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A PULSED SPALLATION SOURCE FOR NEUTRON SCATTERING RESEARCH

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Summary and Introduction

A rapid-cycling 800 MeV proton synchrotron is proposed for the Rutherford Laboratory as the basis of a high intensity, pulsed, spallation neutron source (SNS) to be used for thermal neutron scattering research. The facility will be generally complementary to existing high flux sources but its effective source brightness will be at least an order of magnitude greater than these at neutron wavelengths of 1Å (∿ 100 meV) and below, with an increasing advantage (100-1000 times) over the best reactor source at wavelengths approaching 0.3Å (1 eV).

The accelerator is designed to provide 2.5×10^{13} protons per pulse, at a kinetic energy of 800 MeV, with a pulse duration of approximately 200 ns and a pulse repetition frequency of 50 Hz. These will yield 4×10^{16} spallation and fission neutrons per second in a ^{238}U target within a well shielded target station. The fast neutrons will be slowed to thermal energies by moderator/reflector assemblies close to the target. It is planned to use two moderators, one at ambient and the other at sub-ambient temperature, each serving 7 beam tubes through which the moderated neutrons pass to 14 or 15 time-of-flight instruments located outside the target shield.

Details are given of the design of the accelerator, target and moderators, with emphasis on the more difficult aspects of the design. Large economies are possible in the overall cost of the facility through the use of existing plant and buildings. If the project is started in 1977 and the necessary funds are available, the first experiments could begin by the end of 1982.

Synchrotron Design Features

A schematic lay-out for the facility within the existing laboratory buildings is given in Figure 1. The Nimrod magnet ring is replaced by a new ring of large aperture, separated-function, dipole and quadrupole magnets which are powered in a 50 Hz resonant mode. Components for the magnet power supply will be obtained from the NINA accelerator, and the magnet lattice is designed to be compatible with these units. The large banks of resonating capacitors will be positioned in the central region of the magnet hall and a ring of steel shielding provided between the capacitors and the synchrotron. The injector will be the present 70 MeV proton linac but modified for 50 Hz operation and for H^- acceleration. Charge exchange injection of negative hydrogen ions is then used to provide the intense proton beam in the synchrotron ring. Acceleration to 800 MeV will be at RF harmonic number 1 and the single bunch of 800 MeV protons will be extracted as a 200 ns pulse and transported within a shielding enclosure to the target station at the centre of one of the experimental halls. Existing services are more than adequate for the proposed source and can be used with little modification. Also, most of the shielding for the target station is available on site. The scale of the facility is very similar to the spallation neutron source, the IPNS, proposed by ANL[1].

Components of the synchrotron are arranged in 5 superperiods, each of which has 1 long straight section, 2 dipoles, 3 quadrupole doublets, 1 octupole, plus 1 trim quadrupole next to each main quadrupole. Of the 5 long straight sections 1 is for injection, 1 for extraction, 2 for RF cavities and 1 is free for diagnostics and developments. The trim quadrupoles allow the betatron Q-values to be varied independently of the main magnet resonant power supply. They also enable the main F and main D quadrupoles, which have a common design, to operate with equal current levels and field gradients in the chosen Q range around $Q_h = 4.2$ and $Q_v = 3.9$. The single choke of the magnet power system is designed to feed 10 identical magnet sectors. Such sectors are formed by a series connection of 1 dipole magnet, 1 quadrupole doublet and 1 other F or D quadrupole. Each superperiod subdivides to provide 2 sectors.

The lattice design gives a straight section of sufficient length to allow the fast extraction of a large emittance 800 MeV beam. The large emittance is a consequence of the required beam intensity. Use is made of a 'missing-magnet' separated-function lattice design so that a long straight section is obtained without recourse to the use of special matched insertions. Vertical rather than horizontal extraction is employed because the emittance is smaller in the vertical than the horizontal plane, with $E_v = 0.56E_h$. The dipoles are located near positions of minimum β_v to reduce their vertical aperture. This feature is also an advantage for vertical fast extraction as it enables the fast kicker and extraction septum magnet to be located near positions of minimum β_h and maximum β_v. There are 3 lattice 'cells' in each superperiod and the phase shift of the vertical betatron motion per cell is $\sim\pi/2$.

