Room Temperature Vs Superconducting LINACS

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Abstract

For the proposed accelerator based, pulsed spallation neutron source a linear accelerator is needed. Starting from fundamental relations for the characteristic properties of cavities and linacs a comparison of a room temperature with a superconducting linac is presented. It turns out that the superconducting linac is superior in nearly all parameters, and a rough estimate shows that it is cheaper in investment and in operational costs. The room temperature linac has the advantage of a simple technology. On the other hand it has been shown during operation of superconducting cavities in storage rings that the maintenance of these structures can be carried out by the staff of the room temperature cavities.

Introduction

The initial aim of an accelerator based, pulsed spallation neutron source is a beam power of 5 MW, a beam pulse length of 1-2 µs, and a repetitions rate of 50 Hz. At the Workshop on Accelerators for Future Neutron Sources held at Santa Fe it turned out that the optimum energy of the proton beam is ~ 2 GeV. Different types of accelerators can fullfill these requirements. One option is the linear accelerator followed by one or more accumulator or compressor rings. Some aspects of the question whether this linear accelerator should be a normalconducting or a superconducting one will be discussed in this paper. It cannot be the aim of this paper to present a real and fair comparison, to do so an optimum design of both types must be developed by independent expert groups. The two designs presented here should be looked at as a starting point for further discussions.

History of Technological Progress

The development of room temperature linear accelerators started after world war II when microwave power sources were available. The physics of microwave resonators was known since long time. The iris loaded structure for electron linacs and the Alvarez structure for proton linacs were investigated. Due to a simple handling the structures were manufactured from copper. It was a big step to go from laboratory tests of single resonators to a series production of structures. The small tolerances in the production of structures and in its alignment were severe problems. Moreover the particle sources, the injection and ejection, the focusing system, and last but not least the vacuum system for an up to several hundred meters long accelerator had to be developed. On the way to reach high energy proton beams the biperiodic and side coupled structures were developed by Knapp at Los Alamos National Laboratory [1]. Structures of this type are installed in LAMPF which went to operation in

1972. In the following time the performance of all components have been improved and other types of structures have been developed. But the side coupled structure of the Los Alamos type is still a favoured structure and is designed for new proton accelerators like the injector for SSC [2] or the linac of the Japanese Hadron Project [3] or the 400 MeV upgrade for the Fermilab linac [4]. Among the normalconducting linac types the coupled-cavity linac (CCL) is the simplest, provides the highest gradient, and is the least expensive per meter to fabricate.[2]

The investigation of the properties of superconductors under RF fields was started in 1940 by H. London. About twenty years later the BCS theory gave an insight to the physical origin of the surface resistance of normalconducting and superconducting materials. According to this theory the microwave power losses in superconducting cavities are four to five orders of magnitude smaller than those in normalconducting ones. The first laboratory tests of niobium single cell cavities were done in 1963. Though the first laboratory measurement of high fields (~ 45 MV/m) at a Q-value of ~ 10^{10} in a superconducting single cell cavity were reported in 1968 [5] a proposal for a 2 GeV electron accelerator was presented in 1963 and for a 1 and 7 GeV proton accelerator was published in 1967[6]. In the following time many superconducting structures have been operated in electron, proton, and heavy ion accelerators at field levels of 2-3 MV/m.

A big step forward in getting high accelerating fields was done in 1978 when one side electron multipacting could be analysed. It was shown that this field limiting barrier was absent in cavities of round shape as they are now used in electron machines. From about 1980 there was great interest in operating superconducting cavities in electron storage rings. Unfortunately there was no need to install a superconducting cavity in a high energy proton accelerator.

The next milestone on the way to high fields was the invention of high thermal conductivity niobium sheet metal which was developed in collaboration with industry. Defects and impurities which produce heat on the inner surface or in the bulk near the surface can be stabilized by use of high thermal conducting material. The breakdown or quench field can be increased. As a measure of the temperature dependent thermal conductivity the value of RRR (residual resistivity ratio: R(300K)/R(4.2K)) is often quoted. The niobium material which was delivered from industry till 1983 had an RRR of 30, now it has an RRR of 300-400, i.e. the quench field is increased by a factor of ~ 4. Moreover a further increase of the thermal conductivity can be reached by firing the complete cavity together with Titanium solid state material in a furnace at 1400 C. This purification is especially usefull to cure mistakes during fabrication or to heal after accidents.

