



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-ISR-TH/80-37

PRESENT STATUS OF THE LEP PROJECT

by

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Presented at XIth International Conference on High Energy Accelerators,  
CERN, Geneva, July 7 - 11, 1980

Geneva, Switzerland  
July 1980

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### ABSTRACT

LEP, a large Electron-Positron colliding beam machine to be built adjacent to the CERN site, will have a maximum of eight interaction regions and a circumference of 30 km enabling an eventual top energy of 130 GeV per beam to be reached with superconducting RF cavities. The recent design improvements (e.g. injection from the PS/SPS complex) and the progress on the prototypes of all major machine components (many of which are of novel design) will be described.

### 1. INTRODUCTION

The study of a Large Electron-Proton storage ring (LEP), to be the next major European high energy physics facility, was initiated at CERN in 1976. The steady evolution of the project has been described in several detailed reports <sup>1,2,3)</sup> and various summary papers <sup>4,5,6)</sup>. The most recent report, the so-called Pink Book <sup>3)</sup>, has been accepted by the CERN management as a firm basis for the construction of LEP and as such has been presented to the CERN Council for discussion in the member states. Meanwhile, the LEP Study Group, which includes a wide participation of non-CERN accelerator experts, has continued with the construction and testing of prototypes and, in some instances, there have been major improvements to the basic design (notably in the injection system).

After a brief summary of the general characteristics of LEP, this paper will concentrate on the recent evolution of the project.

### 2. GENERAL DESCRIPTION

LEP is a single ring  $e^+e^-$  colliding beam machine roughly ten kilometres in diameter to be built adjacent to the CERN site almost tangential to the SPS and will be entirely underground (see Fig. 1). Provision is made for a maximum of eight equispaced interaction regions, four for wide angle detectors with a free space of  $\pm 5$  metres and four for small angle detectors with a free space of  $\pm 10$  metres but half the luminosity. One of the interaction regions is at the point of closest approach to the SPS and eventually  $e-p$  collisions could be provided in this interaction region by bringing protons out of the SPS into a bypass.

The RF cavities are situated on either side of the eight interaction regions which is the best place for all pulsing or modulating schemes. The straight sections also help to shield the detectors from synchrotron radiation background. Stub tunnels are foreseen parallel to the straight sections to house much of the RF equipment. The proximity of the RF to the access points is a further advantage of this layout.

The maximum energy of LEP is determined by the amount of installed RF power. The initial RF installation will enable energies of up to 50 GeV per beam to be reached which should be sufficient to produce  $Z_0$  particles. Extension of the room-temperature RF system would permit energies up to almost 90 GeV per beam with a high luminosity, so that the