The operating Q_h, Q_v point (4.2,3.9) is well spaced from the $Q_v-Q_h = 0$ coupling resonance and from all third and fourth order superperiod resonances except for the $4Q_v = 15$ resonance. Alternative operating points (3.7,3.9), (4.2,3.4) and (4.2,4.3) are not as suitable, though the trim quadrupoles will be designed to be adequate to obtain the (4.2,3.4) point, if necessary. In this mode there is an increased threshold for the vertical transverse instability. An octupole is included in each superperiod to introduce Q-spreads in the beam for combatting transverse instabilities and also to provide partial compensation against transverse space charge excitation of the $4Q_v = 15$ resonance. There is a location in each superperiod where the dispersion is small and suitable for siting an octupole magnet.

There are no sextupoles in the synchrotron because it is best, from the standpoint of transverse instabilities, to operate with the natural values of the chromaticities. Care must then be taken in the design of the lattice dipoles to limit their sextupole error components. The absence of sextupoles leads to the requirement for continuous Q-correction during the 470 μs injection interval. The sinusoidal guide field is then decreasing to its minimum, and the 70 MeV injection closed orbit moves from the inside edge to the centre of the aperture. The trim quadrupoles are programmed over this interval to keep the Q-values constant. Injection of H^- is from the inside of the ring, with a stationary stripping foil at an inner machine radius and at an azimuthal position between the two quadrupole doublets in a long straight section. Three bump magnets are used in the injection straight to create a fixed closed orbit bump near the foil for the duration of injection, after which the orbit bump is reduced rapidly to zero so that the circulating beam subsequently misses the foil. The acceptance limitation for protons is set after acceleration has started and the injection process is designed for optimum filling of the subsequent acceptance area.

A choice is made of RF harmonic number 1 to minimise the longitudinal space charge forces and to ease the kicker requirements for fast extraction. The range of RF frequency is 0.672-1.545 MHz. The beam current is large so the RF cavities will have capacitive loads directly across the accelerating gaps and there will be RF feedback in the final stage of each RF power amplifier. Four, ferrite-tuned cavities will be provided, each with 3 accelerating gaps. For a full intensity beam the RF voltage amplitude at mid-cycle is 135 kV and the peak RF power requirement 910 kW.

The magnet system has 10, 4.4 m dipoles and 30, 0.6 m main quadrupoles. Magnet cores will be made from 0.5 mm thick laminations of high permeability steel, glued together and mounted on base plates. Excitation coils are wound with stranded conductor and indirectly cooled via tubes embedded in the coil insulation (glass cloth, impregnated with radiation resistant epoxy resin). The dipoles are made from short, parallel-sided blocks, with part laminations used as inter-block wedges to obtain the required curvature (36°). Shims are provided and the end blocks have flared apertures to reduce the eddy-current heating effects. The good field region in the dipoles is 270 mm x 140 mm and the excitation field varies as a biased sinusoid between the levels 0.176 T and 0.697 T. An asymmetric design is adopted for the quadrupoles with an inscribed radius of 124 mm and a usable aperture of 312 mm x 200 mm.

Two alternatives are being considered for the synchrotron vacuum system. In the one design, there is a 'clean' system with separate glass or ceramic chambers in the magnet units so that ion pumps may be used. In the second design, individual magnets are enclosed in a stainless steel vacuum chamber and the pumping must cope with the outgassing from the surfaces of the magnets and the coils. Oil diffusion pumps will probably be used. To reduce the pumping load in this second scheme, investigations are being made of a type of glass enamel for the glueing of the magnet laminations and also the possibility for wrapping the coils and the outer magnet surfaces. The vacuum design is further complicated by the requirement of a thin segmented RF shield within each magnet to reduce the electromagnetic coupling impedance to the beam. The shield must be subdivided or the eddy current losses will be excessive as a result of the large apertures and the 50 Hz field variations.

The specification for the extraction fast kicker magnet is a 200 ns pulsed field of 0.05 T over a gap of 175 mm, a width of 160 mm and a length of 1.4 m, with a maximum rise time of 430 ns. As with all the machine components, care must be taken to limit the transverse and longitudinal coupling impedances to the beam. The total allowable coupling impedances during the 470 μs injection interval are $Z_{\perp}/n$ = 12.5 kΩ/m (transverse) and $Z_{\parallel}/n$ = 40 Ω (longitudinal). The thresholds are higher after the beam has become bunched. With operation always below transition there is reduced possibility for transverse instability of the long beam bunch, provided the dipoles have small sextupole errors so that the synchrotron has its natural chromaticity.

