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SUPERCONDUCTING RADIO FREQUENCY CAVITIES FOR ACCELERATORS

H. Lengeler
CERN, Geneva, Switzerland

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1. INTRODUCTION

In the beginning of the 70's the first operation of the Stanford recirculating linac inaugurated the area of superconducting (s.c.) linear accelerators.

Since this time s.c. cavities have already found a number of applications for acceleration of electrons and heavy ions as well as for electron storage rings and for free electrons lasers. As the field has been reviewed recently in several papers [1-4] we will mention here only two possible future applications of s.c. cavities for accelerators.

In Italy [5] plans are advanced for a large s.c. accelerator complex for molecular, nuclear and particle physics. This complex would make extensive use of s.c. accelerator cavities for electrons and one considers:

- A small, ~ 50 MeV accelerator for a free electron laser in the infrared and millimeter range.
- A CW recirculating linac with an energy up to a few GeV.
- A $e^{\pm}$ collider for "Charm" and "Tau" physics operating in an energy range of 1.5-2.2 GeV.
- A "Beauty" factory i.e. a $e^{\pm}$ collider with an energy of ~ 10-20 GeV.

- A further extension to an energy range of 50 GeV would be designed as a Z^0 and Toponium factory. This machine could also be considered as an injector for an even larger collider as e.g. CLIC.

The proposed operating frequency of this complex is 500 MHz.

The possible application of s.c. cavities in large linear colliders has been studied [6-7]. These machines will ask in nearly all aspects for a tremendous extrapolation of present day accelerator technology. Cavity performances will have to be brought up from the present ~ 10 MV/m level in multi-cell cavities to at least 25 MV/m if not 50 MV/m. The corresponding Q-values will have to reach $5 \cdot 10^{10}$ or even 10^{11} in order to keep the cost and power of cryogenic systems to a tolerable level. The requirements for economic fabrication methods of cavities, cryostats and all auxiliary items will ask for mass-production techniques not yet applied to accelerator construction.

The use of s.c. cavities as "drive" linacs [8-10] for very large colliders is also considered. The performances of low frequency cavities (350-500 MHz) already under construction for storage rings would already be interesting for this kind of application.

In the following a few general properties of s.c. acceleration cavities will be reviewed and a comparison with n.c. cavities for various applications will be made.

2. ADVANTAGES OF SC ACCELERATORS

At high frequencies and for temperatures below the critical temperature T_c the r.f. resistance of a superconductor decreases exponentially with temperature and its value can be made typically 10^4 to 10^6 times smaller than for copper at room temperature [3]. The corresponding decrease of r.f. losses in s.c. cavities has attracted accelerator constructors because much higher acceleration efficiencies and higher CW accelerating fields than in Cu cavities can be reached.

Due to the Meissner effect the penetration depth of r.f. fields in a superconductor is much smaller than the normal skin depth and ranges in the region of 50-200 nm. r.f. superconductivity is therefore a surface effect.

One may characterise r.f. losses of a superconductor by the surface resistance R_s (in Ohm). For cavities, losses are generally expressed by the so-called quality factor Q . For a given cavity geometry and r.f. mode, quality factor and surface resistance are related by the relation

$$Q = G/R_s, \quad (1)$$

where G is a constant. A typical value for electron acceleration cavities is $G = 280$ Ohm.

2.1 Accelerating fields for CW operation

The low r.f. losses eliminate to a large extent the field limitation due to wall heating encountered in n.c. cavities for CW operation or for long pulse durations ($\tau_p \gg \mu s$)^(*). For practical and economic reasons, CW accelerating fields rarely exceed 1-2 MV/m. Typical r.f. losses are limited to a range of 5-10 W/cm² and can be handled only by a powerful cooling system. As an example we quote the r.f. losses in the 350 MHz, 5-cell Cu-cavities for LEP [12]. At an accelerating field of 1.5 MV/m r.f. losses would amount to 86.5 kW.

In s.c. cavities the theoretical field limit is given by the critical (superheating) field H_{sh} which is ~ 2400 Oe for Nb and 4000 Oe for Nb₃Sn [3]. In a typical electron acceleration cavity this would correspond to acceleration fields of 50 and 88 MV/m respectively. Despite the much reduced r.f. losses one has already to choose wall material of high thermal conductivity ($\lambda \gg 10$ W/m · K) and of sufficiently low residual resistance R_{res} to sustain those maximum fields in a He bath cooled cavity.

