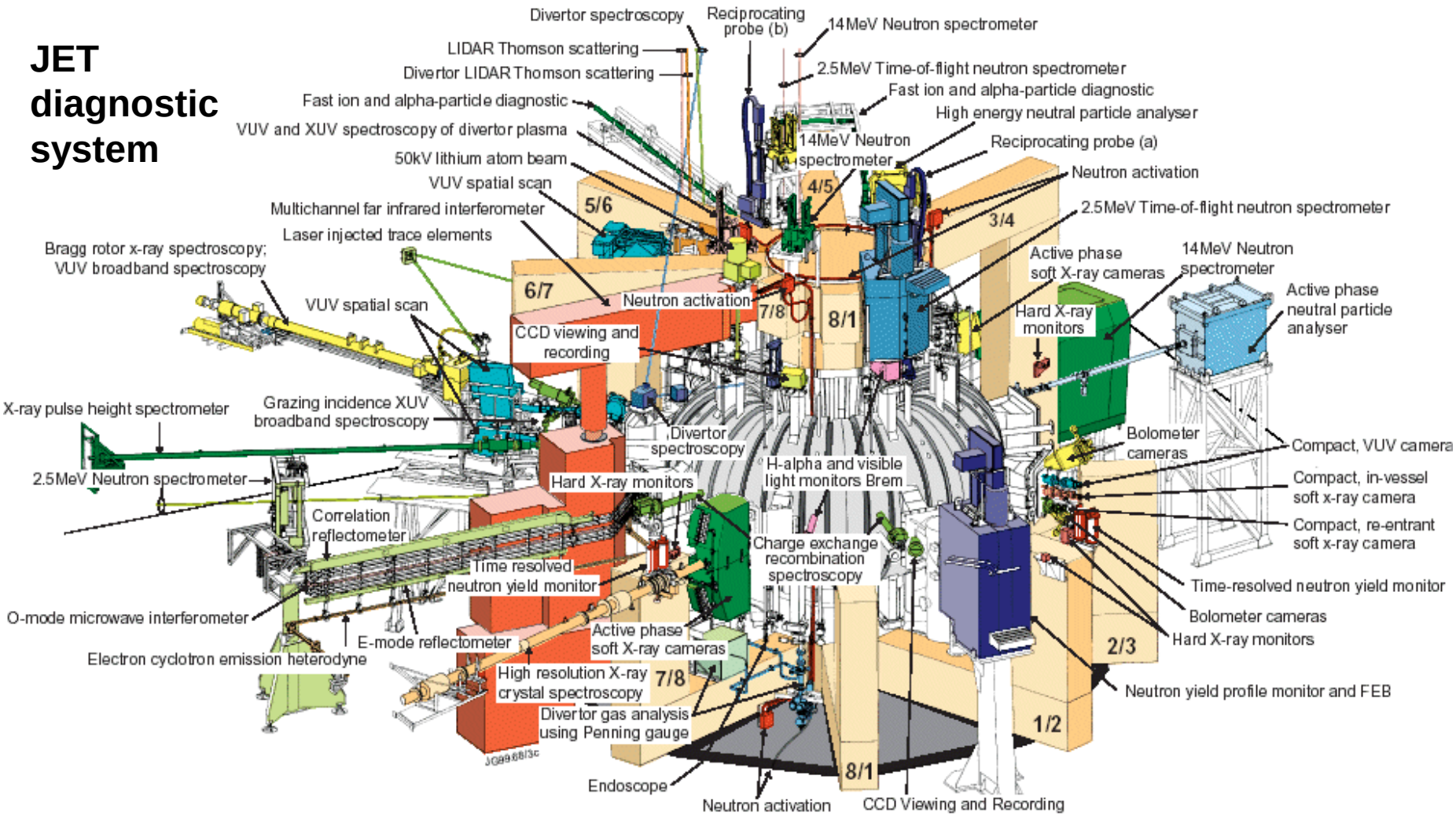
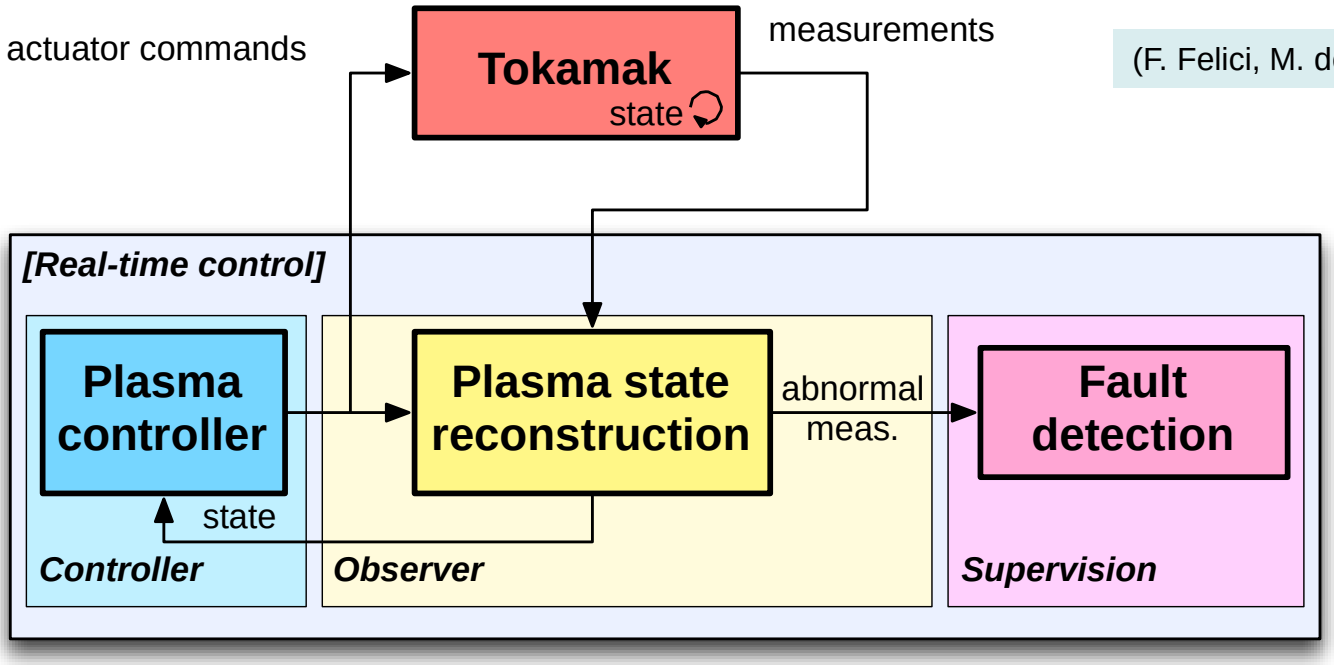
**JET diagnostic system**



# Integrated plasma diagnostics processing & control




- Plasma controller: perform control actions based on full plasma state knowledge
- Plasma state reconstruction: derive plasma state by merging measurements from several diagnostics
- Fault detection: classify unexpected measurements (e.g. off-normal events, faulty signals)
- Diagnostic redundancy in number of channels and number of methods facilitates handling of faults (the better the model, the less measurements are needed)

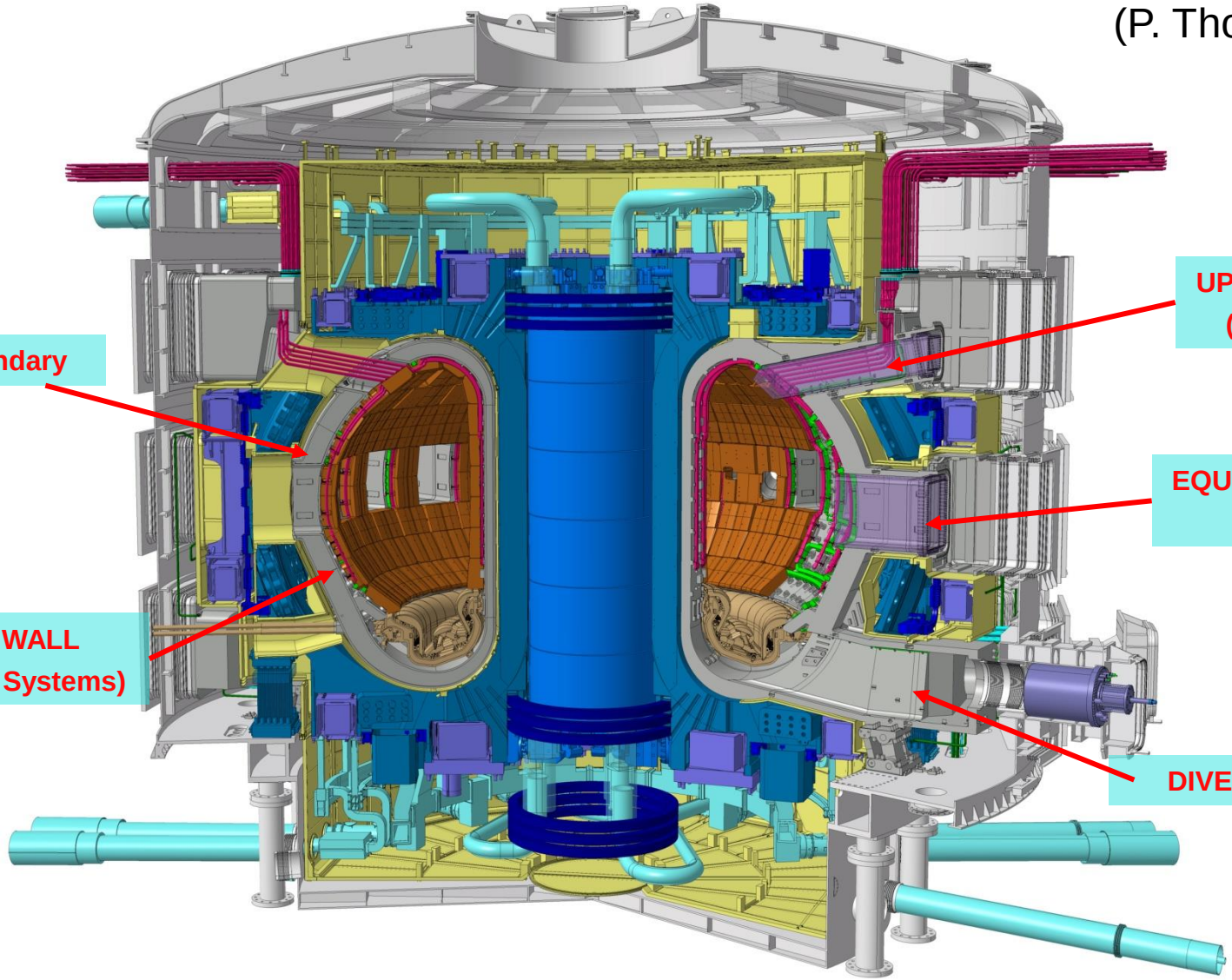
# Two ways of categorisation of plasma diagnostics:

- A) Technical goals of plasma dianostics:
  - *Protection of the fusion reactor and its components*
    - e.g. distance between plasma and first wall, wall temperature, fusion power
  - *Control and optimisation of the plasma properties*
    - e.g. plasma shape, plasma position, plasma current, plasma density, impurity concentrations, radial distributions of plasma quantities
  - *Plasma physics studies (obtain data to be used for as basis for concept improvements)*
    - All plasma quantities

- B) Diagnostic methods / measurement principles:
  - *Magnetic measurements*
  - *Neutron and gamma diagnostics*
  - *Optical / IR diagnostics*
  - *Bolometric diagnostics*
  - *Spectroscopic techniques*
  - *Microwave diagnostics*
  - *Plasma-facing components and operational diagnostics*

# ITER: Diagnostic Implementation Scheme

(P. Thomas, ITER)



# Remote Handling – ITER RH philosophy

(P. Thomas, ITER)

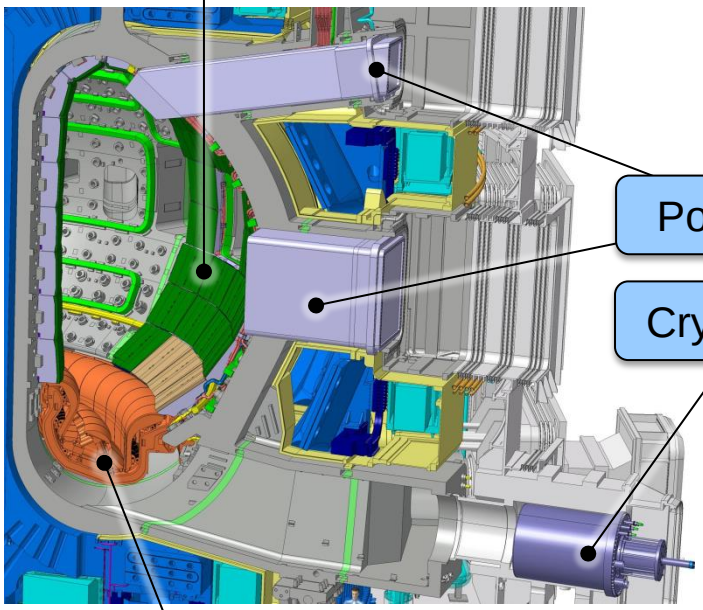
**All of the in-vessel components must be handled and maintained using remote handling methods.**

Blanket Modules

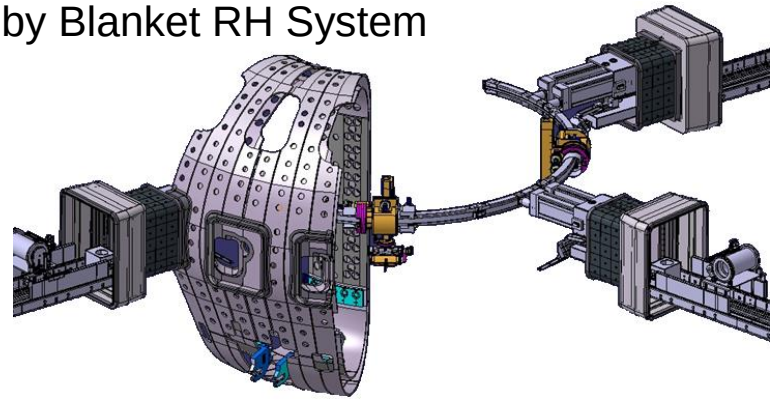
Port Plugs

Cryopumps

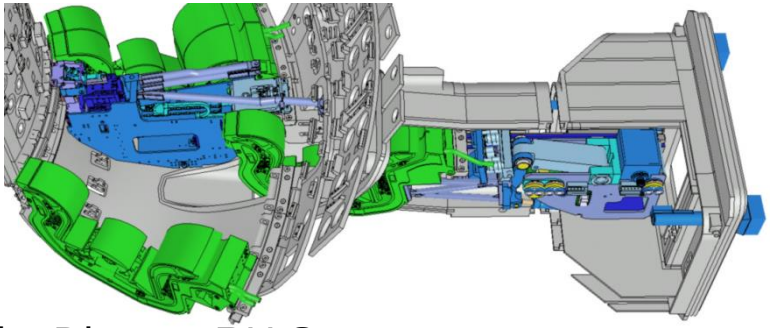
Divertor Cassettes



by Blanket RH System



by Cask & Plug RH System
*(next slide)*

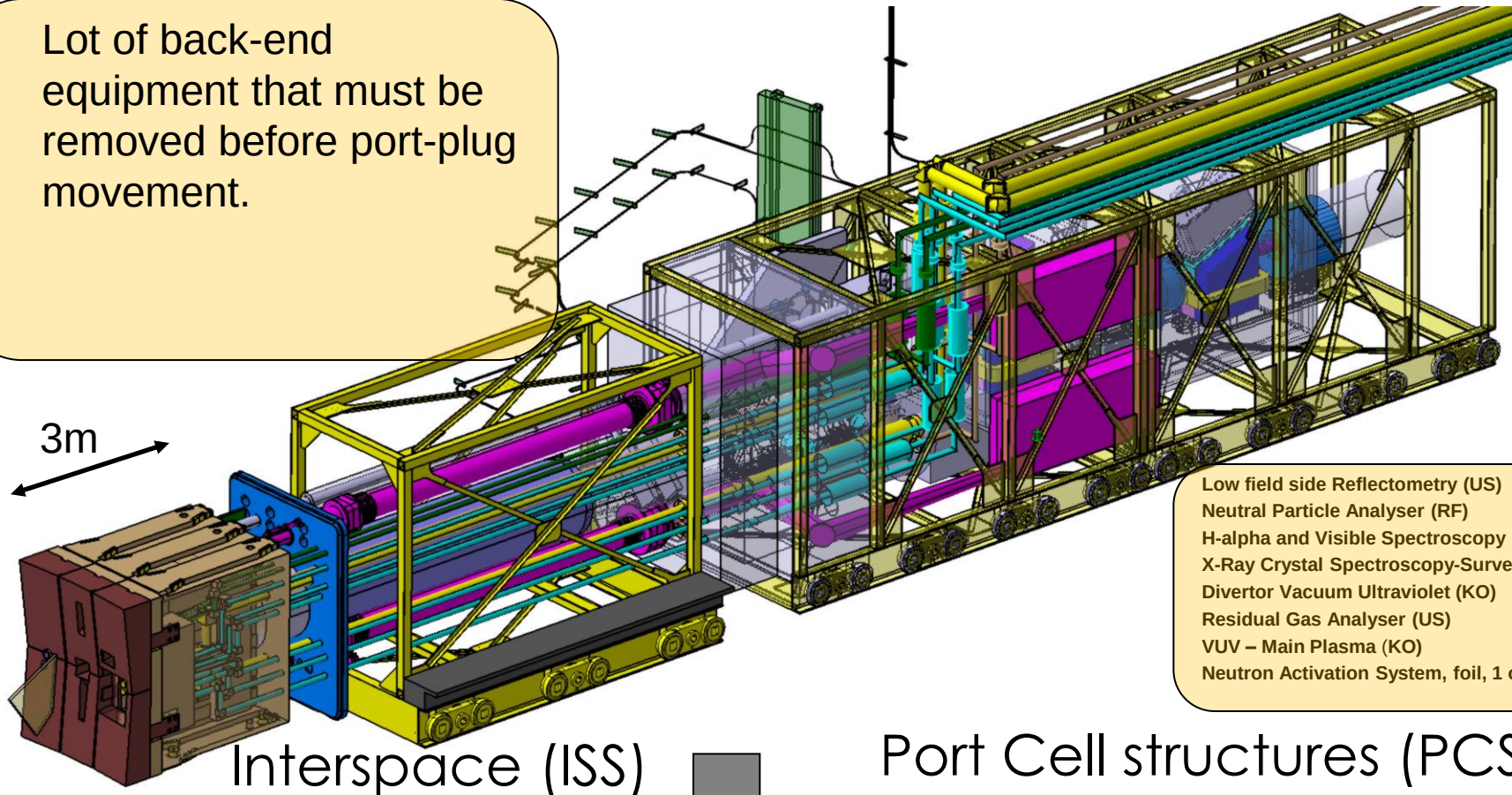


by Divertor RH System

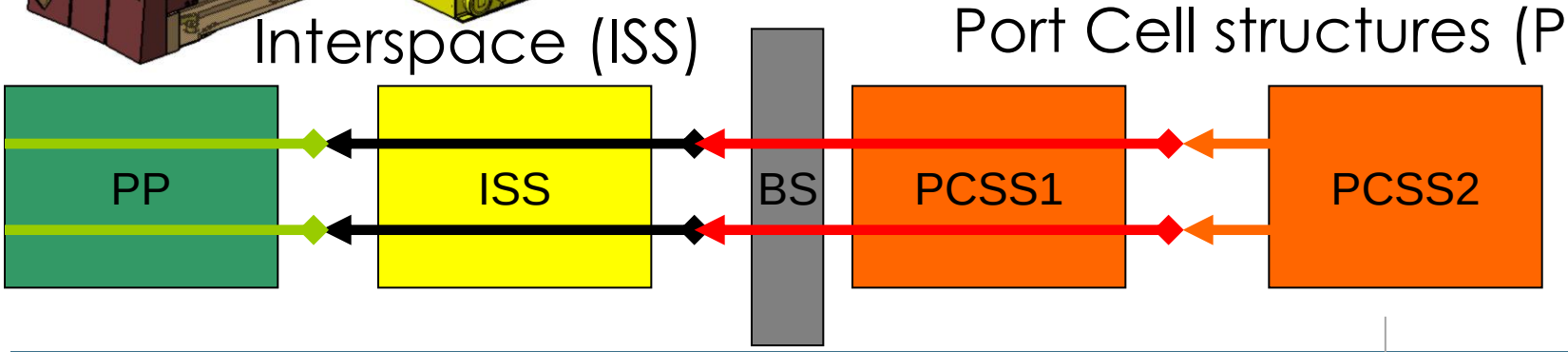
# Port-Plugs - Integration of Equatorial 11 Port Plug

(P. Thomas, ITER)

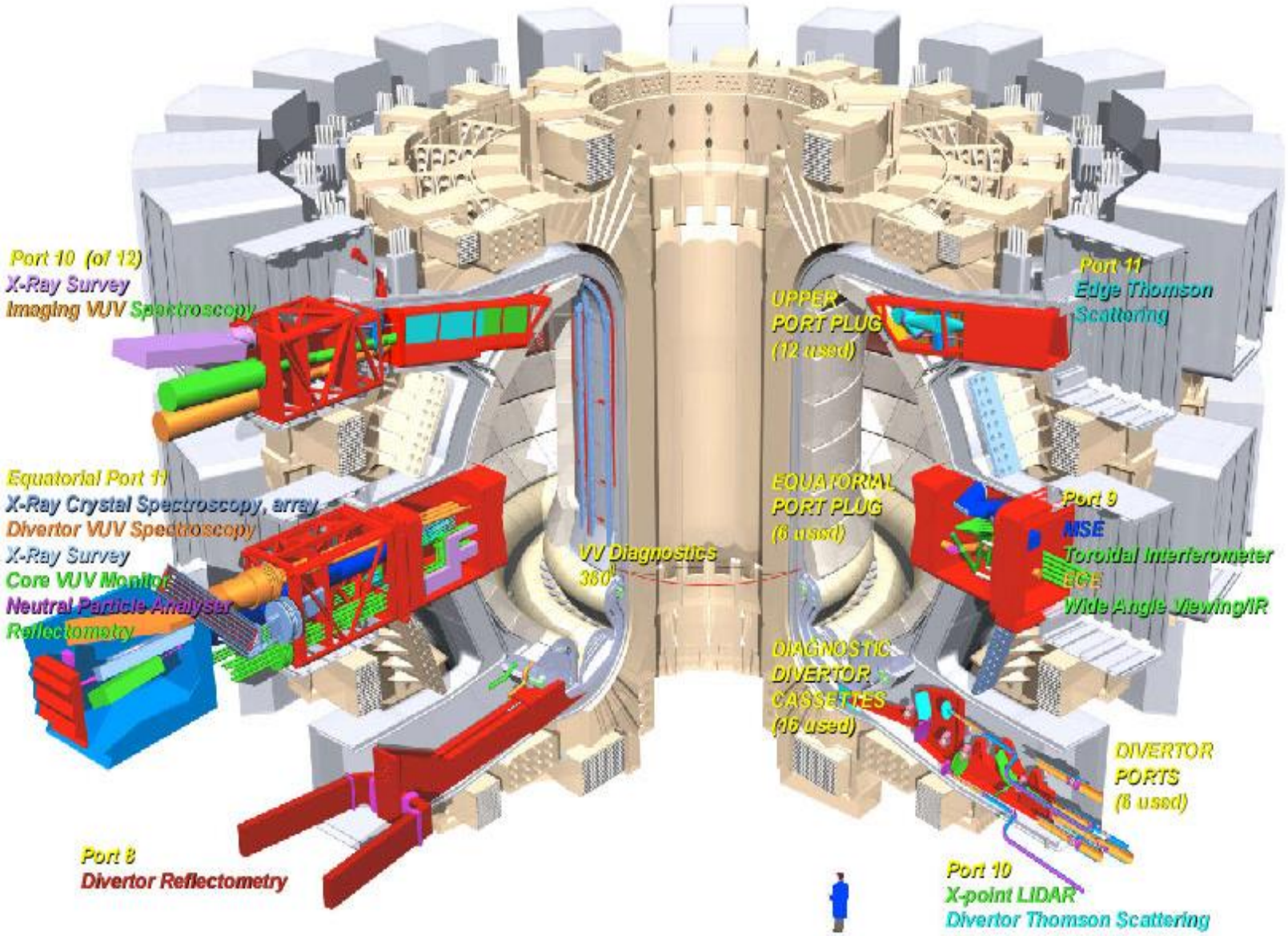
- Lot of back-end equipment that must be removed before port-plug movement.




