TEST OF A 352 MHz SUPERCONDUCTING CAVITY IN THE CERN SPS

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Abstract

A prototype LEP superconducting cavity was installed in the SPS machine in order to gain experience with such a cavity in a real accelerator and also to provide more voltage for the SPS as LEP injector. In the initial experiments the cryostat was cooled down from the surface with dewars via a 100 m long flexible helium transfer line; for the final version a remotely controlled refrigerator has been installed in the tunnel, close to the cavity. The r.f. part is somewhat unusual because the cold cavity must not perturb the high intensity proton beam of the SPS; this is achieved using an r.f. feedback technique. Lepton beams were accelerated with the cavity, which showed no degradation of its performance as compared to the previous laboratory tests.

Introduction

Having in mind the upgrading of the electron positron collider LEP to centre of mass energies beyond 200 GeV by superconducting (s.c.) r.f. cavities, there is a great incentive to test a prototype cavity in the environment of an existing accelerator as for instance the CERN SPS. Such an experiment would give CERN its first opportunity to accelerate particles with a s.c. cavity. Although an early LEP prototype s.c. cavity has already been installed in the PETRA (DESY, Hamburg) beam line and used for acceleration of e^+e^- beams, this was only for a very short period [1]. It was felt that, before any operation in LEP can be considered, a long term test with beam should be attempted in order to accumulate experience with the cavity. In addition, all the ancillary and cryogenic equipment of the cavity (couplers, tuners, liquid helium transfer lines, refrigeration) could be tested for the first time under real operating conditions.

The SPS accelerator receives e^+e^- beams from the CPS and accelerates them up to 20 GeV/c with a series of copper r.f. cavities. With the additional voltage provided by the s.c. cavity, more safety margin for the operation of the room-temperature r.f. system could be obtained or, alternatively a somewhat higher injection energy into LEP could be envisaged. For either reason the increase of available r.f. voltage would be highly welcome.

However, the SPS is simultaneously exploited as a proton accelerator for fixed target physics: in fact proton and lepton accelerating cycles are interleaved in the 14.4 s long supercycle. The high intensity proton beam (more than 3.10^{13} protons per cycle, ≈ 0.2 A DC) accelerated to 450 GeV by the 200 MHz travelling wave r.f. system of the SPS would be made completely unstable by the very high impedance of the s.c. cavity on its fundamental accelerating mode. Therefore, a fast damping scheme (working on a cycle to cycle basis) for lowering the cavity impedance must be applied. Fortunately, the proton r.f. beam current around 352 MHz is relatively small (it does not coincide with any r.f. harmonics at 200, 400, 600 MHz) and therefore the power handling capability of the damping device remains modest [2].

Design of the cavity-cryostat unit

The cavity cryostat unit comprises the four-cell niobium cavity itself, with its stainless steel helium vessel welded around, the cryostat body [3] and the ancillary equipment: tuner [4], r.f. input coupler and higher order mode (HOM) suppressors [5] (c.f. also ref. [6]). The design of the unit was based on the following principles.

Cavity

- Rounded geometry and no openings on cells to avoid multipactoring and to reduce the risk of contamination.
- End cells designed such that for a "flat" accelerating mode the fundamental mode field be sufficiently low and the HOM fields be sufficiently high at the HOM coupler location ("multi mode end cell compensation" [7]).
- Small sensitivity to mechanical tolerances by a sufficiently high cell to cell coupling (1.8%).

Cryostat

- Small volume of helium vessel (200 ℓ) to meet safety requirements.
- High "filling factor" (ratio of active cavity length to total installed length of cryostat) approaching 2/3.
- Only welded joints between cavity vacuum and helium vessel and "Conflat" joints between cavity vacuum and cryostat vacuum.
- Vacuum vessel made from low cost materials (aluminium staves with stainless steel sheet wrapped around).
- Sufficiently rigid cavity support frame such that mechanical resonances be damped and/or appear beyond say 50 Hz.

Ancillary equipment

- Couplers on beam tubes which avoids additional openings in the cells.
- HOM suppressors and r.f. coupler in coaxial form to avoid large openings at the low frequency of 352 MHz.
- No mobile parts for the frequency tuner working at liquid helium temperatures and in vacuum.
- Room temperature r.f. window of the LEP type for the power coupler.
- Easy access to sensitive components (feedthroughs, r.f. connectors etc.).

