Application of superconductivity to intense proton linacs

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Abstract: Three examples of proposed superconducting linacs for intense particle beams are presented and in two cases compared to normal conducting counterparts. Advantages and disadvantages of both types are discussed. Suggestions for future developments are presented. Finally a comparison of estimated operational costs of the normal and the superconducting linac for the ESS is given.

1. Introduction

Linacs for intense proton beams or intense beams of light ions like H^- or H_2^+ have been proposed in the last years for several applications like the Accelerator Transmutation of Waste (ATW), Spallation Neutron Sources (SNS), or the Accelerator Production of Tritium (APT).[1,2] The required beam power ranges from 5 to 200 MW, the proton energy is in the range of one to three GeV. According to the special application the linacs are designed to operate continuously or in a pulsed mode. The required beam quality also depends strongly on the application. E.g. the chopped beam of a linac for a short pulsed spallation neutron source has to be injected into a ring for bunch compression, so it must have a much smaller transverse emittance and a higher energy resolution than a cw beam of a linac for ATW application.

2. History of superconductivity for proton accelerators

The first superconducting proton linac was designed at the end of the sixties at the KfA Karlsruhe.[3] One started to build up a low energy structure for a preaccelerator. It was a helix structure with a phase velocity smaller than 0.1*c. Unfortunately it showed a lot of mechanical resonances and it was difficult to keep the rf resonances locked. Half- and quarter-wave line resonators investigated at several laboratories showed nearly the same behaviour.[4] The problems of the rf control system could be solved in the middle of the seventies and especially the half- and quarter wave resonators are operated since that time with great success in heavy ion accelerators.[5,6] More than about one million hours of operation have been carried out in several accelerators since that time. The availability as well as the reliability are higher than for accelerators equipped with normal conducting copper structures. Unfortunately the activities at the KfA Karlsruhe in this field stopped and there was only one attemp to continue on the way to a high energy proton linac. A superconducting drift tube structure (dtl) with a phase velocity of 0.1*c was constructed and tested in 1978.[7] As the geometry was not optimized for a superconducting structure an accelerating field of only 3 MV/m could be reached limited by multipacting. Nowaday - more than 15 years later - the spoke cavity is an interesting design for a superconducting structure with low phase velocity.[8] It is going to be developed at several laboratories.[9,10] Also a design of a superconducting radio frequency quadrupole (rfq) has been made.[8,9]
Since the efford of the KfA Karlsruhe in the early seventies there was no other design of a high energy superconducting proton linac. But due to the successful operation of superconducting cavities in electron accelerators the application to proton linacs seems to be useful. The

achievable high field levels and the low losses let the superconducting linac become attractive. But nowaday one starts to install superconductive structures in the high energy part of the linac -say above 100 MeV- because this is the longest and the most power consuming part.

3. Proposed superconducting proton linacs

Superconducting structures can usefully be applied when their properties are superior to those of normal conducting ones. In the following three examples of superconducting linacs are presented, in two cases they are compared with a normal conducting counterpart. In each case only the high energy part of the linac is designed superconducting with elliptically shaped structures like those known from electron accelerators. The rfq and the dtl are designed normal conducting. Besides some advantages with respect to beam dynamics the economical are the main issues in which the superconducting cavities are superior to the normal conducting ones. For a comparison it is important whether the linac is operated in a continuous wave (cw) or a pulsed mode or alternately in the one or the other. The superconducting linac may be operated in all three modes with the same accelerating gradient because the dissipated rf power in the structures is small. The amount of additional rf power that has to be installed for cw operation is given by the additional beam power only. In case of a normal conducting linac the dissipated power in the structures is typically a factor 1.2 to 2 larger than the power transfered to the beam.

3.1 The linac for APT at LANL

The first example is a 100 MW cw linac for accelerator production of tritium proposed by Los Alamos National Laboratory.[11] The general layout of the normal conducting version is given in Fig. 1, some important and characteristic parameters are summarized in Table 1.

