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COMPENSATION FOR BEAM LOADING IN THE 400-GeV FERMILAB MAIN ACCELERATOR

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Summary

At the design ramp slope of 125 GeV per second and 5×10^{13} protons per pulse, the RF System in the Fermilab main accelerator must deliver 1 megawatt of power to the proton beam. RF amplitude and phase changes resulting from beam loading during acceleration are compensated for by separate somewhat slow feedback systems. Phase shifts resulting from transient beam loading during injection are compensated for by a third feedback system of broader bandwidth. The feedback systems are described and performance details are discussed.

Introduction

In this paper the term "beam loading" is construed to refer to the interaction of the fundamental frequency Fourier component of circulating beam bunches with the RF accelerating cavities. During acceleration this interaction must be such that the power delivered to the beam results in an increase in kinetic energy consistent with the rate of rise of the magnet guide field. During injection or fixed field extraction only minimal energy need be delivered to the beam but the cavity phase shift resulting from the large component of circulating quadruture current must be compensated for. Energy lost by the beam either through synchrotron radiation or through beam excitation of lossy structures in the beam enclosure is considered to be negligible.

At the design acceleration rate of 125 GeV per second and an intensity of 5×10^{13}, each of 15 accelerating cavities must deliver 66 kW to the beam at a synchronous phase angle of approximately 55 degrees and peak gap voltage of 213 kV.[1,2] The shunt impedance of each cavity is about 667 kohms during acceleration so at the required gap voltage each cavity must dissipate 34 kW. The RF power generator peak current (referred to the gap) required to develop the gap voltage with no beam loading is 0.32 amperes. With a bunching factor of 10, harmonic number 1113, and rotation frequency of 47.7 kHz the peak value of the fundamental Fourier component (53 MHz) of circulating beam current is $\sim$ 0.73 amperes.

Since the circulating beam current is greater than twice the quiescent cavity gap current, performance of the RF Accelerating systems must be governed by a variety of feedback systems, each of which is coupled to the others through the beam current. There are five feedback systems in all, some of which have been described previously in the literature.[3,4,5,6] The five systems presently in use are:

1.) beam bunch phase vs. RF phase comparitor, dc coupled, very low bandwidth, the output is an error signal which controls the RF frequency,

2.) beam radial position control loop, controls radial position by small adjustments of synchronous phase angle, dc coupled, bandwidth $\sim$ 10 kHz,

3.) cavity gap voltage phase vs. RF drive voltage phase correction loop, ac coupled, 5 MHz bandwidth, capable of fast adjustment of cavity excitation phase to compensate for transient beam loading effects such as partially filled ring during injection or uneven beam intensity around the ring,

4.) cavity gap voltage phase vs. RF drive current phase, capable of adjusting cavity tuning such that the load impedance presented to the RF power generator appears to be real, high dc gain ($\sim$ 60 dB) with low bandwidth, corner frequency 1 Hz, and

5.) cavity gap voltage amplitude vs. prescribed amplitude loop, capable of adjusting RF generator drive current such that the voltage amplitude developed at the cavity gap remains at a prescribed level, very high dc gain ($\sim$ 60 dB), corner frequency 5 Hz.

The beam-RF phase loop operates with only minimal coupling with the other loops. The second and third loops, each of which affects the phase of the RF voltage, are strongly coupled by the beam current. The forth and fifth loops, controlling the RF amplitude and cavity tuning are unilaterally coupled electrically in that a detuning of the cavity will cause the amplitude loop to demand more drive current.

