Survey of plasma diagnostics in tokamaks

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Thanks for contributions of Vladimir Weinzettl & COMPASS team

Motto:

Any relevant physical results on tokamak plasma can be achieved only if plasma is well diagnosed !!!!

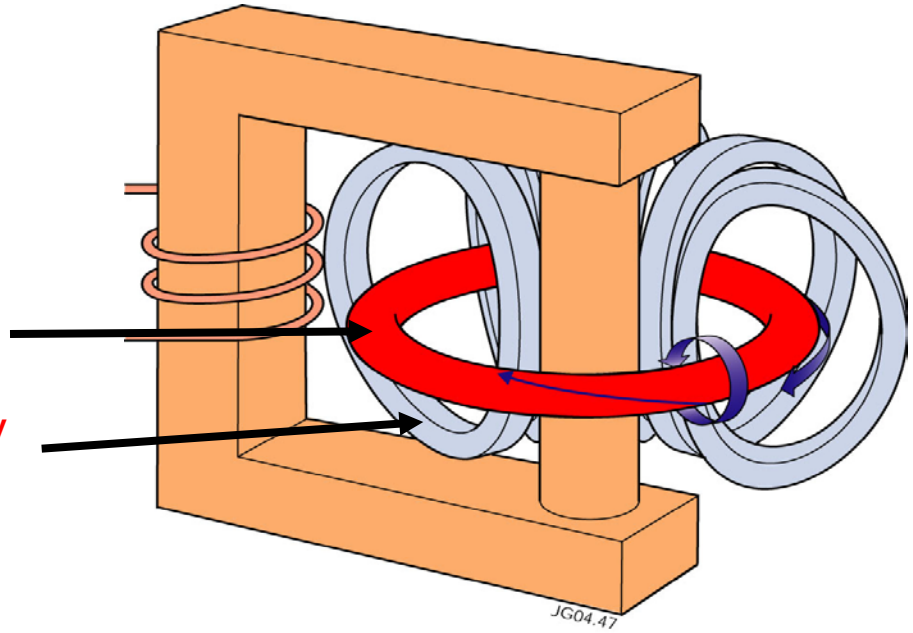
This lecture is based on description of the diagnostic complex on the COMPASS tokamak, which is operational at IPP Prague

Tokamak - basic principle

Tokamak, abbreviation from Russian: TOroidalnaya KAmera, s MAgnitnami Katushkami (means "toroidal vessel" with "magnetic coils")

Tokamak is composed of three basic components

- Large transformer
- Plasma ring as secondary winding
- Coils for confinement of plasma ring by magnetic field (toroidal solenoid)



Electric current I generated in the plasma ring by the transformer

- delivers the ohmic power $P_{ohmic} = I^2R_{plasma}$ to plasma (heating)
- generates the poloidal magnetic field in the plasma ring $B_{poloidal} \sim I/2\pi a$

REMEMBER! Because of the transformer, tokamak is pulse device

What to measure?

Radial profiles of the following quantities:

Electron density, ne	10^17 - 3 10^20 m^-3
Electron temperature, Te	a few eV – 20 keV
Ion temperature, Ti	a few eV – 20 keV
Effective ion charge, Zeff	

Toroidal magnetic field, Bt	up to 3-5 T
Plasma current, Ip	~ 0.1 kA – several MAmps
Loop voltage, Uloop	a few Volts
Plasma position (displacement), Δ_z, Δ _R	1 – 30 mm
Total energy stored in the plasma column W	up to several MJ
Energy confinement time, τ_E	1 ms – several seconds
Beta poloidal, beta_pol	
Line radiation (visible, VUV, IR)	
Brehmstralhung radiation	
Soft X Ray emission, SXR	
Hard X Ray emission, HXR	

Different diagnostic tools have to be used to measure the same quantity in the hot core of the plasma column and at the relatively cold plasma edge!

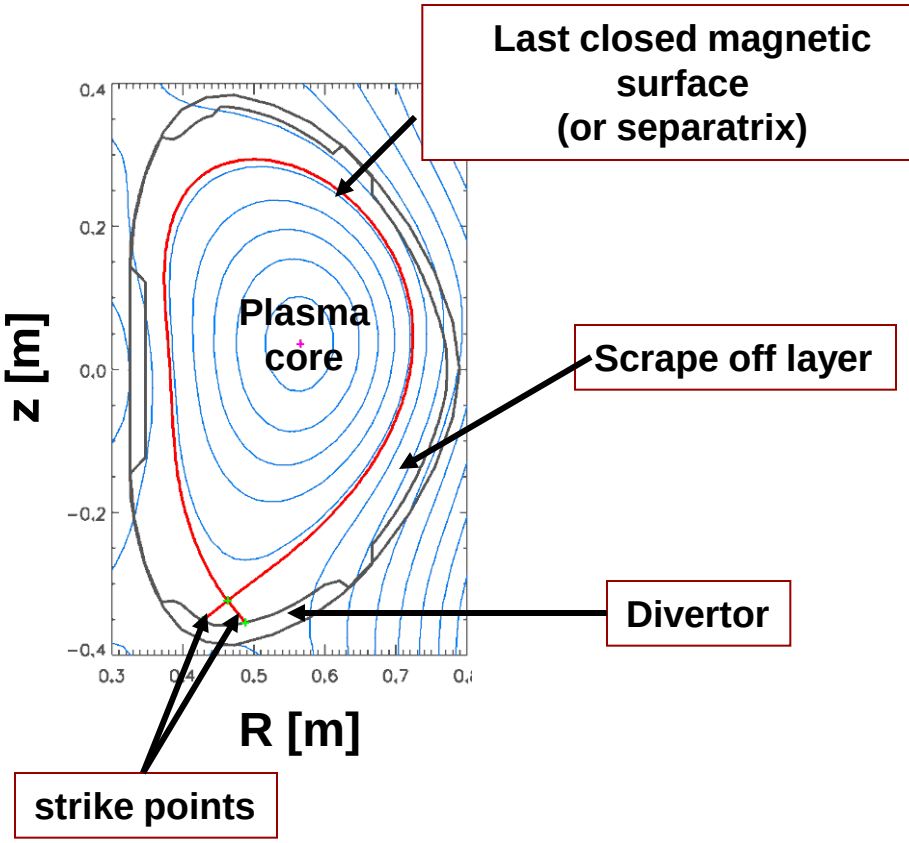
The COMPASS tokamak

Small size, but ITER relevant geometry & magnetic configuration

Originally in Culham Lab, operational at IPP Prague since 2009

Major radius [m]	0.56
Minor radius [m]	0.2
Plasma current [kA]	< 350
Magnetic field [T]	< 1.8 (2.1)
Triangularity	~ 0.4
Elongation	~ 1.8
Pulse length [s]	< 0.5
Working gas	H, D, (He)

Plasma cross section
circular, elongated, D-shape



COMPASS plasma

circular plasma (shaping coils off)

diverted plasma (shaping coils on)

