SYNCHROTRON-DRIVEN SPALLATION SOURCES

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1 INTRODUCTION

The use of synchrotrons for pulsed neutron spallation sources is an example of spin-off from the accelerator development prompted by particle physics. The first proposal for an accelerator-driven source with a thermalised neutron facility was in the 1960s (Intense Neutron Generator, ING) [1], but this project was never built. There was earlier work on 'electrical' breeders [2] and the direct bombardment of a heavy-metal target for spallation had already been foreseen by Lewis [3], but the first demonstration of the spallation source concept was at ANL in 1972 (ZGS Intense Neutron Generator Prototype, ZING-P). A spallation source uses a medium-energy accelerator to excite the nuclei of a heavy-metal target (often Ta or W alloy), from which neutrons 'evaporate'. These 'fast' neutrons are slowed in moderators set around the target. Neutrons make excellent probes for condensed matter [4] as their neutrality ensures deep penetration, their magnetic moment reacts to magnetic structures and their weak interaction minimises radiation damage allowing *in vivo* experiments. Neutron sources are widely used in biology, chemistry, materials science and basic physics, as well as for technological applications such as radiography and materials testing. Spallation sources are environmentally friendly compared to reactors. The time structure of accelerator beams offers some experimental advantages and peak neutron intensities can exceed those of reactors. Although, the present demand for neutrons can be met by reactors, this situation is unlikely to continue due to the increasing severity of safety regulations and the policies of many countries to close down their reactors within the next decade or so. At the same time, the demand for neutrons is expected to grow and, consequently, there has been an increasing interest in accelerator-driven sources.

II. BASIC REQUIREMENTS

Figure 1 shows the generic pulsed neutron source. The target receives short (≈µs), high-intensity, proton pulses with repetition rates of typically 10-60 Hz. The intensity should be as high as possible, as the appetite of the users is currently beyond what the accelerator and target designers can provide. The pulses are formed by accumulating protons from an H^- linac by charge-exchange injection into a large-aperture synchrotron, or accumulator ring, that is filled to its space-charge limit. The final energy of the beam needs to be 500 MeV to 4 GeV, but these are soft limits. The synchrotron can be used to perform the major part of the acceleration (*synchrotron-driven source*), or it can be used as an accumulator/buncher leaving all the acceleration to the linac (*linac-driven source*).

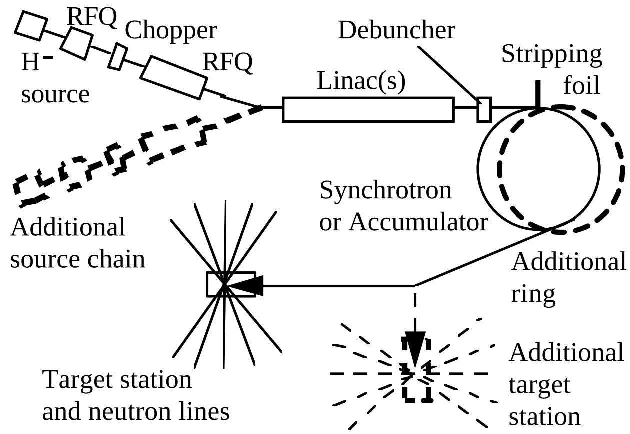

Figure 1: Generic complex for a pulsed source.

When deciding the design of a spallation source, there are a number of practical considerations to be taken into account:

1 In general, it is cheaper to accelerate in a synchrotron than a linac. Fast-cycling synchrotrons typically work over a range of less than 1 to 8 in magnetic field. This keeps the top field below saturation and avoids tracking problems between the different magnetic circuits. By using two synchrotrons of 25 Hz interleaved to produce 50 Hz, many problems can be eased.
2 The higher the injection energy into the synchrotron, or accumulator, the weaker the space-charge and the higher the intensity that can be stored. There is a soft threshold at around 130 MeV, below which the losses are more tolerable from the point of view of induced activity. At this energy, it is also natural to change from an Alvarez to a coupled-cavity linac and go straight to say 800 MeV, or higher. It is true that the injection losses are more potent at higher energies, but it is hoped that a static accumulator is easier to operate than a rapid-cycling synchrotron so that losses can be reduced. At high energies, charge-exchange injection experiences problems with magnetic-field stripping.
3 The targets have a natural threshold at around 200 kW, above which surface cooling is no longer feasible and either the coolant becomes directly irradiated by the beam, or a more complicated dynamic (e.g. rotating) target is needed.

