© 1989 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

LONG-TERM TEST OF A LEP PROTOTYPE SUPERCONDUCTING CAVITY IN THE CERN SPS

D. Boussard, G. Cavallari, H.P. Kindermann, G. Passardi, R. Stierlin,
J. Tückmantel and W. Weingarten
CERN, European Organization for Nuclear Research, Geneva, Switzerland

Introduction

After the commissioning of the LEP e^+e^- collider at CERN, its energy will be upgraded by adding superconducting (s.c.) r.f. cavities. Obviously, there is a great incentive to test a prototype s.c. LEP cavity in one of CERN's existing accelerators, before a production in series of a large number of cavities (256) be launched. Such a test should prove the validity and the long-term reliability of the design in a real accelerator environment. The SPS proton accelerator/proton-antiproton collider/LEP injector was chosen for the implementation of the cavity, being at present CERN's largest accelerator. As a result the whole experiment (comprising cavity, cryostat, refrigerator and r.f. system, installed in the tunnel about 60 m below ground) had to be remotely controlled from the accelerator surface buildings, in order not to interfere with the physics program.

As long as a refrigerator was not yet delivered (during the first phase of the experiment) we used a 100 m long flexible He transfer line for cooldown with dewars located at the surface. Later on a cold box was installed 6 m off the cryostat, the compressor and control unit being placed in a surface building.

For the operation of the SPS as a proton accelerator at high intensity ($I_{d.c.}$ = 0.2 A), on magnetic cycles interleaved with cycles for lepton acceleration, the impedance of the s.c. cavity had to be reduced by several orders of magnitude. This was achieved by damping the cavity's fundamental passband mode impedances by an r.f. feedback including the tetrode power amplifier driving the cavity [1,2].

Experimental results

Long-term performance of the s.c. cavity

In total, during the last two years, the cavity has undergone 20 cooldowns, three in its vertical cryostat equipped with temperature mapping diagnostics, 17 in its horizontal cryostat. The total accumulated time of the cavity at 4.5 K amounts to 8000 h, 6500 h in the SPS accelerator. Since the final chemical treatment of the surface, before the third cold test, the cavity was rinsed, the coupler and gate valves were mounted, the cavity was pumped, and never again exposed to atmospheric pressure. Up till now, after 17 cooldowns, none of the vital accessories (higher order mode couplers, pick up probes, power coupler, tuners) failed. Only once a Pt thermometer, by which the temperature of one of the Ni bars (thermal tuner) is controlled, was damaged and had to be replaced by opening a part of the vacuum tank, the cryostat not being moved or disconnected from the accelerator beam tubes.

All results on the maximum accelerating field E_a^{max} and the Q-value obtained so far for the cavity in its horizontal cryostat are visualized in fig. 1. In particular (a) describes the location of the test, (b) gives the status of the SPS accelerator (FT = fixed target, $p\bar{p}$ = proton-antiproton collider operation), (c) indicates the temperature of the cavity and the number of cold test (e.g. no. 4 corresponds to the first test in the horizontal cryostat), (d) exhibits E_a^{max} and (e) the Q value at E_a = 5 MV/m, the design field.

We conclude, that within the test interval E_a^{max} remained unchanged and is identical (7.1 MV/m, fig. 2) within errors to E_a^{max} from the laboratory test (7.3 MV/m [1]). After each cooldown from room temperature some r.f. conditioning (~ hours) is necessary to pass a multipactor threshold (inducing quenches) at E_a = 5 MV/m. In any case E_a^{max} could be raised beyond the design value (dashed line) without major problems.

