Reaching 200 μA on ISIS

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Introduction.

On Friday 5 February 1993 the ISIS Pulsed Spallation Neutron Source just exceeded its design current of 200 μA at full energy of 800 MeV and repetition rate of 50 Hz. This is extremely good news for the experimental scientists who use the ISIS facility. Particularly so, for the scientists working on the neutrino collaboration KARMEN, since their need for higher intensity engendered additional financial support from the German Ministry of Science, which was particularly helpful in achieving this goal. It was also extremely gratifying for the accelerator physicists, because the full design specification was obtained in spite of the fact that the transverse acceptance of the synchrotron had to be reduced in the final design of the machine, resulting in the acceleration of beams with smaller transverse cross section, which enhances the effects of space charge.

From the beginning of 1986, when ISIS was first turned on for neutron physics, steady progress has been made, year by year, increasing the intensity as shown in Figure 1. By the end of 1991 the intensity had been raised to just over 100 μA and the start of 1993 saw a doubling of the current to 201.6 μA. As well as increasing the intensity, steady progress has also been made increasing the beam availability as can be seen from the plot of micro ampere hours irradiation on the spallation target shown in Figure 2.

Achieving 200 μA with greater machine availability has come from a combination of engineering improvements and better understanding in setting up, tuning and operating the accelerators. A brief account is given of the performance of the spallation source and the steps taken to reach the full design current.

Linac Development.

There has been a gradual and painstaking development[1] that has improved the output intensity and availability of the Penning H^- ion source, as illustrated in Figures 3 and 4. The rate of development of this ion source has been somewhat restricted, because the trial developments have been made on ISIS and not on an off-line test facility.

A significant reduction in the number of trips of the high voltage generator, following a spark down of the accelerating column, has been obtained by increasing the value of the resistor between the storage capacitor and the high voltage terminal from 10 kΩ to 1 MΩ. The column voltage recovers in 2-3 pulses and it is not necessary to shut off the beam into the column. A 'bouncer circuit' is fitted to the earthy terminal of the storage capacitor to inject a current into the 1 MΩ resistor to compensate the voltage droop from the beam loading of the column.

The installation of vertical and horizontal beam steering, at the start of the beam transfer line from the high voltage column to the linac, makes it possible to obtain over 60% transmission through the linac for any ion source fitted to the column. Transmission could at times be less than 50% before installation of the steering magnets

Improvements that allow the linac to be more easily set up for injecting into the synchrotron are the implementation of a ΔT system to optimise the accelerating field and phase of the rf accelerating cavities of the linac and a separate rf power system for the de-buncher cavity. The de-buncher was originally powered from a small loop coupled to the final accelerating cavity of the linac. The use of the de-buncher is critical for high intensity operation of ISIS, but it is found that it is optimum at a field significantly lower than that for maximum de-bunching.

Synchrotron Development.

Injecting into the synchrotron uses charge exchange and it is found that 'painting' the beam simultaneously in both transverse phase-planes is essential. In the horizontal plane injection is on the inside radius and starts a few hundred microseconds before field minimum. Painting is obtained by injecting beam at fixed energy at a point with a finite dispersion function together with a falling sinusoidal excitation of the synchrotron magnet field. In the vertical plane the painting is done by a small vertically deflecting dipole in the injection beam line powered from a programmable power supply. In the initial painting small amplitude horizontal betatron oscillations are correlated with large amplitude vertical oscillations and towards the of injection large amplitude horizontal are correlated with small amplitude vertical. However, it is found that as the intensity increases less particles with small amplitude oscillations can be injected. The maximum intensity injected to date is 4×10^{13} and the injected current rises linearly with time and shows no sign of saturation. However, not all the beam injected can be captured by the synchrotron rf. The intensity for 200 μA was obtained by injecting 3.05×10^{13} protons of which 2.52×10^{13} were trapped and accelerated to 800 MeV

Accelerating high intensities in the synchrotron has required the installation of an additional power tube in parallel with the existing tube at each of the six accelerating stations. Beam loading compensation is provided by a feed forward system[2]. The stability of the feed forward gain is now much improved with the fitting of solid state driver amplifiers to the synchrotron rf systems. For high intensity operation it is necessary to minimise phase transients and to have fine control of the time and amplitude of the accelerating voltage particularly during injection trapping and the early part of acceleration.