Steady State Compensation

In Figure 1 one of the RF cavities is represented by a remotely tunable RL_C circuit which is excited by two infinite impedance current sources, the beam image current and the RF power source current. In order to describe the performance of the feedback control system it is convenient to show the relative phase of voltages and currents on a phasor diagram. In Figure 2a the beam current, used as a reference phase, is shown on the positive real axis at some instant in time, with its wall image current shown equal and opposite. (Small retardation effects are neglected.) In part a of Figure 2 the effect of beam loading is temporarily ignored, the cavity is assumed tuned to resonance ($X_L=-X_C$) and the accelerator is operating above transition. Under these conditions the gap voltage is shown leading the beam phase in time and RF generator current is in phase with gap voltage. The synchronous phase angle θ_s is defined such that the accelerator voltage V_{acc} is;

$$V_{acc} = V_{gap} \sin \theta_s \qquad (1.$$

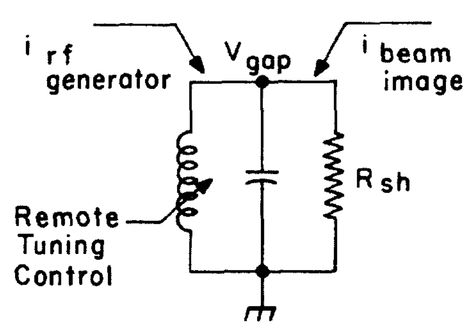

Fig. 1. RF cavity represented by remotely tunable RL_C circuit excited by two infinite source impedance current generators.

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Figure 2b illustrates the onset of beam loading. The beam image current has developed a voltage in the cavity shunt resistance which is in phase with the image current. This voltage phasor is added to the existing gap voltage reducing its amplitude and moving it ahead in time with a resultant decrease in available accelerating voltage. Under these conditions the fast transient feedback loops 2 and 3 will both attempt to restore adequate accelerating voltage by rotating the RF generator current phasor to larger θ_s and increasing its amplitude. The slower amplitude control loop will also begin to respond by increasing the generator drive current in response to a detected reduction in gap voltage amplitude. Finally the cavity tuning loop will detect the fact that the gap voltage is leading the drive current in time (a condition enhanced by the action of the faster loops 2 and 3) indicating an apparent below resonance condition. The loop will respond by tuning the cavity above resonance so that the resultant gap voltage will again be in phase with the RF generator current. In Figure 2c the finally achieved steady-state condition is shown. The cavity Q (about 6500) is such that the magnitude of voltage resulting from any excitation current is very well approximated by:

$$V = iR_{sh} \operatorname{Cos} \theta_t \qquad (2.$$

where θ_t is the tuning angle. The head of such a phasor always resides on a circle constructed about the current phasor (for normalized R_s).

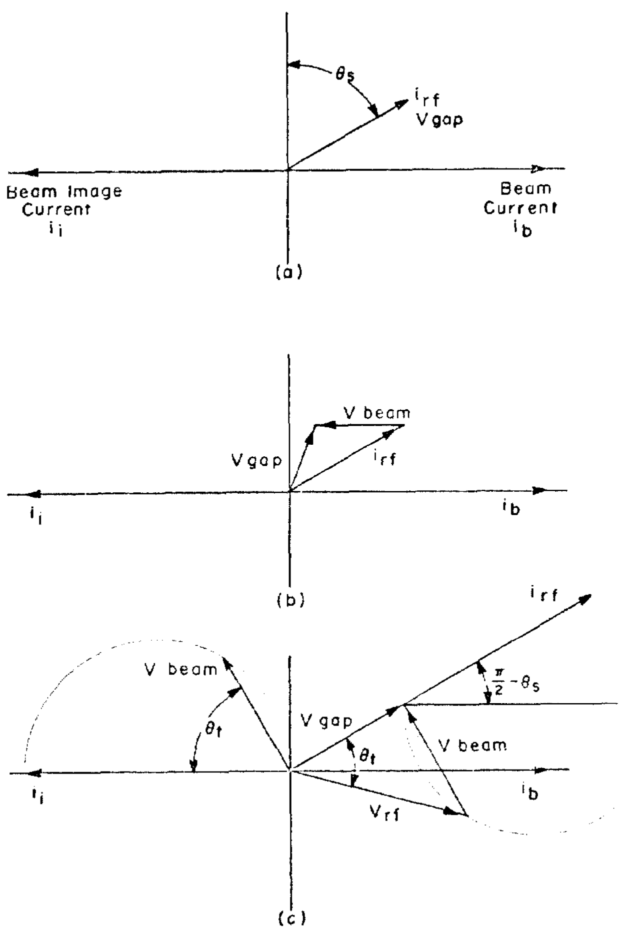


Fig. 2. Three steps in phasor representation of steady state beam loading compensation.

