SYNCHROTRON-BASED SPALLATION NEUTRON SOURCE CONCEPTS

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Abstract

During the past 20 years, rapid-cycling synchrotrons (RCS) have been used very productively to generate short-pulse thermal neutron beams for neutron scattering research by materials science communities in Japan (KENS), the UK (ISIS) and the US (IPNS). The most powerful source in existence, ISIS in the UK, delivers a 160-kW proton beam to a neutron-generating target. Several recently proposed facilities require proton beams in the MW range to produce intense short-pulse neutron beams. In some proposals, a linear accelerator provides the beam power and an accumulator ring compresses the pulse length to the required ≈ 1 µs. In others, RCS technology provides the bulk of the beam power and compresses the pulse length. Some synchrotron-based proposals achieve the desired beam power by combining two or more synchrotrons of the same energy, and others propose a combination of lower- and higher-energy synchrotrons. This paper presents the rationale for using RCS technology and a discussion of the advantages and disadvantages of synchrotron-based spallation sources.

1 INTRODUCTION

Since the late 1970s, four accelerator-based pulsed neutron sources were constructed. They are: Intense Pulsed Neutron Source (IPNS) at ANL (US), KEK Neutron Source (KENS) at KEK (Japan), ISIS at Rutherford-Appleton Laboratory (UK), and Los Alamos Neutron Science Center source (LANSCE) at LANL (US). IPNS, KENS, and ISIS use synchrotron technology to provide the beam power, and LANSCE uses a linac and a compressor. These accelerators typically operate at a 20- to 50-Hz repetition rate with a ≤ 1-µs beam pulse length. All three synchrotron-based pulsed neutron sources have very productive scientific records, and their reliability and availability have been outstanding.

A review of today's technology along with the experience, knowledge, and skill gained from the past 20 years of pulsed spallation source operation around the world is appropriate when formulating concepts for a new source. That includes: 1) The neutron-yield from proton bombardment of a heavy element is roughly proportional to the proton beam power, independent of beam energy. It was previously believed that the optimal proton energy was 800 to 1000 MeV. That a higher-energy proton beam is equally good for neutron generation has important implications in the choice of the accelerator system configuration. 2) Beam loss prevention is extremely important in order not to produce activated accelerator components. 3) High-duty-factor H^- sources need further development to operate reliably.

The feasibility studies since 1990 center around either a linac/compressor ring (CR) arrangement [1, 2, 3, 4] or an RCS concept [2, 5, 6, 7, 8] to reach 1 to 5 MW of beam power. A review of these concepts shows that the beam energy of linac/compressor ring schemes tends to be about 1 GeV, or substantially lower than that of RCS based schemes. The 1-GeV energy choice comes from:

- High linac construction and operating costs and
- Higher-energy H^- ions are more likely to undergo magnetic stripping, causing beam loss.

Synchrotron energies are not limited, but it is difficult to achieve high currents. The record number of protons per synchrotron pulse is 7×10^{13} at the AGS; the record average current is 200 µA at a 50-Hz repetition rate at ISIS. In RCS-based schemes, H^- ions are also used in the injector linacs. The energies tend to be lower, so the H^- velocity is low, avoiding magnetic stripping.

Since neutron yield is proportional to beam power and essentially independent of energy, a synchrotron can be used as a multi-MW proton source. Synchrotrons deliver lower beam current than linacs, but the energy tends to be substantially higher for the same beam power.

The requirements and desirable features of spallation sources are discussed below, along with a detailed description of design steps to achieve the performance goals of a source based on synchrotron technology.

2 PROTON SOURCE PARAMETERS

The proton source for a spallation neutron source has to meet two important criteria. First is the required average beam power, which is proportional to the time-averaged neutron flux. A 30-MeV proton produces one external thermal neutron; thus, a 1-GeV proton can produce 30 thermal neutrons in a well-designed spallation source. Compare this 30 MeV to the 270-MeV required to produce one external thermal neutron in a reactor. We see that a 5-MW spallation source produces as many neutrons [time-integrated] as a 50-MW reactor.

