SUPERCONDUCTING ACCELERATION SYSTEM FOR LEP

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INTRODUCTION

The Large Electron Positron Collider (LEP) is designed to obtain an energy of 100 GeV per beam, and to have the possibility to increase the beam energy to about 125 GeV.

The LEP machine construction will be carried out in phases and the precise future energy levels as well as the power dissipation depend on the development of superconducting RF technology. This is the reason why this Workshop is of great importance for the LEP designers. Any increase in energy will depend on the pressure to explore energies above the threshold of Z° production sooner than was foreseen a few years ago; a limitation will be the funds available to build the new RF system.

My contribution to this Workshop is to describe the superconducting RF acceleration system for LEP. The only acceleration system so far designed is the room temperature copper-cavity RF system; not only has it been designed, but prototypes have been built and contracts have been placed for series production. With this RF system it will be possible to reach about 60 GeV per beam at zero luminosity and 55 GeV at maximum luminosity. In this talk I will present some of our present-day thinking as to how to increase the LEP energy beyond the 60 GeV per beam level. Today, we are not yet ready to present the specifications of the superconducting RF acceleration complex. Too many unsolved problems remain and only at the end of 1985 will we be able to specify the technical characteristics of the superconducting RF system.

The LEP Project includes the construction of two Linacs and an Accumulator Ring (EPA), the necessary modifications to the existing PS/SPS machine complex to enable acceleration of electrons and positrons up to 22 GeV energy, and above all the construction of the main ring of LEP (see Fig. 1).

The circumference of the main ring of LEP is 26.66 km and four of the eight possible experimental areas will be built and equipped with sufficient technical infrastructure to enable the initial experiments to be installed and operated.

In view of the very tight budgetary constraints, initial investments are being strictly limited to the minimum compatible with the aim of reaching about 60 GeV per beam. Investments in view of future extensions, such as the tunnels necessary for future ep operation (protons from the SPS colliding with LEP electrons), and those for the initial RF system, except in points 2 and 6, have been suppressed. The "push-pull" experimental areas were abandoned in favour of simple caverns in view of the growing tendency to build general purpose detectors rather than experiments which would be changed over rapidly. The number of the caverns to be excavated is limited to four, situated at points 2, 4, 6 and 8 (see Fig. 2).

The final choice of circumference and the location of LEP were guided by the geology of the Geneva area. With respect to the Pink Book[1]) this is one of the major changes. Another important change is the use of the PS and SPS as injectors. Since the synchrotron radiation losses are proportional to the fourth power of the energy and the inverse of the bending radius, the reduction of the circumference from the 30.6 km, as described in the Pink Book, to 26.7 km in order to avoid geological difficulties had, as a consequence, that the "ultimate" electron energy decreased from 130 to 125 GeV per beam.

1. The Injector

The 200 MeV electron linac consists of a high-intensity gun, a standing-wave buncher, and four travelling-wave S-band sections. Its intense electron beam produces the positrons in the converter target, just upstream of the 600 MeV low-intensity linac which has 12 travelling-wave sections nearly identical to the sections of the first linac. The electrons for electron filling of LEP are produced by a low-intensity gun located near the converter. Both linacs deliver 12 nsec-long beam pulses at a repetition rate of 100 Hz. The length of the two linacs is approximately 100 m. The linacs are built in collaboration with the Linear Accelerator Laboratory at Orsay, Paris.

The EPA is a buffer between a fast-repetition rate machine and a slow cycling machine. The linac pulses are stored in eight bunches of the 600 MeV

EPA, which has a circumference of 126 m, i.e. one fifth of the PS circumference.

Since the PS is a combined-function machine, in order to avoid beam instability in the PS, a Robinson wiggler must be installed in the PS to control the damping partition. The wigglers together with the additional RF system for acceleration needs straight-section space, which is scarce in the PS. For this reason, it cannot be envisaged to accelerate particles much above 3.5 GeV in the PS. Since the electron/positron emittances are rather smaller than the proton emittances, the particles can be accepted by the SPS at this relatively low energy.

The positrons are sent to the SPS via the existing proton beam line and the electrons travel through the antiproton beam line. The particles are accelerated to about 20 GeV in the SPS by an additional 200 MHz RF system consisting of 32 single-cell cavities and they are extracted from the SPS and injected into LEP through two new transfer channels.

2. The underground civil engineering

The main tunnel consists of eight arcs and eight straight sections, the latter containing the beam collision points. The underground system will consist of a 26.7 km long tunnel with an internal cross-section diameter of 3.76 m. This will lie for approximately 10% of its length in the limestone strata, and for 90% in the molasse. Along this tunnel at locations corresponding to five of the eight beam collision points, will be constructed: the experimental zones at P2, P4, P6 and P8, each incorporating service halls; an equipment hall at P1 and injection tunnels, to allow particle transfer from the SPS complex; additional galleries running parallel to the main tunnel at P2 and P6 to house the klystrons, their power supplies and other RF equipment. Access for personnel and equipment to these tunnels and halls will be by one or more shafts sited at, or close to, the interaction regions (Fig. 3). For more details see Reference 2.

Few more words are needed to explain the RF sections of the main tunnel and the klystron, junction and liaison tunnels. Figure 4 gives an artistic view of one of the four experimental zones of the LEP machine. The surface buildings communicate with the experimental hall located at about 100 m below ground level through vertical shafts. The first shaft of the figure will be used to install the machine elements; the shaft in the middle communicates with an assembly hall and with an experimental hall and the third shaft is for personnel access. Three shafts are generally required to keep pace with the machine installation schedule. Our goal is to have the first collisions between electrons and positrons around the end of 1988.

On either side of points 2 and 6 (Fig. 3) an enlarged tunnel cross-section is required in order to accommodate the RF accelerating and storage cavities. The excavated diameter is increased to 5.04 m to permit a finished internal diameter of 4.40 m.

Running parallel to the RF sections there will be additional tunnels, of a total projected length of approximately 850 m and an internal diameter of 5.50 m, to house the klystrons. They will be connected to the RF tunnel by junction chambers, for the access of personnel and equipment, and by tubular passageways to accommodate the RF wave guides, as shown in Figures 5 and 6. Liaison tunnels will be constructed to allow direct access from the junction chambers and klystron tunnels to the underground halls.

4. Magnet and Vacuum Systems

The magnet system must provide a precise configuration of guiding fields along more than 22 km of beam path. The design and structure of its components are therefore dominated by economic constraints and in an effort to reduce material and installation costs to a minimum, unconventional constructions have been chosen for the main elements, namely the dipole cores and the excitation systems of the dipoles, quadrupoles and sextupoles. The designs based on this unconventional technique have lead to substantial financial savings[3]).

The main pumping system is based also on a novel technique, i.e. the non-evaporable getter (NEG) strip, installed in a pumping channel which runs along most of the vacuum chambers. Its pumping is limited to reactive gases. Noble gases (Ar, He) and CH_4 are not pumped and require additional sputter-ion pumps[3]).

It is not my intention at this Workshop, dedicated to superconducting RF technology, to comment on the different aspects of the project. An upgraded description of the project can be found in the Green Book[3]. I should simply mention that the construction of LEP is advancing according to plan and about two-thirds of the capital investment foreseen has been committed. The more important contracts have been signed to my satisfaction.

4. The Copper Cavities of the RF System

Before explaining our present thinking on the superconducting RF system, let me mention the copper cavity acceleration system (N.C.) that will be installed initially in LEP to achieve 60 GeV per beam[3].

The accelerating structure consists of 128 coupled-cavity units made of copper, each unit containing a five-cell accelerating cavity, side-coupled to a single-cell, spherical storage cavity. This structure is powered by a total of 16 klystrons, each of 1 MW nominal continuous-wave (C.W.) output power. The operating frequency is 352.21 MHz, corresponding to the 31320^{th} harmonic of the LEP revolution frequency. The nominal value of peak RF voltage per revolution is 400 MV at zero beam current.

The RF system is grouped in a pair of stations on either side of collision points 2 and 6. In each of the four stations the accelerating structure occupies four lattice half-periods (i.e. the space between adjacent quadrupoles), each half-period accommodating a group of eight cavities (Fig. 7). Two more half-periods are set aside for future superconducting cavities. Table I gives the characteristics of the main RF system (copper cavities). Figures 8, 9 and 10 show the schematic and the model prototype of a five-cell copper cavity.