Synchrotron-driven sources should work well up to 1 MW average power with final energies in the range 0.5-2 GeV. Linac-driven sources are planned for 1-5 MW with final energies in the range 0.8-1.5 GeV. For higher powers, one can speculate on the future use of superconducting linacs of 3 GeV or so. Table 1 lists the operating, planned and proposed sources of various types, including the continuous, cyclotron-driven sources, such as SINQ at PSI. The following sections, however, refer to synchrotron-driven sources, although many of the considerations apply equally to the accumulator ring in the linac-driven option.

III. INJECTION, RF-TRAPPING AND ACCELERATION

The injection into the synchrotron is the natural starting point for the design of the complex. This is a critical point regarding space charge and it determines the intensity, emittance, momentum spread, duty cycle, debunching and chopping to be achieved in the injection chain. It also determines the final beam characteristics and apertures in the synchrotron and extraction line.

A. Charge-exchange injection

Charge-exchange injection was pioneered in Novosibirsk [17] and is now the preferred method for injection into high-intensity machines. A beam of H^- ions is steered onto a closed orbit in the synchrotron between two dipoles (see Figure 2). This is possible, since the dipoles will bend oppositely charged particles in opposite directions. In the drift space where the two beams coincide, both pass through a thin foil, which strips away the weakly-bound electrons from the H^- ions to create protons for the main beam. Those particles that are not stripped, or are stripped to the H^o charge state, will be separated from the circulating beam by the next dipole. The stripping foil can be made from aluminium oxide. It is a critical element and a good example of the specialised technologies that abound in accelerator engineering. The fringe field of the dipoles is used to guide the stripped electrons onto a collector. The beam could also be injected onto an outer orbit, but the scheme in Figure 2 is more natural, since the injection takes places just before the field minimum and the falling field causes the newly injected beam to spiral outwards from the foil so filling the machine aperture. Making the injected beam cross the main beam also represents a saving in the aperture of the dipoles.

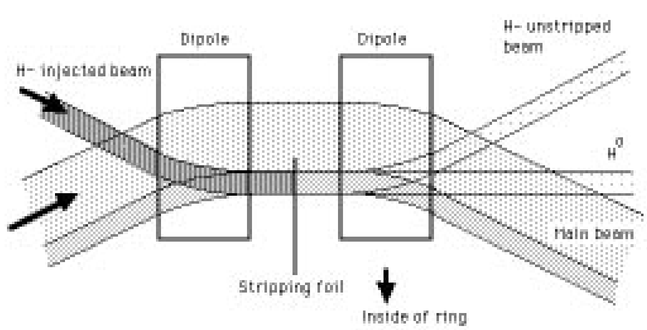

Figure 2: Schematic view of H^- injection.

Typically the stripping foil will be 98% efficient with the 'waste' beams emerging as unstripped ions and neutral H^o particles (some of which may be in excited H^{o*} states). Figure 2 suggests that the simple solution of collectors placed outside the main beam will lead to a very clean injection. At low energies (< 500 MeV), this is possible, but at higher energies strong (and especially inhomogeneous) magnetic fields can strip H^- ions and H^{o*} excited states leading to distributed losses that cannot be collected cleanly. For this reason, higher energy injection schemes use a single, long, weak dipole. It is desirable at high energies to bring the H^o beam right out of the machine before collecting it, but the small angle given by a weak dipole makes this difficult. In the European Spallation Source (ESS), a second stripping foil is proposed in the H^o and H^- beams followed by a septum magnet, once they have left the main beam.

