e-p INSTABILITY IN THE NSNS ACCUMULATOR RING

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Abstract[*]

It has been speculated that the intensity limitation observed in the Los Alamos Proton Storage Ring (PSR) is caused by a coherent instability [1] induced by the presence of pockets of electrons generated by scattering with the molecules of the vacuum residual gas. A theoretical explanation of the e-p instability of course does exist [2], and is similar to the one developed for the ion-induced instability in electron storage rings. Considering the large beam power (2 MW) involved in the NSNS Accumulator Ring [3], and the consequences caused by even a small amount of beam loss, we need to carefully assess the effects of electrons that may be generated in the vacuum chamber.

1 SOURCES OF ELECTRONS

Electrons may be generated in a variety of ways. Negative ions traverse the stripping foil during injection. The average power associated to the electrons is 2.2 kW, corresponding to 1 GeV primary beam with an average power of 2 MW. Leaving the foil, the electrons will drift forward and enter the fringe field region of a 2.5 kG bending magnet [4], which is part of the horizontal set-up for the beam multiturn injection. The trajectory of the electrons in that region is a semicircle of 10 cm diameter, at the end of which they are collected by a water-cooled copper and graphite collector, disposed parallel to the motion of the incoming beam. The acceptability cryterion is that no more than 10^{-4} electrons per protons are left behind in the stripping foil region.

The second mechanism of electron production is the loss of protons on the vacuum chamber wall. If a proton hits the wall, electrons may be desorbed, which in turn may hit the wall again, and desorb more electrons through a process known as “multipactoring”. The effect of this mechanism is controlled by minimizing the loss of the protons to the wall. The design requirement for this purpose is a total loss not exceeding 10^{-4} of the total proton beam intensity, which is achieved by allowing a factor larger than two between physical acceptance and full beam emittance all around the ring, and by insertion of collimators/scrapers in conveniently chosen locations to intercept the beam halo. Also, the vacuum chamber will be made of titanium-coated aluminum, to eliminate or considerably reduce electron desorbtion and multipactoring.

Probably the source of electrons with more serious consequences to the beam stability is the vacuum residual gas. For economic reasons, and simplicity, we have opted for an average pressure of 10^{-9} Torr equivalent nitrogen. The vacuum chamber of the NSNS Accumulator Ring has a large aperture with an average radius b = 10 cm all the way around. Other parameters are shown in Table 1.

Table 1: Parameters of the NSNS Accumulator Ring

Beam Kinetic Energy	1.0 GeV
Beam Average Power	2.0 MW
Number of Protons, N_T	2.08×10^{14}
No. of Injected Turns	1100
Revolution Period, T_0	841.3 ns
Bunch Length, T	546.6 ns
Beam Gap, τ	294.7 ns
Beam Average Radius, a	38 mm
Pipe Radius, b	100 mm
Circumference, $2\pi R$	220.7 m
Betatron Tune (H and V)	5.82
Average Vacuum Pressure	10^{-9} Torr (equiv. N_2)

2 RESIDUAL GAS IONIZATION

The assumed average vacuum pressure corresponds to a residual gas density $n = 6 \times 10^7$ atoms / cm^3 at normal conditions. The expected average ionization cross-section is $\sigma_i = 1.2 \times 10^{-18}$ cm^2. The rate of electron production is then given by

$$d n_e / dt = \beta c n \sigma_i N(t) \qquad (1)$$

where N(t) is the number of protons which varies during injection according to $N(t) = N_r t$, with $N_r = N_T / T_{inj} = 2.25 \times 10^{17}$ protons / s. At the end of the injection process, the beam has been longitudinally compressed and is immediately extracted. Integration of (1) gives

$$\chi = n_e / N_T = 1/2 \ \beta c n \sigma_i T_{inj} \qquad (2)$$

that is a beam charge neutralization $\chi = 0.09$ %.

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3 MOTION OF THE ELECTRONS

To understand the dynamics of the electrons it is necessary to have an idea of the motion in the various components that make up the Accumulator Ring. For this purpose, we shall assume that the proton beam bunch is a cylinder with dimensions given in Table 1, with transverse and longitudinal uniform charge distribution. The beam intensity varies linearly with time during the injection process. We shall assume that the bunch length L remains approximately unchanged, and that the betatron emittance varies linearly with time. Then, the charge density $N(t) / L a^2$ is constant throughout the multi-turn injection process.

