Superconducting Cavities for Neutron Spallation Sources and other High Intensity Proton Accelerators

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A b s t r a c t:

High intensity linear proton or deuteron accelerators are at present intensively studied for applications in pulsed spallation sources, for fusion material research and for nuclear waste transmutation. Superconducting cavities could offer an interesting option for high intensity linacs. The specific merits and the requirements for their use are reviewed and illustrated by the proposal of a 5 MW pulsed European Spallation Source and by a CW linear accelerator considered at Los Alamos for nuclear waste transmutation.

During the last 20 years efforts in the field of superconducting (sc) cavities have been mainly concentrated on low ß structures for ion acceleration [1] and on structures for electron acceleration [2]. For sc cavities in the intermediate ß range a first effort had been attempted at Karlsruhe for a proton accelerator [3]. This ß-range has gained recently renewed interest for the application in high-brightness and high intensity proton and deuteron linear accelerators [4]. In the following we discuss two specific applications of high intensity proton accelerators for pulsed spallation sources and for nuclear waste transmutation [5].

1. Pulsed linear accelerators for spallation sources

Neutron scattering and synchrotron raditation methods have led in the past to major breakthroughs in the study of the structure and dynamics of condensed matter. Whereas synchrotron radiation interacts strongly with the electrons, neutrons interact mainly with the nuclei and to a much lower degree with electrons. As a consequence of this weaker interaction, neutron scattering has always been an intensity limited field, particularly for the study of small and complex samples. For many years nuclear reactors were the main source of neutrons producing a continuous flow of particles. During the last years pulsed neutron sources with high peak intensities and very short pulses (µsec) have found a growing interest [6]. Neutrons are produced by high energy protons (~1 GeV) hitting a heavy metal target and exciting nuclei to energies where neutrons are "evaporated" (spallation). Typical production rates for 1 GeV protons are of the order of 20 neutrons per incident proton.

Neutrons are produced in a large range of energies reaching up to the energy of the incident protons and have to be slowed down in a hydrogen rich moderator to energies adequate for the study of condensed matter (table 1). They emerge from the moderator with a "white" Maxwellian velocity distribution and a wide range of wavelenghs.

Table 1: Typical parameters of neutrons for condensed matter studies

	Cold	Thermal	Epithermal
Energy (mV)	1	25	1000
Temperature (K)	12	290	12000
Wavelength (Å)	9	1,8	0,29
Velocity (m/sec)	440	2200	14000

By compressing the neutron pulses in a short time interval one does not only increase the peak intensities but one can use time-of-flight measurements for the determination of incident neutron energies. This allows - at least in principle - to use a wide band of wavelenghts since each neutron arrives with a specific time tag at the detector. It avoids the neutron monochromatisation used in CW sources which decreases considerably the neutron intensity at the detector, and a more efficient use of neutrons is possible.

In Fig. 1 a typical time-of-flight diagram of neutrons and their velocity (and time)-distribution at the detector is shown. One concludes from this figure that

- a small pulse length sould be used for increasing the time resolution of measurements. Arguments based on the slowing down and lifetime of the neutrons in the moderator show that it is desirable to keep pulse durations below a few µsec;

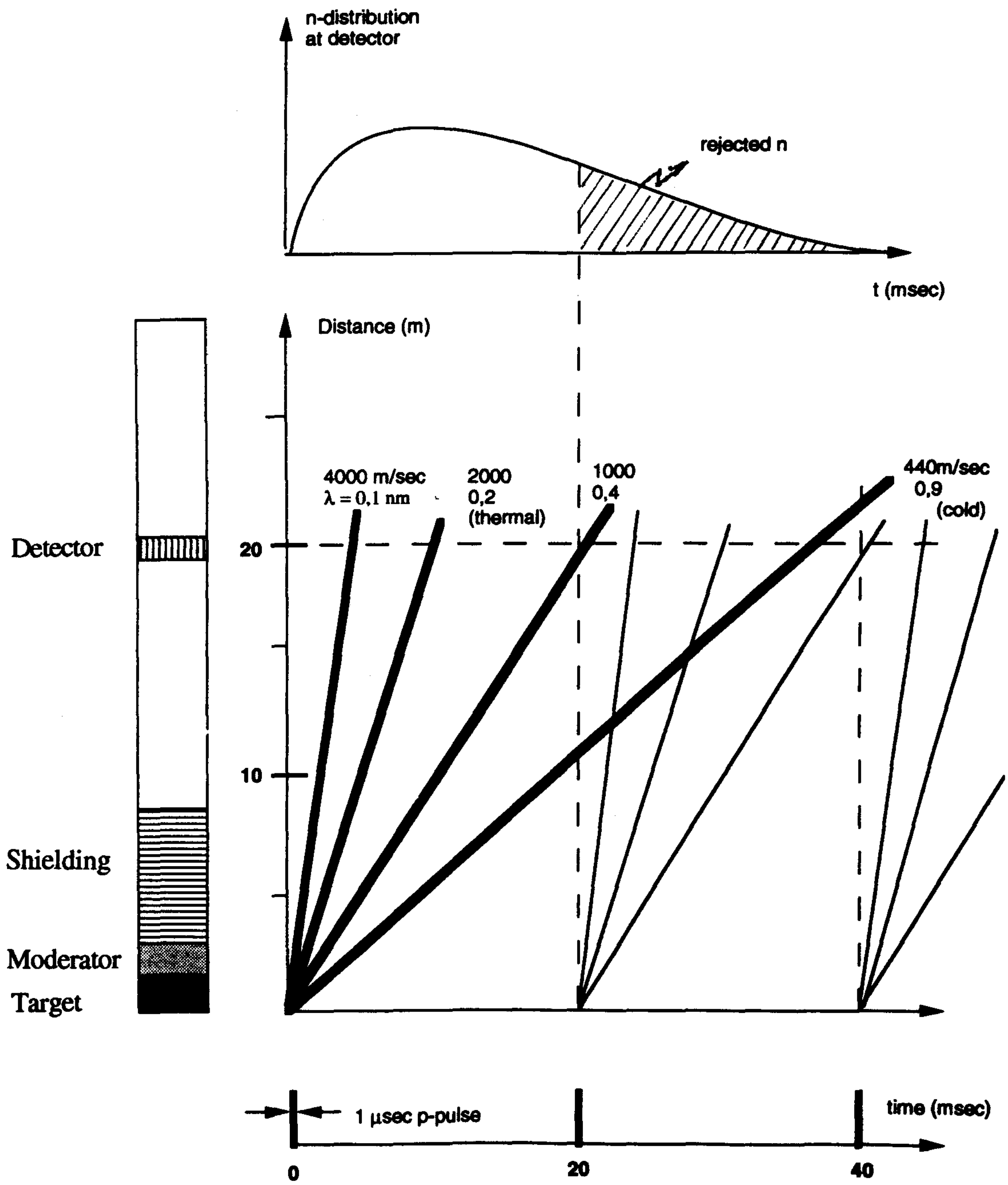


Fig. 1: Typical time-of-flight diagram of neutrons produced by short proton pulses and their velocity (time) diagram at the detector

- small repetition rates of pulses (typically ≤ 50 Hz) should be used in order to avoid the overlap of slow neutrons from one pulse with fast neutrons from the next pulse (frame-overlap).