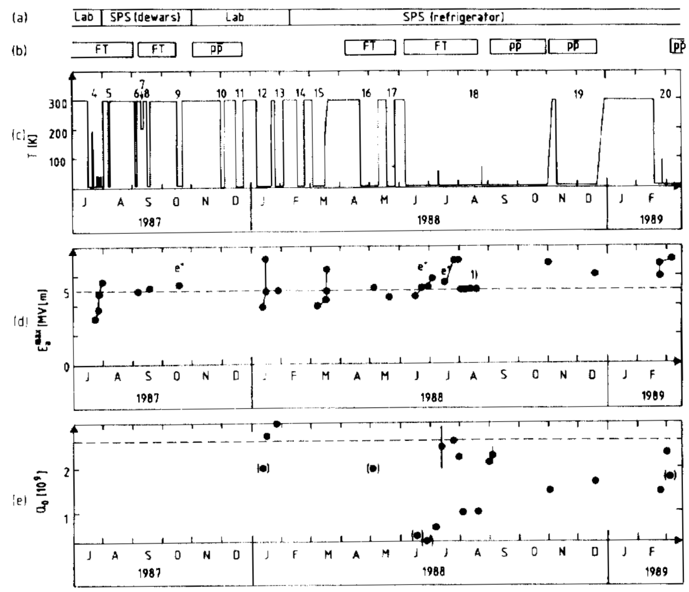

Fig. 1 - Long-term performances of cavity. Symbols: E_a^{max} during conditioning (connected •), acceleration test (e^+), long-term test at 5 MV/m (l), estimated Q-value or Q at $E_a \neq$ 5 MV/m (•). The error bars indicate the typical variation of the measurement error.

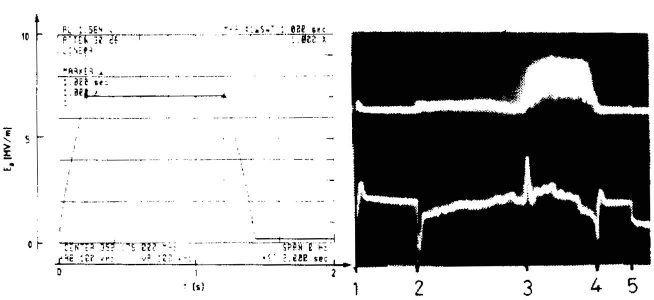

Fig. 2 E_a^{max} (left) and r.f. drive and phase error signal to tuner (right). 1/5 = r.f. on/off, 2 = e^+ injection, 3/4 = high field on/off (.1 s/div.).

On the contrary, the Q value at 5 MV/m shows a large scatter. On the average, for the tests in the SPS, it is lower than the design value $Q_o = 3 \times 10^9$ (dashed line). This observation can be explained by the following. For reasons of convenience of the mechanical design and economy only the static homogeneous ambient magnetic field is compensated. The calculated average value of the residual field at the surface of the cavity is 6 µT. However, the field inhomogeneities, adjustment errors, slowly varying magnetic fields with time from cycling magnets, bus bars (80 µT), stray fields of tuner bars (1 mT) may be trapped in the moment of transition to the superconducting state during cooldown or quench recovery. For instance, the lowest Q value ($(6 \div 8) \times 10^8$) was induced by a quench of the cavity when the magneto- strictive tuner was excited. Warming up the cavity beyond the critical temperature and cooling down again restored the Q-value to 2.8×10^9 at 5 MV/m.

CH2669-0/89/0000-1783$01.00©1989 IEEE

An interlock installed recently cuts the magnetostrictive tuner current in the moment of a quench in about 20 ms. Omitting these occasional magnetic field induced degradations the Q-value (5 MV/m) amounts to $2 \div 3 \times 10^9$.

Another test objective is the assessment of the accelerator vacuum conditions in view of the large pumping speed of the s.c. cavity surface. In order to tackle this problem, a companion experiment was conducted in the laboratory on a LEP type cavity in a horizontal cryostat equipped with one beam tube, by which definite amounts of gas were injected. Its Q_o (E_a) dependence was studied for different exposures of the residual gas composition typical for the SPS accelerator ($H_2 : H_2O : CO : CO_2$ = 69% : 17% : 8% :6%). The results were: (a) up to one monolayer equivalent gas exposure (assuming a perfectly smooth surface and a typical molecular diameter of 1.7 Å) does not affect Q_o and E_a^{max} (near the design values of LEP type cavities); (b) between one and five monolayers the low field Q-value remains the same, the high field Q-value (5 MV/m) is lowered by e^- loading [3].

