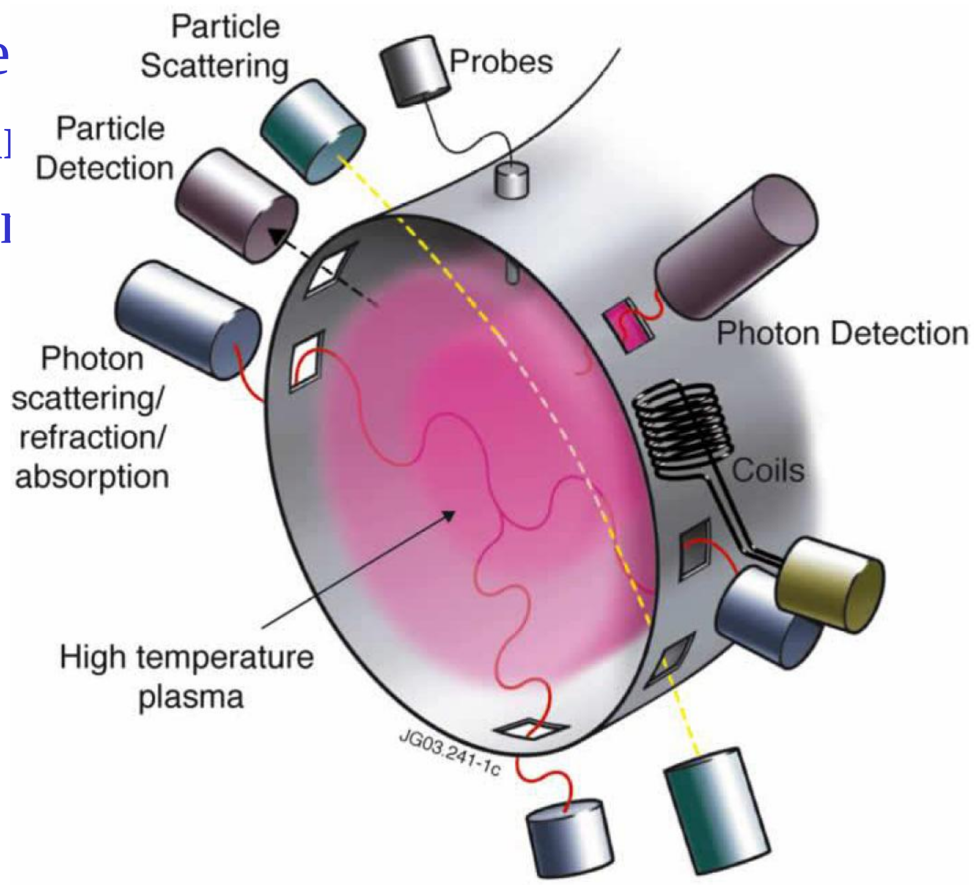
Diagnostics

- Research topics with tokamak diagnostics
- Tokamak Diagnostics
    - Magnetic measurements
    - Electron density measureme
    - Electron temperature measu
    - Ion temperature measureme
    - Radiation measurements
    - q-profile measurements
    - Fluctuation measurements
    - Edge probe measurements



Research Topics with Tokamak Diagnostics

- Establishment of stable plasmas and the investigation of MHD instabilities: magnetic diagnostics, MSE, Polarimetry, soft X-ray array, Mirnov coils, etc
- Determination of energy and particle confinement times, and transport coefficients: diamagnetic loop, interferometry, reflectometry, Thomson scattering, ECE, Doppler broadening of impurity lines, neutron flux, etc
- Development of auxilliary plasma heating methods: X-ray PHA, Neutral particle analyzer, etc
- Study and control of plasma impurities: spectroscopy, Langmuir probes for edge and divertor regions, etc
- Investigation of plasma fluctuations to determine their role in plasma transport: HIBP, e.m. wave scattering, probes, etc

ITER Diagnostic Requirements

Operating Scenario	Special Features	Required Measurements
H phase. Inductive. Ohmic L mode. Limited H Mode		Plasma shape and position, vertical speed, B_{tor}, I_p, V_{loop}, locked modes, m = 2 modes, low m/n MHD modes, q(a), halo current, line-averaged density, runaway electrons, impurity identification and influx, $n_e(r)$ and $T_e(r)$ in core, T_i in core, surface temperature of divertor plates and first wall, P_{rad} from core, line-averaged Z_{eff}, H/L mode indicator, gas pressure and composition (divertor and duct)
D phase. Inductive. ELMY H mode	Exploration of H mode and initial fusion operation	As above plus: β, q(95%), ELM occurrence and type, $n_e(r)$ and $T_e(r)$ at edge, P_{fus}, $P_{rad}(r)$, heat deposition profile in divertor, divertor detachment,
High power D/T phase. Inductive. ELMY H Mode	Full exploration of H mode and fusion performance	As above plus: shape and position (500 s), neutron and alpha source profiles, $v_{tor}(r)$ and $v_{pol}(r)$, impurity profile, $T_i(r)$ in core, $Z_{eff}(r)$, $n_{He}(r)$, n_{He} in divertor, n_T/n_D in core, D and T influx, divertor ionisation front position, neutral density (near wall), n_e and T_e in divertor, impurity and DT influxes in divertor with spatial resolution, alpha loss, neutron fluence, erosion of divertor tiles.
D/T Phase. Inductive ELMY H mode. High β	Extension to high β including stabilisation of NTMs	As above plus: localisation of q = 1.5 and q = 2 surfaces, high sensitivity measurements of n_e and T_e, detection and measurement of NTMs.
Hybrid operation	Extension to long pulse using current drive	As above plus: shape and position (for 1000 s)
Steady state operation	Extension to steady state using current drive, stabilisation of NTMs and RWMs, and possibly ITBs.	As above: plus q(r) (in particular location and value of q_{min}), high resolution measurements of the gradient of T_e and T_i, measurement of RWMs.

ITER Diagnostics I

Selected Diagnostic System	Parameters Measured
Magnetic Diagnostics	
Coils and loops mounted on the interior surface of the vacuum vessel. Halo current sensors mounted on the blanket shield module supports. *Coils mounted between the vacuum vessel skins.* Rogowski coils and *loops* mounted on the exterior surface of the vacuum vessel. Coils mounted in the divertor.	Plasma Current, Plasma Position and Shape, Loop Voltage, Plasma Energy, Locked-modes Low (m,n) MHD Modes, Sawteeth, Disruption Precursors, Halo Currents, Toroidal Magnetic Field, Static error field of PF and TF, High Frequency macro instabilities (Fishbones, TAE Modes)
Fusion Product Diagnostics	
Radial Neutron Camera, *Vertical Neutron Camera*, Micro-fission Chambers (N/C) Neutron Flux Monitors (Ex-Vessel) Gamma-Ray Spectrometer Activation System, *Lost Alpha Detectors (N/C) Knock-on Tail Neutron Spectrometer (N/C)*	Total Neutron source strength, *Neutron/Alpha source profile*, Fusion Power, Fusion power density, Ion temperature profile, Neutron fluence on the first wall, nT/nD in plasma core, *Confined alpha particles, Energy and Density of escaping alphas*
Optical/IR(Infra-Red) Systems	
Core Thomson Scattering Edge Thomson Scattering , X-Point Thomson Scattering, *Divertor Thomson Scattering* Toroidal Interferometer/ Polarimeter, *Polarimeter (Poloidal Field Measurement)* *Collective Scattering System*	Line-Averaged Electron Density Electron Temperature Profile (Core and Edge) Electron Density Profile (Core and Edge) *Current profile* *Divertor Electron Parameters* *Confined alpha particles.*
Bolometric Systems	
Bolometer arrays mounted in the ports, in the divertor and *in the vacuum vessel.*	Total Radiated power, Divertor radiated power *Radiation profile (core and divertor)*

ITER Diagnostics II

Spectroscopic and Neutral Particle Analyser Systems	
H Alpha Spectroscopy, Visible Continuum Array Main Plasma and *Divertor Impurity Monitors,* X-Ray Crystal Spectrometers, Charge eXchange Recombination Spectroscopy (CXRS) based on DNB, *Motional Stark Effect (MSE) based on heating beam, Soft X-Ray Array (N/C),* Neutral Particle Analysers (NPA), *Laser Induced Fluorescence (N/C)*	Ion temperature profile, Core He density, Impurity density profile, Plasma rotation, ELMs, L/H mode indicator, nT/nD & nH/nD in the core, edge and divertor, Impurity species identification, Impurity influx, *Divertor He density*, Ionisation front position, Zeff profile, Line averaged electron density, *Confined alphas, Current density profile.*
Microwave Diagnostics	
Electron Cyclotron Emission (ECE) Main Plasma Reflectometer Plasma Position Reflectometer**,** Divertor Interferometer/*Reflectometer*, *Divertor EC absorption (ECA)***,** Main Plasma Microwave Scattering, *Fast Wave Reflectometry (N/C)*	Plasma position and shape, Locked Modes Low (m,n) MHD Modes, Sawteeth, Disruption Precursors, Plasma Rotation, H-mode indicator Runaway electrons, Electron Temperature Profile, Electron Density Profile, High Frequency micro-instabilities, *Divertor electron parameters.*
Plasma-Facing Components and Operational Diagnostics	
IR/Visible Cameras, Thermocouples, Pressure Gauges, Residual Gas Analysers, *IR Thermography (Divertor), Langmuir Probes*	Runaway electrons: energy and current Gas pressure and composition in divertor Image and temperature of first wall Gas pressure and composition in main chamber and duct, *Escaping alphas*, Ion flux, ne and Te at divertor plates, *Surface temperature and power load in divertor.*

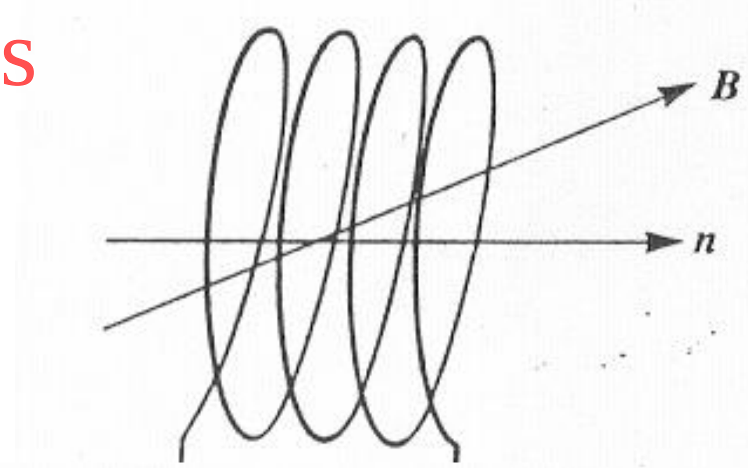
Systems with implementation difficulties, and the physical parameters that currently have an uncertain measurement capability, are shown in italics. N/C: new concept technique.

Diagnostics for Real-Time Feedback Control at JT-60U

Quantity	Objectives	Applications
•Averaged electron density (FIR/ CO_2 interferometer, CO_2 Polarimeter)	• Optimize target and operation density	•Versatile in a variety of exp.
•Neutron emission rate (fission chamber)	• Control stability, fusion burn	•Establish route toward high QDT* in R/S plasmas
•Plasma stored energy (diamagnetic loop)	• Control stability, avoid disruption	•Sustain plasma performance in a steady-state
•Central electron temp. (ECE measurement)	• Optimize target temperature	•Study non-inductive CD, High Te / Ti confinement
•Electron Temperature gradient (ECE measurement)	• Control internal transport barrier	•Sustain bootstrap current for a steady-state operation
•Electron Temperature fluctuations (ECE measurement)	• Suppress neoclassical tearing mode	•Sustain high performance in a steady-state
•Ion Temperature profile (CXRS measurement)	• Control internal transport barrier (Optimize target temperature)	•Sustain AT modes
•Current density profile (MSE polarimeter)	• Control q profile	•Sustain AT modes
•Main plasma radiation (bolometers)	• Improve confinement by enhanced radiation	•Optimize radiation mantle
•Outer gap distance (magnetics & equilibrium)	• Keep stable RF coupling, investigate wall effect on stability	•Sustain R/S plasmas by LHRF, improve stability in R/S plasmas
•Divertor electron density (mm-wave interferometer)	• Optimize divertor density	•Control divertor plasma
•Divertor pressure (ionization gauge)	• Control MARFE/detachment	•Sustain radiative divertor
•Divertor radiation (bolometers)	• Reduce divertor heat load	•Explore radiative divertor

Magnetic Measurements

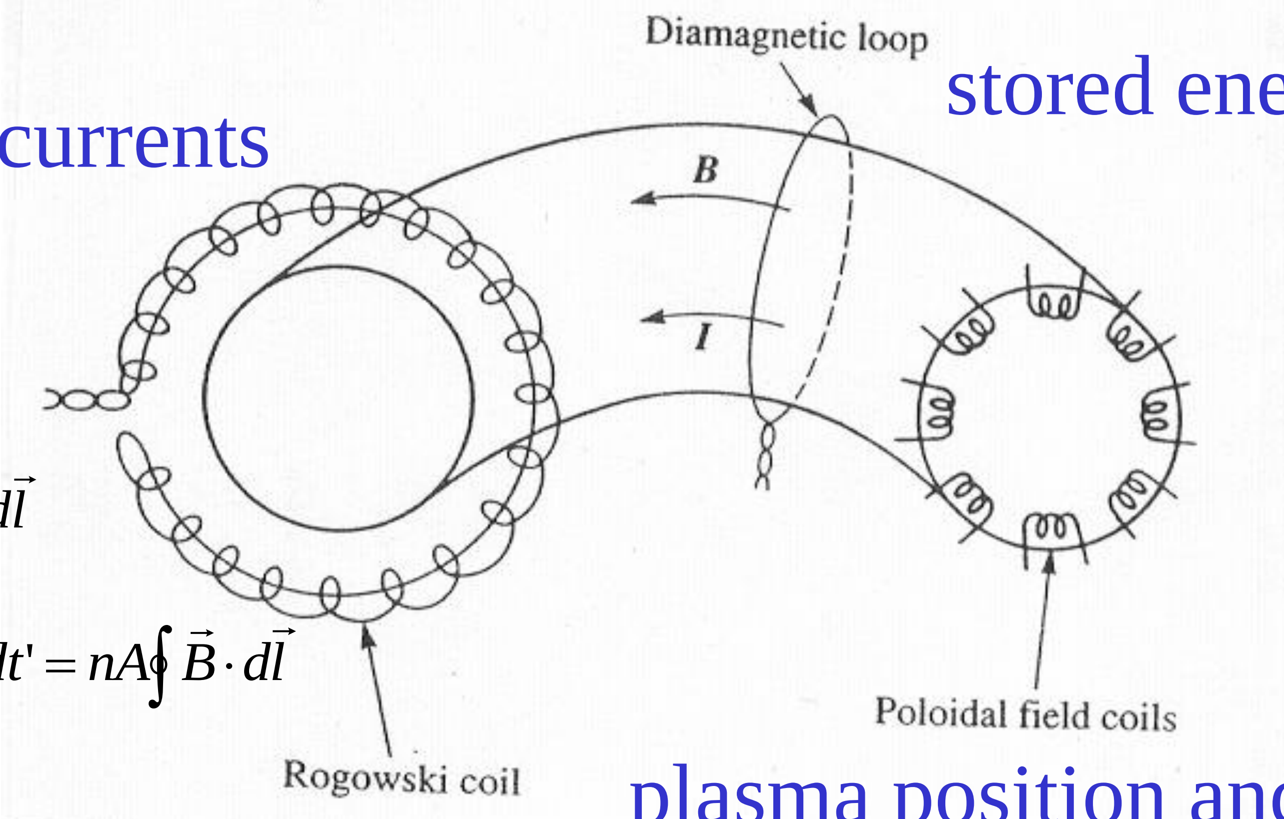
$$\Phi = -\int_{t_0}^{t} V(t')dt' = NA\vec{B}\cdot\vec{n}$$



Measure magnetic field, flux, loop voltage, current, and plasma energy

stored energy

plasma currents



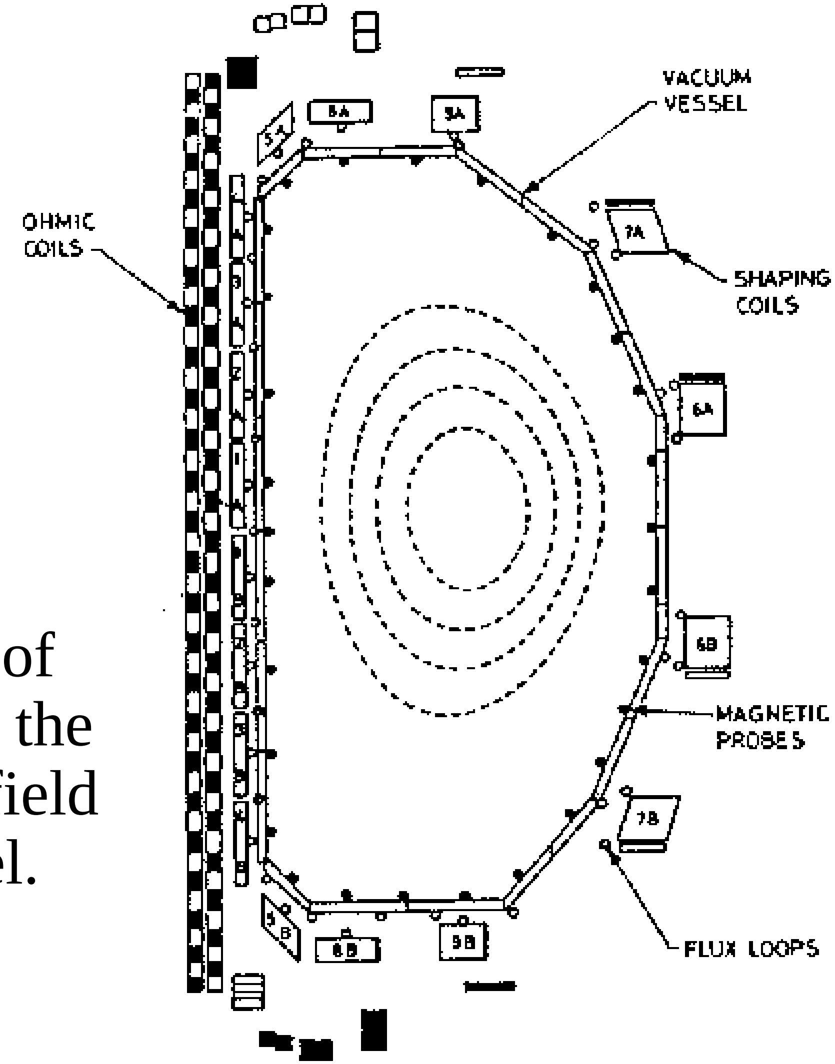
$$I = \frac{1}{\mu_o}\oint \vec{B}\cdot d\vec{l}$$

$$\Phi = -\int_{t_0}^{t} V(t')dt' = nA\oint \vec{B}\cdot d\vec{l}$$

plasma position and shape

Loop Voltage and Plasma Surface

Loop voltage: $V_{loop} = I_p R_p$
voltage induced by flux changes due both to the primary circuit and the plasma current itself



Configurations of OH, shaping and magnetic diagnostic coils in DIII-D.

