Operating Experience with Superconducting Cavities in HERA

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Abstract

The RF system of the HERA e^- ring consists of 82 normal conducting and 16 superconducting 500 MHz cavities. By the end of 1993 16000 h of operating the superconducting system were completed. In that year typically 10 - 20 mA of beam current were handled during luminosity runs and up to 40 mA at machine studies. Early this year 900kW beam power was transferred by the superconducting cavity system. We report about operating experience of the superconducting cavity system with special emphasis on reliability and high beam current loading.

1. INTRODUCTION

The HERA e^- storage ring is equipped with 82 normal conducting (nc) and 16 superconducting (sc) resonators (both at 500 MHz). Two 800 kW klystrons and a system of 9 directional couplers and 6 magic Ts power the sc system. In order to operate HERA at 27.5 GeV a circumferential voltage of 125 MV and a beam power of 5.2 MW (at design current of 60 mA) has to be provided.

The 16 sc cavities are contained in 8 cryostats. One valve box supplies one cryostat with LHe at 4.3 K and GHe at 40/80 K. The cryogenic power of 1 kW at 4.3 K is delivered by the central HERA plant.

Detailed information of the sc system, the interlocks and the cryogenic installation is given in [1,2,3].

The sc cavity system was installed and put into operation during the year 1991. Beam current of typical 3 mA was accumulated at that time. The sc cavity system was successfully used to raise the HERA energy up to the design value of 30 GeV.

During 1992 regular operation of HERA with typical currents up to 12 mA was experienced. Because of the only moderate beam loading the sc cavities were operated at constant forward power of 300 kW, resulting in a circumferential voltage of 50 MV.

In 1993 the HERA beam current at luminosity runs was raised to 20 mA. Since September of that year the cavity vector-sum control was active to keep the cavity voltage constant under various beam-loading conditions. During machine shifts near to the end of 1993 beam currents of typical 30 mA and a maximum value of 40 mA could be reached.

At the beginning of the 1994 luminosity runs typical conditions were 25 mA at 27.5 GeV. The sc system provides up to 50 MV and beam power of 1 MW.
18000 hours of operation at 4.3 K and 21 warm up or cool down cycles were accumulated by the sc system up to now.

2 OPERATING EXPERIENCE

2.1 Operating Conditions

All cavities have been tested prior to installation and reached an accelerating gradient of 5 MV/m [1]. The quality factor was lower than the specified value of 2*10^9 due to the Hydrogen disease [4]. The degradation could be limited to about a factor of two by a fast cool down at the dangerous temperature around 100 K (formation of Niobium Hydride) [3]. The maximum usable gradient in the tunnel is limited to Eacc = 4 MV/m (= 78 MV circumferential voltage) because of these enhanced RF-losses.

The maximum RF power per cavity is restricted to 100 kW due to the power rating of the input coupler window. This power can be completely transferred to the beam because of the negligible cavity RF-losses. At the e^- design current of HERA (60 mA) this corresponds to a cavity gradient of 2 MV/m (synchrotron phase angle of 45°).

The superconducting cavities are cooled by the HERA refrigerator. The LHe and GHe is distributed by a separate cryogenic line [2]. Special care was taken to limit the maximum pressure at the cavities to be lower than 2 bar although the superconducting magnets might be operated at considerably higher pressure.

The operating condition of the sc-system is monitored and interlocks the operation of the klystron or the circulating beam.

2.2 Reliability Statistics

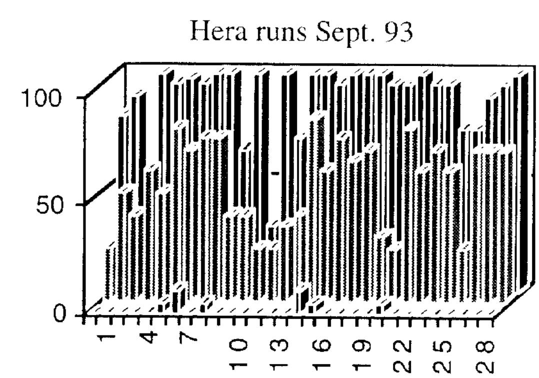

Figure 1: Statistics of beam loss due to sc-system trips (Sept. 93). Bars show (back to front): sc-system active time, beam on time, beam off time due to sc-system trips (in %).

The proper functioning of the sc-system is monitored and interlocks the klystron or beam current. The major circuits are:

- monitor of input coupler by:
  - current pick up in the coaxial coupler line
  - light detector in coaxial coupler line
- monitor of coupler window by:
  - light detector at ceramics
  - infrared temperature sensor at ceramics
- HOM coupler line by:
  - temperature sensor at coaxial line
- quench in cavity by:
  - pressure in LHe circuit

- cryogenic system by:
  several level and pressure sensors

If the klystron is tripped the beam current is lost in most cases because of the substantial loss of circumferential voltage or because of the uncompensated impedance of a sc cavity. The recovery time is typically some minutes.