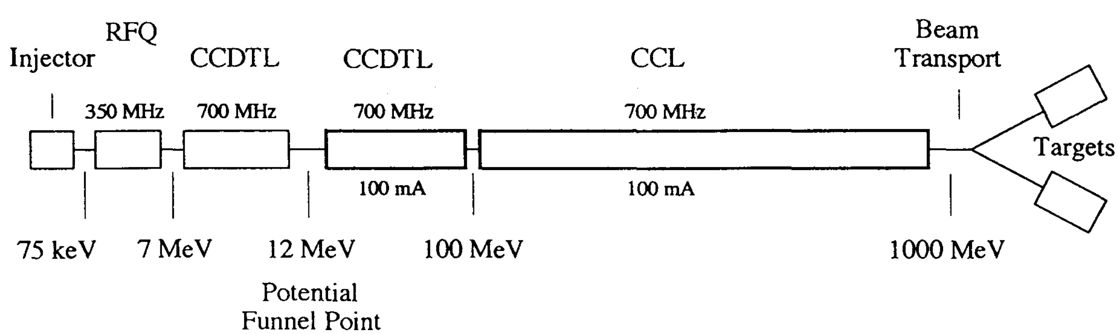

Figure 1a General layout of the normal conducting 100 MW linac

Table 1a Some parameters of the proposed LANL normal conducting cw linac

LANL normal conducting linac, cw operation		
energy range	MeV	100 - 1000
length of accelerator	m	1080
number of structures		300
klystron power	MW	1
accelerating gradient	MV/m	1.3
dissipated power per structure	KW	130
total power consumption	MW	355

Because of the low accelerating gradient the linac becomes very long, and the capital costs which are mostly proportional to the length increase. On the other hand the efficiency (defined as the ratio of beam power to wall plug power) is high at low gradients. Rising the gradient would increase the dissipated power because it scales with the square of the gradient. Therefore the gradient of 1.3 MV/m seems to be a compromise between capital and operational costs.
As there are seven klystrons per module the number of klystrons is very high, but it has the advantage that a fault of a klystron will not influence the operation of the linac. However the structures can not be easily exchanged if one fails. The length of each cell of a structure is adjusted to the velocity of the prarticles. So each structure is different. If one wants to have complete structures as spare parts, one needs as many spare parts as there are structures.

The layout of the superconducting counterpart which is at present a point design and not yet optimized is shown in Fig. 1b, the main parameters are summarized in Table 1b.[12]

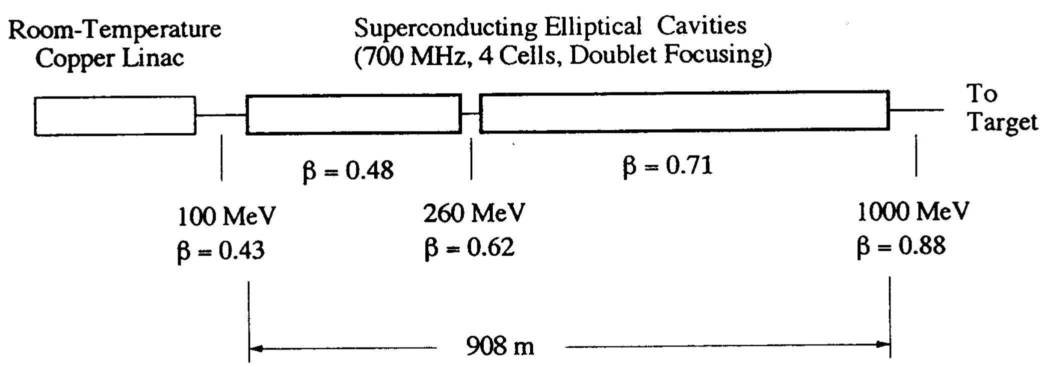

Figure 1b General layout of the superconducting 100 MW linac

Table 1b Some parameters of the proposed LANL superconducting cw linac

LANL superconducting linac, cw operation		
energy range	MeV	100 - 1000
length of accelerator	m	980
number of structures		488
klystron power	MW	0.67 - 1.0
number of klystrons		122
accelerating gradient	MeV/m	4.3 - 5.3
dissipated power per structure	KW	0.006
total rf power consumption	MW	110

The superconducting linac in this design is not much shorter than the normal conducting counterpart. This is due to the for superconducting structures conservative design field of about 5 MV/m and the generally small filling factor (defined as the ratio of the length along the linac where the particles are accelerated to the total length). This filling factor is typically 0.45 to 0.5 for superconducting structures and 0.75 to 0.8 for normal conducting ones. It is mainly determined by the two long cut off tubes needed for each superconducting structure and the cold-warm transitions of the cryostats. To increase the availability the linac is equipped with only two types of structures which have different phase velocities. The medium energy section has cavities with β=v/c=0.48 to accelerate the beam from 100 to 261 MeV, the high energy section has cavities with β=0.71 for the energy range from 261 to 1000 MeV. The structures are only 0.411 m and 0.608 m long (four cells) and as many structures are identical it is easy to have structures of both types as spare parts. The possibility of operating this linac with only two types of cavities is given by the large velocity acceptance of these short and independently phased cavities. Beam dynamics show that the linac performance is excellent over the full range of current from zero to 100 mA.

