

Plasma Considerations in the IPNS RCS

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Abstract. The Intense Pulsed Neutron Source (IPNS) Rapid Cycling Synchrotron (RCS) accelerates 3.0×10^{12} protons per pulse from 50 MeV to 450 MeV, 30 times per second. Average current in the single harmonic ring reaches 2.5 A at extraction, with peak current of 13 A. The background pressure is on the order of 1 μ Torr nitrogen and the ionization cross section is approximately 5×10^{-22} m² at injection. The resulting neutralization folding time is 0.5 ms and is much shorter than the 14 ms acceleration time. After 3 ms into the acceleration cycle, measurements indicate the tune is increasing with time. The tune shift from injection to extraction is measured to be +0.5. Over-neutralization and plasma formation are examined as the possible cause for the positive tune shift in the RCS.

I. Introduction—Beam Neutralization and Plasma Generation

Significant space-charge neutralization and plasma formation should be occurring during the IPNS RCS acceleration cycle based on arguments that will be presented here. Until recently, this has not been a serious consideration for operation of the IPNS. However, as we hope to raise the current limit in the machine with a second harmonic rf cavity in the near future, the effects of self-generated plasma and two-stream instability become topics that merit further investigation.

A. IPNS RCS Parameters

The IPNS RCS accelerates 50 MeV protons to 450 MeV in approximately 14.3 ms, 30 times per second. The RCS is a relatively small, six sector ring consisting of combined function singlet and triplet magnets with a bend radius of 3.68 m and an overall circumference of 42.9 m. Bare tunes are 2.25 in the horizontal plane (ν_{x0}) and 2.35 in the vertical plane (ν_{y0}). A sketch of the RCS plan is presented in Figure 1 showing the primary components of the ring. The notation SM_n and TM_n refer to singlet and triplet magnets in sector *n* where *n*=1,2,..., 6. S_n and L_n indicate “short” and “long” drifts in sector *n*. The horizontal focusing pattern is DOFDFO.

B. Ionization Cross Section and Neutralization Time

Space-charge tends to defocus the beam, and the defocusing effect modifies the transverse tune of the machine. However, space-charge can be neutralized as the background gas through which the beam passes becomes ionized. Readings from ion gauges placed around the ring, indicate the typical RCS background gas pressure is on the order of 1 μ Torr, corresponding to a background gas density, $n_g = 3.3 \times 10^{16}$ m⁻³ (20°C). Typically, 3.5×10^{12} H⁺ ions are injected into the RCS of which 3.0×10^{12} protons are captured in a single rf bucket and accelerated. Near injection, the bunch is assumed to uniformly occupy 50 percent of the RCS circumference, i.e., $L_b = 21.45$ m. The initial line density, $\lambda(t=0)$, is then 1.4×10^{11} m⁻¹. Assuming a round beam of radius 1.5 cm, the average density in the beam is $n_b = 2.0 \times 10^{14}$ m⁻³. At 1 μ Torr, the background gas density exceeds that of the initial beam by more than 2 orders of magnitude.

To determine the neutralization time, τ_n , the ionization cross section is required. Following the discussion from Reiser[1], the cross section, in m², may be expressed as,

$$\sigma(\beta) = \frac{1.872 \times 10^{-24} A_1}{\beta^2} f(\beta) \left[\ln \left(7.515 \times 10^4 A_2 \frac{\beta^2}{1 - \beta^2} \right) - \beta^2 \right] \quad (1)$$

