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RUTHERFORD APPLETON LABORATORY

G. H. REES

Commissioning of the Spallation Neutron Source at RAL

1. Introduction

Low intensity commissioning of the SNS proceeded intermittently through 1984 while construction continued on the synchrotron, the external proton beam line and the neutron target station. The first neutron beam operation was achieved by mid-December. There followed a five month period for completion of the neutron target station after which high intensity commissioning commenced in June of 1985. During the five months, the 70.5 MeV H^- linac injector continued to be tested.

The design specification for the pulsed neutron source called for peak fluxes of thermal and epithermal neutrons $> 10^{16} \text{ n cm}^{-2} \text{ sec}^{-1}$ in pulses of duration $< 12 \mu\text{s}$ at a repetition frequency of 50 Hz. To achieve this goal at RAL, the method adopted has been the construction of a 50 Hz, 800 MeV proton synchrotron to provide $2.25 \cdot 10^{13}$ protons per pulse at a heavily shielded target of depleted uranium 238. The initial reaction in the target is the production of fast neutrons by spallation and fission. This is followed by a slowing down of the neutrons to thermal and epithermal energies in associated moderators. Above the target are 2 ambient temperature moderators and below is a liquid methane moderator at 95°K and a super critical hydrogen moderator at 25°K , all enclosed in a beryllium reflector. Individual moderators provide different energy

ranges of epithermal and thermal neutrons which are directed into up to 18 external neutron beam lines.

At the time of writing, commissioning proceeds while neutron beams are provided to experimenters who proceed with development of their instrumentation. The plans are to increase the operating intensity gradually, studying beam loss mechanisms and effecting cures to prevent undue activation of the facility. The current state of progress is reported in the following sections.

2. Performance of Linac Injector

Typical ion source currents have been 6 mA at pulse lengths up to 450 μ s, leading to linac output currents of \sim 3 mA. This is a factor 6 below the design specification but is adequate for the present state of commissioning. The repetition frequency has been limited by over-frequent breakdown of the 660 keV preinjector medium gradient accelerating column. The breakdown is linked to the enhanced load presented on increasing the repetition rate of the ion source arc discharge and the pulsed extraction voltage. Column breakdown has been found to occur at approximately once every 20 minutes on running the arc discharge at 50/2 Hz and the extraction pulse at 50/4 Hz. New electrodes have just been installed in the column which provide greater shielding for the glass insulators but these have not led to any improvement in the frequency of breakdown.

The next limitation found in the linac has been excessive heating of the anode seal of the main power tubes that power the 4 Alvarez tanks. Until this problem is solved, operation will be restricted to 50/2 Hz.

Output beam emittances from the linac have been found to be as expected, with 95% of the beam within transverse emittances of $20 \pi \mu$ rad m, un-normalised. At currents up to 3 mA, the momentum spread measurements indicate 95% of the beam within $\Delta p/p$ values of $\pm 1.2 \cdot 10^{-3}$. There have been some problems associated with the stability of the linac output energy, related to the stability of the field levels in the 4 Alvarez tanks and these have contributed to beam

loss in the synchrotron.

3. 70.5 MeV H^- Beam Transport

Transport of the 70.5 MeV H^- beam from the output of the linac to an inside synchrotron radius has been routinely established without beam loss, but it has proved difficult to determine accurately the betatron and dispersion functions along the line. It is suspected that the measurement of beam parameters by stepped wire scanners has been complicated by pulse to pulse variations of the linac beam and variations of the beam parameters during the pulse. Beam profiles have also been found to vary, depending on the state of the ion source beam. In general the profiles vary significantly from the design values but the problem is complicated by the accuracy of setting the beam line magnets due to hysteresis effects.

A debuncher cavity in the transport line has been powered from the fourth tank of the linac and appropriate settings have been found to reduce the beam momentum spread to $\Delta p/p$ values $< \pm 5 \cdot 10^{-4}$. There has been a limited range of satisfactory operation, however, for multipactoring problems occur at some field levels in the debuncher cavity.

