EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — SL DIVISION

CERN-SL-2002-057 ECT

LEP Coupler… a Troubled Story of Success

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Abstract

LEP couplers were a success. 288 couplers have been used for years in LEP without even one serious failure. I will briefly resume the history of the development, the problems that appeared during tests and how all these problems were solved , turning the project into a brilliant success.

Geneva, Switzerland
December 2002

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LEP couplers were a success. 288 couplers have been used for years in LEP without even one serious failure. I will briefly resume the history of the development, the problems that appeared during tests and how all these problems were solved , turning the project into a brilliant success.

1 INTRODUCTION

This paper resumes the story of the development for the power coupler of the LEP superconducting cavities and gives some information about their installation and operation with the beam in the LEP machine. The development started at the end of the 70's, and more than 20 years of work are resumed in few pages. Only the main milestones and achievements will therefore be presented, while for all the details the reader can refer to the literature available [1-15 and references therein].

2 FIRST ATTEMPT: A MAGNETIC LOOP

In the beginning of the 80's the team working on superconducting RF at CERN felt the need to test the technology developed up to that moment by putting a cavity in a real accelerator, in view of demonstrating the feasibility of a superconducting RF system to be used in LEP. This was done in collaboration with DESY, and in 1983 a 5-cell 500 MHz cavity was installed in PETRA.

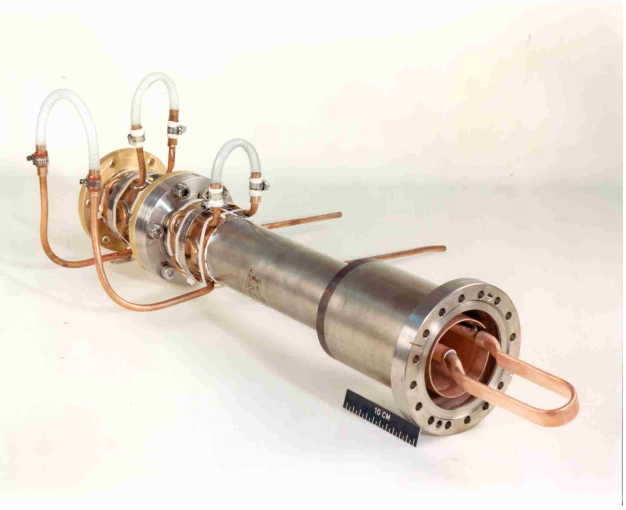

Fig. 1: The power coupler mounted on the 500 MHz cavity in PETRA

For this first attempt the power coupler was inspired to a typical coupler for warm cavities. The power coupler port was on the equator of the central cell, and the RF power was fed to the cavity by coupling with a loop to the magnetic field (fig. 1). In spite of a strategy that is very different from that of the couplers used nowadays, the performance was not bad: a beam was accelerated and 70 kW could be transferred to it [1]. Nevertheless, evidence of multipacting and field emission from the cavity suggested to eliminate all the ports on the cells, and to put all couplers for the fundamental mode and for Higher Order Modes (HOM) on the bore tubes at the two ends of the cavity (cut-off tubes).

3 THE 50Ω OPEN-ENDED COAXIAL COUPLER

Following the decision to put the coupler on the cut-off tubes where nearly no magnetic field exists, the coupling mechanism had to be changed from magnetic to electric. The new coupler, developed this time at 352 MHz[1], was a simple coaxial antenna, matched to a beam of 2 x 3.4 mAmps and to a cavity gradient of 6 MV/m, and had to be dimensioned to feed 60 kW in CW. The starting point for the design was the ceramic window already used for the power coupler of the warm copper cavities already operated in LEP [2]. This window sustained 60 kW CW with beam and was conditioned, in an off-line test stand, up to 180 kW. The conditioning process was straightforward on the warm LEP cavities, the full power was reached in few days and no harmful multipacting levels appeared during operation. Moreover the coupler maintained the conditioning even after long operation on the warm cavities in the LEP tunnel.

