RF Systems Engineering for the SSC Collider Rings

G. Schaffer, P. D. Coleman, R. E. Mustaine, J. D. Wallace, X. Q. Wang, Y. Zhao, J. D. Rogers
Superconducting Supercollider Laboratory*
2550 Beckleymeade Ave., Dallas, TX 75237 USA

Abstract

Acceleration and storage of 70-mA proton beams in the 2 x 20 TeV Supercollider rings can be performed both with normalconducting as well as superconducting 360-MHz rf systems. A normalconducting accelerating structure would use 32 or 24 single-cell cavities per ring, operating with a mean gradient of 2 - 2.6 MV/m to generate the required peak voltage of 20 MV in the beam holding mode. Superconducting cavities would allow operation with mean gradients up to about 5 MV/m, and tolerate higher transient beam loading due to nearly tenfold larger stored energy in the accelerating structure. A superconducting structure could consist of five pairs of single-cell resonators per ring, each pair being fed by a 250-kW cw klystron amplifier. The use of 500-kW or 250-kW klystron amplifiers, six or eight per ring, would seem appropriate for feeding normalconducting structures. Provisions for feedforward and feedback (rf amplitude and phase) are included in the low-level rf system. Furthermore, active damping of undesired modes and corrections of bunch phase deviations are planned by means of auxiliary (broadband) rf systems.

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 synchrotron radiation losses (of the order of 0.12 MeV/turn). The bunch spacing is chosen to be 5 m, leading to a bunch frequency of 60 MHz. For the collider rings, 360 MHz has been chosen as the most convenient rf frequency [1,2,3].

The beam acceleration in the rings takes nearly 25 minutes, requiring about 3.6 MeV energy gain per turn. The rf power transmitted to each of the 70 mA beams will be about 267 kW, the peak rf voltage at injection is 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 circuference.

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 rf power, and 8.8 kW real power for covering the synchrotron radiation losses.

Instead of using 5-cell cavities as proposed in the baseline design, single-cell cavities will be used for beam acceleration. The reason for this change is easier damping of undesired resonant modes as outlined in references [2] and [3].

In the following, we describe some details of technical solutions which are based on either using normalconducting or superconducting cavities. Both options appear feasible and have their specific merits. Using superconducting cavities is more complex but attractive for handling transient beam loading [3,4,5]. Preliminary results of cost studies indicate lower costs for a system based on superconducting cavities [6].

II. REDUNDANCY IN THE RF POWER SYSTEM

The baseline design suggests the use of two 1.1-MW klystron amplifiers per ring to cover the rf power required for eight 5-cell cavities (i.e., 40 cells) in each ring. This amount of rf power would also be sufficient for 32 normalconducting single cells per ring, and there is no concern about the reliability and lifetime of 1.1-MW klystrons as they are used in great numbers at CERN for LEP I (their average life is reported to be 17000 hrs so far [7]). However, any failure in a cavity group of a nature which would enforce an interrupt would inevitably lead to a loss of the stored beam. It would therefore seem to be an advantage for the collider operation if the number of rf power units would at least be doubled. In this case the use of klystrons similar to the PEP design [8] could be considered.

A further reduction of the number of single cells per ring to 24 would lead to a 6 x 500-kW layout of the rf power part whereby each klystron amplifier feeds 4 cavities. We show a corresponding diagram in Fig.1. The system may include one or two spare amplifier units which can be switched into any other channel via a series of 13 waveguide switches.

III. KLYSTRON GALLERY LOCATION AND LAYOUT

The preferred location of the klystron gallery is on ground level. This facilitates swift access for maintenance work, and reduces overall cost for rf buildings and cooling plants. The rf equipment would occupy a ground floor for the klystrons, HV rectifiers, and local controls, and a basement for waveguides (WR 2300), circulators, power splitters, dummy loads, and cooling water distribution.

A possible layout of the ground floor is shown in Fig. 2. An annex may be added to this floor and used for any cavity testing and improvement work while the collider is operating. The standby klystron(s) could be used for this purpose.

