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Plasma Diagnostics:

Bremsstrahlung

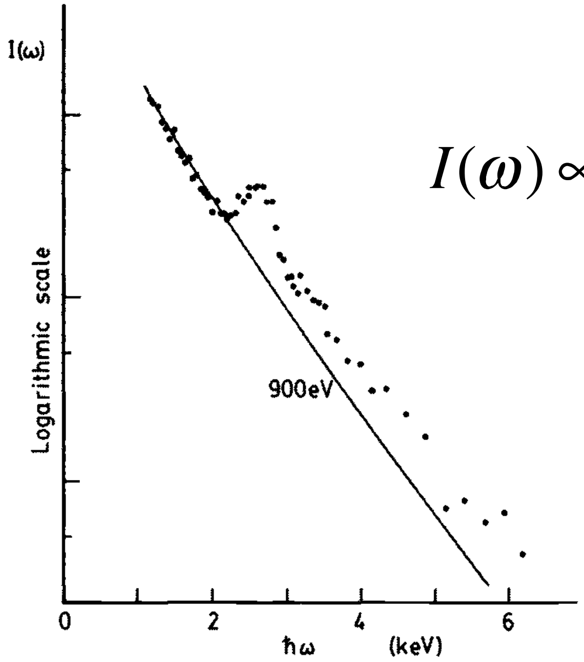
May 2020

Diagnostic Capability

- Emission from electron-ion encounters is a wide band emission from X-ray to infrared.
- In X-Ray spectral range, the emission has a strong dependence with temperature and can be used for T_e measurements (not used in present Tokamak anymore)
- In visible range the emission has a weak dependence on frequency and its level is

$$I_{BS} \propto Z_{eff} n_e^2 T_e^{-1/2}$$

SXR bremsstrahlung

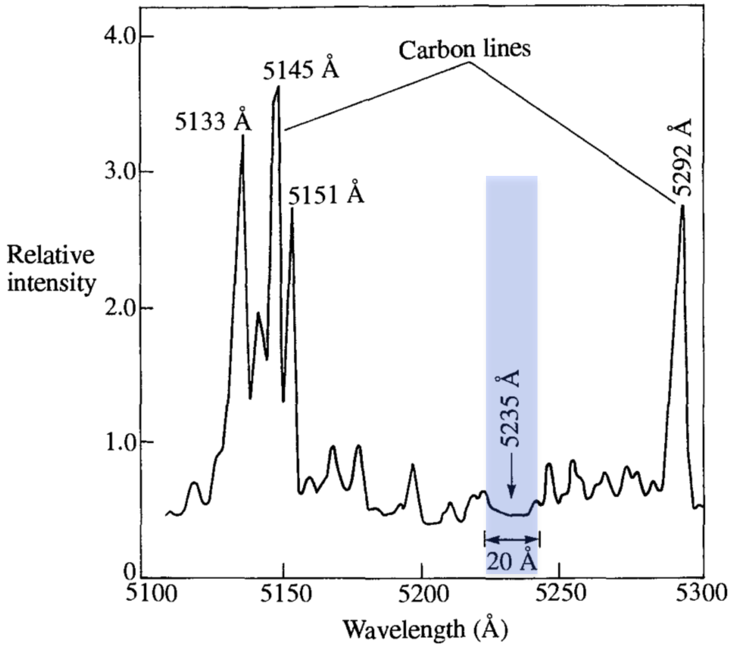


$$I(\omega) \propto Z_{eff} n_e^2 T_e^{-1/2} e^{-\frac{\hbar\omega}{T_e}}$$

Fig. 5.22. Typical emission spectrum from a tokamak plasma, also showing the effects of impurities [after Rice *et al.* (1982)].

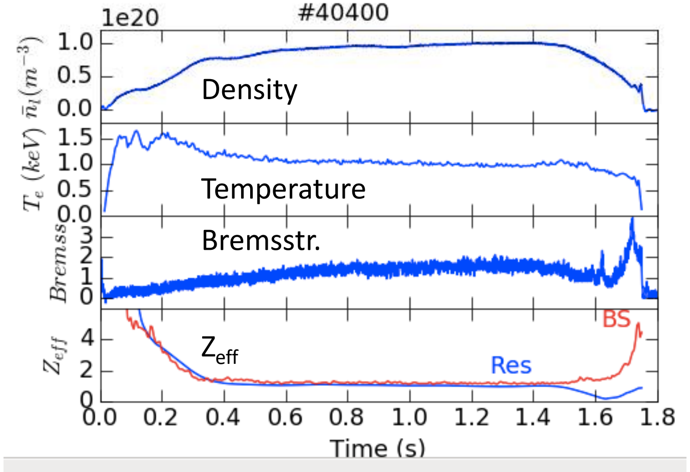
Visible- Bremsstr.

