EUROPEAN SPALLATION SOURCE
General ESS Meeting
October 16-19, 1995
Weinfelden, CH

PULSED SPALLATION NEUTRON SOURCE WITH AN INDUCTION LINAC AND A FIXED-FIELD ALTERNATING-GRADIENT ACCELERATOR

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ABSTRACT

The paper describes an accelerator scenario of a Pulsed Spallation Neutron Source made of an Induction Linac injecting into a Fixed-Field Alternating-Gradient Accelerator (FFAG). The motivations underlying the proposal deal with the concern of removing technical risks peculiar to other scenarios involving RF Linacs, Synchrotrons and Accumulator Rings, which originate, for example, from the need of developing intense negative-ion sources and of multi-turn injection into the Compressor Rings. The system proposed here makes use of a positive-ion source of very short pulse duration, and of single-turn transfer into the circular accelerator.

1. Introduction

There are basically two groups of accelerator architectures to be considered for the application of Pulsed Spallation Neutron Sources. One group makes use of RF Linear Accelerators, which inject into Compressor Rings, either Rapid-Cycling Synchrotrons or Accumulator Rings. The other group uses more exotic machines, that is, Induction Linacs and Fixed-Field Alternating-Gradient accelerators. In the following we review briefly the concepts underlining the first type of accelerator architectures and we shall expose some of their most fundamental technical risks, that is, development of high-intensity negative-ion sources and the control of very low level beam losses during injection into the Compressor Rings. We shall then describe, also briefly, the features of more exotic accelerators, namely, Induction Linacs and Fixed-Field Alternating-Gradient Accelerators. We then finally propose, for consideration of further studies, an architecture which is made of an Induction Linac injecting into a Fixed-Field Alternating-Gradient Accelerator. This combination should in principle eliminate those major technical risks we have mentioned above, peculiar to the first group of accelerators of Synchrotrons and Accumulator Rings.

Keywords: Induction Linac, FFAG Accelerator

2. General Considerations on Accumulators and Synchrotrons

In order to get a short and intense beam pulse, we need to "compress' the proton beam in one or more Compressor Rings [1-4]. The circumference of the Rings is adjusted to yield a revolution period comparable to the required pulse length. The beam intensity needed depends on the intensity of the negative-ion source and on the number of beam turns that is possible to inject. Finally, the average beam power, for a give repetition rate, is given by the product of the average beam current with the final beam kinetic energy. This approach is very simple and straightforward, and very easy to follow. Beam energy and beam current can, to some degree, be traded against each other.

The Compressor Ring can be either a constant-energy Accumulator Ring [1-2], where the beam is stored after it has been injected in many turns, until the final intensity has been reached, or a rapid-cycling Synchrotron where, after multi-turn injection, the beam is accelerated to the final energy. In the former case the beam power is totally produced by acceleration in the Linac, and the Accumulator Rings are needed only to compress the beam. Clearly in this approach the RF Linac becomes a crucial component for achieving the desired beam parameters, and considerable design effort is to be given to it. Rapid-Cycling Synchrotrons [3-4], on the other end, reduce the technical requirements on the performance of the injector. This method should permit high energies (2 - 10 GeV), and most of the beam power is obtained by acceleration in the Synchrotron.

All these accelerator architectures, which assume an RF Linac as injector, have considerable technical risks that can be summarized as follows. Negative-ion sources are required to allow multi-turn injection into the Compressor Rings by charge-exchange method. Considerable high-current sources of negative-ions are thus needed with performance well beyond the capability of the present technology. Very large number (about a thousand) of beam turns are to be injected in the Compressor Rings. This makes quite problematic the control of beam losses during transfer and injection to a level low enough to circumvent possible long-term activation problems caused by the same beam losses. These technical risks can be eliminated by considering different, less well publicized accelerator architectures that do not need negative-ion sources and multi-turn injection. The architecture that we like to propose here for further consideration is a combination of an Induction Linac followed by a Fixed-Field Alternating-Gradient Accelerator.

3. Induction Linacs

Induction Linacs [5] have the very interesting capability to accelerate microsecond-long, and even shorter pulses, at high repetition rate, and with relatively large accelerating gradient (1 MV/m). In principle they can accelerate large beam intensity, few tens of amperes, as directly derived from relatively low duty-cycle positive-ion sources. With an Induction Linac there is in principle no need of Compressor Rings, since beam pulses of the desired short length and power can be directly generated at the exit. Unfortunately, full-energy Induction Linacs are quite long and expensive. But the Linac, as it will be explained later, can also be used as an injector to a Rapid-Cycling Synchrotron, or an FFAG machine, by removing thus the concerns and the problems associated to the multiturn injection and to the development of negative-ion sources, since the positive-ion beam can be simply injected in one single turn. The major technical risk is the development of the (positive) ion source, which considering the large beam intensity has also a large beam emittance, the early stage of acceleration, the overall length, and the cost. The technology, which is of old date, and by now very mature and sophisticated, is not that well known to the large majority of the accelerator expert community, who prefer working on Accumulators, Synchrotrons and RF Linacs. In the past there has been a tendency to dismiss prematurely the technology as a stand-alone application to Pulsed Spallation Neutron Sources. But we believe that if used as a low-energy injector to an FFAG accelerator, as explained below, has very attractive features to be exploited.

