Fast Neutral Lithium Beam for Density and its Fluctuation Measurements at the Boundary Regions of ETE Tokamak

R.M. Oliveira, M. Ueda, and W.A. Vilela

INPE - Instituto Nacional de Pesquisas Espaciais,

P.O Box 515, 12227-010, São José dos Campos, SP, Brazil

rogerio@plasma.inpe.br, fax (12)39456710, phone (12)39456692

A Fast Neutral Lithium Beam Probe (FNLBP) is being developed, in order, to perform measurement of the boundary plasma density in discharges of the Spherical Tokamak ETE, recently built at LAP/INPE. This plasma diagnostic method is adequate for use in fusion devices because it does not perturb the plasma and it provides data with high space and time resolution for the entire discharge lifetime. To obtain reliable measurements, however, FNLB probing depends on high signal-to-noise ratio (S/N) during beam emission spectroscopy of the Li beam injected into the plasma, specially if density fluctuation measurements are sought. Hence, our effort is been focused in the achievement of high intensity Li^0 output. Recently, probing of a low temperature ($T \sim 5$eV) and low density target plasma ($n \sim 10^{10}$cm^{-3}) produced in a plasma immersion ion implantation experiment (PIIIE) was performed by a 2-5keV FNLBP. The method used for the density determination of this glow discharge plasma was based on the comparison of the fluxes of 6708 Å photons emitted from Li^0 beam injected into nitrogen gas that filled the PIIIE chamber and from the same beam injected into the plasma discharge. For this case, the attenuation of the beam was neglected. The plasma density measured was $n_e = 8.5 \times 10^{10}$cm^{-3} for pressure of operation of $p = 7.0 \times 10^{-4}$mbar and $n_e = 7.2 \times 10^{10}$cm^{-3} for $p = 4.6 \times 10^{-4}$mbar. These results are in good agreement with Langmuir probe data. The success of this measurement was only possible after a tenfold increase in the Li$^+$ output and the increase of the lifetime of Li source by vitrification of the β-eucryptite source, besides the optimization of the optical detection system and the neutralization of the beam. Presently, a new 10keV FNLBP is been developed to probe ETE plasma. For this case, where the Li beam will be strongly attenuated by the high density plasma ($n_e \sim 10^{13}$cm^{-3}), the method of density reconstruction from the whole photon flux profile will be used. All the improvements performed during the operation of the old FNLBP device, will be implemented on this new FNLBP.

I   Introduction

Presently, the research in fusion area has been considerably focused in some small specific schemes, mainly due to the low cost involved in their construction because of its modest dimensions for a given plasma current. This is the case of ETE - Experimento Tokamak Esférico - a spherical tokamak that has the following characteristics : major radius $R = 0.3m$, aspect ratio $A = 1.5$, toroidal magnetic field $B_\phi = 0.4 - 0.8T$, and projected plasma current $I_p = 220 - 440kA$.

One of the main features of spherical torus is that it can operate with a high ratio of plasma pressure to magnetic field pressure, due to the increase in plasma stability, a consequence of the large twisting of the magnetic field lines in the central region [1]. This advantage, that only become apparent for $A < 2$, makes relevant the research that will be performed in ETE, for the de-

velopment of future compact fusion reactors. However, the success of all the investigation programme to be carried out in this experiment will be closely linked to the development of specific diagnostic systems needed to measure the particular characteristics of ETE discharge parameters. From this point of view, special attention will be devoted to the investigation of the confinement properties in ETE in which the edge region plays a crucial role, as it was observed in many other fusion devices [2-4]. This paper describes the development of a 10keV FNLBP that will allow the density and its fluctuation measurements at the boundary regions of ETE tokamak. The description of the FNLB diagnostic is presented in Section II. Section III shows the several optimizations performed in order to achieve high intensity beam output and good performance of

the neutralization system. Section IV presents the experimental results of the probing of a target plasma by a 3keV FNLBP. In section V it is described the improvements implemented in a new 10keV FNLBP which will be dedicated to probe ETE discharges. Finally, the summary is presented in section VI.

II   Description of FNLB diagnostic system

The experimental setup needed for the Li beam diagnostic consists basically of: an ion gun, a neutralization chamber and a detection system to the collection of the beam emission light.