The five-cell accelerating cavity forms a single unit, its Q-factor, without storage cavities, is about 40,000 and the effective shunt impedance per unit active length 26 MΩ/m. The large bunch spacing of 22 μsec permits an appreciable increase of shunt impedance by means of storage cavities[4]. The spherical storage cavity[5] is excited in the lowest H-mode, and is coupled to the central cell of the accelerating cavity. The storage cavity is tuned to the H-mode frequency f_π, as is the accelerating cavity. The coupling between these two resonators leads to a split of the resonant frequency into two frequencies f_1 and f_2, closely spaced. The Q-factor of the storage cavity, made of copper, is about 160,000, and the effective shunt impedance per active length of the coupled cavity unit is increased to 40 MΩ/m. The use of the storage cavity thus leads to a gain of about 1.5 in shunt impedance and hence a reduction by the same factor in RF power loss for a given voltage and structure length.

Table I

Characteristics of the main RF system (copper cavities)

Frequency	352.20904 MHz
Wavelength	0.8711776 m
Harmonic number	31320
Number of five-cell cavities per module	8
Cavity active length (5.√2)	2.1279 m
Module active length (20)	17.02355 m
Module physical length (24.)	20.42826 m
No. of klystrons per module	1
Nominal RF power at klystron output	1.0 MW
Waveguide losses	7.5%
Beam hole diameter	100 m
Interaction areas equipped with RF	P2 + P6
No. of RF modules and klystrons	2 x 8
No. of five-cell cavities[a)]	128
Active RF structure length	272.377 m
Effective shunt impedance of accelerating cavities[b)]	26 MΩ/m
Effective shunt impedance with storage cavity	40 MΩ/m
Maximum accelerating voltage[c)]	401.6 MV
Available RF power at cavity window	14.8 MW
Maximum accelerating gradient[c)]	1.474 MV/m
Filling time of coupled systems	56.5 μs
Cavity input coupling	1.21
Fundamental mode loss parameter	0.158 V/pC

a) each coupled to a storage cavity

b) defined as $V^2/P \cdot L_c$

c) zero beam current

5. A Superconducting RF System

Any increase in the LEP energy will be obtained by installing superconducting cavities in the RF tunnel.

5.1 Choice of Frequency

I assume that the frequency of the superconducting system will be the same as the copper cavity system, i.e. 352.2 MHz. Table II shows a few parameters.

Table II

Characteristics of the Superconducting RF System

Frequency	352.21 MHz
Wavelength	0.8511 m
R/Q	278 Ohm/m
Q_o	3×10^9
Iris opening	240 mm

a) The choice of the frequency depends on the possibility to run the cavities at about 7 MV/m, if one has the aim to operate them at 5 MV/m.

The choice of 352.2 MHz will allow the use of the klystrons, the auxiliaries, the RF distribution system, the drivers, the controls, the interlocks, the interfaces and the main power supply designed for the room temperature (copper cavities) system. The use of these items will contribute to reducing the cost of the development and design and to redeploying a number of the personnel involved at present in the construction of the room-temperature RF cavities.

b) To be able to install the eight cavities in the existing half-cells, the number of cells per cavity had to be reduced to four, to provide for the extra length of the "cold-warm transitions" in superconducting cavities.

c) In the "long" half-cell (36.4 m, Fig. 11) synchrotron radiation suppressors and cryopumps will be added.

d) The effective length of each superconducting RF four-cell cavity is l_{eff} = 1.7 m. In each half-cell the active length will be, therefore, 13.6 m.

5.2 Cryogenic Power

It is assumed that cryogenic power will be installed in the LEP machine to allow a gradient at least up to 5 MV/m.

One gets for the power dissipated per unit length

$$\frac{P_{diss}}{L} = \frac{E^2_{acc}}{(R/Q)Q_o} = 30\ \mathrm{W/m}$$

About 10 W/m is added to this figure to provide for the cryostat, the couplers and the He transfer line losses. The total cryogenic power per meter therefore will be 40 W/m, implying 544 W of cryogenic power to operate the cavities in each half-cell (i.e. eight times four-cell cavities).

I should like to point out that the optimal gradient to operate LEP has not yet been studied. It is not clear to me whether E_{acc} = 5 MV/m is the optimal choice, especially if the superconducting RF cavity is able to support a field gradient greater than 7 MV/m up to, let us say, 8 to 10 MV/m. An optimization study is required before the final choice of the frequency and gradient to operate the superconducting cavities is made.

5.3 RF Power

The predicted value of the current, in the initial phase of LEP operation, is 3 mA per beam. If one neglects the higher order mode losses, and if one assumes a value of 125° in the stable phase, then 24.6 kW/m of RF power is required for the two circulating beams. This value implies a total RF power per half-cell of 335 kW.

I should like to recall that the klystron specification calls for normal operation at 1 MW output with 90 kV d.c. input, a nominal efficiency of 68% and the capability of delivering 1.1 MW of test power. With each klystron we will power two half-cell superconducting RF cavities, i.e., 16 four-cell superconducting RF cavities. The output power will be sufficient to power the 16 cavities, including the case of a circulating current of 4 mA per beam (always at 5 MV/m).

6. Total Power, Circumferential Voltages and Energies

In regions 2 and 6 we will install four half-cell superconducting RF cavities (Fig. 11), to be added to the copper-cavity RF system. The total number of half-cells equipped with superconducting RF cavities therefore will be eight, and the total number of four-cell cavities will be sixty-four. The total effective length of the cavities will be one hundred and nine metres. The total RF power required is 4 MW, which includes some reserve, i.e., the possibility to increase either the circulating current or the accelerating gradient. The total refrigeration power is about 6 kW. The RF power at the mains, with a total efficiency assumed to be 60%, is 6.7 MW and for the cryogenics 3 MW power at the mains is required if a technical conversion efficiency of 1/500 is to be reached. The above system will require a total power at the mains of 10 MW.

When points 4 and 8 are excavated, they will be filled with superconducting RF cavities. Table III gives the major characteristics of the main RF system in points 4 and 8.

Table III

Superconducting RF System in Points 4 and 8

No. of half-cell superconducting cavities	24
No. of 4-cell cavities	192
Total effective length	326 m
Total RF power (12 klystrons)	12 MW
Total refrigerator power	16 kW
Power at mains for RF (60%)	20 MW
Power at mains for cryogenics	8 MW
Total power at mains	28 MW

Let me recall that a maximum gradient of 1.47 MV/m will be provided by the copper-cavity system (accelerating cavities side-coupled to storage cavities). The maximum circumferential voltage is about 402 MV (see Table I). For the main RF system and for a quantum lifetime of 24 hours one obtains a circumferential voltage of 360 MV at 55 GeV/c, taking into account high order mode losses[3]. This value allows to establish an approximate relationship between the circumferential voltage and the particle energy[6]:

$$E(\mathrm{GeV}) = 12.63 \sqrt[4]{U(\mathrm{MV})} \qquad (1)$$

In Table IV the values of the circumferential voltages and particle energies are given.

Table IV

Circumferential Voltages and Particle Energies

		U_{max}	E
LEP Phase I	Regions 2 & 6 With 8 half-cell N.C. each (1.47 MV/m)	402 MV	56.5 GeV
LEP Phase II (A)	Regions 2 & 6 8 half-cell N.C. + 4 half-cell S.C. (5MV/m)	946 MV	70.0 GeV
LEP Phase II (B)	(as in (A)) + Regions 4 & 8 (12 half-cell S.C. each) 5 MV/m)	2,580 MV	90.0 GeV
LEP Phase II (C)	All S.C. (2, 4, 6, 8) at 5 MV/m	3,260 MV	96 GeV

I should like to point out that

i) I have left eight half-cells unoccupied, in the superconducting RF acceleration system, because I assume that this half-cell will be needed to install the third harmonic system,

ii) I have assumed that the optimal choice of the accelerating gradient is 5 MV/m. With the help of formula (1) one can evaluate the energy that can be reached in the case that either higher gradients will be used or more length will be available,

iii) In order to attain the ultimate energy of 125 GeV superconducting cavities at 5 MV/m gradient have to be installed in all eight straight sections.

Any increase in energy requires not only the installation of the necessary superconducting cavities in the LEP tunnel, but further, more or less major, modifications to the machine and/or new excavations.

7. Tentative Planning of the Superconducting RF System

As mentioned at the beginning of this talk, LEP is a storage ring of 100 GeV per beam, at least. I suppose that this energy will be reached in successive steps, and how to obtain these steps will be decided in due course. Let me deviate a little from my usual caution and put forward a, perhaps not too realistic, planning.

