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OPEN PRESENTATION OF THE LEP PROJECT

P. Darriulat :

Physics at LEP

W. Schnell :

The LEP design

J.B. Adams :

Consequences of the LEP Construction Project of the CERN Research Activities

CERN
Geneva, 3 December 1979

PHYISCS AT LEP

P. Darriulat

WARNING

This is a very elementary presentation intended for members of the personnel who would like to have some idea of the reasons why physicists are proposing the construction of a new accelerator even larger than the SPS. The text is aimed at those with only a slender knowledge of elementary particle physics and recent developments in the field. Consequently, although the paper may achieve its aim, it is in many ways incomplete or even inaccurate. No mention is made of spin or gauge invariance, nor is there any reference to the pattern of ideas leading up to the new physics and the names of those who contributed to their formulation. Readers wishing to obtain more detailed information should consult the yellow reports CERN 76-12, CERN 76-18 and CERN 79-01.

Nevertheless, LEP physics is so closely linked with the recent advances and new ideas that these must be discussed first. Progress has been made on two fronts : firstly, the number of elementary particles which go together to make up the universe is much smaller than was imagined a few years ago ; secondly, it would seem that the interactions between these particles can be described by a renormalizable field theory which is the only way of reconciling quantum and relativistic effects.

THE ELEMENTARY FERMIONS

In its simplest form, the new picture of the universe contains four families of elementary point-like particles (fermions).

Family		Symbols			Charge
Leptons	neutrinos	ν_e	ν_μ	ν_τ	0
	electrons	e	μ	τ	-1
quarks		u	c	t	2/3
		d	s	b	-1/3

Each family has three almost identical members. The six leptons are grouped in two families, the neutrino family and the electron family, whilst the six quarks also form two families, the structure of which resembles the structure of the lepton families. The proton and the neutron, forming the nuclei of atoms, and hadrons in general (which have been studied at CERN for twenty-five years) are made up of quarks which are strongly bound together.

In order to complete the picture, each particle must have its own opposite number or antiparticle of the same mass and opposite charge. This is a natural consequence of the theory. When matter is created in the form of a particle-antiparticle pair (relativistic equivalence between mass and energy), the total charge is conserved and the symmetry of the universe is maintained.

THE ELECTROMAGNETIC INTERACTION

In order to be meaningful, a description of the universe in terms of its constituent elementary particles must also define the interactions between them since it is these interactions, far more than the particles themselves, which make up the universe as we see it.

For thirty years, quantum electrodynamics has provided us with a remarkably simple description of the electromagnetic interaction between charged particles. Schematically, the interaction consists of the exchange between two charged particles of a new neutral particle (boson), the mass of which is determined by the kinematics before and after the collision. Apart from its mass, the exchanged particle is in all respects similar to a particle existing in the free state in the universe, i.e., the photon (light and electromagnetic radiation).

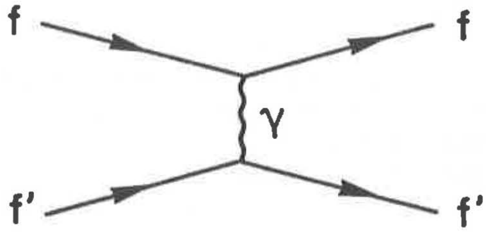


Figure 1 : Electromagnetic interaction between two charged fermions f and f' via photon exchange. Elapsed time runs from left to right.

In this case, the interaction probability is a function of the similarity between the mass of the exchanged particle and the mass of the real photon. It also depends on the probability that the particle will be emitted and absorbed by the interacting fermions. The emission and absorption probabilities are the same and depend only on the coupling of the photon to the fermions. In the electromagnetic interaction the coupling constant is simply the electric charge of the fermion.

All electromagnetic phenomena, and especially the interaction shown in Fig. 1, may be derived from the elementary interaction describing the emission (or absorption) of a photon by a fermion.

This elementary interaction may be expressed by the following diagram which also describes the creation and annihilation of a fermion-antifermion pair.

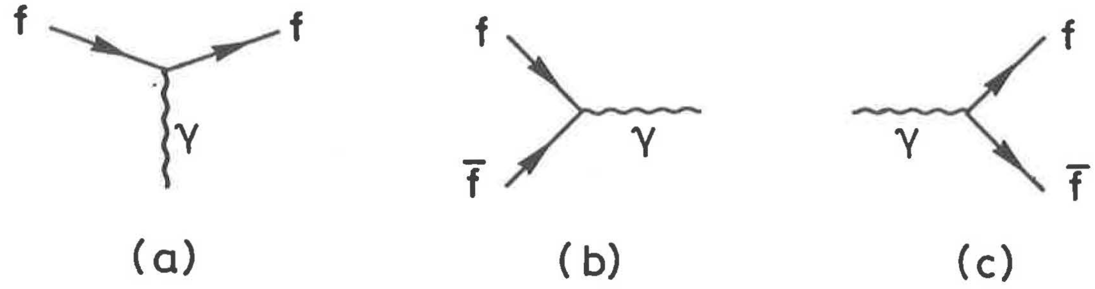


Figure 2 : The elementary electromagnetic interaction :
a) emission or absorption,
b) annihilation,
c) creation of a pair.

e^+e^- RINGS AT LOW ENERGY

Before introducing the other elementary interactions which form necessary parts of the description of the universe, we should linger briefly on the subject of low-energy e^+e^- physics which is governed exclusively by the electromagnetic interaction. A typical process to be studied at e^+e^- rings is the annihilation of the incident particles into a heavy "photon" which in turn creates a charged fermion-antifermion pair.

The production of a $\mu^+\mu^-$ pair, which is a particularly simple reaction, is shown in Figure 3. The production cross-section, which is proportional to the interaction probability, is plotted against the total available energy 2E, i.e. twice the energy E of each of the beam. The cross-section decreases as the mass of the photon in the intermediate state increases, zero being the mass of the real photon. At the bottom of the scale, the 10 pb cross-section corresponds to a production rate of only 3 events per hour (the production rate is the product of the cross-section multiplied by a quantity defining the intensity of the beams and their degree of overlap ; this quantity is known as the luminosity and is assumed here to be 10^{32} cm^{-2} s^{-1}).

Figures 4a, 4b and 4c illustrate three examples of hadronic resonances. When the total energy equals the value of the mass of a particle consisting of a quark-antiquark pair, the production cross-section rises steeply : in this way new particles can be discovered by exploring the energy range,

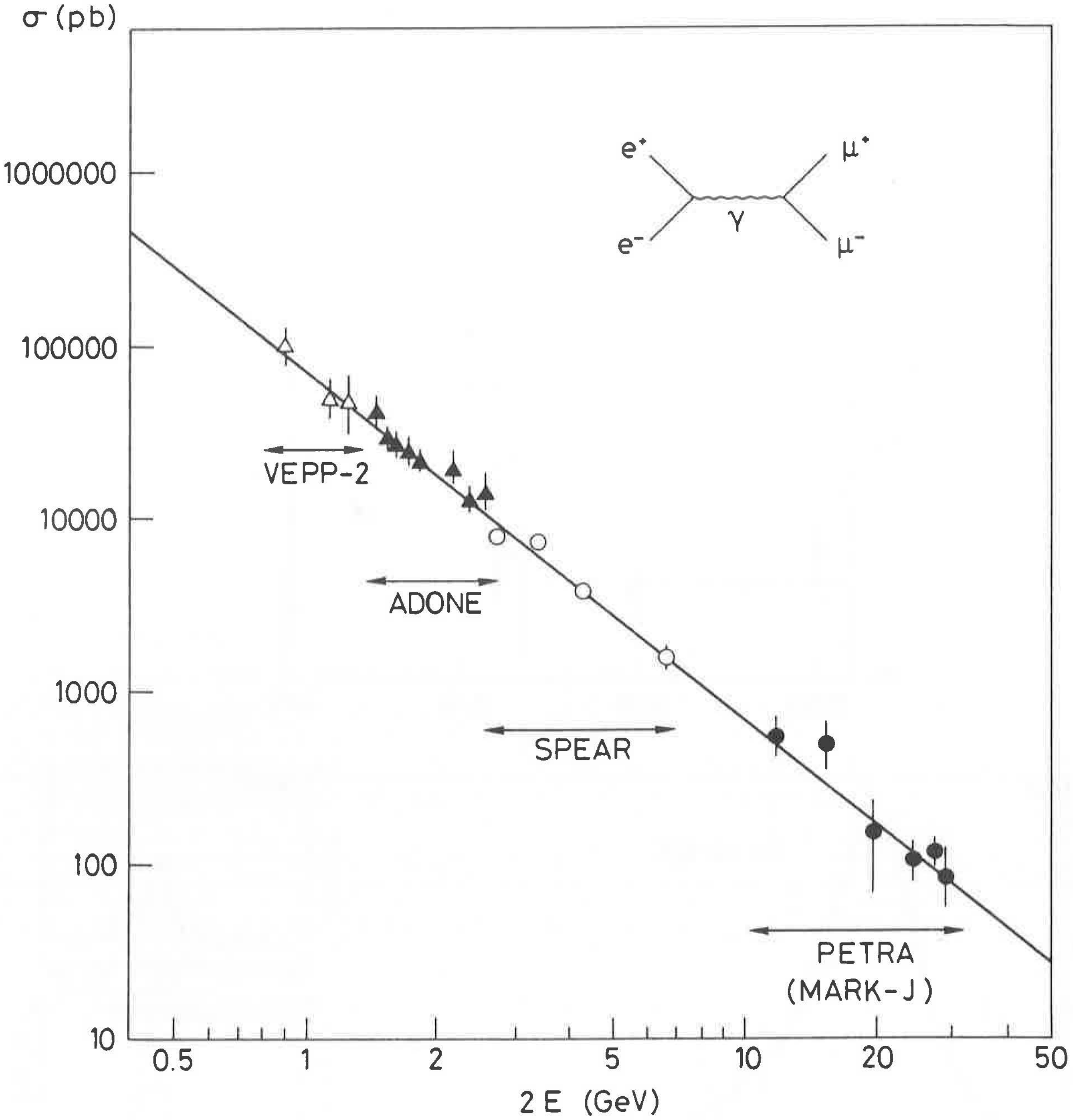
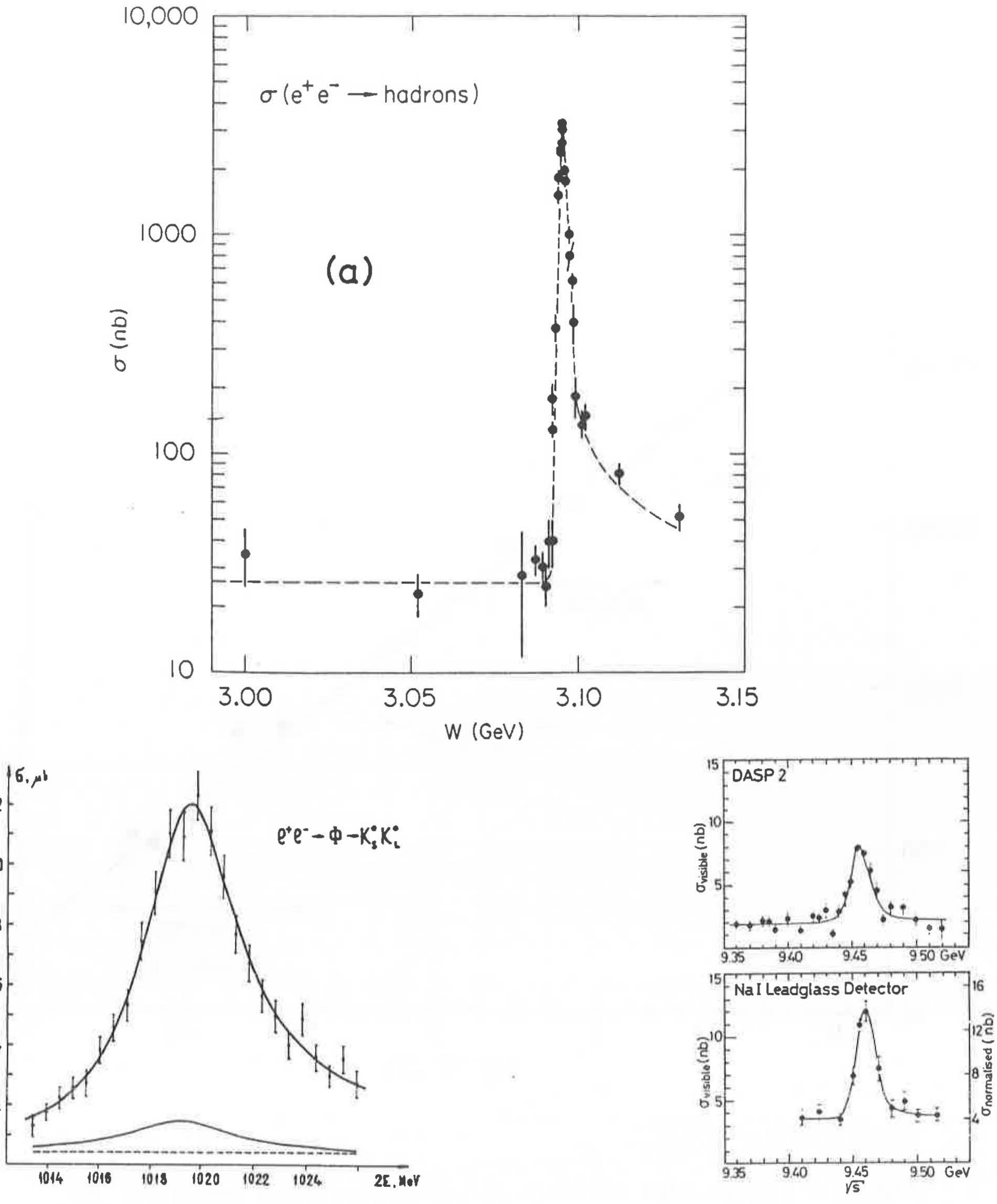


Figure 3 : La section efficace de production d'une paire $\mu^+\mu^-$ en fonction de l'énergie disponible. Le résultat de plusieurs mesures expérimentales est comparé à la théorie (ligne continue).

Figure 3 : The production cross-section for a $\mu^+\mu^-$ pair as a function of the available energy. The theory (solid line) is compared with several experimental results.



(b)

(c)

Figure 4 : Trois exemples de résonance dans une voie quark-antiquark : (a) cc, (b) ss, et (c) b$\bar{b}$.

Figure 4 : Three examples of resonance in a quark-antiquark channel : (a) c$\bar{c}$, (b) s$\bar{s}$, and (c) b$\bar{b}$.

and their various decay modes can be examined in detail by tuning the beam energies to their maximum cross-section.

Figure 5 shows the energy dependence of the ratio R between the cross-section $e^+e^- \to q\bar{q}$ and $e^+e^- \to \mu^+\mu^-$. The structure observed indicates new thresholds ($s\bar{s}$, $c\bar{c}$, $\tau^+\tau^-$) and the production of resonant states.

These three examples show the wealth of information contained in e^+e^- collisions. Many other examples, requiring a more detailed study of the structure of the final state, could have been chosen. In all cases, the pureness of the final state, consisting solely of a fermion-antifermion pair, allows a clear analysis to be made.

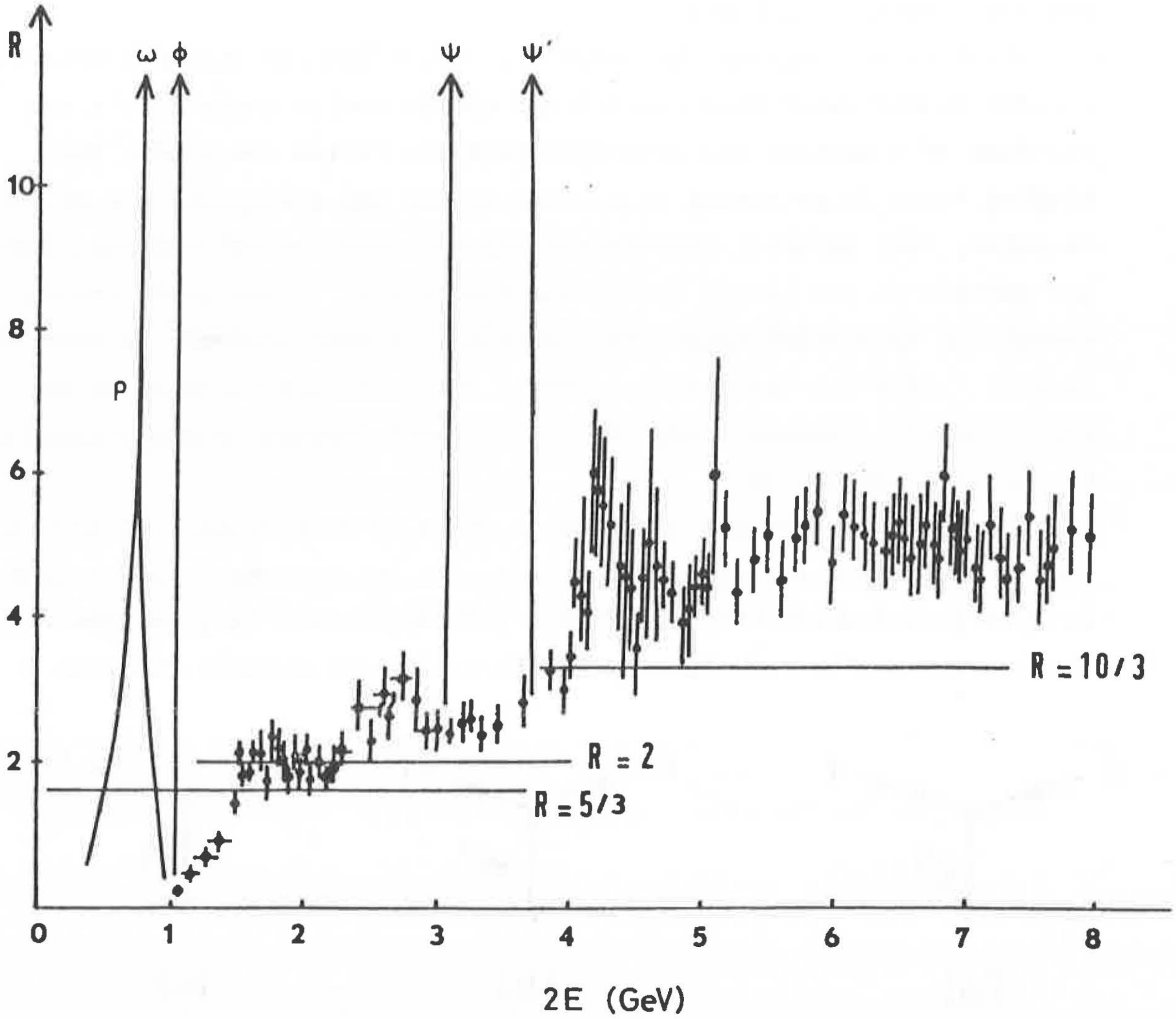


Figure 5 : Te ratio R between the cross-sections $e^+e^- \to q\bar{q}$ and $e^+e^- \to \mu^+\mu^-$ at low energy.

THE OTHER INTERACTIONS

It was only recently that a description akin to quantum electrodynamics was found for the other interactions besides the electromagnetic interaction.

In each case the elementary interaction is portrayed by a diagram describing the emission (or absorption) of a new boson (the equivalent of the photon). The characteristics of the boson and particularly its mass fully define the interaction when the four coupling constants associated with each family of elementary fermions (equivalent to the electric charge) are known.

This is how quantum chromodynamics describes the strong interactions between quarks which bind hadrons and atomic nuclei together via the exchange of a neutral and zero-mass particle called the gluon. The binding force is so strong that, when quarks and antiquarks are produced in pairs, they interact immediately and generate several hadrons. These are emitted in two groups (jets) and the type of parent quark can be identified by careful study. The coupling constant (colour) is zero for leptons : like the (neutral) neutrinos which are not affected by the electromagnetic interaction, the (colourless) leptons do not respond to the strong interaction.

This leaves the weak interaction which is responsible for neutrino-induced reactions and radioactive β decays. Let us take a closer look at this region where LEP will have a privileged role to play. The weak interaction may be described by the following three basic diagrams :

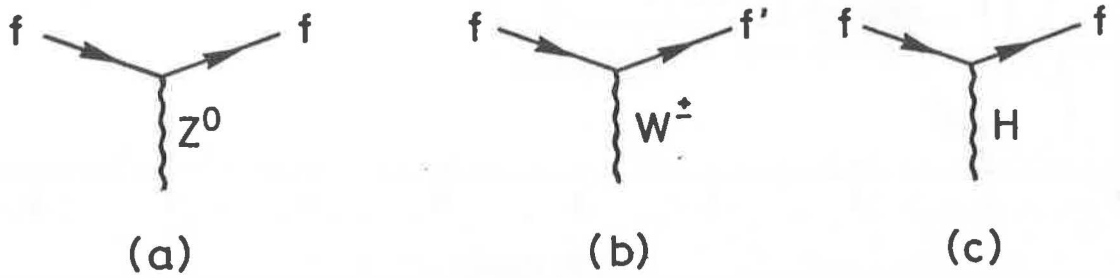


Figure 6 : The three basic diagrams of the weak interaction :
(a) neutral currents,
(b) charged currents,
(c) Higgs boson.

