# Overview of Future Spallation Neutron Sources

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Abstract

Initiatives have commenced, both in Europe and in the U.S.A., towards studies of very intense pulsed spallation neutron sources. Average proton beam powers of up to 5 MW are under consideration, representing an extrapolation of a factor of about 30 over the most intense existing source, ISIS (U.K.). Various options are discussed, and important design areas of the accelerators and targets are outlined.

## I. INTRODUCTION

First generation spallation neutron sources now contribute significantly to slow neutron scattering studies of condensed matter, and their success has led to proposals for higher power, second generation sources. Traditionally, neutron scattering experiments have been made at research reactors, but a number of advantages arise in the use of pulsed neutron beams [1] at spallation sources, making them serious competitors to the reactors. The spallation sources cannot compete, however, in the areas of isotope production and high flux irradiation and activation studies.

Early neutron scattering experiments with pulsed beams used an electron linac target, but studies at ANL [2] showed the advantages of lower power dissipation in proton spallation targets. Four pulsed sources, using such targets, have since been developed, three based around a rapid cycling proton synchrotron (RCS), and the fourth, that at LANL, around a compressor ring fed from the 800 MeV LAMPF linac:

Table 1
Parameters of Existing Pulsed Spallation Sources
(Av. is a typical daily output beam power average)

| Facility | Energy | Rep.Rate | Av. | Pk. |
|---|---|---|---|---|
| KENS (Japan) | 500 MeV | 20 Hz | 2, | 2 kW |
| IPNS (US) | 450 MeV | 30 Hz | 6, | 7 kW |
| LANSCE (US) | 800 MeV | 20 Hz | 40, | 60 kW |
| ISIS (UK) | 800 MeV | 50 Hz | 145, | 160 kW |

In addition to these pulsed sources, there is a c.w. spallation source (SINQ) under construction at PSI in Switzerland [3]. It is based on the existing cyclotron, with 1 MW proton beam power at 570 MeV. The target is a vertical cylinder, with injection from below.

A second generation of pulsed sources has been under consideration for a number of years, but there has been a new emphasis after recent initiatives:

1. The 5 MW SNQ project at KFA, Julich, 1984;
2. ISIS in a European context, 1986;
3. FFAG studies at KFA and ANL, 1986-88;
4. Japanese Hadron Facility, JHP, 1988-93;
5. U.K. - German European initiative, 1991-93;
6. AUSTRON initiative in C. Europe, 1991-93; and
7. Studies at ANL, BNL and LANL, 1992-93.

The European and U.S. initiatives hope to become formal conceptual design reviews (CDR) in 1994, with the former seeking funding from the Commission of the European Community (CEC), and the latter drawing on expertise from ANL, BNL and LANL, but to be centred at LBL. The beam powers selected for the European and U.S. sources are 5 and 1 MW respectively, but with a 5 MW upgrade potential also for the latter.

The repetition frequency of the European source is to be 50 Hz, but with 2 target stations, one at 50 Hz and 4 MW, and the other at 10 Hz and 1 MW. The idea of a 10 Hz target, for the lower energies of the neutron spectrum, first arose at the 1986 Rapallo Workshop [4] for the study of ISIS in a European context.

Source studies have broadened since 1990, following experimental results from JINR [5] which showed that, for a given beam power, the useful neutron yield versus proton energy remains approximately constant in the energy range 1 to 3.7 GeV. This has led to a wider range of spallation sources being considered, e.g:

| | Linac | Ring(s) | Power |
|---|---|---|---|
| AUSTRON | 0.07 GeV | 1.6 GeV RCS | 0.1 MW |
| ANL | 0.4 GeV | 2.2 GeV RCS | 1.0 MW |
| HMI | 0.46 GeV | 1.6 GeV FFAG | 5.0 MW |
| RAL (3) | 0.8 GeV | 0.8 GeV COMP | 5.0 MW |
| LANL (1) | 0.8 GeV | 0.8 GeV COMP | 1.0 MW |
| INR | 0.6 GeV | 45 GeV K.FAC | 5.0 MW |
| LBL (IND) | 1.0 GeV | | 5.0 MW |

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AUSTRON [6] is a projected regional research centre for Austria, Croatia, Czechoslovakia, Hungary, Italy, Poland and Slovenia. Envisaged is a spallation source of the scale of ISIS, but using a higher energy RCS to reduce the repetition rate to 25 Hz, and with the possible addition of a storage ring to reduce further the 25 to 12.5 Hz. JHP [7] also proposes a power level comparable to ISIS, but it is now being reassessed.