Plasma surface:
The shape and position of the outermost closed magnetic surface of the plasma can be determined from the toroidal loop voltage and poloidal field measured around the vacuum vessel.

$$\psi \qquad B_R = -\frac{1}{R}\frac{d\psi}{dZ} \qquad B_Z = \frac{1}{R}\frac{d\psi}{dR}$$

extrapolate across a current-free region

Plasma Energy and Internal Inductance

Diamagnetic flux: difference between the total toroidal flux and that in the absence of plasma

from equilibrium equation, $\dfrac{(\nabla\times\vec{B})\times\vec{B}}{\mu_o} = \nabla p$

cyindrical limit $\dfrac{dp}{dr} + \dfrac{d}{dr}\left(\dfrac{B_\phi^2}{2\mu_o}\right) + \dfrac{B_\theta}{\mu_o r}\dfrac{d}{dr}(rB_\theta) = \dfrac{dp}{dr} + \dfrac{d}{dr}\left(\dfrac{B_\phi^2 + B_\theta^2}{2\mu_o}\right) + \dfrac{B_\theta^2}{\mu_o r} = 0$

integrating over the plasma volume,

$$2\beta_{p\perp} + \beta_{p//} + l_i - \mu = 2(S_1 + S_2) \qquad \beta_{p//} + l_i + \mu = 2S_2 R_T / R_o$$

diamagnetic parameter $\mu = \dfrac{8\pi B_o \Delta\phi}{\mu_o^2 I^2}$

Shafranov integrals

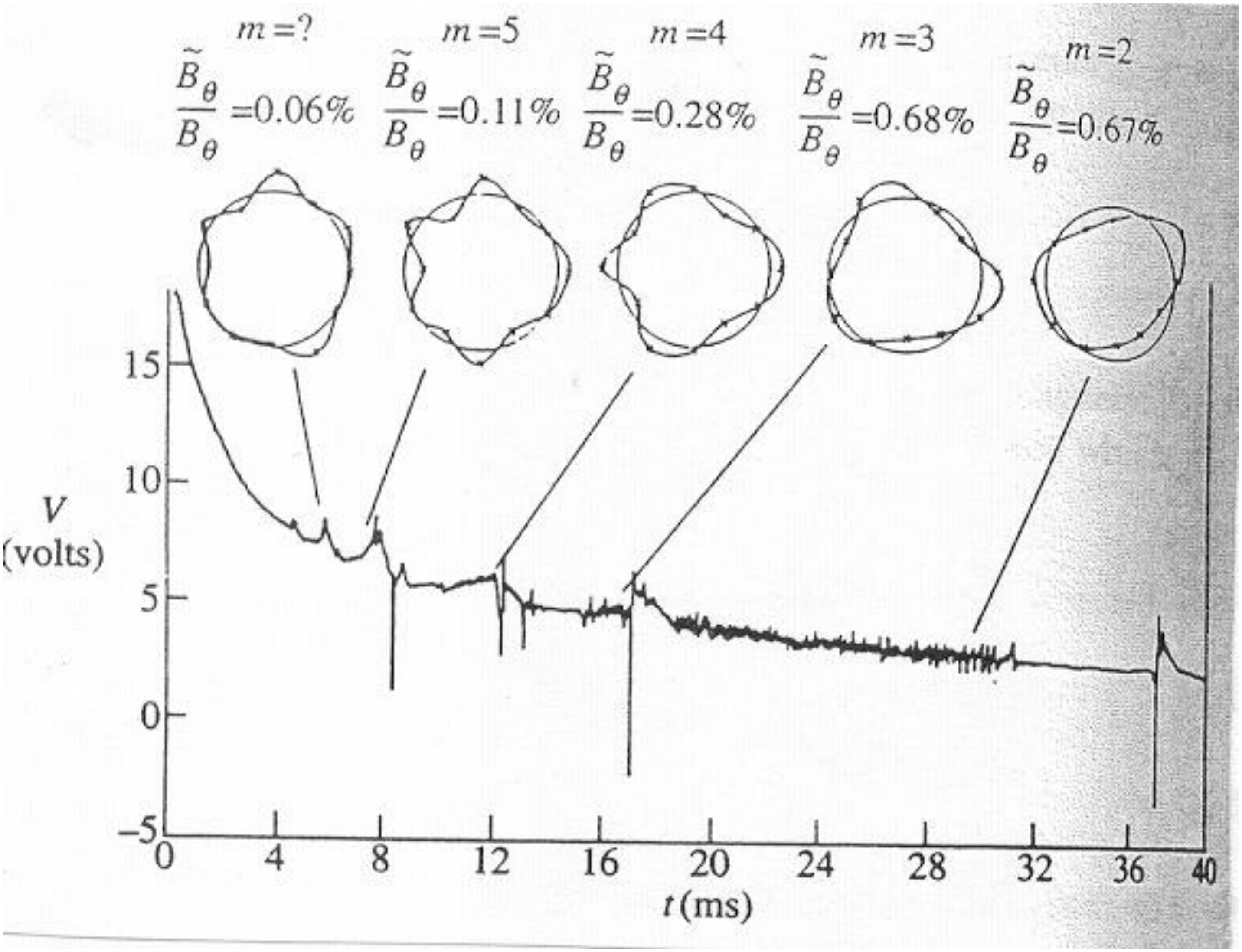
$$B_a^2 = \frac{\mu_o^2 I^2}{4\pi A} = \frac{\mu_o^2 I^2}{l^2} \qquad \beta_p = \frac{8}{3}\frac{W}{\mu_o R_o I^2}$$

$$S_1 = \frac{\int B_p^2 \vec{r}\cdot d\vec{S}}{\mu_o^2 I^2 R_o} \qquad S_2 = \frac{\int B_p^2 \vec{R}\cdot d\vec{S}}{\mu_o^2 I^2 R_o}$$

$$\beta_{p\perp} = S_1 + S_2\left(1 - \frac{R_T}{R_o}\right) + \mu \approx 1 + \mu$$
$$= \beta_{diam}$$

$$(\beta_{p//} + \beta_{p\perp}) + l_i = S_1 + S_2\left(1 + \frac{R_T}{R_o}\right)$$
$$= 2\beta_{mhd} + l_i$$

MHD Instability Measurements



ITER Magnetic Diagnostics

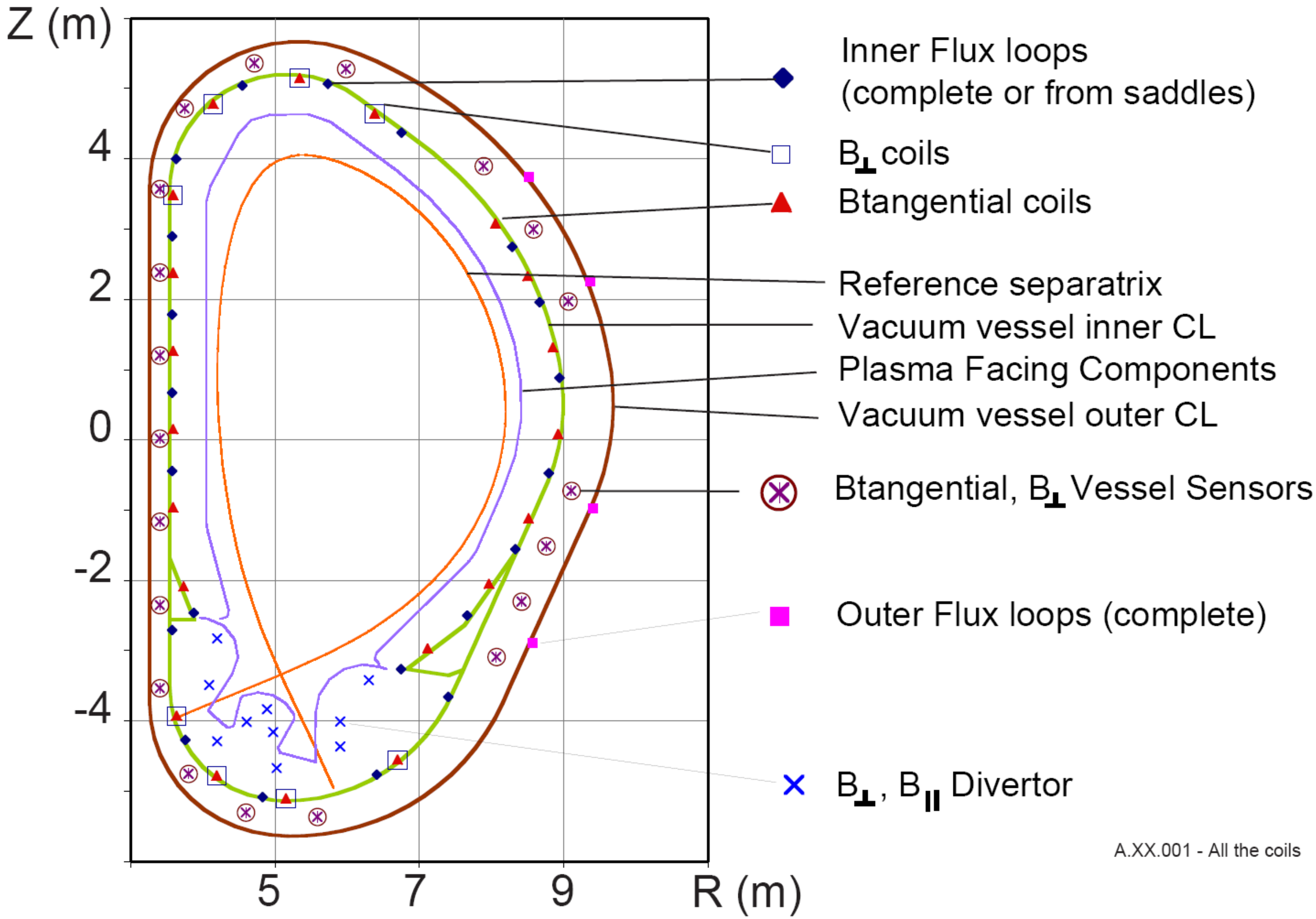
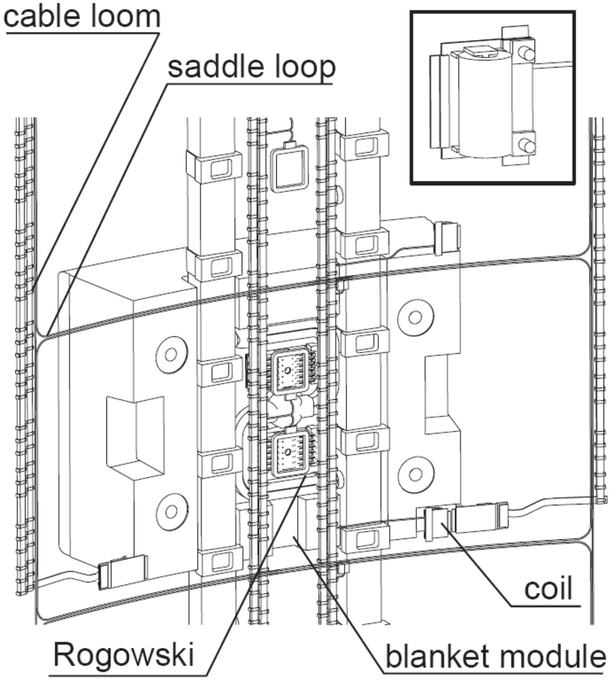
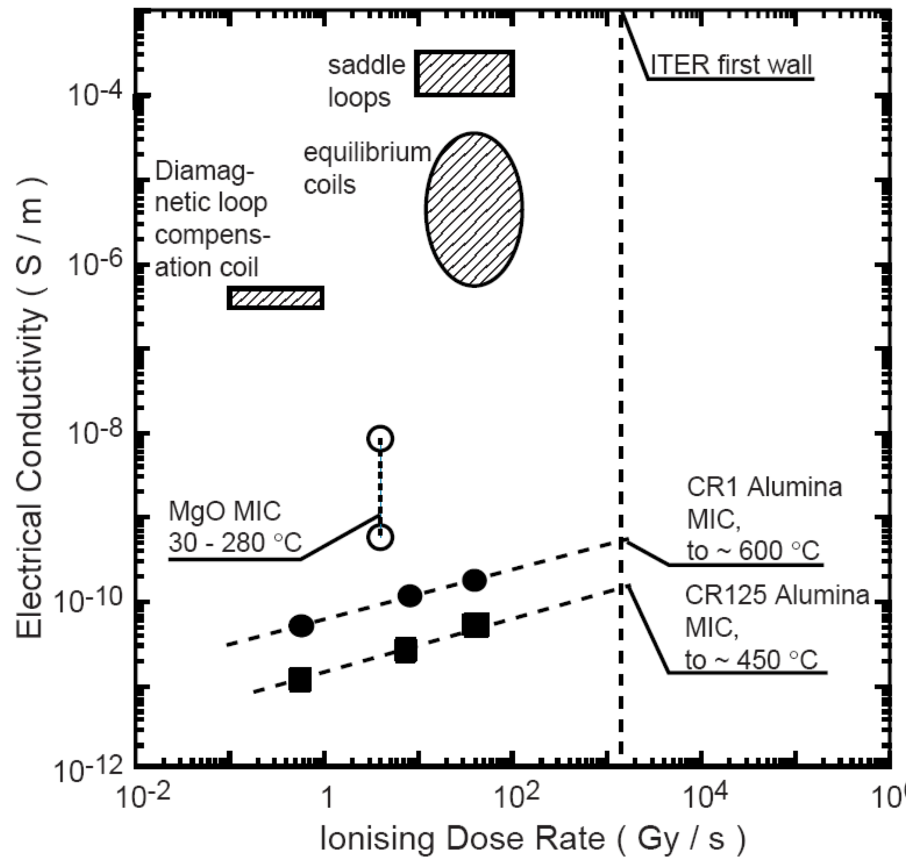


Fig. 1. Poloidal distribution of magnetic sensors. The diamagnetic loops and external Rogowski coils are not shown.

ITER Magnetic Diagnostics

The step to ITER requires that proper account is taken in the design for (i) nuclear heating, (ii) long pulse operation, and (iii) radiation





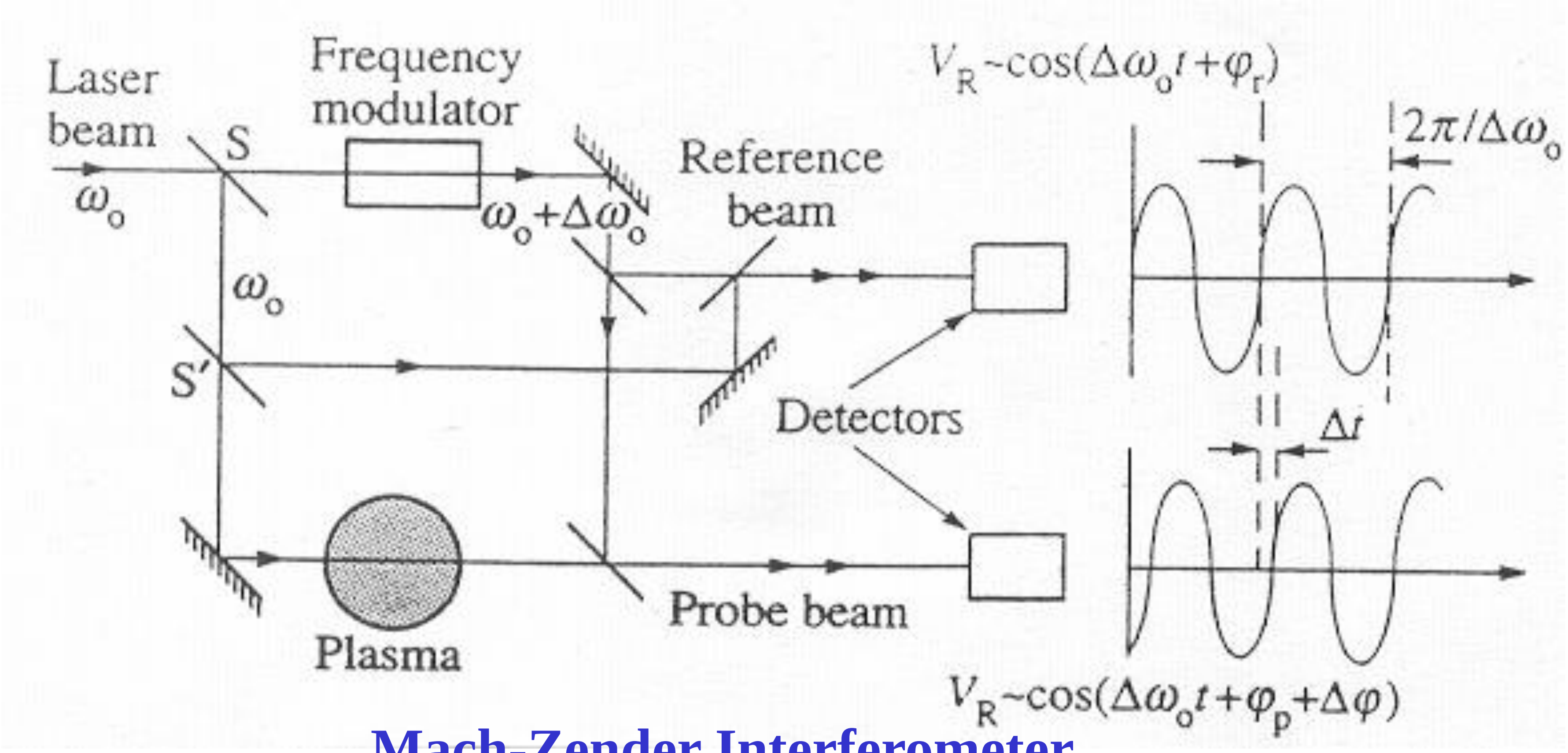
There are two radiation effects that can influence the signals – Radiation Induced Conductivity (RIC) and Radiation Induced EMF (RIEMF). A third radiation effect – Radiation Induced Electrical Degradation →

minimise this: (i) increasing the ratio of effective sensor area to cable length, (ii) reducing the temperature and radiation field asymmetries by adopting an even layer coil structure and choosing areas of expected uniform radiation level, (iii) lowering the coil resistance and hence reducing the differential voltage, and (iv) reducing the integrator sensitivity to common mode voltage by lowering the balanced impedance to ground at the input. Most of these measures

