Proposals for Spallation Sources in Europe

H. Lengeler
CERN and European Spallation Source (ESS), KFA Jülich

Abstract

Neutron scattering has led in the past to major breakthroughs in the study of condensed matter. Because of the weak interaction of neutrons it has been always an intensity limited field. Spallation sources are promising candidates for higher neutron fluxes. During the last years a number of pulsed spallation sources have become operational and a 1 MW, CW spallation source SINQ is under construction at PSI, Switzerland. More powerful pulsed spallation sources are planned in CIS, Europe, Japan and USA. Design issues and parameter choice of high power sources are given and discussed for the planned AUSTRON and European Spallation Source (ESS) facilities.

1. INTRODUCTION

Contrary to synchrotron radiation, neutron scattering has always been an intensity limited field because of the weak interaction of neutrons with matter and more powerful n-sources remain desirable. For many years nuclear reactors have been the main source of neutrons, producing a continuous flow of particles, but their development potential approaches its limits. During the last years spallation sources have found a growing interest. Neutrons are produced by high energy protons (~1 GeV) hitting a heavy metal target (spallation). They are subsequently moderated in hydrogen rich materials to energies adequate for the study of condensed matter.

2. PULSED SPALLATION SOURCES

By imposing a time structure on the proton beam, the neutron pulses can be compressed in a short time interval. This does not only increase the peak intensities but one can use time of flight measurements for the determination of incident neutron energies. It avoids the monochromatisation used in CW sources which decreases considerably the neutron intensity at the detector. In this way a wide band of wavelengths can be exploited simultaneously and a more efficient use of neutrons is possible. Time of flight measurements ask for very short pulse lengths (μs) and for small repetition rates (≤ 50 Hz) in order to avoid the overlap of slow neutrons from one pulse with fast neutrons from the next pulse (frame-overlap). For high intensities this goal cannot be realised by a linear proton accelerator alone. One therefore considers the use of a pulsed linac combined with an accumulator or an accelerator ring filled by multiturn injection and emptied by fast one-turn ejection for reaching the desired peak power and pulse lengths.

Over the past years a number of pulsed spallation sources [1] have become operational at Argonne (IPNS), Los Alamos (LANCSE), KEK (KENS) and Rutherford Appleton Laboratory (ISIS). The most powerful one is ISIS [2]. Since its first operation in 1986 ISIS has seen its intensity steadily raising and has reached recently its design current of 200 μA. This corresponds to a beam power at the target of 160 kW. The proton pulses are delivered at 50 Hz with a pulse length of 450 ns. Much more powerful spallation sources with a beam power in the range of MW are under study at ANL, Argonne; JINR, Moscow; KEK, Japan, LAMPF, Los Alamos and in Europe [1], [3].

3. FUTURE SPALLATION SOURCES IN EUROPE

3.1 SINQ, PSI

A powerful CW spallation source is under construction at PSI, Switzerland [4]. It will be operated with the existing PSI separated sector cyclotron. This accelerator, designed initially for a 100 μA beam at 590 MeV has been gradually upgraded to a current which is at present 1 mA and will be 1.5 mA when the upgrading is finished in 1996. This corresponds to a CW beam power of 0.9 MW. Protons are brought to two muon production targets and will then be refocused and vertically injected into the spallation target producing a CW neutron flux of 2×10^{14} n / $cm^2 \cdot s$ with a Pb or Pb-Bi target. SINQ will offer excellent working conditions for a large cold D_2O moderator and neutron guides with supermirrors. It is also foreseen to perform material irradiation studies for target development in a range not easily accessible to present sources.

3.2 AUSTRON

A pulsed spallation source to be combined with a light ion cancer therapy facility is planned as an international research centre in Austria (AUSTRON) [5]. A tentative layout is shown in Fig. 1. At present a three stage approach is foreseen (see Table 1). AUSTRON II will be comparable in intensity with ISIS. An upgrading to AUSTRON III would include a second target station and a doubling of beam power. In Fig. 1 the proposed layout of the fast cycling synchrotron is also shown. The lattice structure is based on FDF quadrupole triplets and has been chosen a. o. for small beam losses at injection, storage and extraction. The basic rf-system should provide 170 kV/turn (10 cavities) with a frequency swing from 1.1 to 2.8 MHz for protons. Possible upgrades could include a second harmonic system and extra first harmonic cavities for operating at 50 Hz. For the light ion medical facility a dedicated low intensity storage ring is proposed. A muon target area is foreseen as well as a test beam line for detector development. Many technical details have already been studied and will be published as a Feasibility Study middle of this year.