Low field side Reflectometry (US)
Neutral Particle Analyser (RF)
H-alpha and Visible Spectroscopy (RF)
X-Ray Crystal Spectroscopy-Survey (IN)
Divertor Vacuum Ultraviolet (KO)
Residual Gas Analyser (US)
VUV – Main Plasma (KO)
Neutron Activation System, foil, 1 of 2 (KO)



# ITER diagnostics distribution



# Magnetic diagnostics

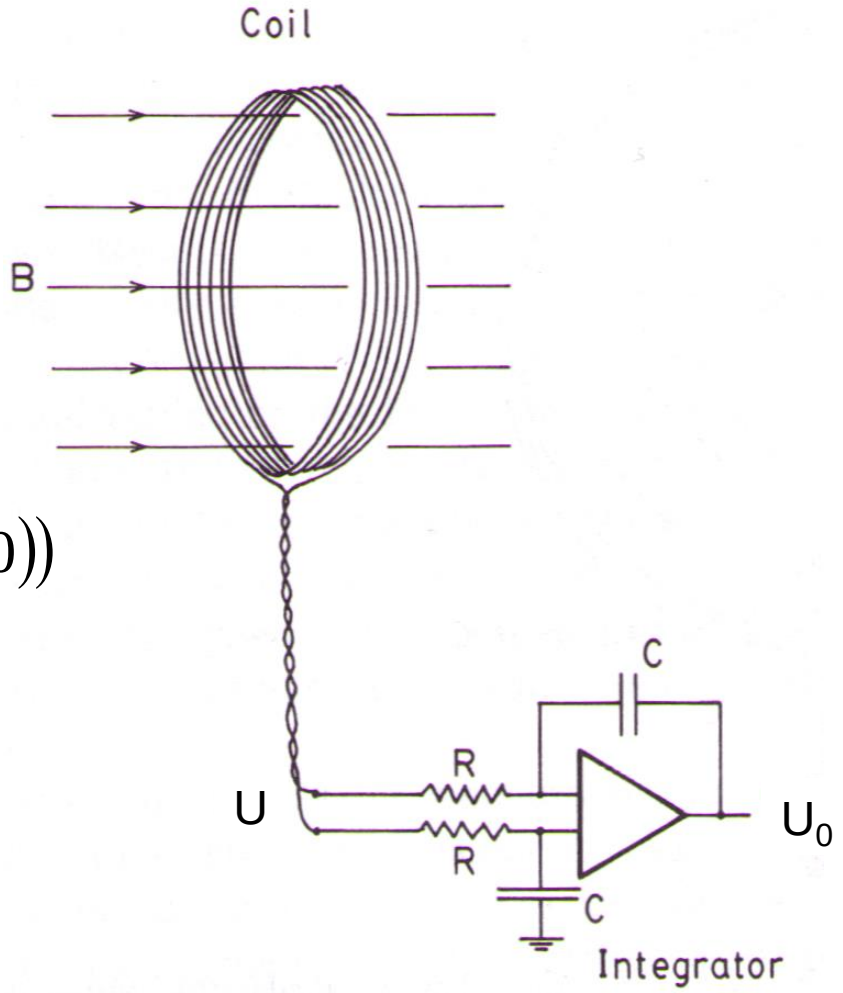
**Basic principle:**

A magnetic field B(t) induces a voltage U in a coil with N windings and area A according to Faraday's law:

$$U = -\frac{\partial \Phi}{\partial t} = -\int_A \frac{\partial B}{\partial t} dA \approx -N\,A\frac{\partial B}{\partial t}$$

From the time integration of the voltage U we may derive the magnetic field B(t):

$$U_0 = -\frac{N\,A}{R\,C}\int_0^t \frac{\partial B}{\partial t} dt = -\frac{N\,A}{R\,C}\left(B(t) - B(0)\right)$$



# Magnetic diagnostics

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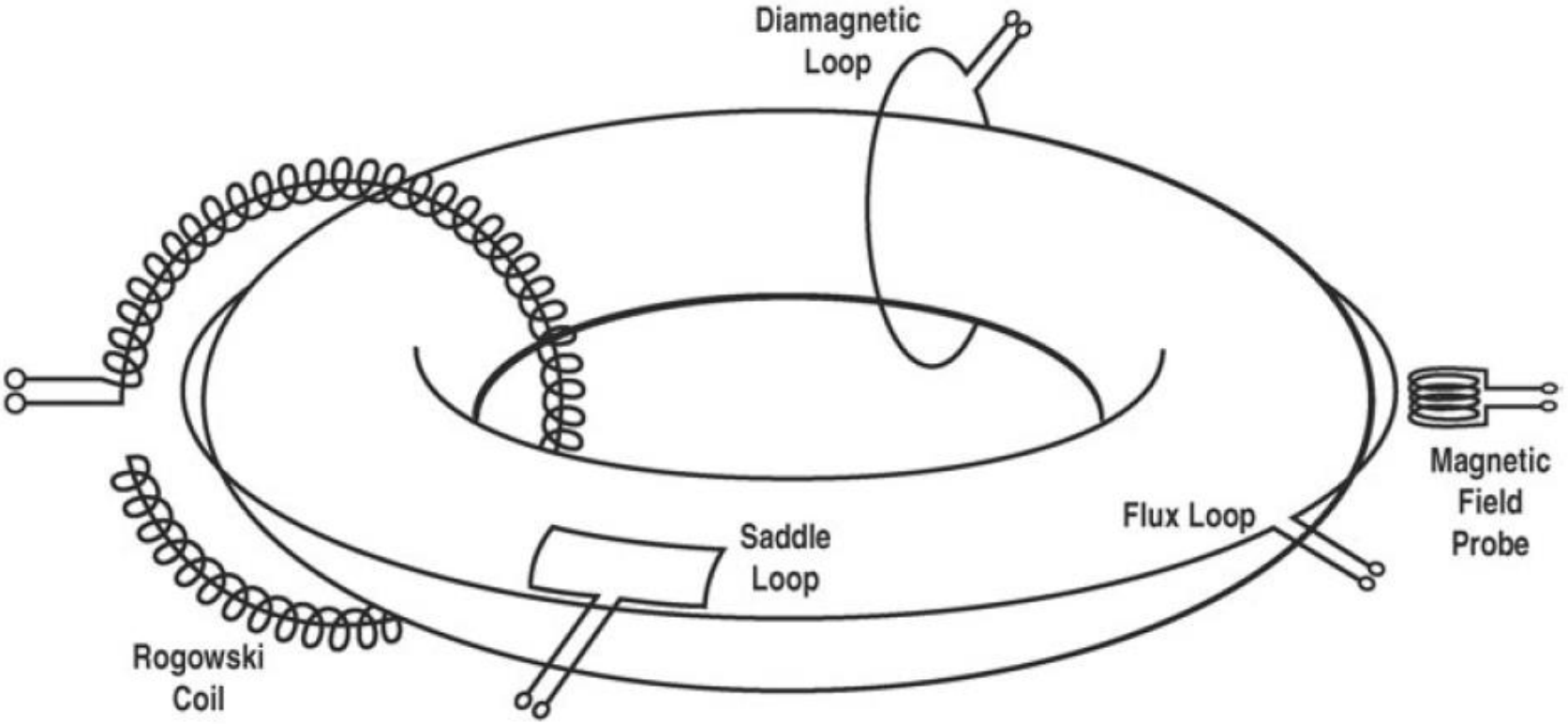
(Φ = magnetic flux)

From the time integration of the voltage U we may derive the magnetic field B(t).

## Technical challenges:

- Signal is zero during phases of constant magnetic field
- Integration of signals is struggling with offset voltages in electronics or spurious voltages
- Finite size of coils → only averaged values of B can be obtained
- Three dimensional structure of magnetic field in a tokamak: $B_t >> B_\theta >> B_r$ , therefore a precise coil geometry is needed to separate between the field components

# Basic types of magnetic sensors




Strait et al., Fus. Sc. Techn. 2008

# Rogowski coil

**Aim:**

Measurement of the plasma current

Solenoidal coil with toroidal shape, windings with uniform cross section and a number of windings per unit length n [1/m]

$$U = \dot{\psi} = n A \mu_0 \dot{I}_{Plasma}$$

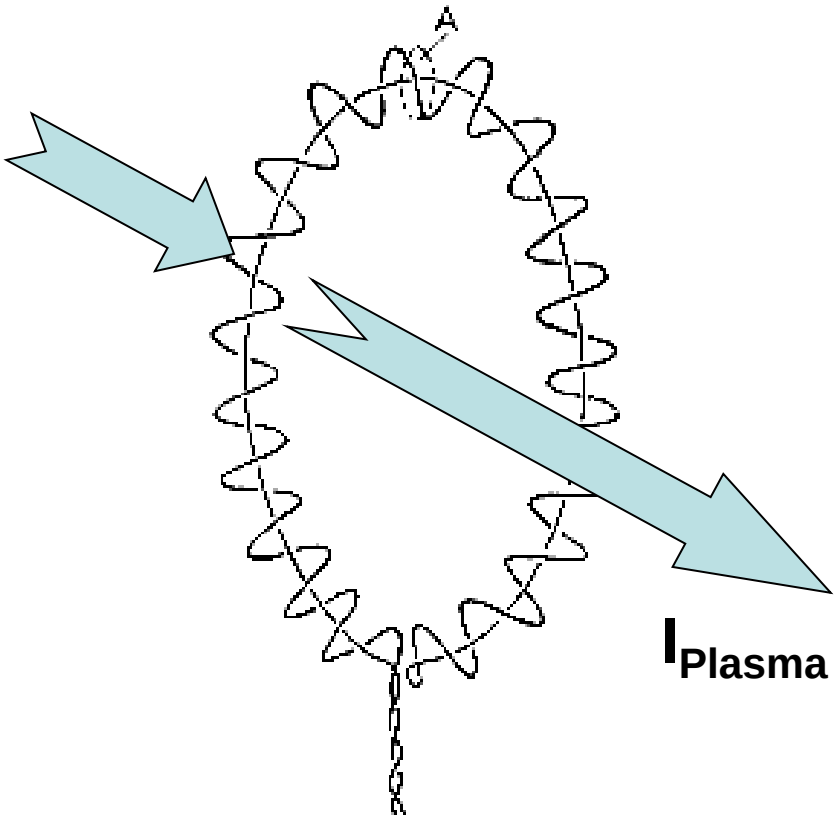
The plasma current can be obtained from the time integral of the voltage

**Important:**

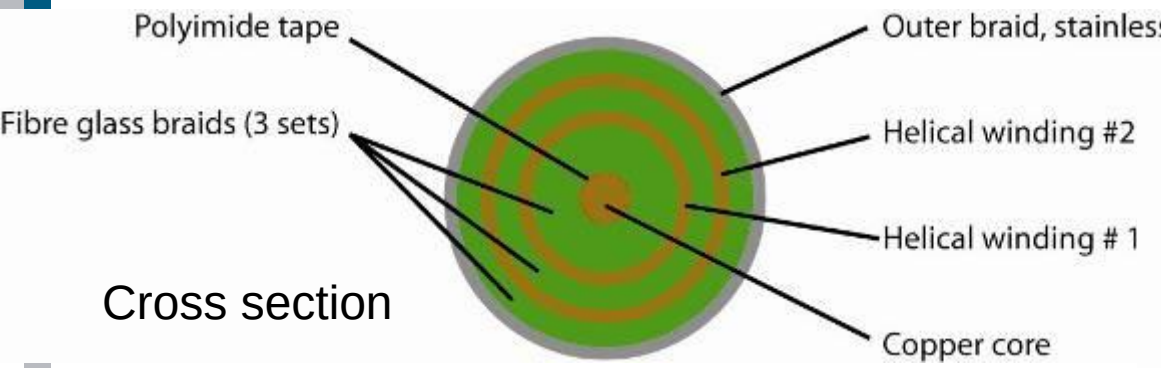
At the end of the coil the conductor is returning through the centre of the coil to the other end

→ Subtraction of toroidal flux change

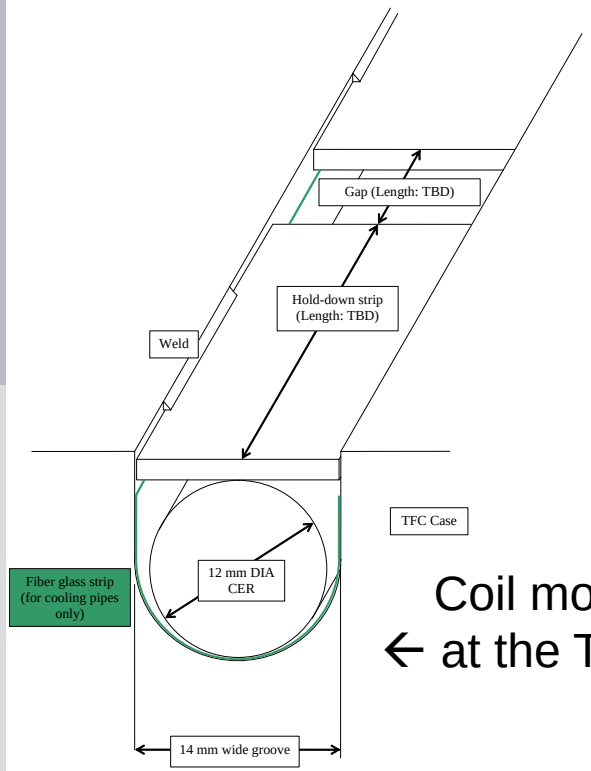
From: Hutchinson, *Principles of Plasma Diagnostics*



# Outer ITER Rogowski coil

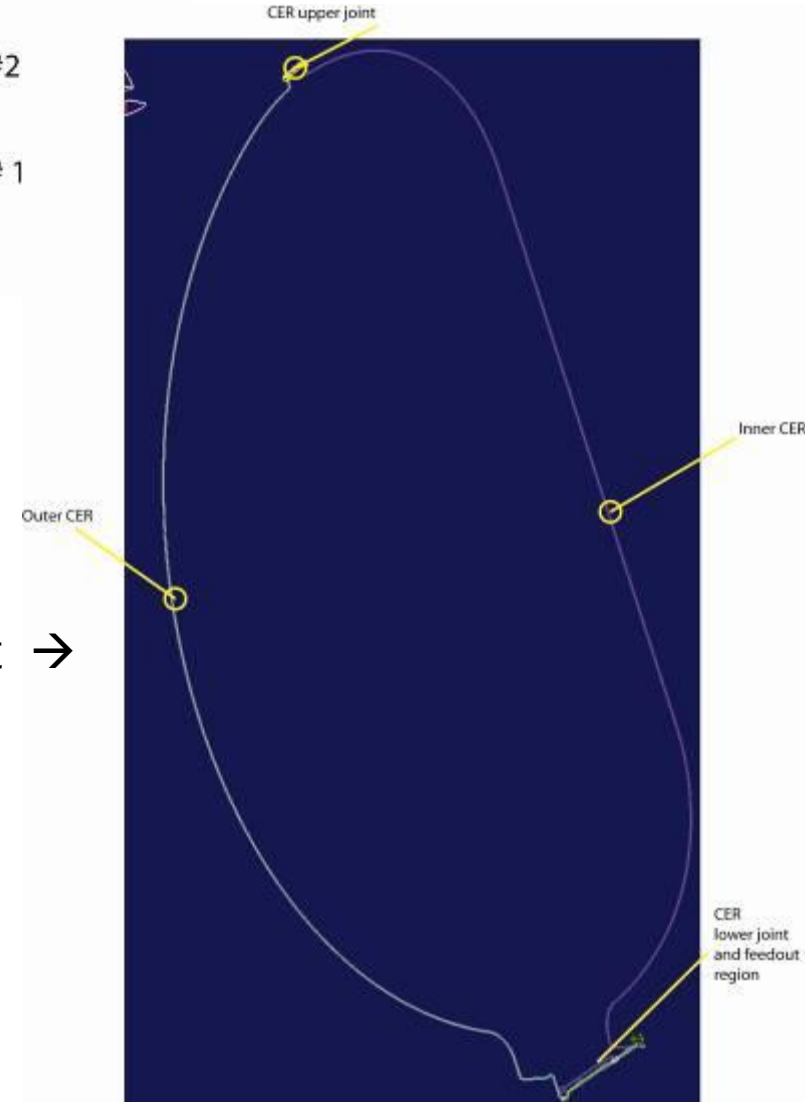



Cross section




Coil mounted in a groove
← at the TF coil casing

Overall layout →
(2 segments)



# Measurement of plasma position

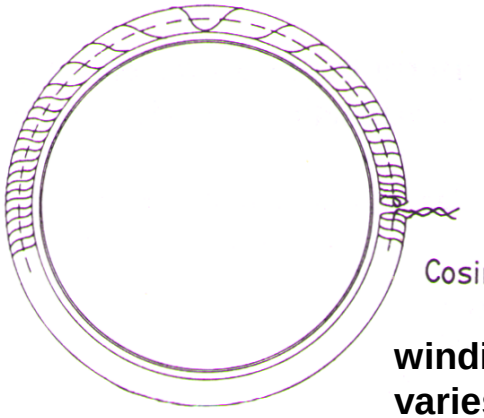
The **plasma position** can be determined via the measurement of the fourier components of the poloidal magnetic field:

$$B_\theta(\theta) \approx \frac{\mu_0 I}{2\pi a}\left(1 + \frac{\Delta_H}{a}\cos\theta + \frac{\Delta_V}{a}\sin\theta\right)$$

**Cosine coil** for horizontal position

**Sine coil** for vertical position (not shown)

**inversion of the winding direction**

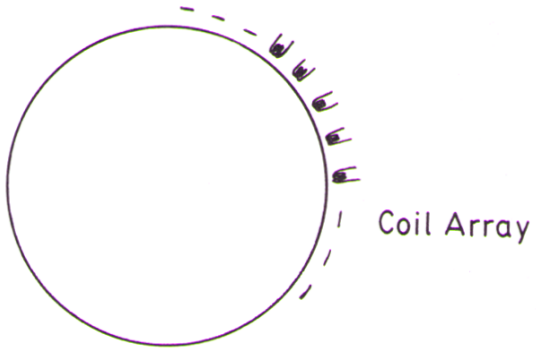



**winding density varies ~ cos θ**

The measured time integrated signal is proportional to the plasma dislocation Δ

**Alternative approach:**

Use discrete coils and perform numeric analysis for plasma position.

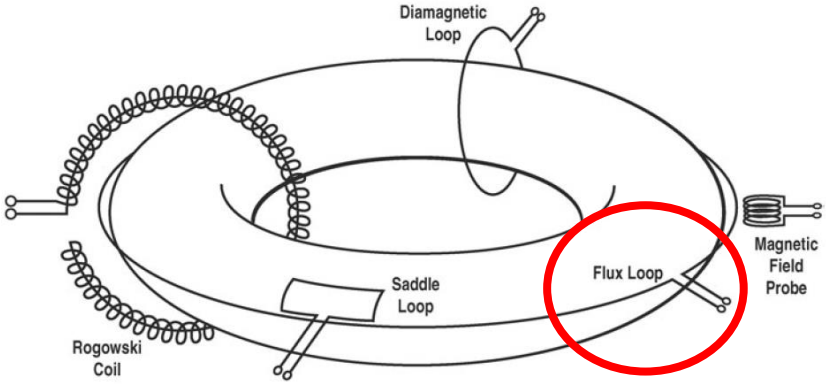


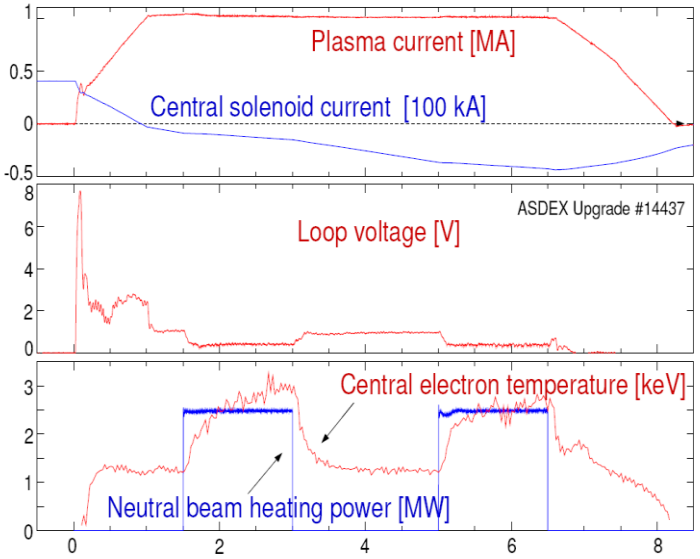

after: Hutchinson, *Principles of Plasma Diagnostics*

# Ohmic heating power and electrical conductivity

The toroidal loop voltage generated from the transformer is driving the (ohmic part of the) plasma current:

- In the stationary plasma phase, the loop voltage depends on the electrical conductivity of the plasma
- ➢ If the electron temperature $T_e$ is known, we can derive the effective ion charge Zeff from the loop voltage.




