LOW INTENSITY AND INJECTION STUDIES ON THE ISIS SYNCHROTRON.

C M Warsop.
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England.

Abstract.

The use of chopped beams to study injected beam conditions and general low intensity behaviour of the ISIS Synchrotron is described. The difficulties associated with measurements at these relatively low intensities and development of the system for on-line diagnostics during operational running are outlined. Some results from ISIS are presented, along with their implications at high intensity.

Introduction.

The value of low intensity studies on a machine like the ISIS Synchrotron, designed specifically for high intensity, may not be immediately obvious, but they can in fact give much detailed information not otherwise available. At high intensity, the large amounts of beam filling most of the machine acceptance make detailed study of particle motion within the beam very difficult. Detailed motions of one part of the beam are obscured by the rest - as far as any practical diagnostics are concerned. However, motions of small beams, which fill a small fraction of the machine acceptance, can be observed directly - allowing detailed study of the beam dynamics in the low intensity limit. The information so obtained is of considerable value, facilitating checks on the lattice and investigations of the injection process, and measurement of properties of the injected beam - all of which have important implications at high intensities.

Background.

ISIS Injection and Beam 'Chopper'.

A high intensity beam is established in the ISIS Synchrotron by means of Multi-Turn, Charge-Exchange Injection [Ref. 1]. Under this scheme, protons are accumulated over about 200 machine revolutions from the 20mA, 25 π mm-mr H^- injector beam. To facilitate filling of the horizontal acceptance (540 π mm-mr), beam of constant energy is injected at constant horizontal angle and position while the (sinusoidal) main magnet field is falling; the resulting movement of the machine closed orbit leads to a suitable distribution in betatron amplitudes. In the vertical plane (acceptance 430 π mm-mr), a spread in betatron amplitudes is achieved by moving the vertical injected position and angle using a programmable steering magnet.

The beam 'chopper', an electrostatic kicker situated in the injection beam line, deflects all but a selected amount of beam, at a selected time, onto a beam dump. In this way, 'chopped' beam bunches of down to 100ns can be injected at any time during the ~200μs injection period. The motion of this relatively small beam (about 0.1% of full beam) can then be easily observed - giving information on the injection process itself, or on more general beam dynamics of the machine.

Measurements Possible with 'Chopped' Beams.

Chopped beams can be useful for a number of measurements, depending on the diagnostics used. In the transverse planes, position monitors and profile monitors allow the investigation of injection and basic beam dynamics. Suitable diagnostics can also measure the longitudinal profile of the chopped beam bunch - thus giving information on motion on this direction. In particular, bunch lengthening measurements (with machine RF off) can give information on the momentum spread of the injected beam.

The main motivation behind chopped beam studies on ISIS is to investigate injection, and this naturally involves measurements on coasting beams (i.e. RF off). The possibility of developing more sophisticated measurements to include longitudinal oscillations, which would allow studies throughout the machine cycle, are not considered particularly profitable and have not been pursued. Work has thus concentrated mostly on transverse dynamics at injection. Measurements with position monitors have been particularly useful and justify some explanation (see below).

It should be emphasised that although much detailed and accurate information can be obtained with chopped beams, it is valid only in the low intensity limit. Essentially, they allow accurate determination of the 'initial conditions' at low intensity, but give no information on the way in which these may be modified by high intensity effects.

Position Monitor Measurements.

Transverse Motion.

Chopped beam measurements using position monitors (i.e. diagonally 'split cylinders', which measure transverse position of the beam centroid), are especially useful because of the amount of information they give. The method is essentially the same as that in [Ref. 2] and is as follows.

A small, chopped, beam bunch is injected into the synchrotron with a length which fills less than one turn or circumference. Such a beam is observed on a position monitor as a series of pulses as it circulates in the machine. Essentially, one sees sampled betatron oscillations of the bunch on each revolution, but these are modified by a number of effects. The changing main magnet field (with constant beam energy) during injection means that Q values and closed orbits change, though slowly, on successive turns. More significantly, the finite spread in betatron frequencies in the beam causes the oscillations to de-cohere after a finite number of turns; on a position monitor, which measures average values, this is seen as damping.

