PRELIMINARY TESTS OF A SECOND HARMONIC RF SYSTEM FOR THE INTENSE PULSED NEUTRON SOURCE SYNCHROTRON*

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Summary

The Rapid Cycling Synchrotron (RCS) of the Intense Pulsed Neutron Source (IPNS) operating at Argonne National Laboratory is presently producing intensities of 2-2.5 x 10^{12} protons per pulse (ppp) with the addition of a new ion source.[1] This intensity is close to the space charge limit of the machine, estimated at ~3 x 10^{12} ppp, depending somewhat on the available aperture. With the present good performance in mind, accelerator improvements are being directed at 1) increasing beam intensities for neutron science, 2) lowering acceleration losses to minimize activation, and 3) gaining better control of the beam so that losses can be made to occur when and where they can be most easily controlled. We are now proposing a third cavity for the RF system which would provide control of the longitudinal bunch shape during the cycle which would permit raising the effective space charge limit of the accelerator and reducing losses by providing more RF voltage at maximum acceleration.[2]

This paper presents an outline of the expected benefits together with recent results obtained during low energy operation with one of the two existing cavities operating at the second harmonic ($2f_o$). These results show that bunch lengthening does occur as expected and switching from harmonic to fundamental operation during acceleration can be done with minimal losses.

Expected Benefits

Recent experimental evidence using the new high current ion source seems to confirm the existance of the space charge limit of the RCS near 3 x 10^{12} *protons per pulse. Figure 1 shows losses during* capture and acceleration as a function of injected current. These curves are typical, but do not indicate the dependence on machine parameters such as trim quadrupoles and injection conditions. Capture losses rise when the injected beam approaches 3 x 10^{12} (equivalent to 14.4 μA) and these losses are too large to permit operation. As neutron users desire high intensities, we have studied ways in which intensity improvements could be compatible with lower losses and improved reliability, both of which are critical in a machine where essential components can reach radiation levels of ~1 rem.

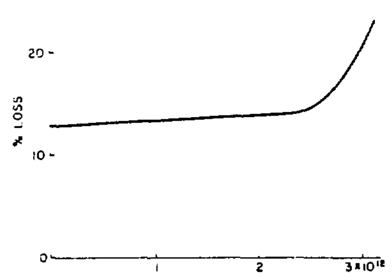

Fig. 1. Total beam losses between injection and extraction. The increase in losses at high intensity is primarily due to capture losses.

Both theoretical and experimental[3,4,5] studies have shown that increasing the bunch length decreases the charge density and increases the maximum space charge limited intensity at injection. Since the sinusoidal acceleration field of the RCS requires that the synchrotron phase and longitudinal phase space acceptance of the accelerator change significantly during acceleration, acceleration losses during midcycle are also a problem that can be improved using RF. Present operation of the RCS is shown in Fig. 2. We have plotted beam energy (E), RF acceleration voltage (V), synchrotron phase (φ_s) and space charge tune shift ($\Delta\nu$) of the beam as a function of time in the acceleration cycle, for typical 500 MeV acceleration.

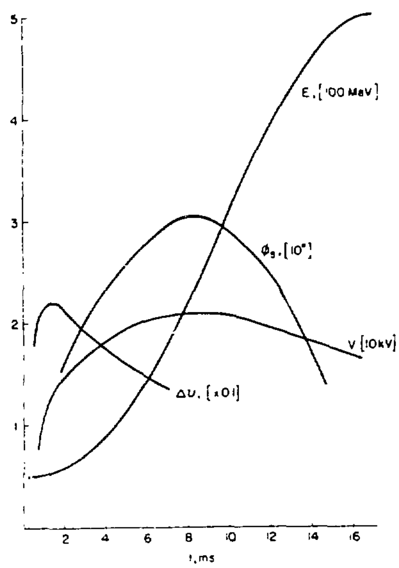

Fig. 2. Present operating conditions of the RCS.

