DEVELOPMENT AND COMMISSIONING OF THE DOPPLER-SHIFT UNIT FOR THE MEASUREMENT OF THE ION SPECIES FRACTIONS AND BEAM ENERGY OF THE ESS PROTON SOURCE

F. Senée*, Y. Lussignol, P. Mattei, O. Tuske, CEA Saclay DRF/Irfu, Gif sur Yvette, France
T. Shea, C.A. Thomas, ESS, Lund, Sweden
Ø. Midttun, University of Bergen, Bergen, Norway
J. Fils, GSI, Darmstadt, Germany
L. Neri, INFN del Sud, Catania, Italy

Abstract

ESS proton source is in going to be soon delivered to the ESS project. In order to qualify the source, a series of beam instrumentation diagnostics have been designed and produced. In particular, a specific spectrograph dedicated to the fraction species measurement is currently commissioned. This instrument not only is capable of measuring the fraction species produced by the source, but also it can measure their energy and energy spread, the mass of the different species, and additional spectral rays coming from the gas species in presence in the vacuum chamber. We present in this paper the commissioning of this instrument, the Doppler Shift unit, dedicated to the measurement of the fraction species.

INTRODUCTION

Understanding the characteristics of the low energy proton beam delivered by the source is critical for optimizing the injection into the next accelerator structure, the RFQ, and for maximizing the current transmission. The CEA[1] is taking part in the ESS linac construction, by designing Emittance Measurement Units (EMU) and Doppler Shift unit (DSu) for the Low Energy Beam Transport (LEBT). The DSu is designed to measure the fraction of the different species produced by the ESS proton source constructed at INFN-LNS[1].

The DSu is a non-interceptive diagnostic and is based on the neutralization of part of the ion beam particles passing through the residual gas[2–4]. It is used for the characterization of the high intensity beams like ATP and LEDA [5] and in particular on the LEBT lines at SILHI, IFMIF and ESS [6], but also for the characterization of neutral beams in tokamaks [7].

The instrument is composed of a high sensitive and high resolution spectrometer[2], a 25 m long fiber bundle in a round to linear ends configuration, and an optimized lens coupling assembly for the geometry imposed by the viewport of the vacuum tank from where the luminescence of the beam can be seen. The spectrograph acquires a spectrum at 14 Hz, triggered by the machine time system. Each spectra is analysed to deliver a fraction species measurement.

* franck.senee@cea.fr

[1] Commissariat à l'énergie atomique et aux énergies alternatives

[2] Shamrock500i with cooled CCD camera Newton 920, from ANDOR

At INFN Catania where the system is installed for the ESS proton source commissioning, there are two positions for the DSu, one in the so-called Preliminary Tank (PTank), directly coupled after the source, and the Commissioning Tank (CTank), after the LEBT. The viewport in the PTank has an angle of $\theta = 25°$ with respect to the beam axis, and the distance to the beam is L = 349 mm, and with a V = 118 mm field of view . In the CTank, $\theta = 25°$, L = 416 mm, V = 90 mm. Thus two fiber optics coupling assembly has been made to optimize the instrument sensitivity in each tanks (see Fig.1).

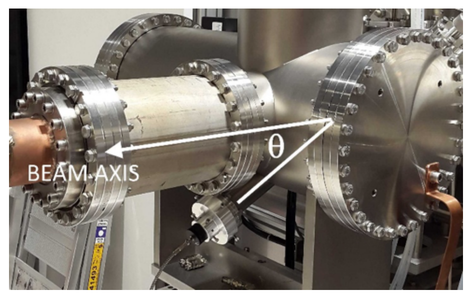

Figure 1: DSu fiber optics coupling assembly located on the PTank, with an observation angle $\theta = 25°$.