The first diagram corresponds to the neutral weak currents which were first observed at CERN in 1973 in the interaction of a neutrino beam in Gargamelle. The corresponding reaction is drawn in Figure 7.

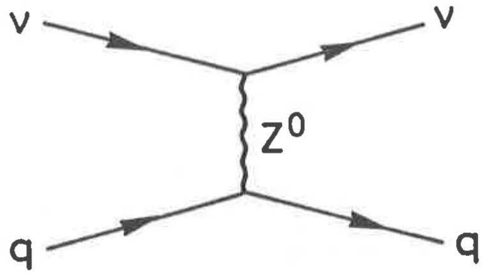


Figure 7 : Neutral currents : interaction between a neutrino and a quark through the exchange of a Z^0 neutral boson.

In contrast to the electromagnetic interaction, the exchanged Z^0 particle is coupled to each of the four families of elementary fermions, including the neutrino family. The very high mass of the Z^0 (approx. 90 GeV/c^2) explains why it has not been seen yet and why we thought the corresponding interaction was very weak.

The second diagram corresponds to the charged weak currents and weak decays of a large number of particles like the muon and neutron.

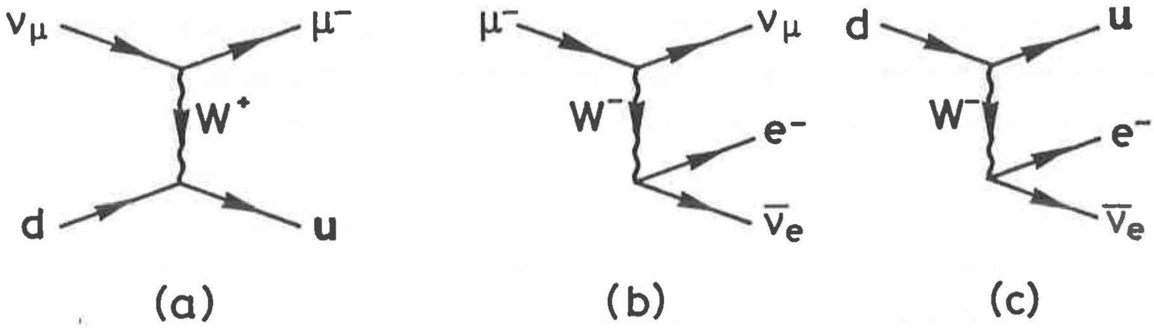


Figure 8 : Three reactions governed by the exchange of a W :
a) charged currents
b) muon decay
c) neutron decay.

The exchanged $W^\pm$ particle is almost as heavy as the Z^0 and has therefore not been seen yet. Since this particle is charged, the fermion which emitted it changes into a fermion belonging to another family, but without mixing the leptons and quarks.

The third diagram represents the emission of a Higgs boson, H, and does not correspond to any known phenomenon. This particle comes as something of a surprise but has to be introduced in order to be able to extend the formal approach of quantum electrodynamics to reactions where the exchanged boson has a mass. Moreover, the coupling constants of H to fermions are proportional to the masses of these fermions and therefore vary from member to member of the same family, thus making the H different from the other bosons. Although not originally required, the Higgs particle would, nevertheless, provide a striking confirmation of the theory if it were observed.

The electromagnetic interaction and the three basic diagrams of the weak interaction (Figure 6) merge into a single system which is fully covered by the new theories, thus bringing about a spectacular and long-awaited unification of the two processes. The distinction between weak and electromagnetic would then be nothing more than a historical accident arising from the relatively low energies which we have been able to produce up to now.

THE WEAK INTERACTION AT LEP

We are now faced with a particularly fascinating situation. On the basis of an apparently complete and well-founded theory, we must now check its various predictions. The questions are clear and only experiments will provide the answers. Whether the theory is proved or disproved, we shall certainly have considerably advanced our knowledge of the universe.

LEP is especially well suited to a detailed analysis of the weak interaction and its three basic diagrams.

The electromagnetic annihilation process :

$$e^+e^- \to \gamma \to f\bar{f}$$

is now accompanied by the weak process

$$e^+e^- \to Z^0 \to f\bar{f}.$$

In the same way that the cross-section of the first process increases as the available energy approaches zero (the photon mass), the second process dominates near the Z^0 mass, i.e. when the energy of each beam nears ½ 90 = 45 GeV. Figure 9 shows the energy dependence of the production rate for $e^+e^- \rightarrow f\bar{f}$. The maximum value is 3300 $f\bar{f}$ pairs per hour ! At LEP energies, the weak interaction becomes stronger than the electromagnetic interaction.

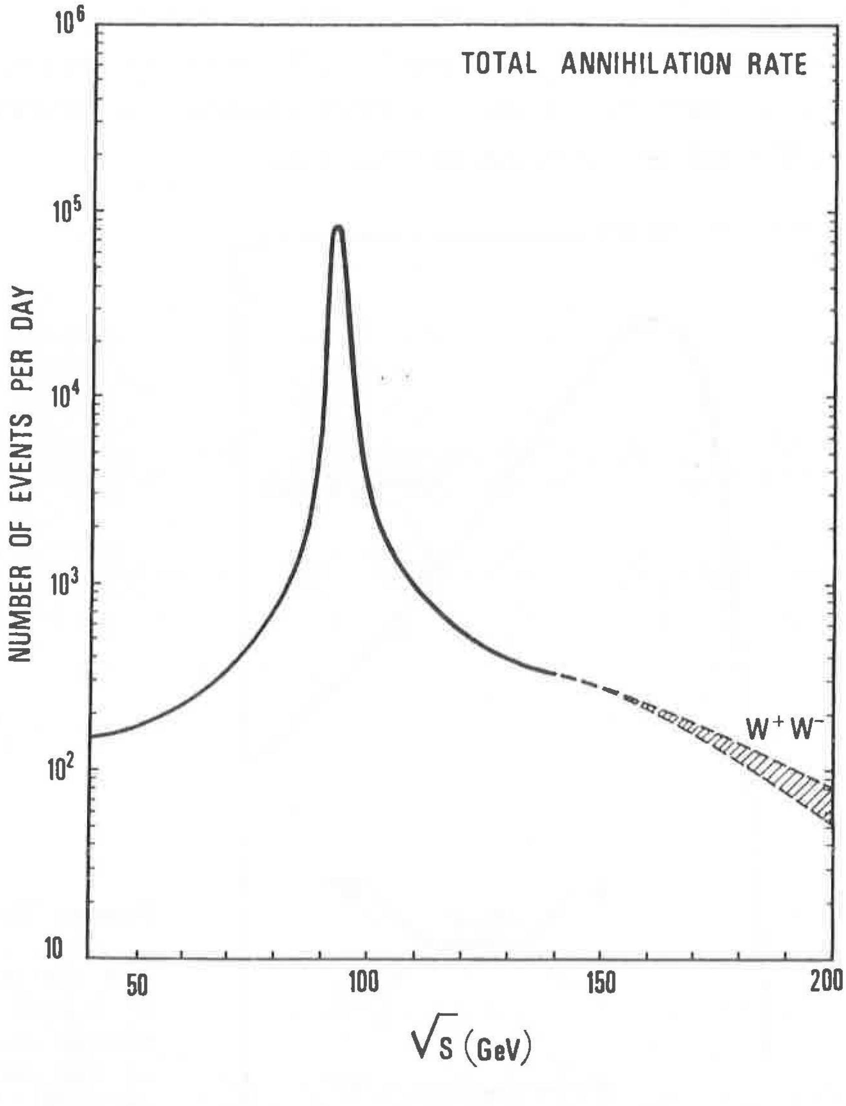


Figure 9 : Daily production rate for $f\bar{f}$ pairs at LEP. The production of W^+W^- pairs at high energy is also shown.

The coupling of the Z^0 to the various fermions, for which the theory predicts quite precise values, may be measured by making a detailed analysis of the final states in this region. Furthermore, in the energy region below the Z^0 mass, where the electromagnetic and weak processes are similar in strength, interference phenomena can be studied which will reveal a great deal about the exact nature of the neutral weak currents.

The charged weak current cannot be studied so directly. W production can occur as soon as the threshold is crossed but the cross-section is small and measurements will be difficult. It is more interesting to study W^+W^- pair production (Figure 10) which involves two annihilation processes (γ, Z^0) and one exchange process (ν).

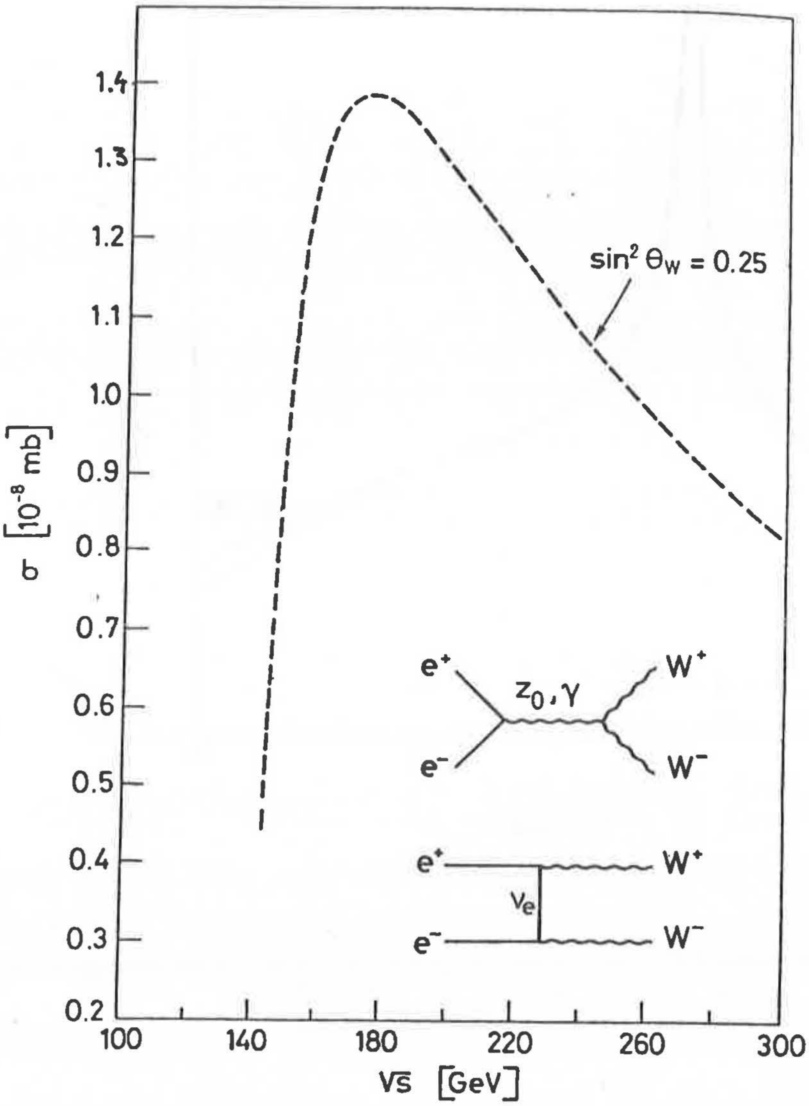


Figure 10 : Cross-section for the production of a pair of W^+W^- bosons as a function of the total energy $\sqrt{s}$ = 2E

The cross-section remains low because the theory predicts strong destructive interference effects between the three processes. However, the slightest deviation between theory and reality could upset this balance and lead to much higher production rates : this region is therefore very sensitive to the exact nature of the coupling (Z^0, W^+,W^-) between the three weak bosons.

Since we do not know the mass of the Higgs boson, it is difficult to assess our chances of finding it. However, its preference for high-mass particles would seem to suggest that the chances should increase with the available energy. The processes shown in Figure 11, where the final states have a straightforward signature, seem to be good candidates.

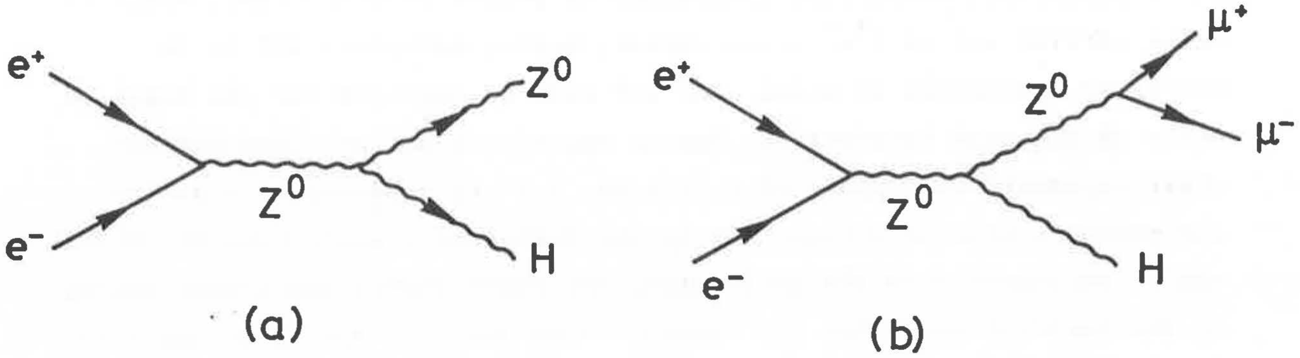


Figure 11 : Two production mechanisms for the Higgs boson at LEP

TWO CRITICISMS

We have so far assumed that the new theories will definitely hold. This is neither an overbold, nor a very scientific assumption to make. If the theories were wrong, would LEP still have a justification ? And even if the theories are right, isn't there a less expensive way of checking them ?

The first criticism can be easily answered. There are a number of possible variations to the theory, all of which are more complicated than the basic version. In every case, new phenomena associated with spectacular fluctuations in the production rates appear when the total energy approaches about 100 GeV. This prediction is based on our knowledge of the weak interaction at low energies and the constraints that we can place on its energy dependence. The neutral weak current increases with the total energy and we shall certainly learn a great deal from its behaviour when it reaches the same strength as the electromagnetic interaction.

The second criticism calls for a more subtle reply.

One may ask whether a proton accelerator, and especially a proton-proton or proton-antiproton colliding-beam machine, would not be better suited than LEP to the study of the weak interaction : for the same cost and size, these accelerators can reach much higher energies. Furthermore, it is hoped that the $p\bar{p}$ project at the SPS will reveal the Z^0 and perhaps even the W before LEP is built. However, the detailed study of the J/ψ and Υ particles, which were discovered at proton machines (BNL, FNAL) is being carried out at e^+e^- rings (Spear, Doris, Cornell), and it is therefore reasonable to think that LEP will be required for the detailed study of the weak interaction. Recent experience has provided several clear arguments in support of this view. A Z^0 is produced in a proton-antiproton collision (Figure 12) by the fusion of a quark from the proton and an antiquark from the antiproton. The other quarks and gluons making up the incident particles are wasted : they are only acting as spectators in the production process, and the energy they acquire during acceleration is lost. What is worse, these disinterested spectators also interact : the products of their interactions make it more difficult to decipher the final state and may prevent the physicist from tracking down the phenomenon in which he is interested.

Another advantage of e^+e^- collisions is that they are more democratic the various members of the quark families being produced with similar probabilities. In contrast, the final states of proton-proton and proton-antiproton collisions consist mainly of u and d quarks which are largely predominant in the initial state.

A further question concerns the maximum energy of LEP. Although the Z^0 region must obviously be properly covered, would it be too ambitious to reach for the W^+W^- region at the same time ? It would certainly be unfortunate if Z^0 physics were delayed too long as a result. However, it would be unreasonable to build a machine larger than the SPS to cover the Z^0 region and then have to build another, even larger machine a few years later to reach the W^+W^- threshold. The LEP project described in the Pink Book offers a very satisfactory solution to these problems since it would be built in several stages.

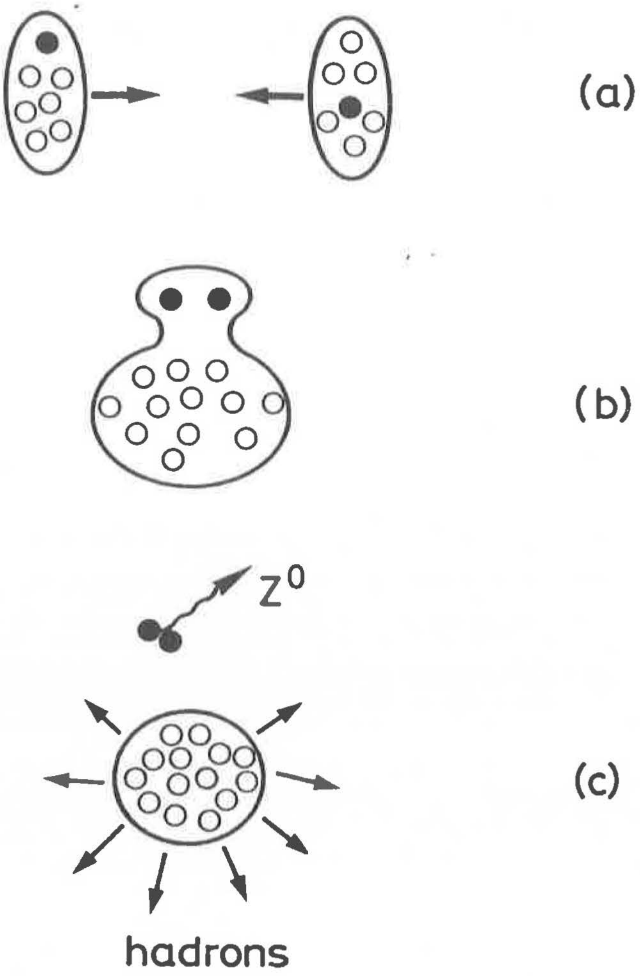


Figure 12 : Production of a Z^0 in a $p\bar{p}$ collision. Only a quark and an antiquark (in black) are involved in the production process. The other constituents of the incident particles (quarks, antiquarks and gluons) are spectators and the fragments from their interaction only complicate the structure of the final state.

CONCLUSIONS

The LEP machine is particularly well suited to the study of the weak interaction and should allow us to answer many of the crucial questions posed by the new theories.

Even if these theories were proved wrong, LEP would still be the ideal tool to study neutral currents because of its energy range and in view of the mass of information to be gleaned from e^+e^- rings.

LEP fits logically into the current scheme for the next generation of accelerators since the Soviet Union, in selecting UNK, and the United

States, in building Isabelle and the Doubler, have opted for proton machines.

LEP also fits naturally into the CERN physics programme since the Laboratory, having discovered the neutral weak current, ought now to follow through this line of research until the exact nature of the phenomenon is understood.

THE LEP DESIGN

W. Schnell

Introduction

The work on LEP started early in 1976 with the formation of two study groups which were to examine the physics potential and the feasibility of a Large Electron Positron collider, larger than anyone had imagined before. A first report was already issued by the physics group in 1976$^{1)}$. This soon led to widespread enthusiasm and to a general consensus that an accelerator of this kind should be made the next major project for European high-energy physics.

In contrast to many other accelerators, LEP is based on a clear physics specification. It should pass certain threshold energies in successive stages, in particular the thresholds for three, as yet hypothetical, particles of very high mass, supposed to mediate the weak interaction, namely the neutral Z^0 particle and the charge pair of W particles. And it should achieve this with electron-positron collisions, the only feasible reaction that is sufficiently clean to permit a detailed study of the new events expected at these energies.

Unlike protons, electrons and positrons lose energy by radiation when being made to circulate in a storage ring. The energy loss per turn is proportional to the fourth power of the particle energy and inversely proportional to the bending radius. It is this fact that gives LEP its two most characteristic features, namely:

- a very large size, required to bend the particles gently round the ring (but at least the magnetic field is low, and so the magnets can be made rather cheaply) and

- an extremely large and powerful radio-frequency system, nevertheless required to compensate for the energy loss per particle revolution.

For our first design study we adopted a ring of 50 km circumference, this being approximately optimum if 100 GeV energy per beam was to be obtained with an entirely conventional RF system. A first report was issued in 1977$^{2)}$, but several basic problems of beam dynamics and technology remained unsolved and the cost was considered prohibitive.