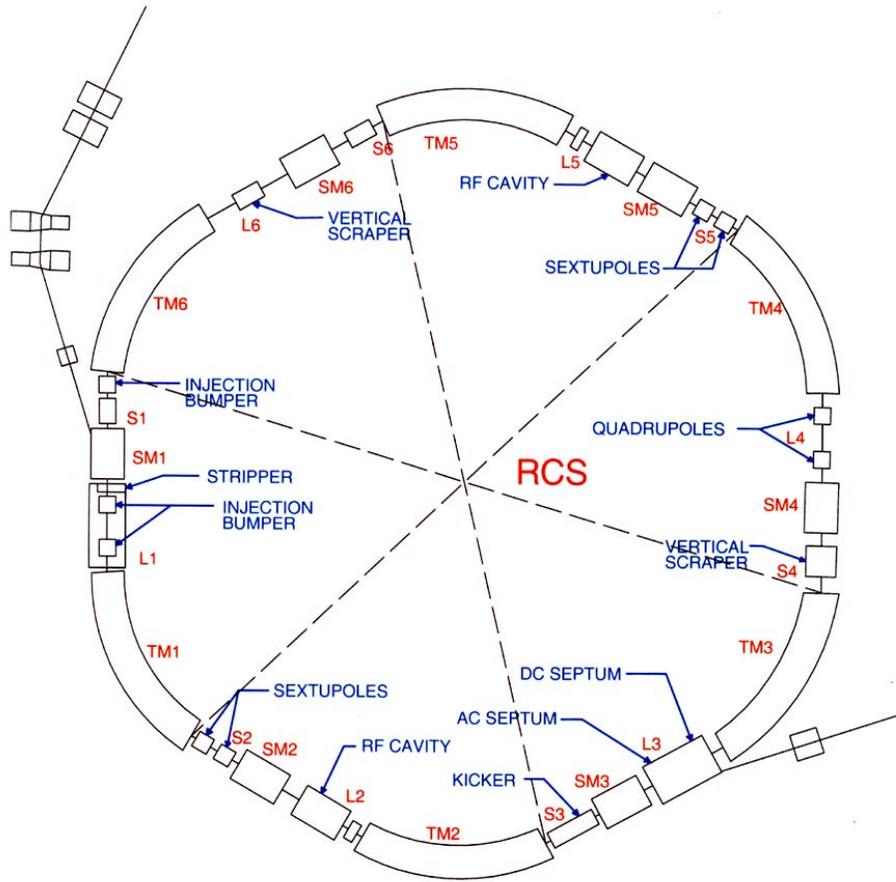


Figure 1: RCS Plan View schematic

where $f(\beta) \approx 1$ and for N_2 , $A_1=3.82$, and $A_2=0.518$. Calculated values of σ during the RCS acceleration cycle are presented in Figure 2 along with β and the magnetic field intensity. The neutralization time is given by,

$$\tau_n = (n_g \sigma v)^{-1} \quad (2)$$

The neutralization time is independent of the beam density and hence the current. The predicted neutralization time is given in Figure 3 for both 1 and 2 μTorr of background gas (N_2). Generally, the neutralization time varies from 0.5 ms at injection to 1.0 ms near extraction at 1 μTorr . Table 1 shows the measured gas pressure at various locations around the RCS ring. The two dates presented in Table 1 correspond to machine research periods when extended beam dynamics studies were conducted. The average pressure readings from the two dates in Table 1 are indicative of the overall improvement to the vacuum system made during the intervening 22-month period and suggest that neutralization should occur more rapidly in the earlier experiment.

The purpose of the beam dynamics studies was to examine tune values during the acceleration cycle when self-excited oscillations were not detectable. The controller for the RCS ring rf includes a "scrambler"[2] that causes 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 cycle. One can obtain indications of the tune by looking at the output of pie-electrodes within the RCS; these electrodes will be discussed shortly. The longitudinal excitation from the scrambler couples into transverse bunch motion.

Table 1: Comparison of RCS ionization gauge pressure readings.

IG Sector No.	December 7, 1999 P (μ Torr)	October 14, 2001 P (μ Torr)
1	2.09	0.96
2	2.71	1.40
3	2.58	3.07
4	1.64	1.85
5	0.90	0.37
6	0.57	0.37
Average	1.75	1.34

II. Plasma Considerations

For the present discussion, important plasma parameters include the Debye length, electron and ion collision frequencies, collision mean free path, and diffusion time[3]. Plasma formation begins when 50-MeV H⁺ ions are injected into the RCS, stripped to protons by a 55 μ g/cm² carbon foil. The stripped electrons possess a kinetic energy of 27 keV and drift in the field-free region to the wall. Coasting beam injection lasts for approximately 80 μ s. The protons are first guided around the ring and then captured as the rf gap voltage begins to rise. The rf voltage begins climbing from its injection value of less than 1 kV within 100 μ s after the end of injection (t=0). After an ionization occurs in the background gas, the motion of the ion and electron pair will depend upon a number of factors including the location where the pair was created. If created in a straight section, the charges may drift freely toward the wall. However, within the combined-function singlet and triplet magnets, motion will be restricted in both longitudinal and horizontal directions. One might therefore expect the confinement time of ions and electrons to be greater in the magnet sections of the ring. Since the magnet sections account for more than half the total RCS circumference (23 m out of 43 m), it is important to estimate the confinement time here. Charge will build up inside the machine as long as the confinement time, $\tau_c > \tau_n$.

With an estimate of beam density, background density, and the neutralization timescale, one can begin to estimate values for the plasma parameters mentioned above. The Debye length is expressed as,

$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e e^2}} \quad (3)$$

If an initially hot plasma is assumed with $T_e=100$ eV and just the density of the beam, 2.0×10^{14} m⁻³, is used then $\lambda_D=5.3$ mm. The electron-ion collision frequency and its inverse, the mean time between collisions, will initially be insignificant in the ionization process,

$$f_{ei} = 2 \times 10^{-12} \frac{Z n_e \ln \Lambda}{T_e^{3/2}} \quad (4)$$

At injection, $f_{ei}=4$ Hz, assuming the Coulomb scattering parameter, $\ln \Lambda=10$. Though this value is small, it is likely to increase during the acceleration cycle. The ion charge state, Z, is initially assumed to be unity. However, Z is likely to increase as nitrogen ions in the background gas (as well as other ions from the wall) are continuously bombarded by the beam and further stripped. In addition, the electron temperature will decrease as cooler, secondary electrons from the wall migrate into the beam path. Assuming the confinement time exceeds ionization time, the ionized background density will continue to rise as well. If at the end of the discharge, $Z=3$, $T_e=10$ eV and $n_e=n_g=3.3 \times 10^{16}$ m⁻³ then $f_{ei}=63$ kHz. Thus, near the end of the acceleration period, electron impact ionization can play a much greater role generating and maintaining