In summary the main advantages of a pulsed neutron source ly in its time structure; one aims at combining short pulses of high peak intensity with low repetition rates.

Over the past 10 years a number of pulsed spallation sources [7] has become operational (table 2), the most powerful being ISIS at the Rutherford Laboratory (UK). It combines a 70 MeV proton injector with an 800 MeV rapid cycling synchrotron.

Table 2: A few existing and planned pulsed spallation sources

Facility	Accelerators	Average current at target (μA)	Repetition rate (Hz)	Beam power at target (kW)	Energy of one pulse at target (kJ)	Number of protons per pulse at target
IPNS, Argonne	50 MeV Linac 500 MeV Synchr.	20	30	10	0,33	$4 x 10^{12}$
KENS, KEK	40 MeV Linac 500 MeV Synchr.	10	20	5	0,25	$3,1 x 10^{12}$
LANCSE, Los Alamos	800 MeV Linac + storage ring	60	12	80	7	$5 x 10^{13}$
ISIS, Rutherford Lab.	70 MeV Linac 800 MeV Synchr.	200	50	160	3,2	$2,5 x 10^{13}$
Austron (planned) [8]	70 MeV Linac 1,6 GeV Synchr.	63	25	100 (200)	4(8)	$1,6(3,2) x 10^{13}$
European Spallation Source ESS (planned)	1,2 GeV Linac 1,2 GeV Accumul. (1-3)	4.200	50	5.000	100	$5,2 x 10^{14}$*

* more than one ring

There exist plans for even more powerful pulsed sources (table 2); as an example one may mention a study of a European Spallation Source (ESS) with the following design parameters [9]

- 5 MW average beam power at the target(s), corresponding to the average flux of the high flux reactor at ILL, Grenoble
- ~1 μsec pulse length
- 10 and 50 Hz repetition rate at two target stations, respectively.

Presently this goal cannot be realised by a linear proton accelerator alone. One therefore considers the use of a pulsed linac combined with a 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. The beam power of 5 MW at the target can be produced by an adequate combination of proton energy and average current; an energy range of 0,8 to 3 GeV is at present under discussion.

In the following we would like to illustrate the possible application of sc cavities in the high intensity linac and we choose as a typical energy 1,2 GeV. The linac could be followed by two accumulator rings or, if higher energies are desired, by a rapid cycling synchrotron.

A schematic layout is shown in Fig. 2 together with the time structure of the linac beam and the proton beam at the target. In order to reduce injection losses in the rings one accelerates in the linac H^--ions and uses charge exchange ($H^- \rightarrow H^+$) in a thin stripper foil for injection. One expects that an accumulator ring at 1,2 GeV with a circumference of 200 m (~0,7 µsec revolution time) can handle up to 2,6 x 10^{14} circulating protons, accumulated in (a few) 1000 turns. These performances are limited by injection losses and fast beam instabilities [10]. At a repetition rate of 50 Hz this corresponds to an average beam power of 2.5. MW and two rings would be needed to reach the design figure of 5 MW.

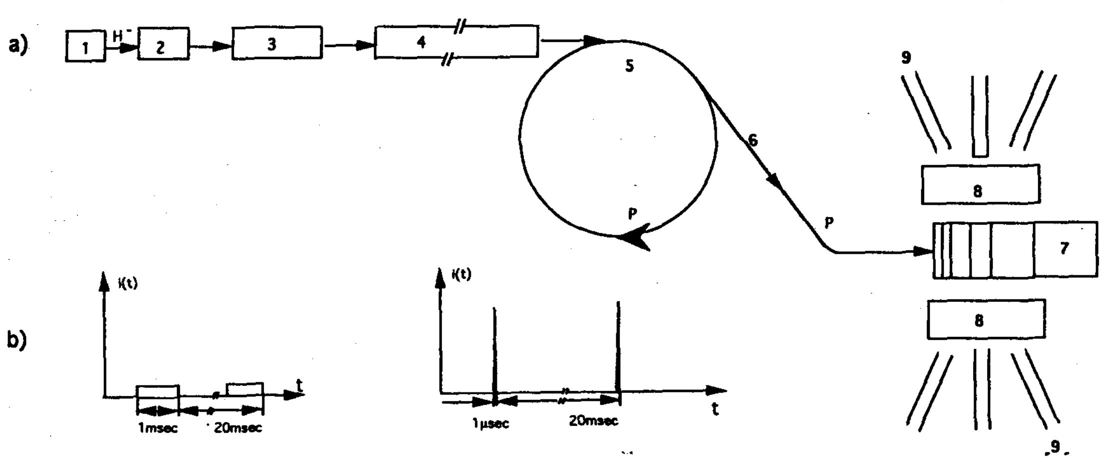


Fig. 2: Schematic view of a pulsed neutron source

a) 1) H^--ion source, 2) RFQ, 3) Drift tube-linac, 4) High energy linac, 5) Accumulator ring with H^--charge exchange injection, 6) Beam transport to target, 7) Target, 8) Moderators, 9) Neutron channels

b) Time structure of beams at linear accelerator and at target

The time structure of the linac evolves as a compromise between H^--ion source performances, a 50 Hz repetition rate and a pulse length not exceeding a few msec for avoiding fast instabilities in the accumulator rings. Furthermore the linac pulse has to be chopped so that a gap in the circulating ring current of about 200 nsec is produced for avoiding beam losses at the fast ejection kicker (rise-time about 200 nsec).

In fig. 3, fig. 4 and in table 3 a possible parameter choice for an nc and an sc linac is shown. At this stage of the ESS-project no detailed optimization has been attempted but it is believed that the parameters chosen are representative for a future layout. For the sc version one has the possibility to choose a peak current of 50 mA without funneling or of 100 mA with funneling.

Table 3: Possible parameter choice for an nc and sc high energy section of the ESS-linac

	nc side coupled cavity	sc iris loaded cavity
Frequency (MHz)	700	350
Iris hole diameter (cm)	4,5	12
ZT^2/Q (circuit def.) (Ohm/m)	753	460
Q_0	$2,2 \times 10^4$	4×10^9
Energy gain E_0T (MV/m)	3	6
Total length including quadrupoles (m)	440	334
Dissipated Power P_c (W/m)	270×10^3	20 (4,2K)
Peak current (mA)	100	50
Chopping efficiency	60 %	60 %
Beam power (kW/m)	180	180
peak rf-power (kW/m)	450	180
pulselength for 2 rings (ms)	1,4	2,8
duty cycle	7 %	14 %
α_{rf} / α_c	0/0	0,35 / 0,35
Q_{ext}	$\sim 2,2 \times 10^4$	$4,4 \times 10^5$
decay / filling time (μsec)	5 / 25	200 / 1000
Total average rf-power (MW)	12,6	6,8
Accelerating efficiency ($\eta_{rf} = 60$ %)	24 %	42 %

Dominant design features for the high intensity linac will be a high efficiency and low beam losses (see below). For the latter aspect the linear accelerator can be divided in three parts (fig. 3).

