SPALLATION NEUTRON SOURCES*

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Abstract

At present mainly two types of neutron sources are in use for neutron scattering research, the steady state source based on fission reactors using highly enriched U^{235} fuel and the accelerator based pulsed source, where the neutrons are produced by spallation of a nonfissile target. Several high intensity spallation sources are under consideration nowadays, and these proposals as well as the existing machines will be reviewed. Besides the general layout of the facilities the problems of the high current linac part will be shortly discussed.

Introduction

Neutrons are very well suited to study the microscopic properties of matter by scattering experiments. This is due to the physical properties of the neutrons, especially to its electrical neutrality, which allows for deep penetration into the samples with only small damages. Together with its spin, its magnetic moment, and the low absorption cross section, neutron scattering can probe the bulk properties of matter and its dynamics, fluctuations of liquids, the structure of polymers, magnetic materials, biological samples, high T_c superconductors etc.. By slowing down fast neutrons by moderators to thermal equilibrium the proper de Broglie wavelength according to the interatomic distances of some 10^{-10} m can be achieved.

Research reactors - especially the high flux reactors at Brookhaven, at Oakridge, at ILL in Grenoble and at Saclay - and spallation sources serve as sources for neutron scattering. The reactors operate in a more or less continuous mode, and are often mainly used for material testing and isotope production. Most of the present research reactors are old, and their life time will end within the next two decades. It became very difficult to build new reactors in the last time: The safety aspects (highly enriched fuel) and the great public concerns require a more and more increasing time to get a license; in many countries new reactors can not be realized for political reasons at all.

A way out of the lack of neutrons are the spallation sources, which are of intrinsic safety - they consume more energy than they produce. They generate the neutrons by intense high energy proton beams which strike a heavy metal target. They offer the possibility to pulse the neutron flux (Pulsed Spallation Source, PSS), which is important for time of flight experiments. They can produce the same neutron fluxes or even higher than reactors, which are already on their limit of tolerable power density in the core. First proposals for spallation sources have been made already in the Sixties [1]. So far only four spallation sources are in operation, but about ten proposals are being discussed.

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Principles of Neutron Spallation Sources

If high energy (e.g. 800 MeV) protons impinge on the target, they do not interact with the nucleus as a whole, but - due to their short de Broglie wavelength - with the individual nucleons, creating an intranuclear cascade inside the nucleus; some high energy (secondary) neutrons and protons escape from the nucleus producing similar cascades in neighbouring nuclei. The nucleus is left in a highly excited state and relaxes mainly by evaporating low energy neutrons. The high energy neutrons are of no use, but the others, produced either by evaporation or directly by the incident protons, can be slowed down to thermal (or - for time of flight experiments - epithermal) velocities by optimized moderators. This optimization is not possible with reactors, since a special moderator layout is needed to sustain the chain-reaction. The energy dissipated in the target per produced neutron is much smaller by spallation then by fission ($\approx$ 30 MeV for 800 MeV primary protons compared to $\approx$ 200 MeV) leading to a lower power load in spallation sources. The number of neutrons produced by protons depends on proton energy, target geometry and target material. For a cylindrical Pb-target ($\varnothing$ = 10 cm, L = 60 cm) the yield Y [neutron/s] is given by:

$$Y = 14.2 \cdot 10^{16} (E - 0.12) \cdot I$$

with E = proton energy [GeV], I = proton current [mA]. 0.12 GeV is the threshold energy. For 800 MeV one proton produces about 15 neutrons; in case of depleted U^{238} the fast fission processes contribute considerably to the number of neutrons ($\approx$ 25 instead of 15). The useful neutron flux for scattering experiments depends on the target and the moderator. The choice of the proton energy is a crucial point. Fig. 1 [2] gives the dependence of neutron production on energy, Fig. 2 [3] the dependence of neutron production normalized to the beam power as function of energy. Above 1.3 GeV the production rate for a given power is nearly independent of the proton energy. From the target side energies ranging between 0.8 and 3 GeV or somewhat more are acceptable. For accelerators high energies are of no principle problem, whereas current limits exist, depending on energy. As a general rule, the most economic solution is given by a layout, where the maximum current limit is utilized, which leads to a corresponding low energy. Two main schemes are used for the accelerator part: short linac plus rapid cycling synchrotron (RCS) and long linac plus compressor rings; both deliver the required short pulses of $\approx$ 1 μs on the target. The RCS demands for high energies and low current, for the pulsed linac with accumulator rings it is just vice versa. For example: Proposals for a 5 MW solution look for 3.6 GeV , 1.35 mA (RCS) or 1.4 GeV, 3.8mA (Linac).