In the ion source, Li ions are emitted due to the heating of a lithium β-eucryptite compound ($Li_2O.Al_2O_3.2SiO_2$) that is placed in a self-heated molybdenum crucible with a front receptacle of 0.6mm diameter and 2mm depth. The ion gun, a Nagoya-type injector [5] that uses a Pierce geometry [6] for the extraction of Li^+, has a total of 3 cylindrical electrostatic lenses that are polarized using the Einzel configuration [7], for the acceleration and focusing of the beam.

The neutralization apparatus plays an important role in this diagnostic system since target plasmas to be probed are usually produced using electric/magnetic fields that would interfere on the trajectory of the beam if it was not neutralized. Basically, small pieces of metallic sodium are vaporized by the heating of a neutralizer cell that is sealed by a pneumatic valve. The sodium vapour fills a small pass through chamber and when needed, the valve is opened and the Li beam is neutralized by charge exchange process.

The detection system configuration varies according to the device to be probed but usually is composed of optical fibers, spectrometer and photomultiplier, as it is the experimental set-up of the detection system of the current experiment.

III   Optimization of the beam output

Achievement of reliable measurements with high signal to noise ratio (S/N) during Beam Emission Spectroscopy (BES) of the Li beam injected into the plasma depends essentially of a well neutralized beam, with high intensity and low divergence. Many optimization tasks, described below, were performed in a 3keV FNLB device, looking for a Li^0 beam with adequate characteristics for the probing of plasmas in which reliable measurements of density and in addition of its density fluctuations were possible.

III.1 High intensity beam output

High intensity beam output was obtained by the transformation of β-eucryptite compound from the traditionally used pasty state, that is the powder of β-eucryptite mixed with amyl acetate solution, to the glassy state, that is obtained by the melting of the paste with its subsequent slow cooling [8]. Fig. 1 shows a factor of $8 - 10$ increase in the current density, in favor of the glassy load for two values of temperature, depending on the used acceleration voltage. Moreover, the confirmation of the superior qualities of the glassy source compared with the pasty one can be seen by the results presented in Fig. 2. In fact, the glassy β-eucryptite source exhibited better beam emission history with slow reduction of the beam output during the first 60 min to about 75% of its initial emission, and then the output remained almost constant for a long period ($\sim$ 190min). In contrast, the beam output in the pasty case falls dramatically to 40% of its initial value in the first 60 min of operation, falling down to only 20% of its initial emission in 150 min of operation.

III.2 Neutralization efficiency

The neutralization efficiency was measured using 2 deflector plates submitted to strong electric field (200V/cm) and placed just after the neutralization cell. Two secondary electron detectors (SED) were installed, the first one (SED 1) being positioned in front of the trajectory of the neutralized beam while the second one (SED 2) was 10cm shifted upward, collecting the non-neutralized particles of Li ions being deviated by the electric field to the SED2. In Fig. 3 it is possible to see the measurement of the efficiency of the neutralization with the variation of the temperature of the metallic sodium element in the neutralization cell, where 100% of neutralization was obtained for temperature of the sodium of 280^0C.
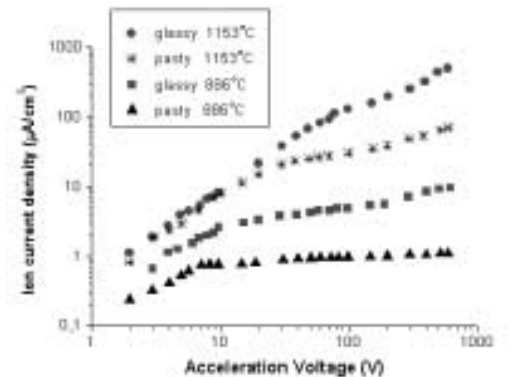