Ohmic heating power:
$P_\Omega = I_p \times U_{loop}$

$$Z_{eff} = \frac{\sum_k n_k Z_k^2}{\sum_k n_k Z_k} = \frac{\sum_k n_k Z_k^2}{n_e}$$

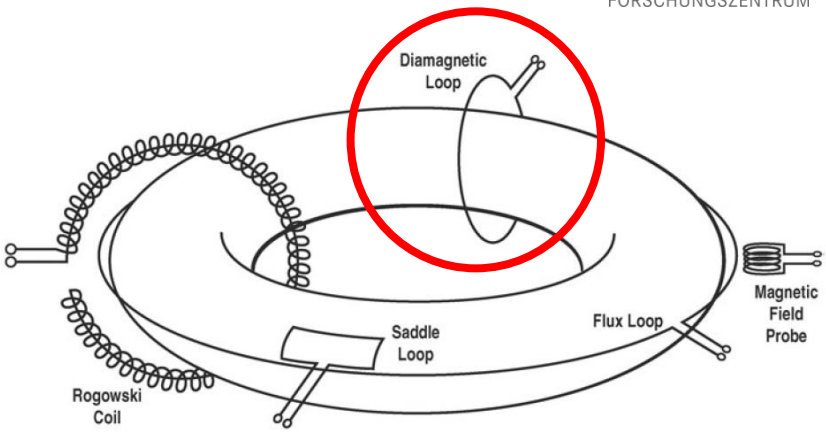
$$\langle\sigma\rangle = 1.92 \cdot 10^4 \left(2 - Z_{eff}^{-\frac{1}{3}}\right)\left(1 + \frac{5a}{R_0} + \frac{8a^2}{R_0^2}\right)^{-1} \frac{1}{Z_{eff}\ln\Lambda}\left(\frac{kT_e}{[\mathrm{eV}]}\right)^{\frac{3}{2}} \frac{1}{[\Omega\,\mathrm{m}]}$$

# Energy content of the plasma

Define the energy confinement time

$$\tau_E \equiv \frac{W_{plasma}}{P_{loss}} = \frac{V_{plasma}\,\frac{3}{2}\sum_k n_k k_B T_k}{P_{loss}}$$

(summation over all particle species k)




The energy confinement time can be determined from the measurement of the loss power (in the stationary case ~ heating power), the particle densities and temperatures)

In a plasma with various ion species and impurities the measurement of all densities and temperatures is a complex task.

Alternatively, the kinetic plasma energy $W_{Plasma}$ can be determined via the measurement of the change of toroidal flux:

$$W_{Plasma} = \frac{3}{8}\mu_0 R_0 I^2\left(1 - \frac{8\pi B_0}{\mu_0^2 I^2}\Delta\Phi_{tor}\right) = \frac{3}{8}\mu_0 R_0 I^2 - \frac{3\pi B_0 R_0}{\mu_0}\Delta\Phi_{tor}$$

(inductive) (kinetic)

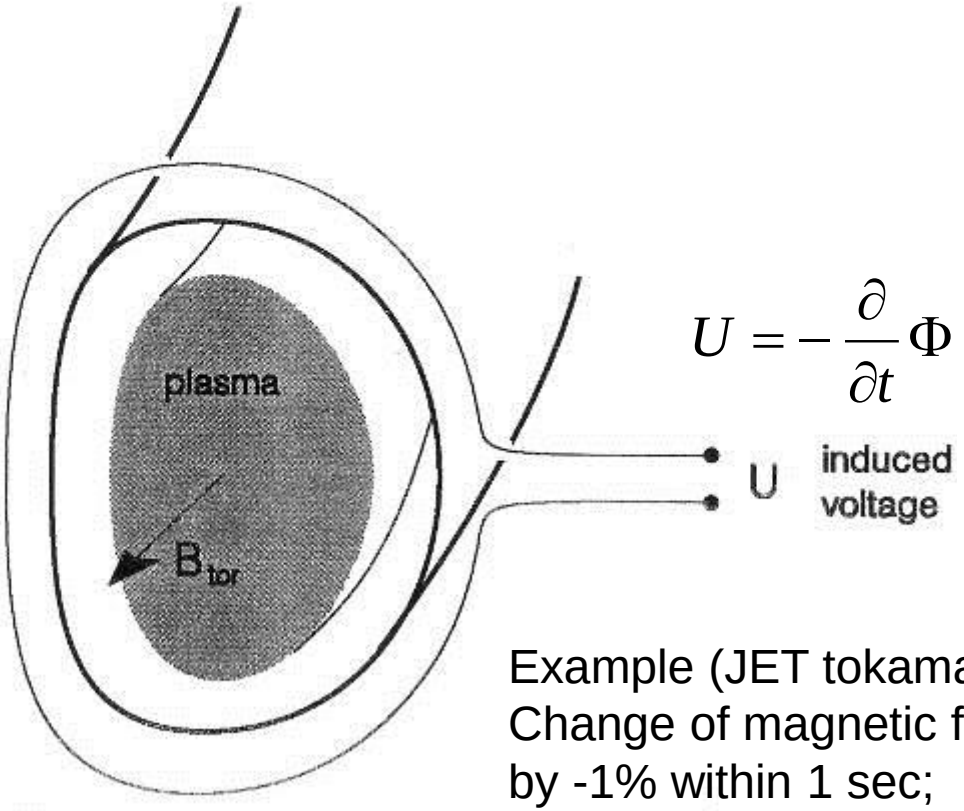
(Assumption: circular plasma cross section)

# Diamagnetic loop

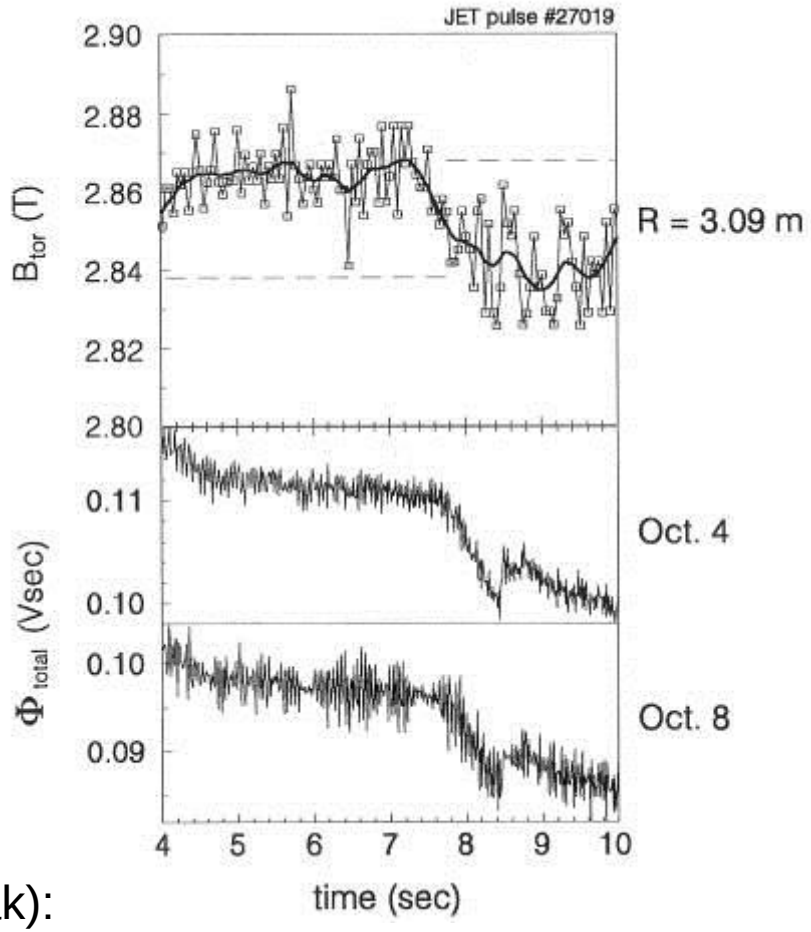
Measurement of the kinetic energy in the plasma

$$W_{Plasma} = \frac{3}{8}\mu_0 R_0 I^2 - \frac{3\pi B_0 R_0}{\mu_0}\Delta\Phi_{tor}$$

(inductive) (kinetic)



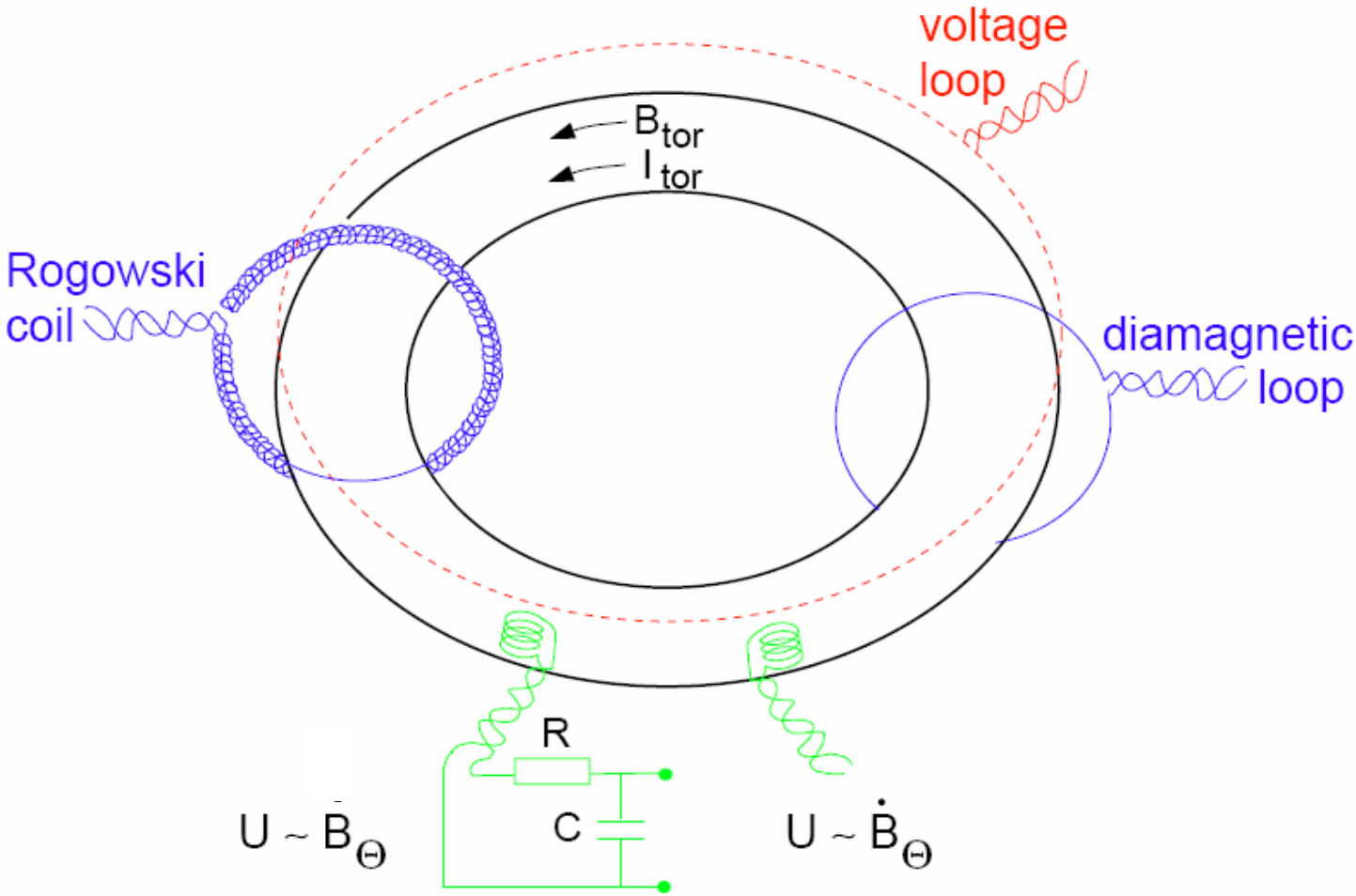

$$U = -\frac{\partial}{\partial t}\Phi$$




Example (JET tokamak):
Change of magnetic field ($B_0$ = 3 T)
by -1% within 1 sec;

N = 1, A = 7 m$^2$ → U = N A dB/dt = 0.2 V

# Mirnov coils: measurement of magnetic field fluctuations

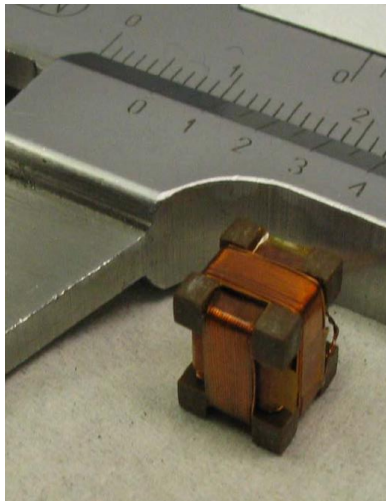



Mirnov coils are used for the local measurement of poloidal and radial magnetic field components $B_\theta$ und $B_r$ near the plasma edge.
Problem: $B_t >> B_\theta >> B_r$, → the coil geometry must be precisely aligned

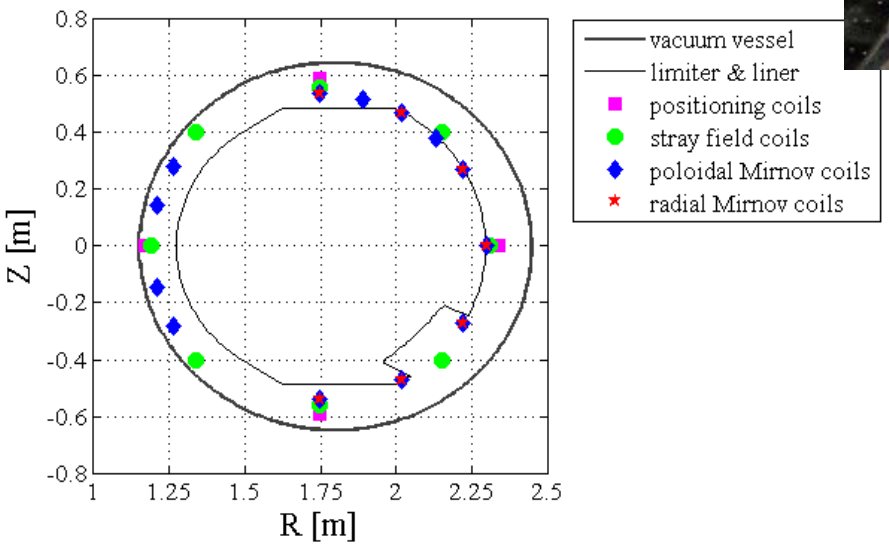
# Magnetic diagnostic: Mirnov coils

Examples for the technical realisation:

Mirnov coils on TEXTOR



Micro Mirnov coil (MAST)



# Requirements for magnetic diagnostics on ITER

| MEASUREMENT | PARAMETER | CONDITION | RANGE | ΔT or ΔF | ΔX or Δk | ACCURACY (2 σ) |
|---|---|---|---|---|---|---|
| 1. Plasma Current | Ip | Default | 0 – 1 MA | 1 ms | Integral | 10 kA |
| | | | 1 – 17.5 MA | 1 ms | Integral | 1 % |
| | | Ip Quench | 17.5 – 0 MA | 0.1 ms | Integral | 30 % + 10 kA |
| 2. Plasma Position and Shape | Main plasma gaps, Δsep | Ip > 2 MA, full bore | - | 10 ms | - | 1 cm |
| | | Ip Quench | - | 10 ms | - | 2 cm |
| | Divertor channel location (r dir.) | Default | - | 10 ms | - | 1 cm |
| | | Ip Quench | - | 10 ms | - | 2 cm |
| | dZ/dt of current centroid | Default | 0 – 5 m/s | 1 ms | - | 0.05 m/s (noise) + 2 % (error) |
| 3. Loop Voltage | Vloop | Default | 0 – 30 V | 1 ms | 4 locations | 5 mV |
| | | Ip Quench | 0 – 500 V | 1 ms | 4 locations | 10 % + 5 mV |
| 4. Plasma Energy | βp | Default | 0.01 – 3 | 1 ms | Integral | 5 % at βp=1 |
| | | Ip Quench | 0.01 – 3 | 1 ms | Integral | ~ 30% |
| 8. Locked Modes | $B_r$(mode) / $B_p$ | | $10^{-4}$ – $10^{-2}$ | 1 ms | (m,n) = (2,1) | 30 % |
| 9. Low (m,n) MHD Modes, Sawteeth, Disruption Precursors | Mode complex amplitude at wall | | TBD | DC – 3 kHz | (0,0) < (m,n) < (10,2) | 10 % |
| 21. Halo Currents | Poloidal current | In disruption | 0 – 0.2 $I_p$ | 1 ms | 9 sectors | 20 % |
| 22. Toroidal Magnetic Field | $B_T$ | | 2 – 5.5 T | 1 s | 2 locations x 2 methods | 0.1 % |
| 27. High Frequency Macro Instabilities (Fishbones, TAEs) | Fishbone–induced perturbations in B,T,n | | TBD | 0.1 –10 kHz | (m,n) =(1,1) | – |
| | TAE mode – induced perturbations in B,T,n | | TBD | 30 –300 kHz | n = 10 - 50 | – |

# Radiation effects on diagnostics + actuators

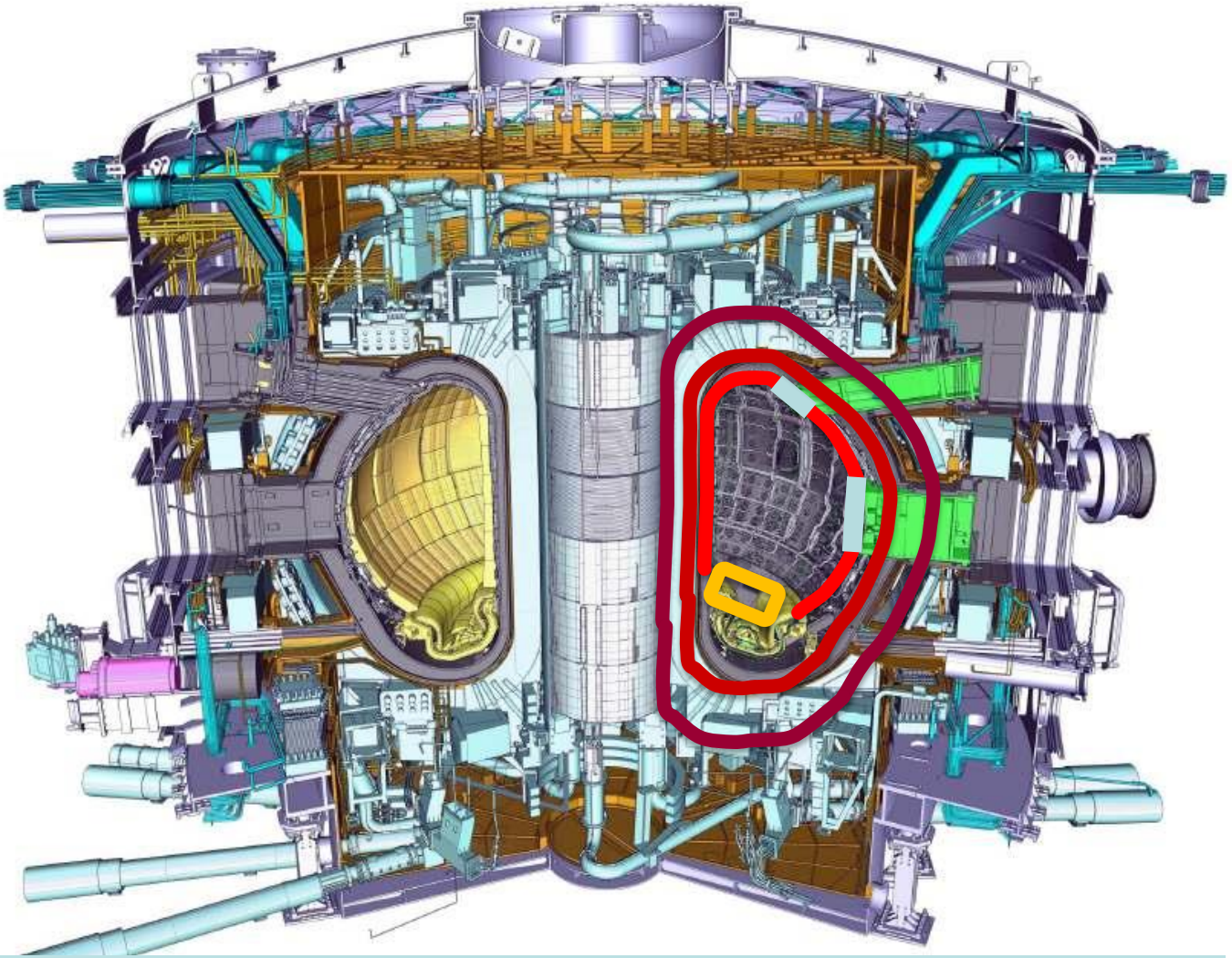
(after G. Vayakis, ITER organisation)

| Effect | Symbol | Explanation |
|---|---|---|
| Radiation-induced conductivity | RIC | Electrical conductivity increases due to the excitation of electrons into the conduction band. |
| Radiation-induced electrical degradation | RIED | Electrical conductivity increases due to radiation and electric field enhanced defect aggregation. |
| Thermal conductivity decrease | – | Thermal conductivity decreases leading to temperature increases. |
| Volume changes | – | Materials swell, or in some cases shrink |
| Radiation-Induced Electromotive Force | RIEMF | Nuclear reactions in the sensor materials induce net current in the sensor circuit |
| Thermoelectric Electromotive Force | TIEMF | Parasitic thermocouple action driven by nuclear-heating |
| Radiation-induced thermoelectric sensitivity | RITES | Additional parasitic thermocouples generated by non-uniform material damage and transmutation |
| Radiation-enhanced diffusion | – | Enhanced diffusion occurs in insulating materials due to the possible existence of different charge states for defects and impurities. |
| Radiation-induced absorption | RIA | Optical absorption increases due to the production of defect related absorption bands, leading to light transmission loss. |
| Radioluminescence or radiation-induced emission | RL or RIE | Light emission due to excitation of defects and impurities. |

# Where are magnetics mounted?

(G. Vayakis, ITER)

- On the divertor (most exposed)
- Just behind the ITER blanket in vessel
- On the outer vessel skin
- Inside the TF coil (least exposed)



Note: backward mounting results in longer lifetime of components but reduced performance due to signal attenuation and shielding by eddy currents

# Wave propagation in plasmas

## Most basic case: cold plasma without magnetic field

(ω = angular frequency; N = refractive index)

$$\omega^2 - \omega_P^2 = k^2 c^2; \quad N = \sqrt{1 - \left(\frac{\omega_P}{\omega}\right)^2}$$

where the plasma frequency is given by

$$\omega_P = \sqrt{n_e \frac{e^2}{\varepsilon_0 m_e}}$$

(this is the oscillation frequency of the electron fluid if the electrons are displaced against the ion background)

In this most basic case any electromagnetic wave with frequency below the plasma frequency cannot penetrate into the plasma → the wave will be reflected → „reflectometry“

## Example:

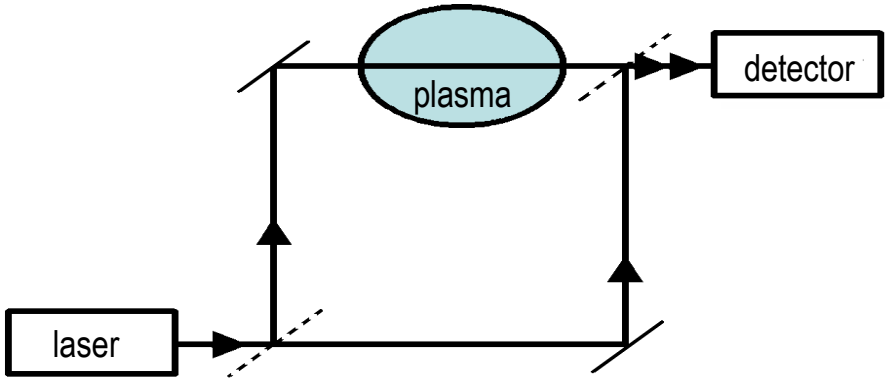
For an electron density $n_e = 10^{20} m^{-3}$ we obtain $\omega_P = 5.6 \times 10^{11} s^{-1}$, $f = \omega_P / 2\pi = 90$ GHz

this translates to a wavelength of $\lambda = c / f = 3.34$ mm (microwave range)

Wave with frequencies above the plasma frequency can penetrate into the plasma, but they experience a phase shift (N < 1).