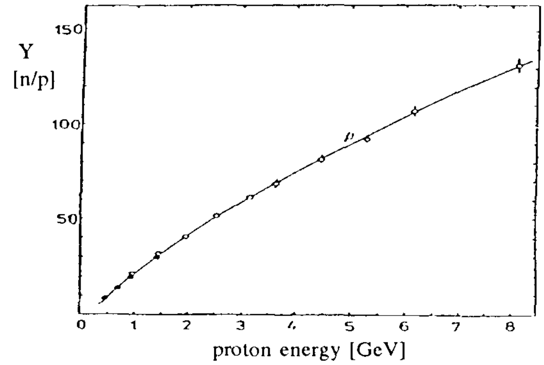

Fig. 1: Neutrons poduced by an incident proton as function of proton energy [2]

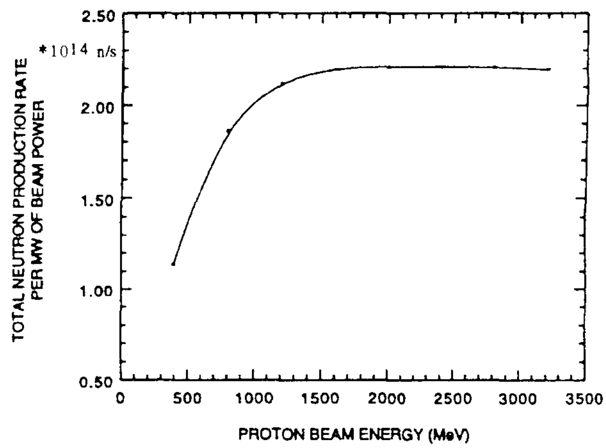

Fig. 2: Neutrons produced as function of proton energy for a constant beam power of 1 MW and a cylindrical tungsten target 1 m-diam x 1.5 m-long [3]

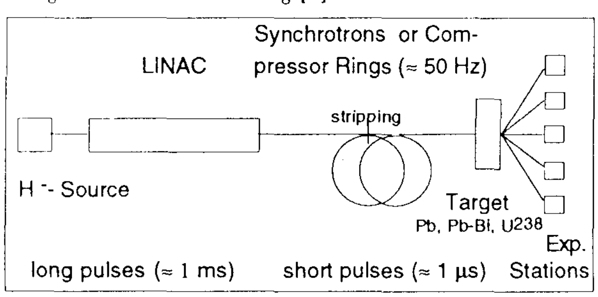

Fig. 3: General layout of a pulsed spallation neutron source

There are other ideas for PSS's, based on the FFAG [4], on the induction linac [5] or on electron accelerators [6], which are not considered in this paper.

Existing Spallation Sources

So far only four spallation sources are in operation with proton energies of 500 MeV (Argonne, KENS) or 800 MeV (ISIS, LANSCE) (see Table 1). The first three ones start with 40-70 MeV H^--linacs which are followed by a synchrotron. The most powerful source is ISIS, with an average power of 160 kW on target. The linac provides an H^-- current of 20 mA in pulse (pulse length ≤ 500 µs) with a repetition rate of 50 Hz; the 50 Hz synchrotron with a circumference of 163.4 m accelerates up to 800 MeV, the circulating current is 10 A, the peak intensity $2.5\cdot10^{13}$ protons per 0.4 µs pulse; injection is done by foil stripping. Upgrading from 200 to 300 µA average is planned by a new rf-system of the synchrotron (doubling the frequency), and an improvement of the linac by substituting the hv-injector by a RFQ (in cooperation with Frankfurt).