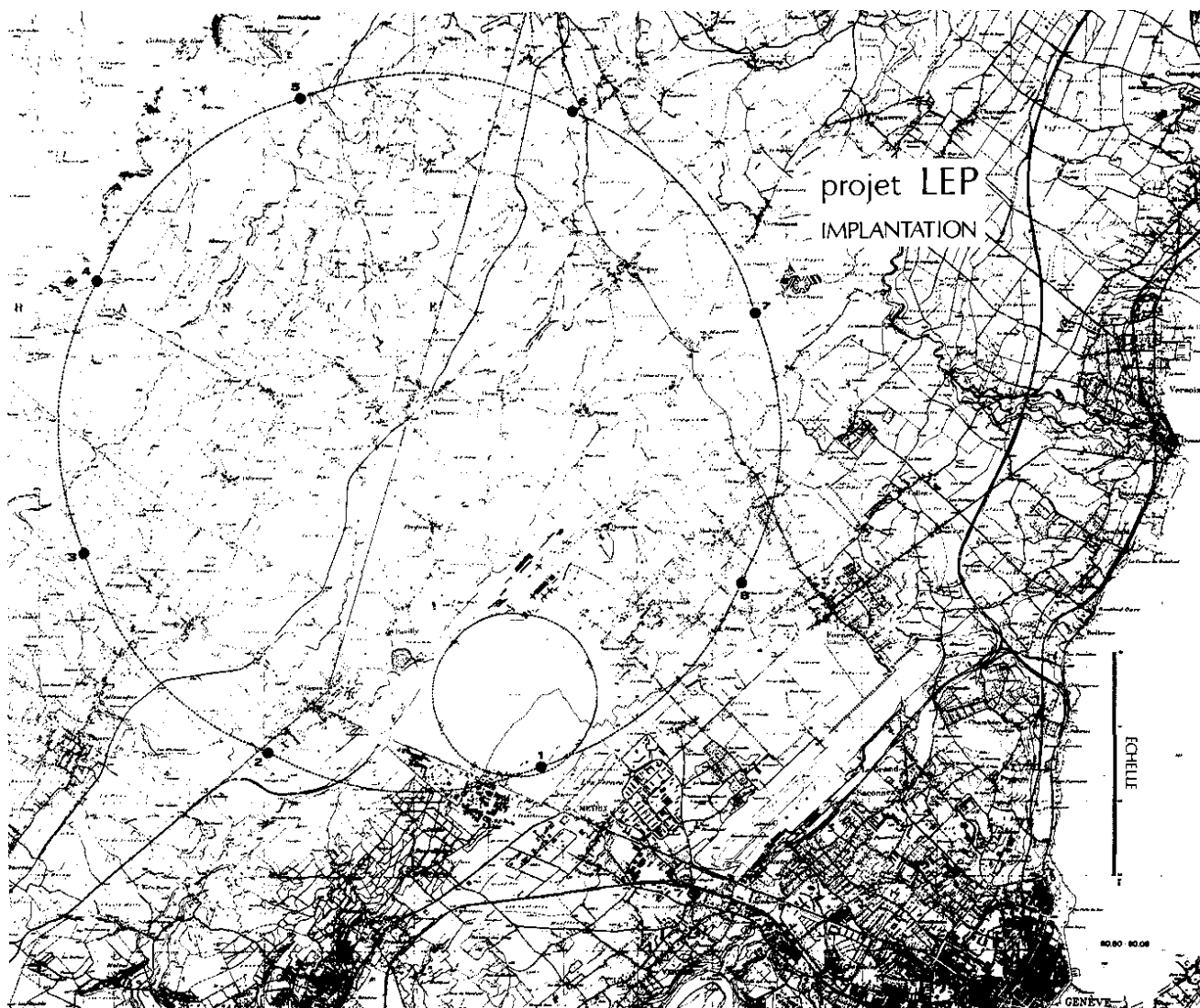


Fig. 1. Layout of LEP near the CERN site

study of  $W$  pairs should be possible. Alternatively (or successively) if superconducting RF cavities were available on a large scale, a maximum energy of 130 GeV should be possible and all the other machine components are dimensioned for this energy.

Since the circumference of LEP is 30.6 km it is vital that the machine components be made as cheaply as possible and a premium is put on techniques which lend themselves to mass production. Some of the components are developments of proven ideas from SPEAR, PETRA, CESR and PEP while some completely new approaches have been made, particularly in the dipoles. The general services of LEP, i.e. power, cooling, ventilation, communications, controls, etc., pose new problems related to the sheer size of LEP, but for lack of space these topics will not be discussed in this paper.

There has been considerable pressure to provide colliding beams at up to 50 GeV per beam at the earliest possible date and preferably within five years of project approval. A major limitation to this is financial so, apart from the continuing search for cheaper technical solutions, only the most vital systems will be provided in the initial installation. Only one sixth of the RF system is required and this will be grouped adjacent to

two diametrically opposite interaction regions to minimize the services and auxiliary buildings. Little can be saved in the vacuum and magnet systems (although some quadrupoles could be left out) and major savings are only possible in the civil engineering, for example by reducing the number of experimental areas provided initially. Completion of the project would then continue in parallel with physics experimentation, albeit at reduced energy and luminosity.

### 3. INJECTION SYSTEM

In the Pink Book, a 22 GeV synchrotron was proposed as injector for LEP which had the attractive feature that the magnets, vacuum chamber and much of the infrastructure of the ISR were incorporated to help keep the cost low. Recently a new idea has been proposed <sup>7)</sup> which will almost certainly be the solution finally adopted. In this proposal, 600 MeV electrons and positrons are produced by a Linac in the conventional way and an accumulation ring ACR <sup>8)</sup> is used as a buffer between the fast cycling Linac and the slower synchrotrons (see Fig. 2). This pre-injector system is being designed by L.A.L. Orsay. The main acceleration is now proposed to take place in the PS/SPS complex, positrons following the standard proton transfer lines and electrons following the new lines installed for the antiprotons. Four bunches are accumulated in ACR and transferred at 600 MeV into the SPS where they are accelerated to 3.5 GeV, mostly with existing 200 MHz cavities. Transfer into the SPS at 3.5 GeV has already been tested successfully during preparatory studies for the antiproton collider. Acceleration from 3.5 GeV to 22 GeV in the SPS will require about 48 metres of 200 MHz standing wave cavities and associated power sources. The electrons remain for a sufficiently short time in the two machines that no problems with synchrotron radiation are expected.

The electron/positron acceleration can be interleaved with proton acceleration with little or no degradation of the fixed target programme but it would be incompatible with colliding protons and antiprotons in the SPS. However, the SPS will only be used as a collider for a fraction of the year and the mutual interference can be resolved by careful scheduling.