Plasma current < 350 kA

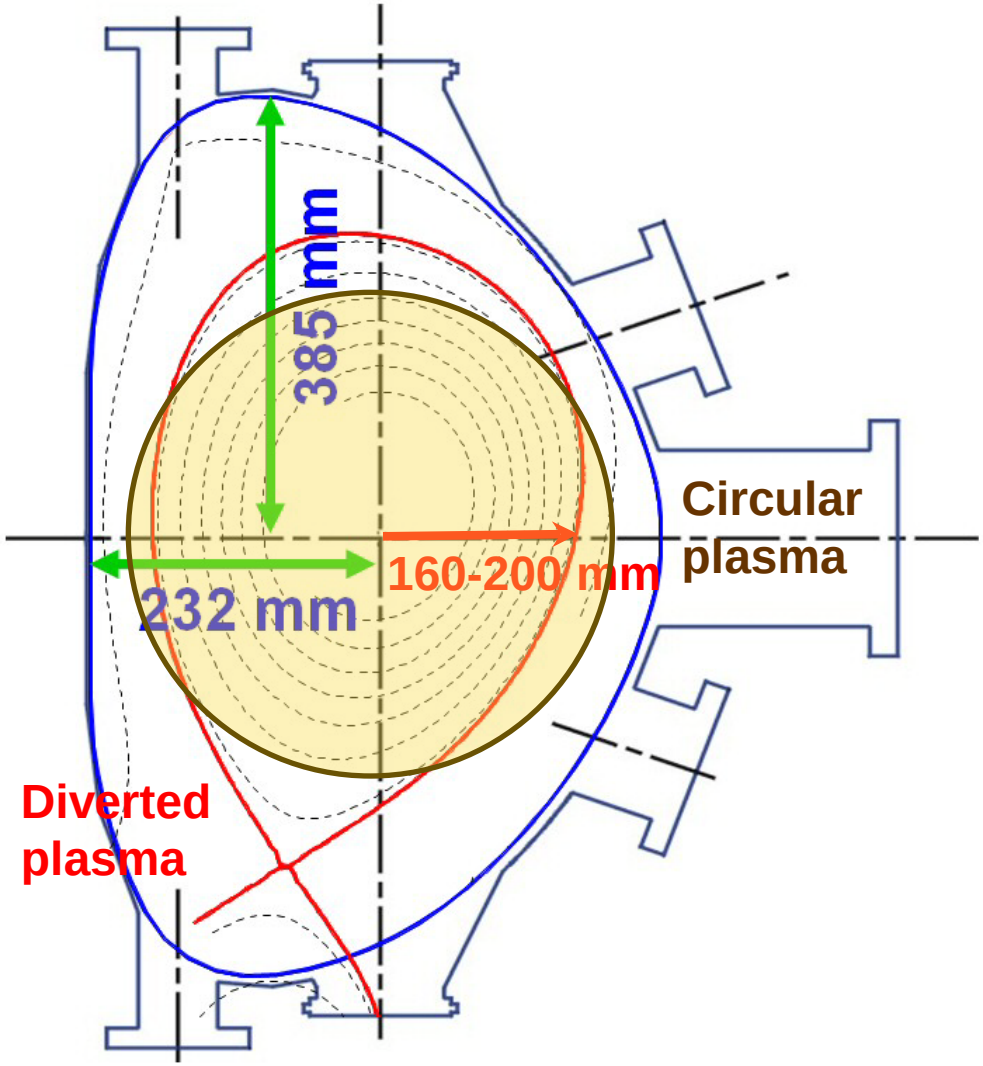
Pulse length < 0.5 ms

Central Density $<2*10^{20}$ m^{-3}

Central Electron Temperature < 1 keV

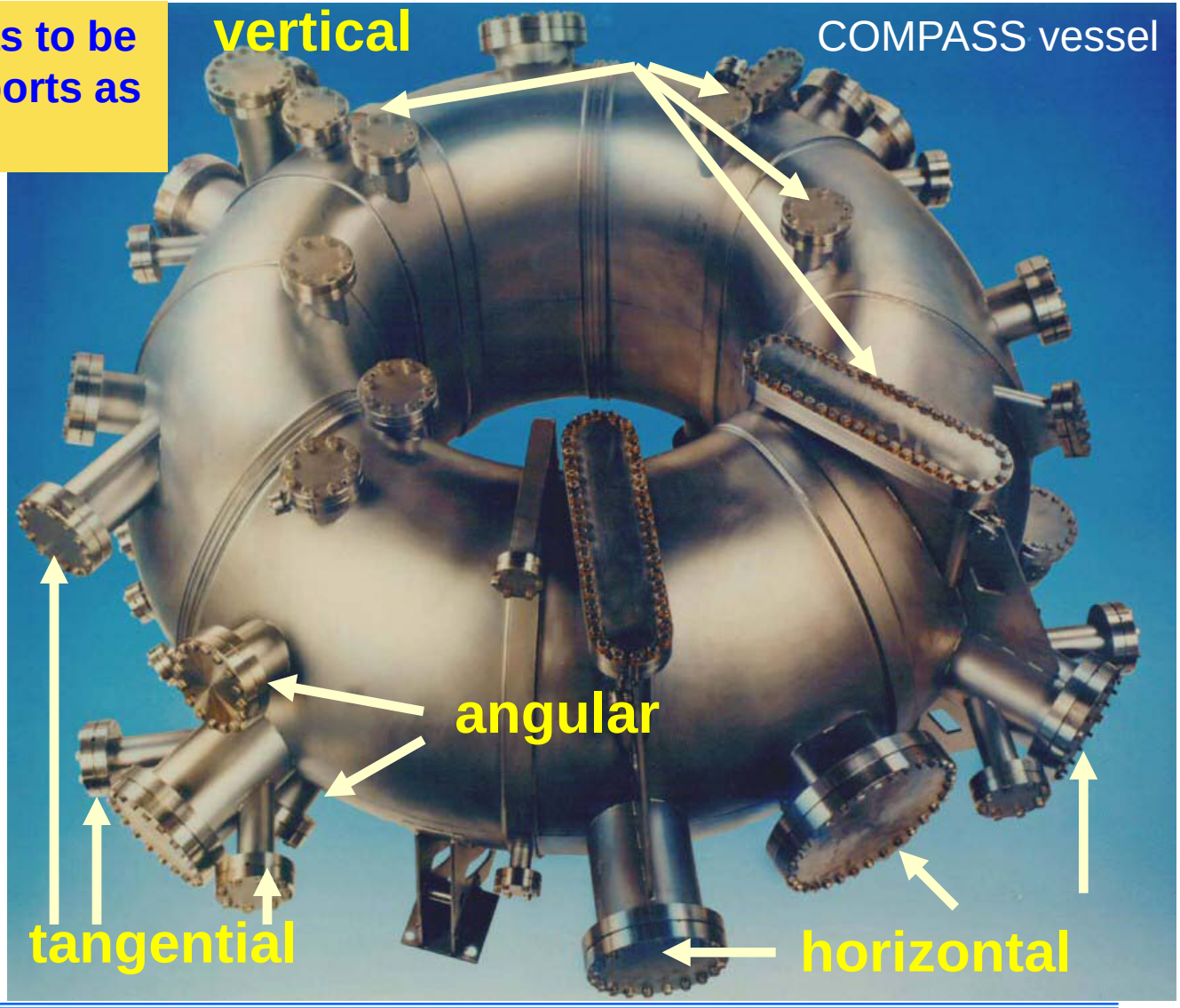
Any diagnostic complex on tokamaks has three main constrains :

1. Financial resourced available
2. Experienced staff
3. A number of diagnostic ports



Tokamak vessel with diagnostic ports

Any tokamak vessel has to be equipped by as many ports as possible - constrains



Example - COMPASS

D-shaped vessel

Major radius 0.56 m

Minor radius 0.23 m

Elongation b/a = 1.8

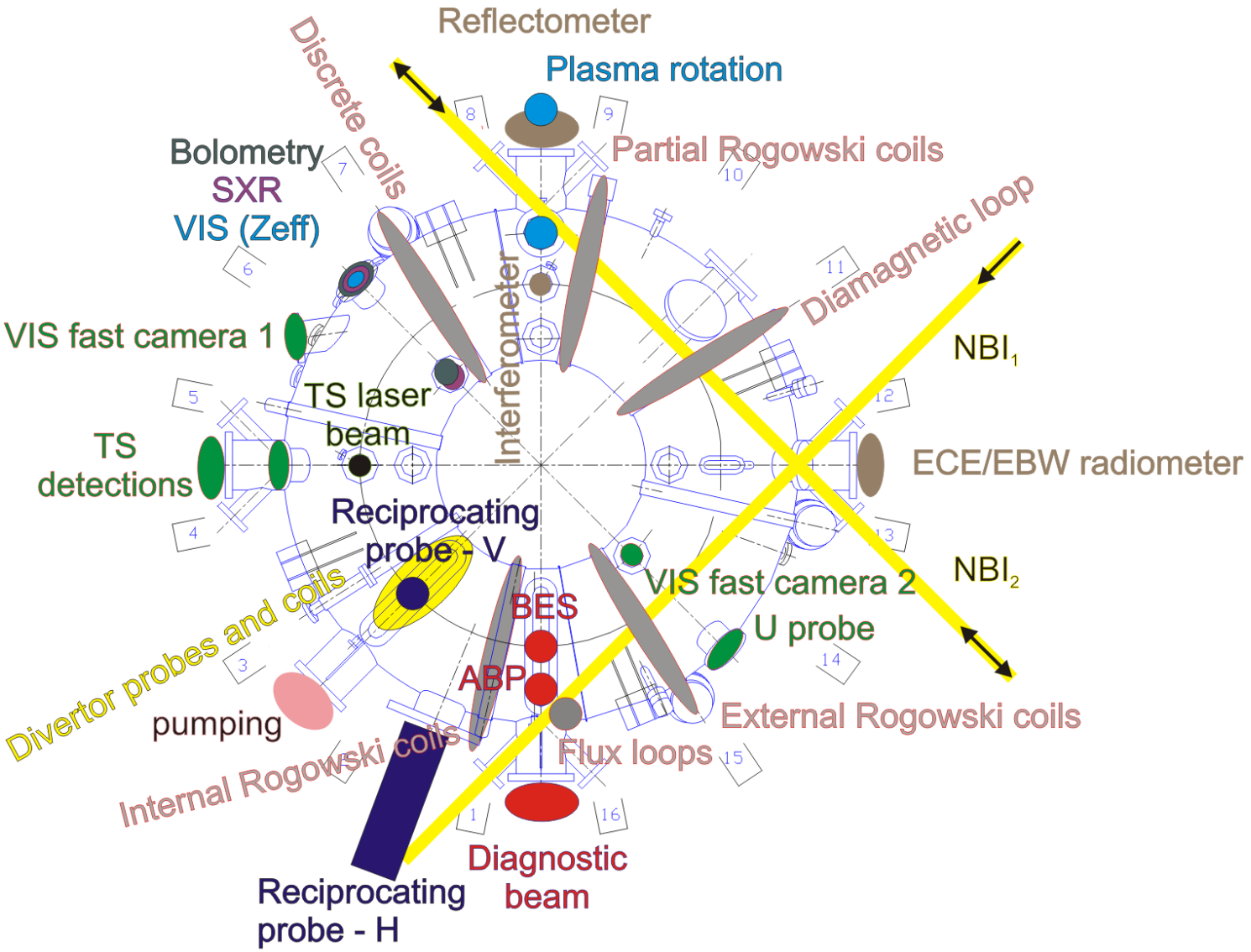
64 diagnostic ports

some of them are already occupied by pumping and additional plasma heating systems

