Measurements of Strongly Localized Potential Well Profiles in an Inertial-Electrostatic Fusion Neutron Source

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Abstract. Direct measurements of localized electric fields are made by the laser-induced fluorescence (LIF) method by use of the Stark effects in the central cathode core region of an Inertial-Electrostatic Confinement Fusion (IECF) neutron (proton) source, which is expected for various applications, such as luggage security inspection, non-destructive testing, land mine detector, or positron emitter production for cancer detection, currently producing continuously about 10^7 n/sec D-D neutrons. Since 1967 when the first fusion reaction was successfully proved experimentally in a very compact IECF device, potential well formation due to space charge associated with spherically converging ion beams has been a central key issue to be clarified in the beam-beam colliding fusion, which is the major mechanism of the IECF neutron source. Many experiments, but indirect, were made so far to clarify the potential well, but none of them produced definitive evidence, however. Results by the present LIF method show a double well potential profile with a slight concave for ion beams with relatively larger angular momenta, whereas for ions with smaller angular momenta, potential but much steeper peak to develop.

1. Introduction

Potential well formation due to space charge associated with spherically converging ion beams plays a key and essential role in the beam-beam colliding fusion, which is the major mechanism of the IECF devices. At present, D-D fusion neutrons of about several millions/sec are successfully produced continuously at several institutions [1].

Many theoretical results so far predicted strongly localized potential well formation, and actually for the past 30 years, many experiments were dedicated to clarify this mechanism using, such as, electron beam reflection method [2], spatially collimated neutrons [3] or proton profile [1,4] measurements, or an emissive probe [5], but, neither could provide definitive evidence [1].

Recently some theoretical predictions [6] call for higher degree of time and spatial resolution of the diagnostics, which was not fulfilled by the conventional methods made so far.

After elaborate survey, we decided to adopt optical diagnostics by using the Stark effects, which is sensitive to the local electric fields [7]. Also to enhance S/N ratio as well as to specify radial potential profile, we introduced the laser-induced fluorescence (LIF) method [7,8]. Detailed examination in applying the LIF method to IECF was made to yield; (1) resolution of wavelength about 0.4 nm is required, (2) spatial resolution of 1 mm^3 requires 2^1S He atom density of more than 10^{10} cm^{-3}. Also, a Nd:YAG laser-pumped dye laser was set up for diagnostics of the potential well of our IECF device. Very recently preliminary measurements were made by the LIF method and show a double well potential profile for the first time in the He plasma [8]. Since the theoretical predictions indicate significant effects of the angular momentum of the spherically converging ion beams on the potential profiles, they are studied in this study [9].

2. Experimental Setup

The LIF system consists of a Nd:YAG laser (Continuum Surelite II-10-JST; 355 nm, 160 mJ) and a dye laser (Continuum ND6000; line width 0.07 ~ 0.08 cm^{-1} at 515 nm and 560 nm) with two spectrometers (Jobin Yvon TR190MS2; dispersion < 4 nm/mm). A polarization rotator is equipped between the dye laser and the IECF injection quartz window, and also a polarization plate between the IECF window and the spectroscope to measure the effects of polarization as is shown in Fig. 1.

In the experiments, we have chosen the IECF device with a hollow cathode, where the IECF device is spherical, made of SS304 with an inner diameter of 34 cm, and the hollow cathode of 5 cm inner diameter at the center, held by the insulator, is made of 5 mm wide curved tantalum sheets of a 0.3 mm thickness, which were precisely cut by the laser processing (Fig. 2).