It is my duty to urge you to speed up the research and development presently being carried out in your laboratories, to achieve the knowledge in superconducting RF that allows the expert to design, specify and, with the help of industry, produce the accelerating superconducting RF system needed for a machine like LEP.

If we want to install such a system in the LEP tunnel relatively soon a major effort is needed to solve problems of great importance, such as how to produce an inexpensive cryogenic system, as well as a high degree of security and reliability of the system. I would, however unrealistic it may seem, like to present a rather optimistic planning.

If, under the careful guidance of Ph. Bernard and H. Lengeler, the CERN experts were able to choose the frequency and the technique to build the cavities (either bulk Niobium or Copper sheets internally Nb sputtered) by the end of 1985, i.e. one and a half years from now, the year 1986 could be used to write the technical specifications, to analyse the offers and to negociate the contracts with industry.

To manufacture up to about two hundred and sixty-four cavities, with the associated cryogenics, would require about four years. If this assumptions proved correct, the cavities could be ready for installation at the end of 1990.

I do realize that this planning is very unrealistic since it takes no account of the stringent financial constraints. The money, and probably the personnel, required will not be available. Moreover, to install all the cavities at once requires a long shutdown (probably one year), one year of excavations, in areas 4 and 8 (the excavation could be carried out in parallel with the operation of LEP), and major changes in the machine components (such as power converters, new coils for the dipoles at the injection sections, redesign of a low-ß section etc.).

I am convinced that it is unreasonable to foresee a full upgrading at once. It would be more realistic to assume that only sixty-four cavities will be produced and installed at the beginning of LEP operation.

Figure 12 shows a tentative planning, based on the assumption that the first e^+e^- collisions will take place at the end of 1988 and that the present phase of LEP construction (about 60 GeV) will be "completely" paid for at the end of 1989. To be able to follow this planning requires a readjustment of the LEP expenditure profile. How this could be achieved is not easy to foresee at present, at such an early stage of the construction. I am convinced that better planning will be possible in one or two years from now and I am confident that at least a few units (about twenty to thirty cavities) will be installed at an early stage in LEP operation.

It is extremely important that the designers of the LEP superconducting RF system be ready to specify their system not later than 1986 if we are to reach:

70 GeV in 1991

and

85 GeV in 1992/1993

It is obvious that the planning could be speeded up if different assumptions, with particular regard to the budget and the organization of the personnel, are made. To be allowed to make different assumptions will depend on the budget constraints and it is too early to speculate about that now.

I hope that my brief passage at this Workshop has conveyed to you my personal feelings and my enthusiasm to see a superconducting RF system of sizeable dimensions installed in a big machine such as LEP in the not too distant future. We must be aware that to achieve this goal requires the well-oriented efforts on the part of those persons involved in the research, development, design and production of such a system, and, last but not least, a well-defined policy and the substantial support of the laboratories or agencies concerned.

My thanks go particularly to Ph. Bernard and H. Lengeler for the stimulating discussions we have had from the start of our collaboration a few years ago on this subject.

Figure Captions

Fig. 1 Schematic layout of the LEP Injector Chain. Of LEP, only the part around the crossing point 1 (P1) is shown.

Fig. 2 Location of the LEP tunnel.

Fig. 3 Schematic layout of the underground areas with a view of the shafts for personnel, installation and experimental equipment.

Fig. 4 Schematic design of one of the four experimental areas of LEP. The surface buildings are connected with the experimental hall located at about 100 m below ground through vertical shafts.

Fig. 5 Layout of point 6. The klystron gallery and the liaison tunnels are visible.

Fig. 6 Artist's impression of the straight sections and of the RF equipment.

Fig. 7 Plan view of an RF station.

Fig. 8 Accelerating cavity side-coupled to a single-cell storage cavity.

Fig. 9 View of a prototype cavity.

Fig. 10 View of one of the first LEP cavities assembled in the West Hall.

Fig. 11 Schematic diagram of one RF Station.

Fig. 12 Tentative (very preliminary) planning of the superconducting RF cavity production and installation.

References

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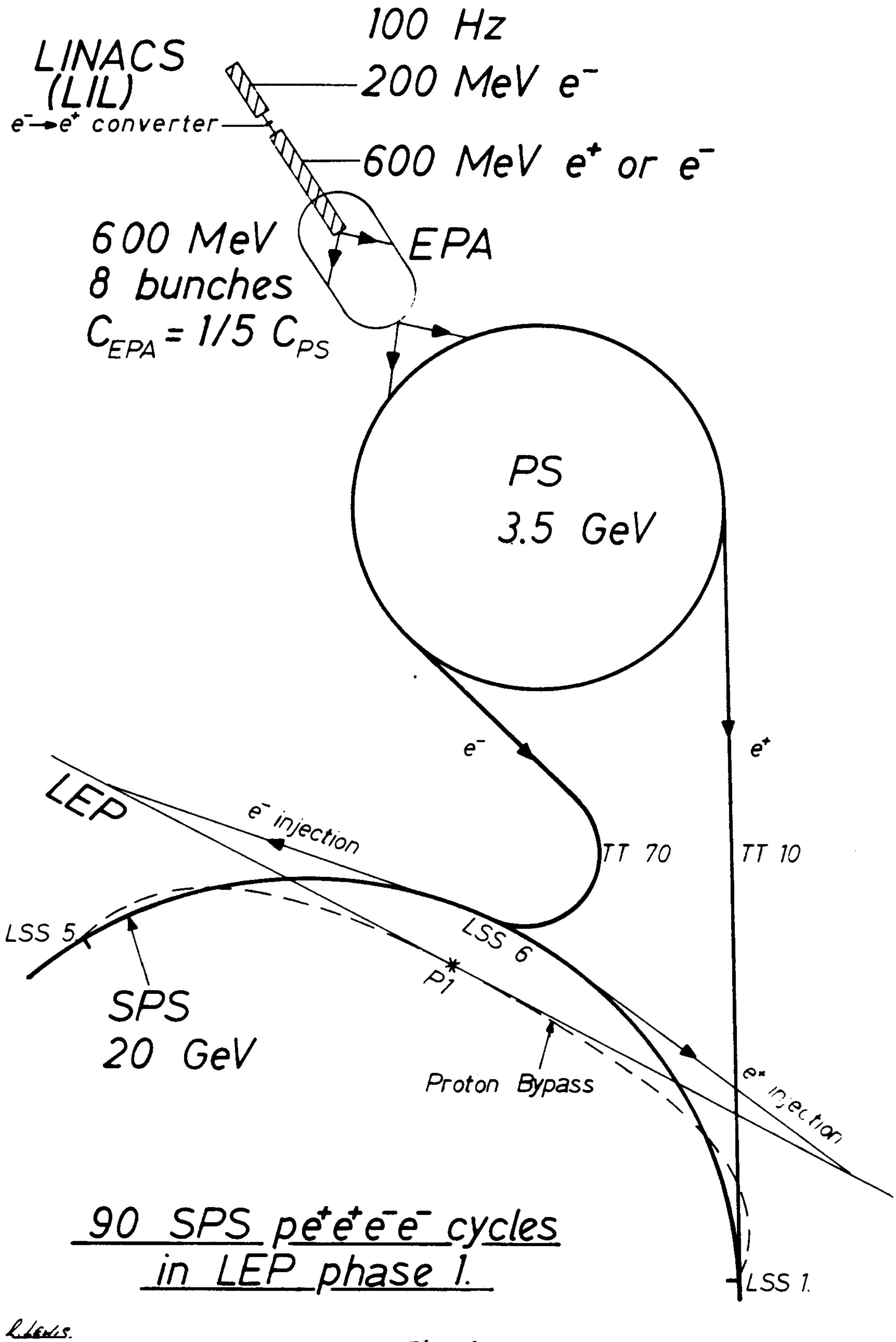
6. G. Guignard. LEP Parameter Note 9. 27 January 1984.


100 Hz
LINACS
(LIL)
200 MeV e⁻
e⁻→e⁺ converter
600 MeV e⁺ or e⁻
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C_EPA = 1/5 C_PS
EPA
PS
3.5 GeV
e⁻
e⁺
LEP
e⁻ injection
TT 70
TT 10
LSS 5
LSS 6
P1
SPS
20 GeV
Proton Bypass
e⁺ injection
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in LEP phase 1.
LSS 1.

