

A BEAM SIZE MONITOR BASED ON APPEARANCE INTENSITIES FOR MULTIPLE GAS IONIZATION*

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Abstract

A method of measuring the spot size or bunch length of intense charged particle beams is proposed. The relation between the size (widths and length) of a charged particle beam and the beam's electric field forms the basis for a sub-micron beam size monitor. When the beam passes through a low pressure gas of high Z atoms, the beam field causes multiple ionizations of the gas atoms. The appearance of ionized atoms in a given charge state gives information about the field of the beam and hence its size. Sample calculations show that appearance thresholds can indicate the spot size of round beams with 10 nm accuracy or the bunch length of round or flat beams with up to 10 μm accuracy.

I. INTRODUCTION

Future colliders for high energy physics call for beams of ever smaller dimensions. Recently, two new techniques for measuring sub-micron beams have been tested, a laser interference technique used at the Final Focus Test Beam (FFTB) at Stanford [2] and a time-of-flight technique proposed by a group from Orsay [3]. The scheme we propose here is complementary to these two and can alternatively be used to measure bunch length if spot size is known. Our approach for beam size measurement is a modification of the appearance intensity diagnostic developed for use with lasers [4].

The beam size diagnostic we propose is shown in Figure 1: the focused particle beam passes through a gas cell. The ions produced by tunnel ionization are accelerated by an external electric field to detectors, and the ionization yields are determined. For a round Gaussian beam, the beam spot size can be deduced by relating it to the highest charge state observed. For flat beams this diagnostic provides no data about the small spot size. However, for a known spot size, the appearance of charge states can be used to compute the bunch length of either flat or round beams. We calculate ionization yields by modelling the interaction of the electric field of a round or flat beam with various gases.

II. THEORETICAL MODEL

The rate of change of atoms in each charge state during the passage of the beam is due to ionization by the beam's electric field.

$$\frac{\partial N_j}{\partial t} = w_j N_{j-1} \quad (1)$$

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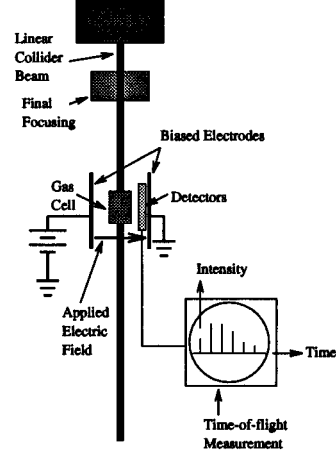


Figure 1. Proposed experimental setup for beam diagnostic.

The N_j represent the fraction of the total gas atoms which are in the j th charge state. The ionization probability, per unit time, is given by the Keldysh formula

$$w_j = w_0 \frac{E_j^{\frac{5}{2}}}{E} e^{-\frac{2E_j^{\frac{3}{2}}}{3E}} \quad (2)$$

where E_j = ionization potential for the j th ionization state, normalized by 13.6 eV; E = transverse beam electric field ($E_r(r)$ for round beams), normalized by the atomic field 5.1453×10^{11} V/m; $w_0 = 1.635 \times 10^5$ /ps. The total ionization yields are obtained by integrating Equations (1) in time.

A. Round beams

The round beam is modelled by a cylindrical bi-Gaussian distribution,

$$N_b(r, z) = N_{b0} e^{-\frac{r^2}{2\sigma_r^2}} e^{-\frac{z^2}{2\sigma_z^2}} \quad (3)$$

where N_{b0} = maximum particle density, σ_r = beam spot size, and σ_z = bunch length. The beam number N_b is related to N_{b0} by

$$N_{b0} = \frac{N_b}{(2\pi)^{\frac{3}{2}} \sigma_r^2 \sigma_z} \quad (4)$$

The radial electric field is found using Gauss' Law, with time dependence brought in through

$$z = c(t - t_p) \quad (5)$$

where t_p is the time when the beam particle density is a maximum.

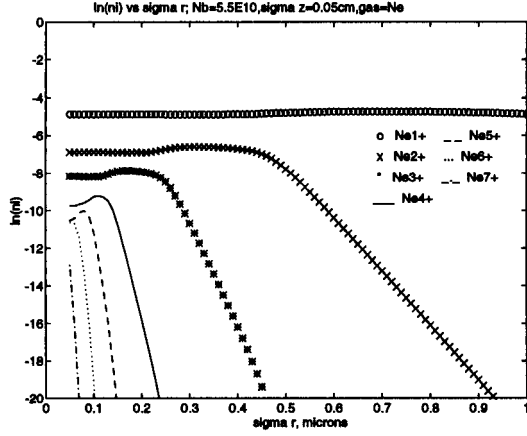


Figure 2. Logarithm of fractional charge state densities for Ne^{1+} through Ne^{8+} vs. σ_r for $N_b = 5.5 \times 10^{10}$ and $\sigma_z = 0.05$ cm.