The second important criterion is the time structure of the proton beam including both the proton beam pulse length, and the beam pulse repetition rate. A typical pulse length at existing sources is 100 to 300 ns. The neutron moderation time in a typical moderator is 10 to 20 µs, so a proton beam pulse-length less than 1 µs is desirable since it has little effect on the neutron beam pulse structure after moderation. The repetition rate controls the peak neutron flux and the time between pulses; it is perhaps the most important time parameter.

The peak flux is usually expressed in terms of the average flux divided by the beam duty-factor. The duty factor of a thermal neutron beam is the product of the moderation time and the repetition rate. Moderation times of 20-Hz and 60-Hz sources are similar; thus, the duty factor of a 20-Hz source is a third of that of a 60-Hz source. The peak flux of a 20-Hz source is three times that of a 60-Hz source with the same beam power, though both sources provide the same time-integrated number of neutrons to their experimenters.

Figure 1 [9] shows the increase in "effective" thermal neutron flux since the discovery of the neutron in 1932. For a pulsed source, the figure represents its peak flux, and for a steady-state source, it represents the steady-state flux. To use a steady-state source for neutron scattering experiments, the steady-state beam must be chopped to allow time-of-flight (TOF) measurements of the neutron energy to be made. The time that the beam is blocked during a TOF measurement at a steady-state source is equivalent to "the time between pulses" at a pulsed source. A lower repetition rate at a pulsed source gives a longer time between pulses, and avoids "frame-overlap."

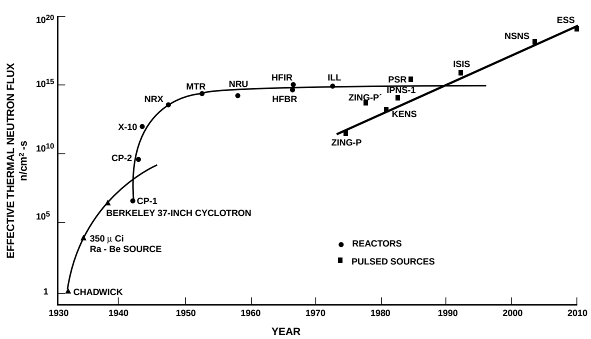

Figure 1: Increase in effective thermal neutron flux since the discovery of the neutron in 1932.

If a neutron scattering instrument is located 15 m from a neutron-generating target at a machine with a 60-Hz repetition rate, neutrons with wavelength λ=0.5 Å arrive at the detector in ~2 ms, 2.5-Å neutrons arrive in ~9 ms, and 5-Å neutrons arrive in 18 ms. Pulses at a 60-Hz machine are separated by 16.6 ms. Frame overlap causes confusion and occurs because the 5-Å neutrons arrive at the detector at the same time as faster neutrons from the next pulse. This is shown in Figure 2.

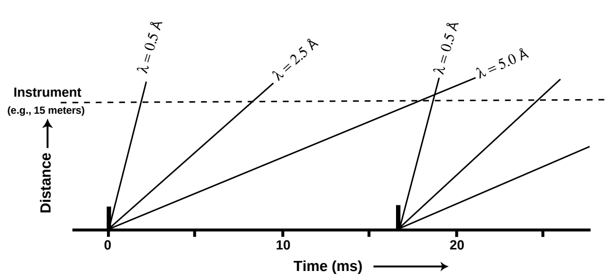

Figure 2: Frame overlap: Slow neutrons from one pulse and fast neutrons from the next pulse arrive concurrently.

A recent scientific case workshop [10] determined that about half of the 40 neutron scattering instruments being considered for the Oak Ridge spallation source prefer 20 Hz to avoid frame-overlap problems. The Oak Ridge source is designed for 60-Hz operation, with one target operating at 60 Hz and the other at 20 Hz. The 20-Hz target receives 1/3 of the accelerator beam power.

