Superconducting Cavities for Beauty Factories

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ABSTRACT

The possibilities and merits of superconducting accelerating cavities for Beauty-factories are considered. There exist already large sc systems of size and frequency comparable to the ones needed for Beauty-factories. Their status and operation experience is discussed. A comparison of normal conducting and superconducting systems is done for two typical Beauty-factory rings.

1. INTRODUCTION

At present the construction of Beauty-factories is considered in several laboratories [1]. Beam currents of the order of 1 A will be needed with hundreds of bunches spaced at a few meters to reach luminosities in the range of $10^{33}$ to $10^{34}$ cm$^{-2}$ sec$^{-1}$. These parameters are orders of magnitude above the present day values and very large and powerful rf-systems will be necessary for the acceleration and longitudinal focusing of particle bunches. It is therefore natural to consider the use of superconducting (sc) cavities for this task.

The specific requirements and design issues for Beauty-factories have been reviewed by M. Zisman in this conference [2] and we will recall here only shortly those aspects which are of particular relevance to the acceleration system.

The first task of the rf-system is to accelerate particles and to compensate the beam losses due to synchrotron radiation and horn excitation. A second requirement is to supply longitudinal focusing of particle bunches with a length $\sigma_z$. The total peak accelerating voltage $V_{RF}$ needed for this is:

$$V_{RF} = \text{const} \cdot \alpha \cdot E^3 / \left( f_{RF} \sigma_z^2 \right)$$

(1)

with $\alpha$ : momentum compaction; $E$ : energy; $f_{RF}$: frequency of rf-system; $\sigma_z$ : bunch length. From

(1) one derives that low $f_{RF}$ and short bunches lead to large accelerating voltages.

The rf-system has also to supply the rf-losses at the cavity walls $P_c$ given by:

$$P_c = \frac{V_{\text{acc}}^2}{2 R_{sh}} = \frac{V_{\text{acc}}^2}{2 \left( \frac{R_{sh}}{Q} \right) Q_0}$$

(2)

with $V_{\text{acc}}$ : accelerating voltage of cavity; $R_{sh}$ : shunt impedance; $(R_{sh}/Q)$ : normalised shunt impedance; $Q_0$ : unloaded quality factor.

In a Beauty-factory the total CW rf power needed amounts to many MW.

The task of acceleration and longitudinal focusing can be performed with the same rf-system. This leads to values of the synchronous angle $\phi_s$ with $\sin \phi_s = 0.05$ to 0.2. As a consequence beam loading will be largely reactive and a large cavity detuning will be needed. One has also considered the use of hybrid systems [3] where acceleration and focusing are done with separate rf-systems. Sc cavities would be particularly well suited for focusing where large voltage and small rf-power is needed. However, the stability of such systems remains to be demonstrated.

Acceleration and longitudinal focusing fix essentially the product $V_{RF} \cdot \sin \phi_s$ and one has to discuss in which way a few other requirements for the accelerating systems can be fulfilled.

invited talk at the SLAC B-Factory Conference: The State of the Art in Accelerators, Detectors and Physics, Stanford University, April 6-10, 1992.
In a Beauty-factory the higher order made (hom) issue is of overwhelming importance for at least two reasons. Hom losses may amount to a large percentage (10 to 30%) of the total beam losses and they are responsible for the most stringent current limitation and that is longitudinal coupled bunch instability.

The growth rate $\tau_{cb}$ of a given coupled bunch instability follows the relation

$$\tau_{cb} \propto i_b \cdot n_{cav} \left( \frac{R_{sh}}{Q} \right) Q_{ext,j}$$

(3)

with $i_b$: total beam current; $n_{cav}$: number of rf cavities; $j$ characterises the hom's responsible for the coupled bunch instability considered.

We note that for scaled cavity geometries $R_{sh}/Q$ is proportional to $\sqrt{\text{RF}}$.

Besides the coupled bunch instabilities one has to care also about longitudinal single bunch instabilities; the bunch threshold current $I_p$ follows the relation.

$$\frac{1}{I_p} \propto \Sigma \left( \frac{R_{sh} \cdot \omega_0}{Q \cdot \omega} \right)_j$$

(4)

$\omega_0$: revolution frequency; $\omega$: frequency of the $j^{th}$ hom; $\Sigma$ has to be taken over all hom contributing to the broadband impedance.

In general the limit $I_p$ is less stringent than the coupled beam instability limit.

Instabilities due to transverse hom are of less concern in a typical Beauty-factory surrounding.

The rf cavities contribute for a large part to the sum of hom impedances seen by the beam. Obvious ways to reduce their contribution are:

- A decrease of $R_{sh}/Q$.
  This can be obtained by choosing a low rf-frequency and an adequate cavity geometry, essentially a large iris-opening. The drawback of this solution is an unavoidable decrease of $R_{sh}/Q$ for the accelerating mode. For sc cavities with their extremely large $R_{sh}$ this is an affordable solution, for nc cavities it is not.

