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Experimental Study of Passive Compensation of Space Charge Potential Well Distortion at the Los Alamos National Laboratory Proton Storage Ring

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Abstract

The inductance of the vacuum chamber of the Proton Storage Ring (PSR) at the Los Alamos National Laboratory (LANL) was intentionally increased by the introduction of ferrite rings, to counteract the longitudinal space charge effect of the intense beam. The permeability of the ferrite could be adjusted by introducing current into solenoids which were wound around the ferrite cylinders. Results show that the minimum rf voltage necessary to stabilize the beam against e-p instability was reduced over that previously measured. The injected bunch length was observed to be longer when the ferrite was heavily biased so that its effect was reduced. The gap in the beam created by the applied rf was the cleanest ever observed.

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1 Introduction

Several relatively small ($\sim 20-100$ m circumference) proton rings, to be operated at very high intensity (10^{14} protons per cycle), are under consideration as integral parts of programs such as neutron spallation sources or meson/hadron facilities. H^- ions are to be injected into the rings for many turns at relatively low energy (~ 1 GeV). In the spallation sources, in order to preserve an extraction gap as well as to allow electrons to escape from the potential well created by the stored protons, gated linac pulses are to be injected into preset stationary rf buckets at the rotation frequency ($h = 1$). In the hadron/meson sources the ring is to be part of a series of rapid cycling synchrotrons and some form of rf capture (quasi-adiabatic capture or possibly longitudinal painting into preset rf buckets) at low harmonic number is anticipated.

In each case longitudinal space charge fields generate substantial distortion of the rf generated potential wells. The effective space charge ring voltage [1, 2] is proportional to the slope of the line charge distribution $\lambda(s)$, where s is a distance coordinate along the particle closed orbit. Below transition energy, the space charge forces spread particles apart longitudinally; i.e., they counteract the effectiveness of rf generated bunching forces. To first order, the reduction in rf generated bucket area (rf phase space) can be compensated for by increasing the rf voltage at the chosen harmonic. But even with increased rf voltage, the space charge fields distort the bucket shape, affect the incoherent synchrotron frequency, and have the potential for causing instability and longitudinal emittance growth. In the meson source case, it is planned to reduce the bunch length to the minimum possible value prior to extraction. Longitudinal emittance dilution during acceleration will adversely affect the final achievable bunch length. In the case of the Los Alamos Proton Storage Ring (PSR), the space charge force may reduce drastically the effectiveness of the installed rf system.

The major Fourier components of the beam current in such machines will be at relatively low frequency, in the MHz range. At low frequencies the vacuum chamber impedance seen by the beam will be predominantly inductive. The wall image of the beam current will generate an effective voltage in the ring inductance which is again proportional to the slope of the line charge distribution or, effectively, to the time derivative of the beam current. Below transition the phase of the beam induced voltage (with respect to the phase of the Fourier component of beam current which is generating it) is such that it will induce self bunching of the beam. This implies that the vacuum chamber induced voltage which is induced by a beam Fourier component resulting from externally applied rf voltage, will add to that voltage. The net effective voltage per turn *seen by a particle within the bunch* resulting from ring inductive wall impedance and the space charge self-voltage is expressed:

$$V_s = \frac{\partial \lambda(s)}{\partial s} \left[\frac{g_0 Z_0}{2\beta\gamma^2} - \Omega_0 L \right] e\beta c\bar{R} \ , \tag{1.1}$$

or

$$V_s = 2I_{\rm dc} \frac{d}{dt} \sum_{m=1}^{\infty} F_n(m\omega_{\rm rf} \cos(m\omega_{\rm rf} t) \left[\frac{g_0 Z_0}{2\beta\gamma^2\Omega_0} - L(\omega) \right] \ . \tag{1.2}$$

In these expressions $g_0 = 1+2\ln(b/a)$, where b and a are the nominal vacuum chamber aperture and beam radii [3]. $Z = 377$ Ohms. $\Omega_0 L$ is the vacuum chamber inductive reactance at the rotation frequency, nominally $15-25$ Ohms, and referred to as Z/n. In Eq. (1.1), L is usually assumed to be constant, independent of frequency. The signs in the equations are consistent with the sign of the applied rf voltage *below transition*. In Eq. (1.2) the expression $L(\omega)$ is meant to imply that the vacuum chamber inductance may be a function of frequency (i.e. part of the inductance may be due to presence of intentionally inserted ferrite etc.).

The constant g_0 may range from 2 to ~ 3 for the machines under consideration. The space charge term in Eq. (1.1) may fall in the range $100 - 250$ Ohms. It appears reasonable to conclude that, at some chosen energy, the space charge effect may be canceled exactly by intentionally increasing the ring inductive reactance and forcing the term in brackets to a very small value, approaching zero. This concept was proposed in 1968 by Sessler and Vaccaro [4] and later by R.K. Cooper et al [5] and by T. Hardek [6] in 1982.