Eqs. (1) were time-integrated numerically and averaged over r . N_b was taken to be 5.5×10^{10} and the gas sample is assumed to have a radius $r_{max} = 30$ microns for our round beam calculations.

B. Flat beams

The flat beam is modelled by a tri-Gaussian distribution,

$$N_b(x, y, z) = N_{b0} e^{-\frac{x^2}{2\sigma_x^2}} e^{-\frac{y^2}{2\sigma_y^2}} e^{-\frac{z^2}{2\sigma_z^2}} \quad (6)$$

where σ_x = beam width and σ_y = beam height $\ll \sigma_x$; N_{b0} and σ_z are defined as in the round beam case, and the same relation between z and t applies. N_b is related to N_{b0} by

$$N_{b0} = \frac{N_b}{(2\pi)^{\frac{3}{2}} \sigma_x \sigma_y \sigma_z} \quad (7)$$

For these calculations, the beam is treated as a 2-D problem ($\frac{\partial \rho}{\partial z} = 0$). This assumes that the gas cell is shorter than the beam beta functions [6] β_x^* or β_y^* . The gas cell is divided into rectangular boxes of grid sizes δx and δy in the region $-\sigma_x \leq x \leq \sigma_x$, with $\frac{\partial E_y}{\partial x} \ll \frac{E_y}{\delta x}$; over most of the ionization volume $E_x \ll E_y$ and we neglect E_x . Applying Gauss' Law with these approximations allows calculation of E_y . Net ionization yields are obtained by time-integrating Eqs. (1) in each box and summing using a box-based weighting.

III. RESULTS

A. Spot size

Figure 2 plots ionization yields for Ne logarithmically against σ_r for bunch length $\sigma_z = 0.05$ cm. Two points should be noted. First, a charge state will not appear unless σ_r is below some threshold value which allows tunnelling to occur. If σ_r is below the threshold, the ionization yield increases rapidly, then begins to level off. Second, as each successive charge state appears, the yield for the preceding state is decreased by that of the new charge state.

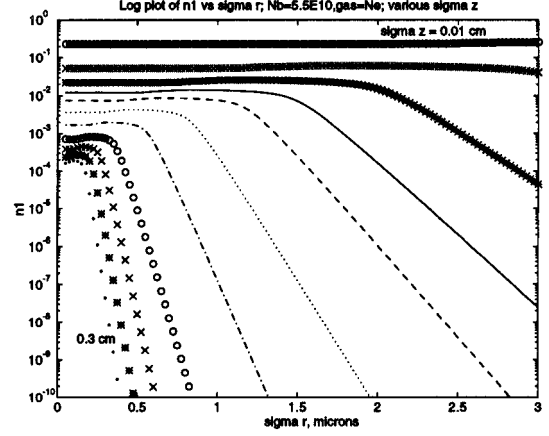


Figure 3. Logarithmic plot showing the variation in ionization yield for Ne^{1+} vs. σ_r as σ_z is varied from 0.01 cm to 0.3 cm. Notice the reduction in N_1 and the threshold value of σ_r for higher values of σ_z . $N_b = 5.5 \times 10^{10}$ in these calculations. The data for the higher charge states show a similar variation.

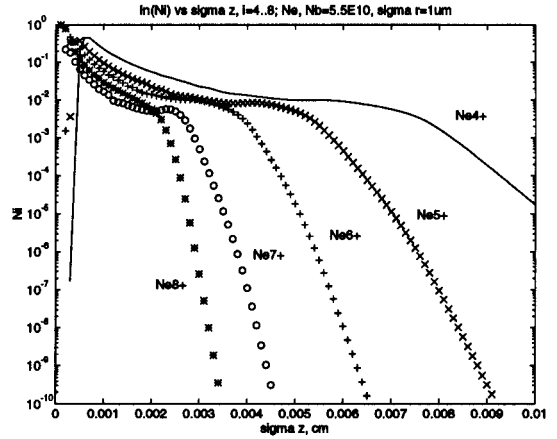


Figure 4. Logarithmic plot of round beam ionization yields for Ne plotted against small values of bunch length. $N_b = 5.5 \times 10^{10}$ and $\sigma_r = 1 \mu\text{m}$. At these small values of σ_z , there are clear appearance thresholds for Ne^{5+} and higher charge states.

It is clear that no significant production of Ne^{2+} occurs until the spot size is below $1 \mu\text{m}$; thus the appearance of Ne^{2+} indicates a spot size below this value. Similarly, the appearance of other charge states gives spot size information from $1 \mu\text{m}$ to $0.07 \mu\text{m}$ with accuracy up to about $0.03 \mu\text{m}$.