3.3 THE EUROPEAN SPALLATION SOURCE (ESS)

In a series of workshops neutron experimentalists together with accelerator and target designers have proposed the following basic design parameters for ESS:

- An average beam power of 5 MW (about 30 time the one of ISIS).
- A short beam pulse at the target with less than 3 μsec length
- A repetition rate of 50 Hz
- Two target stations, one operated at 50 Hz, 5 MW and the second one at 10 Hz, 1 MW.

In June 1993 work for ESS has been started. From middle of 1994 onwards it will be continued in a two years, site independent study which is supported by seven European countries and by the European community. A first review will be prepared for end of 1994.

The proposed 5 MW beam power can be obtained by a combination of a linac with an accumulator ring, a rapid cycling synchrotron or a fixed field alternating gradient synchrotron (FFAG) [6]. Due to lack of resources and time it has been decided to concentrate work on the combination of a high intensity linac followed by an accumulator ring or a rapid cycling synchrotron and for an energy range between 0.8 and 3 GeV.

For a first ESS option (Fig. 2) an energy of 1.334 GeV has been chosen, the precise choice being fixed by the requirements of a low loss H^--injection into the rings [7]. A 1.334 GeV linac with 1.23 ms pulse length and 50 Hz repetition rate will inject H^--ions in two accumulator rings, operated in parallel. For the ring ejection the linac pulses have to be chopped. This combination offers great flexibility because it can give an average 5 MW beam power for 1 μsec pulses, using both compressor rings, or 2.5 MW beam power in 0.4 μsec with one compressor ring only. In addition, by operating the linac in a "dual pulse mode" (i. e. with every fifth pulse lengthened to 2 msec and unchopped) one can feed directly 2.7 MW beam power to a third 10 Hz target and 4 MW to the 50 Hz target behind the compressor rings. This kind of operation necessitates an increase of the linac duty cycle from 6.2 to 7 %.

A second option uses two 25 Hz Rapid Cycling Synchrotrons in alternating cycles, accelerating the beam from 0.8 to 3 GeV. This solution will be considered if there are strong arguments from the target or the users' point of view for this high energy. The accelerator ring option is more expensive and less flexible than the two compressor ring solution. More details about the design issues and layout of the rings will be presented at this conference [7].

Besides the linac and rings, target stations for a beam power in the MW-range present a big challenge and exceeds present operation experience in many respects. For ESS three target options are considered: a 1 MW stationary (solid) target operated at 10 Hz and a 5 MW rotating (solid) or liquid metal target operated at 50 Hz. In all three cases one is faced with an unusual combination of material problems produced by the protons and by the high neutron flux. In solid materials (target and target windows) the density of defects and the amount of H and He produced by transmutation lies in a poorly explored range. The high average power and the high energy content of each proton pulse of 100 kJ (or even 270 kJ for dual mode operation) creates shock wave effects and temperature transients in solid and liquid targets. Theoretical and experimental investigations of these effects have been started. An improved understanding will be crucial for an estimation of lifetimes and replacement cycles. New and innovative approaches will also be needed for many aspects of target engineering.

4. A FIRST PROPOSAL FOR THE ESS LINAC

As an example for the design constraints and layout of high intensity linacs for pulsed spallation sources the first proposal for the ESS linac is discussed in somewhat more detail. In Fig. 3 a schematic drawing of the linac is given . The main linac and ring parameters are listed in table 2.

