ICANS May 1993,
Rutherford Appleton Laboratory.

The ISIS Synchrotron RF System at High Intensity

P.J.S.B. Barratt

Abstract.

A summary of the RF system of the ISIS Synchrotron was published[1] in 1990 when the operating beam intensity was about half the present level and the extraction energy was 750 MeV instead of the current 800 MeV. A fuller description is given here reflecting the developments that have been carried out since then to facilitate operation with a beam of the design intensity of 200 μA.

Introduction.

The requirement to accelerate a beam of such a high intensity imposes some uncommon demands on the rf system. The ISIS synchrotron rf system allows a wide dynamic range of accelerating voltage which may be necessary to trap the coasting injected beam from the Linac into bunches of sufficient length to minimise space charge forces and peak momentum spread. The short acceleration time of 10 ms leads to a high maximum rate of change of accelerating frequency, necessitating the use of special techniques to keep the cavities in tune during acceleration. During the early stages of acceleration, the ratio of beam current to cavity current is such that the use of a fast feedforward beam compensation scheme is necessary to maintain stability. An additional constraint is that all components in the synchrotron ring must be radiation hard.

RF System Configuration and Parameters.

The synchrotron has ten superperiods; six of which contain a ferrite tuned rf accelerating cavity, three in adjacent superperiods 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 dipole magnets have a dc biased, 50 Hz sinusoidal excitation giving a continuously increasing field over the 10 ms accelerating period. Injection from the 70 MeV Linac occurs during the 500 μs prior to the field minimum after which the unbunched beam is trapped and then accelerated by the rf cavity voltages. The large dynamic range of the accelerating voltage is achieved by supplementing the 200:1 dynamic range of a conventional amplitude control loop with an additional factor of 10:1 obtained by using a cavity phase loop that allows the phase angle between diametrically opposed cavities to be varied from -180° to 0°. Opposed cavities are thus brought rapidly into phase (in less than 30 μs) towards the end of the injection period.

Further rf system parameters are:-

Energy range	70 - 800 MeV
RF frequency range	1.3-3.1 MHz
Transition Gamma	5.032
Max Acceleration rate	124 GeV/sec
Max power transferred to beam	496 kW
No of gaps per cavity	2
Peak RF voltage per gap	14kV
Accelerating voltage per turn	168kV

The rf control electronics comprises:-

1. An oscillator whose frequency is controlled (from 1.3 to 3.1 MHz) by the contents of a block of memory that is interrogated according to the instantaneous central field in the ring gradient bending magnets.

2. Individual loops to control the amplitudes of each rf cavity voltage.

3. Individual loops to control the relative phasing of each cavity according to its position around the ring, the rf phase angle between adjacent cavities being 72°. It is this loop that is also used to "antiphase" opposing cavities during the injection period to reduce the vector sum of the accelerating voltage to zero.

4. Individual loops to tune each cavity by maintaining a 180° phase difference between the cavity voltage and an appropriate input drive voltage.

5. Three beam control loops which operate by varying the acceleration frequency: a radial loop to keep the beam on the correct orbit, a beam phase loop to damp beam coherent dipole phase oscillations, and another loop, driven by variations in bunch length, to damp quadrupole motion of the beam.

The Accelerating Cavity.

Fig. 1 shows the main elements of an ISIS cavity. The water-cooled plates which cool the ferrite can be seen separating the 35, 50 cm OD ferrite rings in each resonator. The centre is made from two co-axial tubes. The outer tube is made from copper to provide a low impedance path for the bias field current and the rf. The inner tube is made from nickel-plated mild steel to provide the vacuum pipe and to shield the beam aperture from any magnetic field produced on the beam axis by the bias field.

