Application of Superconducting Cavities to the Collider Rings of the SSC

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Abstract

The rf parameters of the SSC collider rings are briefly characterized by 20 MV peak rf voltage, 3.9 MeV acceleration per turn, and 2 MW rf power per ring at a multiple of the 60-MHz bunch frequency of the proton beam injector. 360 or 480 MHz are preferred frequency choices. In the reference design, a normalconducting accelerating structure is foreseen which would operate with gradients of typically 1 MV/m. In contrast to this, superconducting cavities can generate fields of 5 MV/m, or possibly more. In combination with a low R/Q-value, the total stored energy in the rf structure could be increased by an order of magnitude. This would help to reduce the undesired effects of transient beam loading, of rf generator noise, and of imperfections in the generator feedforward current, resulting in reduced phase modulation of the particle bunches at the collision area. For 70 mA circulating beam current, eight superconducting single-cell cavities would be required per ring, instead of 32 to 40 single-cell normalconducting cavities. The savings in tunnel space, and a lower coupling impedance would allow a later upgrade of the beam current to and beyond 200 mA, if desired, for a higher collider luminosity.

I. INTRODUCTION

The SSC collider rings have to raise the energy of the injected beams from 2 to 20 TeV, maintain the tight bunching during collisions, and compensate for energy losses by synchrotron radiation /1,2/. The maximum radiation loss will be of the order of 0.12 MeV per turn; it will practically not influence the overall rf power requirements.

The SSC injector scenario is based on a regular bunch spacing of 5 m. A multiple of 60 MHz must therefore be chosen for the layout of the rf systems of the SSC collider rings. The 360-MHz rf system of PEP has served as guide. Other multiples of 60 MHz, between 240 and 480 MHz, may also be considered if they offer technical advantages.

480 MHz, for example, would mean that cw power amplifiers similar to the 500-MHz klystrons developed for DESY could be used. On the other hand, 360-MHz and 352-MHz cw klystrons are in operation at PEP and LEP, respectively.

The acceleration cycle of the SSC collider rings is nearly 25 minutes long, requiring about 3.9 MeV energy gain per turn. The rf power transmitted to each of the 70 mA beams will be about 275 kW, the peak rf voltage 6.6 MV, bucket area approximately 3.3 eV-s. The particles circulate with a frequency of 3.44 kHz on the 87120 m long machine circumference.

In the storage mode the rf peak voltage has to be raised to 20 MV, corresponding to a bucket area of about 18.3 eV-s. The rms bunch length is kept to 6 cm. Each of the 70-mA beams requires about 1.4 MVA reactive power from the rf power source, and 8.8 kW real power for covering the synchrotron radiation losses. For reasons of beam stability, the accelerating cavities will not be detuned.

If PEP-type cavities (5-cell units) are chosen, their number per ring would be eight /2/. Approximately 1 MW per ring would be required for covering the cavity losses at 20 MV total peak rf voltage. Each cell would operate at 0.5 MV, corresponding to an average gradient of 1.2 MV/m. At this gradient, the power loss in each cell is 25 kW.

II. CHOOSING SINGLE-CELL CAVITIES

In addition to the reference cavity design, three alternatives have so far been considered: (a) normalconducting single cells, (b) superconducting single cells, and (c) superconducting multicell cavities. The main reasons for considering alternatives are higher-order mode damping, and options to increase the collider current, if neccessary, at a later stage.

It was felt that HOM damping in normal- and in superconducting structures would be easier with single cells /3/.

The power handling limits of rf input couplers cause additional restrictions on the number of cells per unit. For example, a superconducting 4-cell structure of LEP would create a peak voltage of 8.3 MV, with an average gradient of 5 MV/m. The power transmitted to a 70 mA beam would then be approximately 600 kVA. This surpasses the practical limit of the input coupler, which is considered to be of the order of 200 kVA /4/. Average gradients of 5 MV/m in superconducting structures are operational values in LEP II- and HERA-cavities /5-7/. These 360-MHz and 500-MHz structures are in large-scale production. Copper cavities with sputtered niobium surfaces can be operated with even higher gradients, e.g. up to 10 MV/m.

If we assume for the SSC eight superconducting single-cell cavities per ring, the required 20 MV peak rf voltage could be achieved with an average gradient of 6 MV/m, and each power coupler would have to transmit 175 kVA to the beam.

In the following, we will discuss the advantages and disadvantages of superconducting and normalconducting cavities in a somewhat more elaborate manner.

