DEVELOPMENTS AND PLANS FOR DIAGNOSTICS ON THE ISIS SYNCHROTRON.

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Abstract

Developments of diagnostics on the 800 MeV High Intensity Proton Synchrotron of ISIS, the Spallation Neutron Source at the Rutherford Appleton Laboratory in the UK, are described. Recent upgrades to instrumentation and control computers have made much more information readily available, which is valuable for control of a loss limited, high intensity machine. Measurements on high intensity beams have fundamental limitations in terms of accuracy, detail and interpretation. However, it is found that use of specially configured low intensity *diagnostic beams* can provide much detailed information not otherwise available, which is extremely valuable after careful interpretation. The methods and systems being developed to help trouble shooting, to find optimal conditions rapidly and systematically, and to improve understanding of high intensity performance are described.

1. INTRODUCTION

Previous papers [1,2,3] have detailed diagnostics developments and progress on the ISIS Synchrotron. Here, overall progress and plans are reviewed. In particular, specialist methods developed in the context of optimising a high intensity machine are highlighted.

The ISIS Synchrotron cycles at 50 Hz, accelerating $2.5\text{x}10^{13}$ protons per pulse from 70 to 800 MeV. Mean beam current and power are 200 µA and 160 kW respectively. The 22 mA H^- injector beam is stripped to H^+ with an aluminium oxide foil as it enters the ring acceptance; ~$2.8\text{x}10^{13}$ protons accumulate over the 200 µs, 120 turn injection process. 2D transverse phase space painting minimises the space charge effects. The initially unbunched beam is trapped and accelerated to 800 MeV in 10 ms by the h=2 RF system. There are six ferrite-tuned RF cavities, which provide up to 140 kV/turn and sweep over 1.3-3.1 MHz. Beam is extracted in a single turn with a fast kicker and transported to the target.

Running intensity is limited by the maximum tolerable losses, which are carefully controlled to keep activation levels low enough for hands on maintenance. Dominant losses of 10 % occur in the first 2 ms of acceleration and are a result of non-adiabatic trapping and space charge. These loss levels depend critically on many parameters, which require careful optimisation. Methods for measuring, optimising and understanding these parameters are the aim of this work.

2. DIAGNOSTICS AT HIGH INTENSITY

2.1 Type and Use of Diagnostics

The ISIS Synchrotron was built with a comprehensive suite of diagnostic devices [4], including 15 capacitative position monitors per plane, residual gas profile monitors, intensity toroids and 40 beam loss monitors spread around the circumference. These give much beam information, including detailed measurement of losses, which ultimately determine running intensity. The beam is set up so that loss levels, times and locations are within strict limits; most is localised on the collector system. Standard use of these devices at high intensity has been very effective over the years, and allowed ISIS to run beyond its design intensity.

Two developments, using the same diagnostic devices, are now making much more information available: improved data acquisition and use of low intensity beams. It is expected that the more detailed knowledge of the machine this gives will allow more consistent running at the highest intensities.

2.2 High and Low Intensity Diagnostics

Though diagnostics on high intensity beams provide much essential information, they do not give all that is available and important. A high intensity beam often fills a large fraction of the available acceptances. This means that any measurement of the, necessarily small amplitude, coherent motion, is of limited accuracy. Generally, much detailed motion is masked from external observation by incoherent motion of particles. Equally importantly, observed motion is also difficult to interpret because of high intensity effects. As a result, the ability to measure many beam parameters in detail, most of which affect high intensity running, is severely limited.

Many of these problems can be overcome with a specially configured, low intensity *diagnostic beam*, which occupies a small fraction of the ring acceptances. Large coherent oscillations can be accurately measured, with negligible high intensity effects, providing detailed information not otherwise available.

Parameters measured at high and low intensity are not generally comparable, but they are complementary; with correct treatment differences illuminate high intensity effects. Comparison of measurements at varying levels of intensity is also valuable. Low intensity diagnostics are valuable probes of ‘zero intensity’ beam dynamics, and allow study of initial conditions before high intensity effects become significant. These measurements can also be valuable in identifying precise machine set-up, when parameters have been empirically optimised at high intensity.

2.3 Hardware Changes

The diagnostic devices used are essentially the same for low and high intensity. Most important are capacitative monitors for transverse centroid position and longitudinal pulse shape measurements. Some electronics modifications have been required to allow for smaller, low intensity signals.