In 1966 V.K. Neil and R.J. Briggs proposed intentional insertion of inductance into particle beam vacuum chambers [7, 8], but this was intended as a proposal to stabilize ion beams against negative-mass instability. These proposals were directed at situations where the beams were above transition so that introduction of inductance would have a stabilizing effect.

In the experiment to be considered here, the opposite is true.

2 LANL Proton Storage Ring

The PSR is a 90.20 meter proton storage ring which is filled by multi-turn H^- injection from the LAMPF 797 MeV linac. The rotation period of the ring is 357.7 ns, $\beta = 0.8412$, $f_0 = 2.796$ MHz, transition $\gamma_t = 3.1$, and the slip factor $\eta = -0.1883$. The total injected momentum spread is between 0.5% and 1% (± 3 to ± 6 MeV). The ~ 12 mA linac pulses are gated during normal operation to ~ 250 ns and the injection rate is synchronized to the rotation period such that injected pulses are superposed, allowing initially a ~ 100 ns gap in the beam. Injection for 1600 turns, requiring 572 μs, would fill the ring with 3×10^{13} protons. If nothing is done to prevent it, protons, under the influence of space charge forces and natural azimuthal motion due to the slip factor η and the injected momentum spread, will drift into the gap during injection.

At beam intensity greater than $\sim 2 \times 10^{13}$ stored protons, the PSR suffers from a serious instability which limits operation at higher intensity because of transverse beam loss [9, 10, 11]. Strong evidence exists that the instability is caused by electrons trapped in the proton beam potential well [12, 13]. Preservation of a gap of ~ 90 ns in the beam, required for extraction kicker clearance in any case, has been shown to increase the threshold for the putative e-p instability. The required gap is presently maintained with an installed $h = 1$ (2.8 MHz) rf cavity [6] capable of operating at ~ 15 kV. Evidence for improvement in the threshold for the limiting instability by raising the rf voltage is shown in Fig. 1 (extracted from LANL SPSS Technical Reference Document).

At injection, the nominal operating rf voltage is set at 6 kV and is increased grad-

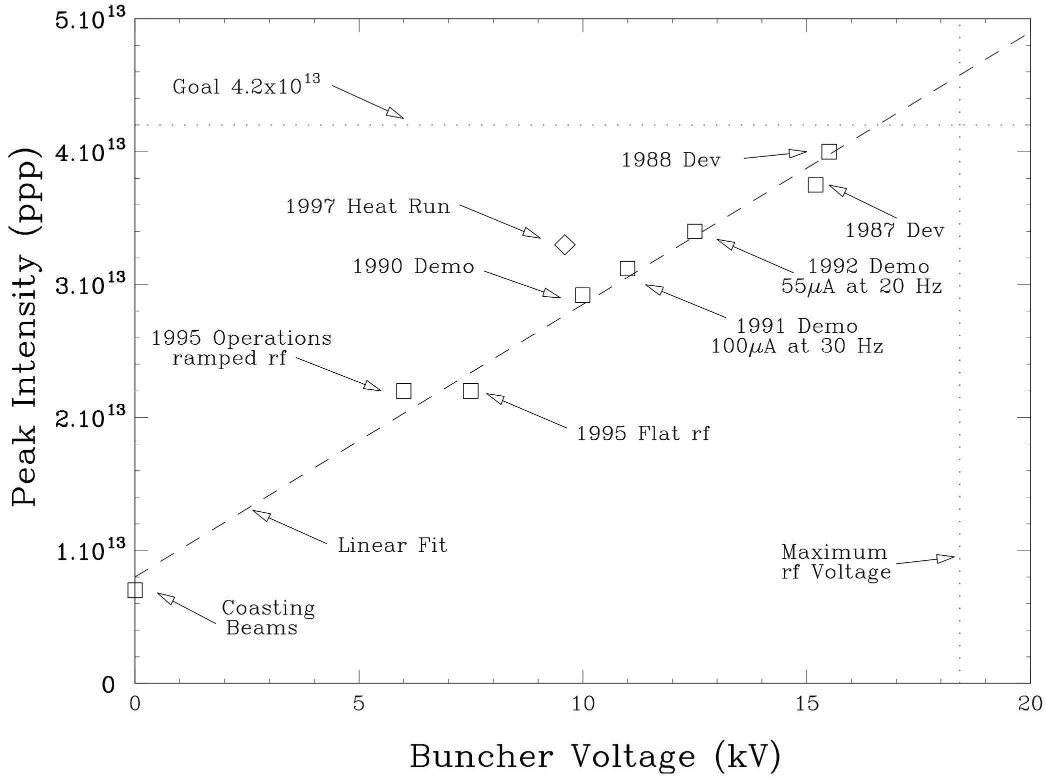

Figure 1: Maximum stable stored beam intensity as a function of rf bunching voltage.

