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BNL FEASIBILITY STUDIES OF SPALLATION NEUTRON SOURCES*

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ABSTRACT

This paper is the summary of conceptual design studies of a 5 MW Pulsed Spallation Neutron Source (PSNS) conducted by an interdepartmental study group at Brookhaven National Laboratory. The study was made of two periods. First, a scenario based on the use of a 600 MeV Linac followed by two fast-cycling 3.6 GeV Synchrotrons was investigated. Then, in a subsequent period, the attention of the study was directed toward an Accumulator scenario with two options: i) a 1.25 GeV normal conducting Linac followed by two Accumulator Rings, and ii) a 2.4 GeV superconducting Linac followed by a single Accumulator Ring. The study did not make any reference to a specific site.

1. Introduction

Since the beam power can be expressed as the product of beam kinetic energy and beam intensity, the design goal of 5 MW average beam power can be obtained by trading proton beam intensity for proton energy. Depending on the relative balance between these two parameters, two basic approaches, for the design of the PSNS facility may be considered. One choice is a relatively low proton energy accompanied by a higher beam intensity, which can be realized with a full-energy linac followed by a number (one or more) of constant energy accumulator rings. This approach has the advantage of a cheaper circular component (the accumulator ring) which may be also easier to design and to operate. The disadvantage is an expensive linac and higher beam intensity with consequences on cost, reliability and safety of the whole facility. The second choice is a higher proton energy accompanied by a commensurate lower beam current. Higher beam energy could be obtained with a linear accelerator, for example, with superconducting cavities; the cost, however, would be high and reliable operation difficult. At the present stage only fast-cycling synchrotrons seem appropriate for proton acceleration to high energy, with high average beam intensity. The two basic approaches: a full-energy linac followed by accumulator rings, and a low-energy linac followed by a fast-cycling synchrotron have been considered in various design proposals for similar PSNS facilities [1-5]. They have a layout schematically shown in Figure 1.

Initially, we have considered a scenario [6,7] based on the use of a 600 MeV Linac injector followed by two 3.6 GeV Rapid-Cycling Synchrotrons (RCS). The choice of design energy influ-

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ences directly the proton to neutron yield and design of the target system. Higher beam energy was preferred because it eases many design considerations regarding beam performance. The synchrotron scenario alleviates considerably the design considerations of the injector linac, but requires careful examination of design issues which are peculiar to synchrotrons and not to accumulator rings. At the conclusion of the first period of studies, it was determined that a 5 MW synchrotron scenario holds several difficult technical issues. We thus initiated a second phase of studies for an accumulator scenario. At the end of the comparison, this was indeed proven to be less difficult, with only marginal cost differential. In the accumulator scenario, the beam energy choice is an open parameter, and two options have then been investigated: one at 1.25 GeV which can be obtained with either a normal- or a super-conducting linac, and the other at 2.4 GeV, definitively with a superconducting linac.

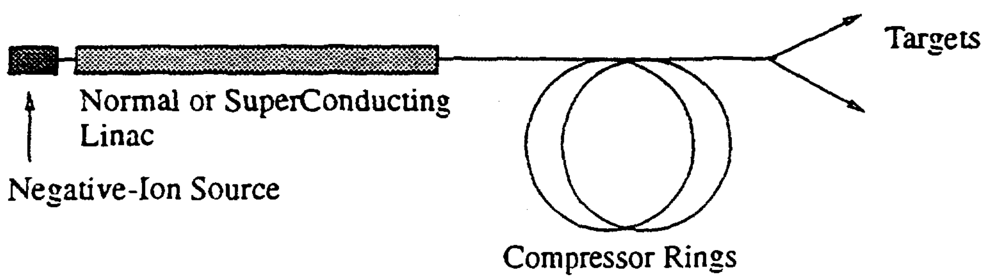

Figure 1. A Pulsed Spallation Source with Linac and Compressor Rings

Though which of the two energy and linac options to be preferred are still left to be determined, at Brookhaven we have nonetheless at the moment a preference for the accumulator scenario as the PSNS facility.

2. The Rapid-Cycling Synchrotron Scenario

The most important issue of the synchrotron scenario is the choice of the linac energy. One might suggest as low a beam energy as possible, with most of the energy increase to take place in the synchrotron in order to favor linac reliability and minimum cost. Yet the low-energy injection into the synchrotrons creates a bottleneck in the beam performance because of the space charge effects. These can be reduced either by raising the final energy, so that the total amount of beam intensity is lowered, or by increasing the injection energy. The scenario we have investigated takes as a compromise one 600 Mev Linac followed by two 3.6 GeV Synchrotrons.

The number of synchrotrons (two) is driven by two additional considerations. One is again space charge: two synchrotrons, running in parallel, need half of the total amount of beam current and therefore half of the amount of space charge effects. A second consideration is that the overall repetition rate of 60 beam pulses to the target per second is better achieved with two synchrotrons each running 180^{o} out of phase at the repetition rate of 30 Hz.