A detailed study of the injection paths from the SPS to LEP is still under way. A preliminary conclusion is that injection into the straight section of LEP seems preferable to injection into the arcs. A review of the bypass required for e-p collisions has given

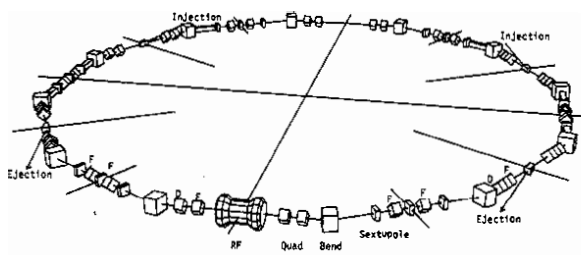
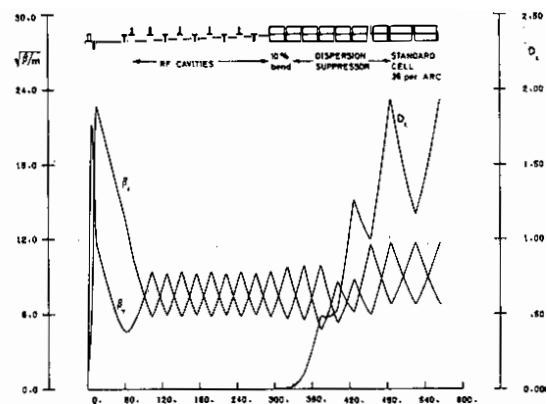


Fig. 2 Layout of the accumulator ring ACR

Fig. 3 Lattice layout and orbit functions near high-luminosity interaction point (horizontal scale in metres)



a strong preference to an internal bypass. The injection paths could then follow more or less the trajectory of the proton bypass.

The exact circumference of LEP and the bypass length must be chosen to ensure correct cogwheeling for both e-p collisions and for injection. Several possibilities have been found but the final decision is awaiting completion of the injection and bypass studies. The circumference of LEP will not differ from that in the Pink Book by more than a few percent. The scheme of using the PS/SPS as the LEP injector saves not only money but also manpower leading to a considerable reduction in the construction time of LEP.

#### 4. LATTICE LAYOUT

The arcs of LEP have a standard separated function FODO lattice. The dispersion suppressors which join the arcs to the dispersion-free straight sections (in which the RF cavities and interaction regions are situated) are of a novel design<sup>9)</sup> having no unnecessary straight sections (see Fig. 3). The dispersion is brought down to zero by strengthening the horizontal focussing but the increase in vertical beam size due to the associated vertical defocussing is avoided by reducing the spacing between quadrupoles. Thus, in the main arcs there are six dipole cores between quadrupoles and in the dispersion suppressors only four, with standard components being used throughout. A useful consequence is that the quadrupole spacing in the straight sections can be adjusted to fit snugly around the RF cavities while respecting the phase relationship between cavities. A space in the dispersion suppressor has been left for the wiggler magnets required for emittance control.

It has now been decided to abandon the concept of variable tune proposed previously for LEP. Instead, a single high tune has been chosen which reduces the overvoltage factor required to provide a stable bucket and hence reduces the dissipation in the RF cavities. The phase advance per period is high ( $\pi/2$ ) to maximize the dipole filling factor, to make optimum use of the aperture and to reduce the number of lattice periods minimizing the cost of machine components.

At lower energies, the beam size is initially enlarged by decreasing the horizontal damping partition number  $J_x$  until some limiting minimum value has been reached ( $J_x=1/2$  ?). At even lower energies wigglers are used in addition. Compared to the Pink Book this proposal raises the energy of maximum luminosity ( $10^{32}\text{cm}^{-2}\text{s}^{-1}$ ) with 96 MW RF power and room temperature cavities by 2.7 GeV to 88.8 GeV (see Table 1). A side advantage is that the synchrotron tune  $Q_s$  is reduced considerably which may obviate the need for a higher harmonic system, at least in the initial installation.

Chromaticity correction and successful tracking of particles with more than 15 standard deviations in all three planes simultaneously has been demonstrated using eight families of sextupoles (four in each half-octant). Adjacent sextupoles of the same family are  $\pi$  apart in phase so that their effect on off-momentum particles adds, while their effect on particles with large transverse amplitudes cancels. The phase advance from the insertion quadrupoles to the first sextupole is an important ingredient of the correction scheme and this has to be reconciled with restrictions on the machine tune from other considerations.

TABLE 1  
LEP PARAMETERS AT 88.8 GEV

Machine circumference	30.6 km
Length of lattice period	79 m
Installed RF power	96 MW
Number of interaction points	8
Number of bunches per beam	4
Horizontal tune	~97
Vertical tune	~101
Synchrotron tune	0.10
Momentum compaction factor	$1.46 \times 10^{-4}$
Horizontal damping partition $N^{\circ}$ .	0.5
Beam lifetime	5.6 hr.
Free space in interaction region	$\pm 5 + 10$ m
Vertical amplitude function	0.1 0.2 m
Horizontal amplitude function	1.6 3.2 m
Beam-beam tune shift	0.6 0.6
Maximum luminosity/ $10^{32}$	1.0 0.5 $\text{cm}^{-2}\text{s}^{-1}$

## 5. PERFORMANCE

Figure 4 shows the estimated luminosity of LEP as a function of energy for three different RF installations. With the nominal 96 MW RF power and associated cavities, a maximum luminosity of  $10^{32}\text{cm}^{-2}\text{s}^{-1}$  can be reached at 88.8 GeV. At lower energies the luminosity falls as the square of the energy by maintaining the emittance constant.