Fig. 1

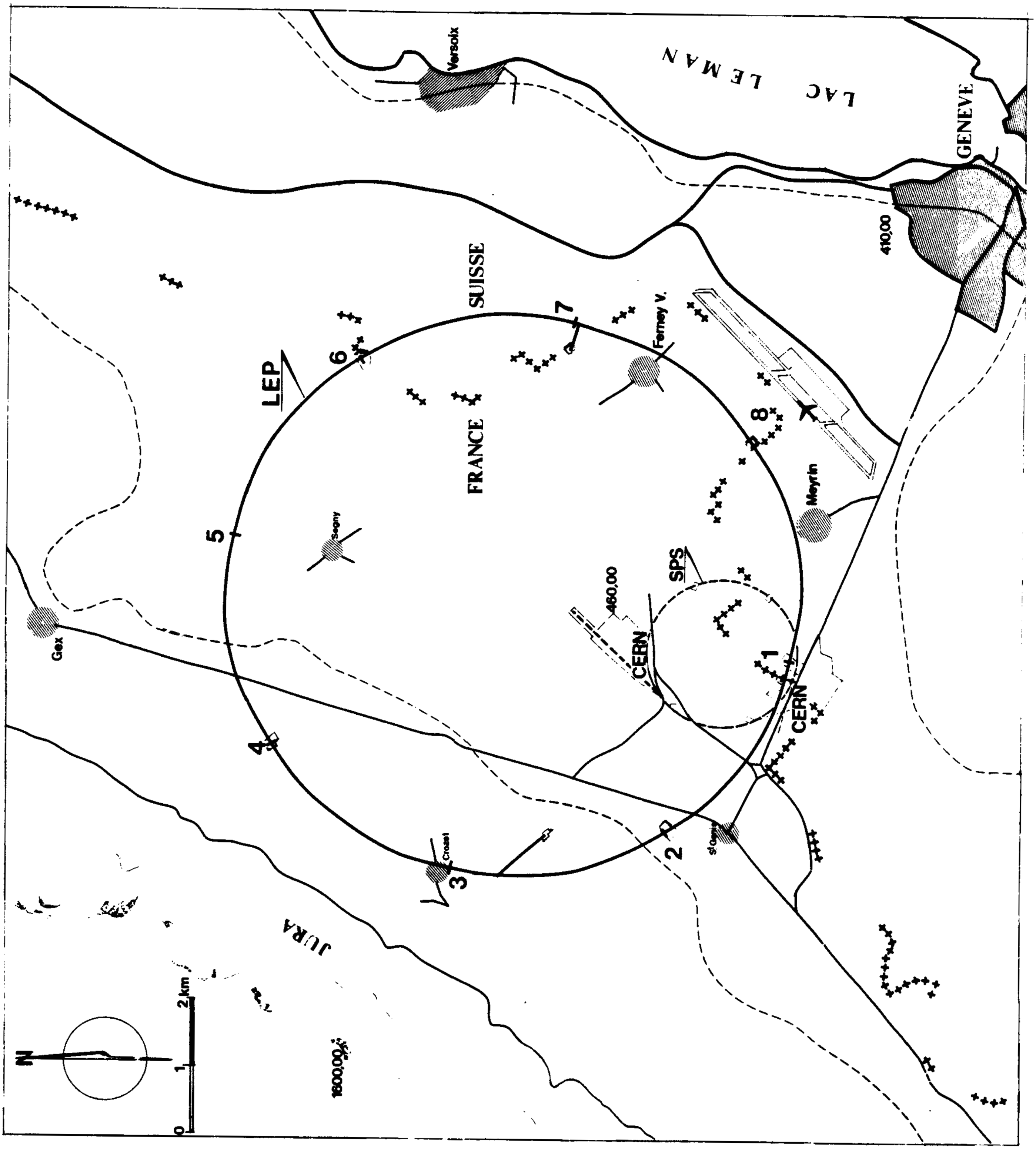
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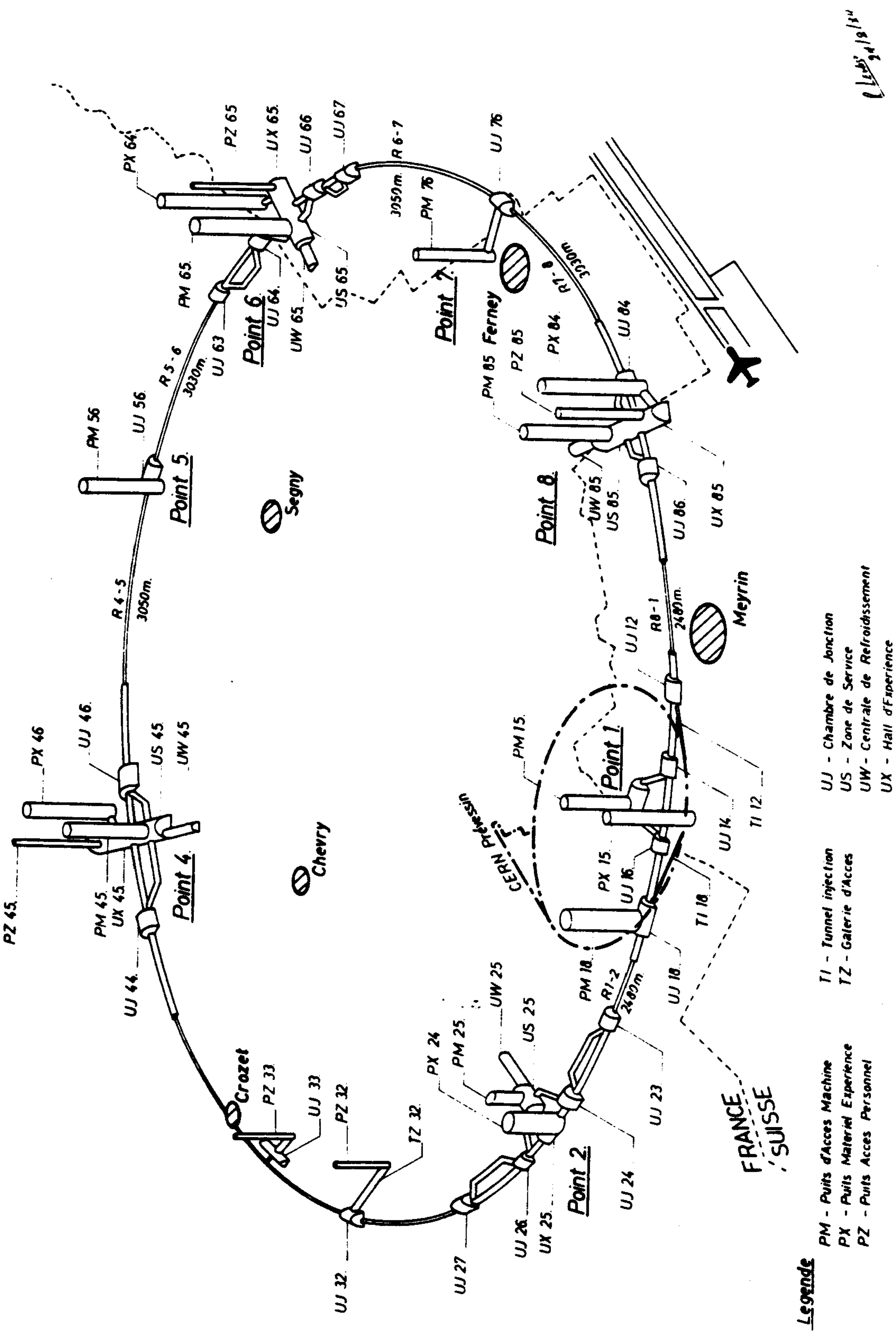
Fig. 2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R 8-1 2480m.
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Legende
PM - Puits d'Acces Machine
PX - Puits Materiel Experience
PZ - Puits Acces Personnel
TI - Tunnel injection
TZ - Galerie d'Acces
UJ - Chambre de Jonction
US - Zone de Service
UW - Centrale de Refroidissement
UX - Hall d'Experience