The most important upgrades [2] have been: addition of many fast digitiser channels, introduction of powerful computers with ability to control accelerator and acquisition hardware, and improved high level processing and display software. The principle applications of digitisers are acquiring data from many position monitors and detailed longitudinal pulse shapes. Automatic signal switching into the digitisers is included, which allows linking in with other diagnostics in the future. The system is designed for automated measurement. The aim is for quick, convenient access to more beam information, with appropriate analysis and correction software to exploit it.

2.4 Practicalities of Diagnostic Beams

On the ISIS ring a diagnostic beam is conveniently produced with an electrostatic chopper in the injection line. This reduces the normal 200 μs (120 turn) injected pulse down to a well-defined ‘chopped beam’ pulse of ≥100 ns, (≥1/15 of a turn). This beam occupies small fractions of all acceptances, as required, and may be injected at any time during the normal injection pulse length.

Most chopped beam measurements so far have been at injection, when the beam is ideally configured, with undiluted small emittances and convenient mechanisms available for excitation. In principle, chopped beams can be accelerated and used at any time in the machine cycle, as long as mismatches are controlled and small emittances conserved. Work is underway to achieve this, and measurements throughout the cycle are planned.

Beam can be chopped on 1 in every 128 of the 50 Hz pulses, leaving interleaved pulses unaffected. Many machine parameters can also be pulsed to experimental values at this rate. This means experimentation is possible during operational running, with a very small loss of operational current (<1%). The low power associated with chopped beams is also an advantage, making them an ideal non-destructive probe.

3. INJECTION

3.1 Importance of Injection Set up

Most beam loss occurs early in the cycle, at low energy, when space charge forces are most important and occupancy of acceptances peaks. Transversely, the painting process aims to approximate a uniform real space distribution, to minimise losses associated with incoherent Q shifts. Longitudinally, the non-adiabatic capture is a major cause of loss, and its minimisation requires precise control of injected momentum spread. As a result, beam loss levels are highly dependent on injection parameters. Chopped beams are particularly valuable for checking the variation of all key parameters through injection.

3.2 Transverse Painting and Matching

On ISIS, painting of the ~ 20 π mm mr injected emittance over the ~ 400 π mm mr acceptances is anti-correlated in the transverse planes. Vertically, the injection point is moved with a steering magnet in the injection beam line; horizontally, the closed orbit is swept by the falling main magnet field. A schematic of injection is shown in Figure 1. Optimal set up depends on many parameters in the ring and injector and is thus easily perturbed. Standard measurements on the accumulating high intensity beam, e.g. positions and profiles, give useful information, but chopped beams provide a direct measurement of the painting process.

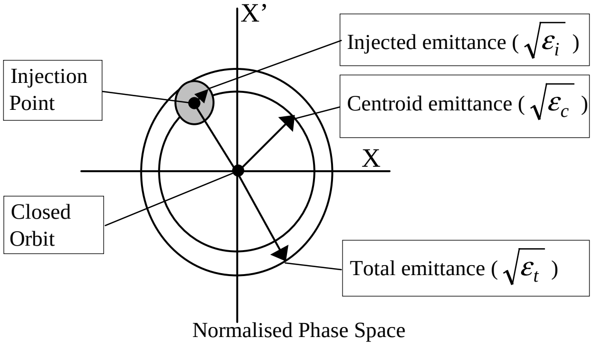

Figure 1: Injection Painting.

A chopped beam occupying a fraction of a turn is injected, and the centroid transverse positions at a monitor measured over the first ~ 40 turns. These are then least squares fitted to a function of the form (1) giving the position y_n on the n^{th} turn. This describes the sampled betatron oscillation and includes decoherence damping due to an assumed Gaussian Q spread [3]. Good measurements of betatron amplitude (A), Q, phase (ϕ), Q spread (δQ) and closed orbit (y_{co}) can all then be extracted. Note that this allows betatron amplitude *before* damping to be calculated. Chopped beams can be injected at any point during the normal injection process, thus variation of betatron amplitude and closed orbit through injection can be determined. This is a direct measurement of the injection painting of the beam centroid, Figure 2. Knowledge of lattice functions and apertures allows this to be related to machine acceptance.