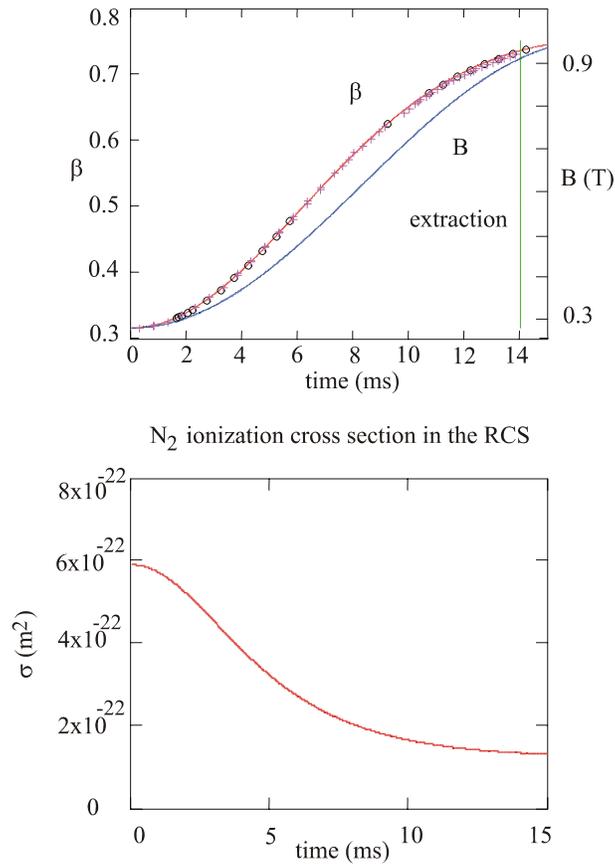


Figure 2: Measured RCS B-field and β during the acceleration cycle (upper) and predicted N₂ ionization cross section (lower).

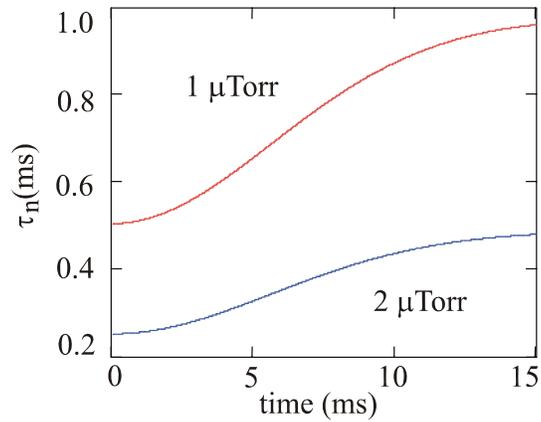


Figure 3: Neutralization times in the RCS for 1 and 2 μTorr, N₂.

the plasma. Note also, that the Debye length will have dropped to 0.19 mm at extraction. In hydrogen, the collision mean-free-path between ions and electrons can be written as,

$$\lambda_{ei} = 3.4 \times 10^{17} \frac{T_e^2}{n \ln \Lambda} \quad (5)$$

For the conditions mentioned above, $\lambda_{ei}=1650$ km at injection, and 232 m near extraction. This means ions created in straight sections will hit the wall before interacting with other ions in the beam pipe. On the other hand, inside the magnets a more relevant length parameter is the Larmor radius,

$$\rho_L = \frac{v_{\perp}}{\omega_{ce}} = \frac{\beta \gamma m_o c}{qB} \quad (6)$$

For electrons, again using the conditions assumed above, $\rho_L=0.121$ mm at injection and 0.011 mm at extraction. Therefore, aside from their motion along magnetic field lines, ions are confined in a small region after they are created. Ions which are lost or do not contribute to the ionization process are probably moving radially across the field lines. To get an estimate of the radial confinement time, Bohm diffusion is used,

$$\tau_B = \frac{r^2}{2D_B} = \frac{8r^2 eB}{kT_e} \quad (7)$$

where $r=10$ cm. The predicted confinement times from Bohm diffusion vary from 0.22 ms at injection to 7.52 ms at extraction. Thus confinement time may transition from injection where $\tau_c < \tau_n$ to extraction where $\tau_c > \tau_n$. Charged particles traveling along field lines very quickly strike a stainless steel liner. The liner is approximately elliptical in cross section with an aperture 7.6 cm in height by 20.3 cm in width.

III. RCS Beam Bunch Characteristics

A. Pulse length and Bunching Factor.

As the beam is accelerated, it becomes more tightly bunched. The peak current in the machine is a function of both circulation frequency and bunching factor, B_f . The circulation frequency, $f_o=2.21$ MHz at injection and increases to 5.14 MHz at extraction. Bunching factor is calculated as follows,

$$B_f(t) = \tau_p(t) f_o(t) \quad (8)$$

where τ_p is the FWHM pulse length of the beam. Pulse length and frequency as a function of time are determined by fitting measured values with fourth-order polynomials of the form,

$$g(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 \quad (9)$$

Pulse length and frequency data are presented in Figure 4 along with least-squares fitting curves. The coefficients for these curves are given in Table 2. The bunching factor falls from slightly less than 0.5 at injection to 0.2 near extraction. In both cases, the correlation coefficient between the data and polynomial

Table 2: Coefficients for fourth-order polynomial curve fit of RCS frequency and pulse length data.

	a_0	a_1	a_2	a_3	a_4
f_o (Hz)	$2.255 \times 10^6 \text{ s}^{-1}$	$-9.103 \times 10^7 \text{ s}^{-2}$	$7.704 \times 10^{10} \text{ s}^{-3}$	$-5.932 \times 10^{12} \text{ s}^{-4}$	$1.379 \times 10^{14} \text{ s}^{-5}$
τ_p (s)	$2.117 \times 10^{-7} \text{ s}$	-3.062×10^{-5}	$2.073 \times 10^{-3} \text{ s}^{-1}$	0.0638 s^{-2}	0.6629 s^{-3}