Figure 1. A comparison of the extracted Li^+ current density from pasty and glassy β-eucryptite sources, for two temperatures.
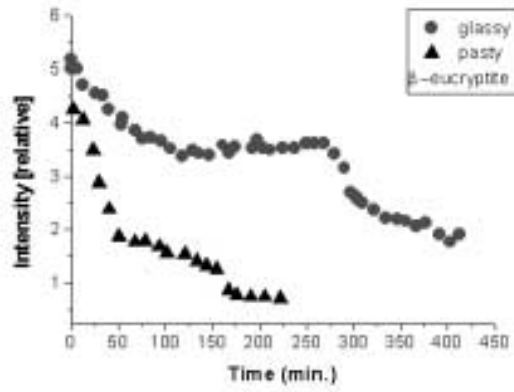
Figure 2. The lithium-emission history for pasty and glassy β-eucryptite sources.
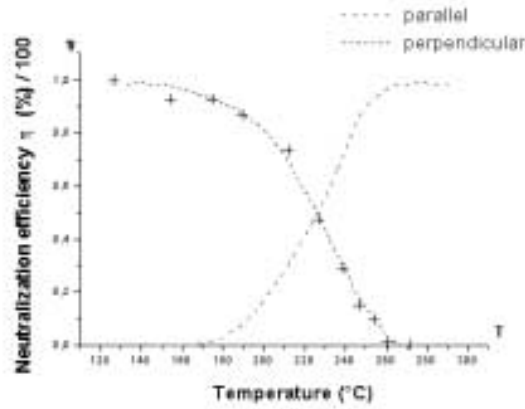

Figure 3. Measurement of the neutralization efficiency according to the heating of the metallic sodium element.

III.3 Other optimization tasks

Other optimization tasks related to the polarization of the electrostatic lenses, which allowed extraction of high beam output and small beam diameter, were also performed. Best results were reached with the following conditions: the difference of potential between the ion gun ($V_{GUN} = 3$kV) and the first lens responsible for the extraction of the beam ($V_1 = 1.7$kV) was of $V = V_{GUN} - V_1 = 1.3$kV; the second lens, used to focus the beam, was submitted to a potential of 2.3kV; finally, the third lens, used to accelerate the beam, was connected to the ground. With such conditions of polarization the current density measured at the end of the flight tube, 1.5m far from the ion source was about 30μA, and the beam diameter was about 1.0cm.

IV   Experimental results

This section presents the experimental results of the probing of a target plasma, a glow discharge pro-

duced in a plasma immersion ion implantation experiment (PIIIE), by a 3keV FNLB device. Here, the method used for the plasma density determination was based on the comparison of the fluxes of 6708 Å photons emitted from Li^0 beam injected into argon gas that filled the PIIIE chamber (used for calibration purposes) and from the beam injected into the plasma discharge. For this low density case ($n_e \sim 10^{10}$cm^{-3}), the attenuation of the beam was neglected and the photon flux resulting from excitation of beam atoms by impact with electrons of the plasma is $N_{vp} = K_1 n_e n_b Q_p$, where n_b is the beam neutral atom density, Q_p the effective excitation cross section, n_e the electron density, and K_1 is a constant of proportionality which includes optics geometry and detector sensitivity factors [9]. On the other hand, photon emission in the gas is given by $N_{vg} = K_2 n_g n_b Q_g$, where n_g is the gas density, Q_g the excitation cross section for collision of beam atoms with neutral atoms in the gas, and $K_1 = K_2$, since the same geometry of observation and the same detection methods were used during calibration and plasma density measurement.

IV.1 Density determination

Fig. 4 shows the 6708 Å Li I photon flux, measured for different values of p, the pressure of argon gas. Then, the local plasma density was directly obtained according to equation 1, since cross section data was available [10], and n_g and the ratio $N_{vp}(r)/N_{vg}$ were measured. Here it must be taken into account that the absolute value of the photon flux in the plasma has to be discounted from the photon flux in the gas.

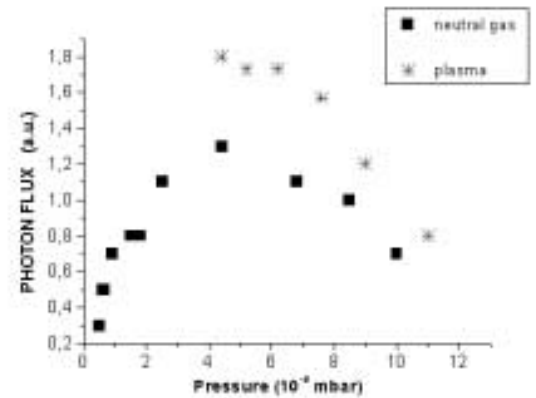$$n_e(r) = \frac{N_{vp(r)}}{N_{vg}} \frac{Q_g}{Q_p} n_g \qquad (1)$$

Figure 4. Evolution of 6708 Å Li I photon flux profile with the pressure of the discharge.