The remaining source options are all for 1 MW beam power or above. Two are for high power $H^-$ linacs and proton compressor rings: RAL [8] considers an 800 MeV linac and 3 rings or a 1200 MeV linac and 2 rings; LANL [9] considers an 800 MeV linac and 1 ring for a 1 MW source, and either increasing the linac energy or adding more rings for a 5 MW upgrade. In Germany, a source based on a $H^-$ linac and an FFAG accelerator is favoured. Initially, an energy of 3.2 GeV was proposed for the FFAG [8], but HMI now considers lowering the energy to 1.6 GeV and making use of beam stacking techniques. At ANL, the 1 MW proposal [10] is based around a 2.2 GeV RCS, at a repetition frequency of 30 Hz. BNL has recently commenced studies, and all the sources of power $\geq$ 1 MW now plan to use 2 target stations, as proposed at Rapallo.

Two different types of source complete the options. INR, Troitsk, suggests the use of the proton beams available at the KAON Factory projects, either at the highest energy (eg 45 GeV) of the main ring synchrotron or that of its booster injector [11]. The engineering of the target stations is very different for this approach. Finally, there is the suggestion to use an induction linac accelerator [12], at 0.8 or 1 GeV, to create the required proton pulse at the target without any associated ring. This approach has had the least attention to date, but is likely to receive detailed assessment at the CDR in LBL.

## II. SOURCE CONSIDERATIONS

The most important initial consideration is the choice of kinetic energy for the high power proton beam. This choice impinges on the designs of the accelerator, targets and moderators, and so involves neutron scatterers, and accelerator and target designers. A range of energies appears acceptable, which extends the task of finding an overall cost and reliability optimisation.

For the European source study, target designers from SINQ, KENS, RAL, IPNS and LANSCE recommended restricting the proton kinetic energy to the range between 0.8 and 3 GeV. Within this restricted energy range, the following comments may be made for the targets T, moderators M, and accelerator A, assuming 5 MW of proton source power in each case:

T: the material needs to be W, Ta, Pb or U238; the target is horiz. or vert. and may be split; the required length has to increase with energy; the power in the input window falls with energy; the useful neutron yield per MW is ~ constant, but with some enhancement around 1.1 GeV; the peak target power density falls with energy, but with more power in escaping secondaries; the neutron backgrounds increase with energy; shutters are more extensive for higher energies; stationary $H_2O$ cooled plates may work at 5 MW.

M: the design is integrated for target - M - reflector; the layout is slab, wing, fluxtrap or backscatter, the last two of which require a split target; there is some downstream adjustment with energy; the materials are ambient temp. $H_2O$, liquid $H_2$, liquid $CH_4$, or a liquid $H_2$ cooled metal hydride; use is made of poisoning, coupling and decoupling; heating from target secondaries rises with energy, as does the radiolysis for some materials eg $CH_4$; radiation damage and heat deposition need study.

A: the FFAG and RCS options favour 1.6 to 3 GeV; the induction linac favours an energy $\leq$ 1 GeV; the compressors proposed are 3 rings at 0.8 GeV, or 2 rings at 1.2 GeV, or 1 ring at 2 - 2.4 GeV; the injection energy depends on ring/source power; low loss in the linac and rings is a key issue; optimised $H^-$ ring injection schemes are essential; collection of beam lost in the rings is required; ring activations vary with local power loss level; the activated volume rises somewhat with energy; the cost of beam line to target rises with energy; and overall T-M-A availability of > 90% is required.

The technology of a 5 MW target was assessed at a 1992 PSI workshop [13]. The highest power density case was studied, that for an 800 MeV target. It was concluded that, "Of the options considered, the stationary water cooled plate target was considered to offer the best overall prospects. Its design will be a technical challenge, but the working group felt there was every prospect for success. A rotating target based on the SNQ design [14] was recognised as a viable option, which could be adapted for the new source if the difficulties of the stationary target proved insurmountable."