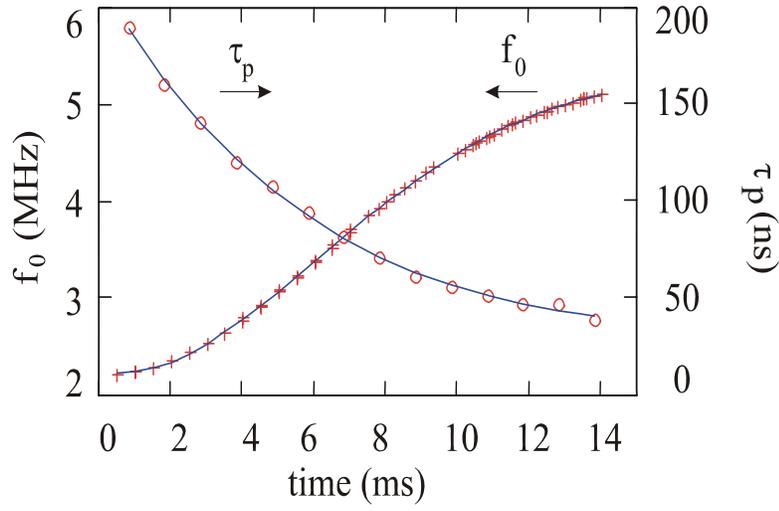


Figure 4: RCS bunch circulation frequency and pulse length.

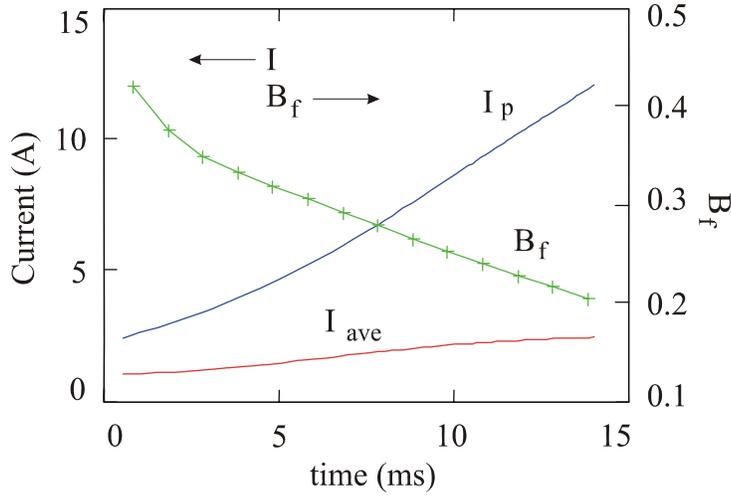


Figure 5: RCS Current and Bunching Factor

are very close to 1. With a functional form for frequency and pulse length, the bunching factor can be determined. The RCS bunching factor is given in Figure 5. The average current in the bunch is just the average current in the ring divided by the bunching factor. For the present, the average current in the bunch is referred to as the peak current, $I_p = I_{av}/B_f$. Ignoring losses in the machine after capture, assuming a charge of $0.48 \mu\text{C}$, the average current in the ring rises from 1.06 A at injection to 2.47 A at extraction.

B. Beam potential.

A simple calculation of voltage potential generated by the beam is given as follows: A round, single bunched beam of radius, $a=1.5 \text{ cm}$ circulates in a beam pipe of radius, $b=3 \text{ cm}$ with 3×10^{12} protons ($Q=0.48 \mu\text{C}$). Because $L_b \gg b/\gamma$, end effects are ignored and the electric field is assumed to be purely radial. From Maxwell's Equation, $\nabla \cdot \mathbf{D} = \rho$, the potential in the beam is determined by substituting $\mathbf{E} = -\nabla V$, and may be expressed as,

$$V(r, t) = \begin{cases} \frac{\rho(t)}{4\epsilon_0} \left[(a^2 - r^2) + 2a^2 \ln\left(\frac{b}{a}\right) \right], & r < a \\ \frac{\rho(t)a^2}{2\epsilon_0} \left(\ln\left(\frac{b}{a}\right) - \ln\left(\frac{r}{a}\right) \right), & a < r < b \end{cases} \quad (10)$$

with boundary conditions, $E_r(0)=0$ and $V(b)=0$. As an example, shortly after injection with local charge density $\rho(t=0)=\lambda/\pi a^2$, the potential at the edge of the beam is +292 V, while the potential at the beam center is 211 V higher. Thus, a potential of 503 V exists between the beam center and the beam pipe. This potential grows as the beam is accelerated and further bunched. Figure 6 shows how the potential grows with time in the acceleration cycle. Near extraction, the potential at the center of the beam approaches 1.2 kV with respect to the wall.

The profiles described above are not static but rather appear and disappear with the bunch. Thus the beam acts as an applied, oscillating potential on the background gas. (The plasma response to the applied potential profile will modify the total potential.) In addition to generating ions through collisions, the AC potential of the beam may also act to ionize the surrounding gas. Depending on geometry, confinement, and gas pressure, volume plasma discharges can be maintained with excitation between 2 and 5 MHz. In addition to the AC nature of the potential, the presence of plasma with a Debye length on the order of 1 mm will also alter the radial field profile due to shielding.

