Space-charge compensation for high-intensity linear and circular accelerators at Fermilab*

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Abstract

Space-charge effects have long been recognized as a fundamental intensity limitation in high-intensity linear and circular accelerators. As the mission of the US high energy physics program is pushing the Intensity Frontier, it is very timely to explore novel schemes of space-charge compensation that could significantly improve the performance of leading high-intensity proton accelerator facilities such as Project-X. In this work, we present two activities at Fermilab on the space-charge compensation experiments based on residual gas ionization: 1) neutralized beam transport of continuous-wave (CW) H- beam in Project-X Injector Experiment (PXIE); and 2) trapped electron plasmas for space-charge compensation in the newly proposed Integrable Optics Test Accelerator (IOTA) ring. Characteristics of the stability in the beam-plasma system, the dynamics of beam neutralization, and the transition between neutralized and un-neutralized beam transports are discussed for each configuration.

INTRODUCTION

The main idea of space-charge compensation considered in this work is based on the long-known fact that the negative effect of Coulomb repulsion can be mitigated if beams are made to pass though a plasma column of opposite charge. The plasma column can be formed by beam-induced residual gas ionization and/or by external plasma sources. This idea has been successfully applied to transport high-current low-energy proton and H- beams into the RFQ in many linacs [1]. In circular machines, partial neutralization by ionization electrons was attempted with notable improvements in beam intensity, namely an order of magnitude higher than the space-charge limit [2].

BASIC DEFINITIONS

The time needed to generate enough election-ion pairs for full space-charge compensation is called charge-neutralization time [1], $\tau_n = 1/n_g\sigma_i v_b$. The number density of the oppositely charged particles n_p (electrons for positive ion beams; positive ions for negative ion beams) grows linearly with time, and we have $n_p \approx n_b$ or $f_n \approx 1$ after the time duration of τ_n. Here, $f_n = n_p/n_b$ is fractional charge neutralization. Note that the background gas density $n_g[\mathrm{m}^{-3}] = 3.54\times10^{22}\times p[\mathrm{Torr}] \gg n_b$ for nominal pressure range ($p = 10^{-7}$–10^{-5} Torr). For 30 keV H$^-$ beam for PXIE LEBT, $\sigma_i = 5\times10^{-20}\mathrm{m}^2$ and $\tau_n \approx 236\ \mu$s for $p = 10^{-6}$ Torr. For 2.5 MeV proton beam for IOTA electron column, $\sigma_i = 1.5\times10^{-21}\mathrm{m}^2$ and $\tau_n \approx 862\ \mu$s for $p = 10^{-6}$ Torr.

The resultant electrostatic potential created by the uniform beam is $\phi(r=0) = V_s\left[1 + 2\ln(r_w/r_b)\right]$, where, $V_s = I_b(1-f_n)/(4\pi\epsilon_0 v_b) > 0\ (<0)$ for positive (negative) ion beams. Note that $\phi(r=r_b) = 2V_s\ln(r_w/r_b)$ and $\phi(r=r_w)=0$. Here, r_b is the radius of the beam with constant density n_b, and r_w is the radius of a perfectly conducting cylindrical wall.

PLASMA PROCESSES

We consider two cases: H$^-$ beam and proton beam in the H_2 dominated vacuum. Here, we listed only the dominant mechanisms.

H$^-$ beam:

$$\mathrm{H}^- + \mathrm{H}_2 \rightarrow \mathrm{H(fast)} + \mathrm{H}_2 + e \quad (1)$$
$$\mathrm{H}^- + \mathrm{H}_2 \rightarrow \mathrm{H}^- + \mathrm{H}_2^+\mathrm{(slow)} + e \quad (2)$$
$$e + \mathrm{H}_2 \rightarrow \mathrm{H}_2^+\mathrm{(slow)} + 2e \quad (3)$$

