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Low Intensity and Injection Studies on the ISIS Synchrotron.

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Abstract.

Recent diagnostic work on the 800 MeV, High Intensity Proton Synchrotron of ISIS, the Spallation Neutron Source at RAL, is presented. The use of a beam 'chopper' to provide very short injected pulses, 0.1% of normal intensity, for machine studies is described. The measurements made possible with these 'chopped' beams, their application in optimising the machine, and the techniques employed are reported.

1. INTRODUCTION.

The ISIS Synchrotron accelerates 2.5×10^{13} protons per pulse, at 50 Hz, from 70 to 800 MeV. At normal operating intensities, a large fraction of the available transverse and longitudinal acceptances of the machine are occupied by beam. As a result, measurements are limited to averages over large beams; any detailed information on motion within the beam is not obtainable. This is a basic problem in studying high intensity machines. However, it is possible to study motion of low intensity beams which fill a small fraction of the machine acceptances. In doing so, all high intensity effects are lost, but a great deal of information on the precise set up of the machine, and properties of the injected beam are made available.

2. INJECTION PROCESS AND BEAM 'CHOPPER'.

2.1 *Injection Process.*

The high intensity beam is established in the ISIS synchrotron using H^- multi-turn, charge-exchange injection. During the injection process (200 μs, 130 beam revolutions), the sinusoidal fields in the main lattice magnets fall, and separately programmed trim quadrupoles are used to correct for chromatic effects. This keeps the constant energy injected beam away from resonances. The transverse phase spaces of the synchrotron are 'painted' such that space charge effects are minimised. Horizontally beam is injected at a fixed point, and movement of the closed orbit caused by the falling magnet fields provides a suitable spread in betatron amplitudes. Vertically, the injection point is moved about the stationary closed orbit with a programmable steering magnet in the injection line, to similar effect. Optimising momentum spread of the injected beam is also important. The number of changing parameters, and the importance of precise injection set-up for high intensity running, means that ability to make detailed measurement of the process is extremely useful.

2.2 *Beam 'Chopper'*

On ISIS, an appropriate 'diagnostic' beam is obtained by using an electrostatic kicker or 'chopper' in the injection beam line, which allows pulse lengths of down to 100 ns to be injected. This occupies a fraction of the circumference (revolution time at injection is 1.48 μs) and so allows studies of longitudinal motion. The injected beam has transverse emittances of 25 π mm-mr and occupies a small fraction of the synchrotron acceptances (~ 500 π mm-mr), which allows motion in transverse planes to be easily observed. With appropriate diagnostic techniques these 'chopped beams' have become a powerful tool for accurately measuring and specifying machine set-up.

3. TRANSVERSE MEASUREMENTS.

3.1 *Method.*

The technique and some applications of transverse measurements have been covered in a previous paper [1]. This work will be briefly reviewed and updated here.

A 600 ns chopped beam is injected, and the transverse position of its centroid monitored at a single machine azimuth over about 40 successive turns. Signals from an electrostatic pick-up are digitised and processed on a PC. The 'sampled' betatron oscillation measured on each turn, is modified by (i) the changing lattice magnet fields and (ii) the finite spread in betatron frequencies. The former leads to a slow change in frequency and other characteristics of the oscillation, whilst the latter causes a relatively fast 'damping' of the measured centroid motion. A theoretical function (1) for the positions on each turn can be derived [2], and by least squares fitting of the measured positions to this, accurate estimates of many key parameters can be obtained.

$$y_n = A \cdot \exp\left(- \frac{(\pi \cdot n \cdot \delta Q)^2}{2} \right) \times$$

$$\cos\left(2\pi \cdot n \left[Q_0 + \frac{n \cdot \Delta Q}{2} \right] + 2\pi \cdot \phi \right) + n \cdot \Delta R + R_0 \quad (1)$$

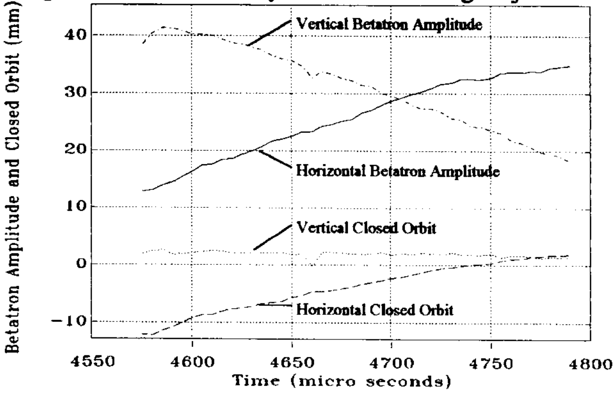
where y_n - position on n^{th} turn,
A - initial betatron amplitude,
Q_0- initial Q value,
R_0- initial closed orbit,
δQ- Q spread,
ϕ - initial betatron phase/2π,
ΔQ- change in Q per turn.,
ΔR- change in R per turn.