The experience we had gained was, however, carried over into the design of a new ring, which we made smaller - 22 km circumference - so as to create the basis for a realistic project. In this we certainly succeeded. A detailed report$^{3)}$, which soon became known as the "Blue Book", was issued in August 1978. It showed that such a machine was entirely feasible. This design, as well as all our subsequent work, was thoroughly debated inside the physics community, mainly in the framework of ECFA, the European Committee for Future Accelerators. A large ECFA LEP working group actually examined details of machine design as well as all aspects of physics experimentation. The main criticism of the "Blue Book" design was that, because of its relatively "small" circumference, this machine would fall short of reaching the threshold energy for W-pair production with conventional RF cavities and that the development of superconducting cavities had to be awaited for this.

Work almost immediately began, therefore, on a ring of 30 km circumference, the design of which was also to contain a number of substantial improvements made in the meantime. A new design report 4), the "Pink Book", was issued in August this year. It is this design, the one I am going to describe, that is now universally supported - in formal proposals by the Scientific Policy Committee and by ECFA to the CERN Council - as the basis for the next major project of CERN.

Main parameters

We propose to construct LEP in stages, as shown in Table 1.

Table 1 : Energy stages

Stage	1/6	1/3	1	4/3	2	
Design energy	49.4	62.3	86.11*)	92.86*)	130	GeV
Luminosity	0.385	0.616	1.07	1.15	1.04×10^{32}	cm^{-2} s^{-1}
Current	5.71	7.20	9.15	9.15	6.16	mA
RF power	16	32	96	128	96	MW
Length of RF cavities	272	543	1629	2172	1629	m
	Cu cavities				s.c. cavities	
Estimated cost		1064	1275			MSF

*) 2 to 3 GeV more may be possible: under study.

The first main objective, called Stage 1, was intended to reach 85 GeV per beam (the centre-of-mass energy is twice that) with RF cavities made of copper, and at a luminosity of $10^{32} cm^{-2} s^{-1}$. The luminosity is proportional to the collision rate and hence sets the scale for the frequency with which a given process -- for instance W-pair production -- occurs. Thus, the inverse of luminosity determines the time it takes to carry out a certain experiment; whether it takes weeks, months, or years.

Actually, the top energy turned out to be 86 GeV per beam, and we hope we can even gain 2 to 3 GeV more by refinements of beam optics now being studied. With copper cavities the top energy is limited by power dissipation in the cavities. The Stage 1 configuration contains sufficient reserve space to permit pushing the energy to at least 93 GeV (a possibility called Stage 4/3) simply by installing more RF cavities and RF power sources, but the additional expense and the increase in power consumption would be considerable.

We have good reason to hope, however, that ultimately the power losses in the RF cavities can be drastically reduced by means of RF superconductivity. Therefore, the magnet system, the vacuum system, and other vital parts of LEP are designed from the start so as to permit energies of up to 130 GeV as soon as superconducting RF cavities of adequate performance become available. Obviously this final step, which we call Stage 2, must not be gambled away by attempting to construct the full length -- about 2 km -- of superconducting structure before the technology is ripe. It is not ripe now, but it looks promising in the long term.

Towards the end of the construction time, physics research can already be started with only a fraction of the RF system installed, and symmetry suggests that one sixth or one third of the Stage 1 RF system may be used for this. We have made a cost estimate for Stage 1/3, but the Stage 1/6 is equally interesting. The energy of this stage is sufficient for physics research in the energy region of Z^0 production; all the more so, as the useful energy range of this stage goes up to about 55 GeV at somewhat reduced luminosity.

A list of main parameters is shown in Table 2. LEP is a single storage ring of 30 km circumference, in which electrons and positrons, owing to their opposite charge, circulate in opposite directions. The average current per circulating beam is kept quite small, about 10 mA, in order to keep the RF power and the injector size within reasonable limits. But each beam is compressed into only four bunches, which collide precisely at the eight interaction points where the physics research will take place. As the bunches are only about 10 cm long and spaced about 8 km apart, the peak beam current within a bunch is of the order of 1000 A. The field in the bending magnets is low.

Four of the eight interaction regions will be designed for the maximum luminosity and will have a free space of ±5 m for experimentation. The other four will have twice the free space and half the luminosity. The transverse beam dimensions at the collision point are extremely small.

Layout and Experimental Areas

The proposed layout of LEP is shown in Figure 1. The ring and the experimental areas will be built underground, with nothing on the surface other than the buildings in the immediate vicinity of the eight access points. In this, we follow the very successful example of the SPS tunnel, whose presence is strictly unnoticeable at the surface over most of its circumference.

Table 2 : LEP at 86 GeV

General Parameters			
Machine circumference		30.608	km
Number of interaction points		8	
Number of bunches per beam		4	
Circulating current per beam		9.15	mA
Horizontal betatron wave number		70.32	
Vertical betatron wave number		74.54	
Transverse damping time		12.8	ms
Beam-beam bremsstrahlung lifetime		8.18	h
Over-all beam lifetime		5.79	h
Natural r.m.s. energy spread		1.2×10^{-3}	
Regular Cell Parameters			
Length of regular cell		79	m
Bending field		0.081	T
Bending radius		3.545	km
Horizontal or vertical phase advance		60°	
Horizontal aperture in normal cell		±59	mm
Vertical aperture in normal cell		+33	mm
Interaction Region Parameters			
Luminosity	1.07×10^{32}	0.53×10^{32}	$cm^{-2}\ s^{-1}$
Horizontal amplitude function	1.6	3.2	m
Vertical amplitude function	0.1	0.2	m
Maximum beam-beam tune shift	0.06	0.06	
Free space around crossing	+5	+10	m
Vertical r.m.s. beam size	0.017	0.025	mm
Horizontal r.m.s. beam size	0.359	0.508	mm

The LEP ring is made to almost touch the SPS ring so that electron-proton collisions in an SPS by-pass or the injection of protons into the LEP tunnel may become possible later, if so desired. The tunnel will be bored into the underground molasse and the Jura limestone by tunnelling machines like the one that was used for the SPS, and the tunnel will have the same width, namely 4 m (Figure 2). This layout may still change by up to a few hundred metres as a result of the test borings now being carried out to find the exact depth of the molasse rock below the surface.

Power lines (Figure 3) and a supply of make-up cooling water, both of sufficient capacity, are already available in the SPS area. Contrary to the case of the SPS, for which cable trenches were tolerated, we plan to feed power and water through the LEP tunnel itself, so as to avoid any disturbance of the surface between the eight access points.

The experimental areas will also be underground. Three of them are situated fairly deeply inside the Jura and are accessible by means of roughly horizontal tunnels. Cross-sections of the outer two of these areas are shown in Figure 4. They are caves, following almost exactly the design of the LSS4 area now being built around the SPS for proton-antiproton work. Each of these areas offers room for one large experiment that can be withdrawn from the beam whenever required. A separate service tunnel keeps the main access tunnel free. The central of the three areas under the Jura, and the deepest one, is of similar but somewhat simpler design, and its use will be limited to a more modest experiment.

Three areas, situated in the molasse beneath the level ground, are also of similar design but much longer transversely to the beam (Figure 5) so as to allow the housing of two large experiments which can be exposed to the beams alternately, as is now being done in one area of PETRA. These underground halls will be accessible via two vertical access shafts, a very large one (9 m diameter) and a smaller one.

Finally, we hope to be able to tilt the LEP ring in such a way as to bring two experimental areas close enough to the surface to permit open excavation from the top. The resulting rectangular pits (Figure 6) of 30 × 70 m^2 will also contain two large experiments each.

Lattice

Figure 7 (upper part) shows the lattice of the main arcs; that is, the regular sequence of bending magnets, focusing quadrupoles, sextupoles for the correction of chromaticity (the energy dependence of focusing), and orbit correctors. This is the classical layout of a separate-function machine. The lattice period for a ring as large as LEP turns out to be rather long -- 79 m. This is fortunate, as it means that a large fraction of the circumference can be filled with bending magnets.

The lower part of Figure 7 shows the transition to the interaction area, which is also where the RF system is located. In this transition the beam's so-called dispersion has to be suppressed, i.e. particles of different energies within the beam have to be superimposed on to the same orbit. The same moduli of bending magnets are used for this as in the regular lattice.

Finally, Figure 8 shows schematically the lattice and lattice functions in the neighbourhood of the collision point. The curves labelled $\sqrt{\beta}$ are proportional to the beam-size and show how the beams are subjected to very strong local focusing near the collision point.

The luminosity can be optimized within a limited energy range only. It has been optimized for the top energies (Figure 9) where the maximum achievable value is needed for studying the physics events of the very low cross-section one expects to find there. At lower energies a drop in luminosity cannot be helped, and an effort is required (namely an artificial beam blow-up by wiggler magnets) to prevent an even faster drop than that which is shown in Figure 9. This does not matter much, however, as the cross-sections of interesting events will be higher at lower energies.

The absolute limit for the luminosity is given by a rather fundamental effect of electromagnetic interaction between the two, very dense, beams. The electromagnetic field of one beam is quite strong, and it varies extremely rapidly, and in a non-linear fashion, over small distances. This field delivers regular kicks to the particles of the opposite beam, throwing them out of orbit if the effect becomes too strong. It has become customary to describe this complicated effect in terms of the change of transverse oscillation frequency that one beam imposes on the other, and an empirical limit for this beam-beam tune shift ΔQ -- that on which our design is based -- is 0.06.

One way of increasing luminosity in the face of this fundamental limit would be to increase the beam current. This works, because the electromagnetic field of one beam increases linearly with its intensity whilst the collision rate between equal beams increases with the square of their intensities. However, increasing the beam current much beyond the value of the 10 mA that we have adopted, would be prohibitively expensive in terms of RF power and of injector size.

Another way is to make the beams go through the interaction point at a large angular spread so as to reduce the ratio of the unavoidable beam-beam kick to the angular spread already present. This is precisely what is being done by strong local focusing -- in a so-called low-β insertion -- as visible on the left-hand edge of Figure 8. A small improvement in this direction might still be possible by making the insertion quadrupoles very slim, so that the physics experiment can tolerate them at a position even closer to the collision point than the ±5 m nominal distance foreseen so far.

Magnet System

Bending magnets of about 22 km total length will have to be manufactured. The magnets will have a C-shaped profile and will be made of precisely punched steel laminations (Figure 10). This method of magnet fabrication is conventional, but it is an excellent method for mass fabrication because one stamping die can control the precision of field configuration of a very large number of magnets. The field is very low, however -- about 1 kG -- and we want to take advantage of this in introducing a few unconventional design concepts.

Firstly, the magnets will not be excited by conventional coils but by a simple pair of water-cooled bar conductors, made from extruded aluminium. The bars will be insulated by a pair of clamp-on plastic shells, also fabricated by extrusion. All bars are connected in series so as to form a two-turn circuit all around LEP. These bars are much cheaper than the usual multi-turn coils, and they permit magnet blocks of convenient length to be put end-to-end, so as to fill the long lattice periods without waste of space.

Secondly, the low field permits a reduction of the steel filling factor to less than one third, without leading to saturation. To this end, spacers are pressed into the laminations by the punching die, so that the luminations are spaced at more than three to one pitch once they are stacked on a jig (Figure 10, lower part). To turn this into a mechanically rigid magnet core, a filler has to be introduced between the laminations. We propose to surround the whole assembly by a suitable mould and fill it with concrete. Pre-stressed tie rods, cast into the assembly, will give it about 10 tons built-in compression, so that each magnet core forms a block of reinforced concrete, about 6 m long. This method leads to a saving of almost a factor of 2 in the estimated cost, a factor of 2 reduction in magnet weight, and about an order of magnitude improvement in mechanical rigidity over the usual magnets in which the laminations are held together by welded-on straps.

After having made three reduced-scale models, we have so far made and tested one full-size model, with very satisfactory results. The concrete -- which should really be called 'mortar' because of the obvious absence of gravel in the mixture -- is composed of cement, fine silica sand, water, and additives to prevent shrinkage. To make the mortar penetrate between the laminations, the assembly is vibrated during the casting. Excess water segregates out very rapidly and is pumped off, especially from the inner part of the mould. We plan to continue this model work, up to the point of testing half a lattice period containing six bending magnets. During LEP construction, of the order of five magnets per day will have to be made.

The quadrupoles and sextupoles have to be quite strong, and hence must have conventional steel cores. However, we plan to save money by fabricating the excitation coils from anodized aluminium strip conductors with external, glued-on cooling pipes. Altogether there will be 1400 lattice quadrupoles and sextupoles.

The insertion quadrupoles, those bordering the collision point, have to combine considerable strength with a large aperture. They can be made of steel and copper, but it may be preferable to make them superconducting. Figure 11 shows a design based on the successful superconducting insertion quadrupoles which are being manufactured at present for the ISR.

Vacuum System

The design of the main lattice vacuum chamber, of which about 26 km total length is required, is governed by the hard and intense synchrotron radiation it has to absorb. The linear power density of this radiation is 1.2 kW/m at 86 GeV, increasing to 4.3 kW/m at 130 GeV.

Figure 12 shows a cross-section of the chamber in the bending magnets. This chamber is made from extruded aluminium, water-cooled and equipped with a linear, distributed sputter-ion pump immerged in the field of the main magnets. This is now the standard design, first introduced for the SPEAR storage ring and later improved for PETRA. In our case, Compton scattering will spread about half of the radiation power around the perimeter of the chamber section, obliging us to introduce two more cooling channels in addition to the one at the place of first incidence. A thick lead shield, bonded on to the chamber, will keep the radiation from penetrating into the tunnel air, where it would induce chemical reactions in the tunnel air and humidity. The chamber with its grown-on shielding will be made and installed in pieces of 12 m length, weighing about 600 kg each.

About 22 km of distributed sputter ion pumps are required. Their anodes will be fabricated in a novel way, namely from superimposed layers of thin stainless-steel strips which can be made in a continuous process, and sufficiently thin to avoid excessive heating by the scattered radiation. The pump cells are unusually large in order to ensure that the pumps ignite at the low injection field. A model has been made and successfully tested.

Injector

The injection channel (Figure 13) starts with an electron linac, followed by a conversion target, another linac, and an accumulation ring for positrons. The main injector is a synchrotron of 22 GeV top energy and 1.7 km circumference, with the relatively moderate cycling rate of one every 2.5 s. The choice of injection energy is determined mainly by space-charge problems in the LEP main ring, and our choice is as low as we dare to go, considering the beam current we have chosen. Increasing the injection energy would make the size and cost of the injector grow very rapidly.

The injector synchrotron, like the main ring, will contain four bunches, but they will be of much reduced intensity, so that it takes about 10 minutes repetitive acceleration of positrons and 2 minutes acceleration of electrons to fill LEP to nominal intensity.

We plan to build the LEP injector under the present ISR site (Figure 14), making use of the existing infrastructure. We also plan to build the synchrotron magnet system and much of its vacuum system from ISR parts. In fact all ISR magnets of both the present rings will be used for the combined-function lattice of the injector synchrotron (Figure 15). The RF will be made of the same modules as those of the main-ring RF system.

Radio-frequency System

Table 3 gives a list of RF parameters for Stage 1. The RF system has to make up for about 1.4 GeV of energy loss per turn due to synchrotron radiation. Multiplying this with the sum of the two average beam currents gives 25 MW of power loss due to the synchrotron radiation of both beams. To cover the unavoidable electromagnetic losses (110 MeV per turn) and to provide overvoltage for sufficient quantum lifetime, a peak RF voltage of almost 2 GV is required. This is basically equivalent to a fairly large linear accelerator.

About 2 km of total RF structure length will be used, this being an approximate economic optimum. A shorter structure would cost less in itself but require more cost for power sources and for running, and vice versa. The total length of the structure will be divided into 16 equal stations, one on each side of each interaction area. Figure 16 shows the layout of one such station, equipped -- in Stage 1 -- with 48 five-cell cavities and six 1 MW klystron power amplifiers. Also shown is the location of a harmonic RF system which will be added to permit control of the bunch length and of the synchrotron tune Q_s. In the beginning, only half the stations will be equipped (with one third and two thirds of their nominal main RF equipment for Stages 1/6 and 1/3, respectively).

Figure 17 shows the arrangement of the RF power amplifiers in pieces of separate tunnel that originate from the interaction area and run parallel to the main tunnel for a certain distance.

The accelerating structure itself (Figure 18) will be made of copper and will follow established design principles and manufacturing methods. But the spherical storage cavity shown in the upper part of the figure is a novelty. This cavity is excited in a mode (an H-mode, avoiding electric field perpendicular to the walls) that permits energy storage at low losses. By exciting both resonant frequencies of the coupled system, the stored energy can be made to oscillate between the two cavities, spending, on the average, half the time in the low-loss environment, yet generating the maximum accelerating field when the bunches pass by. In practice, this method saves a factor of 1.5 of power dissipation in the cavity walls, at given RF voltage. Figure 19 shows the computed modulation of voltages in the cavities and the superimposed sawtooth due to beam loading.

We have tried the storage-cavity method at low power (using a 500 MHz PETRA cavity kindly lent to us by DESY), and we have built and tested a half-scale model of the actual spherical cavity. High-power tests are in preparation.

Table 3 : Main RF system parameters, Stage 1

Design energy	E	86.1	GeV
Design luminosity	L	1.07×10^{32}	$\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
Synchrotron energy loss/turn	U_0	1370	MeV
Parasitic energy loss/turn	U_{hm}	110	MeV
Peak RF voltage/turn	V_{RF}	1949	MV
Stable phase angle (from zero crossing)	ϕ_s	130.6	degrees
Frequency	f_{RF}	353.4	MHz
Number of synchrotron oscillations/turn	Q_s	0.158	
Length of active RF structure	L_c	1628.8	m
Shunt impedance/unit length	Z	40.0	$\mathrm{M\Omega \cdot m^{-1}}$
Fundamental mode cavity dissipation and reflection	P_d	61.7	MW
Synchrotron power (two beams)	P_b	25.1	MW
Waveguide losses		7.2	MW
Parasitic mode losses (two beams)	P_{hm}	2.0	MW
Number of RF stations		16	
Total number of klystrons		96	
Total number of five-cell cavities (each one coupled to a storage cavity)		768	

Power Consumption and Improvements under Study

The design I have described so far, although containing quite a number of novel ideas, is essentially based on present-day technology. Figure 20 shows the estimated consumption of electric power as a function of energy. It is about 90 MW for Stage 1/6 (assumed to carry already the maximum number of physics experiments at that stage), going up to about 250 MW for the nominal Stage 1. About 60% of the last figure is due to the main RF system and is based on the assumption of 70% d.c. to RF conversion efficiency, this having been demonstrated with a PETRA klystron, run at slightly higher voltage.

Development work is going on at present, aimed at increasing this conversion efficiency, either with klystrons or with alternative sources of RF power, namely tetrodes or gyrocons. Raising this efficiency from 70% to 80%, which seems possible, would save 19 MW at the top energy of Stage 1.

Even after completion of Stage 1, LEP will not always be run at top energy. For running at reduced energy the power consumption, although decreasing steeply, does not decrease quite as fast as it ideally should, since the efficiency of available RF power sources drops rather rapidly when they are run at reduced output -- so much so that it pays to run with part of the RF system switched off for lower energies. There is good hope, however, that this may be improved, leading to additional savings at lower energy.

More ambitious proposals aim at reducing the power dissipation by a higher degree of modulation at the bunch repetition frequency -- beyond what is already achieved by the storage-cavity system shown in Figures 18 and 19 -- in order to reduce unnecessary dissipation at times when there is no beam in the cavities. One possibility is to add a semiconductor RF switch to the coupler connecting the two cavities, so as to keep the stored energy in the low-loss cavity for a larger fraction of the time. The main problem is the high load on the switch (in excess of 1 MVA). No suitable switch is yet available, but we have started development work on this subject, aimed at possibly saving another factor of about 1.5 in cavity dissipation.

RF Superconductivity, Stage 2

The most drastic reduction in power input might ultimately be obtained by making the RF cavities superconducting. In this way, cavity dissipation can be reduced by a factor down to about 10^{-5}, but the necessary helium refrigerators will require substantial input power that must not be neglected. Nevertheless, an estimated saving of 90 MW in total power consumption at 90 GeV, that is a reduction from 250 MW to 160 MW, could be made if a suitable superconducting RF structure were already available for Stage 1.