Overview of diagnostic system on COMPASS

1. **Magnetic diagnostics**
   - Mirnov & Rogowski coils, flux loops, …
2. **Microwave diagnostics**
   - 2-mm interferometer
   - reflectometer
   - ECE radiometer
3. **Spectroscopic diagnostics**
   - Thomson scattering
   - Fast cameras
   - Hard X-rays
   - Visible light detection
   - Bolometry
   - Soft X-rays
   - Plasma rotation
4. **Beam & particle diagnostics**
   - Beam Emission Spectroscopy
   - Neutral Particle Analyzer
   - Neutron diagnostic (Deuterium plasmas with the NBI)
5. **Probe diagnostics**
   - Probe array in the divertor tile
   - Reciprocating probes

Layout of diagnostic complex



Magnetic diagnostics

440 coils for magnetic diagnostics

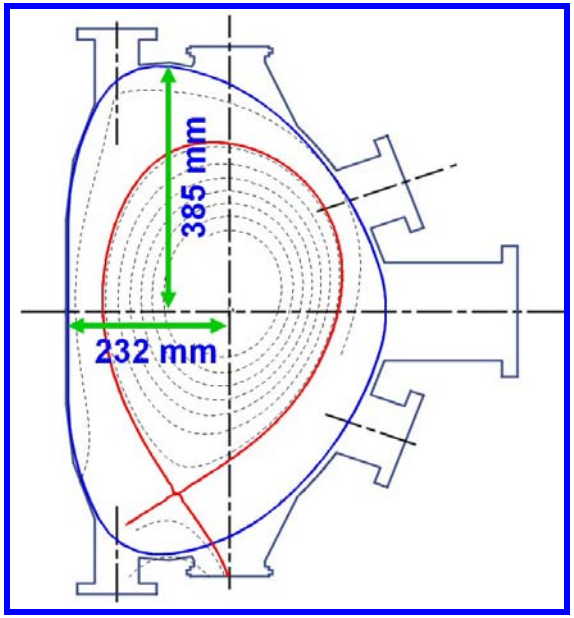
- 24 3D Mirnov coils – measure all three component of B
- External and Internal Rogowski coil – I_{plasma} and I_{vessel}
- 16 Internal Partial Rogowski coils – measure the local B_θ
- 8 flux loops – loop voltage
- 6 commercial Rogowski coils – to measure currents in poloidal field coils

Measurements of plasma current, loop voltage, plasma position, ...

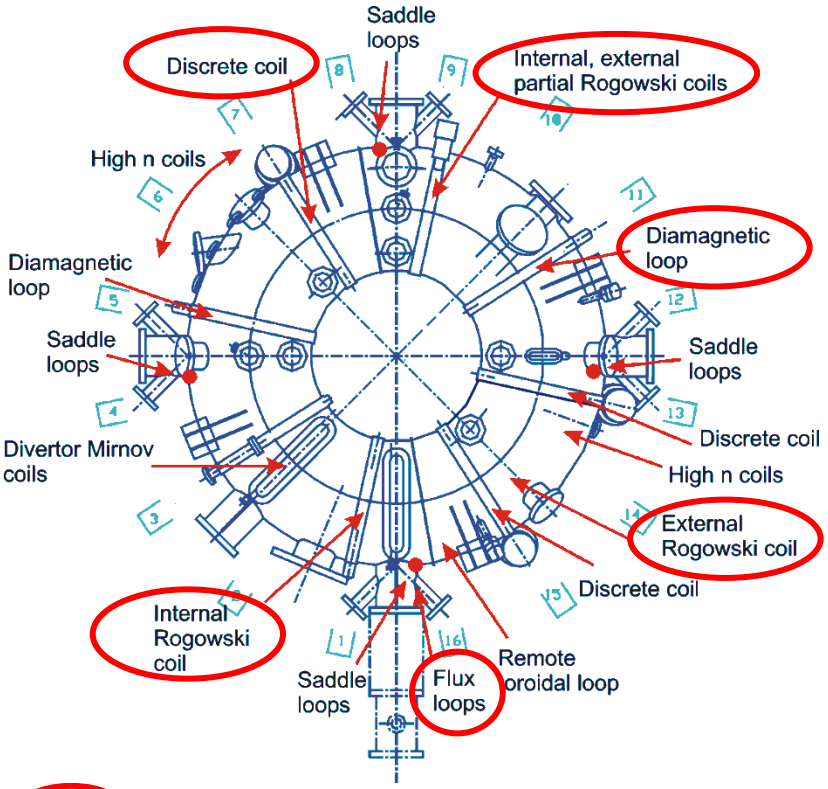
The most important is to perform the reconstruction of magnetic surfaces based on calculation of equilibrium

- 2D Coordinates of magnetic surfaces
- Position of separatrix, X point, strike points
- Total kinetic energy stored in plasma
- Poloidal beta
- And other ~ 30 important quantities

Equilibrium code EFIT – off line calculation with the temporal resolution 0.1 ms

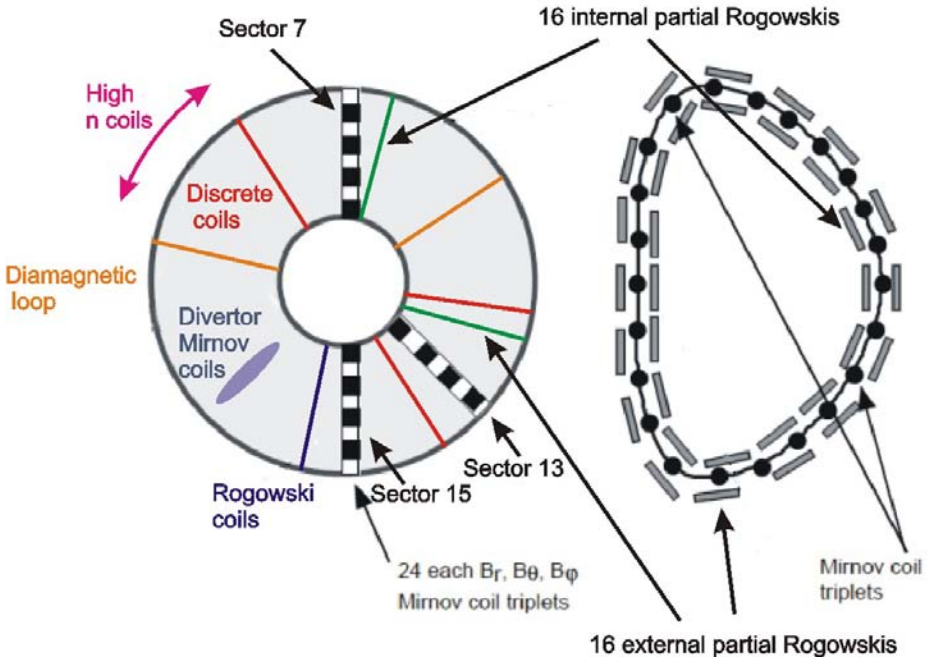


Magnetic diagnostics



. . . calibrated and routinely measured coils.

