STATUS REPORT ON ISIS

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Summary

The recent performance of the ISIS spallation neutron source is described and possible developments for the future are outlined. Aims for the near future are to raise the energy and intensity of the 50 Hz proton synchrotron to the design specification. Longer term aims are being evaluated by an International ISIS Project Group and an International Science Advisory Group. The hope is to develop the project in an international context to an improved specification.

Introduction

The spallation neutron source, ISIS (previously called the SNS), is based on a 50 Hz, 800 MeV proton synchrotron, designed to provide 2.3 10^{13} protons per pulse at a heavily shielded U 238 target. A system of neutron moderators and reflectors provides slow neutrons for up to 18 neutron beam lines and instruments. Status reports have been presented at the 1983 and 1985 IEEE Particle Accelerator Conferences and a full report on the operational experience up to March 1986 is available in the report[1] 'ISIS 1986'.

Planning has involved progressive development of the high intensity synchrotron. Initial running has been with a peak proton energy of 550 MeV and typical currents of 24 µA at the U 238 target. Reliability has been steadily improved and it is planned to progress to 750 MeV or 800 MeV in 1987 at higher average currents. A new extraction septum magnet is presently being used and all six RF accelerating cavities are being made fully operational.

Neutron beam experiments have been carried out on six scheduled and four development spectrometers and provision has been made for three further instruments. An intermediate target has been installed in the beam line to the target, and an associated beam line is being added to provide a 28 MeV/c pulsed muon beam for condensed matter research, using µSR techniques.

Commissioning experiments have concentrated on understanding the behaviour of the 70.4 MeV linac, the injection and acceleration in the synchrotron and on the detailed performance of the target. Experiments have also been made with the synchrotron operating as a 70.4 MeV storage ring. Studies have begun on the possibility of reducing the beam loss in the early part of the acceleration cycle.

The International ISIS Project Group has been formed following a Memorandum of Understanding between France, Italy, Sweden and the UK. There have been two detailed workshops involving participants from these and other countries. To consider the development of ISIS beyond the present specification, the work has been organised in three sections. An Instrument Section has evaluated twenty possible new neutron spectrometers. The Target Section has studied minor improvements of the present target and a number of options for a second target station. The Accelerator Section has studied and provided preliminary costings for both a 70.4 MeV replacement linac injector and a higher current, 800 MeV linac. In the latter case, the proposed target current is 1.6 mA at 50 Hz, provided via an 800 MeV compressor ring, with 20% of the current at 10 Hz to one target station and the remaining 80%, four pulses out of every five, to a second target. The 800 MeV compressor ring would be built from the existing synchrotron. A four year period is envisaged for a detailed study of the various options.

Recent Performance

By the end of 1986, the ISIS facility was operating for neutron scattering science on the basis of an operating sequence of 4 weeks for science and 1 week for maintenance and development. During the period from September to December 1986, the synchrotron operated at 550 MeV, 50 Hz and provided 18,500 µA-hours of beam to the U 238 target. Average currents of 28-32 µA were frequently achieved, with 24 µA mean obtained over several 24 hour periods. In the first commissioning run of 1987, the mean current on the target has been improved to 48 µA mean, with 6 x 10^{12} protons at 50 Hz. Though these figures are below the peak specification of 800 MeV and 184 µA average, the neutron scattering programme has been able to proceed with considerable success.

Up to March 1986, the performance had been limited to 4,270 µA-hours at 550 MeV, mainly due to problems of reliability with the H^- injector for the synchrotron. Extensive improvements were undertaken in the March to August shut-down period, both to the 665 keV H^- preinjector and to components of the 70.4 MeV H^- linac.

On the 665 keV column, the voltage gradient was carefully adjusted at the top of the column to improve the spark-down rate from once every 10 minutes at 10% of the design mean current to once every few hours at the 15% level. Additional shielding was added to the column to prevent damage to low-level components, following a spark.

On the 70.4 MeV linac, modifications were made to the 4 high voltage modulators used in conjunction with the RF systems that power the 4 Alvarez tanks. Improved reliability was obtained by simplifying the circuitry and replacing many of the high voltage capacitors. The cooling for the high power RF tubes was also improved; overheating of the anode seals was corrected by using an air-cooling manifold but the overheating of the grid seals is still being tackled. The present limitations of the linac performance are set by the ion source output current, the column breakdown at high mean currents and by the overheating of the RF power stages.