ually to 12 kV. The bucket height changes from ~ 5 to ~ 7 MeV, and the synchrotron period for small amplitude decreases from 935 to 661 μs. At this voltage program, it appears that some fraction of the injected beam falls outside of the (cosine contour) bucket separatrices. Such particles will move on orbits which will carry them into the gap region, where only a small fraction of the injected beam is capable of preventing escape of electrons. Protons injected within the separatrices early in the injection process complete less than one phase oscillation prior to extraction. If the $h = 1$ rf voltage is increased in order to capture more of the injected beam, some orbits within the increased bucket height may carry particles beyond the ring momentum aperture, causing beam loss.

As part of a major upgrade in the PSR beam delivery capability [14], there is a multi-stage program to upgrade the ring rf system. The fraction of beam captured within synchrotron separatrices could be increased with minimal increase in the total momentum spread by adding harmonics to the $h = 1$ rf voltage in order to *flatten* the orbits near the center of the phase space. To this end, it is proposed to increase the $h = 1$ voltage capability to 18 kV, and to add 15 and 4 kV capability at the second and third harmonics respectively. This, in effect, will create a longitudinal barrier by appropriate phasing of the additional Fourier components. Because each of these rf systems will operate on integer harmonics of the rotation frequency, relatively large Fourier components of beam current will exist at each cavity frequency, making beam loading compensation a major problem for each system.

In an *ad-hoc* review of the proposed upgrade of the PSR rf systems it has been suggested [15] that the proposed longitudinal barrier be generated by a single rf system operating as an isolated sinusoid generator at $h = 2.5$ or 3.5. In this way the cavity will not be excited by large components. *In addition it was proposed that the rf requirement be augmented by insertion of passive broad band space charge compensation inductors.*

3 Stability Considerations

Below transition, effective ring voltages developed by Fourier components of beam current in vacuum chamber *inductance* are of such a phase as to develop bucket area capable of bunching some fraction of the beam longitudinal emittance. If the ring inductive reactance at some frequency hf_0 is sufficiently large so that the a beam Fourier component at that frequency can generate a ring voltage sufficiently large to generate h buckets large enough to contain the entire beam longitudinal emittance, then the ring impedance has exceeded the Keil-Schnell instability threshold [16]. This is essentially an instability situation, which may be stabilized to some extent by counteracting space charge forces.

By examining the growth rate for longitudinal instability in the PSR (after the proposed upgrades), an acceptable longitudinal impedance has been calculated by Wang and Channell [17] to be $Z/n \leq 300\ \Omega$. The value of g_0 been reported [18] to be ~ 3. Recent increases in the vertical beam size may have reduced this value to near 2.5. Depending on the choice of g_0, the space charge impedance term is $\sim 160 - 200\ \Omega$ at 2.8 MHz. Introduction of inductive reactance of this magnitude, if approximately compensated for by the space charge term, should not exceed the instability threshold. But in any case, the controlled spontaneous self bunching would only present a problem during the short storage time if it resulted in momentum spread sufficiently large to exceed the ring momentum aperture.

An analysis of the wake fields developed by a relativistic particle beam in a dielectric-lined waveguide has been presented by K.Y. Ng [19]. Based on that work a detailed analysis of the stability conditions associated with introduction of an inductive region (ferrite waveguide) into the vacuum chamber by coating the inner wall of the chamber with ferrite has been completed by K.Y. Ng and Z. Qian [20, 21].

Introduction of a ferromagnetic liner with the same beam clearance diameter as the original vacuum chamber has negligible effect on the beam to wall capacitance per unit length. The ferrite material has relative permittivity $\epsilon_r \sim 9$ and very little electric field energy is stored within the ferrite. In some sense it amounts to placing a large capacitance in series with a small one. The net capacitance is not changed by a significant amount.

4 Recent Experience

Spontaneous self bunching has been demonstrated in a PSR experiment by operation of the ring with the rf power amplifier disabled and the cavity tuned below, near, and above resonance. In normal operation each side of the rf cavity accelerating gap is driven by a cathode follower amplifier with driving point impedance of $\sim 20\ \Omega$, the reactance presented to the beam is very low and quite insensitive to cavity tuning.

At the time of described experiment (February 1997) the power amplifier system was turned off, and rf voltage was developed at the cavity gap by beam excitation alone. Using reasonable estimates for the beam current and momentum spread during the experiment, the threshold for inductive wall 'instability' can be set between 100 and 200 Ω.

The amplitude of the rf signal developed by the 2.8 MHz Fourier component of beam current on the accelerating cavity gap was recorded during filling and storage for each of the tuning conditions. Plots of the voltages are shown in Fig. 2. The figure is a copy of a PSR log book page, provided by H.A. Thiessen. The details of the cavity tuning are a bit unclear. The data at 311 A bias show clearly that the cavity gap voltage is increasing during the store. This is the result of an increasing Fourier component of beam current which is caused by beam induced bunch narrowing.