4 MOTION IN THE DRIFTS

The equations of motion are very simple. In the region where the beam bunch is present

$$d^2 (x,y) / dt^2 + \Omega_e^2 (x,y) = 0 \qquad (3)$$

In the beam gap region the motion is a pure drift, where the electrons have an opportunity to leave the beam and reach the vacuum chamber wall. It will require a transverse velocity $v_e = 0.34 \times 10^6$ m / s to escape, which corresponds to an energy of 0.33 eV, less than the 2 keV potential energy in the proton beam. Thus most of the electrons produced by the residual gas ionization, in the drift regions, will be able to escape the beam. It derives that the neutralization coefficient χ given by equation (2) is expected to be considerably lower by several orders of magnitude.

In the presence of the proton bunch, the bouncing angular frequency

$$\Omega_e^2 = 2 N(t) r_e c^2 / a^2 L \qquad (4)$$

where $r_e = 2.82 \times 10^{-15}$ m, and $L = \beta c T = 143$ m. The bouncing frequency is constant during the injection process: $\Omega_e / 2\pi = 113.6$ MHz.

Each electron receives a periodic transverse attractive kick when is traversing the proton bunch, followed by a drift between two consecutive passages. The system of Eq.s (3) can be solved with the matrix method. The transfer matrix over one period, which includes one beam gap and one beam bunch, is

$$M = \begin{vmatrix} \cos\phi - \Omega_e \tau \sin\phi & (1/\Omega_e) \sin\phi + \tau \cos\phi \\ - \Omega_e \sin\phi & \cos\phi \end{vmatrix} \qquad (5)$$

where $\alpha = \Omega_e \tau / 2$ and $\phi = \Omega_e T$. The stability of motion, that is of electron trapping, is determined by the condition $| \mathrm{Tr}\, M | < 2$, that is

$$| \cos\phi - \alpha \sin\phi | < 1 \qquad (6)$$

It is seen that when the beam is completely debunched, that is $\tau = 0$, the motion is always stable and the electrons are trapped. But with a beam gap of $\tau = 295$ ns the motion is unstable.

One can also estimate the time that is required for the electrons to leave the beam and reach the wall, since that is also given by the trace itself of the transfer matrix if we write,

$$| \cos\phi - \alpha \sin\phi | = \cosh\mu \qquad (7)$$

The escape rate is $1 / \tau_{esc} = \mu / T_0$, which for $\tau = 295$ ns gives $\tau_{esc} = 178$ ns. The actual number of electrons present in the vacuum chamber in a drift section is then given by the balance of the escape rate and the production rate, that is when

$$d n_e / dt = \beta c n \sigma_i N(t) - n_e / \tau_{esc} = 0 \qquad (8)$$

At the end of the injection process, we estimate that 0.7×10^8 electrons remain in a drift section, which yields a neutralization coefficient $\chi = 3.4 \times 10^{-7}$.

5 BEAM LEAKAGE IN THE BUNCH GAP

It has been speculated [1] that the ep instability observed in the PSR ring could be caused by an amount of proton beam which leaked in the bunch gap. In the NSNS Accumulator Ring the design calls for the provision of an rf system which compresses the beam in a single bunch during the injection process. The system will guarantee a gap completely clear of beam to a level of 10^{-4} of the total proton intensity. In the case that a small fraction η of the proton beam could be present in the gap, the transfer matrix (5) will be modified to yield a new stability condition

$$| 2 \cos\phi_B \cos\phi_G - (\Omega_G / \Omega_B + \Omega_B / \Omega_G) \sin\phi_B \sin\phi_G | < 2 \qquad (9)$$

where

$$\Omega_B^2 = \Omega_e^2 (1 - \eta), \qquad \Omega_G^2 = \Omega_e^2 \eta \qquad (10)$$

$$\phi_B = \Omega_B T, \qquad \phi_G = \Omega_G \tau \qquad (11)$$

It is seen that already with a 1% of the proton beam leaked in the bunch gap, stability and instability conditions alternate during the injection process. For larger value of η, the chances of electron trapping increases considerably. It is thus important that the bunching process will exclude protons to penetrate the gap at a rate larger than 0.1% of the total proton intensity.