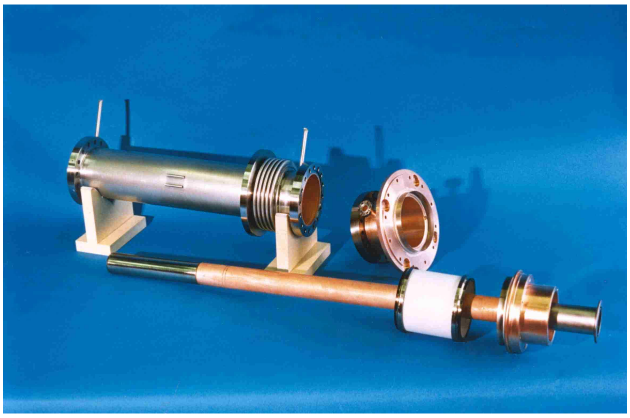

Fig. 2: The first version of the LEP power coupler.

The first coupler for the LEP superconducting cavities is shown in fig. 2. The ceramic window, made of Al_2O_3 of 97.5% purity, has an internal diameter of 103 mm. To match the impedance of the waveguide coming from the klystron the characteristic impedance for the coaxial line was chosen to be 50Ω, leading to a diameter of 44.8 mm for the inner conductor. The antenna was made of copper

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[1] The same frequency of the warm LEP RF system

with the ending part in niobium, the two materials being welded by Electron beam. The reason for that was to avoid projections of copper into the niobium cavity in case of arcing between the antenna and the external conductor. In the last version of the coupler (75Ω, fixed coupling) this niobium end was abandoned since there was never evidence of arcing in all tests done, even at power levels much higher than the nominal one.

The ceramic window was outside the cryostat and a separate extension of the outer conductor connected the cavity flange to the cryostat flange (fig. 2). This extension was double walled and cooled by Gaseous Helium (Ghe) to intercept the thermal flow from outside the cryostat and had to sustain a thermal gradient of ~300K along its length (53 cm). It was made from sheets of stainless steel rolled and welded. The internal side was copper plated (10 µm) to reduce RF losses. A thin layer of sputtered Ti (1µm) insured the adherence of Cu to the stainless steel.

The ceramic window was also coated with thin layers of Ti, to have a small electrical conductivity (10 µSiemens) between the two ends. The thin layer helps to evacuate the charges accumulated on the surface of the ceramic, to avoid a breakdown due to electrostatic discharge.

4 THE 50Ω VARIABLE COUPLER

This version was soon replaced by a variable coupler to cope with the changing specifications of the LEP beams. The current of the beams in the specifications was brought up to 2 x 7 mAmps, raising the nominal power to 120 kW and giving a Qext to match the beam of $1.9 \cdot 10^6$[3]. The margin to the known capabilities of the window used were therefore extremely reduced, and having a fixed coupling implied the risk of having to more forward RF power in case of a significant difference of the real value of the Qext from the nominal one.

The variable coupler was very similar to the fixed one: the characteristic impedance was 50Ω, and most of the components were unchanged. A sliding finger contact was inserted between the input and output conductor, and protected from high RF currents by a 25Ω choke folded inside the coupler itself. As we will see in the following, this choke was identified as one of the main sources of problems, but it was impossible to fold it out of the volume that was seeing the RF power because there was no room in the LEP tunnel for a λ/4 line in top of the coupler.

There were two big advantages in using a variable coupler:

- The possibility to compensate for any difference in the value of Qext on different cavities on the same klystron. In LEP each klystron fed eight cavities, so a spread in Qext corresponded to an equivalent spread in the accelerating field in the cavities.
- The design range in Qext of the variable coupler was $3 \cdot 10^9 \div 5 \cdot 10^5$. This allowed to measure Q(Eacc) even with the power coupler mounted, reducing the risk of surface pollution while mounting first a critically coupled antenna for the acceptance test, and then going in clean room to mount the power coupler.