5 Proposed Experiment

The space charge compensation under consideration differs from the introduction of inductive reactance at the beam fundamental rf frequency (i.e., a detuned resonant cavity) in that it is proposed to insert untuned inductance which is to remain reasonably constant over a large frequency range, spanning as many rotational harmonics as possible. Operation of such a passive compensation system has not been documented in a high current storage ring. The possibility that such a system may not work as planned and that it may well introduce unanticipated instabilities should not be ignored. Therefore, as a test of the feasibility, stability, and efficacy of such a system, a short term *ad-hoc* collaboration between LANL and Fermilab was proposed. Fermilab would fabricate and measure two 'ferrite waveguides' with inductance equal to approximately half of that necessary to compensate for the expected space charge impedance generated by the PSR beam. Just prior to the long PSR shut-down necessary for the first stage of the proposed upgrade, the inductors would be installed in the PSR and several shifts of beam study would be devoted to as much understanding of the performance as possible in the time available.

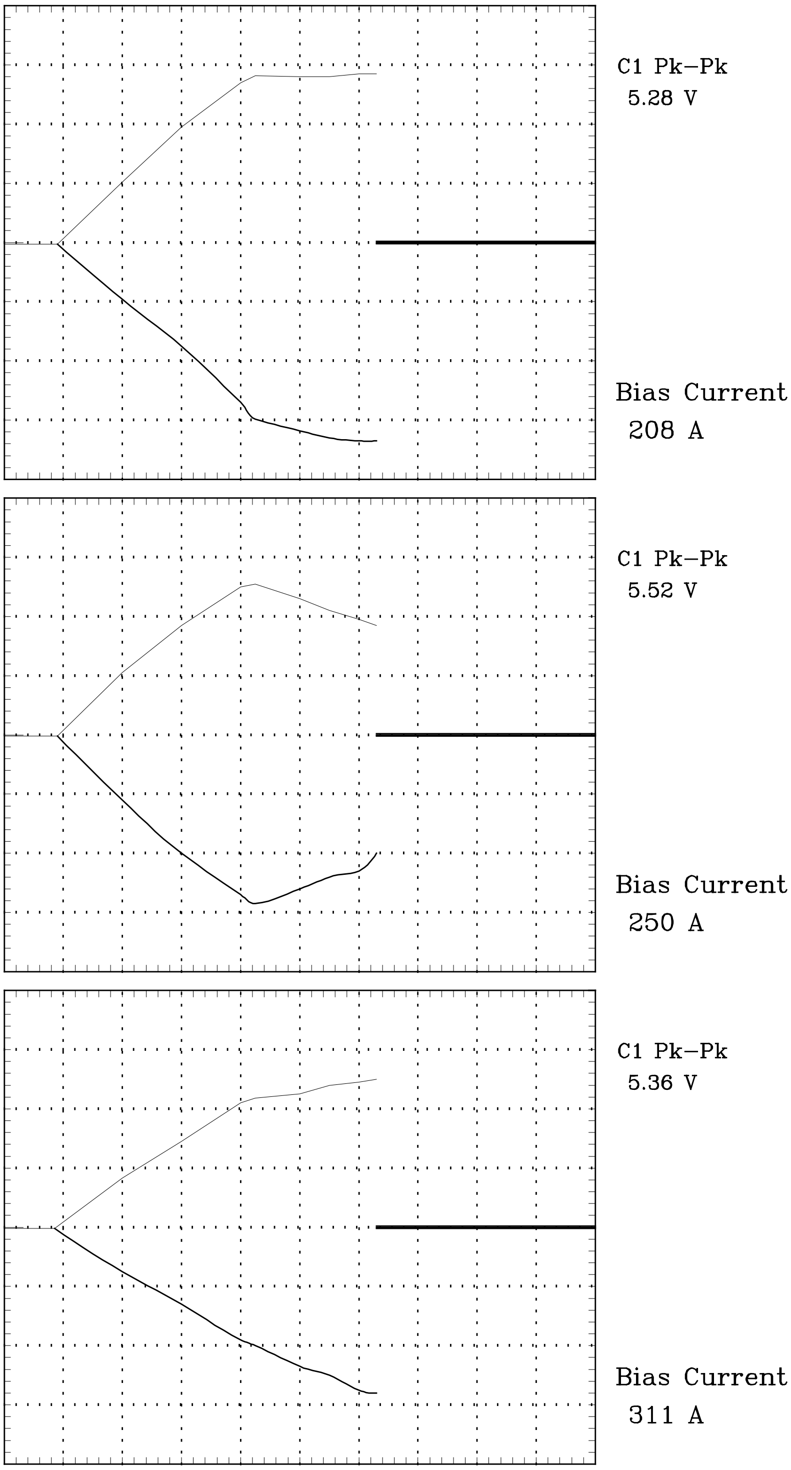

Figure 2: Beam induced rf voltage on LANL PSR accelerating cavity for three conditions of resonance tuning; near, below, and above the beam rotation frequency.