# Plasma interferometry

Interferometry: measurement of electron density integrated along the sightline



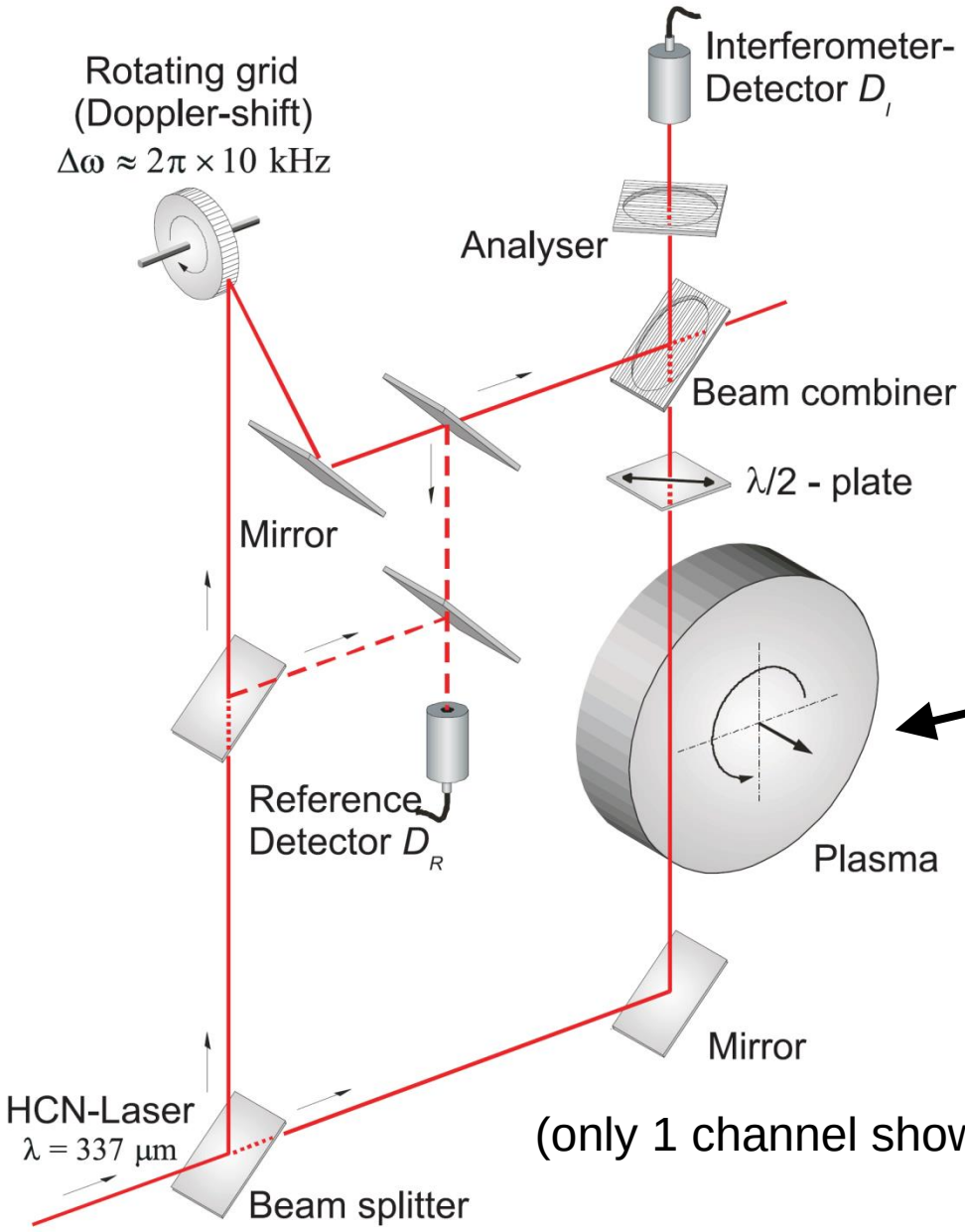

- The refractive index N of a plasma depends on the electron density and on the wavelength

$$N = \sqrt{1 - \left(\frac{\omega_P}{\omega}\right)^2}, \quad \omega_P = \sqrt{n_e \frac{e^2}{\varepsilon_0 m_e}}$$

- The interferometer measures the phase shift due to the plasma (phase angle $\Phi$)

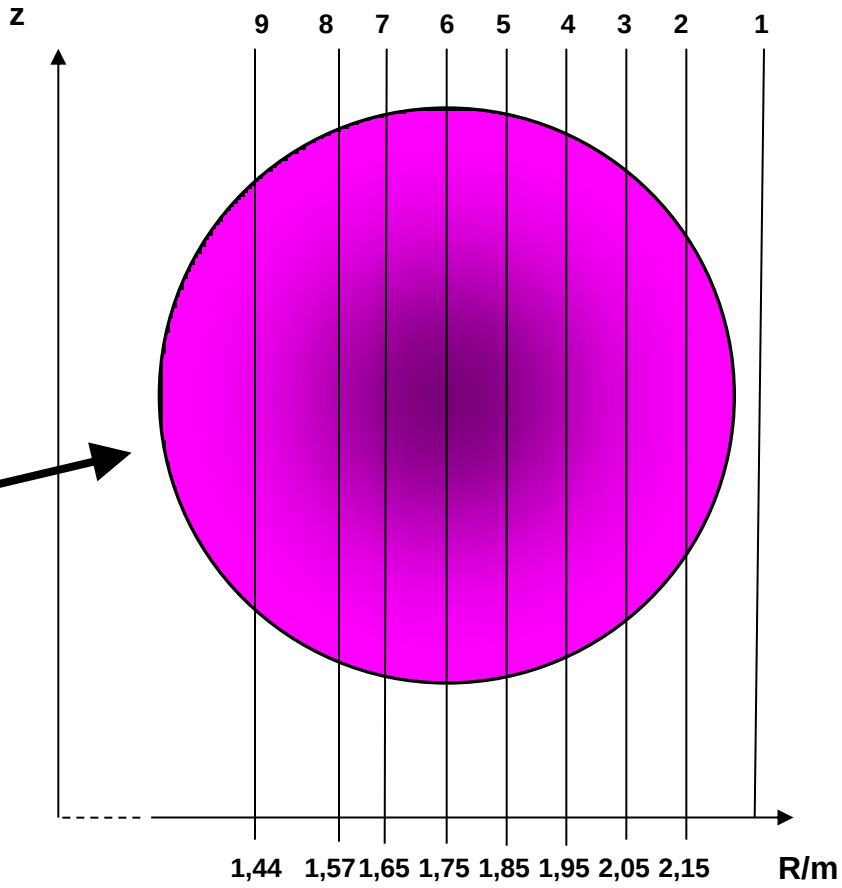
$$\phi = \frac{e^2}{4\pi\epsilon_0 c^2 m_e} \lambda \int n \, dl$$

# HCN interferometer on TEXTOR




(only 1 channel shown)

arrangement of 9 channels



# Infrared polarimetry

Propagation of a laser beam in a plasma with electron density $n_e$ and a magnetic field component $B_{||}$ oriented along the beam

→ rotation the beam polarisation (= Faraday rotation):

$$\Delta\theta = 2.62 \times 10^{-13} \lambda^2 \int_{Z_0}^{Z_1} n_e B_{\|} \mathrm{d}Z$$

Z = coordinate along $B_{||}$

$\lambda$ = laser wavelength [m]

$n_e$ = electron density [$m^{-3}$]

$B_{||}$ = magnetic field component along the beam [T]

Example: $\lambda$ = 10 µm, $Z_1$-$Z_0$ = 10 m, $B_{||}$ = 5 T, $n_e$ = $10^{20}$ $m^{-3}$ → $\Delta\theta$ = 0.113

# Current density measurement in a tokamak via polarimetry

H. Soltwisch, Rev. Sci. Instrum. 1986

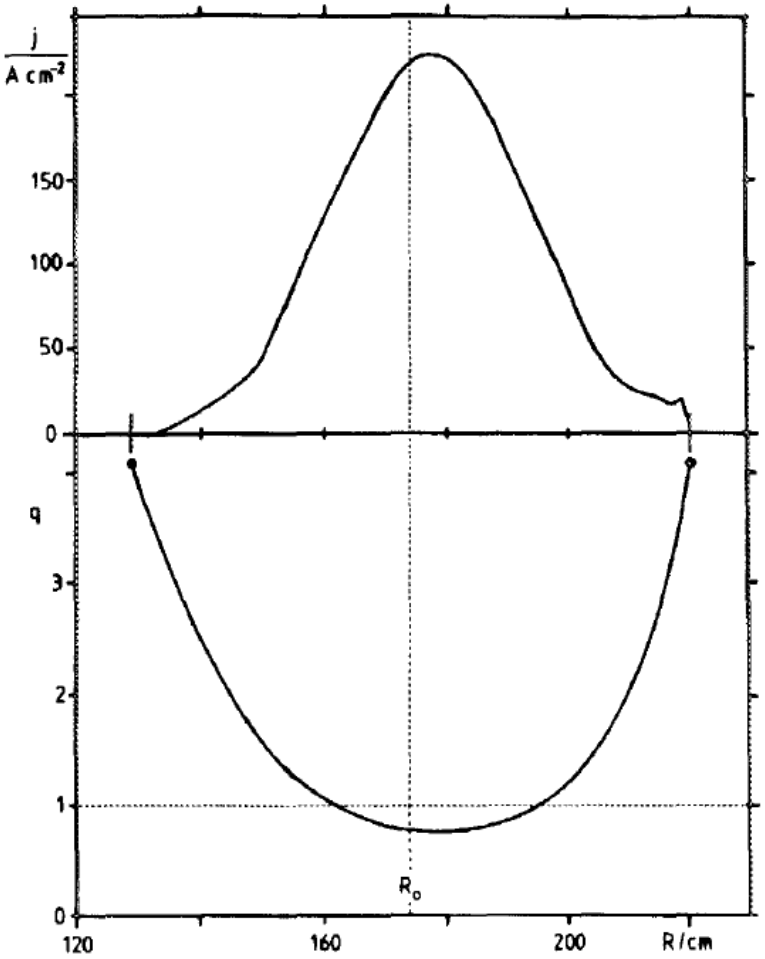
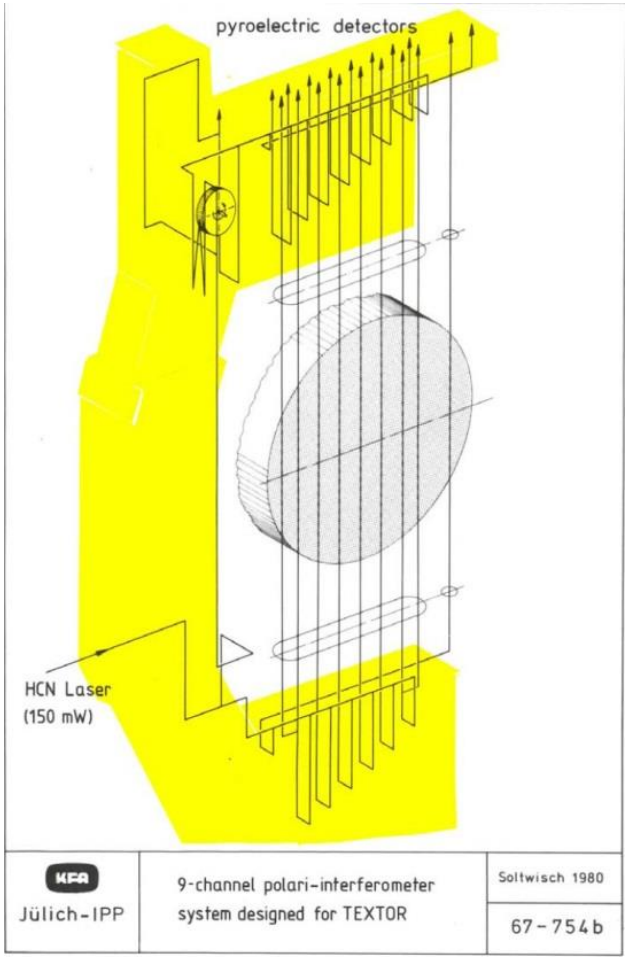



FIG. 8. Current density (upper trace) and safety factor (lower trace) vs major radius as derived from the data shown in Fig. 4 at $t = 1$ s.



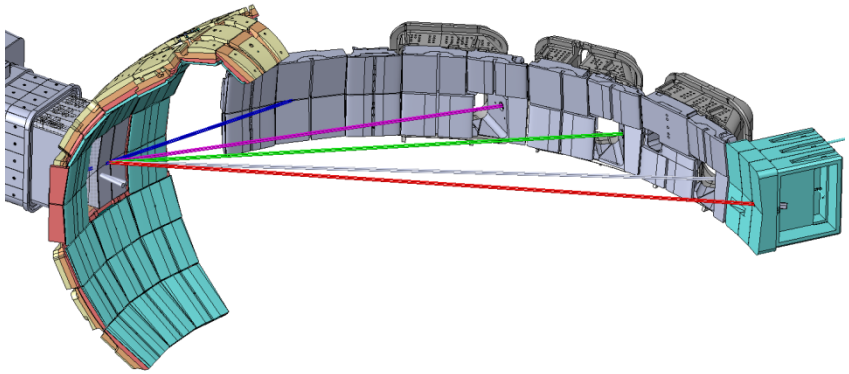

The current density in a tokamak is stronger peaked than expected → q < 1 in the plasma centre possible

# Tangential and poloidal I/P systems in ITER

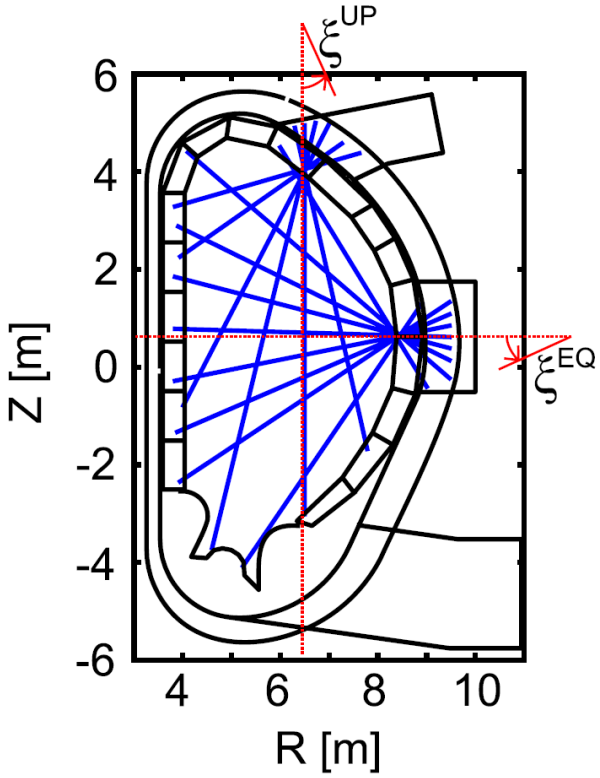
***Interferometer:***
***max. phase: ~ 10 fringes***

***polarimetry***
***max. phase: << 1 fringe***

V.V. Mirnov et al.
Varenna Conf. 2013



*(M. A. van Zeeland, Rev. Sci. Instrum, 2013)*




Polarimetry data analysis has to take into account:

- Faraday effect (**B** II beam)
- Cotton-Mouton (C-M) effect (**B** ⊥ beam)
- Temperature dependence of rotation angle and relativistic effects

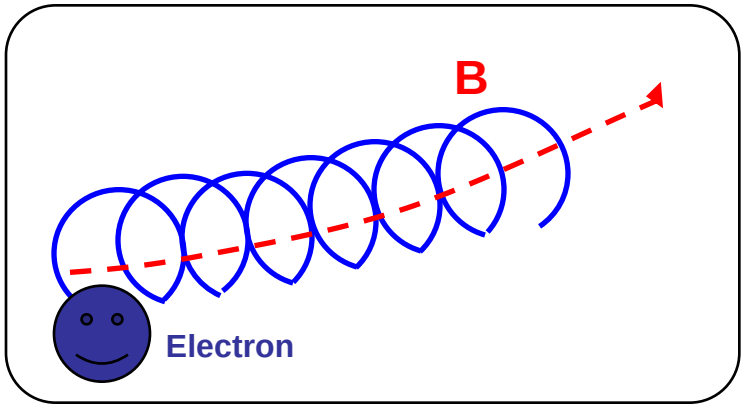
# Measurement of electron cyclotron emission (ECE) to determine the electron temperature

Electrons and ions gyrate around the magnetic field lines → centrifugal forces

Classical electrodynamics:
Accelerated charged particles emit electromagnetic radiation

The frequency of the ECE radiation is the gyration frequency $\omega_{ce}$ (and in principle also $\omega_{ci}$) and their higher harmonics $n\omega_{ce}$ (and $n\omega_{ci}$), with n = 2, 3, …

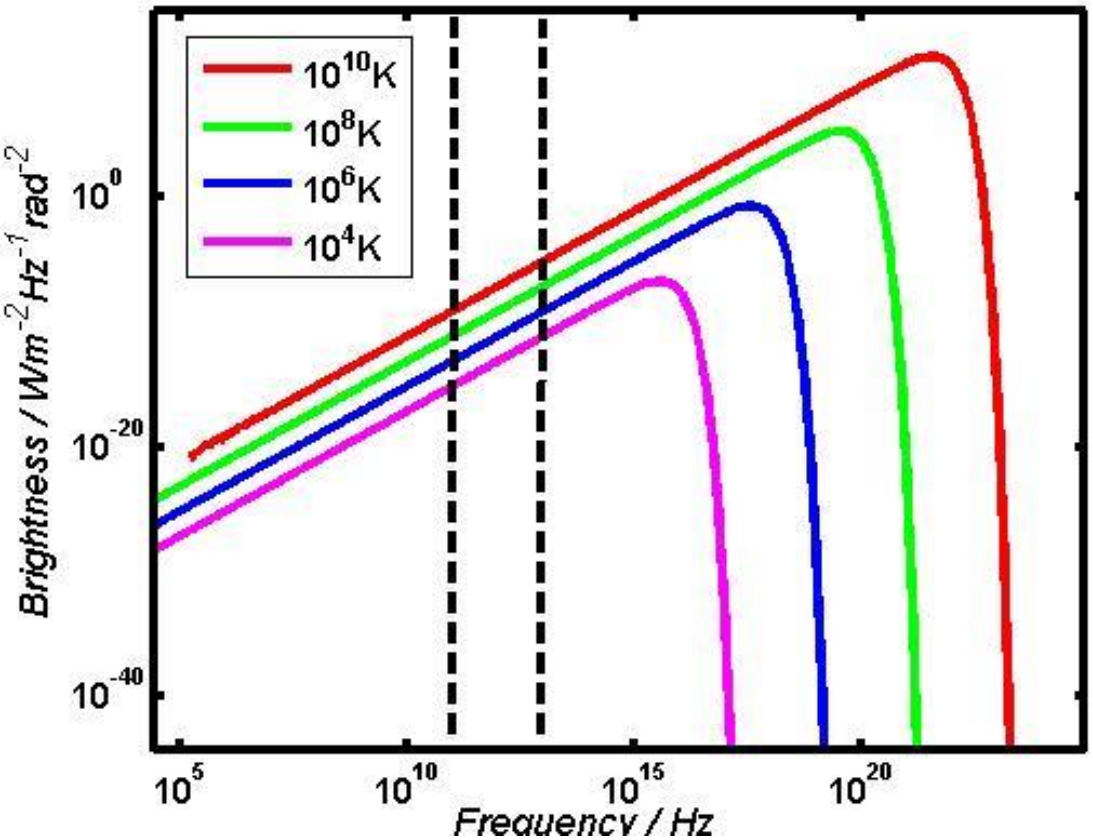
In a fusion plasma the radiation at the fundament frequency $\omega_{ce}$ is optically thick.
The emitted photons will be absorbed and re-emitted several times in the plasma.
→ ECE is black-body radiation




$$\omega_{ce} = \frac{eB}{m_e}$$

# Determination of the electron temperature $T_e$ from ECE measurements

Optically thick radiation can be described by a **Planck curve:**




$$B(\omega) = \frac{\hbar\omega^3}{8\pi^3 c^2}\left(\frac{1}{\exp\left(\frac{\hbar\omega}{k_B T_e}\right)-1}\right)$$

The electron temperature can be determined from an intensity measurement

# Analysis of ECE measurements

In a fusion plasma with magnetic field the gyrating electrons radiate at the cyclotron frequency $\omega_{ce} = eB/m_e$ and at their higher harmonics.