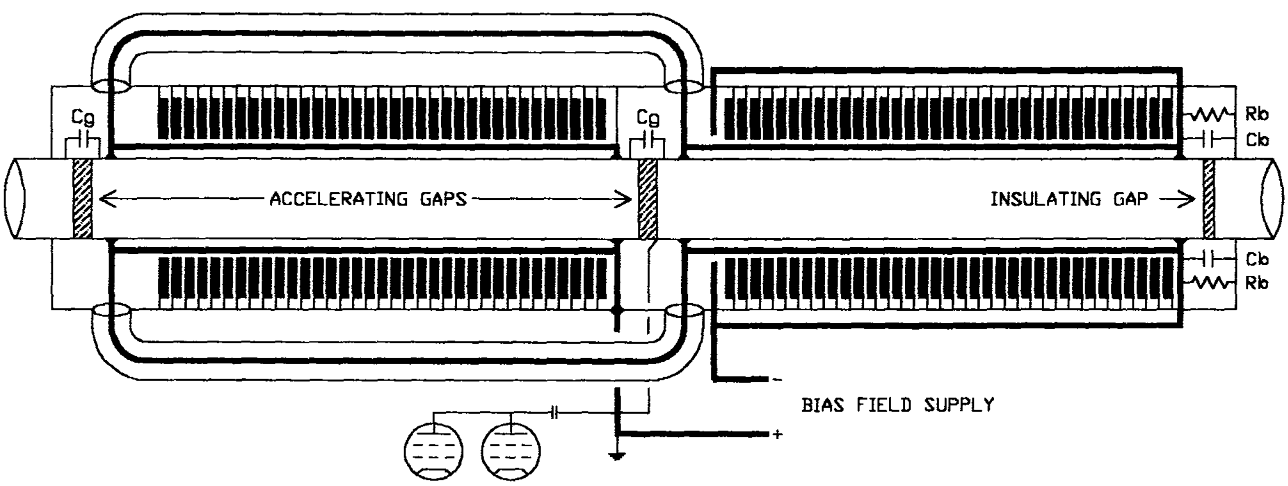

Fig. 1 The ISIS synchrotron accelerating cavity.

The two accelerating gaps are made from ceramic which is metallised on the ends and welded to the mild steel. Cg represents the total capacitance at a gap and is about 2.2 nF. The two gaps are connected in parallel by two 70 Ω co-axial lines which carry both the bias field current and the rf voltage. Cb is approximately 17 μF and forms an rf by-pass capacitor providing a low impedance for the circulating rf current in one of the resonators but allows the bias field current to be fed around both resonators which are in series to the bias current. The bias field is parallel to the rf field but in opposite direction in each resonator. With a gap voltage of 14 kV peak Cb limits the rf voltage appearing across the bias supply to less than a few volts. Cb and the two resonators form a tuned load for the bias supply. This resonance, at a minimum value of 10.4 kHz, is damped by Rb (6Ω).

The high Q-factor of the cavity ferrite results in an operational gap impedance of about 4 kΩ which would give rise to an excessively high beam-induced component of cavity voltage and thereby compromise the stability of acceleration. To avoid this, each gap is loaded with a Q-damping resistor in which the resistive element is formed from continuously pumped copper sulphate solution. By varying the concentration of the solution, the effective gap impedance can readily be controlled down to 1kΩ with a corresponding reduction in induced voltage. Each resistor can dissipate a peak rf power of 100 kW and presents very little reactive loading.

The High Power Driver Stage.

The high power driver stages are located adjacent to the cavities, and are now powered by a paralleled pair of RCA (Now Burle Industries inc) 250 kW tetrodes type 4648 operated in class AB with a grounded cathode and an anode voltage of 18 kV. No special matching of the tetrode characteristics is done; the standing currents of each of a pair are simply equalised (at 2A) by setting the grid bias. Each tetrode is required to deliver a maximum rf current of about 25 A peak into the cavity. The total current is nominally within the capabilities of a single tetrode of this type, and until recently only one was used, but operation at this higher level in our enclosure was then complicated by the sporadic onset of parasitic high frequency oscillations. These tetrodes have proved very reliable in operation. The shortest lived one so far was returned to Burle Industries for rebuilding after 16,000 hours of operation but another is still giving good service after 47,000 hours.

The rf drives for the tetrode grids of up to 150 v peak are provided from 2-channel 500 Watt water-cooled solid-state amplifiers, made by Herfurth GmbH of Hamburg, located in a low radiation environment in the centre of the synchrotron ring.