At Fermilab there is a large supply of unused ferrite rings (Toshiba $M4C_{21}$). These rings have been removed from the tuners in the Fermilab Booster because of large 'dynamic loss factor'. (At low tuning bias, where the frequency and the tuning bias current are changing rapidly, the ferrite Q is reduced by almost one-half due to interaction of domain wall motion and Co^{+++} 'pinning' sites in the spinel lattice. This loss should not affect the ferrite performance at rf frequencies with either no dc bias or constant bias.) The cores are 5 in. O.D., 8 in. I.D. and 1 in. thick. The relative permeability is ~ 50, $Q \sim 100$, and each of these properties remains approximately constant up to ~ 40 MHz.

At 2.8 MHz the requisite space charge compensation impedance, $\jmath 200\ \Omega$, requires installation of $\sim 11\ \mu$H. A 'ferrite waveguide' using the proposed cores has inductance $\sim 4.7\ \mu$H/m. Complete compensation would require 234 cm (92 in.), or 92 one inch cores. Two vacuum tight welded stainless steel containers were prepared, each containing 29.7 inches of continuous ferrite. It was intended to insert thirty cores in each container. Due to a minor error the chambers were 0.3 inches too short and one core in each chamber was ground down to fit. Each container has 5 in. I.D. stainless steel tubes terminated in vacuum flanges at each end. In order to prevent charge build-up on the inner surface of the cores, each of the cores was coated with a very thin (1 MΩ per square) baked on conducting coating (Heraeus R8261) on the inner and outer surface. Additional radial conducting 'spokes' were added to provide conductivity from the inner surface to the outer wall of the chamber.

With $Q = 100$, at 2.8 MHz the power lost to the ferrite due to the fundamental Fourier component of beam current (clearly the largest component), is negligible. Assuming that the 2.8 MHz component of beam current is 20 A, the magnetic energy stored in the ferrite per meter is $W_{\rm avg} = LII^*/4 = 4.2 \times 10^{-4}$ J/m. The dissipated power $P_{\rm dis} = \omega W_{\rm avg} =\sim 74$ W/m or ~ 107 W total. This amounts to a decelerating voltage ~ 5 V per turn. The sum of the power delivered to the ferrite in all of the remaining harmonics, even with deteriorating Q above 50 MHz, probably will not exceed this value.

In order to provide a variable 'knob' so that the effective inserted inductance could be varied in place, an 88 turn solenoid of welding cable was wrapped on the outside of each tank. Previous experiments with the same ferrite in a similar geometry, effectively a Fermilab style tuner geometry, showed that the relative permeability could be reduced by more than a factor of two by application of $\sim 10^5$ At/m 'orthogonal' dc bias in this way [22].

Because of limited time, very few electrical measurements were done on the inductors at Fermilab prior to shipping to LANL. By centering a 0.065 in. wire through the unit and shorting at the far end, impedance measurements were at 0.5 through 100 MHz. At 500 kHz the measured impedance was $0.7 + j12.5\ \Omega$. If the unit was treated as a lumped inductance, and ignoring stray inductance (i.e., H field stored between the wire and the ferrite, and in the end pipes) this is consistent with $\mu_r = 56$.

At 2.8 MHz the measured impedance was $0.6 + j70.2\ \Omega$. Here the inductance of the transmission line composed of the wire and a 5 in. pipe becomes significant. The characteristic impedance of such a line is 261 Ω and the length, including the extensions is 1 m. The input impedance of such a line, $jZ_0 \tan \beta\ell = j15.5\ \Omega$. If the ferrite insert is here considered to be a lumped impedance in series with the transmission line impedance, the ferrite inductive reactance becomes $j54.5\ \Omega$. This implies inductance 4.1 μH/m and $\mu_r = 44$. By introducing 600 A dc in the bias solenoid, with no external iron reluctance path return, the impedance at 2.8 MHz was reduced to $j30\ \Omega$. This is a larger impedance change that can be explained by the μ_r change predicted by the above described data. The discrepancy is not understood but it is probably related to uncertainty in calculation of reluctance path length in each case.

Shorted wire measurements at higher frequencies are compounded by multiple mode velocities and reflections, causing resonances which would not be seen by unidirectional plane wave beam fields. Superfish and Mafia calculations on the proposed geometry showed TM_{010} resonances above 100 MHz [23].

