RF SYSTEM AND BEAM LOADING COMPENSATION ON THE ISIS SYNCHROTRON

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Abstract

The rf system of the 800 MeV rapid-cycling proton synchrotron is described. With the present operational beam intensity of greater than 100 µA, acceptable acceleration efficiency is dependent on good performance of the cavity tuning loop and the feedforward beam compensation system. Descriptions are given of the operation of these systems.

Proposed system developments to enable the beam current to be increased towards the design intensity of 200 µA are discussed.

Introduction

The ISIS synchrotron has a complex, low frequency rf system that operates with high levels of beam loading. A wide dynamic range of accelerating voltage is required to trap an unbunched injected beam in the synchrotron while maintaining relatively long bunch lengths to reduce space charge forces and peak momentum spread. A feedforward beam compensation system is provided to cancel the effects of beam loading in the early stages of acceleration. An additional constraint on the design is imposed by the requirement that all components in the synchrotron ring must be radiation resistant.

RF System Configuration and Parameters

The synchrotron has ten superperiods: six contain a ferrite tuned rf accelerating cavity, three adjacent on one side and three diametrically opposite. With a harmonic number of 2, there is then an rf phase angle of 72° between adjacent cavities of a group.

The ring magnets have a dc biased, 50 Hz sinusoidal excitation giving a continuously increasing field over the 10 ms acceleration period. Injection from the 70.44 MeV Linac occurs during the 500 µs prior to the field minimum after which the unbunched beam is trapped and accelerated by the rf cavity voltages. The large dynamic range required of the cavity voltage is achieved by supplementing the usual amplitude control loop with a cavity phase loop that allows the phase angle between diametrically opposed cavities to be varied from -180° to 0°. Opposed cavities are brought rapidly into phase (in less than 30 µs) towards the end of the injection period.

Further rf system parameters are:-

Injection energy	70.44 MeV
Transition Gamma	5.032
Extraction energy	800 MeV
RF frequency range	1.3 - 3.1 MHz
Max acceleration rate	115 GeV/sec
No of gaps per cavity	2
Peak RF voltage per gap	14 kV

Table 1. RF System Design Parameters

Each cavity is powered by one RCA (now Burle Industries) 250 kW tetrode type 4648, operated in class B. The power amplifiers were originally equipped with two such valves with the second intended for class A operation as a beam compensation source. However, feedforward beam compensation is currently achieved via the class B stage (see below). The driver stages are Herfurth GmbH 500 W solid state amplifiers, located in a low radiation environment away from the radiation-hard tetrode power amplifiers adjacent to the cavities.

The rf control electronics comprises: -

1) A variable frequency oscillator to provide an output frequency related to the instantaneous central field in the ring gradient bending magnets.

2) A loop to control the amplitude of each rf cavity voltage.

3) A loop to control the phasing of the cavities according to their positions around the ring. This, together with the amplitude control loop, gives an effective dynamic range of accelerating voltage of >2000:1 and enables the voltage profile to be optimised to reduce trapping loss.
It is this loop that is used to "antiphase" opposing cavities during the injection period to reduce the vector sum of the accelerating voltage to zero.

4) A loop to tune each individual cavity by maintaining a 180° phase difference between the cavity voltage and an appropriate input drive voltage. The operation of this loop is described below.

5) A beam phase loop to vary the acceleration frequency to damp beam coherent dipole phase oscillations.

6) A radial control loop to vary the acceleration frequency to keep the beam on the correct orbit.

The Cavity Tuning Loop

Due to the short acceleration time on ISIS, the cavity tuning loop has to cope with a rate of change of frequency of up to 330 MHz/s. This, coupled with a bandwidth of 5 kHz for the cavity bias current source and a similar bandwidth due to the cavity Q, leads to excessive cavity tune errors during the frequency sweep. The method used to correct this error, which is highly repetitive, is shown in Fig. 1.

The phase detector error is reduced by feeding a computer-generated analogue signal as a "demand" for the servo control. This is obtained as follows.

The phase detector signal is digitised at 2000 points throughout the full cycle. The signal is then Fourier analysed and each harmonic component is multiplied by an appropriate gain and phase, obtained from the measured closed loop transfer function from the function generator output to the phase detector output, so as to reproduce the phase detector signal. These components are then subtracted from the existing function generator signal thus progressively reducing the phase detector error signal.