- A decrease of the number of cavities $n_{cav}$.

This goes along with an increase of accelerating gradient. For CW fields as needed in Beauty-factories sc cavities have a much higher potential.

- A decrease of $Q_{ext}$ for all hom.
  Typically $Q_{ext}$ have to be lowered below 100, a value exceeding by orders of magnitude, not only the "natural" damping in nc cavities ($Q_{ext} \approx 10^4$) but also anything realised up to now in sc cavities. In addition the damping systems have to cope with rf-powers in the range of many kW.

- Even with $Q_{ext}$ of the order of 100 the use of powerful feedback systems will be needed for an additional damping of specific coupled bunch modes excited by hom and by the off-resonance operation of the fundamental cavity mode. The rf power needed for those feedback systems scales with the square of the growth rates.

Accelerating fields in nc and sc rf-cavities may be limited by the power handling capacity of input couplers even if one uses monocolle cavities and low $\sin\phi_s$. CW power levels of many hundred kW with $Q_{ext}$ in the range of a few $10^5$ will be needed.

Stationary and transient beam loading is another problem in Beauty-factories.

The average effect of beam loading has to be corrected by a cavity detuning.

$$\Delta f / f_{RF} = \frac{1}{2} \left( \frac{R_{sh}}{Q} \right) \frac{i_b \cos\phi_s}{V_{acc}} = \frac{1}{4 \omega_{RF}} \frac{i_b V_{acc} \cos\phi_s}{W_{st}}$$

with $W_{st} = V_{acc}^2 / [2(R_{sh} / Q)\omega_{RF}]$

(5)

(6)

$W_{st}$: stored energy.

A strong transient beam loading is caused by a gap in the bunch train needed for ion clearing. With a largely reactive beam loading in Beauty-factories this causes a phase modulation of the accelerating voltage given by [4].

$$\Delta \phi_{RF} = \frac{1}{2} \left( \frac{R_{sh}}{Q} \right) \omega_{RF} \frac{i_b \Delta t}{V_{acc}} = \frac{1}{4} \frac{V_{acc} i_b \Delta t}{W_{st}}$$

with $\Delta t$: length of gap.
$\Delta \phi$ causes a variation in the longitudinal bunch position which may lead (for some interaction regions) to a displacement of crossing points of the order

$$\Delta s = \frac{\Delta \phi RF}{2\pi} \cdot \lambda RF$$

(8)

$\Delta s$ should not exceed the $\beta$–function values at the interaction points $\beta_x^*, \beta_y^*$ for avoiding a decrease in luminosity.

Both effects can be kept smaller by the use of sc cavities which may have larger $W_{ST}$ than nc cavities because of their higher $V_{acc}$ and lower $R_{sh}/Q$ (Table 1).

<table>
<thead>
<tr>
<th>Table 1 – Comparison of nc and sc monocell cavities (typical values)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>------------------</td>
</tr>
<tr>
<td>$f_{RF}$ (MHz)</td>
</tr>
<tr>
<td>$E_{acc}$ (MV/m)</td>
</tr>
<tr>
<td>$Q_0$</td>
</tr>
<tr>
<td>$V_{acc}$ (MV)</td>
</tr>
<tr>
<td>Iris diameter (cm)</td>
</tr>
<tr>
<td>$R_{sh}/Q$</td>
</tr>
<tr>
<td>$P_C$ (kW)</td>
</tr>
<tr>
<td>$W_{ST}$ (Joule)</td>
</tr>
<tr>
<td>$\eta_{acc} = P_{by}/P_{mains}$</td>
</tr>
<tr>
<td>Filling factor</td>
</tr>
<tr>
<td>$\Delta \phi_{RF}$ (transient beam loading)</td>
</tr>
<tr>
<td>Costs/unit ($\times$)</td>
</tr>
</tbody>
</table>

A frequency of 500 MHz for sc cavities appears to be a good compromise between the requirements of low impedances, large stored energies and voltages needed for longitudinal focusing of bunches. A decisive advantage of the low frequency if that quality factors in the range of $10^9$ can be reached without operating at temperatures below 4,2K.

The efficiency of the large rf-systems needed in Beauty-factories is of obvious importance.

For a comparison of acceleration efficiency $\eta_{acc}$ we use

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

(9)

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

For a nc system one gets (neglecting cooling power)

$$\eta_{acc} = \frac{P_b}{(P_b + P_C) / \eta_{RF}}$$

(10)

with

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

(11)

and

$$P_C = \frac{E_{acc}^2}{2(R_{sh}/Q)Q_0}$$

(12)

$P_C$: cavity losses/m.