Electron Density Measurement: Interferometry

Refractive index $\mu = 1 - \omega_p^2 / \omega^2$

Phase change due to plasma density $\Delta\phi = \dfrac{\lambda e^2}{4\pi\varepsilon_o m_e c^2} \int n_e dl$

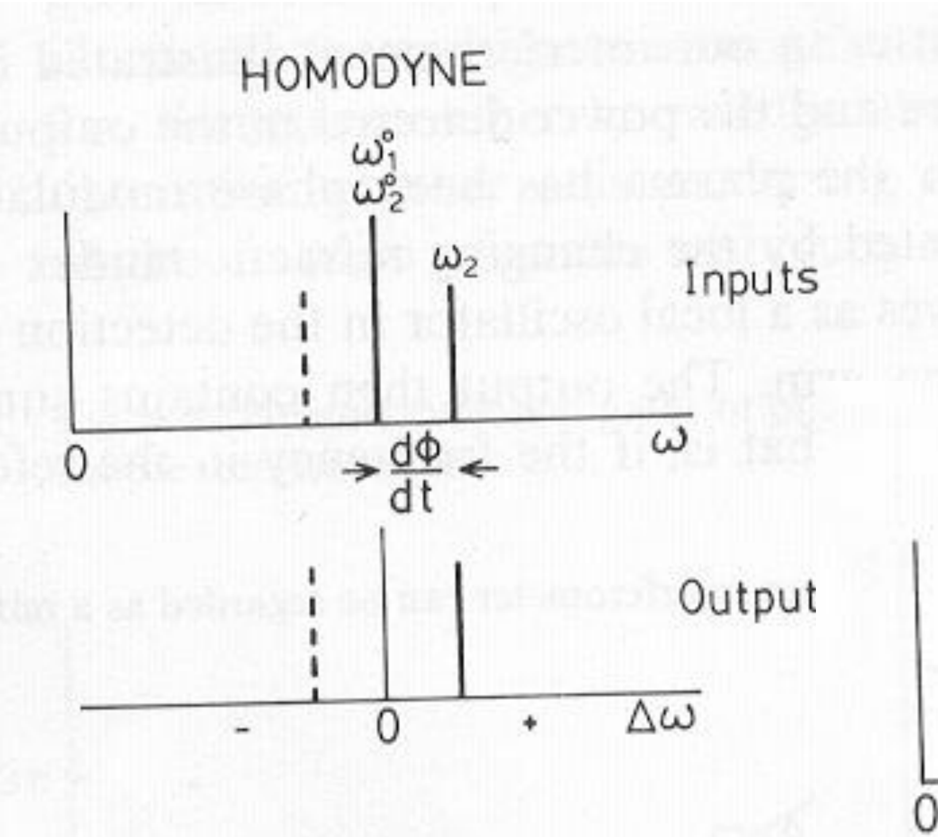


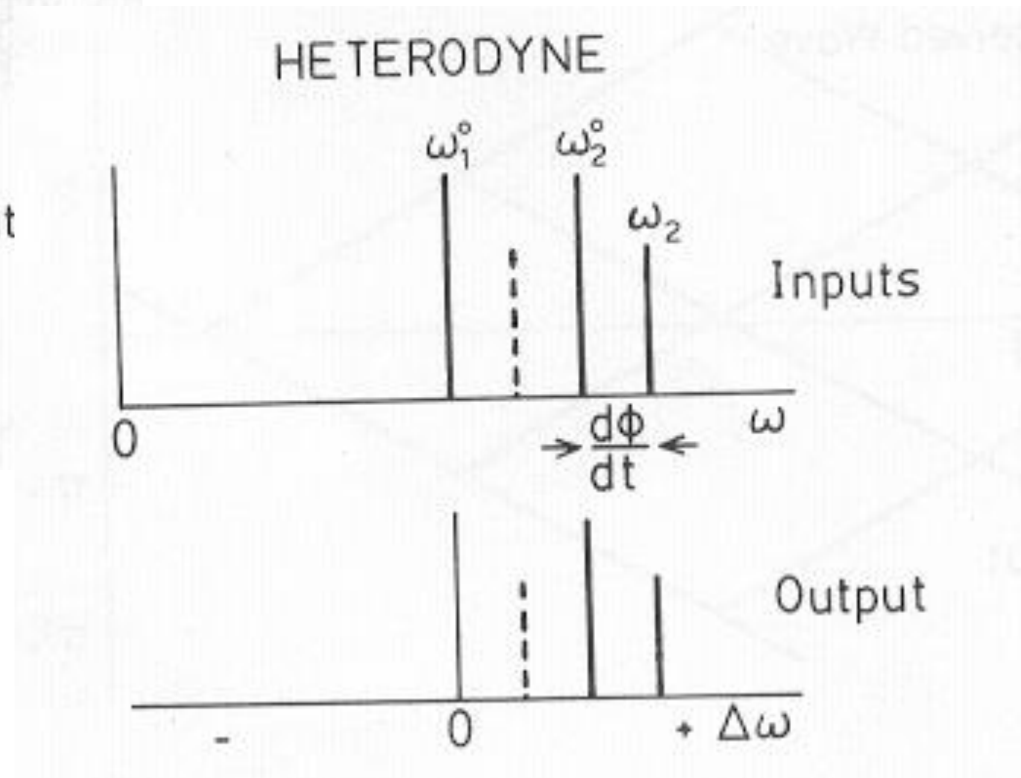
Mach-Zender Interferometer

Design of Interferometry

- Types of interferometers
  - Michelson, Mach-Zender, Fabry-Perot interferometers
  - homodyne and heterodyne
- Frequency sources
  - sensitive to the electron density: $\Delta\phi \propto \lambda \int n_e dl$
  - insensitive to mechanical vibrations: long wavelength
  - small refraction of the beams: short wavelength
  - wavelengths between 10 and 2000μm are used
- Beam detectors
  - room temperature pyroelectric detector: simple, inexpensive
  - liquid helium-cooled indium antimonide crystals: high sensitivity
  - Schottky diodes: good response at high frequencies
- Phase counters
  - multi-fringe, high phase resolution counter
- Inversion of line-integrated density profiles
  - Abel inversion
  - inversion using iso-density flux contours

Types of Interferometers





Relevant Parameters for Various Sources

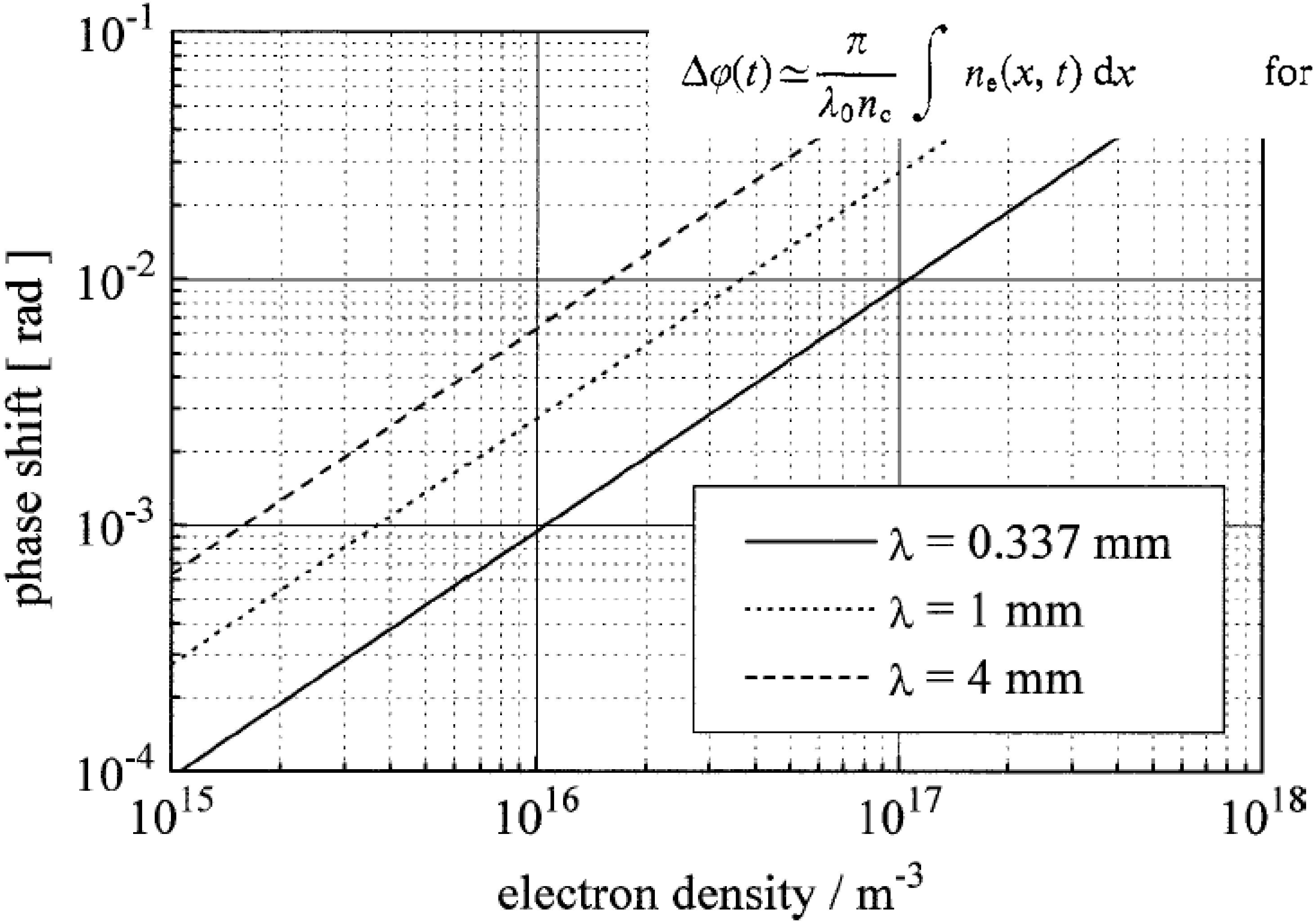
Table 1. Summary of relevant parameters for various wavelengths for a tangential ($\theta_i = 0.77$) double pass beam in ITER. The density resolutions assume $\Delta\phi$ resolution of 1/100 radian and polarization resolution of 1/1000 radian.

λ (μm)	Port Penetration Size (cm) Retroreflector/ Mirror	θ_i n_e (o) ($\times 10^{19}$ m^{-3})	Total Phase Shift (rad)	Faraday Rotation (rad)	Interferometer $\Delta \bar{n}_e / \bar{n}_e$ ($\times 10^{-2}$)	Faraday Rotation $\Delta \overline{n_e B} / \overline{n_e B}$ ($\times 10^{-2}$)
195	74/91	13	1969	73	0.0005	0.0014
		1	151	5.6	0.006	1.8
119	44/57	13	1202	27	0.008	0.0037
		1	92	2.1	0.01	0.048
50	22/30	13	505	4.8	0.002	0.02
		1	39	0.37	0.026	0.027
10.6	10/13	13	107	0.21	0.0093	0.48
		1	8	0.016	0.12	6.2
3.39	6/8	13	34	0.022	0.029	4.5
		1	2.6	0.017	0.38	60
1	3/4	13	10	0.0019	0.1	52
		1	0.78	0.0005	1.3	666

Sensitivity for Various Frequency Sources

$$\Delta\varphi(t) = \frac{2\pi}{\lambda_0}\int\left[1-\left(1-\frac{n_e(x,t)}{n_c}\right)^{1/2}\right]dx$$

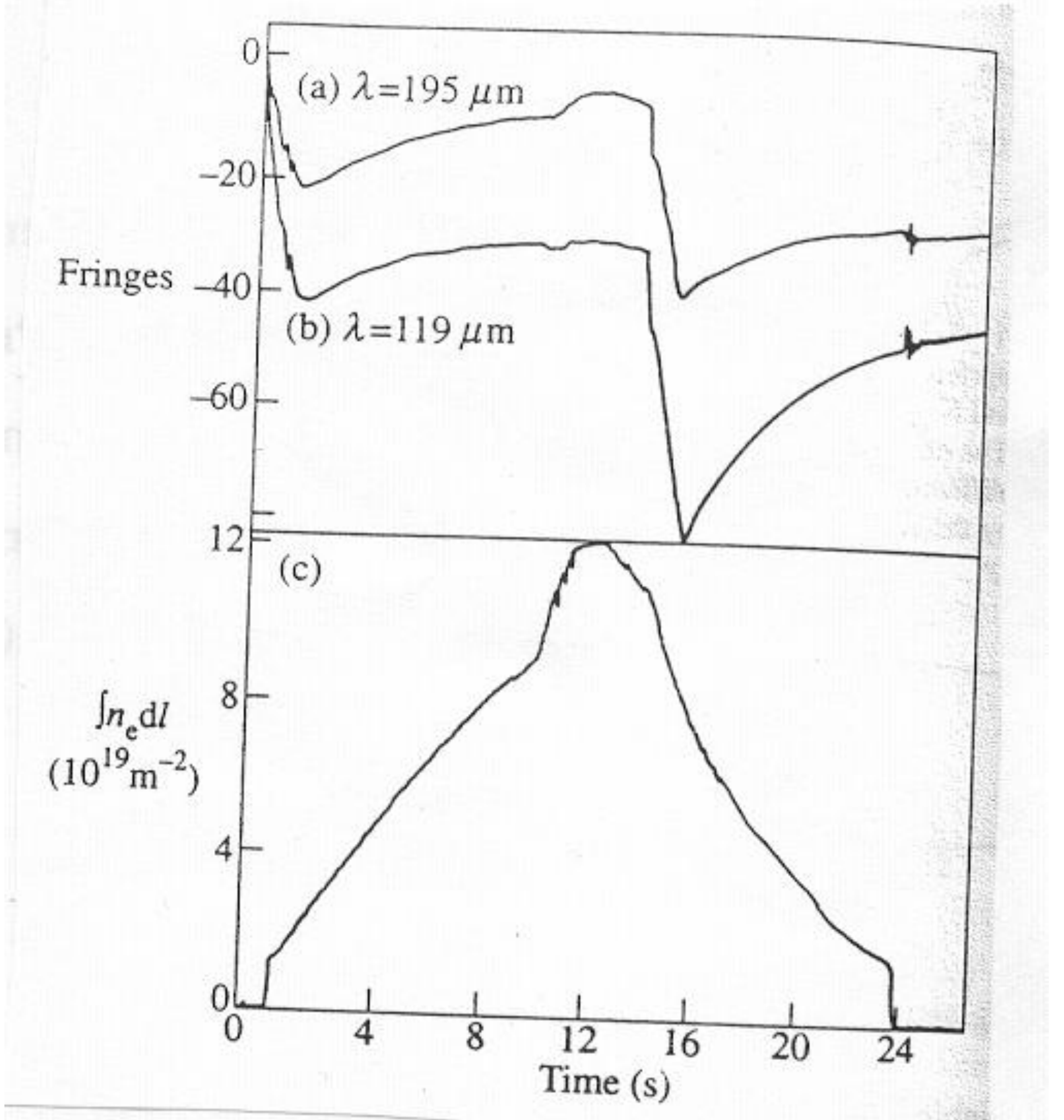
$$\Delta\varphi(t) \simeq \frac{\pi}{\lambda_0 n_c}\int n_e(x,t)\,dx \qquad \text{for } n_e \ll n_c$$



Two-Color Interferometry

Mechanical vibration: inversely proportional to the wavelength

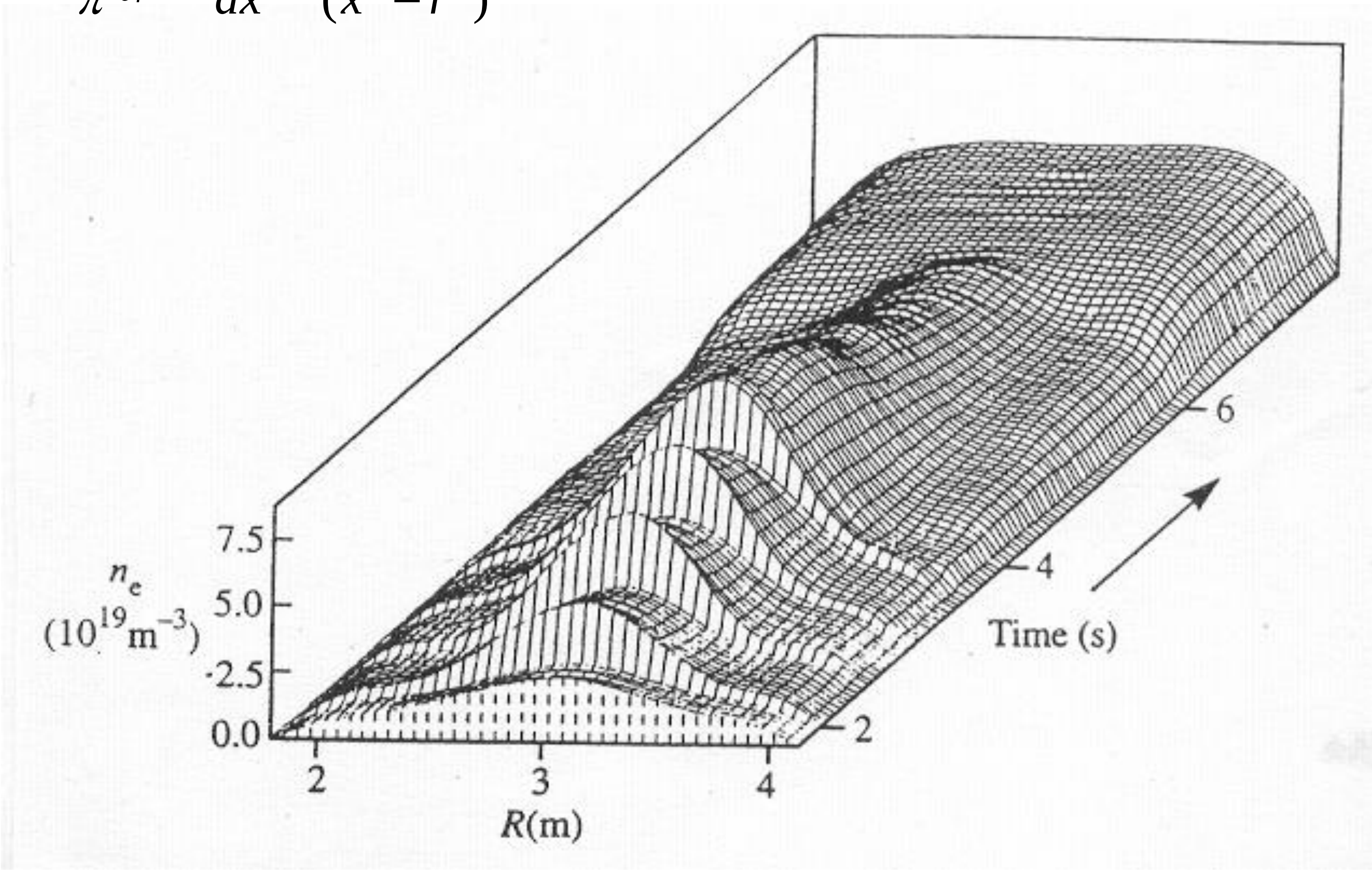
- JET (119μm, 195 μm)
- C-Mod (10.6μm, 0.633 μm)