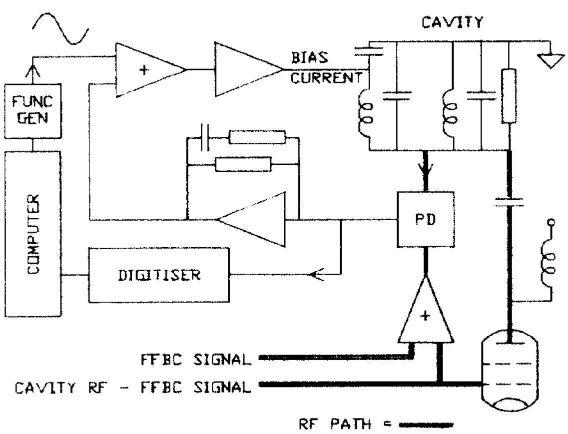

Fig. 1 The Cavity Tuning Loop

The original system, running on an ISIS control system GEC 4070 computer, took 10 minutes per correction. A new system using an IBM AT now takes 15 s per correction.[1]

It is also practicable to use the system to reduce beam-induced cavity tuning perturbations for any given operating intensity. It can be seen from Fig. 1 that while the FFBC (see below) is active, the cavities are kept on tune as if no beam were present. Subsequently, they are detuned for reactive beam-loading compensation.

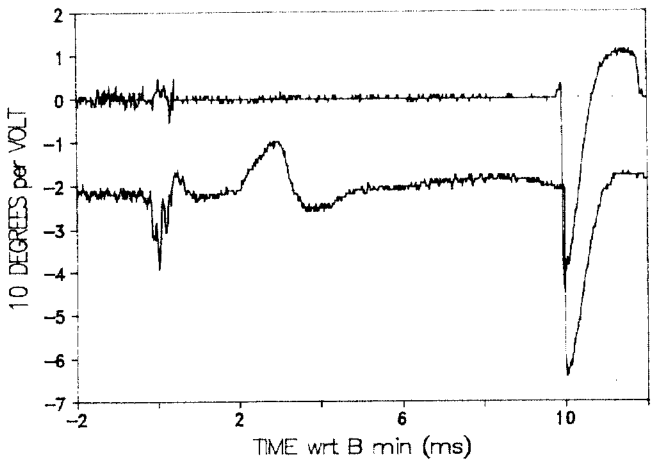

Fig. 2 Tuning Loop Phase Detector Output

Fig. 2 shows the phase detector output for one acceleration period with a beam intensity of 1.35 X 10^{13} ppp. The upper trace shows the remanent error after ten iterations. The initial error, after tuning the cavity with no beam, is shown offset beneath it for comparison. The large perturbation at 10 ms represents the abrupt disappearance of the 40° tuning angle at extraction during which the correction is gated off. During the acceleration period, the tuning error is less than ± 5°

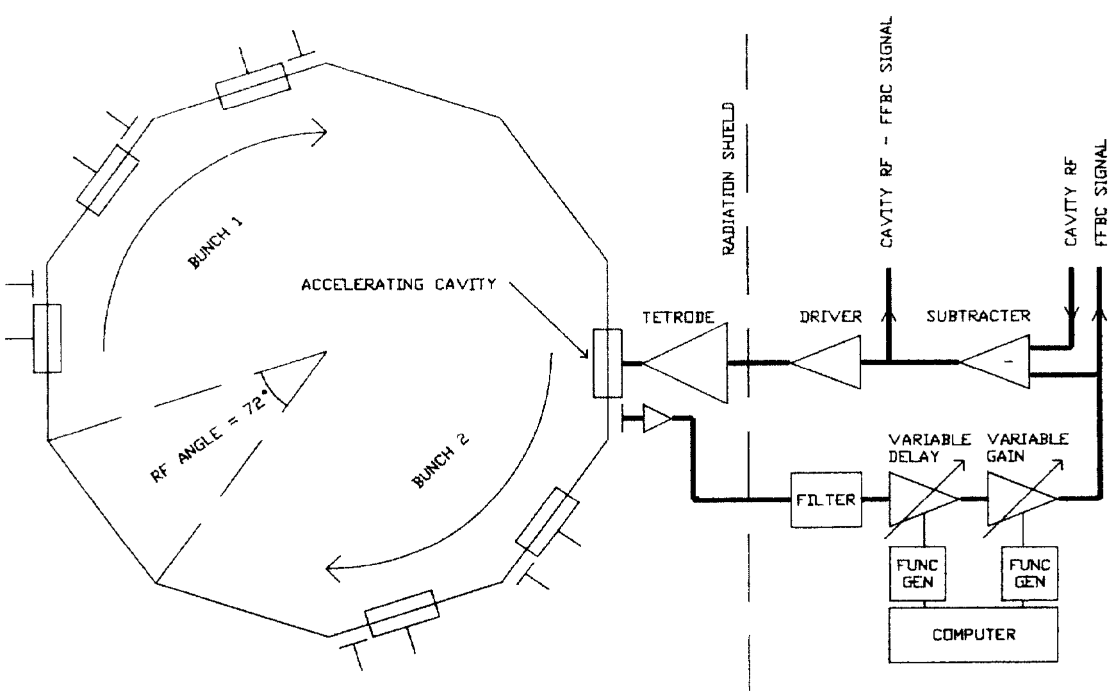

Fig. 3 The synchrotron ring layout and the feedforward beam compensation system.