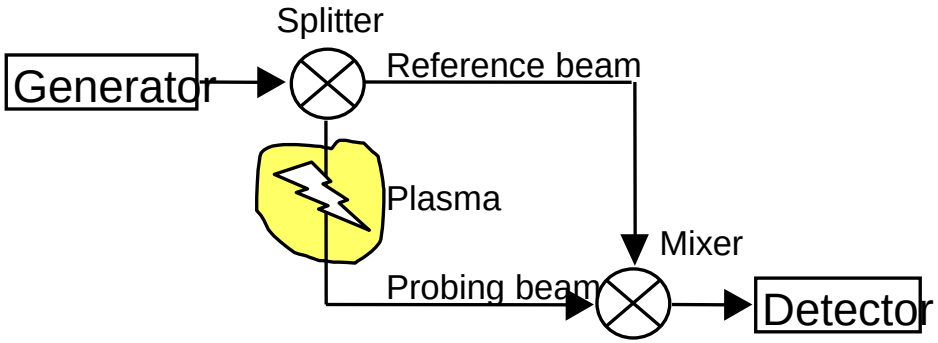
Magnetic sensors (coils and loops) distributed over the whole vessel (inside as well as outside) at several toroidal positions, because some phenomena are 3D (MHD instabilities, disruptions, …



Microwave diagnostics

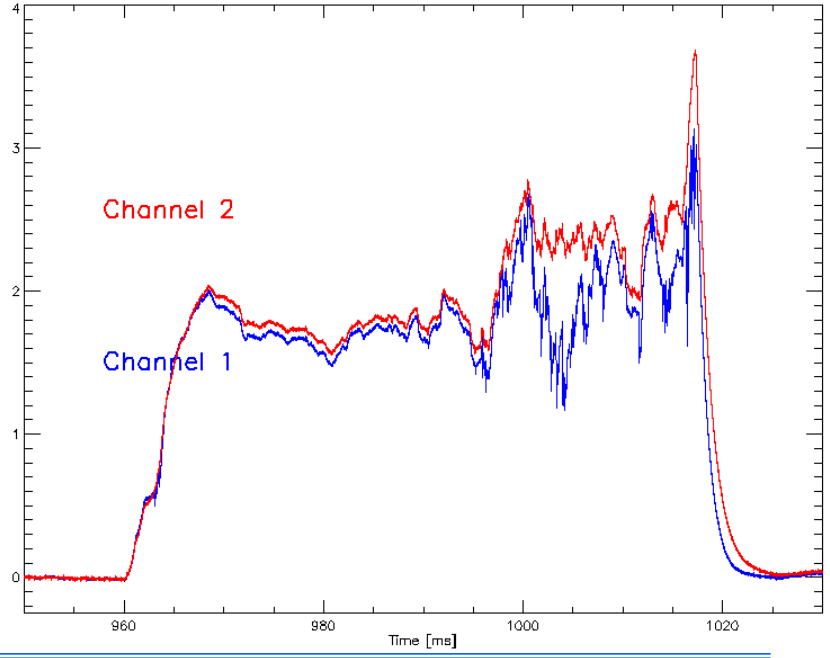
- 2-mm interferometer – to measure the line average density
- Reflectometer – to measure the radial profile of the plasma density at the edge of plasma column
- Radiometer – to measure the Electron Cyclotron Emission

Microwave interferometer



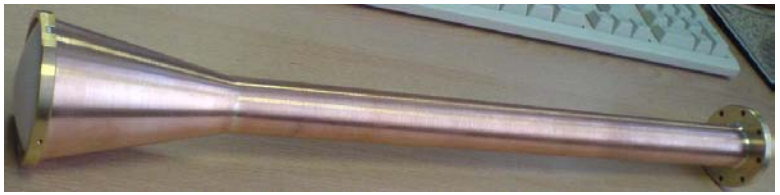
Phase difference between the probing beam and the reference beam of microwaves (λ = 2 mm) is proportional to plasma density averaged along the beam path.

Line integrated electron density [10^{19} m^{-3}]

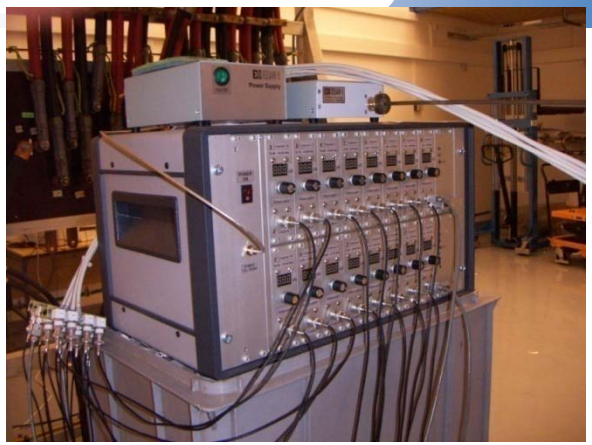


- ***The line-averaged electron density with temporal resolution in microsecond time scale***
- ***Exploited also for feedback control of the plasma density***

EBW / ECE radiometer



horn antenna



16-channel receiver

16-channel radiometer

- **Electron Bernstein Waves (EBW) studies on fundamental ECE harmonics at Ka-band 26.5-40 GHz**
  - **absolutely calibrated**
- **ECE measurements – temperature profile on second harmonics at E-band 60-90 GHz**

Reflectometer

Electromagnetic wave is injected into the plasma
Wave reflected from the cut-off layer is analyzed

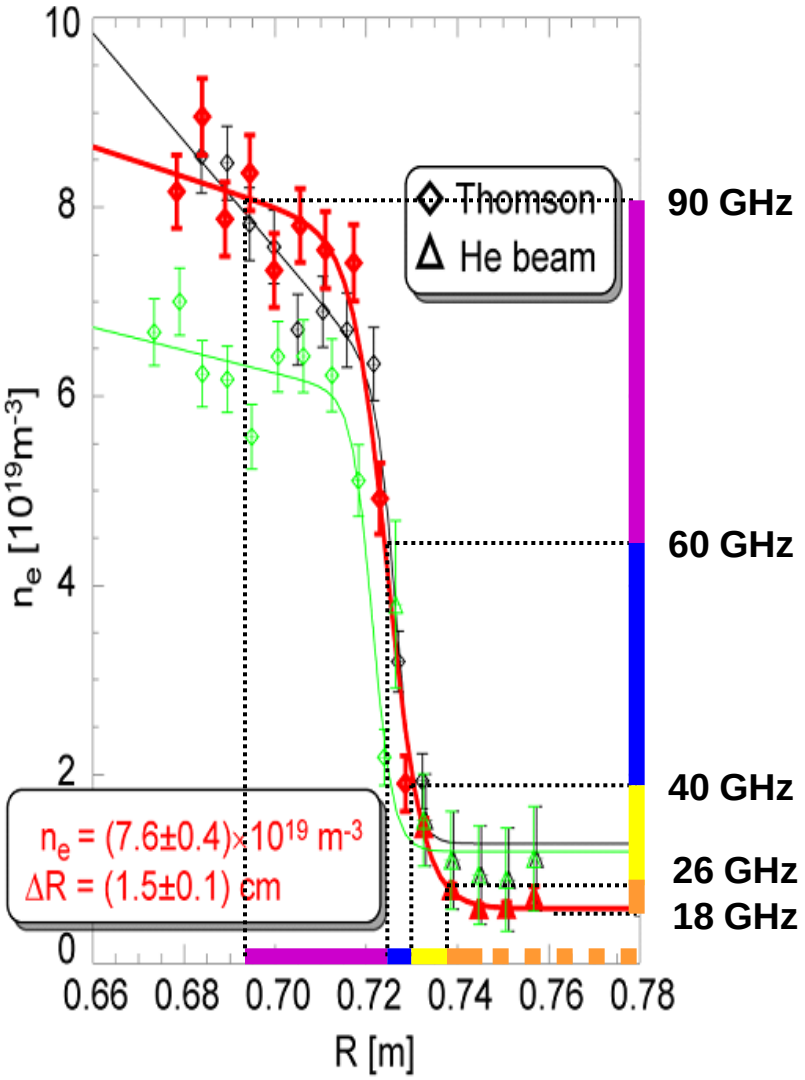
Radial profiles of electron density

with temporal resolution in microseconds

- Fast transient events in pedestal region
- Plasma turbulence

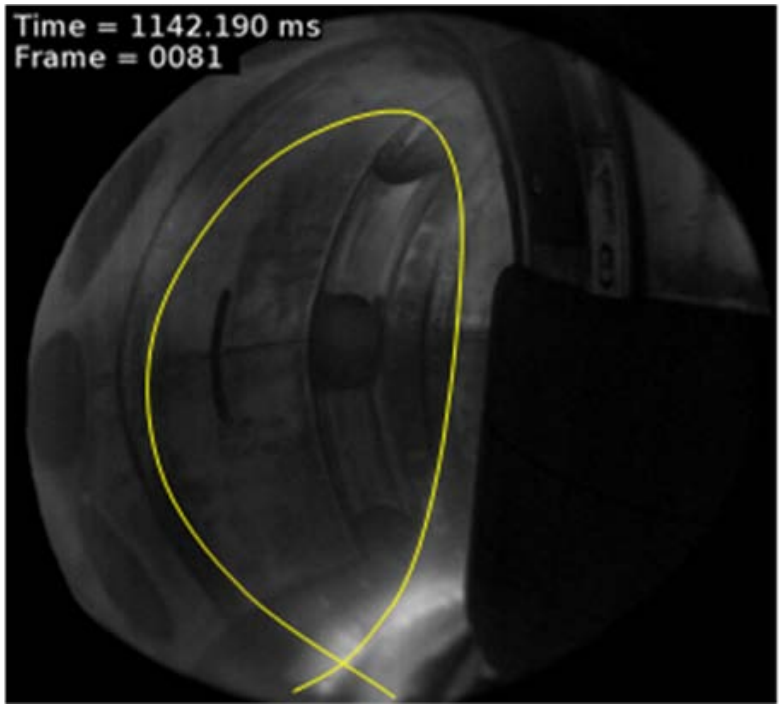
four O-mode reflectometers in K, Ka, U and E bands (18 – 90 GHz range)