A list of the most important issues relevant to the design of high beam intensity rapid-cycling synchrotrons is as follows: space charge effects at injection; RF capture during injection; RF acceleration; ramping of the guide field; and, vacuum.

Space charge effects are particular important to synchrotrons because of the low injection energy. The indicative parameter is the depression $\Delta\nu$ of the betatron tune given by

$$\Delta\nu = Nr_p / 2B\beta^2\gamma^3 \varepsilon \qquad (1)$$

where N is the total number of protons circulating, $r_p = 1.535 \times 10^{-18}$ m, B the bunching factor which during the early part of the acceleration cycle is about 0.3, β and γ are the usual relativistic factors, and ε is the beam emittance. We have adopted the limit $\Delta\nu = 0.25$. Thus Eq. (1) relates closely injection energy, beam intensity and beam dimension, which also determines the gap of the magnets and therefore their feasibility and cost. The choice of two 3.6 GeV synchrotrons together with the 600 MeV linac requires a magnet gap close to 15 cm, which is technically and financially acceptable.

The scenario works as follows. Beam pulses of negative ion sources are accelerated to 600 MeV in the linac at the repetition rate of 60 Hz. The pulse duration is long enough to allow injection of many turns in one synchrotron at the time. Injection occurs by charge exchange, letting the beam cross a stripping foil. The beam is then accelerated to 3.6 GeV and immediately extracted and transported to one of two experimental targets. As the beam is being extracted from the first synchrotron, the second synchrotron is being filled with a linac beam pulse of the same duration and intensity which it accelerates to the same final energy and at same repetition rate. The procedure then repeats periodically alternating filling and acceleration from one synchrotron to the other, thus creating a beam pulse sequence at the repetition rate of 60 Hz.

It was determined that rf capture and multiturn injection is difficult to control in a rapid-cycling synchrotron because of the fast ramping of the guide field. It is important to control the total beam losses to a low level (about 10^{-4}) during the entire acceleration cycle. In particular, it is crucial to demonstrate capability of controlling beam losses to a 10^{-5} level during multi-turn injection and rf capture. This was proven to be difficult, and eventually with no more than 300 beam turns. This required a low linac duty cycle (3%) and a large ion source beam current (in excess of 100 mA). General linac parameters are shown in Table 1.

Other problems also appeared in the synchrotron scenario. The rf system for acceleration had to provide a peak power of 7 MW, with a total voltage of 0.8 MV at 1 - 1.5 MHz. The bending field were ramped at the large rate of 50 T/s. The vacuum system was complex, made of a sophisticated and costly ceramic vacuum chamber with screening metallic wires.

3. The Accumulator Scenario

The accumulator scenario was proven to have less technical difficulties, at least during the feasibility study, than the synchrotron scenario. Moreover, since no substantial cost difference was found, it is the currently preferred scenario at Brookhaven. The required beam power is entirely generated in the linear accelerator, and thus the linac is the most crucial component which requires special care and attention during design. On the other end, the design of the accumulator ring is simplified, and expected to be less critical. Because of the lower energy, in principle the accumulator scenario requires larger average beam current. Again the largest energy value and the largest number of beam turns injected are preferred, since they would lead to a lower beam current and thus a less demanding ion source. There are two possible options, which have indeed been investigated: a normal conducting linac which cannot exceed the energy of 1.25 GeV because of cost, and a superconducting linac that can reach an energy as high as 2.4 GeV. In the first option one needs two accumulator rings, whereas only one should suffice for the large energy option.

With the accumulator scenario several technical problems disappear or become less important. For instance, the vacuum system is greatly simplified, by adopting a solid metallic vacuum chamber. The rf system is needed only to compress the beam in one single bunch, and not for acceleration. At most, a peak voltage of 30 kV is needed at the frequency of about 1 MHz. Similarly the operation of the accumulator ring is at constant field without pulsed excitation.

Though the injection energy is larger, nevertheless space charge effects are still important and determine the performance of multi-turn injection as well as beam dimension and magnet aperture. Numerical simulations have demonstrated that it is possible to control beam losses to an acceptable level also with one thousand (or more) turns injected. Also, it was possible to prove that multi-turn injection by charge exchange is feasible, essentially without appreciable negative ion stripping due to crossing of magnetic fields, also [8] at the injection energy of 2.4 GeV.

The scenario works as follows. A long beam pulse is generated by the linac at the repetition rate of 60 Hz. Half of the pulse is injected in one accumulator ring, and the second half in the second ring. Both beam pulses are compressed to a length of 400 ns, simultaneously in the corresponding rings, and then extracted in sequence with a 200 ns interval. The overall pulse on the target is thus about 1 ms long. In the 2.4 GeV option, the total beam pulse can be directed, if desired, to a single accumulator ring.

