COMMISSIONING AND OPERATING EXPERIENCE WITH THE H^- INJECTION SYSTEM FOR THE FAST CYCLING SYNCHROTRON OF ISIS

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Abstract

The synchrotron for the Spallation Neutron Source ISIS, uses multiturn H^- charge-exchange injection through a stripping foil to inject 5×10^{13} protons per pulse at 50 Hz. The injection system is described together with results obtained during commissioning and operation. Up to 250 turns can be injected and the injected intensity is observed to rise linearly up to the maximum injected to date of 2.6×10^{13}. Injection efficiency is in the range 96-98% with approximately 2% loss as partially stripped H° ions. The synchrotron can now operate at 100 µA with foil lifetimes in excess of 10 mAh injected current.

Introduction

In a previous conference proceedings the basic design of the multiturn charge-exchange injection system for ISIS (previously named SNS) was described. This system is now fully operational and here a description of the hardware is given together with results obtained during its commissioning and operation. The development of large area ultra-thin stripping foils with relatively long operational life times is also presented.

ISIS Negative Ion Injection System

The negative ion injection system for ISIS is confined within one straight section of the synchrotron and is illustrated in Figure 1.

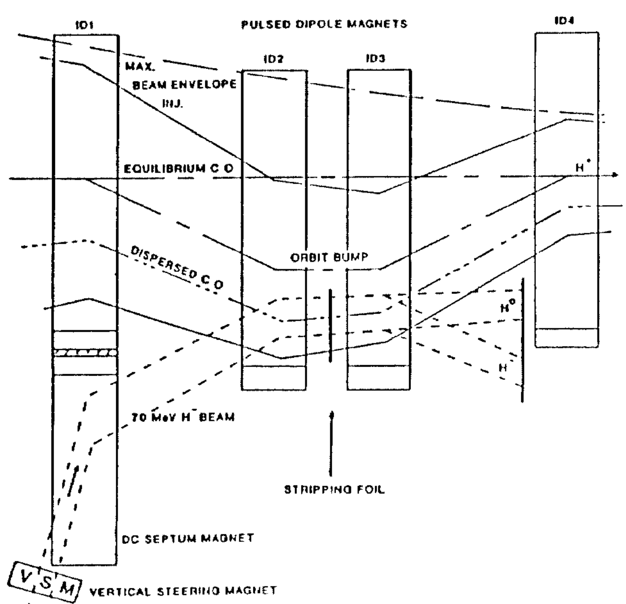

Figure 1 ; LAYOUT OF ISIS H^- INJECTION SYSTEM

During injection the four dipoles in the injection straight are pulsed to produce a symmetrical localised bump in the synchrotron closed orbit. A DC septum magnet injects the 70 MeV H^- ions on the inside radius of the synchrotron between the first and second dipoles. The ions pass through the field of the second dipole onto the stripping foil, positioned between the second and third dipoles. The injected protons on average circulate through the foil a further 25 times [1] approximately, before the closed orbit bump is removed.

In both planes the injected emittance is approximately 20π mm mrad and in the horizontal plane this is painted over the acceptance of 540π mm mrad by a combination of dispersion and betatron motion. In the vertical plane the beam is painted over the betatron acceptance of 430π mm mrad by using the vertical steering magnet , VSM, ahead of the DC septum magnet.

The 4 pulsed dipoles are identical in construction and are powered in series. It was recognised from the outset that induced activity could be a serious problem in such a high intensity machine, particularly in the regions of injection and extraction. For this reason radiation hard materials are used throughout the construction of the dipoles and they are designed to be easily installed and removed from their vacuum chambers. Each dipole has a single turn septum coil with a ferrite yoke (Philips 3H2). The magnet yoke is in vacuum and the ferrite 3H2 was chosen for its high saturation of approximately 0.4 T, to minimise the volume of ferrite in vacuum. However, the ferrite has a relatively low resistivity, approximately 10 Ωm, which necessitated insulating the coil with a layer of alumina. Also the 27 mm thick C-core laminations formed from the blocks of ferrite are insulated from each other by 0.15 mm glass cloth. Around the ferrite is a C shaped calliper carrying pressure pads to each of the ferrite blocks. The whole magnet assembly is in a rectangular vacuum box and is suspended from the lid as illustrated in Figure 2.