one X-mode reflectometer in Ka band

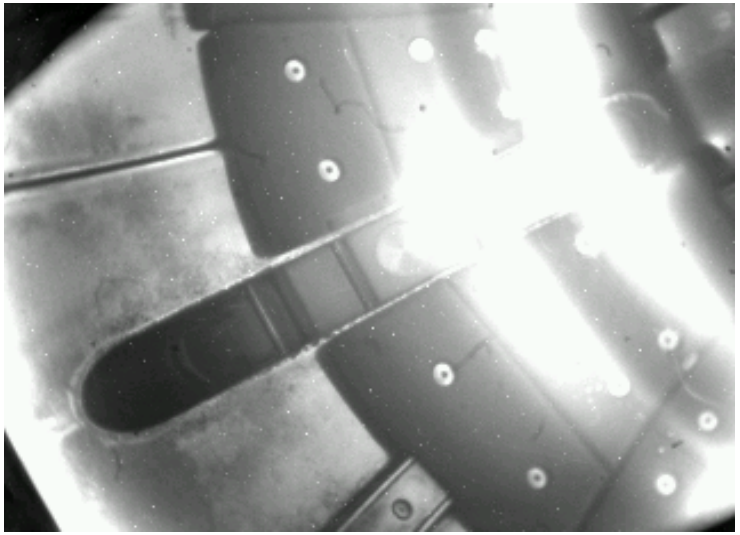


Visible cameras - diverted plasma

Tangential view



View from the top to divertor tiles

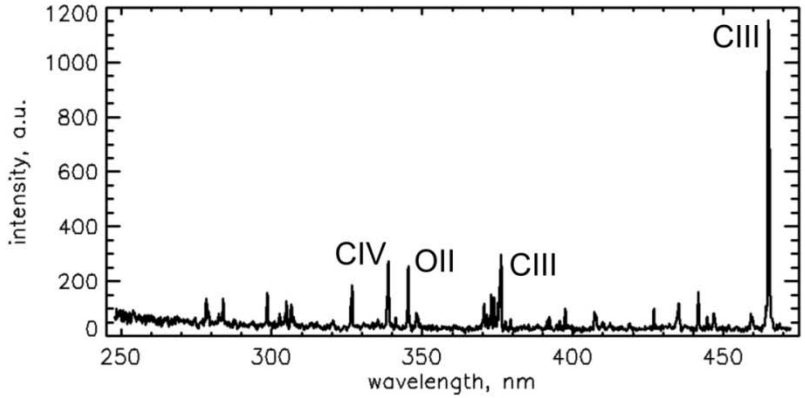


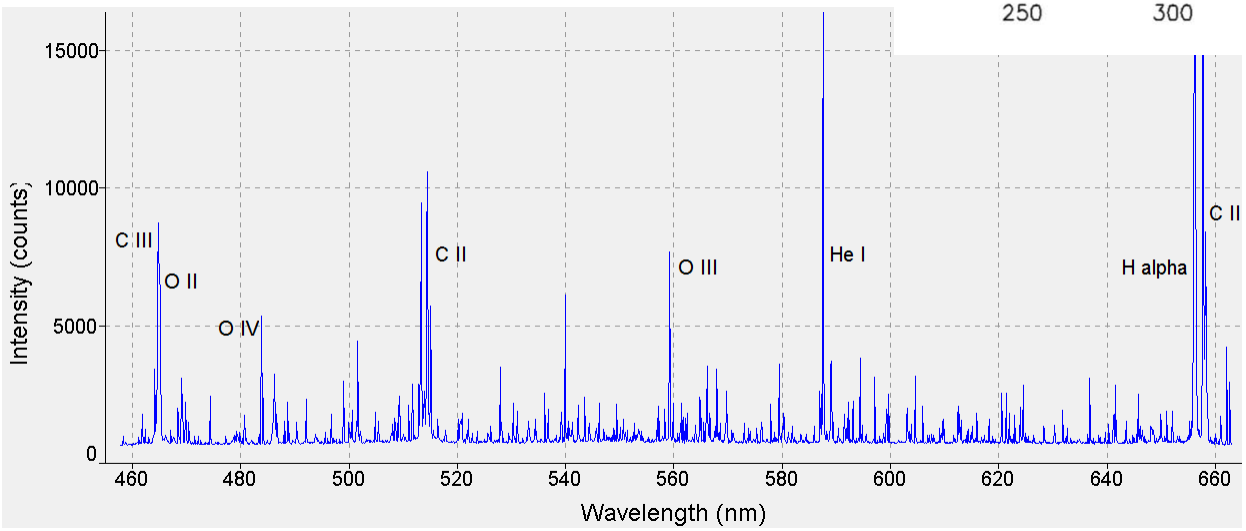
Plasma wall interaction

Impurity survey spectrometers

Spectrometer HR2000+

Detector range	248-472 nm; 460-660 nm
Optical resolution	~ 0.15 nm
Temporal resolution	~10 ms



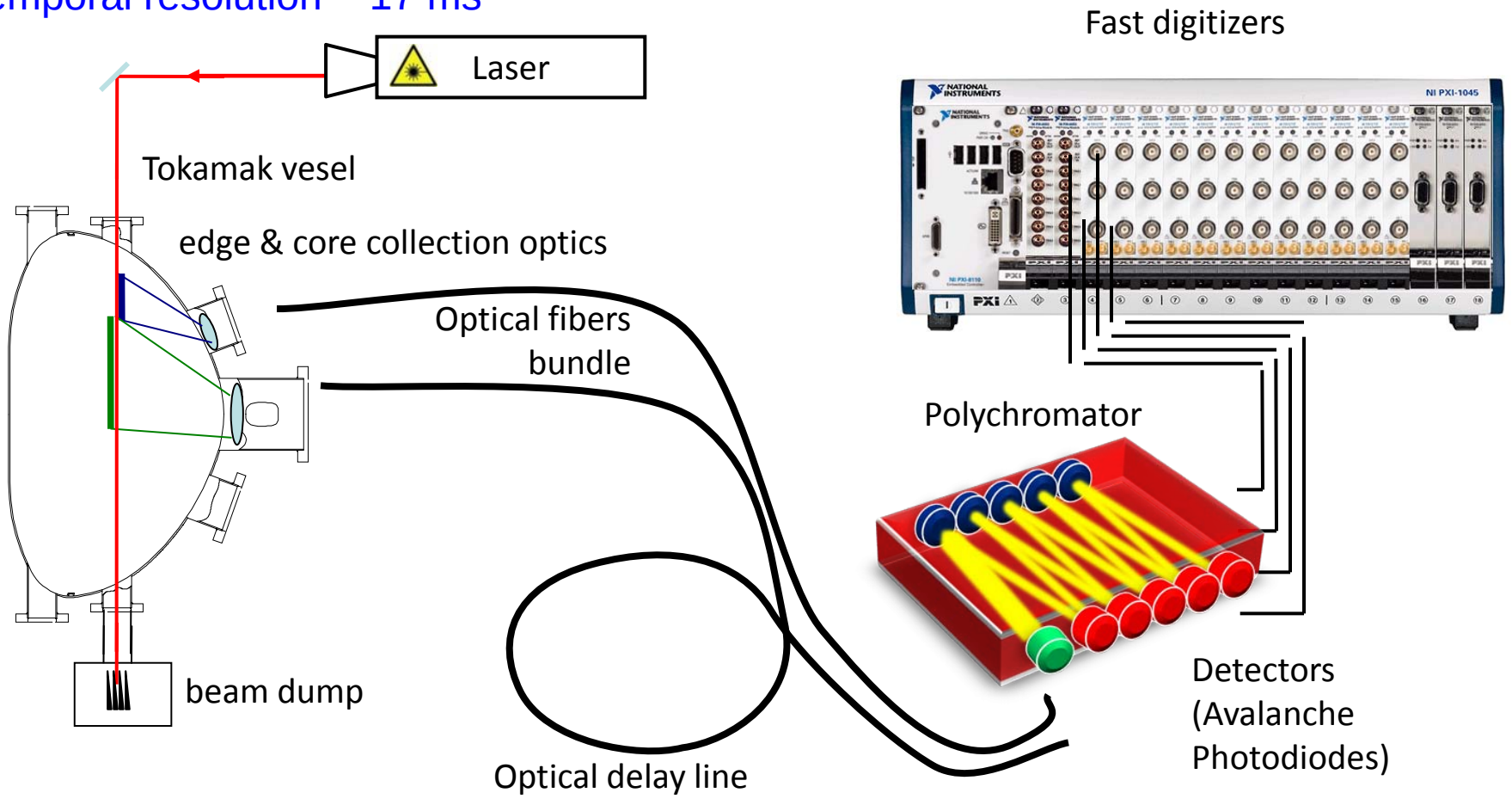


Content of impurity ions

Thomson scattering

Radial profiles of the electron temperature and density
Spatial resolution ~ several millimeters -52 channels
Temporal resolution ~ 17 ms