Typical performance for the present Penning type H^- ion source is a pulse current of 10 mA, a pulse length of 300 µs and a repetition rate of 50 Hz. For routine operation, the pulse length is reduced to 120 µs, the transmission through the linac and injection beam line is ∿ 55% so 4 10^{12} H^- ions are injected into the synchrotron.

The H^- beam is injected into a synchrotron straight section of length 5 m via a septum magnet. There are 4 septum-type dipole magnets in the straight for creating a localised bump of the closed orbit and the injection septum magnet is adjacent to the first of these. The region between the 2 central magnets houses the foil which strips the H^- ions to protons. Large aluminium oxide foils have been developed in the laboratory and have proved highly satisfactory. They have a thickness of 0.25 microns and an average life-time of 1600 μA-hours.

The routine injection pulse length of 120 μs corresponds to 80 injected turns and these are injected with high efficiency, typically, 96%. Pulse lengths up to 450 μs have a similar high efficiency. A vertical steering dipole is included in the injection beam line to provide filling of the vertical acceptance but it has not been used to achieve the present intensities. Horizontal filling results automatically with a fixed orbit bump and with injection from an inside machine radius, while the synchrotron guide field is falling.

Injection studies indicate ∿ 98% of the input H^- beam is stripped to protons and ∿ 2% to H° particles. The subsequent loss of protons at injection, after optimisation, is ∿ 2%, all occurring at the point where the injection beam line merges with the synchrotron vacuum chamber. A mechanical design error has been identified at this point and it has only just been rectified. The H^- beam has to be mis-steered ahead of the injection septum magnet and the best overall efficiency is found when the H^- beam momentum spread is reduced by the linac debuncher cavity.

Acceleration to 550 MeV has been achieved with 4 of the 6 RF cavity systems in operation. Switch-on has been 145 μs before the guide field minimum (T = 0), with the RF voltage and frequency constant until T = 0. Acceleration efficiencies up to 95%, but more typically 90%, have been achieved with an RF voltage program rising from 3.5 kV/turn at T = 0 to 75 kV by T = 1 ms and 112 kV by T = 5 ms and with a frequency program keeping the beam centred in the aperture. Protons undergo a quarter of a synchrotron oscillation by T = 0, at which time 2 smooth bunch shapes have developed (harmonic number 2). Later motion is non-adiabatic with filamentation present and the development of non-equilibrium bunch distributions. The complexity of the bunch shapes is enhanced because of the small momentum spread in the injected beam. Beam feed-forward compensation is used with each RF cavity and has been adequate for accelerated beams up to $5\ 10^{12}$ protons per pulse. Recent improvements are described in the next section. A beam phase control loop has been used routinely.

A horizontal beam loss collector has been very effective in containing the beam loss in early acceleration. It is located at the upstream end of the extraction straight section. Activation levels of the collector, on contact, 10 days after the last run, were 25,000 μSv/hour, an order of magnitude higher than any other ring component apart from the extraction septum and the injection bump magnets.

Beam loss in the linac, injection line, synchrotron and extraction beam line is monitored via a system of ionisation chambers. The beam repetition rate is reduced to 50/32 Hz to assess any high beam loss conditions. Beam trips are activated by the ionisation chamber monitors in the linac and injection line but by intensity monitors in the synchrotron and extraction line.

The high energy beam is extracted by fast kicker magnets and a dc extraction septum magnet, used with an orbit bump. Extraction efficiency exceeds 98%. The reliability of the kicker pulsing units is being steadily improved.

Trim quadrupole magnets are excited to keep the betatron tunes constant; three nominal working points are available. The uncorrected closed orbit in the ring is ∿ 3 mm rms, and this is corrected to ∿ 1.2 mm rms in the horizontal plane by a set of 4 steering magnets. Final alignment of the proton beam at the neutron target is indicated by a halo plate monitor with temperature sensors. A profile monitor supplies additional position information.

Commissioning Experiments

The recent experiments of most interest involved the small beam loss at injection, the bunch shapes in acceleration, improvements to the RF system, and the operation of the synchrotron as a 70.4 MeV storage ring.