$$I_{BS} \propto Z_{eff} n_e^2 T_e^{-1/2}$$

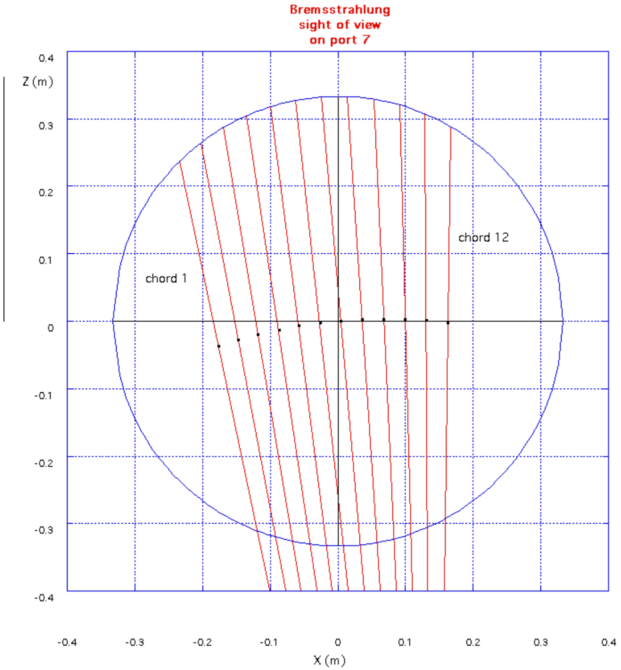


- For $h\nu << T_e$, frequency dependence disappear
- Frequency range must be free from strong impurity line radiation.
- Absolute calibration is needed (easier in visible range)
- If n_e and T_e is known Z_{eff} can be measured

Measurement Example



Example of Zeff obtained on FTU from BS and compared wit resistive Zeff



Layout of FTU Bremsstrahlung line of sight.

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Plasma Diagnostics:

Charge Exchange Spectroscopy

CXS

(CXRS, CES, CERS)

May 2020

CXS principle

- Neutral atoms in the plasma (from, for example, a neutral beam) donate electrons to fully ionized impurity ions, producing hydrogen-like ions. As the electrons decay from excited states they emit photons from which the impurity temperature, rotation and density can be measured using conventional spectroscopy

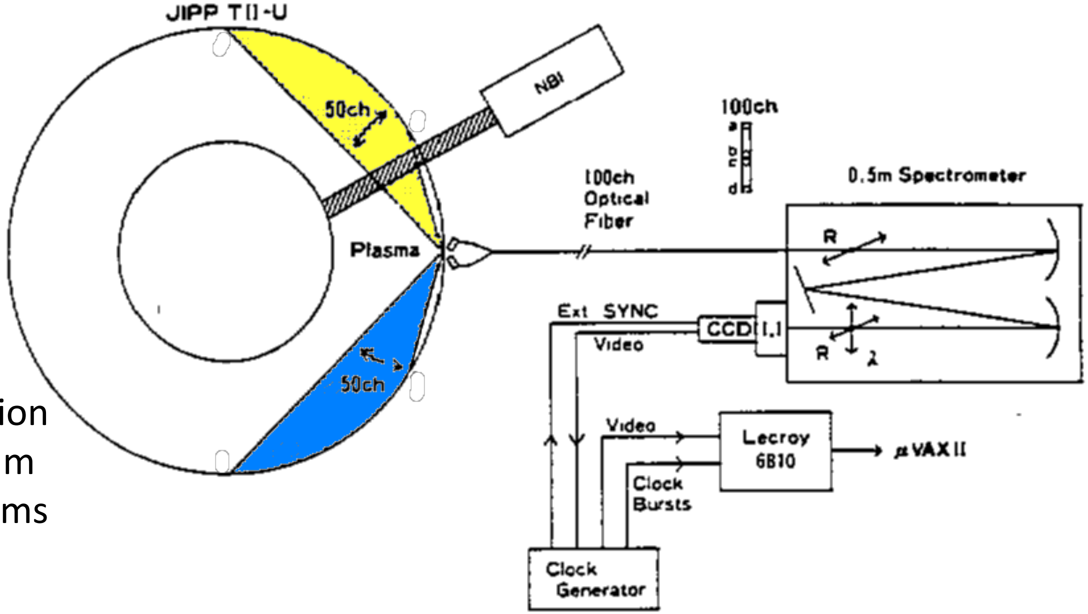
$$H^0 + A^{+q} \longrightarrow H^+ + [A^{+(q-1)}]^*$$

CXS

- The CXS is achievable only with active beam have the following capabilities:
  - The dominant, fully ionized stages of low-Z impurities can be studied through detection of the cascade radiation from the hydrogen-like stages
  - Spatial resolution can be achieved without the necessity of inverting chordal data by viewing across the beam
  - Emissions are at wavelengths long enough for making accurate Doppler broadening and shift measurements

CXS lay-out

Emission from plasma background is subtracted by a second symmetric array of channels. In some devices the background is negligible and only an array is used



Resolution
Δr ~5 mm
Δt ~ 16 ms

Figure 1. Schematic view of a multichannel CXS system on JIPP T-IIU (Ida and Hidekuma 1989).