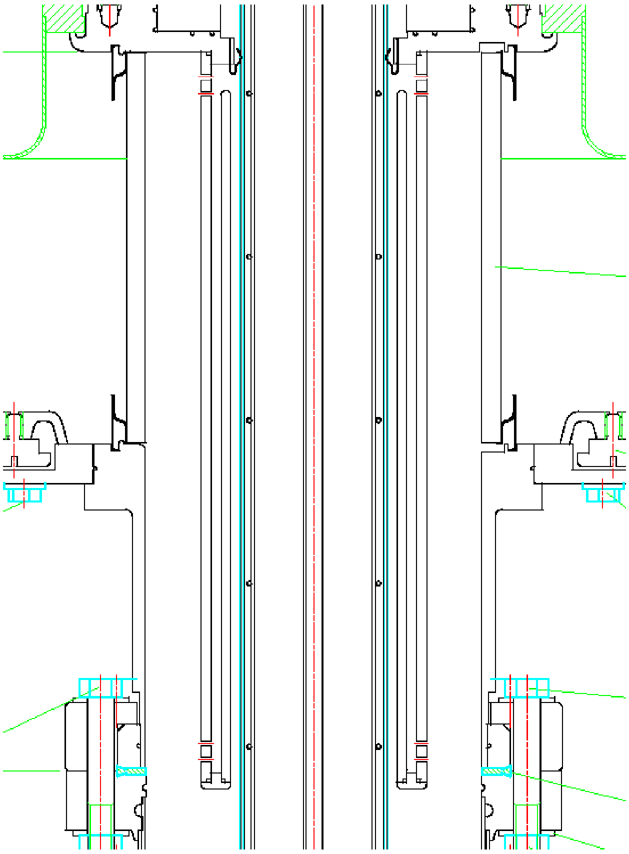

Fig. 3: The region of the ceramic window: the 25Ω line is formed by the outer conductor and the external part of the double folded λ/4 stub.

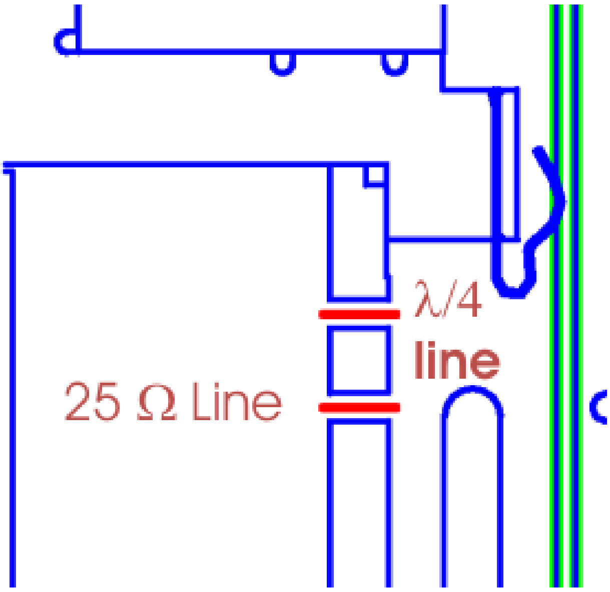

Fig. 4: The sliding finger contact and the top of the 25Ω choke (zoomed view).

The conditioning of this coupler on cold cavities immediately appeared to be very difficult. Even if the nominal power could be reached after few hours, when going back to low power the multipacting levels appeared again, little memory of the conditioning already performed was kept. Moreover by switching off RF for several hours, the coupler lost completely its conditioning on at least 75% of the couplers tested. This phenomenon was called "de-conditioning".

In order to understand and solve the problem, several directions were investigated at the same time. The source of the problem was identified quite soon in the adsorption of gases by the cold surfaces during conditioning. In practice all the gases evaporated during RF conditioning were adsorbed again on the cold surface nearby, so that the pumping system could never evacuate all the gases and clean once and for all the surface. This was demonstrated with an experiment on the "warm" conditioning test stand, by cooling the extension with liquid Nitrogen. The details of this experiment are reported in ref. [4]. Several actions were taken to reduce at the same time the cause (by reducing preventively the quantity of the gases adsorbed before the conditioning) and the effect (by trying to push the levels of multipacting towards higher forward RF power levels). The main actions taken were the following[5,6]:

- To increase the characteristic impedance of the coaxial line. The multipacting levels depended in fact not on forward power but on the level of the electric field at the surface. By increasing the impedance, the level of the electric field for the same forward power decreased because the same electromagnetic energy is stored in a bigger volume. For mechanical reasons the new diameter of the antenna was chosen to be ~30 mm, leading to a characteristic impedance of 75Ω and pushing the levels of multipacting higher by 50% in power, as verified experimentally and by simulations.
- Suppress the 25Ω choke, which was the main source of two points multipacting levels. As a consequence the coupling returned to be fixed because the finger contact could not stand the RF currents without the choke. The consequence of that decision was a loss of flexibility, and the need to foresee a bigger margin in forward power to compensate for a spread in Qext on cavities fed by the same klystron.
- In order to reduce the gases adsorbed on the coupler even before the conditioning, it was decided to bake out the ceramic before the test (150ºC for 24 hours). This remedy proved to be very effective in reducing the conditioning time. The risk of breaking the ceramic during conditioning was also reduced since it was observed that vacuum outbursts due to RF fields were also reduced.
- Last but not least, the introduction of DC bias that ultimately suppressed all the remaining multipacting levels. According to simulations positive or negative bias of the antenna would have been both effective. For tunnel operation –2.5 kV were applied. A consequence of biasing the antenna was to stop cooling it by Ghe, and going for air cooling trough plastic insulating tubes, to have a good insulation to ground.