By assuming a functional form for the Q spread and allowing for the changing magnet fields, one can derive a theoretical function for turn by turn positions. Note that this assumes no longitudinal oscillations, i.e. synchrotron RF is off. In this work a Gaussian Q distribution is assumed and this leads to a function of the form [Ref. 2];

$$y_n = A \cdot \exp\left[\frac{-(\pi \cdot n \cdot \delta Q)^2}{2}\right] \cdot \cos\left[2\pi \cdot n \cdot \left(Q_0 + \frac{n \cdot \Delta Q}{2}\right) + 2\pi \cdot \Phi\right] + n \cdot \Delta R + R_0 \qquad \{E\ 1\}$$

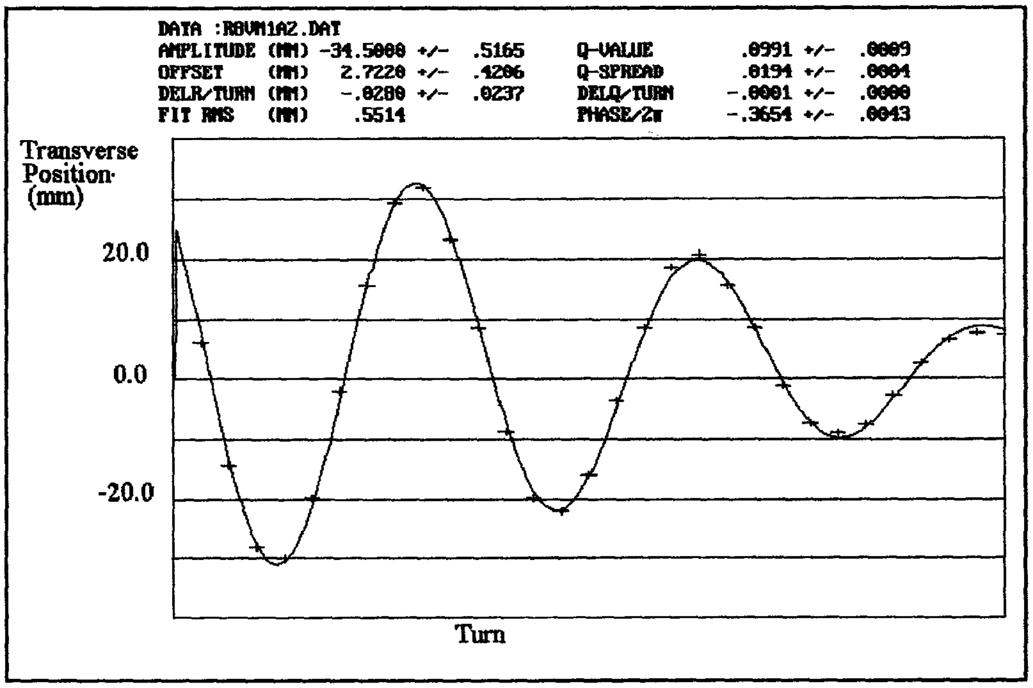
where;

- y_n - Transverse position on n^{th} turn
- A - Initial Betatron Amplitude
- δQ - Q Spread [due mainly to momentum spread in the beam]
- Q_0 - Initial Q value
- ΔQ - Change of Q per turn
- Φ - Initial Phase
- ΔR - Change in closed orbit per turn
- R_0 - Initial close orbit

By least squares fitting measured positions to this function (see Figure 1), estimates of the above parameters are obtained, allowing values on the first turn to be calculated. These parameters give information on the lattice (Q, Φ), injection (A, R, Φ) and momentum spread (δQ), as will be detailed below. On ISIS, the particular values of momentum spread and chromaticity mean that the oscillations 'damp' out after about 30-40 turns; this gives enough data to obtain good estimates, with uncertainty in the betatron Q value being about ±0.002, and in position related measurements about ±1mm.

The short time over which the measurements are taken, 40 turns or 60μs, means that approximations in E1 associated with (i) the *assumed* Q spread distribution, and (ii) the changing magnetic fields, have minimal effect. The quality of fits obtained experimentally confirms that the approximations are reasonable.

Figure 1. Example of Least Squares Fit.



Momentum Spread.