When the accelerating field reaches 10 MV/m or more - the surface field is still a factor of 2 higher - field emission becomes the dominant field limiting effect. The superconducting surface is very sensitive against additional heat input so that field emitted currents can produce a quench. The most likely sources are metallic or dielectric dust particles on the surface. But also "irregularities" like etch pits or intrinsic surface properties can emit electron currents. Special cleaning techniques and preparation methods like those known from micro chip production have been developed. Recently field level of 25 MV/m could be reached in single cell 1.5 GHz cavities reproducibly. Fianally with the high power processing method there is a tool to repair cavities after a dust accident. High peak power RF pulses (300KW to 1MW and 100μs to 1ms) are fed via an adjustable input coupler into the cavity. From several tests it is concluded that the dust particles are heated during the RF pulse so that they evaporate immediately.

This short overview [7] shows that superconducting cavities are under use in electron and heavy ion accelerators since more than ten years in several laboratories. The cavities run under routine conditions and the operating experience exceeds 10,000 h. Also the decision to build CEBAF as a fully superconducting machine shows that the superconducting technology is available and reliable.

Basic Relations

The main differences between the normalconducting (nc) and the superconducting (sc) structure are demonstrated by the calculation of the power loss in the structure walls. If P is the rf power per unit length necessary to maintain an effective accelerating field E_a in an unloaded cavity and r is the shunt impedance per unit length of the accelerator structure then it is (by definition of r)

$$(1) \qquad P = \frac{E_a^2}{r} .$$

The quality factor Q of a cavity is defined by the relation

$$(2) \qquad Q = \frac{\omega W}{P}$$

where ω is the angular frequency, W is the stored energy, and P the power loss (per second) of the cavity. As the stored energy is proportional to $\int E^2 \, d\tau$ over the volume of the cavity it can be shown that the quantity r/Q is a geometrical constant, independant of the material of the walls. So the above relation can be written as

$$(3) \qquad P = \frac{E_a^2}{\frac{r}{Q} Q} .$$

This shows that the power loss is inversely proportional to the specific shunt impedance r/Q and the quality factor Q. The r/Q can be expressed as $r/Q * d \sim 150 \, \Omega$, where d is the length of a cavity cell, which is $\beta\pi c/\omega$. As the power loss P in equation (2) is given by

$$(4) \qquad P = \frac{1}{2} R_s \int H^2 \, ds$$

where R_s is the surface resistance - which is assumed to be homogenous over the surface of the cavity - and E is proportional to H the quality factor Q can be expressed as

$$(5) \qquad Q = \frac{G}{R_s}$$

where G is the geometrical factor (by definition).
For a normalconducting high frequency cavity the surface resistance is given by

$$(6) \qquad R_s = \sqrt{\frac{\mu\omega}{2\sigma}} = \frac{1}{\sigma\delta} .$$

If the mean free path length l is greater than the skin depth δ the surface resistance is determined in the Pippard limit by the relation

$$(7) \qquad R_s = \frac{8}{9} \left(\frac{\sqrt{3}}{16\pi} \frac{\mu_0^2 \, \omega^2 \, l}{\sigma} \right)^{1/3}$$

where σ is the conductivity.
This gives for copper at 500 MHz a value of R = 5 mΩ. The Q is of the order of $3 * 10^4$.

The superconducting surface resistance is given by

(8) $$R_s = A(\lambda, \xi, l, v_F)\,\frac{\omega^2}{T}\,\exp\left\{-\frac{\Delta(0)}{kT_c}\frac{T_c}{T}\right\} + R_{res}$$

or approximately for niobium with $\Delta(0) = 1{,}95\ kT_c$ and $T_c = 9{,}25$ K for commercially available niobium

(9) $$R_s\,(n\Omega) = 10^5\ f^2(\mathrm{GHz})\,\frac{1}{T(K)}\,\exp\left\{-\frac{18}{T(K)}\right\} + R_{res}$$

A typical value is R = 30 nΩ at 4.2K, the residual resistance is about 20nΩ, best values are 1 nΩ. The Q is of the order of $5*10^9$.