3.2 *Measurements.*

(i) Specifying Operational Injection Set Up.

Injecting chopped beams at different times and fitting the function (1) to measured beam positions, as described, one can determine the time variation of parameters. The change of betatron amplitude and closed orbit through the injection period show how the transverse phase spaces are being painted. Typical, empirically optimised values for high intensity are shown in Figure 1. Q values are also determined by these measurements and give a useful indication of machine set-up.

Figure 1: Variation of Key Parameters Through Injection.



The beam is chopped once in every 128 of the 50 Hz pulses; interleaved high intensity pulses are unaffected. The resultant loss in user beam (<1%) is acceptable and so allows many measurements during operational running. Many machine parameters can be pulsed to experimental values for the chopped pulse, which has expanded the scope for on-line experiment considerably.

(ii) Q Value and Chromaticity Measurements.

The accurate measurement of Q values (±0.002) has allowed checks on the lattice, the operation of the trim quadrupoles, and optimum correction of Q to avoid resonances. The change in Q of the constant energy chopped beam with changing main magnet field through injection (trim quads off) yields values of chromaticity. On ISIS the relation ΔQ/Q vs $[\Delta B/B]_p$ is highly linear, both ξ_h and ξ_v are -1.4 ± 0.1.

(iii) Beta Function Measurements.

The variation of Q with current in a quadrupole gives a measurement of the synchrotron beta function - at the quadrupole. From [3]

$$\Delta Q \approx \frac{1}{4\pi}\int \Delta k \cdot \beta(s) \cdot ds \approx \frac{\overline{\beta} \cdot S}{4\pi} \cdot \frac{e}{P} \cdot G \cdot \Delta I \quad (2)$$

where all notation is standard except: G - gradient/amp, $\overline{\beta}$ - mean beta over quad length S. The gradient of the approximately linear relation ΔQ vs ΔI thus measures beta.

The ISIS Synchrotron consists of 10 superperiods, each with 2 independently programmable trim quadrupoles, where beta may be measured. This method depends on the accurate measurement of Q, as allowed by chopped beams. Variation of beta around the machine at equivalent lattice positions, and comparison of absolute values with theory, has given valuable information on the machine.

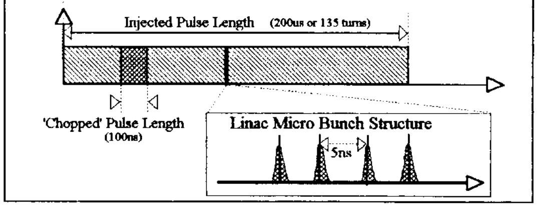
(iv) Betatron Phase Advances.

Simultaneous measurements at many monitors around the ring, would give azimuthal variation of ϕ in (1), and thus the phase advance between monitors. On ISIS, limited number of digitising channels available, and inappropriate electronics on most monitors (optimised for high intensity) have made such measurements difficult. However, measured phase advances (ϕ) between monitors, agreed in most cases with theoretical values to within the estimated accuracy of ±0.02.

4. LONGITUDINAL MEASUREMENTS.

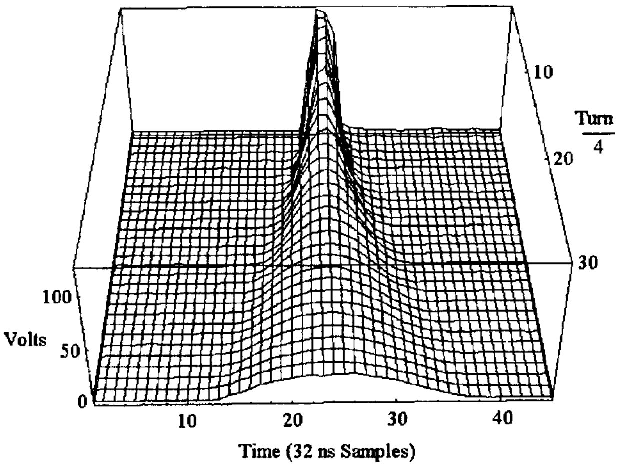
4.1 *Longitudinal Beam Structure at Injection.*

Figure 2. Bunch Structure At Injection.



The 202.5 MHz linac provides a 200 μs macro pulse length, composed of 1 ns micro-bunches, spaced by 5 ns. These debunch while drifting over 35.8 m, to a sinusiodally excited debuncher cavity, which is used to optimise momentum spread for the synchrotron. Particles then drift 16 m to the stripping foil where they enter the synchrotron.