Fig. 3

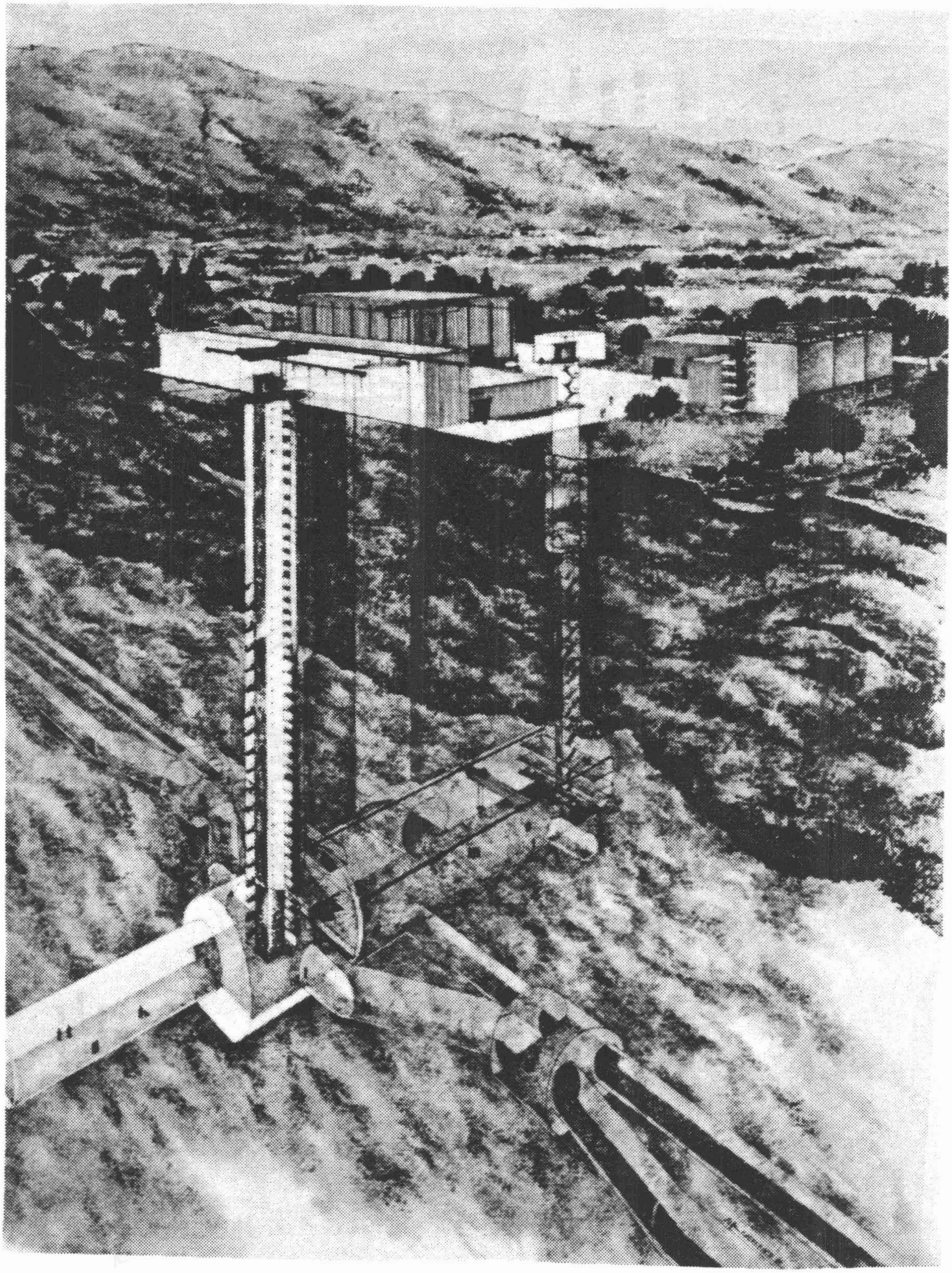
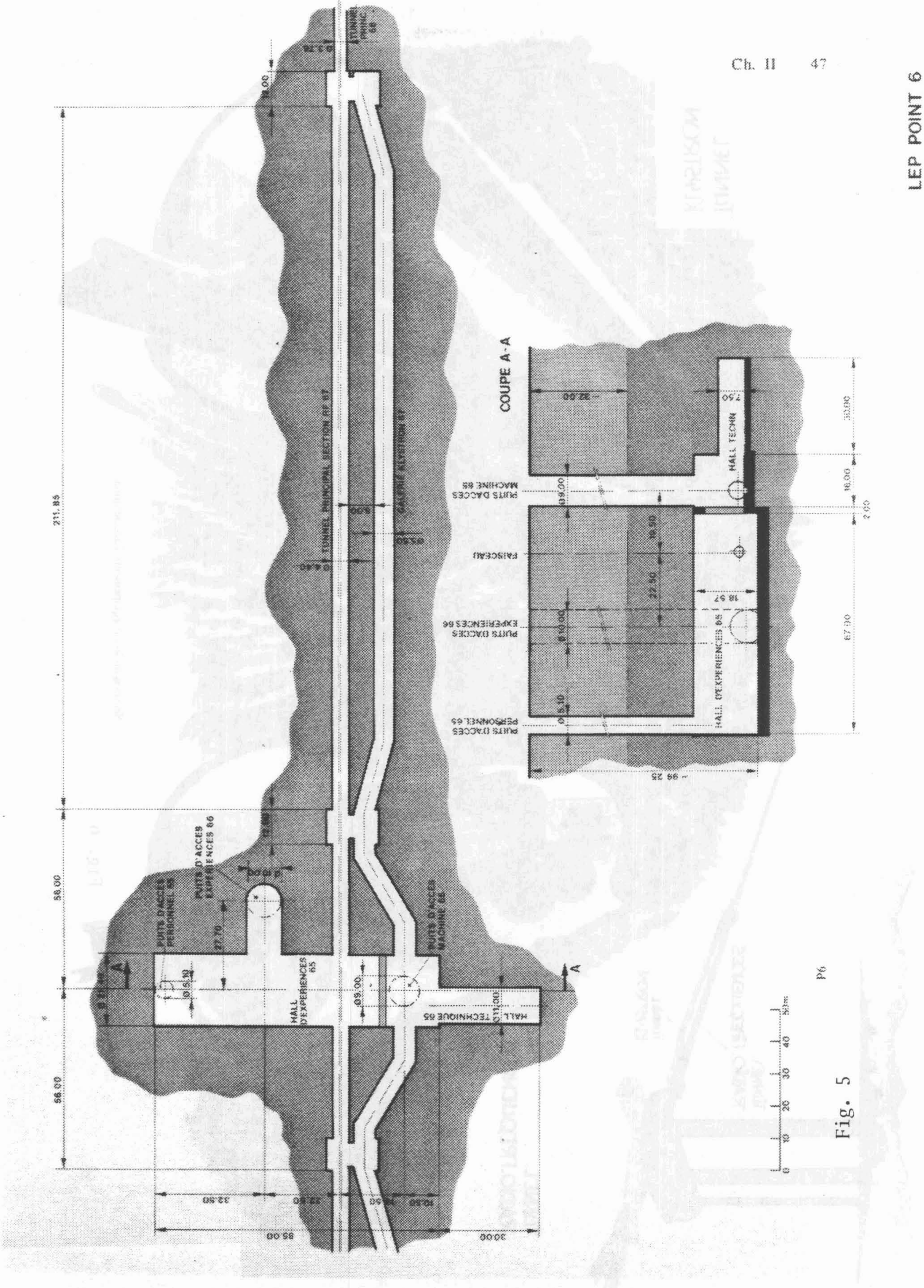