The Cavity Tuning Loop.

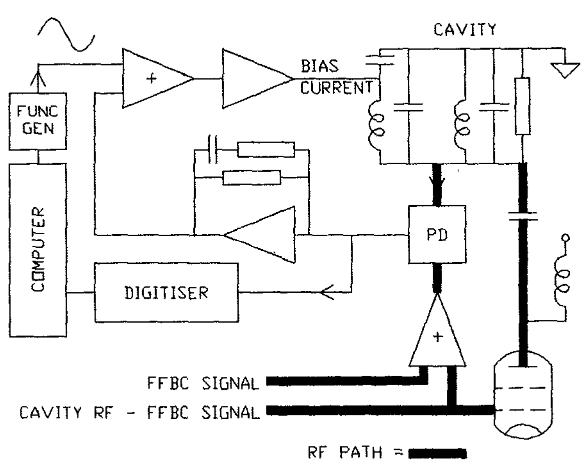

Fig. 2 The cavity tuning loop.

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 cavity Q, would lead to excessive cavity tune errors during the frequency sweep. The method used to correct this error, which is highly repetitive, is shown in Fig. 2.

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.

This procedure is normally carried out during maintenance periods with perhaps ten iterations being necessary to minimise a large tuning error but it is also practicable to use the system to reduce the beam-induced cavity tuning perturbations for any given operating intensity.

It can be seen from Fig. 2 that, while the FFBC (see below) is active, by nulling out the FFBC signal, the cavities are kept on tune as if no beam were present. Subsequently, they are detuned for reactive compensation. The tuning loop error, as monitored on the output of the tuning loop phase detector, is a useful indicator of the performance of the tuning loop, the beam compensation, and the general health of that rf system. During the acceleration period, the tuning error is generally less than $\pm\ 10°$, the largest error usually occurring during trapping.

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. 4 shows the principal components of the system.

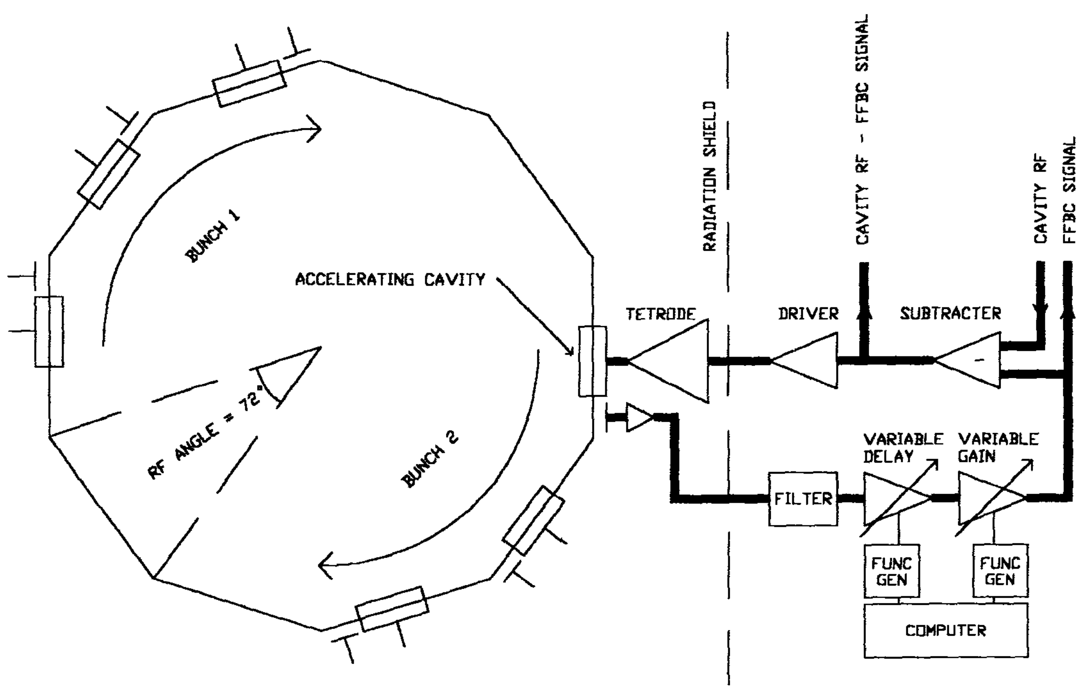

Fig. 3 The synchrotron ring layout and the feedforward beam compensation system.