In this design each cavity is equipped with two coaxial line couplers each carrying 105 KW. It has been demonstrated at Los Alamos National Laboratory that it is possible to feed the rf power through several couplers to one structure. On the other hand it has been demonstrated at CERN, DESY, and KEK that today about 150 KW can be carried by a coupler under beam conditions. The rf power of one klystron is split among four cavities. The requirements to the rf feedback system are very moderate. Beam dynamics calculations have shown that it is sufficient to control the field level of a cavity to only five degree in phase and three per cent in amplitude, a benefit of using short and indepently phased cavities.

The power consumption of the APT system with normal conducting linac has been estimated to 355 MW. For the version with the superconducting linac the Los Alamos Group calculates that more than 20 M$ of operational cost may be saved per year.

3.2 The superconducting linac for a SNS at BNL

The second example is a linac for a spallation neutron source designed by A.Ruggiero at BNL.[13] The general layout is shown in Fig.2, the main parameters are summarized in Table 2. Again the low energy front end of the linac is designed to be normal conducting, only the high energy part is superconducting. The accelerator can be operated in three modes, cw and pulsed with short and long pulses. This can be done economically only with a superconducting linac.

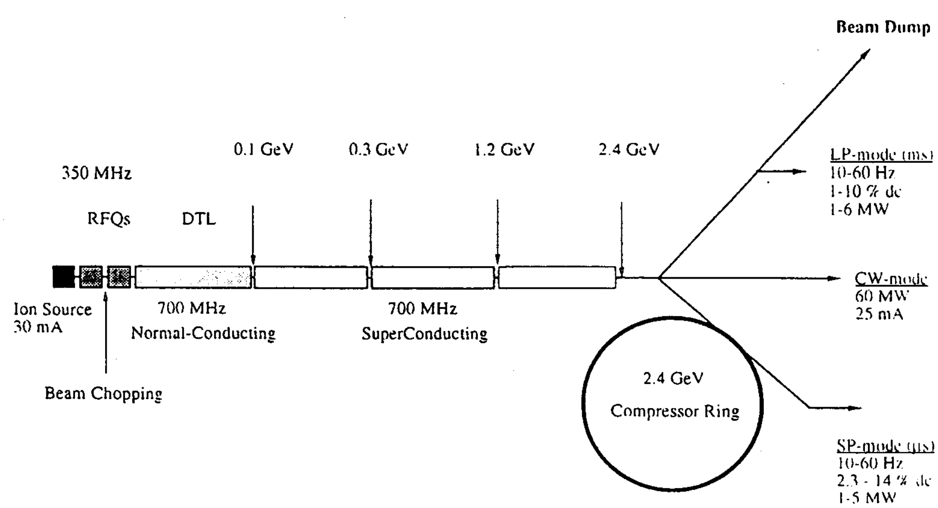

Figure 2 General layout of the BNL design of a spallation source

Table 2 General parameters of the BNL design of a spallation source

BNL superconducting linac, cw and pulsed operation		
beam power (cw - long-short pulse)	MW	60-<6-<5
final proton energy	MeV	2400
initial kinetic energy	MeV	100
beam current	mA	25
frequency	MHz	700
operating temperature	K	4.2
accelerating gradient	MV/m	7.3
cells per cavity		4
cavities per klystron		2
normalized rms emittance	π mm mrad	0.29

3.3 The linac for the ESS

The third example is the linac for the European Spallation Neutron Source (ESS).[14,15] It is a pulsed spallation source with a proton beam power of 5 MW at a repetition rate of 50 Hz. The pulse lengths on the target are 1 μs or less. A 50 Hz target station accepts up to 5 MW and a 10 Hz target station up to 1 MW of beam power. Fig. 3 shows the general layout.