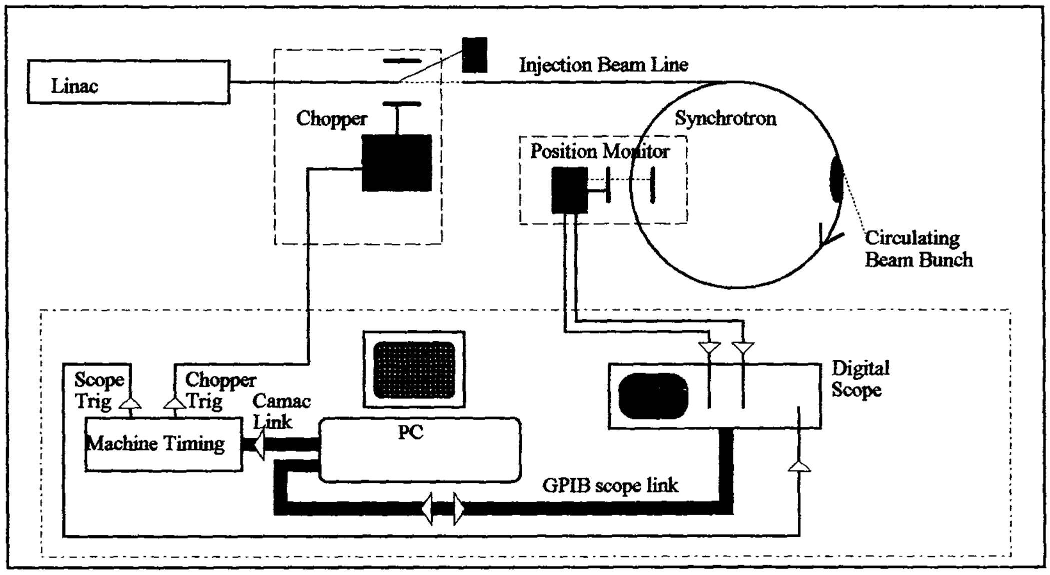
The above method gives an estimate of the momentum spread of the injected beam, assuming that this is the only cause of Q spread and that chromaticity is known [$\Delta P/P=(\Delta Q/Q)/\xi$]. A better method is measurement of longitudinal debunching of coasting chopped beams, which can be observed conveniently on ISIS using the sum of position monitor electrode signals. Work is presently underway to allow such measurements.

Implementation.

The position monitor measurements are controlled by an IBM PC/AT compatible, which sets timing pulses, controls a digital sampling scope and processes the data (see Figure 2). A measurement time is selected and the PC sets up trigger pulses for the chopper and 'scope. The signals from the position monitor are passed to the sampling scope, where they are digitised, averaged and then transferred to the PC. After some processing, the turn by turn positions are determined, and fitted to the above function. The process is automated, so that a 'scan' through the injection cycle, measuring parameters at time intervals down to 5μs, is possible - with speed being limited by the repetition rate of the chopper.

The chopper can be programmed to run at a number of repetition rates; the machine runs at 50Hz and the chopper can be triggered on one in every 32, 64 or 128 of these pulses. Loss of one pulse in 128 causes a tolerably small reduction in neutron production, and thus experimentation/optimisation is possible during normal running.

Figure 2. Schematic of Chopper System.



The 40 horizontal and vertical position monitors distributed around the ISIS Synchrotron were all originally intended for use with high intensity beams, and therefore give rather small, noisy (though just about usable) signals with 'chopped' beams (about 0.1% of normal beam). To overcome this problem, two 'dedicated' 'chopper' monitors, one for each plane, have been selected and the gain of their associated electronics increased. To allow measurements during normal running, where interleaved high intensity pulses would saturate electronics, some 'gating' of signals has also been necessary.

Profile Monitor Measurements.

Transverse Profiles and Matching.

Clearly, for any real understanding of injection, one needs information on beam widths. Use of profile monitors with chopped beams should give information on the matching of the injected beam into the synchrotron, and thus ultimately some idea of optimum conditions for high intensity.

Implementation.

Only a little preliminary work has been attempted with profile measurements on chopped beams to date, however it is worth mentioning the diagnostics installed and their intended use.

There are two types of profile monitor installed on the ISIS synchrotron, (i) residual gas ionisation monitors and (ii) a secondary emission grid or 'wire' monitor.

The residual gas ionisation monitors are regularly used with high intensity beams and have the advantage of being non destructive. Some initial tests indicate that these can be used with chopped beams despite the relatively small signals. Limitations to the speed of the electronics mean that profile measurements are averaged over about 10 revolutions of the chopped beam, but this still gives valuable information on the width of the injected beam.

The destructive secondary emission monitor is intended mainly for use with a beam stop also installed in the synchrotron. The beam stop prevents scattered, recirculating beam from distorting profiles. With the beam stop in (it is placed downstream of the profile monitor!), chopped beams of differing pulse lengths and at differing times can be injected, and their profile on the first turn seen directly.