Fraction Species Measurement

The measurement of the fraction species is based on the separation of the spectral emission of the species due to their different velocities related to their mass difference. The Doppler shifted rays can be calculated with the expression:

$$\frac{\lambda}{\lambda_0} = \frac{1}{1 + \beta cos\,(\theta)} \quad (1)$$

where λ and λ_0 are the Doppler shifted and non-shifted wavelengths respectively; θ is the observation angle with respect to the beam direction; $\beta = \frac{v}{c} = \frac{1}{c}\sqrt{\frac{2E}{m_p}}$ is the relative speed of the observed particle of mass m_p, c is the speed of light, E the accelerating voltage of the extraction electrodes of the source. The measured Doppler shift on the spectrum identifies the specie and its energy.

In addition, the intensity of the rays on the spectrum are assumed to be proportional to the number of particles of each ion species and to their neutralization, which is given by the electron capture cross-section [8]. For the ESS proton

ISBN 978-3-95450-182-3

source, there are three main species in presence in the beam, H^+, H_2^+ and H_3^+. The fraction of the species is then given by the expression:

$$\eta_{H_i} = \frac{\sigma_{n,H_i}^{-1} I_{H_i}}{\sum_j \sigma_{n,H_j}^{-1} I_{H_j}} \quad (2)$$

with σ_{n,H_i} the electron capture cross-section, I_{H_i} the intensity of the ray associated with the H_i particle.

A typical spectrum is shown in the Fig. 2. It was acquired during the commissioning of the instrument, with the beam conditions: energy set to 75 keV, but not measured, beam current approximately 70 mA, as measured with the designed Faraday Cup; emittance is not known, as the EMU was not installed at the time of the measurement.

In this spectrum, one can identify the Balmer α ray at 656.3 nm coming from the light emission of the excited residual gas. On the foot of the main ray appears a continuum, and four rays on the left. Using Eq. (1), one can identify the species H, H_2, and H_3. The fourth ray is not identified yet and we do not discuss it in this paper, but note the additional information brought by the spectrum of the DSu.

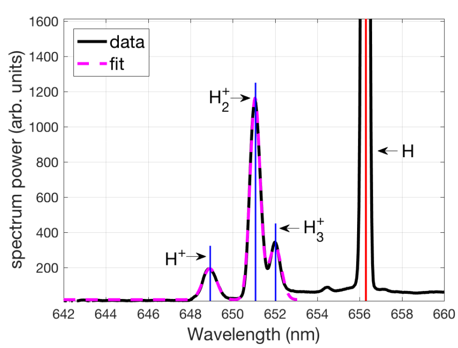

Figure 2: Typical spectrum from the DSu showing the Balmer α ray and Doppler shifted rays of H, H_2 and , H_3. The vertical lines are positioned using Eq. (1).

LIGHT COLLECTION EFFICIENCY

The essential point is to optimize the signal-to-noise ratio of spectral measurement. It reduces the acquisition time, and increases the precision of the measurement. For that, an optical system is designed to collect the maximum of beam light through an optical fiber up to the spectrograph. To achieve this, we used photometry to define the fiber optics coupling system using a numerical code (APILUX) to model the fiber coupling. The results of the code is compared to measurement with the system built for each of the two tanks configurations.

The Fiber Optical Coupling by APILUX

A single lens system was designed with the optical and photometrical software APILUX using sequential propagation. The pertinent calculated photometrical parameter is irradiance, i.e. the radiant flux per unit area (W.m^2) on a receiver. To select lenses for the two tank designs, the light transmission is calculated vs. the distance, d, between the fiber bundle and the lens with 3 different focal lengths F (Fig. 3): if $d \leq dA$, observed area is larger than the beam; if $d_A \leq d \leq d_B$, observed area is smaller; if $d_B \leq d$ system diaphragms cut optical rays. For the PTank, we selected F = 50 mm and d = 20 mm, and for the CTank F = 75 mm and d = 39 mm, ensuring 82% and 85% transmission respectively.