At the same PSI workshop, three conceptual target-moderator-reflector layouts were discussed, one for a horizontal, one for a vertical and one for a split vertical target; the last of these is shown schematically in Figure 1. A neutronic analysis for all three options was recommended, including an evaluation of radiation damage and heat deposition in moderators, reflectors and decouplers. Also recommended was R & D towards a viable high hydrogen density cold moderator.

At this stage, engineering solutions appear to be within reach for the targets, moderators and reflectors of a 5 MW source throughout the 0.8 to 3 GeV range. It seems therefore that the choice of proton energy will be set mainly by detailed accelerator considerations.

## III. ACCELERATOR CONSIDERATIONS

The simplest concept is a 1 GeV induction linac with no associated ring. It has the longest length at ~ 1 km, however, so it may prove too costly. Also, its design is based on very high space charge detunings and exact matching, so the effect of variations in ion source current (50A, 1 MeV, 2 μs) needs careful assessment.

The most challenging option is the FFAG. Initial studies at KFA and HMI have shown that a 0.46 to 3.2 GeV, wide aperture, superconducting magnet FFAG is overexpensive. This has led HMI to studies of a higher frequency, 1.6 GeV ring, using beam stacking at high energy to build up the beam current. An alternative has been suggested by ANL, with a 100 Hz low energy FFAG feeding 2 successive pulses for each 50 Hz cycle of a higher energy ring.

For a 1 MW source, ANL prefers a 30 Hz, 0.4 to 2.2 GeV, RCS, with the high output energy reducing the number of protons to be handled each pulse. The design will have the potential for a 5 MW upgrade. An RCS has also been considered in Europe, with the parameters 50 Hz, 0.8 to 3 GeV, and 5 MW. The 0.8 GeV injection is the same as in one compressor ring option, which is favoured due to its shorter beam storage, lower beam power per ring and more rugged design (an RCS has a low impedance, uncooled, shield and chip capacitors in its ceramic vacuum chamber).

The $H^-$ linac-compressor ring options of RAL and LANL have already been outlined, and the individual pros and cons are as follows. The $H^-$ ion source performance is a limiting factor, so 2-stage funneling is assumed, with the same linac peak current in all options. The linac duty cycle then increases with the number of rings, so favouring a high linac energy. Nearly all other factors favour a low energy, however, eg. cost, linac length, debunching, momentum ramping, shielding, $H^-$ injection, reliability (losing a ring leads only to lower intensity), beam loss collimation, lower beam power per ring (with more loss acceptable per ring), beam extraction, high energy transport, and previous experience with spallation targets. A possible exception is that of beam instabilities, which have been relatively benign at ISIS, but not so at the PSR, LANL.

Another factor linked to the choice of energy is the cost of the $H^-$ linac, which may be room temperature, RT, or superconducting, SC. Initial designs have assumed frequencies of ~ 350 and 700 MHz for the pre and post funneling stages of a RT linac, with half these values for the SC case. Q values of 2 $10^4$ have been taken for the former, and loaded Q's of $10^6$ for the latter, values typical for cavities used in $e^-$ storage rings. The pulsed nature of the linac leads to revised SC parameters, however, as the 1 ms cavity filling time is too long. This would give slow rise and fall times for the cavity fields, with added cryogenic and generator power; high power klystrons, with circulator and load, are assumed for the generators. A factor of 10 reduction in filling time is obtained by using the RT frequencies, and lowering the loaded Q to 2 $10^5$. Comparisons then, between a RT and SC linac, include a reduced linac length and lower power for the latter, as against its complexity, enhanced maintenance, less reliable windows, and probably larger activation (gamma danger parameters for Nb are ~ 4 times those for Cu).

The most important accelerator considerations are: ion source performance, overall induction linac and $H^-$ linac optimisations; RFQ, chopper and funneling characteristics; and the ring designs for $H^-$ injection, beam loading compensation, extraction and beam loss collimation and protection. $H^-$ injection and ring collimators are discussed further.

Low loss injection is such an important feature that the lattice for the rings has to be designed around the preferred arrangement of the injection components. This, together with the constraint of obtaining specific lattice parameters at a stripping foil location, result in a low superperiodicity, S, for the rings. It is very desirable, however, to choose S > 2, to reduce the number of betatron resonances, close to the working point, that may be excited by space charge forces.