A major contribution to obtaining high intensities in ISIS is believed to be the combination of fast programmable supplies for both trim quadruple and dipole correction magnets together with the rf shielded ceramic vacuum chambers. This allows fast correction of betatron tunes and closed orbits during injection trapping and acceleration. The minimisation of closed orbits throughout the acceleration cycle is very critical to controlling and minimising beam loss around the ring.

The required rapid control of the betatron tunes is illustrated in Figure 5. During the injection interval the tunes are steadily raised in both planes to compensate for the large space charge tune shift. After trapping the vertical tune is moved rapidly away from the integer to avoid a vertical resistive-wall head-tail instability with mode m=1, see Figure 6. This is a lower mode than predicted by accepted theory and a modified theory has been proposed by Rees to explain the low mode number. The betatron tune in the horizontal plane is gradually reduced after trapping and then rapidly moved closer to the integer in the latter half of the cycle to avoid a coupling resonance that is believed to be either the $Q_H + Q_V = 8$, or the $2Q_H + 2Q_V = 16$.

All trim quadrupoles are programmed initially with identical functions to produce the desired betatron tune profile. However, it has been found that compensating for gradient errors by superimposing small 7th and 8th harmonic variations in the gradients around the ring, reduces beam loss and allows more efficient trapping of the beam.

The only other coherent beam motion observed in the synchrotron develops during injection. This appears to be excited by residual rf structure on the injected beam at the linac frequency and its harmonics. The motion damps above an injected intensity of 4×10^{12}, but begins to grow again as the intensity approaches 1×10^{13}. The motion damps immediately injection stops and is also damped by a very small amplitude of the synchrotron rf, by use of the de-buncher to control the momentum spread and by increasing the vertical beam size, see Figure 7. To obtain the highest intensities it is necessary to optimise the amplitude and phase of the de-buncher, the amplitude and form of the excitation of the vertical sweep magnet, and also to have a small amplitude excitation of the synchrotron rf.

Several unsuccessful attempts have been made to excite in ISIS the instability observed on the PSR at Los Alamos.

The maximum tune shifts in ISIS, whilst accelerating 2.52×10^{13}, are estimated[3] to be approximately -0.4 in each plane. This assumes that the maximum tune shift occurs for particles with small horizontal but maximum vertical betatron amplitudes, which is considered a reasonable assumption due to the form of the ISIS H^- 'painting'. Thus it appears that at peak intensity some particles cross the resonances $Q_H = 4$, $Q_H = 8$ and $2Q_V = 7$.

Progress to full specification has been dictated in part by the need to control and reduce beam losses to an acceptable level. Beam losses in the synchrotron are confined to approximately one tenth of ring azimuth, between the injection and extraction dipoles, by a system of longitudinal and transverse beam scrapers and collectors. Typical beam losses at an intensity of 180 μA are shown in Figure 8. Some loss occurs at injection (2-3% $H^\circ$from partially stripped H^-) and most of the remainder at low energy in the first 2 ms of trapping. Losses at high energy and in the transfer line to the target are less than 1 part in 10^4. The ability to effect rapid control over the closed orbit and betatron tunes are, as mentioned earlier, considered to be critical in controlling and minimising these losses. The beam loss in the extraction beam line at monitor 9-10 of Figure 8, results from a 1% beam loss at a full transmission carbon target, a little upstream of the spallation target, that is used to produce surface muons for the ISIS pulsed muon facility.

Tolerances on beam losses are shown in Figure 9. The tolerances operate on running averages and are classified into two categories. The first trips the machine and effectively forces it back to a repetition rate of 1 Hz until the beam spill is corrected. The second category is a warning system that does not trip the machine, but indicates that some parameter is beginning to drift and needs retuning. Action can be taken to correct this condition without reducing the output intensity or repetition rate of the machine.

Sets of sextupoles and octupoles have been installed in the synchrotron ring to control the focusing of particles with large momentum deviation and with large betatron amplitude. All attempts to excite these multipole elements at different times in the trapping and acceleration cycle have resulted in increased beam losses It would appear that in such high intensity machines there is a need to be as linear as possible and to avoid large orbit perturbations that produce a super period one condition.