Under operating conditions the average residual pressure in the sector of the SPS which houses the s.c. cavity is $1\text{-}3 \times 10^{-10}$ mbar. The cavity is pumped by two 25 ℓ/s ion pumps connected to one beam tube, and a 500 ℓ/s ion pump immediately behind the gate valve. No precaution was taken against a potential transport of charged dust particles along the accelerator vacuum tube.

After two months at 4.5 K, the total amount of absorbed gas was 0.34 mbarℓ (not corrected for the vacuum gauge sensitivity for the different gas species), corresponding to 0.05 monolayer. On the occasion of warming up the cryostat the different gas species showed up with increasing temperature (fig. 3), giving at hand an independent method to evaluate the quantity of absorbed gas confirming the above result. In summary, for the residual gas pressure of the SPS and one monolayer equivalent gas exposure as an upper tolerable limit, the cavity can most likely be kept at 4.5 K without degradation for a period of ~ 3 years.

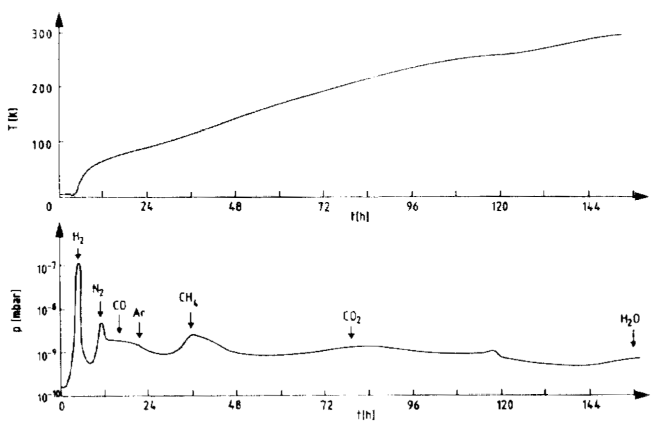

Fig. 3 - Cavity pressure (beam valves open) during warm-up.

The γ radiation measured by an ionization chamber (fig. 4) in the vicinity of the cryostat is another diagnostic tool of the long-term performance. Comparing data from today and two years ago shows that they can be represented by a common relation.

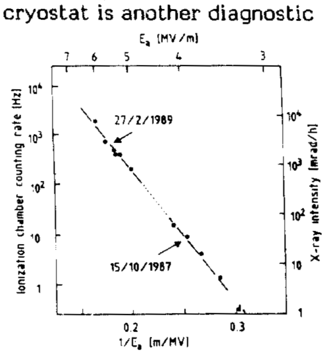

Fig. 4 - Signal of ionization chamber underneath cryostat.

The cryogenic system

The cooling power for the s.c. cavity is provided by a Sulzer TCF20 refrigerator [4]. Long-term behaviour of the plant is presented in fig. 5 where the available refrigerator power (at 4.5 K) and the measured "free" power available for r.f. (i.e. the refrigerator power minus the sum of the static loads due to cryostat, He transfer system and to a He liquefaction of 0.2 g/s for shields and thermal tuners) are plotted as a function of the operating period. The accumulated running hours at 4.5 K for the refrigerator and the cavity is also indicated. The system has been operated almost continuously with two long interruptions in March/April 1988 (refrigerator control problems due to r.f. induced electrical noise) and January/February 1989 (refrigerator maintenance).

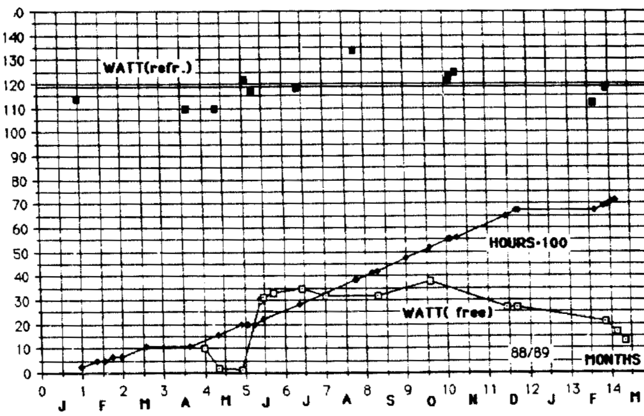

Fig. 5 - Long-term refrigerating system cooling power.

