STATUS REPORT ON SUPERCONDUCTING NB CAVITIES FOR LEP

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ABSTRACT

During the two last years the main effort of our group has been directed towards the installation of the first s.c. cavities in LEP. Four Nb cavities have been produced – two by CERN and two by industry – and equipped with all auxiliaries for operation in LEP. All 4 Nb cavities have exceeded the design field of 5 MV/m and reached Q values between 2 and 3×10^9. The status of cryostats, main couplers, higher order mode couplers, frequency tuners and control systems is presented and experimental results are discussed. The first 4 Nb cavities will be assembled inside a common cryostat system and this unit will be installed in LEP. Considerable long-term operation experience has been obtained with a LEP Nb cavity installed inside the CERN SPS and operated for more than 8000 h by now. No irreversible degradation of cavity performances has been observed. For the upgrade of LEP energy beyond 55 GeV, the first step will consist installing 32 s.c. cavities; 24 Nb cavities and 8 Nb coated Cu cavities. Orders for the construction of 20 Nb cavities with all auxiliaries have been placed at industry.

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1. INTRODUCTION

Already at an early stage of LEP design [1] it was considered to upgrade energies to the design value of LEP (~ 100 GeV) by installing superconducting (s.c.) cavities. Because of the much higher acceleration efficiencies and acceleration fields of s.c. cavities the sixteen 1 MW klystrons needed for operation of LEP at 55 GeV with 128 Cu cavities are sufficient to obtain ~ 90 GeV with s.c. cavities [2]. A new cavity geometry (fig. 1 and Table 1) matched to the specific requirements of LEP was designed [3] and a first series of three 4-cell Nb cavities (LEP0 + LEP2) were constructed and tested at CERN. The design values of accelerating fields $E_{acc} = 5$ MV/m and of quality factors at design field $Q_0 = 3 \times 10^9$ were exceeded and maximum fields up to 7.5 MV/m were reached [4].

TABLE 1

A few parameters of 4-cell LEP cavities

Frequency f	352.209 MHz
Cavity active length	1.70 m
Iris hole diameter	241 mm
Shunt impedance/quality factor r/Q	276 Ohm/m
E_p/E_{acc}	2.3 [(a)]
H_p/E_{acc}	39 G/(MV/m)
Geometry factor G	280 Ohm
$2(f_\pi - f_0)/(f_\pi + f_0)$	1.76%
$-\Delta f/\Delta p$	~ 2 Hz/mbar [(b)]
$\Delta f/\Delta \ell$	45 Hz/μm

(a) 2.13 at beam-tube iris.
(b) Inside cryostat.

For a large storage ring, reliability and good long-term stability are of great importance. Two long-term tests were therefore performed. Cavity LEP0 was operated during 2200 h, CW, at 7.2 MV/m and submitted to a few warm-up cycles. No degradation of cavity performances were observed [4]. Cavity LEP2 with all auxiliaries like cryostat, main coupler, higher-order mode (hom) couplers and frequency tuners was installed in the CERN SPS for an extended operation period [5,6]. Working conditions were complicated by the fact that an interleaved operation with a high intensity proton beam and an $e^{\pm}$-beam had to be performed. During the two last years the cavity LEP2 has undergone in total 20 cooldown cycles and has accumulated more than 8000 operation hours at 4.5 K. No degradation of cavity performances has been observed and no major system failures have occurred.

These results incited us to launch the fabrication of four more Nb cavity-cryostat systems, two of which were produced at CERN and two at industry (LEP3, 4, 5, 6). It is intended to install these cavities in LEP after an initial start-up period of the storage ring.

2. RESULTS WITH THE FIRST FOUR LEP CAVITIES

Results obtained with the first four s.c. Nb-cavities for LEP are described in detail in ref. [7].

A few results of the individual cavities are given in Table 2 and a typical Q_0 versus E_{acc} curve is shown in fig. 2.

TABLE 2

A few experimental results

	LEP3	LEP4	LEP5	LEP6
Manufacturer	Interatom	Interatom	CERN	CERN
RRR of Nb	180	150	110–230	110–160
Maximum acceleration field (MV/m)	5.4	8.6	9.0	5.5
Field limitation	Quench	RF power	Quench	Quench
Low field Q-value	3.0	2.7	–	–
Q_0 at 5 MV/m	2.2×10^9	2.2×10^9	3.3×10^9	2.0×10^9
Cavity fabrication and treatment: Spinning (d = 3 mm Nb), internal welding, CP of ~ 100 μm, long rinsing with ultrapure water, drying by pumping.				