The linac design is dominated by low loss injection and extraction of the compressor rings. For achieving this requirement, the linac beam has to be chopped (60 % chopping efficiency). Longitudinal halo containment at high energy is mandatory. Therefore emittance increase all along the linac including the low energy transfer lines should be kept small. The number of injected turns per ring should not be greater than 1000, limiting the linac pulse length to about 1.2 msec. This results in a peak current of 100 mA after funneling, well below the space charge limit of the 350 MHz drift tube linac (DTL). The use of two independent 70 mA H^--sources and two front ends will increase the availability of the linac. The low emittance, 70 mA, 50 kV, 10 % d.c. H^--sources are not state of the art. At Rutherford Appleton Laboratories, a test stand with a modified H^--Penning source and a 200 MHz, 665 keV RFQ is being built and will replace the 665 keV injector platform. It is designed for 100 mA H^--current and one expects initially a current of 20 mA [2]. At Frankfurt University a modified LBL rf-driven volume source is under construction, which should deliver a 35 mA, 8 % d.c., H^--beam in the middle of 1996 [8].

The fast beam chopper is installed behind RFQ 1 in order to avoid too many partly filled bunches. These bunches cannot be properly rotated at the linac end due to their severe longitudinal mismatch. By placing the fast chopper element between ion source and RFQ 1, the edges of each 400 nsec long chopped pulse would see strong longitudinal space charge forces, especially at the RFQ entrance. The ensuing smearout of the edge would lead to partly filled bunches. With a fast chopper behind RFQ 1, only the edges of the 1.2 msec long pulse suffer from this difficulty. The beam is kept bunched between the two RFQs to maintain longitudinal emittance. Because of the 60 % chopping efficiency a water-cooled absorber has to be incorporated in the transfer line, collecting an average power density of about 4 kW/cm^2. Pre-chopping the H^--source helps reducing this power load. As the transfer line includes no bending magnets the layout should be not more complex than the single leg and double leg funnel lines, tested at Los Alamos [9]. The second RFQ, which accelerates the beam up to 5 - 7 MeV, can operate either at 175 or at 350 MHz. The lower frequency is preferred from beam dynamics point of view.

After combining both beams, the particles are accelerated up to 150 MeV in a 350 MHz DTL, stabilised by post couplers. The design of the front section of this DTL