Target Development.

The increased intensity and beam availability have increased the irradiation of the spallation targets. Neutron production has totalled 1.33 mg, but seven uranium targets have already been used and one tantalum target is currently operating, see figure 10. The lifetime of a uranium target is shorter than predicted, despite a large reduction in beam trips coupled with the ability to switch on the current gradually after a trip. The most probable cause of failure was considered to be the thermal fatigue/stress corrosion cracking induced by such beam trips. From measurements on the cooling of the targets[4] it appears that the tantalum target is following a similar pattern to the uranium and is also deteriorating and approaching the end of its useful life albeit after a considerably longer irradiation in excess of 1 mAh. Reasons for the failure of targets are under investigation and developments of the uranium target, such as smaller crystal size and alloying with molybdenum are to be tried as a possible ways of extending their useful life.

Acknowledgements.

The work reported here represents the successful culmination of several years of intense effort by all the staff of the ISIS facility.

References.

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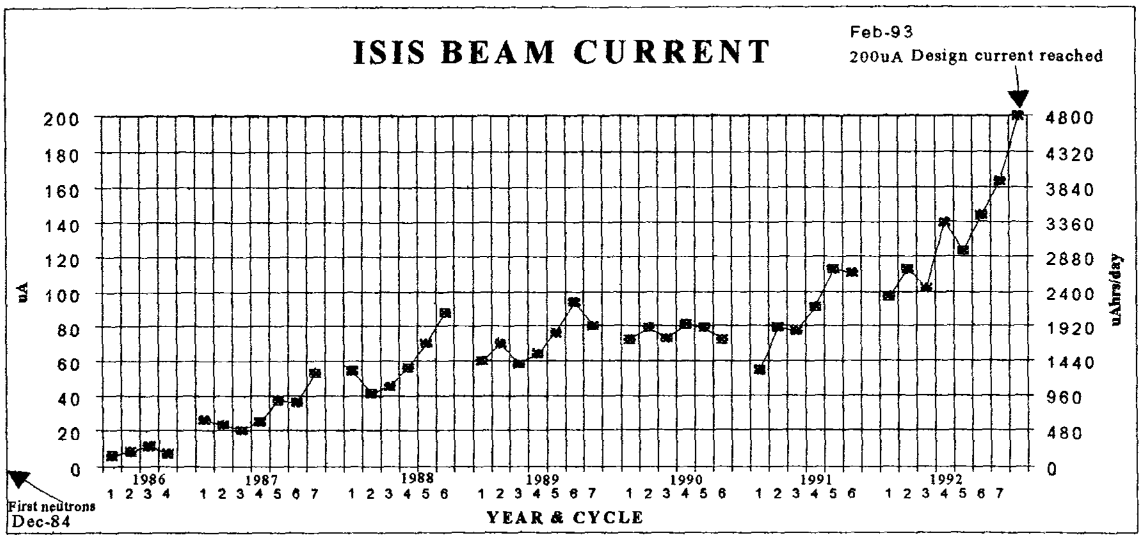

Figure 1. Increase in ISIS proton beam current.