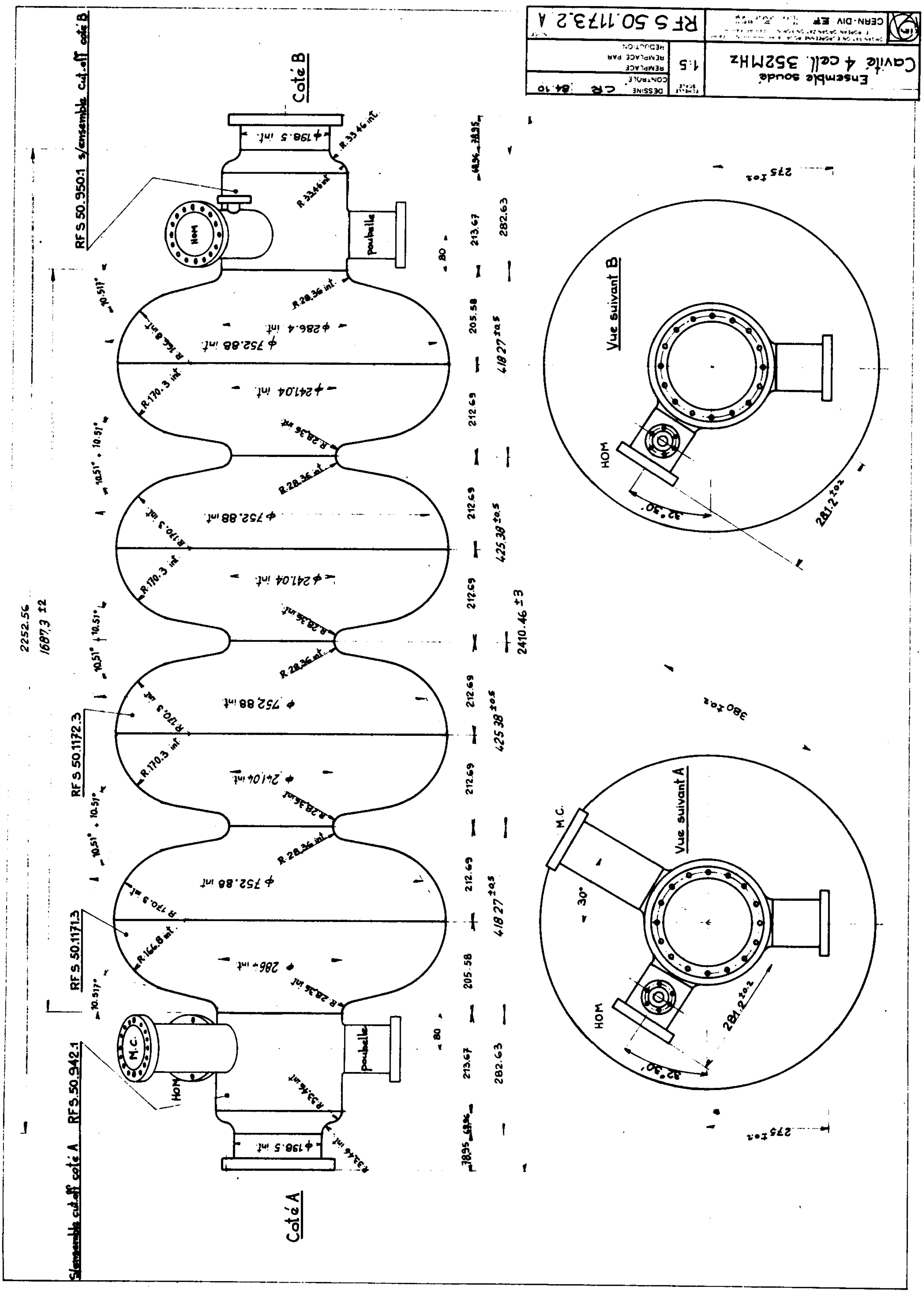

Fig. 1 - Geometry of the LEP cavity (4 cells, 350 MHz).