Cavity tuning is achieved by axial deformation using three symmetrical nickel bars parallel to the cavity axis. Temperature control of the bars gives a slow response but a large tuning range, whereas the magnetrostrictive effect on the nickel bars permits a fast control of the cavity tune. The measured performance of the tuner device are given in table 1.

Table 1 - Performance of the tuner device

Thermal tuner	Speed $\Delta f_o/\Delta t$ at nominal He mass flow (0.1 g/s)	10 Hz/s
	Δf_o^{max}	50 kHz
Magneto-strictive tuner	Speed $\Delta f_o/\Delta t$	20 kHz/s
	Δf_o^{max}	2 kHz

At the operating liquid He level (HOM coupler immersed), the measured standby heat load of the cryostat amounts to 25 W. This figure decreases at a lower liquid He level (15 W). The beam tubes, radiation shields, tuner coils and r.f. coupler are actively cooled by 0.1 g/s He gas flow; a second independent He gas flow of 0.02 - 0.1 g/s cools the tuner bars.

The HOM couplers designed for LEP operation are more than adequate for lepton acceleration in the SPS, as here the e^+e^- beam current is much smaller. However, the high intensity proton beam might become unstable on the lowest longitudinal modes around 640 MHz. It was therefore decided to slightly modify the LEP design to achieve better damping around these modes at the expense of the higher part of the HOM spectrum. The results are summarized on table 2.

Table 2 - Most prominent higher-order modes

R/Q [Ω] (cf. ref. [5]	f [MHz]	Mode	Q_{ext} (meas.) [10^3]
108	639	TM011	13
46	636	TM011	8
26	689	TM111	18
~ 23	1003	TM012	25

The r.f. system

Power requirements

The r.f. system is used to damp actively the cavity during proton acceleration. This is achieved by an r.f. feedback circuity whose function is to inject into the cavity (via the power amplifier) an r.f. current which just cancels that of the proton beam. At 352 MHz and within the 1 MHz bandwidth of the feedback system, the latter amounts to 10 mA at most [8]. Therefore, the r.f. generator should be capable to deliver, at the cavity accelerating gap, the opposite r.f. current I = 10 mA during proton acceleration.

With the same cavity to amplifier coupling (no moving parts!) it should also provide the V = 10 MV gap voltage for e^+e^- acceleration (max. beam load = 5 kW). These requirements are summarized on table 3; they can be met by an amplifier having a capability P = VI/8 [8] = 12.5 kW, if optimum coupling is chosen. In fact we chose a cavity to amplifier coupling stronger than optimum, in order to permit a better passive damping of the cavity. As a result the required power increased to 50 kW. In all cases, most of the power delivered by the generator is reflected by the cavity into the amplifier. This precludes the use of a klystron amplifier unless a (costly) circulator is inserted between amplifier and cavity. A tetrode amplifier which can operate in a stable way, even with high reflection, is much better suited for our application. In the companion paper [8], a complete description of the amplifier (50 kW tetrode TH571B, Thomson) and its coupling to the cavity is given.

Table 3 - The various operating conditions of the s.c. cavity

		E_a [MV/m]	V [MV]	I [mA]	P [kW]
1	Conditioning of cavity	6	10	10^{-5}	10^{-1}
2	$e^{\pm}$acceleration	6	10	1	5
3	p compensation	0	0	10	0

P = Power delivered to cavity.

Damping by r.f. feedback

The cavity accelerating voltage is monitored by one of the cavity probes. That signal is fed back into the r.f. amplifier. For a high enough open loop gain the feedback system generates an accelerating voltage which is a replica of the reference r.f. voltage V_{ref}. During proton acceleration V_{ref} is set to zero, which corresponds ideally to V = 0 and therefore a zero impedance seen by the beam. For e^+e^- acceleration, V_{ref} is programmed to the desired field value: the feedback circuit automatically generates the required tetrode drive to obtain the field in the cavity. Conditioning the cavity could also be done in the normal way (no feedback).

As usual in feedback systems, stability conditions determine the maximum open loop gain, and hence the performance of the system. In the case of a single isolated resonance, the minimum impedance that can be achieved only depends on the geometric parameter of the cavity and the total time delay in the feedback loop [8], but not on the Q value of the cavity. Whether the cavity is warm or superconducting does not change the impedance seen by the beam; only the open loop gains at resonance are very different.