At LANL the assemblies were pumped to moderately acceptable pressure, 10^{-5} to 10^{-6} Torr before installation. The inductors were installed adjacent to each other with a cryopump system between them. The solenoid currents were oriented such that the external fields were opposing. Each solenoid was provided with two steel sheet flux return paths, mounted about 0.3 m above and below.

Fire safety considerations limited the solenoid current to 1000 A for periods no longer than one minute.

6 The Experiment

Two twelve hour shifts on August 2 and 3 were allocated to the study of passive compensation. The goals of the experiment were, first, to ascertain that the installation of the inductors did not adversely affect normal operation or beam losses in the PSR, or introduce any new instabilities. The second goal was to establish that the inductors did indeed interact with the beam as broad band inductors and to determine the degree to which the installation counteracts the space charge forces. Thirdly, under the assumption that the PSR instability is in fact caused by electrons and that reducing the number of protons in the rf generated gap will increase the instability threshold, it was planned to make a comparative measurement of the instability threshold with and without solenoid bias at several beam intensities.

Some incomplete results of the various experiments are described here, not necessarily in the order in which they were measured. A more detailed account and explanation of results may be available only after a several month cool-down period, when the equipment can be removed from the PSR enclosure and more complete impedance measurements can be made. Also, there exists a torrent of digitized data detailing each measurement. Recovery and analysis of these data will require many man-hours of effort on the part of LANL personnel.

1. Normal operation of the PSR was established without incident. It was determined that the presence of the inductors, with and without bias, did not affect the previously established PSR magnet settings or closed orbit. No unusual beam losses

or instabilities were observed.

2. In preparation for this experiment, Filippo Neri (LANL), completed many multi-particle simulations which were to predict bunch length for short proton bunches with a given rf voltage augmented by the effect of the installed inductors, with and without bias. The injected bunch length (termed 'pattern width') was to be 50 ns and the rf voltage set to 8 kV. Injection for 2000 turns (720 μs) provides $\sim 8 \times 10^{12}$ particles per pulse. For total effective inductance 7.1 μH the simulations predict rms bunch length $\sim$ 18 ns. Raising the solenoid bias current to 900 A is expected to reduce the ferrite relative permeability and the inserted inductance by slightly more than a factor of two. The simulations indicate that this should increase the rms bunch length to $>$ 23 ns. In Fig. 3 the results of one of several such measurements is shown. The trace with larger amplitude was observed with the full effect of the inductors. That trace is reasonably well matched to a $\cos^2$ line charge distribution with rms width 19 ns and full width at base 105 ns. This is consistent with the simulation prediction. The lower amplitude curve, presumably with the same area, is not easily measured, but it is not inconsistent with the simulation prediction. The differences between the unbiased and biased traces is not as large were predicted, but the simulations represented larger decreases in μ_r than were obtained with the bias current available. In each observation the bunch amplitude was smaller and the bunch broader after application of the solenoid bias.

3. In an attempt to isolate the effect of the inductors on the instability threshold, the machine parameters were adjusted so that incipient instability could be observed at relatively low intensity, $\sim 1.5 \times 10^{13}$ ppp, with the rf voltage set to $\sim$ 3 kV. It was expected that application of 900 A dc bias on the solenoids would decrease the effectiveness of the inductors, and space charge effects would increase the number of protons in the gap. The rf voltage would then have to be increased to re-establish the threshold for instability. This measurement failed. As soon as the solenoid bias was increased from zero, the instability, instead of becoming more pronounced, disappeared. (Law of unintended consequences.) Because of the time limitation on application of dc bias to the solenoids, it was not possible to re-establish the threshold for instability with the bias applied. (It had been suggested previously that solenoidal bias windings

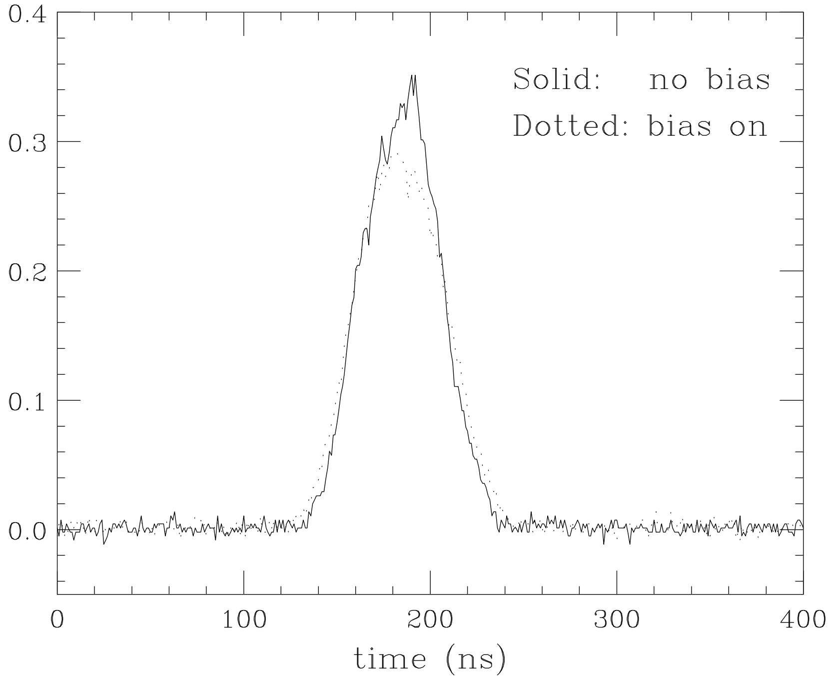

Figure 3: PSR beam bunch shapes with unbiased and biased ferrite compensator.