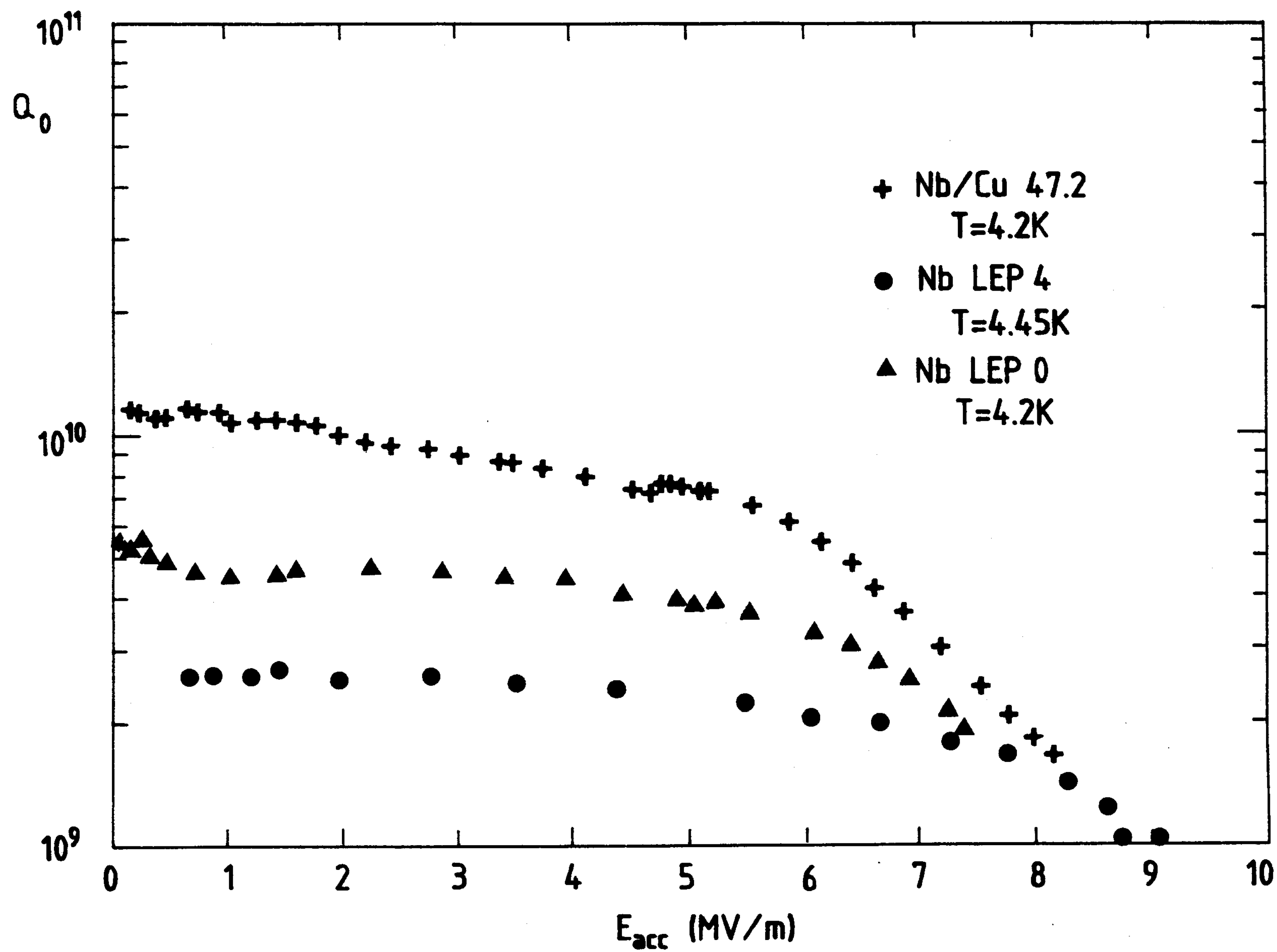

Fig. 2 – Quality factor versus accelerating field for LEP cavities (Nb and Nb coated Cu cavities). For the Nb cavity LEP4, the reduced Q-values are due to an insufficient shielding of the external magnetic fields.

After fabrication of cavities [8,9] and welding of the He vessel, cavities were submitted to a final chemical polishing of the inner cavity surface followed by a thorough rinsing with ultrapure water. All cavities were then measured inside their horizontal cryostat. For LEP3 and LEP4 this first measurement was performed without main coupler and higher order mode (hom) couplers. Cavities LEP5 and LEP6, fabricated at CERN, were directly measured with main and hom couplers and with frequency tuners.

All cavities exceeded design fields of 5 MV/m and fields up to 9 MV/m were reached (Table 2). The very long processing experienced on earlier 4-cell cavities could be shortened to an RF processing of a few hours only. We believe that this is due to the improved rinsing procedure. Fields were limited either by a fast thermal quench or by maximum RF power available. For three cavities, Q_0 values at 5 MV/m remained somewhat below the design value. It has been shown that this is due to an insufficient shielding of the surrounding magnetic field. For an ideal magnetic shielding one extrapolates for low fields a residual Q_{res} of 2×10^{10}, a Q_{BCS} (4.2 K) of 5.2×10^9 and consequently Q_0 (4.2 K) $= 4.1 \times 10^9$ [7]. This is sufficient to reach a Q-value of 3×10^9 of 5 MV/m.

Cold tests were performed with a 450 W, 4.5 K refrigerator plant. A 60 kW, CW tetrode without circulator was used for the RF tests and the RF processing.

3. AUXILIARY EQUIPMENT

Besides cavity development, a considerable effort has gone into the design, construction and testing of cryostats, couplers and tuners which present about 50% of the total cost of the cavity system.

3.1 Cryostats

The main guiding lines for the construction of LEP type cryostats were the following [10]:

- Modular design allowing assembling of many s.c. cavities in a common insulation vacuum.
- Excellent accessibility to all critical parts for inspection, repair or removal.
- Welded LHe vessel without joints between LHe circuits and cavity or insulation vacuum.
- Low costs by extensive use of Al-alloy materials.

As a compromise between a reasonable filling factor (~ 60%) and the transport possibilities inside LEP a basic unit containing 4 s.c. cavities with a total length of 11 m was chosen (fig. 3). These units are assembled under clean conditions in a mounting hall [9], and then transported to their final location inside the machine tunnel.