It is believed today that no fundamental effect is limiting fields below H_{sh} but in practice and in particular for large multicell cavities typical fields range considerably below the theoretical values. This is due to localised regions with increased r.f. losses or to electron emitters [3]. In large multicell cavities for electrons, acceleration fields between 5 and 10 MV/m can be obtained with reasonable reliability. Progress will be bound almost certainly to improvements in the technology of cavity fabrication, surface treatments and assembly methods.

(*) Under pulsed operation condition with pulse durations $\tau_p \leq 5 \mu s$ very high fields are achieved in Cu cavities. At SLAC acceleration fields up to 130 MV/m have been reached in 3 GHz test cavities [11].

2.2 Acceleration efficiency

Besides higher CW accelerating fields the reduced losses of s.c. cavities lead also to an increased acceleration efficiency which is particularly important for large systems. It is worthwhile to consider the dependence of this efficiency in some parameters like acceleration field E_{acc} , beam current i_b and cryogenic conditions.

We define the acceleration efficiency η_{acc} by

$$\eta_{acc} = \frac{P_b}{P_{mains}} = \frac{P_b}{(P_b + P_c) \frac{1}{\eta_{r.f.}}} , \quad (2)$$

- P_b : power given to the beam,
- P_{mains} : mains power needed for the production of P_b and P_c ,
- P_c : r.f. losses at cavity walls,
- $\eta_{r.f.}$: overall efficiency of r.f. production. It depends very much on the type and output power of the r.f. generator. For large CW klystrons (350 MHz-1 GHz) one reaches an efficiency of 70%; the overall efficiency is reduced by transmission losses and by higher order mode losses in the accelerator to $\sim 60\%$; for pulsed high power klystrons as used e.g. in n.c. electron linacs we assume $\eta_{r.f.} = 50\%$.

The r.f. power given to the beam is:

$$P_b = i_b \cdot E_{acc} \cdot \sin\phi_s , \quad (3)$$

- i_b : mean beam current,
- ϕ_s : synchronous phase angle; a typical value for electron linacs and storage rings is $\phi_s = 0.8-0.9$

The r.f. losses per unit length of a cavity are given by

$$P_c = E_{acc}^2 / r , \quad (4a)$$

- r : shunt impedance (linac definition!).

For a comparison with n.c. cavities it is convenient to write

$$P_c = \frac{E_{acc}^2}{(r/Q) \cdot Q_0} , \quad (4b)$$

- Q_o : unloaded quality factor of cavity, dependent on operating temperature, wall material and possibly field level.
- r/Q : shunt impedance/quality factor^(*). This parameter does depend on the cavity geometry and the r.f. mode but not on the r.f. losses, it is therefore a figure of merit of a given geometry and allows a more meaningful comparison between s.c. and n.c. cavities.

For n.c. cavities one gets from (2), (3) and (4b)

$$\eta_{acc} = \frac{i_b E_{acc} \cdot \sin\phi_s}{\left[i_b E_{acc} \cdot \sin\phi_s + \frac{E_{acc}^2}{(r/Q) \cdot Q_o} \right]} \cdot \frac{1}{\eta_{r.f.}} \quad (5)$$

For a given cavity with fixed r/Q and Q_o the efficiency depends on the gradient and on the beam current.

For illustration we give the efficiencies of the n.c. and s.c. acceleration systems for LEP in table 2 of sect. 4. Part of the low efficiency of the n.c. cavities is due to the fact, that the LEP design current is comparatively small ($i_b \leq 2 \cdot 3$ mA). Higher efficiencies are possible at TRISTAN (KEK) or HERA (DESY) where beam currents of 30 mA and 60 mA respectively are considered.

For s.c. cavities, $P_c \ll P_b$ and P_c can be neglected in the r.f. power balance. However, it cannot be neglected for the electric power production because it is dissipated at low temperatures. In addition the static cryogenic losses P_s of cryostats and He transfer lines have to be taken into account. One gets for s.c. cavities with (2), (3) and (4b)

$$\eta_{acc} = \frac{i_b E_{acc} \cdot \sin\phi_s}{\frac{i_b E_{acc} \cdot \sin\phi_s}{\eta_{r.f.}} + \left[\frac{E_{acc}^2}{(r/Q) \cdot Q_o} + P_s \right]} \cdot \frac{1}{\eta_{cry}} \quad (6)$$

This efficiency depends in addition on the cryogenic losses and on the (total) efficiency η_{cry} for evacuating these losses at a given operating temperature.