The proposed system would utilize a third cavity capable of operating at the second harmonic ($2f_o$) for the first part of the acceleration cycle to stretch out the bunch length, and at the fundamental (f_o) for the remainder of the cycle to provide additional acceleration voltage. The voltage and frequency of the two components (f_o and $2f_o$) are plotted in Fig. 3. The phase space acceptance (A) as a function of accelerating voltage and time in the acceleration cycle for both the existing and proposed systems, together with the measured longitudinal emittance (ε_z) are shown in Fig. 4. This plot also shows how the present RF voltage program limits the acceleration efficiencies to roughly 85%.

It has been shown on the RCS (described below) and other accelerators[3,4,5] that the second harmonic RF component can increase the space charge limit of an accelerated bunch by 30-40% when used through the whole acceleration cycle. Because of the low peak RF voltage[3] (21 kV) and the undesirably large losses of 1 x 10^{13} protons/s in this 30 Hz synchrotron, it was decided that the third cavity should also be capable of operating at the fundamental frequency to provide additional longitudinal acceptance when needed. This constraint made operation above 5.5 MHz inefficient,

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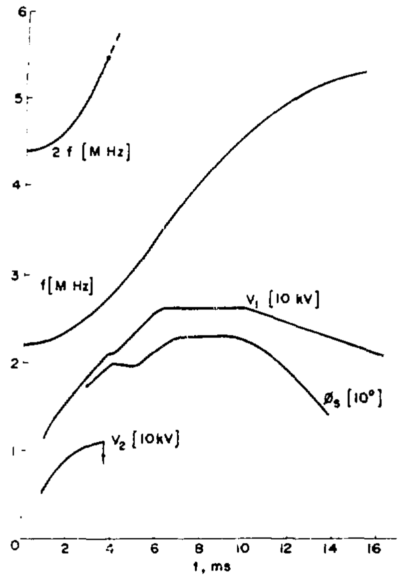

Fig. 3. Voltage and frequency programs for the two harmonics.

and slightly reduced the available gains in the space charge limit to

$$G = \frac{\Delta\nu_{max}}{\Delta\nu(t)}$$

where $\Delta\nu_{max}$ is the maximum space charge induced tune shift and $\Delta\nu(t)$ is the incoherent tune shift when the harmonic component is turned off, that is,

$$\Delta\nu(t) \propto \frac{Nf(\varphi)f(x/a)f(y/b)}{\nu\gamma^3\beta^2 a(a+b)}$$

where N is the number of particles in the bunch, ν is the tune, γ and β are the relativistic energy and velocity factors, a and b are the half width and height, and $f(\varphi)$, $f(x/a)$, and $f(y/b)$ are dependent on bunching and the beam distribution in the x and y planes. A detailed computer analysis was done of bunch shapes and areas using experimental data (Fig. 4) and a variety of RF voltage programs, assuming constant, and slowly varying, invarient emittances ε_x, ε_y and ε_z, with the result that the gain in intensity is essentially determined by $1/\gamma^2\beta$ at the instant the harmonic is shut off. If the harmonic is turned off too early, space charge effects will produce beam losses and if the additional RF voltage at the fundamental is provided too late, additional losses will be produced due to insufficient longitudinal acceptance. Optimum beam efficiency is obtained when beam losses due to space charge detuning and phase space are both minimized. This requires that the transition between second harmonic and fundamental must be made as quickly as possible at roughly 4 ms into the acceleration cycle.

Two other operating modes are possible. If space charge considerations become less important than losses, it would be possible to maintain the third cavity at the fundamental through the whole cycle. It is also possible to operate the third cavity at the second harmonic through the whole cycle, if problems occur with switching or if maintaining a long bunch through the acceleration cycle becomes important. At PETRA, it has been found that the addition of a higher harmonic cavity increases the threshold of the vertical instability that limits the beam current. This threshold has been increased by a factor of five

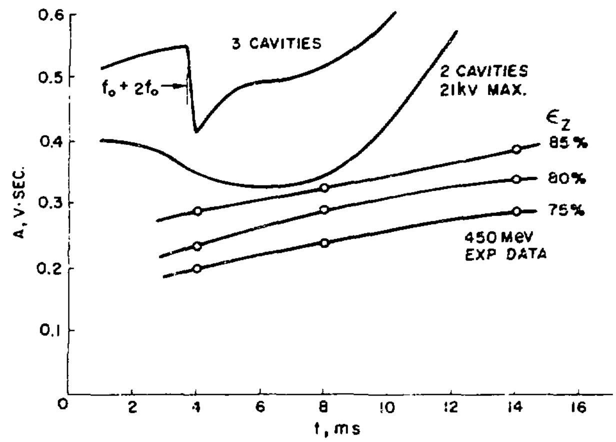

Fig. 4. Phase space acceptance and measured longitudinal emittance as a function of time, for 2 and 3 cavities.

