OBSERVATIONS OF ELECTRONS IN THE INTENSE PULSE NEUTRON SOURCE (IPNS) RAPID CYCLING SYNCHROTRON (RCS)*

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Abstract

In the process of accelerating protons from 50 to 450 MeV at 30 Hz, low-energy electrons are generated within the IPNS RCS vacuum chamber. Electrons from background gas stripping are detected using an Ionization Profile Monitor (IPM) to generate integrated, horizontal charge distributions of the single-harmonic bunch during acceleration. Recently, a Retarding Field Analyzer (RFA) was installed in the RCS to look for evidence of beam-induced multipacting by measuring the electrons ejected by the space charge of the beam. A wide-band, high-gain transimpedance amplifier has been built to observe time structure in the electron signal detected with the RFA. Though a noisy power supply prevented full I-V characteristics from being obtained, interesting features are observed; especially, after the period of phase modulation between the rf cavities that is deliberately introduced during the cycle. The phase modulation generates a longitudinal quadrupole oscillation in the bunch, which is believed to enhance beam stability. Preliminary results indicate that electron multipacting is not significant in the RCS. The effects of background gas neutralization are considered and details of the RFA measurements are presented.

INTRODUCTION

Space-charge neutralization can play an important roll in the transport properties of an ion beam, especially if the fractional neutralization becomes substantial. For example, in the IPNS accelerator, nitrogen gas is introduced between the H^- ion source and 750-kV, Cockcroft-Walton pre-accelerator, to mitigate space-charge blow-up of the beam[1]. Neutralization allows efficient transport of ions between the source and linac. In this case, the effect is primarily electric neutralization. In the RCS, the effects of neutralization are again present; due to the ionization of background gas; however, in this case, the magnetic field of the beam may also be involved.

ANALYSIS

The beam space-charge generates an electric field which drives positive background ions out of the beam channel, while attracting and trapping electrons. A uniform beam density is assumed across an average radius, r_b, and zero density outside to the wall radius r_w. The radial electric field may be expressed as, $E_r(r)=\rho(t)r/2\varepsilon_0$, for $r<r_b$, and $E_r(r)=\rho(t)r_b^2/2r\varepsilon_0$, for $r_b<r<r_w$, where $\rho(t)=e(n_i(t)-n_e(t))$ and $n_i(t)=Z(t)n_{bk}(t)+n_b(t)$. The background ion density, $n_{bk}(0)$ is initially assumed to be zero. Though this is a simple model, it is useful in examining the dynamics of the background ions. The average electric field, E_{av} across the inner radius can be used to compare non-relativistic transit times, $\tau_{tt}=(2mr_w/eE_{av})^{1/2}$ for the ions and electrons. For 3×10^{12} protons uniformly distributed within r_b=1.5 cm and occupying half of the 43 m RCS circumference (B_f=0.5), E_{av}=154 V/cm, assuming r_w=3.8 cm. The one way transit times for an electron and a singly-charged nitrogen ion, both starting with zero initial velocities are 1.7 ns and 270 ns. This can be compared with a bunch length of 225 ns near injection (h=1).

Analysis shows that beam space-charge can trap and release electrons[2]; in addition, secondary electron yield (SEY) from the wall may exceed unity leading to a build-up in the electron density and the development of an e-p instability[3,4]. The process of SE is distinct from background gas neutralization; in the former case, the creation of low-energy (free) background ions does not occur, and any positive background ions are quickly ejected by the beam space charge playing no roll in the process. However, if the electron density builds up quickly during the period of coasting beam injection and capture, the space-charge of the beam may be neutralized, preventing the ejection of background ions.

Determination of the neutralization time, τ_n, requires that the ionization cross section, σ be known. Following the discussion from Reiser[5], the calculated values of σ are presented in Figure 1 along with the neutralization folding times for background gas pressures of 1 μTorr and 2 μTorr N_2. The average background gas pressure in the RCS falls within this range. The neutralization folding time is given by, $\tau_n=(n_g\sigma v)^{-1}$, where n_g is the neutral background gas density. As shown in Figure 1, for 1 μTorr, τ_n varies from 0.5 ms to 1.0 ms during the acceleration period. For purpose of comparison, in the PSR at Los Alamos, τ_n = 20 ms.

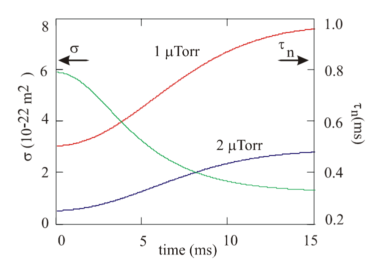

Figure 1: Ionization cross section and neutralization times in the RCS for 1 and 2 μTorr, N_2.