III. NORMALCONDUCTING SINGLE CELLS

High-field, normalconducting single-cell resonators are in operation at CERN to accelerate e+/e- beams in the SPS; their frequency is 200 MHz /8/. The Daresbury photon source uses a 500-MHz electroformed cavity of similar (pillbox) shape /9/. The most attractive example for the SSC is the 352- MHz cavity shown in Fig.1. This pillbox-type cavity will be used for the Advanced Photon Source (APS) at Argonne. Eighteen cavities will be constructed A prototype is under test /10/. B-factories (high-luminosity e+e- colliders) also require single-cell cavities due to the relatively high circulating beam currents /11,12/. Typical rf system requirements are: (a) lowest possible number of cavities to achieve the desired voltage,

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(b) minimaum higher-order impedance, (c) compact length, etc., resulting in high gradients (up to 3-5 MV/m). This can be realized either with specially designed, low-impedance conventional cavities, or with superconducting cavities /12/. Limits are set (1) by vacuum windows to transmit 1 or 0.5 MW cw power, and (2) -for room temperature cavities- by cooling the surface of the ellipsoidal, almost spherical cavities. The cooling problem does not exist with superconducting cavities.

A severe concern with high-current machines are coupled multibunch instabilities, which are driven by narrow, resonant higher-order modes of the rf cavities. Such instabilities may require extraordinarily powerful feedback systems if they cannot be avoided by adequate HOM dampers on the cavities.

IV. SUPERCONDUCTING SINGLE CELLS

A typical case for the application of superconducting single-cell resonators is the 400-MHz rf system for the Large Hadron Collider of CERN. The LHC is a high-energy collider (max. 2 x 7.7 TeV for protons) for currents up to 0.85 A per beam /13,14/. The (ellipsoidal) cavity shape is sketched in Fig. 2.

Another example is the 500-MHz rf system for the Cornell B-Factory /15,16/. The cavities have a shape similar to Fig. 2 but a much larger specially formed beam tube for HOM damping, and are designed for 500 kW input power. Three ceramic disk windows are inserted as vacuum windows in an external rectangular waveguide.

Generally, for normalconducting as well as superconducting cavities, the rf power coupler is one of the most critical items for reliable operation. Windows are manufactured for klystrons with cw output levels up to 1.1 MW (e.g., as required by LEP). It must be emphasized, however, that the operation conditions are different for couplers placed inside accelerating cavities. A klystron output coupler usually transmits rf power at a low standing wave ratio which is ensured whenever necessary by the insertion of a ferrite circulator. Input couplers for accelerating cavities, however, must be designed for practically infinite VSWR. The transmission of 1 MW into a matched load is equivalent, in terms of maximum voltage and maximum current, to the transmission of 250 kW forward power to a purely reactive load.

Couplers for superconducting cavities must also limit the heat flow into the cryostat. The same applies for HOM couplers. As to power input couplers, development efforts at CERN /17/, DESY, KEK and other laboratories suggest that 200 kW may be considered, at this stage, a limit for reliable operation /4,7/.

Superconducting cavities have an unloaded Q in excess of 10^9. Thus, the bandwidth of an unloaded 360-MHz cavity would be below 0.4 Hz. The operational bandwidth can be trimmed to higher values by stronger coupling. Typically, a factor beta = 1000 would bring the bandwidth in our case to a desirable value for stable beam operation.

Cavity tuning can be accomplished, as shown on LEP 4-cell cavities, by small changes of the cell length. Three Ni tubes outside the He vessel are equipped with magnetostrictive devices. In addition, slow tuning can be achieved by small temperature changes of the tubes /18/.

Cryostat and cryosystem: The need of cryostats and of a cryosystem (4.5 K LHe) is a definite disadvantage for superconducting cavities. Some differences from cryostats for superconducting magnets should be mentioned, however: the cold masses are well below one ton, and quenches will be nondestructive since the stored energy is below 100 J; the rf power can instantly be switched off. The cavities have to be protected

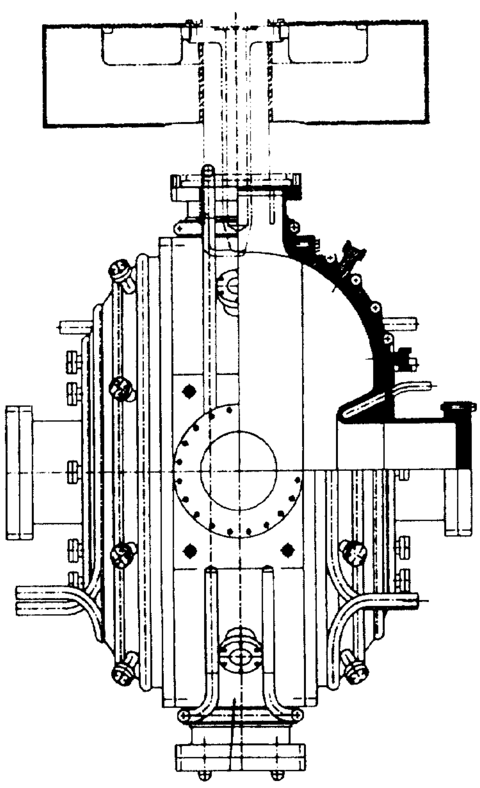

Fig. 1. Cavity for the ANL Advanced Photon Source /10/. Test voltage 1 MV at 352 MHz cw operation.