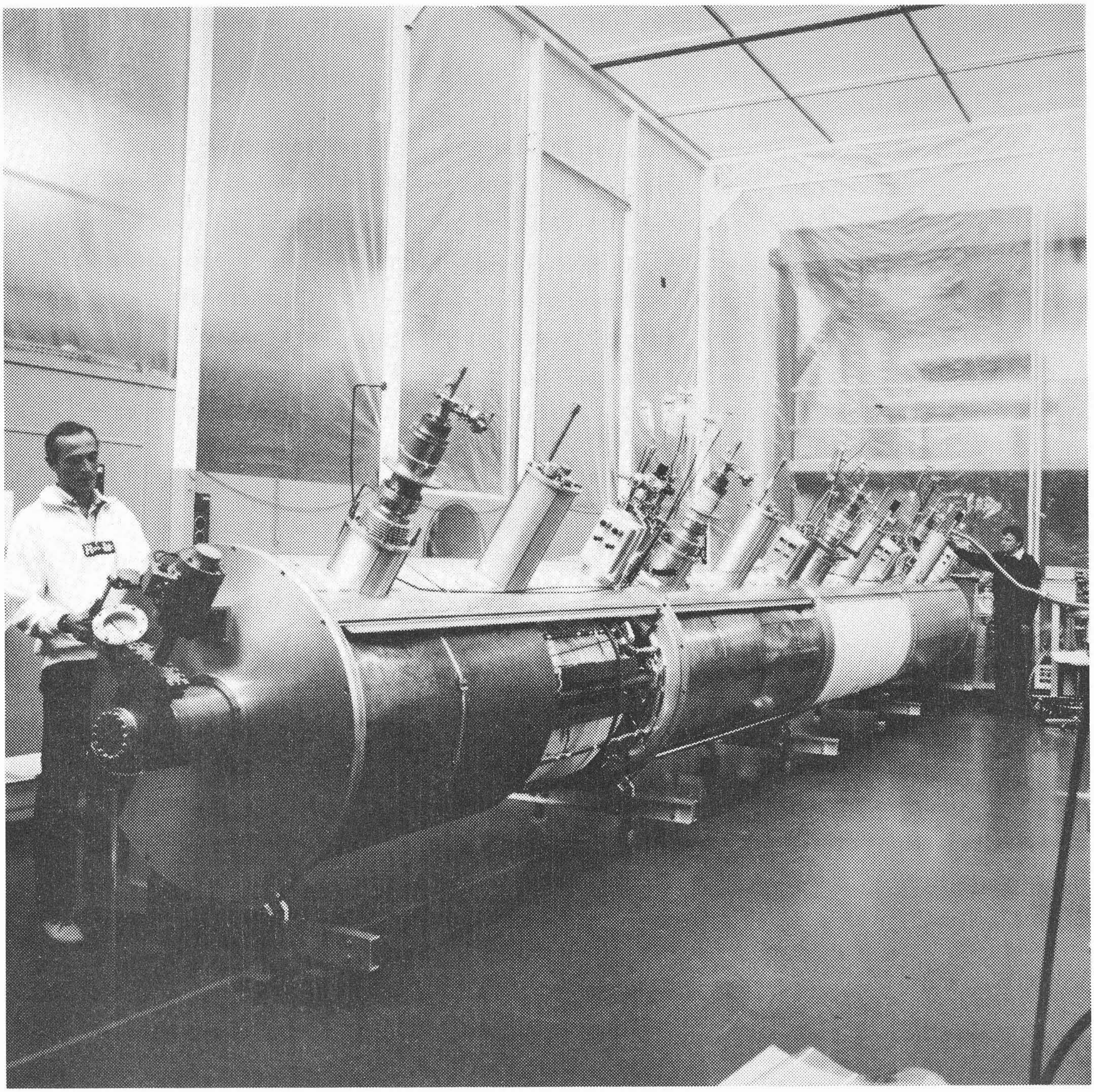

Fig. 3 – Four 4-cell LEP Nb cavities assembled in a common vacuum vessel. The assembly is seen just before closing the four cryostats with their sealing envelope.

Cryogenic tests on individual cavity–cryostat units equipped with main and hom couplers, with frequency tuners and beam tube transitions to 300 K have been performed. At operating liquid helium level and with 0.2 g/s of cold gas flow through the various heat exchangers, tuners and radiation shield, static losses of less than 16 W at 4.4 K have been measured. Safety tests [11] simulating the most dangerous vacuum failure, i.e. a break of the ceramic window of the main coupler, have been performed with a peak heat load of 200 kW to the LHe bath (180 ℓ/cavity); a rupture disk of 50 mm i.d. appeared to be sufficient to handle this extreme situation.

3.2 Main couplers [12]

An antenna type coaxial coupler, located at one of the beam tubes of the cavity has been developed. The cylindrical r.f. window, of the type developed for the LEP Cu cavities is placed outside the cryostat at room temperature and can be easily replaced without opening the cryostat. Ten couplers have been constructed and tested for TW conditions up to power levels of 40 kW, CW. Couplers are baked out and conditioned on a special test stand with typical processing times well below 24 h. Cryogenic losses have been measured while countercooling the external conductor by 0.04 g/s of GHe and the internal conductor by GHe around 80 K. Losses at 4.2 K amount to 2.1 W.

