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Time-Resolved Measurement of Electron Beam Neutralization

Carl Ekdahl and Martin Schulze

I. INTRODUCTION

AN intense relativistic electron beam (IREB) incident on a target generates positive ions by stimulated and thermal desorption of adsorbed gas, and subsequent electron impact ionization [1, 2]. These ions are accelerated upstream by the beam space-charge potential, thereby partially neutralizing the beam. If there is enough neutralization, the repulsive space-charge force can be overcome by the magnetic-pinch force due to the beam current. This so-called ion focusing is responsible for time dependent defocusing of the radiographic source spot [3]. Since a single monolayer of adsorbed gas has a surface density of about $10^{15}/\text{cm}^2$ and is formed in about one second in a one micro-Torr vacuum [4], there is always enough adsorbed gas to make this a concern in our accelerators. Therefore, time-resolved measurements of the degree of neutralization are valuable for better understanding of this process with an eye to mitigation for improvement of our radiography Moreover, these measurements would aid quantification of uncertainties due to these effects when using invasive beam diagnostics, such as OTR imaging targets.

II. EXPERIMENTAL METHOD

DARHT has many beam position monitors (BPM) with inductive B-dot loop detectors [5], and inductive detection BPMs are planned for the Scorpius accelerator. Measurements of beam neutralization by back-streaming ions have been made with a BPM having eight (8) or more detector positions that has half of its inductive B-dot detectors replaced by capacitive E-dot detectors [6]. If the BPM is located upstream of the target, the magnetic field is due to the net current (electrons plus back-streaming ions), and the electric field is due to the net line charge (beam space-charge partially neutralized by ions). For a centered beam, the fields at the wall are the same as for a filamentary current and line charge. After suitable calibration and integration, the average of the integrated B-dot data yields the magnitude of the magnetic field at the beam tube wall

$$B_W = \frac{\mu_0 I_{net}}{2\pi R_W} = \frac{\mu_0}{2\pi R_W}\left(I_e + I_i\right) \tag{1}$$

Likewise, after suitable calibration, the average of the integrated E-dot data yields the magnitude of the electric field at the wall

$$E_W = \frac{eN_{net}}{2\pi\varepsilon_0 R_W} = \frac{e}{2\pi\varepsilon_0 R_W}\left(N_e - Z_i N_i\right) \tag{2}$$

.

Here, I_{net} is the net current in Amperes, eN_{net} is the net line charge in Coulombs/meter, Z_i is the ionic charge, and R_W is the beam-pipe wall radius. Defining the electrical neutralization fraction as $f_e = Z_i N_i / N_e$, and noting that charged particle current is related to line density by $I = ZeNv$ one can rewrite Eq. (1) and Eq. (2) as

$$B_W = \frac{\mu_0 I_e}{2\pi R_W}\left[1 + f_e\left(v_i / \beta c\right)\right] \tag{3}$$

and

$$E_W = \frac{eN_e}{2\pi\varepsilon_0 R_W}\left(1 - f_e\right) = \frac{I_e / \beta c}{2\pi\varepsilon_0 R_W}\left(1 - f_e\right) \tag{4}$$

Dividing these expressions yields

$$E_W / B_W = \frac{c}{\beta}\frac{\left(1 - f_e\right)}{\left(1 + f_e v_i / \beta c\right)} \tag{5}$$

which is a direct measurement of neutralization to within the uncertainty of knowledge of electron and ion velocities.

III. DISCUSSION

Consider the terms in the denominator of Eq. (5). The space-charge neutralization factor is bounded by $f_e \le 1$, because a fully neutralized beam has no space-charge potential well to attract ions. Also, for our IREBs β is nearly unity. Even for the 2.0 MeV beam injected into the Scorpius accelerator $\beta = 0.97907$. Furthermore, the back-streaming ion velocity is expected to be much less than c. For example, the space charge depression for a uniform beam with outer radius R_b is [7]

$$\Delta\varphi \approx 30\frac{I_e}{\beta}\left[1+2\ln\left(R_W / R_b\right)\right] \quad (6)$$

In the 6-inch diameter beam pipes of our downstream transport (DST) regions the beam is greater than 0.5-cm radius, and less than 2.0 kA, so the space-charge potential is expected to be less than 400 kV at most. Protons, the lightest of ions produced in beam-target interactions, would only achieve velocities less than 3% the speed of light when accelerated into such a well.

Taking the above points into consideration, it seems that ignoring the small term in the denominator of Eq. (5) introduces an error of no more than about 3%, if one analyzes the data with the approximation

$$f_e \approx 1 - E_W / cB_W \quad (7)$$

where the fields are measured with well-calibrated inductive and capacitive sensors.

Interesting values of the fraction f_e can be quite small, so attention to detail is a requisite. For example, the envelope equation shows that the space-charge force on the beam switches from defocusing to focusing when $f = 1/\gamma^2$ [8], which would be $\sim 4\times10^{-2}$ for the Scorpius injector, or $\sim 5\times10^{-4}$ for the Scorpius DST[1]. Much larger values occur where there is copious ion production (e.g., near targets on which the electron beam is focused to a small spot).

IV. Conclusion

Although fraught with the usual difficulties of differencing large experimental numbers to get small answers, this technique has yielded useful results in exploratory experiments on DARHT-II [6]. Implementation on the Scorpius injector and integrated test stand (ITS) could answer some of the questions that will arise when fielding interceptive diagnostics on these space-charge limited beams. Moreover, implementation on Scorpius and DARHT could help to resolve some of the remaining questions concerning multiple-pulse radiographic target design.

Acknowledgment

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[1] Here $f = f_e + f_m$ where $f_m = I_i / I_e$. The factor f can be thought of as a total neutralization factor including the back-streaming ion current.

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