Fig. 4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LEP POINT 6
COUPE A-A
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GALERIE KLYSTRON 67
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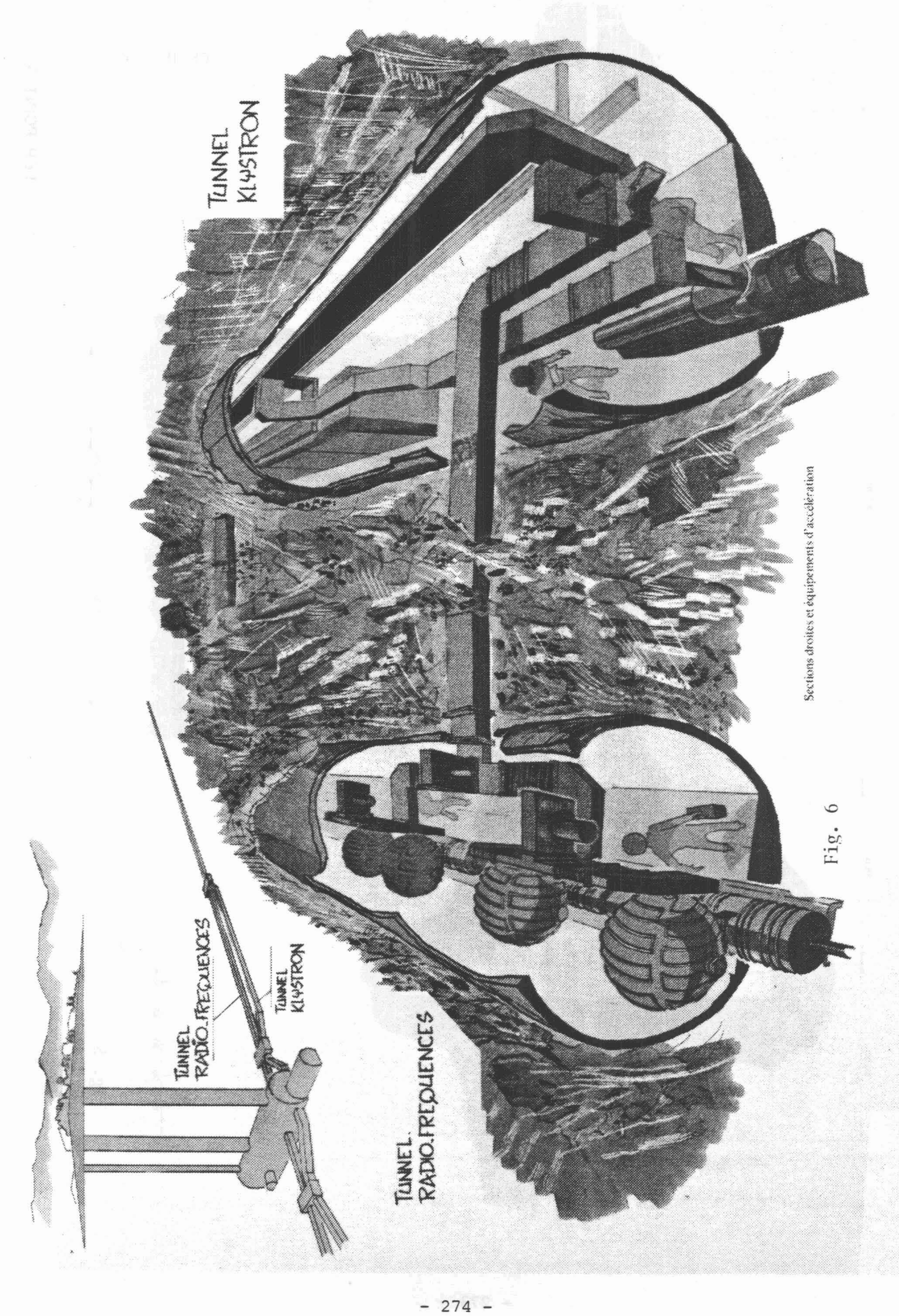
Fig. 5



Sections droites et équipements d'accélération

Fig. 6

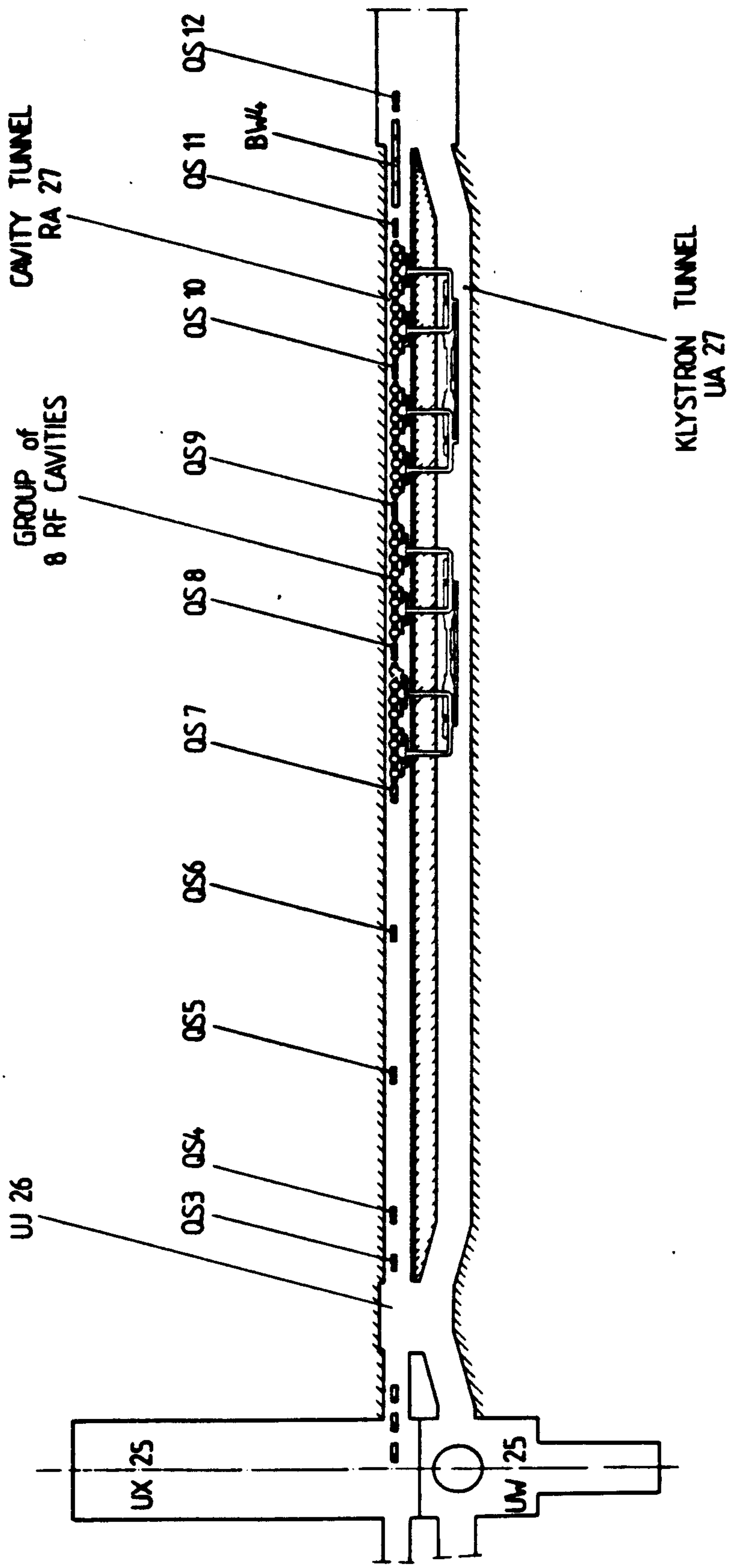

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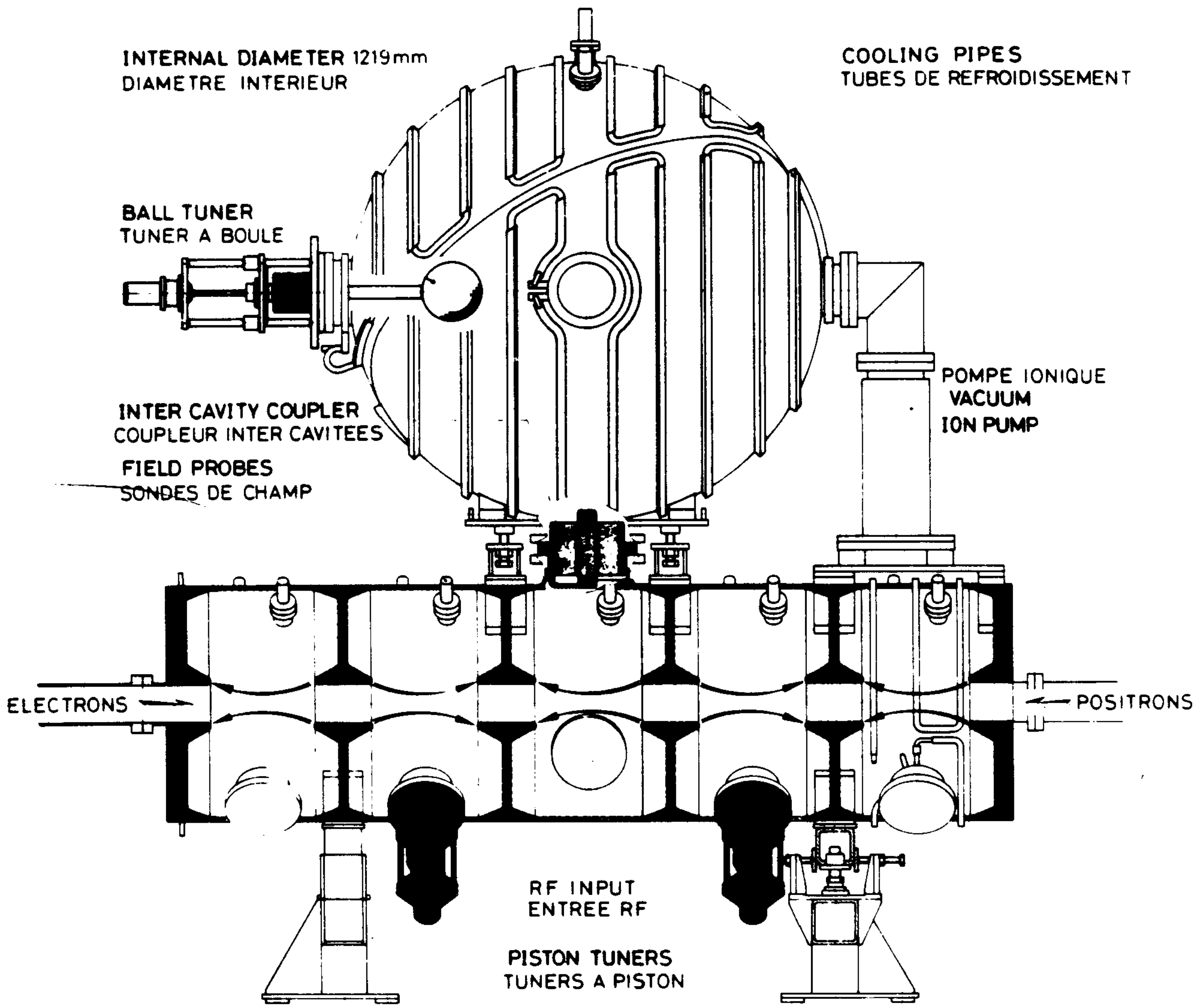
Fig. 7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ION PUMP
INTER CAVITY COUPLER
COUPLEUR INTER CAVITEES
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RF INPUT
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TUNERS A PISTON