B. 'Painting'

The transverse emittances of the linac beam are small compared to the synchrotron acceptance and 'painting' is used to fill the machine acceptance to its space-charge limit. Ideally, a Kapchinskij-Vladimirskij (K-V) distribution is created by injecting a zero-emittance beam over *N* turns, on the locus shown in Figure 3(a). The position of the *n*th injected pulse [$x(n),z(n)$] with respect to the closed orbit in the synchrotron follows a square-root law as shown in Figures 3(b) and (c). 'Painting' occurs over hundreds of turns (e.g. AUSTRON- 130, SNS-ISIS at RAL- 200, PSNS at BNL - 300, IPNS-Upgrade at ANL- 500 and ESS- 1000 turns).

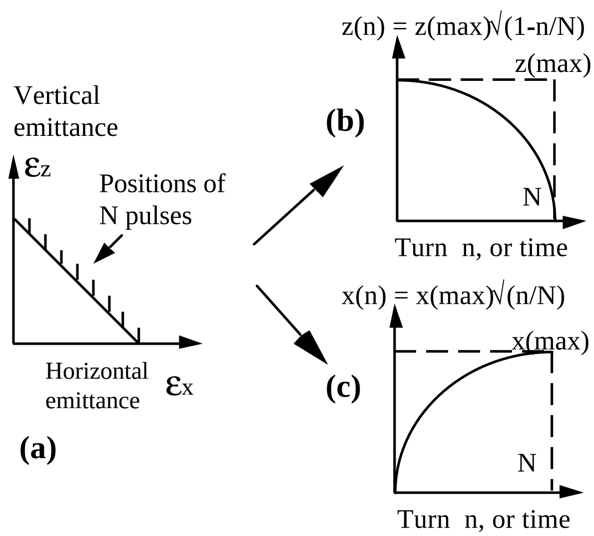

Figure 3: 'Painting' a K-V distribution.

The sinusoidal fall of the main field is not ideal for 'painting' so the position of the beam's equilibrium orbit has to be controlled in another way. This can be done by fast bumpers in both planes, starting with the maximum vertical amplitude and minimum horizontal amplitude and sweeping through to the opposite situation. Two sets of bumpers may be difficult to fit into the synchrotron lattice, so one alternative is to sweep vertically using a bumper in the transfer line. Another possibility is to use a cavity in the injection line to modulate the beam energy while injecting into a region of high dispersion in the synchrotron. This is proposed for the ESS in conjunction with a 'corner' stripping foil (see Section IIIC).

			into ring(s) [MeV]	energy [GeV]	power [MW]	pulse [kJ]
IPNS [1], ANL, USA	Operational 1981	Synchrotron-driven	50	0.5	0.0075	0.25
KENS-I, KEK, Japan	Operational 1980	Synchrotron-driven	40	0.5	0.005	0.25
SNS-ISIS, DRAL, UK	Operational 1985	Synchrotron-driven	70	0.8	0.16	3.2
LANSCE, LANL, USA	Operational 1977	Linac-driven	800	0.8	0.08	3.9
TNF, TRIUMF, Canada	Operational 1974	Cyclotron-driven	-	0.5	0.15	-
SINQ, PSI, Switzerland	Operational 1996	Cyclotron-driven	-	0.59	0.9	-
LANSCE-II, USA	Study	Linac-driven	790	0.79	1 (5 upgrade)	16.7
IPNS-Upgrade, ANL, USA	Study	Synchrotron-driven	400	2.0	1	33
PSNS, BNL, USA	Study	Synchrotron-driven	600 (2 rings)	3.6	5	83
ANS, Moscow, Russia	Study	Synchrotron-driven	1000	10	5	100
AUSTRON III, Austria	Study	Synchrotron-driven	130	1.6	0.41	8.2
KENS-II, KEK, Japan	Study	Linac-driven	1000	1.0	0.2	4
ETA-based SNS, Japan	Study	Linac only	-	1.5	15	150 (1 ms)
ESS [3], Europe	Study	Linac-driven	1334 (2 rings)	1.334	5	100

Table 1: Operational, planned and proposed spallation sources.