In order to limit the radiation damage to machine elements there will be careful choice of components, good control of the high intensity beam and appropriate use of beam scrapers. Remote handling systems are required for major maintenance.

Synchrotron Parameters

Design Intensity	2.5 10^{13} ppp
Max Kinetic Energy	800 MeV
Injection Energy	70 MeV
Repetition Frequency	50 Hz
Mean Radius	26 m
Bending Radius	7 m
Number of Superperiods	5
Q_v	3.9 (or 3.4)
Q_h	4.2
γ_t	6.4
Length of long straight	7.99 m
β_v (max)	15.4 m
β_h (max)	18.8 m
β_v, β_h (dipoles)	7.2, 14.7 m
α_p (max)	5.7 m
α_p (min)	0.2 m
Rad. acceptance (Area/π)	950 10^{-6} rad m
Vert. acceptance (Area/π)	530 10^{-6} rad m

Target

The proposed target material is depleted Uranium 238 which has a neutron yield roughly twice that of non-fissile heavy metals. The increased production is due to fissions that occur in the interactions with the primary protons and the cascade nucleons and to fissions by the fast evaporation neutrons. The yield of neutrons from the ^{238}U target for 800 MeV incident protons is expected to be 30 neutrons/proton and the heat of production 55 MeV/neutron. At the design intensity the total yield is 4 x 10^{16} neutrons/s and the target heating 350 kW (though the target as designed allows a 20% greater heating). Experiments are being prepared on Nimrod to optimise the target and target-assembly parameters.

Because of the poor thermal properties of uranium, the target is segmented into a number of plates to allow heat removal. Each plate is clad in Zircaloy-2 to provide a corrosion and contamination barrier and is cooled by parallel water flow through 2 mm cooling channels. The length of the target is 300 mm, the cross-section 80 x 80 mm^2 and the total thickness of uranium 250 mm, approximately one range length for 800 MeV protons. The thickness and number of plates are determined by the radial and axial distribution of heat in the target, the maximum acceptable temperature in the uranium, the temperature distribution within a cladded plate, and the type of coolant used.

The beam size at the target is an ellipse with semi-axes 25 mm and 35 mm and the distribution is assumed parabolic. The maximum heat deposition occurs about 30 mm into the target. The maximum temperature in the uranium is set at 600°C, well below the α-β transition temperature; the minimum temperature lies in the range 300°C to 220°C, whilst the temperature at the outside of the cladding is 167°C. Under these conditions cooling by nucleate boiling of water is feasible, with a saturation temperature of 131°C and a channel flow of 12 m/s. The maximum steady state flux from a plate is less than 80% of the 'burn-out' flux and the pulsed effects show only small variation from the steady state values. The plate thickness varies with axial position in the target; however, for simplicity, the 26 plates are grouped into either 3 or 4 batches of constant thickness. The expected target lifetime will be in the range of 10 to 25 weeks.

Moderators and Reflector

Adjacent to the target will be moderators operating at ambient or sub-ambient temperature and surrounded by a reflector. A possible horizontal target arrangement is illustrated schematically in Figure 2. There are 2 moderators, each with 7 beam tubes viewing one of its surfaces, and serving perhaps 15 instruments in all. In the configuration shown, the moderator arrangement prevents fast neutrons from reaching the experimental areas directly. The number of neutrons from the moderator is improved substantially by the use of a beryllium reflector of dimensions 800 x 800 x 400 mm^3. The resulting neutron flux at the 100 x 100 mm^2 moderator surface is estimated to be, at 1 eV, approximately 10^{13} neutrons/(eV · ster · s).

Shielding

Shielding for the incoming 800 MeV beam transport line and the target station will reduce the radiation levels in the experimental area to permissible biological levels. The required thickness of the main bulk shielding material, steel, is approximately:

800 MeV proton beam line	2.5 m
Target forward direction	5 m
At 90° to target	4 m (horizontally) 3 m (vertically)

In addition, a number of intermediate layers of concrete at the target station will absorb low energy neutrons. This increases the shield thicknesses by some 20%. Lead may be used in some local areas where concrete is unsuitable. High density linings are planned for the beam holes and other channels through the shielding.