For a fixed beam power, a proton source operating at the lower repetition rate is preferred as this discussion indicates.

3 RATIONALE FOR USING SYNCHROTRONS

There are several reasons to consider synchrotrons as base accelerators for multi-MW spallation source designs. Since neutron yield is proportional to beam power, one can do trade-offs between the repetition rate, average current, and energy for a given beam power.

3.1 Repetition Rate

A synchrotron-based facility is capable of achieving high power at a low repetition rate and with a reasonable construction cost. A 20- to 30-Hz multi-MW short pulse source based on RCS technology can be less costly to build than a linac-based source.

3.2 Beam Loss Considerations

The most important consideration for a high-power short-pulse proton accelerator system is the prevention and control of beam loss during injection, acceleration, extraction, and transport. Excessive beam loss makes hands-on maintenance, service, and repair of the accelerator extremely difficult, and remote handling capabilities are required. Substantially fewer protons must be accelerated in a synchrotron compared to a linac-based source, as illustrated by the following example:

A 1-GeV linac/compressor ring requires a beam current of 5 mA to achieve 5 MW of beam power. A 10-GeV synchrotron needs 0.5 mA, a factor of 10 fewer protons than the linac, to achieve the same power level. The factor of 10 difference implies that beam-loss control in the linac must be a factor of 10 better than in the synchrotron. If a 0.1% beam loss is acceptable for the synchrotron, the linac/accumulator ring must operate with less than 0.01% beam loss. The least beam loss routinely achieved in existing circular accelerators is a few percent. An extensive simulation study to understand the causes of early beam loss in circular accelerators was recently performed [11]. The study concluded that a carefully designed injection system and an appropriately chopped linac beam, together with programmable radio-frequency acceleration, could achieve loss-less injection, capture, and acceleration to within the accuracy of the simulation.

3.3 Availability of Negative Hydrogen Ion Sources

A third factor is the availability of an ion source suitable for a short-pulse proton source. A beam of negative hydrogen ions is injected into a circular machine (RCS or compressor ring) through a stripper foil, removing two electrons from each H^- ion and leaving a beam of protons circulating inside the circular machine. This charge exchange injection is used to “paint” the circular accelerator's transverse phase-space acceptance. Phase-space painting shapes the particle phase-space distribution and minimizes undesirable space-charge effects. Use of a thin foil permits multi-turn injection while ensuring that the circulating beam does not hit the inflector magnet, as would be the case for injection of a positive beam. Limited injection efficiency and severe beam loss, obvious results in that case, are avoided.

The H^- ion source requirements for various proposals differ substantially, but source emittance, peak current, repetition rate, pulse-length, and duty factor, the product of repetition rate and pulse-length, are all important. All requirements must be achieved simultaneously, and demonstrated reliability and availability are essential.

In October 1994, at a workshop on ion source issues relevant to pulsed neutron sources, details of required performance parameters for all proposed concepts were presented and discussed [12]. A conclusion of the workshop was that there was only one H^- ion source capable of delivering the required peak current, duty factor, and proven reliability and availability, and that was the ISIS ion source. Its best performance could meet the ANL concept's minimum requirement of 50-mA peak current and 1 to 1.5% duty factor. The workshop recommended intense R&D efforts to improve ion source performance. Some proposals require 70-mA peak current and 12% duty factor, and although there has been much progress in ion source development, no source operates reliably at 70 mA and 6 to 12% duty factor.

The synchrotron-based source, which relies on high energy rather than high current, makes the least demand on ion source performance. With small improvements, an ISIS-type source can satisfy its requirements.

