SPECTRAL MODELLING OF NEUTRAL BEAM FOR DOPPLER SHIFT SPECTROSCOPY DIAGNOSTICS OF INTF

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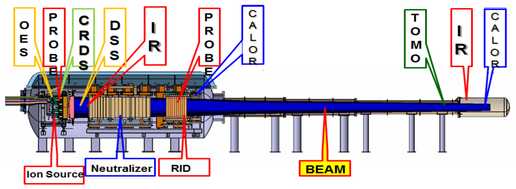
Objective

- The Doppler shift spectroscopy diagnostics set up is envisaged for measurement of beam divergence ,beam uniformity and stripping losses for 100 keV DNB of ITER.
- Establish the diagnostics set up by beam spectral modelling of the H^- beam.(To be tested on Indian Neutral Beam Test Facility INTF)
- Chose diagnostics set up parameters for obtaining good signal to noise ratio and error in divergence measurements as < 10%.
- Modelling of Doppler Shifted spectrum for all operational conditions.

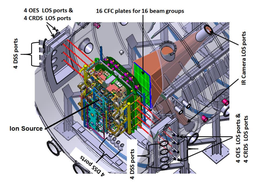


Indian Neutral Beam Test Facility - INTF

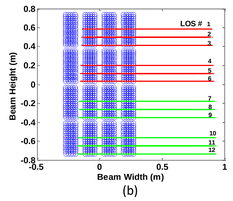
Parameter	Specifications
Beam Energy	100 Kev (H-)
Beam Current	60 A
Pulse Length	3600s
Current Density	300 A/m^2
Beam Divergence	~ 7 mrad
Source Size	1.6 m x 0.6 m

Beamlets & Line of Sight (LOS)	
Apertures	1280
Aperture Arrangement	4 x 4 Group 5 x 16 Matrix
LOS (Horizontal)	24
LOS (Vertical)	12
Beam Path Length	20 m
LOS path length ~ side Typical LOS path length (bottom)	1.25 m 3.2 m

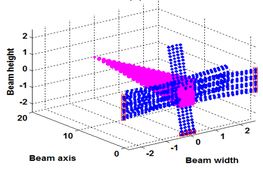
Table 1



(a)



(b)



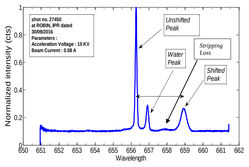
(c)

(a) – The ion source and the location of the DSS Line of Sight (LOS) ports

(b) – The grounded grid and the 12 LOS of the side port

(c) – The beam path of 20 m and the 36 LOS interacting with the beam

Doppler Shift Spectroscopy



Shifted Peak

$$H^-_{beam} + H_2 \rightarrow H^*_{beam} + H_2 + e$$

$$H^0_{beam} + H_2 \rightarrow H^*_{beam} + H_2$$

$$H^+_{beam} + H_2 \rightarrow H^*_{beam} + H_2^+$$

Unshifted Peak

$$H^-_{beam} + H_2 \rightarrow H^*_{beam} + H^* + e$$

$$H_{beam} + H_2 \rightarrow H^*_{beam} + H + H^*$$

$$H^+_{beam} + H_2 \rightarrow H^+_{beam} + H + H^*$$

$$\Delta\lambda_D = \lambda_o \frac{v}{c} \cos\theta \quad \text{- (1)}$$

A spectral line emitted from a particle moving relative to an observer appears shifted in wavelength due to Doppler effect.

Beam Emission Spectrum Modelling

$$I(\lambda) = \frac{1}{\sqrt{\pi}\cdot\lambda_{beam}} \cdot \exp\left\{-\frac{(\lambda-\lambda_0)^2}{\lambda^2_{beam}}\right\} \cdot \frac{1}{4\pi} \cdot n_{gas} \cdot Q_{beam} \cdot \int_{l.o.s} ds \cdot n_b \cdot \Delta\varepsilon_{sp} \cdot \Delta\lambda \quad \text{- (2)}$$

I = Intensity of the spectrum(Photons/sec)
λ_o = Wavelength of the unshifted peak
n_{beam} = Beam Density
λ_{beam} = 1/e width of the shifted peak
n_{gas} = Gas Density
$\Delta\varepsilon_{sp}$ = Etendue of the spectrometer
Q_{beam} = Reaction Rate ($\sigma \times v$)

Get Beam Geometry, Beam parameters, Ion source parameters

LOS geometry, LOS description

Compute intersection for each Beamlet –LOS (1280X36)

Interaction volume for each Beamlet-LOS

Sample active beam lets for each LOS . Compute contribution of beam current density to each interaction point on LOS.