when the bunch length increases by a comparable factor.[6] Operation of the proposed cavity above 5.5 MHz requires changes in the cavity design however, either a reduction in ferrite or gap capacitors accompanied by a change in the cavity bias system.

System Description

Existing System

The existing system is described in detail elsewhere[2,7] so only a short overview will be provided here. The present RF accelerating system for the RCS produces a total peak accelerating voltage of 21 kV across two single gap ferrite loaded cavities located 180° apart. The frequency swing of the fundamental operating mode is 2.2 to 5.3 MHz. The frequency program is generated from an integrated $\dot{B}$ signal using a third order polynomial expansion. Beam phase and position signals are added to correct the program. The low level electronics, located in the main control room, generate the low level drive and phase control signals required by the two cavities. Two separate amplifier systems, located near the accelerator, generate the cavity gap and bias potentials. A block diagram of the existing system is shown outside the dashed box in Fig. 5.

Proposed Addition

The third cavity system would have the capability of operating in three modes: 1) fundamental mode throughout the whole acceleration cycle, 2) second harmonic operation for the first 4 ms and fundamental operation for the remainder, and 3) second harmonic through the whole acceleration cycle. The system, in the first two operating modes, would provide additional voltage requirements at $\dot{B}$ maximum and, in the last two modes, would be capable of increasing the space charge limit of the RCS. In addition to the previously stated advantages, other considerations are: 1) all three cavities could be operated at lower levels decreasing component stresses if the full voltage increase is not required, and 2) failure of one of the systems would not significantly hinder the IPNS experimental program since the RCS could quickly resume operation with two acceleration cavities at reduced intensity, with repairs postponed to the next shutdown period. Space for the third cavity in the RCS ring can be provided by combining the trim quadrupole and octupole magnets.

For the third accelerating system, the cavity and amplifier chain would be identical to the ones presently in use, simplifying the design and construction. The construction can be accomplished without jeopardizing any existing accelerator components or significantly interrupting the anticipated IPNS operating schedule. Costs will be held down by using existing spare ferrite and cavity parts, as well as the existing reserve of the final stage dc power supply. Some additions and changes will be required in the low level controls. The main electronic design effort will center on the problems of switching from the harmonic to the fundamental mode and phase locking to the other cavities under the various conditions. A block diagram of the proposed system is shown in the upper portion of Fig. 5.

Experimental Results

Limited experiments on the feasibility of the planned approach have been done by modifying the existing system. In one experiment, the low level electronics of one of the cavities was modified by adding a diode frequency doubler to allow operation on the second harmonic. Another doubler was added to the output of the capacitive divider on the fundamental cavity permitting the measurement and control of cavity to cavity phase. An additional function generator was added to allow independent control of the voltage functions to each of the cavities. During initial tests, no attempt was made to revert the system operating on the second harmonic back to the fundamental. Also, since the high level RF equipment is limited to a maximum of 5.3 MHz, the harmonic system could not be operated beyond several milliseconds after beam capture.

Initial tests were conducted with the normal 450 MeV magnet program. Although stability of the beam was not optimized, the beam was captured into a visibly larger bunch. Since only one cavity was operating on the fundamental, only half of the required voltage was available and all of the beam was lost by $\dot{B}$ maximum. The peak energy was then lowered to 225 MeV, which decreased the maximum $\dot{B}$ and allowed beam to be accelerated and extracted at full energy with only a single cavity. Cavity to cavity phase problems were corrected with regulator accuracy $<\pm10^{\circ}$. Under these conditions, the effects of fundamental and harmonic voltage, as well as cavity to cavity phase programming were studied. A typical set of conditions is shown in Fig. 6. A photograph showing the bunch formation under fundamental and harmonic operation and the transition to fundamental