The laser wavelength was precisely calibrated within 1 pm through the optogalvanic effects by the galvatron (GT in Fig. 1). To measure the spatial profile, the laser injected in the *y*-direction was scanned horizontally in the *z*-direction (vertically in Fig. 3). A He gas was chosen, and the metastable atoms (2^1S) are excited to 3^1D by the laser (504.2 nm) with two

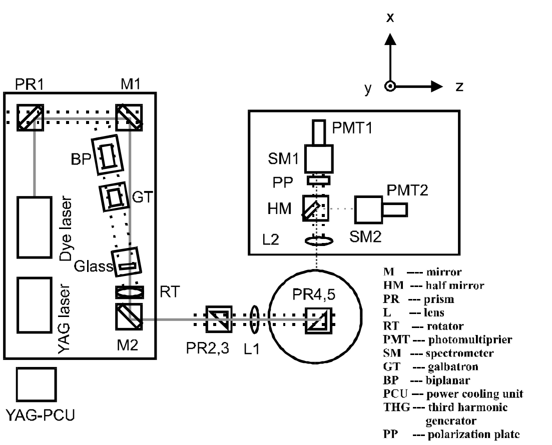


FIG. 1. Experimental setup for LIF diagnostics.

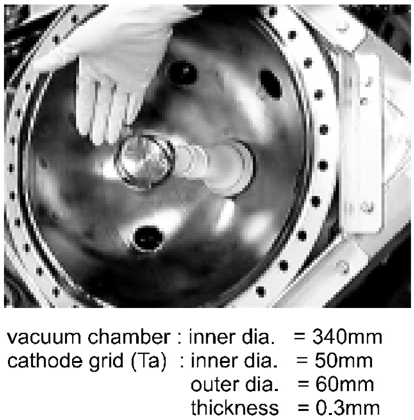


FIG. 2. A hollow cathode made of Ta in an IECF device.

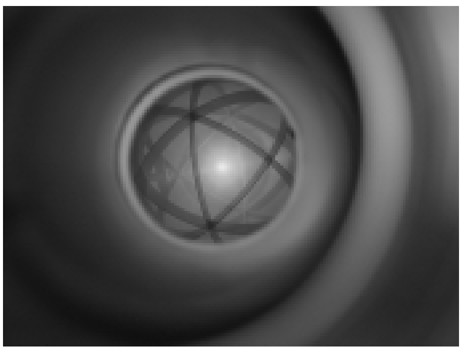


FIG. 3. An IEC plasma core at the center of the hollow cathode taken from laser exit (in the y-direction).

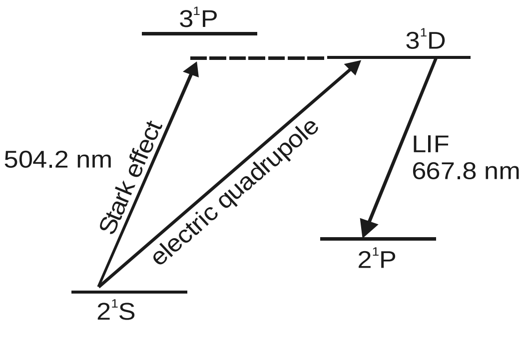


FIG. 4. Relevant energy diagram for the LIF process of HeI in electric field.

different polarization ($\boldsymbol{e}_{Lx}$, $\boldsymbol{e}_{Lz}$) through the forbidden transitions, i.e., the Stark-induced electric dipole moment, and electric quadrupole moment (QDP) transitions (Fig. 4) [10].

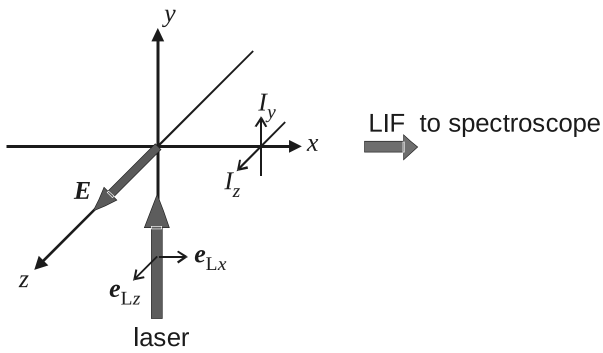


FIG. 5. Observation geometry for LIF.

