

# PROGRESS ON DUAL HARMONIC ACCELERATION ON THE ISIS SYNCHROTRON

A. Seville, D. Adams, D. Bayley, N. Farthing, I. Gardner, M. Glover, A. Morris, B. Pine, J. Thomason, C. Warsop, CCLRC, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., UK.

## Abstract

The ISIS facility at the Rutherford Appleton Laboratory in the UK is currently the most intense pulsed, spallation, neutron source. The accelerator consists of a 70MeV H<sup>-</sup> Linac and an 800MeV, 50Hz, rapid cycling, proton Synchrotron. The synchrotron beam intensity is 2.5E13 protons per pulse, corresponding to a mean current of 200 μA. The synchrotron beam is accelerated using six, ferrite loaded, RF cavities with harmonic number 2. Four additional, harmonic number 4, cavities have been installed to increase the beam bunching factor with the potential of raising the operating current to 300 μA. As ISIS has a busy user schedule the time available for dual harmonic work has been limited. However, much progress has been made in the last year and encouraging results have been obtained. This paper reports on the hardware commissioning and beam tests with dual harmonic acceleration.

## INTRODUCTION

Over the last twenty years, acceleration of the ISIS synchrotron beam has been provided by six two-gap RF cavities. With this arrangement  $\sim 2.5 \times 10^{13}$  protons can be held in the synchrotron throughout the 10 ms accelerating cycle from 70 to 800 MeV during which the RF sweeps from 1.3 to 3.1 MHz. The maximum mean beam current which can be accelerated by the synchrotron is  $\sim 200$  μA. The addition of a second harmonic component [1] to the RF waveform, as shown in figure 1, should allow the acceleration of higher currents by extending the phase stable region and therefore increasing the bunching factor.

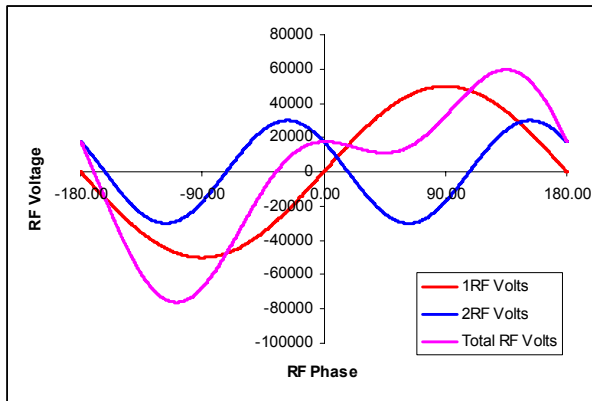


Figure 1: Addition of 1RF and 2RF components.

Figure 2 shows the optimum values as simulated in [2], of fundamental frequency (1RF) and second harmonic (2RF) accelerating voltage per turn,  $\theta$ , the phase offset relative to the 1RF volts, and  $\phi_s$ , the stable phase angle.

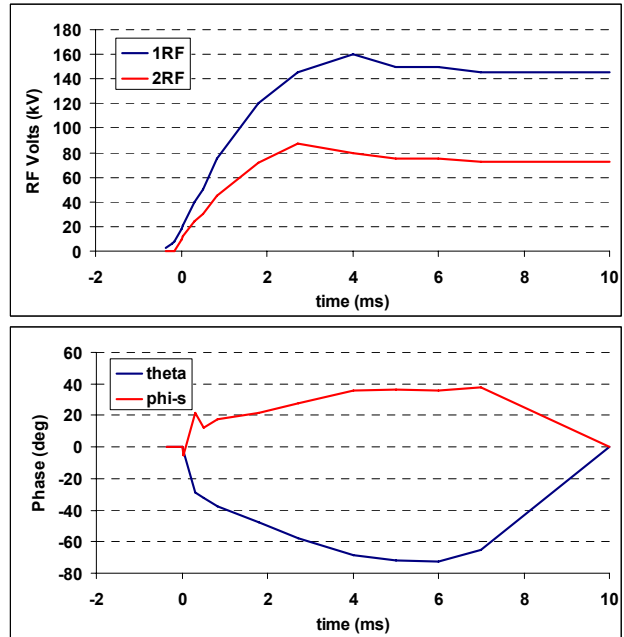


Figure 2: Theoretical values for the 1RF and 2RF voltages,  $\theta$  and  $\phi_s$  for optimum trapping.