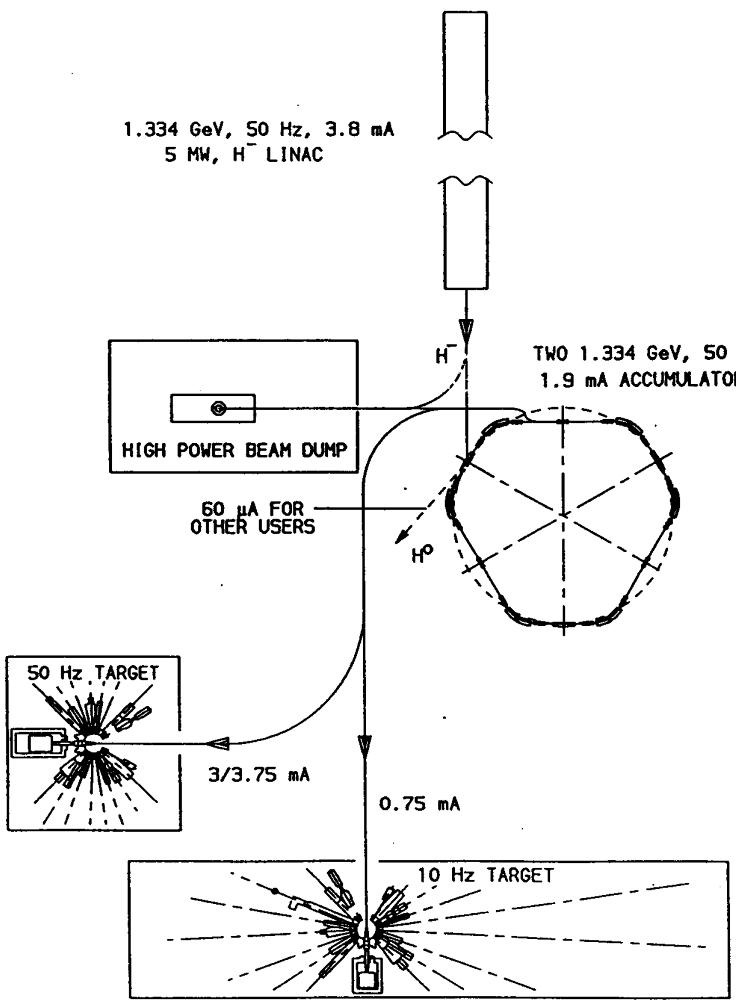

Figure 3 Schematic layout of ESS

In a linac H^- ions are accelerated to 1.334 GeV and via a bunch rotator and energy ramping system injected into two accumulator rings over 1000 turns for each ring. During injection the ions are stripped. The rings are emptied in one turn and the proton beam is guided to the target stations. The time structure of the linac beam pulses is determined by the accumulator rings. For a ring revolution frequency of 1.67 MHz the beam pulse length is 360 ns and the gap for ejection is 240 ns. For switching from one ring to the other a gap of about 100 μs is necessary. The pulse duration is 1.3 ms, the peak current of a pulse is 107 mA, the average current during pulse 64 mA, and the average current during 1 s 3.8 mA, For a low loss injection the energy resolution of the linac beam must be better than 1 per mille. Table 3 summarizes these data.

Table 3 Some parameters of the proposed Spallation Neutron Source ESS

Pulsed Spallation Neutron Source, ESS		
beam power	MW	5
proton energy	MeV	1334
repetition rate	Hz	50
pulse duration	ms	1.3
chopping time (beam on - beam off)	ns	360 - 240
number of accumulation rings		2
number of turns for injection in each ring		1000
time for switching from one ring to the other	μs	100