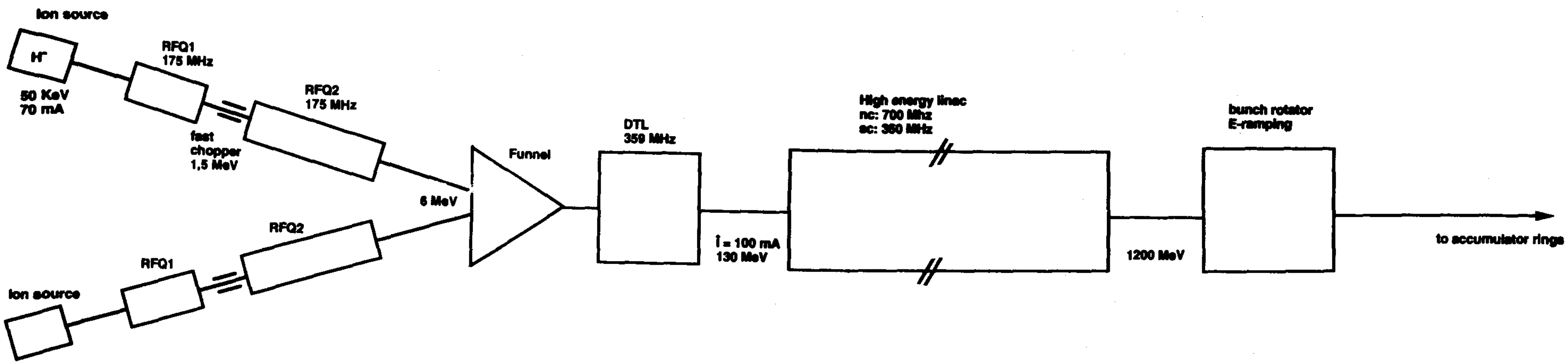


Fig. 3: Schematic layout of a possible ESS linac with an nc or sc high energy section

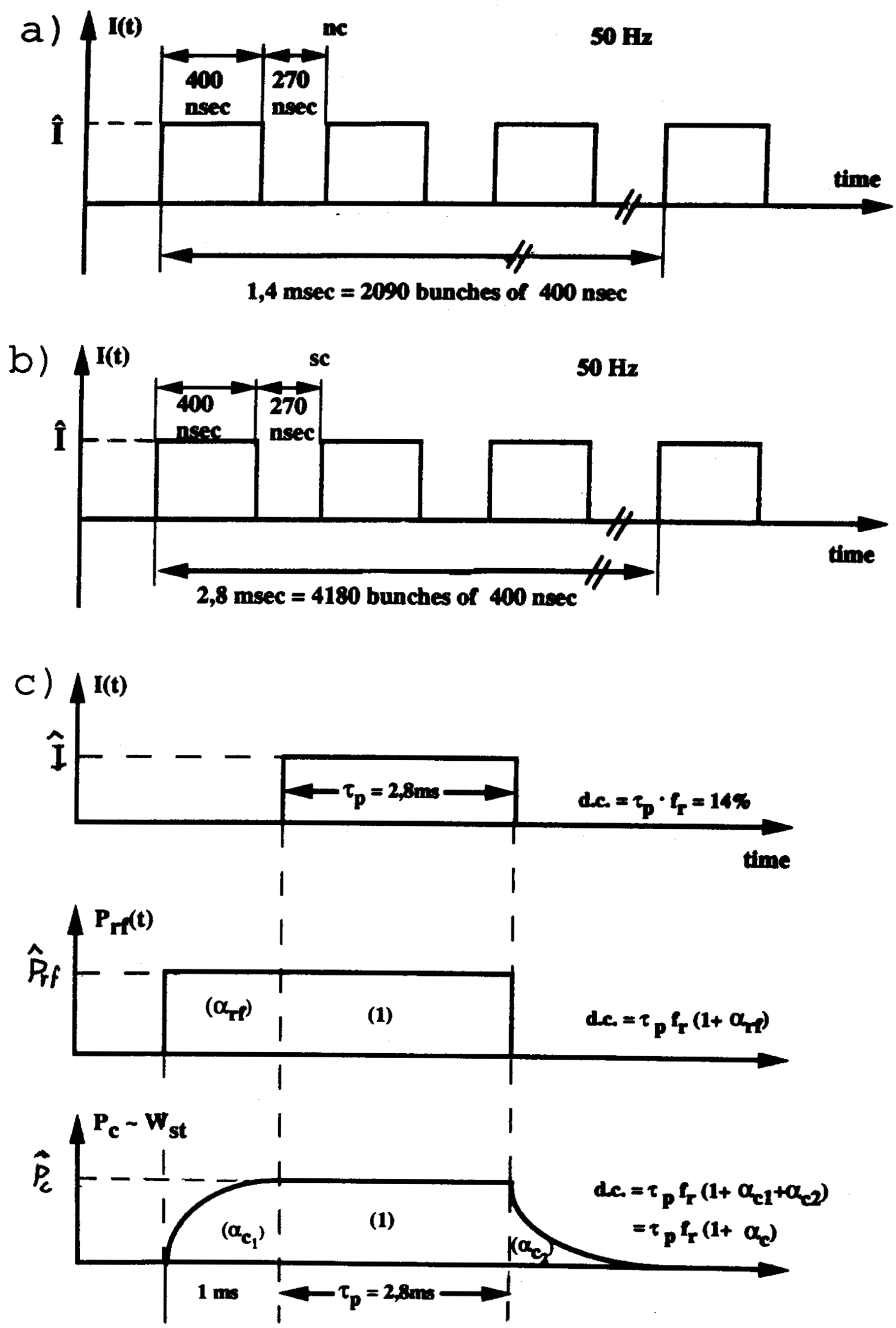


Fig. 4: **A possible time structure for the ESS-linac beam (cf also table 3)**

a) Chopped beam for an nc version
b) Chopped beam for an sc version of the high ß-section with an increased pulse length and duty cycle
c) Detailed time structure of beam pulse, rf-pulse and cavity losses.
During beam-on time every rf-bucket is filled with particles

- A low energy part including the H^--source, RFQ's, a chopping section and possibly a beam funnel. This section would cover an energy range up to~10 MeV; it is considered as a beam shaping section and beam losses will be high (at least 10 %). Because of the high losses and the low duty cycle this section will be made normal conducting.