The longitudinal phase acceptance is increased due to the addition of the 2RF component, giving a higher trapping efficiency. Simulations indicate that up to  $\sim 3.75 \times 10^{13}$  protons, or  $\sim 6$  μC of protons, can be held and accelerated using this technique. In ISIS the 2RF component is to be provided by four 2RF cavities, installed in Super-periods (SP) 4, 5, 6 and 8. One of which is shown in figure 3.



Figure 3: ISIS 2<sup>nd</sup> Harmonic RF Cavity

The cavities are similar in design to the existing fundamental frequency cavities, but are approximately half the length. As with the 1RF cavities, the resonant frequency of the 2RF cavities has to sweep throughout the acceleration cycle (at twice the fundamental frequency,

2.6 to 6.2 MHz) to match the changing RF frequency. This sweeping is effected, by loading the 2RF cavities with ferrite and then sweeping the ferrite bias current throughout the acceleration cycle to change the permeability of the ferrite and hence the inductive element of the equivalent L-C circuit.

The hardware necessary for driving the new 2RF cavities is based on that used very successfully over the last twenty years for the fundamental cavities, and is described in [3], but the electrical and electronic hardware has been updated where appropriate.

### THE 2RF CAVITY LOCK SERVO

Precise control of the 2RF cavity phase with respect to the fundamental system, is required. Figure 4 shows the low power RF (LPRF) system used to control the phase of the 2RF system.

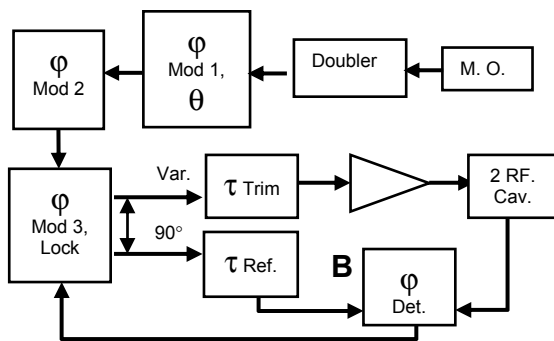


Figure 4: 2RF cavity phase loop

The 2RF system consists of the same configuration as the fundamental system, with a frequency doubler in line after the master oscillator MO. The phase shift between the fundamental and 2RF waveforms may be changed

throughout acceleration by an amount,  $\theta$ , by adding an additional phase modulation to the 2RF signal. The locations of the new 2RF cavities were determined by the available space, and so they are not symmetrically positioned. The required phase to account for each cavity location around the ring is provided by phase modulator 2, together with antiphasing of the cavity pairs during beam injection, which are then brought into phase in 20  $\mu$ s for the start of acceleration, providing an increase in the voltage control range. System delays are equalised such that the 1RF and the 2RF reference signals at points A and B track each other within 5° of fundamental frequency.

Whilst previous results [3] had proved encouraging, and even shown a slight increase in trapping efficiency, much work had to be done to fully commission the 2RF control system. A full investigation of the cavity phase loop found that two of the four intermediate amplifiers were inverting the 2RF signal. These were replaced and the phase loop reconfigured so that each system was phased correctly wrt each other and at the mid-range value of  $\theta$  wrt to the 1RF systems with no voltage applied to the phase modulators.