4. Linac Configurations

The accumulator scenario sets clearly the priority and the emphasis of the design to the linear accelerator. Five different linac structures are summarized in Table 1. The first column (A) is the 600 MeV normal conducting linac used in the study of the synchrotron scenario. The other four columns (B to D) describe possible linac configurations for the accumulator scenario.

A schematic layout of the linac is given in Figure 2. It is made of a front-end, a low-energy section, and a high-energy section.

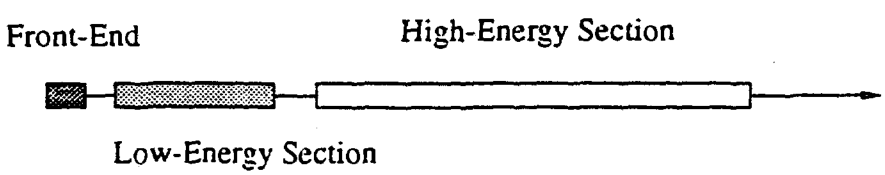

Figure 2. Schematic Layout of the Linear Accelerator

The front-end is made of a negative-ion source on a 50-kV platform, followed by either a single 2.5-MeV, 350-MHz RFQ (options A to C) or by a sequence of two 350-MHz RFQ's at energies 2 and 5 MeV (options D and E). The low-energy section is in all cases a normal-conducting 700-MHz Drift Tube Linac with the output energy of 70 MeV for cases A to C, and 100 MeV for cases D and E. The high-energy section is a 700-MHz Cavity-Coupled Linac for options A to C, and a 700 MHz superconducting linac for options D and E. The final energy varies from one option to the other.

Table 1: Comparison of few Linac Configurations

	A	B	C	D	E
PSNS Scenario	Synchr.	Accumul.	Accumul.	Accumul.	Accumul.
Beam Power, MW	0.84	1.0	5.0	5.0	5.0
Final Energy, GeV	0.6	0.8	1.25	1.25	2.4
H^- Source Current, mA	120	70	120	120	30
Pulse Length, ms	0.360	0.533	1.024	1.111	2.315
Duty Cycle, %	2.2	3.2	6.1	6.7	13.9
Chopping Factor, %	65	65	65	60	60
Beam Current, mA	100	60	100	100	25
Beam Turns injected	236	747	770	1000	1000
RFQ, frequency, MHz	350	350	350	350	350
RFQ, energy, MeV	2.5	2.5	2.5	2 - 5	2 - 5
DTL, MHz / MeV	700 / 70	700 / 70	700 / 70	700 / 100	700 / 100
CCL, MHz / MeV	700 / 600	700 / 800	700 / 1250	--	--
Superc. Section, GeV	--	--	--	0.1-1.25	0.1-2.4
Peak Power, MW	90	30	135	125	60
Length, m	290	390	650	480	850

Configurations B and C apply to a phased mode of construction for the accumulator scenario. In a first phase the linac provides only 1 MW of average beam power, at the energy of 800 MeV, and it is followed by one single accumulator ring. In a second phase, the linac energy is raised to 1.25 GeV, and a second accumulator is added. At the same time the ion source intensity is increased to obtain a 5 MW beam power. Clearly, option beam B requires less beam current. If the number of turns injected is increased to one thousand, the required source current is 50 mA. Configuration D is the superconducting option of the 1.25-GeV, 5-MW linac, and it should be compared to option C. Though the length of the superconducting version is shorter, nevertheless a preliminary estimate has shown that they have comparable cost.

Finally, the high-energy superconducting option E, explores the possibility of larger energies with the intent of minimizing development of negative-ion source [8, 9]. As it is shown in the Table 1, the energy of 2.4 GeV would match to an accelerated beam current of 25 mA, and thus to an ion source peak current of 30 mA. Of course, this may require a longer pulse length, and eventually, two accumulator rings. Nevertheless, the high-energy superconducting option is perceived as the most flexible since would allow adjustments in case higher intensity ion sources should be developed, or in case of funneling two ion sources in one DTL.

5. Conclusion

We have described the results of feasibility studies done at Brookhaven for a Pulsed Spallation Neutron Source. We have compared two scenarios: one which makes use of Rapid-Cycling Synchrotrons, and the other of Accumulator Rings. We have determined that the Synchrotron scenario present some technical difficulties at the level of 5 MW beam average power, and that the Accumulator scenario is to be preferred. This conclusion is supported by the fact that there was no major cost estimated difference between the two approaches. Nonetheless, the Accumulator scenario requires a more careful and detailed study and design of the linear accelerator, which provides the entire beam power. In our opinion technical risks are still represented by the development of the negative-ion source, which can be mitigated with a high-energy superconducting linac, and by the feasibility of thousand-turns injection by charge exchange. These options require more careful evaluation and more numerical simulations.

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