- Between 10 and ~130 MeV the use of an nc drift tube linac (DTL) or of sc, low ß spoke resonators [4] can be considered. Beam losses can be hopefully kept to a level where beam component activation and degradation of sc cavities remains tolerable. As this section is relatively short, efficiency is not of highest concern.

- For the high energy part (130 MeV to 1200 MeV, ß = 0,47 to 0,9) one may consider the use of nc side coupled, disk and washer cavities or of sc iris loaded cavities [11, 12, 13].

A high power spallation source will serve about 1000 experiments per year and a high reliability and availability will be essential. Therefore a "fault-tolerant" layout [13] should be aimed at, so that the failure of one cavity will not stop operation. A design with two-cell 350 MHz cavities could fulfill this requirement.

Cavities needed for the high energy part of the linac will have a design similar to the one of the sc 350 MHz LEP cavities. However, instead of the 24 cm iris opening of these cavities an opening of about 10 cm is proposed because beam instabilities linked to high impedances are not to be feared, and because the avoidance of H^--Lorentz stripping (cf chapter 5) will ask for small transverse beam dimensions in the quadrupoles. The radius dependence of the longitudinal and transverse field components cannot be neglected as in the ß = 1 case. This is another reason for keeping transverse beam dimensions small.
The low frequency of 350 MHz will permit operation at 4.2 K.

2. CW linear accelerators for nuclear waste transmutation

Four decades of civilian and military nuclear power and material production has left us with large quantities of radioactive wastes, the safe disposal of which poses not only considerable technical problems but also increasing political concern. At present about 400 GW, corresponding to about 17 % of the world electricity consumption, is produced by nuclear reactors and will add large amounts of nuclear wastes to the already existing quantities.

Geological and sea-bed disposal of long-lived and highly concentrated wastes is under active study in a number of countries. Many experts consider that geological storage will be an unescapable issue but the task may be alleviated by nuclear transmutation, i.e. the transformation in an intense neutron flux of long-lived radioactive species to isotopes with shorter half-life.

The idea of using high-intensity accelerators to produce fissionable material by transmutation was already advanced around 1950 by E.O. Lawrence and others at Berkeley [14] and it seems a natural idea to extend transmutation to unwanted radioactive species. Today accelerator technology has been developed to a level of sophistication and reliability where a new approach to its role for waste transmutation seems justified. Recenctly a new proposal has been advanced at Los Alamos [15]. It is based on the production of extremely high fluxes of *thermal* neutrons ($>10^{16}$ n/cm^2 sec, 100 x standard reactor fluxes) by a high power proton accelerator. Neutrons are produced by a high current proton beam of 1 to 1,6 GeV energy impinging on a flowing, liquid Pb-Bi-target generating about 35 spallation neutrons per proton. The primary target is surrounded by a D_2O blanket moderating neutrons to thermal energies. Waste material is carried continuously in pipes through the moderator and transmuted in the high thermal neutron flux.

This proposal is claimed to have a few advantages with respect to earlier ideas involving mostly fast neutrons. The cross sections for thermal neutron capture are large and the neutron flux is high enough so that the probability of absorbing two neutrons in succession in one target nucleus is high: The higher actinides (e.g. Np 237) are converted by a fast neutron capture to daughter products that are fissioned by a second neutron interaction before they can decay to non-fissionable isotopes. The average neutron yield is about 2.7 and actinides act as net neutron producers or fuel.

This approach may allow to use different target layouts for transmutation, breeding, energy production or combinations of them. It should be mentioned that the waste must be separated chemically or electro-chemically "on line", and that a continuous flow of material through the target will be necessary.

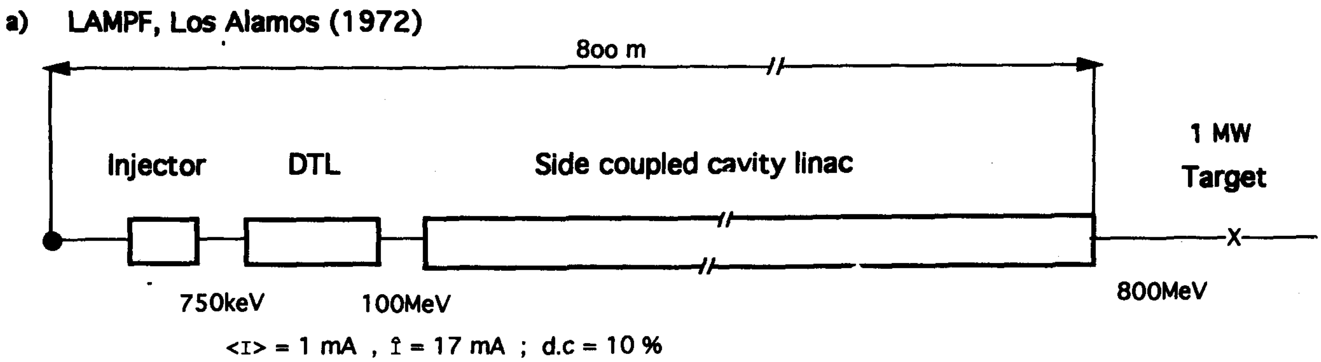
CW linear proton accelerators in the GeV range operated with several 100 mA and a beam power of many hundred MW present another big step with respect to existing accelerators or H^--accelerators considered for spallation sources.

In table 4 and fig. 5 a comparison of the most powerful existing linear accelerator for protons (LAMPF Los Alamos) with a possible accelerator for nuclear waste transmutation [16] is given.

Table 4: A comparison between the Los Alamos proton accelerator LAMPF and an AWT accelerator

	LAMPF	AWT
Energy	800 MeV	1 600 MeV
Average Current	1 mA	250 mA
Beam power	~1 MW	400 mA
Duty cycle	10 %	100 %
Particle/bunch	$0{,}5 \times 10^9$	$2{,}2 \times 10^9$
Beam loss	0,2 nA/m	<5 nA/m
Aperture/rms beam size	6,3	20

Because of the CW operation the number of protons per bunch which determines space charge forces is only a factor 5 higher than in the pulsed spallation source linac but the enormous CW current will ask for new solutions for some components in particular in the low ß sections where the combined problems of high space charge and CW operation have to be mastered. Superconductivity may allow the needed field gradients at much reduced thermal losses and larger openings may somewhat alleviate the problem of beam losses.