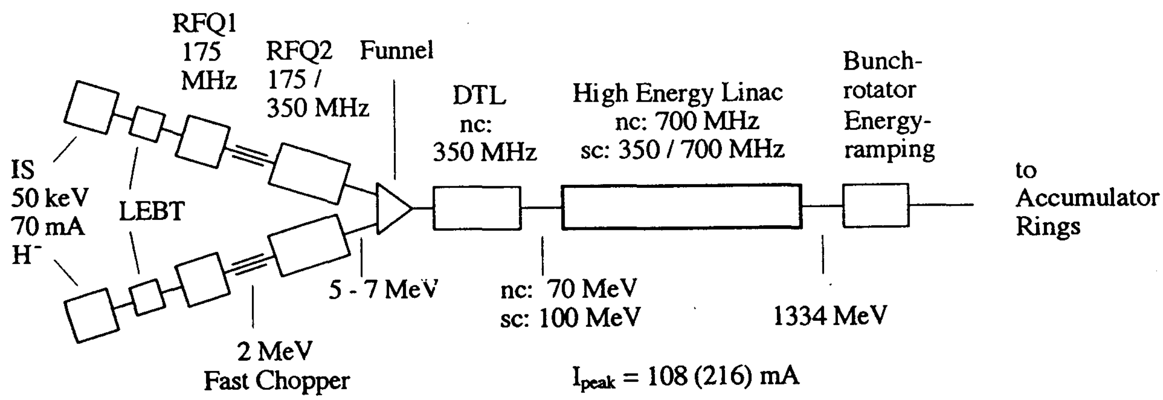

Figure 4 Scheme of the ESS linac

Fig.4 shows the scheme of the ESS linac.[16] The beams of two front ends, each consisting of an ion source, the low energy beam transport system (LEBT), an rfq, a beam chopper, and a second rfq are funneled at 5 MeV. After funneling the beam is accelerated in a drift tube linac to 70 MeV resp. 100 MeV. All these components are operated at 350 MHz. Further the beam is accelerated by a normal conducting or superconducting linac. Not all part of the linac are up to now fully developed. Due to the high beam intensity this applies to the ion source, the rfq's, the chopper, the low energy beam transport system, and the funneling device as well as to components of the high energy linacs. E.g. the setup of the front end could be simplified if one would use positively charged hydrogen molecules, H_2^+. Powerful sources exist and so there would be no need for funneling. Due to the high accelerating gradient of superconducting structures the linac would become not longer than a normal conducting linac with half of the energy.

The normal conducting linac

Table 4a summarizes the main parameters of the normal conducting linac.[15] Though the front end is operated at 350 MHz the high energy linac is proposed to run at 700 MHz. A normal conducting 350 MHz version seems to be difficult to realize, a superconducting one will be shown below. The obvious advantages of 700 MHz are a higher shunt impedance and a smaller size. But the beam has to be matched to the acceptance of the structures with the higher frequency. This matching may be a source of particle losses and these should be kept below 1 nA/m because it is essential to have the possibility of hands-on maintenance. Also a large aperture may help to reduce particle losses. The proposed normal conducting 700 MHz structure has an aperture of 4.4 cm. Unfortunately it can not be proved -up to now- by computer simulations whether this diameter is sufficient or not. Superconducting structures may have apertures of 10 or even 20 cm because they are not necessarily optimized with respect to a high shunt impedance.
In contrast to example 1 the normal conducting structures have a moderate length (1.3 m to 2 m) and have 16 to 10 cells which are not all different in shape. The design has been changed, in the first design the structures were 3.6 to 5.5 m long and had 30 cells.[17] The gradient was increased from 2.4 to 2.8 MV/m. Both effects improve beam dynamics. The klystron rf power of 4 MW (including 1 MW for control) has to be fed into four tanks coupled by bridge couplers. In contrast to example 1 a failure of a klystron would stop the linac. The availability seems to be less than that of example 1.

Table 4a Some parameters of the proposed normal conducting linac for ESS

ESS normal conducting linac, pulsed operation		
energy range	MeV	70 - 1334
frequency	MHz	700
length of accelerator	m	663
rf duty cycle	%	6.0
current (peak-average bunch, average)	mA	107-64-3.84
number of tanks		264
klystron power	MW	4
number of klystrons		66
accelerating gradient E_0T	MV/m	2.8
synchronous phase	deg	-25
dissipated rf power per meter (peak)	KW	230
dissipated rf power in structures (peak)	MW	113
peak rf power for beam acceleration	MW	81
total rf power consumption (average)	MW	12

The superconducting linac, conservative version

For the superconducting counterpart two options have been designed. The first is a conservative one for which may be stated that it can be built according to the present state of the art. The linac may be operated at 350 or 700 MHz. The second is a realistic one which consists of some components which are not yet tested, but for which one would fairly estimate that these components will be available at that time when the construction of the ESS linac starts. Also this realistic version may be operated at 350 or 700 MHz.
Fig. 5 shows a cryo module equipped with a four cell superconducting 350 MHz structure. The four cells of one structure have the same phase velocity. This is changed ten times along the linac. It has been demonstrated at CERN [18] that an accelerating gradient of 10 MV/m at