$$y_n = A\cdot\exp\left[-\frac{(\pi\cdot n\cdot\delta Q)^2}{2}\right]\cdot\cos[2\pi\cdot n\cdot Q+\phi]+y_{co} \quad (1)$$

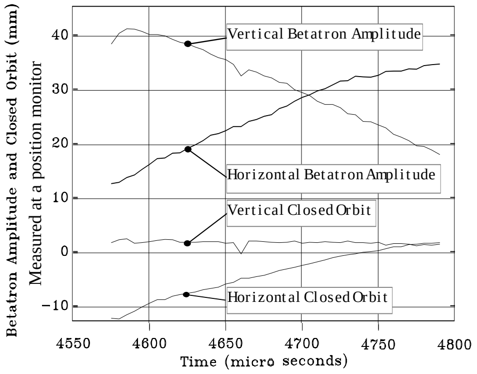

Figure 2: Measurement of Centroid Painting

Severe transverse mismatch can also prevent optimal painting. Again, a chopped beam occupying less than a turn is injected, its centroid motion is monitored as above, and its width measured simultaneously at a profile monitor. Time response of profile monitors on ISIS means measured widths are averaged over about 10 turns. Figure 1 shows the essentials; the total emittance of a painted beam ε_t, is related to the centroid emittance ε_c and effective injected emittance ε_i by

$$\sqrt{\varepsilon_t} = \sqrt{\varepsilon_c} + \sqrt{\varepsilon_i} \quad (2)$$

Assuming beta functions are known, ε_c is deduced from betatron amplitude $A=\sqrt{(\beta\varepsilon_c)}$ in equation (1), and ε_t deduced similarly from full width, many turn measurements at the profile monitor. From this ε_i can be estimated. Measurements on ISIS by this method indicate emittance dilution by up to a factor of ~ 3, but this is not yet a well developed diagnostic.

3.3 Longitudinal Set up

During the normal injection process, a continuous ‘DC’ beam is accumulated, which occupies the whole ring circumference. Later, the ring RF provides focusing for formation of two bunches. A very important property of the injected beam is its momentum spread, which directly affects trapping efficiency. Chopped beams allow direct measurement of the momentum distribution.

A short (100 ns) ‘square’ pulse, occupying a small fraction of a turn (T_{rev}=1.48 μs), is injected. Its debunching is then observed on a pick-up over ~100 turns with the Ring RF off. The 200 MHz microstructure from the linac disappears over the first few turns in the ring and has little effect. However, this structure means that, to a good approximation, the distribution of momentum along the length of the 100 ns diagnostic bunch is uniform. Debunching in the ring is emittance dominated, and this means the profile on the nth turn (D[t,n]) is a convolution of the momentum distribution (f[dP/P]) with line density on the first turn g[t]:

$$D[t,n]=\int g[t_e]\cdot f\left[\frac{(t-t_e)}{n\cdot\eta\cdot T_0}\right]\cdot dt_e \quad (3)$$

Here $\eta=(\Delta f/f)/(\Delta P/P)$ and T_o the revolution time [3]. The momentum distribution may therefore be extracted from the debunching data D[t,n]. Repeating measurements at different times gives the momentum distribution through injection. This is a direct check on longitudinal injection conditions. Problematic conditions of the linac are quickly picked up and corrected using a debuncher cavity in the injection line. An example of measured momentum spread against debuncher setting is shown in Figure 3.

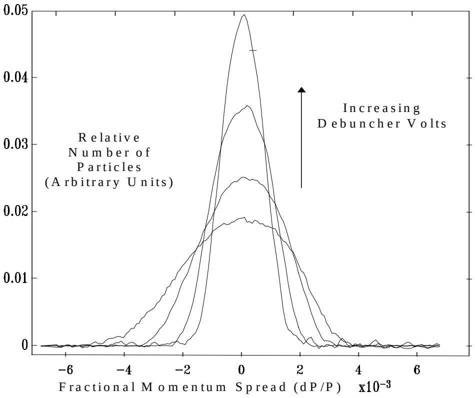

Figure 3: Measured Debuncher Action

4. BETATRON Q VALUES

4.1 Introduction

Optimisation of Q is critical for high intensity running, and essentially it involves minimising particle resonance crossing. Many mechanisms shift and spread Q values by varying amounts through the machine cycle; this demands time dependent correction. Nominal Q values are Q_h=4.31, Q_v=3.83; dominant resonances are the nearest half and whole integers.