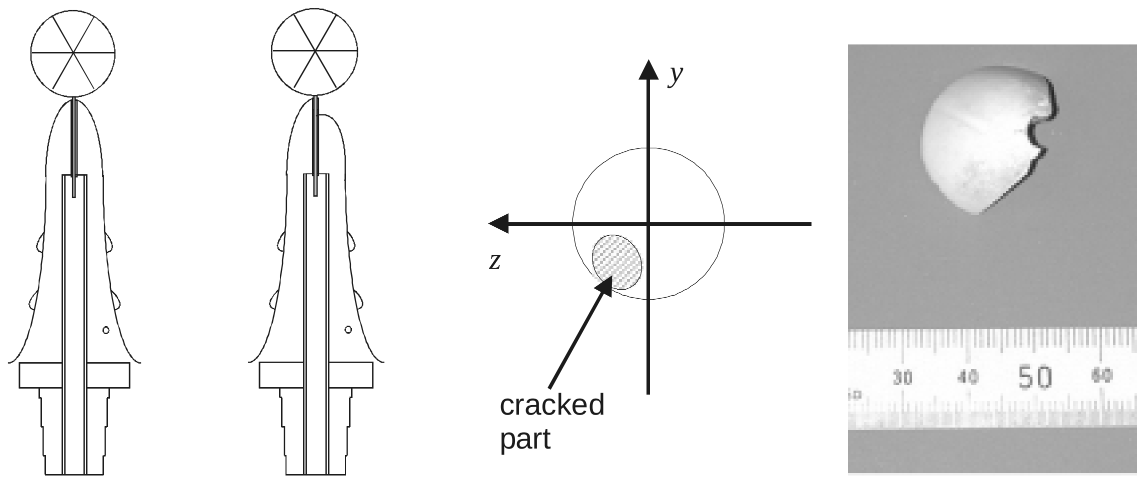
3. Method of Polarized Laser-Induced Fluorescence for Measurements of Local Electric Fields

Use of the fact that the polarization of fluorescence (667.8 nm; 3^1D to 2^1P) due to the Stark excitation is quite different from that due to the QDP excitation thus makes it possible to evaluate the local electric field by measuring 4 kinds of polarized radiation (I_z ($\boldsymbol{e}_{Lz}$), I_y ($\boldsymbol{e}_{Lz}$), I_z ($\boldsymbol{e}_{Lx}$), I_y ($\boldsymbol{e}_{Lx}$)), in terms of the degree of polarization (see Fig. 5) [10]. The LIF (667.8 nm) is then observed along the x-axis. Both the polarized components I_z and I_y are detected. The degree of polarization is defined by

$$P = \frac{I_z - I_y}{I_z + I_y}. \qquad (1)$$

In the experiments, a He pressure of 31 mTorr, a cathode voltage of 7.5 kV, a cathode current of 40 mA were typically chosen to enhance beam perveance. And two kinds of operation were studied with respect to the ion beams with relatively larger and smaller angular momenta which were, respectively, provided by the shape of the cathode insulators, i.e., asymmetric or symmetric as is seen in Fig. 6 with theoretical potential profiles (Fig. 7) for the normal insulator of Fig. 6(a).

Although the insulator made of Macerite (basically made of Mica and Ceramics with an approximate dielectric constant of 6) was manufactured to have the original shape as is shown in Fig. 6(a), during the discharge experiments, however, some part of the top was cracked down due most likely to frequent breakdown as is shown in Fig. 6(c, d). This eventually was expected to cause the asymmetrically converging ion beams, i.e., with enhanced (larger)



(a) Normal shape. (b) Cracked shape. (c) Position of cracked part (d) Photo of cracked part

FIG. 6. Insulator (Macerite) shape; (a) original (normal) shape, (b) cracked shape, (c), (d) cracked part.

angular momenta. We could thus have made measurements of both cases, i.e., under the condition of complete insulator shape and cracked shape cases for comparison.

According to theoretical predictions, double well potential profiles with depressed potential peaks are expected to develop for the former, while for the latter case it would result in a relatively steep potential profile [9].

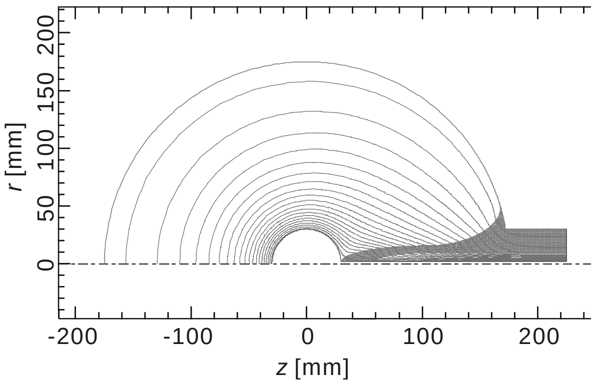


FIG. 7. Potential distribution for normal insulator (upper half is shown).