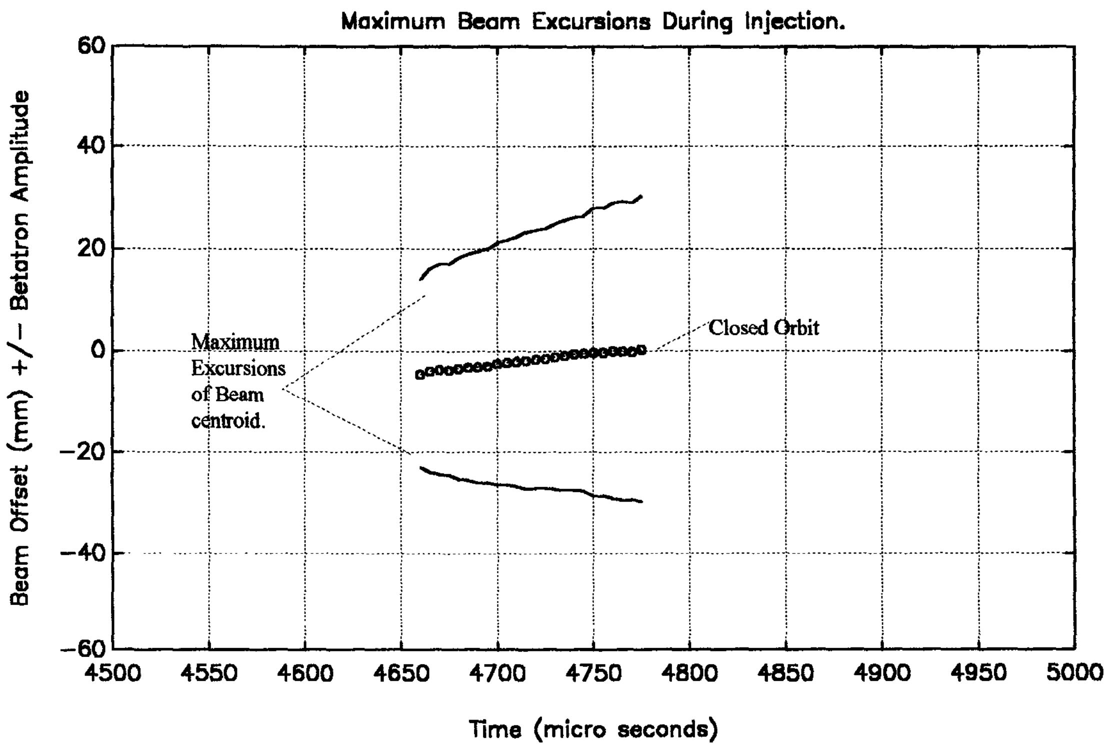
Long Term Objectives.

Integrating the position monitor measurements with those of profile monitors, and with appropriate use of computer lattice programmes, it is hoped that a largely automated system for setting up and optimising all important aspects of injection will result. In addition, by allowing more machine parameters, e.g. steering magnet currents, trim quads etc. to be programmed with experimental values during the chopped/experimental pulse only, a system for doing far more experimentation during normal running is planned.

Measurements on ISIS.

Work with chopped beams is far from complete, however many useful results have been obtained with the position monitor measurements, and these are outlined below.

Figure 3. Typical Horizontal Injection



Injection Set up.