The main lattice magnet fields scale together sinusoidally and determine the basic Q values. There are also two independently programmable trim quadrupoles in each of the 10 superperiods, which allow independent control of horizontal and vertical Q through the machine cycle. It is convenient to discuss low and high intensity effects separately.

4.2 Low Intensity Effects and Correction

The low intensity factors determining Q are main lattice magnets, trim quadrupoles and momentum via chromaticity. The fast cycling magnets are susceptible to eddy current and saturation effects, which must be corrected. Similarly, the 20 programmable trim quads must all operate to within tight limits to give desired corrections. To allow for Q spread and offsets caused by momentum spread, momentum offset, or main magnet scaling errors, chromaticity (ξ=(dQ/Q)/(dP/P)), must be known. Chopped beams allow detailed measurement and control of all these optical effects.

Chopped beam Q measurements, based on fitting function (1) to turn by turn positions, are accurate (~ ±0.004) and unambiguous, effectively at zero intensity. Such measurements have been effective at injection and are planned throughout acceleration. This allows all systems determining Q to be checked and corrected: the Q of the main lattice magnets (trim quadrupoles off); the expected change of Q due to trim quadrupoles; and the final resulting Q. Chopped beams are also ideal for chromaticity measurement. Basic procedures measuring Q as a function of energy, or main magnet scaling provide accurate values. Measurements on ISIS give values, in both planes, of about ξ=-1.4±0.1. Collectively, these measurements give all the information required to optimise low intensity Q.

4.3 High Intensity Effects

As intensity increases Q values shift and spread from the single zero intensity value and occupy a larger area in the Q plane. In a high intensity beam the coherent Q, the oscillation of the whole beam, and incoherent Q, the oscillation of particles within the beam, differ and must be allowed for. To optimise Q, both coherent and incoherent Q must be kept away from resonances. Shifts and spreads in Q are caused by direct space charge forces and image effects in the beam surroundings. Q shifts are functions of many parameters [5], e.g. intensity, energy, beam distributions and geometry, many of which vary through the machine cycle.

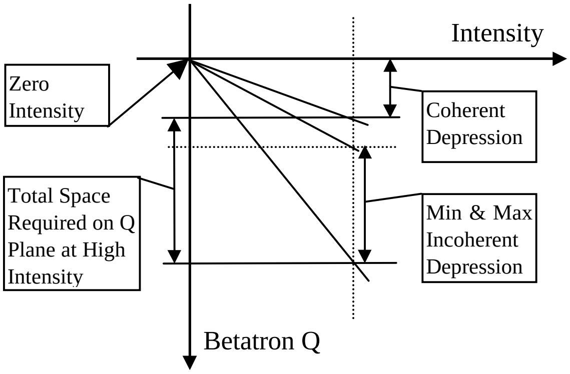

Figure 4: Schematic Change of Q with Intensity

Q set up is most important at low energy, when direct space charge tune shifts are largest, and the total Q spread peaks. Spreads increase with intensity, and this gives rise to a high intensity limit, when all regions in the Q plane free of dominant resonances are occupied. Optimisation consists of (i) moving the spread of Q's optimally between resonances and (ii) minimising all factors contributing to Q spread.

On ISIS, maximum incoherent tune shifts in both planes peak at -0.4 early in the machine cycle [6], and force particles to reach the dominant resonances. At these times the coherent Q depressions are about -0.1, and so lie above the minimum incoherent shift. The Q changes are shown schematically in Figure 4. The basic aim is to place the coherent Q value as high as possible *below* the nearest resonance in the working diagram, allowing maximum space below for tune depression.

4.4 Practical High Intensity Q Optimisation

The basic principles of high intensity Q optimisation described are well established, and have been crucial in achieving high ISIS currents. However, much more detailed routine measurement and optimisation is planned, exploiting improved diagnostics. Two sets of measurements are required: (i) coherent Q as a function of intensity, and (ii) loss as a function of Q, as it is swept between resonances with trim quadrupoles. These are required at regular intervals through the machine cycle.