4. Fixed-Field Alternating-Gradient Accelerators

FFAG accelerators have also been proposed in the past as possible Spallation Neutron Sources [6-9]. They need an injector, usually a modest RF Linac, but they can provide otherwise most of the acceleration once the beam velocity has reached a large enough value. The good feature is that they provide acceleration in a constant (fixed) field environment. In the past the use of an FFAG was based on the idea to inject 300 to 500 turns pulse trains arriving from an injection linac. During that time the RF-system of the FFAG was turned off. When the DC-beam in the FFAG had reached the space charge limit, the RF was turned on slowly and the beam adiabatically captured into the RF-bucket. Then the beam was accelerated to full energy, spiraling out to the extraction radius, where it was then kicked out in one single shot, and directed onto the neutron production target. The output power of such a linac-FFAG combination is determined by the space charge limit at injection, the FFAG repetition rate and the output energy of the FFAG. The major technical difficulty for the past linac-FFAG combination was the low loss requirement for the multiturn injection, the lossfree adiabatic trapping of the injected beam, and the disposal of the excited H^0-states at a suitable beam stop. The design of the sector magnets and of the rf cavity is also not trivial. Most of these problems can be removed by using an Induction Linac as the injector. Because of the initial short beam pulse length, in this case, there is no need for multiturn injection, which simplifies considerably the design.

The technology of FFAG accelerators is also of old date, but recently has acquired maturity and has become quite sophisticated. Several new features can be incorporated [10]. For instance, long drift spaces can be inserted. To minimize the cost of the magnets, transverse focussing may be obtained not only with a conveniently chosen field profile, but also with the shaping of the entrance and exit angles of the bending magnets. With specially adjusted focussing elements, it is also possible to introduce isochronism and zero or small dispersion regions where to locate more compact rf cavities for acceleration.

5. A Scenario based on an Induction Linac injecting into a FFAG Accelerator

The scenario which makes use of the best combined features of the Induction Linac and of the FFAG accelerator is as outlined in Figure 1. The combination in sequence of the two types of accelerator complement each other's features, removes some of their major technical difficulties, and, most important, eliminates problems peculiar to negative-ion sources and multi-turn injection.

As a reference, we shall assume an average beam power of 5 MW at the repetition rate of 200 Hz. The final energy in exit of the FFAG accelerator is in the range 1-3 GeV, so that the average proton beam current will range between 0.42 and 1.25 mA, as shown in Table 1. A preliminary conceptual design of the Induction Linac [5] has shown that an intermediate energy of

260-600 MeV is possible with an initial accelerating gradient of 36 kV/m and a final gradient of 1 MV/m. The total length would be 380-720 m. These values are also shown in Table 1. The positive-ion source operates at the duty cycle of 0.04%, delivering a pulse length of 2 µs and a peak current of 4.2-12.5 A depending on the final energy of the facility.

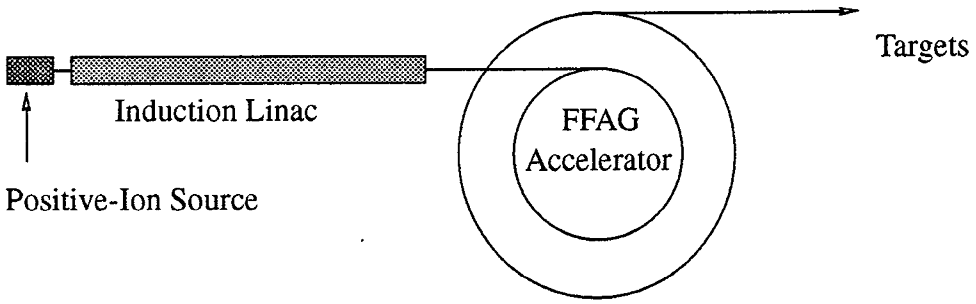

Figure 1. A Pulsed Spallation Source with an Induction Linac and a FFAG Accelerator

During acceleration the beam is compressed in length to 100-150 ns. In fact, higher accelerating gradients can be reached at the end of the Linac with a shorter beam pulse and when space-charge forces are less important. Typical normalized beam emittance is 10-30 π mm mrad. Total beam dimensions are thus of the order of few centimeters, whereas the inner core diameter can be made of 60 cm.