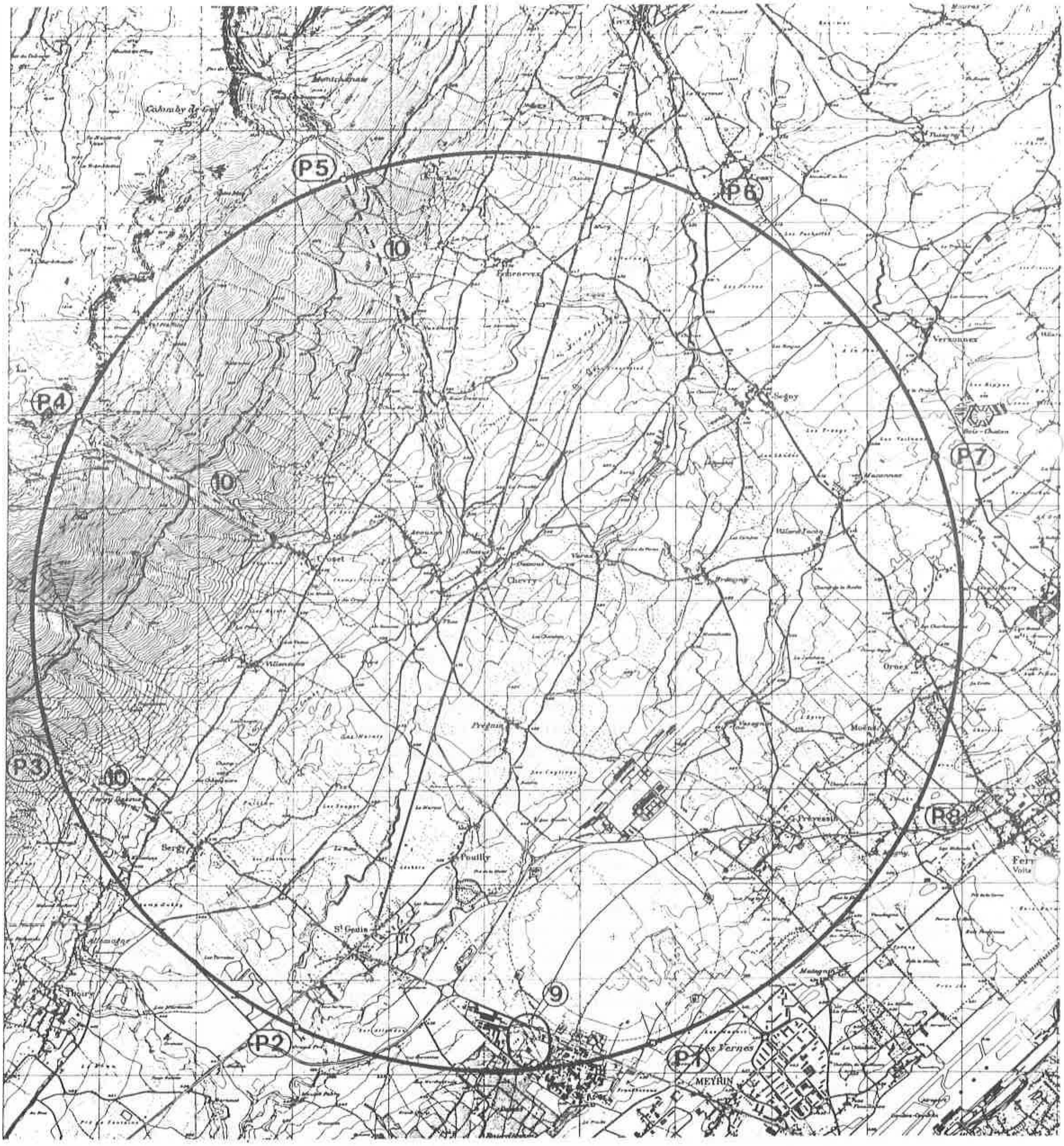
To push the energy to the ultimate Stage 2 level of 130 GeV, a superconducting structure capable of 5 MV/m accelerating field will be required (Fig. 21). With superconducting cavities, practically all the installed RF power of 96 MW can be converted to beam power, and LEP has been designed to give exactly 10^{32} cm^{-2} s^{-1} luminosity at 130 GeV under these conditions. The total power consumption at this ultimate energy will be larger, however, than in Stage 1, because of an estimated 50 MW power consumption of the refrigeration system and because of increased magnet power.

No superconducting RF structure suitable for LEP is available now. The requirement of 5 MV/m accelerating field for 130 GeV is put in perspective in Figure 22, showing the highest accelerating fields so far obtained in laboratory models at different frequencies.

Active development work is now going on in several European laboratories. One of the centres for this work is the Karlsruhe Kernforschungszentrum, where two 500 MHz single-cell test cavities (Figure 23) are being prepared for experiments with beam at the DORIS storage ring in Hamburg. The Karlsruhe cavities are of rectangular section. This represents one of two recent ideas of how to suppress multipactoring, which is an effect of resonant electron-multiplication and one of the numerous difficulties to be covercome. These cavities also incorporate novel designs for the couplers, through which the input power is to be coupled to the beam, and beam-induced power at higher frequencies extracted -- two more examples of difficulties to be solved. An accelerating field of 3.7 MV/m has been obtained in the laboratory so far, and tests with the beam will begin early next year.

Another centre of activity is now forming at CERN, in collaboration with Wuppertal University. Firstly, we have started systematic investigations of surface technology, making use of the expertise and special equipment available for ultra-high vacuum work at the ISR. Secondly, we want to try cavities of an alternative shape, namely of semicircular section as shown in Figure 24, representing another and more recent idea of how to eliminate the multipactoring effect. A 500 MHz cavity of this shape is being built and laboratory tests will start soon.

Clearly this work is still at the level of feasibility studies, with reliable and economic mass production of multicell structures not in sight as yet. However, the present rate of progress looks encouraging and LEP, as I presented it, is designed in such a way that a progressive conversion to RF superconductivity is possible at any stage, whenever the new technology is ready.



(P 1,7,8)	UNDERGROUND EXPERIMENTAL HALLS
(P,2,6)	SURFACE EXPERIMENTAL HALLS
(P 3,4,5)	DEEP UNDERGROUND EXPERIMENTAL HALLS
⑨	INJECTOR SYNCHROTRON
⑩	ACCESS TUNNELS TO THE DEEP UNDERGROUND EXPERIMENTAL HALLS

Fig. 1. General layout

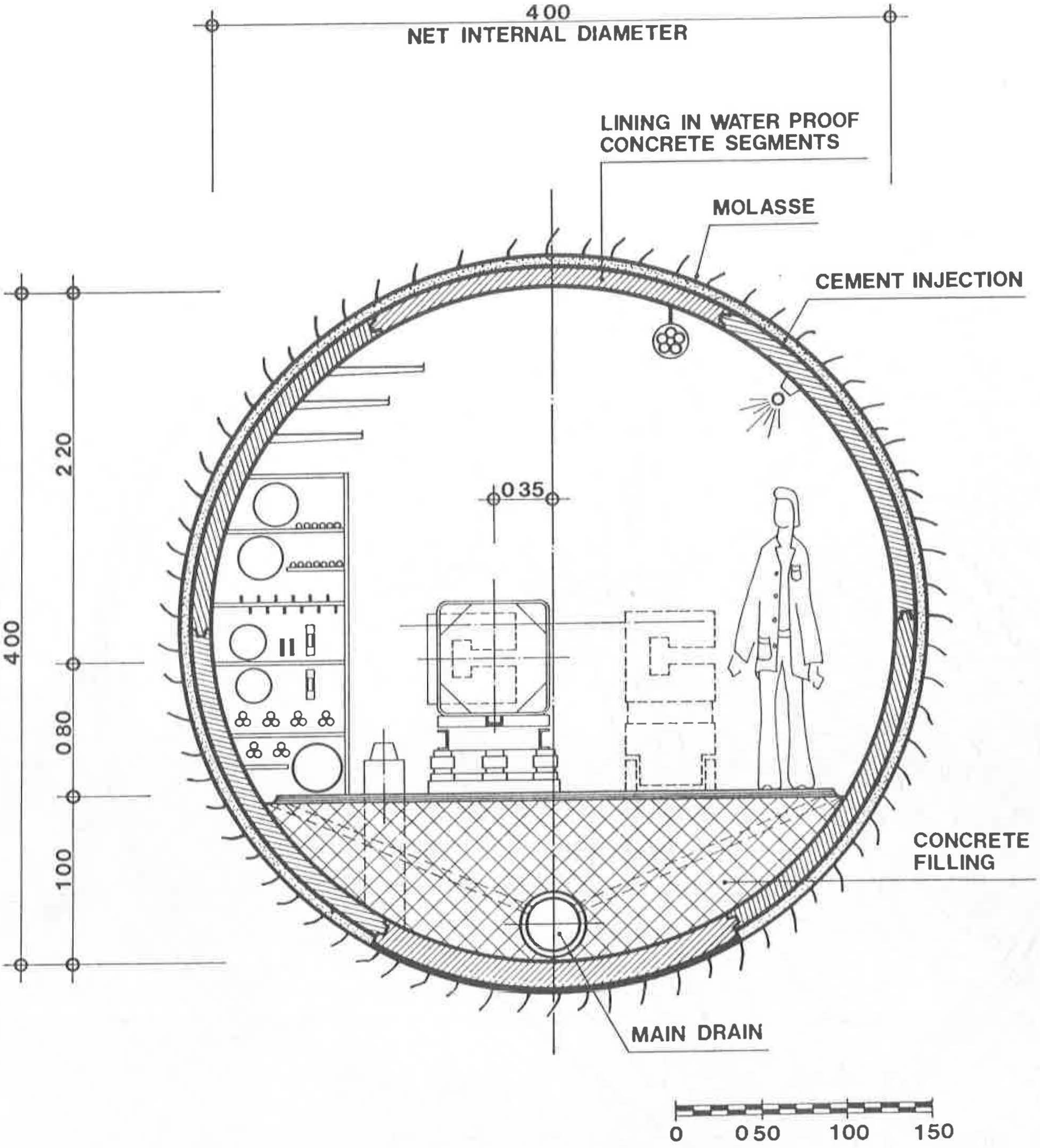
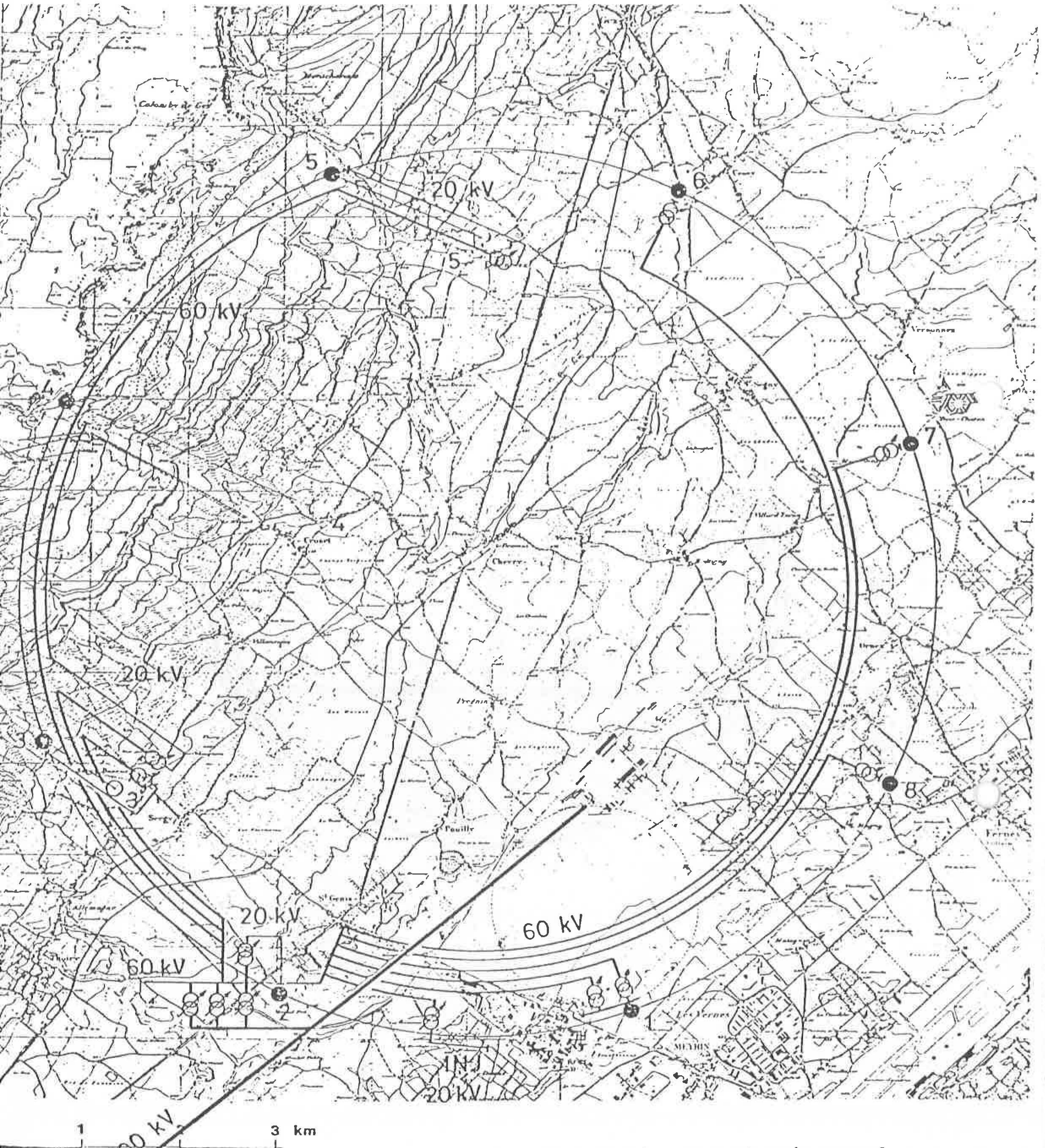
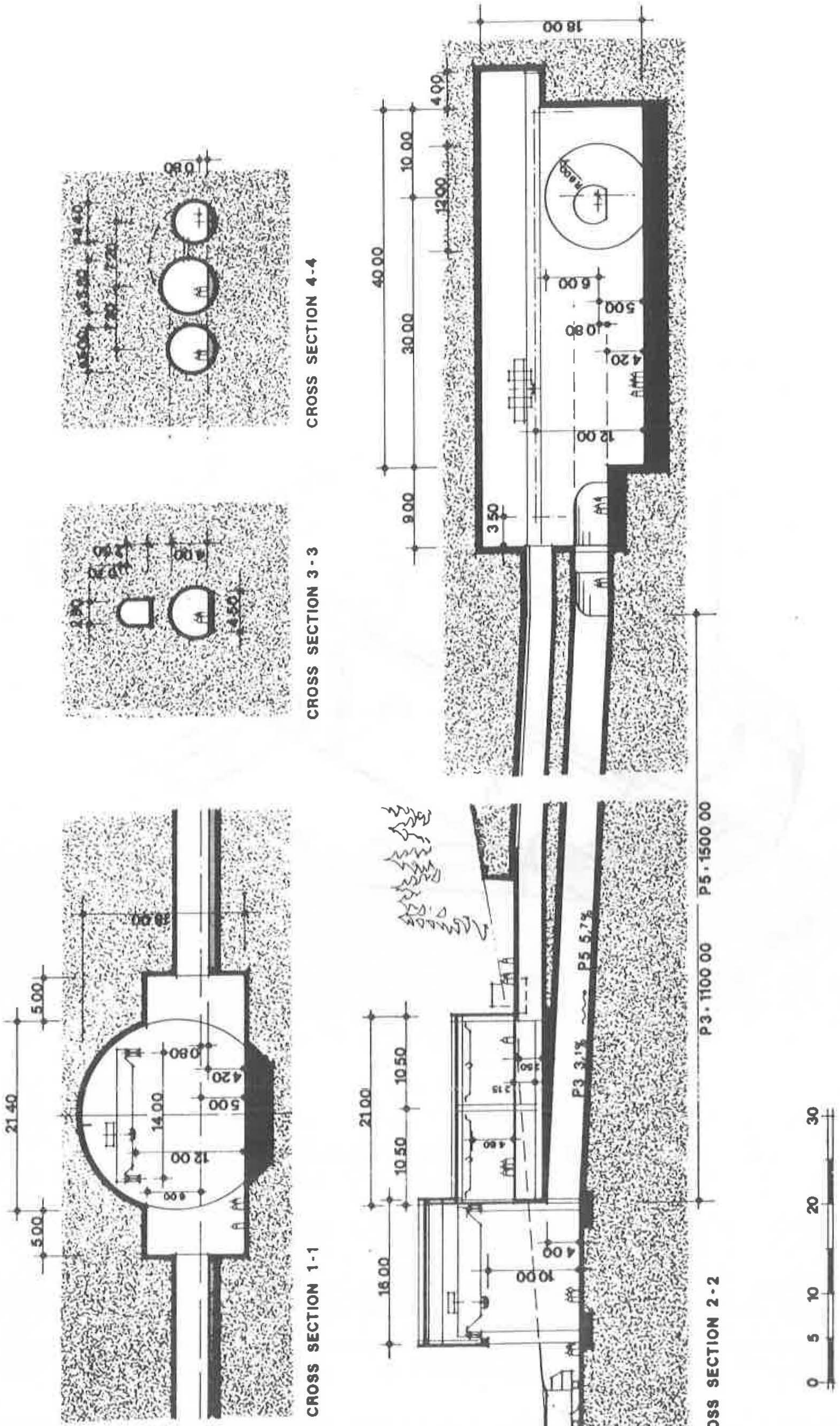