$\eta_{RF}$: overall efficiency for producing rf power.

For sc cavities, one has to take into account in addition cryogenic losses which have to be cooled away with a (technical) efficiency $\eta_{cryo}$ and one gets
\[ \eta_{acc} = \frac{i_b E_{acc} \sin \phi_s}{i_b E_{acc} \sin \phi_s + \frac{E_{acc}^2}{\frac{2}{2} (R_{sh} / Q) Q_0} + P_{st}} \eta_{cryo} \] (13)

Here, we neglect \( P_{c} << P_{b} \) in the rf balance and add the static cryogenic losses/m \( P_{st} \) of the cryostat.

For large CW-klystrons, overall efficiencies \( \eta_{rf} \) (including klystron efficiency and transmission losses) are of the order of 60%. Large cryogenic installations with cooling capacities > 1kW can have technical efficiencies of 0.4% at 4.2K [5].

From formulae (9) to (13), one concludes that the efficiency of systems depends on the accelerating fields and the beam current; for very large currents the efficiencies of nc and sc cavities approach. On the contrary for small currents (or small \( P_{b} \)) and large \( E_{acc} \), sc cavities have much higher efficiencies.

**RMS bunch length = 1.0 cm**

- \( K \) (HOM only) = 0.34V/pc
- \( R/Q \) (fundamental) = 265 \( \Omega/\text{cell} \)

- 0.21 V/pc
  - 117 \( \Omega/\text{cell} \)
  - \( Q_{ext} \) (fund.) = \( 2 \times 10^6 \)

- 0.11 V/pc
  - 89 \( \Omega/\text{cell} \)
  - \( Q_{ext} \) (fund.) = \( 3 \times 10^5 \)

**Cavity Comparison**

2/2/90
All Cells 500 MHz

**Fig. 1** Comparison of typical nc and sc cavity shapes. The nc cavity may be equipped with a main coupler and waveguide hom couplers. The sc cavity for Beauty-factories cell is a monomode cavity with external hom absorbers [7] (cf. Fig. 2)
2. CHOICE OF CAVITY LAYOUTS

Different approaches have been chosen for nc and sc accelerating cavities in Beauty-factories. (Fig. 1 and Table 1).

For nc cavities 500 MHz monocell Cu cavities with small beam tube diameter are under development. Gradients of 4.2 MV/m leading to wall losses of about 120kW/all are considered [6]. Input couplers for many hundred kW, CW rf power levels will be needed; these levels exceed even the ones now reached in large storage ring cavities. Hom damping is obtained by waveguide couplers located at the cell walls and should reach $Q_{ext}$ of about 70.

For sc cavities a radically different approach has been chosen at Cornell [7]: Nb monocell cavities with very large beam opening (Fig. 2).

Fig. 2  Conceptual design of a sc cavity with "fluted" beam tube, a waveguide input coupler and surrounded by a cryostat. The external hom absorbers are located outside of the cryostat (courtesy of M. Tigner, this conference).
A specially designed beam tube (fluted or ridged waveguide tube [8]) has been designed enabling transmission of all hom including the two lowest frequency modes TM11 and TM110. In this way one approaches the ideal of a mono-mode cavity and gets rid of hom couplers at the cavities. Hom power will be absorbed at hom absorbers located outside of the cryostat at the room temperature beam tubes. New types of absorbers must be developed which are able to handle hom power levels of many kW in a frequency range up to at least 30 GHz. They have to be in good thermal contact with room temperature supports. They must be compatible with uhv operation and should not contaminate the sc cavity surfaces. Developments of adequate absorbers are going on at Cornell [8] and CEBAF [9] and the influence of their impedance on the beam is studied.

A waveguide input coupler handling up to 500 kW CW rf power is under study [7]. Perturbation of the beam by the coupling region and direct interaction with the beam are kept low by a resonant coupling slot similar to the ones developed in the past at Karlsruhe for the DORIS storage ring at DESY [10]. Particular care has to be given to the rf-window design at these high power levels. A window failure is a very serious accident for sc (and nc) cavities and will lead almost inevitably to a deterioration of sc surfaces. Therefore a very efficient window protection system will be essential.

At Saclay [11] a cavity layout is under study which couples two cavities with a large beam tube whereas the outer beam tubes have a smaller diameter equal to the one of the vacuum chamber so that tapers are avoided (Fig. 3).

For the fundamental mode cavities are only weekly coupled whereas the intermediate region presents a resonator for the hom and may permit a strong damping of all hom below cut-off. As for input couplers one may try to enhance coupling of hom by using resonant layouts [10] near the coupling elements. More studies will be needed for this layout which would have a better filling factor than the mono-mode cavities, each surrounded by its own cryostat.