Apply the low frequency approximation: $e^{-\frac{\hbar\omega}{kT}} - 1 \approx \frac{\hbar\omega}{kT}$

In this case the Planck curve $B(\omega) = \frac{\hbar\omega^3}{8\pi^3 c^2}\left(\frac{1}{\exp\left(\frac{\hbar\omega}{k_B T_e}\right) - 1}\right)$

simplifies towards the Rayleigh-Jeans law: $B(\omega) = \frac{\omega^2 k_B T_e}{8\pi^3 c^2}$

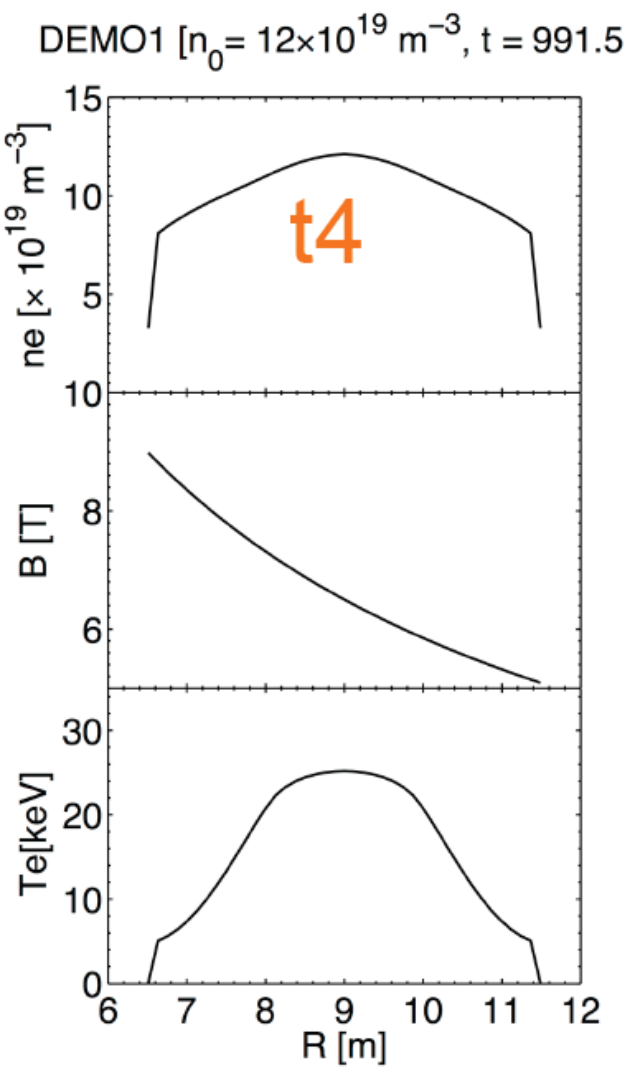
The measured ECE intensity is proportional to the electron temperature.

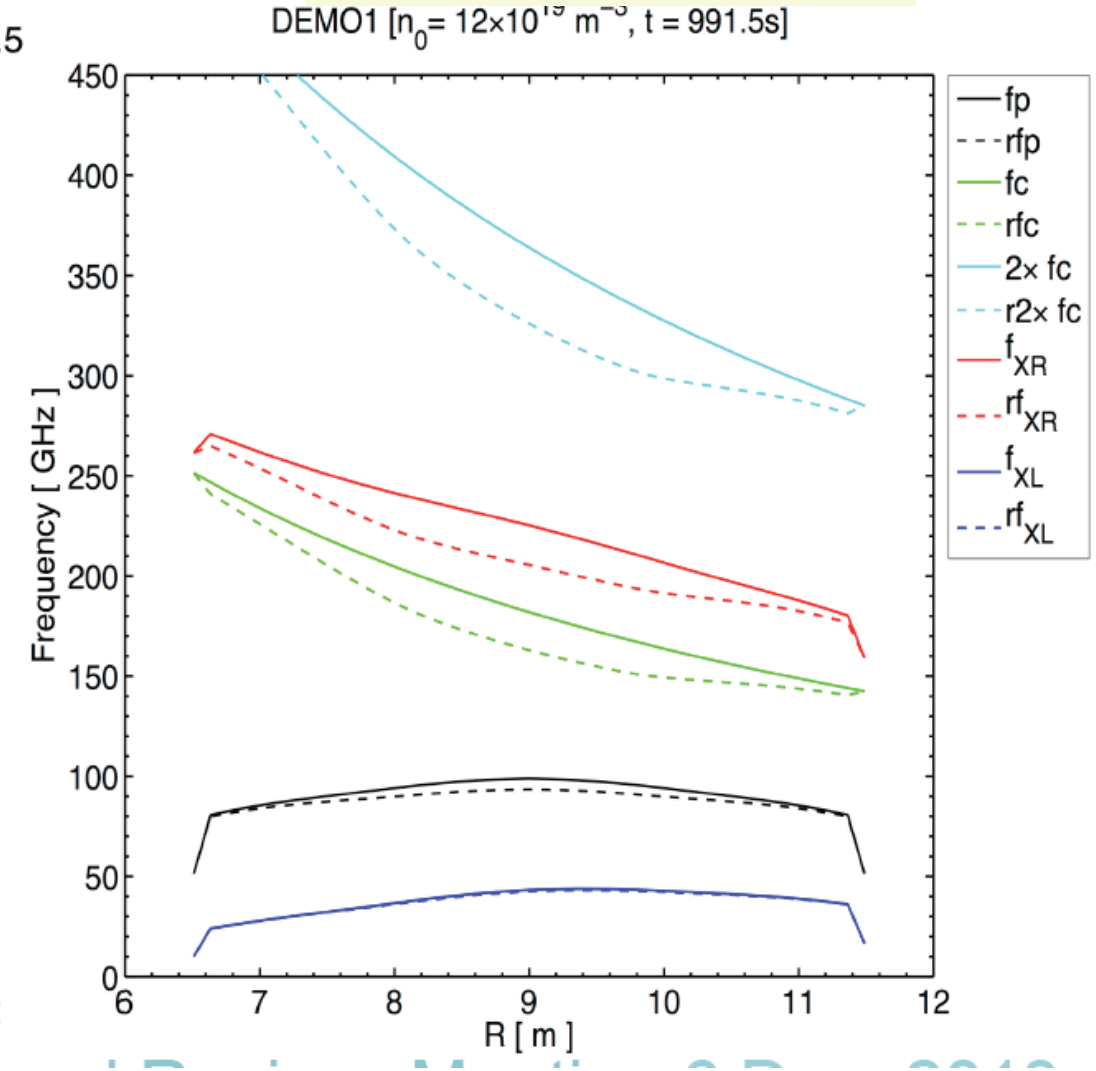
The ECE diagnostic needs an intensity calibration.

# Radial dependence of frequencies for microwave diagnostics on a DEMO reactor

(A. Silva et al.)

$$B(R) = \frac{B_0 R_0}{R}; \quad \omega_{ce} = \frac{eB}{m_e}$$



# ECE measurement: necessary corrections

1. Relativistic correction: For high electron temperatures, the relativistic dependence of the mass has to be considered:

$$\omega_{ce} = \frac{eB}{m_e \gamma} \qquad \gamma = \sqrt{\frac{1}{1 - \frac{v^2}{c^2}}} > 1$$

   - For a given frequency, the actual place of measurement is shifting towards the high field side of the torus, i.e. to lower values of R

2. Diamagnetic correction: The sum of kinetic plasma pressure and magnetic pressure is constant:

$$p + \frac{B^2}{2\mu_0} = const = \frac{B_0^2}{2\mu_0}$$

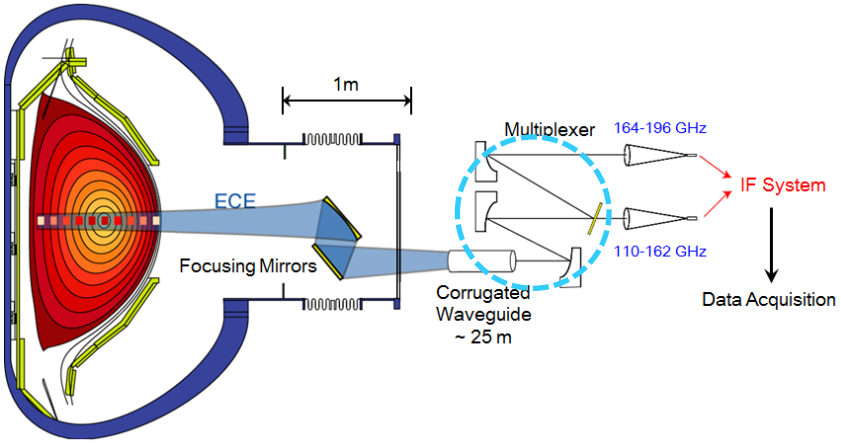
   - Again, for a given frequency, the actual place of measurement is shifting towards the high field side of the torus, i.e. to lower values of R

# KSTAR ECE System : 110-196 GHz

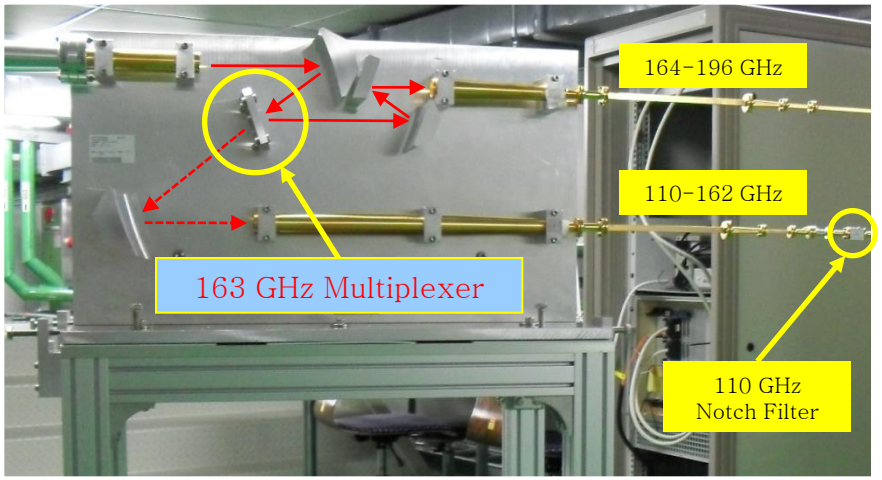
K. D. Lee and Seong-Heon Seo, NFRI (Korea)

JÜLICH FORSCHUNGSZENTRUM

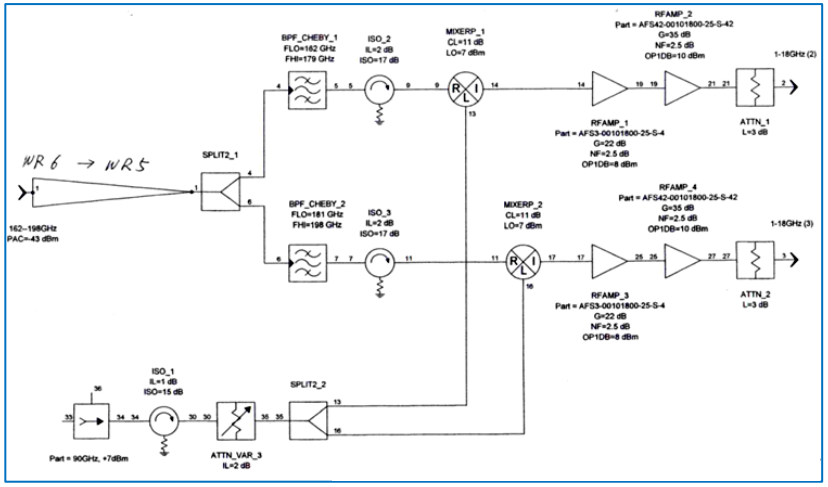
## Schematic of KSTAR ECE System

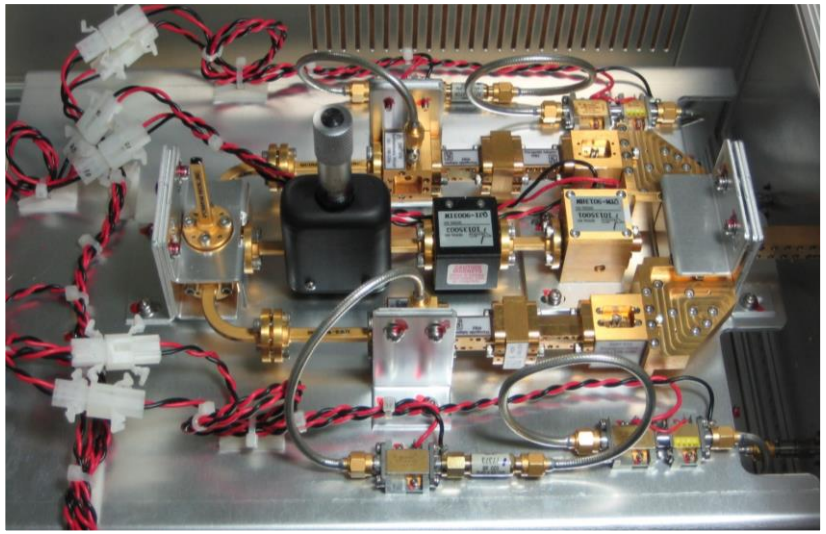



- **Multiplexer Optics (2010-2012)**




## Overview of ECE Radiometer



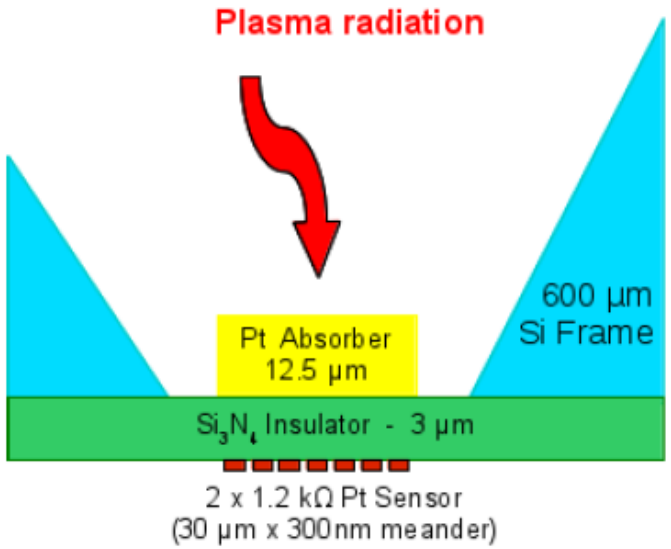



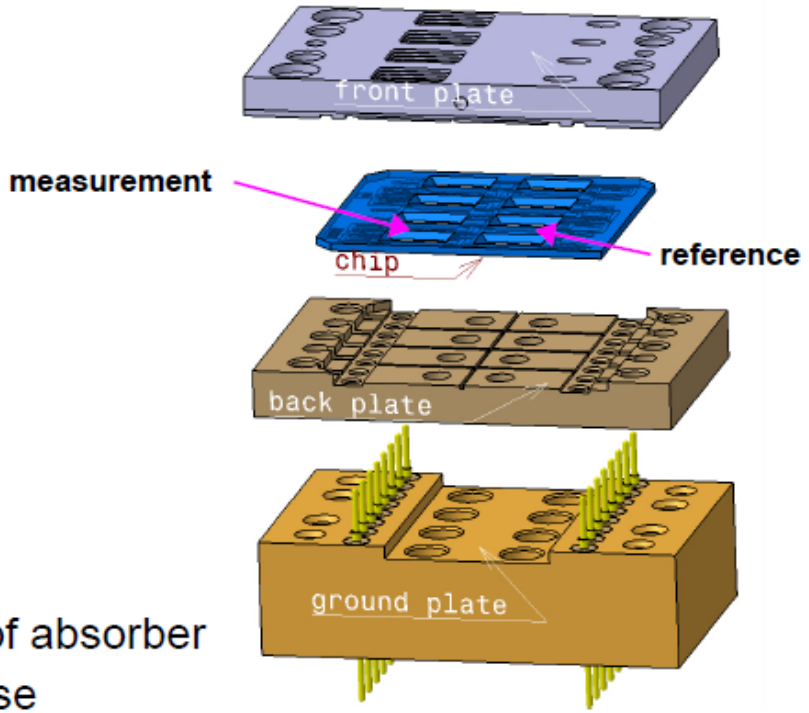
# Bolometry: Detector - principle

R. Reichle (ITER), H. Meister (IPP)

- Bolometers measure the plasma radiation, part of the energy balance:

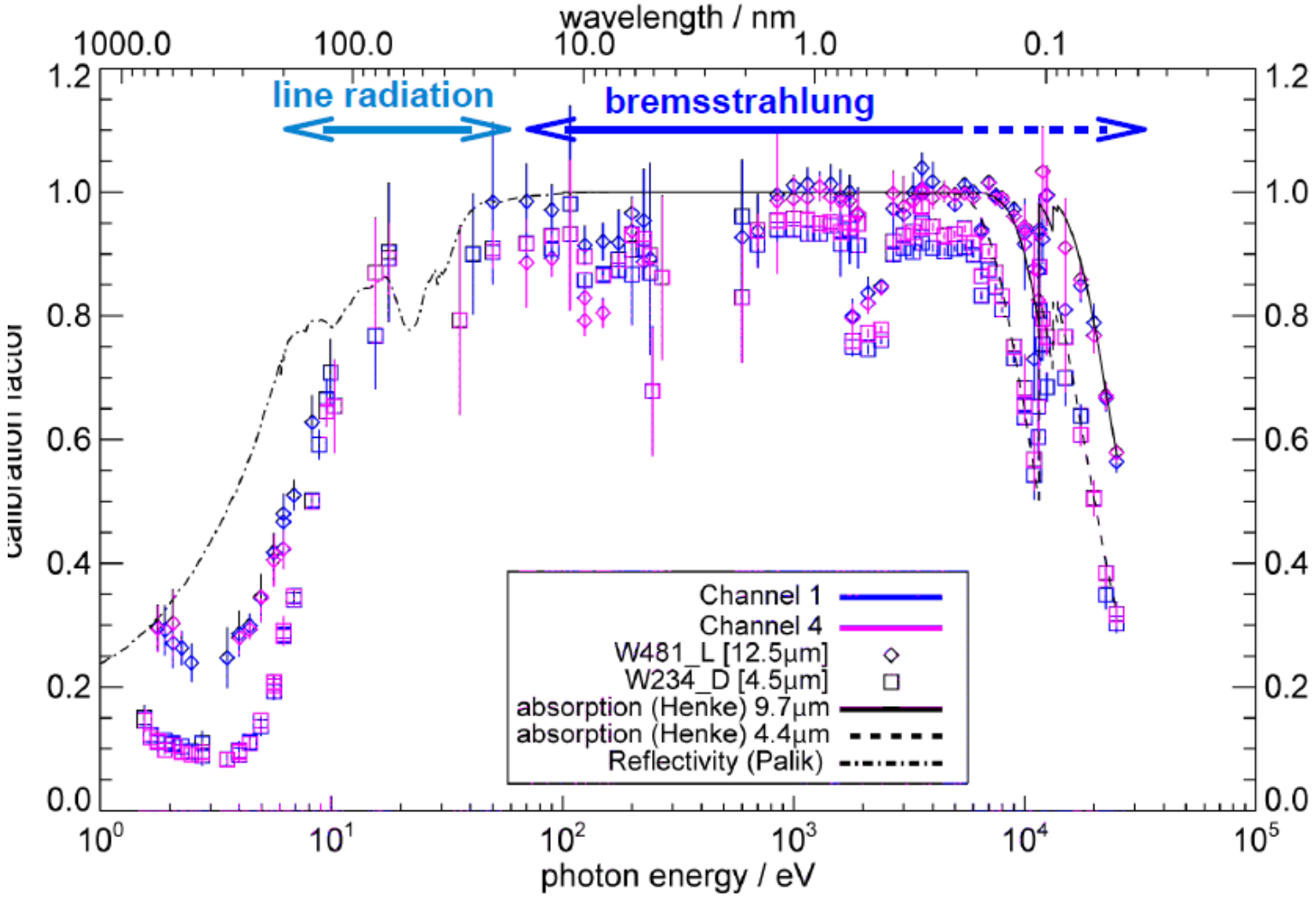
$$P_{\alpha} + P_{ext} = P_{loss} + P_{rad}$$




- Plasma radiation increases temperature of absorber
- Metal resistor detects temperature increase
- To compensate temperature changes from environment, additional reference absorber – shielded from plasma radiation – is used

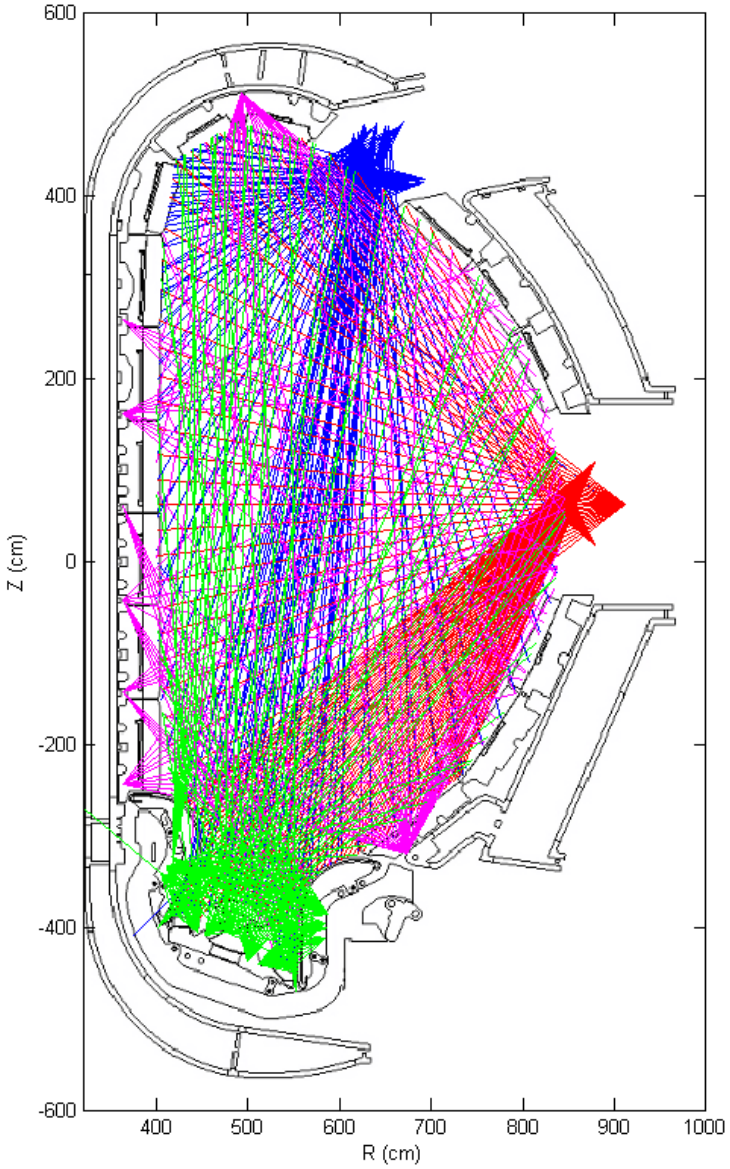
# Spectral sensitivity range of bolometers




The diagnostic is the most important contributor to the measurement of the total radiated power

[ H. Meister , IPP Garching, Ringberg seminar 18.4.2013]