4. Charge Exchange Injection into Synchrotron

Up to 300 turns have been injected into the synchrotron with high efficiency by appropriate stacking in horizontal betatron phase space following the stripping of H^- ions to protons. Large aluminium oxide stripping foils, 120 mm x 30 mm have been developed within the SNS group and have proved highly satisfactory in operation. They have a thickness of 0.25 μ .

Injection involves an injection septum magnet and four high current, septum type, pulsed ferrite magnets for control of a local horizontal orbit bump. The magnets are pulsed to 13,500 A for the injection interval after which the current pulse decays in $< 100 \mu s$. The four magnets are powered in series at the 1 Ω impedance level. Operation has been limited to 50/2 Hz due to heating problems which are now thought to be solved.

Exact matching of the linac beam to the synchrotron has not been established. However, the synchrotron acceptance is a factor 20 larger than the linac beam emittances and no loss of injection efficiency due to the mismatch has been observed. The maximum beam injected to date has been 10^{13} protons, resulting from a 400 μs injected pulse of H^- ions at a current level of 4 mA. The only injection loss is believed to be that associated with the stripping process, where over 98% of the H^- ions are stripped to protons and about $1\frac{1}{2}\%$ to H^0 particles.

The H^0 particles are observed on an internal scintillation screen viewed via an external TV camera. Fluctuations of the injected beam are readily seen on this monitor. A second internal scintillator has been used to observe the injected beam after one revolution in the ring. The monitors have been used together to obtain correct vertical alignment of the injected beam.

Injection occurs over intervals up to 450 μs , commencing 550 μs before the minimum of the biased sinusoidal guide field of the synchrotron magnets. Stacking in horizontal phase space is automatically obtained by holding all bump magnet fields constant while the main guide falls during this interval. The input distribution may be altered by programming all bump magnet fields.

A convenient sequence for setting up injection is the following:

- a. Alignment of the H^- beam in the 70.5 MeV transport line.
- b. Vertical alignment of the beam injected into the synchrotron ring.
- c. Setting the ac and dc components of the synchrotron guide field so that B (minimum) corresponds to 70.4 MeV and B (maximum) to the peak proton kinetic energy required.
- d. Adjusting the timing and the RF frequency for optimum trapping.
- e. Fine tuning the dc component of the guide field so that beam is trapped on the central orbit at the guide field minimum.
- f. Re-adjusting the peak field, keeping the injection field

constant and

- g. Adjusting the horizontal alignment of the injected beam by the last bending magnet in the transfer line and the input septum magnet and bump magnet fields.

5. Beam Behaviour in Synchrotron

The maximum beam injected to date has been 10^{13} protons per pulse and the maximum beam accelerated, $4 \cdot 10^{12}$. The accelerated beam is limited by beam loading effects and possibly by instabilities. Typical efficiencies from injection to extraction are 80% up to accelerated beam levels of $4 \cdot 10^{12}$ protons per pulse, with heavy beam loss above this level.

Only 4 of 6 RF cavity systems have been installed in the ring and this limits the peak proton kinetic energy to 550 MeV. The remaining 2 cavities and power amplifiers are planned for installation in 1986 and will allow acceleration to 800 MeV.

The synchrotron cycles at 50 Hz but injection has been limited to $\leq 50/4$ Hz while beam loss effects have been investigated. The stability achieved for the dc component of the magnetic field has been better than ± 1 part in 10^4 and that for the ac component better than ± 1 part in 10^3 . The resonant magnet power supply has operated locked to a fixed 50 Hz frequency and insufficient stability has been obtained when locking to the nominal 50 Hz mains frequency.

The ceramic vacuum chambers have functioned reliably and have reached pressures of 10^{-8} torr after extended pumping periods. Initially it was planned to move the quadrupoles and their associated vacuum chambers for closed orbit correction. However, in practice, it has been deemed unwise to do this because of the associated stress put on the ceramic end flanges by the neighbouring bellows sections and their internal RF shields. Some discolouration of the ceramic has been observed at locations in the ring where associated beam loss has been detected.