Inversion of Line-Integrated Density Profiles

Abel inversion:

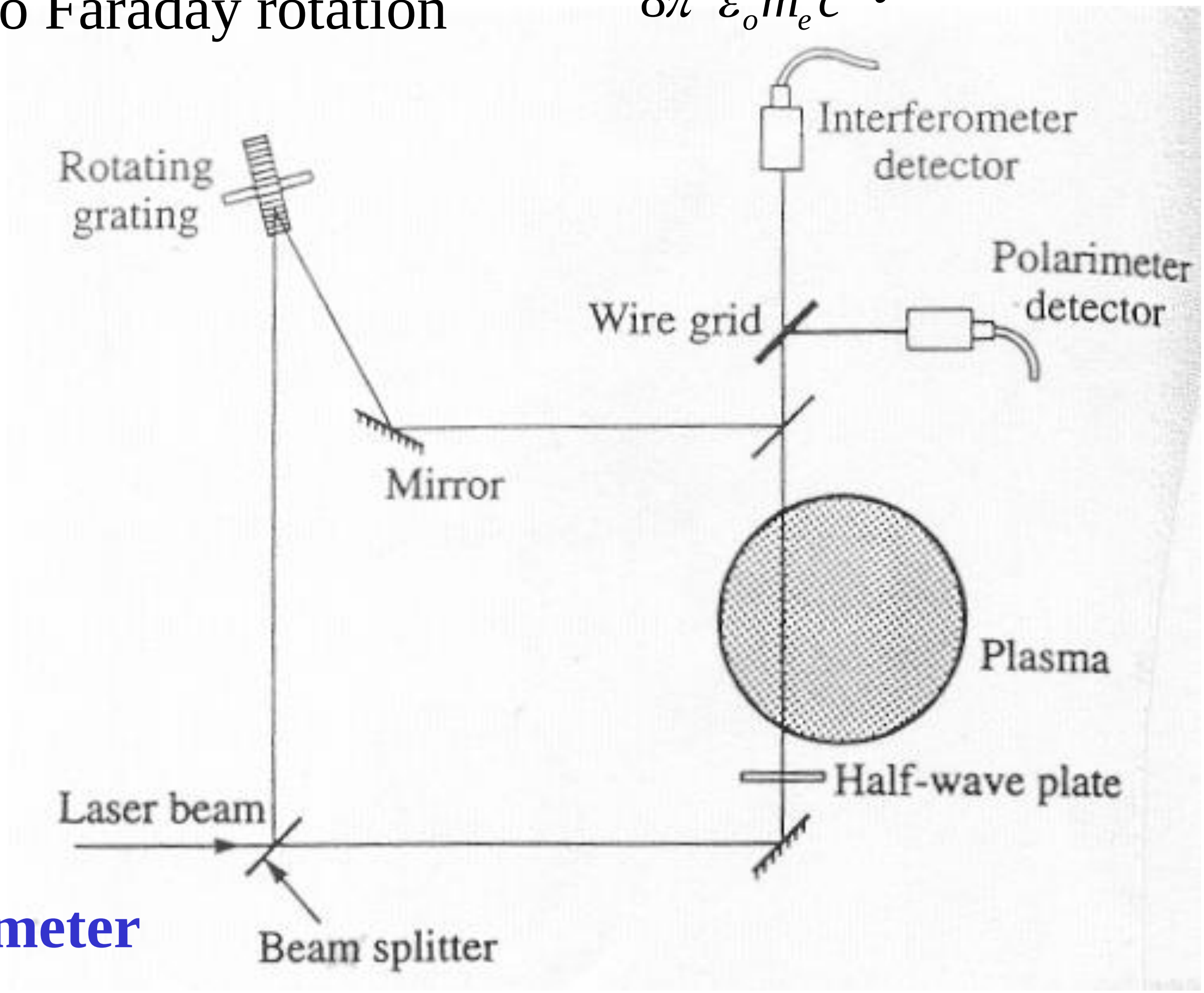
$$n_e(r) = -\frac{1}{\pi}\int_r^a \frac{dN_e(x)}{dx}\frac{1}{(x^2 - r^2)^{1/2}}dx$$



Polarimetry: Faraday Rotation

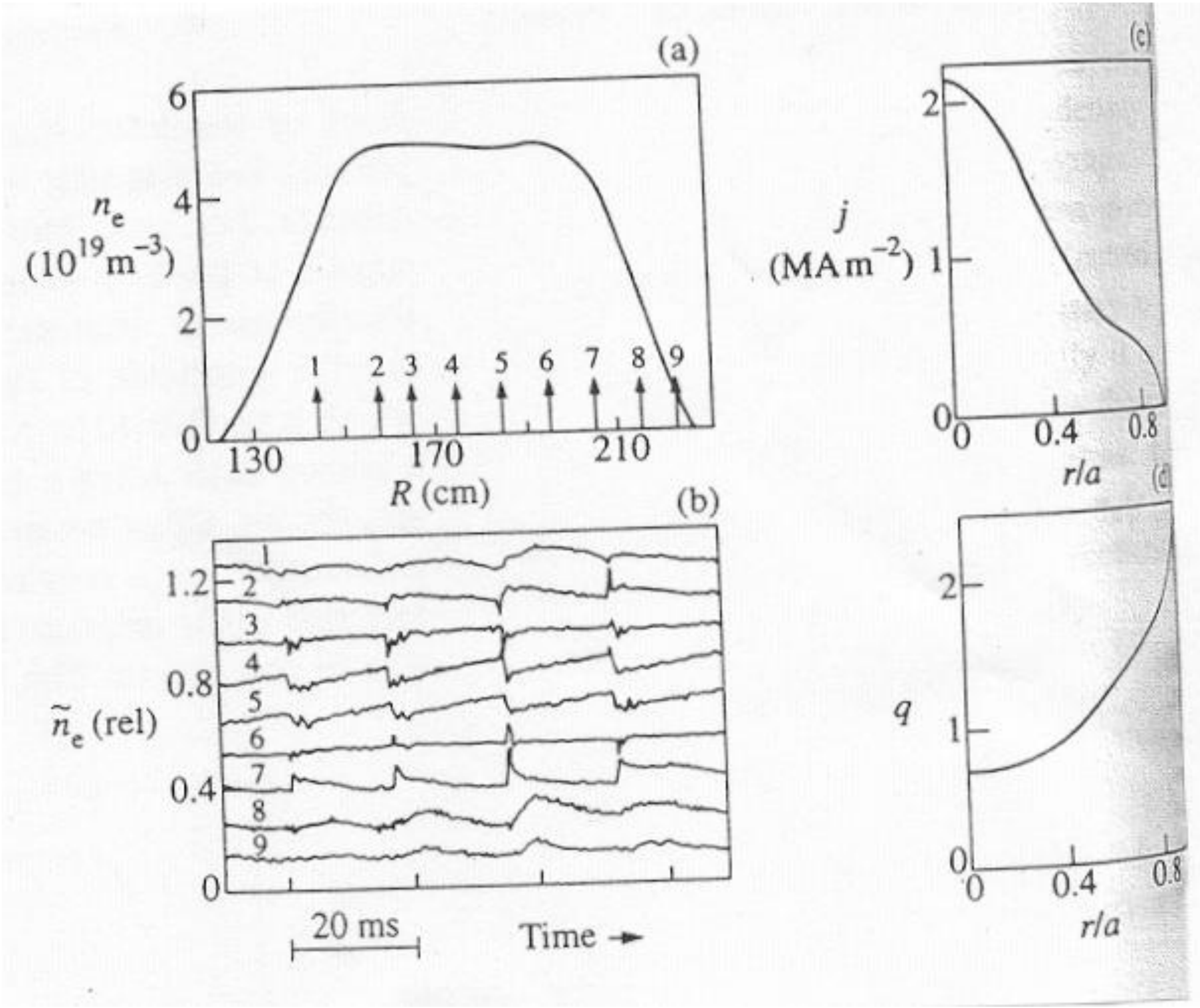
Refractive index $$\mu_{\pm} = 1 - \frac{\omega_p^2}{\omega^2}\frac{\omega}{\omega \pm \omega_{ce}}$$

Rotation angle due to Faraday rotation $$\theta_F = \frac{\lambda^2 e^3}{8\pi^2 \varepsilon_o m_e^2 c^3}\int n_e B_{//} dl$$



TEXTOR Polarimeter

Polarimeter Data for a Sawtoothing Plasma



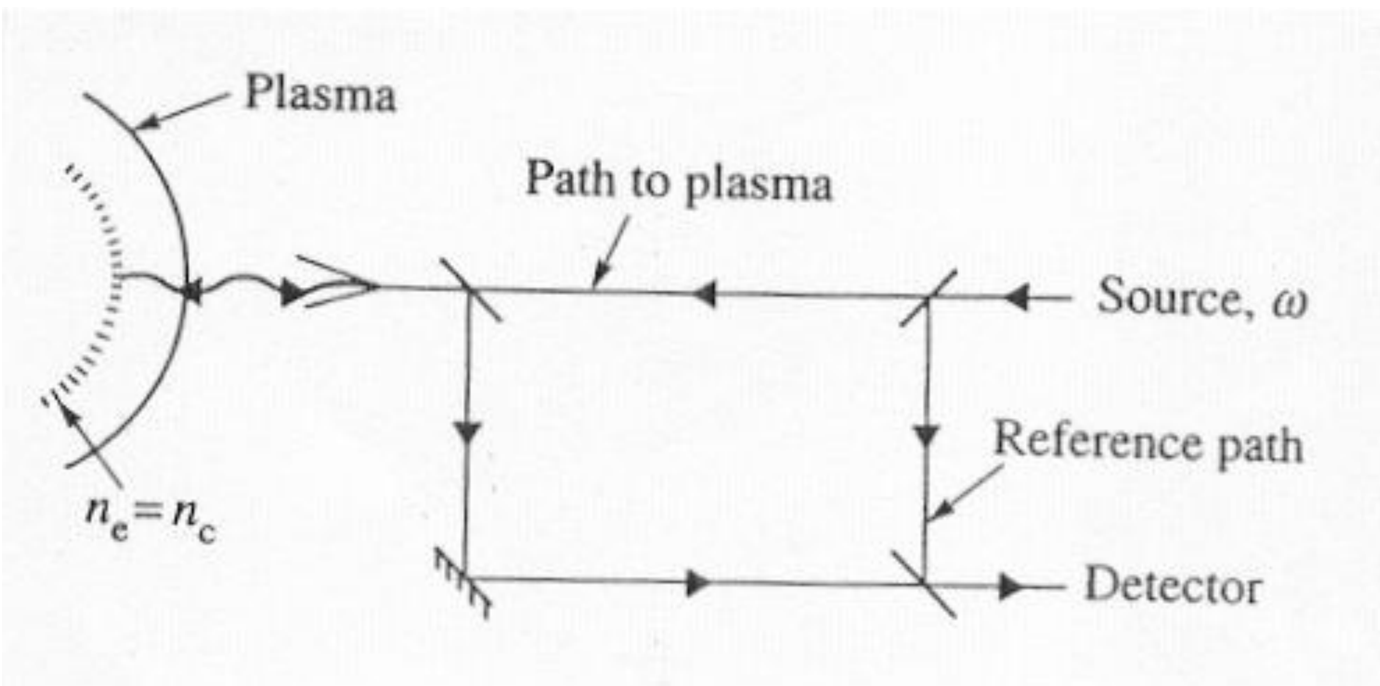
TEXTOR

$q_o \sim 0.7$

Reflectometry

The plasma density can be obtained by detecting the wave reflected at the cut-off positions. Different techniques are

- Linear frequency sweep
- Dual frequency differential phase
- Amplitude modulation
- Pulsed radar, pulse compression radar, noise correlation radar