(*) r/Q can be obtained e.g. by a computer calculation or by a perturbation measurement at room temperature. In this case the value of Q at room temperature has to be taken.

From a survey of η_{cry} for various large scale cryogenic installations the following typical values were derived [13]

$$\eta_{\text{cry}} = \begin{cases} 0.33\% & \text{at } 4.2 \text{ K} \\ 0.1\% & \text{at } 2\text{K} \end{cases}$$

For s.c. cavities the r.f. losses are generally the dominant contributions to the losses dissipated at He temperature. One tries to keep the static losses P_s of cryostats and He transfer lines well below 10-20% of the r.f. losses.

For "pulsed" bunch operation encountered e.g. in e^- storage rings and FEL's or anticipated in linear colliders with typical bunch intervals of 10-1000 μs , the difference in efficiency can be illustrated in another way.

The Q-value of a cavity is related to the decay constant τ_d of r.f. fields by

$$\tau_d = \frac{Q_o}{2\omega_o} . \quad (7)$$

For n.c. cavities the decay constants are typically of the order of μs and do not allow to store r.f. energy inbetween bunch passages. The bunch can only remove a few percent of the stored energy in order to keep the energy spread between head and tail small; the remaining stored energy is lost leading to a much reduced acceleration efficiency. In addition peak powers to be delivered by the r.f. generator have to match the peak bunch current [8].

For s.c. cavities τ can easily reach values of many ms and the r.f. power decay remains negligible inbetween bunches. The r.f. (peak) power taken away by the bunches is supplied by the stored energy which is restored under CW conditions inbetween bunch passages. Therefore the r.f. generator has only to deliver a CW r.f. power corresponding to the mean beam current.

2.3 Shunt impedances

Another advantage of s.c. cavities is linked to the fact that the shunt impedances for the fundamental (accelerating) mode and for Higher Order Modes (hom) can be made widely different.

2.3.1 Fundamental mode

As explained before, the low r.f. losses (or high Q-values) of s.c. cavities lead to extremely large shunt impedances

$$r = (r/Q) Q_0.$$

One should note that the high value of r is essentially given by the value of Q_0 and not so much by the geometry dependent parameter r/Q which can be varied for several reasons by hardly more than a factor $2 \div 3$. The large value of r is of course responsible for the high accelerating efficiency of s.c. cavities.

2.3.2 Higher order modes

The advantage of storing in a nearly lossless way r.f. power in a s.c. cavities turns out to be a disadvantage for higher order modes.

Particle beams have an r.f. spectrum which can excite higher order modes in cavities. Bunched particle beams with a bunch spacing τ_b and a bunch length σ_b correspond to a comb like frequency spectrum with a line distance $1/\tau_b$ and which extends up to frequencies of at least c/σ_b . The excited r.f. fields increase r.f. losses to be dissipated at He temperatures, modify electric and magnetic peak fields and affect the beam stability.

The basic features of hom excitation can be best visualized in the "time domain" and are largely influenced by the relative values of decay constants for r.f. fields inside the cavity ($\tau_d = Q_0/2\omega$) and the bunch intervals τ_b (we assume that the bunch length does not exceed the filling time of the cavity).

The fundamental theorem of beam loading [14] states that a "point" bunch with charge q crossing a cavity excites a voltage given by

$$\Delta V_b = \frac{\omega}{2} \frac{r}{Q} \cdot q = kq, \quad (8)$$

ΔV_b has a phase such to maximally oppose the motion of the inducing bunch. It is specific for each excited resonant cavity mode with frequency ω and normalised shunt impedance r/Q and it is proportional to the loss parameter $k = \frac{\omega}{2} \frac{r}{Q}$.

For a single bunch passage, ΔV_b therefore depends on ω and, via r/Q , on the geometry of the cavity but not on the r.f. losses or Q-factor.

For a train of equally spaced bunches the total voltage induced will depend on the fact whether the induced r.f. fields decay or not to a negligible value inbetween bunch passages.