be wrapped on some of the PSR straight section beam pipes in an attempt to affect and perhaps interpret electron motion in the ring. Previous to this experiment, this had never been done. This may be a serendipitous result of this experiment.)

In a similar set of experiments which did not involve biasing the ferrite, the rf voltage necessary to hold the instability just at the threshold was recorded for four beam intensities; 1, 1.5, 2, and 3×10^{13} ppp. At the highest intensity the required rf voltage was reduced to 60% of that which had previously been necessary to maintain stability. These data, added to the historical data of Fig. 1, are shown in Fig. 4. This improvement in stability may not be entirely attributed to the influence of the passive space charge compensation inductors. In this experiment the vertical beam size injected into the ring had been increased by approximately a factor of two. This increase in beam size results in a decrease in the g_0 factor in the space charge impedance expression, which may improve stability. There may be additional advantages accorded to increased beam size, as predicted by Neuffer [11], so that possibly less than half of the improvement can be attributed to the installed inductors.

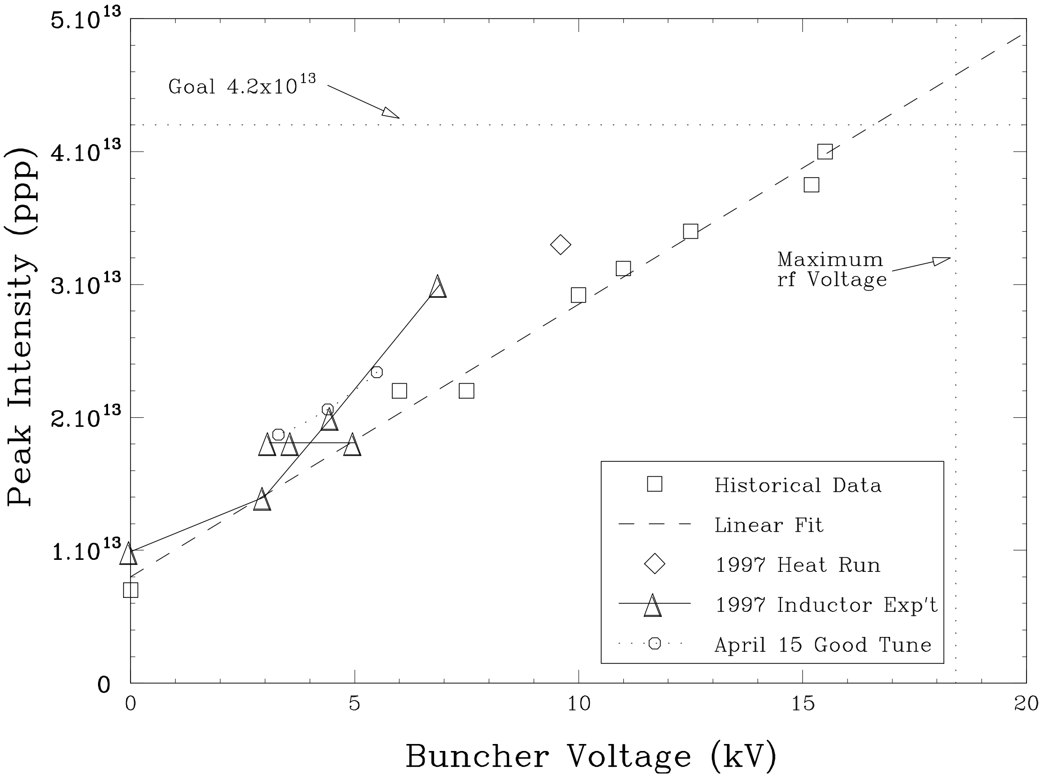

Figure 4: Stability threshold versus rf voltage improvement. Results of this experiment are depicted by triangles.