The beam tube geometry in a string of monocell cavities with large openings has to be carefully studied. Tapers and diameter changes may have total loss factors comparable or even larger than the ones of the cavity cells.

Frequency tuning should not be a difficult task for sc cavities. The matching of the rf generator to the cavity will need a $Q_{ext} = 5 \times 10^8$ to $10^9$ and a corresponding bandwidth of 10 to 5 kHz. Compared to the bandwidth used in present sc cavities for storage rings of about 100 to 500 Hz this is a very comfortable value. Slow tuners with a range of about 100 kHz exist and should be sufficient for operation.

A low gradient, high intensity application which bears many similarities with the application in particle factories is planned for the large p-p collider LHC at CERN [12], [13].

Fig. 3 A 2-cell resonator for Beauty-factory applications [11].
(a) the resonator 2-cell structure.
(b) Electric field lines of fundamental mode.
(c) Electric field lines of the resonator TM021 mode.
A current of 851 mA per beam is considered, with 4725 bunches, a bunch length of 7.5 cm, and a bunch spacing of 4.5 m. The 400 MHz rf system is designed for a voltage of 16MV per beam in order to keep bunches sufficiently short during collisions. This has to be compared to the rf voltage needed for ramping the energy (during 20 min) and for compensating the synchrotron radiation losses which amount to less than 0.5 MeV per turn. As a consequence, the beam loading is mainly reactive as in Beauty-factories. The bunch train will have a few gaps of length \( \Delta t \) between 100 nsec and 3 \( \mu \)sec to avoid losses at injection and beam dumping. This causes heavy transient beam loading similar to the one encountered in Beauty-factories. At present it is foreseen to use a chain of single cell cavities coupled by large diameter beam tubes similar to the system proposed in ref. 11 (Fig. 4).

For very high luminosities the use of bunch rotation by deflecting "crabbing" cavities [7,14] is considered. Sc deflecting cavities at 3 GHz have been used in the past for rf particle separators [15]. In 4 cell cavities deflecting fields up to 5 MV/m have been reached. A particular problem for "crabbing" cavities is the attenuation of the fundamental mode which has a lower frequency than the deflecting mode. It is foreseen to damp this mode by a coaxial layout at the beam tubes [14].

![Fig. 4 Possible geometry of a four cell structure for acceleration of two beams in the planned LHC collider at CERN.](image)

### 3. STATUS OF LARGE SC RF SYSTEMS FOR \( e^+ e^- \) STORAGE RINGS

#### 3.1 Cavities

At present there are sc rf systems operated in the large \( e^+ e^- \) storage rings TRISTAN, HERA and LEP [16], [17]. These systems are of a size and frequency (Fig. 5) comparable to the ones needed for Beauty-factories but beam currents are only of the order of 5 to 20mA. In Table 2 a number of parameters and performances are collected. We have added to this table parameters for the large sc recirculating linac CEBAF [18]. Although this system works with a higher frequency and is foreseen for nuclear physics it has a few aspects of relevance for Beauty-factories.

The largest experience has been gained at KEK with 32 installed sc cavities and with about 16000h of operation (50% for physics) [17]. At CERN a very large system is under construction for the upgrade of LEP [19]. Besides 12 sc cavities installed in LEP another 3 LEP cavities are operated since 1987 in the CERN SPS [20]. At DESY [21] 12 sc cavities are operated in the HERA electron ring and at CEBAF 18 sc cavities are used in the injection line of the recirculating linac [18].

A very typical behaviour of sc cavities can be deduced from Table 2 and Fig 6, Fig. 7. Average accelerating fields gradients well above the design value of 5MV/m are obtained in individual cavity tests and in horizontal cryostats installed in the storage rings but without beams. For operation with beams performances are lowered by a typical factor 2. A closer inspection of this situation reveals that fields are limited more by auxiliaries like input couplers (KEK, CEBAF) or horn couplers (CERN) than by the cavities themselves. In addition the field limit is often set by the trip rates of interlock systems which increase strongly at higher field levels.
Table 2 Typical se cavity performances