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Given the ionization cross section and the background gas and beam densities, the average incremental ion and electron density created per cycle (Z=1) is $n_g n_b \sigma\beta c\Delta t$, where Δt is the revolution period. Assuming a round beam of radius r_b=1.5 cm, the average beam density is n_b=2.0x10^{14} m^{-3} (BF=0.5). At 1 μTorr, the background gas density exceeds that of the initial beam by more than 2 orders of magnitude.

Self-focusing may occur if the background plasma traps a portion of the beam's magnetic field. As the beam travels around the synchrotron, its current creates a magnetic field. A stationary plasma in the vicinity of the beam will have a tendency to maintain some of the impressed field for a period, τ_m. the magnetic decay time. The beam will experience the trapped magnetic field and respond to it. It is assumed that the trapped field, $\mathbf{B}_t$ is maintained by a current that travels in the same channel as the beam[6]. From the Lorentz force expression, $\mathbf{F}=q(\mathbf{E}+\mathbf{v}\mathrm{x}\mathbf{B})$, it can be seen that the primary force on the beam protons is in the radial direction ($v_z=\beta c$, $\mathbf{B}\sim B\mathbf{a}_\phi$). The radial force may be expressed as,

$$F_r(r) = q\beta c \frac{\mu_o I_m(r)}{2\pi r} \qquad (1)$$

where $I_m(r)=f_n I_b(r)$ and f_n is the fractional neutralization. Assuming a uniform current density, $I_m(r)\propto r^2$ and the focusing length is independent of radius within the beam. The focal length of the plasma lens is $f_{pl}=r/r'$ where $r'=v_r/v_s$ and $v_r=a_r\Delta t+v_{ro}$. Letting v_{ro}=0, and again writing Δt as the cycle time, $2\pi R/\beta c$, the focal length becomes,

$$f_{pl} = \frac{\beta\gamma mc}{q\mu_o I_m R} r_b^2 \qquad (2)$$

where I_m now represents the total magnetic current and R=6.83 m. Assuming the background plasma traps the average current (~2 A, B_f~0.2), the focal length of the plasma lens is 45 m, approximately the circumference of the ring. This is a relatively weak lens. In this simple model, though the lens is linear, its strength varies as r_b^{-2} (current density). In reality, the beam density is more like a Gaussian distribution and the trapped field likely will not vary linearly with r. In this case, the nonlinearity of the lens acts to couple longitudinal beam energy into the transverse planes.

Most treatments of electron cloud instability ignore the presence of background ions [7,8]. When the background gas pressure is low or the beam cycle time is short compared to the neutralization folding time, τ_n, this assumption may be acceptable. In the case of the RCS, the acceleration period is significantly longer than τ_n. The presence of a background plasma can alter the beam self-field and applied fields within the vacuum chamber.

EXPERIMENTAL ARRANGEMENT

The phase controller for the RCS rf includes a "scrambler" that causes a phase modulation in the rf accelerating voltage near the second harmonic of the synchronous frequency (~10 kHz). The scrambler is typically switched on between 8.5 ms and 9.5 ms into the acceleration period. Scrambler excitation couples longitudinal energy into transverse bunch motion and may help to disrupt the plasma channel growing with the beam. Without the scrambler, the beam sustains a substantial loss near the end of the cycle[9].

The Profile and Position System (PAPS)

The PAPS consists of two arrays of stainless steel grids, one on the bottom and the other on the side of the S6 straight section, detecting integrated horizontal and vertical electron currents, respectively[10]. The PAPS is a form of ionization profile monitor (IPM) and depends on the ionization of the background gas in an applied electric field to provide profile information. The horizontal PAPS is presented schematically in Figure 2.

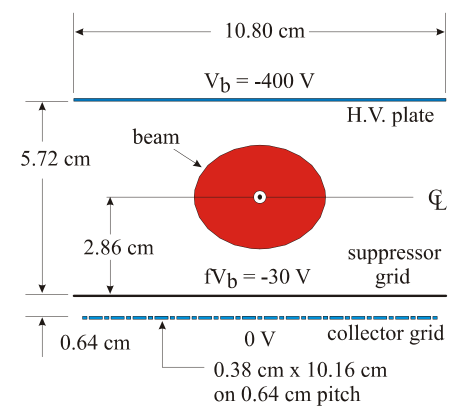

Fig. 2. Horizontal Profile and Position System (PAPS).

Typically, the PAPS bias plate voltage is set at -400 V. The horizontal PAPS device has a more desirable aspect ratio (plate width/beam gap) relative to its vertical partner, so here we will discuss only horizontal PAPS data. The horizontal device is made up of 16 stainless steel collector strips arrayed across the bottom of the diagnostic with a 0.25-in. (.64 cm) spacing from center to center as shown in Figure 2. Between each collector strip is a grounded guard strip. The PAPS bandwidth is 5 kHz. The amplitude of the PAPS profile is sensitive both to bias voltage and background pressure as shown in Figure 3. The PAPS data show processes associated with injection and the phase-modulating scrambler period. The profiles become multi-peaked and noisy after the scrambler burst around 10 ms; in addition, the peak amplitude is substantially reduced. The suppressor bias is maintained at a small fraction of the main bias. It is interesting to note that with zero bias, the profile inverts slightly, indicating a positive current, perhaps due to SE.