# Bolometry: Spatial resolution and LOS




R. Reichle (ITER), H. Meister (IPP)

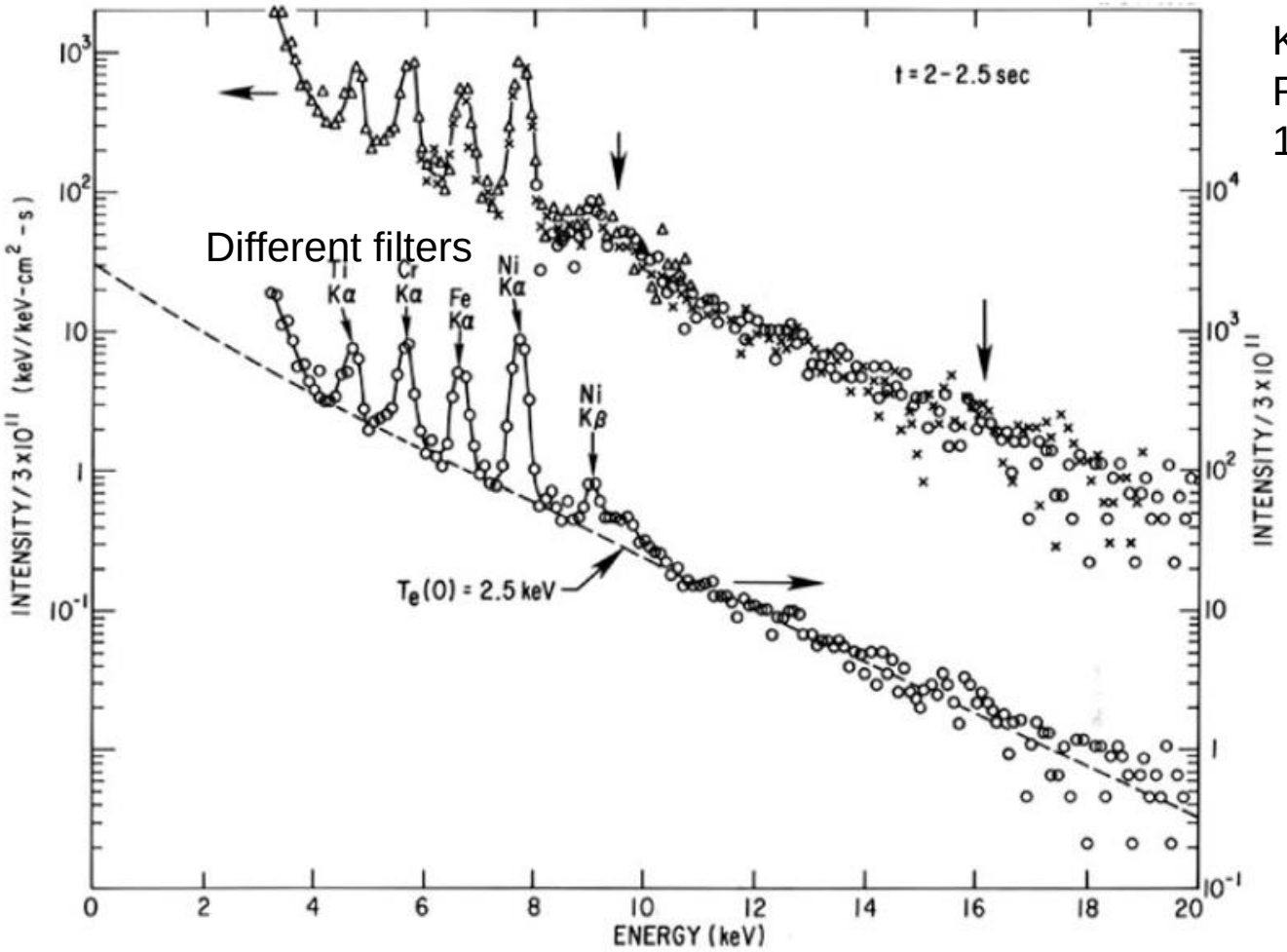
Emphasis is on divertor area (5 cm) monitoring of the detachment of the divertor plasma and the formation of X-Point-MARFEs.
But also good resolution of main plasma area (1/30$^{th}$ of the minor plasma radius) for studying the edge radiation profile in various areas of the plasma, the upper target area, radiation phenomena related to transport barriers or impurity transport and accumulation in the centre and the temporal evolution of MARFEs.

Total Radiation is a very robust measurement and does need only a small subset of the LOS.
The profiles will need tomographic reconstructions. For this we are in sparse data domain.

For tomography the LOS need to be toroidally clustered together.

Some toroidal resolution is however also needed for disruption mitigation investigations.

# Spectroscopy in the plasma core – Pulse hight analysis SXR spectra in TFTR




K. Hill et al., Rev. Sci. Instr. 1985

From the measured Bremsstrahlung background, the electron temperature and electron density can be determined:

$$I_\omega \, d\omega \propto e^{\frac{\hbar\omega}{kT_e}} d\omega$$

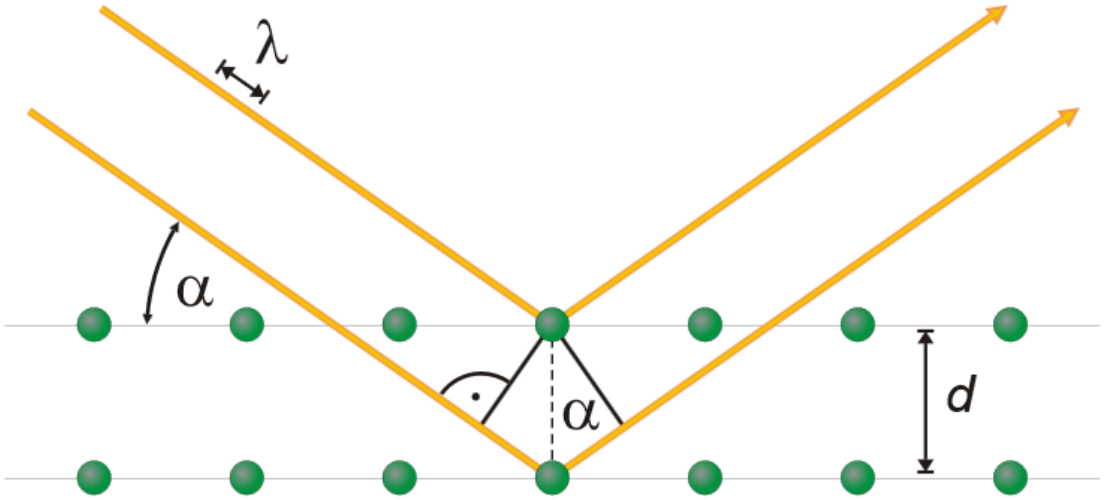
and

$I \sim n^2$

(low spectral resolution via measurement of charge pulses generated from photon energies deposited in the semiconductor detector)

# High-resolution x-ray spectroscopy (1)

Using Bragg reflection for wavelength separation:




(image source: https://lp.uni-goettingen.de/get/image/1539)

$$n\,\lambda = 2\,d\,\sin\alpha$$

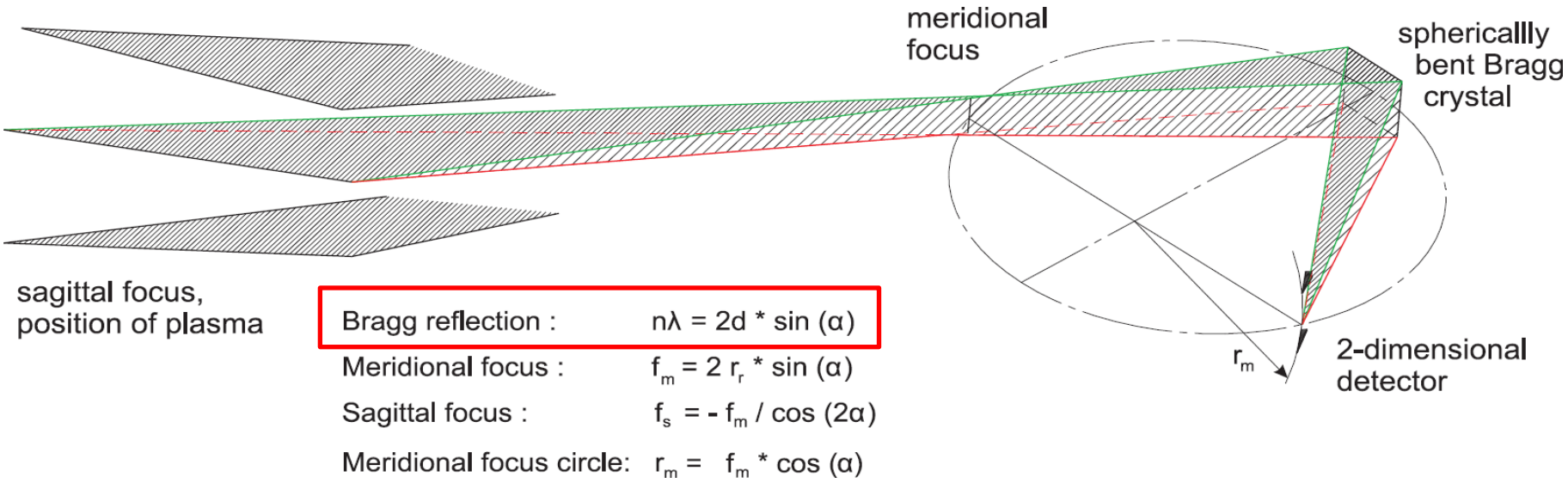
Advantages of Bragg crystal spectroscopy:

- Good reflectivity in the x-ray wavelength range
- Very high spectral resolution possible due to small distance of planes ***d***

# High-resolution x-ray spectroscopy (2)

(G. Bertschinger, O. Marchuk)

Bragg reflection in a perfect crystal can be used for wavelength separation:




| | |
|---|---|
| Bragg reflection : | $n\lambda = 2d * \sin(\alpha)$ |
| Meridional focus : | $f_m = 2\, r_r * \sin(\alpha)$ |
| Sagittal focus : | $f_s = - f_m / \cos(2\alpha)$ |
| Meridional focus circle: | $r_m = f_m * \cos(\alpha)$ |

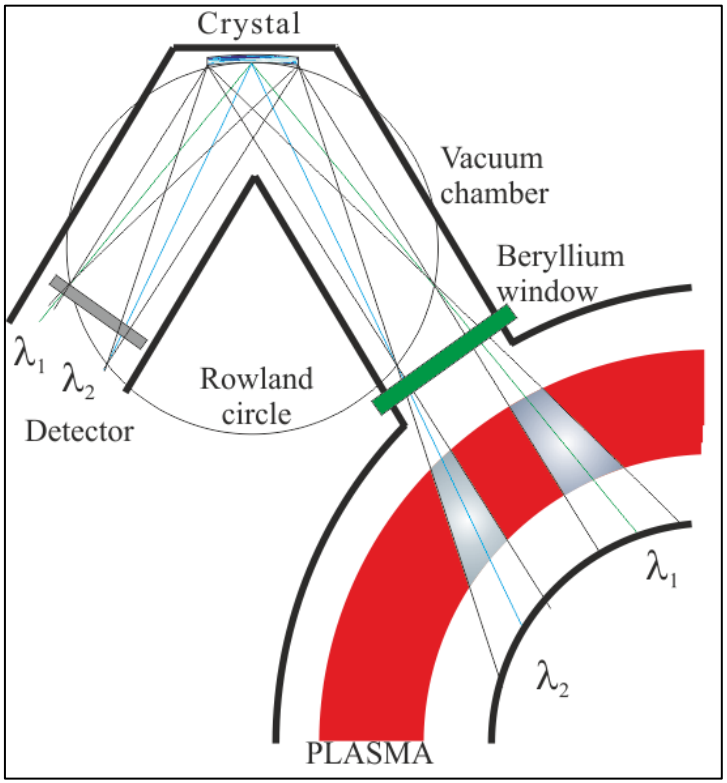
## Modified Johann spectrometer:

- Spherically bent crystal used to image the plasma light onto the 2-D detector (wavelength axis and radial coordinate)
- Spectral resolution governed by Bragg condition and by Rocking curve (crystal reflectivity as function of wavelength//angle)

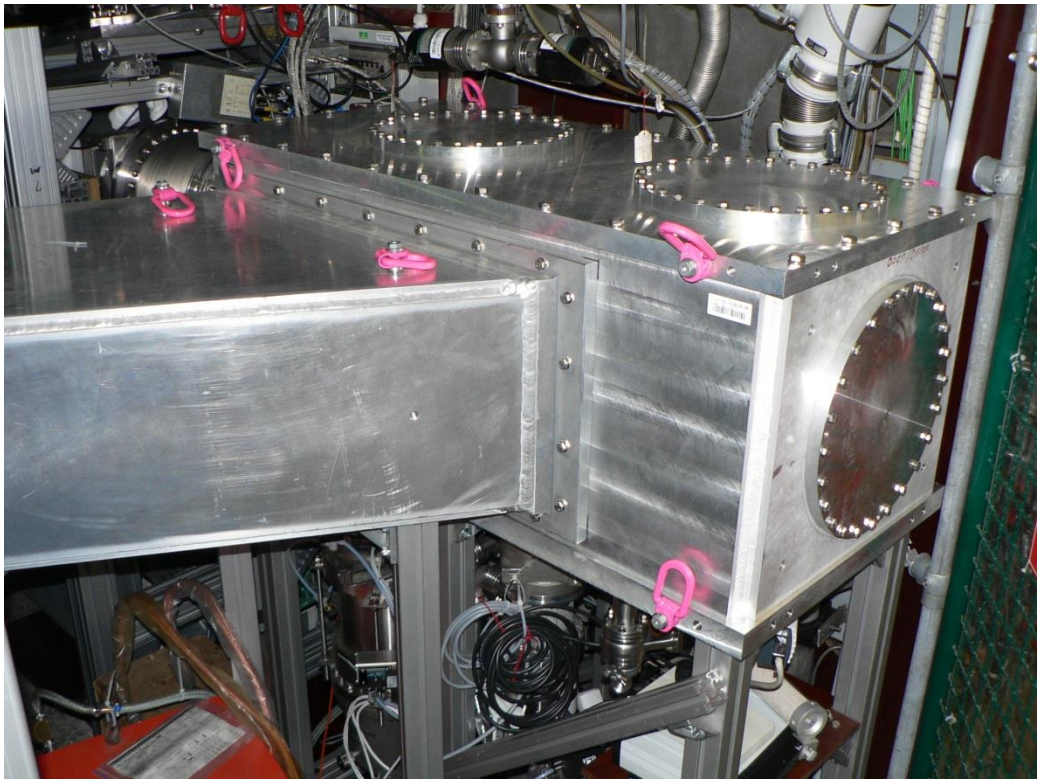
# Bragg spectrometer on TEXTOR / W7-X

(G. Bertschinger, O. Marchuk)

Principle:

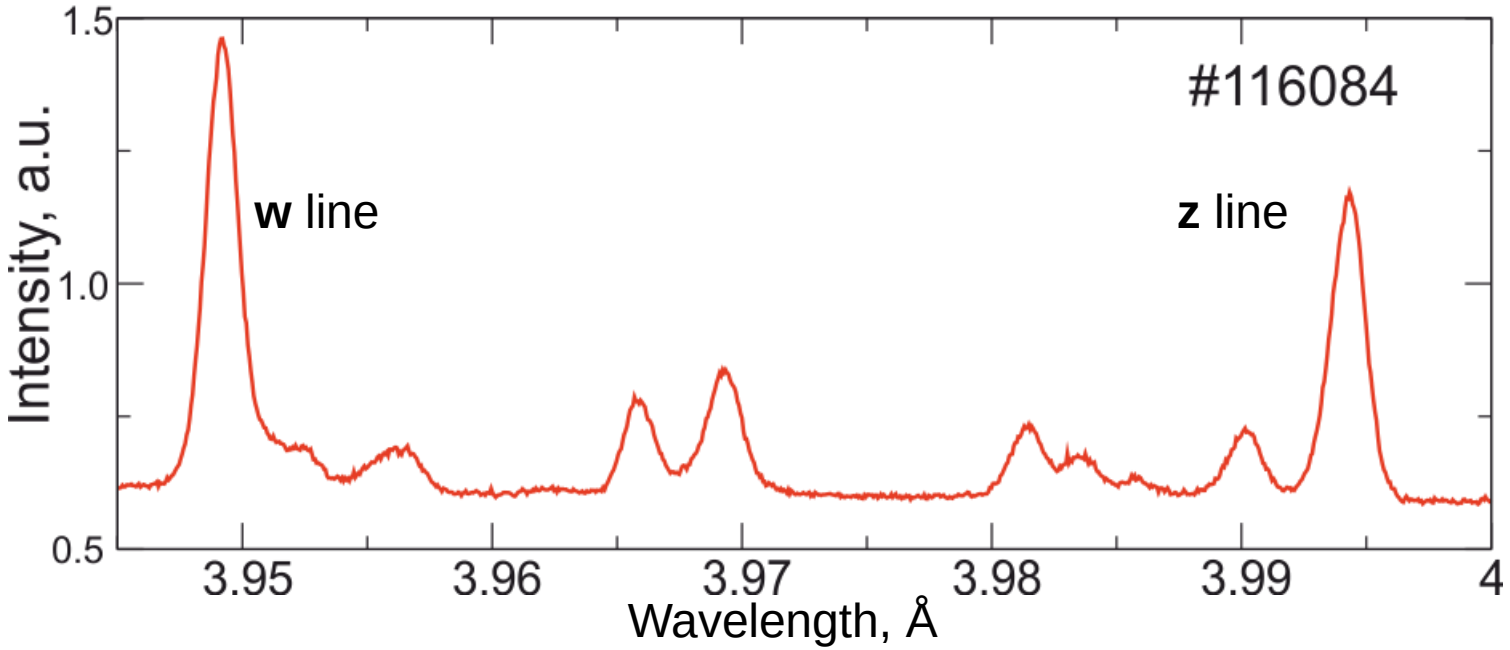



Bragg spectometer on TEXTOR (2008):



# Example for x-ray spectra: He-like Argon ($Ar^{16+}$)

(G. Bertschinger, O. Marchuk)




- The He-like x-ray spectrum consists of several components, which are excited via different processes
- The ion temperature can be derived from Doppler broadening
- The electron temperature can be obtained from line intensity ratios

# Charge exchange recombination spectroscopy

Process:

$$I^{z+} + A(n) \rightarrow I^{(z-1)+*}(n,l) + A^{+}$$

FWHM

$$T_i = \frac{m_i}{k_B}\left(\frac{c\lambda_w}{\lambda_0\sqrt{8\ln 2}}\right)^2$$

**Ion temperature**

Line shift:

$$v_{rot} = -c\frac{\Delta\lambda_{rot}}{\lambda_0}$$

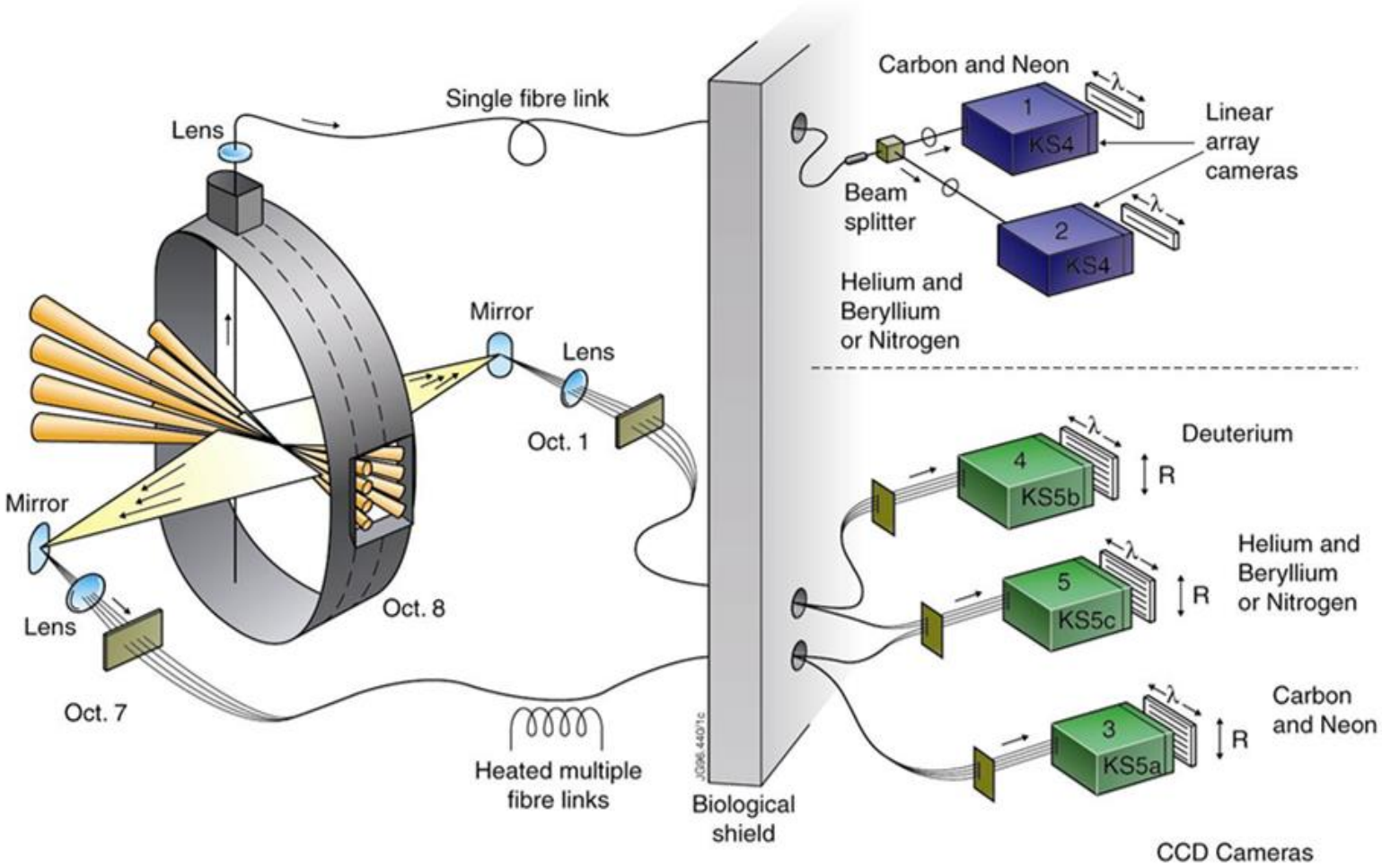
**Rotation**

integral

$$\phi = \frac{1}{4\pi}\int n_{I^{z+}} n_{beam}\langle\sigma_{em} v_{beam}\rangle d\ell$$