It is foreseen to match couplers for the maximum power level of ~ 60 kW which can be delivered to 16 s.c. cavities by one 1-MW klystron. This corresponds to $Q_{ext} = 2.6 \times 10^6$ or at design field $E_{acc} = 5$ MV/m to a beam current of ~ 2 x 4 mA.

3.3 Higher order mode couplers [12]

A compact hom coupler of coaxial design (type I of ref. [12], fig. 4) has been developed for the first Nb cavities. Up to now 14 of these couplers have been constructed and tested and have given satisfying results with respect to mode attenuation, cryogenic losses and tunability. Q_{ext} reached for the most dangerous hom lie in the range of a few 10^4 and satisfy largely the criteria adopted for operation in LEP with 2 x 4 bunches and beam currents up to at least 2 x 3 mA.

Every cavity has two hom couplers located at the beam tubes and with an azimuthal angle difference of 32° for the coupling of dipole modes.

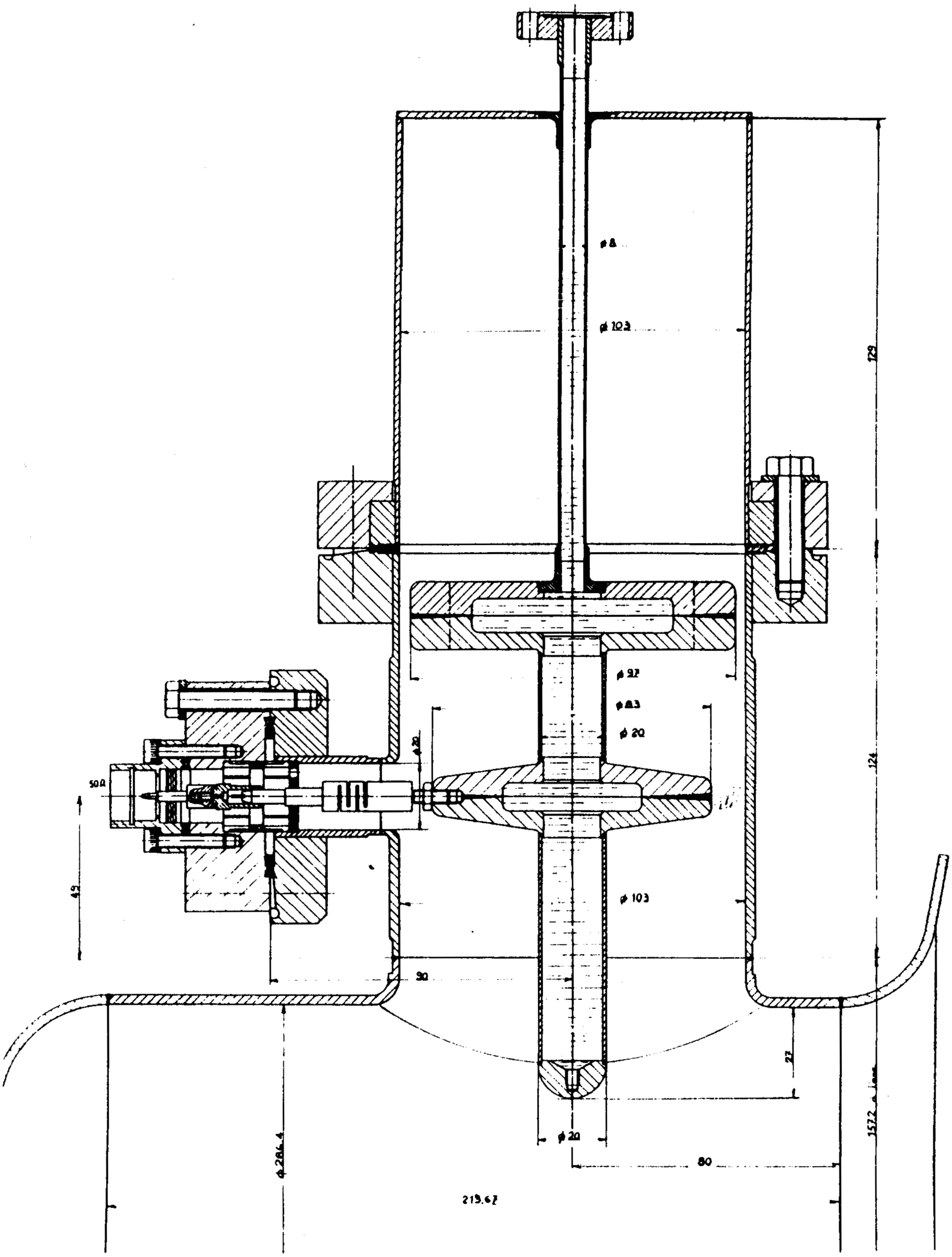

Fig. 4 – The HOM coupler (Type 1) for the LEP Nb cavities.