### DUAL HARMONIC ACCELERATION

A low intensity beam ( $\sim 4.2 \times 10^{12}$  protons) was accelerated using the dual harmonic RF (DHRF) system consisting of six fundamental cavities and three of the four second harmonic cavities, the fourth having developed a power supply fault. Two second harmonic cavities were running at a peak voltage of 8.4kV and one at a peak voltage of 7.2kV, as this system was prone to spurious tripping of the anode power supply. Figure 5 shows the line intensity of the beam pulses as they evolve throughout the 10ms of acceleration.

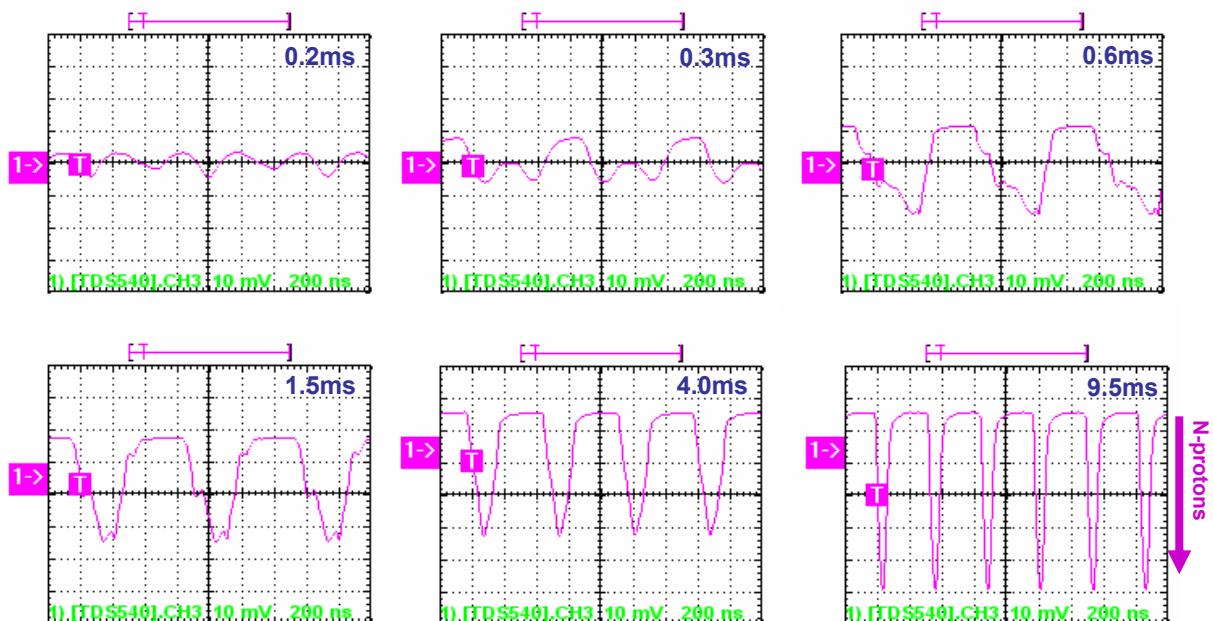


Figure 5: Evolution of beam pulse shape throughout 10ms DHRF acceleration period.

One can see the presence of the second harmonic in the early pulses, and the progression towards narrow, intense pulses later in the cycle.

In addition to limitations on experimental work by the demands of the ISIS schedule, much of the work with the 2RF systems was hampered by spurious tripping of the anode power supplies. An investigation into the cause of these trips was made by monitoring the current provided by the anode power supply whilst a full intensity beam ( $\sim 2 \times 10^{13}$  protons) was accelerated by two 2RF cavities in addition to the fundamental cavities. Figure 6 shows the monitored current and the RF voltage envelope of one of the cavities during a 20ms cycle, with no accelerated beam in the synchrotron and figure 7 shows that with beam present.