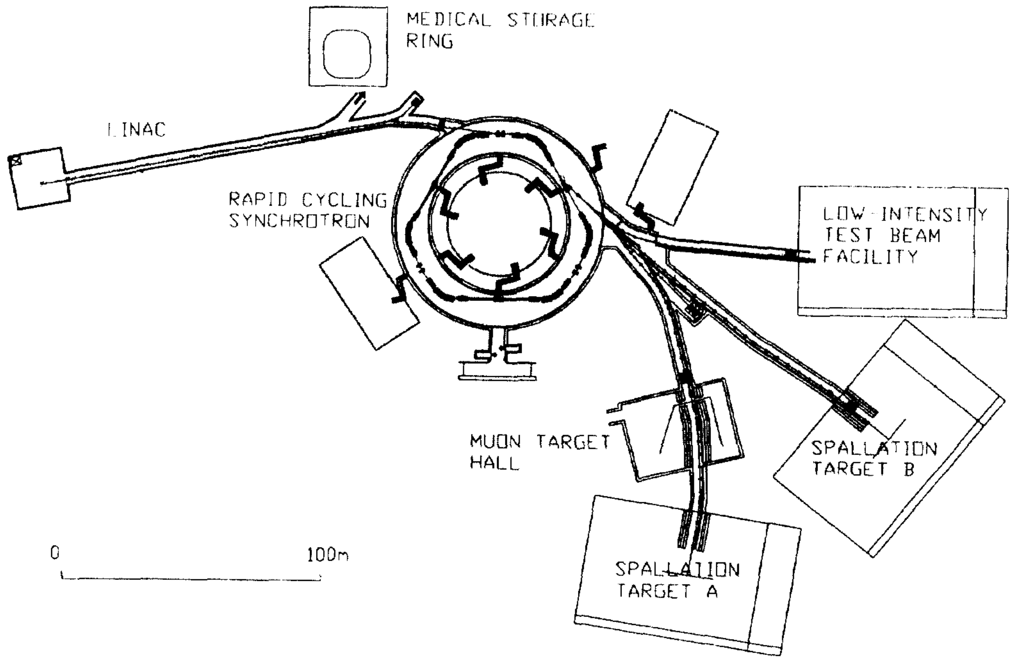

Fig. 1: Layout of AUSTRON

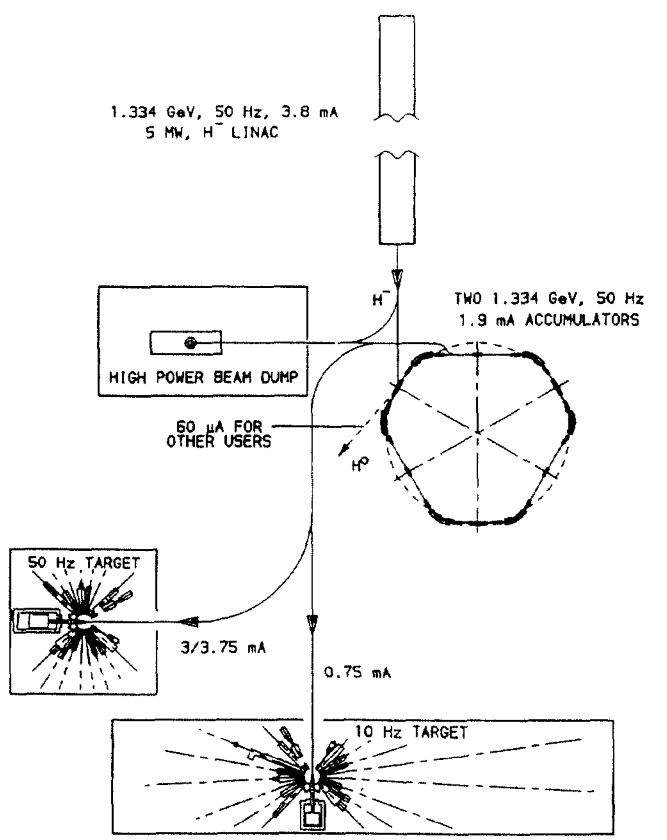

Fig. 2: A first option for ESS

could profit from a 400 MHz DTL which was also tested recently at Los Alamos [9]. For increasing the shunt impedance towards the high ß end, the outer tank diameter is changed around 30 MeV. The peak surface field is kept below the Kilpatrick limit of 18 MV/m. At the low energy end, one needs quadrupole gradients of 100 T/m and a 1 cm bore radius for a FD focusing scheme.

For the high ß linac either normal conducting (nc) or superconducting (sc) structures can be used. Side coupled copper cavities at 700 or 1050 MHz are considered which are similar to the high gradient, 805 MHz structures successfully operated at Fermilab [10]. DAW structures are also possible candidates. The use of these nc cavities will imply a frequency jump between the DTL and the high energy part of the linac, always prone to increased beam losses. An optimisation of capital and operation cost (for 50.000 h) leads to a gradient of about 2.8 MV/m in the 700 MHz cavities. Nose cooling will be no problem at this gradient even with a 10 % duty cycle. High rf-efficiency will be crucial and one considers 3 MW klystron units with an efficiency of 60 %. This will allow feeding 3 accelerator tanks connected by bridge couplers with one klystron. Transverse focusing is obtained by quadrupole singlets located between tanks.

For the interesting "dual mode" operation mentioned already, it is possible to design a klystron modulator with increased pulse length capable of delivering this combination of pulses. Such a "bouncer" modulator for 2 msec pulses has been tested recently at DESY for the superconducting TESLA test facility (with a measured modulator efficiency of 85 % and a bouncer circuit recovery time of 8 msec) [11]. A feasibility study is going on for evaluating this dual mode operation in more detail.

A major advantage of sc cavities [12] is their high acceleration efficiency which, at 60 mA and for CW conditions is more than a factor 2 larger than for nc cavities. Sc standing wave multicell cavities have been successfully tested at gradients above 10 MV/m. A similar cost optimisation as for the nc version leads to a gradient around 10 MV/m which would necessitate for two cell cavities rf couplers with a peak power of 450 kW. More experimental work will be needed to reach this value; even at a duty cycle of 5 to 10 % the temperature build-up in the coupler at 50 Hz operation may be a limiting factor.