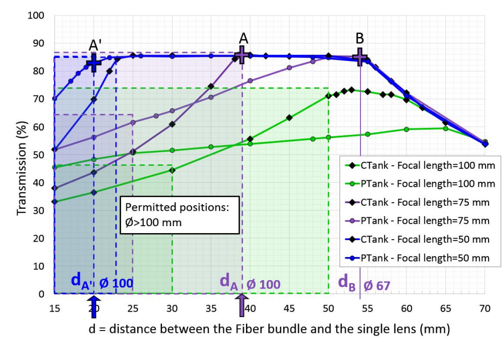

Figure 3: Light transmission calculated with APILUX.

For each tank, an optical setup in reversed mode checked the interaction area diameter observed by the fiber bundle with corresponding one-lens optical system. The fiber bundle is reversely fed by a desk lamp, i.e. an isotropic source to cover the whole fiber numerical aperture (NA), and the system illuminates a screen. The spot size on a screen is measured as function of the position d. It matched by 1% the 100 mm diameter of the interaction zone to be detected with DSu. This consistency is checked in situ with the PTank. The spectrum power measured on the spectrometer from the interaction zone and for different focal lengths and distances lens-fiber. It is compared to the APILUX prediction (Table 1). The comparison is within less than 10% difference.

Table 1: Power transmission of the system measured and compared with APILUX results for several focal lenses, F, and fiber-lens distances.

F (mm)	d (mm)	Measured power (%)	APILUX (%)
50	20	86	85
75	34	65	64
75	26	48	54

The Fiber Bundle

The optimization of the fiber-spectrograph coupling is done by matching the NA of the fiber to the NA of the spectrograh (F/# - matching), and by using a fiber bundle with 19 fiber cores, in a round to linear configuration. The F/# - matching technique is described in numerous textbooks[3]. For the DSu, the size of the bundle, which is given by the

[3] see for instance `www.horiba.com/scientific/products/optics-tutorial/throughput-etendue/`

ISBN 978-3-95450-182-3

magnification of the F/# - matching optical assembly, is larger than the spectrograph sensor height, resulting is 12% intensity loss. Compared to a single fiber, this systems improves the captured flux by a factor 16.7.

FRACTION MEASUREMENT AND STATISTICS

As seen on Fig. 2, the analysis of the peaks in the spectrum verifies the species present in the beam. The analysis of the peak intensities is given by the result of the fit, as shown in the Table 2. The confidence is provided by the calibration of the spectrograph, and the linearity of its camera. The main factors of uncertainty in the measurement are the knowledge of the cross-section σ_{n,H_i}, and the statistical fluctuation coming from photon noise and camera acquisition noise, and from beam itself. The cross-section is known from the literature[9]. The uncertainty due to statistics can be measured by measuring mean and standard deviation values of single shot acquisitions data sets. Figure 4 shows the results this statistical analysis. The standard deviation is measured for fraction measurement performed after accumulation in software of a number of single shots, from 1 to 140. The curves decrease as expected in a square-root low, with a constant component, as shown with the fitting lines. The square-root of the calculated constant fitted constant is 3.7%. This is in agreement with the 2% given by the current measurement, although on a different day, so possibly on a different beam settings.

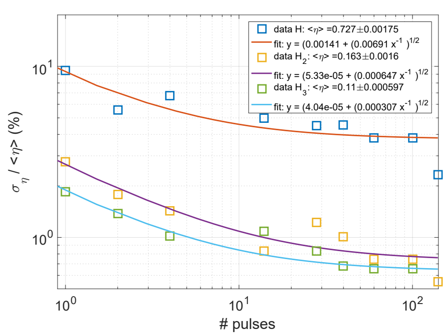

Figure 4: Statistical fluctuation of the fraction species measured with the DSu, in single shot acquisition of 3 ms exposure. The trigger delay is 3 ms. The current is 70 mA, the pulse length is 6 ms. The graph shows the standard deviations of the fractions (squares) as function of number of pulses acquired and averaged in software.