The spallation source at Los Alamos uses the 800 MeV linac (LAMPF), then the beam is compressed into 0.27 µs long pulses by an accumulator ring (90.2 m in circumference) with a peak intensity of $5\cdot10^{13}$ p/pulse and an average power of 80 kW. Plans exist to extend this system in two steps, leading to 1 and 5 MW respectively by changing the front end of the linac (RFQ, new 400 and 800 MHz DTL's, funneling), improving the CCL and adding up to three compressor rings.

Proposals and Studies for New Spallation Sources

The spallation source SINQ at the PSI in Switzerland is a special case, because it is based on the existing 600 MeV isochronous 8-sector cyclotron. By improving the accelerator system from originally 100 µA to the present 1 mA and further upgrading to 1.5 mA a very powerful beam of 0.9 MW will be achieved and will produce a neutron flux of $2\cdot10^{14}$ n/(cm$^2\cdot$s) with a Pb or Pb-Bi target. Due to the cw operation of the cyclotron, this neutron flux will be continuous like in a reactor. SINQ shall be operational as soon as 1996.

For the high power proposals the linac energy has been generally increased to 0.4 - 1.5 GeV, since the current limits of rings are proportional to $\beta^3\cdot\gamma^3$.

At Argonne, IPNS-Upgrade is proposed; in fact it is more then an upgrade, providing 1 MW with one RCS, 2 GeV, 30 Hz, using all the experience of IPNS. At BNL a 5 MW PSS is discussed with two 3.6 GeV RCS's. An even higher energy of 10 GeV is foreseen in the ANS study of the INR Moscow to decrease the radiation damage of the first wall and so improving the reliability of the target.

AUSTRON is a project of seven countries (A, CS, H, I, PL, Slovenia, Croatia) with the assistance of CERN. It combines a spallation source with a light ion cancer therapy facility. Fig. 4 shows the layout. The 70 MeV linac injects into a 1.6 GeV, 25 Hz synchrotron, which delivers 1 µs pulses to the target (102 kW average beam power). Raising the linac energy to 130 MeV (second step) increases the current limit at injection by a factor of 2, doubling the repetition frequency to 50 Hz (third step) would finally result in a power of 410 kW. The light ions are expected to have an intensity of 10^9 part./s at a maximum energy of 400 MeV/nucl. They have their own low energy linac part, but use the same main linac. The injection into the RCS is complicated since it combines injection schemes by charge exchange for the H^--beam and a classical one with fast kicker and septum for the light ions.

Table 1: Survey of existing and planned spallation sources and their main parameters