Table 1: Requirement and Induction Linac Parameters

Average Beam Power	5 MW	
Repetition Rate	200 Hz	
Final Energy	1 GeV	3 GeV
Average Beam Current	1.25 mA	0.42 mA
Positive-Ion Source		
Pulse Length	2 µs	
Duty Cycle	0.04 %	
Peak Current	12.5 A	4.2 A
Normalized Emittance	30 π mm mrad	10 π mm mrad
Induction Linac		
Final Energy	260 MeV	600 MeV
Final Pulse Length	0.15 µs	0.1 µs
Initial Accel. Gradient	36 kV/m	
Final Accel. Gradient	1 MV/m	
Total Length	380 m	720 m
Internal Core Diameter	60 cm	

The design, construction and operation of this Induction Linac should not present insurmountable difficulties. Also, considering the very short beam pulse length and the large ratio of inner core diameter to beam size, no problems of radiation activation due to latent beam losses are expected. Such a short beam pulse can be injected in one single turn in a circular accelerator for further acceleration. The circular accelerator could be a FFAG Accelerator because it avoids fast-ramping magnetic fields, as in the case of Synchrotrons, which require a complicated vacuum system and vacuum chamber, among other things, and limit the pulse repetition rate.

The actual value of the injection energy, between 260 and 600 MeV, can be chosen as a compromise between conflicting requirements. One would prefer a large value of the injection energy to avoid too severe space-charge effects, to reduce the cost of the FFAG accelerator, to narrow the required momentum acceptance and thus the size of the magnets. On the other end high-energy Induction Linacs are long and more costly. The optimum choice can be determined only after careful trade studies. Table 2 summarizes typical parameters of the FFAG accelerator for a range of injection and final energy values.

Table 2: FFAG Accelerator Parameters

Final Energy	1 GeV	3 GeV
Injection Energy	260 MeV	600 MeV
Circumference	200 m	200 m
Packing Factor	40 %	40 %
Bending Radius	12.74 m	12.74 m
Bending Field	1.95-4.44 kG	3.19-10.01 kG
Momentum Aperture	± 40 %	± 50 %
max. Dispersion	2.0 m	2.0 m
max. Beta Function	20 m	20 m
Magnet Aperture	1.6 m	2.0 m
Magnet Gap	30 cm	20 cm
Space-Charge $\Delta\nu$	0.3	0.3
Normalized Emittance	400 π mm mrad	220 π mm mrad
Acceleration Period	5 ms	5ms
Harmonic Number	1	1
rf Frequency	0.93-1.31 MHz	1.19-1.46 MHz
rf Peak Voltage	400 kV	600 kV

A preliminary design of the FFAG accelerator has been made which includes drifts of few meter length to accommodate equipment for injection and extraction, and zero-dispersion regions for rf cavities. It is to be noted that one single-turn transfer and extraction into and from the FFAG accelerator can be made at a high confidence level, with high efficiency (99.99% or better).

6. A High-Performance Neutron Facility

For many years, indeed since the early days of the SNQ-project [11], the discussion on the "best" design parameters of a spallation neutron source have been going on and, as far as long pulses (or strongly coupled moderators yielding high average neutron flux) are concerned, have been revived recently. There are clear arguments for short pulse spallation neutron sources which allow to exploit hot and epithermal neutrons, and to perform powder diffraction, in an unparalleled way. Their most desirable parameters are proton pulses of a few hundred nanoseconds length and a repetition rate of about 50 Hz. Furthermore, pulsed spallation neutron sources have also been shown to be quite successful in the cold neutron regime, but, due to the long flight times of these neutrons, lower repetition rates, of the order of 10 Hz, are desirable. For this reason, almost all new spallation source proposals include two target stations. These concepts leave aside, however, a large and well developed suite of instruments which have proven extremely successful on reactors and which could benefit by an order of magnitude, on average, from a time structure of the neutron source [12-15]. The important point is that for these instruments, a low repetition rate of the source is not necessary; many of them can easily work with moderately long pulses (200 μs or so) and at 100 Hz or above [16]. (Thermal time-of-flight, triple axis spectrometers, multiplexing instruments, etc.).