CONCLUDING REMARKS

The DSu for the ESS proton been has been commissioned. The spectrograph selected to measure the spectra from the beam-gas interaction has the required sensitivity and resolution to measure the Doppler shifted Balmer α rays. The light collection optics and fiber has been optimized in each tank configurations. The transmission of the optical systems is over 85%, and the addition of the 19-core bundle in round to linear ends increases the light input by the factor 16.7. The analysis of the fraction is running automatically in the control software, providing a fraction measurement for each pulse delivered by the source. The sensitivity of the DSu provides a measurement confidence interval in the percent range.

Extraction of more information on the beam could be provided from the spectra. For instance, energy and energy spread is related to the peaks center and width. Measurement within the pulse could also be performed, by setting the exposure and the trigger delay of the spectrograph combined with a global shutter camera. These measurements not presented here, will be studied and integrated in the measurement software in a near future.

Table 2: Example of results from the spectrum analysis as shown in Fig. 2. The cross-section σ_{n,H_i} is in 10^{-18} cm^2 and for a 75 keV proton energy; σ_{λ,H_i} is the width of the peak associated with the specie H_i. It is corrected from the spectrograph resolution, $\delta\sigma_{sp}$ = 0.14 nm

Specie	σ_i (pixel)	I_{H_i} (counts)	N_{H_i}	σ_{n,H_i}	η_{H_i} (%)	σ_{λ,H_i} (nm)
H^+	9.18	177.0	4073.1	3.42	42.23	0.29
H_2^+	6.65	1145.0	19083	14.52	46.22	0.19
H_3^+	8.24	303.3	6261.6	19.29	11.5	0.25

REFERENCES

[1] A. Ponton *et al.*, "ESS Normal Conducting LINAC Status and Plans", in *LINAC*, 2014, pp. 948–950, ISBN: 9783954501427.
[2] L. Philpot, R. Hugues, and C. Fan, "Spectra Induced by 200keV Proton Impact on Nitrogen", *Physical Review*, vol. 123, no. 6, 1961.
[3] M. S. D. Jong and N. Rowlands, "Proton Bram Diagnostics Using Optical Spectroscopy", *Nucl. Instrum. Methods Phys. Res. B*, vol. 10, pp. 822–824, 1985.
[4] G. Bolme *et al.*, "A DC Proton Injector for Use in High Current CW LINACS", in *EPAC*, 1998, pp. 1424–1426.
[5] J. H. Kamperschroer, J. D. Sherman, T. J. Zaugg, A. H. Arvin, A. S. Bolt, and M. C. Richards, "Doppler-Shift Proton Fraction Measurement on a Cw Proton Injector", in *LINAC*, Chicago: JACOW, 1998, pp. 511–513.
[6] F. Senée, G. Adroit, R. Gobin, B. Pottin, and O. Tuske, "Beam Species Fraction Measurement Using Doppler Shift Method With Fujikura Fiberscope for Ifmif-Eveda Injector", in *DIPAC*, Hamburg, 2011, pp. 407–409.
[7] R. Uhlemann, R. S. Hemsworth, G. Wang, and H. Euringer, "Hydrogen and deuterium ion species mix and injected neutral beam power fractions of the TEXTOR-PINIs for 20-60 kV determined by Doppler shift spectroscopy", *Review of Scientific Instruments*, vol. 64, no. 4, pp. 974–982, 1993, ISSN: 00346748. DOI: 10.1063/1.1144100.
[8] I. Williams, J. Geddes, and H. Gilbody, "Balmer a emission in collisions of H , H+, H2+ and H3+ with H2", *Journal of Physics B Atomic Molecular Physics*, vol. 15, p. 1377, 1982.
[9] B. Pottin, "Etude D'un Profileur Optique de Faisceaux Intenses de Protons par Absorption Laser", PhD thesis, Université de Paris XI - Orsay Institut de Physique Nucléaire, 2001, p. 194.