The distance between ground level and beam paths is approximately 58 m. Straight waveguide runs in 2-m shafts from the basement to the beam tunnel sidewall, followed by rainbow-shaped shielded entrance arcs to an enlarged portion of the beam tunnel would transport the rf power down to the power splitters and cavities in the tunnel as shown in Fig.3.

The lengths of the waveguide runs add to the group delay which limits the maximum loop gain in the case of fast feedback. The analysis shows that the total group delay is still acceptable [9].

IV. KLYSTRONS

High-power CW klystron amplifiers for frequencies near 360 MHz have been produced by commercial manufacturers and by SLAC. The power levels range from 125 kW (SPEAR II, 1975) to 500 kW (PEP, 1980-) [8], to 1.1 MW (LEP I, 1989-) and 1.3 MW (LEP II, to be operational end of 1994).

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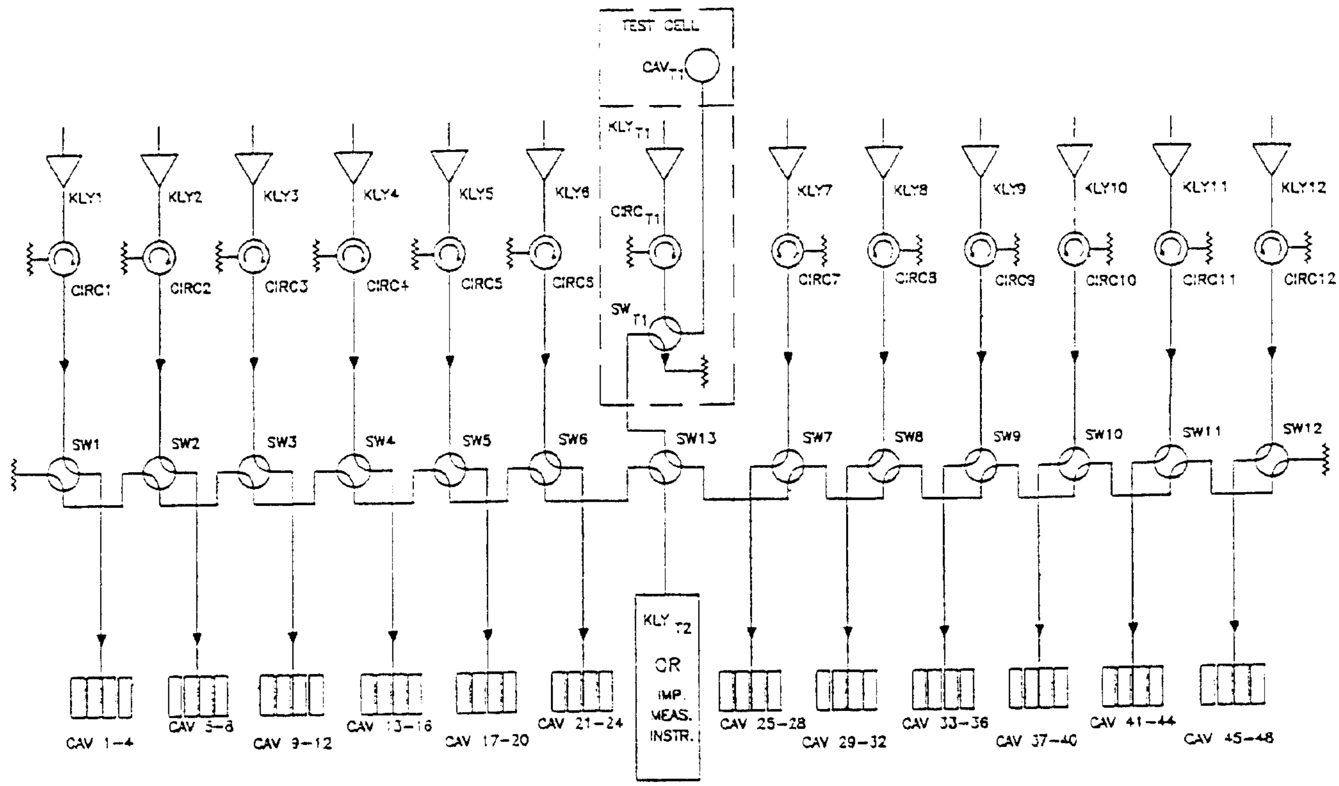

Fig. 1. RF switching system for 2 x 6 klystrons (500kW) with 1 or 2 spares.