The He metastable atoms (2^1S) are excited to a given magnetic sublevel in 3^1D by laser through the forbidden transitions, i.e., the Stark-induced electric dipole moment, and electric quadrupole moment (QDP) transitions as shown in Fig. 4 [10].

According to the alignment of atoms achieved with the polarized laser excitation and the selection rules for the relevant radiative transition between sublevels in the upper and lower states, electric fields E can be related to P [10] in the following,

$$E = C^{x}\sqrt{\frac{2(P+1)}{1-3P}}, \; C^{x} = 1.96 \text{ kV/cm for } \boldsymbol{e}_{\mathrm{Lx}} \text{ excitation.} \qquad (2)$$

Integration of E thus yields potential profiles.

4. Result and Discussions

Spatial profiles of LIF peak intensity are plotted in Fig. 8 for ions with enhanced angular momenta together with the intensity profile of the radiation at 587.6 nm which corresponds to the visible image to eyes. Profiles of three polarization components, I_z ($\boldsymbol{e}_{\mathrm{Lz}}$), I_y ($\boldsymbol{e}_{\mathrm{Lz}}$), and I_y

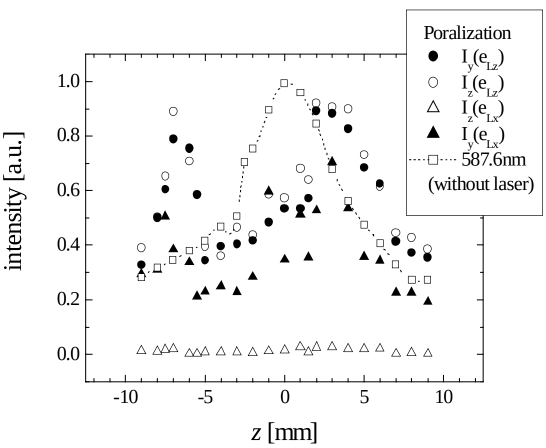


FIG. 8. Profiles of 4 polarized components.

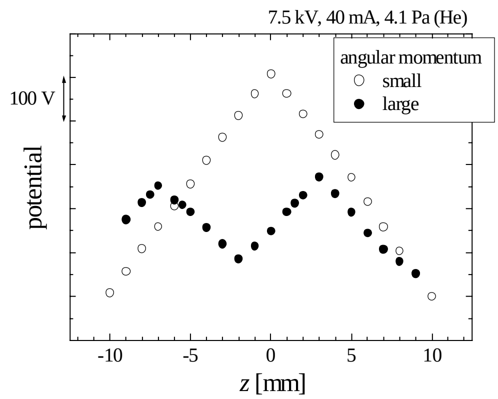


FIG. 9 Potential profiles for ions with relatively larger (solid circle), and smaller (open circle) angular momenta .

($\boldsymbol{e}_{Lx}$) are approximately considered as the profile of collisionally-excited He metastable atoms (2^1S), which are sensitive to the electron temperature in the range of $T_e \leq 20$ eV. The peaks are thus thought to correspond to the potential peaks where the ample energetic electrons are expected to exist.

On the other hand, the intensity of $I_z(\boldsymbol{e}_{Lx})$ is due to the Stark effect, with which electric fields can be evaluated together with $I_y(\boldsymbol{e}_{Lx})$ based by Eqs. (1) and (2). Potential profiles for two cases thus obtained are shown in Fig. 9. It is clearly seen that, a double well potential well forms for ion beams with larger angular momenta, but for ions with smaller angular momentum the potential is seen to have only one peak but much more steeper compared with the former, and this is consistent with theoretical predictions [9].

Intentional production of the ion beams with specific angular momenta will need to be explored for further detailed experiments on the potential well profiles.

Acknowledgements

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