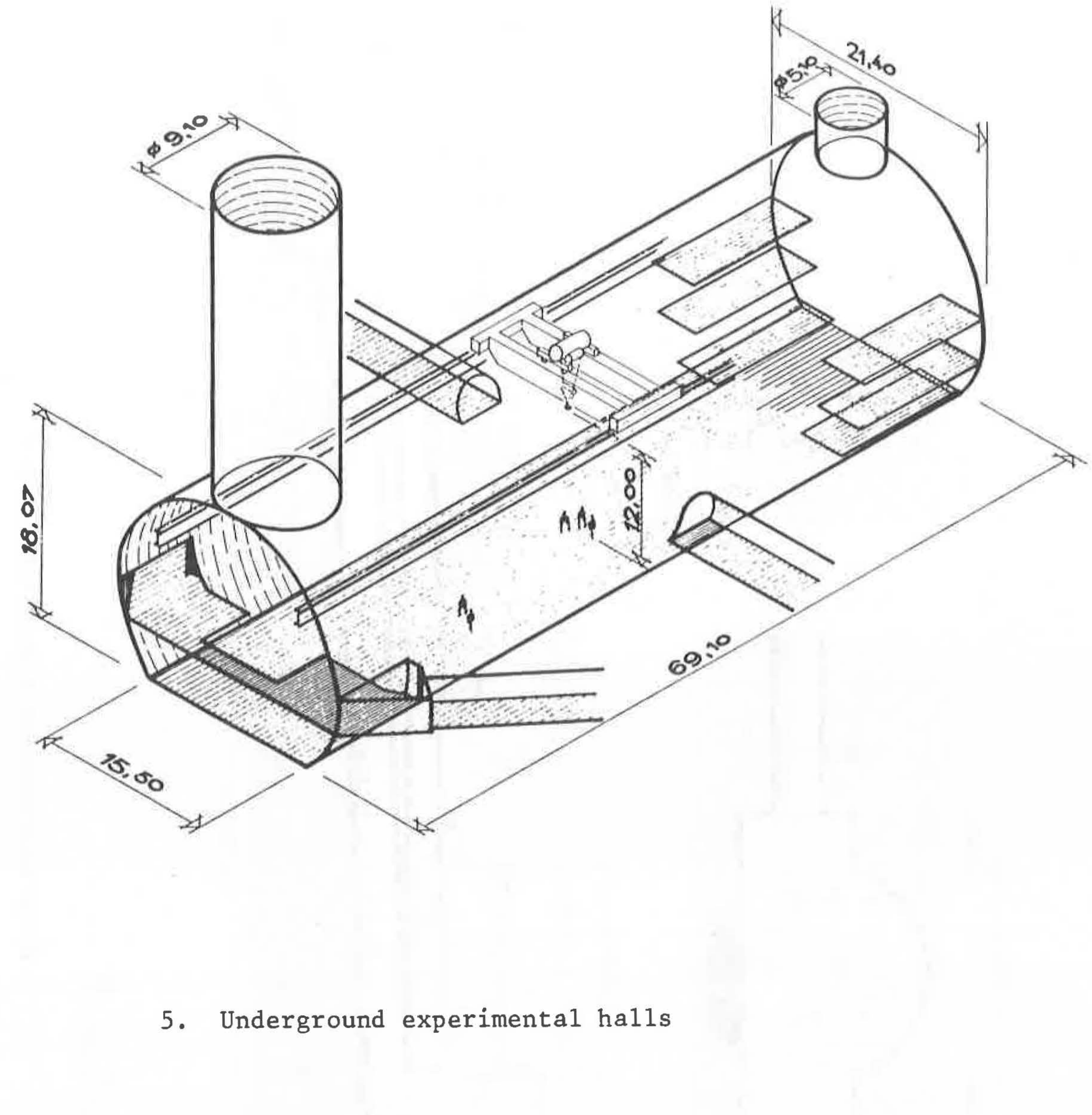
Fig. 2. Main tunnel cross-section



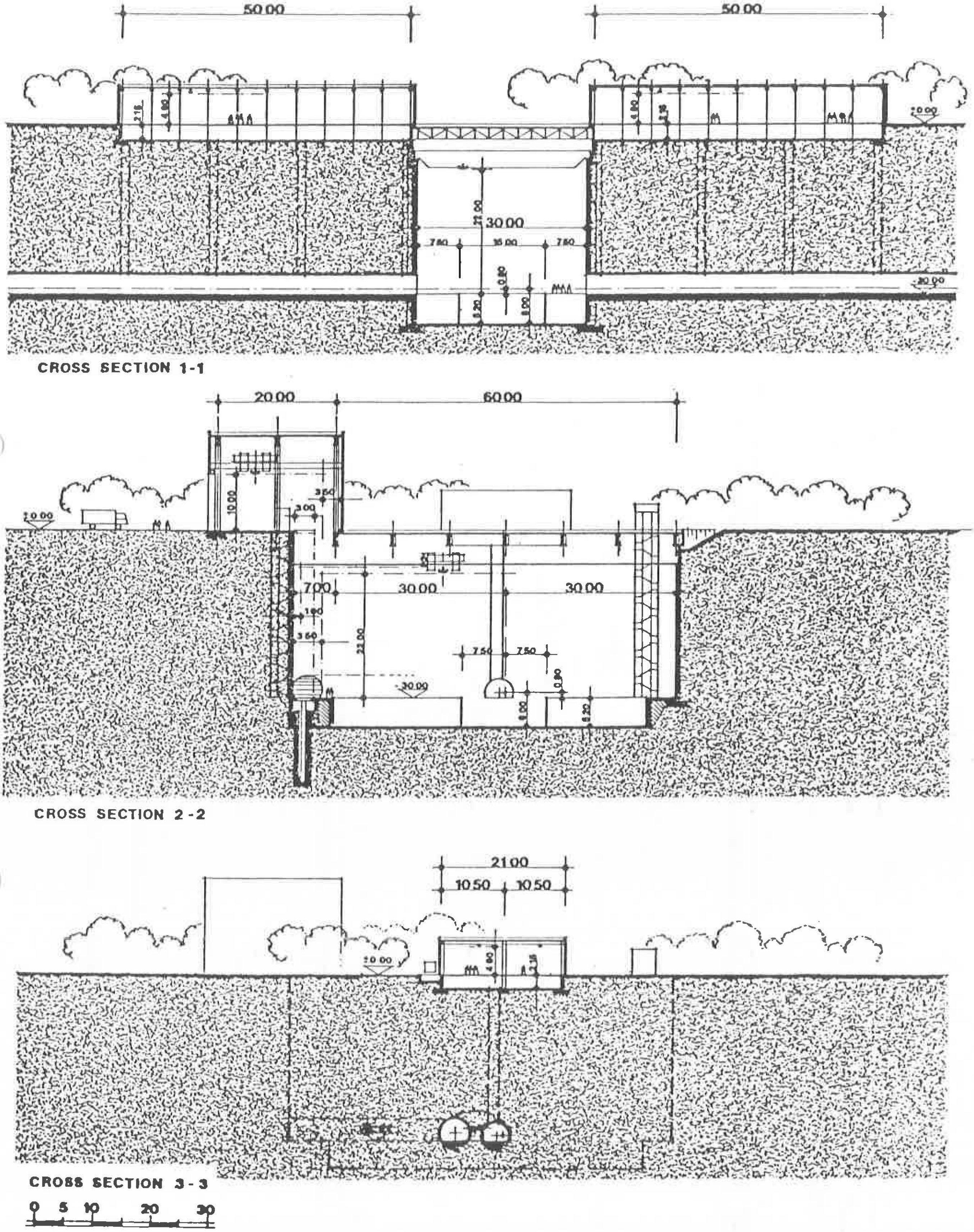
3. Power distribution through main tunnel



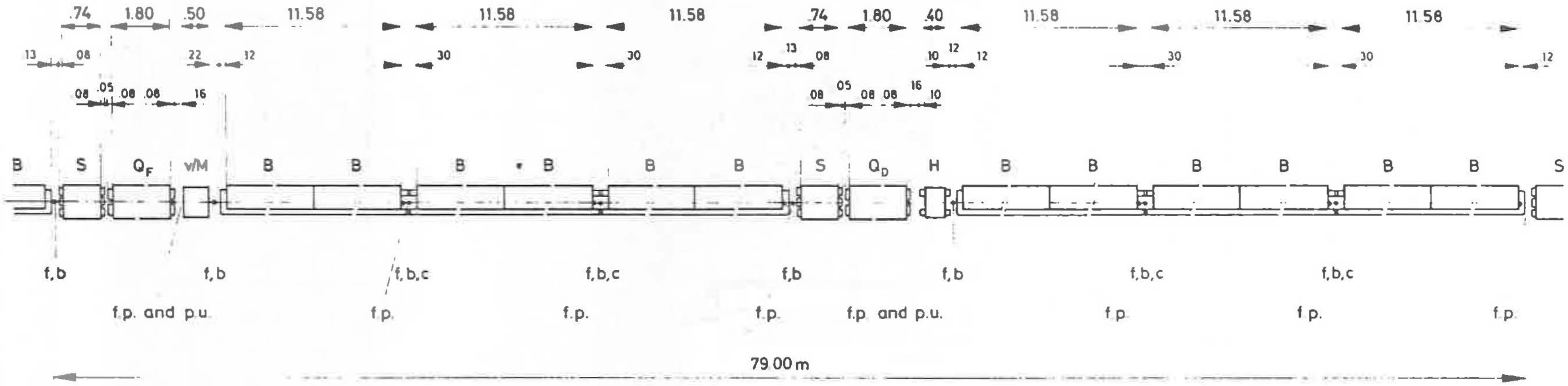
4. Deep underground experimental halls



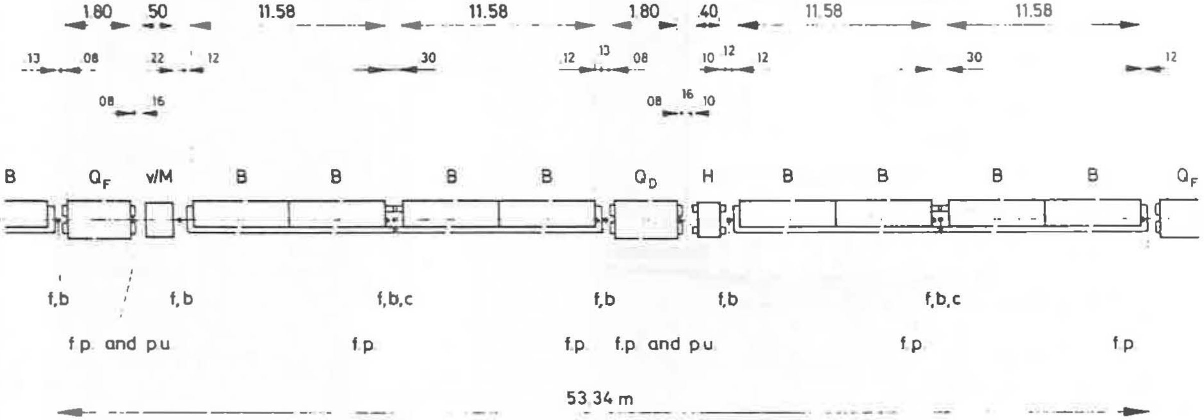
5. Underground experimental halls



6. Experimental hall made by excavation from surface



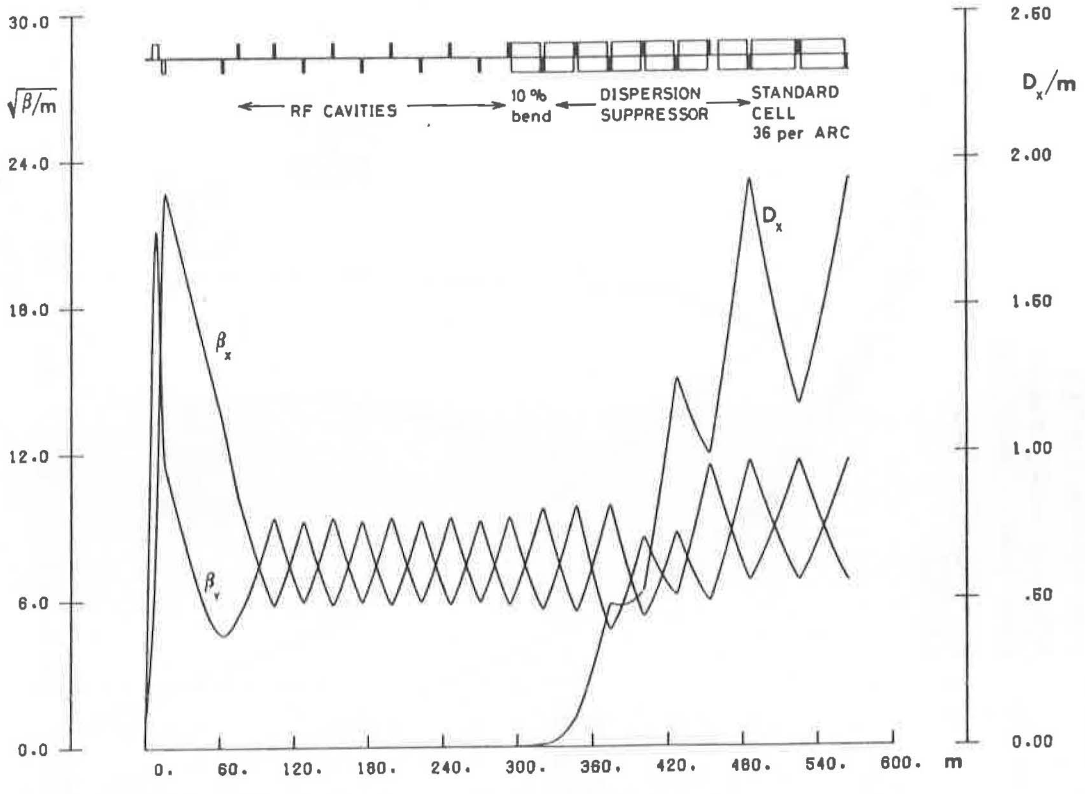
STANDARD CELL



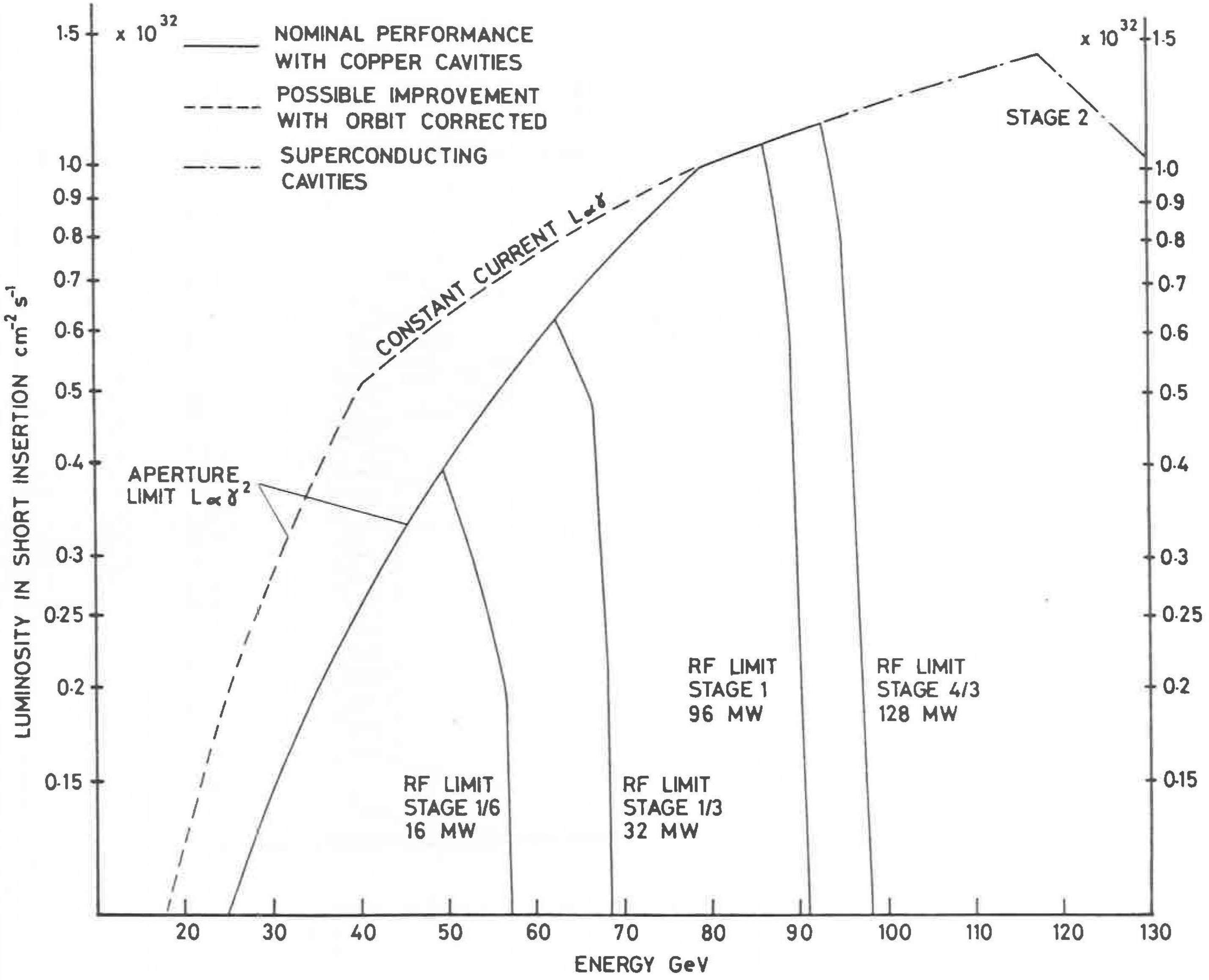
B	- bending magnet
Q_F, Q_D	- quadrupoles
S	- sextupole
H	- horizontal-field dipole
M	- multipole
f	- flange
b	- bellows
c	- connections
f.p	- fixed point
p.u.	- pick-up
v	- valve

DISPERSION SUPPRESSOR CELL

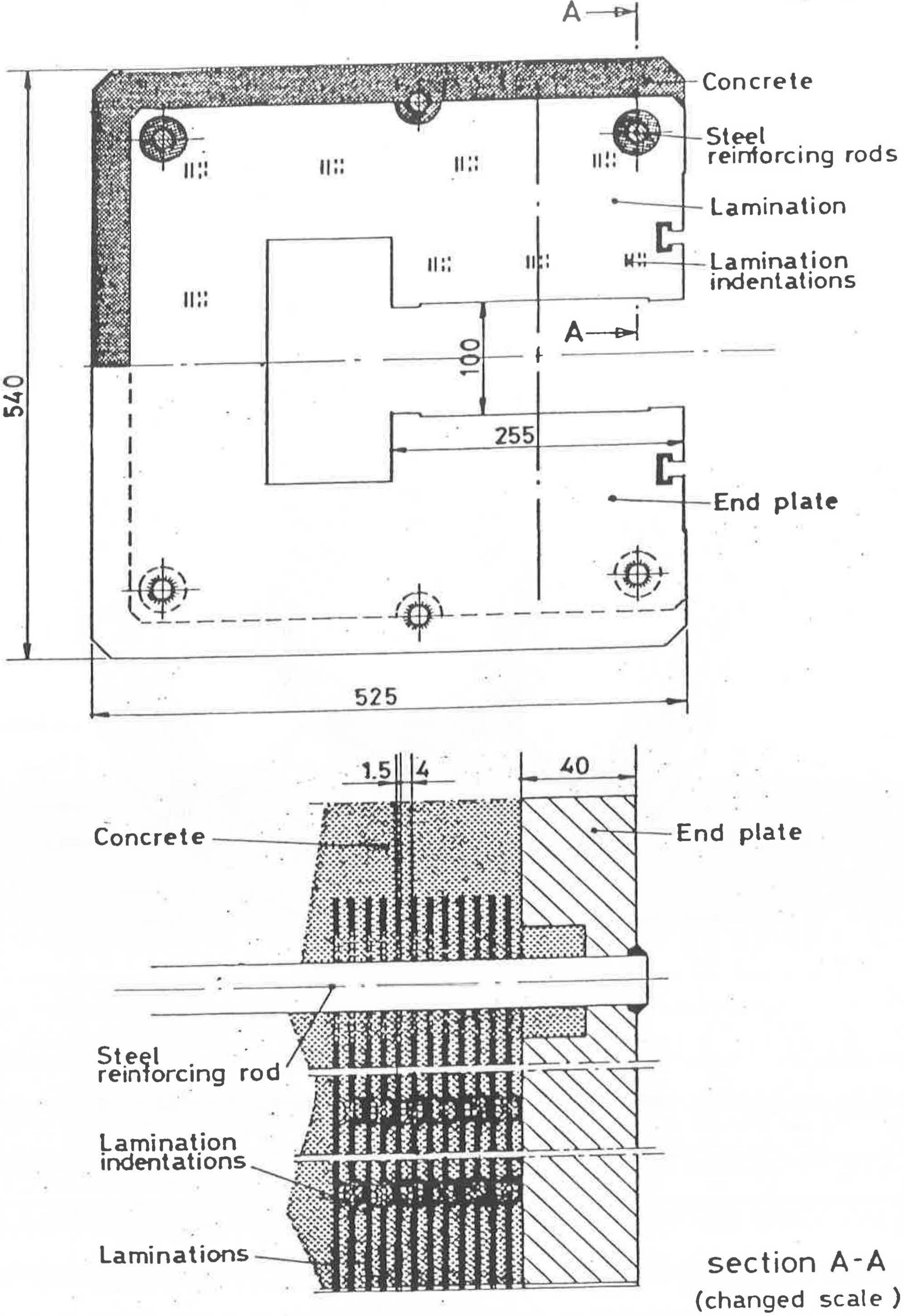
7. Regular lattice period and dispersion-suppressor period



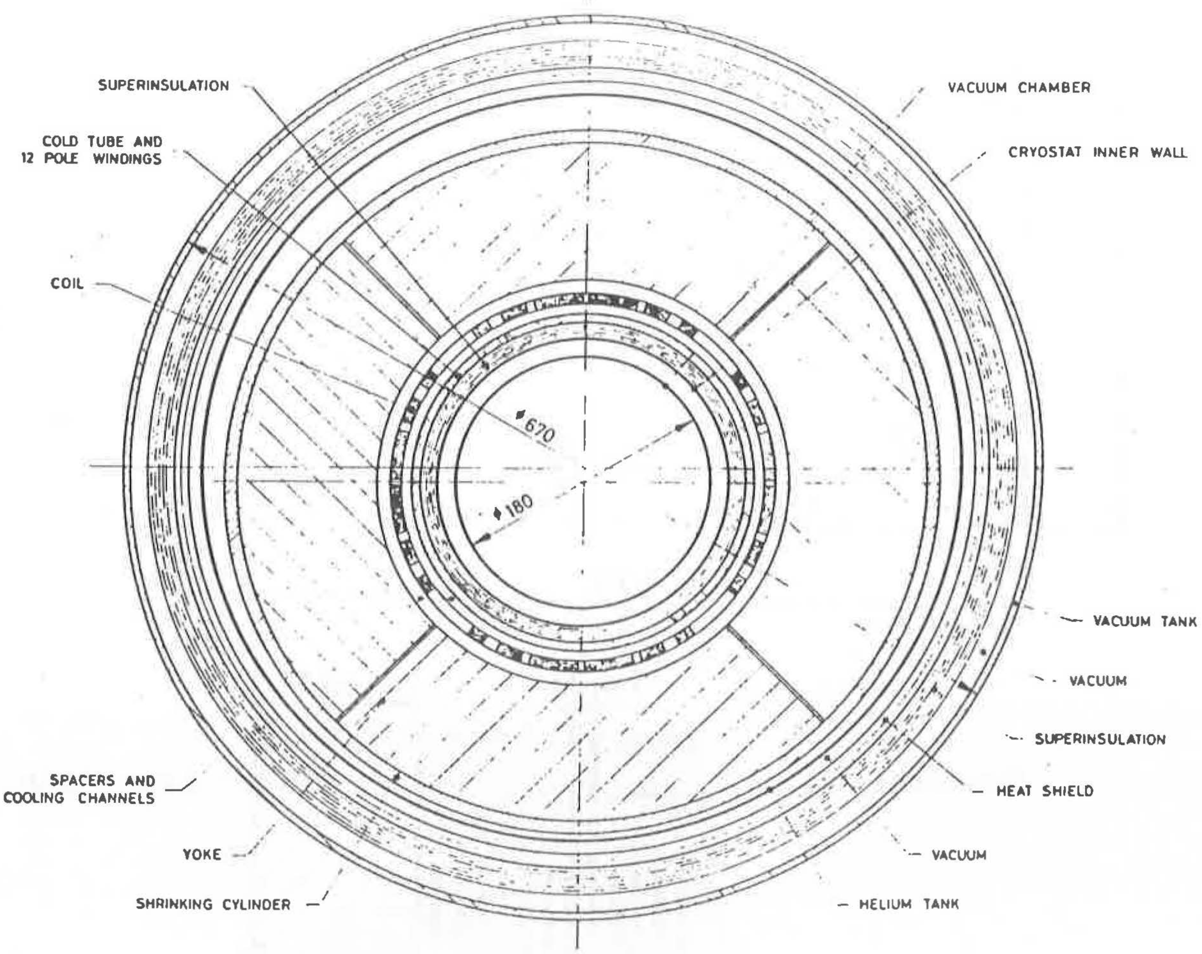
8. Lattice and lattice functions near collision point