For $\tau_d \ll \tau_b$ fields do not superpose significantly and the amount of r.f. power deposited inside the cavity and in a specific mode is, with $q = i_o \tau_b$

$$P_b = \frac{q}{\tau_b} \Delta V_b = i_o^2 \tau_b \frac{\omega r}{2 Q} . \quad (9)$$

This power does not depend on the Q-factor and is the minimum power deposited by a bunch train (τ_b, q) in a cavity of a given geometry and a given mode. It can be reduced by lowering r/Q (e.g. by a larger iris opening).

Typical beam instabilities produced by this type of cavity excitation are the single bunch, single passage instabilities (short range wakes) where the fields induced by the head of a bunch affect the tail of the same bunch but not the following bunches.

For $\tau_d \geq \tau_b$ fields can be built up by superposition from subsequent bunch passages.

The final voltage in the limit $\tau \rightarrow \infty$ is obtained by summing up the fields induced by all previous bunch passages and by taking into account the correct phase relations and the field decay. The result is (for the real part of beam loading) for a given mode with frequency ω [14]

$$V_b = \frac{\Delta V_b}{2} \cdot F(\tau) = \frac{\omega r}{4 Q} \cdot q \cdot F(\tau) , \quad (10)$$

$$\text{with } F(\tau) = \frac{1 - e^{-2\tau}}{(1 - 2e^{-\tau} \cos \delta + e^{-2\tau})} , \quad (11)$$

$$\text{and with } \tau = \frac{\tau_b}{\tau_d} = \frac{\tau_b \omega}{2Q_o} \quad (12)$$

$$\delta = (\omega - \omega_h) \tau_b , \quad (13)$$

- Q_o : quality factor of hom.

$\omega_h = h \cdot \omega_r$ (h : integer) is the frequency of a specific line of the beam spectrum i.e. a multiple of the revolution frequency ω_r (in storage rings) or the bunch repetition frequency (in linacs).

One can easily show that $\delta = 0$, or $\omega = \omega_h$ corresponds to the case where the (exciting) frequency ω_h falls on the cavity resonance frequency ω (resonance case). For $\delta = 180^\circ$, ω lies in the middle between two adjacent beam lines (anti-resonance case).

For the resonance case where $\delta = 0$ a maximum built-up of excited hom fields occur.

For large decay constants τ_d (or large Q_o) where $\tau \ll 1$ one gets

$$F(\tau) = \frac{1 + e^{-\tau}}{1 - e^{-\tau}} \sim \frac{2}{\tau} = \frac{4Q_o}{\omega\tau_b} \quad (14)$$

Combining (10) and (14) one gets

$$V_b = \frac{q}{\tau_b} \cdot \left(\frac{r}{Q}\right) \cdot Q_o \quad (\tau \ll 1) \quad (15a)$$

Similarly one obtains for the power deposited by the bunch train (q , τ_b) in an excited mode

$$P_b = i_o^2 \left(\frac{r}{Q}\right) Q_o \quad (\tau \ll 1) \quad (15b)$$

The field built-up and deposited power thus depends on $(r/Q) \cdot Q_o$. This shows the danger of hom field built-up in s.c. cavities where Q_o is large.

It is the domain of another class of beam instabilities based on the fact that the cavity develops a "memory" for preceeding bunches or preceeding passages of the same bunch (long range wake). Typical examples are coupled bunch instabilities in storage rings or cumulative break-up in (recirculating) linacs.

Fortunately there exist a well proven method to reduce the value of the decay constant for hom in s.c. cavities; this is by loading a specific hom by dedicated couplers (hom couplers).

In analogy to the (unloaded) quality factor of a cavity

$$Q_o = \frac{\omega W_{st}}{P_c} \quad (16)$$

- P_c : r.f. losses inside the cavity,
- W_{st} : stored r.f. energy,

we define for each coupler and each hom

$$Q_{\text{ext}} = \frac{\omega W}{P_{\text{ext}}}, \quad (17)$$

where P_{ext} is the r.f. power of the hom removed by the coupler from the cavity.

The total (loaded) Q_L of the cavity for this mode becomes

$$Q_L = \frac{Q_o Q_{\text{ext}}}{Q_o + Q_{\text{ext}}} \quad (18)$$

if $Q_o \gg Q_{\text{ext}}$ one has simply $Q_L = Q_{\text{ext}}$ and $\tau = \frac{\tau_b \cdot \omega}{2Q_{\text{ext}}}$.