<table>
<thead>
<tr>
<th></th>
<th>TRISTAN KEK</th>
<th>LEP CERN</th>
<th>SPS CERN</th>
<th>HERA DESY</th>
<th>CEBAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>508</td>
<td>352</td>
<td>352</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>Number of cells</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>(planned) installed number of cavities</td>
<td>32</td>
<td>(192)12</td>
<td>3</td>
<td>(16)12</td>
<td>(338)25</td>
</tr>
<tr>
<td>Average accelerating field (MV/m)</td>
<td>9,2</td>
<td>7,2</td>
<td>7,2</td>
<td>6,1</td>
<td>9,2</td>
</tr>
<tr>
<td>* individual tests</td>
<td>6,9</td>
<td>5</td>
<td>7,1</td>
<td>6,1</td>
<td>7,6</td>
</tr>
<tr>
<td>* assembled in cryostat</td>
<td>4,7</td>
<td>3,7</td>
<td>5,5</td>
<td>2,6</td>
<td>6,3</td>
</tr>
<tr>
<td>* with beam</td>
<td>16'000</td>
<td>1000</td>
<td>20'000</td>
<td>&gt; 1000</td>
<td>&gt; 1000</td>
</tr>
<tr>
<td>Hours in beam</td>
<td>3 out of 32</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Permanent degradation</td>
<td>(dust)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5 Cryostat and two 4-cell, 500 MHz Nb cavities for the HERA electron ring. Each cavity is surrounded by its He-vessel (courtesy D. Proch).
Fig. 6
Distribution of $E_{acc}$ for the first 16 KEK sc cavities.

a) vertical (individual) tests. $<E_{acc}> = 9.25$ MV/m
b) horizontal test after assembly in pairs and mounting of couplers. $<E_{acc}> = 6.9$ MV/m

Fig. 7
Distribution of $E_{acc}$ for 16 and 32 KEK sc cavities [17]

a) at start up in beam
b) after 1 year of operation
c) after 2 years of operation
The operation of two sc LEP cavities in the CERN SPS accelerator [20] is an example of a particular complex operation mode performed with a sc cavity.

The operation combines acceleration of a high intensity proton beam with 4 short acceleration cycles for \( \pm \) bunches to be injected in LEP. An rf feedback system with a 50kW rf tetrode is used: during the high current proton operation (where 200mA of protons are accelerated by a normal conducting 200MHz system), the tetrode injects an opposite rf-current into the 350MHz sc cavities and compensates the induced rf-voltage to zero. For the acceleration of \( \pm \) bunches, an accelerating field of 4.5MV/m is used. Without the feedback system, the sc cavity would produce a strong dipole instability in the proton beam.

It is foreseen to test a sc single cell, 400MHz cavity with a high power tetrode at the SPS [22]. Problems of operation under heavy beam loading at the highest possible gradients and of power requirements for feedback systems will be studied.

It is noteworthy to mention a few vacuum and radiation conditions under which the sc cavities have been operated over long periods. At KEK a standard vacuum near the sc cavities is \( 5 \times 10^{-10} \)mb without beam and 0.5 to \( 1 \times 10^{-9} \)mb with beam. After 2 months of operation a gas desorption has been observed at warm-up [17]. As expected it is maximum for the sc cavities located nearest to room temperature vacuum chambers and amounts to an equivalent of 4.7 absorbed monolayers. No degradation of cavity performances has been observed.

At the CERN SPS the base vacuum at the location of the sc cavities is \( 10^{-9} \) mbar. A total of more than 20000 hours of operation has been reached without irreversible degradation of performances. We note that LEP cavities are not baked out before installation and cooldown.

At KEK cavities had to operate under heavy radiation [17]. Sc cavities near the arcs were submitted to synchrotron radiation dose rates up to 40 krad/MAh and to total dose rates estimated well above 1000 Mrad. At CERN integrated dose rates of the order of 1 Mrad were produced during cavity processing at higher fields. Again no degradations in gradients and Q-values have been observed.

Sc cavities in large \( \pm \) storage rings are already operating under heavy beam loading conditions. At KEK beam induced voltages comparable to operation gradients are reached (5MV/m at 12mA). It appears that operation conditions can become very sensitive to some parameters as e.g. the detuning of cavities which has to be carefully programmed during energy ramping.

Another subject of concern is a fast quench protection system which has to work with large beam loading, high accelerating fields and with a large klystron feeding a few cavities. The system should also permit an automatic return to operation after a cavity quench. At present operating accelerating fields are mainly limited by the trip rates of the interlock systems.

The very harsh environment of Beauty-factories combined with low \( Q_{ext} \) of input couplers increases the danger of cavity quenches with large power dissipations. Therefore it does not seem advisable to use Cu cavities with a thin layer of superconductor instead of solid Nb cavities.

3.2 High power input couplers

In the frequency range of 500MHz sc (and nc) cavities have been equipped predominantly with compact coaxial high power input couplers rather than with waveguide couplers [23]. In almost all cases warm rf-windows are used (Fig. 8).