a quality factor of $5*10^9$ can be achieved routinely in structures of this type but with a phase velocity equal to the speed of light. The length of the structures is 0.72 m at the low and 1.54 m at the high energy end. The peak rf power which has to be coupled to the cavity for beam acceleration is 950 KW at maximum, the dissipated power in the cavity is only 60 Watts (at high energy end). As has been pointed out the presently existing couplers can carry about 150 KW the four cell structure is equipped with eight couplers, four on each side.(In Figure 5 only one coupler on each side is shown.) The structure is driven by a 1.2 MW klystron. Operated within a self-exited loop the klystron frequency is locked to the frequency of the beam. Self-exited rf control loops are well developed and used in superconducting heavy ion linacs with arbitrary amount of beam loading. [19,20] Also in a medium energy electron accelerator it is operated with great success.[21] As can be seen on Fig. 5 the structure can be tuned by lengthening. A tuning frame which is fixed at the cut off tubes also stiffens the structure. Further stiffening bars have to be welded on the outside of each cell to reduce deformations of the cells due to pressure variations in the helium vessel or due to the radiation pressure.
The cryostat system is designed to be built up in a modular way, the 96 structures are housed in four cryo units each consists of 24 cryo modules. The magnets for focusing and steering are also superconducting and installed within the cryostat between the structures. Focusing is done by quadrupole singlets positioned after each second structure.

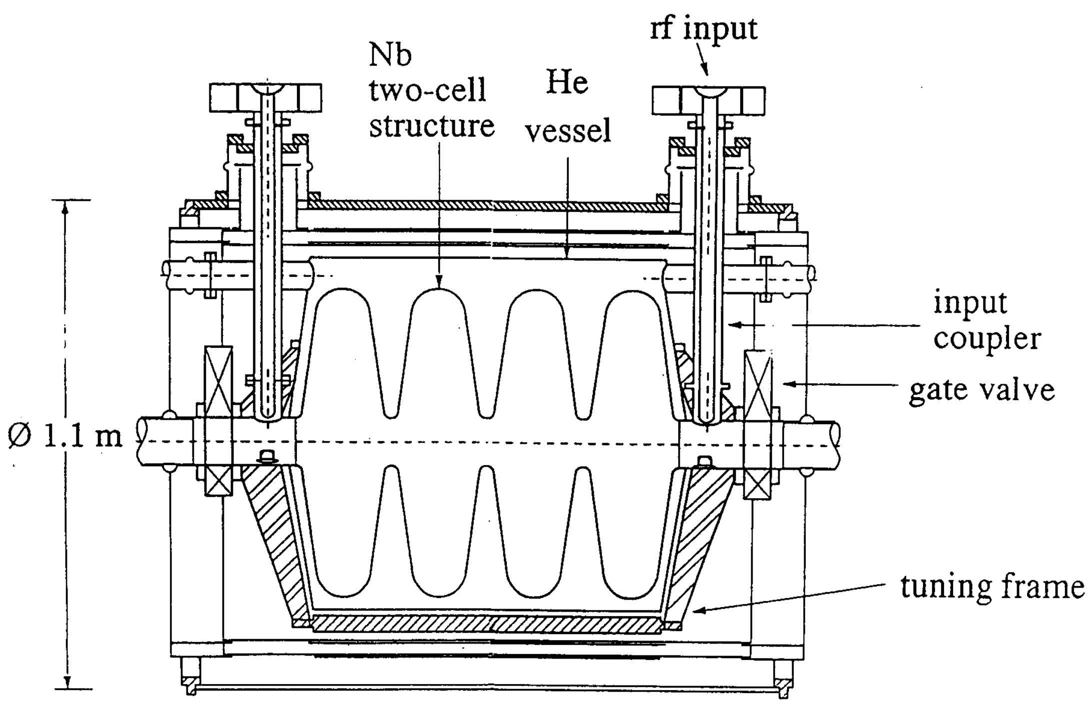

Figure 5 Cryo module of the superconducting linac

The main parameters of the superconducting 350 MHz structures are summarized in Table 5a. As can be seen from Table 5a the field rise time of the structure is not neglegible compared to the pulse duration which is 1.3 ms. It is given by $\tau = Q_L / 2\omega$ where Q_L means the loaded Q value. As the beam gains in the low energy structure nearly only half the energy it gains in the high energy

Table 5a Parameters of a 350 MHz superconducting structure

Energy of H^-	MeV	100	200	600	1200
$\beta = v/c$		0.428	0.57	0.79	0.9
E_{peak}/E_0T		2.59	2.12	1.87	1.81
H_{peak}/E_0T	Oe/MV/m	52.2	44.9	34.5	34.2
r/Q	Ω/m	236	293	360	387
Transit time		0.764	0.751	0.737	0.732
Q (design)		$3*10^9$	$3*10^9$	$3*10^9$	$3*10^9$
Q_{ext}		$9.5*10^5$	$6.2*10^5$	$5.2*10^5$	$4.9*10^5$
Q_L		$4.8*10^5$	$3.1*10^5$	$2.6*10^5$	$2.4*10^5$
$\Delta f_{1/2}$	Hz	368	564	675	720
τ_{field}	ms	0.86	0.56	0.48	0.44
E_0T	MV/m	8	10	10	10