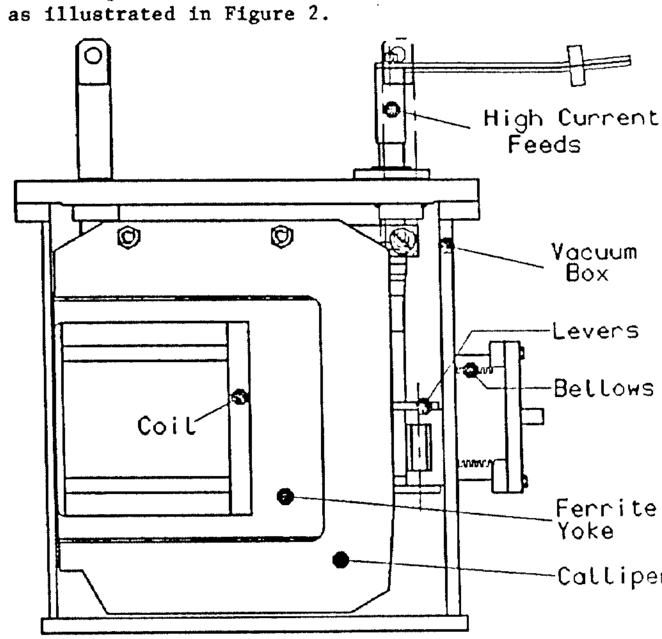

Figure 2; Pulsed Injection Dipole Magnet

The magnet current feeds and water cooling pipes pass through the box lid to make installation and removal easy. Levers operating on the back of the calliper automatically force the septum side of the magnet against a machined datum face as the box is evacuated, and clamp the ferrite blocks.

The DC septum magnet has a 6 turn septum with a laminated iron yoke. The yoke is enclosed in a hinged C-calliper so that the yoke and coil open in two halves to allow fast installation and removal from around the vacuum chamber of the injection beam line.

Commissioning The Injection Dipoles

During commissioning of the dipoles it was found that considerable outgassing of the ferrite occurred as the power levels were increased.

Initially, at the high voltage end of the first dipole in the series chain a plasma arc was formed between the coil and ground at the pressure pads. This resulted in several ferrite blocks being shattered with long narrow tunnels being formed in the ferrite by melting. The effect was reproduced in the laboratory by passing a few hundred amps through a block. The ferrite has a negative temperature coefficient of resistance and the current is concentrated in a thin line below the surface where cooling is least efficient. Eventually the narrowing of the channel results in melting of the ferrite. The pressure pads were subsequently insulated from the ferrite and the coil insulation thickness increased from 4 μm to 8 μm plasma sprayed alumina.

When running up the magnets the power input is limited by controlling current and repetition rate to ensure outgassing does not raise the pressure above 3×10^{-7} m bar. Outgassing the ferrite in this way takes approximately 8 days to get to full power. The outgassing has to be repeated every time the ferrite is exposed to atmosphere. Recently, additional cooling has been added to the ends of the coils and this has reduced the outgassing and conditioning time to 2 days.

Powering The Injection Dipoles

The dipoles are powered in series by a solid-state pulsed power supply developed in collaboration with NEI [2]. A pulsed current of up to 14 kA at 50 Hz is fed to the magnets via 20 x 8 Ω co-axial cables in parallel, 120 m long. The current pulse has a rise and fall time of 100 μs and a flat top of 500 μs.