3.4 Cascading Synchrotron Concept and Upgrade Path

The fourth reason is that a cascaded synchrotron facility can have a well-defined upgrade path, reaching high power operation in stages. Recently, there have been three independent feasibility studies of synchrotron-based 5-MW spallation sources [2, 5, 7]. Of the three, two (Brookhaven National Laboratory [5] and the European Spallation Source [2]) are based on two equal-energy (~ 3 GeV) synchrotrons to achieve 5 MW. The required beam current is ~ 1.6 mA in this configuration. The Argonne National Laboratory study also has a two-synchrotron arrangement, but with low- and high-energy machines [7]. The low-energy (2-GeV) synchrotron is the booster injector for the high-energy (10-GeV) one. The required beam current to reach 5 MW with the 10-GeV machine and 1 MW with the 2-GeV machine is 0.5 mA. The ANL system accelerates a factor of three less protons than the stacked-synchrotron schemes and has less stringent requirements on ion source performance. This concept of a 2-GeV ring followed by a 10-GeV ring to achieve a 5-MW facility can be used to implement a two-step construction program. A 1-MW facility is built and operated first, and the 5-MW facility is built later.

4 SYNCHROTRON DESIGN FEATURES

4.1 Lattice

Desirable features of the lattice are very high transition energy, dispersion-free straight sections, and straight sections that are long enough to accommodate the ~20-m-long radio-frequency cavity system.

The synchrotron should be operated below the transition energy for best beam stability. Furthermore, in order to have a large slip factor, $\eta = 1/\gamma^2 - 1/\gamma_t^2$, the transition energy, γ_t, should be as large as possible. A large η makes the instability thresholds due to high currents high, makes faster synchrotron motion, and makes rf voltage programming easier. Dispersion-free straight sections are desired to allow 6-dimensional phase-space painting without momentum and radial position correlations. Placing the rf systems in dispersion-free areas eliminates synchro-betatron coupling.

A 2- to 3-GeV synchrotron operating at 20 to 30 Hz with a revolution frequency of 1 MHz may require a peak rf voltage of ~200 kV. For neutron generating purposes, the rf system’s harmonic number should be 1 or 2, thus, the rf frequency is 1 to 2 MHz. In this frequency regime, the typical voltage gradient one can obtain is ≈10 kV/m. Depending on lattice details, the required rf straight section length could be 20 or 30 m.

One can use a FBDB type cell with ~ 90° phase advance in each of the transverse planes to incorporate all of these features. The choice of 90° allows a large horizontal tune, which is proportional to γ_t. A dispersion-suppressor cell can be made by removing one dipole from the normal cell. A long dispersion-free space is obtained by adding FODO (standard normal cells without dipoles) to dispersion suppressor cells. Figure 3 shows a lattice designed for the ANL 2-GeV RCS. Normal, dispersion-suppressor and FODO straight-section cells are shown. A 10-GeV lattice can be designed with similar features [7].

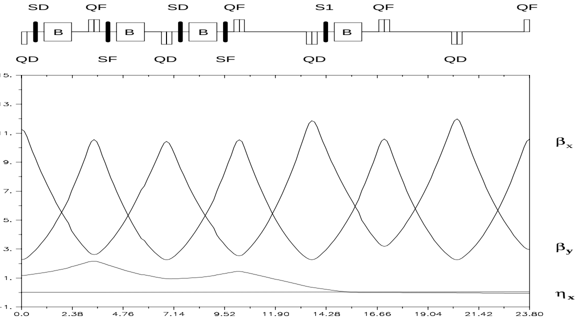

Figure 3: Lattice functions for 1/2 superperiod.

4.2 Acceptance, Injection Energy, Space-charge Limit, and Injection

Using the lattice beta-function and reasonable magnet apertures, one can choose the ring acceptance and the beam-stay-clear region (BSC). We define the acceptance as the phase space on which the injected beam is stacked. The BSC is a larger phase-space area, providing extra space to allow for misalignment tolerances. The physical space between the acceptance and the BSC is used for scrapers and catchers to handle beam loss in a controlled manner. The ratio between the two phase-space areas is a matter of choice. The ANL design has a 750 π mm mr BSC and a 375 π mm mr acceptance. The 750 π mm mr BSC gives a magnet aperture similar to that of ISIS.