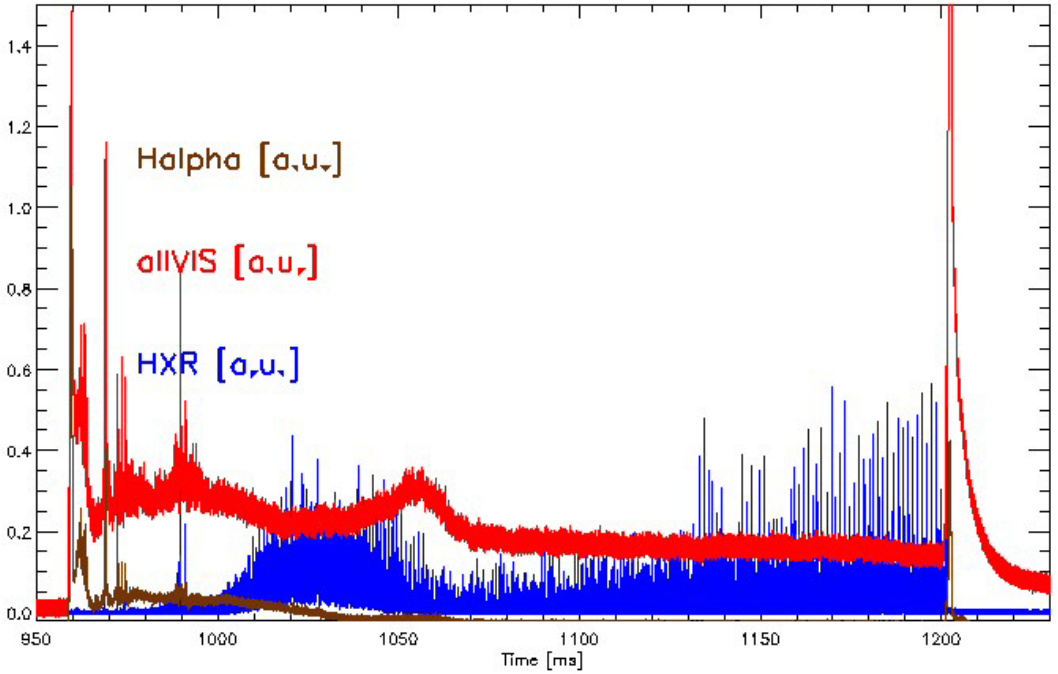
Detail description tomorrow



Photomultipliers

Provide information on:

- ***hydrogen and impurity radiation and hard X-rays***



- **visible light:** optical fibers (+ interference filter with FWHM ~ 10 nm)

  - bremsstrahlung for Zeff (FWHM ~ 2 nm)

- **hard X-rays:** direct far view + NaITl scintillator

Fast bolometry & soft X-rays

AXUV photodiodes (bolometers)

6 arrays with 20 detectors each

temporal resolution 1MHz

spectral range: 7eV – 6 keV

Radiation power losses

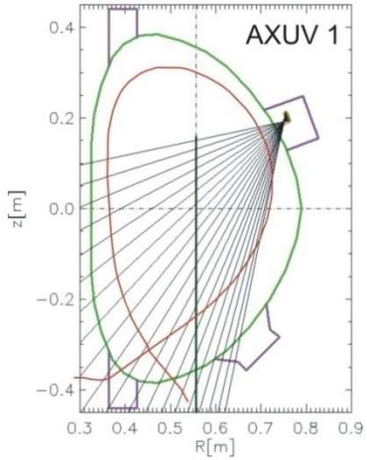
Photodiodes (windowless)

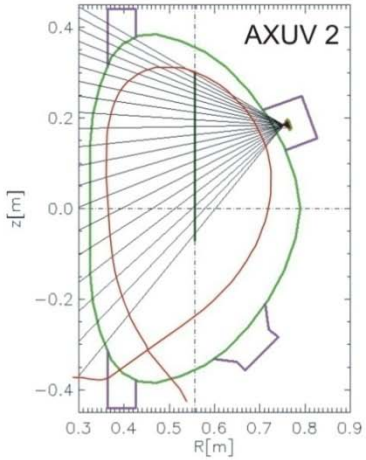
up to 4 arrays with 35 detectors each

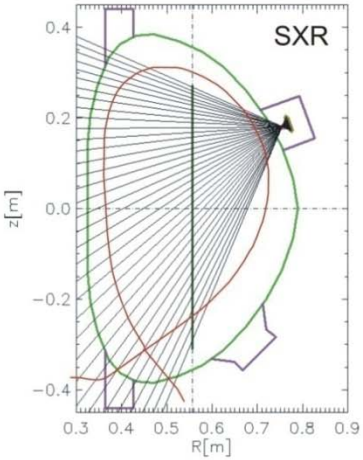
temporal resolution 1MHz

spectral range: 0.5 (Be foil) – 10 keV

Phenomena in the hot core of the plasma column (saw tooth and kink instabilities, …)