**Impurity density**

# Core CXRS diagnostic at JET

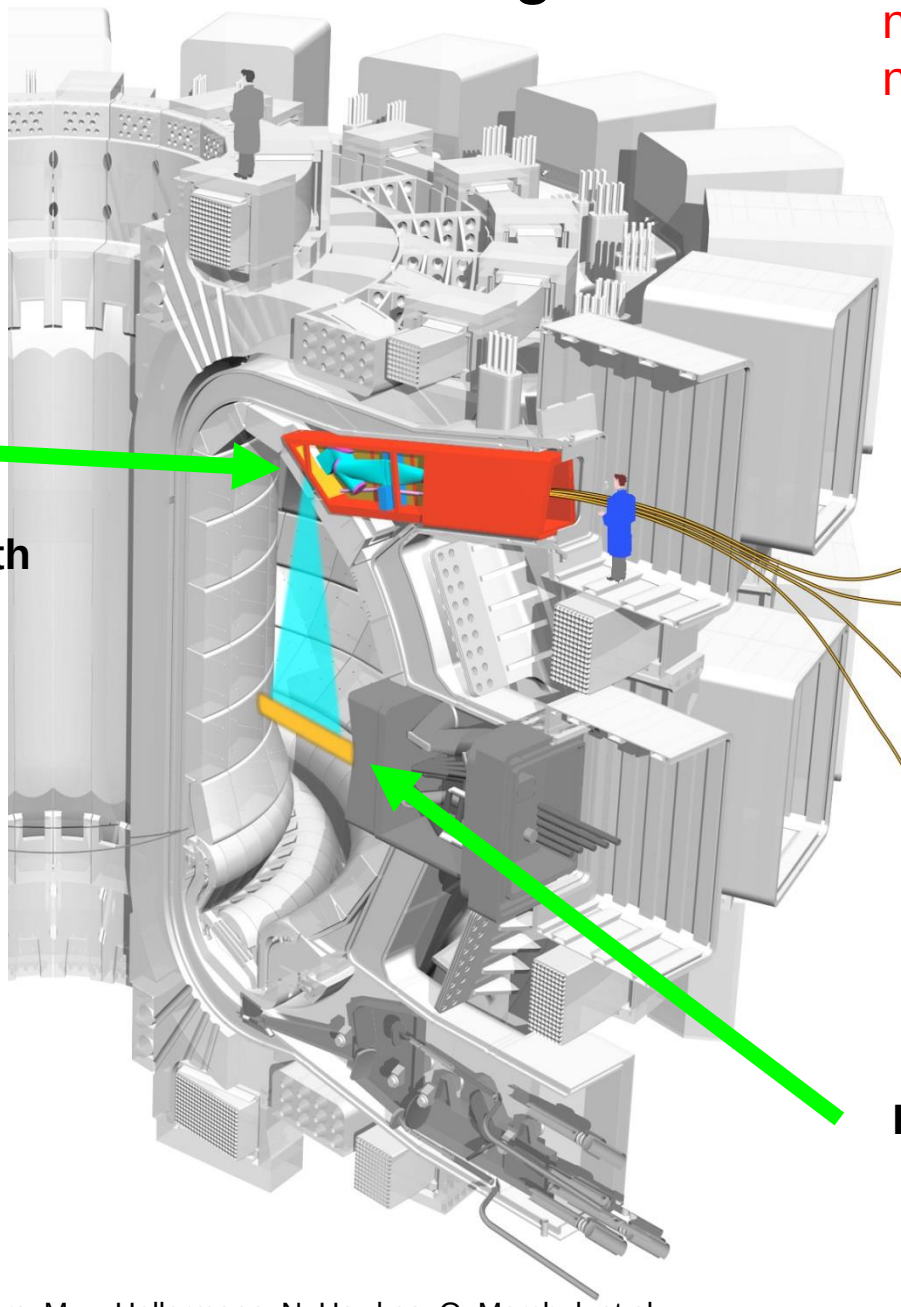



Courtesy: Carine Giroud

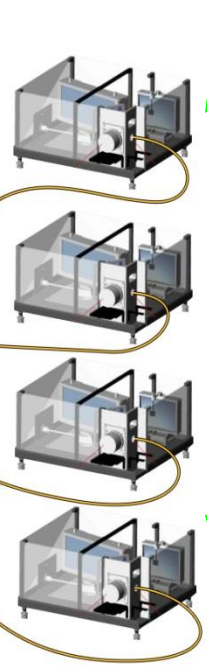
# ITER core CXRS diagnostics

$$H(E) + He^{2+} \rightarrow H^{+}(E) + He^{+*}$$

Measurement of
$n_{He}$, $T_i$, $v_{rot}$, $Z_{eff}$,
$n_{Be}$, ***B***, D/T



**CXRS spectrometers**



**CXRS port plug with mirror labyrinth**

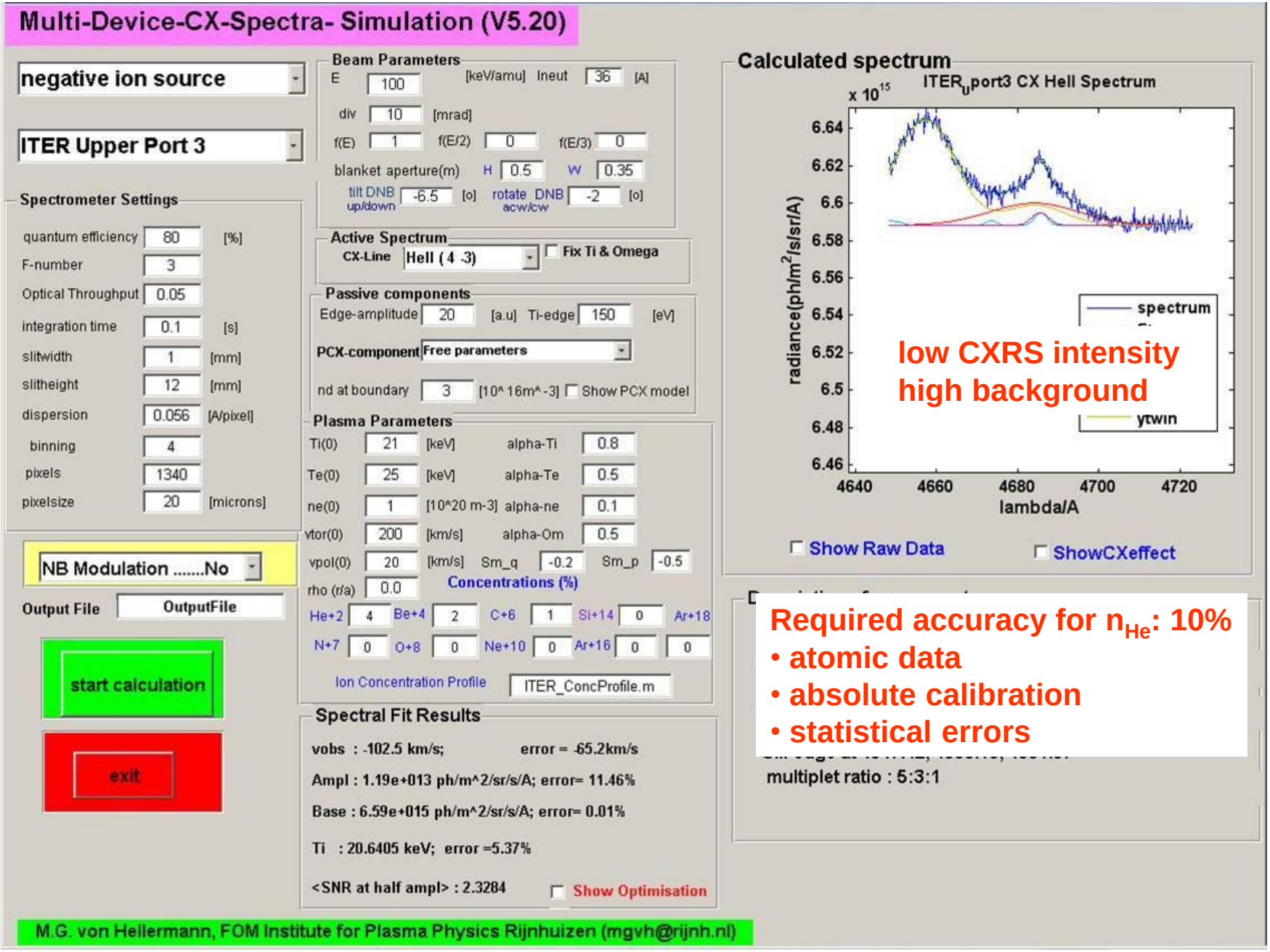
**....**

**Hydrogen Injector (100 keV)**

Ph. Mertens, W. Biel, R. Jaspers, M. v. Hellermann, N. Hawkes, O. Marchuk et al.

# ITER CXRS: spectra modelling

M. v. Hellermann et al.

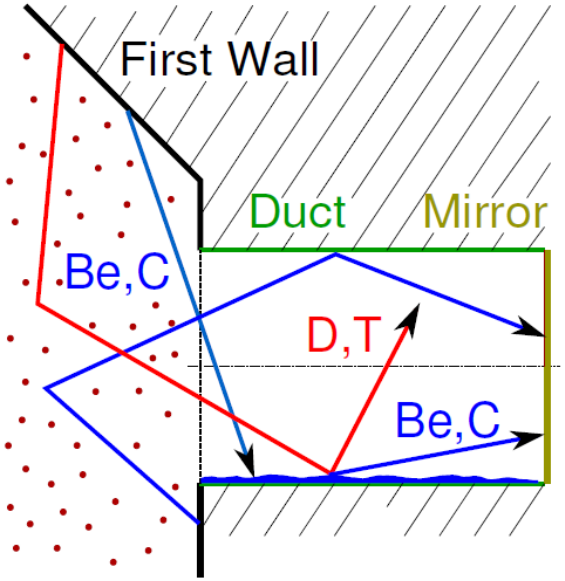


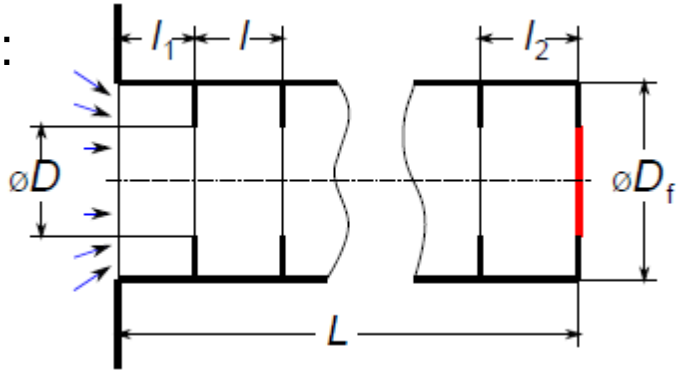
# Modelling of first mirror erosion and deposition

(V. Kotov, FZJ)

Neutral particle and ion fluxes for hydrogen isotopes and impurities are modelled using the B2-EIRENE code package.

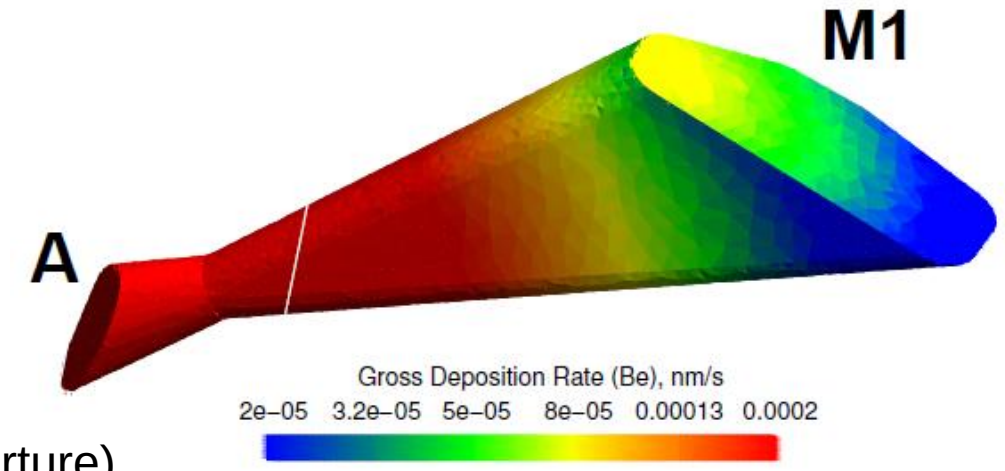
Principle geometry (with baffles):



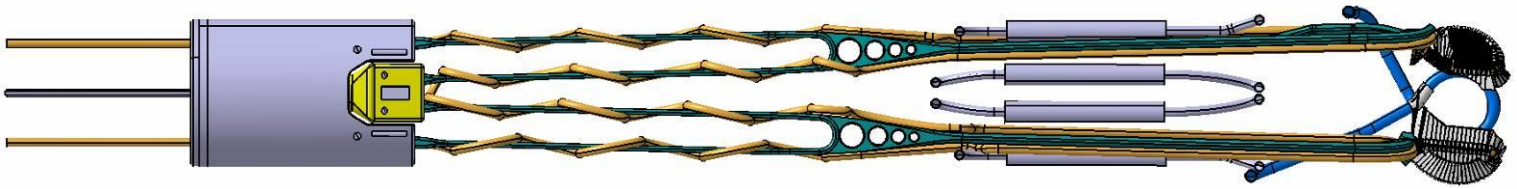




(aperture)

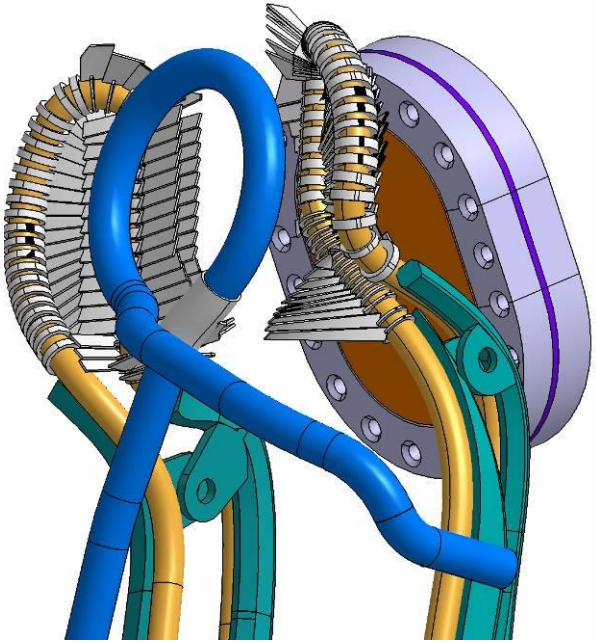
(first mirror)

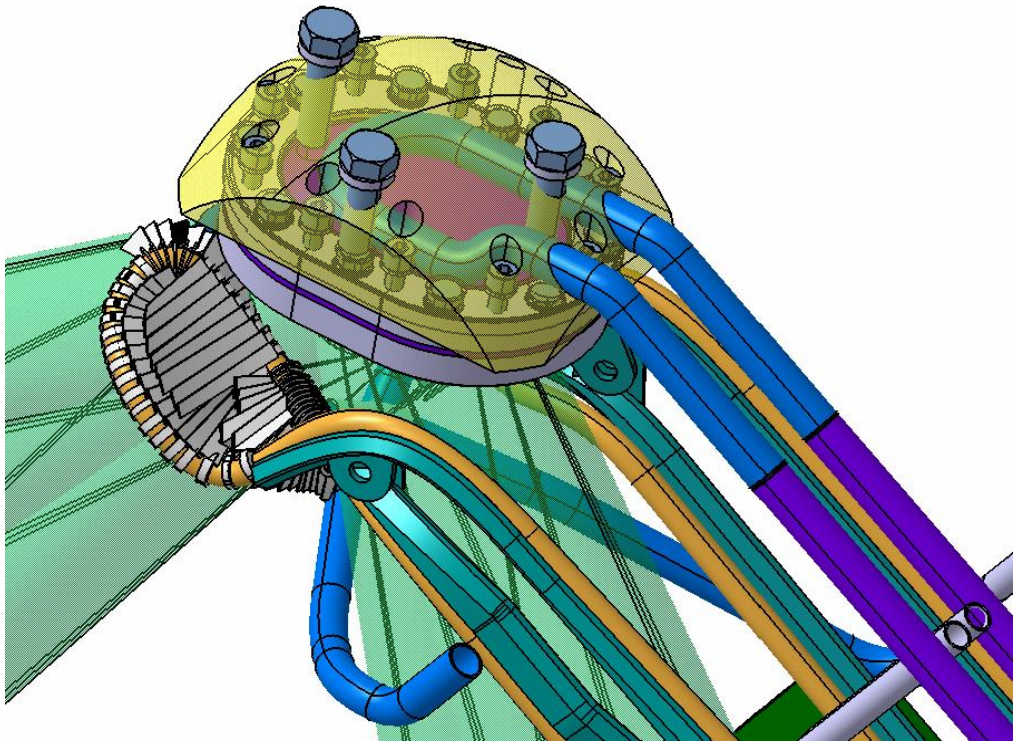


# ITER core CXRS: development of a fast shutter



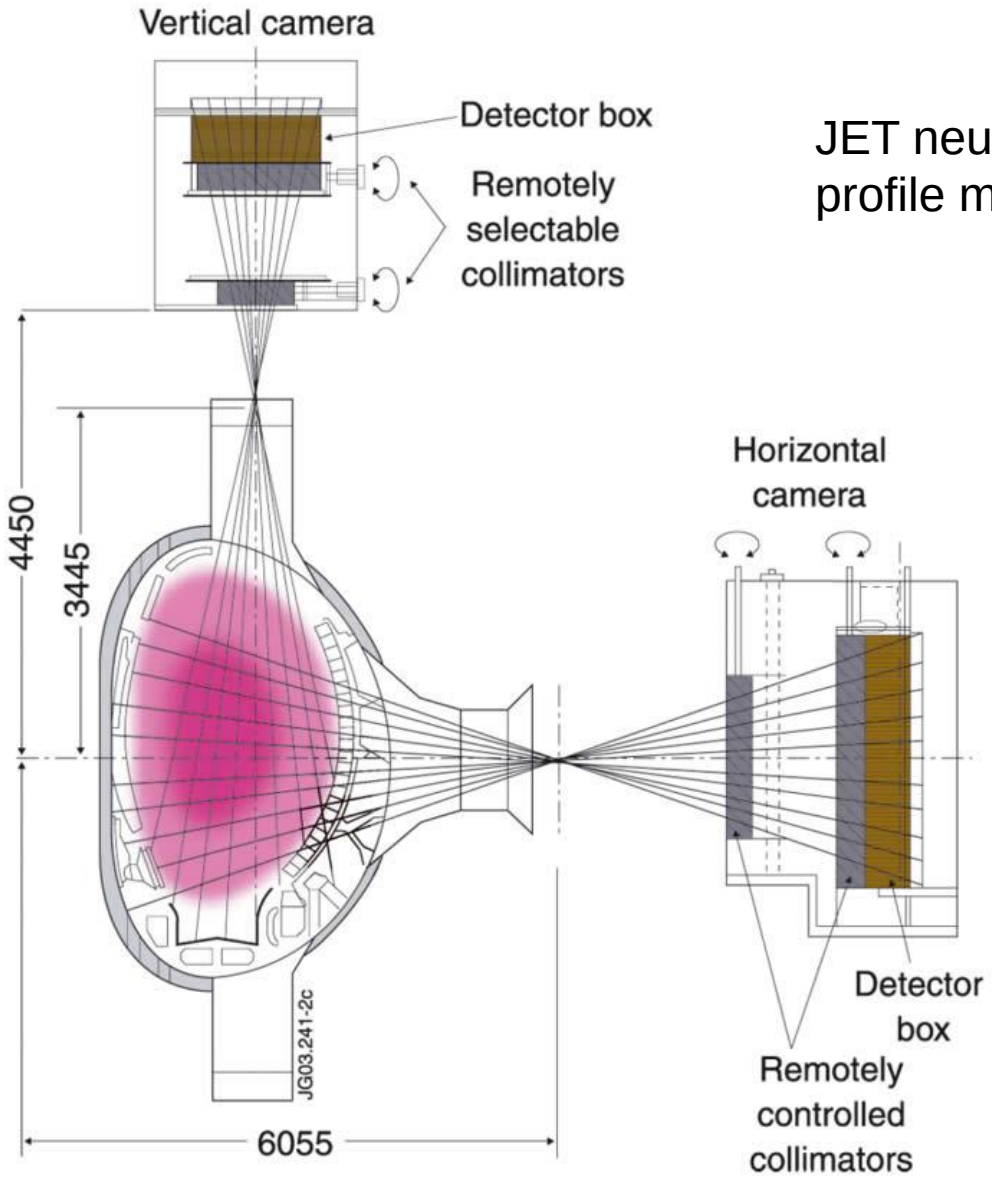
shutter with flaps and actuator





mirror 1 attachment with thermal conditioning loops, shutter flaps and alignment screws

# Passive diagnostics: example of neutron detection
## w/o probing beams or lasers



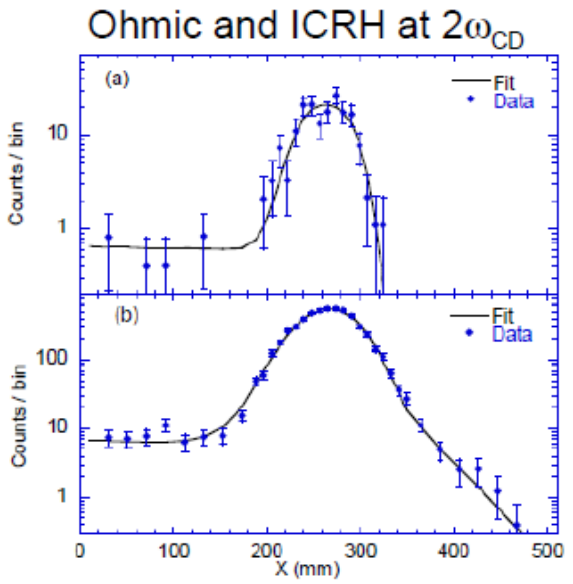

JET neutron / gamma profile monitor

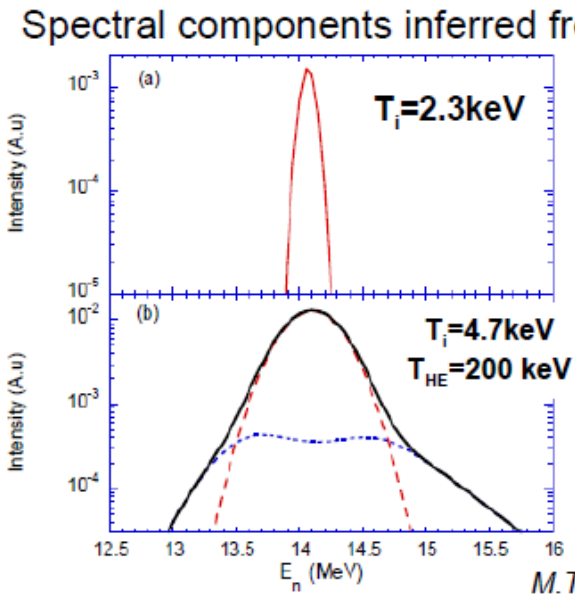
Allows measurement of:

- fusion power density
- n, Ti profiles
- Ti from neutron spectra

# Neutron spectroscopy of DT plasmas

(M. Tardocchi et al.)