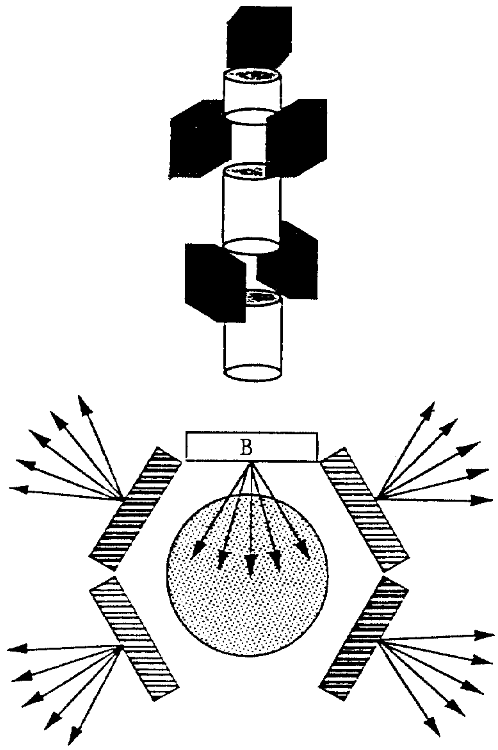


Fig. 1 SCHEMATIC OF FLUX-TRAP AND BACK-SCATTER (B) MODERATORS

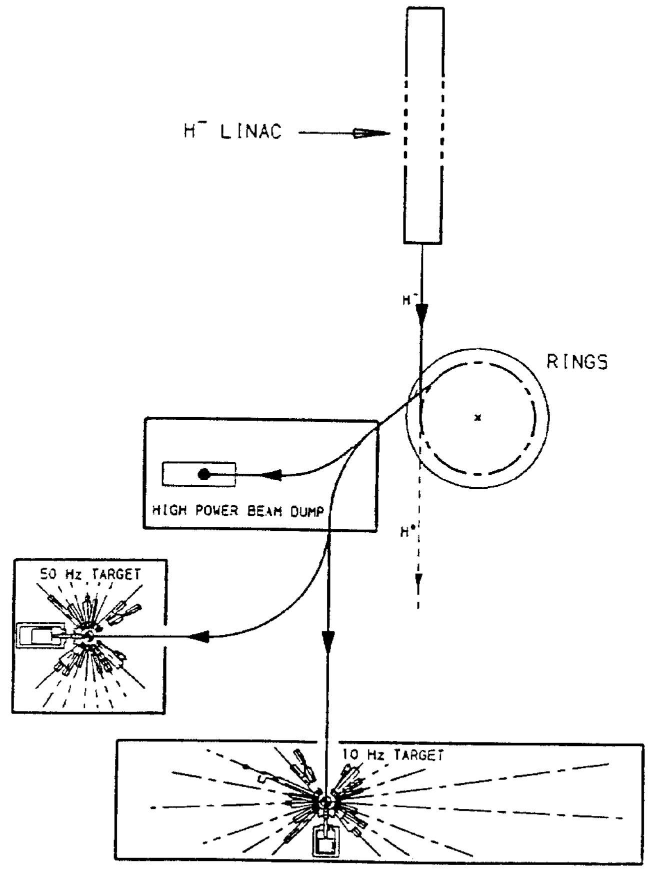


Fig. 2 SCHEMATIC OF 5 MW SOURCE

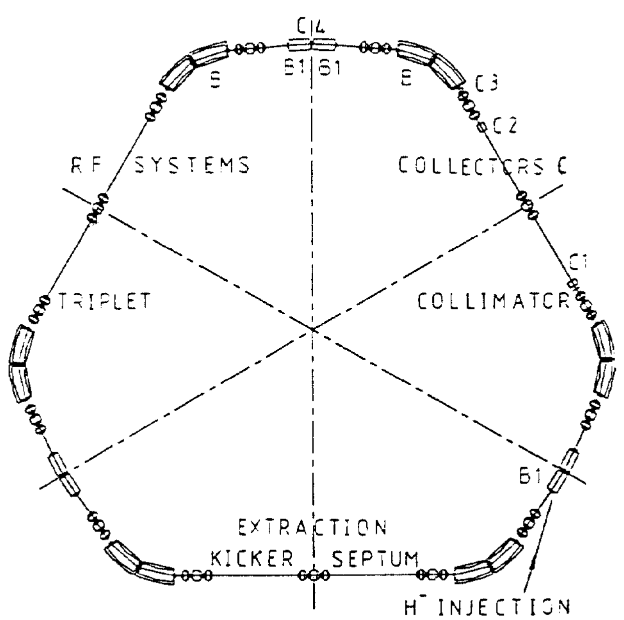


Fig. 3 COMPRESSOR RING

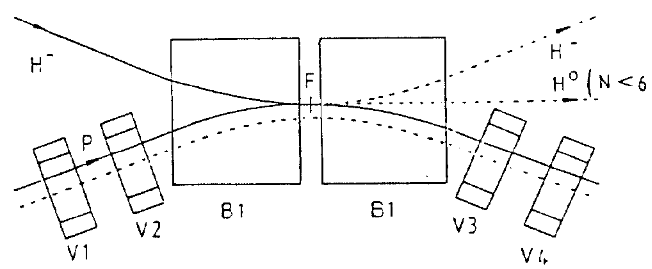


Fig. 4 OPTIMISED H⁻ INJECTION SYSTEM

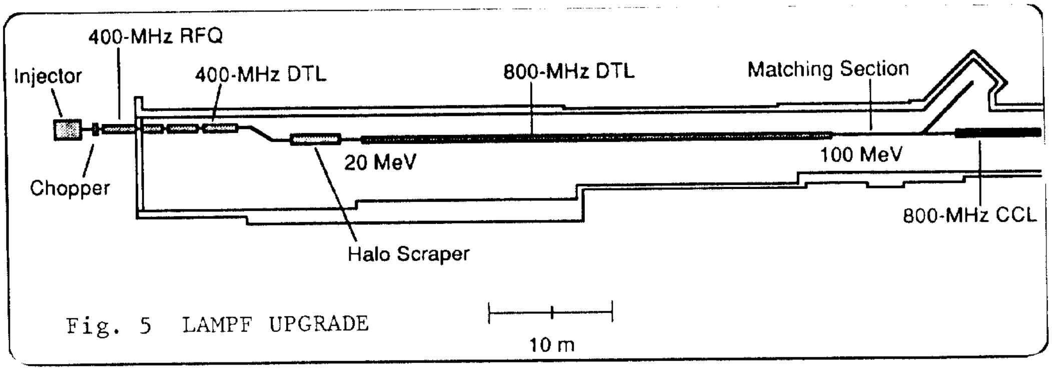


Fig. 5 LAMPF UPGRADE

Schematics are shown of a 5 MW source layout in Fig. 2, a 0.8 GeV compressor lattice in Fig. 3, an optimised $H^-$ injection system in Fig. 4, and the low energy part of the LAMPF upgrade in Fig. 5. The ring of Fig. 2 may be an FFAG, an RCS, or one or more compressors. The lattice of Figs. 3, 4 has S = 3, zero dispersion for rf systems, collimation and extraction, and the betatron and dispersion parameters at the B1 dipoles for optimised injection. In B1, the $H^-$ beam merges with the protons that circulate after charge exchange stripping. For Fig. 5, there may be 2 ion sources and linacs, funneling into 1 at 20 MeV.

Optimised $H^-$ injection involves simultaneous 'painting' in all 3 phase planes. There is momentum ramping of the input beam for longitudinal and horizontal betatron painting, and programming of 4 bump fields for vertical painting. Large horizontal amplitudes are correlated initially with small vertical and energy amplitudes, and the correlations are slowly reversed during injection. The use of a foil with 2 free edges then reduces the foil traversals by protons. Fields near the foil, F, are chosen to allow collection of stripped $e^-$, and to control the partially stripped metastable $H^0$ states; the scheme proposed by RAL is given in [15]. On injection, the equipartition of energy in the 3 phase planes is lost, with a larger increase of longitudinal than transverse emittances.

Collimators and loss collectors are essential for the high power beams. Betatron collimation is important for the FFAG and compressors, and momentum collimation for the RCS. Primary collimators are followed by collectors, with equal horizontal and vertical phase shifts to the downstream units. The system must limit the areas of activation and also protect the rings, particularly the chamber of the RCS. Angled, not straight, collimators are used as they result in greater penetration depths and reduced outscatter. Such an angled unit is to be tested soon in ISIS.

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