The electrical characteristics of each magnet are:

Inductance	1.5 μH
Resistance	120 μΩ
Field	∿0.1 T
Current	13300 A

The principle of operation of the supply is shown schematically in figure 3. Capacitors charged to approximately + 1.5 kV and - 1.5 kV are switched in to resonantly charge and discharge the energy in the magnets. During flat-top 40,000 μF capacitors charged to approximately 100 V are switched in as required to maintain a flat-top of ± 0.5%. Between pulses the energy stored in the magnets is recovered into the capacitors. The supply can be programmed to produce a flat-top pulse or pulses with up to a 17% droop.

The cables are terminated at the magnet and with an AC coupled 0.4 Ω matching resistor. This is primarily to ensure the protron beam sees a low coupling impedence during acceleration when the magnets are not powered. The lowest (n-Q) vertical instability mode is approximately 100 kHz. The termination also prevents high frequency reflections when powering the magnets. Only a small amount of power is dissipated in the termination during the current rise and fall.

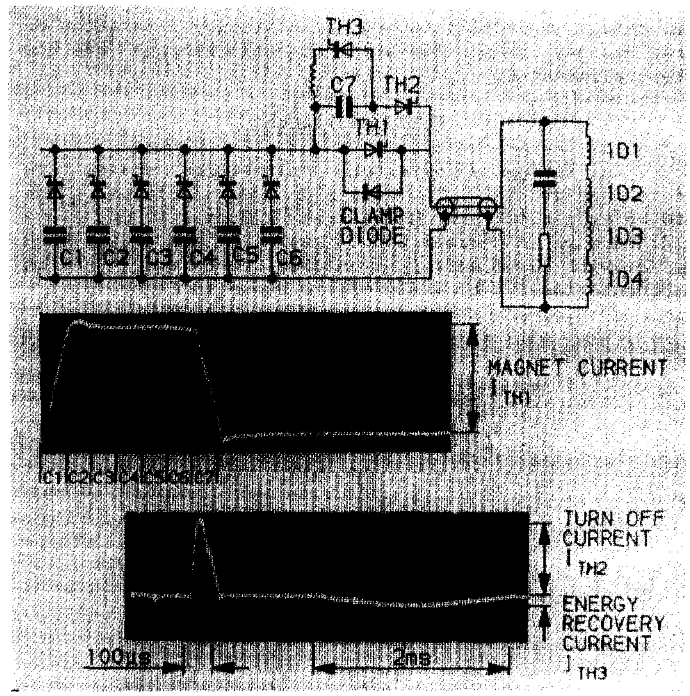

Figure 3; Pulse Power Supply and Current Waveforms

A simple compression-fitting termination was developed for the co-axial cable to enable a low inductance transition between the 20 cables and parallel plate bus-bars. The transition shown in Figure 4 is in the form of 4 banks of 5 connections.

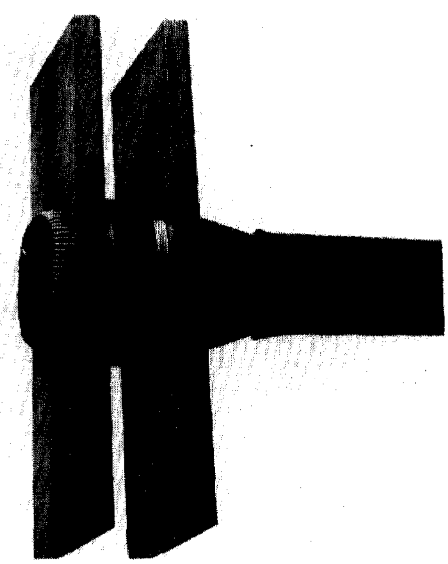
Figure 4; Co-axial Line to Bus-bar Transition

Such transitions are required at each end of the 120 m long cables and at each magnet connection. Just after each transition the parallel plate bus-bars are formed as jaws on the inside of mechanical clamps. Five pairs of jaws are ganged together so that all the high current connections to the 4 magnets and the transmission cables are made simultaneously by moving a lever through 180°.