1) The Intense Pulsed Neutron Source was preceeded by the ZING-P’ (1972), which was the proof-of-principle for the spallation s
2) Split frequency indicates pulse sharing between two targets.
3) ESS also has a synchrotron-driven option using two rapid-cycling synchrotrons operating from 800 MeV to 3 GeV with the sam

C. Stripping foil traversals

Figure 4 illustrates some foil geometries. In Figure 4(a), the equilibrium orbit of the beam is moved to the right by a horizontal bump, so increasing the horizontal emittance, while the injection spot is scanned downwards by a bumper in the injection line. In Figure 4(b), the bottom half of the foil is removed to reduce unwanted traversals. Figure 4(c) shows a 'corner' foil. In this case, bumps move the equilibrium orbit diagonally. More aperture is needed in the injection region, but this case does offer fewer foil traversals.

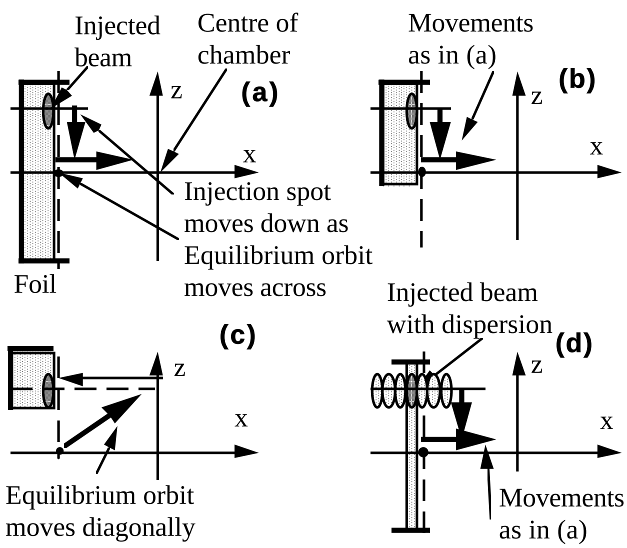

Figure 4: Stripping foil geometries (real space).

Injection usually occurs into a dispersive region of the lattice and the question arises as to whether the linac beam should be dispersion-free or matched to the ring. A dispersion-free beam is smaller and can be drawn off the foil faster, despite the fact that it suffers an emittance dilution due to the dispersion mismatch. On the other hand, the dispersion-matched beam (typically D=5 m, β=1 m) offers a special advantage with the 'strip' foil in Figure 4(d). The 'strip' foil will select a narrow momentum bite from the beam, while allowing the off-momentum halo to leave the machine along the same path as the unstripped ions.

D. RF trapping and acceleration

In synchrotron-driven sources, the rate of energy rise is usually too high for the trapping to be fully adiabatic and a tracking program that includes space charge is needed. When designing the RF programme, the optimisation is directed to reducing particle losses. Apart from the losses that occur directly from the RF bucket, limits have to be set upon the incoherent tune shift that affects losses on non-linear resonances and the momentum spread that affects the aperture. The description below is based on the design experience gained with the AUSTRON, but the basic features should be universal.

The RF cycle splits naturally into four stages starting with the injection and trapping that takes place on the falling magnetic field just before the minimum. The RF voltage is applied smoothly from a very low value and rotation in the bucket is optimised for uniformity of filling. The leading particles rotate by ~90° during injection and reach ~180° at the field minimum. Too much voltage during this first stage will increase the momentum spread in the next step. The second stage starts at the minimum field point and continues to where the momentum spread is maximum (the incoherent tune shift peaks a little earlier). This first critical point occurs typically 1 to 2 ms into the acceleration and, since the adiabatic damping has had little time to be felt, the beam reaches its maximum radial size in the dispersive regions. The smoothness and rate of rise of the RF voltage are optimised to reduce losses. Once this aperture limit is past, the third stage is entered, which runs until the middle of the acceleration cycle when the synchronous phase angle is maximum. During this stage, the RF voltage has to be increased smoothly and rapidly to maintain the bucket area. The fourth and final stage up to the top energy poses no particular problems.