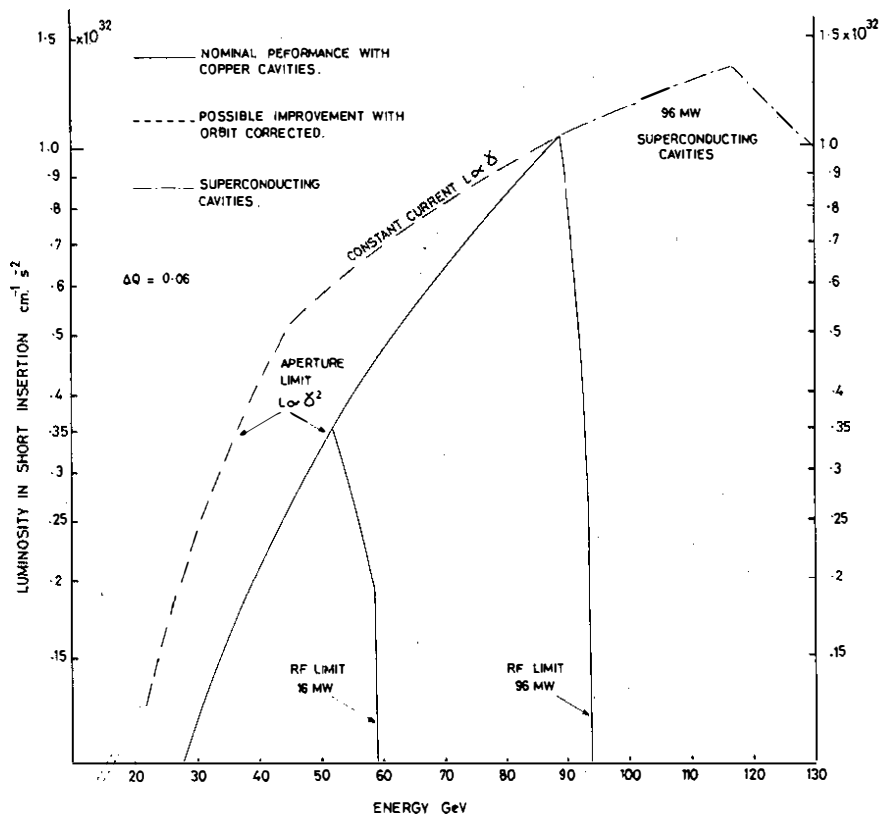


Fig. 4

Luminosity as a function of energy for three different RF installations

As the machine is run in, it is expected that the tolerance required for closed-orbit errors can be progressively reduced, leaving space for an increase of the emittance and hence the luminosity. This increase is limited by the maximum number of particles per bunch which can be handled at the injection energy mainly due to transverse collective effects. With constant current, the luminosity will only fall linearly with energy if the emittance is increased as the inverse of the energy, but the aperture would only be sufficient to maintain this variation down to about 45 GeV.

The luminosity attainable with only 16 MW installed RF power is also shown with a maximum of  $0.35 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$  at 51.8 GeV while at 59 GeV the luminosity is still above  $10^{31} \text{cm}^{-2}\text{s}^{-1}$ . This is more than sufficient for a vigorous Z<sub>0</sub> physics programme.

With superconducting cavities, the luminosity is again limited by the number of particles per bunch until, at an energy of 117 GeV, all the RF power is delivered to the beam. At even higher energies, the beam power is kept constant so the luminosity falls as the inverse cube of the energy.

The luminosity is estimated for a beam-beam tune shift of 0.06, the design value for PETRA, CESR and PEP. This corresponds to the maximum value observed at ADONE, SPEAR and VEPP-2M but recent data from DCI, SPEAR and PETRA have thrown some doubt on this value. Analysis of all the available experimental data<sup>10)</sup> indicates that a reasonable lower bound for the tune shift limit is 0.03. By suitable adjustment of the emittance, the luminosity would drop proportionally for the same circulating current. The uncertainty in the luminosity estimate is therefore not more than a factor of two. The evolution of the luminosity in PETRA, CESR and PEP will be followed with great interest since the data should be more relevant to LEP than that obtained from the lower energy electron rings.