In case of a cryogenic interlock the klystron is switched off and all cavities are tuned to a minimum impedance position (tuning between machine lines to eliminate power transfer from the beam to the cavity). In such a case the beam is lost too.

During a quench in a cavity, the pressure is increased from 1.05 to about 1.3 bar and some liters of LHe are lost. The typical recovering time is 20 minutes. If for some reason the pressure in the cavity system increases above 1.5 bar, safety valves are opened. If the pressure increases further to above 2 bar, burst discs (one per cryostat) are activated. In this case the cryostat has to be emptied from LHe (6 hours), the disc has to be replaced (1 hour) and the cryostat has to be refilled (1 hour). During more than three years of operation of the sc-system this event happened three times. In all cases it was caused by errors in the logic of the computer control system.

In Fig. 1 the typical operating statistics of the sc-system is displayed (September 1993). The three bars show the percentage of

- RF voltage in sc cavities
- e- beam in HERA
- beam off time due to interlock trips of the sc-system

In the last case the time is counted from the beam loss until successful injection in HERA again. The data shown are typical for the operation during the 1993 luminosity runs.

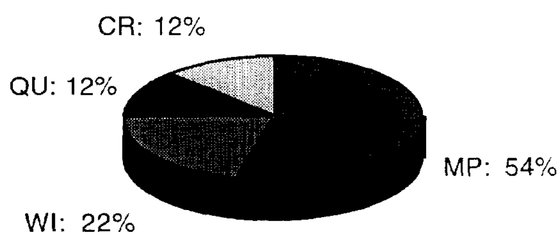

Figure 2: Reasons for interlock trips in the sc-system summarized over the 1993 luminosity runs (in total 67 trips).

Fig. 2 shows the relative contribution of

- multipacting in the input coupler (mp)
- problems at the window (wi)
- quench in a cavity (qu)
- problems with cryogenics (cr)

as reason for interlock trips (summarized over the 1993 luminosity runs). More than 50 % of the interlock trips are caused by multipacting in the coupler.

2.3 Multipacting in Input Coupler

The dominant reason for trips in the sc-system is multipacting in the coaxial input coupler line (see Fig. 2). Multipacting is observed by detection of charged particles at the outer coax line (by a pick up probe) or by light seen through a window by a photo multiplier. Multipacting occurs at definite values of the forward RF power under total reflective conditions. Recently these multipacting phenomena have been described by single surface trajectories (at the outer conductor) at the location of the maximum electric field [5].

The occurrence of multipacting can be suppressed by RF processing, i.e. by RF operation at the threshold field. Pulse processing is more effective than cw operation. In HERA the sixteen cavities were typically processed up to 1.2 MW at pulse length of 6 msec (rep. rate 100 Hz). After cool down the processing time is 10 hours for the whole system. It turned out that multipacting reappears after operation for 8 weeks. Then a short processing of 3 hours is sufficient to suppress multipacting again.

The current detector switches off the klystron for values above 10 μA within 1 msec. It has been observed that during such an event several kW of RF power is absorbed in the coupling line. To avoid damage of the coupler by this power a klystron shut off is necessary. For the future it is foreseen to coat the copper surface by Ti or TiN to reduce the secondary yield and thus to avoid mutipacting.

2.4 Beam Loading at Injection

During injection only a few MV of circumferential voltage is needed. A high transfer efficiency needs a large over voltage ratio so that the synchrotron phase is very small (about 87°). If the phase adjustment of a cavity is not better than this value, a negative synchrotron phase might be established. Under those conditions the beam will deliver RF-power to the cavity rather than taking energy out of the cavity. This can also happen in a normal conducting system, but here the cavity impedance is about a factor of 10 smaller than in the superconducting case. For example at Ib = 27 mA, Pcavity = 30 kW and a synchrotron phase angle of 98° the amount of 50 kW is induced by the beam. This power will travel backward in the RF distribution system and load the absorbers at the magic T or the directional coupler. During the 1993 luminosity run several coaxial connectors in the line from magic T to the absorber were damaged and had to be exchanged. We believe that beam induced power during injection destroyed those connectors. Careful adjustment of the sc-cavity phasing and regular checking of the synchrotron phase helps to avoid this problem.