The average cooling power at 4.5 K of the refrigerator is 119 W. The cryostat heat input in liquid phase (level at nominal value) has remained constant with time at 25 W. The maximum achieved "free" power is about 35 W (June to October 1988) corresponding to a total static load of 84 W. During the initial phase of the experiment (May 1988) the "free" power dropped to almost 0 W and was restored to its maximum value after warming up the transfer line and cryostat and repumping their insulation vacua.

To study the origin of the total static losses we performed laboratory tests on a very similar cryostat [5]. Starting from the cryostat only equipped with the helium tank, we added one after the other the different components and measured the static losses (He tank with superinsulation (10.5 W), beam tubes (ϕ 15 cm, 6 W), power coupler (4.5 W), access holes for mechanical tuner (3 W), r.f. cables (1.8 W) = 25.8 W in total). Furthermore, the transfer line contribution (39 W) was determined by subtracting from the refrigerator power (119 W) the measured power (80 W) available at the transfer line terminals [4]. The total static heat load at 4.5 K from the measurements of the individual contributions is: 25.8 W (cryostat) + 20 W (equivalent to 0.2 g/s He liquefaction rate) + 39 W (transfer line) = 84.8 W in good agreement with the above value (84 W).

The liquid helium volume in the cryostat was controlled by an electrical heater to ± 0.5 l and the pressure was set to a stable value (± 5 mbar) by the compressor suction control. The refrigerator liquid helium supply valve and the sump gas return valve were adjusted to a position that no phase separation and helium level control were necessary in the cold box.

An important feature of the system is the constant entropy load for the refrigerator (i.e. the sum of cavity bath electrical heating and the total static load). The adopted system logic allowed determination of the Q value by the decrease of the heater power needed to keep the cavity level constant in case the r.f. power is switched on.

During the early (autumn 1987) cavity tests liquid helium was supplied from dewars at ground level by means of a 100 m long coaxial transfer line constructed from two previously used [6,7] 50 m long lines. In spite of the long distance and the very unfavourable geometry (60 m vertical, 30 m horizontal sections and inlet/outlet loops) the flow stability and level control [4] in the underground phase separator (especially built for the test) were satisfactory. Measured heat loads for mass flows in the range 0.9 to 1.6 g/s are ~ 13 W in the inner line (at 4.5 K) and 420 W in the return shield (the measurement includes a small contribution due to an intermediate connecting line). The shield temperatures during the test are 60 to 90 K at gas outlet with the inlet at 4.5 K.

The acceleration test

With the SPS operating in the interleaved mode, the positron beam (.28 mA) is accelerated on one of the lepton cycles (18 or 20 GeV flat-top level) using the new Standing Wave Cavities (SWC) [8].

For the s.c. cavity tests with beam, the s.c. cavity voltage was switched on long enough before positron injection so that the tuner transients have disappeared. However, the voltage was kept as low as possible (≈ few 100 kV) during injection and the early part of acceleration in order not to perturb the capture of long bunches ($\sigma_s \approx 16$ cm) from the CPS. Towards the end of the cycle the field in the cavity was rapidly (≈ 100 ms) pushed to the maximum (up to 5.5 MV/m with beam) thanks to the fast response of the r.f. feedback system.

To cope with an extremely high beam loading, especially at injection when the r.f. voltage is very low, the tuner circuitry measures the normalized reactive power [9] instead of the usual phase difference between cavity field and tube current. This results in a perfectly stable operation of the tuner (fig. 2) even under these unfavourable conditions.

An excessive level of drive power on the tetrodes switches off the reference r.f. voltage to the feedback circuit. This fast interlock is very convenient when the r.f. losses in the cavity increase very rapidly at the highest fields (quench, e^- loading).

An independent check of the cavity field was done by reducing the SWC voltage such that complete beam loss occurred on the magnetic field ramp. At the point of the loss the r.f. bucket shrinks to zero (stable phase $\phi_s = \pi/2$) and the total r.f. voltage can be calculated from the beam energy or bending magnetic field (B) and dB/dt. Putting the s.c. cavity in operation pushed the maximum energy higher (15 GeV/c → 18.8 GeV/c); from these values the s.c. cavity voltage was calculated to be 9 MV which corresponds to a field of 5.5 MV/m, in good agreement with the cavity antenna calibration.