The rf drive current to each cavity gap at the end of the injection period is about 1 A peak. At 200 μA (2.5×10^{13} protons per pulse), the injected beam will subsequently bunch to over 4 A peak. The FFBC system acts to compensate the resultant large beam-induced cavity voltage and thus preserve the critical acceleration voltage profile. This has the effect of reducing the cross-coupling between the various rf control loops thereby increasing the threshold of instability. Without the FFBC system in operation, it would not be possible to accelerate more than about 25 μA.

The instantaneous beam charge is sensed just downstream of each cavity and the signals are filtered to leave only the fundamental component. 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 driver amplifier. The purpose of the variable delay is to compensate for the revolution period that varies from 1.4 to 0.6 μs throughout acceleration, 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 used to determine the optimal delay and gain throughout the compensation period is to accelerate a low intensity beam (3×10^{12} ppp) with only five cavities powered and find experimentally the values that minimise the beam-induced voltage on the remaining unpowered cavity. Fig. 4 shows the envelopes of the resultant voltages induced in a cavity by such pulses with and without compensation.

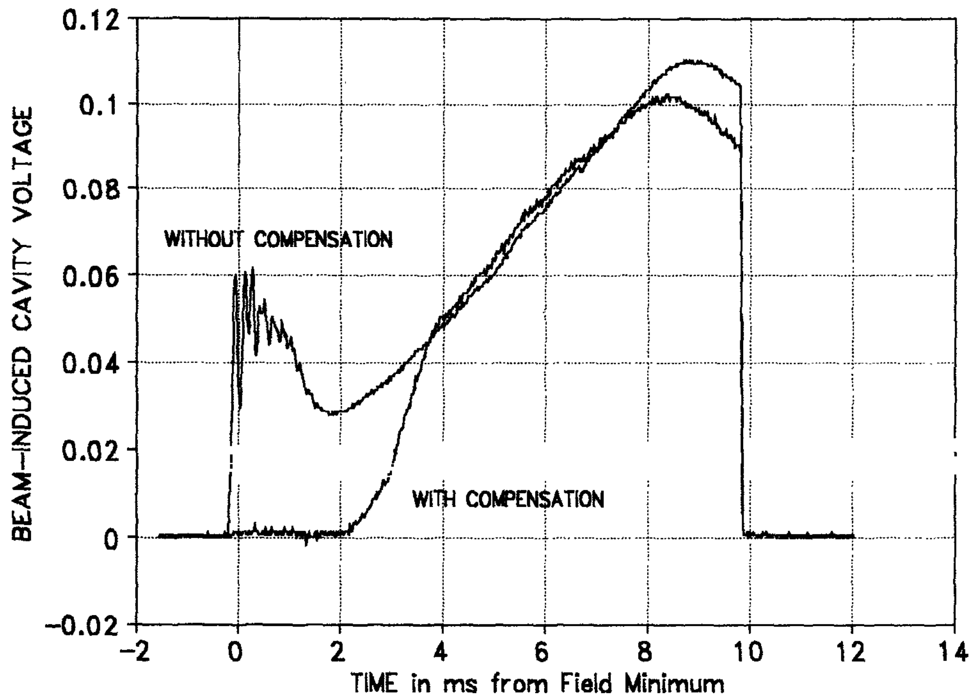

Fig. 4 - FFBC cancellation of beam-induced cavity voltage.

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 reactive compensation provided by the tuning loop which allows operation with less drive power. While the FFBC is active, the high power drive is working into an unmatched load.

Performance.