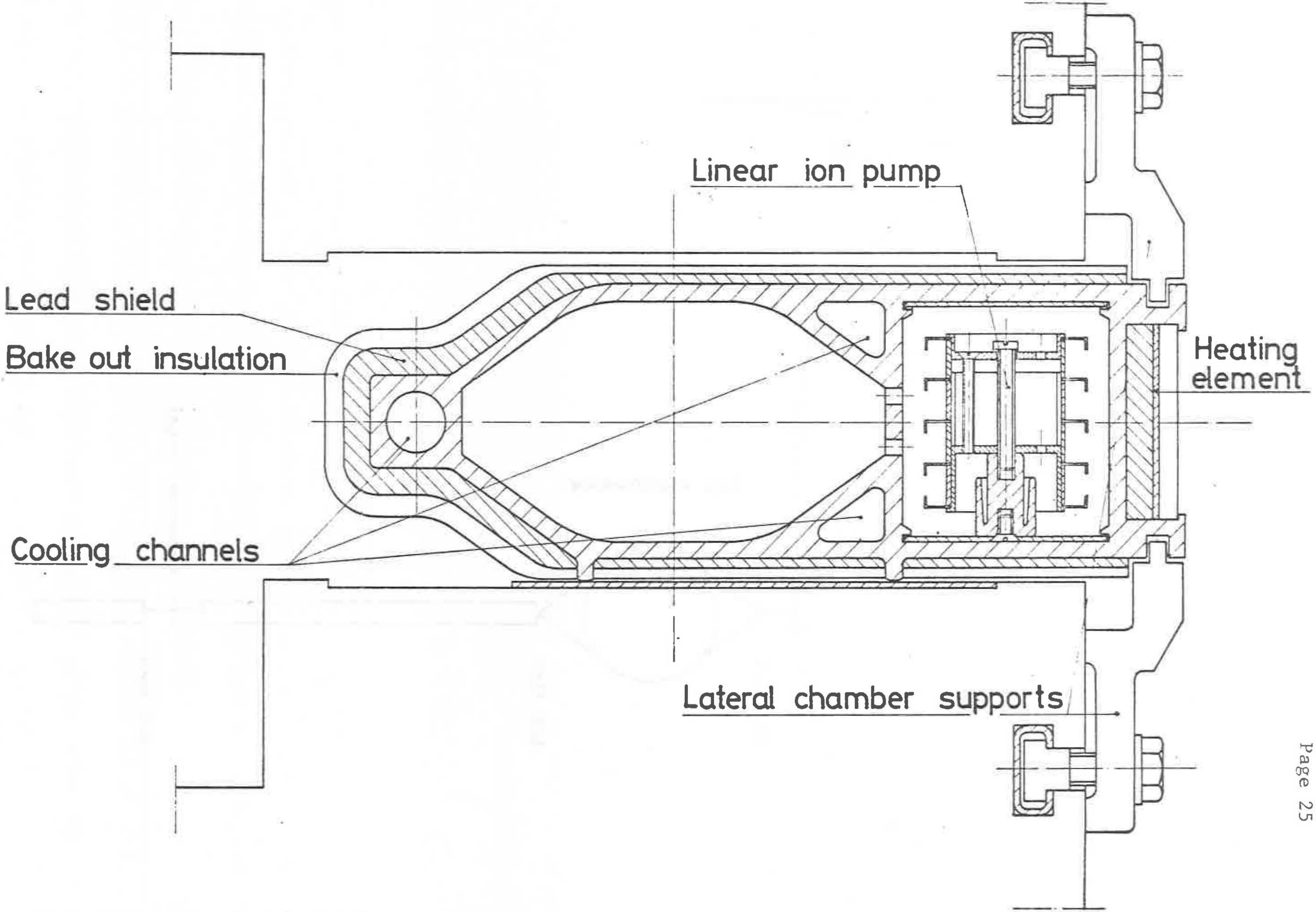
9. Luminosity versus energy for the different stages



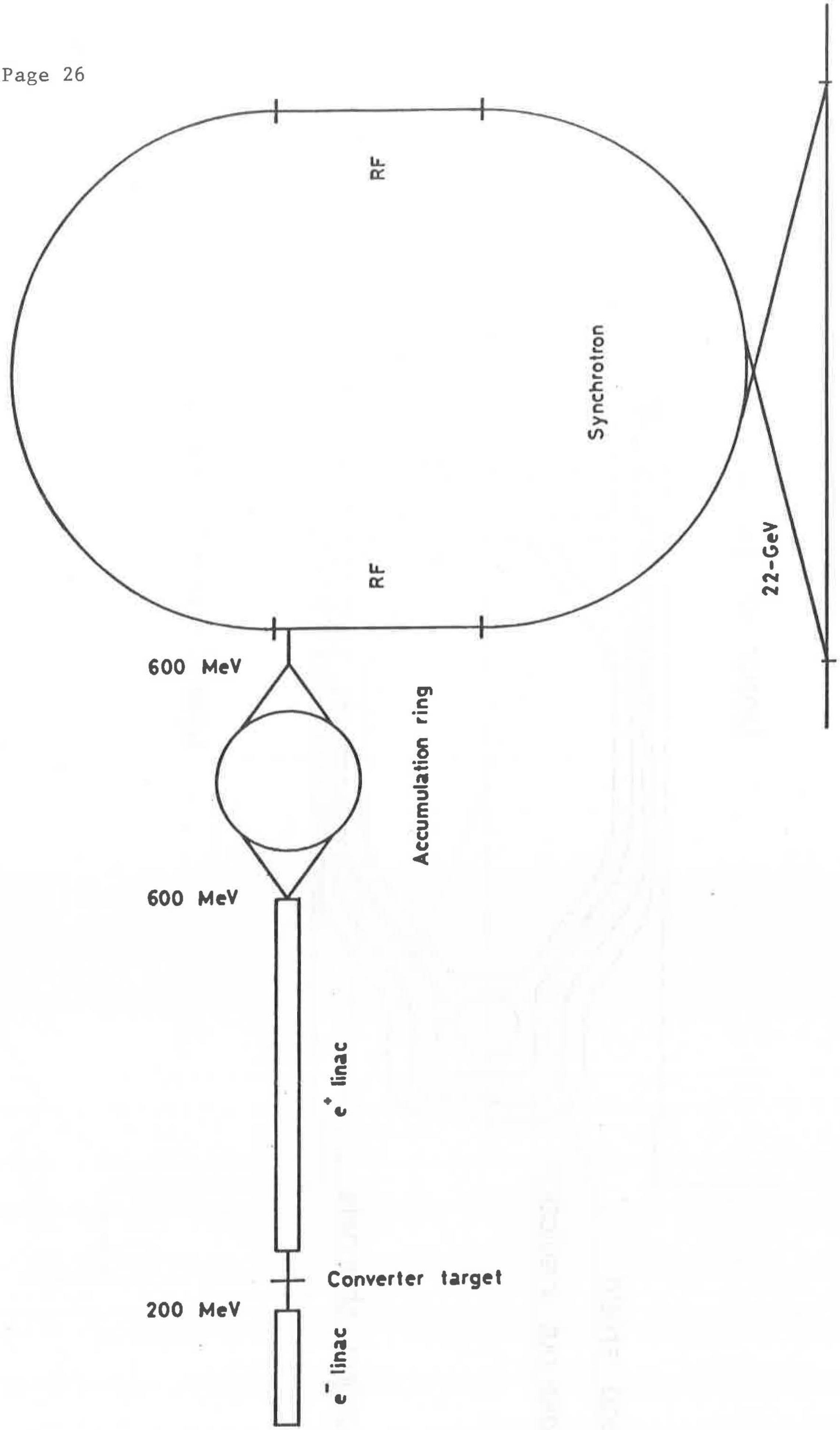
10. Steel-concrete magnet core



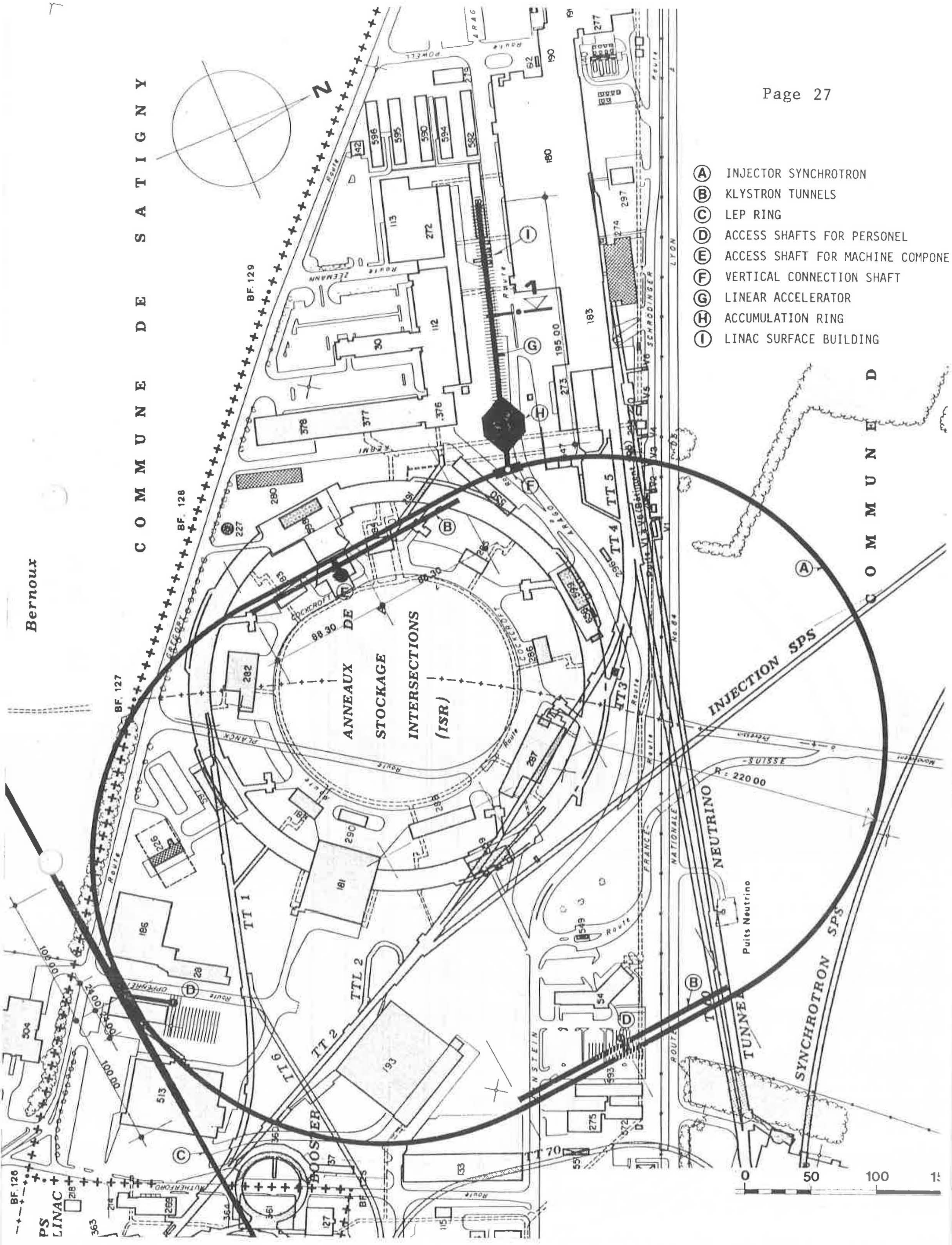
11. Superconducting insertion quadrupole, cross-section



12. Vacuum chamber in bending magnet, cross-section

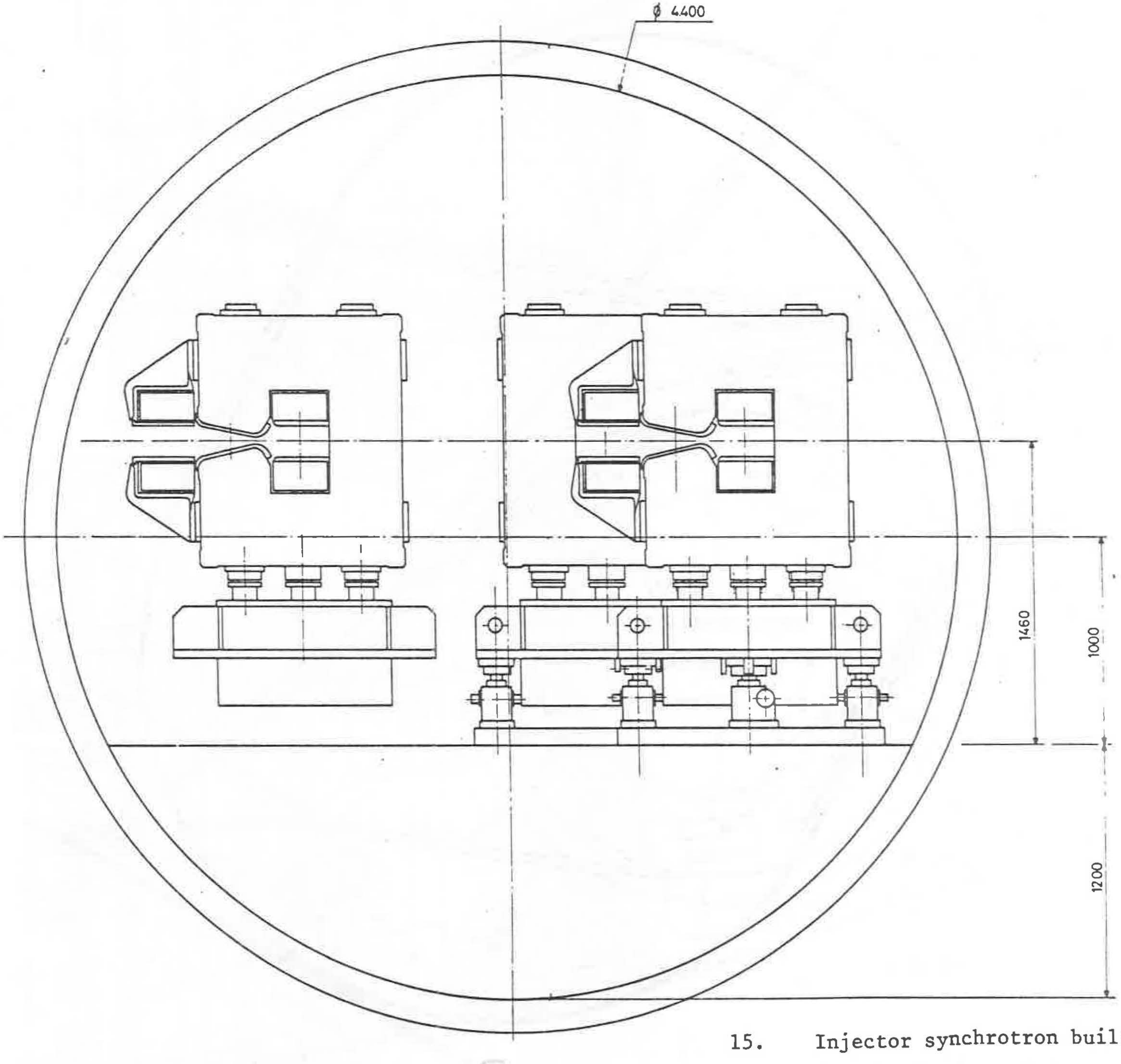


13. General layout of injector, schematic

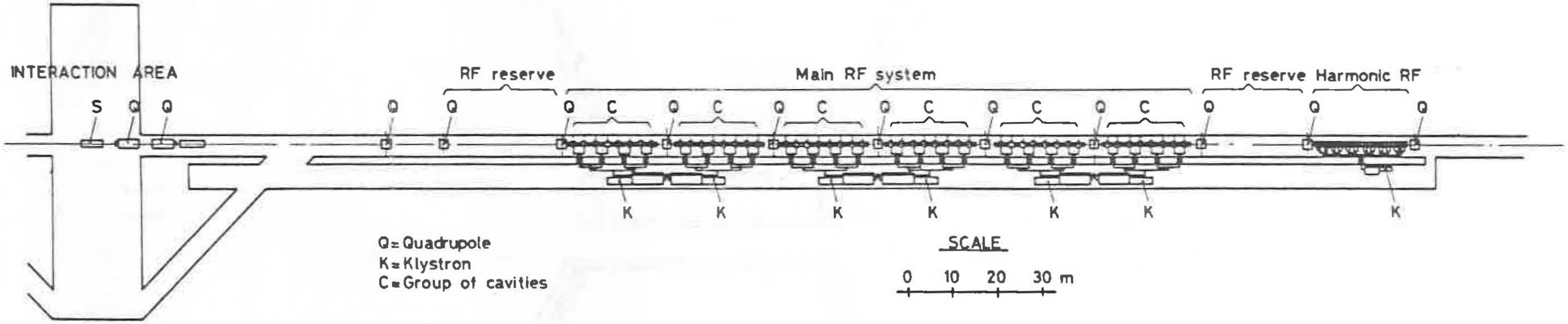


Ⓐ INJECTOR SYNCHROTRON
Ⓑ KLYSTRON TUNNELS
Ⓒ LEP RING
Ⓓ ACCESS SHAFTS FOR PERSONEL
Ⓔ ACCESS SHAFT FOR MACHINE COMPONE
Ⓕ VERTICAL CONNECTION SHAFT
Ⓖ LINEAR ACCELERATOR
Ⓗ ACCUMULATION RING
Ⓘ LINAC SURFACE BUILDING

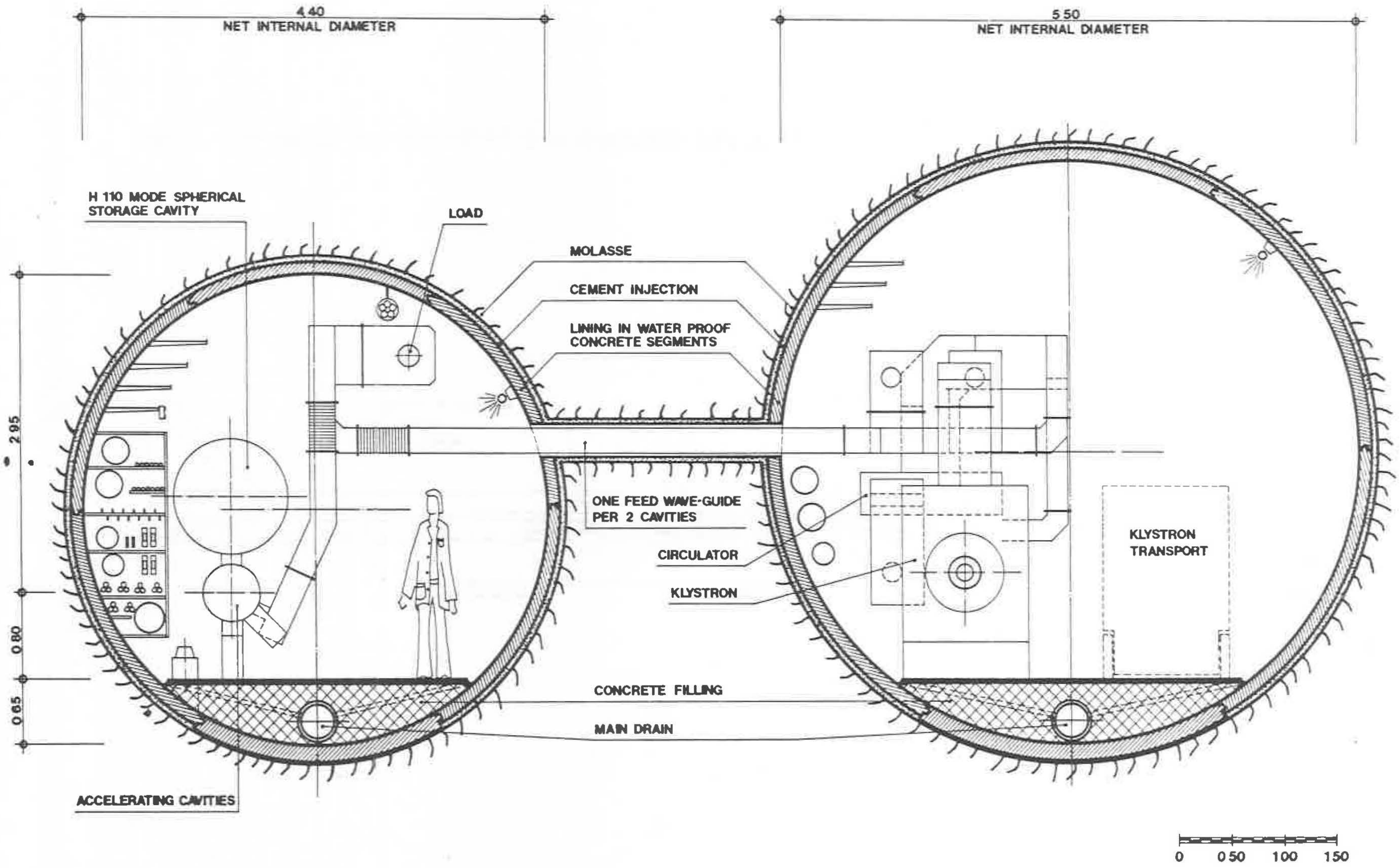
14. Injector layout under present ISR site