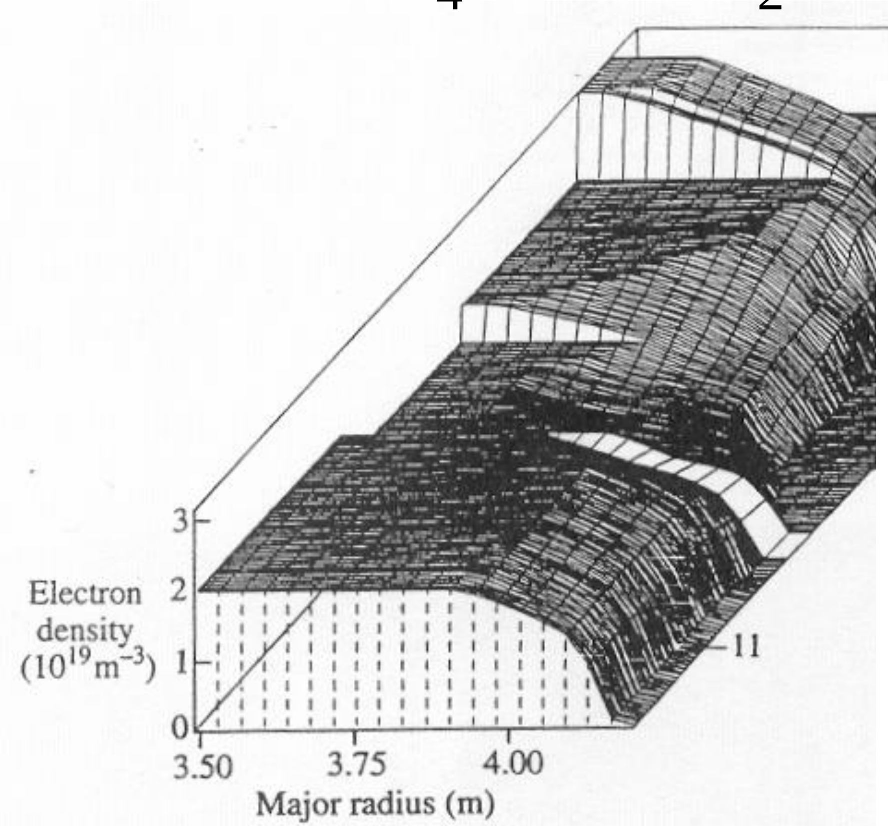


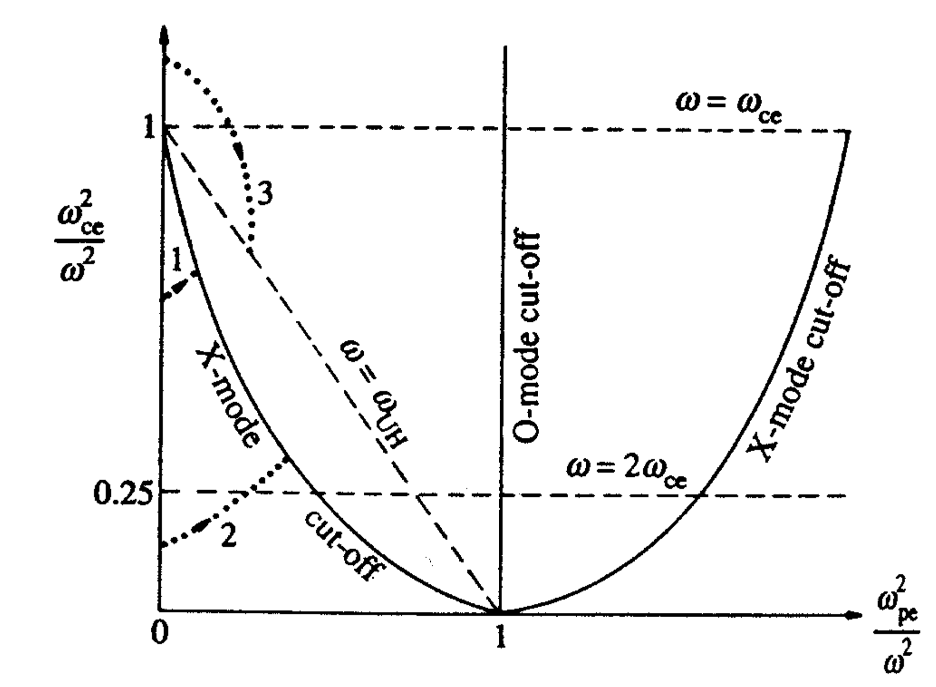
Reflectometry

Accessibility makes reflectometry in two independent modes

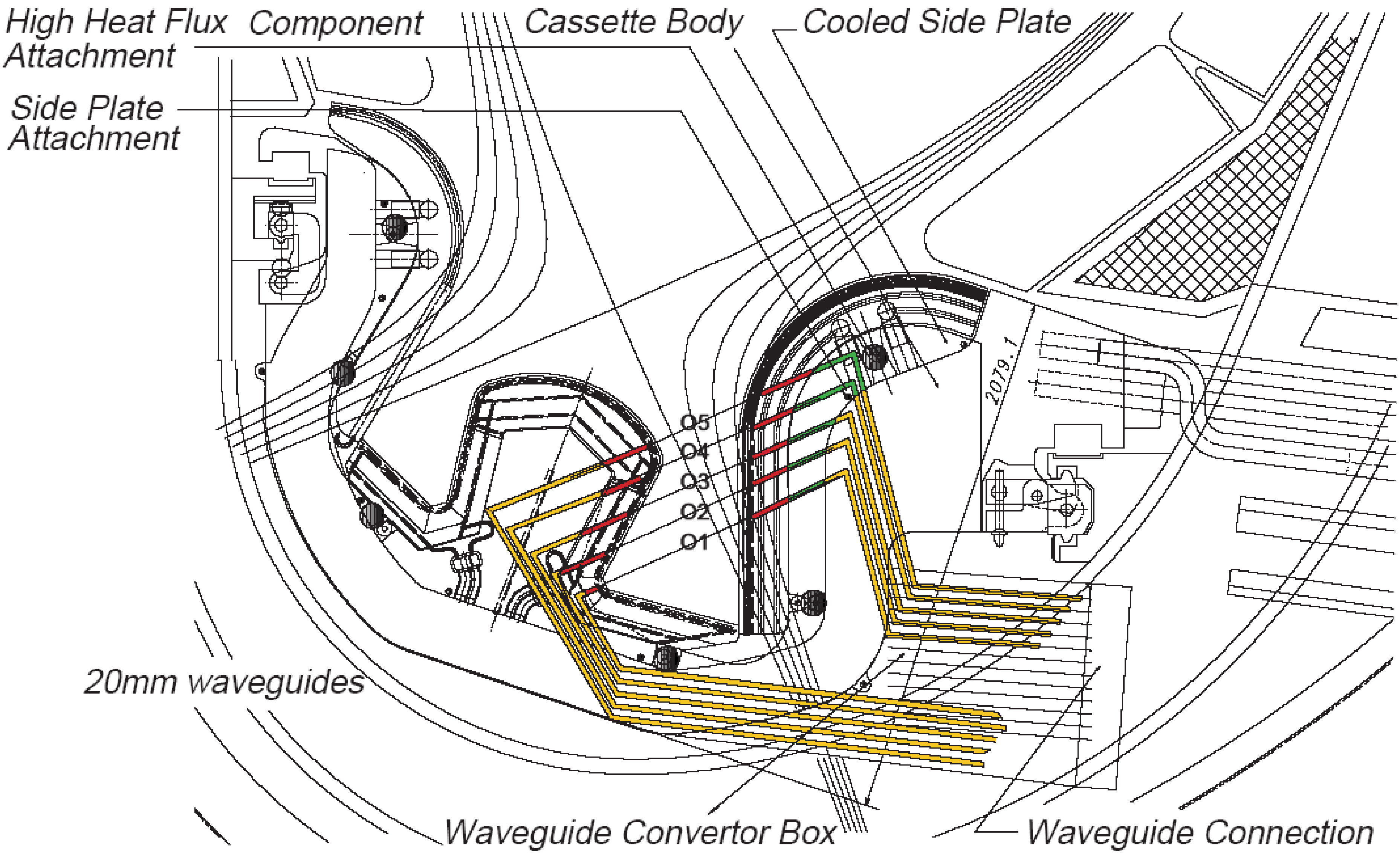
- O-mode : cut-off at plasma frequency $\omega = \omega_{pe} = (n_c e^2 / \varepsilon_o m_e)^{1/2}$
- X-Mode: critical density depends also on magnetic field strength

$$\omega = \omega_{U,L} = \left(\frac{\omega_{ce}^2}{4} + \omega_{pe}^2\right)^{1/2} \pm \frac{\omega_{ce}}{2}$$

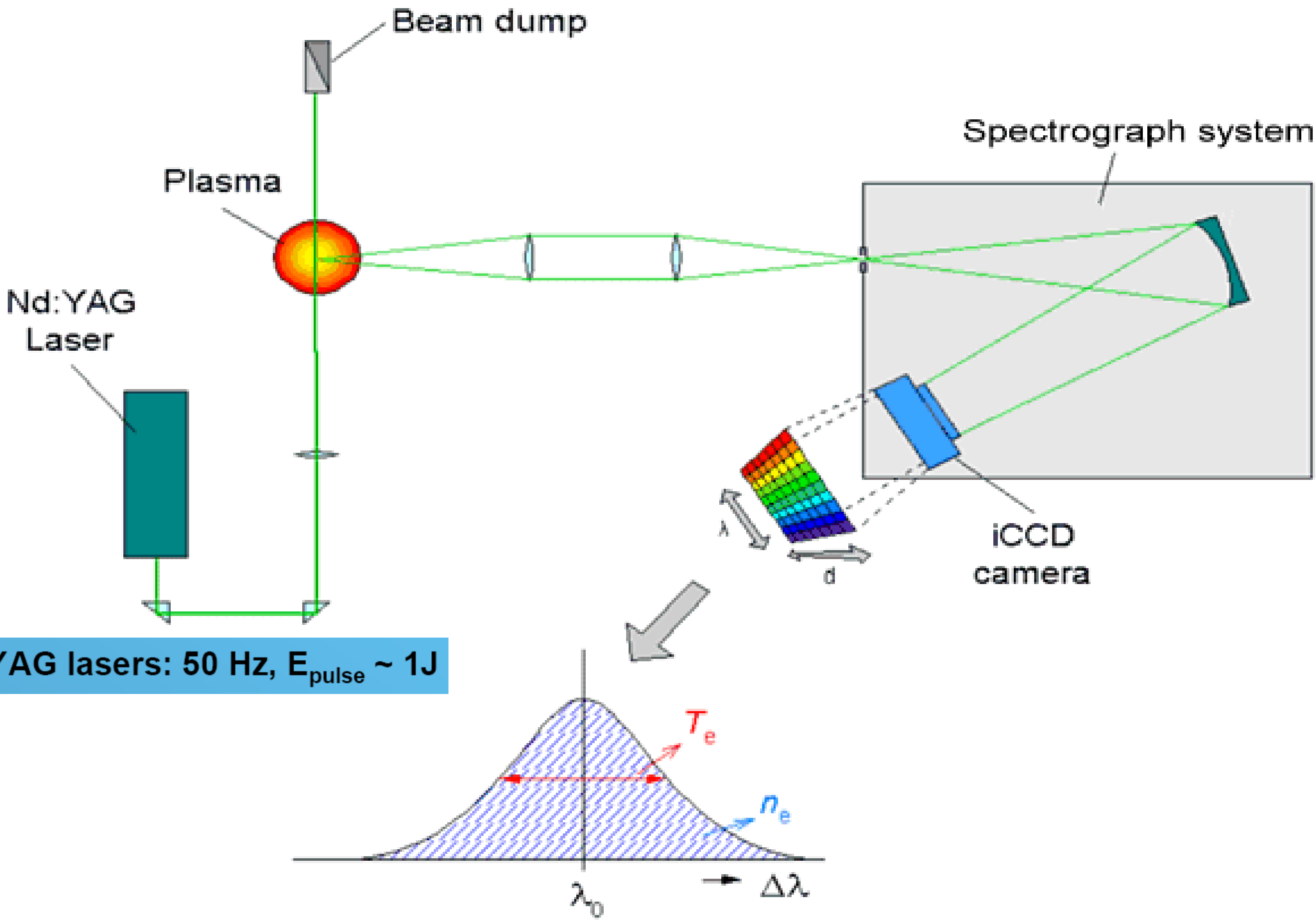




ITER Divertor Interferometer/Reflectometry

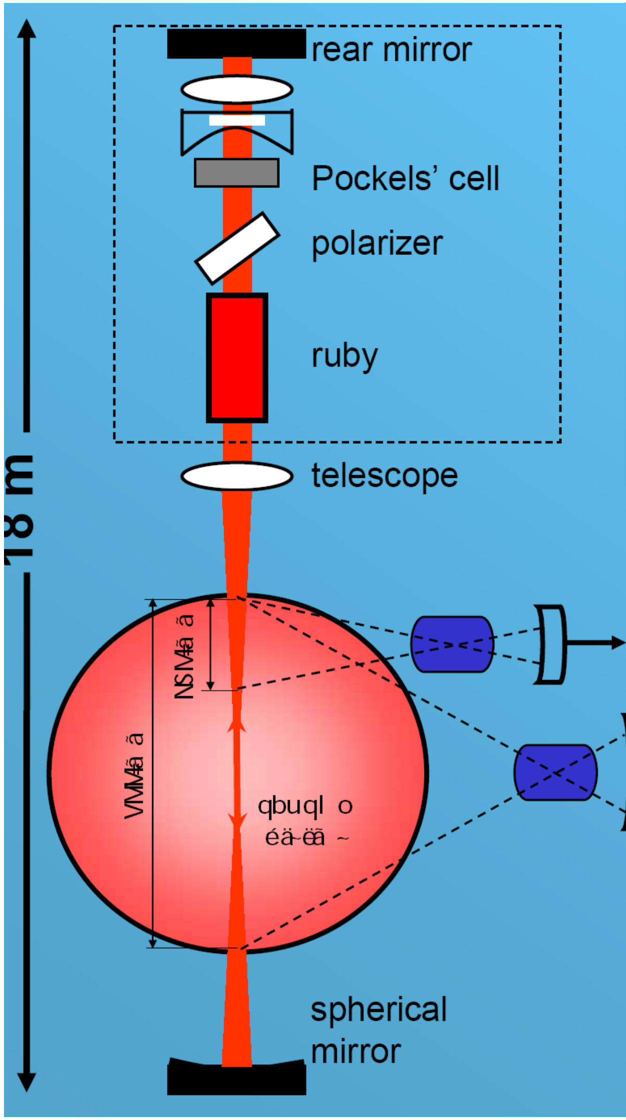


Principle of Thomson Scattering



Nd:YAG lasers: 50 Hz, E_{pulse} ~ 1J

Multi-Pulse TEXTOR TVTS System



Achieved specifications:

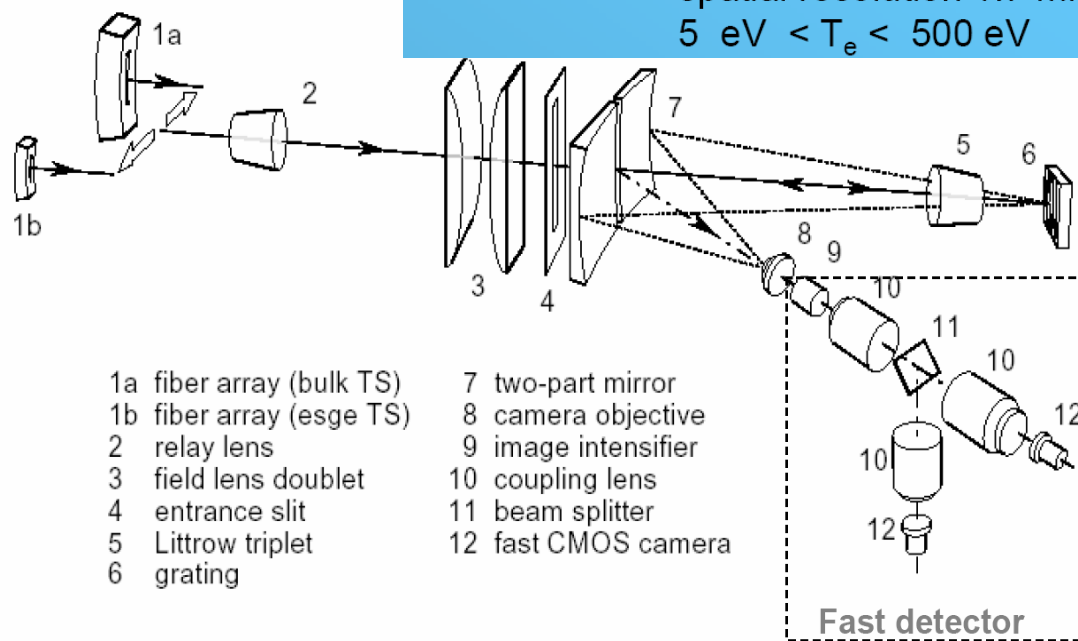
- **pulse energy 12-15 J**
- **pulse width at FWHM 1 μs**
- **rep. rate 5 kHz**
- **Number of pulses ~ 20**
- **burst length ~ 4 ms**
- **divergence ≤ 0.5 mrad**
- **number of bursts 1**

Fast repetitive high spatial resolution Thomson scattering system

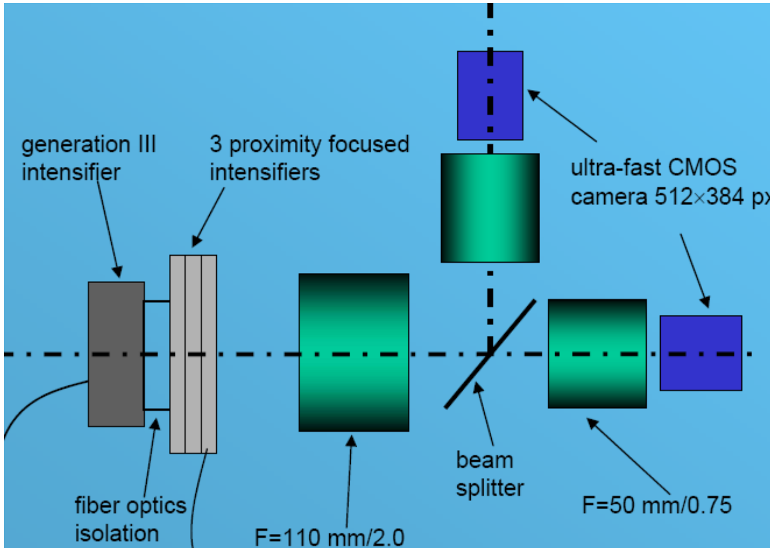
- Fast repetitive high power laser
- Spectrometer equipped with fast detector

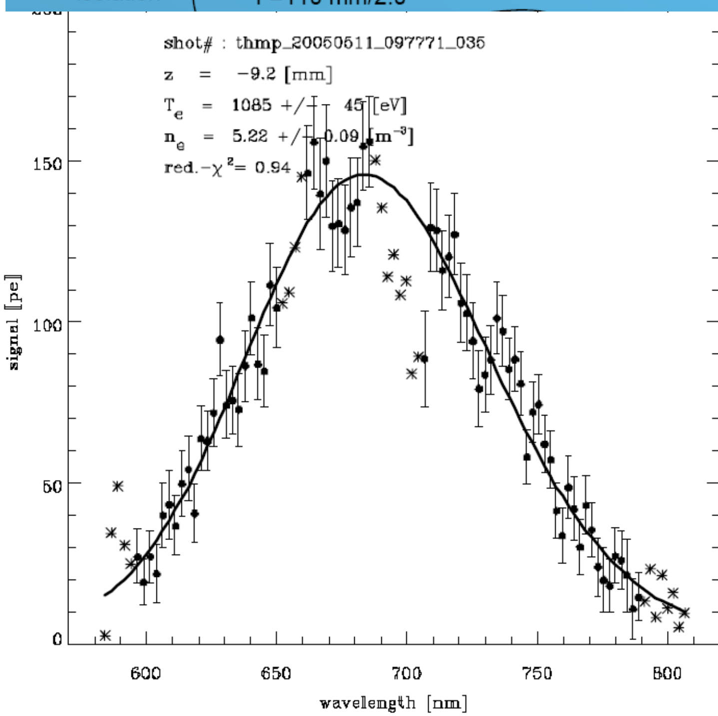
Full chord TS: -450 mm < z < +450 mm
spatial resolution 7.5 mm
50 eV < T_e < 5 keV

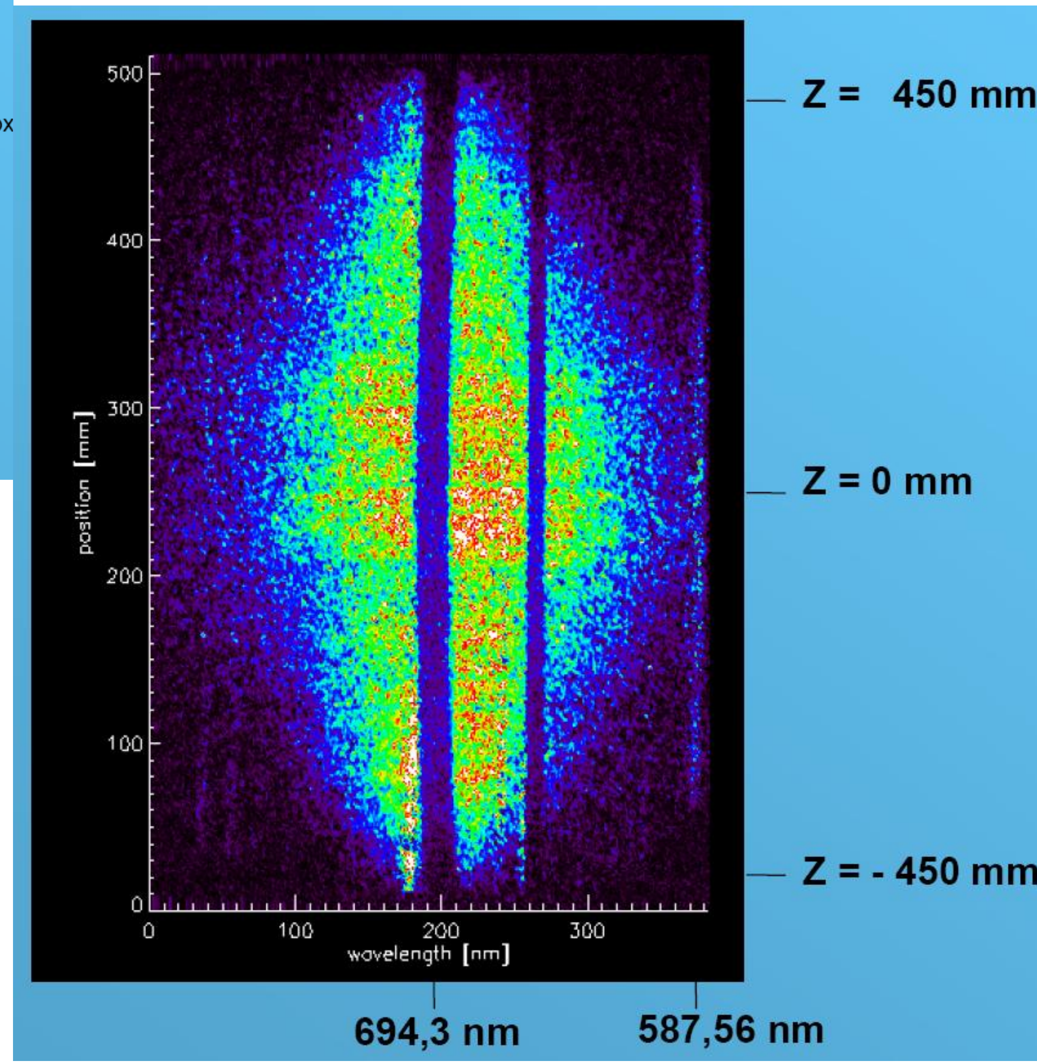
Edge TS: +340 mm < z < +500 mm
spatial resolution 1.7 mm
5 eV < T_e < 500 eV