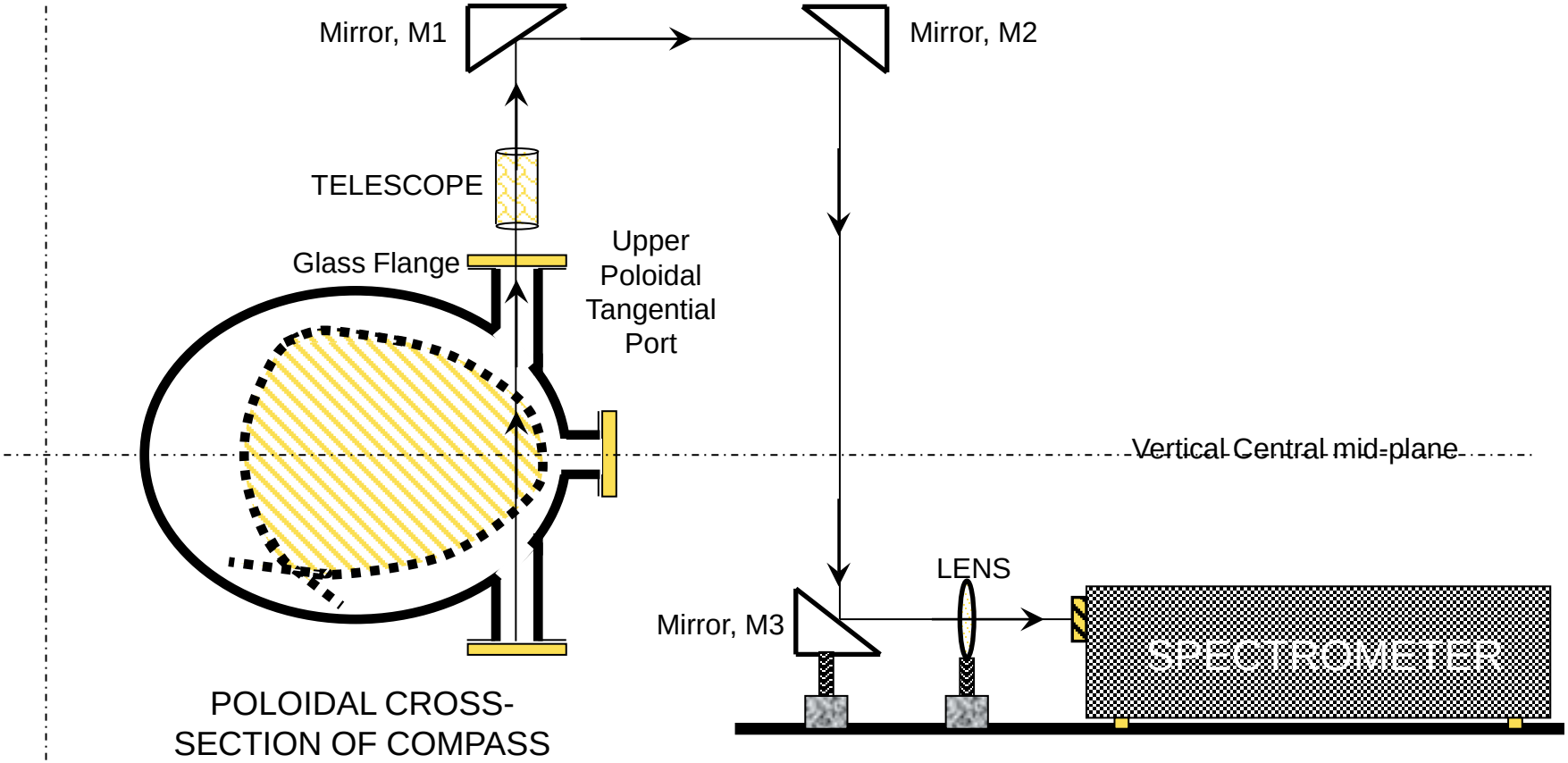




Several pin hole cameras
Integrated in I single port plug

Tomography reconstruction possible

Plasma rotation



High resolution spectroscopy of the CIII spectral line (sub-nanometer resolution)

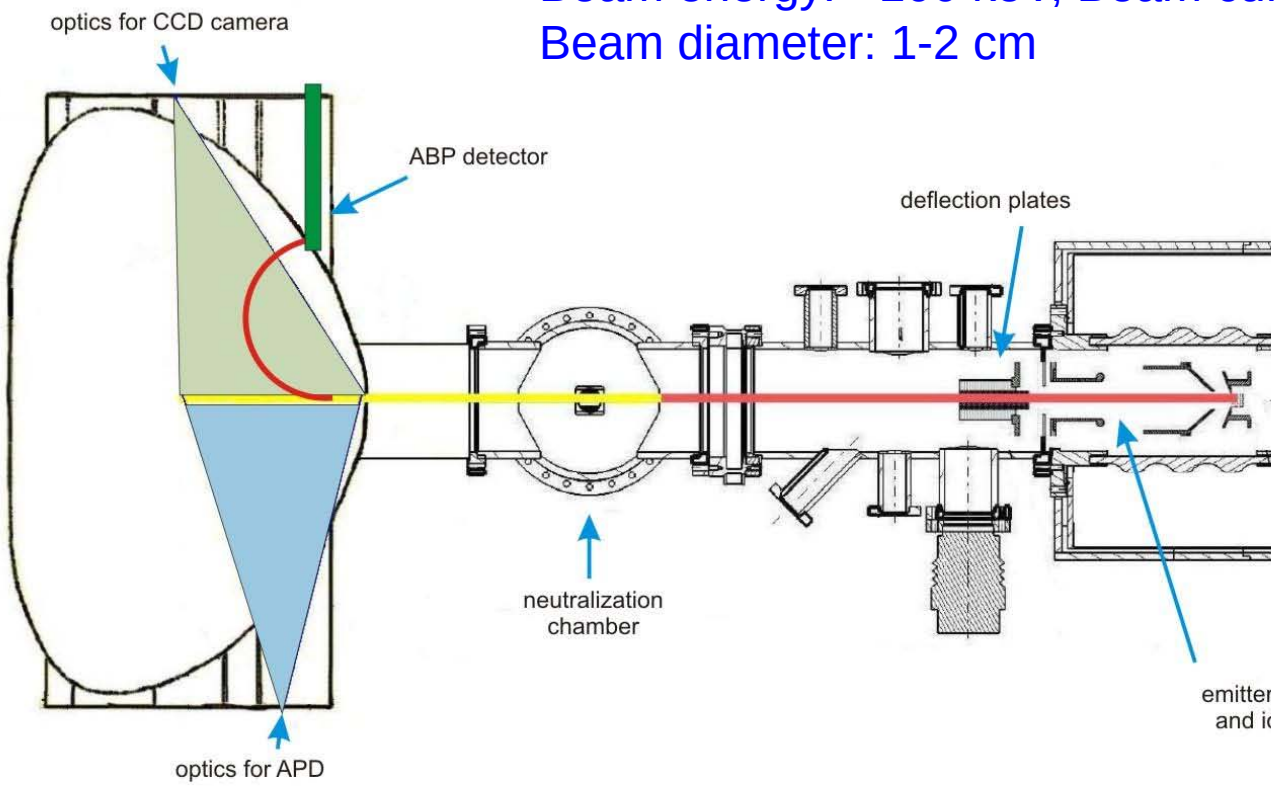
Doppler broadening – ion temperature

Doppler shift - poloidal velocity of CIII ions (radial electric field)

Beam Emission Spectroscopy

Beam Emission Spectroscopy is used to measure the radial profile of the electron density at the edge of the plasma column

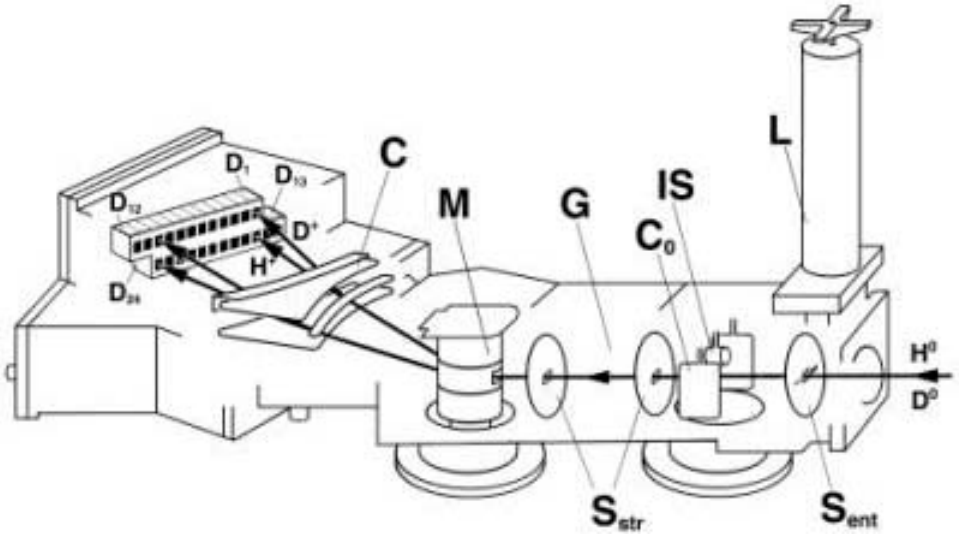
Beam of Lithium atoms is injected into the plasma
Beam energy: <100 keV, Beam current: several mA
Beam diameter: 1-2 cm



Neutral particle analyzer

Fast neutral atoms escaping plasma are analyzed according their energy and momentum

Energy distribution function of neutral atoms – the ion temperature



Neutral Particle Analyzer
ACCORD 24

Manufactured by
Ioffe Institute – StPetersburg

collaboration

Detail description tomorrow

absolute calibration

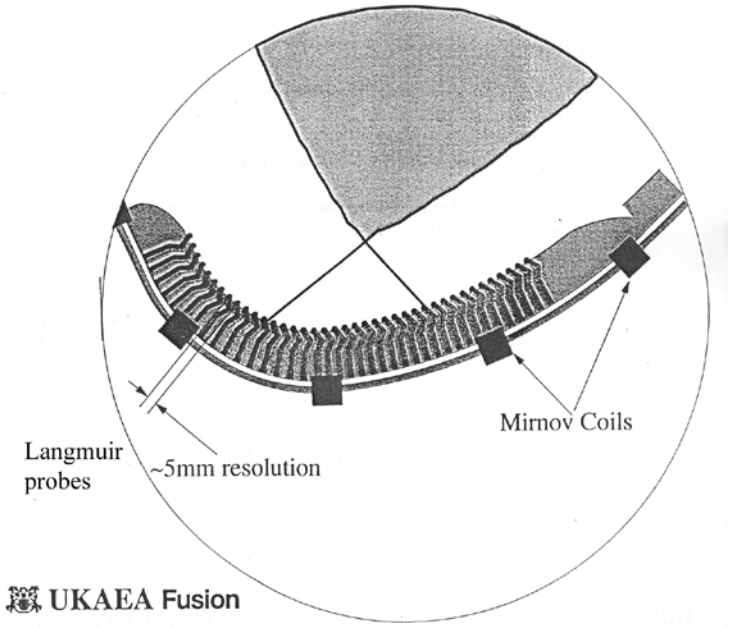
- 12 energy channels for hydrogen	250 eV – 40 keV
- 12 energy channels for deuterium	400 eV – 25 keV