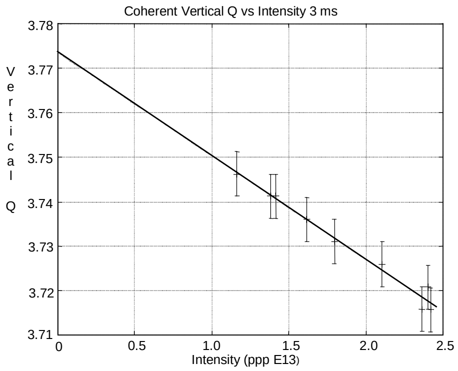

Figure 5: Measured Coherent Q vs Intensity

An example of a coherent Q-intensity measurement is given in Figure 5, and shows the expected linear form. These measurements are complemented by 'zero' intensity Q values provided by chopped beams. Once the Q-intensity relations are known they form a basis for optimisation. To be consistent, low intensity effects, e.g. chromaticity and magnet variation must be allowed for. Generally, early in the cycle coherent Q will be placed as high as possible, and adjusted with the intensity.

Measurement of loss as a function of Q gives an empirical optimisation of Q, and an estimate of total Q spread. Increase of loss as Q changes indicates more particles crossing known resonances; differences between these and coherent Q give the total Q spread. Factors affecting Q distribution are beam transverse and longitudinal distributions, which are functions of injection and RF set-up. Tuning these parameters and remeasurement of Q spread allow it to be minimised. Repetition of the total Q spread measurement as a function of intensity can also be useful, indicating when the high intensity limit is reached. It is hoped some consistent tie up with theory will be possible, relating measured longitudinal and transverse distributions to measured Q spread. Full Q optimisation must include all effects, high and low intensity, as they vary through the cycle; the above measurements give most of the relevant information.

5. TRANSVERSE DYNAMICS

5.1 Introduction

Good instrumentation is making large amounts of detailed information available, with low and high intensity beams. Appropriate systems allow these measurements to be taken quickly, automatically, and with minimal impact on operations. Below, an outline of the measurements presently being implemented [1] is given.

5.2 Low Intensity Measurements

Use of many digitisers linked to position monitors enables simultaneous acquisition of turn by turn positions at many points around the ring. If a chopped beam is introduced and excited, its betatron motion can be fitted to a function of the form in equation (1) at all monitors, and the parameters A, ϕ, y_{co}, are now given around the ring. From these values, relative beta functions at monitors, local phase advance, and detailed beam trajectories can be deduced. Use of chopped beams again provides accurate values, effectively at zero intensity.

The measurement of beam position at all monitors as a function of current in all steering magnets allows steering coefficients to be measured. These give data on lattice functions and valuable checks on correct operation of steering magnets and position monitors. The measurement of Q as a function of current in each trim quad provides beta at 20 lattice locations. This measurement also serves as a useful check on trim quadrupole operation. Collectively, these measurements should form the basis of an excellent zero intensity lattice model, which is valuable for error correction.

5.3 High Intensity Measurements; Correction

Most of the measurements described can also be taken at high intensity, which is valuable for two essential parts of machine optimisation; closed orbit and gradient error correction. The systems for correcting closed orbits are already much improved [1]. Detailed studies at various intensities, optimising orbit corrections which show some interesting high intensity properties [6], are planned.

6. LONGITUDINAL DYNAMICS

6.1 Introduction

Work studying longitudinal dynamics in more detail is now underway, and is particularly important in view of the proposed dual harmonic RF upgrade [7]. Set-up of the RF system is essential for high intensity running, as it affects all main loss mechanisms.

These measurements are based on digitising longitudinal bunch shapes from a capacitative pick-up over thousands of turns. The RF waveform is simultaneously digitised, which allows the instantaneous intensity verses RF phase to be reconstructed on every turn through the cycle. From this data most features of longitudinal dynamics can be probed, e.g. analysis of first and second moments yields dipole and quadrupole synchrotron oscillations.

6.2 Low and High Intensity Measurement

Many features of longitudinal motion can be directly observed with a low intensity beam filling a fraction of an RF bucket. A chopped beam can be placed at any RF phase during injection. Observation of its motion gives zero intensity synchrotron frequency, synchronous phase, and limits of stability. In principle, development of the RF bucket structure can be probed.

Measurements on a high intensity beam give detailed information on the size of stable regions, and the size of dipole and quadrupole oscillations. A more detailed optimisation of the RF should result, providing optimal longitudinal distributions and thus lowest losses. This work is still in progress [1].

7. CONCLUSIONS

Coupled with appropriate hardware, low intensity diagnostic beams are a powerful tool for optimising and understanding a high intensity machine.

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