Compute gas density for each interaction point on LOS

Compute n^+ and n^0 and n^- at each interaction point on LOS

Local Beam emissivity at each Beamlet
- LOS intersection point
-LOS integrated emissivity
(Brightness)

Define Spectrometer and CCD
Dispersion ,F#, Slit height and width
Pixel size, No. of pixels and quantum efficiency

Calculate the calibration factor for spectrometer and light collection set up

Intensity observed by spectrometer (cts)

Atomic cross sections for n=3 state for n^-, n^+ and n^0 for projectile and target excited atoms produced from H_2

Atomic cross sections for computing formation of beam fractions (H^+ and H^0)

Gas Pressure profile code (MCGF)

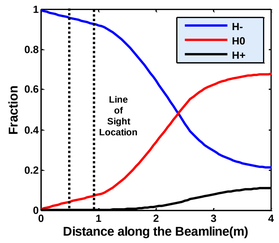
Modelling for apparent broadening of the Doppler shifted spectral line for beam parameters, light collection and spectrometer

Modelled Doppler shifted spectrum and Signal to noise ratio

$$\textbf{Total Width}, \Delta\lambda^2_{beam} = \Delta\lambda^2_N + \Delta\lambda^2_{Instr} + \Delta\lambda^2_{coll} + \Delta\lambda^2_f + \Delta\lambda^2_\varepsilon + \Delta\lambda^2_{ripple} \quad (3)$$

Broadening Parameter	Estimated value	Error
Natural Broadening ($\Delta\lambda_N$)	0.0132 nm	0
Instrument Broadening ($\Delta\lambda_I$)	0.045 nm	< 0.005 nm
Light Collection ($\Delta\lambda_{coll}$)	0.065 nm	10 % of $\Delta\lambda_{coll}$
Beam Focussing ($\Delta\lambda_f$)	0.321 nm	10 % of $\Delta\lambda_f$
Beam Divergence ($\Delta\lambda_\varepsilon$)	0.083 nm	10 % of $\Delta\lambda_\varepsilon$
Voltage Ripple ($\Delta\lambda_{ripple}$)	0.023 nm	1 % of $\Delta\lambda_{ripple}$

Table 2



Rate Equations to calculate the beam fractions along the beamline

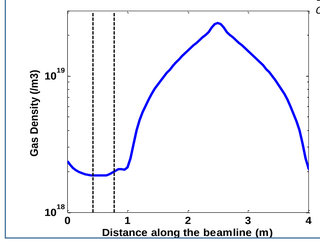
$$\frac{dn^-}{dX} = n_g(-\sigma_{-10} - \sigma_{-11})n^-$$

$$\frac{dn^0}{dX} = n_g\{(-\sigma_{-10})(n^-) - (\sigma_{01})(n^0) + (\sigma_{10})(n^+)\}$$

$$\frac{dn^+}{dX} = n_g\{(\sigma_{-11})(n^-) + (\sigma_{01})(n^0) - (\sigma_{10})(n^+)\}$$

-1,0,1 are the charge states of H (H^-, H^0 and H^+)

Cross Section Ref : C. Barnett, "Redbook atomic data for fusion," ORNL, New York, vol. 1990, p. 148, 1990.



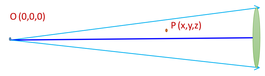
Gas Density Profile computed using MCGF* code

Ion Source Pressure : 0.3 pa
Gas Flow from Ion source : 4.8 Pa m^3/s
Gas Flow from Neutraliser : 5.8 Pa m^3/s

**MCGF code developed by Alexander Krylov of the Russian Federation*

Beam Current Density Distribution

η_p = Neutral Beam Density at point P (vacuum beam density)

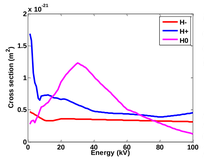


$$\eta_p(x,y,z) = \frac{j_0}{e\upsilon_b \pi\varepsilon^2 z^2} \exp\left(-\frac{x^2}{(\tan\varepsilon.z)^2}\right) \exp\left(-\frac{y^2}{(\tan\varepsilon.z)^2}\right)$$

η_o (*peak value* of the beamlet density) (m^{-3})

$$\eta_0 = \frac{j_0}{e\upsilon_b} \quad (m^{-3}) \qquad j_0 = \text{beamlet current density}$$

$$\upsilon_b = \text{beamlet velocity} = \frac{I_b(\text{neutral\_beam\_current})}{Ng(\text{no.\_of\_grid\_apertures})} \quad (\text{Particles/sec})$$



Balmer alpha emission cross section for the collision of H^-,H^+ and H^0 with H_2