In fig. 1 the resonance factor $F(\tau)$ is shown as a function of Q_{ext} and for three different δ . For low Q_{ext} , $F(\tau)$ tends to a constant value where the excitation is independent of Q_{ext} . For high Q_{ext} the resonance (and antiresonance) effect can be seen.

Fig. 1: Resonance factor $F(\tau)$ as a function of $Q_{\text{ext}} = \frac{\tau_b \cdot \omega}{2\tau}$ ($\tau_b = 22 \mu\text{s}$, $\omega = 2\pi \cdot 6.4 \cdot 10^8 \text{ Hz}$, $Q_o = 3 \cdot 10^9$). The inserts show qualitatively the behaviour of r.f. power excited by a bunch train of distance τ_b and in a given mode.

The development of adequate hom couplers has been pushed to a high degree of perfection and at present hom coupler designs exist for many types of accelerators and operation conditions [15]. Q_{ext} well below the ones naturally existing in Cu cavities and due to the high r.f. losses ($Q_{\text{ext}} \sim 10^4$) can nowadays be achieved. In same time the loading of the fundamental mode is kept to a negligible level by using adequate filtering methods. Therefore the use of hom couplers allows to combine the advantages of low losses for the fundamental mode and of strong attenuation for the higher order modes.

Hom couplers reaching Q_{ext} well below 10^4 for the most dangerous modes are rather sophisticated and complex devices because stringent and sometimes contradictory requirements of r.f., tuning facilities and cooling by liquid He have to be fulfilled. This task can be alleviated somewhat by choosing adequate cavity geometries.

As the basic beam excitation by a single bunch is proportional to r/Q one tries to reduce this quantity. The simplest and most usual way (in disk loaded waveguides) is a large iris opening $2a$. r/Q scales approximately with a^{-2} for longitudinal modes and with a^{-3} for transverse (dipole) modes. The corresponding inevitable decrease of r/Q for the fundamental mode can generally be tolerated and can often be compensated by a slightly enlarged Q_0 and a smaller E_p/E_{acc} . It should be stressed that this solution is generally not acceptable for n.c. cavities because a large r/Q for the fundamental mode is essential for an efficient use of r.f.

For high power FEL where very high bunch charges and repetition frequencies are needed one decreases Q_{ext} by reducing the number of cells to 1 or 2 [16]. Each cell can be equipped by hom couplers located at the beam tubes. In this way, Q_{ext} below 10^3 can be reached [15].

3. FREQUENCY CHOICE FOR SC CAVITIES

For n.c. linacs with high gradients as needed e.g. in linear colliders one tends to keep the mean and peak r.f. power low and to achieve a high efficiency η for power transfer to the beam (cf below).

The scaling of these quantities with frequency is [8]

$$P \sim \omega^{-2}, \quad \hat{P} \sim \omega^{-1/2} \quad \text{and} \quad \eta \sim \omega^2. \quad (19)$$

In addition the maximum gradient which can be achieved in Cu cavities for short pulses ($\tau \sim \mu\text{s}$) is found empirically to scale with $\sim \omega^{1/2}$ [17].

This are decisive arguments for a high operation frequency. They have however to be balanced against wake field effects which increase with frequency.

The situation is different for s.c. cavities where many arguments favour low frequencies.

A first argument for low frequencies is related to the frequency and temperature dependence of r.f. losses [3]. With

$$R_{\text{BCS}} \sim \frac{\omega^2}{T} \exp \{-\alpha T_c/T\} , \quad (20)$$

and T_c : critical temperature, $\alpha = 1.76$, $Q_o = G/R_{\text{BCS}}$, $r/Q \sim \omega$, one gets

$$P_c = \frac{E_{\text{acc}}^2}{\left(\frac{r}{Q}\right) Q_o} \sim \omega \exp \{-\alpha T_c/T\} . \quad (21)$$

Cavity losses thus increase with frequency.

The temperature dependence tells us for a given superconductor and a given operating temperature up to which frequency we can work in order to keep r.f. losses below a given level. One tends of course to work at 4.2 K where relatively simple and much more economic refrigeration systems can be used (sect. 2.2). In Nb cavities where Q-values of a few 10^9 are needed one can work at 4.2 K up to frequencies of ~ 700 MHz; for Nb₃Sn cavities frequencies well above 3 GHz still could be used [3].