Name, Location, Status	Accelerator Energy	average power on target	aver. curr. on target	Linac duty cycle, Ipeak	rep.rate	pulse length on target	current dur. pulse on target	energy of one pulse	p per pulse	Ref.
IPNS, Argonne USA; operational	50 MeV H- Linac 500 MeV RCS	7.5 kW	15 µA	0.3% 5 mA	30 Hz	0.1 µs	5 A	0.25 kJ	3*10^12	[7]
KENS-I, KEK, Japan operational	40 MeV H- Linac 500 MeV Synchr.	5 kW	10 µA	0.1% 10 mA	20 Hz	0.05 µs	10 A	0.25 kJ	3.1*10^12	[7,8]
ISIS, RAL, Appleton UK; operational	70 MeV H- Linac 800 MeV Synchr.	160 kW	200 µA	1% 20 mA	50 Hz	0.45 µs	10 A	3.2 kJ	2.5*10^13	[7,9,10]
LANSCE, Los Alamos USA; operational	800 MeV H- Linac storage ring	50/80 kW	60/100 µA	10% 17 mA	12/20 Hz	0.27 µs	18.5 A	3.9 kJ	3*10^13	[7,11]
SINQ, PSI, CH 1996 operational	590 MeV cyclotron	900 kW	1.5 mA	cw						[7,12]
NCNR, Los Alamos USA; design study	800 MeV H- Linac accumulator ring	1 MW (5 MW opt)	1.25 mA	7.2% 30 mA	20/40 Hz (2 targets)	0.5 µs	41.6 A	16.6 kJ	1.3*10^14	[13,14]
ANL, IPNS-Upgrade design study	400 MeV H- Linac 2 GeV RCS	1 MW	500 µA	2.5% (*) 33 mA	10 / 30 Hz (2 targets)	0.3 µs	53.3 A	32 kJ	1*10^14	[15,16]
PSNS, BNL, USA feasibility study	600 MeV H- Linac 2 x 3.6 GeV RCS	5 MW	1.35 mA	2.8% 100 mA	2 x 30 Hz (RCS, 2 targets 40/10 Hz)	1.3 µs	34.5 A	160 kJ	2.8*10^14	[17,2]
ANS, Moscow, Russia feasibility study	1 GeV Linac 10 GeV RCS	4/1 MW	0.4/0.1 mA	5%	40/10 Hz (2 targets)					[18]
AUSTRON I, Austria design study	70 MeV H- Linac 1.6 GeV RCS	102.5 kW	63 µA	0.25% 30 mA	25 Hz	1 µs	2.5 A	4 kJ	1.6*10^13	[19,20]
AUSTRON II	130 MeV H- Linac 1.6 GeV RCS	205 kW	125 µA	0.33% 40 mA	25 Hz	1 µs	5 A	8 kJ	3.2*10^13	
AUSTRON III	130 MeV H- Linac 1.6 GeV RCS	410 kW	250 µA	0.65% 40 mA	50 Hz	1 µs	5 A	8 kJ	3.2*10^13	
KENS-II, KEK, Japan planned as JHP-part	1 GeV H- Linac compressor/stretcher	200 kW	200 µA	3.3% (*) 20 mA	50 Hz	0.2 µs	20 A	4 kJ	2.5*10^13	[8,21]
ETA-based SNS, Japan feasibility study	1.5 GeV p(H-)Linac (compressor)	15 MW (2 MW)	10 mA (1.3 mA)	10%	100 Hz (50 Hz)	1 ms	100 mA	150 kJ (40 kJ)	6.3*10^14 (1.6*10^14)	[22]
ESS, EC design study	1.334 GeV H- Linac 2 x compressor	5/1 MW	3.8 mA	6.6% 100 mA	50 / 10 Hz (2 targets)	1 µs	75 A	100 kJ	4.7*10^14 (2 rings)	[23,24]

(*): 60% chopping effiency assumed

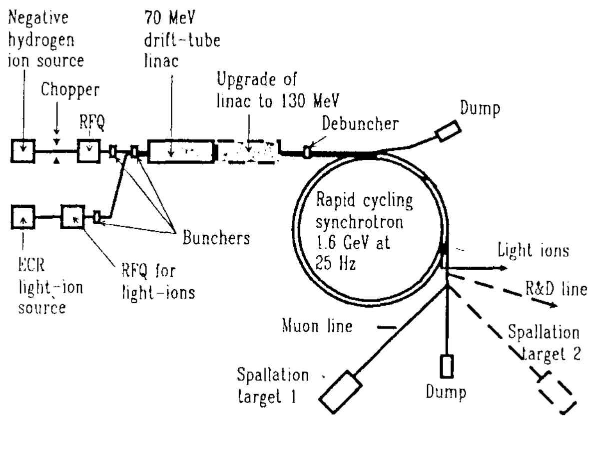

Fig. 4: Proposed layout for the AUSTRON PSS with the additional light ion input line for the cancer therapy facility

In Japan the so called KENS-II PSS as an important part of the Japanese Hadron Project (Fig. 5) is proposed. A 1 GeV, 0.4 mA H^--linac feeds a compressor/stretcher ring (50 Hz), which allows for pulse lengths of 20 ns, 200 ns and 20 ms. In discussion is also at JAERI the construction of a very powerful (15 MW) 1.5 GeV p-linac (10 mA average current, pulse length 1 ms, rep. rate 100 Hz) for the transmutation of nuclear waste. This linac could be used as a next-generation 2 MW PSS, using H^- ions and a compressor ring (50 Hz).