This simple analyses shows that the power loss is reduced by 4.5 orders of magnitude in a superconducting cavity compared to a normalconducting one with the same shape. Quantitatively at an effective accelerating field level of 10 MV/m and an r/Q of 1000 Ω/m the nc cavity dissipates in cw operation 400-500 KW/m whereas the sc cavity only several W/m. This shows a cooling problem for the nc cavity which has to be operated in a pulsed mode, i.e. at a low field level for a long pulse duration or at a high field level for a short pulse duration. The sc cavity can be operated in a cw mode because the cooling limit of 1 W/cm^2 is by far not reached. Field limitations are caused by other effects as mentioned above. In pulsed operation the lower limit for the pulse duration is given by the filling time of the cavity which is in the range of 1 ms. With respect to the efficiency and to the effective wall plug power one has to keep in mind that in the superconducting case the losses are produced at a temperature of 4.2 K. Assuming an efficiency of the refrigerator of 20% of a carnot cycle the power consumption is 350W at room temperature per Watt at 4.2K. Nevertheless the sc linac needs less power than the nc one. If one defines the efficiency as the ratio of beam power and the net wall plug power the efficiency of a nc linac is given by

(10) $$\eta_{nc} = \frac{P_{beam}}{\dfrac{P_{beam} + P_{diss}}{\eta_{rf}}},$$

with $P_{beam} = i_{av} * E_a * \cos(\Phi)$ and $P_{diss} = (E_a^2/r) * dc$. Here i_{av} is the average current, $E_a * \cos(\Phi)$ the effective accelerating field seen by the particle, and dc the duty cycle. As the power dissipated in the cavity scales with E_a square but the beam power only with E_a the efficiency decreases rapidly with increasing E_a. The efficiency has a maximum equal to the efficiency of the RF for $E_a = 0$. The efficiency of a sc linac is given by

(11) $$\eta_{sc} = \frac{P_{beam}}{\dfrac{P_{beam} + P_{diss}}{\eta_{rf}} + \dfrac{P_{diss} + P_{stat}}{\eta_{cryo}}}$$

Due to the static losses P_{stat} the efficiency is zero for vanishing fields but increases rapidly. It shows a maximum and decreases slowly because of the increase of the cavity losses at very high fields. For the parameters given in the following Table 1 the efficiencies of the nc and the sc linac are shown in Figure 1. It should be mentioned that these arguments are based only on the power consumption of the linacs, there are up to here no capital costs included. These would ask for even higher accelerating fields because of saving costs due to a short length of the accelerator.

		pulsed nc linac	pulsed sc linac
Average current i	mA	2.5 (6.25)	2.5 (6.25)
Shunt impedance (av) r	Ω/m	$4.29 * 10^7$	$1.95 * 10^{12}$
Phase angle Φ	deg.	24	24
Pulse duration t	ms	2	2
Filling time t_f	ms	0.05	1
Repetition rate	1/s	50	50
RF-efficiency		0.6	0.6
Cryo-efficiency		-	$2.8 * 10^{-3}$
Static power loss	W	-	5

Table 1.: Typical parameters of nc and sc linacs. These parameters were used in efficiency calculation

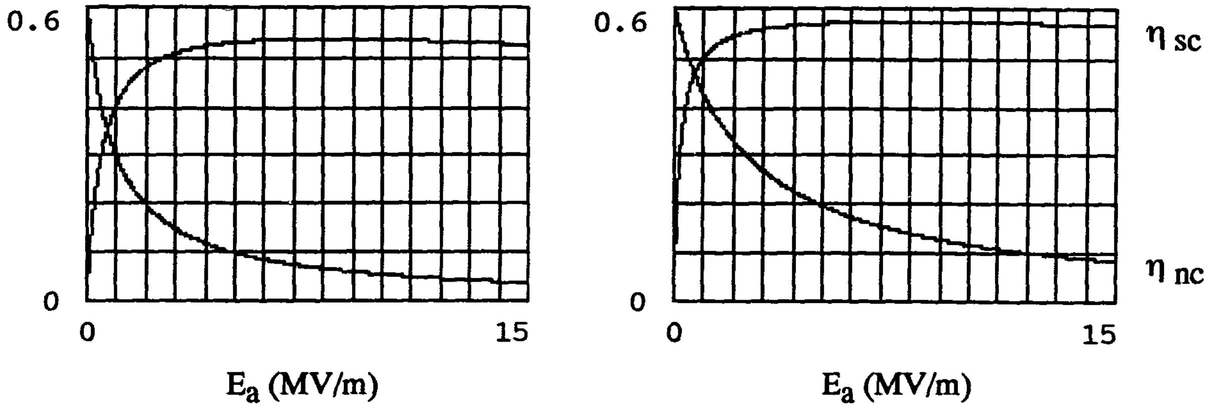

Fig. 1: Efficiency of nc and sc linac as a function of accelerating field; left for i_{av} = 2.5 mA and right for i_{av} = 6.25 mA. Further parameters see Table 1.