A second argument is linked to longitudinal and transverse beam instabilities. Longitudinal and transverse r/Q scale like ω and ω^2 respectively for a given bunch length. This argument is of particular importance in large storage rings, FEL and linear colliders where large bunch charges are needed.

A third argument for low frequencies concerns the amount of energy removed by a bunch from the cavity. The stored energy per unit length is

$$W_{\text{st}} = \frac{E_{\text{acc}}^2}{\left(\frac{r}{Q} \cdot \omega\right)} . \quad (22)$$

It has to be compared with the energy per unit length taken away by one bunch of charge q

$$W_b = qE_{acc} \quad (23)$$

The ratio

$$\eta = \frac{W_b}{W_{st}} = \frac{q \left(\frac{r}{Q}\right) \omega}{E_{acc}} \quad (24)$$

should be kept small for various reasons:

- the variation of acceleration field

$$\frac{\Delta E_{acc}}{E_{acc}} = \frac{1}{2} \frac{\Delta W_{st}}{W_{st}} = \frac{1}{2} \eta, \quad (25)$$

produced by the bunch during its passage should remain small as it leads to a dispersion in particle energy.

- ΔW_{st} produces transients which change the matching of the r.f. generator to the cavity and causes additional power reflection. Another advantage of CW operation with small transients is that phase, amplitude and frequency regulation systems can be made simpler and more precise. This results also in a smaller energy dispersion of particles.

From formula (24) it appears that one should use low frequencies for keeping η low. For s.c. cavities η can be made even smaller because of the smaller r/Q (see above) and their much higher E_{acc} as compared to n.c. cavities operating under CW conditions.

A fourth argument for low frequencies are cavity, cryostat and coupler costs. These costs are strongly influenced by the number of couplers per unit length (very much the same way as the number of feedlines per unit length of s.c. magnets dominate costs).

We would like to specify this argument more in detail for electron acceleration structures. By now disk loaded cavities with rounded geometry (fig. 2) have been adopted nearly everywhere and there is a strong tendency to locate hom couplers at the beam tubes [18] and no longer at the individual cells. As a consequence the number of cells per cavity has to be kept small if efficient coupling of hom is to be achieved, and this irrespective of the frequency chosen. For high intensity and/or high peak currents this leads to typical cell numbers between 4 and 6. Low frequencies therefore keep the number of couplers per unit length low.

Fig. 2: A 350 MHz, 4-cell Nb cavity for LEP. All couplers are located at the beam tubes whose geometry has been chosen for decreasing end-cell effects of the fundamental and some higher order modes.

4. EXAMPLES FOR THE CHOICE OF SC CAVITIES

The arguments given in the previous chapter will be illustrated by a few examples where s.c. cavities are compared with n.c. cavities. It is not tried to give arguments in great detail and only the most important aspects will be discussed.

4.1 Acceleration of heavy ions [19]

The potential of s.c. cavities has already been realised at a very early stage. They are usually used as post-accelerators for Tandem electrostatic machines and have to handle only small currents ($\sim \mu\text{A}$) and a comparatively small energy range ($< 100 \text{ MeV}$). As a consequence arguments of efficiency, power consumption and higher order mode attenuation are of less concern.

Heavy ion accelerators ask for CW operation and much higher gradients as in n.c. cavities can be obtained. The much lower r.f. losses and the small currents allows one to use a r.f. power per cavity in the range of a few Watt. Therefore single cell cavities, each one equipped with a r.f. coupler become affordable. The great flexibility of a string of single cell cavities for adjusting widely different velocity profiles at different ion masses is considered today one of the greatest advantage of s.c. cavities.

There are a few specific problems connected with s.c. low velocity (low β) structures. The concentration of electric fields in the region of drift tubes leads to large E_p/E_{acc} ratios (typically ≥ 4 , E_p : peak electric r.f. surface field). As a consequence field levels are nearly always limited by field emission loading originating from these regions.

A typical problem of these cavities is their low mechanical stiffness which leads to vibrations and mechanical deformations by field stresses. As the small beam loading asks for weak couplings (and small bandwidth), vibrations and the coupling between mechanical and electric forces (ponderomotive forces) can produce large and fast frequency and phase shifts. Sophisticated frequency and phase regulation systems had to be developed to master these problems.