To gain some insight into the variation of the ionization yields with σ_z , the calculations were repeated for several values of σ_z ranging from 0.01 cm to 0.3 cm. Figure 3, a logarithmic plot of N_1 vs. σ_r , shows the decrease in N_1 and the lowering of the threshold σ_r below which tunnelling is allowed as σ_z is increased. Although only the data for N_1 are plotted here, the results are similar for the higher charge states.

B. Bunch length

B.1 Round beams

Ne was chosen as the sample gas, with $\sigma_r = 1 \mu\text{m}$. In Figure 4, the bunch lengths are small enough that significant

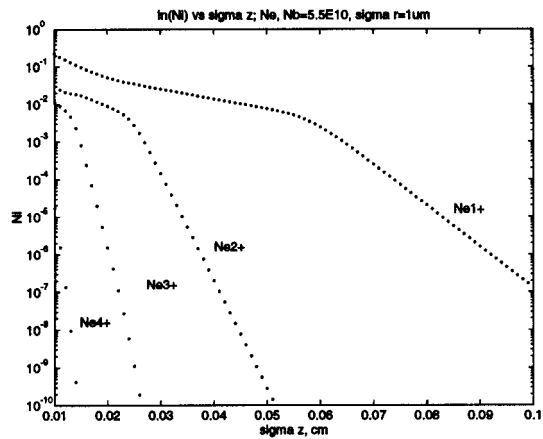


Figure 5. Logarithmic plot of round beam ionization yields for Ne plotted against larger values of bunch length. $N_b = 5.5 \times 10^{10}$ and $\sigma_r = 1 \mu\text{m}$. The appearance thresholds for Ne^{1+} through Ne^{4+} are visible on this scale.

amounts of Ne^{4+} and higher charge states are produced. Figure 5 shows data for longer bunch lengths in the range $0.01 \text{ cm} \leq \sigma_z \leq 0.1 \text{ cm}$. Here, only Ne^{1+} through Ne^{4+} appear in significant numbers. Similar to the data for spot size determination, there are threshold values of bunch length for the appearance of higher charge states. The charge states from Ne^{2+} up give information on bunch lengths ranging from 0.05 cm down to 0.0035 cm with accuracy up to about 0.001 cm.

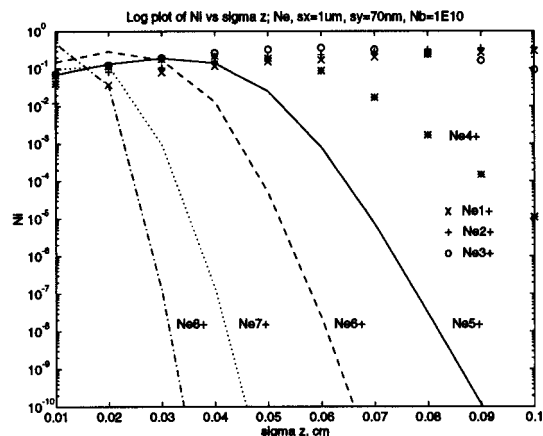


Figure 6. Logarithmic plot of flat beam ionization yields vs. bunch length. The sample gas is Ne, $N_b = 10^{10}$, $\sigma_x = 1 \mu\text{m}$, $\sigma_y = 70 \text{nm}$. Appearance thresholds for charge states Ne^{5+} and higher are evident.

B.2 Flat beams

The flat beam data were calculated for a beam containing 10^{10} electrons with $\sigma_x = 1 \mu\text{m}$, $\sigma_y = 70 \text{nm}$, and Ne in the gas cell. These data are shown in Figure 6. As in the round beam case, there are well-defined bunch length thresholds below which charge states will not occur. Bunch length information from 0.09 cm down to about 0.035 cm may be obtained with accuracy up to about 0.01 cm within the limitations of the simplifications made in the calculations.

IV. CONCLUSION

A diagnostic for particle beam size based on field ionization has been described. Calculations of the ionization yields versus spot size for round beams show fairly sharp thresholds for the appearance of the various charge states involved. Similar calculations using different bunch lengths yield curves with the same form, with maxima and threshold spot size decreasing as the bunch length is increased. Plots of ionization yields versus bunch length for both round and flat beams also display thresholds for the appearance of successive charge states. These thresholds can be used to determine the beam size given the beam number and either a known spot size or a known beam length.

An experiment to test this diagnostic could also be useful in atomic physics. Previous tests of DC atomic tunneling theory with lasers [4] have yielded discrepancies between theory and experiment attributed to the AC nature of the laser. As the particle beam does not oscillate, the data obtained through an experiment using the gas cell-beam apparatus described here with beam intensities comparable to those of the laser would be useful in separating the DC and AC effects.

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