Fig. 8

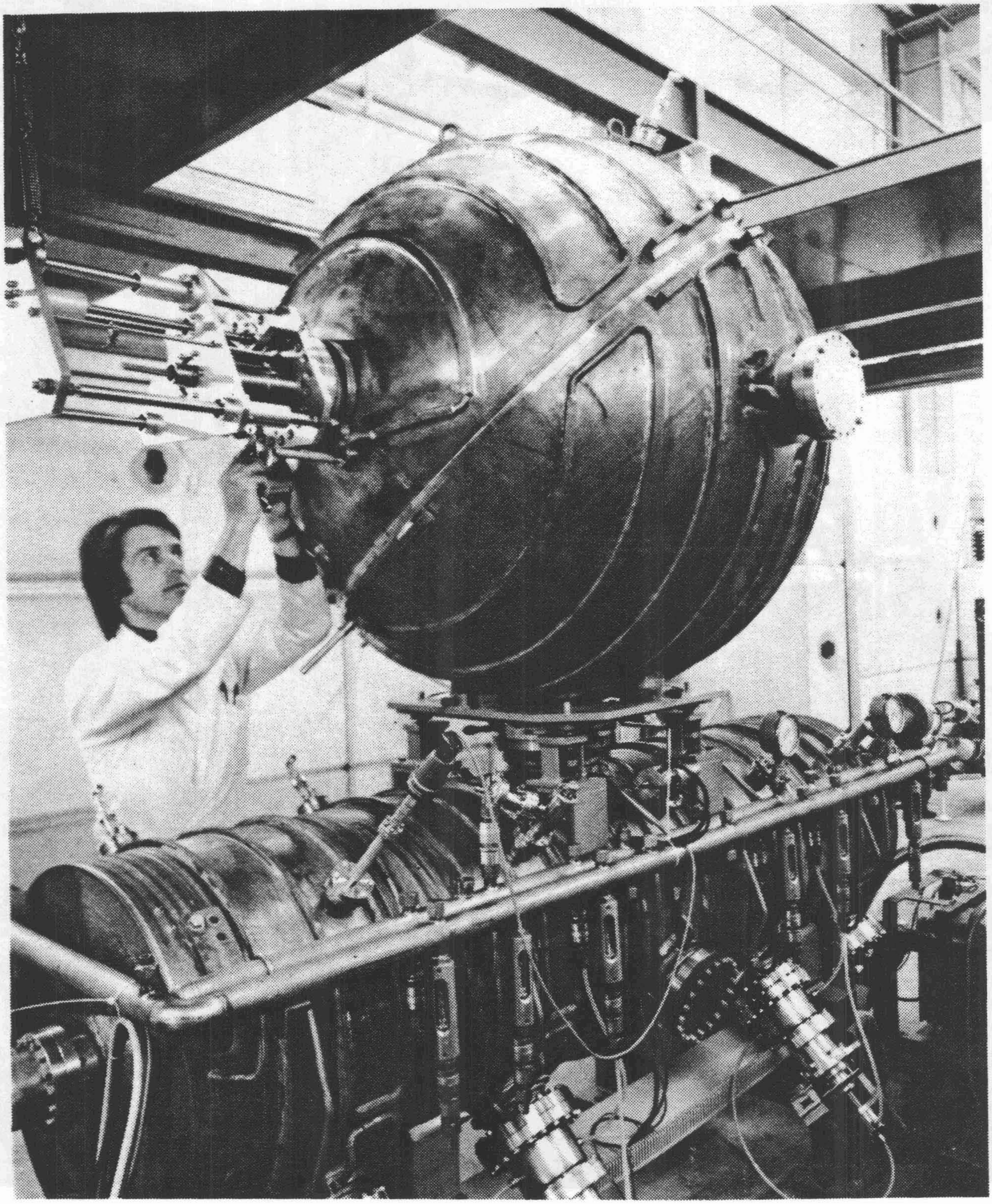


Fig. 9

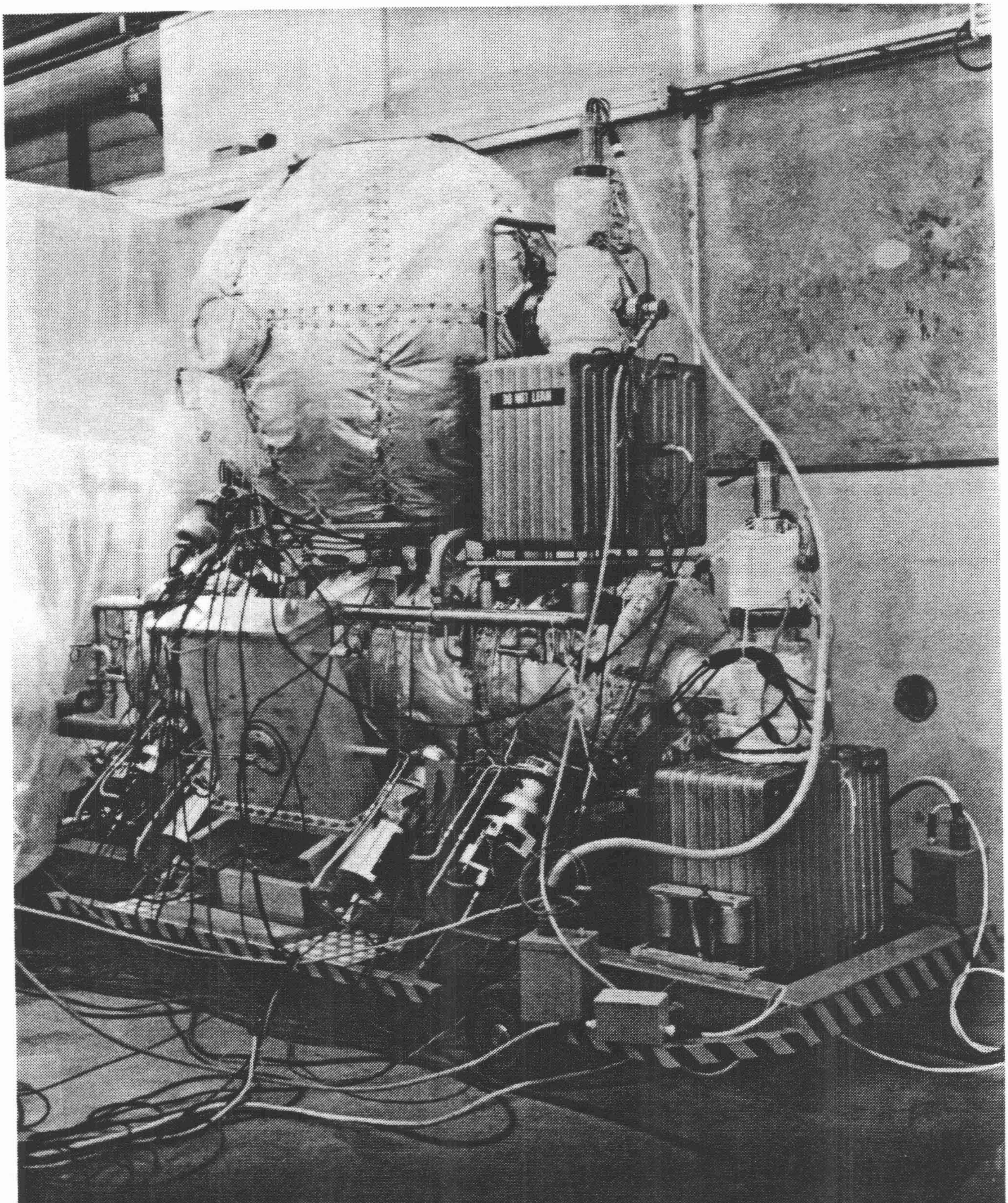
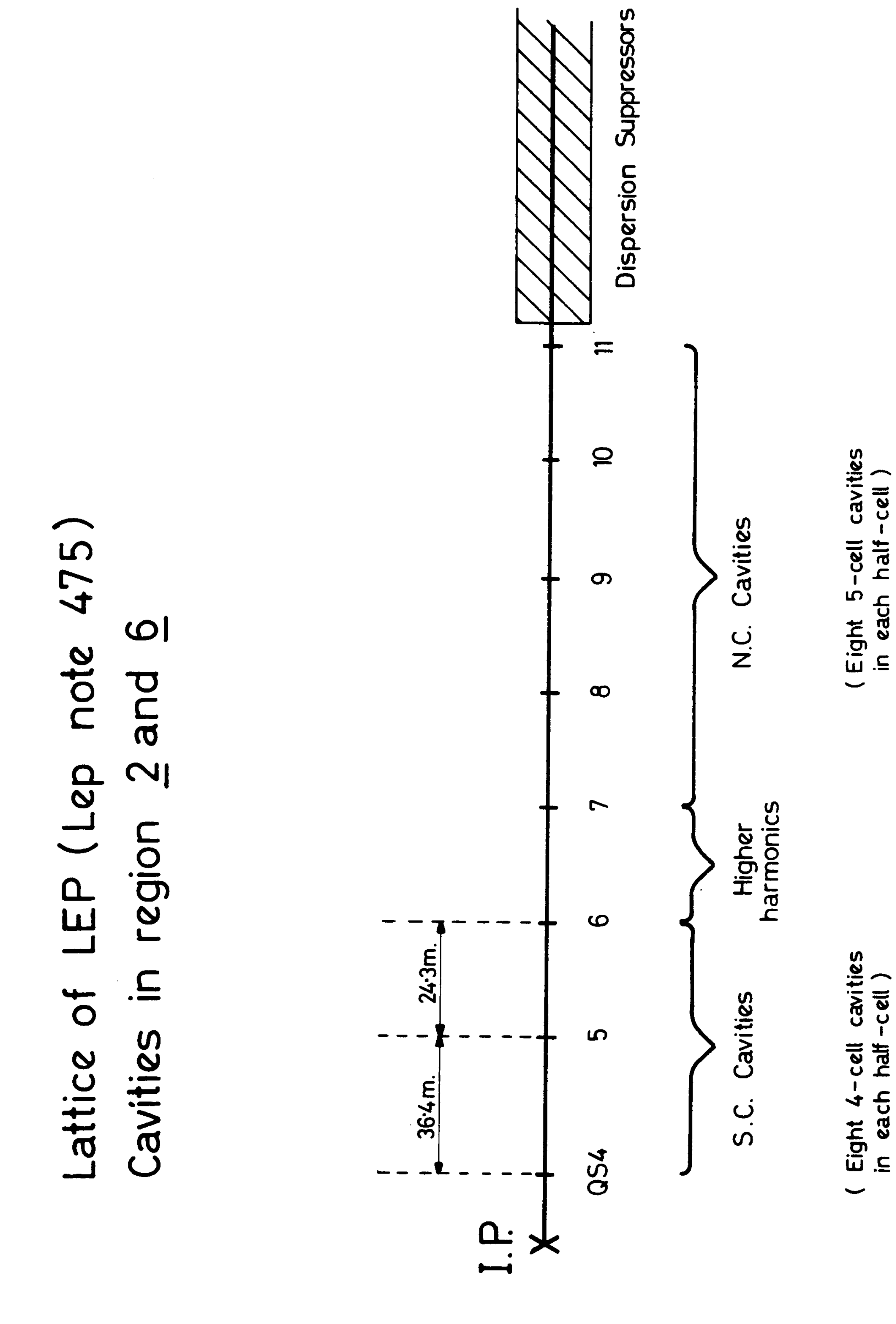


Fig. 10


Lattice of LEP (Lep note 475)
Cavities in region 2 and 6
I.P.
QS4
5
6
7
8
9
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36·4m.
24·3m.
Dispersion Suppressors