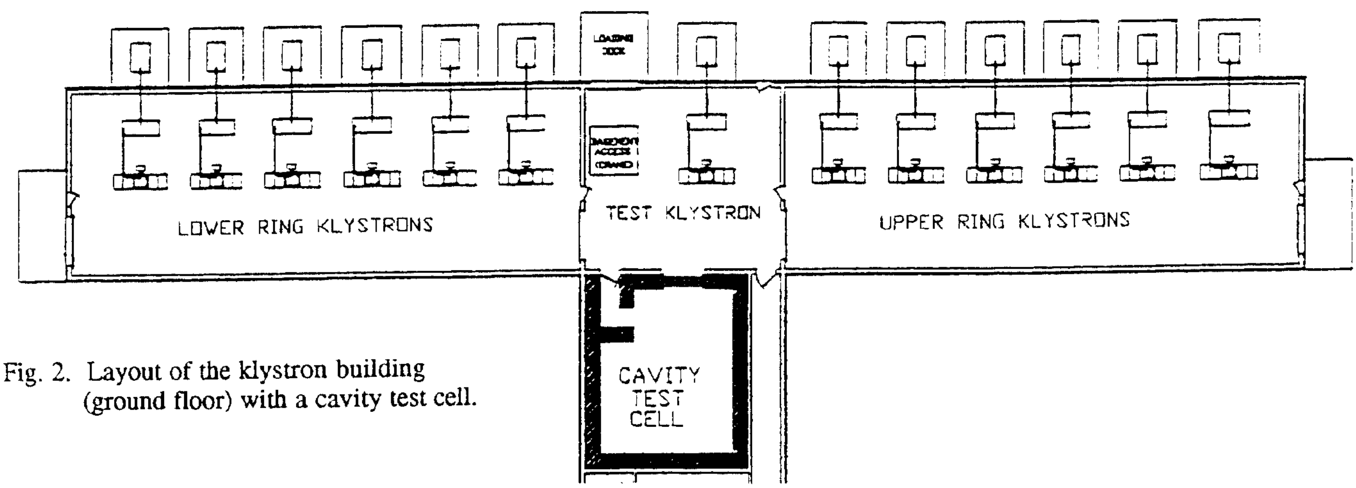

Fig. 2. Layout of the klystron building (ground floor) with a cavity test cell.

Typical klystron beam voltages are 35 kV (for 125 kW), 50 kV (for 250 kW), and 65 kV (for 500 kW). These values permit the use of air-insulated guns. Oil insulation of other HV components inside the klystron building can also be avoided.

Klystron output windows require protection against excessive reflected power. Ferrite circulators will be used (see Fig.1).

Klystron damages due to sudden beam- or body current rise will be prevented either by crowbar discharge circuits or by application of high-power pulse-step modulators [10].

V. NORMALCONDUCTING SINGLE CELL CAVITIES

A system using 24 single-cell cavities and six klystrons per ring (as shown in Fig.1) would require the installation of a total of twelve magic T's, twenty four 3-db hybrids, and 36 balancing absorbers in a larger beam tunnel section for proper power splitting. Part of the installation is sketched in Fig.3.

A modular cavity-to-cavity distance of 1.5 wavelengths has been chosen. This distance permits the insertion of ion pumps between adjacent cavities. The 3-db hybrids supply counterphase signals to their cavities. Each subsequent cavity pair is excited by inversely oriented coupling loops to maintain the mode pattern. Installation length is 30 m per ring.

To supply 833 kV effective acceleration voltage per cavity requires an electric field of 2.6 MV/m if an ANL-APS type cavity [11] is chosen. At this (gap) gradient, the power loss per cell is 62 kW. Total losses for 2 x 24 cells are 3 MW.

In the case of 2 x 32 cells (and 2 x eight 250-kW klystrons) the loss per cell would be 35 kW, and the total 2.2 MW.