4.2 The Continuous Electron Beam Accelerator Facility (CEBAF)

At CEBAF plans for an accelerator for nuclear physics in the energy range of a few GeV, with a current of 200 μA and a very large duty cycle have been advanced [20,1].

Original designs were based on a n.c. pulsed and recirculating linac followed by a storage ring to stretch beams to an 80% duty cycle beam. A few parameters of this version are given in table 1.

Table 1 Baseline specifications for CEBAF: pulsed n.c. linac with pulse stretcher ring and CW s.c. linac [20]

	n.c. linac	s.c. linac
Frequency (MHz)	2856	1500
Duty factor	> 80%	100%
Emittance (πm)	$2 \cdot 10^{-7}$	$< 10^{-8}$
Energy spread ($\Delta E/E$)	$2 \cdot 10^{-3}$	$< 2 \cdot 10^{-4}$
Simultaneous CW beams at different energies	1	3
Design energy (GeV)	0.5 - 4	0.5 - 4(6)
Possible upgrade energy (GeV)	~ 6	~ 16
Current (μA)	200	200
Amount of accelerating structure (GeV)	2.0	1.0
Number of recirculations	1	3
Passes through linac	2	4

A s.c. version [20] has been finally preferred for the following main reasons (table 1): CW operation with 100% duty cycle and with an acceleration field $E_{\text{acc}} \geq 5 \text{ MV/m}$ was considered on overwhelming asset for high intensity nuclear physics experiments. It is combined with an improved beam quality (essentially due to the fact that bunches are distributed evenly over all r.f. cycles), savings in operation costs and the ability to deliver simultaneously CW beam at three different energies.

The choice of CORNELL type 5-cell s.c. cavities [21] with very large disk openings ($\frac{2a}{\lambda} = 0.35$) and very strong hom coupling ($Q_{\text{ext}} = 10^3 \div 10^5$) has allowed to increase the number of recirculating

passes and to remain nevertheless below the most dangerous thresholds for multipass regenerative beam break up. The expected beam emittance and momentum spread are given in table 1. As a conservative gradient of 5 MV/m allows already to reach energies of 4 GeV there is room for a substantial upgrading in energy.

4.3 superconducting cavities for LEP

LEP will be equipped initially with 128 n.c. acceleration cavities [12] but the use of s.c. cavities has always been considered for a later upgrading of energies from 55 GeV to ~ 100 GeV [22]. Therefore a comparison of both versions is of particular relevance (table 2). Similar plans exist incidently for two other large storage rings: HERA at DESY and TRISTAN at KEK [1].

For large storage rings equipped with many hundred meters of accelerating cavities, acceleration efficiencies and operating costs are of course of highest importance. For LEP the main current or luminosity limitation stems from transverse instabilities linked to the internal modes of individual bunches (short range wake fields).

These arguments have led to a frequency choice of 350 MHz for the n.c. cavities [23] where the cost and efficiency of large r.f. power sources balances favourably with cavity costs and with sufficiently low loss factors for higher order modes. For simultaneous acceleration of electrons and positrons a π -mode was chosen. An iris opening of only 100 mm ($\frac{2a}{\lambda} = 0.12$) was chosen and irises are made slightly re-entrant for getting a high r/Q. By using slot-coupling and by choosing only 5-cells per cavity machining tolerances could be kept to an acceptable value. The economics of cooling systems limit gradients to 1.5 MV/m (CW). With this design the accelerating efficiency was still considered too small: the large bunch spacing of LEP (22 μ s) triggered the idea of a sophisticated modulated r.f. system where the r.f. energy is stored inbetween bunch passages in a high Q (spherical) storage cavity. This elegant method [24] brings up the effective r/Q of the cavities from 650 Ohm/m to 1000 Ohm/m.

The n.c. Cu cavities cause the major contribution to the total transverse loss factor of LEP [25]: for 128 Cu cavities it is $1.1 \cdot 10^5$ V/pC as compared to $\sim 0.4 \cdot 10^5$ V/pC for the vacuum chambers (and as compared to $0.2 \cdot 10^5$ V/pC for 256 s.c. cavities).

For the s.c. cavities the same frequency of 350 MHz as for the n.c. cavities has been finally adopted [22]. Once it had been shown that in 4-cell prototype Nb cavities the design gradient of 5 MV/m could be achieved this low frequency has been favoured because very high quality factors in excess of $3 \cdot 10^9$ can be reached already at 4.2 K.