The highest level of activation in the ring has been observed

in the extraction straight, at the input region of the extraction septum magnet. It has not been established if this is due to beam loss at the septum input or at a graphite beam loss collector some metres upstream from this point. Beam loss occurs at two instants in the acceleration cycle, first at 1 ms after the minimum field point and then after a further 3 ms. The first loss is expected and corresponds to a minimum in the longitudinal phase space acceptance. The second loss, which does not always occur, is related to the stability of the linac energy and is thought to be a beam loading or instability effect resulting from the consequent hollow-type distribution in longitudinal phase space. When the second loss point develops it extends for many ms, sometimes for the remaining 6 ms of acceleration. The beam loss collector is of a length sufficient to stop protons lost early in the cycle but not those subsequently. For the latter case, beam scatters or emerges from the collector and then continues downstream. It probably contributes significantly to the high activation level at the input of the extraction septum magnet. Fast extraction is achieved with 3 ferrite kicker magnets, powered by 6 pulsing systems triggered by ceramic-bodied deuterium thyratrons. The kicker rise time is 200 ns.

No correction elements have been used to achieve the accelerated beam. Trim quadrupoles are installed but have not been used, not even during the injection interval when the chromatic effects are considerable for the initial off-momentum orbits. Horizontal and vertical closed orbits have been measured and the rms levels are approximately 5 mm. Correction in the horizontal plane has been achieved by the use of four horizontal steering magnets. These have been set to minimise the effect of fourth harmonic errors with some reduction in the third and fifth harmonic components. The horizontal tune is 4.31 and the orbit correction has reduced the rms error to 1.3 mm. Ideally, two further steering magnets are required to complete the third and fifth harmonic correction.

The 4 RF cavities have been powered by Class B amplifiers, but

in addition have been provided with feed-forward beam-loading compensation. The feed-forward has been influential in improving the maximum accelerated beam from $2.8 \cdot 10^{12}$ to $4 \cdot 10^{12}$. The accelerating field is set at 3 kV per turn in the 150 μ s interval prior to the minimum field ($T = 0$) and this has been found to improve the trapping efficiency as predicted by tracking studies. Ahead of this interval, diametrically opposite cavities are antiphased to provide zero net volts per turn. After $T = 0$ the voltage is increased rapidly from 3 to 80 kV per turn at $T = 1$ ms by adjusting the relative phases of pairs of cavities. Trapping is non-adiabatic and unusual bunch shapes are observed early in the cycle. With an input energy spread of ± 50 keV, a double humped distribution in line density results at time $T = 0$, with some particles from the neighbouring bunch ($h = 2$) moving inside the boundary of the phase stable region. When the energy spread is increased to ± 150 keV, the double humped distribution is less pronounced and develops later. Superimposed on the main distribution are the particles near the periphery of the bunch which appear as local perturbations of the line density. Some persist after the first loss region at $T = 1$ ms.

The effect of the longitudinal distribution on the acceleration efficiency has not been studied yet as the measurements are complicated by the variability of the linac input energy. The distribution may prove important as the beam intensity is increased and the longitudinal space charge forces are enhanced.

The future development of the RF system is not completely determined and final decisions will be deferred until after further commissioning studies. Initially envisaged was the addition of a Class A power amplifier in parallel with the Class B stage in each system to provide linearity for the feed-forward compensation.

6. Target Station Status

The target station is largely completed with all 4 moderators in operation. The low intensity run in December 1984 was accomplished

with water cooling of the uranium target plates but this has now been replaced by a D₂O cooling system. All services to the target are complete and operating experience is gradually being obtained. There has not been the opportunity to obtain detailed experience in the use of the remote handling cell.

7. Personnel Involved

The commissioning work reported has involved the SNS operations group together with the following experimenters: Robin Bendall, Tony Borden, Mike Clark-Gayther, Ian Gardner, Mike Harold, Vince Kempson, Charles Planner, Vyvyan Pugh, Grahame Rees, Nigel West and Harold Wroe. A group headed by Alan Carne has been responsible for the construction and commissioning of the neutron target station.