For the case with no solenoidal fields, ionization electrons are expelled by the beam space-charge immediately and the slow ions are oscillating inside the potential well of the beam. Initially, the ion density profile becomes highly peaked around beam center [3]. After a time duration of τ_n, a steady state is obtained. There is a critical value for the gas density, $n_{g,cr}$, in which $\tau_{i,exit} = \tau_n$, i.e., $n_{g,cr} \approx (1/\tau_{i,ext})/v_b\sigma_i$ [1]. Here, $\tau_{i,exit} = r_b/2v_i$ is the average time for an ion to exit the beam, and $v_i = \sqrt{T_i/m_i}$ is the ion thermal velocity. It is often assumed that T_i is on the order of 0.1 eV [1]. When $n_g = n_{g,cr}$, the potential difference between the beam center and edge, $V_s = 0$ and $f_n = 1$ at the steady state. For $n_g < n_{g,cr}$, $V_s < 0$ and $f_n < 1$. In this case, the beam is not fully neutralized and the system is essentially two component one ($n_e \ll n_i \sim n_b$). For $n_g > n_{g,cr}$, the beam becomes overcompensated, i.e., $V_s > 0$ and $f_n > 1$. In this case, $eV_s \sim T_e$ and $v_i \approx \sqrt{T_e/m_i}$.

For the nominal pressure range of the PXIE, we always have $n_g < n_{g,cr}$, which is good for minimizing stripping loss, but not favorable for achieving full compensation. To achieve full compensation, use of Xe as a background gas is often considered, which decreases the critical density by a factor ~ 45. Also, to reduce the loss of the H_2^+ ions through the longitudinal drift, positively biased electrodes will be used.

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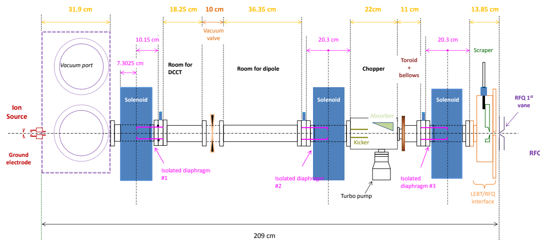

Figure 1: Mechanical layout of the PXIE LEBT.

proton beam:

$$p + \mathrm{H}_2 \;\rightarrow\; \mathrm{H(fast)} + \mathrm{H}_2^+\mathrm{(slow)} \quad (4)$$

$$p + \mathrm{H}_2 \;\rightarrow\; p + \mathrm{H}_2^+\mathrm{(slow)} + e \quad (5)$$

$$e + \mathrm{H}_2 \;\rightarrow\; \mathrm{H}_2^+\mathrm{(slow)} + 2e \quad (6)$$

Positive ions are expelled by the beam space-charge, but much slower rate than the electrons. Therefore, space-compensation could exhibit a nonlinear phase in the beginning, particulary at the high gas pressure. The ionization electrons have considerably higher thermal velocity than the ions, thus as V_s approaches to zero after a time duration of τ_n, the electron loss increases and the space-charge compensation process slows down [3].

When we apply a uniform solenoidal field, on the other hand, the ionization electrons are confined close to the transverse position they are born, and their density profile is similar to that of the proton beam. For non-relativistic electrons, the Larmor radius is $r_L = (3.37[\mu\mathrm{m}])\sqrt{T_\perp[\mathrm{eV}]}/(B_0[\mathrm{T}])$. In a 0.5 T normal-conducting solenoid considered in the IOTA, the Larmor radii are $r_L < 0.1$ mm for perpendicular kinetic energy $T_\perp < 200$ eV.

PXIE LEBT: H$^-$ BEAM

The PXIE will have a DC H$^-$ source (30 keV, up to 10 mA), a low energy beam transport (LEBT) system with three solenoid magnets (see Fig. 1), a CW RFQ, a medium energy beam transport (MEBT) system with wide-band chopper, and two superconducting cryomoules (HWR and SSR1). The functions of the PXIE LEBT are 1) to transport and match the beam to the RFQ optical inputs; 2) to act as the first layer of the machine protection system; and 3) to provide pulsed (chopped) beam for commissioning of the beam line downstream [4].