The question whether to operate a sc linac at 4.2K or at 2K can be answered by the ratio of the BCS part of the surface resistance to the residual resistance. As the BCS part increases with the square of the frequency one can conclude that cavities at 500 MHz and below can be operated at 4.2K whereas cavities at 800 MHz and above should be operated at 2K. From the cryogenic point of view an operation at 4.2 K is favoured because of its simple construction and handling

The amount of the power dissipated in the walls of a nc cavity asks for a high shunt impedance. In former time cavities were optimized with respect to increase shunt impedance. This gave a strong condition to the shape of the cavity. One consequence was the small bore hole of the irises. As the surface resistance of a sc cavity is orders of magnitude lower there is not such strong impact for shunt impedance optimization. On the other hand the sc cavity is much more sensitive against additional power losses on the surface as they are caused by multipacting or field emitted currents the shape of a sc cavity was optimized long ago to be multipacting free and to lower the field enhancement factors E_{peak}/E_a and H_{peak}/E_a. This is now also true for nc cavities which shall be operated at high field level and short pulse duration (like SSC and JHP).

Figure 2 shows the shape of the nc cavity for the 400 MeV upgrade of the Fermilab linac. It operates at a frequency of 1284 MHz. This shape is typical for nc cavities for proton accelerators. The typical shape of a sc structure for two different phase velocities is shown in Figure 3. Significant is the simple shape without nose cones and the large bore hole which may have a diameter of 20 cm in a 350 MHz cavity compared to about 3 cm in the nc cavities. This is essential for a low loss beam transport through the structures because the typical transverse dimensions of a proton beam are 1 - 2 cm [10]. For the reason of radiation protection and hands on maintenance losses of the order of 10^{-7} are required. Careful particle dynamics calculations have to be carried out but it seems that a beam tube size of several standard deviations of the beam is favourable.

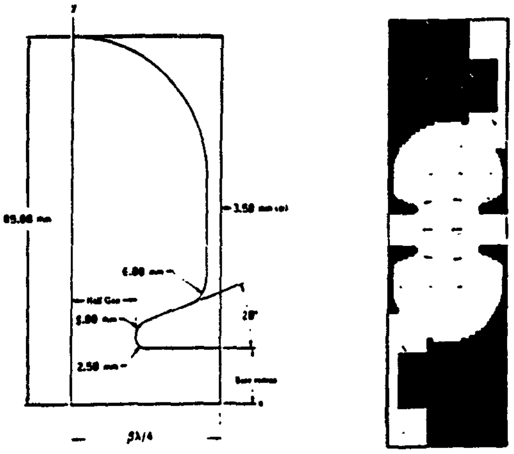

Fig. 2: Typical shape of a normalconducting cavity (injector linac for SSC)

The surface resistance of the nc material scales with $\omega^{1/2}$ resp. $\omega^{2/3}$ according to equation (6) resp. (7) whereas the surface resistance of a super-conductor scales with ω^2 according to equation (9). Consequently according to (2) the power loss scales with $\omega^{-1/2}$ resp. $\omega^{-1/3}$ for a nc linac and with ω for a sc linac. Therefore nc cavities favour high frequencies, and sc cavities favour low frequencies. This is important specially for high current machines because also space charge effects are reduced in low frequency structures. The spacing of two bunches in a train is proportional to the wavelength, and the dimensions of a bunch can be chosen larger in low frequency cavities so that the space charge density is reduced. The space charge forces scale with ω^2.

Due to the simple shape of the sc cavity the overall parasitic mode loss factor as it can be calculated with the TBCI code is considerably (a factor of three or more) smaller for the sc cavity than for the nc one. In addition due to the high accelerating field level that can be achieved in sc cavities the amount of structures - that is the number of sources for wake fields - is in a sc linac a factor of three lower than in a nc linac.

