A PROPOSED SECOND HARMONIC ACCELERATION SYSTEM FOR THE INTENSE PULSED NEUTRON SOURCE RAPID CYCLING SYNCHROTRON*

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Introduction

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. On the basis of preliminary measurements, 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.

Theory

Both theoretical and experimental[2,3,4] studies have shown that increasing the bunch length decreases the charge density and increases the maximum space charge limited intensity. An additional constraint is provided by the sinusoidal acceleration field of the RCS which requires that the synchrotron phase and longitudinal phase space acceptance of the accelerator change significantly during acceleration. Present operation of the RCS is shown in Fig. 1. 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.

The proposed system would utilize a third cavity capable of operating at the second harmonic ($2f_0$) the first part of the acceleration cycle to stretch out the bunch length, and at the fundamental (f_0) for the remainder of the cycle to provide additional acceleration voltage. The voltage and frequency of the two components (f_0 and $2f_0$) are plotted in Fig. 2. 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) is shown in Fig. 3.

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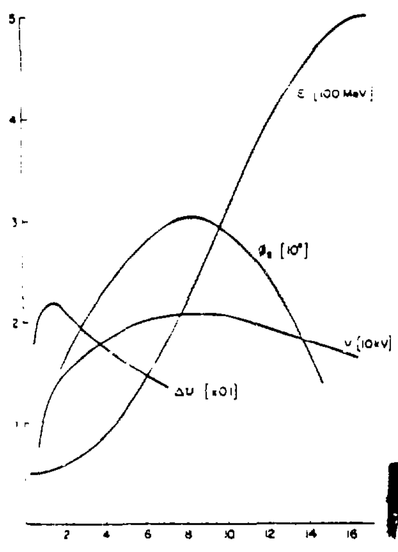

Fig. 1. Present operating conditions of the RCS.

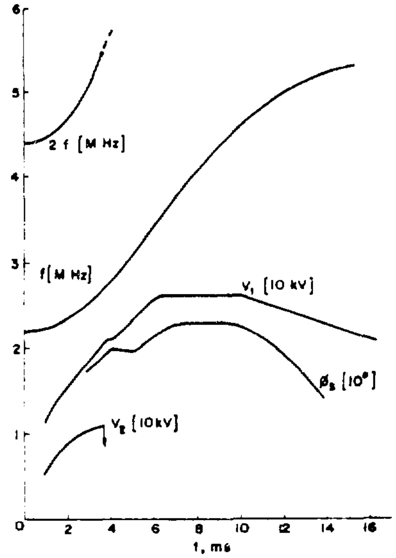

Fig. 2. Voltage and frequency programs for the two harmonics.

It has been shown on the RCS (described below) and other accelerators[2,3,4] 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 (21 kV) and the comparatively 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,

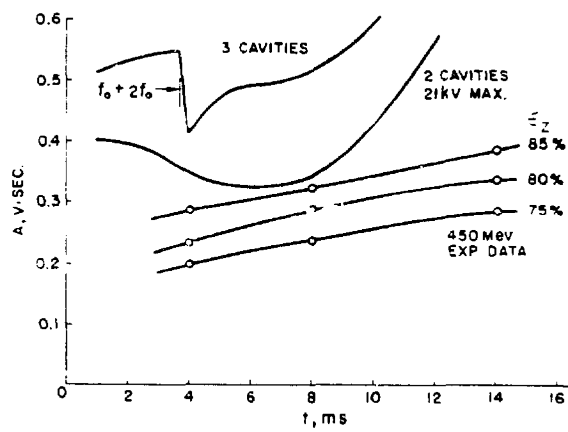

Fig. 3. Phase space acceptance and measured longitudinal emittance as a function of time, for 2 and 3 cavities.

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,

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

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 $f(\phi)$, $f(x/a)$, and $f(y/b)$ are dependent on the beam distribution in the x and y planes. Assuming constant emittances ϵ_x, ϵ_y and ϵ_z, the energy dependance is essentially determined by $\gamma^2\beta$ 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.

System Description

Existing System

The existing system is described in detail elsewhere[5] 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. 4.

Proposed Addition

The third cavity system would have the capability of operating in two modes: 1) fundamental mode throughout the whole acceleration cycle, and 2) second harmonic operation for the first 4 ms and fundamental operation for the remainder. The system, in either operating mode, would provide the additional voltage requirements at $\dot{B}$ maximum and, in the second mode, 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 systems 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 accelerating systems at reduced intensity with repairs progressing during 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 sing existing spare ferrite and cavity