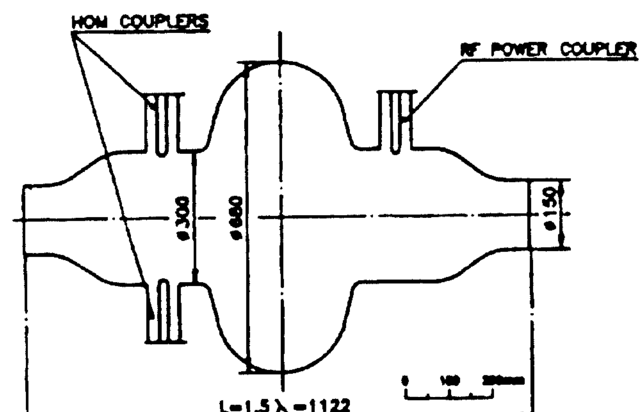

Fig. 2. Shape of the 400-MHz single-cell cavity proposed for LHC /14/. Trapped HOM's are 470 and 542 MHz (transverse), and 706 MHz (longitudinal).

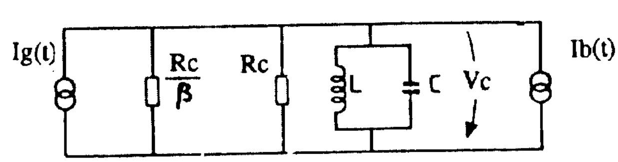

Fig. 3. Equivalent circuit of a cavity with beam. Generator and beam currents Ig(t), Ib(t), cavity voltage Vc and resistance Rc, coupling factor beta.

against overpressures of about 3 bar /7/. According to experience gained with HERA cavities, using a separate cryosystem for rf cavities will increase reliability /4,7/. Assembly and joining has to be done either with cavities under vacuum or with slight overpressure, and under clean, dust-free conditions.

V. TRANSIENT BEAM LOADING AND FEEDFORWARD

Transient beam loading of the collider rf cavities occurs during filling, acceleration as well as storage of beams. Only a precise cancellation of beam-induced voltages can maintain cavity amplitudes and phases at correct values, i.e. avoid nontolerable phase excursions of the rf signals and consequently of the bunches which otherwise would shift the collision point(s) of the beams. The lumped circuit shown in Fig. 3 with generator current Ig(t) and beam current Ib(t) will operate at constant voltage and phase only as long as (sudden) changes of beam current, ΔIb, will be answered by simultanous changes ΔIg of the generator current such that ΔIg(t) = -ΔIb(t). Practically, this can be done only with limited accuracy in amplitude, phase and time. The system can be stabilized /14, 21, 22/ by measuring Ib(t) and feeding a correction signal with minimum (ideally zero) time difference forward to the rf amplifier. Remainig oscillations must be damped by feedback.

It is important to remember that the speed of phase excursions is proportional to R/Q and Ib, and inversely proportional to the cavity voltage Vc. Bunch phase excursions should stay below three degree. Superconducting cavities have relatively low R/Q values, e.g., about 40 ohm compared to about 150 ohm for normalconducting cavities; they also can operate at much higher voltage. Consequently, the critical beam current will be an order of magnitude higher.

VI. SPACE REQUIREMENTS

A string of 32 normalconducting single cells (360 MHz), with 2λ spacing, occupies 54.5 m straight-section length /19/. The same space could be used for 24 to 32 cryostats of superconducting cells. The space for UHV pumps is included. In case of an upgrade of the collider current by a factor 3, the use of superconducting cavities would not need extra space.

VII. POWER DISTRIBUTION

The output levels of the individual rf power sources may be chosen to be between 250 kW and 1.1 MW. Individual feeding of cavities by dedicated power sources, as well as feeding of groups of cavities, via 3-db power splitters, is considered possible. Ferrite circulators will be necessary.

VIII. COMMENTS ON COST

Cost studies for normalconducting and superconducting extensions of the 800-MeV LAMPF proton linac have revealed a slight advantage (-5%) for a 400-MHz superconducting structure /20/. The CERN tender results for 20 LEP cavities (1989) were used for a consolidated estimate. The cryoplant (for 10 W/m rf losses and 10 W/m stand-by losses) was included..

IX. CONCLUSIONS

Although normalconducting single-cell cavities are a good solution to fulfill the rf requirements of the SSC main rings for the specified current of 70 mA, any upgrade of the collider current up to and beyond 200 mA requires a closer look at the potential application of superconducting single-cell cavities to reduce the total coupling impedance, bunch phase modulation and space requirements. Precise feedforward control of the rf power delivered to the beams will be required.

X. ACKNOWLEDGEMENTS

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