Injection loss has been studied with an H° monitor, the ionisation loss monitors and a high frequency monitor supplied by R L Martin, ANL. A non-destructive monitor is obtained by using an internal scintillator and an external TV camera to view the H° beam which separates from the proton beam in the bump magnet just downstream of the foil. Fluctuations of the injected beam are readily seen on this H° monitor.

The small injection loss leads to signals on the ionisation chamber monitors and these are used for injection tuning. All the loss may be identified as occurring in the injection line or in the injection straight section. The initial loss observed is mainly the 2% loss at the time of H^- stripping. After injection the loss continues, decreases and then increases again, finally ceasing when the orbit bump is reduced. The late loss occurs even though the equilibrium orbit in the ring is spiralling away from the injection septum. For the first commissioning run of 1987, the fault on the injection flange has been corrected and the late injection loss no longer occurs.

Experiments showed that the late loss occurred for circulating beams greater than 10^{12} protons, with enhanced loss as the intensity was increased in the range 10^{12} to 10^{13}. The loss was reduced as the momentum spread of the injected beam, $\Delta p/p$, was increased, but the loss was independent of the betatron tunes. The loss threshold corresponds to the longitudinal microwave instability threshold for the lowest available injected $\Delta p/p$ value of $\pm\ 7\ 10^{-4}$. To study the topic, use was made of the ANL high frequency monitor to search for the growth of 202.5 MHz signals. The residue of the linac bunch structure in the circulating beam is at this frequency and so it is the unstable mode most likely to be seen. A 202.5 MHz signal was duly observed to grow for 100 μs, then decrease and disappear before RF switch-on. Next, it is hoped to establish the magnitude of the negative momentum tail that develops in the beam.

The bunch shapes in acceleration have been compared with the predictions of a one-dimensional longitudinal space charge tracking code[2], developed by S Koscielniak. The shape of both bunches is double humped by T = 100 μs and periodically returns to this form but with more complexity at intermediate times. At increased intensity, the bunch shapes become smoother due to enhanced longitudinal space charge forces. Even though the bunch shapes are complex, there is reasonable agreement between observed and predicted shapes, see Figure 1 for a beam of 5.3 10^{12} ppp at T = 225 μs. The non-equilibrium bunch distributions lead to low bunching factors at times in the acceleration cycle and, at higher intensities, it will be necessary to inject a beam of larger $\Delta p/p$.

During the first 1 ms of acceleration, the accelerating fields are low and the beam loading is high. The effect is enhanced due to the non-linearity of the cavity ferrites, which have a high Q at low RF excitation. Beam feed-forward compensation reduces the effects of this beam loading. In 1986 the RF system routinely accelerated beams of 3.5 10^{12} protons, had reasonable efficiency up to 5 10^{12} but reduced efficiency at 6 10^{12}. Recent developments[3] have been to include resistive loads on the cavities. Resistors using copper sulphate have been used and the concentration changed to adjust the value. These lower the Q at the onset of acceleration but have little effect at mid-cycle when the RF system has to supply maximum power. In a first experiment, the loading has been set at 11 kΩ per cavity and this has allowed 6.5 10^{12} protons per pulse to be accelerated with good efficiency. In future developments, the resistance values will be progressively decreased.

Beam lifetime experiments have been made while operating the synchrotron as a 70.4 MeV storage ring. The change from biased ac to dc guide fields is readily achieved. Circulating beams up to 10^{13} protons have been obtained and beam survival studied for a beam of 3.5 10^{12}. The beam is lost after a coherent transverse instability develops. The lowest $(m - Q_v)$ mode becomes unstable, with m = 4 and Q_v in the range 3.7 to 3.9. The growth rate increases as Q_v approaches m = 4, which indicates an instability of the resistive wall type. Survival times vary from 2.5 to 10 ms, depending on the Q_v value and the vertical emittance. Larger emittance beams have a reduced growth rate. No higher vertical transverse modes have been observed nor any horizontal transverse instability. In reverting to normal synchrotron operation, the vertical $(4 - Q_v)$ mode has not been seen for beams up to 1.4 10^{13}.

Near Term Plans and Studies

Further reductions are needed in the breakdown rate of the 665 keV preinjector column. Breakdown is thought to begin with H^- stripping in the gas at the high voltage end of the column; electrons are formed, deflected in the stray magnetic field of the ion source and accelerated to the column electrodes, producing X-rays and charging up of the column insulators. The X-rays have been detected where predicted, and field coils are now in place to modify the electron orbits. Experiments using the field coils will begin shortly.