structure the rise time of the low energy structure is twice. It is remarkable that the rise time is proportional to the inverse of the frequency, therefore high frequencies are favoured. As a consequence of such a long rise time the klystrons have to be switched on a time t before the bunch enters the cavity. t is given by $t = (\tau*\ln 2)/\cos^2(\Phi)$ where Φ is the synchronous phase. The rise time increases the rf pulse duration and increases the needed average klystron power, not the peak power. The operational costs are increased by a factor $(t+t_0)/t_0$ where t_0 means the beam pulse duration.
Changing from 350 MHz to 700 MHz does not effect the whole system very much. The structures have eight cells instead of four, but the cells are probably more stiff. The operating temperature should be decreased from 4.2 K to 2 K. In any case the cavities and the cryostats become smaller and probably cheaper. The rise time is shorter and therefore the efficiency higher. The power needed for field rise is about 7 % of the power for beam acceleration in case of the 700 MHz version and about 25 % in case of the 350 MHz version. In Table 5b general parameters of the conservative version of the superconducting ESS linac are given.

Table 5b Some parameters of the proposed superconducting linac for ESS

ESS conservative superconducting linac, pulsed operation		
energy range	MeV	100 - 1334
frequency	MHz	350 / 700
length of accelerator	m	310
rf duty cycle	%	8.5 / 7.0
current (peak-average bunch, average)	mA	107-64-3.84
number of structures		96
klystron power	MW	1.2
number of klystrons		96
accelerating gradient E_0T	MV/m	10
synchronous phase	deg	-15
dissipated rf power per meter (peak)	KW	0.09 / 0.08
dissipated rf power in structures (peak)	MW	0.013 / 0.011
peak rf power for beam acceleration	MW	78
total rf power consumption (average)	MW	6.1 / 5.2

The realistic superconducting version

A disadvantage of this conservative version is the large number of klystrons needed. It is more efficient to use more powerful klystrons, e.g. a 5 MW multi beam klystron which drives four structures. Each structure is equipped with two couplers each carrying up to 450 KW. This is beyond the present state of the art. On the other hand it has been found recently [22] that multipacting causes breakdown in high power coaxial rf couplers and windows. The power scales like $(f^*d)^4$ Z, where f is the rf frequency, d is a size parameter, e.g. the diameter of the outer conductor, and Z is the line impedance. This scaling law favours high frequencies, e.g. 700 MHz, a large size, and a high impedance, e.g. 75 Ohms. Scaling the 150 KW achieved in CERN couplers at 352 MHz to 700 MHz and keeping the other parameters fixed, a coupler carrying 450 KW seems to be realistic. Furthermore it has been shown that applying a polarizing voltage across the coaxial line increases the maximum power of the coupler. An advantage of these couplers is that the external Q-value can be adjusted to the beam load in situ. The linac may be operated efficiently at a lower beam current.

Two effects come up which make the low level rf control more difficult: the detuning of the cavity due to Lorentz force or radiation pressure, and the detuning by microphonics. In order to have a good cooling the superconducting cavity has to be constructed from sheet metal, so it is mechanically much weaker than a normal conducting one which is constructed from solid material. The radiation pressure deforms the thin walls of the cavity. If the linac is operated cw the frequency shifts once during field rise when the linac is switched on. This does not effect the operation. But in a pulsed maschine the frequency shifts during each pulse. Unfortunately the time constant is in the range of a few msec, and the frequency shifts typically several hundred Hertz in case of structures not stiffened like the ones discussed here.

A low level rf control system is presently going to be designed at DESY for TESLA (TeV Energy Superconducting Linear Accelerator) to control an rf distribution system in which one klystron feeds eight superconducting nine cell structures. Evaluation of the analog and digital prototype feedback system has demonstrated that the design goal of 1% amplitude stability and 1 degree phase stability can be achieved.[23] Nevertheless each control loop asks for an additional amount of rf power. This has been taken into account by increasing the average rf power by 20 %. In Table 5c those parameters of the realistic version are given which are different from the conservative version.