Divertor Langmuir probes

characterization plasma of divertor region (density, temperature, floating potential)

Array of 39 Langmuir probes in divertor tile

spatial resolution 5 mm

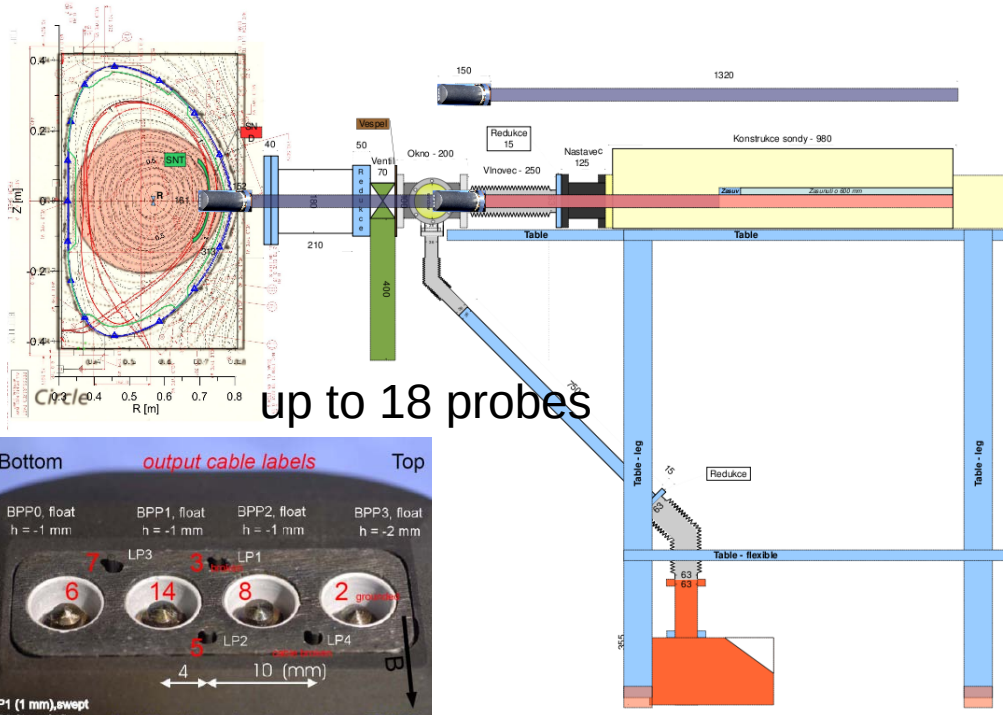


Reciprocating manipulator for Langmuir probes

characterization of scrape-off layer (density, temperature, floating potential)

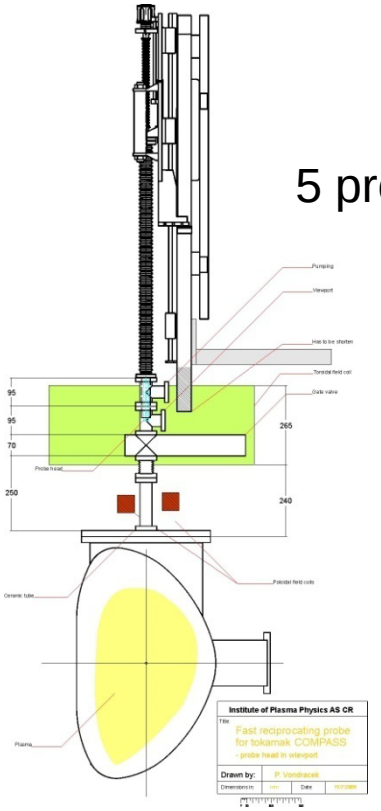
two reciprocating manipulators with about 4g acceleration

probe heads exchangeable with the ASDEX Upgrade tokamak

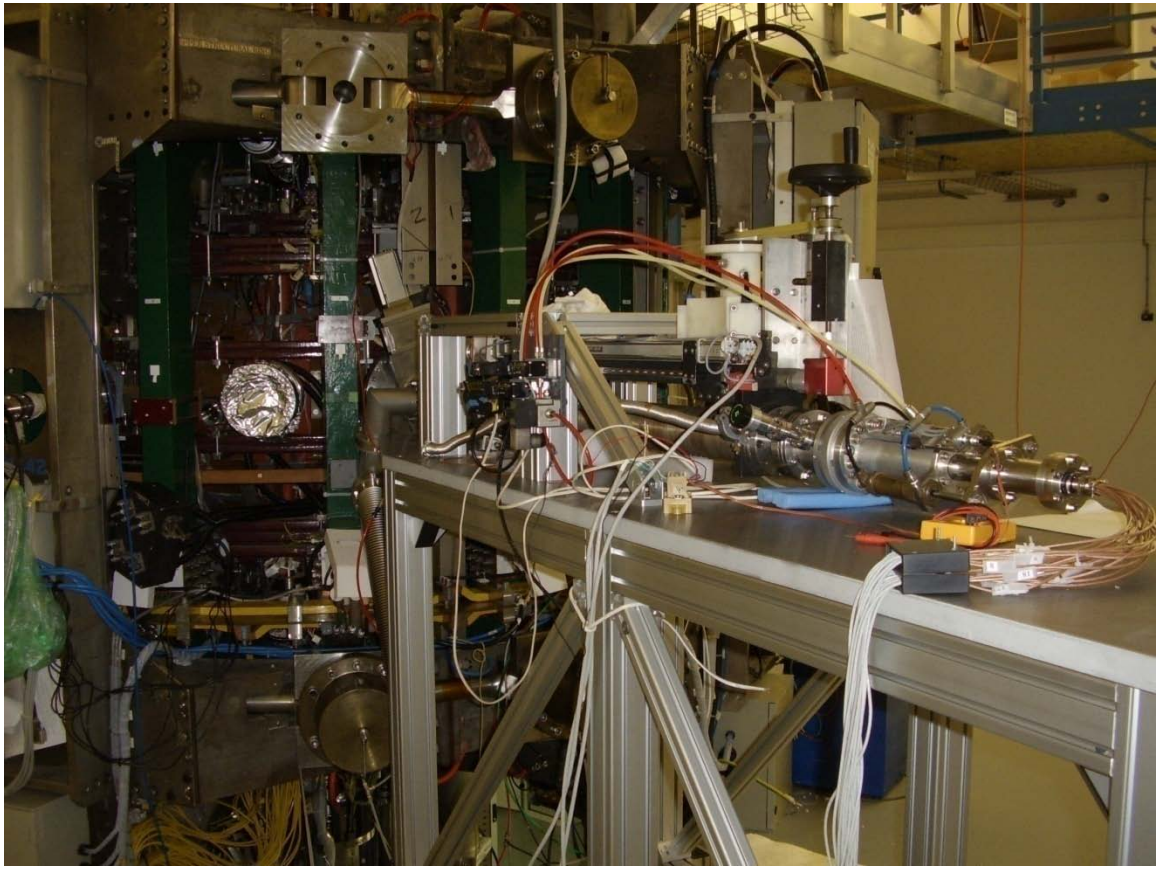


up to 18 probes

5 probes



Reciprocating probes



Horizontal reciprocating manipulator

High-heat flux head

Multiple probe head

Probe head with Langmuir and Ball pen Probes

Provide information on:

- ***density, electron and ion temperature***
- ***floating and plasma potential***

at the edge of the plasma column

Electric probes will be discussed
This Friday in more detail

Data acquisition system & database

Extremely essential part of the diagnostic complex!!!!

On COMPASS:

- Around 1000 DA channels
- Professionally manufactured (National Instruments, …..)
- Several sampling ranges (HR TS - 2000 Ms/s, 200 Ms/s – reflectometer. 5 Ms/s – probes, 2 Ms/s – remaining diagnostics

- Several Gigabytes of data are stored for every tokamak discharge

- Well organized database has to be designed – not available on marked

- Manpower demanding – 2-3 experts

To summarize

• Diagnostics complex on tokamaks is rather expensive (e.g Thomson scattering in COMPASS ~ 1 milion Euro

• Development and implementation of any diagnostics is rather complicated and time consuming – it requires usually several year effort

• Requires experienced staff for design, implementation, data processing and finally for interpretation of achieved results

•Manpower demanding - every diagnostic tool should designed by 1 – 3 physicists (depending on complexity)

•Any kind of international collaboration is beneficial!

•Any relevant physical results on tokamak plasma can be achieved only if plasma is well diagnosed !!!!