Fig. 5: the 75Ω fixed couplers. Note the two ports for the vacuum gauge and the electron monitor close to the ceramic.

5 THE 75Ω FIX COUPLER

The new coupler, used on most of the cavities in the tunnel, is shown in fig. 5.

The procedure for the preparation of the coupler before mounting on a superconducting cavity was also reviewed several times and finally the main steps were the following:

- High pressure rinsing of all the components, excluding the ceramic, before assembly;
- Assembly always done in clean environment;
- Transport and storage under controlled atmosphere (N_2);
- Pre-conditioning at full RF power on a warm cavity (300K) after bake-out of the whole system;
- Assembly on the cavity in clean room class 100;
- Bake-out of the ceramic;

- Conditioning at 4.5K at full power.

Some other minor changes were done, e.g. the procedure of fabrication of the extension tubes, with the goal of obtaining smoother surfaces and to reduce field emission.

All these action and procedures revealed to be very effective and finally the production of the couplers was launched and all the couplers achieved successfully the nominal power without being spoiled by multipacting and could be installed in the tunnel.

6 OPERATION IN LEP

The main problem during operation with the beam was the spread in Qext of the different cavities fed by the same klystron [7-14]. Spread of more than 20% were observed and several cavities were limited to a low gradient just because a cavity on the same klystron had a more favourable coupling, and showed much higher gradients than the other cavities, attaining the maximum field and limiting the others to a lower field. To overcome this limitation, a campaign of measurements was performed to identify the worst cases that were corrected by introducing $\lambda/4$ slabs in the waveguides and by readjusting the waveguide length in order to have less than 3º of error in phase from the waveguide system. In any case the problem could be solved only partially since LEP was always run with several different values for the beam current.

Several interlocks were foreseen to protect the coupler during the operation (most of them were mounted also on the test benches):

- Fast monitoring of vacuum near the ceramic window through a Penning gauge installed on one of the two ports visible in fig. 5, driven by a fast electronics (< 1msec delay);
- Arc detectors in the waveguides, made by optic fibers connected to photo multipliers. This system was abandoned at the end since responsible for several false alarms;
- Electron current monitor near the ceramic, to detect dark currents due to field emission and multipacting that could harm the ceramic. Since the level of current measured was always very low (~ pAmp) it was abandoned at the end, not being reliable;
- Monitoring of the air flow through the input antenna and close to the ceramic were installed, as well as several temperature probes (PT100), to be sure that all components were operating at the right temperature;

As a result, the downtime for physics due to main coupler faults was reduced to a very low level (~4% of the RF down time, that was ~20% of the total downtime for the LEP machine).

7 CONCLUSIONS

The absence of severe failures and the limited downtime of the LEP machine due to Power Couplers faults are the evidence of the success of LEP couplers. Several improvements to the initial design were necessary before getting to a satisfactory result, and this was only possible with the intervention of different skills: RF, vacuum, metallurgy, thin film coating, chemical treatments etc… Without these joint efforts, the project would probably have suffered more in terms of machine downtime.

At the end the couplers could sustain easily the nominal 120 kW CW forward power, and were tested in offline test benches up to 4 times that value [15]. The main lessons learned are:

- Involve from the beginning all the experts from the different domains involved;
- Use the highest possible characteristic impedance for the coaxial line;
- Bake out the ceramic before cooling down the cavity for the first time;
- If possible, go for a variable coupler;
- Apply DC bias to the antenna;
- Protect the ceramic with interlocks driven by fast vacuum gauges.

8 ACKNOWLEDGMENTS

This paper reviews the work of many people, whose work led to the success of LEP. In particular I had many useful discussions on this subject with Ernst Haebel and Joachim Tuckmantel, who participated from the beginning to the development. Useful information about conditioning procedures for LEP couplers came from H. P. Kindermann and M. Stirbet, S. Calatroni told me everything about surface preparation and coatings, and O. Brunner about operation in LEP. I wish to thank E. Chiaveri and J. Tuckmantel for reading and commenting this paper.

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