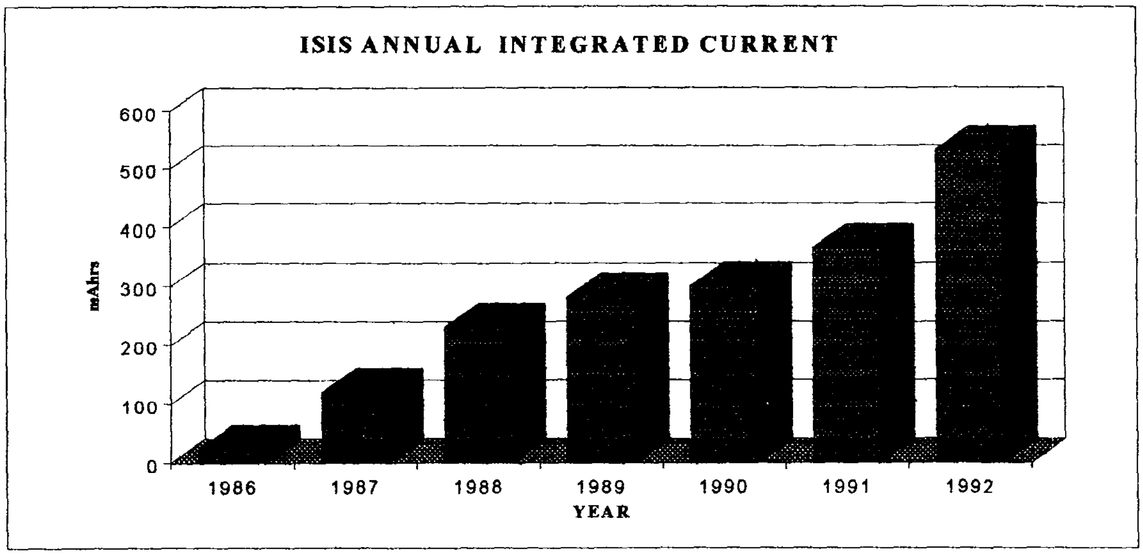

Figure 2. ISIS integrated proton irradiation

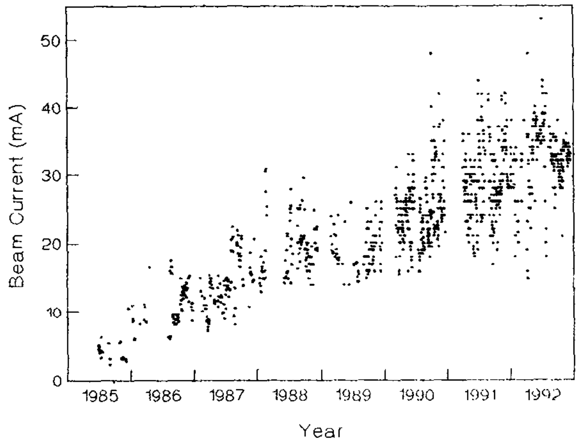

Figure 3. Development of output beam current for operational ISIS ion sources..

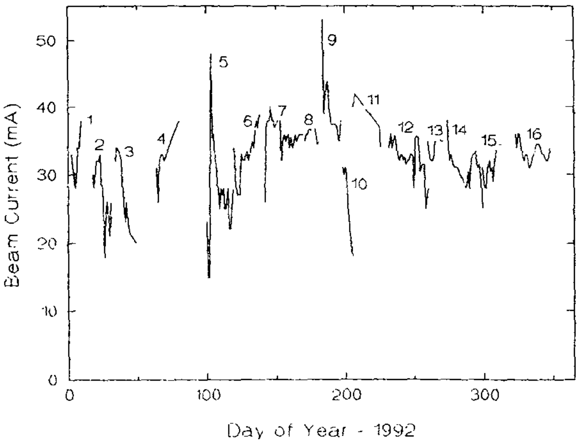

Figure 4 Beam current performance of ISIS operational ion sources.