There has been continuing interest in polarized beams which would greatly enhance the physics potential of LEP. Recent studies in collaboration with the Novosibirsk group<sup>11)</sup> have led to increased optimism that depolarizing effects can be made sufficiently small by careful correction of the closed orbit, and in particular, of a few harmonics of the vertical closed orbit which are close to the spin precession number (about 110 at 50 GeV). The preferred polarization mechanism uses asymmetric wigglers which may well be the same as those required for emittance control. Polarization at the Z<sub>0</sub> peak seems to be well within reach; at higher energies progressively better orbit correction is required but polarization is not excluded at up to 90 GeV.

## 6. MAGNETS

In the last year two full sized prototypes of the by now famous LEP concrete dipole<sup>12)</sup> have been built and their performance carefully evaluated. The cores are 5.79 m long and made from precision stamped C-shaped laminations whose profile determines the field distribution in the gap (see Fig. 5). The low field requirements (0.123 T at 130 GeV) permit the iron filling factor to be reduced to less than 0.3 without saturation. The laminations are 1.55 mm thick and are spaced at 5.5 mm pitch by indentations pressed by the punching die. The spaces are filled with low-shrinkage, corrosion resistant mortar consisting of cement and fine-grain silica sand (a spread in the grain size from 0-3 mm improves the strength) which acts as both filler and binding

agent. Six longitudinal tie rods are used to apply a precompression of  $5 \text{ kg cm}^{-2}$  to the 4.6 ton magnet and mechanically the magnet acts exactly like a reinforced concrete girder. The rigidity in torsion is very high so three point support will be used. The magnetic properties are at least as good as conventional magnets and cost less than 60%. Several complete additional cores have been ordered from specialized civil engineering firms to gain experience with industrial production.

The dipoles are excited by long water-cooled extruded aluminium bars, insulated electrically by two overlapping U-shaped channels of extruded glass-fibre reinforced polyester. The bars run straight through six cores arranged in pairs which minimizes the space lost at the ends and permits rapid installation. The two excitation bars are mounted above and below the median plane out of the region of the most intense synchrotron radiation. Return bars are mounted on the front of the cores to minimize the stray field in the tunnel and to reduce the magnet size (less induction in the return yoke). The excitation and return bars are interconnected to make a single loop around each arc with only two bars in the straight sections.

The quadrupoles are designed to run close to saturation at top energy (130 GeV), so the cores are of conventional all-iron construction. The excitation coils are made from solid anodized aluminium strips wound in flat pancake coils. The inter-turn insulation is provided by the 7 micron anodized layer which has a high thermal conductivity. The coil can therefore be cooled by an external water-cooled aluminium strip in close thermal contact with the windings. This simple construction increases the aluminium filling factor in the coil giving a more compact magnet and reduces the coil costs by about 30%. Prototype coils are on order from industry and will be delivered ready for mounting in magnetic mirrors, with the performance guaranteed by the manufacturer. Extensive tests will then be carried out before finalizing the designs of the quadrupole and sextupole.

## 7. VACUUM SYSTEM

The extruded aluminium vacuum chamber is equipped with linear sputter ion pumps using the dipole fringe field and lumped holding pumps as in SPEAR<sup>13</sup>), PETRA, CESR and PEP. The high critical energy of the synchrotron radiation (400 keV at 86 GeV and 1.4 MeV at 130 GeV) means that a large fraction of the energy is Compton scattered in all directions.