Each coupler is equipped with a connector T followed by two separate type N connectors and RF cables (RG 142, teflon dielectric, outer diameter 4 mm) located inside the insulation vacuum vessel. Cables are contacted at a distance of 20 cm to the cold shield of the cryostat. It has been checked experimentally that cables can transport without excessive heating at least 100 W, CW of RF power. Additional cryogenic losses (static and RF) at 4.2 K are estimated to remain below 1.2 W per cable. Hom couplers have been operated with a LEP 4-cell cavity up to field levels of 9 MV/m; mounted on a single cell 350 MHz cavity their power handling capability has been checked up to 200 W at 506 MHz (TM_{110} mode). As under LEP operation conditions the total RF losses for all modes up to 1200 MHz remain below 200 W, the present layout of hom coupling should be adequate.

The final rinsing with ultrapure water of the cavities and the final tuning of couplers is performed after mounting of the hom couplers. All couplers have exceeded after cooldown of cavities an external Q of 3×10^{10} for the fundamental mode.

Another type of hom coupler, i.e. a one-post coupler with cut-off characteristic (Type III of ref. [12]) has been studied in more detail. This coupler has no parts in direct contact with coupling port walls and would be well suited for Nb deposited Cu cavities. First tests have shown that this coupler induces thermal quenches at a field level of about 5.5 MV/m. At present efforts are continuing to overcome this limit by an improved evacuation of RF losses and by additional measures against possible multipactor inside the hom coupler.

3.4 Frequency tuners [13]

Frequency tuning of the cavities is achieved by a change of total cavity length (40 kHz/mm). Two tuning modes are used in parallel: a fast one based on magnetostriction of Ni bars supporting the cavity with a range of ± 1 kHz and a speed of 1 kHz/50 ms and a slow one based on temperature changes of the same Ni bars with a range of 50 kHz and with a speed of ~ 8 Hz/s. These values may be compared to the loaded bandwidth of the cavity B = 134 Hz ($Q_{ext} = 2.6 \times 10^6$). A He gas flow of some 0.03 g/s per tuner has been found adequate for the thermal tuning. As the magnetic field needed for the magnetostrictive tuner is located near the cavity walls and may be trapped after a cavity quench, where parts of the Nb walls become normal conducting, a fast switch-off (< 20 ms) of tuner coils has been installed and tested.

Altogether 18 tuners have so far been produced and tested at CERN. A first set of three tuners has been operated for more than 8000 h with LEP2. It could be matched without major problems to the combined proton-lepton operation needed for the SPS (sect. 4).

3.5 Control systems [14]

It has been tried to use at maximum the existing RF control system for the Cu cavities and RF generators. A particular aspect for s.c. cavities is the need for a fast quench protection system. A system based on fast variations of RF field level inside s.c. cavities has been developed and already sucessfully applied at LEP2.

4. LONG-TERM TEST OF A LEP SC CAVITY IN THE CERN SPS [5,6]

Two years ago the installation of a LEP type cavity in the CERN SPS gave us an excellent and welcome opportunity to perform a long-term test of a s.c. cavity and to gain experience in an accelerator environment for the operation and control of a cavity with its cryogenic and RF system.

For operation with the high intensity proton beam (I = 200 mA) the impedance of the s.c. cavity had to be reduced by several orders of magnitude. This was achieved by damping the fundamental passband modes by an RF feedback system [15] including a tetrode power amplifier. Lepton acceleration was also tested in an interleaved operation of a high intensity proton beam and a 0.28 mA e^+-beam. Field levels up to 6 MV/m were used for acceleration. To cope with an extremely high beam loading, especially at injection when the RF voltage is very low, the tuner circuitry measures the normalized reactive power instead of the usual phase difference between cavity field and tube current. This results in a perfectly stable operation of the tuner even under these unfavourable conditions. An excessive level of drive power on the tetrodes switches off the reference RF voltage to the feedback circuit. The fast interlock is very convenient when the RF losses in the cavity increase very rapidly at the highest fields (quench, e^- loading).

A remarkable feature of the feedback system is the high degree of field stability achieved. Measurements performed under CW conditions with a moderate gain (open loop unity gain frequency of 50 kHz) give a r.m.s. phase noise of 4×10^{-4} and an amplitude noise of 1.3×10^{-4} in a 1 MHz bandwidth. These values include 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 (e.g. 51, 63 and 73 Hz, amplitude ~ 10 Hz).

Another test objective was the influence of accelerator vacuum conditions in view of the large pumping speed of the s.c. cavity surface [6]. It has been shown in an independent test that exposure with a typical residual gas composition of the SPS vacuum does not affect Q_0 and E_{acc} (near the LEP design values) up to an equivalent of one monolayer. Above this value additional e^- loading is observed at high fields. Relating these values to the residual gas pressure of the SPS (~ 1 ÷ 3 x 10^{-10} mbar) one finds that the cavity can most likely be kept at 4.5 K without degradation for a period of ~ 3 years.