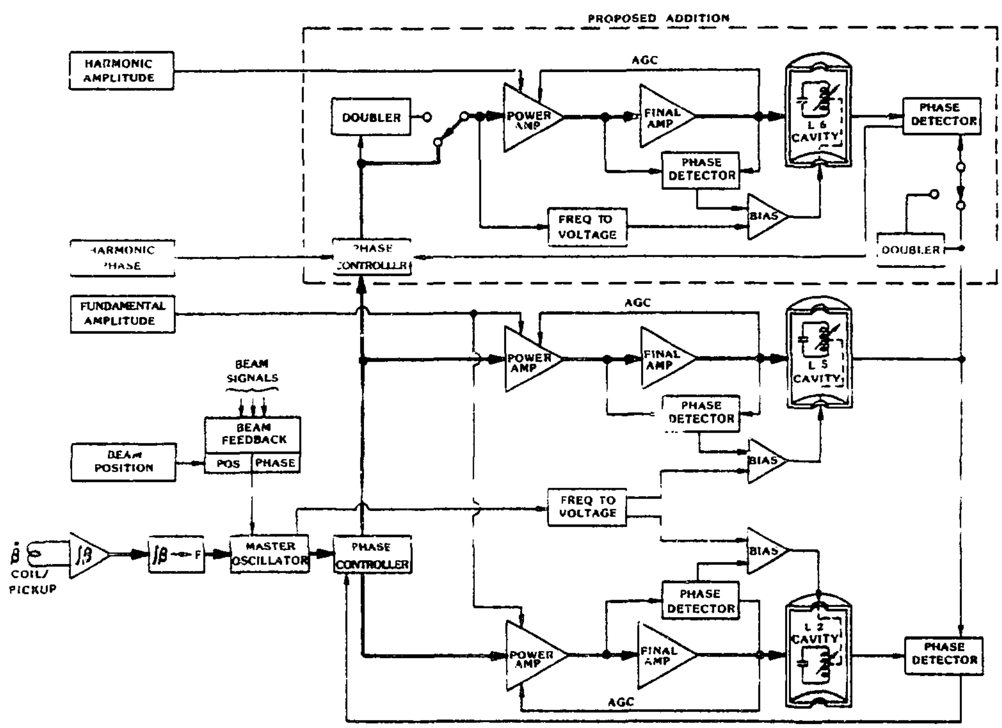

Fig. 4. Block diagram of the existing and proposed accelerating systems.

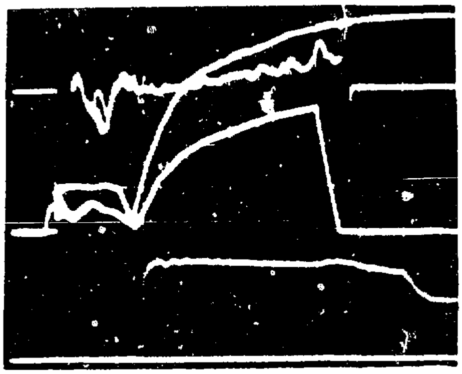

Fig. 5. Typical harmonic operating conditions.
Cavity to cavity phase - 25^{o}/division.
Fundamental voltage - 2 kV/division.
Harmonic voltage - 2 kV/division.
Circulating beam intensity - 10^{12}/division.
Horizontal scale - 1 ms/division.

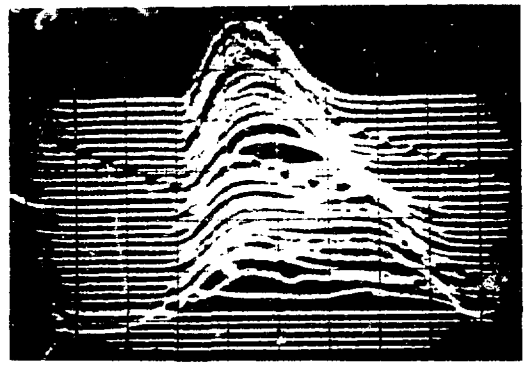

Fig. 6. Mountain range display of fundamental and harmonic bunch structure and the transition to the fundamental.
Horizontal scale - 50 ns/division.

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. 4.

Experimental Results

Before embarking on a full scale project, it was decided to perform limited experiments on the feasibility of the planned approach by modifying the existing system. 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 these 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.

The initial tests were conducted with the normal 450 MeV magnet program. Although stability of the beam was not optimized, the beam was bunched into a visibly larger bucket. In addition, 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 $<\pm 10^{o}$. 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. 5. A photograph showing the bunch formation under fundamental and harmonic operation and the transition to fundamental is shown in Fig. 6. 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 ($\tau \sim 100$ μs = 1/2 synchrotron period).

Further tests are planned with changes in the beam phase system, which presently is referenced to the cavity operating on the harmonic. This will allow injecting more beam than the 2.5 x 10^{12} protons per pulse injected during the previous tests. Plans are also underway to allow the harmonic cavity to dynamically switch over to the fundamental mode so that the whole concept can be tested with the existing system.

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, will have a positive impact on the whole IPNS experimental program. Initial tests have shown that bunch lengths can ' 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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