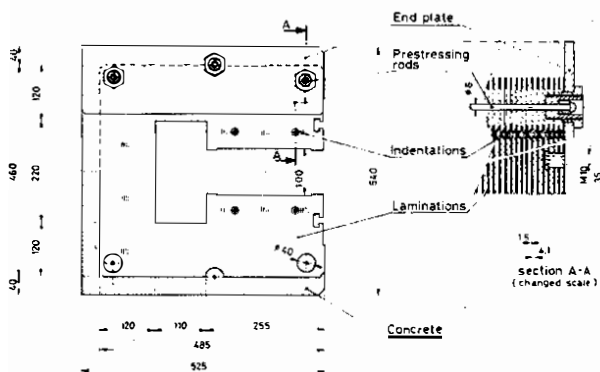


Fig. 5 Magnet profile and construction technique

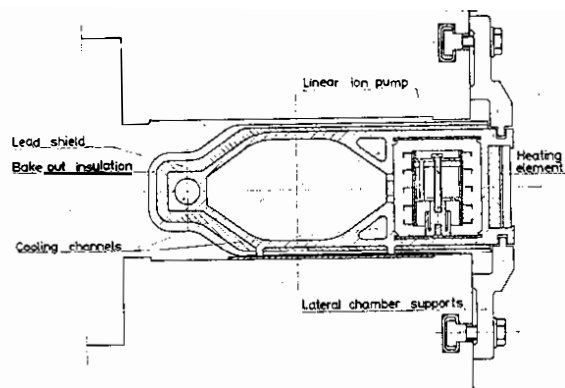


Fig. 6 Vacuum chamber cross-section



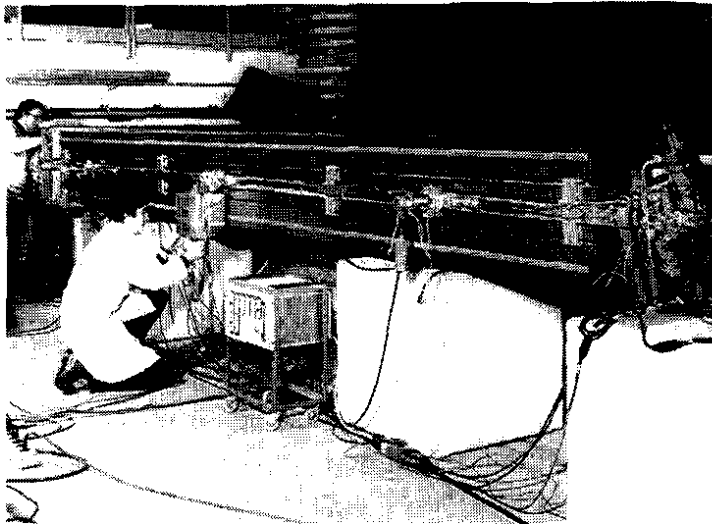


Fig. 7 General view of the prototype dipole with vacuum chamber mounted

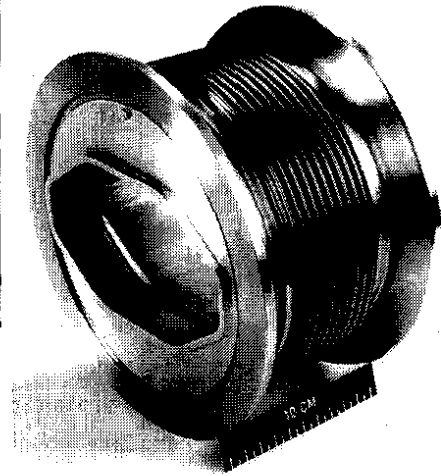


Fig. 8 Connecting unit for the vacuum chamber

Cooling channels on both sides of the chamber are therefore required to avoid large thermal gradients (see Fig. 6) and the chamber is clamped to the magnet every metre to avoid distortions, as can be seen in Fig. 7 which shows the vacuum chamber mounted in the prototype concrete dipole. The radiation which leaves the aluminium is very hard and intense and would give doses exceeding  $10^9$  rads/year to the magnet. It is therefore proposed to coat the vacuum chamber with lead to reduce the radiation level by a factor of about twenty. Under these conditions the amount of nitric acid and ozone produced by ionization of the air is rather small and it is unlikely that the concentration of nitric acid can exceed the vapour pressure, so no condensation on machine components will occur.

The anodes of the linear pumps are made of five superimposed stainless-steel strips in which holes are punched corresponding to the pump cell diameter. These are placed between the titanium cathodes to produce a light, transparent structure which minimizes the heating due to scattered radiation ( $\Delta T < 30^\circ\text{C}$ ). The low bending field necessitates large diameter cells if the pump is to be ignited at the injection energy. The fringe field of the dipole enables holes of up to 50 mm diameter to be accommodated with, on average, 95% of the field on the beam axis. By suitable choice of the high voltage the pumps will always be ignited at the injection energy of 22 GeV corresponding to about 195 gauss at the pump cells (at even lower fields the ignition of the pumps depends on the speed and direction of the magnetic field cycle because of a hysteresis effect).

At higher fields, smaller diameter cells would be sufficient and even preferable since the pumping speed increases with the number of pump cells. Anode plates with mixed diameter holes ( $\varnothing = 50$  mm and 25 mm) were proposed to try and maximize the pumping speed over the whole energy range. Laboratory tests show that if the high voltage is optimized as a function of magnetic field, equally good results can be obtained with cells of a single diameter ( $\varnothing = 50$  mm). This is because in the case of the mixed diameter cells, the voltage cannot be separately optimized for each diameter and a compromise must be chosen.

Even when the linear pumps are carefully optimized, the pumping speed at injection is rather low ( $5-10 \text{ l s}^{-1} \text{ m}^{-1}$ ) so lumped holding pumps are required every 6 metres. A mild bake-out ( $150^\circ\text{C}$ ) is also envisaged, probably with superheated water in one of the cooling

channels. Glow discharge cleaning using the distributed pumps as electrodes would also be desirable to reduce the beam cleaning time (estimated as 1000 mA-hr.). Laboratory tests are under way to find suitable conditions under which the discharge propagates uniformly from the pump compartment into the beam compartment.