TEXTOR TVTS System







JET LIDAR Thomson Scattering

1J ruby laser (wavelength 694nm)

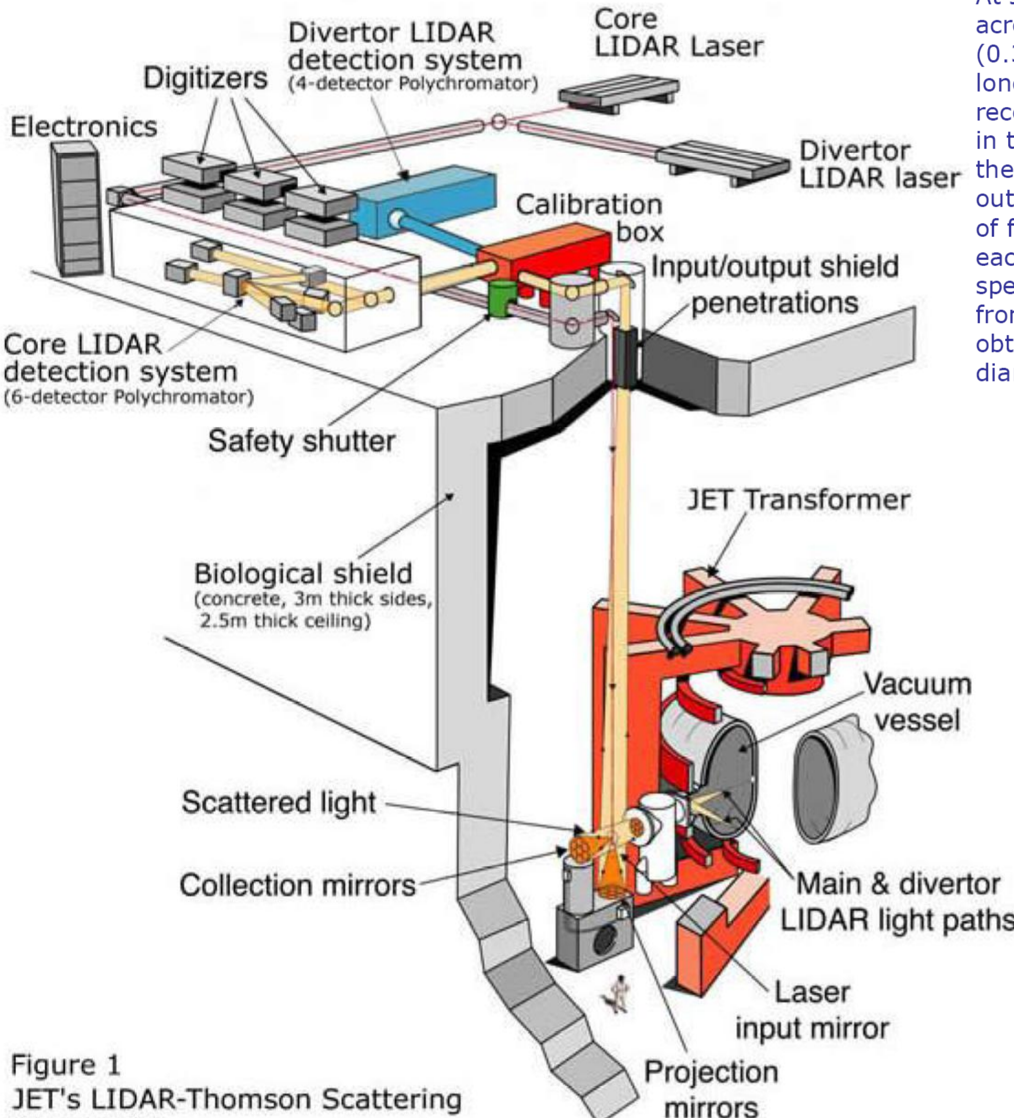
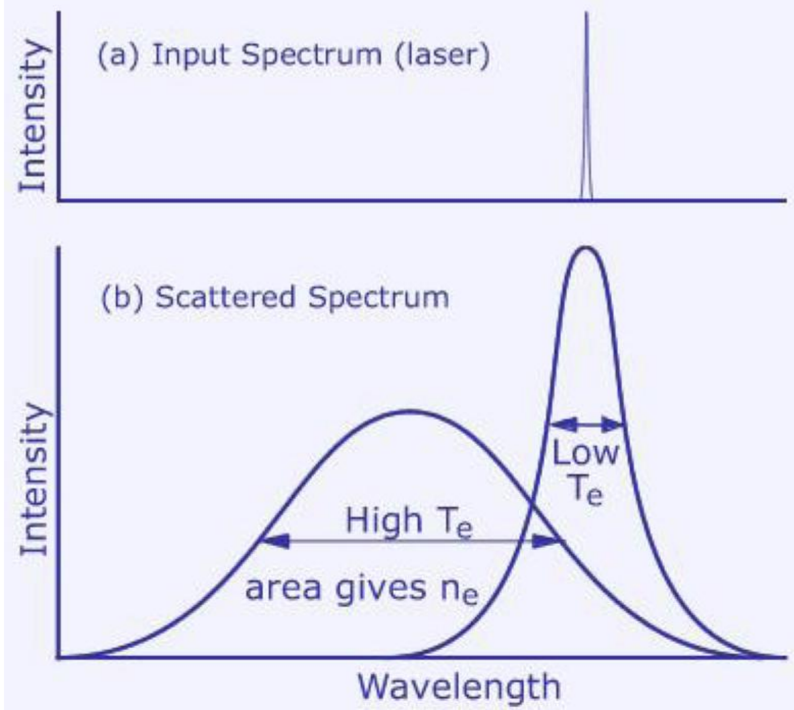


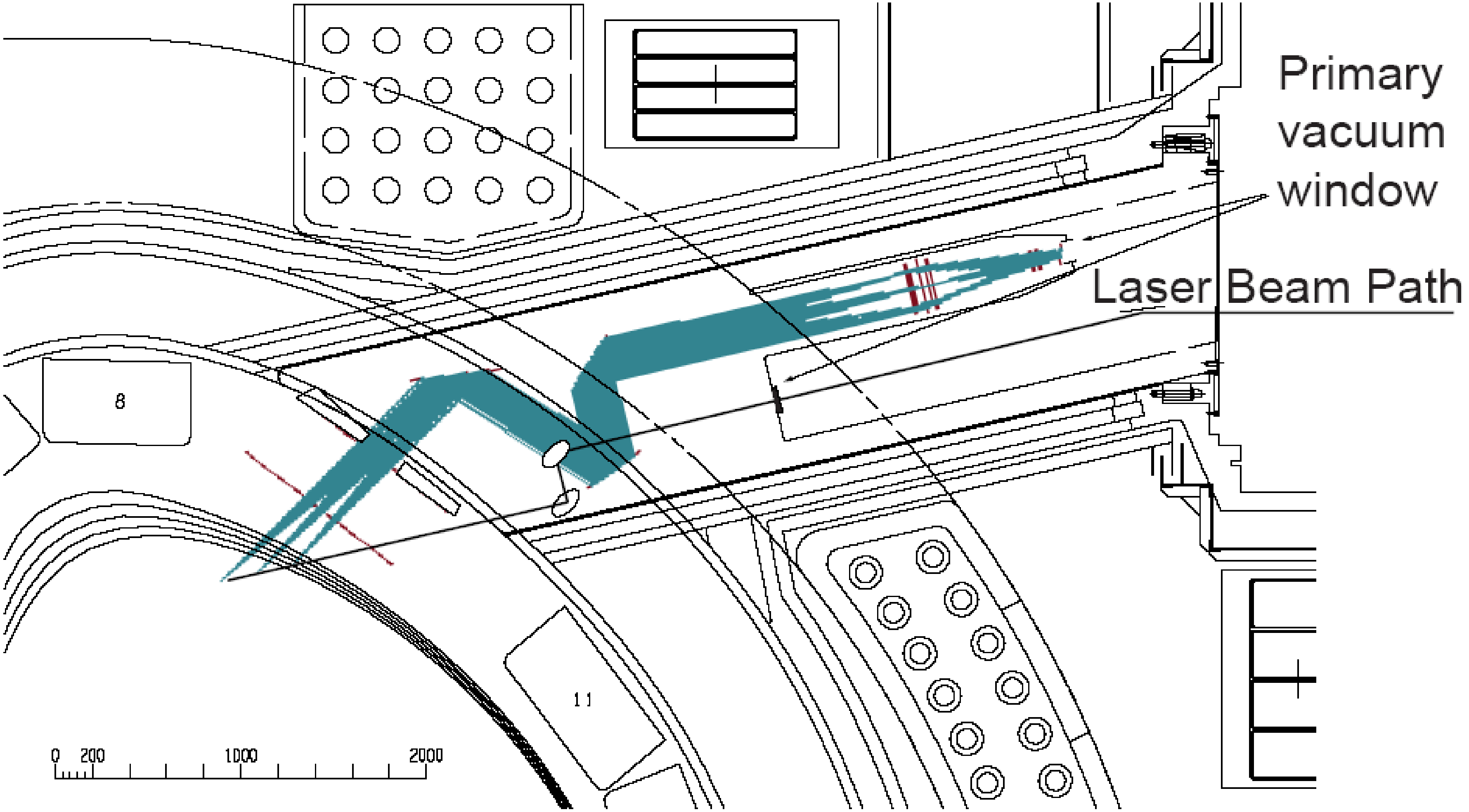
Figure 1
JET's LIDAR-Thomson Scattering Diagnostic

At JET we also want to know how the temperature and density vary across the plasma. To get this information we send a short laser pulse (0.3 nano-seconds duration which, at the speed of light, is only 10 cm long) across the plasma diameter. By using a fast detection and recording system, we can observe its progress by capturing the changes in the back-scattered spectrum. We can then analyse these changes as the pulse passes from the relatively cool edge, through the hot core and out again through the opposite plasma edge. Since we know by the time of flight, or LIDAR, principle where the laser pulse is in the plasma at each instant, we can compute from the instantaneous scattered spectrum the local values of temperature and density in the plasma, ie. from the time of flight of one laser pulse through the plasma we can obtain the temperature and density variations across the whole diameter.

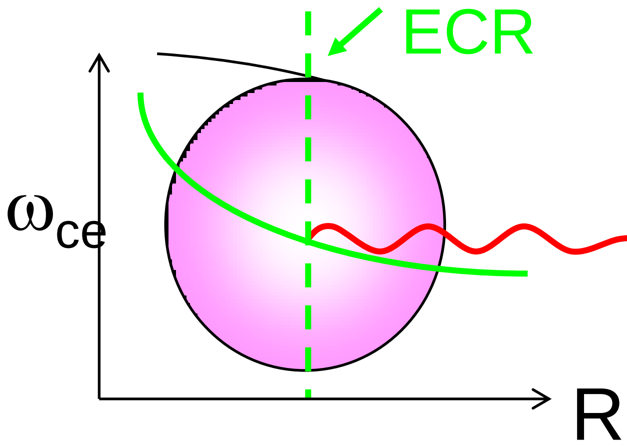
Figure 2 Input and Scattered Spectra

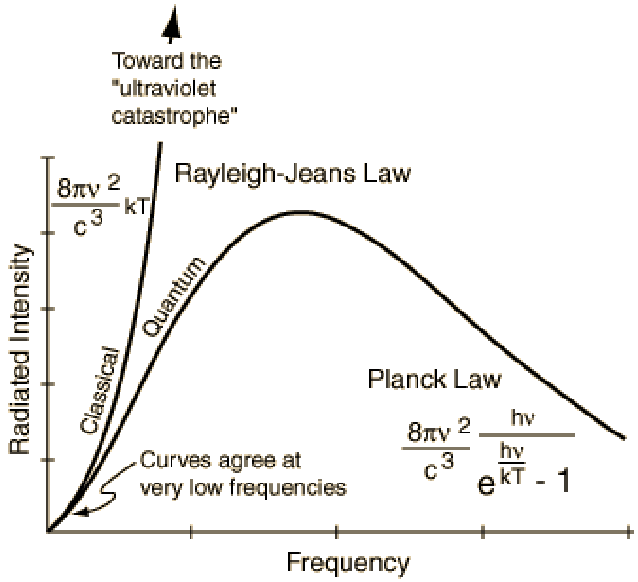


ITER Thomson Scattering System



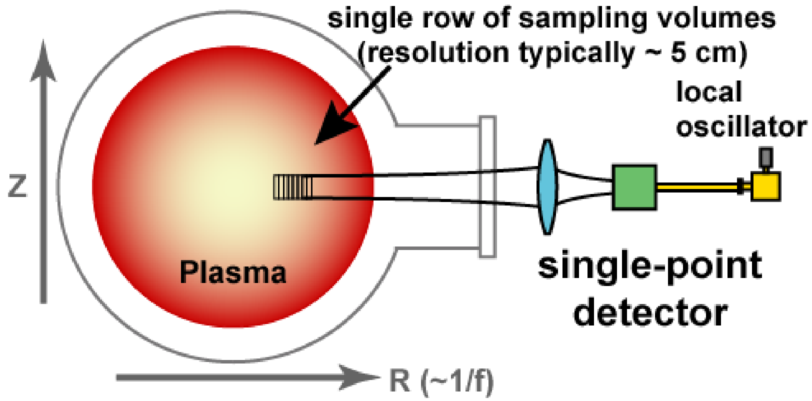
Electron Cyclotron Emission (ECE)



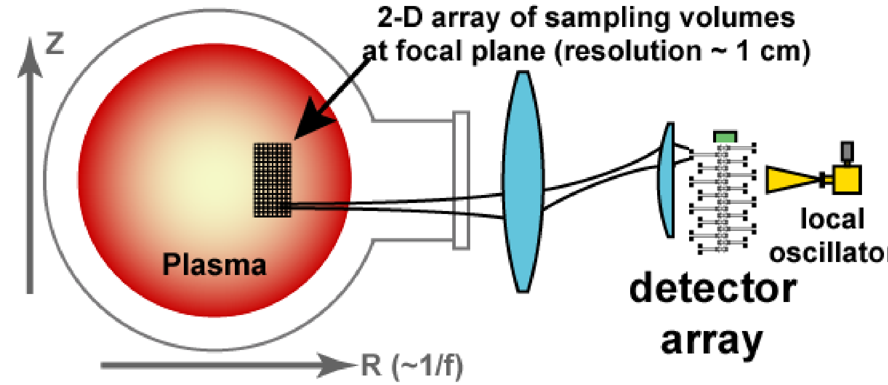


- Electromagnetic (EM) waves are emitted at the electron cyclotron resonance (ECR) layer at a series of discrete harmonic frequencies:
  - $\omega_n = n\omega_{ce}$, $\omega_{ce}(R) \propto B \propto 1/R$
  - If the plasma is Maxwellian and optically thick, the emission can be described as blackbody radiation in the Rayleigh-Jeans law
  - Intensity: $I(\omega) = I_B(\omega) \approx \dfrac{T_e \omega^2}{8\pi^3 c^2}$

2D ECE Imaging System



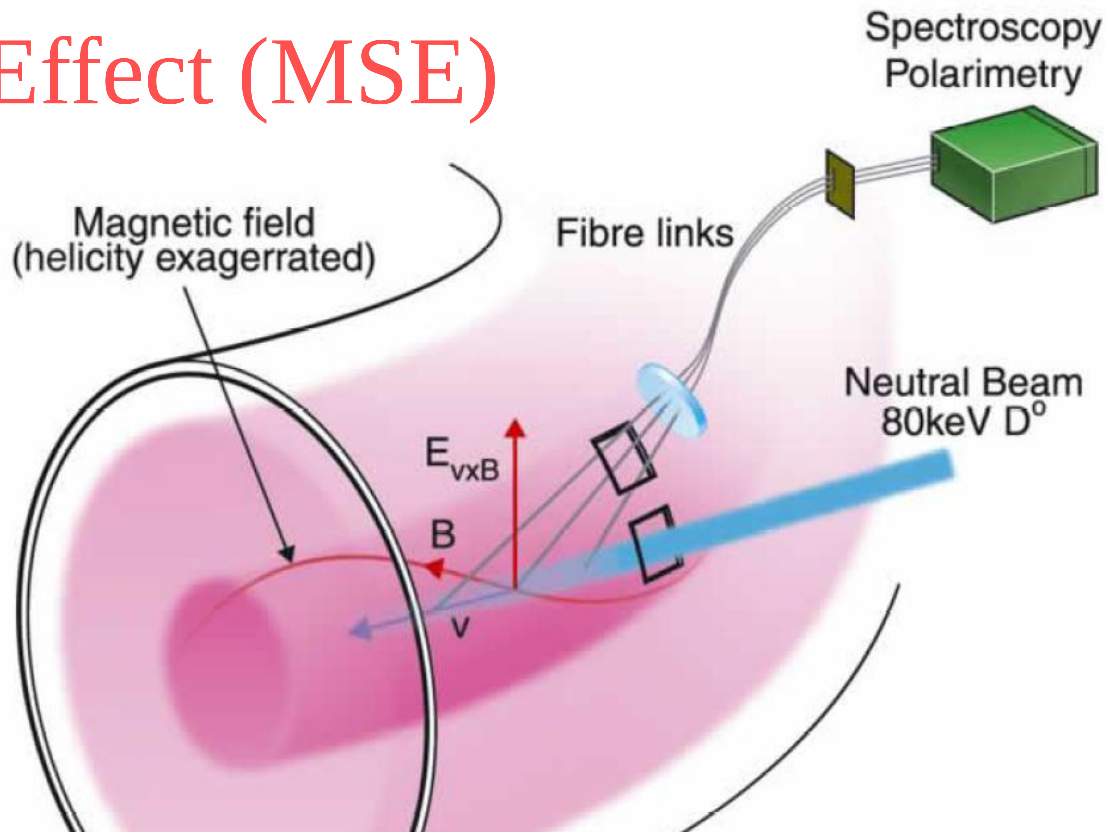
Conventional 1-D ECE system



2-D ECE imaging system

- ECE measurement is an established tool for electron temperature measurement in high temperature plasmas
- Sensitive 1-D array detector, imaging optics, and wide-band mm wave antenna, and IF electronics are required for 2-D imaging system
- T_e fluctuation measurement
  - Real time fluctuations can be studied up to ~1% level
  - Fluctuation studies down to 0.1 % level have been performed using long time integration