Feedforward Beam Compensation (FFBC)

FFBC is used to cancel the initial, beam-induced cavity fields so allowing the tuning loop to work effectively, for its 5 kHz bandwidth is not high enough otherwise to reduce the cavity tuning errors to a sufficiently low level during the bunching, trapping and initial acceleration period.

Fig. 3 shows the principal components of the system.

The quiescent rf drive current to each cavity during the 500 µS injection period is about 0.1 A peak. At the present operating level of 110 µA (1.38 X 10^{13} ppp), the injected beam will subsequently bunch to about 2 A peak after 0.2 ms. The FFBC system acts to compensate the resultant large beam-induced cavity voltage and thus preserve the critical acceleration voltage profile.

The instantaneous beam charge is sensed just downstream of each cavity and the signals are filtered to leave only the fundamental. In each system, the signal is passed through a computer programmable variable delay - variable gain amplifier and then subtracted from the input signal to the appropriate driver amplifier. The purpose of the variable delay is to compensate for the revolution period which varies throughout acceleration (1.4 - 0.59 µs) and that of the variable gain is to scale the charge signal into a current signal and compensate for variations in system gain with frequency.

The method currently used to determine the optimum delay and gain throughout the compensation period is to determine experimentally the values that minimise the induced voltages.

One cavity at a time is beam-excited only with the remaining cavities providing acceleration. This can be done only at much reduced beam intensities (less than 3X10^{12} ppp). Fig 4 shows the gap voltage induced by a beam of 3 X 10^{12} ppp with and without such compensation.

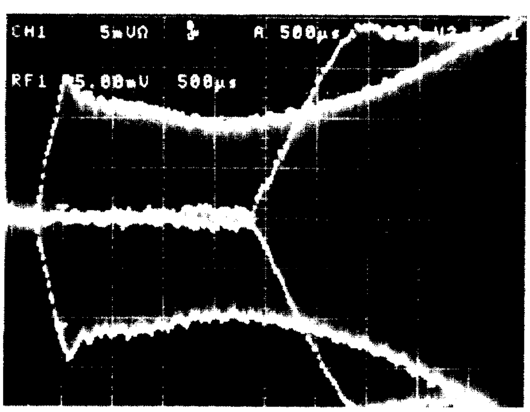

Fig. 4 FFBC cancellation of beam-induced cavity voltage

The cut-off frequency of the low pass filter in the FFBC signal path is chosen to give adequate suppression of the second harmonic component of the beam signal at the beginning of the acceleration period and its roll-off rate, together with that of the FFBC gain function, is chosen to give an orderly transition from FFBC to the reactive compensation provided by the tuning loop which allows operation with less rf drive power.

The high Q-factor of the cavity ferrite results in an operational gap impedance of about 4k Ω. The consequent beam-induced cavity voltages restrict effective operation to intensities of less than 40 µA. This limitation has been overcome by installing pumped liquid resistors as Q-dampers across the accelerating gaps. The electrolyte currently used is copper sulphate and, by varying its concentration, the effective gap impedance can be controlled down to 2 kΩ with a corresponding reduction in induced voltage. Each resistor can dissipate a peak RF power of 100 kW and presents very little reactive loading.

Present Performance and Future Development

The present system gives good reliable operation at 750 MeV and beam currents of 110 µA. Trapping efficiencies of 90% are obtained with loss of beam of less than 1% during the acceleration cycle, the lost beam being caught by the collectors in the ring.

Studies have shown[2] that the capture efficiency is critically dependent on the phase transients of the cavity rf voltages during the trapping process and, in order to maintain or improve the present phase transient levels, when the beam energy and intensity are increased towards the design levels of 800 MeV and 200 µA (2.5 X 10^{13} ppp) respectively, some development of the system is required. Work has begun[1] towards making the tuning loop adaptive so that its efficacy is not compromised by changes in the Q of the cavities caused, for example, by variations in the values of the liquid resistors which may have to be lowered at higher intensities.

In addition, the present single tetrode power amplifier has only just adequate power. The future system will use the two tetrodes in each power amplifier in parallel.

References

[1] L.K.Mestha, C.W.Planner, "Application of System Identification Techniques to an RF Cavity Tuning Loop," Proceedings of this Conference.

[2] I.Gardner et al, "Progress at ISIS and Possible Future Developments," Proceedings of this Conference.