The vacuum chambers, which extend through two dipole cores are about twelve metres long and, because of the lead, weigh about 600 kg. The stainless steel connecting units have bellows and sliding RF contacts to provide a smooth transition for the beam-induced wall currents. These connecting units (with stainless steel flanges) are directly clamped to the aluminium flanges of the vacuum chamber using a new technique with a thick copper-alloy gasket which permits temperature excursions of up to 200°C (see Fig. 8). Several of these joints have been tested for a total of 400 thermal cycles of 200°C with excellent results.

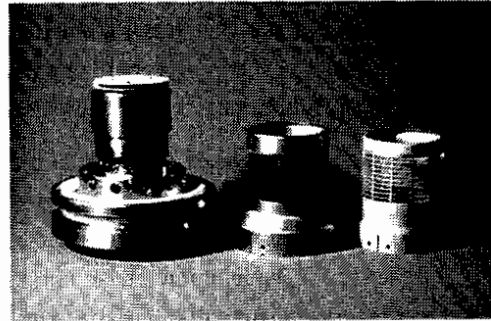
## 8. RADIOFREQUENCY SYSTEM

The performance of LEP is based on the use of the klystrons at 353 MHz, the lowest frequency that can economically be accepted. An alternative idea of using pulsed tetrodes is also being pursued and for this system a lower frequency (200 MHz) is possible. Superconducting cavities are the only hope for reaching the maximum energy of LEP (130 GeV) and recent developments on single cells at relatively low frequencies (500 MHz) have been most encouraging. However, the step to industrial production of fully equipped multi-cell cavities is not yet in sight.

The nominal RF installation consists of 96 1 MW klystrons, each klystron being associated with eight five-cell slot-coupled copper cavities very similar to those in PETRA and PEP. Only about a quarter of this power is actually transferred to the beam and appears as synchrotron radiation while most of the power is dissipated in the cavities in order to produce the accelerating voltage required. In LEP, a low-loss storage cavity is coupled to the accelerating cavity<sup>14)</sup> and the system excited at both its resonant frequencies so the stored energy oscillates between the two cavities. The energy is all in the accelerating cavity when the bunches pass and spends, on average, half of the time in the low-loss environment, thus reducing the dissipation by a factor 1.5. Calculations and recent laboratory measurements at low power have demonstrated that adequate field flatness can be obtained with a single storage cavity per accelerating cavity.

Initial ideas for a cylindrical storage cavity were quickly abandoned due to the mechanical distortion of the end-plates under atmospheric pressure. The present proposal is to use a spherical storage cavity (Fig. 9) made of 5 mm thick copper sheet. The input power coupler, the cavity-cavity coupler and the ball tuner which ensures the correct field polarization are mutually orthogonal and the cavity, which is composed of two welded hemispheres, is split so as to avoid all the flanges. The cavity is cooled by water pipes brazed onto the outside, a solution which avoids welded or brazed water-vacuum separation.

The modulated power input is obtained by mixing the output from two klystrons operating at slightly different frequencies; the in-phase component is delivered to eight accelerating cavities via cascaded magic-tees, the out-of-phase component is similarly delivered to the storage cavities of another eight accelerating cavities. This has the advantage that all the power sources operate CW.



Tetrode  
the cathode with unmounted grids

Fig. 10 Prototype of the pulsed tetrode

Fig. 9 Spherical storage cavity being tested

A 500 MHz test stand is currently operating at CERN consisting of a 250 kW Thomson CSF klystron, kindly made available by DESY, and a single five-cell cavity. A spherical storage cavity has now been completed and is being installed for high power tests of the coupled cavity system. A 353 MHz, 0.5 MW klystron has been delivered from SLAC and orders for two prototype 353 MHz 1 MW klystrons have been placed with two different European manufacturers. A 353 MHz clamped aluminium cavity is presently being evaluated prior to ordering the first copper cavity.

A parallel development is being carried out on a 200 MHz system using pulsed tetrodes<sup>15)</sup>. Single cells are proposed, each with their own tetrode which are pulsed just prior to the passage of the bunches. A large fraction of the stored energy is extracted by the bunches and the fields in the cavity then decay until the next pulse. By modulating the anode with a ringing circuit, it is possible to match the tetrode to the cavity during the pulse to improve the efficiency.

A maximum of about 4000 tetrodes would be installed so they must be cheap and reliable and the power conversion efficiency must also be high. A contract has been placed with European industry for the development of such a tube and the first prototype has been delivered (see Fig. 10). Orders have also been placed for the single cell accelerating cavities and the resonant tetrode enclosure so that a complete model system should be operative by autumn 1980. It is hoped that a detailed evaluation of the system will be available by the middle of 1981. The pulsed tetrode system would have a higher power-conversion efficiency than klystrons and, since the waveguide maze is not needed, would lead to a reduction in the tunnel requirements.