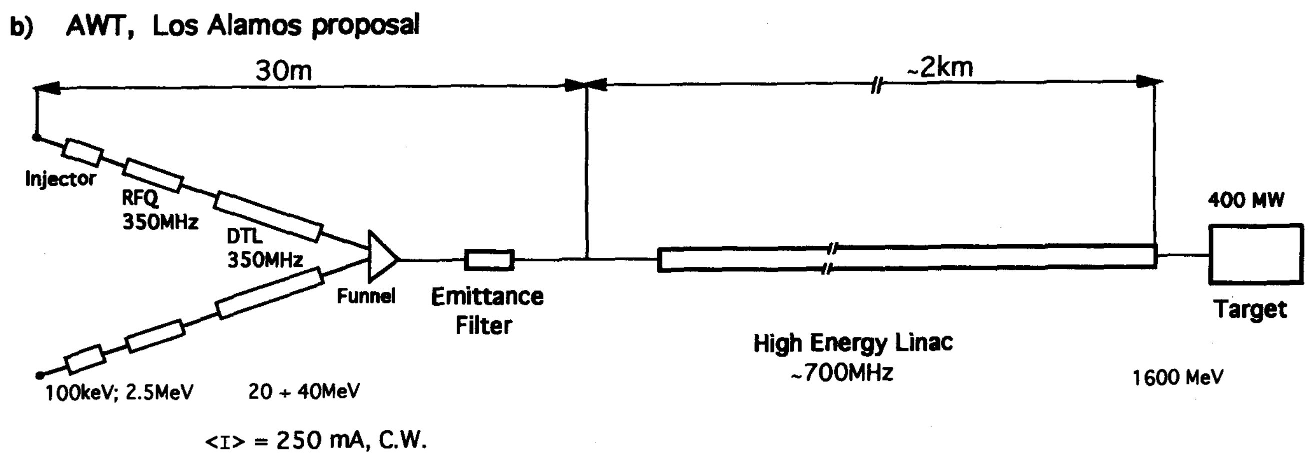


Fig. 5: **Schematic layout**

a) LAMPF accelerator,

b) Los Alamos proposal for an AWT

For the high energy part of the accelerator the large efficiency of sc cavities will be a major asset although at currents in the range of 100 mA the gain with respect to nc cavities is reduced (see table 5). As protons (and not H^-) are accelerated larger quadrupole fields and iris openings are possible. Together with strategically placed scraper families the large openings will certainly offer more flexibility for reducing beam losses inside the sc cavities.

3. Efficiency

For a comparison of acceleration efficiency η_{acc} between nc and sc cavities we use

$$\eta_{acc} = \frac{P_b}{P_{mains}}$$

with P_b : rf power/m given to the beam;
P_{mains} : electric power/m needed for operation.

For a cw nc system one gets, neglecting cooling power

$$\eta_{acc} = \frac{P_b}{(P_b + P_c) / \eta_{rf}}$$

with $P_b = i_b E_{acc} \sin \phi_s$

and $E_{acc}^2 / (R/Q) Q_0$ (linac definition)

or in the writing often used for proton linacs

$$P_c = \frac{1}{2} \frac{(E_0 T)^2}{(\frac{ZT^2}{Q}) Q_0} \quad \text{(circuit definition)}$$

P_c : cavity losses/m; i_b : beam current; ϕ_s:: synchronous phase angle,
$\phi_s = 90°$ for maximum acceleration

$$R_{sh}/Q = 2 (\frac{ZT^2}{Q}) \quad \text{normalised shunt impedance/m}$$

T: transit time factor

Q_0:: unloaded quality factor

η_{rf}: overall efficiency for producing rf power, it is expected that in future η_{rf} = 60 % can be reached (e. g. by using multibeam, high power klystrons with large duty cycle).

For sc cavities one has to take into account in addition cryogenic losses which have to be cooled away with a (technical) efficiency η_{cryo} and one gets

$$\eta_{acc} = \frac{P_b}{\frac{P_b}{\eta_{rf}} + (P_c + P_{st})\frac{1}{\eta_{cryo}}}$$

Here we neglect $P_c << P_b$ in the rf balance and add the static cryogenic losses per unit lenght P_{st} of the cryostat. For large cryo-installation one may assume

$\eta_{cryo} = 1/250$ *at 4,2 K.*

For pulsed operation where the filling and decay times of cavities are not negligable compared to the pulse length τ_p one has to take into account the additional rf-power needed for field built-up and the cavity losses during field built up and decay (see fig. 4).

Introducing the duty cycle d.c = τ_p x f_r (f_r: repetition frequency) and peak powers one gets for s.c cavities

$$\eta_{acc} = \frac{\hat{P}_b}{\hat{P}_b \frac{(1+\alpha_{rf})}{\eta_{rf}} + [\hat{P}_c(1+\alpha_c) + \frac{P_{st}}{d.c.}] \cdot \frac{1}{\eta_{cryo}}}$$

with $\hat{P}_c << \hat{P}_b$ and $\hat{P}_b = \hat{P}_{rf}$ (matched conditions); for the significance of α_{rf}, α_c see fig. 4.

η_{acc} does not only depend on $\hat{P}$ (or $\hat{I}_b$, ϕ_s) and $P_c(E_{acc}, R/Q, Q_0)$ but also on the duty cycle and the filling times (via α_{rf} , α_c).

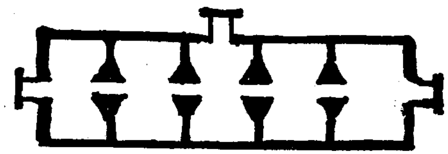
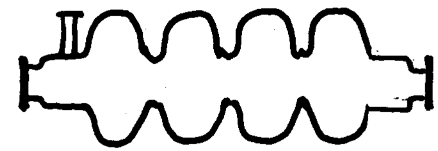
In table 5 the accelerating efficiency is compared for an nc and an sc cavity of the LEP type [17,18] and for different beam currents and duty cycles showing that efficiencies of nc and sc cavities approach for very high peak currents and low duty cycles.

In table 3 the efficiencies are similarly compared for the high energy part of the ESS linac

(ß = 0,8 to 0,9 , E = 1,2 GeV , <I> = 4,2 mA , 50 Hz , <P_b> = 5 MW)

Beam and cavity parameters as well as the time structure of the beam have been optimised according to the specific requirements of cavities and the accumulator rings, in particular the duty cycle and gradients have been increased in the sc version. An accelerating efficiency of 24 % and 42 % have been obtained for the nc and sc cavities, respectively. Peak rf-powers per unit length are also larger for the nc version and the average rf power for the high energy part of the linac is increased almost by a factor 2 leading to a corresponding increase in operation costs for the rf-system. The circumference of the following accumulator or accelerator ring may have to be increased for reducing the number of injected turns per ring

Table 5: Comparison of acceleration efficiency of an nc and sc LEP cavity (ß =1) for different beam currents and duty cycles. Typical cavity parameters are given.

	nc Cu cavity 	s c Nb. cavity 
Frequency	350 MHz	350 MHz
Iris hole diameteter	100 mm	240 mm
R/Q	650 Ohm/m	276 Ohm/m
Q_o	$4x10^4$ (300 K)	$4x10^9$ (4,2K)
Design acc. field	1,5 MV/m , CW	6 MV/m , CW
Dissipated power: P_c	86 kW/m (300 K)	33 W/m (4,2K)
stored energy W_{st}	1,6 Joule/m	60 Joule/m
Accelerator efficiency*		
$\eta_{acc} = P_b/P_{mains}$		
CW: i_b = 5 mA	5 %	50 %
i_b = 100 mA	38 %	59 %
i_b = 250 mA	49 %	60 %
pulsed $<i_b>$ = 5 mA		
d.c. = 10 %	27 %	56 %
d.c. = 5 %	38 %	58 %

* η_{RF} = 60 % , η_{cryo} (4,2 K) = 1/250 , P_{st} = 5 W/m

For sc cavities and for ß around 0,5 the R/Q value is decreased by about a factor 4 (as compared to ß = 0,9) due to the transit time factor [13]. Therefore at pulsed mode operation the accelerating gradient has to be lowered for keeping the filling time constant.