However, for the multicell LEP cavity special measures have to be taken to ensure simultameous stability for the four fundamental modes [8]. A solution has been found in which the π phase shift between the accelerating π mode (352 MHz) and its neighbour (3π/4 mode, 351 MHz) is corrected by the loop delay phase shift (180° for 500 ns). This gives a minimum impedance of ~ 300 kΩ [8], acceptable for proton operation. In case of a failure of the tetrode the cavity could also be damped by an external resistive load to the power coupler [9].

The Cryogenic System

The main problem for the cooling system is the unaccessibility of the cryostat during operation of the accelerator. The distance from the cavity in the SPS tunnel to the nearest accessible place is 100 m, of which 60 m are in vertical direction. During early tests in autumn 1987, liquid helium was provisionally supplied from a dewar station at ground level via a coaxial transfer line assembled from two existing flexible lines of a former CERN-ISR installation [10]. Liquid helium consumption was of the order of 2000 ℓ/day, a typical run lasted 3 days, cool-down and filling of the cryostat took between 7 and 10 hours. Since February 1988, a Sulzer TCF 20 helium refrigerator (measured capacity ~ 115 W at 4.5 K) is installed in the SPS tunnel close to the cavity; it is fed by a helium compressor (120 kW) on ground. The refrigerator is entirely remote-controlled; initial problems of the traditional measuring and control system in the presence of the high level of electro-magnetic noise in the accelerator environment were overcome by shielding and filtering of various sensors. The refrigeration power at the cryostat terminals was ~ 80 W. This means that after deduction of 25 W static heat load of the cryostat ~ 55 W were available for shield cooling and filling (or operation), corresponding to about 14 ℓ/h. This agreed with measurements in February 1988, but a degradation was observed in the meantime for reasons not yet understood.

Experimental results

Cavity cryostat unit

The fabrication and treatment of the cavity is described elsewhere [6]. First, in a vertical test, the cavity surface was checked by determining the maximum accelerating field and Q-values (table 4, N° 1 and fig. 1). As the design values for LEP (E_a = 5 MV/m, Q(5 MV/m) = 3 x 10^9) were surpassed, it was decided to weld the He vessel around the cavity. Only alcohol and water rinsing were applied to remove potential contaminations (a chemical polishing would have resulted in a surface of unknown performance). The cavity was then mounted in the horizontal cryostat and equipped with the power coupler. There was not enough time available for reconditioning the cavity; consequently, the maximum field was limited to 4.5 MV/m by quenches due to electron multipacting (N° 2). During a short period of access it was installed in the SPS accelerator (< 10^{-9} mbar vacuum at room temperature), the maximum accelerating field remaining constant (N° 3). Then the first acceleration test was performed (Oct. 87). For a prolonged conditioning the cavity was removed from the SPS, and the original field and Q-value were reconfirmed within measurement errors (N° 4 and fig. 1). Hence the performance of the cavity has remained unchanged. Afterwards, it was reinstalled in the SPS for a second time, the maximum accelerating field being at 6.5 MV/m (N° 5). The "technical" Q-value, determined by substitution of the r.f. losses by an electrical heater, was estimated to 2×10^9. The cavity vacuum had not been broken since test N° 2. The cryostat was cooled down 14 times with no significant change in cavity performance being observed. After each cooldown the cavity had to be reconditioned for a short time.

TABLE 4 - Cold tests in horizontal cryostat

No.	Place	Treat-ment(a)	E_a^{max} [MV/m]	Q_o (5MV/m) [10^9]	Field limit(b)
1(c)	Lab	CP, W	7.3	3.9	e^-(FE)
2	Lab	C_2H_5OH,W	4.5	-	e^-(MP)
3	SPS	-	4.4	-	"
4	Lab	-	7.2	3.4	P
5	SPS	-	6.5	2(d)	P

(a) CP = Chemical polishing.
W = Water rinsing.
C_2H_5OH = Alcohol rinsing.

(b) e^- (FE) = Field emission electron loading.
e^- (MP) = Multipactor electron loading.
P = Power rating of some component.

(c) Laboratory test without power coupler.

(d) Estimated value.