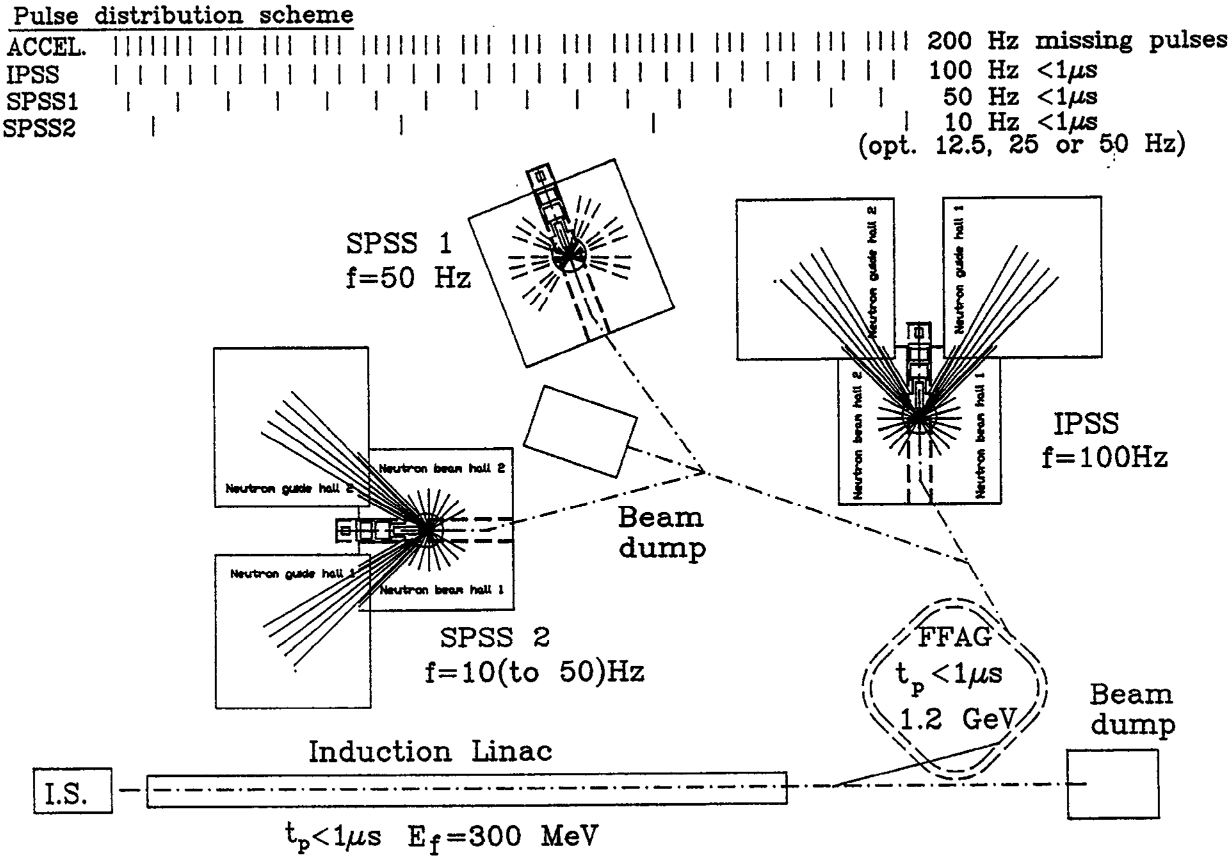

Figure 2: A High Performance Neutron Facility Based on a 200 Hz Short Pulse Accelerator System

If an accelerator system is available that can deliver pulses at 200 Hz, as the one described here, this offers a unique possibility to satisfy the needs of the traditional reactor user community and the short pulse users by supplying pulses to three target stations according to the scheme at the top of Figure 2. Every other pulse goes to the 100 Hz target, and 1 of 4 goes to the 50 Hz target. Of the remaining 50 cycles, 10 have protons and 40 are empty. These 10 pulses go to the 10 Hz - low rep rate target. (There are, of course, other options, e.g. 12.5 Hz, 25 Hz, etc., at corresponding beam average power). This combination, at a total beam power of about 5 MW (3 MW for the 100 Hz target, 1.5 MW for the 50 Hz target and 0.3 MW for the 10 Hz target) would make a unique world class facility which could serve about 100 neutron spectrometers with unprecedented performance, making the system very cost effective.

Due to the short proton pulse, slowing-down neutrons would be usable on all three targets. It should be noted that the power in each pulse is of the order of 30 kJ, less than one third of what is presently considered as feasible in the ESS-project. All three targets could be identical, differing only in their average power and their moderator-reflector systems.

7. Conclusion

We have described a Pulsed Spallation Neutron Source concept which is made of an Induction Linac and a FFAG accelerator, and serves 3 target stations of different design. Such project is feasible and has considerable attractive features which include the availability of high-intensity, low duty-cycle positive-ion sources, and the control of beam losses by eliminating the need of multi-turn injection. The short beam pulse, of sub-microsecond length, is beneficial to a sharp rising edge of the neutron pulse from the moderator. Due to the moderate pulse power of only 30 kJ, no serious problems in the target are anticipated.

8. References

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