Figure 3: Typical Debunching Profile.

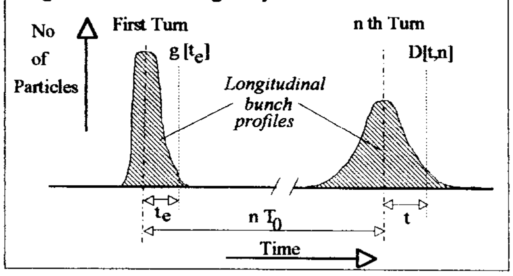


4.2 *Measurement of Injected Momentum Spread.*

The 200 μs injection macro pulse is chopped to 100 ns. This pulse consists of 20 micro-bunches, which merge in the first few turns in the synchrotron. The 20 micro-bunches will, *on the first turn*, have just started to run into one another. The periodic structure resulting approximates to a uniform momentum distribution with time. This assumption allows a fairly simple treatment for deconvoluting the momentum spread.

Longitudinal profiles are obtained from an electrostatic pickup. Digitising chopped beam signals over 100 turns, with RF off, gives the debunching profile as in Figure 3. From this momentum spread can be obtained as follows.

Figure 4. **Debunching Analysis.**



A particle starting at time t_e relative to the bunch centre on the first turn (Figure 4), will arrive at time t on the n^{th} turn if ΔT, the change in revolution time per turn due to momentum error, is such that:

$$t = t_c + n \cdot \Delta T \quad (3)$$

From the definition of η

$$\Delta T = \frac{\eta \cdot (P - P_0)}{P_0} \cdot T_0 \quad (4)$$

Let $g[t_e]$ be the bunch profile on the first turn, and $f[\Delta P/P]$ the normalised momentum distribution of the bunch, which is assumed to be uniform with time *on the first turn*. The number of particles arriving at time t, from those starting at time t_e, is given by:

$$d\left[t, t_e\right] = g\left[t_e\right] \cdot f\left[\frac{P_e - P_0}{P_0}\right] \quad (5)$$

where P_e is defined by (3) and (4), so that:

$$\frac{P_e - P_0}{P_0} = \frac{t - t_e}{n \cdot \eta \cdot T_0} \quad (6)$$

Substituting into (5), and integrating over the profile on the first turn, gives the profile on the n^{th} turn D[t,n].

$$D[t,n] = \int d\left[t, t_e\right] \cdot dt_e = \int g\left[t_e\right] \cdot f\left[\frac{\left(t - t_e\right)}{n \cdot \eta \cdot T_0}\right] \cdot dt_e \quad (7)$$

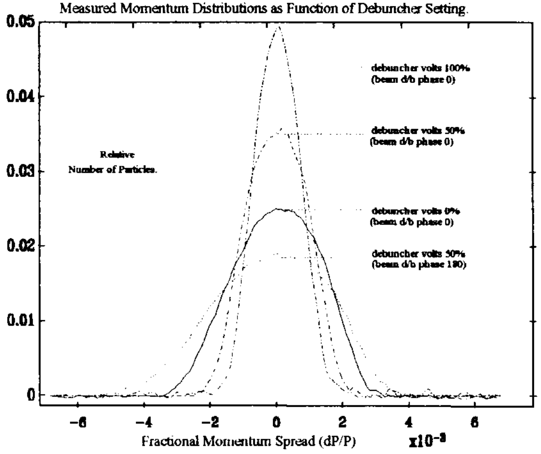
This is a convolution of the function $g[t_e]$ on $f[\Delta P/P]$. The debunching profile over ~100 turns gives $g[t_e]$ and D[t,n] for many n. A numerical deconvolution of $g[t_e]$ into D[t,n] yields the function $f[\Delta P/P]$, the momentum distribution. The numerical algorithm used is described in [4]. The simplest method involves a process identical to polynomial long division, but has a tendency to be unstable. However, with suitable local smoothing, good results can be obtained. More sophisticated numerical methods are presently being considered.

4.3 *Application.*

The above method allows routine measurement of injected momentum spreads during operational running, throughout the injected pulse. Usual operational values of 95% full width in fractional momentum spread, are about 4.5×10^{-3}, with typical scatters being $\pm 0.2 \times 10^{-3}$. Measured momentum spread distributions, as a function of debuncher setting are shown in Figure 5. The effect of the debuncher is clearly demonstrated.

Figure 5.

Measured Momentum Distributions as Function of Debuncher Setting.



5. CONCLUSIONS.

The use of very low intensity chopped beams on the ISIS synchrotron has allowed much detailed and accurate measurement, not really possible in any other way.

6. ACKNOWLEDGEMENTS.

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