For example, for $p = 7.0 \times 10^{-4}$mbar, the curve of Fig. 4 indicates $N_{vg} = 1.1$a.u. and $N_{vp} = 0.5$a.u.

Through the known cross section values of $Q_g = 4.2 \times 10^{-16}$cm^2 [10] and $Q_p = 3.0 \times 10^{-14}$cm^2 [10], and the measurement of n_g, the local density value obtained was of $n_e = 8.5 \times 10^{10}$cm^{-3}. Using for example other point of the curve plot in Fig.4, with $p = 4.6 \times 10^{-4}$mbar, the plasma density obtained was of $n_e = 7.2 \times 10^{10}$cm^{-3}. These results are in good agreement with Langmuir probe data [11] for similar discharge conditions.

IV.2 Determination of the real energy of the Li^0 beam

The observations of the 6708Å Li I resonance line through two windows, the first one positioned in front of the propagation of the beam and the second one positioned in a perpendicular direction to the propagation of the beam, allowed to infer the real energy of the beam. As can be seen, the plot shown in Fig. 5 is Doppler shifted, with a displacement of $\Delta\lambda = 5.5$Å. Using the relation $E = h\nu = hc/\lambda$, we obtained $E = 2.2$keV for the energy of the Li beam atoms.
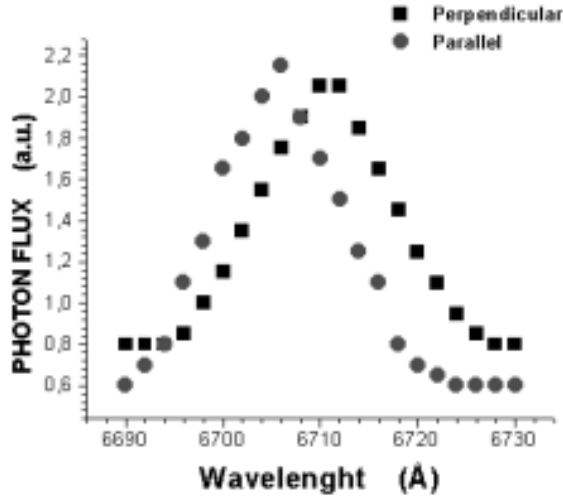

Figure 5. Photon flux of 6708Å Li I captured by the detection system installed in a parallel and in a perpendicular direction to the propagation of the beam.

V   Development of FNLB diagnostics for ETE tokamak

The development of this new FNLB system that will be used to probe the edge plasma region of ETE is in course, with several important modifications included. The ion gun was redesigned in order to accommodate ion sources of 3 different diameters ($\phi_1 = 0.6$cm, $\phi_2 = 1.0$cm, $\phi_3 = 1.7$cm), allowing the achievement of higher ion current densities after beam focusing. Higher voltage power supplies ($V = 10$kV) will

be used to increase extraction current and better focusing and acceleration of the beam. Special care has been taken here to avoid any influence of FNLB operation on the tokamak operation and vice-versa. The schematic drawing of the FNLB set-up in the ETE is shown in Fig. 6.

The pollution free condition of the extremely clean vacuum required for the tokamak operation is guaranteed by the negligible effect of the Li^0 beam (small quantity and deliberately low atomic number). To avoid that Na vapour enter the tokamak chamber, a differential pumping will be used with two strategically located turbomolecular pumps. The Li$^+$ source region will be shielded, to avoid the effects of the spurious toroidal magnetic fields which would deviate the beam before its neutralization. The optical detection system will be of a multichannel type, allowing simultaneous multipoint measurements of the photon emission on the beam propagation direction into the plasma. The typical high density plasmas produced in tokamaks ($n \sim 10^{12} - 10^{13}$cm^{-3} even in the edge region), require the use of the method of density reconstruction [12] from the whole photon flux profile, for the determination of the local densities, represented here by equation 2.

$$n_e(r) = \frac{v_A}{\langle\sigma_{em}\nu\rangle_{eff}} \frac{N_{\nu p}(r)}{\int_0^r \frac{\langle\sigma_{i,cx}v\rangle_t}{\langle\sigma_{em}\nu\rangle_{eff}} N_{vp}(r')dr'} \quad (2)$$

Here v_A is the velocity of the monoenergetic Li^0 beam atoms, $N_{\nu p}(r)$ the photon flux, $\langle\sigma_{em}\nu\rangle_{eff}$ the effective emission rate coefficient and $\langle\sigma_{i,cx}v\rangle_t$ the total cross section of ionization and charge exchange of the beam atoms.