It is useful to reconstruct the voltage loci semicircle as shown on the right of Figure 2c. The voltage resulting from the RF generator current lags that current by the tuning angle θ_t. The beam induced voltage V_{beam}, which lags the beam image current by θ_t, is added to the RF generator voltage to produce the gap voltage which resides at the correct synchronous phase angle.

From the triangle produced by the three voltages V_{rf}, V_{gap} and V_{beam}, its included angles, and Equation (2. the required RF generator current and the required tuning angle θ_t can be deduced.

$$\theta_t = \tan^{-1} \left\{ \frac{i_i R_{sh}}{V_{gap}} \cos \theta_s \right\} \qquad (3.$$

$$i_{rf} = \frac{V_{gap}}{R_{sh}} + i_i \sin \theta_s \ . \qquad (4.$$

For the condition in which the accelerator is operating below transition this phasor analysis applies exactly if the picture is simply turned over about the real axis. The beam current then leads the cavity gap voltage in time and the cavity must be tuned below resonance to compensate for beam loading. Only the sign of the error signal in the radial position loop need be changed at transition.

Equations (3. and (4. indicate that during injection and fixed field extraction, when $\theta_s = 0$, the steady-state RF generator current required is minimum and maximum cavity detuning is required.

Figure 3a and b shows the RF gap voltage amplitude and the required power amplifier current during the entire accelerating cycle for conditions of no beam and for a beam of 10^{13} protons. No variation in RF amplitude is observed between beam and no beam conditions. During injection the RF generator currents are the same for both conditions while during acceleration of 10^{13} protons the RF generator current is increased by 20 per-cent.

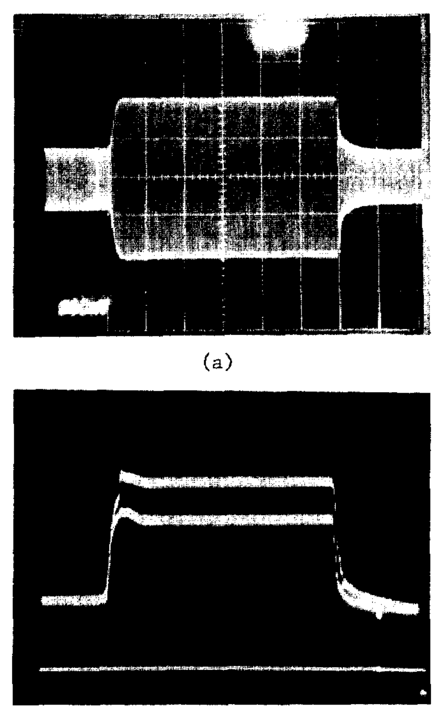


Fig. 3. RF envelope and current drive during acceleration cycle for no beam and 10^{13} protons.

Transient Compensation

Protons are injected from the booster into the main ring in thirteen consecutive batches of 80 bunches each at intervals of 66 ms. Under these conditions of a partially filled ring during injection, or in conditions when it is necessary to accelerate a partially filled ring, the cavity tuning feedback system has insufficient bandwidth to perform its tuning function since the fundamental rotation period of the machine is 21 μs. During injection each cavity has a Q of about 5000 and consequently a time constant of 30 μs and a shunt resistance of 500 kΩ. During the period when the ring contains seven booster batches (567 bunches) a large quadruture voltage will be developed during passage of the current and decay during its absence. At maximum design intensity the beam developed voltage will be:

$$V_{beam} = i_i R_{sh} \left(1 - e^{-\frac{\omega t}{2Q}} \right) = 113 \text{ kV}. \qquad (5.$$

During injection each cavity is required to develop stationary bucket gap voltage of 66 kV and an additional quadrature voltage of 113 kV would cause the gap voltage phase to be displaced by 60°. In this situation it is necessary to utilize the additional fast loop 3 to introduce quadrature current to the existing RF generator current to compensate for the transient beam current. This loop is capable of adding plus or minus quadrature currents up to $\sqrt{3}$ times the existing RF drive current to the input of the power amplifier as shown in Figure 4. During injection each power amplifier is being operated nearly class A so that additional input current appears as generator current in the cavity. The response time of this loop is limited by a loop transit time of 300 ns (about 16 bunch periods) during which time a phase shift of only about 3 degrees can develop.