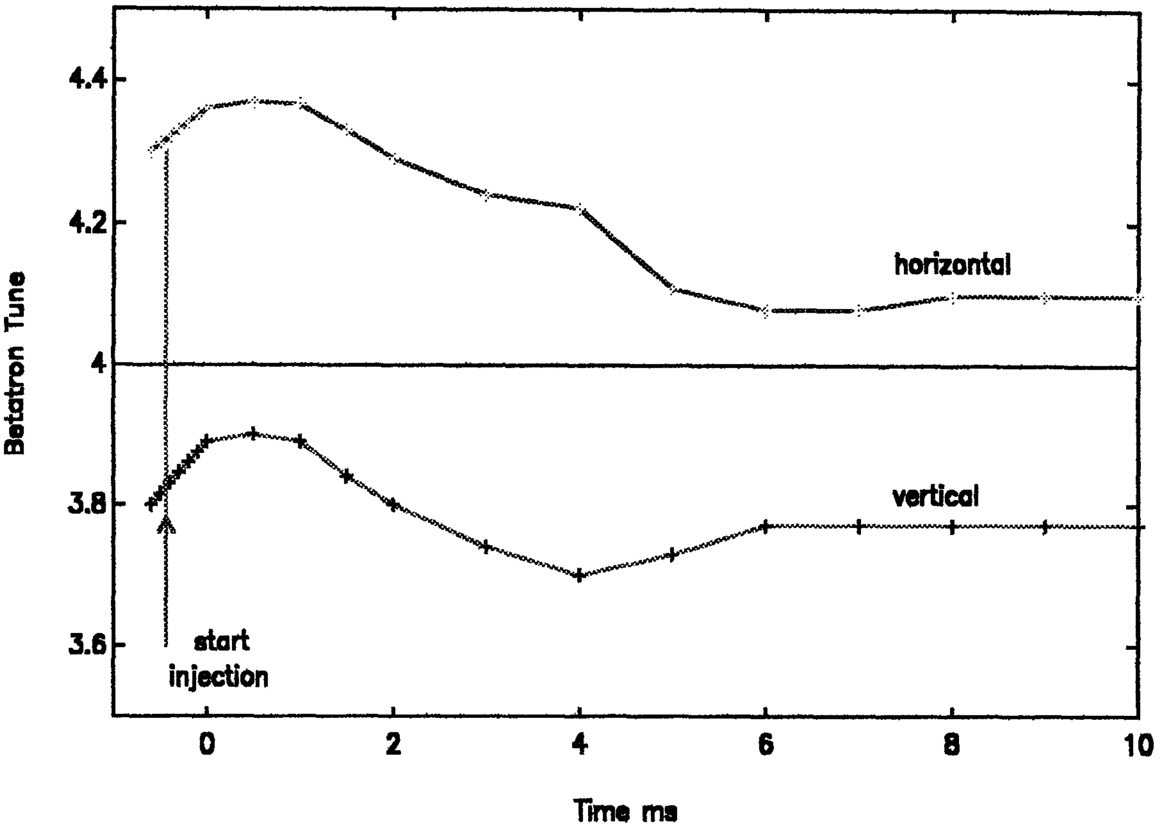

Figure 5. ISIS Betatron Tunes for high intensity operation.

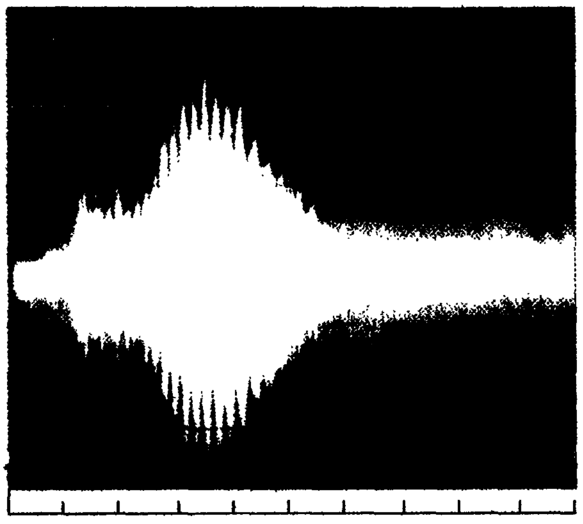

Figure 6a. Development of resistive wall head-tail instability.

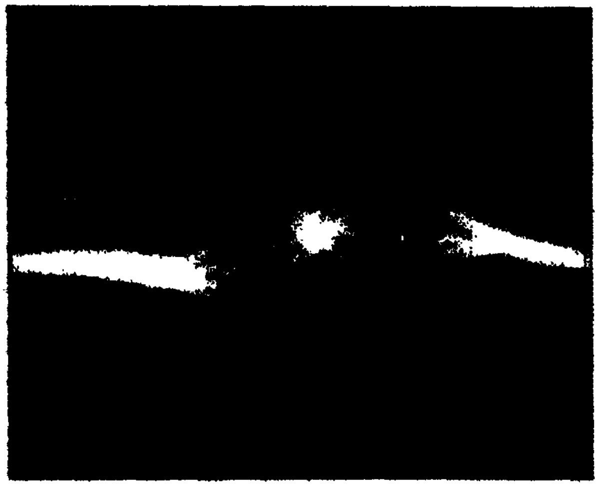

Figure 6b. Resistive wall head-tail mode m=1.