4. An attempt was made to repeat the above described self-bunching experiment so that by changing the amount of rf cavity detuning, the effective value of the inserted inductors might be determined. The rf power amplifiers were shut down and the filament power removed. An access was made to the accelerator enclosure and the final power amplifier tube grids were attached to the cathodes. This was thought to be prudent in order to prevent the voltage developed by the beam on the cathode follower cathodes from exceeding the maximum rated grid to cathode voltage. However, the grids of the tubes are connected through 100 Ω resistors to approximately half-wave length transmission lines from remotely located driver amplifiers. By transforming the output reactance of the driver tubes through the transmission line and matching transformers to the cathode follower grid-cathode connection, the maximum reactance

at any tuning condition is found to be only a few hundred Ohms. The inductive reactance in this condition at the 'above resonance' bias current, 320 A, has been measured to be $j220\ \Omega$.

Attempts were made to observe self bunching at several different rf cavity tuning biases which were believed to be consistent with the previous (February 1997) experiment. No evidence for spontaneous self bunching of the beam was observed at any of the tuning biases. It is suggested that during the previous experiments, the detuned cavity impedances may have been much higher than in the present experiment. There is some evidence that the grid to cathode connection was not made during the previous experiment, which would account for the higher gap impedance.

5. The amount of proton beam current in the gap created by the rf bucket(s) is believed to be related to the threshold for the onset of e-p instability. The 'beam in the gap' can be observed by looking at signals from a fast current transformer in the extraction line. Extraction time is set 100 ns early so that a small signal from the tail of the bunch is observed first, followed by the 'beam in the gap' current, and finally followed by the main extracted bunch current. This observation was made during this experiment and, while only approximate quantitative results are available ($< 10^{-3}$ beam in the gap), the qualitative observation was that this was the 'cleanest gap ever observed'.

7 Conclusion

The contention [4] that longitudinal space charge fields in high current proton rings can be passively compensated for below transition is supported by the results of this experiment and by a concurrent KEK Proton Synchrotron experiment [24] (see below). The anxiety that introduction of additional inductive reactance to the vacuum chamber of such a ring will cause undesirable instabilities appears to be unwarranted. No such instabilities were observed in the LANL PSR up to intensity 3×10^{13} ppp.

The disagreement between the measured bunch length changes with and without ferrite bias is likely to be related to inexact knowledge of the relative permeability of the inserted inductance as a function of frequency and bias current. There was insufficient time to obtain good measurements prior to installation. This problem can certainly be resolved by careful network analyzer measurements of the inductors after removal from the ring.

Problems resulting from the time limitation placed on application of ferrite bias during the experiment can be resolved by design of water cooled bias windings.

With regard to the failure to observe spontaneous self bunching, better measurements of the rf cavity gap impedance are being completed at present. This may not resolve the issue however. It is difficult to find a beam current and momentum spread configuration in which the instability threshold is exceeded by an amount which would result in observable self bunching for any detuning of the cavity as long as the grid drive transmission lines are connected and the cathode follower grids are connected to the cathodes. There is still some mystery associated with the observations during the previous experiment.

These results are sufficiently encouraging to warrant construction of additional passive inductors similar to those used in the experiment. In a storage ring such as the PSR the gated linac beam is injected with some fixed ‘pattern length’. This causes the line charge distribution to be nearly rectangular, with short, steep, exponentially decaying edges. The longitudinal space charge fields, being proportional to the derivative of the line charge distribution along the orbit, will have large high frequency components at each end of the bunch. It is important to preserve the bandwidth of the compensation system to sufficiently high harmonics of the rotation frequency to effectively compensate for the high frequency components. If this is not done the large fields at each end of the bunch will force protons into the gap and the effectiveness of the system will be lost. The ferrite chosen seems ideally suited to the application, and a sufficient quantity is available. A different ferrite, with higher μ_r, might be chosen in order to obtain the required inductance with a shorter structure. This would cause the bandwidth over which the inductor retains its value to be compromised.

Note Added in Concurrence

In early 1997, a related experiment was started at the KEK Proton Synchrotron main ring [24] in Japan. At injection energy, 500 MeV, the space charge impedance of that machine is $\sim 440\ \Omega$. An impedance consisting of eight FINEMET cores was installed in the ring. (FINEMET is a very high μ_r material, which is also very lossy at MHz frequencies. The Q of the inserted cores was less than one over the frequency range of the experiment.) The rings were encircled by a figure eight bias winding coil so that the inserted inductance could be reduced substantially under controlled conditions. In the experiment, the incoherent synchrotron phase oscillation frequency, inferred by measurement of the quadrupole bunch motion frequency, was measured as a function of beam intensity. Between 3×10^{11} and 9×10^{11} protons per bunch, the slope of the incoherent synchrotron frequency was reduced by half over the same measurement with no compensating inductance. This is consistent with the predicted result since only half the required compensation inductance was placed in the ring. No deleterious effects have been reported. It is planned to insert an additional inductor by the end of this year.

A salient point regarding this result is that it indicates clearly that rf components of beam image current and the associated E and H fields can link lumped inductances introduced into the vacuum chamber in such a way as to generate effective longitudinal E fields.

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