Work on ion sources includes development of the existing Penning source and the construction of a small volume source, similar to the type[4] under test at Culham. To study the enhanced beam loading in the linac, a time-of-flight system has been developed with an analog output showing the energy variations of the 70.4 MeV beam. The synchrotron beam loading will be evaluated with the resistive loads on the cavities and with improved feed-forward systems.

Acceleration to 750 MeV is to be attempted in late March 1987. The magnetic guide field of the synchrotron has been powered to the correct level, a new extraction septum magnet is installed, the 6 RF cavities are in place and commissioning has begun of the final 2 RF driver amplifier systems. The extraction kicker magnets will have to operate at higher field levels.

Studies are in progress of means to reduce the synchrotron beam loss in early acceleration. Tracking studies, using the space charge code[2], show reduced loss for the following scheme. A h = 2, saw-tooth RF field, amplitude 12 kV, is applied to the unbunched circulating beam. After a quarter of a linear synchrotron oscillation (130 μs), the saw-tooth field is replaced by the sinusoidal field of the main RF system. The initial amplitude is 25 kV/turn and this is increased to 150 kV/turn by T = 2 ms. Figure 2 showns the beam phase space distribution at the quarter synchrotron point; the saw-tooth case is compared with that of an initial sine-wave field and with that of initial combined h = 2 and h = 4 fields. In the saw-tooth case, the longitudinal beam loss is almost eliminated, even at full intensity.

On the experimental side, it is planned to commission the μSR beam in the near future. Development of new neutron instruments and the neutrino facility will proceed as scheduled.

ISIS International Project Group

The results of the two workshops held in 1986 have been included in a report submitted for assessment by the member countries. Three main future options are discussed. In the first two, the proton intensity remains unchanged, minor improvements are made to the present target and a second target station is added. There is a replacement 70.4 MeV linac and either a new non-fissile target or a new target employing some fissile material. In the third option, the proton intensity is increased by a factor of 8 and there are very different target requirements.

After considering[5] RF linacs, induction linacs, FFAG accelerators and compressor rings, the recommendation, for the factor of 8 increase in proton intensity, is an 800 MeV, 50 Hz, 1.6 mA H^- linac together with an 800 MeV, 50 Hz compressor ring, built from the existing synchrotron. The major cost item is the new linac and conventional and superconducting alternatives have been considered. At first, a 100 Hz, 3.2 mA linac was proposed and the power savings of a superconducting design appeared attractive. On lowering the repetition frequency, however, the added complexity of a superconducting design is questionable.

References

[1] ISIS 1986, RAL Report 86-061.

[2] S Koscielniak, Ox. Univ. Thesis, 1987.

[3] I S K Gardner, Commissioning, Feb. 1987.

[4] M. Nightingale & A Holmes, Rev. Sc. Inst., 57(10), 1986.

[5] K Bongardt, J Le Duff, D A Gray, M R Harold, M Olivier, G H Rees, V G Vaccaro, N D West and G Wustefeld.