The flexibility and reliability of cryogenic systems for the operation in an underground area (-60 m) has been demontrated. In a first test cooling was realized by dewars at ground level and linked to the cavity by a 100 m long flexible He transfer line [16]. At a later stage a 125 W/4.5 K refrigerator was used with a cold box inside the SPS tunnel [6]. This system has been operated almost continuously since its installation in January 1988. The liquid helium volume in the cryostat was controlled by an electrical heater to ± 0.5 l and the pressure was set to a reference 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 allowed determination of the Q value by the decrease of the heater power needed to keep the cavity level constant in case the RF power is switched on.

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, of which 6500 h in the SPS accelerator. Since the final chemical treatment of the cavity, it was never again exposed to atmospheric pressure. Up till now, none of the vital accessories (higher order mode couplers, pick up probes, power coupler, tuners) failed.

Within the measuring accuracy the maximum field of 7.3 MV/m has not been degraded. After each cooldown a short (~ h) RF conditioning is necessary to pass multipactor levels around 5 MV/m.

Q-values have shown a scatter between various cooldown cycles of 8×10^8 to 3×10^9. This is due to our magnetic shielding system (an arrangement of Helmholtz coils) which compensates only the static homogeneous ambient magnetic field. It could not cope during a cavity quench with time varying external fields nor with the magnetic field of the magnetostrictive tuners. 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 $2 \div 3 \times 10^9$.

The s.c. cavity has been kept also inside the SPS ring at low temperature during many months of proton-antiproton collider operation. At present the 350 MHz cavity is operated routinely for $e^{\pm}$ injection into LEP and serves as a supplement for the new standing wave Cu-cavities operating at 200 MHz.

5. PREPARATION OF THE FIRST SUPERCONDUCTING CAVITY OPERATION IN LEP

It is foreseen to install a unit of four s.c. cavities in LEP, as soon as possible after its start-up. The assembly [9] of the four cavities after their individual tests has been finished and has allowed to appreciate fully the excellent accessibility conditions offered by the cryostat design. Assembling and alignment of individual cavities is easy and not hampered by mechanical overconstraints or excessive mechanical tolerances. The mounting of additional items like couplers, RF-probes, beam tubes, intercavity bellows and vacuum valves is done after a thorough cleaning and storage under dustfree conditions of these items.

All assemblies of cavities and most installations of auxiliaries are done in a clean environment (class < 10000) and under dust control. It was not tried to keep cavities under vacuum after their final dustfree rinsings. Instead we rely on a slight overpressure of dry, dustfree nitrogen gas inside cavities and on very short exposure times (s) to the surrounding atmosphere. In the past many operations of this type have been applied on one-cell and four-cell cavities and it has been demonstrated that this procedure does not affect in an noticeable way acceleration fields and quality factors in the range foreseen for LEP. Sometimes a slight increase of electron activity is observed but could be processed away easily.

Vacuum valves are only installed at both ends of a four-cavity unit. The final pumping (or venting) is done at much reduced pumping speed (typically many hours) so that contamination by dust originating from the pumping systems is avoided.

After assembly, the four cavity units have been transported with the help of a dedicated support and transport system to the test mock-up previously used for a basic module of 16 Cu cavities [17]. RF tests are performed by using the existing klystron-circulator-waveguide system and large parts of the associated control and regulation units. Liquid helium at 4.5 K is supplied by a 450 W refrigerator. Cavities can be cooled either independently or simultaneously by a He distribution line similar to the one already installed in LEP for the first s.c. cavities. First tests on a two-cavity unit have shown that cooling by "overflow" of LHe from one He-vessel to the next is possible. This would greatly simplify the LHe distribution system and reduce the number of cold valves.

For the first operation in LEP a RF system with one 1 MW klystron similar to the one used for the Cu cavities has been prepared. He transfer and distribution lines are already installed as well as a 1 kW refrigerator (modified ex-ISR liquefier) whose cold box is located inside the klystron tunnel (fig. 5). The control systems for RF, cryogenics and vacuum are operational. It will therefore be possible to install the first four s.c. cavities unit during a relativity short shutdown period following the initial start-up period of LEP. With four cavities and with a gradient of 5 MV/m a total acceleration voltage of 34 MV is obtained. This should give a possibility for storing and accelerating LEP beams up to ~ 30 GeV with the s.c. cavities only.

6. A FIRST STEP FOR UPGRADING LEP ENERGIES

In parallel to the installation of the first four s.c. cavities in LEP a first step of upgrading by 32 s.c. cavities is under preparation [2]. Twenty s.c. Nb cavities with cryostats, tuners and couplers have been ordered at industry. An additional eight Nb deposited Cu cavities [18,19] are under construction at CERN. Cavities will be installed on either side of interaction region 2 together with two 1 MW klystron systems. A more powerful refrigerator will be ordered from industry for installation in 1991; it should provide some 5 kW at 4.5 K for cooling both sides via a transfer line system.