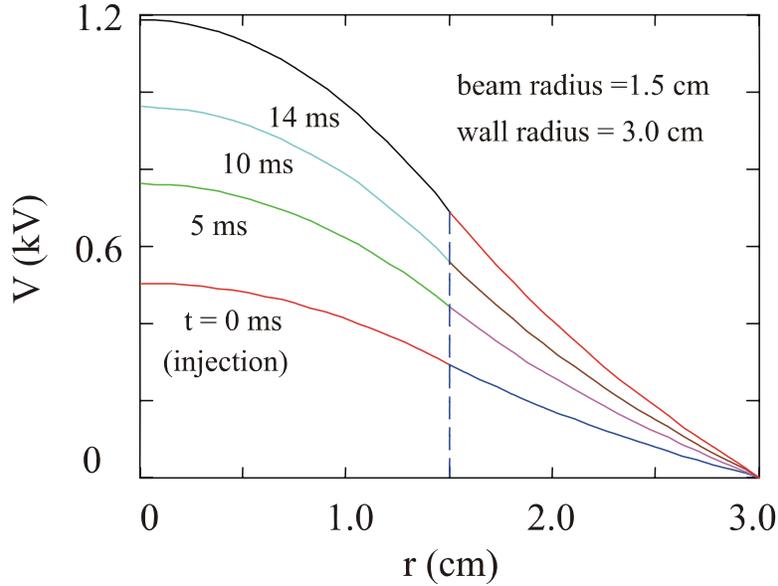


Figure 6: Beam potential profile with time into the acceleration cycle a parameter.

IV. Spectral Tune Measurements

A. RCS Pie-Electrodes

Spectral data from the RCS is obtained using split-can electrodes of rectangular cross section. The split faces (horizontal plane for the horizontal electrodes and vertical plane for vertical electrodes) are along a diagonal giving the electrode something of a pie-shaped appearance; hence these diagnostics are referred to as “Pie” electrodes, see Figure 7. The dimensions of each electrode pair in x, y, and z are 11.4 cm, 6.8 cm, and 2.5 cm, respectively. The vertical electrode pair sits adjacent to and just upstream of the horizontal pair. The total length of the electrode set (H and V) in the beam direction is 6 cm. Each sector, except No. 3, has both a horizontal and vertical pair of pie electrodes. The horizontal pair in sector 1 provides beam

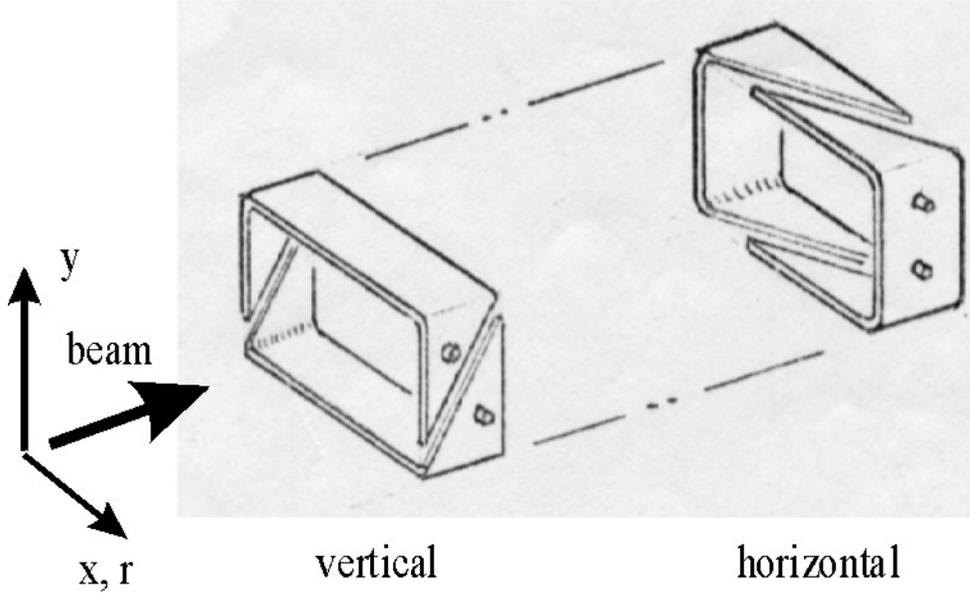


Figure 7: Exploded view of the pie-electrodes only.

position signals both for Operators and control of the rf. A single-ended signal from the S1 horizontal electrode provides phase control for the rf. Aside from control purposes, the signals provide a useful, fast diagnostic of beam motion. Beginning in 1999, signals from the pie-electrodes have been recorded using a Hewlett-Packard 4396B Spectrum Analyzer.

The two pie-electrode pairs exhibit reasonably good isolation between particle motion in the x and y planes. The degree of isolation can be measured shortly after injection as the beam undergoes significant capture motion in the in both transverse directions. Figure 8 shows the spectra from vertical and horizontal electrodes approximately 200 μs after injection is complete. Spectra presented here are typically obtained in gated, 100 μs windows. Also, the data presented in Figure 8 represents the averaged signal of 10 spectrum analyzer sweeps. The relative amplitudes of the betatron tune sidebands indicate about 20 dB of isolation between the principal planes. The data in Figure 8 show the vertical tune to be slightly larger than that of the horizontal as expected from the bare tune values given earlier.