Induced Radioactivity in Target

There is a gradual build up of induced radioactivity in the target. When the source is operated at full intensity, the long-lived radioisotope ^{239}Pu is produced at the rate of about 2 g/month. Of more consequence is the volatile radioisotope ^{131}I, a fission product of ^{238}U, for which the saturation activity is of the order of 10 kilocuries. The total activity one day after shutdown is of the order of 100 kilocuries. Irradiated targets will be handled entirely by remote methods and the target design conforms with appropriate safety standards.

Scientific Use of Source

The scientific case for providing the facility has been based on the work of four groups of UK scientists covering the fields of solid state physics, fluids and amorphous solids, molecular and biological sciences and structure determination. The advantages of the SNS source stem from its pulsed nature and very high peak intensities, especially in the short wavelength region of the spectrum. This implies, particularly when compared with a reactor source:

a. Wide regions of momentum and energy transfer are accessible to the experimenter. The available domain of $(Q,\hbar\omega)$ is expected to be between (0.3 Å^{-1}, ∿ 0 eV) and (100 Å^{-1}, ∿ 0.5 eV).

b. Measurements can be made at higher rates of data collection.

c. Improved resolution will be available, particularly at higher energy transfers.

d. Smaller crystals and samples may be used.

e. Experimentation will also be possible on samples which are 'small' in the geometrical sense (eg surfaces or thin films) or in the chemical sense (eg dilute solution where the behaviour of the solute is of particular interest).

f. The use of fixed scattering angle enables studies of samples to be undertaken under extreme conditions of temperature and pressure.

g. The use of energies up to and beyond 1 eV allows studies of highly absorbing samples and promotes the use of anomalous scattering techniques.

h. Kinematic corrections at high incident energies, particularly for fluid systems, are smaller and better controlled.

The very high flux of 'hot' neutrons is likely to lead to new and unexpected experiments, just as occurred with the availability of 'cold' neutrons at the high flux reactor in the Institut Laue-Langevin, Grenoble.

Possible Future Developments

A second experimental hall is available for future developments. One possible use is the installation of a second neutron target station. Alternatively, the hall is suitable for developing as a multi-disciplinary facility, using protons, neutrons, pions or muons derived from the SNS beam. For many applications, a stretcher/storage ring is desirable to modify the duty-cycle of the SNS beam. Two separate modes of operation of such a storage ring have been examined; one a long duty-cycle mode and one with a proton beam in the form of 5 ns pulses spaced at about 1 μs time intervals.

Cost of SNS

The estimated capital cost of the new accelerator components, target station and neutron scattering instruments is approximately £10M. The cost would be about three times greater were it not for the availability of the existing buildings, services and components.

References

1. J M Carpenter and D L Price, 'An intense pulsed neutron source for Argonne National Laboratory', Proc. U.S. National Acc. Conference, IEEE Trans. Nucl. Sc. NS-22, No. 3, June 1975, p.1768.