ACCELERATING SYSTEM BLOCK DIAGRAM

EXISTING AND PROPOSED ADDITION

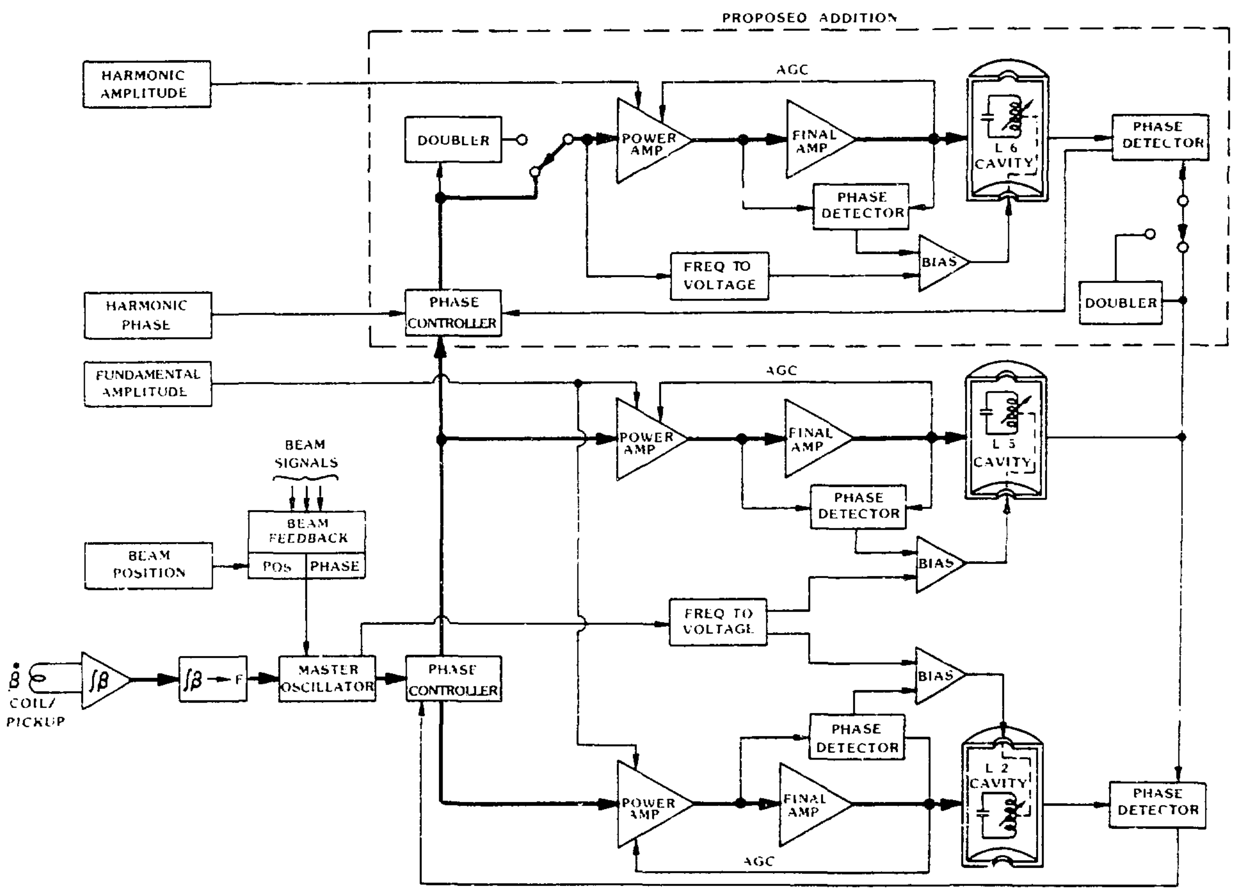

Fig. 5. Block diagram of the existing and proposed accelerating systems.