S.C. Cavities
Higher harmonics
N.C. Cavities
(Eight 4-cell cavities in each half-cell)
(Eight 5-cell cavities in each half-cell)

Fig. 11

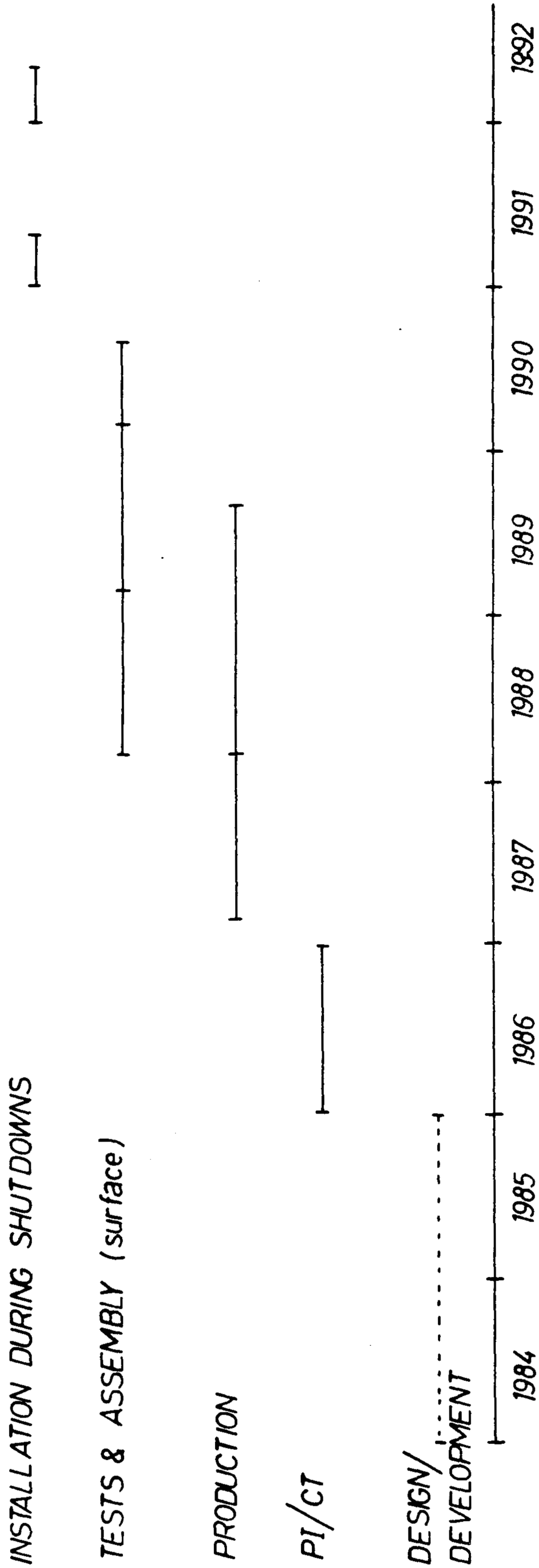
INSTALLATION DURING SHUTDOWNS
TESTS & ASSEMBLY (surface)
PRODUCTION
PI/CT
DESIGN/
DEVELOPMENT
1984
1985
1986
1987
1988
1989
1990
1991
1992

Fig. 12