4. Beam losses

One of the most important design aspects of high intensity proton accelerators is small beam losses; component activation along the linac should be kept sufficiently low to permit maintenance and repair with short notice access.

At energies above 120 MeV activation is mainly produced by spallation neutrons and is proportional to $E^{0,9}$ [19]. At energies between ~10 and 120 MeV activation is lower but depends in a complex way on the energy and nuclear cross sections of the material. The range of protons in Cu or Nb is approximately:

at 10 MeV	0,3-0,4 mm
at 100 MeV	11 - 13 cm
at 1 GeV	60 cm

There exist reliable data on beam losses and component activation at LAMPF [20]. For the high-energy part of the accelerator beam losses are kept below 1 nA/m, corresponding at 800 MeV and after 1 day of deactivation to a dose rate near the cavities of 20 mrem/day. This dose rate will already limit exposure times of persons to a few hours. In copper cavities the main activity is due to Cu^{64} with a half-life of 13 h. Activation in Nb components decays with a half time of about 1 month.

Beam losses in high intensity linear accelerators are today under intensive studies [21-24]. One uses multiparticle tracking codes and tries to describe losses and in particular halo formation by additional analytical modelling. Codes taking into account space charge forces in a (simplified) transverse and longitudinal focusing channel can predict today relative beam losses down to about 10^{-4}. A much better understanding of beam behaviour, in particular halo formation will be needed to cope with relative beam losses in the range of 10^{-6} to 10^{-7} needed for AWT accelerators (see below). Avoiding beam losses at this level will be a major challenge for the realisation of high intensity accelerators.

Another cause of beam losses is cumulative beam break-up which has been studied for a large range of parameters in low and high ß linear accelerators [25]

Remedies against beam losses imply careful matching of beam channels in all six dimensions especially between linac sections with different frequencies and cavity types. Matching has to be realised not only for the rms beam sizes but also with respect to particle distributions which have to be kept as much as possible near a 3 D equilibrium distribution. Abrupt changes in focusing strength should be avoided.

A large aperture ratio in the transverse and longitudinal planes (iris diameter / rms beam diameter and longitudinal acceptance / bunch length) are obvious advantages for small beam losses.

The large openings of sc cavities offer great flexibility in the design and optimization of aperture ratios. A balance between iris openings, shunt impedance, cavity length and quadrupole openings and distances has to be determined by tracking of particle trajectories. Extensive studies will also be needed for strategically placed beam scrapers which may concentrate beam losses and activation at well defined regions where good access and remote handling can be realised.

Sc cavities in high intensity proton linacs present several specific problems linked to beam losses. A thorough treatment will not only involve a more detailed knowledge of loss mechanism but may also require further studies for the behaviour of solid Nb or Nb/Cu cavities and their sc properties under high energy proton bombardement.

For an order of magnitude estimation we assume a loss rate in the order of 1 nA/m which has been found typical in the operation of LAMPF with a proton beam of 600 μA [20]. We estimate losses for two typical regions in the ESS linac and the AWT linac:

Losses may be particularly big at the entry of the sc low ß section following the RFQ and funneling section (see fig. 3 and fig. 5b), which is a region of potential mismatch. We assume therefore an enhanced beam loss of 5 nA/m over the first cavities.

At the high energy end of the linac beam losses are particularly dangerous because of the $E^{0,9}$-dependence of activation, but matching will be easier and we assume beam losses of 1 nA/m. This corresponds for a spallation source linac of 1200 MeV, average current of 4.2 mA and about 400 m total length of the high energy part to a relative beam loss of $\sim 10^{-4}$ which may be just predictable by present tracking codes.

For an AWT linac of 1,600 MeV, 250 mA average current and a length of ~500 m the relative beam loss is 2×10^{-6}, far beyond the prediction range of existing tracking codes.

In table 6 a typical layout of sc cavities in these two regions is shown [11]. The iris surfaces where beam impingement occurs preferentially and the volume of Nb affected are estimated. Losses are concentrated in a region of high electric and low magnetic surface fields.

Amongst the effects linked to proton beam losses in sc cavities one may mention:

- Energy deposition at L He-temperatures (cavities and cryostats); the power loss should remain small compared to the static cryostat losses (5W/m) and to the average rf-losses (3 W/m) and should not exceed ~1 W/m. One may mention that the energy content of one ESS linac pulse at 1.2 GeV correponds to 100 kJ, but because of the large range of protons it will be distributed in case of total bunch loss over a large length of cavities and cryostats.

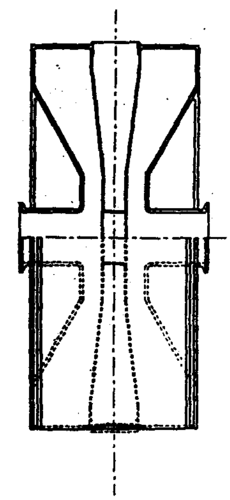
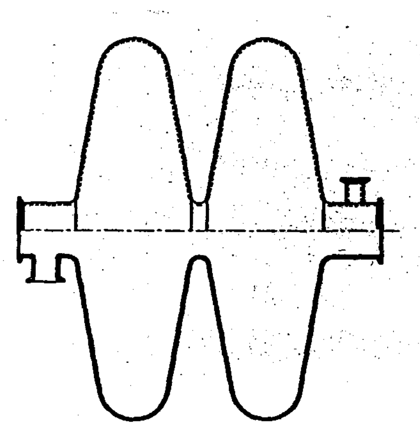
- Hydrogen penetration into the Nb-lattice producing after one warm up-cooldown cycle Nb-hydrid and causing Q-degradation [26].In high purity Nb (RRR = 300) the H-concentration should not exceed a few100 ppm corresponding to $\leq 10^{19}$ H-atoms/cm^3. Obviously this effect will be strongest at low energies where the range of protons in Nb is small.

- Q-degradation by proton-impingement on a Nb-surface. In the past tests have been performed on low quality Nb (presumably RRR = 40) by exposing the cylindrical wall of a resonator to 180 MeV protons [27]. At a total number of 10^{15} p/cm^2 an irreversible degradation of the residual Q was observed for 5 different modes. A slight degradation of the achievable maximum surface magnetic field was also found. The exact cause of this degradation is unknown and more detailed studies will be needed to clarify the exact loss mechanism (radiation damage?).