B. Neutralization Tune Shift

The tune shift introduced by partially compensated space-charge, may be expressed as,

$$\Delta\nu(\tau) = -\frac{I_p R (1 - \gamma^2 f_c(\tau))}{I_0 \epsilon_n \beta^2 \gamma^2} \quad (11)$$

where f_c is the fractional neutralization. Initially, the neutralization fraction, $f_c(\tau)$ was interpreted as the ratio of average to peak current, i.e., $f_c(t) = B_f(t)$. The reasoning for this argument is that neutralization occurs only up until the average beam current is compensated. In this model, the bunch is only partially neutralized, especially near the end of acceleration where the bunching factor is lowest. However, this does not explain the temporal behavior of the spectral features observed on the RCS during extended scrambler studies. As was stated above, the background density in the IPNS RCS is much greater than the beam density even near the end of the cycle, it is conceivable, therefore, that the beam channel may become over-neutralized. If over-neutralization is allowed for and $f_c(t) = t/\tau_n$, where t is time into the acceleration cycle, the tune shift may be written as,

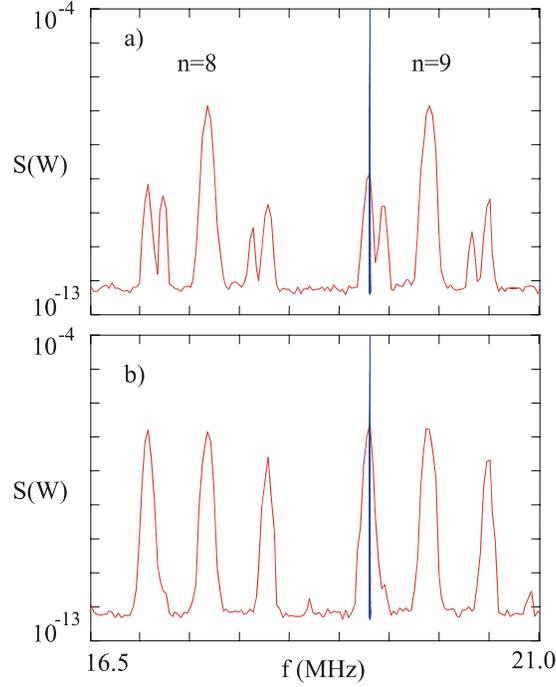


Figure 8: a) Spectra showing the 8th and 9th bunch harmonics 200 μ sec after injection from S5 a) right and b) top pie-electrodes. Markers lie on a vertical betatron tune lower sideband.

$$\Delta v(t) = - \frac{I_p(t) R \left(1 - \gamma^2 \frac{t}{\tau_n} \right)}{I_0 \epsilon_n \beta^2 \gamma^2} \quad (12)$$

The tune may be written as,

$$v_\xi(t) = v_{\xi_0} + \Delta v_\xi(t) \quad (13)$$

where $\xi \in x, y$ and v_{ξ_0} are the bare tunes referred to earlier. Defocusing effects from space-charge as well as compensating neutralization should be present in both x and y tunes. As mentioned above, extended scrambler studies were conducted in December of 1999 and repeated again in October 2001. In these studies, one of the two phase modulators available to act on the beam through the rf accelerating voltage was used at various times in the RCS acceleration cycle. Phase modulation of the rf stimulates the bunch longitudinally and causes oscillations that are detected with the pie-electrodes. The oscillations of interest here are primarily transverse. Because the synchronous frequency changes during the acceleration cycle, the scrambler frequency must be adjusted during the experiment to efficiently couple to the bunch. Examples of excited spectra obtained during the October 2001 experiment are presented in Figure 9. Combining tune data obtained from the two extended scrambler experiments with self-excited data visible both before and after the extended scrambler period, the tune as a function of time in the machine is presented in Figure 10. Also shown in the figure are the predicted x and y tunes including space-charge and neutralization assuming an average background gas pressure in the RCS of 1 μ Torr N_2 . Pulsed quadrupole current waveforms are given at the bottom of the figure to indicate their timing in the RCS cycle.