The operation with msec pulses and high gradients will pose special problems for sc cavities: The filling time of cavities, proportional to the gradient, is no longer negligible in comparison to the pulse length. This will reduce the acceleration efficiency. Lorentz force detuning, proportional to the square of the gradient and with a typical time constant of 1 msec has to be taken into account. Transients related to the heavy beam loading caused by 60 mA pulses may cause energy fluctuations. Detailed numerical simulations will be needed to analyse the amplitude and phase errors as a function of frequency, synchronous phase, pulse length, bunch current fluctuations, gradient and generator matching.

The use of iris loaded Nb cavities at 350 or 700 MHz is considered. Operation at 350 MHz would have a. o. the advantage of operation at 4,2 K, no frequency jump between DTL and high energy section and a large longitudinal acceptance. At 700 MHz the filling time will be shorter and the bandwidth larger.

The large iris opening of the cavities will be an asset for reduced cavity activation. An iris opening with 5 cm radius is easily achievable and about a factor 2 larger than for the side coupled structures. However, the beam radius must be limited in any case to much smaller values. At 150 MeV the radial dependence of the accelerating fields has to be taken into account. For a 350 MHz cavity at 10 MV/m the beam radius must be kept below 2.6 cm for avoiding momentum tails intolerable for a low loss injection. At high energy Lorentz stripping in the focusing quadrupoles leads to additional beam losses. An extrapolation of measured beam losses and activation levels shows that an unconstrained access for hands on maintenance to the high energy part of the accelerator will only be possible if beam losses can be kept below 0,4 nA/m [13]. Even halo distributions at a 10^{-3} level must be limited to a radius of 1.75 cm inside a quadrupole with a (typical) 20 T/m gradient.

The low loss ring injection scheme will also put stringent and new constraints to the high energy transfer lines between linac and compressor rings. The momentum spread of the linac bunches has to be decreased by a factor 3 while the average beam momentum has to be ramped during the ring injection time. The most severe demand is the limitation of the longitudinal halo to less than 10^{-4} particles with momentum tails above 10^{-3}. The decrease of the momentum spread can be done by a bunch rotation cavity. Varying its phase will ramp the average beam momentum. The needed drift space and the bunch rotation voltage are strongly affected by direct longitudinal space charge forces, leading to an increase of the momentum spread before rotation by a factor 3 [14]. A promising approach distinguishing between core and halo particles is presently pursued to define phasing of the last linac section together with the correct setting of the bunch rotation cavity.

5. OUTLOOK

The high power pulsed spallation sources under planning ask for a considerable increase in beam power and average current over existing linacs and accelerator rings. Small beam losses and a high acceleration efficiency are dominant design issues. The low repetition rates and very small pulse lengths needed for time of flight measurements make the use of accumulator or accelerator rings mandatory. As a consequence the linac must operate with pulsed and chopped H^--beams and peak currents of the order of 100 mA. The planned high power linacs with a beam power up to a few MW will be interesting prototypes for even more powerful accelerators considered for nuclear waste transmutation or energy production which can however be operated under CW-conditions and with an unchopped proton beam.

Acknowledgements

I would like to thank my colleagues from the ESS linac and ring groups, in particular K. Bongardt for many discussions. Thanks also to G. Bauer and P. Bryant for information on SINQ and AUSTRON, resp.