CXS: Emission lines

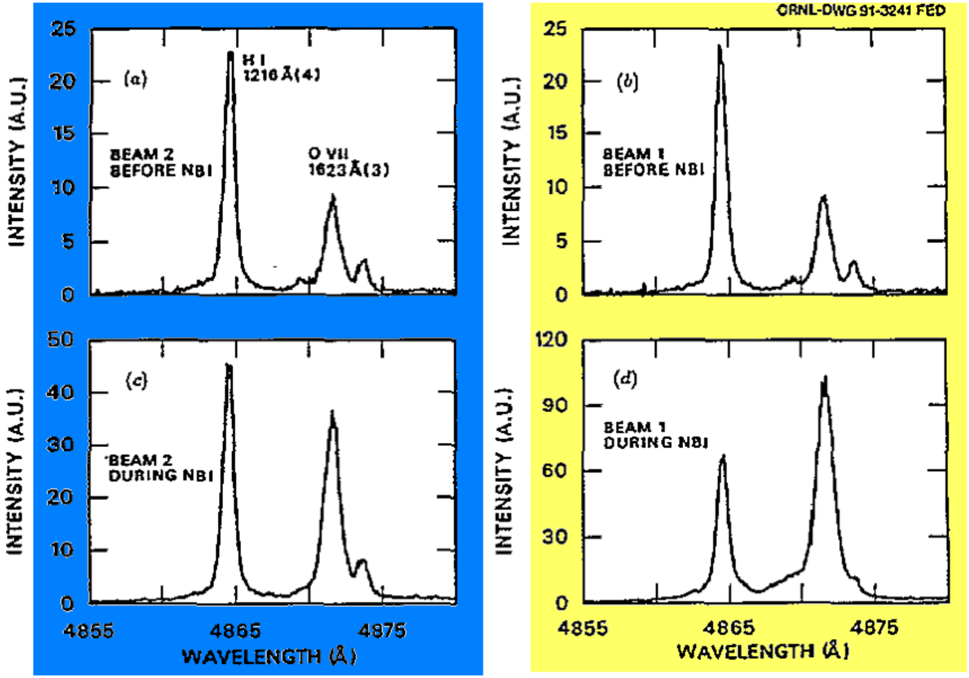


Figure 2. Spectra taken before and during neutral-beam injection in the ATF stellarator. Beam 1 crosses the field of view of the spectrometer; beam 2 is on the opposite side of the machine.

CXS : Measurements

Charge-exchange spectroscopy as a plasma diagnostic 203

the magnetic field B is given in T, and $M - M' = 0, \pm 1$. Making the imation $g = g' = 1$, leads to a maximum wavelength shift (given by $\Delta M = \pm 1$)

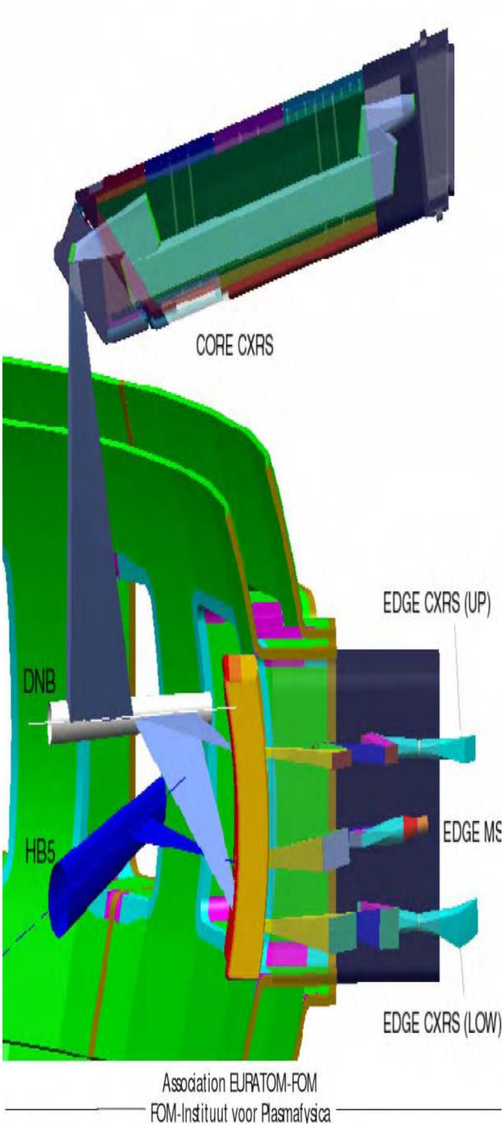
$$\left(\frac{\Delta\lambda_Z}{\lambda}\right) = 4.669 \times 10^{-9} B(T) \lambda(\text{Å}) \tag{9}$$

$$\frac{\Delta\lambda_Z}{\Delta\lambda_D} = 6.06^{-5} \left(\frac{M(\text{amu})}{T(\text{eV})}\right)^{1/2} B(T)\lambda(\text{Å}). \tag{10}$$