The Retarding Field Analyzer (RFA).

The RFA is an electron energy analyzer which has been described elsewhere[11]. The RFA assembly is mounted onto a 2.75 in. (7.0 cm) diameter stainless steel flange between the L5 cavity and triplet magnet 6 on the outboard side of the beam pipe at beam elevation.

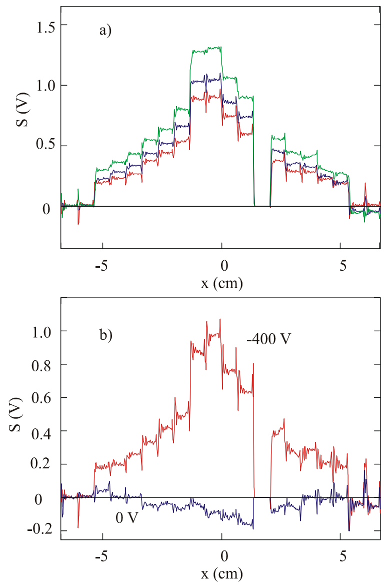

Figure 3. PAPS profiles with a) three background pressures increasing in ascending order from 0.4 µTorr to 1.2 µTorr 1 ms after injection, and b) -400 V and 0 V on the H.V. plate, 2 ms after injection. Ch. 11 is inactive.

Based on background gas ionization alone, the output signal from the RFA is expected to be small. An amplifier has been constructed with a transimpedance gain of 300 kΩ.; the voltage gain of the circuit into 50 Ω is 6000 (76 dB). Using the ionization cross section for nitrogen given above, the electron current per unit length, I_{el} is 46 µA/m at injection. The output amplifier voltage is calculated to be 2.4 mV. It is difficult to definitively say that electrons have been observed using the RFA. "Electron-like" signals are seen sporadically, for example the data in Figure 4 strongly suggests a burst of electrons during beam bunching early in the RCS cycle; however, such data are rarely repeated. This is under investigation.

Pie Electrodes

Another indication that electrons are present in the RCS come from broadband noise observed on split-can or "Pie" electrodes located in the short straight sections of the ring. The Pie electrodes are short striplines and therefore provide a differentiated current signal with respect to time. Beam position data is generated from this diagnostic using analog summing and differencing circuits. A sample of the broadband noise spectrum detected with the Pie electrodes is presented in Fig. 5. In the figure, the two spectra shown are obtained from an 80 µs slice of time data (20 kS at 250 MS/s) starting 10.88 ms after injection and approximately 2.5 ms after the scrambler period begins. The primary shape harmonics are visible in both spectra; however, in the scrambler spectrum, broad sidebands are in evidence. The sidebands move to higher frequency with time. It is the cycle without the large sidebands (and scrambler) that exhibit a 70 percent loss of beam prior to extraction.

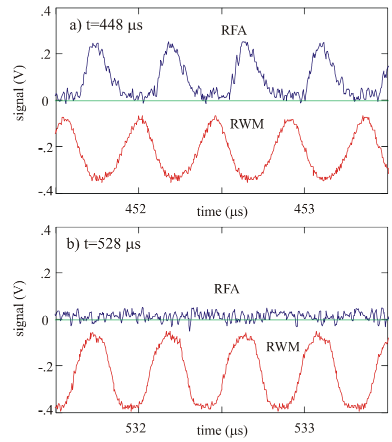

Figure 4: RFA and RWM data recorded just after injection, V_{ret}= 0 V, V_{col}=30 V (1 MΩ), a) t_{start}=448 µs, b) t_{start}=528 µs. The signals are temporally aligned.

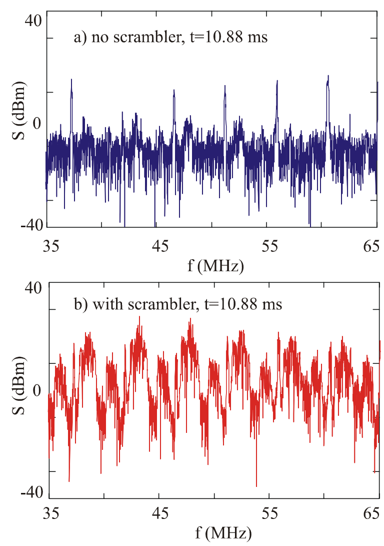

Figure 5: Pie spectra for an 80 µs slice of time data starting at 10.88 ms; a) no P and b) with PM.

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