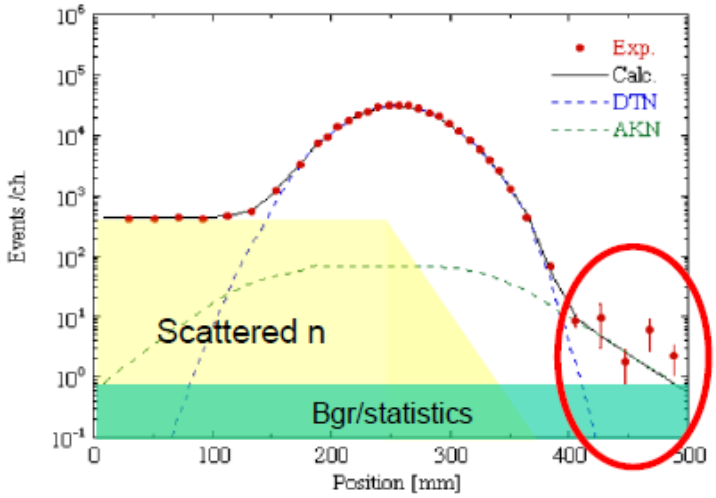



**Measure tail temperature of fast D**

*M.Tardocchi, PhD thesis,Uppsala (2000)*

## Alpha heating in DT; MPR 1997




Alpha knock-on signatures in the neutron spectrum
Weak component

**Measure fusion α.**

*J. Kaellne et al, PRL 85(2000)1246*

# Two ways of categorisation of plasma diagnostics:

- A) Technical goals of plasma dianostics:
  - *Protection of the fusion reactor and its components*
    - e.g. distance between plasma and first wall, wall temperature, fusion power
  - *Control and optimisation of the plasma properties*
    - e.g. plasma shape, plasma position, plasma current, plasma density, impurity concentrations, radial distributions of plasma quantities
  - *Plasma physics studies (obtain data to be used for as basis for concept improvements)*
    - All plasma quantities

- B) Diagnostic methods / measurement principles:
  - *Magnetic measurements*
  - *Neutron and gamma diagnostics*
  - *Optical / IR diagnostics*
  - *Bolometric diagnostics*
  - *Spectroscopic techniques*
  - *Microwave diagnostics*
  - *Plasma-facing components and operational diagnostics*

# Outline of a control concept for a fusion reactor

| No. | Control function | Relevance / operational limits | DEMO1 | DEMO2 |
|---|---|---|---|---|
| **1.** | Plasma current, position and shape control | | | |
| 1.1. | Plasma current | q95 limit | Global | Profile |
| 1.2. | Gaps (LCFS position at a number of poloidal locations) and divertor strike points | Wall loads | X | X |
| 1.3. | Vertical stability | Wall loads / disruption avoidance | X | X |
| **2.** | Kinetic control | | | |
| 2.1. | Core density | Density limit | Global | Profile |
| 2.2. | Fusion power | Wall load | X | X |
| **3.** | Exhaust control | | | |
| 3.1. | Core radiation | Radiation limit / H mode threshold | X | X |
| 3.2. | $P_{SOL} > P_{LH}$; edge radiation | H mode threshold / Divertor loads | X | X |
| 3.3. | First wall loads | 1st wall loads | X | X |
| 3.4. | Divertor radiation and detachment control | Radiation limit / Divertor loads | X | X |
| 3.5. | Divertor target peak loads + temperatures | Divertor loads | X | X |
| **4.** | MHD control | | | |
| 4.1. | Sawtooth instability | Confinement / disruption avoidance | X | X |
| 4.2. | Neoclassical tearing modes | Confinement / disruption avoidance | X | X |
| 4.3. | Locked modes | Confinement / disruption avoidance | X | X |
| 4.4. | Edge localised modes | Confinement / disruption avoidance | X | X |
| 4.5. | Beta limit | Confinement / disruption avoidance | n.a. | X |
| **5.** | Event handling | | | |
| 5.1. | Impurity release | Radiation limit / wall loads | X | X |
| 5.2. | Control failure | Disruption avoidance/mitigation | X | X |
| 5.3. | Disruption mitigation | Limitation of machine damage | X | X |
| 5.4. | Runaway electron occurrence | Limitation of machine damage | X | X |

# Candidate diagnostic systems for DEMO (1)

## Diagnostics which are most likely feasible:

- Microwave diagnostics (reflectometry, ECE)
  - *Measurements:* *$n_e$ (gradient region), $T_e$, plasma position and shape, instabilities*
  - *Characteristics:* *mm waves, robust front-end (horn antenna + metallic waveguide)*
  - *Problems:* *location and shape of antennae might need to be adapted to optimisation of TBR and to maximisation of lifetime, reducing gain and signal quality*
- Polarimetry/interferometry
  - *Measurements:* *$n_e$ (plasma core)*
  - *Characteristics:* *far infrared radiation (0.1 mm waves), retro-reflectors deep in blanket (?)*
  - *Problems:* *large beam diametre, beam duct requiring blanket modification*
- Neutron + gamma diagnostics
  - *Measurements:* *fusion power density, contribute to n + $T_i$ profiles, $T_i$ from neutron spectra*
  - *Characteristics:* *need only tube-like access, detectors can be placed behind the shield*
  - *Problems:* *difficult analysis of data (variety of processes, neutron scattering)*
- Plasma radiation / spectroscopy
  - *Measurements:* *impurity composition ($Z_{eff}$), $P_{rad}$, divertor thermography, $T_i$ (?), $v_{rot}$ (?)*
  - *Characteristics:* *tube-like access, first mirror behind blanket*
  - *Problems:* *Low etendue, low coverage, low performance*

Feasible
Low performance
Critical

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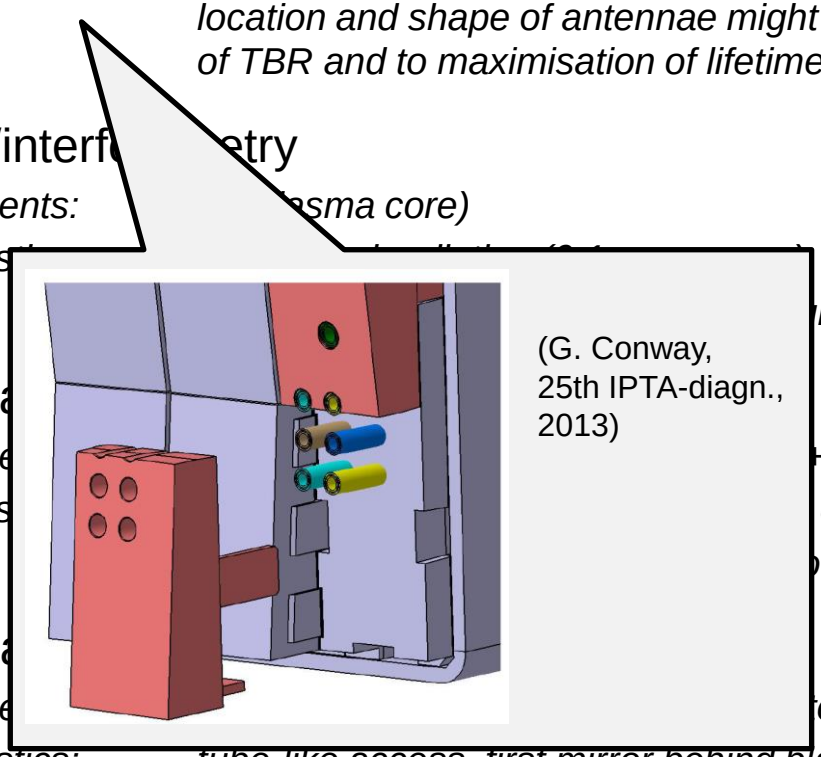

(G. Conway, 25th IPTA-diagn., 2013)

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Low performance
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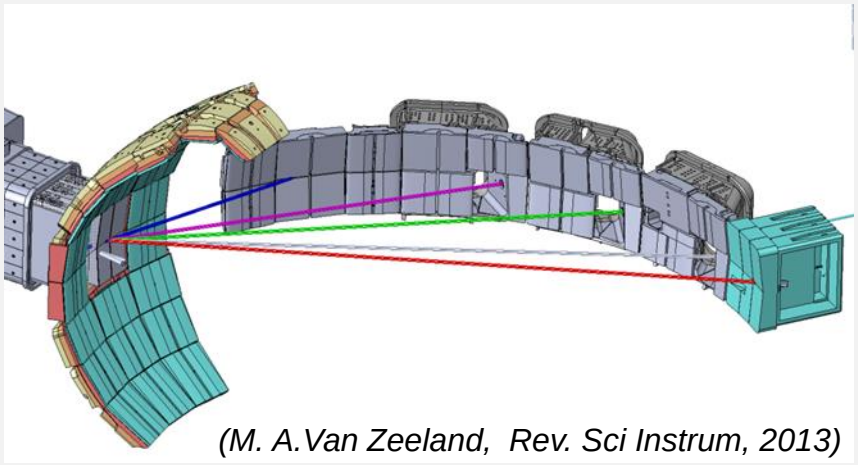

*(M. A.Van Zeeland, Rev. Sci Instrum, 2013)*

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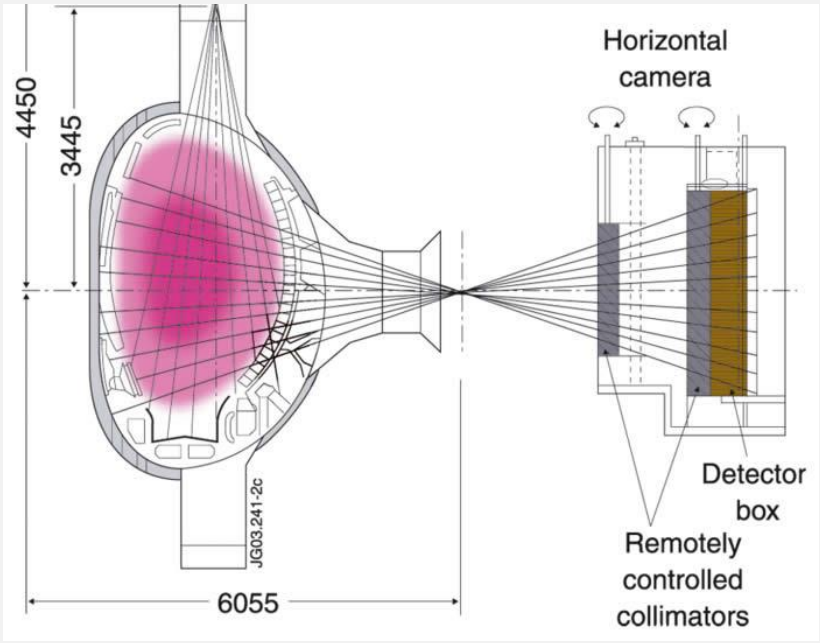
  - *Measurements*
  - *Characteristics*
  - *Problems:*

*stabilities*
*waveguide)*
*pted to optimisation*
*and signal quality*

- Polarimetry/
  - *Measure*
  - *Charac tics*
  - *Proble s:*

*deep in blanket (?)*
*dification*




*(JET neutron camera)*

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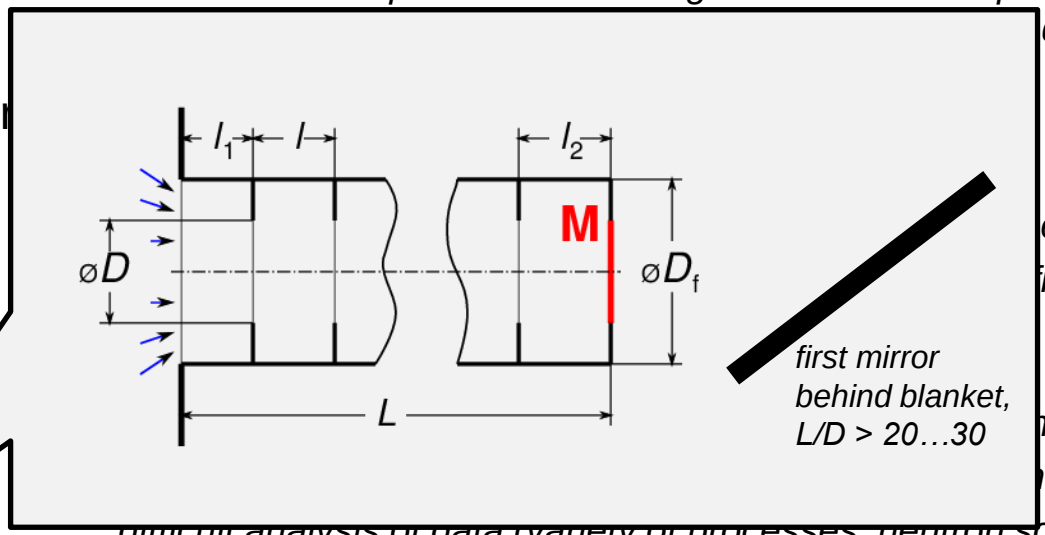


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  - *Measurements: impurity composition (*$Z_{eff}$*),* $P_{rad}$*, divertor thermography,* $T_i$ *(?),* $v_{rot}$ *(?)*
  - *Characteristics: tube-like access, first mirror behind blanket*
  - *Problems: Low etendue, low coverage, low performance*

Feasible
Low performance
Critical

# Candidate diagnostic systems for DEMO (2)

## Diagnostics which are most likely feasible:

- Magnetic diagnostics
  - *Measurements:* $U_{Loop}$, $I_p$, $E_{Dia}$, *(plasma position and shape?)*
  - *Characteristics:* *Magnetic sensors behind blanket/shield, Hall probes behind shield*
  - *Problems:* *Low time resolution, long integration time*
- FW and divertor …lant temperature, flow and pressure
  - *Measurements:* …solute measurement of thermal power
  - *Characteristics:* …rs outside the tokamak
  - *Problems:*
- Current dens… …target plates
  - *Measureme…*
  - *Characteris… …, measurement of current + voltage*
  - *Problems:* …*divertor load requirements (?)*
- Measuremer… …exhaust
  - *Measureme… …xhaust gas composition*
  - *Characteris…*
  - *Problems:* *slow and indirect*

(typical pick-up coil)

(metallic Hall sensor prototype, I. Duran et al.)

(A. Kallenbach et al., PPCF 2010)

Feasible
Low performance
Critical

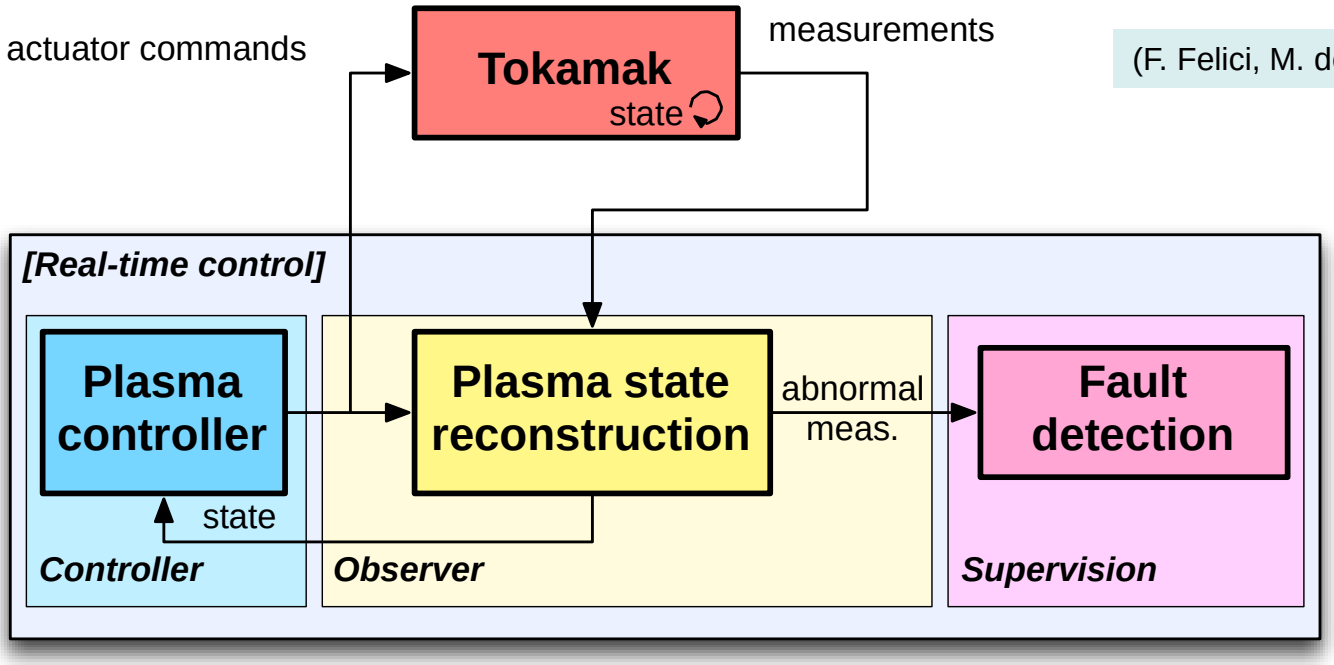
# Candidate diagnostic systems for DEMO (2)

## Diagnostics which are most likely feasible:

- Magnetic diagnostics
  - *Measurements:* $U_{Loop}$, $I_p$, $E_{Dia}$, *(plasma position and shape?)*
  - *Characteristics:* *Magnetic sensors behind blanket/shield, Hall probes behind shield*
  - *Problems:* *Low time resolution, long integration time*
- FW and divertor coolant temperature, flow and pressure
  - *Measurements:* *absolute measurement of thermal power*
  - *Characteristics:* *sensors outside the tokamak*
  - *Problems:* *slow and low spatial resolution*
- Current density / voltage measurement at divertor target plates
  - *Measurements:* *Perspective for detachment control* (A. Kallenbach et al., PPCF 2010)
  - *Characteristics:* *isolated mounting of divertor modules, measurement of current + voltage*
  - *Problems:* *divertor scenario // compatibility with divertor load requirements (?)*
- Measurement of gas/beam/pellet fuelling and gas exhaust
  - *Measurements:* *Injected particles, neutral pressure, exhaust gas composition*
  - *Characteristics:* *sensors in remote positions*
  - *Problems:* *slow and indirect*

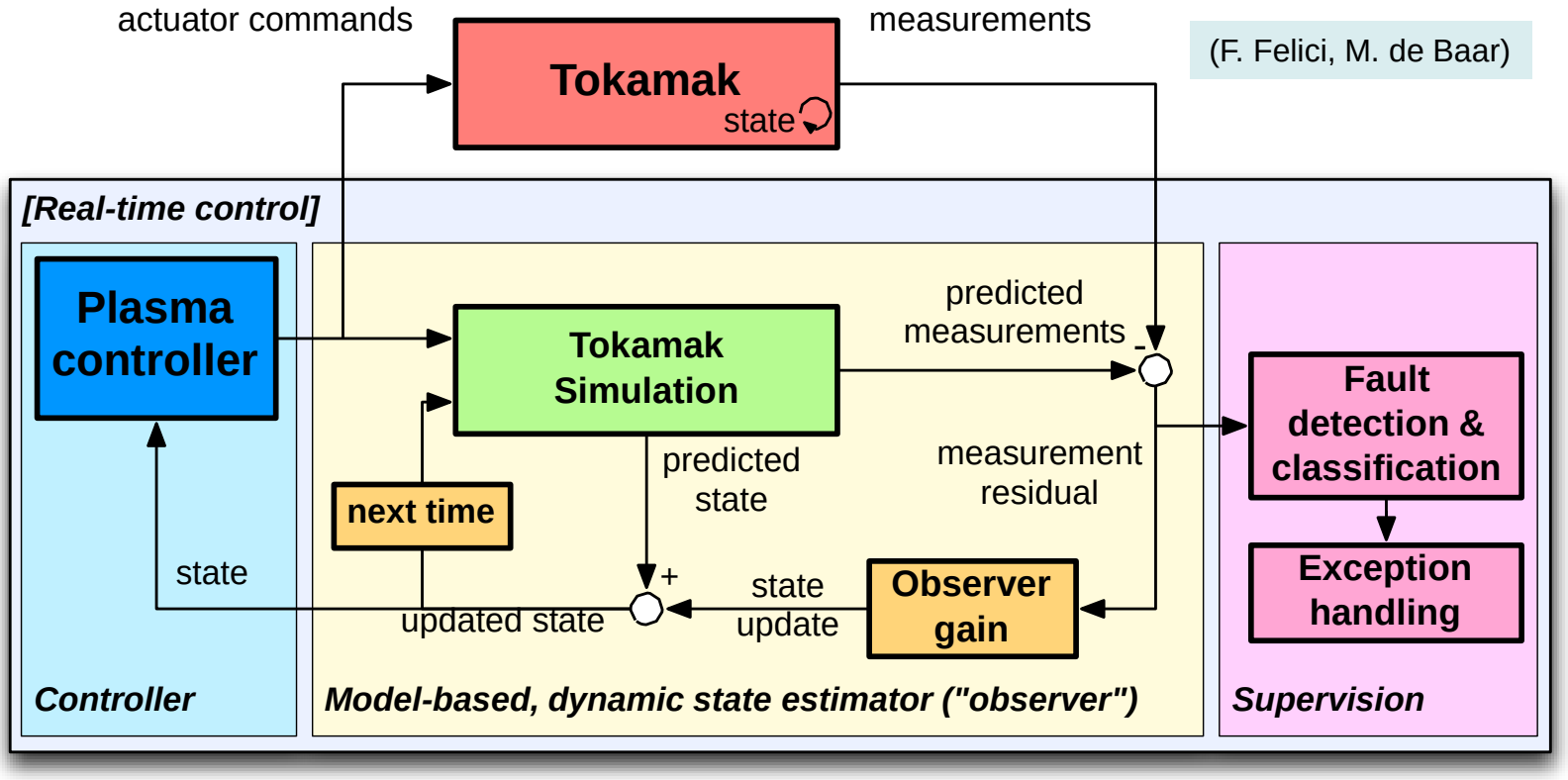
Feasible
Low performance
Critical

# Integrated plasma diagnostics processing & control




- Plasma controller: perform control actions based on full plasma state knowledge
- Plasma state reconstruction: derive plasma state by merging measurements from several diagnostics
- Fault detection: classify unexpected measurements (e.g. off-normal events, faulty signals)
- Diagnostic redundancy in number of channels and number of methods facilitates handling of faults (the better the model, the less measurements are needed)

# Dynamic observer for tokamak plasma state




- Run tokamak simulation in parallel with plasma evolution
- Correct simulated state estimate based on difference between predicted and true measurements
- Detection & classification of excessive discrepancies
- The plasma controller may initiate fast rampdown or disruption mitigation if a discrepancy cannot be resolved otherwise