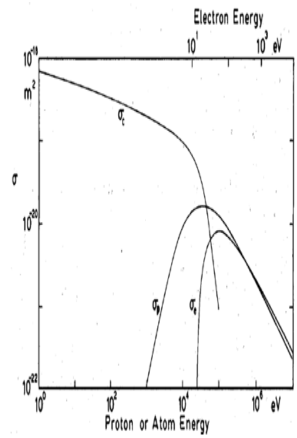
$^+$, 5292 Å at 1000 eV

$$\frac{\Delta\lambda_Z}{} = 0.105 \tag{11}$$

CXS on ITER

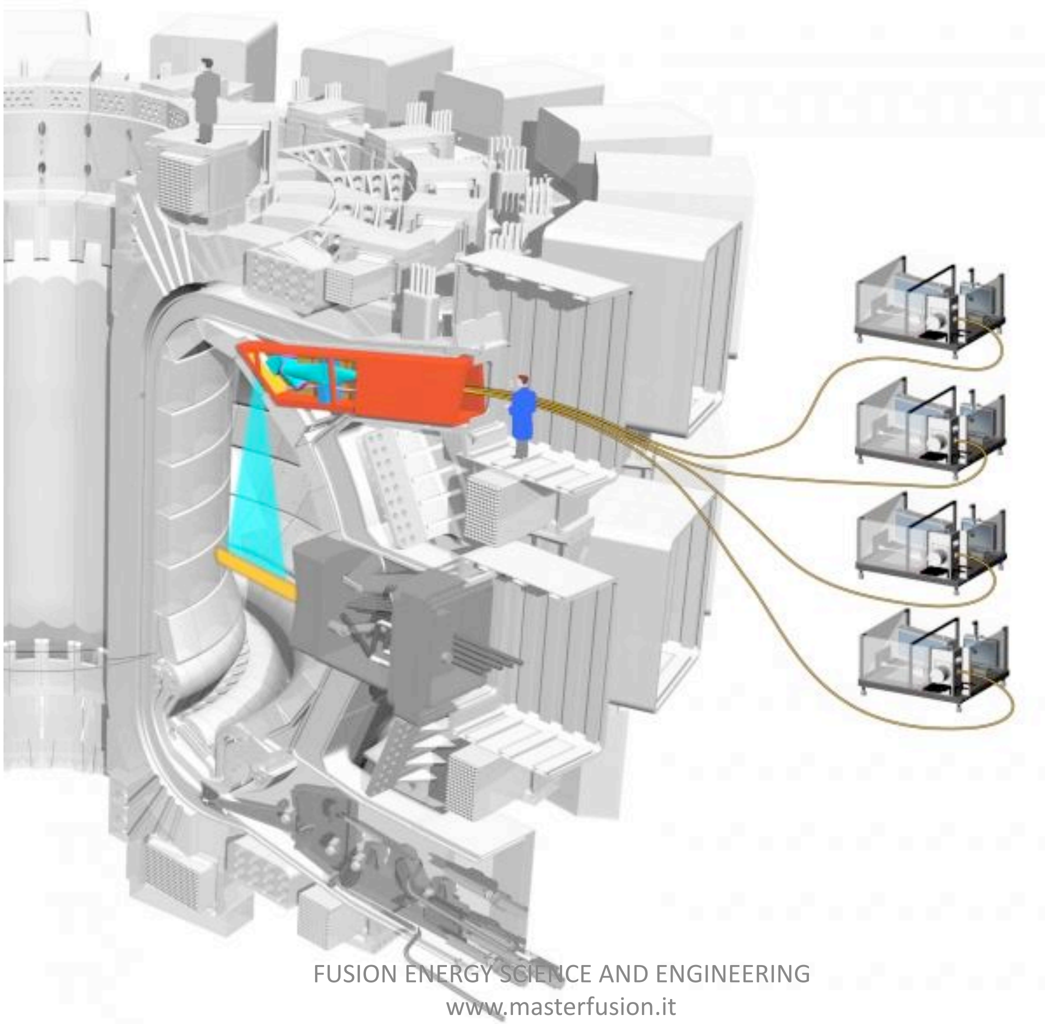


- Measures Ti, v, impurity densities
- Dedicated 100keV 4MW (?) H diagnostic beam because 1MeV heating beams have very low CX cross section



- Core and edge systems with different requirements for resolution
- Poor penetration: ok for r/a>0.4
- Optical relays to outside VV, then optical fibre arrays to VIS spectrometers

CXS on ITER



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Plasma Diagnostics:

Motional Stark Effect

May 2020

MSE principle

A neutral particle which moves inside the plasma with a speed v, undergoes to an electric field

$$\mathbf{E} = \mathbf{v} \leftrightarrow \mathbf{B}$$

The electric field induces emission line splitting and polarization of emitted line (Stark Effect)

- The $\Delta m = 0$ transition (π lines) are linearly polarized parallel to E
- The $\Delta m = \pm 1$ transition (σ lines) are polarized perpendicular to E

when viewed transverse to the field

Neutral beam is used to inject neutral particle inside plasma.