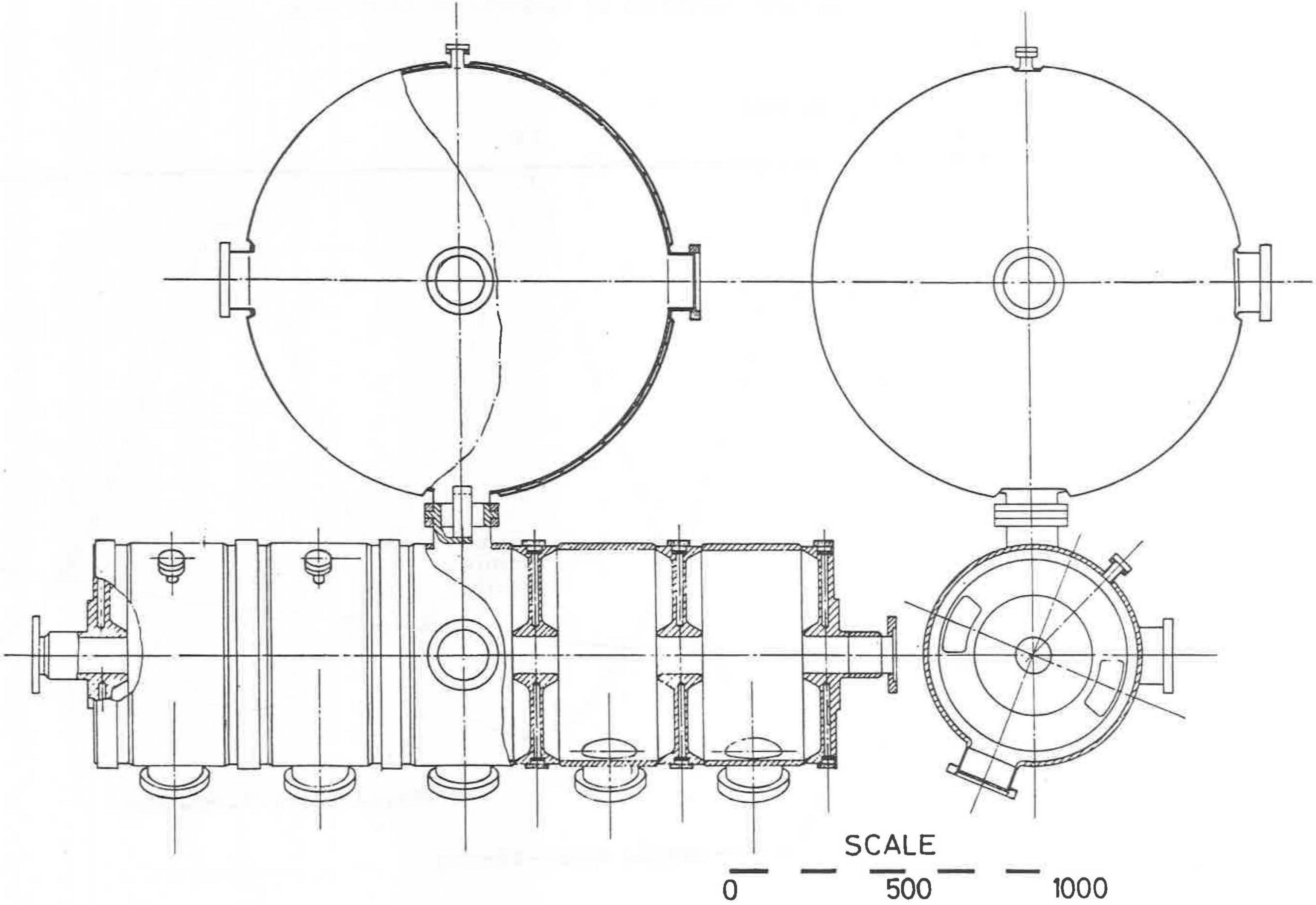
15. Injector synchrotron built with ISR magnets
(on the le : position of magnet during transport)



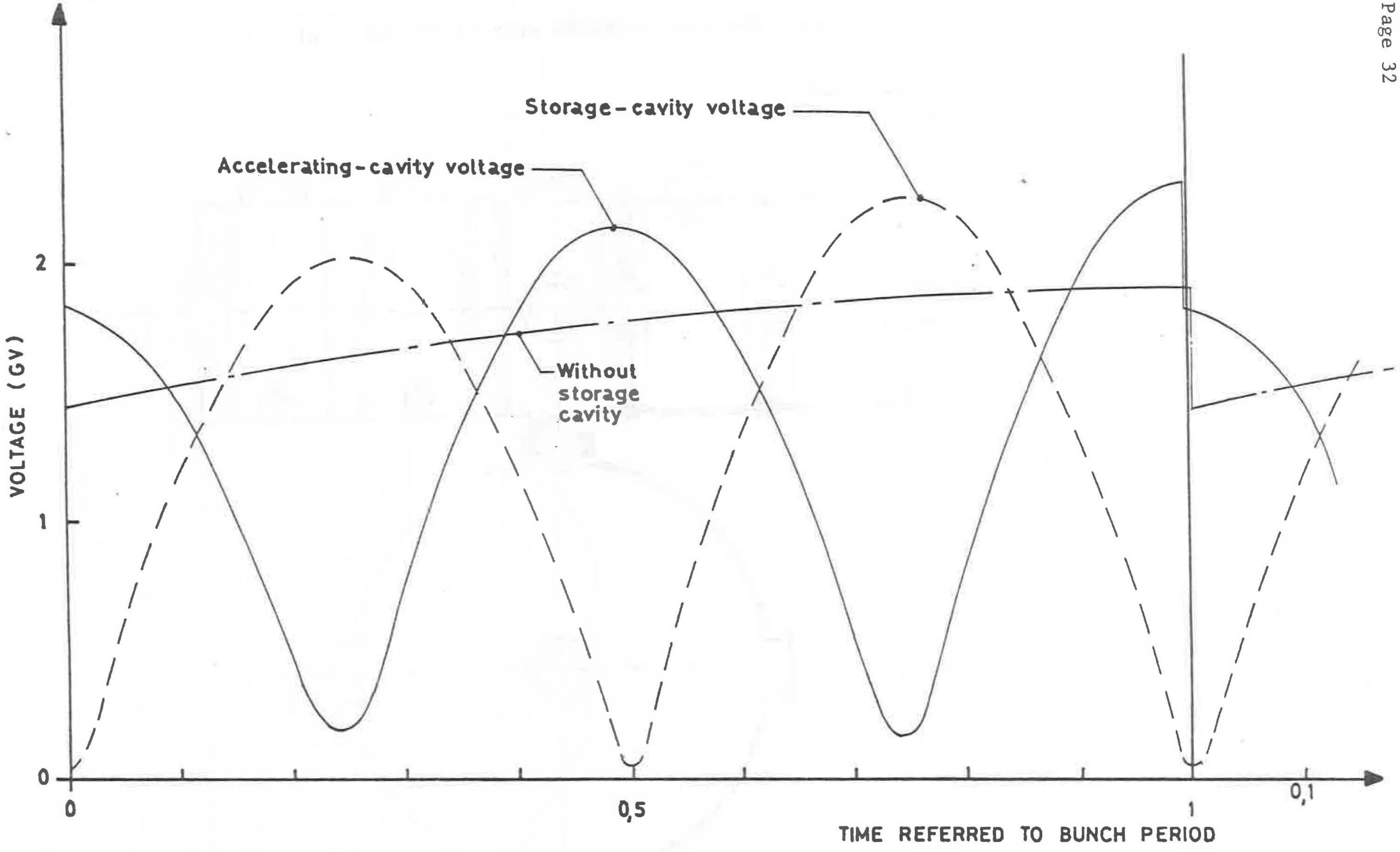
16. One of 16 RF stations, with cavities and klystrons



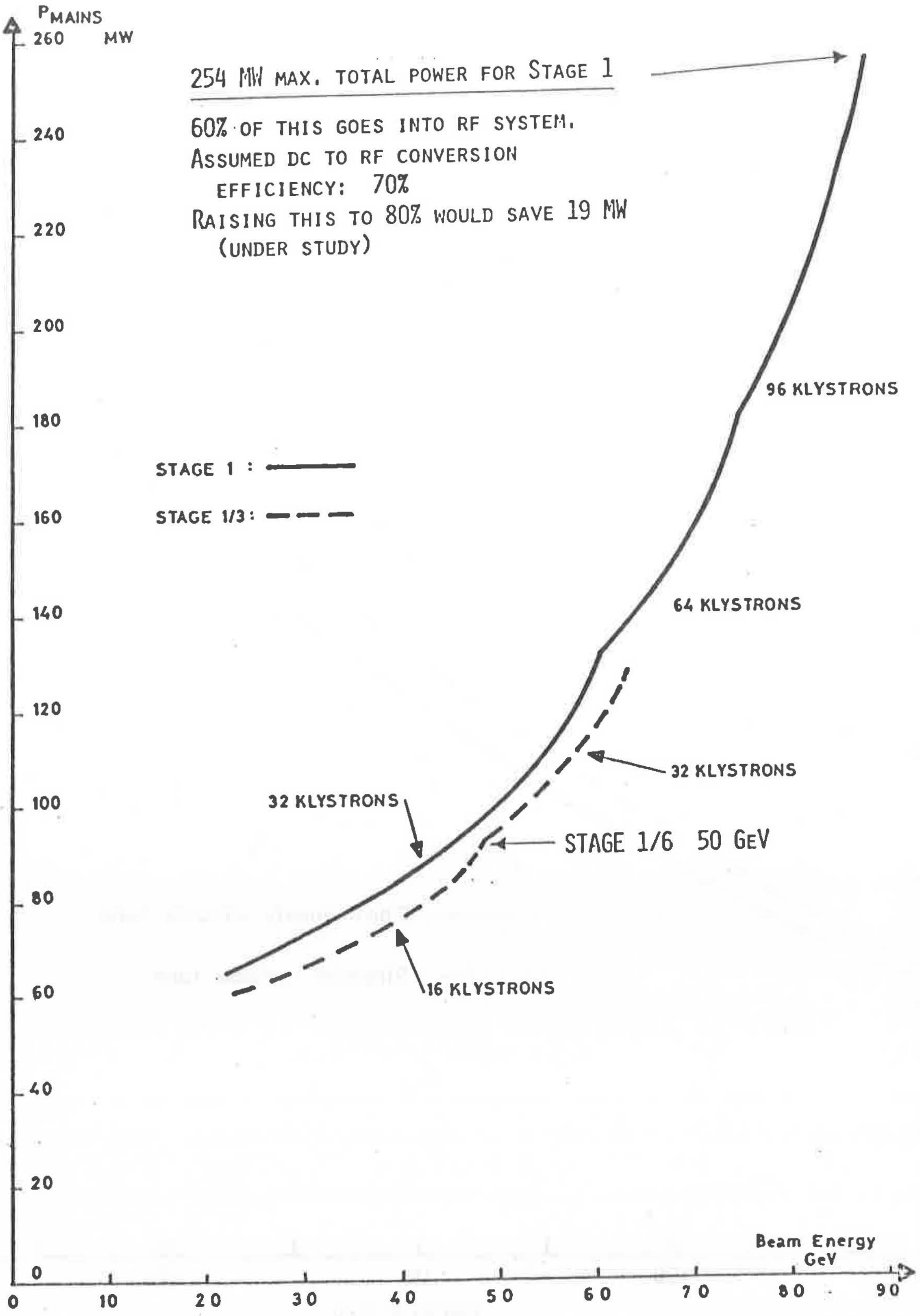
17. Main tunnel at RF station with klystron tunnel



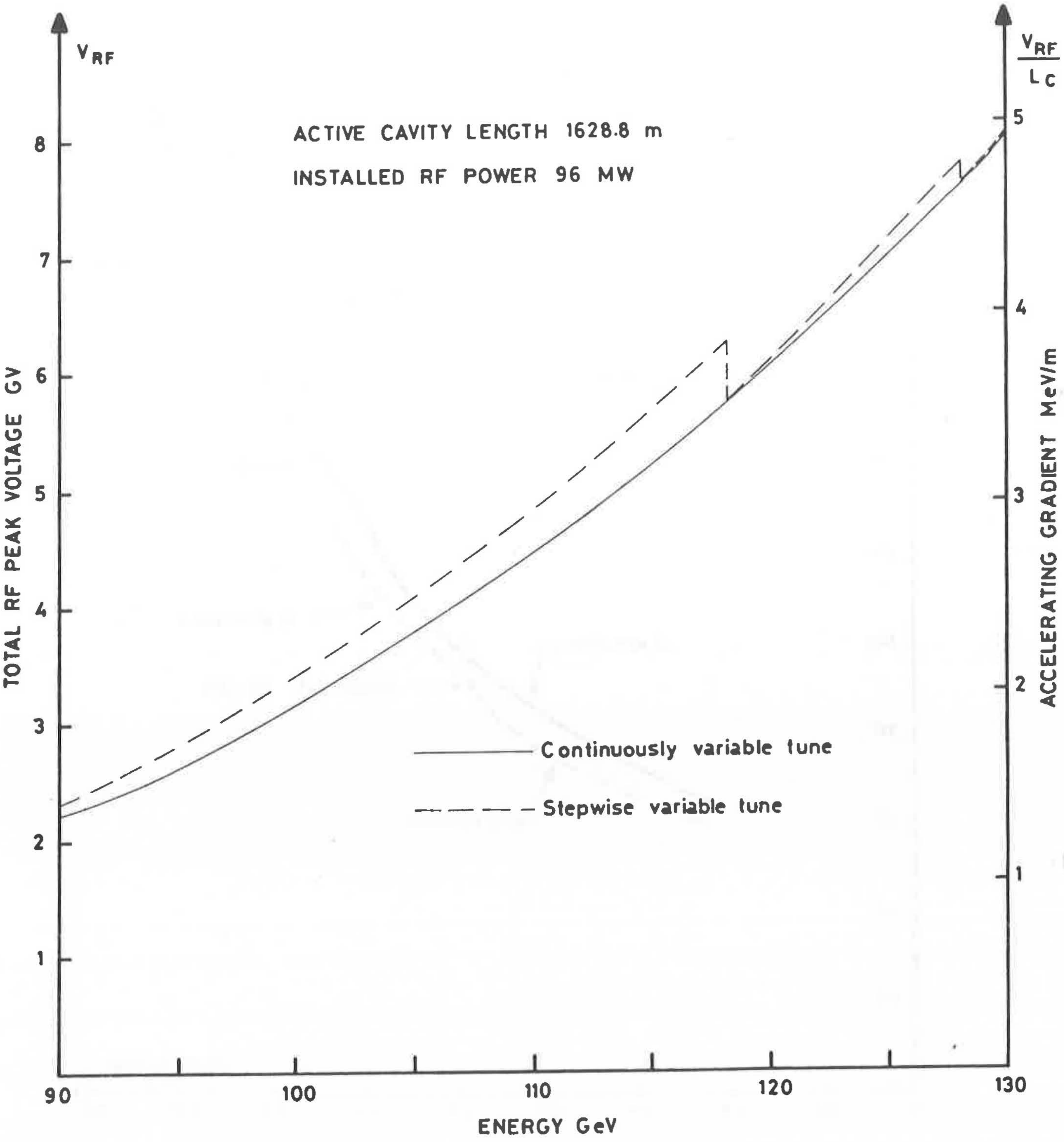
18. RF cavity with spherical storage cavity



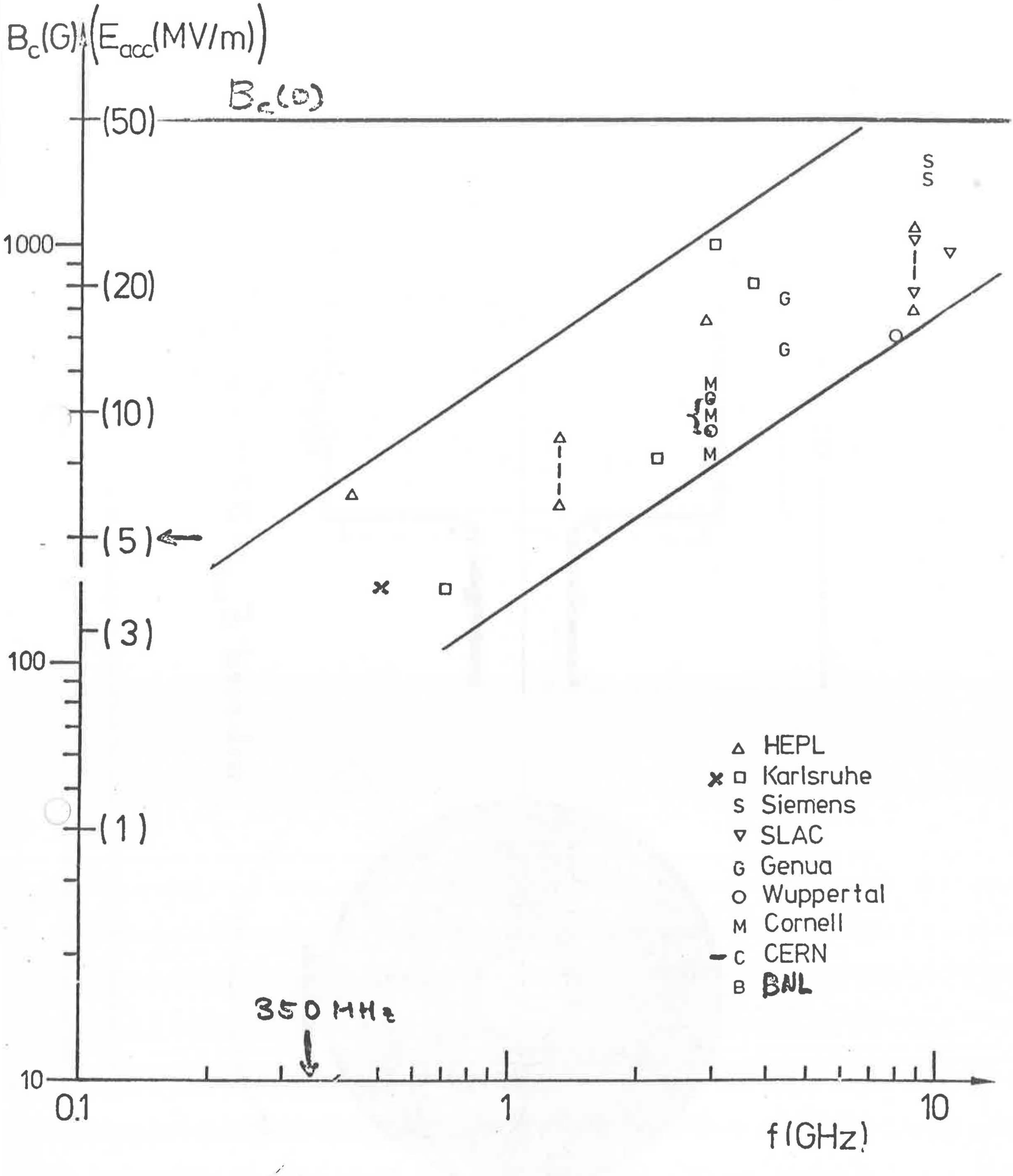
19. Modulation of voltages in cavities, including beam-loading