In Table 3 a number of input coupler parameters and performances with sc cavities are listed. At room temperature processing CW power levels up to 300 kW have been reached [24], whereas the power transferred to the beam at LHe-conditions has not exceeded 60 kW. During (long term) operation in beams some window leaks have develop at KEK. At CERN and DESY one has not yet observed window failures with sc cavities. High power rf-windows are equipped with diagnostic systems including detectors for arcs, light, electron phenomena and anomalous temperature increases which can protect windows efficiently against failures.
Table 3 High power input coupler performances

<table>
<thead>
<tr>
<th></th>
<th>KEK</th>
<th>CERN</th>
<th>DESY</th>
<th>Karlsruhe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>508</td>
<td>352</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Type</td>
<td>coaxial</td>
<td>coaxial</td>
<td>coaxial</td>
<td>coaxial (transformer)</td>
</tr>
<tr>
<td>Window</td>
<td>planar</td>
<td>cylindrical</td>
<td>cylindrical</td>
<td>planar</td>
</tr>
<tr>
<td>Warm</td>
<td>warm</td>
<td>warm</td>
<td>warm</td>
<td>cold</td>
</tr>
<tr>
<td>CW power (kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- during processing at room temperature</td>
<td>200</td>
<td>50</td>
<td>100 (300)</td>
<td>100</td>
</tr>
<tr>
<td>- In beam</td>
<td>60</td>
<td>12</td>
<td>17</td>
<td>?</td>
</tr>
<tr>
<td>Failures</td>
<td>5 window leaks</td>
<td>none</td>
<td>none</td>
<td>window broken</td>
</tr>
</tbody>
</table>

3.3 Hom couplers

The development of hom couplers has been pushed vigorously in view of their applications for large e± storage rings and recirculating linacs [25]. They have allowed to combine the benefit of a very high shunt impedance for the fundamental mode with an adequate damping of hom. In Table 4 a few performances reached with hom couplers in sc cavities are given. Hom couplers have been located at the beginning at the cavity cells (eg. near the equator) but later on it was found more convenient to place them at the beam tubes of cavities.

Table 4 HOM coupler performances ($f_{hom} < 3 f_{RF}$)

<table>
<thead>
<tr>
<th></th>
<th>CERN</th>
<th>DESY</th>
<th>Karlsruhe</th>
<th>CEBAF</th>
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<tr>
<td>Frequency (MHz)</td>
<td>352</td>
<td>500</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>Number of cells</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Type of hom</td>
<td>compact</td>
<td>compact</td>
<td>compact</td>
<td>waveguide</td>
</tr>
<tr>
<td>Typical $Q_{ext}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for hom coupler located at:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Beam tube</td>
<td>$10^4$-$10^6$</td>
<td>$10^3$-$10^4$</td>
<td>-</td>
<td>$300$-$10^4$</td>
</tr>
<tr>
<td>- Cell</td>
<td>$10^4$-$5.10^6$</td>
<td>-</td>
<td>$300$-$10^4$</td>
<td>-</td>
</tr>
<tr>
<td>Power (W)</td>
<td>&lt; 200</td>
<td>~ 1000</td>
<td>&lt; 1000</td>
<td>~ 1</td>
</tr>
</tbody>
</table>
In the frequency range of 500 MHz one prefers (as for input couplers) compact horn couplers (Fig. 9) equipped with filters for rejecting the fundamental mode rather than big waveguide couplers. At higher frequencies waveguide couplers located at the beam tubes are in use at CEBAF (Fig. 10).

The present horn couplers fail by a large amount to fulfill the requirements of Beauty-factories i.e. $Q_{ext}$ for all horn below 100 and power levels of many kW. This is the reason why a new cavity concept without horn couplers has been proposed at Cornell.

4. COSTS

Industry has been associated at various degrees to the development, construction and installation of the sc cavity systems in HERA, LEP and TRISTAN. Therefore the costs of large sc systems can be estimated with some confidence. We have taken into account particularly the costs of the LEP system because of a few special aspects:

- The upgrading of LEP needs a large number of cavities: 192 sc cavities with a total active length of 326m.
- The fabrication order has been divided amongst 3 manufacturers in different countries (D, F, I).
- CERN has developed cavities, cryostats and all auxiliaries so that a system with proven performances existed prior to tendering.
- Firms had full support from CERN for a detailed transfer of know-how for all manufacturing steps.
- Costs have been rechecked after a one year construction period.

The LEP system uses a layout where four 4-cell, 352 MHz Nb-cavities ($l = 1.7m$) are integrated in one independent cryomodule of 10 m length.

The following steps and items are included in the cost estimation:

- Fabrication and surface treatments of cavities
- Nb-material.
- He-vessel, piping, cold shields, superinsulation.
- Vacuum vessel.
- Tuner systems
- One input coupler per cavity.
- Two horn couplers per cavity.
- Vacuum components (pumps, valves, ...).
- Assembly under clean conditions.
- Cabling.
- Warm and cold rf-measurements (individual and in cryomodule)
- Transport and installation.
Fig. 9 A compact horn coupler for the HERA electron ring designed for currents up to 60mA. The coupler is an all welded Nb version with LHe cooling.