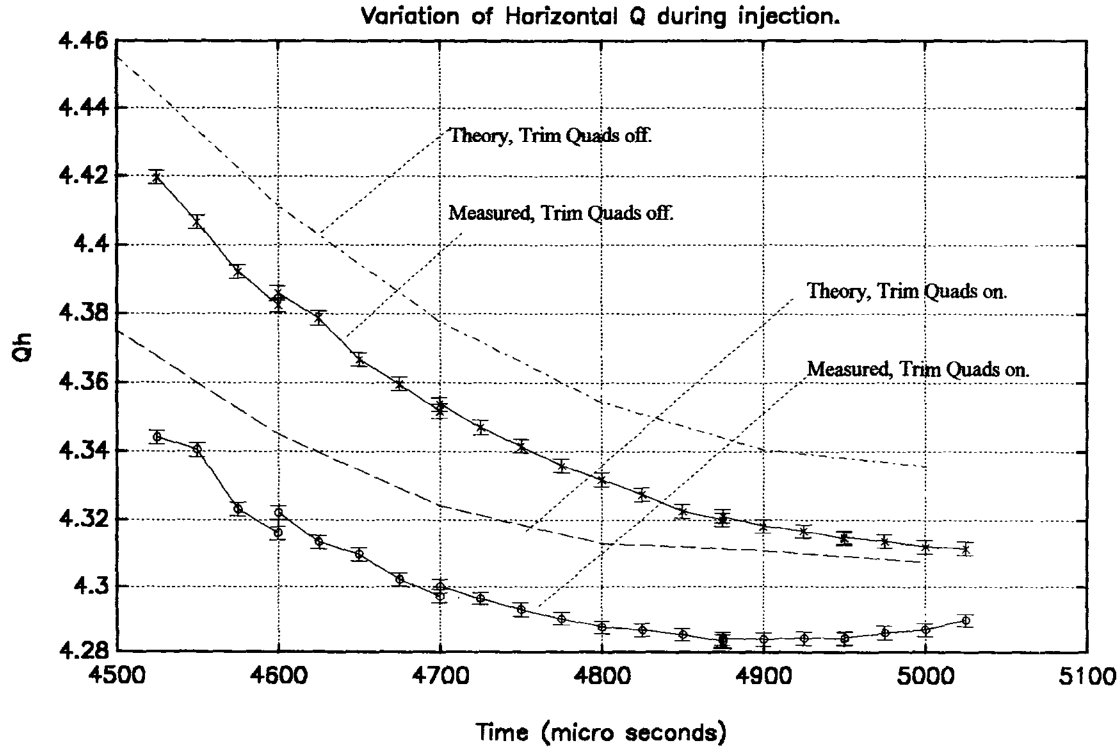
Repeating position monitor chopper measurements throughout the injection process, allows the betatron amplitudes of the injected beam, and the position of the closed orbit at the position monitor, to be obtained as a function of time. These show how the synchrotron acceptance is being filled or 'painted' in both transverse planes, in the low intensity limit. A typical example for the horizontal plane is shown in Figure 3, which indicates the maximum excursions of the injected beam centroid about the closed orbit, as a function of injection time. This information allows injection to be set up in a consistent way, with checks being possible during normal running.

It is known that at high intensity, the transverse beam distributions can change significantly from those 'predicted' by chopper measurements at low intensity. However it is also clear that the initial distributions at injection have a definite effect on trapping efficiencies etc. later on in the machine cycle. These measurements allow definite identification of the optimum set up, as well as showing whether injection alignment, closed orbits or other parameters are in need of correction. The planned profile measurements will give further essential information on the injection process.

Q Values at Injection.

Chopped beams allow accurate determination of the (low intensity) betatron Q values throughout injection, and thus provide a valuable check on the basic lattice and on the operation of the separately programmed trim quadrupoles [Ref. 3], as well as allowing optimum tuning to avoid resonances.

Figure 4. Q Values



Typical results for the horizontal plane are given in Figure 4; these show measured and theoretical values for trim quads on and off. Similar results are found in the vertical plane, and indicate roughly constant offsets between measurement and theory of the order of -0.05, in both planes. Work is under way to explain these differences, as it is possible that the underlying cause may be affecting high intensity performance. Ignoring the offset, the variation of Q with time and the change due to trim quads is in reasonable agreement with theory.

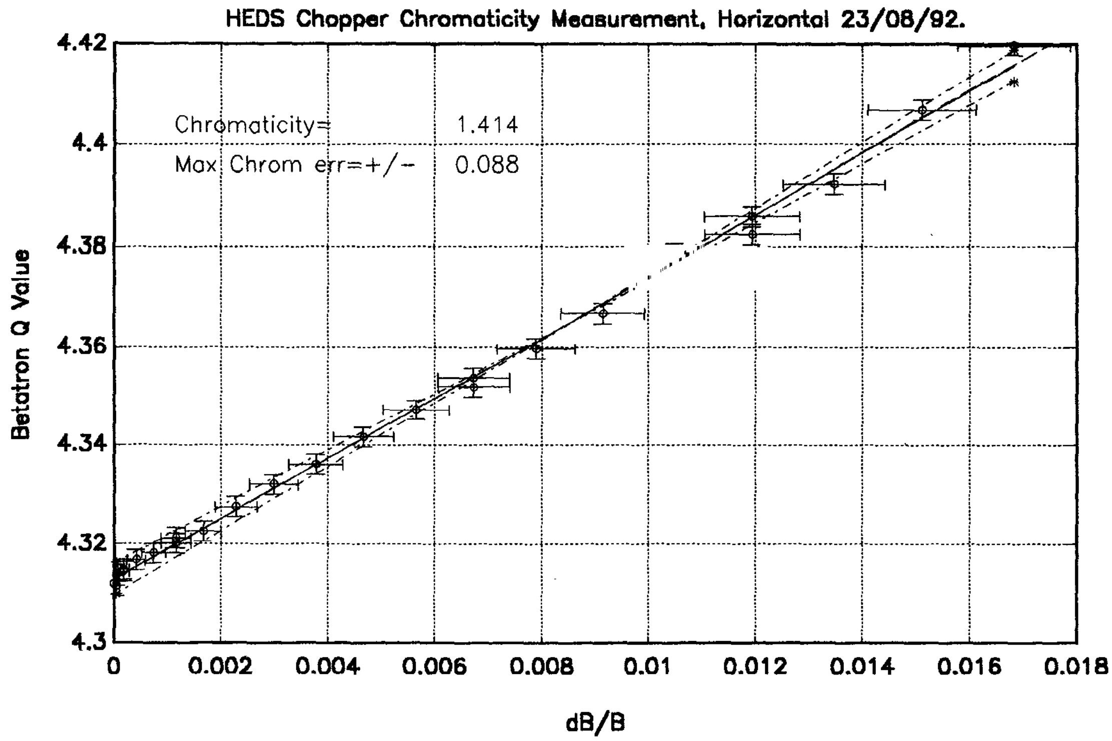
Chromaticity.