Typically, the beam exiting an ion source is neutralized within a time duration of τ_n. Neutralization greatly reduces the beam space charge effects, most importantly, the emittance growth. As mentioned above, the PXIE LEBT should be operating in both pulsed and DC modes. In the pulsed mode, a chopper removes the neutralizing particles, and the beam becomes uncompensated and may behave quite differently. For PXIE, the 5-mA beam space charge is relatively low, for instance, compared to the beam at SNS

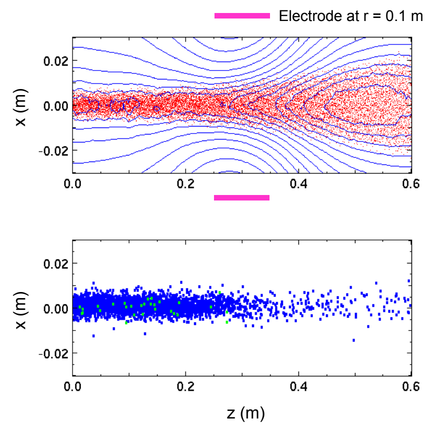

Figure 2: WARP 3D simulation of the transition from neutralized to un-neutralized transports in the PXIE LEBT. Electrode keeps positive ions (blue dots) from drifting into the un-neutralized region. For the un-neutralized region, we assume the vacuum is so good that there is little ionization processes. Note that most electrons (green dots) are expelled.

($\sim$ 50 mA). Simulations showed that a scheme where the beam would be uncompensated in a part of the LEBT is possible, and such scheme was devised [4]. This scheme will minimize difference of the beam transport characteristics between the pulsed and DC mode operations, and allows for more space after the chopper for the absorber and diagnostics. Un-neutralized transport can be realized by properly biasing the electrodes, ensuring a good vacuum, and adjusting the strengths of the three solenoids. On the other hand, the beam emittance may increase during the transition between neutralized and un-neutralized transports. In this regard, it is important to investigate whether the emittance growth is acceptable or not (e.g., by measuring emittance using Allison emittance scanner).

Up to the second solenoid, on the other hand, neutralization of the beam is maintained in a steady-state manner. Stability of this beam-plasma system can be affected by the collective processes, such as dynamic decompensation, and electron and/or ion oscillations [5]. While beam neutralization experiments have been carried out elsewhere, space-charge compensation in the CW negative hydrogen beams is relatively less well understood. The PXIE LEBT configuration is quite unique as it allows to investigate both transient and steady-state nature of the space-charge compensation of the negative hydrogen beam. A beam dynamics study, using WARP 3D PIC code, is in progress to address those unique characteristics of the PXIE LEBT (see Fig. 2) [6].

IOTA E-COLUMN: PROTON BEAM

A new storage ring (IOTA) is under construction at Fermilab to demonstrate the concept of the nonlinear inte-

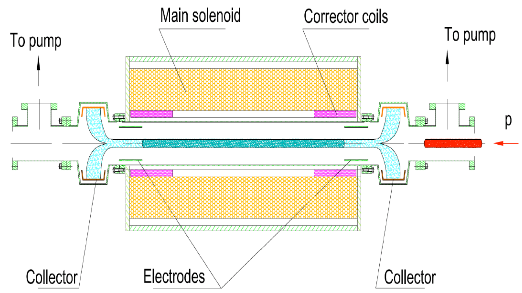

Figure 3: A conceptual layout of electron-column apparatus for space-charge compensation in the IOTA ring.