One way to reduce losses during trapping is to pre-bunch the beam by chopping at a much lower energy in the injection line. This scheme features in the proposals for most future machines. Gaps of 25-40% are usually considered.

IV. LATTICE AND RESONANT SUPPLY

In order to keep the voltages applied to the magnet coils within reasonable limits (i.e. <10 kV for safe operation), the lattice should be divided into as large a number as possible of identical cells. One solution is to select an asymmetric cell (to get long and short drift spaces) and to contrive to fit all functions into these cells. SNS-ISIS follows this philosophy with 10 identical cells. At higher energies, a custom-designed lattice with superperiods becomes essential. To keep the voltages down, the upper and lower magnet coils can be separated to increase the number of identical cells as 'seen' by the resonant supply. Magnet lengths are adjusted so that field levels and saturation effects are about equal in quadrupole and dipole circuits. At around 1 GeV, a threefold symmetry is popular (e.g. AUSTRON, ESS). Fast-cycling machines use a resonant circuit with DC-biased, AC excitation known as the 'White circuit' [18,19].

V. RF-CAGE

Fast-cycling machines use insulating (ceramic) vacuum chambers to avoid power loss and field distortions due to eddy currents. To reduce static charging of the chamber walls, define the beam potentials and reduce the longitudinal transverse space-charge impedances, which are proportional to the g-factors, metallic RF shields are used that ideally follow the beam contours. A proven design for RF shields is the stainless steel cage of axial wires with vertical side plates used in the SNS-ISIS machine, but thin metallisation of the chamber walls has been discussed as an alternative. Recent analytical work on the fields excited by longitudinally and transversely modulated beams in a wire cage can be found in [20] with approximations for the *g*-factors in [12]. The *g*-factors for a beam with elliptical cross-sectional variations in a circular, metallised chamber are also reported in [12].

VI. TRANSFER LINES

The transfer line from the linac to the ring will exhibit strong space-charge forces that will be of importance for the calculation of the debunching cavity. The injection line may also require a bend and a long straight section for momentum and betatron collimation to limit losses at injection (e.g. ESS). Space-charge effects are minimal in the high-energy, large-aperture extraction lines. A transmission target (≤ 5% interception) may be proposed for a muon experimental area and this will require a zero-dispersion, low-β insertion in the line. The background from a muon-target will need shielding and a bend in the line before entering the neutron experimental area is advisable. In order to have the maximum space for neutron lines, the target can be entered vertically (e.g. SINQ). However, this does complicate maintenance in an area that is likely to have a high level of induced activity.

VII. RADIATION MANAGEMENT

The high intensity and repetition rate of pulsed spallation sources makes radiation management of prime importance. The activation of the exhaust air and waste water must be monitored and kept below limits agreed with licensing authorities. Ventilation systems need low replacement rates (< 2 per hour). High-loss areas can be sealed and the air slowly leaked to lower-loss areas. An under-pressure is needed to prevent out-leaks. Storage of active air may be needed. All exhaust air must be filtered to remove ^{7}Be and other aerosols. Intermediate storage of waste water, shielding of ground water and secondary cooling circuits are all standard considerations. The degradation of materials such as the coil insulation needs to be estimated and radiation-hard elements used in critical places. Remote handling will be needed for the stripping foil. Care must be taken concerning dust, especially from fractured stripping foils, and exhaust air from roughing pumps must be filtered. Tight tolerances and high efficiencies for the collimator and beam control systems will be needed and machine operation should be interlocked to a beam loss measurement system. Where losses are not continuous, aluminium vacuum chambers show less induced activity than steel ones, but for steady losses over many years the reverse can be true due to the build up of ^{22}Na. Similarly, 'heavy' concrete has a shielding advantage, but after many years it can build up more long-lived isotopes than ordinary concrete.

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