A very advanced cavity design (fig. 2) has been worked out [18] involving computations of higher order modes beside the fundamental modes and for which all hom couplers are located at the beam tubes. A sufficient (internal) coupling of hom from the middle cells to the end cells and couplers is obtained by increasing the iris opening and by restricting the number of cells per cavity to 4. In table 2 a few cavity parameters are compared with the ones for the Cu cavities; the Q_{ext} compare favourably with the ones of the n.c. cavities and are below the design values for LEP ($5 \cdot 10^4 \div 10^5$).

Despite the low r/Q for the fundamental mode a much higher acceleration efficiency is obtained (table 2). A particularly striking consequence of this is given by the fact that the total installed r.f. power of 16 MW, which allows to reach 55 GeV with the n.c. cavities, is sufficient for an upgrading to more than 90 GeV once (256) s.c. cavities are installed.

At a design current of 3 mA per beam and with 4 bunches per beam each bunch in LEP has a peak current of 1330 A and a bunch charge of 67 nC. With the formula (24) and the parameters of table 2 one calculates the percentage of stored energy removed by one bunch. As LEP cavities are located near the interaction regions the passages of e^+ and e^- bunches are so near in time that the r.f. energy cannot be restored entirely inbetween. Therefore η has to be doubled and one gets the values given in table 2 which confirm the small amount of transients for s.c. cavities

TABLE 2

A few LEP cavity parameters

	Cu cavity	s.c. cavity
Frequency f	352.209 MHz	352.209 MHz
Wavelength λ	0.851 m	0.851 m
Number of cells	5	4
Cavity active length	2.13 m	1.70 m
Iris hole diameter	100 mm	241 mm
Shunt impedance/quality factor r/Q	650 Ohm/m ^(a) 1000 Ohm/m ^(b)	276 Ohm/m
Q (Cu, 300K)	40 000	--
Q (Nb, 4.2 K)	--	$3 \cdot 10^9$
$2(f_{\pi} - f_o)/(f_{\pi} + f_o)$	1.28%	1.76%
Design accel. field E_{acc}	1.5 MV/m	5 MV/m
Accel. efficiency η_{acc} $\left\{ \begin{array}{l} 2 \cdot 3 \text{ mA} \\ 2 \cdot 6 \text{ mA} \end{array} \right.$	7.5% 13.3%	47% 53%
Percentage of W_{st} taken by 2 bunches η_{st}	12.8%	1.6%
Total loss factor/unit length	$403 \frac{V}{pC \cdot m}$	$46 \frac{V}{pC \cdot m}$
Q_{ext}	Cu-attenuation	2 hom couplers at beam tubes
TM_{011}	$\left. \begin{array}{l} \\ \\ \\ \end{array} \right\} \sim 3 \cdot 10^4$	$2.7 \cdot 10^4$
TM_{012}		$7 \cdot 10^3$
TM_{110}		$4 \cdot 10^4$
TM_{111}		$1.4 \cdot 10^4$

(a) without storage cavity.

(b) with storage cavity.

5. CONCLUSIONS

The small r.f. losses of s.c. cavities allow CW operation at much higher acceleration fields than the ones in n.c. cavities. Together with the large stored energy which can be conserved with negligible losses over periods of hundreds of ms the possibility of CW operation provides great flexibility of operating conditions. In heavy ion accelerators or electron accelerators for nuclear physics particles can be distributed evenly over all r.f. periods and allow excellent detection conditions. In electron storage rings or free electron lasers large bunch charges combined with high repetition rates can be handled equally well. The use of hom couplers allows to combine small shunt impedances for the fundamental mode with Q_{ext} for higher order modes which can be made equal or even smaller than the "natural" Q_{ext} of n.c. cavities. High acceleration efficiency and large attenuation of higher order modes are therefore compatible.

For s.c. cavities many arguments favour low frequencies and large iris openings. Both choices decrease longitudinal and transverse wake fields effects. This is particularly welcome for high power, free electron lasers and for linear colliders where not only bunches with high electron populations have to be handled but where, all along the accelerator, phase space blow up and energy dispersion has to be kept small and where energy recovery is very desirable.

For linear colliders we still remain faced with the problem of achieving much higher energy gradients. As far as we can see today there exists no fundamental limit but progress will be bound to developments in the technology of s.c. cavity fabrication and surface treatments and of new s.c. materials.

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