References

[1] For an overview see Proc. ICANS XII, Abingdon, UK 1993, Ed. U. Steigenberger et al., RAL Report 94-025 (1994)
[2] I. Gardner, Status Report on ISIS, this conference
[3] G.H. Rees, Proc. IEEE PAC, Washington 1993, p. 3731
[4] PSI Users Guide, Ed. H.C. Walter et al., Villigen, March 1994
[5] F. Baumann et al., The Accelerators for the Austron Spallation Source, this conference
[6] S. Martin and C.W. Planner, Proc. EPAC92, Berlin (1992) 435
[7] G.H. Rees, Important Design Issues of High Output Current Proton Rings, this conference
[8] K. Volk et al, A compact high brilliance ion source for RFQ injection, this conference
[9] A. Jason, K.F. Johnson and S. Nath, in ref. [1], p. A-49
[10] E. McCrory, "Commissioning and Initial Operation of the Fermilab 400 MeV linac", APS Spring Meeting, April 1994
11] H. Pfeffer et al, "The TESLA Modulator", internal TESLA Report 93-30, July 1993, DESY and:
H Pfeffer, A. Gamp, private communication
[12] H. Heinrichs, in ref. [1], p. A-144
[13] Proceedings: Technical Review for Next Generation Spallation Neutron Source, Los Alamos, LA-UR-93-4440, Jan. 1994, p. 2-68
[14] K. Bongardt, in ref. [1], p. A-115

Table 1: Principal parameters for the three stages of AUSTRON

	I	II	III
Proton operation			
Injection to RFQ [keV]	100	100	100
Injection to DTL [keV]	750	750	750
Injection to RCS [MeV]	70	130	130
Energy on target [GeV]	1.6	1.6	1.6
#of particle/cycle [10^{13}]	1.6	3.2	3.2
Repetition rate [Hz]	25	25	50
#of spallation targets	1	1	2
Average power [kW]	102.5	205	2 x 205
Light-ion operation (C,O)			
#of particle/s	10^9	10^9	2 x 10^9
Energy from DTL [MeV/nu]	16.13	28.01	28.01

Table 2: A few ESS linac and ring parameters

Linac	with accumulator ring	with RCS
Proton energy at target (GeV)	1.334	3
Linac kinetic energy (GeV)	1.334	0.8
Linac beam power (MW)	5.1	5.1
Linac repetition rate (Hz)	50	50
Linac average current (mA)	3.75	1.67
Linac peak current during pulse (mA)	100	100
Ion surce current (mA)	2 x 70	2 x 70
Linac duty cycle (%)	6.2	2.75
Linac pulse length (msec)	1.23	0.55
(60 %) chopping ratio (nsec)	400 / 270	340 / 226
total linac length (m)	~660	~400
Rings	**2 accumulator rings at 50 Hz**	**2 RCS at 25 Hz**
Main harmonic number	1	2
Circumference (m)	163	284
Number of circulating protons (10^{14})	2.34	2.08
Bunch length/ring at ejection (μs)	0.4	0.15
Pulse length at target (μs)	1	0.7
Energy content of combined pulses at target (kJ)	100	100

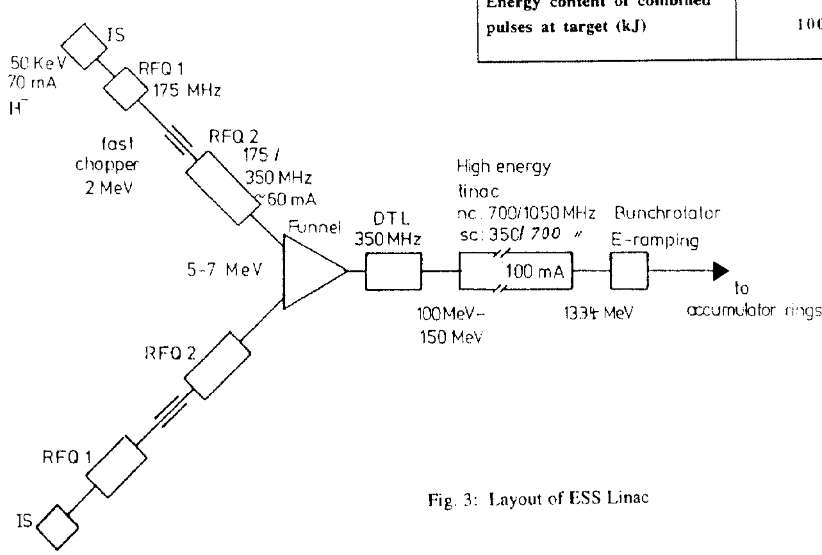

Fig. 3: Layout of ESS Linac