The synchrotron injection energy is determined using the following assumptions and steps. In all synchrotrons, beam loss occurs during the injection, capture, and early acceleration processes, during which time space-charge effects are most severe. Space-charge effects manifest themselves in terms of an incoherent betatron tune shift. Typical values of the tune shift for operating machines vary from 0.25 to 0.5 or greater. To eliminate beam loss originating from this effect, the ANL design uses a tune shift of $\Delta\nu = 0.15$. Since the space-charge limit, the maximum number of protons one can inject into a ring, is proportional to $\Delta\nu$, $\beta^2\gamma^3$ of the incoming beam, and the acceptance, one can obtain a unique relationship between the space-charge limit and the injection energy with fixed values of the acceptance and $\Delta\nu$. Details of this discussion can be found in reference [6].

The injection process involves two considerations. Transverse phase space must be filled so as to minimize space-charge effects, and the longitudinal phase space must be filled so as to assure 100% rf capture while compensating for longitudinal space-charge effects.

Two extensive studies using two different schemes addressed transverse phase space filling. The ESS study [2] favors a correlated injection to do radial space and momentum space painting. This method requires a large dispersion function at the injection stripper and ramping of the linac energy during injection to coincide with the radial phase-space area and the bucket height in longitudinal phase space. To accomplish this, the instantaneous energy spread of the linac beam must be very small. The demand on the linac performance is somewhat high. The ANL study [6] uses a completely uncorrelated filling of radial, vertical, and longitudinal phase spaces. This method requires zero dispersion at the stripper, no ramping of the linac energy, and an energy spread equivalent to the bucket height, which is about 0.5% of the linac energy.

In the longitudinal filling, both studies require chopped incoming linac beam to avoid capture losses. The chopping varies from 60% to 75% and is done near the ion source or at very low energy. “75% chopping” means that 75% of beam is used and 25% is discarded.

4.3 Capture, Acceleration, and Rf Voltage Program

An extensive study of the capture and acceleration processes for the ANL 1-MW source was performed using Monte Carlo tracking techniques. A unique feature of this study was that the initial phase-space coordinate of each tracked particle was recorded. Initial phase-space positions of particles lost during the capture process are known, so capture losses are prevented if that phase space is not filled. Tracking results also show how best to chop the beam to eliminate losses. A few points still need to be addressed. Injection takes place in about 500 turns, so when the last turn arrives in the ring, the first turn has to have undergone synchrotron motion without loss. The rf bucket must be able to contain all of the particles. As protons are being accumulated, the space-charge potential increases and distorts the rf potential. The space-charge potential can be big enough to collapse the rf bucket and cause beam loss. The rf voltage must be raised to maintain a large enough bucket area to contain the beam during injection, and rf voltage programming must continue through the acceleration cycle.

Particles of the 75%-chopped beam arriving at the first turn, the phase-space distribution at various times in the acceleration cycle, and the rf voltage programming can all be found in reference [6].

Rf voltage programming is also used to bring the beam's momentum spread ($\Delta p/p$) to predetermined values during the acceleration cycle. The $\Delta p/p$ can be used to prevent the onset of instabilities, as discussed next.

4.4 Impedance and Beam Stability

The coupling impedance between the circulating beam and its surroundings is dominated by the space-charge potential for an RCS of this type. The transverse impedance, $Z_\perp$, varies as $1/(\beta\gamma^2)$ while the longitudinal impedance, $Z_\parallel$, varies with $1/(\beta^2\gamma^2)$, where β and γ are the standard relativistic variables. Therefore, the space-charge impedance is largest at injection. $Z_\parallel$ is proportional to the geometrical factor, $g_o = 1 + 2\ln(b/a)$, and $Z_\perp$ is proportional to the geometrical factor, $g_\perp = 1/a^2 - 1/b^2$, where a, the transverse beam radius, decreases during acceleration, and b is the transverse beam pipe radius. To minimize effects of the geometrical factors, a beam-pipe contour-following rf shield can be constructed inside the ceramic vacuum chamber as is done at ISIS. The contour-following scheme reduces $Z_\parallel$ by 30% at injection and by 20% at extraction. $Z_\perp$ is reduced by 35% at injection and 10% at extraction.