In Europe a two years study for a European Spallation Source (ESS) has been aproved by the EC now. A study group has been established under the auspicies of a council in which nine member states of the EC are represented.

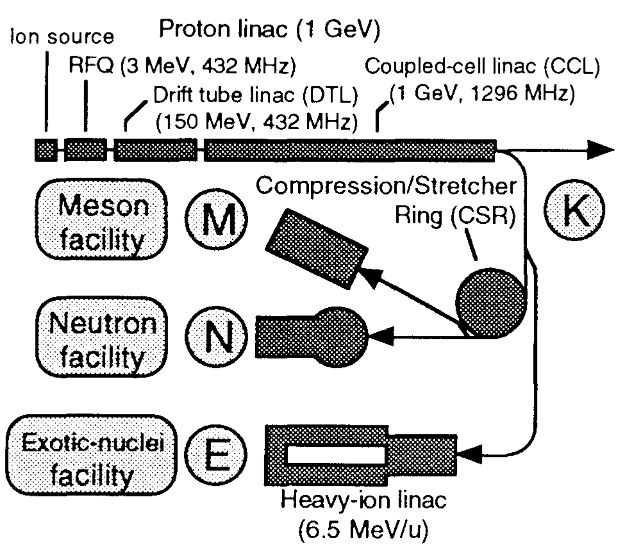

Fig. 5: General layout of the Japanese Hadron Project (JHP)

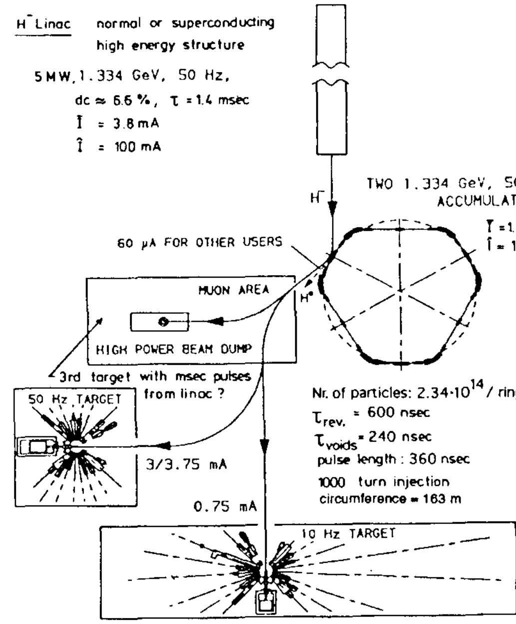

Fig. 6: Proposed layout and main parameters of ESS

The preliminary ESS-layout is given in Fig. 6. 5 MW average power are achieved by a 1.334 GeV, 50 Hz linac followed by two compressor rings, which provide 1 µs-pulses. The linac energy has been chosen to minimize beam losses at injection; the H^0 particles behind the stripper foil are then mostly in an excited state with relatively long life time, those with a short life time, preferably produced at other energies, would decay into H^- shortly after the foil, first captured, but then being lost in the ring [25]. The particle loss is the major problem in PSS's for hands on maintenance! For the linac it should not exceed 0.4 nA/m. Two targets are foreseen with short pulses, a third target with 2 ms long pulses direct from the linac is possible. In the next chapter some problems of the high intensity linacs are discussed, taking ESS as an example.