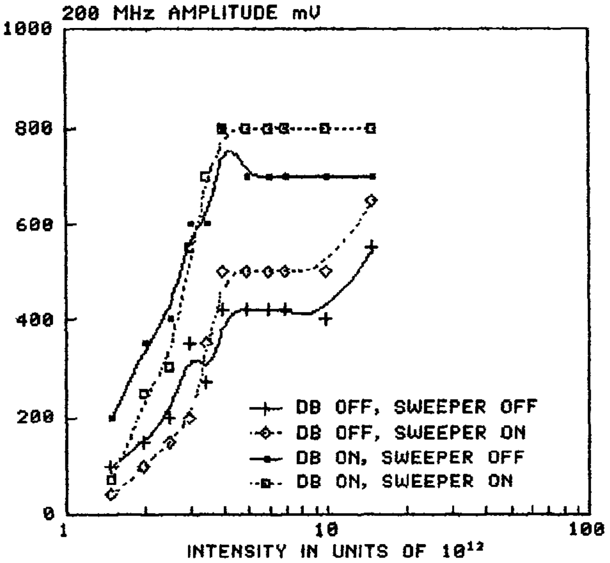

Figure 7. Growth of 200 MHz signal with increasing intensity

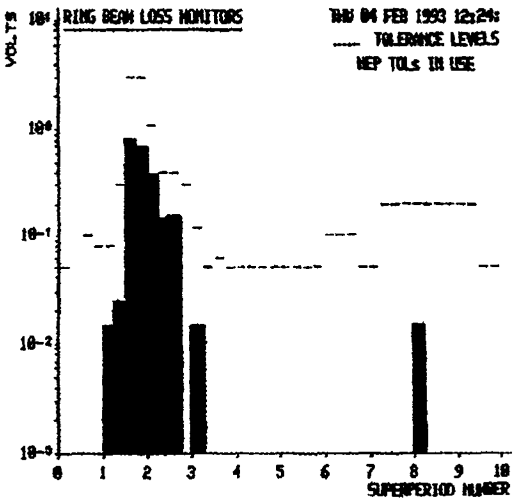

Figure 8a. Beam losses in ISIS synchrotron and tolerance levels.

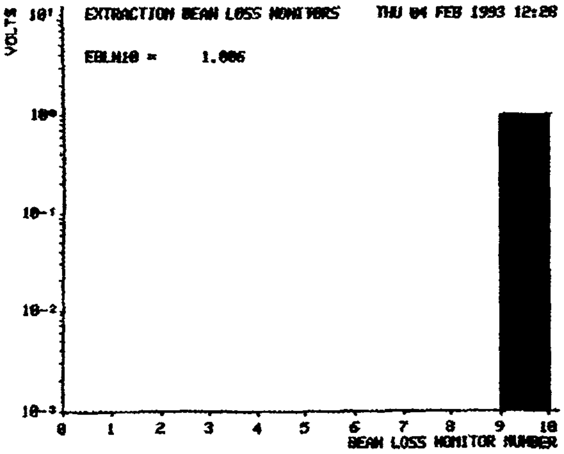

Figure 8b. Beam losses in extraction beam line to muon transmission target

Loss at	Immediate Trip $\times 10^{12}$	Averaging Trip $\times 10^{12}$	Seconds Warning $\times 10^{12}$	Minutes Warning $\times 10^{12}$
Injection	4.9	1.1	0.80	0.6
Trapping	4.9	4.0	3.30	3.1
Acceleration	2.0	0.5	0.25	0.2
Extraction	1.0	0.5	0.20	0.1
Extraction Beamline	1.0	0.6	0.50	0.4
Total Loss	4.9	4.8	4.20	4.1
Period	3 pulses	25 pulses	30 secs	20 mins

Figure 9 ISIS Beam Loss Tolerances

Target Material	Gross Thermal Cycles	Integrated Current mAh	Neutron Production mg
U#1	Not Measured	92.4	75
U#2	40000	53.1	52
U#3	10389	174.9	163
U#4	4147	138.8	128
U#5	5074	295.6	273
U#6	2628	126.1	116
U#7	1805	107.2	99
Ta#1	43164	905.7	424
	Total	1893.8	1330

Figure 10. ISIS Target Performance Summary to 31/1/93