The adsorption of protons at sc Nb surfaces could be a problem at the front end region of the linac where proton-ranges are very small and beam losses of many % are expected.

In table 6 a comparison of the different effects is made. In the low energy section a lower limit of beam losses will be set by activation and by radiation damage. At the high energy end limits are set by activation, power loss at LHe-temperatures and by radiation damage.

Table 6: Particle losses for two typical cavity layouts

	Low energy E = 10 MeV	High energy E = 1200 MeV
		
Assumed beam losses	5 nA/m	1 nA/m
Range of p in Nb	0,4 mm	~50 cm
Iris surface hit by protons	330 cm^2	300 cm^2
Nb-volume hit by protons	13 cm^3	—
Number of protons/cm^2 6000 h of operation	6,8 x 10^{14} p/cm^2	3 x 10^{14} p/cm^2
Allowed number of protons/cm^2	< 2 x 10^{15} p/cm^2	2 x 10^{15} p/cm^2
Number of protons/cm^3	1,7 x 10^{16} p/cm^3	—
Allowed value	10^{19} p/cm^3 (100 ppm)	—
Power loss/m	0,05 W/m	1,2 W/m
Allowed value	1 W/m	1 W/m

5. A special problem in a H^--beam: Lorentz-stripping

In a spallation source the injection from a linac into the ring accelerator is done by stripping of H^--ions because this process permits small injection losses. Consequently one has to produce and accelerate H^--ions in the linac. As the extra electron in the H^--ion is very weakly bound it can be dissociated by the electric field created in its rest-system by an external magnetic field and in particular by bending magnets and by the quadrupole fields needed for focusing along the linac. The probability of neutralisation [28] depends on the H^--kinetic energy and on the strength of the quadrupole field which increases linearly with the distance from the axis. For a typical focusing quadrupole in the high ß region one needs a gradient of about 20 T/m and a quadrupole length of 30 cm (independently of the use of nc or sc cavities). In fig. 6 the loss rate per quadrupole doublet as a function of H^--kinetic energy and of the distance from the axis is shown [29]. This loss rate should not exceed a value of about 1 nA/m which corresponds at an average current of 4,2 mA to a loss rate of 0,25 x 10^{-6} and forces one to keep beam dimensions well below 2 cm.

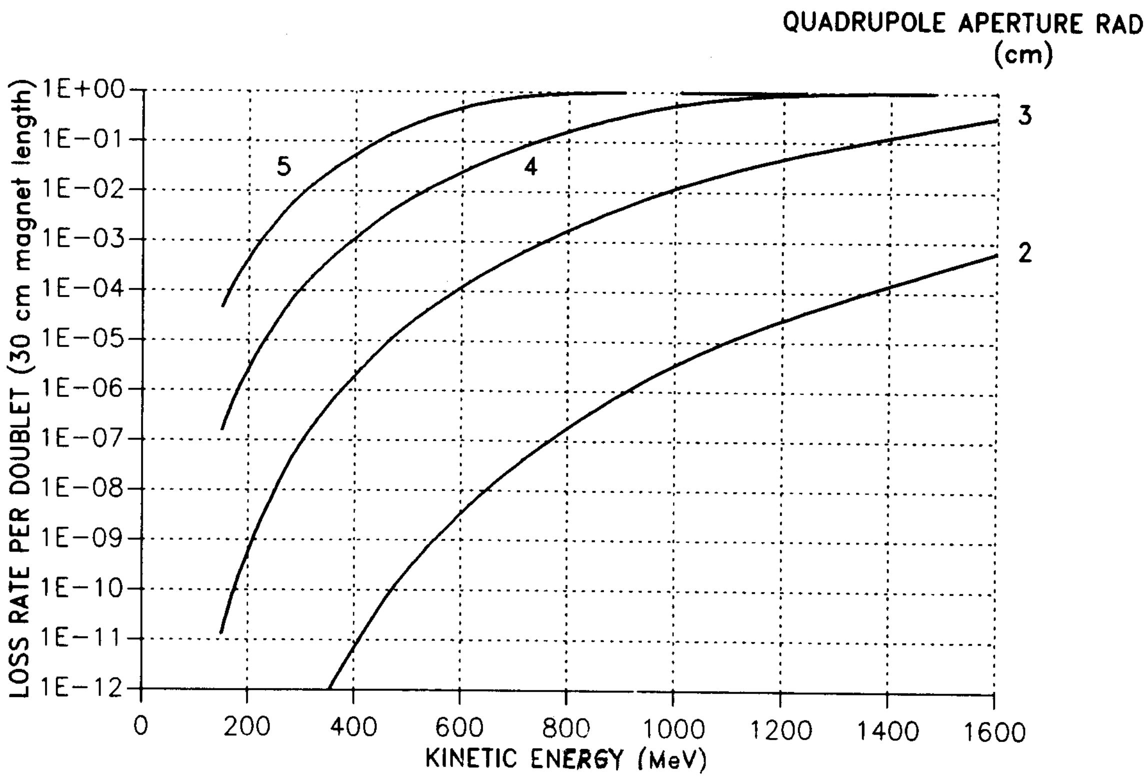


Fig. 6: Neutralisation rate of H^- in a typical quadrupole doublet for an ESS-linac as a function of H^- ion kinetic energy. Parameter: distance of particles from axis inside quadrupoles [29].

With focusing quadrupoles between all cryostats the large iris openings of sc cavities cannot be exploited for larger beam dimensions because of the limited quadrupole openings. To alleviate the problem the use of doublet focusing between cavities has been proposed [13]. Fortunately this problem does not arise in a linac for AWT because one accelerates protons.

6. RF-problems

We assume in the following for the spallation source linac the beam and cavity parameters given in table 3 as well as the time structure shown in fig.4. For the AWT linac a current of 250 mA and a gradient of ~6 MV/m is assumed (1,5 MV/cell).

6.1 Beam loading

The ESS linac will have transient beam loading conditions similar to TESLA [30]: the energy removed by the beam during a pulse of 2,8 msec length is about eight times the stored energy in the cavity (see table7). Therefore the peak RF-power has to be matched to the peak power removed by the beam. Beams are chopped with intervals of 270 nsec. This is sufficiently short for keeping transients in amplitude and phase at a level of 10^{-3}. For comparison we have also included in table 7 the conditions for LEP (with 16 bunches of 0,75 mA average current) where less than 1 % of the stored energy is removed by one bunch. If nc cavities are used in the ESS linac the chopping causes already transient beam loading at the level of a few % and adequate rf control will be needed for stabilising the acceleration fields.

In an AWT linac stationary beam loading is very large but because of the CW operation transient loading is of no concern; (it may however be a problem during start-up periods of current).