VI   Summary

Since the edge region plays an important role in the confinement properties of the whole plasma[2-4], the FNLBP technique will be a valuable diagnostics in the investigation of the plasma to be produced in ETE. Moreover, several advantages could be explored by the use of FNLBP as the non perturbation and the low pollution of the plasma, the high accuracy reached in the measurements and the spatial and time resolved measurements during the entire discharge lifetime. In ETE it is expected a time resolution of the order of nanoseconds, given by the time response of the photomultiplier, and a spatial resolution of the order of 0.2cm, limited basically by the optical system used for the observation of the photon flux resulting from the interaction of the Li^0 beam with the electrons of the plasma. The FNLB was designed to attain good penetration, of the order of 7cm far from the last closed flux surface, by the implementation of the new ion sources with bigger diameters and by the use of higher voltage power
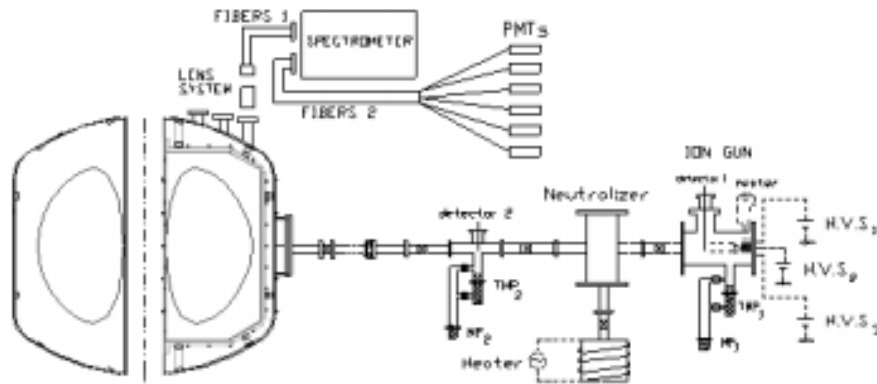
Figure 6. Schematic drawing of FNLB device probing the ETE tokamak.

supplies to better focalize and accelerate the beam. These improvements will open possibilities to the measurements of density fluctuations, since higher intensity beam output is being expected, allowing measurements with high signal to noise ratio. Special care has been taken in the construction of this new device to avoid any kind of interference of this diagnostics to the ETE discharge and vice-versa.

The probing of a target plasma with an old 3keV FNLBP was sucessful, with the density values obtained in good agreement with Langmuir probe data. All the optimization tasks that were performed in this device will be incorporated in the new FNLBP.

References

[1] Y-K.M. Peng and D.J. Strickler "Features of spherical torus plasmas", Nuclear Fusion, **26**, 769 (1986).

[2] G.L. Jackson *et al.*, Phys. Rev. Lett. **67**, 3098 (1991).

[3] P.C. Stangeby and G.M. McCraken, Nucl. Fusion **30**, 1225 (1990).

[4] L. Carraro *et al.*, Rev. Sci. Instrum. **72**, 967 (2001).

[5] H. Iguchi *et al.*, Rev. Sci. Instrum. **56**, 1050 (1985).

[6] J.R. Pierce, Van Nostrand 177-181 (1954) Toronto.

[7] E. Harting and F.H. Read, "Electrostatic Lenses", 1-322 (1976).

[8] M. Ueda *et al.*, J. Phys. D: Apll. Phys. **30**, 2711 (1997).

[9] M. Ueda *et al.*, Journal of Nuclear Materials **196-198**, 923 (1992).

[10] K. Kadota *et al.*, Plasma Physics **20**, 1011 (1978).

[11] L.A. Berni *et al.*, J. Phys. D: Appl. Phys. **33**, 1592 (2000).

[12] P. Bogen and E. Hintiz, eds. D.E. post and R. Behrish (Plenum, New York, 1986) p.211.