For H beam of 55 keV, B_T= 1.3 T, E = 40 kV/cm

MSE measurements

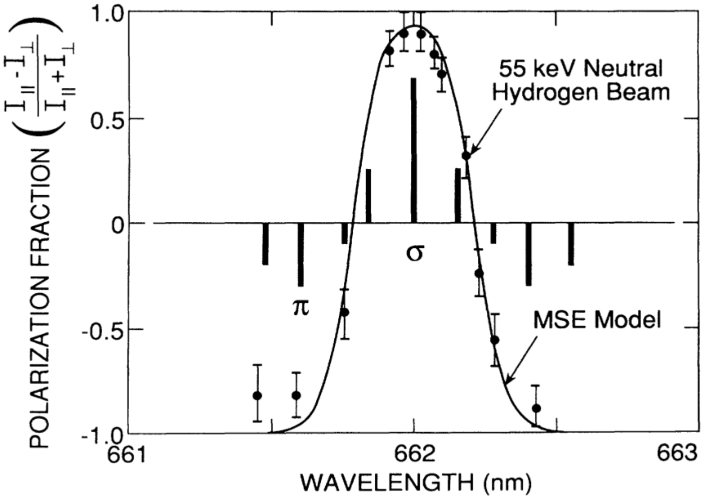


FIG. 1. The Stark-effect pattern of the Balmer-alpha (H_α) transition is shown by the vertical lines. The data points are from a spectral scan of the fractional polarization and the solid curve is numerically calculated.

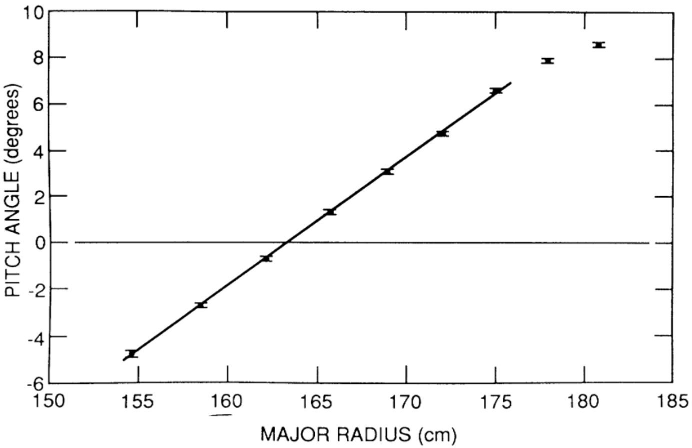
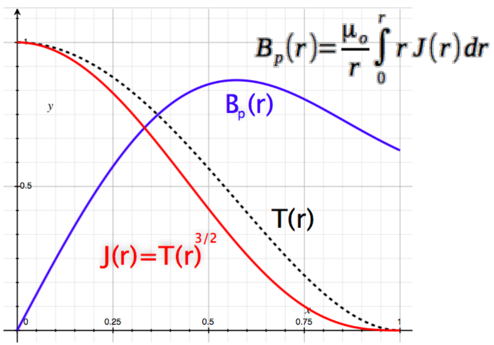


FIG. 4. Radial scan of the pitch angle.