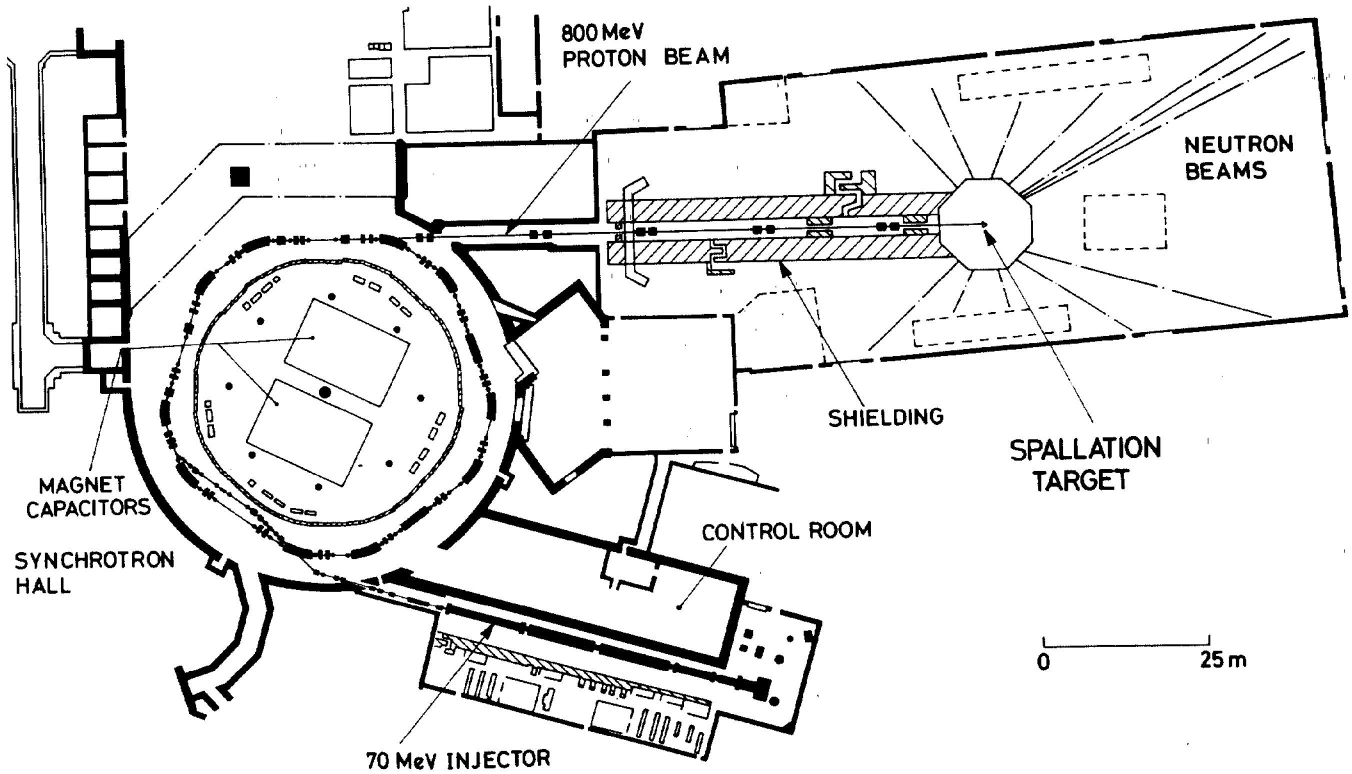

FIG.1. SPALLATION NEUTRON SOURCE

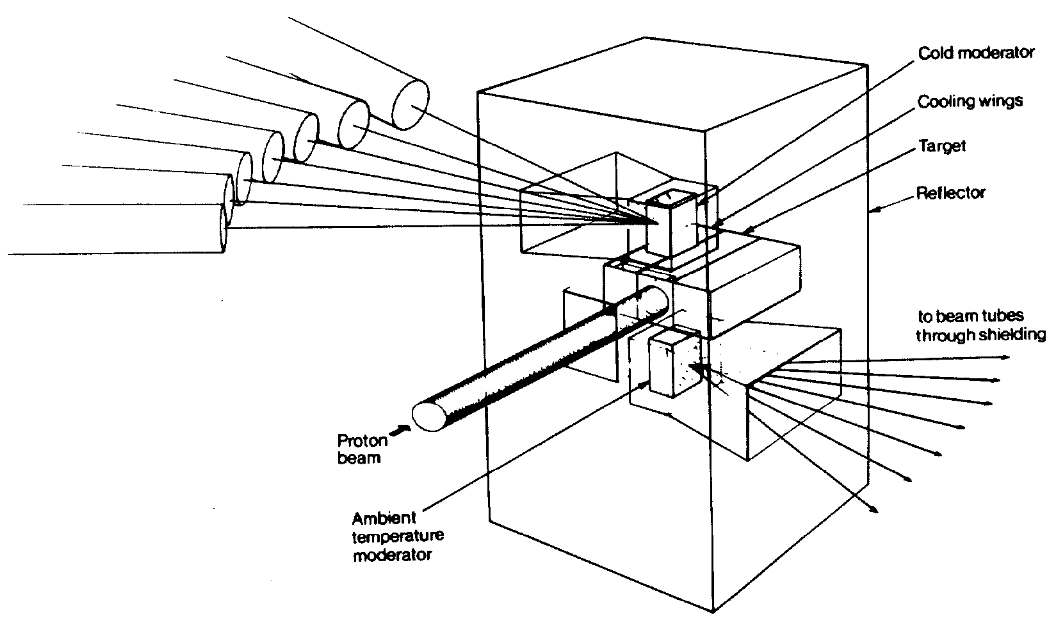

FIG.2. SCHEMATIC OF CENTRAL REGION OF TARGET STATION