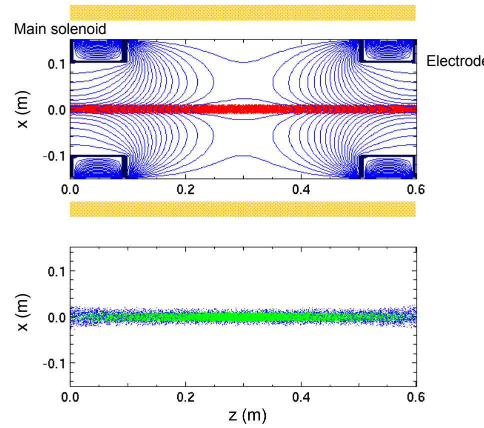

Figure 4: WARP 3D simulation of the plasma formation and trapping in the e-column. Uniform solenoid keeps both electrons (green dots) and ions (blue dots) stay in the beam path. Ions are slowly escaping longitudinally. To resolve cyclotron motion of the electron, time step has been set $\Delta t \leq 0.25 \times 2\pi/\omega_{ce}$.

grable lattice [7]. After the dedicated machine studies using electron beams as probes, performance demonstrations in the space-charge dominated regime using proton beams will be followed [8]. One of the key R&D items is to investigate whether the space-charge compensation can be realized in the ring. The necessary conditions for the effective space-charge compensation in rings will be 1) the impact of electrons is equal to the total impact of beam space charge over the ring; 2) the transverse profile of the electron density is the same as that of the proton beam; 3) the system of electrons and protons is dynamically stable. For the electron column concept considered here, electrons are generated internally through beam-induced residual gas ionization without special electron sources and optics. In the electron column concept, conditions 2 and 3 can be achieved if protons and electrons are immersed in a longitudinal magnetic field which is a) strong enough to freeze the electron density distribution; b) strong enough to suppress the e-p instability; c) weak enough to allow positive ions to escape transversely, in addition to longitudinal draining; and d) well matched to the ring optics to avoid beta-beat excitations.

The interaction between the trapped electrons and circulating proton beams is two-stream in nature. It will degrade the quality of both the electron column and the main beam. It is well-known that the increase of the confining solenoidal field and Landau damping through momentum spread can suppress the instability. In addition, there are two unique instability suppression possibilities in the proposed experimental setup. One is self-stabilization of the e-p instability by the accumulation of secondary ions. It is observed [2] and also theoretically confirmed [9] that if there are not only electrons but also some residual ions in the cloud, the ions tend to short-out the electrostatic perturbations whose wavelengths are less than the transverse beam size r_b. The residual ion formation could be controlled by the proper choice of working pressure, solenoidal field, and electrode voltage (e.g., see a conceptual apparatus in Fig. 3). The other is the increased Landau damping by a broad tune spread enabled by a special nonlinear lattice in the IOTA ring. This nonlinear lattice is designed to be integrable, and thus can create a large tune spread and zero resonance strength.

Simulation of the plasma formation and trapping in the e-column is in progress using WARP 3D code (see Fig. 4). The simulation will eventually be coupled to a tracking code for the ring, to understand the effects of the nonlinear lattice and e-p instability.

CONCLUSION

Two unique experiments on space-charge compensation (one in the linac, and the other in the ring) are planned at Fermilab. Advanced simulation tools (e.g., WARP 3D PIC code [6]), and dedicated beam/plasma/gas diagnostics and controls will enable detailed understanding of the space-charge compensation processes, and eventually allow to achieve intense beams with improved stability and quality.

REFERENCES

[1] M. Reiser, *Theory and Design of Charged Particle Beams*, Wiley-VCH, Weiheim, 2008.

[2] G. I. Dimov et. al, Particle Accelerators 14, 155 (1984).

[3] A. BenIsmail et. al, Phys. Rev. ST. Accel. Beams 10, 070101 (2007).

[4] L. Prost et. al, Project X Document 1098-v3 (2012).

[5] I. A. Soloshenko, AIP Conf. Proc. 380, 345 (1995).

[6] Q. Ji et. al, Proceedings of HB2012, 546 (2012).

[7] V. Danilov et. al, Phys. Rev. ST Accel. Beams 13, 084002 (2010).

[8] V. Shiltsev et. al, *ASTA proposal*, Fermilab, 2013.

[9] R. A. Bosch, Phys. Rev. ST Accel. Beams 6, 074201 (2003).