Fig. 5 shows the envelope of the rf accelerating voltage per cavity, the normalised beam intensity (a beam toroid signal divided by rf frequency) and the envelope of the peak beam charge signal derived from a pick-up. The acceleration efficiency at this intensity, about 2×10^{13} ppp, is around 90% with, as can be seen, most of the loss occurring at relatively low energy at trapping. Most of the untrapped beam is caught by the collectors in the ring.

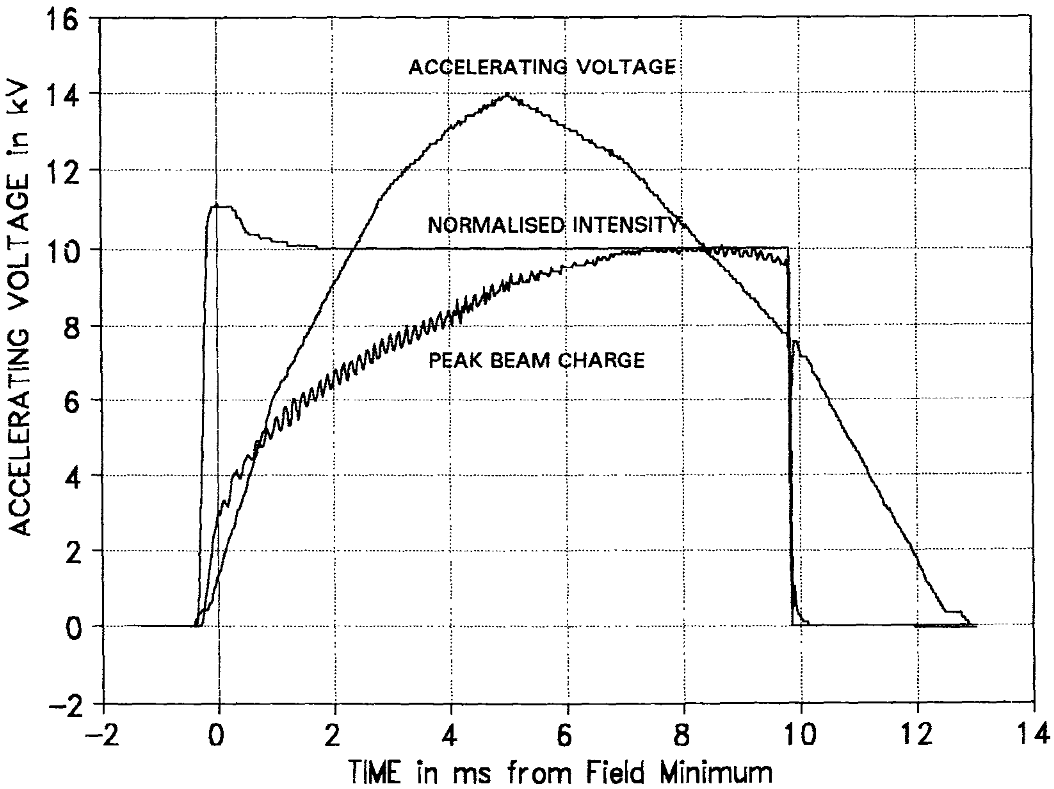

Fig. 5 RF voltage and beam intensity during acceleration.

It was anticipated that to minimise the loss at trapping, the rf voltage throughout the injection period should be kept as low as possible. However, at higher intensities, it is found experimentally that the trapping loss is lower if, as shown in Fig. 5, the accelerating voltage is turned on well before acceleration starts at the field minimum. This may be because the voltage suppresses the onset of a coasting beam instability during the injection period but this aspect requires further investigation.

The recorded trapping efficiency during the recent tests at 200 μA intensity was 86%. This figure is expected to improve with further experimentation and development. There is as yet no evidence that the performance of the present rf system will limit the efficiency.

Acknowledgements.

The author would like to thank I.S.K Gardner and other members of the ISIS accelerator division for their help and contributions to this work.

Reference.

[1] P. Barratt, I. Gardner, C. Planner, G. Rees, "RF System and Beam Loading on the ISIS Synchrotron" EPAC-90, Nice.