The power dissipated in the cavities can be virtually eliminated by the use of superconducting cavities enabling a much higher energy to be reached with the same installed RF power. The recent results obtained with superconducting single cells are reported elsewhere in this conference<sup>16)</sup> but some points relevant to LEP should be noted.

Firstly, accelerating gradients in excess of 3 MeV/m can now be obtained routinely in single cells at 500 MHz with no degradation in the Q-value due to electron loading and with breakdown never occurring below 4 MeV/meter. For comparison, a gradient of 5 MeV/m corresponds to the energy limit of LEP for which all the other components are designed. The presently obtained Q-values in 500 MHz single cells at 3 MeV/m are about  $2 \times 10^9$  at 4.2°K, half the theoretical limit. The single cell cavities are therefore rather close to attaining performance acceptable for LEP. The construction of multi-cell structures is now going ahead and the first tests are scheduled for the beginning of 1981.

The cryogenics system required is a significant problem in its own right. A preliminary estimate of the compressor power is about 50 MW for a Q of  $1.3 \times 10^9$  and the helium distribution system must be correspondingly dimensioned.

## 9. CIVIL ENGINEERING

The LEP ring and the experimental areas are underground and by passing all services through the tunnel will cause little disruption to the local environment, and, like the SPS, the tunnel will be excavated by full face boring machines. Two thirds of the tunnel are in molasse of which CERN has considerable experience and about thirty borings have been made around the planned trajectory to determine its exact depth. The remaining third is in limestone of the Jura about which little is known so it is planned to bore a reconnaissance tunnel to gain information on the difficulties that may be encountered.

Since the access points are almost four kilometres apart, the tunnel width (four metres) must be adequately dimensioned to permit rapid installation of the machine components (see Fig.11). The height of the beam is only eighty centimetres above the floor and this leaves space for the eventual installation of a superconducting proton ring above the electron ring as well as helium transfer lines for superconducting RF cavities and/or magnets.

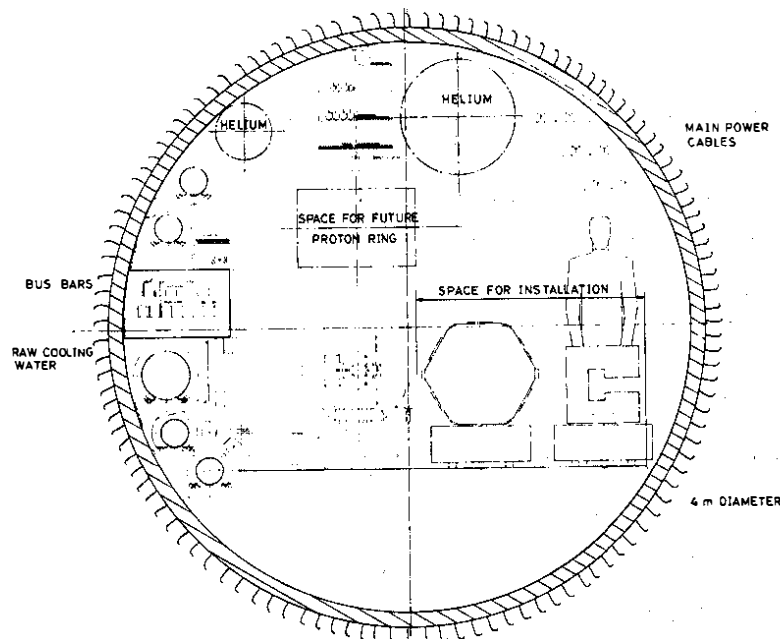


Fig. 11 Tunnel cross-section

The size of the experimental areas are based on estimates of the future LEP detectors and the experience gained from the two halls being built at the SPS for the pp colliding beam experiments. Some of the areas will permit two full sized detectors to be operated in push-pull mode as is the case in one of the PETRA halls. The halls proposed in the Pink Book are being used for cost estimates but the final designs will be delayed as long as possible to take into account the latest detector developments.

Access to the five experimental areas in the plain is by vertical pits, while for three areas under the Jura approximately horizontal access shafts are preferred (one of which would probably be the reconnaissance tunnel). The installation of the machine and access to the ring is via the same shafts. Surface buildings will house the rectifiers, power supplies, substations, cooling, controls, ventilation equipment etc. and will be the only part of LEP visible on the surface, all services and interconnections passing via the tunnel.

#### 10. FUTURE PROSPECTS

At the CERN Council session on 27th June 1980, approval for the LEP project was formally requested from the delegates of the member states. It was decided that, if approved, LEP can be considered as part of the Basic Programme of the Organization and thus treated by the normal CERN budget procedures. This considerably simplifies the approval procedures and we now hope for the go-ahead in six to twelve months.

#### 11. ACKNOWLEDGEMENTS

This paper describes the work of a large number of people whose names may be found in the Pink Book. We at CERN would particularly like to thank our colleagues in other laboratories who have collaborated on the project.

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