2.5 Beam Loading at High Energies

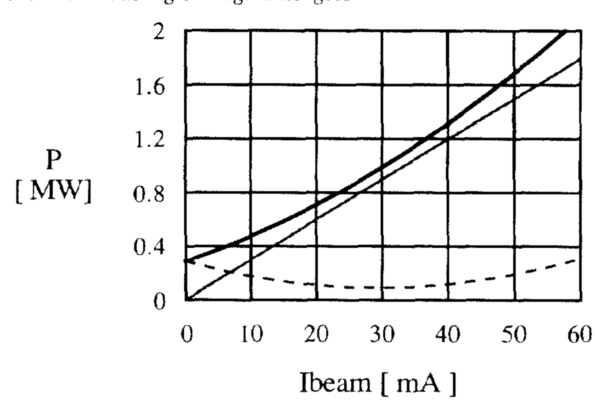

Figure 3: Forward power (upper curve), beam power (middle curve) and reflected power (lower curve) of the sc-system with vector voltage control (40 MV)

At high energy (26.7 GeV) the sc-system is operated up to 50 MV and at a synchrotron phase angle of 45°. The vector voltage control raises the klystron power to keep the cavity voltage constant. At the beginning of a luminosity run with high beam current typically 1 MW of klystron power is transferred to the sc cavity system. Fig. 3 shows the klystron forward power, the reflected power and transferred beam power for different current values. It can be seen, that there is a broad optimum of power transfer. The maximum efficiency (klystron to beam power) is 92 %. 8 % RF power is lost in the WR1600 wave guide system. For comparison the best value for the nc system is 50 %.

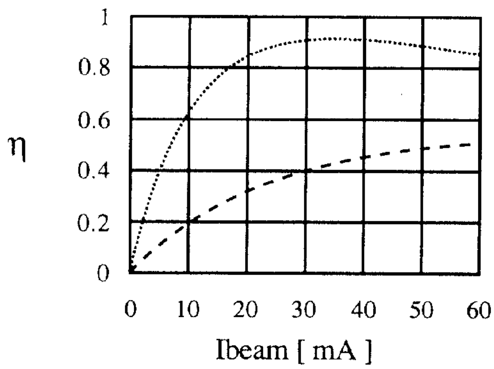

Fig. 4: Efficiency (beam power/forward power) of the sc-(upper curve) and the nc system(lower curve) in HERA.

2.6 High Power Distribution

The RF power of two klystrons (maximum 1.6 MW) is transferred into the tunnel by WR1600 wave guide. Four cavities are directly coupled to the main line via directional couplers. The other 12 cavities are fed by a 3 dB magic T. The balanced arm of the T is connected to a 100 kW coaxial absorber; the input line is powered by a directional coupler in the main line. This distribution system is balanced in the sense that there is no power in the absorbers (at the magic Ts or the directional couplers) for equally performing cavities. All reflected power is transferred back to the circulator at the klystron. If two neighboring cavities behave differently, however, the distribution system is unbalanced and problems might arise. Two cases of unbalance are described which happened during the operation in HERA.

2.6.1 Two cavities have different Qext values

One cavity was adjusted with a stronger coupling value in order to establish a lower gradient. In a frequency sweep the high Q cavity shows a slightly distorted resonance curve. The low Q cavity has a considerable dip at the resonance maximum. As consequence the low Q cavity will be tuned to an incorrect resonance frequency (because the cavity frequency loop locks to the maximum field). This will lead to a wrong phase setting of this cavity and might result in tuning problems especially during injection (see sect. 2.4). The reason for the distortion of the resonance curve is a modulation of the forward power by reflection at the magic T absorber (power reflection is 6 %).

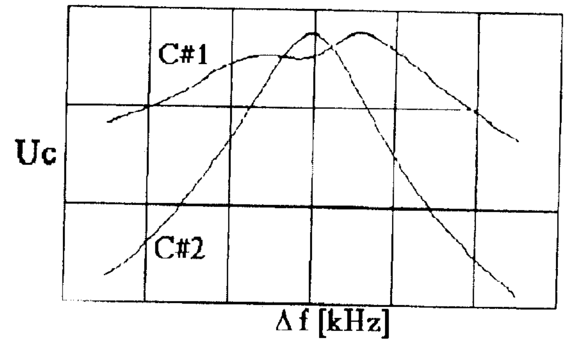

Fig. 5: Measurement of the distorted cavity transmission curve. Cavity 1 with low Qext, cavity 2 with high Qext.

2.6.2 One cavity is out of tune

It happened that one cavity was operated out of resonance due to erroneous behavior of the tuning control loop. The reflection coefficient of this cavity is different by 180° as compared to the well tuned cavities. The reflected power of this cavity will induce power in the absorber of the directional coupler. In the worst case this power is as high as four times the reflected value (by vector addition of the reflective waves) so that unexpected high power loading of this absorber will occur.

3. ACKNOWLEDGMENT

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