6 MOTION IN THE BENDING MAGNETS

To evaluate the motion of the electrons in a dipole magnet, one has to modify Eq.s (3) to include the contribution from the dipole field. Within the bunch the equations of motion are

$$d^2x / dt^2 \quad + \quad \Omega_e^2\, x \quad = \quad - \, \Omega_L \;\, dz / dt \qquad (12a)$$

$$d^2y / dt^2 \quad + \quad \Omega_e^2\, y \quad = \quad 0 \qquad (12b)$$

$$d^2z / dt^2 \quad = \quad \Omega_L\, dx / dt \qquad (12c)$$

where $\Omega_L = e\, B / m_e\, c$ is the angular Larmor frequency with B the strength of the bending field. Within the bunch gap $\Omega_e = 0$. Thus the vertical motion remains unchanged as in the drift sections, with the same consequences that have been described earlier. The horizontal and longitudinal components of the motion are now coupled to each other through the bending field. The motion on the horizontal plane is dominated by a tight precession movement at the Larmor frequency. In the NSNS Accumulator Ring, B = 0.74 Tesla and $\Omega_L = 124$ GHz.

7 MOTION IN THE QUADRUPOLE MAGNETS

All the components of motion are now coupled to each other by the quadrupole gradient G. Moreover the equations of motion are now nonlinear and difficult to solve exactly. In the interval of the beam bunch Eq.s (12) are modified as follows:

$$d^2x / dt^2 \;+\; \Omega_e^2\, x \;=\; - \; K_L\, x\, dz / dt \qquad (13a)$$

$$d^2y / dt^2 \;+\; \Omega_e^2\, y \;=\; K_L\, y\, dz / dt \qquad (13b)$$

$$d^2z / dt^2 \;=\; K_L\, (\, x\, dx / dt - y\, dy / dt\,) \qquad (13c)$$

where $K_L = e\, G / m_e\, c$. Within the bunch gap again $\Omega_e = 0$. Eq.s (13) can be partially integrated to show that

$$dz / dt \;=\; v_{init} \;+\; K_L\, (\, x^2 \;-\; y^2\,) / 2 \qquad (14)$$

is a prime integral.

The system of Eq.s (13) can be integrated with some approximations in special cases [5]. For instance, in the case $x^2, y^2 << a^2$ and $dz / dt \sim 0$, one can show that the motion is unstable at least on one plane of oscillations. On the other hand, if one takes $x = 0$ and $y \sim a$, it can be seen that $K_L\, a^2 / 2$ is much larger than v_{init}. In this case there is a large frequency variation with the amplitude of the electron motion. This spread will quickly smear any coherent motion that may appear within the electron beam which cannot then feedback to the proton beam motion.

8 THE E-P INSTABILITY

A coherent instability of the proton beam bunch can be triggered by the electromagnetic interaction with the cloud of electrons, when both beams have a finite displacement of the centers of mass Y_p and Y_e. The equations for Y_p and Y_e are then [1,2,5]

$$d^2Y_p / dt^2 \;+\; \Omega_\beta^2\, Y_p \;=\; (\chi\, r_p / \gamma\, r_e\,)\, \Omega_e^2\, (Y_e - Y_p) \qquad (15a)$$

$$d^2Y_e / dt^2 \;=\; \Omega_e^2\, (Y_p - Y_e) \qquad (15b)$$

where Ω_β is the angular betatron frequency. We shall look for a solution of the form

$$Y_{p,e} \;=\; \overline{Y}_{p,e} \;\; \exp i\, (k\theta - \Omega t) \qquad (16)$$

where Ω is an unknown collective angular frequency, which we expect to be a complex quantity, θ is the angular coordinate around the circumference of the ring, and k is a mode number which, of course, is expected to have only integer values. It is to be noticed that

$$d\, Y_p / dt \;=\; -i\, (\Omega - k\omega_0)\, Y_p \qquad (17a)$$

$$d\, Y_e / dt \;=\; -i\, \Omega\, Y_e \qquad (17b)$$

where $\omega_0 = 2\pi\, f_0$. Substituting (16) into the system of Eq.s (15), and requiring that the resulting determinant of the amplitudes $\overline{Y}_p$ and $\overline{Y}_e$ vanishes, give the following dispersion relation

$$1 \;=\; \Omega_p^2 / [\, (\Omega - k\omega_0)^2 \;-\; \Omega_\beta^2\,] \;+\; \Omega_e^2 / \Omega^2 \qquad (18)$$

where

$$\Omega_p^2 \;=\; (\chi\, r_p / \gamma\, r_e\,)\, \Omega_e^2 \qquad (19)$$

and $r_p = 1.535 \times 10^{-18}$ m.

The dispersion relation (18) is then solved to derive Ω versus the mode number k. The growth rate of the instability is given by the imaginary part of Ω.

The results for the NSNS Accumulator Ring are summarized as follows [5]. It is seen that with $\chi = 1\%$ three modes k = 152, 153 and 154 are unstable. But if $\chi < 0.1\%$ the instability can be avoided by letting the betatron tune change between 5.5 and 5.8.

9 REFERENCES

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