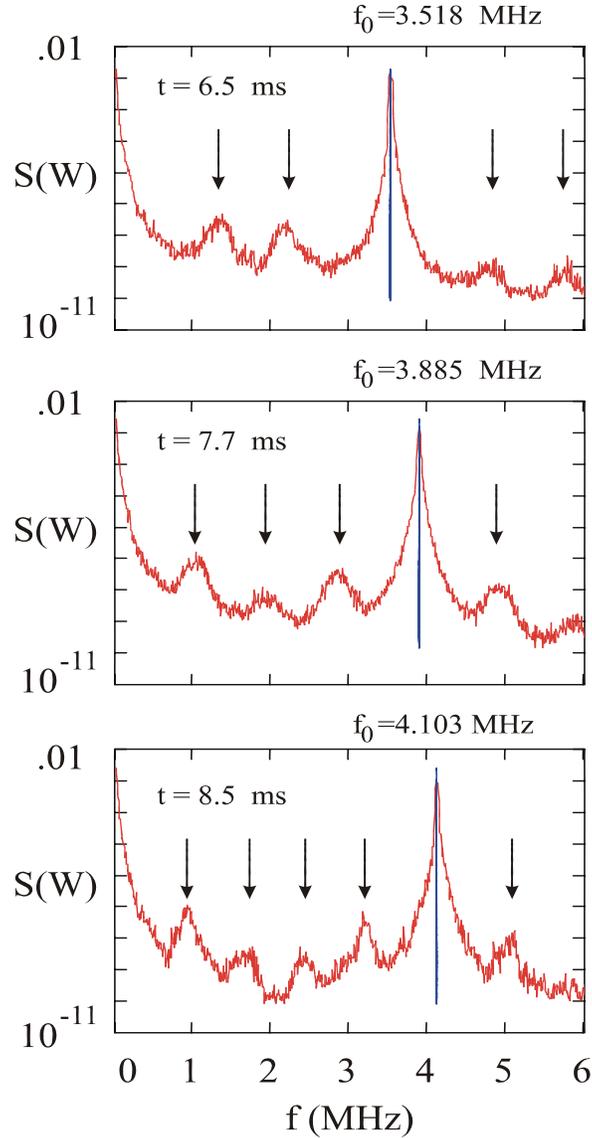


Figure 9: Pie electrode spectra obtained during extended scrambler studies.

V. Discussion

Figure 10 shows measured data from the pie-electrodes compared with the predictions of Equations 12 and 13. The prediction given by Equations 12 and 13, though not following the exact path of the data, does indicate a tune-shift increasing with time because of over-neutralization of the beam. The observed tune shift appears to be delayed relative to the start of acceleration in the RCS. The measurements show both x and y tunes to be rising with time. It also appears that the x and y tune trajectories do not cross one another, although at times they come close. The y-tune starts out higher than the x-tune and remains that way for the duration of acceleration. After approximately 6 ms, the fractional tune in y is in excess of 0.5 while the x-tune lags behind. The horizontal tune crosses 0.5 at approximately 8 ms. As acceleration proceeds, the vertical tune shift increases above 0.5 and the vertical tune begins approaching the integer tune at $Q=3$. The modulation of the main harmonic by the vertical tune appears to occur at a smaller frequency shift than the horizontal. This is consistent with the tune rising as discussed above. Comparing spectra from horizontal and vertical pie-electrodes at 10.7 ms and 14.3 ms, Figure 11 shows the vertical