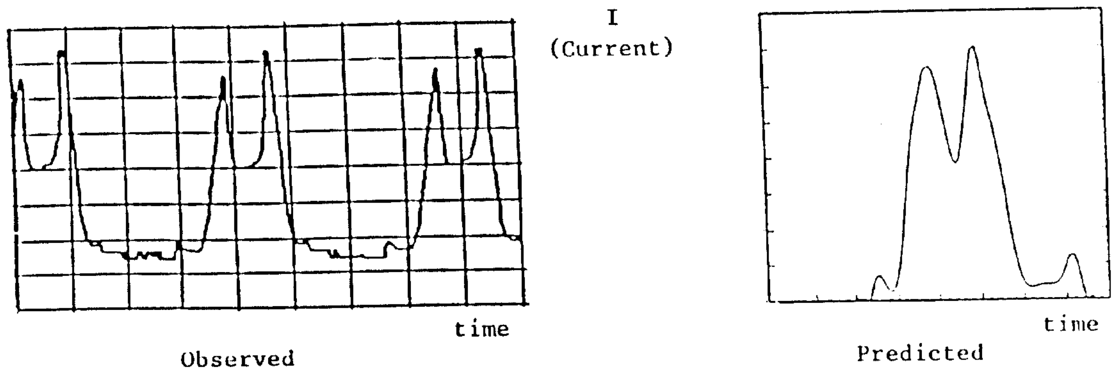

Figure 1 Bunch Shapes at T = 225 μs

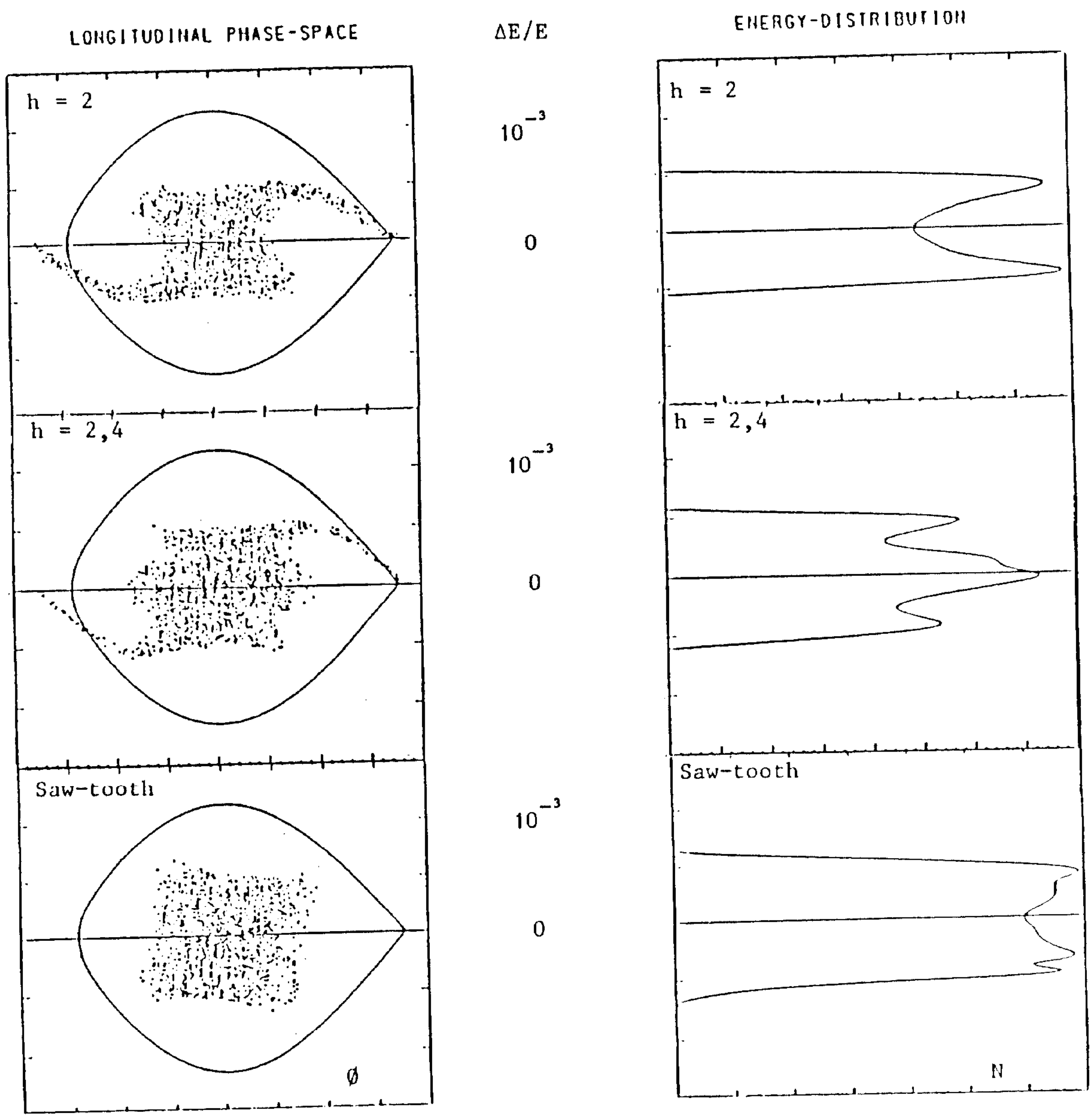

Figure 2 Distributions after 130 μs