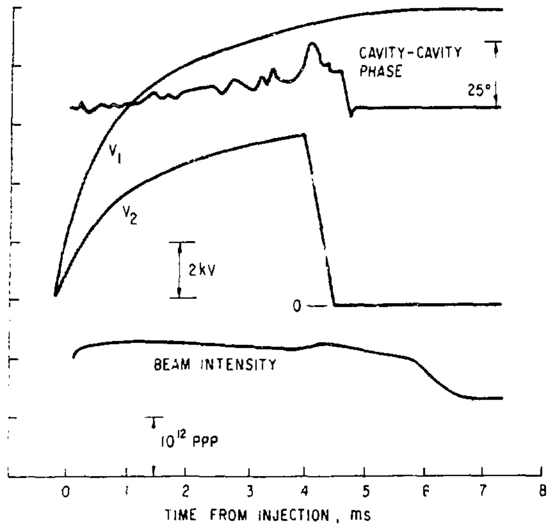

Fig. 6. Typical harmonic operating conditions.

is shown in Fig. 7. No increase in beam losses or instabilites was noted because of the harmonic voltage operation. In addition, no instabilities or bunch oscillations were encountered when the harmonic system was shut down rapidly ($\tau \sim 100\ \mu s \sim 1/2$ synchrotron period).

Most recently, switching one RF cavity from the second harmonic to the fundamental was done during acceleration to 450 and 300 MeV using one cavity operating at the fundamental. During these tests, the voltage on the second harmonic cavity was reduced to zero in 0.5 ms, the cavity was off for ~0.7 ms while the cavity was switched to the fundamental and the voltage was then raised to ~10 kV in ~0.5 ms. Beam losses during this transition period were consistent with predictions based on the available longitudinal phase space (Fig. 4) and the small losses which did occur during switching seemed to be directly related to the RF voltage during this period as shown in Fig. 8. Additional effort will be required on the cavity to cavity phase and beam phase servo systems.

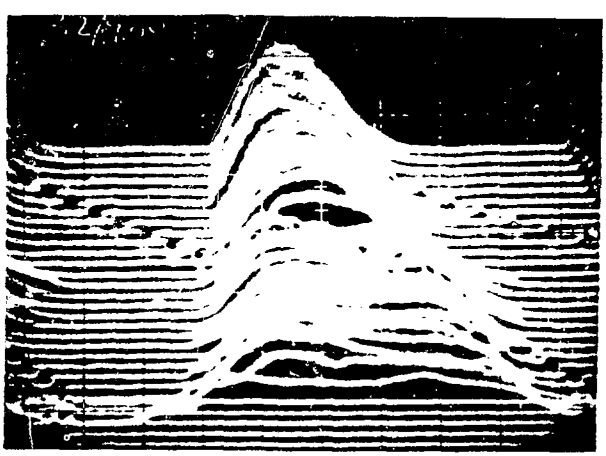

Fig. 7. Mountain range display of fundamental and harmonic bunch structure and the transition to the fundamental.
Horizontal scale - 50 ns/division.

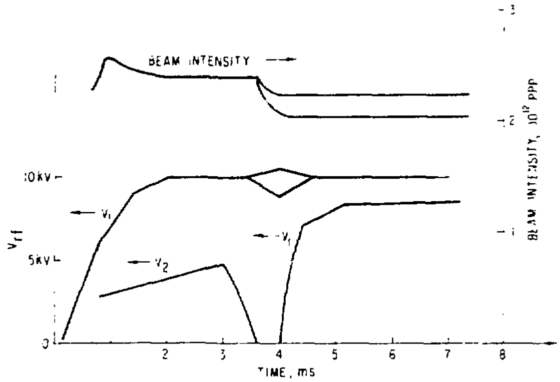

Fig. 8. Beam intensity during transition from harmonic to fundamental operation. The range of beam losses due to changes in the fundamental voltage is shown.

Conclusions

The limitations of inadequate RF voltage in the present accelerating system are clearly evident. A third cavity system has many advantages, even when operating on the fundamental frequency. Since the RCS is approaching the theoretical space charge limit, the added "bonus" of using the harmonic mode to increase this limit, should have a positive impact on the whole IPNS experimental program. Initial tests have shown that bunch lengths can be extended and the transition from harmonic to the fundamental acceleration seems to produce no adverse effects on the beam bunch or beam stability.

References

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