Switching trim quads off and measuring Q values as a function of the main magnet field (at constant beam energy), allows an accurate measurement of the machine chromaticities ξ.

$$\xi = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta P}{P}} = -\frac{\frac{\Delta Q}{Q}}{\frac{\Delta B}{B}} \quad \{E\,2\}$$

where P is the particle momentum and B the mean quadrupole field. Figure 5 shows the results in the horizontal with $\xi_h = -1.41 \pm 0.09$, a similar value of $\xi_v = -1.42 \pm 0.08$ was obtained in the vertical. These compare reasonably with theoretical values of $\xi_h = -1.45$ and $\xi_v = -1.24$, and indicate minimal errant sextupole components. It can be seen that the Q vs ΔB/B relation is highly linear, implying absence of significant octupole components.

Figure 5. Horizontal Chromaticity.



Closed Orbits at Injection; 'Many Monitor Measurements'.

Chopped beam measurements described so far have made use of the two specially modified 'high gain' position monitors. However it has been possible to take measurements at most other ('low gain') position monitors, albeit with lower precision, and this gives parameters in E1 as a function of azimuthal position around the synchrotron. This method has been used to measure closed orbits (R in E1) at injection, when the normal unbunched beam is difficult to measure using the AC coupled monitor system. Measurements of this type also have potential for detailed lattice checks, by giving betatron phase advances between monitors.

Momentum Spread Measurements.

As already mentioned, transverse position monitor measurements give an estimate of the injected beam momentum spread. Values for $\Delta P/P$ 95% full widths come out at about 4.5×10^{-3}, and this agrees reasonably with magnet spectrometer measurements in the injection beam line of about 4.0×10^{-3}, under similar conditions. These are to be checked with the bunch lengthening measurements mentioned above, and will provide valuable information on the operation of the debuncher cavity in the injection line, which is used to optimise injected momentum distribution for high intensities.

Commissioning of Non Linear Correction Elements.

Chopped beams are presently being used to check the installation of sextupoles and octupoles on ISIS. Fairly simple experiments, observing the changes in Q with radial beam position and multipole current, give clear indications of their operation.

General Applications.

The system has also been used to check the linearity and calibration of the position monitors, and to investigate amplitude dependence of Q.

Conclusions.

Low intensity, or 'chopped' beam studies on the ISIS Synchrotron have allowed many accurate and detailed measurements, not really possible with high intensity beams. The low intensity information these give is of great potential value in setting up the machine and 'trouble shooting' during operational running, as well as forming an excellent basis for high intensity work.

Acknowledgement.

The author would like to acknowledge the help and advice of A I Borden, I S K Gardner, M R Harold, C W Planner and G H Rees during the course of this work.

References.

[1] 'Injection Dynamics and Multiturn Charge Exchange Injection with Fast Cycling Synchrotron for the SNS.'; V C Kempson *et al.* IEEE Tr Nu Sci Vol NS-28, No 3 June 1981.

[2] 'A Method for Determining the Position, Angle and other Injection Parameters of Short Pulsed Beams in the AGS.'; L Ahrens *et al.* IEEE Tr Nu Sci Vol NS-32, No 5 Oct 1985.

[3] 'Spallation Neutron Source, Description of Accelerator and Target', B Boardman. Rutherford Appleton Laboratory Report, RL-82-006.