The ESS linac part

This chapter is only a short overview, for more details see [24] and the references quoted therein. The scheme of the ESS linac part is shown in Fig. 6. The beams of two lines with ion source, LEBT, two RFQ's with a fast chopper in between

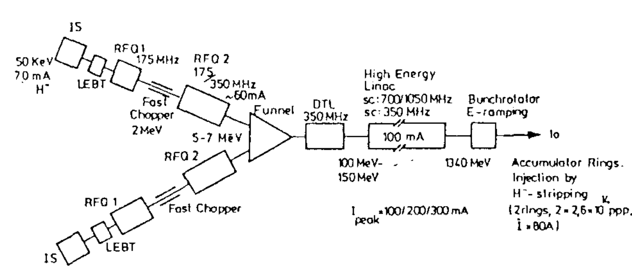

Fig. 7: Linac section, proposed for ESS

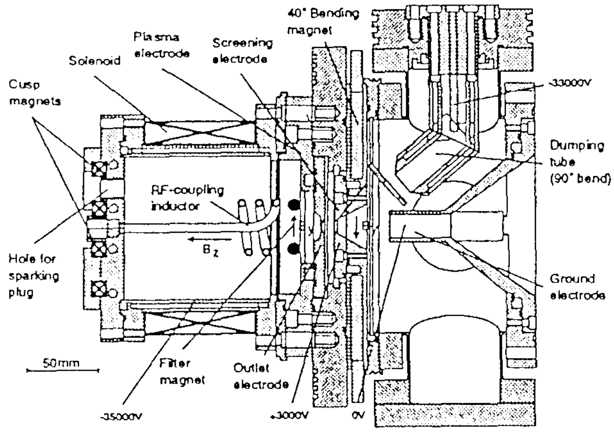

Fig. 8: Schematic drawing of the HIEFS-source with extraction system [29] under test for ESS

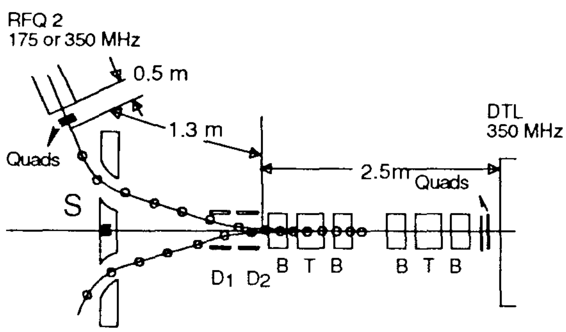

Fig. 9: Funneling-section, proposed for ESS; D: rf-deflectors 175 MHz, S: septum-magnet, T: triplett, B: buncher cavity 350 MHz

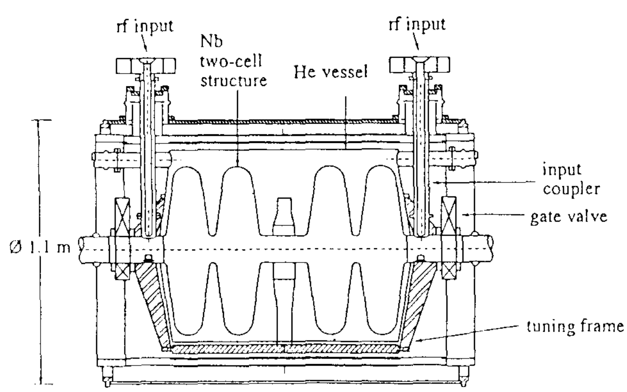

Fig. 10: Superconducting accelerator module, proposed for ESS

are funneled at 7 MeV and further accelerated by a DTL and a high energy linac. Funneling is preferred since it reduces the required current from the ion source in the space charge dominated part of the linac (70 instead of 140 mA) through the LEBT and the RFQ's. It facilitates by this the realization of these components, promises a better beam quality and allows for chopping between the RFQ's at a low frequency of 175 MHz.

Table 2: Examples of parameters of the ESS-injector-RFQs

	RFQ1	RFQ2	or RFQ3
f [MHz]	175	175	350
T in [MeV]	0.05	2.0	2.0
T out [MeV]	2.0	5.0 (7.0)	5.0 (7.0)
L [m]	2.9	5.5	2.9
N rf [kW]	350	700	350
N beam [kw]	100	150	150
I limit [mA]	100	100	200

Even for the relieved requirements there is no ion source available at the moment, which provides the necessary parameters at the same time (70 mA, $\varepsilon_{rms} \leq 0.1\ \pi$ mm mrad, pulse length 10 ms, 50 Hz rep.rate, high reliability, long lifetime). Best candidates so far are the volume sources developed in Berkeley [26, 27] and Culham [28].