Another important difference between nc and sc linacs is the stored energy which is much higher in sc cavities than in nc ones. Specially in pulsed high current accelerators a high stored energy is needed because as the stored energy is proportional to the square of the field it "stabilizes" the accelerating field when the bunch takes energy from the cavity. It can be shown [8] that the energy spread $\Delta E/E$ of a chopped beam can be expressed as

$$(13) \qquad \frac{\Delta E}{E} = \sqrt{1 + \frac{P_{beam}}{W} * \frac{\Delta t1 * \Delta t2}{\Delta t1 + \Delta t2}} - 1 ,$$

where $\Delta t1$ und $\Delta t2$ are the time intervalls for "beam on" and "beam off". It can be seen that the bigger the stored energy W the smaller the energy spread.

Comparison of Linear Accelerators

The following Table 2 summarizes the main parameters for three types of linacs for a 5 MW spallation neutron source.

		normalc. pulsed	superc. pulsed	superc. cw
Beam power	MW	5		
Endpoint energy	MeV	2000		
Repetition rate	Hz	50		
Pulse duration	ms	2		20
Duty cycle	%	10		100
Chopping cycle		0.86		
Average current	mA	2.5		
Peak current	mA	33		3.3
Accelerating field	MV/m	3	10	

Table 2: Main parameters of three high energy linacs

For a comparison of a nc and a sc linac which fullfill the above requirements only the high β-part of the linacs will be taken into account. The energy range will be from 100 MeV to 2 GeV, which corresponds to a range of β=0.43 to β=0.95. These linacs are by far the largest part of the whole accelerator. All of the arguments which are given below for the high energy part also hold for the low energy part.

The parameters of Table 2 characterize three different linacs: a pulsed nc, a pulsed sc, and a sc linac operated in a cw mode. The main advantage of the latter is that the peak current is reduced to the value of the average current. It can be used in pulsed spallation source only if the following accumulator ring is designed to accept an injection over a factor of at least ten times more turns. Such an accumulator ring is presently under design [9]. Moreover such a cw linac is a powerful device - for example - for the application of accelerator transmutation of waste (ATW) because it seems to be quite easy to increase the beam power by a factor ten by increasing the current to the value of the pulsed linacs. As there is no need for an accumulator ring in this application the chopping cycle is not necessary. Therefore possible design parameters for a 200 MW cw linac could be 3 GeV and 67 mA.

Table 3 summarizes the main design parameters of a pulsed nc and sc linac for a 5 MW spallation neutron source.

		nc linac	sc linac
Frequency	MHz	800	350
Number of cells/cavity		12	2
Acc. field Ea	MV/m	3	10
Number of cavities		396	277
Unloaded Q		21400	$5*10^9$
Shunt impedance (av)	Ω/m	$4.29*10^7$	$1.95*10^{12}$
Joule losses during pulse	W	37800	5
peak rf input powe	KW	500	175
klystron power	MW	2	2.8
Cavities per klystron		4	16
Number of klystrons		100	18
Wall plug power (rf)	MW	33.3	8.4
Operating temperature	K	290	4.2
Stand by losses	W	-	5
Total cryogenic loss	W	-	3200
Design capacity	W	-	4800
Wall plug power	MW	-	1.62
Total wall plug power	MW	33.3	10.02
Effect. length of structure	m	717	220
Length fill factor		0.75	0.5
Total length	m	960	440

Table 3: Parameter list of a normalconducting and a superconducting pulsed high beta linac for a spallation neutron source

Due to the high accelerating field the number of structures in the sc linac is lower than in the nc linac. The high shunt impedance reduces the peak input power. Both effects together reduce the number of klystrons remarkable. Also the effective accelerating length of all sc structures is much shorter - 220 m to 717 m. As can be seen from Figure 3 each sc structure needs "cut-off tubes" on both sides. The "length fill factor" which is the ratio of the total linac length to the structure length is smaller for the sc linac. The total length is therefore "only" a factor of two shorter. The consumption of wall plug power is a factor of three lower, the efficiency of the sc linac is about 50%, that of the nc linac about 15%.