The 32 cavities alone will produce, at 5 MV/m, a total accelerating voltage of 272 MV and one should be able to reach particle energies of 51 GeV. Together with the Cu cavities an energy of 64 GeV can be reached. This is the limit where some machine components, as for instance the 24 concrete dipole cores in the injection regions and some quadrupoles (low β quadrupoles), need not yet be upgraded.

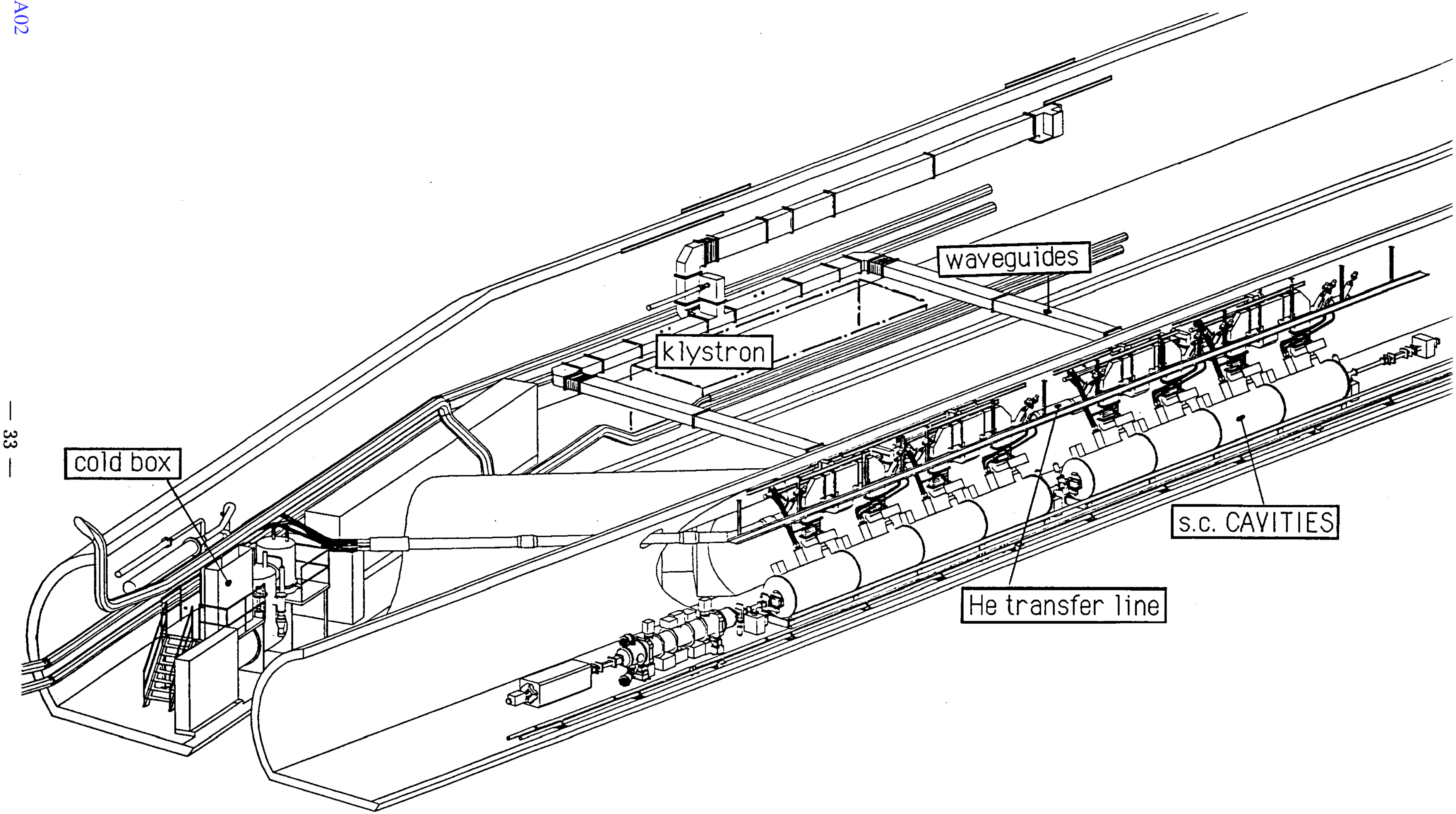

Fig. 5 – Layout of the first eight s.c. cavities in LEP. In front the accelerator tunnel; behind, the klystron gallery.

7. OTHER ACTIVITIES

Besides the main activities some theoretical work on cavity behaviour is going on. A simple criterion for determining multipactor levels in s.c. cavities and its auxiliaries has been established [20] and applied to the choice of a s.c. cavity for the planned large hadron collider (LHC) at CERN [21].

A relation between the matching of a s.c. cavity and the Robinson instability limit has been established. It has been shown that the matched conditions are at the limit of instability if no additional beam loading compensation schemes are foreseen [22].

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