For the Beauty-factory system we assume 500MHz, monocell, Nb cavities with a 500 kW, waveguide input coupler and with external horn absorbers. Each cavity is housed inside an independent cryostat of ~1.5m length [Fig. 2]. The cost estimate includes all items given above and amounts to ~180 k$/unit. The distribution of costs is approximately:

- Cavity: 20%
- Cryostat: 35%
- Couplers and tuners: 14%
- Others: 31%

We have also tried to give a cost estimate of nc cavity systems for Beauty-factories. We assume monocell copper cavities at 476 MHz, 1 MV accelerating voltage, 120 kW wall losses, one high power coaxial input coupler and three horn waveguide couplers with rf-loads. The costs include also fixed and mobile tuners, vacuum components, a cooling system and handling and installation equipment.

The cost per unit are 160 k$ and are comparable to the ones of sc systems.
Beauty-factories will use large RF systems based presumably on 500 MHz, 1 MW, CW klystrons feeding a few cavities. A cost estimation has to include:

- 1 klystron.
- 1 circulator.
- Mains and HT-power supply.
- RF power distribution system.
- Low power rf-system.
- Controls and interlocks.

- Installation.

We have estimated 1.5 M$ per 1 MW klystron system.

An overall efficiency (klystron and transmission) of 60% is assumed.

CERN has ordered during the last years a few large cryogenic systems for an operating temperature of 4.2K. From these orders a cost formula has been derived [26].

\[ C = 0.7 \left( P_{\text{cryo}}^{0.5} + 0.5 P_{\text{cryo}} + 0.5 \right) \]  

(C in M$; P_{\text{cryo}} \text{ in kW}; P_{\text{cryo}} > 1 kW; T = 4.2K)
This estimation includes a basic control system but not the costs for He-storage and cold He transfer lines. We note also that the overall technical efficiency of large 4,2K systems is expected to be 0,4%.

With an efficiency of 60% the mains power needed for one 1MW-klystron is 1,7MW. The mains power for the complete cryogenic systems remains well below this value (Table 5 and 6). As a consequence the operating costs of a Beauty-factory are dominated by the rf-system. Assuming 4000h of operation during 5 years the operating costs are comparable to the investment costs of the rf-system.

5. COMPARISONS

For the comparison of nc and sc accelerating systems for Beauty-factories we assume two different but typical high energy ring (HER) layouts.

Low accelerating voltage  High accelerating voltage
E = 9 GeV  E = 8 GeV
V_{acc} = 18,5 MV  V_{acc} = 45 MV
E_{acc} = 4,2 MV/m  E_{acc} ≤ 10 MV/m
i_b = 1,4 A  i_b = 0,9 A
P_b = 5,8 MW  P_b = 5,4 MW
σ_z = 10 mm  σ_z = 8 mm

In the case of sc cavities we have also compared layouts for different accelerating fields of cavities.

The following additional assumptions have been made:

- The number of cavities has been obtained from the total accelerating voltage and the cavity gradients, irrespective of the input coupler power.
- The cryogenic power levels differ only by about 15% for the different gradients of sc cavities. Therefore we have assumed for all cases a constant power including a reserve of about 100%.
- The assumed number of klystrons may have to be changed for a specific layout of cavities; we have tried to keep the number to a minimum.

In Table 1 a few important parameters of nc and sc cavities are compared. In Table 5 and 6 comparisons are made for the two Beauty-factories rings mentioned above.

Sc cavities at high gradients have as expected an advantage with regard to the total k_{hom}, R_{sh/Q} and W_{st} for the fundamental mode. This advantage is more pronounced for the ring with large accelerating voltage. Investment and operating costs are dominated by the rf-system; this is also found for the sc system despite the additional cryogenic system.

For sc cavities a comparison is made for different accelerating fields. The important parameter k_{hom} stays below 50% of the nc case for gradients between 10 and 7MV/m. Lower gradients lead to k_{hom}-values comparable to the nc versions. The total R_{sh/Q} values remain for all gradients considered much below the values of the nc cavities. Costs increase by not more than 10% for gradients between 10 and 7MV/m. Operation costs are almost not influenced by the gradients.

Similar differences, although less pronounced are found for low energy rings.

6. CONCLUSION

At present there are already a few large sc accelerating systems operated in large e^± storage rings. Their frequency range and power requirements are comparable to the ones needed for Beauty-factories. The advantages which have led to the choice of sc cavities are similar for the case of Beauty-factories: higher CW accelerating fields and higher efficiencies.