Ref : I.D. Williams, J. Geddes, and H. B. Gilbody, J. Phys. B 15, 1377 (1982)
J. Geddes, J. Hill, F. B. Yousif, and H. B. Gilbody, J. Phys. B 20, 3833 (1987)

Determination of Calibration Factor of DSS Diagnostic set up

$N_{beam} = I_{beam} \times T \times \varepsilon_{spec} \times \Delta\tau$
N_{beam} : No. of photons
I_{beam} : Brightness(ph/m^2.str.sec)

$N_{photoelectrons} = N_{beam} \times \eta$
No. of photo electrons falling on the CCD detector

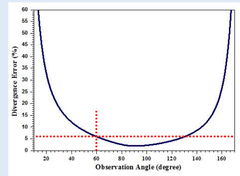
$I_{detector}$ (cts) = $N_{photoelectrons}$ x conv. factor of detector (ADU)

$\frac{I_{detector}}{I_{beam}}$ = conv.fact x T x η x ε_{spec} x Δτ
Absolute Calibration Factor of the detecting system

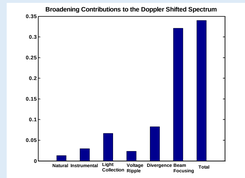
Solid angle of spectrometer , $\Delta\Omega_{sp} = 0.0242\ str$ $\quad \Delta A_{sp} = 2e-8\ m^2$
Etendue of spectrometer : $\varepsilon_{spec}\ \Delta\Omega_{sp}\ x\Delta A_{sp} = 4.83e-10 str\ m^2$
Absolute Calibration Factor (ACF) = 7.25e-10 str m^2 s

Instrument Parameters	
Spectrometer Focal Length F#	0.5 m
Number of Pixels	1024 x 1024
Pixel Size	13 um
Binning	1
Linear Dispersion (nm//pixel)	0.012
Slit width	50 um
Slit Height	400 um
Integration Time (Δτ)	0.1 s
Optical Transmission Losses (T)	0.5
F number	5.7
Quantum Efficiency of CCD (η)	0.5
Lens Diameter	12 mm
No. of Fibers (channels)	20

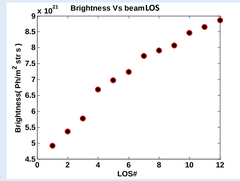
Modelling results : LOS #5, Energy : 100 keV and Source pressure : 0.3 Pa



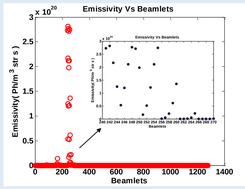
Divergence error less than 10% for LOS angle 60° *@100 KeV*, Taking the values from table 2



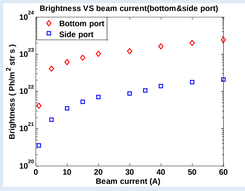
Width of spectral line due to various broadening phenomena calculated from table 2 and Eq. 3



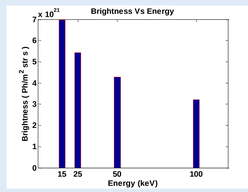
The variation of the LOS integrated beam emissivity across the beam cross section



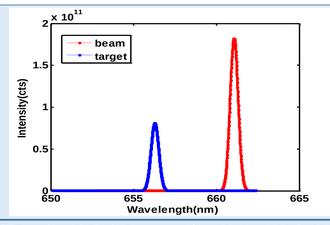
The number of beamlets contributing to the signal of one LOS



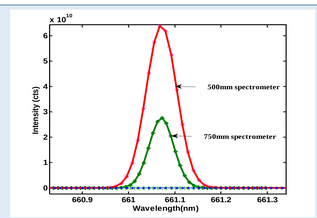
The brightness of the beam at various operational beam currents



The brightness of the beam decreases with the increasing beam energy as the Balmer alpha cross section decreases



Modelled Doppler Shifted Spectrum for 30 A , 100 keV H- Beam considering the parameters in Table.2. The SNR is > 10^4 Target emissions (emissions from dissociative excitation of background gas) are also shown in this figure.



Modelled spectrum using two standard spectrometers (750mm and 500 mm). The CCD is specifications are same only spectrometer focal length and linear dispersion are different.

Conclusion

- **The Doppler Shift Spectrum based on optical emission spectroscopy for neutral beam (H^-) of 100 KeV energy is modelled and the parameters for the diagnostic setup have been established.**
- **The modelling shows that a relatively high signal to noise ratio (>100) even for low beam current (1A) has been achieved for the proposed diagnostic setup**
- **The beam divergence measurement can be measured with error < 10% considering the parameters in Table.1.**

Future Work

- Model the stripping loss of the beam
- Model the spectra for a non-homogenous beam
- Hardware procurement for testing and installation