Table 5c Parameters of the proposed realistic superconducting linac for ESS different from the koservative version

ESS realistic superconducting linac, pulsed operation		
klystron power	MW	5
number of klystrons		24

The proposed superconducting structures are short and the phase slip of the particles relative to the accelerating wave is small. Due to the high and adjustable accelerating gradient the acceptance for beam particles is huge and as each structure may be independently phased the bunches can be matched longitudinally. Calculations on beam dynamics show no critical behaviour of the beam along the linac. According to the present calculations the rms emittance is slightly increasing (20%) but the specifications for ring injection are met. Due to the large number of free parameters further calculations are needed.

Table 6 presents a comparison of the power consumption and the operational cost of the two superconducting 700 MHz linacs and the normal conducting linac.

The table clearly shows that the main advantage of the superconducting linacs is the saving of electrical power. The prices are listed in $ because it is convenient, but in addition prices are also given in DM because the price for electrical power is in Germany at least three times higher than in US. The cost for renewing of klystrons is also remarkable. The advantage of the realistic superconducting version is the use of a small amount of high power klystrons. The capital costs are further determined by the small length of the superconducting linacs which is less than half of that of the normal conducting one.

4. Future Developments

The description of the superconducting linacs showed that the design could be optimized if rf couplers would be available which carry about 500 KW. High rf power couplers are needed world-wide in all laboratories. The discussions on this workshop showed [24] that CERN needs more powerful couplers for the structures in LEP2 and LHC, FNAL and DESY for TESLA, and KEK for TRISTAN and KEKB. At KEK 800 KW have been reached on a test stand without beam load.[25] The aim is to get couplers for 600 KW under beam conditions available in two years.[26]

The rf feedback control system has to be developed further. For the author the main problem is the stiffening of the cavities to reduce detuning by microphonics and the radiation pressure. The frequency shift should be reduced mechanically to some value which may be tolerated by an rf feedback system of reasonable extent. An analog as well as a digital control system is going to be developed for 8 resp. 16 cavities driven by one klystron at DESY for TESLA.

According to the increased number of free parameters like accelerating gradient and phase, phase velocity of the cavity, etc. numerous calculations on beam dynamics have to be carried out to optimize the layout of the linac. The number of cavities with different phase velocities as well as the number of cavities influence costs and availability. Beam quality may be optimized with respect to the purposes of the project.

5. Conclusions

Three examples of superconducting linacs operated continuously or in a pulsed mode have been discussed. It turned out that superconducting linacs -for electron as well as for high intense proton beams- may be constructed with the present state of the art in this field. The main advantages compared to normal conducting linacs are energy saving and cost reduction. Depending on the operational mode and the degree of optimization the reduction may be about 30 to 50 % of the costs of the comparable normal conducting linac. The beam quality depends strongly on the special layout and must be optimized for each linac and the special application. For example a beam with high energy resolution may be accelerated in a superconducting cw linac. The short high gradient and independently phased cavities of a superconducting linac offer more possibilities for beam matching than normal conducting tanks. Further calculations on beam dynamics have to be investigated.

Table 6 Comparison of power consumption and operational costs

Version		SC konserv.	SC realistic	NC
frequency	MHz	700		
total RF power	MW	5.2		12
efficiency of klystron	%	55		
efficiency of modulator	%	85		
wall plug power	MW	11.1		25.7
hours of operation per year	h	6000		
energy consumption per year for RF	KWh	$6.6*10^7$		$15.4*10^7$
life time of a klystron	a	5		
within 10 (25) years of operation the klystrons have to be replaced .... times		1 (4)		
klystrons to be renewed in 10 (25) a		96 (384)	24 (96)	66 (264)
estimated cost of klystrons	M$ MDM	19 (77) 29 (115)	12 (48) 18 (72)	31 (124) 46 (185)
capacity of refrigerator	KW	2.9 (2K)		--
efficiency compared to Carnot-cycle	%	20		
wall plug power	MW	2.1		--
hours of operation per year	h	6300		--
energy consumption per year	KWh	$1.3*10^7$		--
price of one KWh	$ DM	0.05 0.2		
cost for electrical power per year	M$ MDM	3.9 15.7	3.9 15.7	7.7 30.8
costs for el. power in 10 a and for renewing of klystrons	M$ MDM	58.5 186	51.3 175	108 354
as above, but in 25 a	M$ MDM	175 509	146 465	316 955
estimated investment cost	M$ MDM	210 315	150 225	275 415
investment plus operational costs in 10 a	M$ MDM	269 501	201 400	383 769
as above, but in 25 a	M$ MDM	385 824	296 690	591 1370

1 $ ~ 1.5 DM

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