An additional overwhelming argument for Beauty-factories is that the use of sc cavities can decrease
Table 5 - Comparison of nc and sc cavities for HER

\[ V_{\text{acc}} = 18.5 \text{ MV} \]

<table>
<thead>
<tr>
<th></th>
<th>NC</th>
<th>SC</th>
<th>NC</th>
<th>SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{acc}} ) (MV/m)</td>
<td>4.2</td>
<td>10</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>( V_{\text{acc}}/\text{cavity} ) (MV)</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>number of cavities</td>
<td>20</td>
<td>6</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>power at input coupler (kW)</td>
<td>422</td>
<td>1000</td>
<td>580</td>
<td>500</td>
</tr>
<tr>
<td>number of 1MW - klystrons</td>
<td>9</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total cryogenic power* at 4.2K (kW)</td>
<td>-</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Total mains power for cryogenics (MW)</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Total ( k_{\text{hom}} ) (V/pC) including tapers**</td>
<td>6.8</td>
<td>1.8</td>
<td>3</td>
<td>3.6</td>
</tr>
<tr>
<td>Total ( R_{\text{sh}}/Q ) of fundamental (Ohm)</td>
<td>2400</td>
<td>270</td>
<td>450</td>
<td>540</td>
</tr>
<tr>
<td>Costs (M$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* CAVITIES</td>
<td>3.2</td>
<td>1.1</td>
<td>1.8</td>
<td>2.2</td>
</tr>
<tr>
<td>* RF</td>
<td>13.5</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>* Cryogenics</td>
<td>-</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Total investments (M$)</td>
<td>16.7</td>
<td>11.9</td>
<td>12.6</td>
<td>13.0</td>
</tr>
</tbody>
</table>

* 100% reserve; ** 3 monocells grouped.

substantially impedances, in particular the hom impedances responsible for multibunch instabilities.

It turns out that the unit costs of nc and sc cavities are comparable and that the total investment costs are largely dominated by the rf generator systems. Similarly the major contribution to operating costs comes from the rf-systems, exceeding by far the operation costs of the cryogenic systems for sc cavities.

Therefore the higher efficiency of sc cavities can lead to a substantial cost reduction. The advantages of sc cavities are particularly evident at higher luminosities where short bunches and large accelerating voltages are needed.

However, presently the operation of sc cavities in large storage rings is hampered by the fact that operation gradients do not reach the values obtained in cavity tests without beams. Gradients are limited at 4 to 5
Table 6 Comparison of nc and sc cavities for HER

\[ V_{\text{acc}} = 45 \text{ MV} \]

<table>
<thead>
<tr>
<th></th>
<th>nc</th>
<th>sc</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{acc}}) (MV/m)</td>
<td>4,2</td>
<td>10</td>
</tr>
<tr>
<td>(V_{\text{acc}}/\text{cavity}) (MV)</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>45</td>
<td>15</td>
</tr>
<tr>
<td>Power of input coupler (kW)</td>
<td>246</td>
<td>373</td>
</tr>
<tr>
<td>Number of 1 MW - klystrons</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Total cryogenic power* at 4.2K (kW)</td>
<td>-</td>
<td>3,6</td>
</tr>
<tr>
<td>Total mains power for cryogenics (MW)</td>
<td>-</td>
<td>0,9</td>
</tr>
<tr>
<td>Total (k_{\text{hom}}) (V/pC) including tapers**</td>
<td>16,6</td>
<td>5,1</td>
</tr>
<tr>
<td>Total ((R_{\text{sh}}/Q)) of fundamental (Ohm)</td>
<td>5400</td>
<td>675</td>
</tr>
<tr>
<td>Costs (M$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* CAVITIES</td>
<td>7,2</td>
<td>2,7</td>
</tr>
<tr>
<td>RF</td>
<td>16,5</td>
<td>9</td>
</tr>
<tr>
<td>Cryogenics</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Total investments (M$)</td>
<td>23,7</td>
<td>14,7</td>
</tr>
</tbody>
</table>

*: 100% reserve; **: 3 monocells grouped.

MV/m and depend in a very sensitive way on beam loading and beam stability.

High trip rates of interlock and protection systems are amongst the main limiting factors for higher gradient tests without beams. The planned operation of sc cavities at high currents in CESR, Cornell and SPS, CERN will be extremely useful for studying operation conditions approaching the ones of Beauty-factories. A closer look into the choice of acceleration gradients for sc cavities in Beauty-factories reveals that hom losses remain below 50% of the "nc" values even for a gradient of 7 MV/m and that costs increase only by about 10% in going from 10 to 7 MV/m.

Considering the much larger beam currents and the strong radiation environment of Beauty-factories it seems therefore advisable to keep operation gradients below 10 MV/m. Lower gradients would also alleviate the problem of high power levels for the input couplers.
A great challenge for sc (and nc) cavities remains the achievement of sufficiently low $Q_{ext}$ for all horn. The development of a sc "monomode" cavity with external absorbers is a very interesting alternative.

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REFERENCES

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