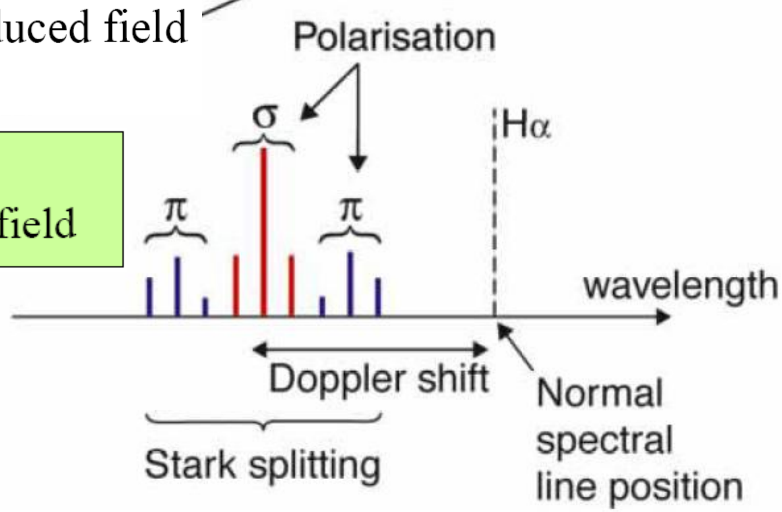
Motional Stark Effect (MSE)



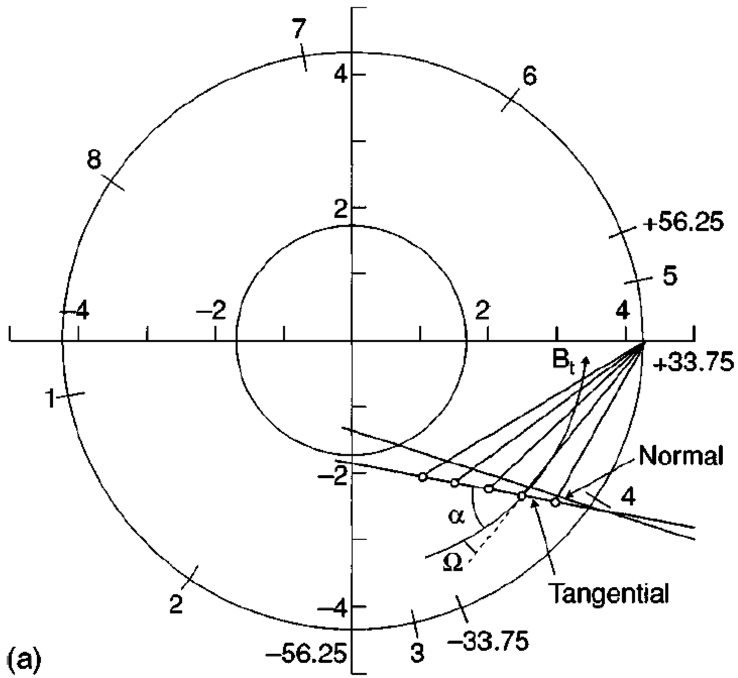
$$\underbrace{\boldsymbol{E}}_{measured} = \overbrace{\boldsymbol{V}}^{known\ from\ DNB} \times \underbrace{\boldsymbol{B}}_{unkown}$$

♣ If we can measure the polarization angle of the σ (or π) components in the Stark spectra with respect to the induced field $\boldsymbol{E}$, we can know the direction of $\boldsymbol{B}$ (pitch angle)

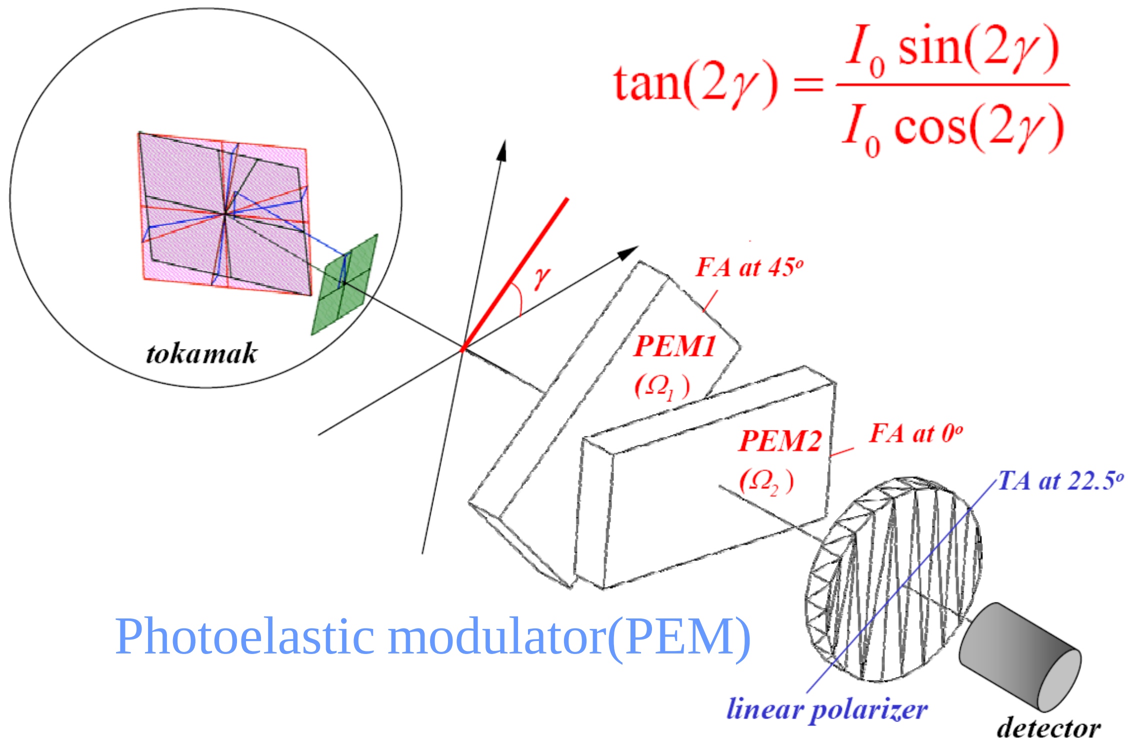
π components : polarized **parallel** to the local E field
σ components : polarized **perpendicular** to the local E field

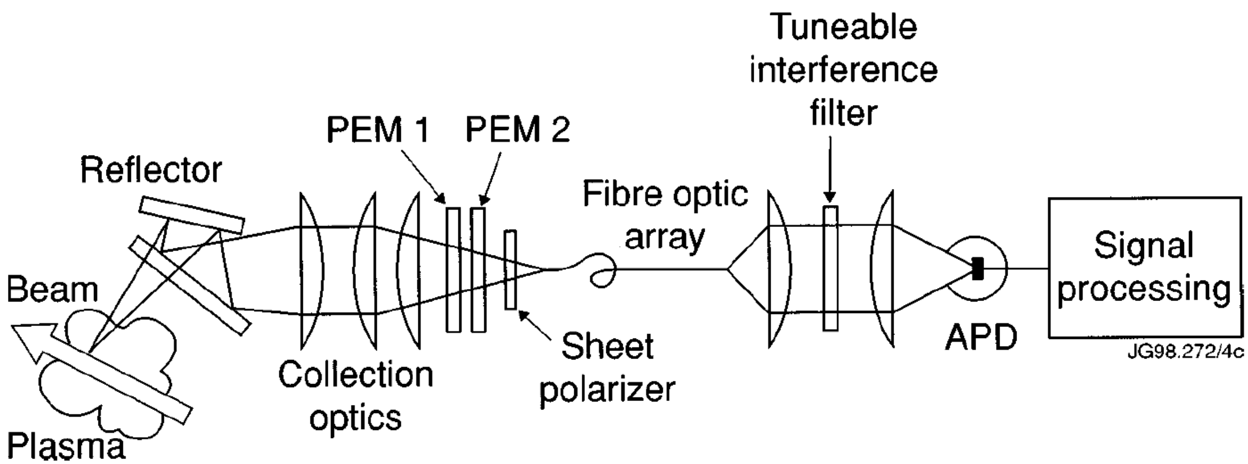


Motional Stark Effect (MSE)

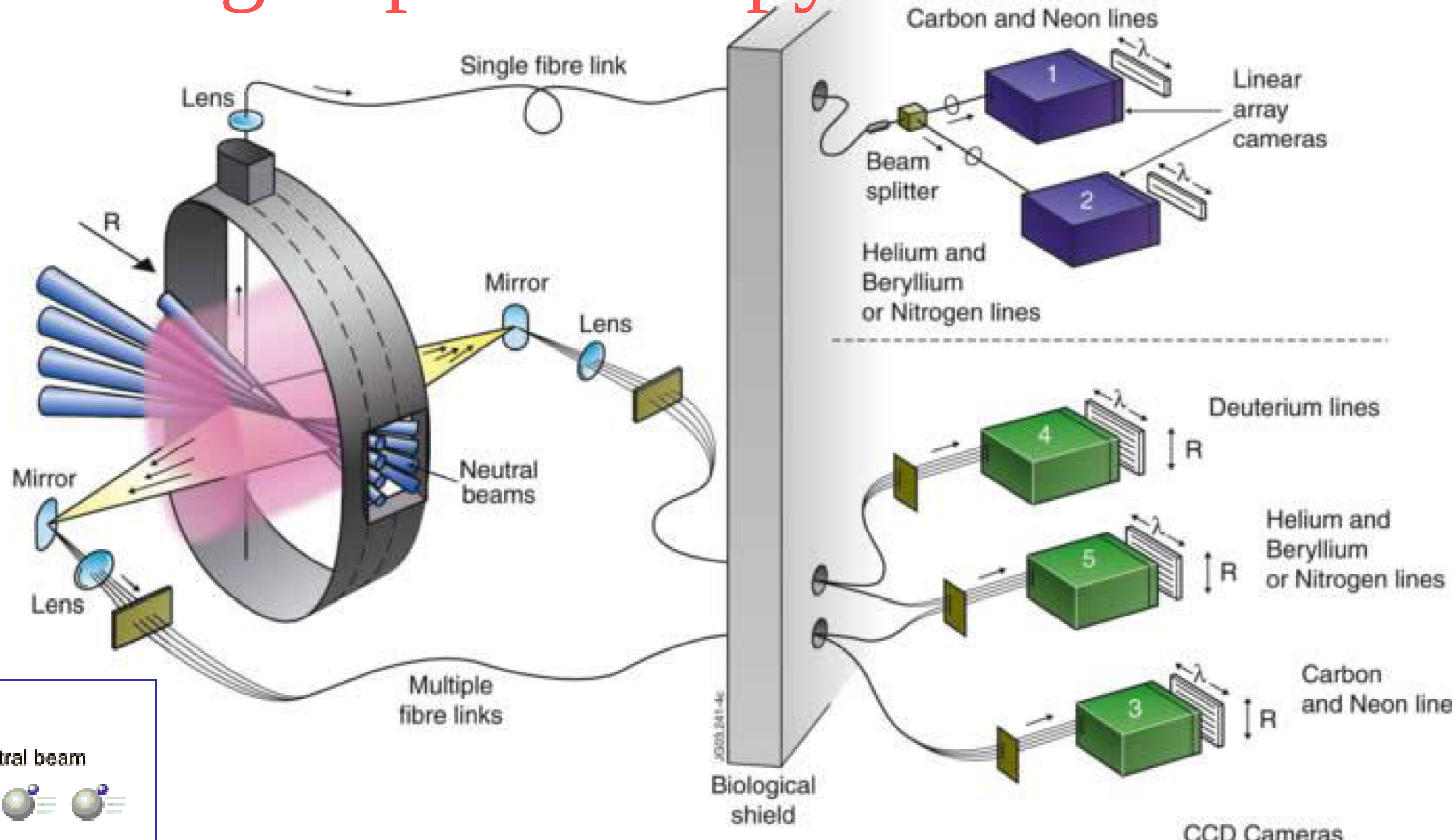


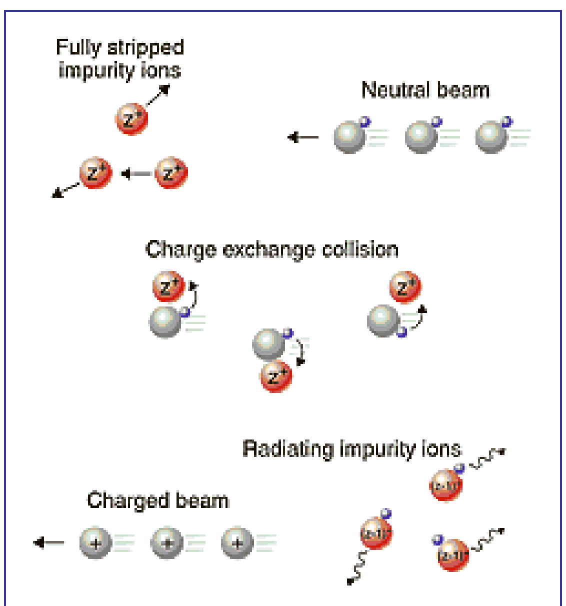
$$\tan(2\gamma) = \frac{I_0 \sin(2\gamma)}{I_0 \cos(2\gamma)}$$





Charge Exchange Spectroscopy





$$X^{+z_0} + D^0_{beam}(1) \rightarrow X^{+z_0}(nl) + D^+_{beam}$$

Subsequently the hydrogen-like impurity ion radiates as

$$X^{+z_0-1}(n'l') \rightarrow X^{+z_0-1}(n''l'') + h\nu$$

→ densities of fully stripped low-Z ions and ion temperatures and plasma rotation

Beam Emission Spectroscopy (BES)

To obtain two-dimensional measurements of density fluctuations in the confined regions of hot plasmas, the Beam Emission Spectroscopy (BES) diagnostic system has been utilised on a number of US tokamaks, such as DIII-D, NSTX, etc. The BES diagnostic system measures local, long wavelength density fluctuations by observing the fluorescence of the ITER diagnostic neutral beam. BES measures density fluctuations by observing the Doppler-shifted D_α emission. Fluctuations in the light emission intensity are proportional to the local density fluctuations that depend on the local plasma density, temperature, beam energy and Z_{eff}. The optical viewing sightlines are deployed so that they are nearly tangent to a magnetic flux surface at the intersection point with the neutral beam volume to achieve good radial and poloidal resolution.

Heavy Ion Beam Probe (HIBP)

heavy ion beam diagnostic (HIBD) as a candidate to perform the measurements of the B_p and E_r edge profiles in the ITER.

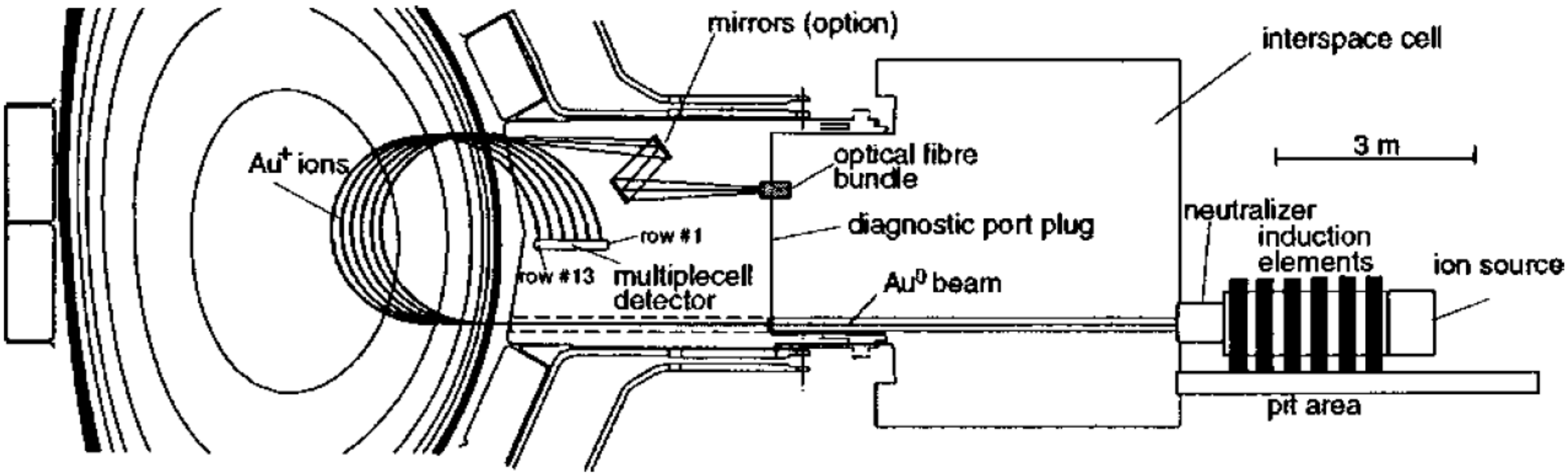


FIG. 2. Schematic layout of a HIBD for the ITER based on the injection of a Au^0 neutral beam. The Au^+ probing ions are collected in a matrix multiple cell detector. Also shown is an optional optical arrangement which can be used for imaging the emission light from the individual Au^+ beams into a spectrometer for measuring the ions speed.