6.2 Power couplers

For the matching of the peak rf-power to the peak beam power in the ESS-linac one has to take into account the chopping efficiency of 60 %. With the parameters of table 3 and $\hat{I}$ =50 mA, E_0T = 6 MV/m, 2 cell cavity, ß = 0,8 one gets

$$P_{rf} = 90 \text{ kW/2cells}$$

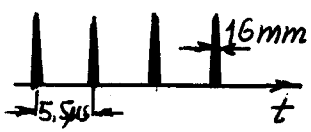
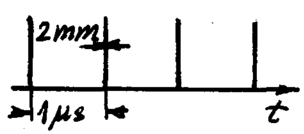
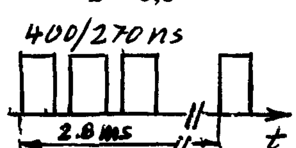
The finite filling time of 1 msec asks for an increase in rf-pulse length by 1 msec. The peak power remains well below the values foreseen for TESLA (table 7).

For an AWT linac with 250 mA the power coupler will limit the number of cells and E_{acc}. Even with E_{acc} = 6 MV/m and a one cell cavity (1,5 MV per cell) one will already obtain a power of 375 kW and waveguid couplers like in B-factories should be considered [31].

6.3 HOM couplers

LEP or TESLA are operated with very short, high intensity pulses at a distance of 5,5 µsec and 1 µsec, respectively. This gives raise to a very dense line spectrum extending up to many GHz and it is prudent to decrease the Q_{ext} of HOM couplers - at least for the most dangerous HOM's to a value which inhibits resonant built-up of HOM fields. The condition for this is
$Q_{ext} = \omega_{hom} \times \tau_b$ where ω_{hom} is the frequency of a given HOM and τ_b is the bunch distance. This gives for LEP and for TESLA Q_{ext} of 1.8×10^6 and $3{,}9 \times 10^6$, respectively (table 7). As the line spectrum reaches up to frequencies far above the cut-off frequencies of beam tubes and tapers it may be necessary to absorb propagating hom in adequate absorbers located at higher temperature regions between cavities.

Table 7: Comparison of several rf parameters for a few sc cavity systems

	Pulse length (msec)	duty cycle (%)	V_{acc} (MV)	q (nC)	q V_{acc} (Ws)	W_{st} (Ws)	P main coupler (kW)	Q_{ext}	P_{HOM} off resonance (W)
LEP 16 bunches, 4 cells, 350 MHz 	(CW)	100	10	66 one bunch	0,77	102	110	$1{,}8 \times 10^6$	345
TESLA 800 bunches, 9 cells, 1,3 GHz 	0,8	1	25	8,2 one bunch	162 (800 bunches)	79	200	$3{,}9 \times 10^6$	550
ESS 2 cells, 350 MHz, ß = 0,8 	2,8	14	3	0,14 per rf-period	250	30	90	$4{,}4 \times 10^5$	0,3
AWT 1 cell, 350 MHz, ß = 0,8	(CW)	100	1,5	0,7 per rf-period	2×10^{-3}	30	375	2×10^4	45

In a linac for a spallation source the conditions are different because under beam-on conditions every RF-bucket is filled as in a CW linac. We can therefore consider the pulse sequence as an amplitude modulated rf with modulation frequencies in the range of 50 Hz and 1,5 MHz (670 nsec from the chopping). The particle bunches have a length of about ± 10° at 350 MHz corresponding to about 5 cm. The corresponding spectrum has the maximum possible line distance of 350 MHz and each line has side bands up to a few MHz; it extends to about 6 GHz. Under these conditions one can try to escape to resonant built-up by avoiding the overlap of dangerous cavity modes with the beam lines. Broadband hom couplers will only be needed for evacuating the total non resonant hom losses given by

$$P_{HOM} = k_m q^2 \text{ x number of bunches/sec}$$

where q is the charge of a single bunch and k_m is the total loss factor.

The total loss factor k_m has been extrapolated from LEP cavities including the effect of tapers for a frequency range 350 MHz < f < 2,2 GHz [32] and for an iris opening of 12 cm; one finds for a 2 cell cavity k_m = 0,5 V/pC.

In table 7 the corresponding total hom losses are given for an ESS and AWT linac and compared with corresponding figures for LEP and TESLA. As expected the CW trains of the ESS and AWT linacs do not need high power hom couplers (provided resonant built-up can be safely avoided).

7. Conclusions

During the last years an increased interest in proton and deuteron accelerators with high peak and average beam currents has arisen. The use of sc acceleration cavities can offer interesting options at high intensity acelerators with large duty cycles.

Two applications of high intensity accelerators in the GeV-energy range have been considered.

Pulsed linear H^--accelerators for spallation sources will be operated with pulse length of msec, duty cycles of a few percent and with peak currents of about 100 mA. Sc cavities offer a possibility for increased acceleration efficiency which can be made larger than for nc cavities by about a factor 2 with a concomitant reduction of operating costs. The large iris openings of sc cavities can be an advantage for the handling of beam losses. However, because of the Lorentz dissociation of H^--ions in the magnetic field of focusing quadrupoles transverse beam sizes have to be kept small. At low energies one would probably use nc cavities which can handle duty cycles of a few percent with adequate accelerating gradients and are less sensitive to beam losses.

Another advantage of sc cavities is their large stored energy which comes to bear in the case of chopped beam needed for operation of the linac with accumulator or accelerator rings. Transient beam loading will be not an issue for sc cavities whereas nc cavities need an adequate rf control for keeping energy variations well below a few percent.

For nuclear waste transmutation CW linear proton accelerators have been proposed with average beam currents of hundreds of mA and beam powers of hundreds of MW. The high acceleration efficiency of sc cavities remains an overwhelming asset at these power levels although nc cavities have increased efficiency at current levels of 100 mA.

For CW operation sc cavities can be operated with large accelerating gradients. This advantage could hopefully be exploited for RFQ and for the energy range normally covered by DTL's, provided beam losses can be kept at tolerable level and adequate vacuum conditions at the front end can be handled. At the high energy section of the linac gradients will be limited by the power levels to be handled by the main couplers even if the number of cells per cavity is reduced. A balance between power levels and costs will be an essential design aspect.

The control of beam losses and their reduction to very small values (typically nA/m) will remain a major challenge for high intensity proton or deuteron accelerators. Whereas this task seems to be in reacch for spallation source intensities, it exceeds by orders of magnitude the possibilities of present beam dynamic codes for an AWT-accelerator. It can be expected that the large iris openings of sc cavities will offer some additional flexibility in beam design.

In contrast to large $e^{\pm}$ ring and linear colliders the beam for spallation sources and AWT applications is not concentrated in short bunches but in each pulse train every rf-bucket is filled with particles. This should keep hom losses small provided resonant built-up due to an overlap of spectral beam lines with HOM modes can be avoided.

For a spallation source where a large number of experiments per year is foreseen, a high availability and reliability of the accelerator will be essential. Therefore any linac layout has to be "fault-tolerant" so that the failure of a single cavity should not stop operation.

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