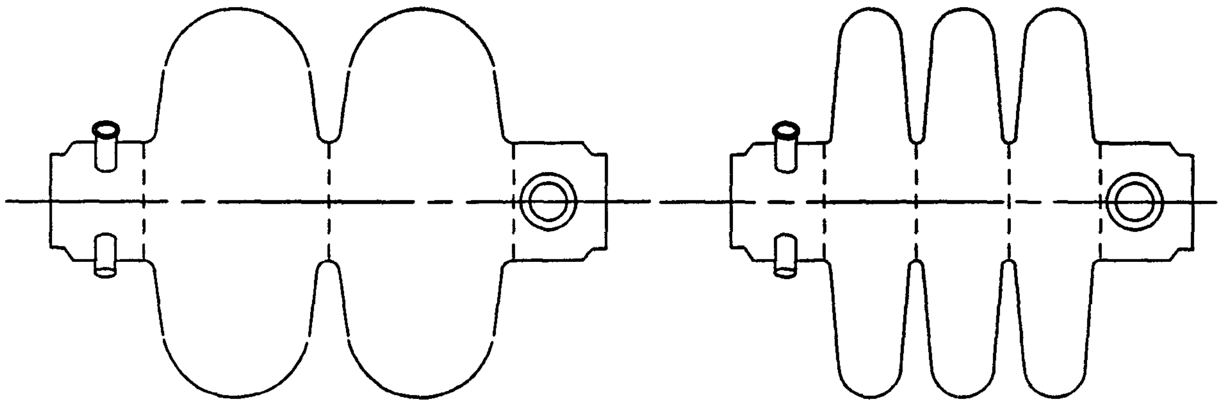

Fig.3: Shape of superconducting structures for two different phase velocities

A rough estimate of the investment cost with the presently available prices ends up at about 200 M$ for the superconducting linac while the normalconducting one is more than twice as expensive. The power bill for 10 years operation (accelerator 5000 h and refrigerator 8750 h per year) will be about 45 M$ for the superconducting and about 130 M$ for the normalconducting linac.[11]

Conclusion

On the basis of fundamental relations of cavities and linacs the advantages of a superconducting pulsed high current linac over a normalconducting one are discussed. Besides the advantage of being cheaper in investment and in operational costs it seems that the superconducting linac has less beam losses due to the large bore hole and the excellent vacuum at cryogenic temperatures.

References

[1] B.C. Knapp et al., IEEE Trans. Nucl. Sci., **NS-12,** 159 (1965)

[2] J. Watson et al.., Proc. IEEE Part. Acc. Conf., San Francisco, 1991, p.572
C.R. Chang et al., ibid. p.2993

[3] M.Kihara, Proc. XIVth Intern. Conf. High Energy Acc., Tsukuba,1989, and Part. Acc., 1990, Vol. 32, pp. 1-8

[4] D.E. Young and R.J. Noble Proc. XIVth Intern. Conf. High Energy Acc.,Tsukuba,1989, and Part.Acc.,1990, Vol.26, pp.205-210

[5] J.P. Turneaure and I.Weissmann, J. Appl. Phys. 39, (1968), p.4417

[6] A. Citron and H. Schopper, in Linear Accelerators, Ed. P. Lapostolle and A. Septier, North Holland Pub.,1970

[7] The progress in RF superconductivity is well described in the Proceedings of the RF Superconductivity Workshops. Up to May 1993 there were five workshops: 1st 1980 at Karlsruhe, 2nd 1984 at CERN, 3rd 1987 at Argonne, 4th 1989 at KEK, KEK Report 89-21, and 5th 1991 at DESY, DESY M 92-1. The 6th will be held Oct. 1993 at CEBAF.
H. Piel, Proc. CERN Accelerator School, Oxford 1985, CERN 87-03, p.736
W. Weingarten, Proc. XVth Intern. Conf. High Energy Acc., Hamburg, 1992, p.678

[8] G. Spalek, Proc. Workshop on Accelerators for Future Spallation Neutron Sources, Santa Fe, 1993

[9] S.A. Martin et al., Proc. Part. Acc. Conf., 1993, Washington, to be published

[10] SNQ Project Proposal, 1984

[11] H. Heinrichs, Proc. Workshop on High Intensity Proton Linear Accelerators for Future Spallation Neutron Sources, Witten, 1993, to be published