X-ray Spectroscopy

- **High resolution X-ray spectroscopy has made invaluable contributions** to tokamak experiments by providing data on the **central** ion and electron temperatures, $\mathbf{T_i(0)}$ and $\mathbf{T_e(0)}$, the **central toroidal** plasma **rotation**, $\mathbf{v_t(0)}$, and the **ionization equilibrium**. *It has also been important for experimental verifications of atomic theories and interpretation of stellar flares.*

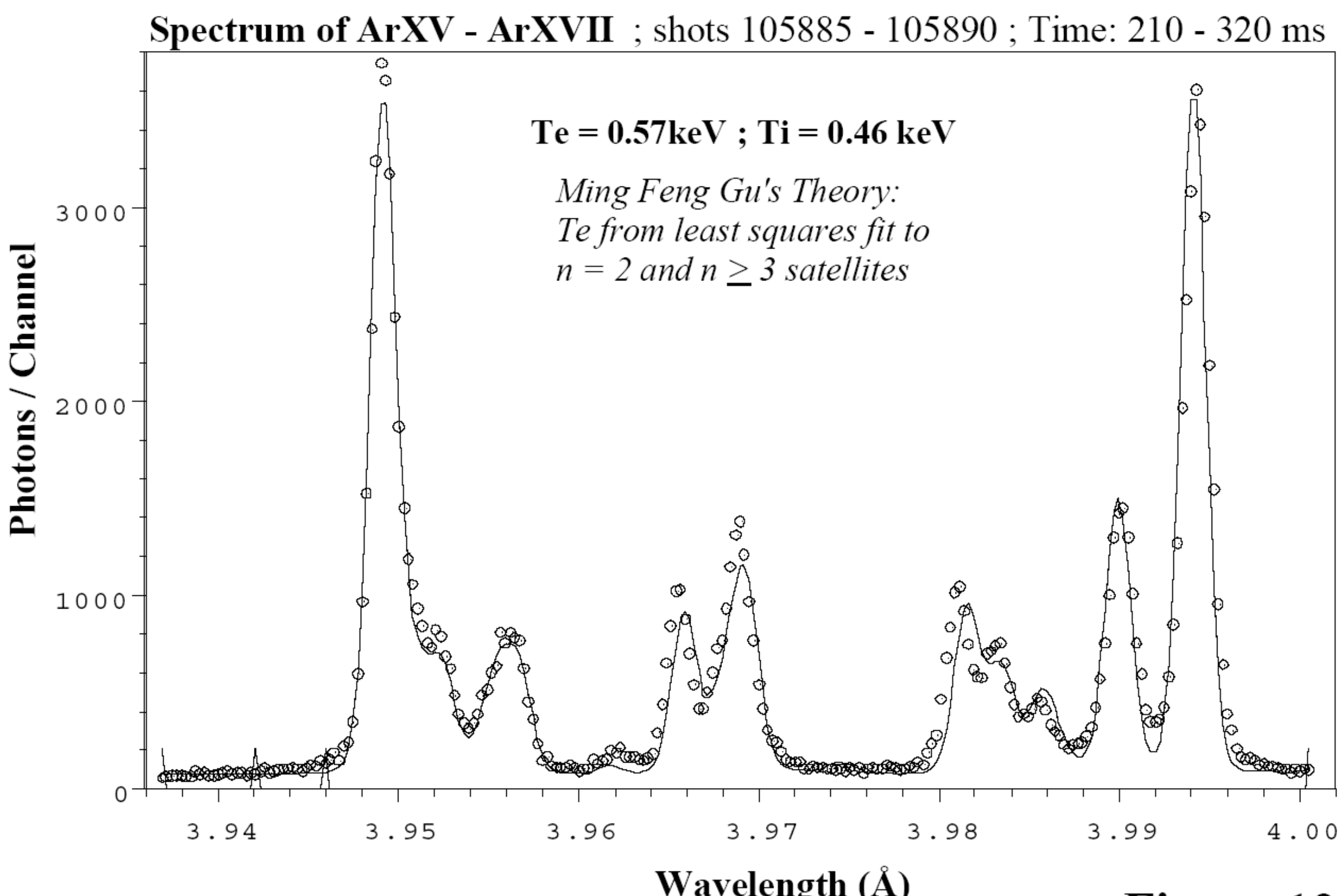
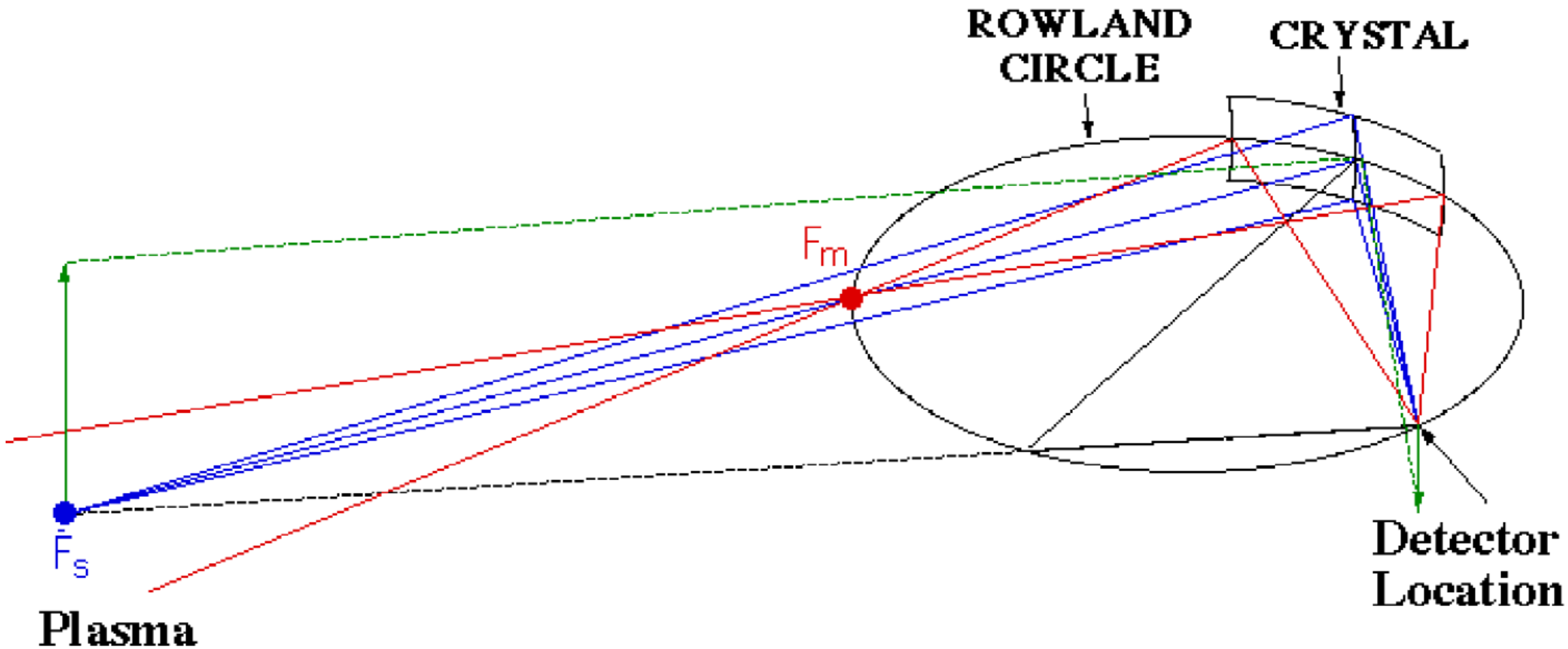


Figure 12

X-ray Imaging Crystal Spectroscopy



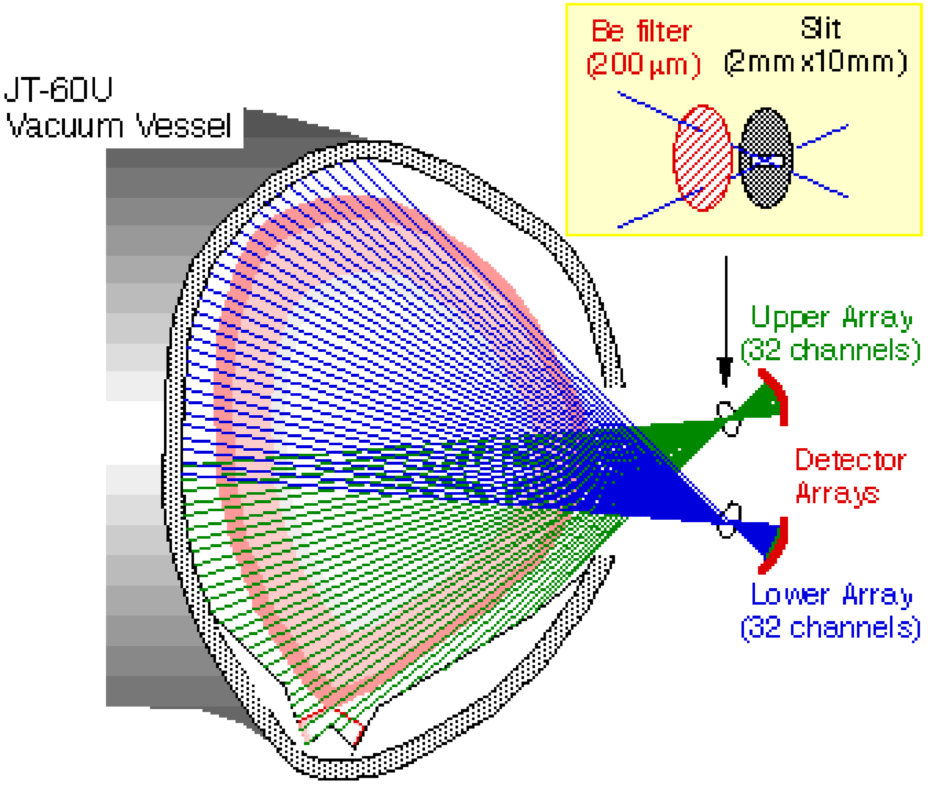
Parameters of the upgraded X-ray Imaging Crystal Spectrometer

- **Crystal:**
  spherically bent circular 110-quartz crystal: $2d = 4.913$ Å
  radius of curvature $\mathbf{R_c} = 375$ cm
  crystal disc diameter $d = 8$ cm

- **Bragg angles for Lines of ArXVII:** $53.5 < \theta < 54.5$ degrees

Soft X-ray Array

To observe collective behavior (density, temperature etc.) of electrons and magnetohydrodynamic activity in a high temperature plasma



A schematic picture of viewing lines of upper and lower detector arrays.

[Detectors, Diagnostic Method]

Soft X-rays emitted as bremsstrahlung by free electrons in a plasma are detected by PIN diodes and a Beryllium (Be) filter with 200 μm thickness.

Bremsstrahlung is a function of electron density, temperature, and impurity contamination and is sensitive to electron temperature in the energy range of the soft X-ray. Evolution of the soft X-ray intensity profile suggests the collective motion of electrons or magnetohydrodynamic activity in a plasma.

[Specifications]

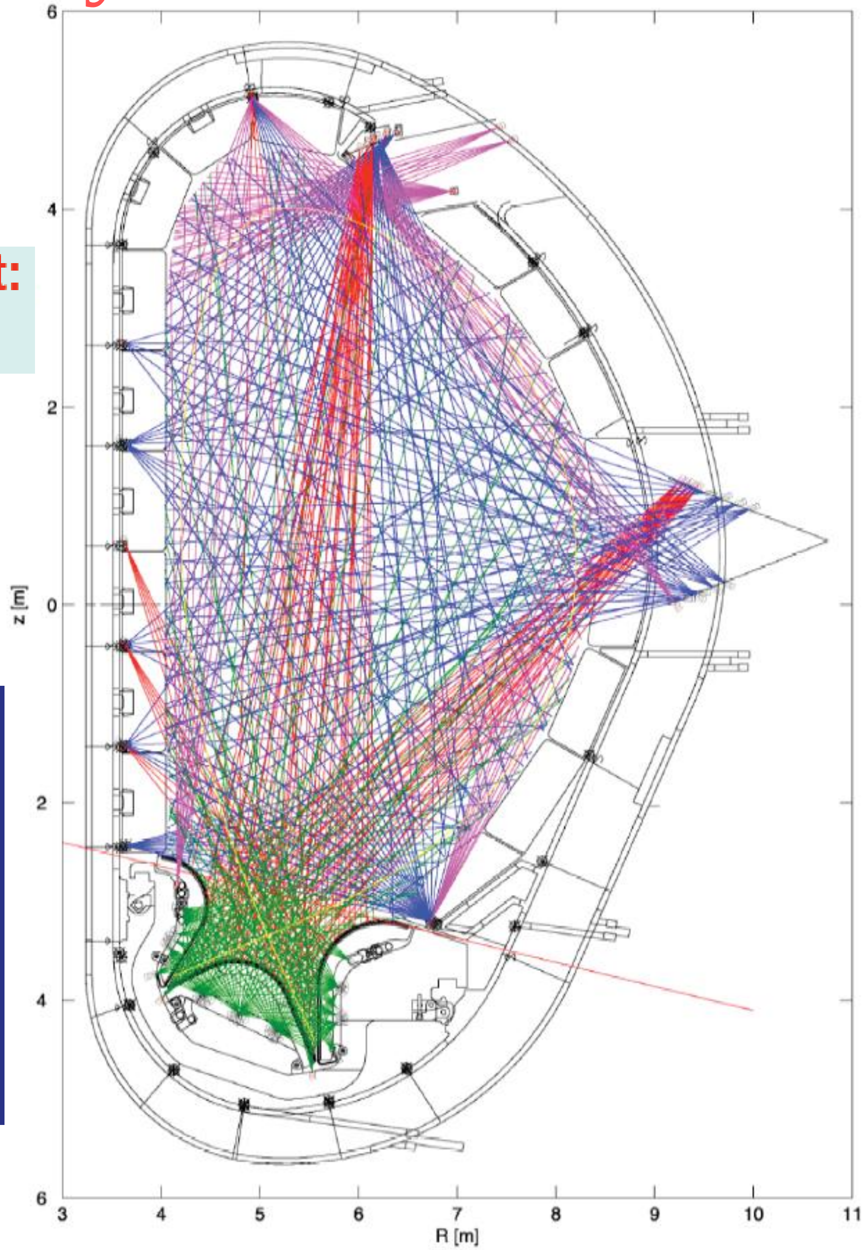
Time resolution : 80 ms

Spatial resolution: 3 - 5 cm

Bolometry

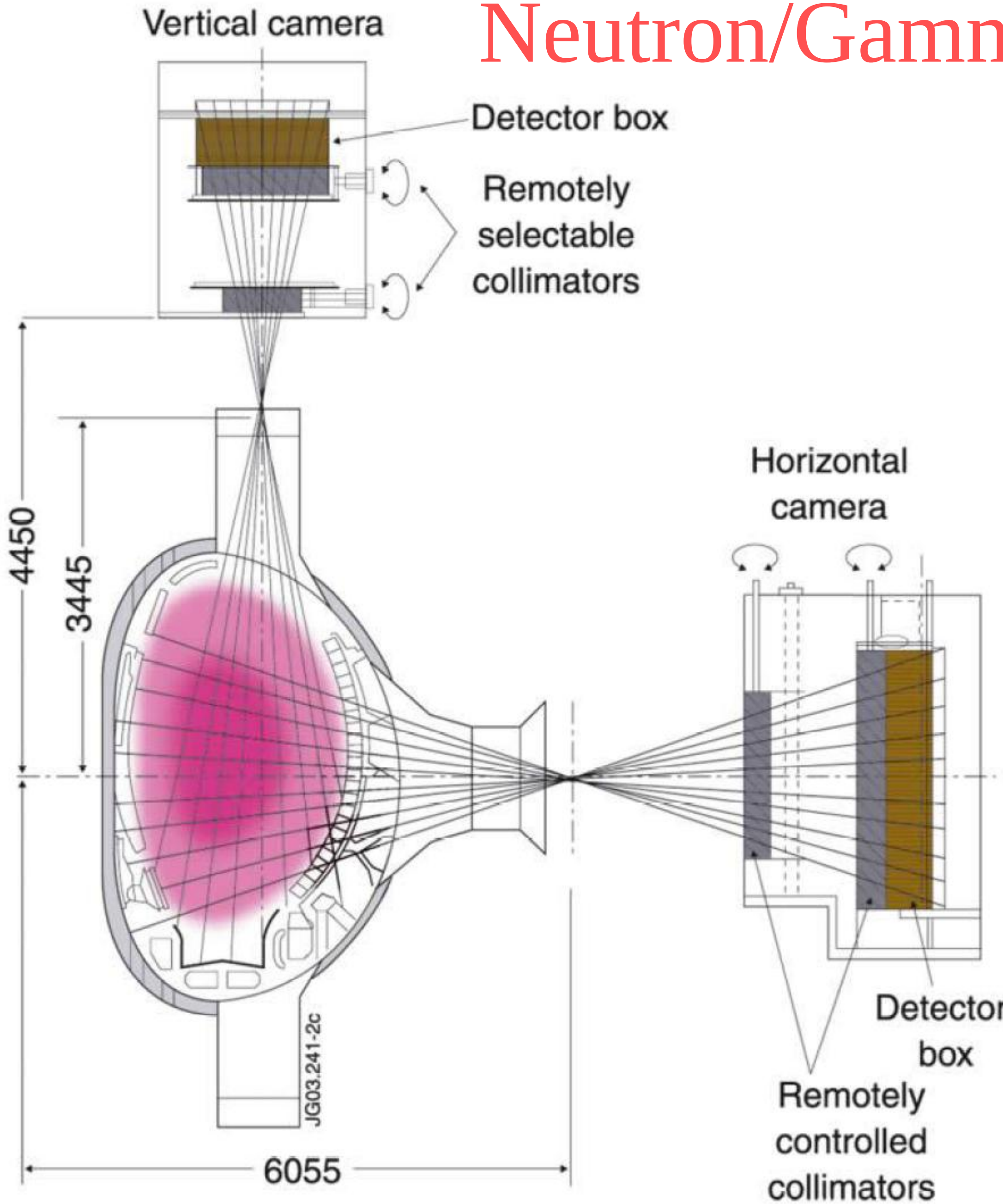
ITER Bolometry

Bolometry lines of sight:
300 - 400 channels



- **Bolometry provides time and space resolved 2D profiles of plasma radiation:**
  - sensitive from infrared to X-ray region
  - radiation-hard version of the resistive absorbing film bolometer currently in use is under development
  - access, cooling and radiation hardness are all issues for bolometer cameras

Neutron/Gamma Profile Monitor



The neutron and gamma-ray profile monitor represents just one of tens of passive diagnostic methods applied at JET. The monitor has two cameras that allow observations of plasma radiation from ten horizontal and nine vertical directions. In this way we can localize the source of the radiation, in this case the **neutrons produced by fusion or gamma-rays produced by nuclear reactions**. The latter can serve us to trace the presence of fast-ions, in particular helium nuclei (alpha particles).

Overview of JET Plasma Diagnostics