Since the ring operates below the transition energy, the longitudinal microwave instability is not expected. However, the Keil-Schnell criterion is used to further assure longitudinal stability. The criterion states that the threshold current for onset of the instability is inversely proportional to $Z_\parallel$ and is proportional to $(\Delta p/p)^2$. Since $Z_\parallel$ and the accelerated current are known, an adjustment in

Δp/p is made to assure that the threshold current stays above the machine current. Figure 4 shows the longitudinal instability threshold expressed in terms of Δp/p according to the Keil-Schnell criterion, and Δp/p of the accelerating beam bunch from the tracking study with rf programming. The figure shows that Δp/p of the beam bunch is always in the stable region.

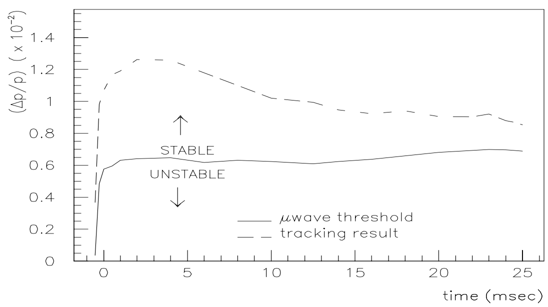

Figure 4: Threshold Δp/p compared to that of the beam obtained from tracking. Small variations are statistical.

4.5 Low- and High-Energy Synchrotrons; Beam Transfer

It is desirable for the circumference of the 10-GeV 5-MW synchrotron to be a multiple of that of the 2-GeV 1-MW machine, so that the rf frequency of the 10-GeV ring can be a harmonic of the rf frequency of the 2-GeV ring. The 10-GeV ring's circumference is four times that of the 2-GeV ring in the ANL study. In addition, ANL uses a harmonic jump of 2 between the 2-GeV and 10-GeV rings so that the rf frequencies between the two rings are harmonically locked. The use of the harmonic jump improves the efficiency of the rf cavity system. The rf systems are phase locked, allowing beam transfer between the 1-MW and 5-MW rings to be done by bunch-to-bucket transfer. Past experience indicates that the efficiency of bunch-to-bucket transfer can be 100%.

The phase-space shape of the bunch just before extraction from the 2-GeV RCS can be tailored by adjusting the rf voltage. The bucket must be matched into a phase-space contour of equal area within the bucket of the 10-GeV ring.

5 DISCUSSION AND R&D ITEMS

A potential disadvantage of the synchrotron concept compared to the linac/compressor ring concept can come from a relatively longer dwell-time of the beam in the accelerator. A typical dwell time in the RCS could be 10 to 20 ms, and the dwell time in a compressor ring would be 1 to 2 ms. The dwell time should be compared to the growth time of various instabilities that may manifest themselves during the acceleration time. Several points should be made in this connection. Although the beam dwell-time in the RCS is an order of magnitude longer than in the linac/compressor scheme, the peak current in the ring is several times smaller than in the linac/compressor so there is no clear advantage to the linac/compressor scheme. All known instabilities have been studied for the ANL RCS case, with the conclusion that the beam can be stable. In any case, cures have been found for all ring instabilities known to date.

In addition to the ion source R&D needs already mentioned, a concerted R&D effort on a very low-impedance rf system, such as the cathode-follower system, should be pursued for both the synchrotron and compressor ring schemes. It is particularly important to have such a system available for the bunch-to-bucket transfer schemes mentioned above.

6 SUMMARY

Synchrotron technology is mature, and the advantages of using synchrotron technology to achieve 1- to 5-MW short-pulse spallation sources are summarized. Detailed discussions and descriptions of the past studies are available in the references cited in this paper.

7 ACKNOWLEDGMENTS

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