In Frankfurt we have designed a source based on the HIEFS [29] with a longitudinal magnetic field and RF excited plasma (Fig. 7), first experiments will be done in the next months.

The LEBT has to transport and to focus the beam into the RFQ; electrostatic and magnetic (2 solenoids) solutions are under consideration, taking into account space charge decompensation and its rise time, nonlinear external and self field, emittance growth etc. [30].

The first RFQ operates at 175, the second with 175 or 350 MHz (Tab. 2), both are not state of the art [31, 32, 33, 24].

Chopping is necessary to produce 240 ns long voids in the beam for clean injection and ejection into and from the rings. Funneling [34] can be achieved by bending magnets and rf-deflectors and rebunchers (Fig. 8). The main problems are the rf-cavities (preferable IH-structures) and the proper electrode geometry for emittance preservation.

The drift tube linac (350 MHz, L = 75 m, cavity peak power = 13 MW) has to accelerate from 5 (or better 7) MeV to 150 MeV. It is in principle state of the art, a post coupled Alvarez structure has been considered so far, but a bridge or cavity coupled DTL or an IH-structure are also possible structures.

The high energy linac will accelerate to the final energy of 1.334 GeV and may be normal or superconducting. For the n.c. linac a frequency of 700 MHz seems to be appropriate, leading to a peak current of 200 mA; but a frequency of 1050 MHz is not out of discussion. As a first option we consider side coupled cavities as used at LANL or Fermilab; the new SCC-linac at Fermilab serves as a good basis for the production techniques and cost estimations. An upgrade to the higher duty cycle of ≈ 7 % seems to be no severe problem. But other structures like the DAW are in consideration also. For reviews of structures see [35, 36]. An economic field gradient is about 2.8 MV/m, leading to Joule losses of about 100 MW peak in addition to the beam power of 70 MW peak. The linac length is about 570 m, the aperture radius 22 mm. For more details and beam dynamics see [37].

For a superconducting version a frequency of 350 MHz is preferred at the moment. The optimum acceleration field is about 10 MV/m ($Q_0 = 3 \cdot 10^9$, $Q_{load} = 3 \cdot 10^5$) leading to a much shorter ($\approx$320 m) and cheaper linac [38]. The large aperture of 10 cm reduces the non linear field components near the axis; this will reduce the emittance growth and the particle losses in the structure. Due to the pulsed operation (the pulse length is fixed by the 1000 injection turns allowed maximum) the s.c. linac looses a part of its intrinsic efficiency by the long build up time in the order of 0.5-1 ms, which has to be taken into account. Fig. 10 shows an accelerator module. With one rf-coupler only a two cell structure is fed, and even then the neccessary power per rf-window with 400 kW is much larger than the power that can be handled nowadays (150-200 kW); therefore developments to improve the couplers are going on at several places. Of course one could reduce the accelerating field, but then the s.c. linac will loose some of its advantages. Other concerns connected with the low frequency and the high electric field are the detuning by the Lorentz force and the dark currents. In both cases a higher frequency (700 MHz) would help, but possibly cooling with superfluid Helium at about 2 K might then be neccesary due to the increased rf losses. In any case, the use of superconducting cavities is very promising, but needs further investigations.

Conclusions

Many proposals for future pulsed neutron spallation sources are in discussion worldwide to overcome the increasing shortage of high flux neutron facilities. Two solutions, namely the combinations of high energy linacs with compressor rings or of linacs with low energy and rapid cycling synchrotrons, are mainly in competition. The R&D activities for these high intensity accelerators are also of great interest for several other projects like energy production, radioactive waste trans-mutation, material irradiation test facilities, or inertial fusion.

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