Diagnostic capability

Measure the profile of pitch angle of magnetic field

$$\gamma_p(r) = \tan^{-1}\left(B_p / B_T\right)$$

$$q(r) = \frac{r}{R} \tan \gamma_p(r)$$

MSE lay-out

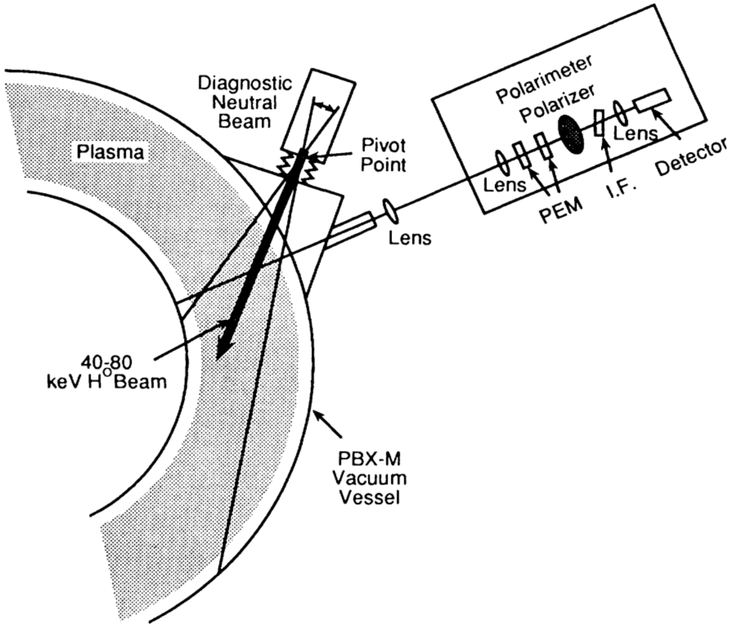
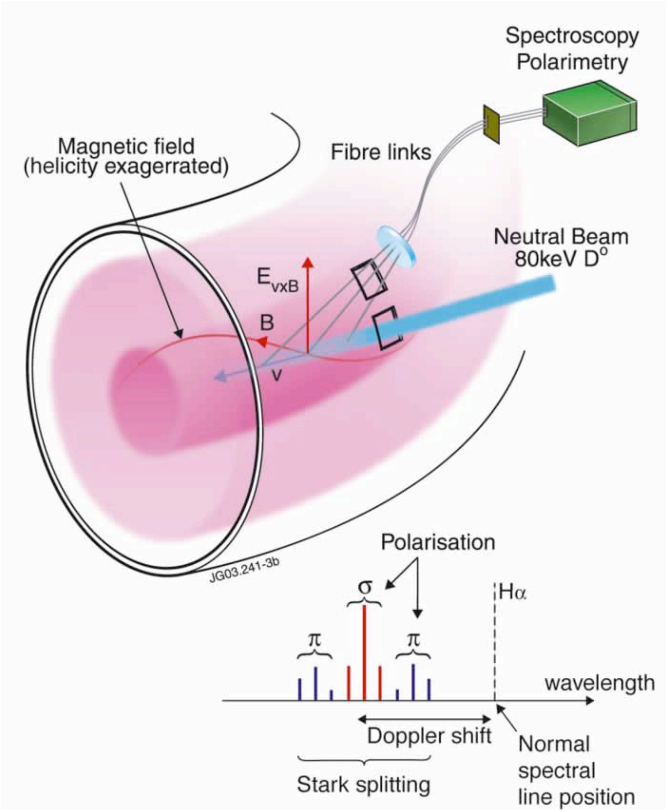
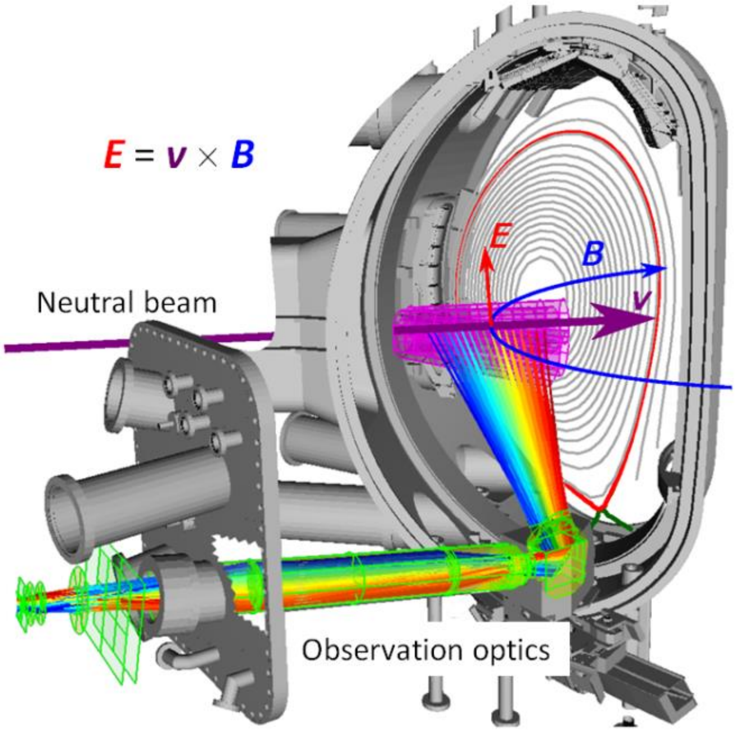


FIG. 2. Experimental setup of the diagnostic neutral beam and polarimeter on PBX-M.



ASDEX MSE



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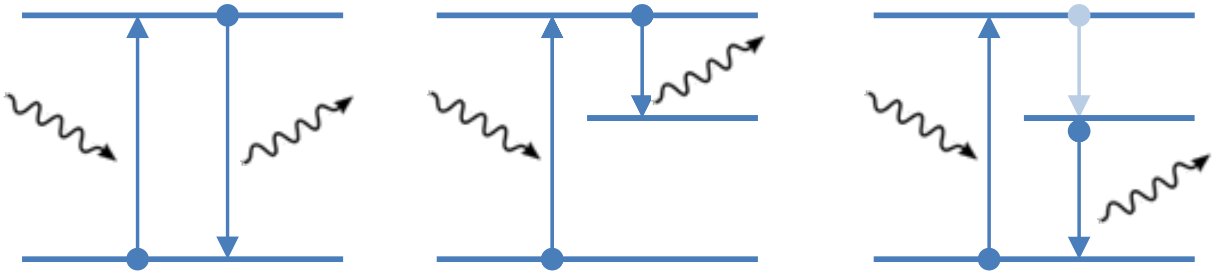
Plasma Diagnostics:

Laser Induced Fluorescence
(LIF)

May 2020

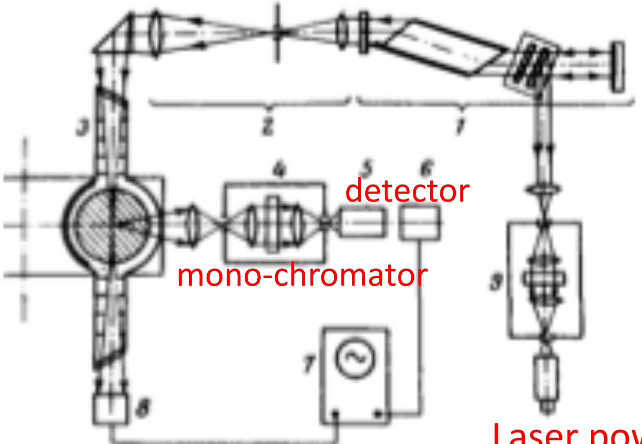
LIF principle

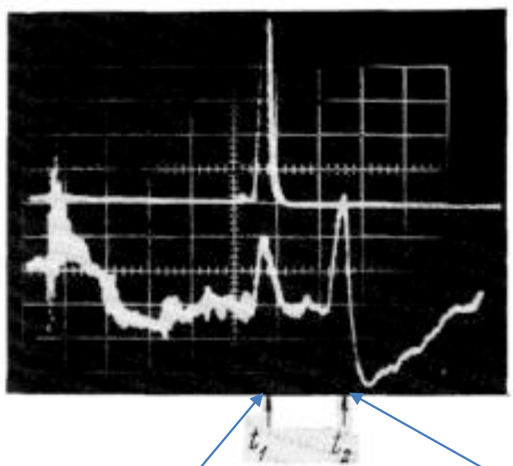
- Impurity can be detected forcing ions to step to high energy level by a laser.
- The ions decay to the ground level emitting a photon (fluorescence)



First measurement of neutral particles

V.S. Burakov, 1977 – on FT-1 tokamak (USSR)





Quantitative measurement of the neutral particle density : min detect. $n_o > 10^{11}\ m^{-3}$

Impurity measurement

Neutral iron density on ISX Tokamak ('79)

- High power tunable laser is required.
  - All particles in the illuminated volume must step to higher energetic level
- Low ionized states can be detected
  - Edge diagnostic
  - Frequency dobbler are used to increase the pumping laser range
- Very good precision

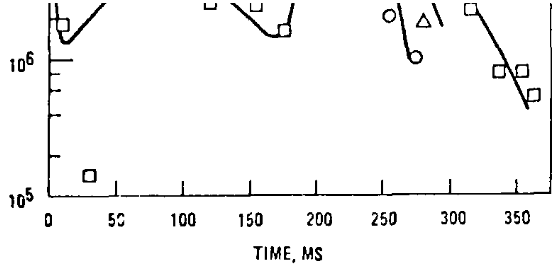
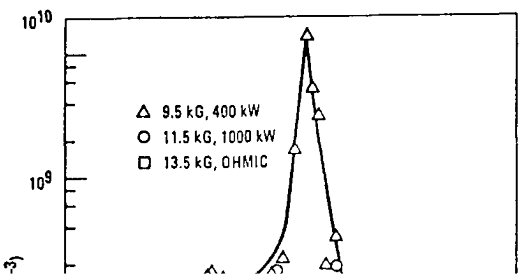


Fig. 28. Time evaluation of neutral iron densities for ohr plasma (squares) and for neutral beam (+ ohmic) heate 0.4 MW and 1.0 MW neutral beam power (triangulars respectively) (from [76]).



plasmas. Three schemes using fluorescence spect presented in Fig. 27 from [75]. Of course, most eff is resonance spectroscopy, but direct-line and fluorescence can also be useful for atom density me Existing dye lasers with nonlinear frequency doub can be operated in the spectral range above 2000 Å up to several MW. Such light sources are most measuring atom densities in the plasma edge [76]. region of the ISX tokamak, laser fluorescence tech applied for measurement of atom densities and velc

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Plasma Diagnostics:

HXR & SXR Tomography

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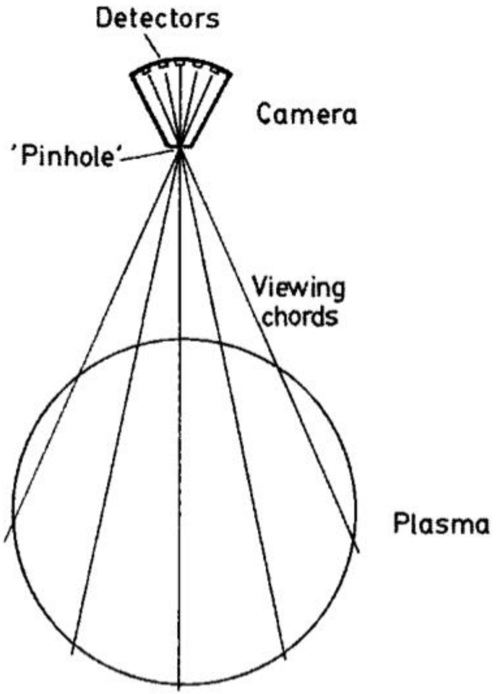
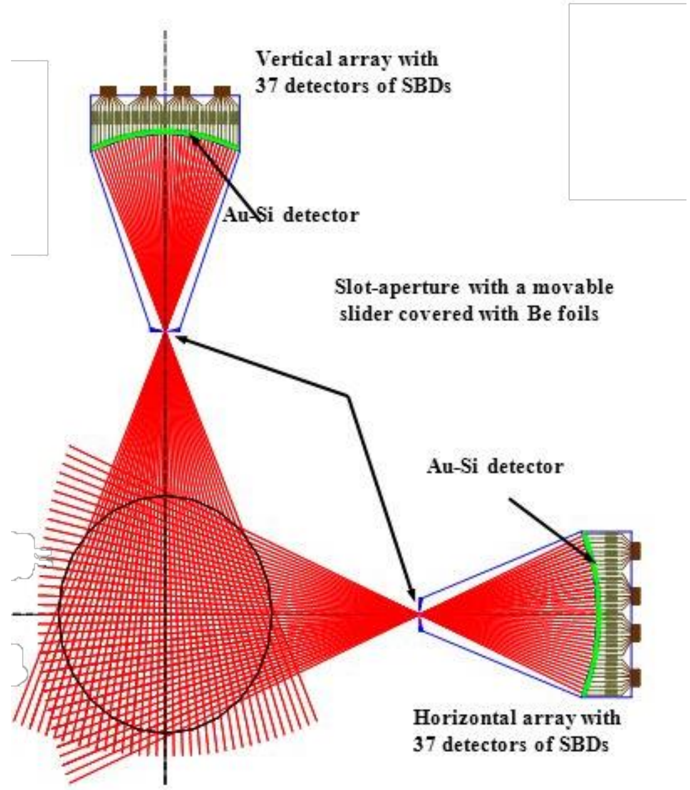
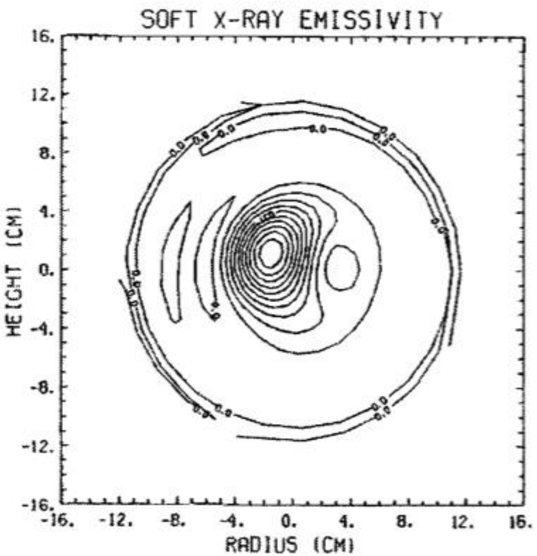
Tomography : schematic



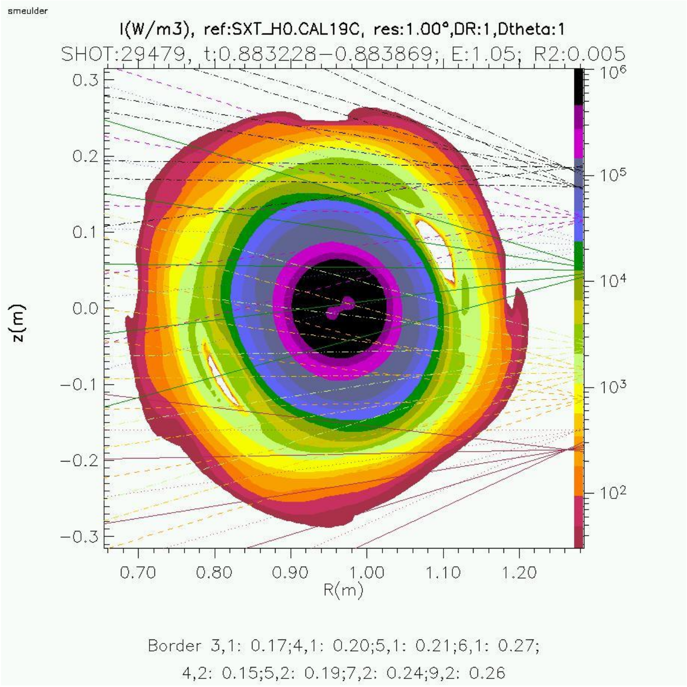


MHD island from tomography

Alcator: Granez 1985



FTU



Fast Electron Bremsstrahlung : schematic

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HXR- Tomography : Detect the bremsstrahlung from fast electron generated by LH