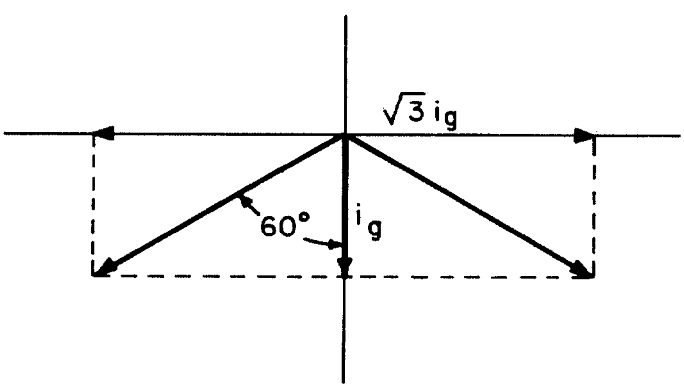
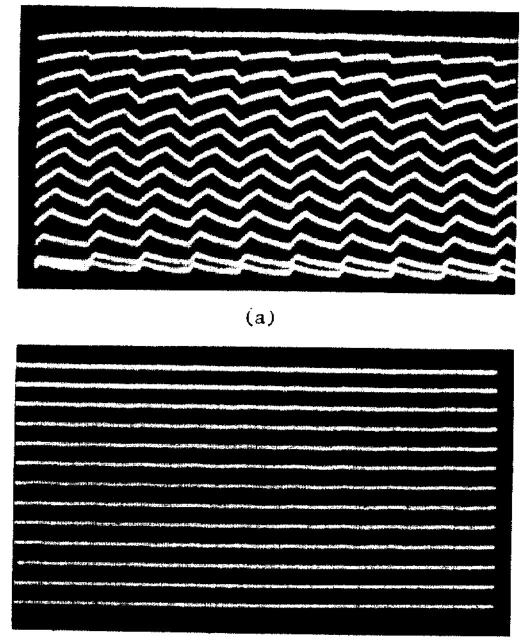


Fig. 4. RF generator current phase and amplitude capability of transient loading compensation system.

In Figure 5a a series of gap voltage phase shift oscilloscope traces are shown, the successive traces being triggered after injection of successive batches of protons from the booster with no transient phase feedback. The beam intensity in this case is 1.2×10^{13} protons total and it is clear that maximum phase deviation per turn occurs when the ring is partially full. The maximum phase shift is about 15 degrees. There is sufficient aperture in the ring so that injection errors of 15 degrees are tolerated. Part b of the figure shows the same cavity gap voltage phase shift with the fast transient feedback loop enabled. At this beam intensity the beam induced phase shift is almost unobservable.



(a)

(b)

Fig. 5. RF cavity gap voltage phase shift during injection of 13 booster batches of beam totalling 1.2×10^{13} protons. a) Fast phase compensation disabled. b) Fast phase compensation enabled.

Stability

The stability of beam-cavity interactions has been examined extensively[7,8,9] but a complete analysis of the five coupled systems is prohibitively difficult. The high-gain low bandwidth phase and amplitude loops have been individually stabilized by standard phase-margin techniques and they have been shown to respond in a docile manner to transient stimulus when coupled. These loops respond only very slowly to beam loading stimulus and their stable response to transient stimulus would appear to ensure their stability in transient beam loading situations.

The two faster phase adjustment loops are similar to those discussed by M. Lee and his conclusion is that such loops can always be stabilized by appropriate gain and transfer function adjustment. Experience with these loops is that stability can be achieved with minimal and straightforward adjustment.

The operational combination of the five loop system performs its stabilization function routinely up to beam intensities of 1.5×10^{13} protons per pulse which is close to one-third of the anticipated beam intensity. Higher beam intensities may tax some aspect of the system beyond its capability but this is not anticipated to be a major obstacle.

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