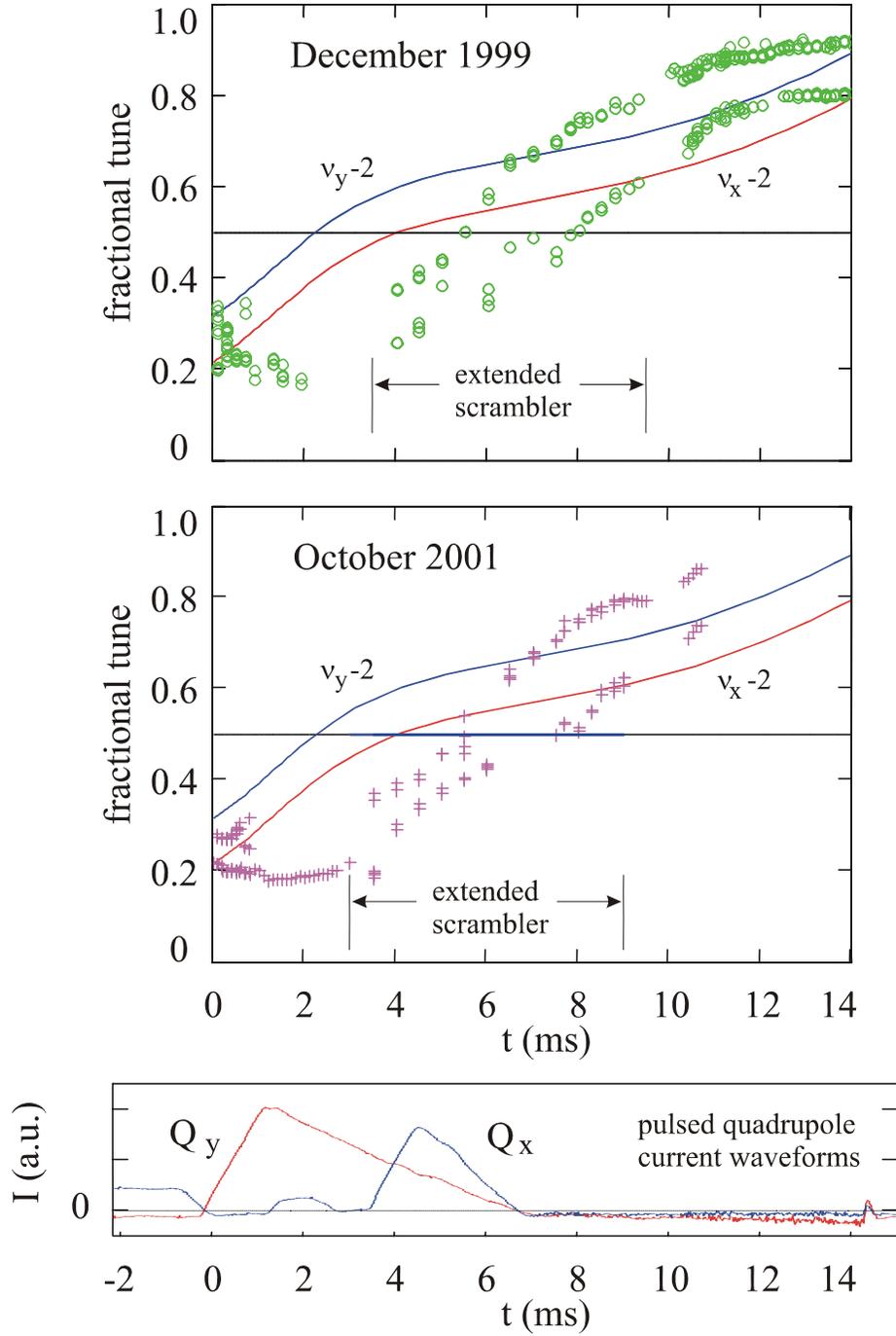


Figure 10: Extended Scrambler tune measurements

tune closest to the bunch harmonic. Also in the 14.3 ms data, vertical sidebands have emerged. These narrowband sidebands are precursors of a vertical instability that is believed to be resistive wall.

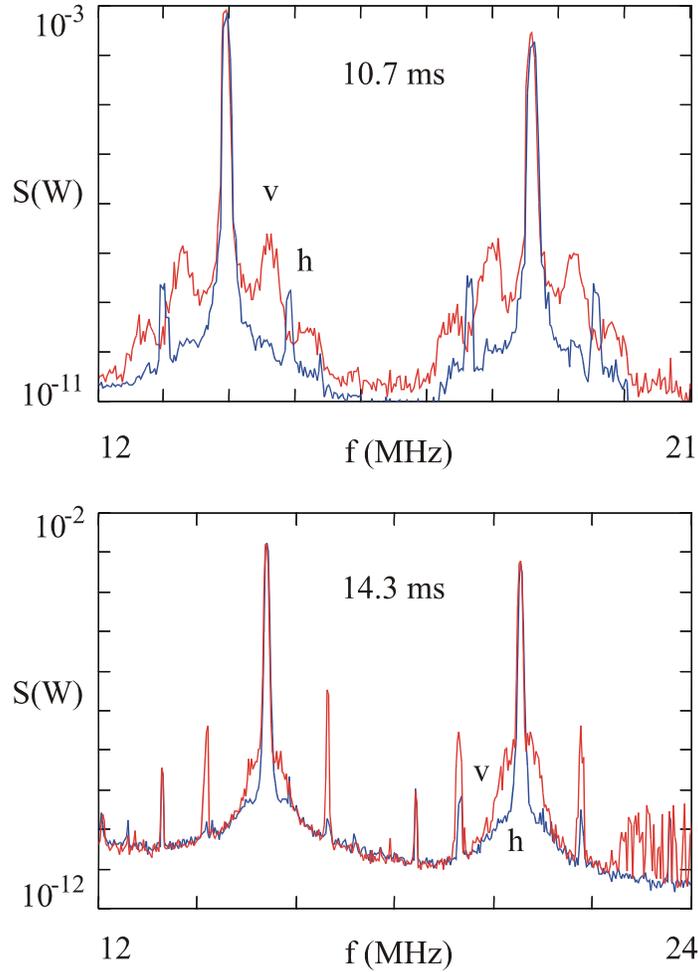


Figure 11: Comparison of horizontal and vertical pie-electrode signals at 10.7 ms and 14.3 ms

Electrons will be attracted to the space charge of the beam when it is present, then repelled as the beam passes. This motion will be modified somewhat by ambipolar field in straight sections but more significantly by the magnetic guide fields and plasma shielding in the magnet sections. The beam is constantly generating plasma but the density may not build until the confinement time increases and exceeds the ionization (neutralization) time. The plasma provides neutralization for the beam and the data suggests that it may actually over-neutralize the beam. Over-neutralization could account for the fact that the tune increases during the acceleration cycle. The value of the background pressure on the two dates when tune data was obtained does not appear to have significantly affected the tune-shift as function of time. A significant oscillating beam potential may aid in the ionization process especially later in the cycle.

It has been suggested [4] that the generation of secondary plasmas can add stability to the beam. In comparison to the RCS, the PSR at Los Alamos typically runs with an average background pressure of 5×10^{-8} Torr (.05 μ Torr). With an injection energy of 800 MeV, the neutralization time in the PSR may be in excess of 20 ms. Measurements presented by R. Macek at this workshop suggest that the neutralization fraction in PSR is on the order of 1 percent or less, consistent with a longer folding time.

VI. Conclusions and Further Work

Significant ionization appears to occur in the RCS during its 14 ms acceleration period leading to plasma formation and neutralization. The beam may in fact be over-neutralized, causing the tune to increase during the acceleration cycle. The overall tune shift in the RCS appears to be close to +0.5. The presence of plasma may help explain why longitudinal phase modulation can so quickly couple to transverse motion. In addition, plasmas tend to be inductive and the RCS appears to exhibit a relatively high inductance.

Measurements of the electron cloud and plasma densities adjacent to the beam should be made. In addition to the RFA and Swept Analyzer diagnostics mentioned at the Workshop, other techniques might be attempted. If plasma is present, then a small, biased-probe might be useful (e.g., a Langmuir probe), or with the proper choice of geometry, an optics-based measurement for line density (e.g., an interferometer) might be employed, perhaps using microwaves for increased sensitivity.

Acknowledgment

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