The superconducting cavity was also operated for 12 h at a field of 5 MV/m for e^+ injection into the first octant of LEP during reconditioning of two SWC groups, after the exchange of a faulty vacuum bellows.

In case of failure of either the feedback circuitry or the power amplifier, the high intensity proton beam cannot be accelerated. Without feedback the cavity impedance is so high that all beam is lost just after transition. In this case, the cavity must be damped passively via its main coupler [5,10].

Field stability

To achieve the minimum impedance seen by the high intensity proton beam, r.f. feedback must have the highest possible open loop gain compatible with the usual stability requirements. In our case the electronic gain (approximately constant) is ultimately limited by the distance between the two closest cavity modes (351 and 352 MHz) [2]. As a result one can expect a very high degree of field stability in the s.c. cavity over a large frequency range. If we assume an ideal, noise free, reference voltage V_r, the fluctuations of the cavity field V_c are proportional to $V_c - V_r$, i.e. the error signal of the feedback loop. Knowing the electronic gain of the amplifier chain $V_c - V_r$ can be obtained by looking at the tetrode drive voltage. To discriminate amplitude and phase noise components, the fluctuation voltage $V_c - V_r$ is measured by a synchronous detection method. When the reference phase is changed by 90° one selects either the phase or the amplitude fluctuations.

Measurements were done at a relatively low CW field (2 MV/m, limited by the refrigerator "free" power) and with a moderate gain (open loop unity gain frequency ≈ 50 kHz). One obtains a r.m.s. phase noise of 4×10^{-4} in a 1 MHz bandwidth and 2×10^{-4} in 10 kHz. Amplitude noise is typically an order of magnitude lower ranging from 1.3×10^{-4} in a 1 MHz bandwidth down to 3.3×10^{-5} in 10 kHz. It should be emphasized that these values include also the effect of the amplitude and phase noise of the reference itself.

Low frequency phase fluctuations are primarily generated by mechanical vibrations of the cavity, which show up at for instance 51, 63 and 73 Hz in different signals (tetrode driver power, anode current, tuner phase detector, He pressure, accelerometer signal fixed at the He transfer line). It was found that these vibrations were the major source of field fluctuations in the cavity. They seem to be related to the liquid He evaporation rate. Their amplitude can be estimated by measuring the fluctuating anode current and were found to be of the order of 10 Hz [5].

Conclusion

By a s.c. LEP prototype cavity an e^+ beam was accelerated at $E_a = 5.5$ MV/m. After 8000 h at 4.5 K E_a^{max} remained unchanged (7.1 MV/m), the Q-value (5 MV/m) was $2 \div 3 \times 10^9$. No major system failure occurred. R.f. feedback guaranteed very low fluctuations of the cavity field amplitude and phase.

Acknowledgements

We thank all technicians involved in the continuation of the test for their untiring enthusiasm. The help of T. Linnecar was indispensable for the acceleration test. Last not least we thank Ph. Bernard, H. Lengeler and E. Picasso for their continuous interest and support.

References

[1] Ph. Bernard et al., CERN/EF 88-6 and Proc. EPAC, 7-11 June 1988, Rome, Italy.
[2] D. Boussard, H.P. Kindermann and V. Rossi, ibid ref. 1.
[3] W. Weingarten, XIIIth Int. Symp. Disch. Electr. Insul. Vac. 27-30 June 1988, Paris, France.
[4] G. Passardi et al. (in preparation).
[5] D. Boussard et al., CERN/EF/RF 88-3
[6] H. Blessing et al., Cryog. Eng. 27 (1982) 761.
[7] H. Blessing et al., Proc. 12th Int. Cryog. Eng. Conf., 12-15 July 1988, Southampton, UK, p. 222.
[8] P.E. Faugeras et al., this conference.
[9] F. Pedersen, IEEE Trans. Nucl. Sci. NS 32 (1985) 2138.
[10] E. Haebel, CERN/EF/RF 87-3.