Highly efficient watercooling of the cavities is crucial.

VI. POWER COUPLERS AND HOM DAMPERS

Adjustable loop (or antenna-) couplers with waveguide-to-coax transitions and cylindrical alumina vacuum windows will be used for feeding power into normal- (or super-)conducting cavities. Power handling limit is estimated to be 200 kW [5].

At least two HOM couplers per cavity will be added, similar in design to the types used for CERN-LEP [12].

VII. SUPERCONDUCTING SINGLE CELL CAVITIES

The application of superconducting cavities has been discussed in various notes, reports and committees, see for instance ref. [2, 3, 5, 9]. Transient beam loading of the collider rf cavities during filling, acceleration and storage of beams is the main reason to consider cavities capable of operating at much higher voltages than regular copper cavities. Based on a mean fieldstrength of 5 MV/m, single-cell superconducting cavities would operate at about 2 MV effective acceleration voltage. A total of 2 x 5 pairs of cavities would be used for the SSC. They would occupy 2 x 17 m tunnel space. It is envisaged to put at least 2 cavities into one 4.5-K cryomodule, and to leave sufficient room between modules to install vacuum pumps. The (preferably separate) cryoplant has to cool about 700 W.

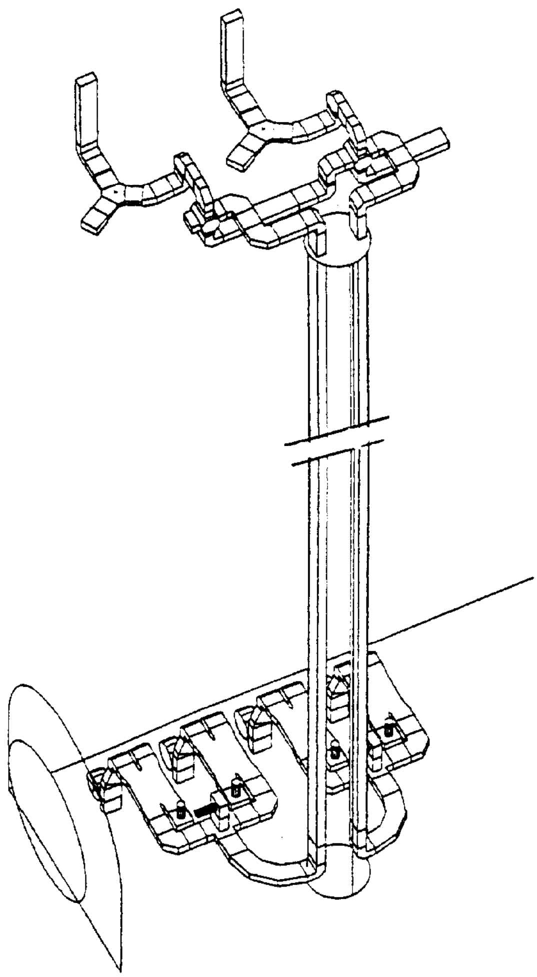

Fig. 3. Waveguide connection from two klystron outputs to two groups of normalconducting cavities in the beam tunnel. The length of the vertical shaft is approximately 55 m.

The cavity geometry will be similar to the LHC cavity under development at CERN [4]. The low R/Q value which is about 40 ohms versus 150 ohms for copper cavities, in combination with a 2.4-fold increase in cavity voltage, reduces the speed of phase excursions due to transient reactive beam loading by a factor 9. Higher loop gain is applicable for fast controls [4,9]. Furthermore, the cavity can supply reactive power to the beam in half-detuned operation. With a practical margin for linear klystron characteristics, the nominal klystron output power for a pair of cavities should be about 250 kW.

Critical issues for superconducting cavities are the "relative delicacy of the superconductive state, sensitivity to contamination, assembly complexity, complexity of cooling system, thermal isolation, vibration sensitivity. These properties have made themselves felt but are being overcome" (statement by M. Tigner in ref.[11]).

VIII. SUMMARY

At this point in time, two valid solutions are competing in how to achieve the best performance of the rf system for the SSC collider rings. More engineering work is required to complete the layout studies and to decide on the final choice.

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