These connections have worked well. Overheating initially occurred at one end of the system where one bus-bar is necked down to pass through a pulse transformer but this is now air-blast cooled. Also some cables had to be replaced between two magnets due to damage initially caused by a brazing operation on the bus-bar jaws. The need for this brazing has now been eliminated.

Foil Development

The stripping foils for the injection system were developed at RAL. They are made from aluminium oxide 50 $\mu g/cm^2$ thick, with an area 122 mm x 40 mm. One 122 mm edge is unsupported. The foils are coated each side with 0.01 μm of aluminium to prevent charge accumulation. A typical foil is shown in Figure 5.

Figure 5; ISIS Stripping Foil

The foils are made in their support frame by anodising aluminium in a weak electrolyte to the required thickness and then dissolving away the unwanted aluminium. Before dissolving the aluminium, the foil is heat treated to 'stretch' the foil. This results in a loose wrinkled foil in the support frame which allows thermal expansion of the support frame without overstressing the foil. The slackness also allows considerable shrinkage to occur with irradiation before overstressing results in breakage. The foils have extremely uniform thickness and with experience, acceptable foils can be made with an 80% success rate.

Initially, with the foils unsupported along the 122 mm edge, foil life times were typically 1500 μAh injected current. Now the foils are also slit along the lower 40 mm edge and foil life times have increased to 10 mAh. These life times are for injected current: the actual irradiation is approximately 25 times these figures due to the circulation of the protons through the foil.

Injection Experience

Successful injection and circulation of beam was obtained at the first attempt. Early injection studies diagnosed a few percent beam loss which was eventually located at the manifolding of the injection beamline with the synchrotron vacuum chamber. This area was redesigned to remove the obstruction.

Scintillators downstream of the foil provided very useful diagnostics for the injected beam. When running at lower intensity, the partially stripped H° ions could be used to keep a continuous check on injected beam stability during normal operation.

The only operational problem observed is with the pulsed dipoles. After running for some time at full power a large closed orbit error developed during injection. This was a thermal effect and it was believed that the temperature of parts of the ferrite yoke was being raised above the Curie point of 160°C. Additional cooling has recently been added to the ends of the coils which has eliminated this problem.

The synchrotron dipoles and quadrupoles are excited by a 50 Hz biased AC current. Injection starts approximately 500 μs ahead of the minimum field of the synchrotron. In Figure 6 is shown the maximum injected beam of 2.68×10^{13} protons. It can be seen that the

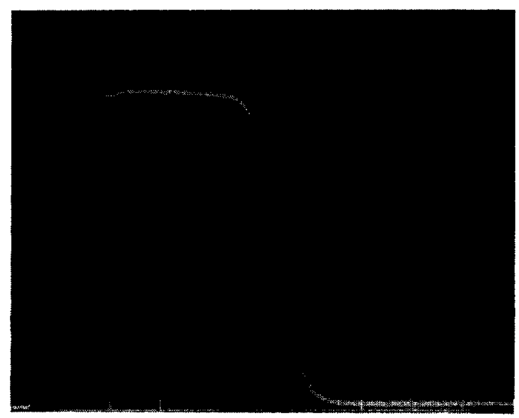

Figure 6; Beam Intensity v. time (200 μs/cm)

injected current rises linearly with no sign of saturation. The picture is taken with the RF accelerating cavities switched off. Beam should survive until about 500 μs after field minimum and then be lost as the field rises. It has been found that the survival is very sensitive to Q-values, particularly the vertical tune and also to increases of the vertical beam size by exciting the VSM. The injection efficiency obtained so far at this intensity is 94-96%. The longitudinal microwave instability is observed at injection and results in a small growth in beam size and a small loss. The growth rate appears to be a maximum around 4×10^{12} protons injected and then damps with increasing intensity.

Acknowledgements

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References

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[2] R G Rodwell, V A Lowe. 2nd Int Conf on Power Electronics and High Speed Drives. Conf pub 264 pp 200-203 Nov 1986.