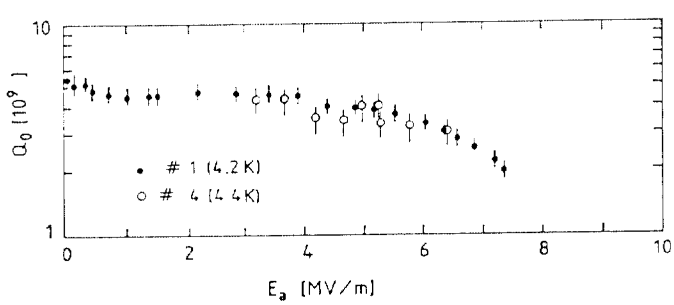

Fig. 1 Q-value vs. accelerating field.

Radio Frequency equipment

The r.f. system with its complicated, very high gain, feedback circuitry needed careful implementation (i.e. filtering out of the HOM signals at the feedback input, r.f. damping of the long DC feeder lines of the tetrode) in order to minimize parasitic couplings. With these precautions taken, r.f. feedback worked very smoothly on the high intensity proton beam, with non critical gain and phase adjustments.

If a failure of the feedback occurs when the high intensity proton beam is being accelerated, a violent dipole instability develops in a few ms resulting in a complete beam loss and very high voltages being induced in the cavity and the tetrode (the "crowbar" protection usually fires at this occasion). A safety interlock is now installed which dumps the proton beam in case of amplifier failure and prevents any damage to the cavity or amplifier.

As a result of r.f. feedback, the field in the cavity is controlled (in amplitude and phase) with an exceptional accuracy. The first measurements indicated a field stability of the order of 10^{-4}. Monitoring the tetrode drive signal is useful to properly set the tuner circuitry (minimum drive). In addition, it shows directly the fast cavity losses (bursts of electrons presumably) for a given stabilized field level. The field stability mentioned above seems to be related to these fast losses. The maximum field controlled by r.f. feedback was 5.5 MV/m.

Tests with beam

Positrons are accelerated in the SPS using the 200 MHz r.f. systems (travelling wave cavities and/or new single cell cavities [11]), locked on a subharmonic of the fixed LEP r.f. frequency (352.209 MHz). The s.c. cavity with r.f. feedback was driven by the LEP frequency transmitted over 1.5 km. The field was established in the cavity prior to e^+ injection to make the tuner lock properly, but at a very low level ($\simeq$ 100 kV). The r.f. voltage in the cavity was raised to $\sim$ 5 MV during the ramp and that pushed the maximum energy of the SPS up to 18 GeV. Beam measurements confirmed the cavity field calibrations.

Conclusion

Up till now, no obvious sign of degradation of the cavity performance in an accelerator environment can be found. We successfully applied two methods of cooldown of the cryostat in the tunnel without having access to the accelerator: by a liquid He station at ground level and by a remote controlled cold box in the tunnel. Radio Frequency feedback proved to be a very efficient means to damp the cavity and to control the accelerating voltage. A tetrode amplifier without circulator was particularly suited to this mode of operation. Accelerating a positron beam proved the validity of the design of the whole system. Only the first results of the test, which is still underway, are reported here, certainly there is room for future improvements.

Acknowledgements

We like to thank E. Picasso, who proposed and supported this experiment. We also thank all the technicians of our groups for their untiring enthusiasm. The test with dewars would not have been possible without the vigorous help of the cryogenic group of EF division. Many thanks are due also to the people in the SPS division who enthusiastically supported the idea and provided most of the infrastructure.

References

[1] Ph. Bernard et al., Proc, Int. Conf. High Energy Acc. Fermilab, Batavia, Ill, USA, 11-16 August 1983.

[2] D. Boussard, CERN, SPS/ARF/Note 86-1.

[3] R. Stierlin, Proceedings 3rd Workshop RF-Superconductivity, Ed. K.W. Shepard, Argonne, Ill., USA (1987) p. 639.

[4] G. Cavallari et al., ibid. ref. [3], p. 565.

[5] G. Cavallari et al., ibid. ref. [3], p. 47.

[6] Ph. Bernard et al., this Conference.

[7] E. Haebel et al., Proceedings 2nd Workshop RF-Superconductivity, Ed. H. Lengeler, Geneva (1984), p. 281.

[8] D. Boussard et al., this Conference.

[9] E. Haebel, CERN/EF/RF 87-3.

[10] H. Blessing et al., to be presented at the 12th Int. Cryogen. Eng. Conf. 1988, Southampton, U.K.

[11] P.E. Faugeras et al., Proc. Particle Acc. Conf., Washington, USA, (1987).