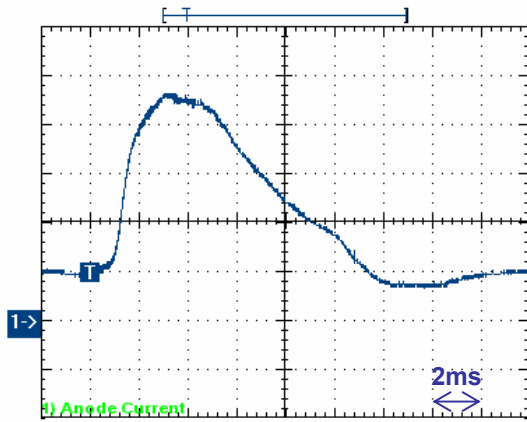


Figure 6: Anode current with no beam.

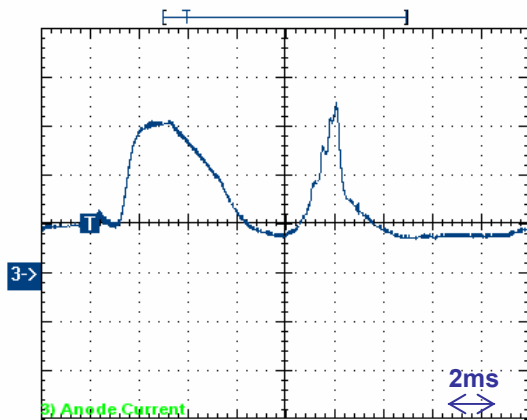


Figure 7: Anode current with beam.

The beam reduces the anode current dramatically from around 3ms into the acceleration cycle onwards. The current above was produced with a fixed theta phase offset between 1RF and 2RF systems of  $-36^\circ$ . By applying the theoretically optimized theta phase function to the 2RF cavity, the anode current was made to hold up, as shown in figure 8, though this gives rise to oscillations of the beam phase later in the cycle.

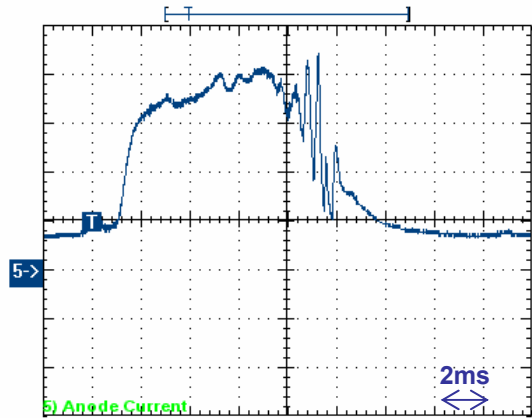


Figure 8: Anode current with beam,  $\theta$  function applied.

The phase oscillations late in the cycle are thought to be due to instabilities in the 2RF cavity tuning and automatic level control loops. To this end, the bandwidths of the loops have been reduced. It is thought that by reducing the oscillations in the anode current, the anode power supplies may be less susceptible to tripping.

## CONCLUSIONS AND FURTHER WORK

The four 2RF cavities and their services have now been installed in the ISIS synchrotron, and the 2RF systems commissioned. The trials of dual harmonic operation in the ISIS synchrotron show encouraging results. Reliable operation of the 2RF systems, particularly the anode power supplies, has proven a challenge. However, a solution to the tripping problem has been found and will be test during the next period of machine physics at the end of the current user run. The 2RF systems will then be gradually phased in during the next few user cycles in order to increase the beam current. The “second generation” low power RF equipment developed for the 2RF system can now be duplicated and installed as replacements for ageing low power RF equipment incorporated at present in the fundamental RF systems.

## REFERENCES

- [1] M. Harold *et al*, “A Possible Upgrade for ISIS”, PAC’97, Vancouver, 1997, p. 1021.
- [2] C. Prior, “Studies of Dual Harmonic Acceleration in ISIS”, ICANS XII, RAL Report 94025, 1994, p. A11.
- [3] A. Seville *et al*, “First results from the use of dual harmonic acceleration on the ISIS synchrotron”, PAC’05, Knoxville, 2005, p.1872.