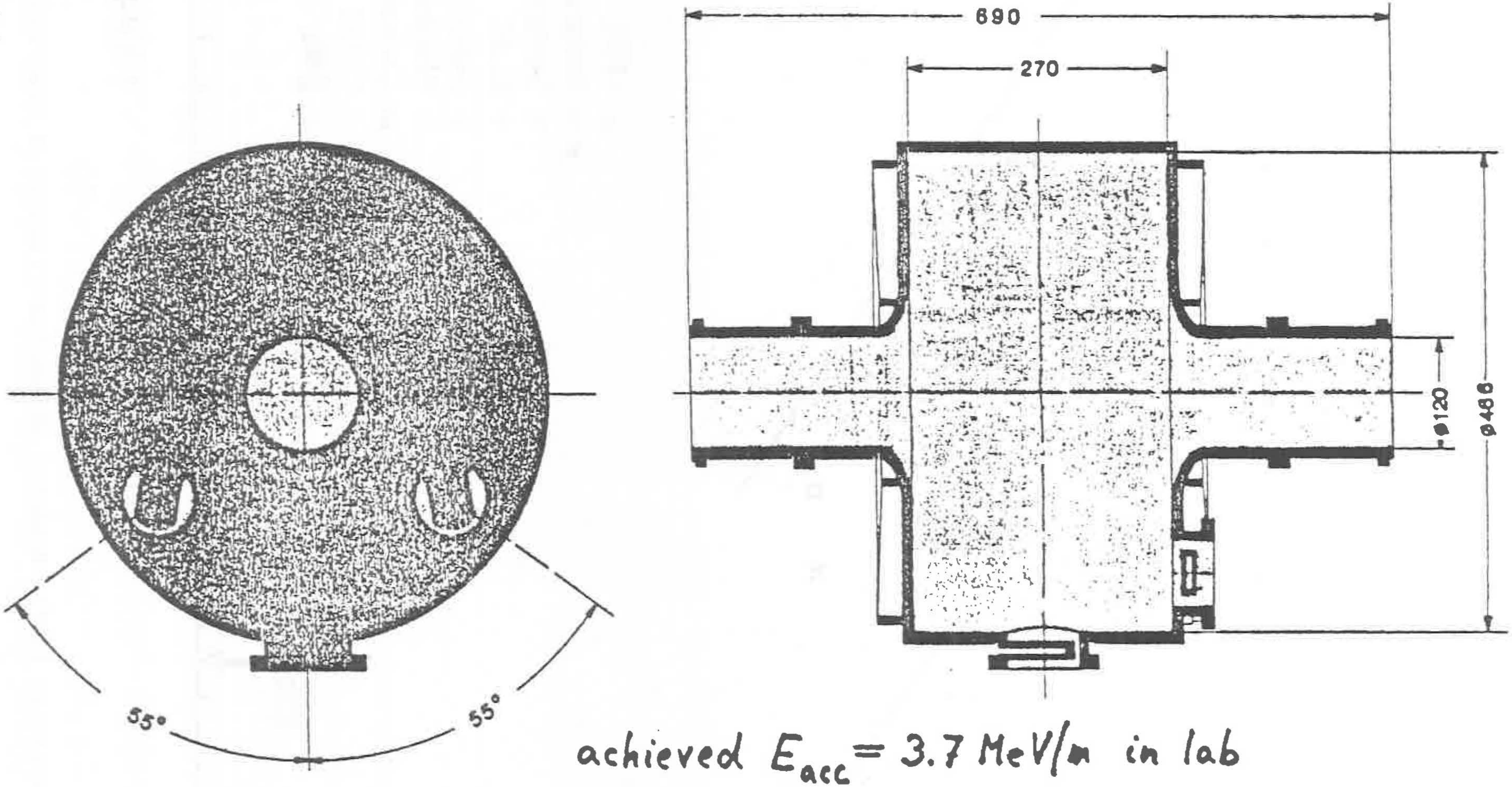
20. LEP input power as a function of beam energy



21. Peak RF voltage and accelerating field above 90 GeV

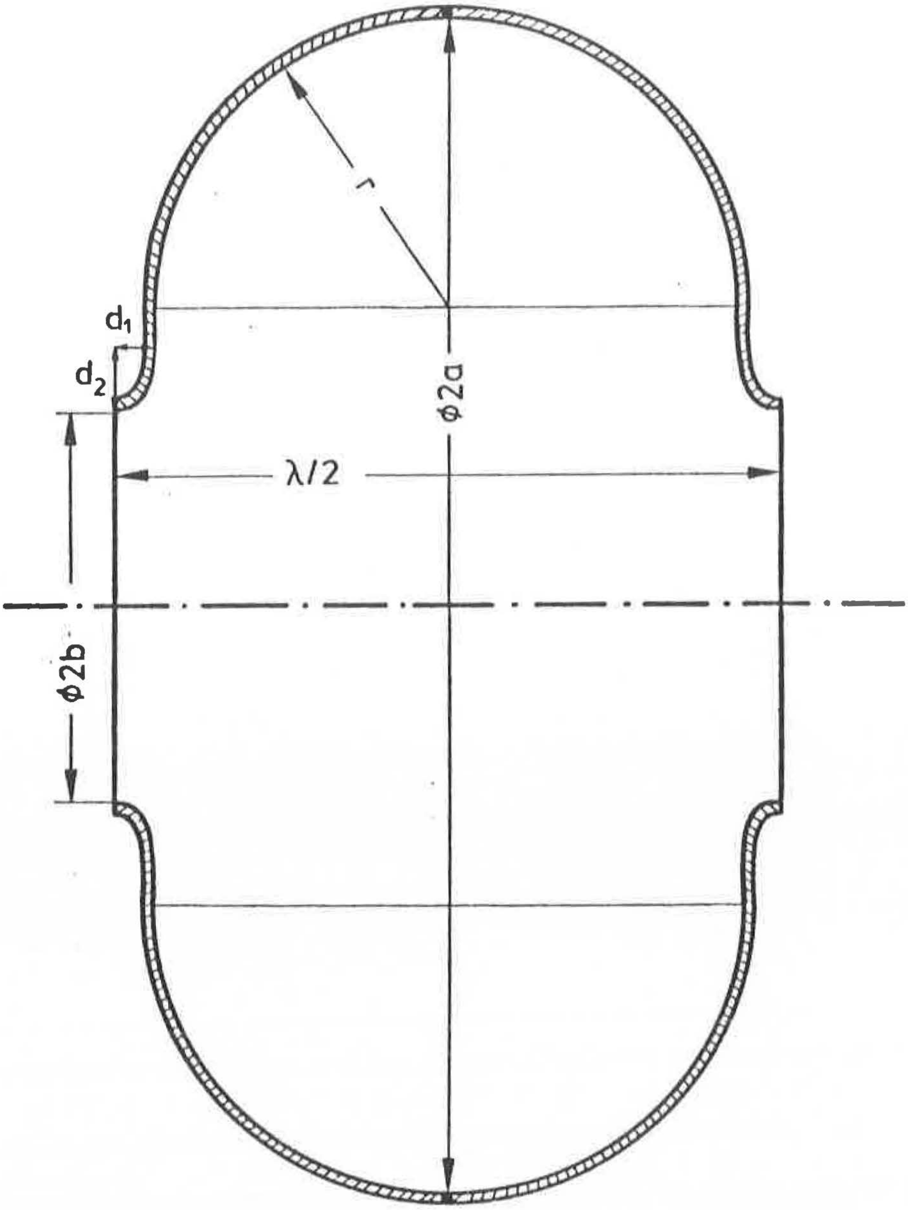


22. Accelerating fields achieved in laboratory models of superconducting cavities at different frequencies

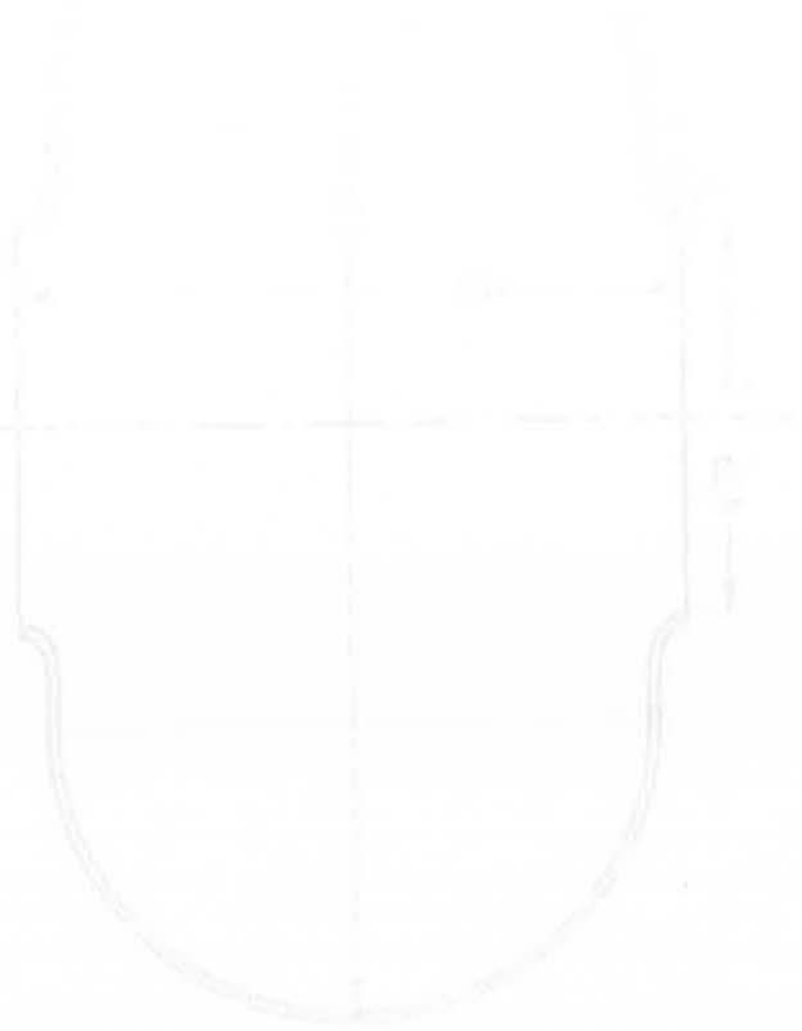


achieved $E_{acc} = 3.7$ MeV/m in lab

23. Superconducting test cavity made by Kernforschungszentrum Karlsruhe for tests in DORIS Hamburg



24. CERN/Wuppertal University superconducting cavity.



CONSEQUENCES OF THE LEP CONSTRUCTION PROJECT ON THE CERN RESEARCH ACTIVITIES

J.B. Adams

Introduction

1. Report CERN/ISR-LEP/79-33 describes in detail the design of a large electron-positron colliding beam machine (LEP) which seems to satisfy the requirements of the European high-energy physics community for the next major accelerator to be built at CERN. This report, hereafter referred to as the "Pink Book", estimates that the capital cost for Stage $^1/3$ of the LEP will be 1064 million Swiss francs (MSF) at 1979 costs, and at the beam energy of Stage $^1/3$, which is 62 GeV per beam, the report says that the first physics experiments could begin during the seventh year after approval of the project. Apart from technical considerations, other factors, not discussed in the Pink Book, could limit the duration of the initial construction period of LEP. These are the total CERN budgets, the staff available at CERN, and the required level of operation of the remaining CERN research activities during the construction period.

2. This note describes the consequences of the LEP construction project on the CERN research activities during the construction period in terms of a model which is based on certain assumptions concerning the total CERN budgets and the manpower available. It also points to the problem of the electrical energy consumption of CERN which may become a more serious restriction on the operation of the Laboratory in the future than it is at present.

Basic Assumptions

3. In order to make a meaningful model for the LEP construction period it is necessary to define the basic constraints which will operate during this period.

4. In the first place, it is assumed that the total budgets of CERN will be stabilized at a constant level. When this idea was first put forward by the Directors-General over a year ago, the figure they proposed was 600 MSF per year at 1978 costs. It was stated that LEP could be built and an adequate physics programme run using the SPS and PS machines during the LEP construction period, but that the ISR and SC machines would have to be phased out when LEP construction started.

5. During the course of this year the future of the ISOLDE facility, which uses the SC machine, has been examined and two solutions have been advanced. One is to move the facility, probably in an improved form, to the SIN machine and the other is to operate the SC machine only for the ISOLDE facility after the start of LEP construction. No decision has yet been reached but it is assumed for the model that the SC machine will continue in operation for ISOLDE only.

6. The present financial assumptions during the LEP construction period are therefore:

- constant total CERN budgets of 610 MSF per year at 1979 costs (equivalent to 600 MSF per year at 1978 costs);

- the ISR machine is phased out when LEP construction starts;

- operation of the SC machine for ISOLDE alone after the start of LEP construction.

7. The second important assumption concerns CERN staff numbers. The present planning for CERN staff numbers is to slow down the rate of reduction of previous years by adding 2 MSF per year to the Personnel Budget in 1980 and subsequent years, and to stabilize CERN staff numbers as soon as possible. In the middle of the 1980's, the number of CERN staff reaching retirement age each year will increase considerably and some of them can be replaced by young recruits whose salaries will be less than those of the retiring CERN staff. It is therefore possible to stabilize the number of staff during the first half of the 1980's by adding 2 MSF per year to the Personnel Budget. If in the second half of the 1980's the same constant staff numbers are maintained it is then possible to stabilize the Personnel Budgets. As a result of this assumption, CERN staff man-years (including laboratory staff) will decrease from the present figure of 3550 to a constant level of 3430, and the Personnel Budget will rise from 272 MSF (1979 costs) in 1980 to a constant level of 284 MSF in the mid-1980's. No account is taken in these calculations of the possible financial consequences of the present review by the Finance Committee of the salaries and social conditions of CERN staff. It is assumed that any consequent increase in personnel costs will be added to the budgets.

8. On the basis of these assumptions, a model has been made for the period of LEP construction which shows how the financial constraints and the limitations in available man-years influence the LEP construction time and restrict the remaining research activities of the Organization.

A Model for the LEP Construction Period

9. Following the assumptions mentioned above, one can begin to construct the model on a financial basis by tabulating the total CERN budgets, the Personnel Budgets and the consequent Materials Budgets during the years of LEP construction taking, for example, the year 1982 as the start of the construction period. The result of this calculation shows that the average budget for materials during the years of LEP construction is 329 MSF per year (1979 costs).

10. The next step is to divide the Materials Budget between LEP construction and the research activities which CERN will be running during this period (SPS, PS and SC for ISOLDE, and Theory). Clearly, there are many ways of doing this and the consequences are different in each case. What is presented by this model is a reasonable compromise between the stated desire of the European high-energy physics community to have LEP operating at the Stage $^1/3$ energy as soon as possible, and the requirement of the same community to maintain their research activities based on CERN at the highest level possible during the LEP construction period.

11. Of the average budget of 329 MSF per year available for materials, 139 MSF per year are allocated in this model to LEP construction and 190 MSF per year are allocated to the remaining research activities. The consequences are examined in the following paragraphs.

12. The Stage $^1/3$ LEP is estimated to cost 1064 MSF and to this is added 100 MSF as the contribution from CERN budgets to the cost of constructing LEP experiments. If the CERN contribution to the cost of LEP experiments is, as in previous years, about one half of the total cost of these experiments, the other half coming from national funding, then 200 MSF will be available to design and build LEP experiments during the LEP machine construction period. This would allow the construction of six or seven experiments if they cost on average about 30 MSF each together with their technical infrastructure. At an average materials expenditure of 139 MSF per year on LEP and its experiments, the period of construction would be 8.4 years compared with the technically feasible time-table given in the Pink Book of seven years. Since the materials expenditure on a big project such as LEP usually continues for a time after the first operation of the machine, the first physics experiments using LEP could start, according to this model, towards the end of the eighth year after the start of the construction instead of during the seventh year as given in the Pink Book.

13. For the research activities at CERN during LEP construction 190 MSF is allocated. It is clear that most of this materials budget must be used for operating the remaining accelerators and their experiments and that very little can be made available for new capital projects. Since by 1982 all the present expenditure on improvements and additions to the PS and SPS machines (including $p\bar{p}$) will be over, only 10 MSF per year is allocated to new capital projects not associated with LEP and its experiments, and the remaining 180 MSF is all allocated to operational costs of the other CERN research activities and to the materials costs of CERN overheads for all activities, including LEP construction. It should be noted that the 10 MSF per year allocated to new non-LEP projects would have to cover the CERN share in any new experiments for the PS and SPS research activities, the materials costs of the CERN share in financing European experiments on non-CERN machines such as the Tevatron and ISABELLE, and any further additions or modifications to the PS and SPS machines and to the CERN computing facilities.

14. Some measure of the effect of this allocation of materials budgets to CERN research activities during the years of LEP construction may be obtained by comparing a typical year of LEP construction with the situation this year. The result is given in the following table (MSF at 1979 costs).

	1979	Typical LEP Year
LEP design and construction (including its experiments)	3	139
Operating costs of research activities (accelerators, experiments and CERN overhead costs)	215	180
Non-LEP projects	102	10
Total	320	329

The sharp drop in non-LEP projects follows the completion of the present improvement and additions projects (mainly $p\bar{p}$) as already mentioned, and is essential in order to recover capital money to finance LEP construction. The reduction in the operating costs of the research activities at CERN during the LEP construction years is partly accounted for by the ISR being stopped and the SC being operated only for ISOLDE but offsetting these reductions will be additional operating costs, for example, for the new $p\bar{p}$ facilities for the SPS including the AA ring, and for LEAR. Taking all these into account the present operating costs of 215 MSF can be reduced to 196 MSF. The remaining

16 MSF to reduce operating costs to 180 MSF per year can only be achieved by real reductions below the present operation levels of the PS and SPS research activities and, although it does not appear a large reduction, it unfortunately affects the amount of research that can be carried out. It could mean, for example, reductions in the operating hours of the PS, SPS complex and taking out of operation some of their major experimental facilities which are now in use. Reducing operating hours of the accelerators and their experiments mainly reduces materials expenditures on consumable items such as electricity and water, bubble chamber film and short-lived components. The effect of taking out of operation some of the present experimental facilities can be measured by noting that BEBC materials operation costs amount to about 8 MSF a year including electrical power costs and that to operate the West Hall with its experiments costs about 6 MSF in materials expenditure each year. The choice of how to reduce operating costs by 16 MSF a year would clearly have to be decided in the light of physics priorities at the time.

15. The third step in this model building is to see whether the assumptions made about staff numbers give sufficient staff to construct LEP and its experiments and to operate the remaining research activities of CERN.

16. LEP, unlike the SPS machine, is not a single main ring but a complex of machines each one needing staff to design, construct and bring it into operation. It has two linacs, a positron storage ring, an injection synchrotron much larger than the ISR, and a main ring four and a half times the circumference of the SPS. A recent estimate of the number of staff needed for LEP machine construction gives a figure of 580, and about 100 staff are needed in addition for building LEP experiments (a number similar to those now engaged in building $p\bar{p}$ experiments). Adding the staff needed for operating the remaining research activities of CERN during the LEP construction period and the service staff required to support LEP and the remaining research activities gives a total which exceeds the number of staff available during the LEP construction period, which was 3430 according to the assumption made at the beginning. It therefore appears that staff numbers will also limit the construction time-table for LEP unless measures can be taken to reduce further the staff numbers needed to operate the remaining research activities during the LEP construction period.

17. In conclusion, this model of the allocation of resources, both financial and manpower, gives a consistent plan which fits the assumptions made on the total CERN budgets and the staff available. Its main characteristics are:

- a construction time for LEP which is about a year and a half longer than the technical time-table given in the Pink Book;

- a reduction in the present operation level of the SPS and PS machines and their experiments during LEP construction which in financial terms amounts to an 8% reduction in operating costs and whose practical effects may involve closing down some of the present major experimental facilities of these machines and reducing machine operating hours per year. Clearly, this should only be done if all other ways of reducing operating costs have not produced the required reductions.

Variations on the Model

18. The model used in this note illustrates the problems which will arise in reaching a balance between the materials budgets allocated to LEP and those allocated to the research activities which will be in operation at that time. Within the financial and manpower constraints which have been assumed for the model it is not possible to construct LEP in the time-scale proposed in the Pink Book and at the same time maintain the remaining research activities at their present level of operation. To do this would require total CERN budgets about 41 MSF per annum more than the 610 MSF per annum assumed in this note. Even if this extra money were made available there may be insuffient staff to carry out all the programmes. The Directors-General in proposing that LEP could be constructed within total CERN budgets of 610 MSF (or 600 MSF at 1978 costs) realized the problems that this would present and pointed out that the years of LEP construction would be lean years at CERN in terms of the research activities that could be operated for the European high-energy physics community. Since that time, the budgets of CERN have been reduced and for 1979 the budget is 590 MSF.

19. The variations on the model presented in this note may be summarized as follows:

- Seek an increase in the CERN budget level during the years of LEP construction to about 650 MSF per year to allow LEP construction to go ahead on the Pink Book time-table and to maintain the remaining CERN research activities at their present level.

- Establish a different balance in the allocation of materials budgets to LEP construction and the remaining CERN research activities within a total CERN budget of 610 MSF a year, either to speed up LEP at the expense of the research activities or to maintain the present spending on the remaining research activities by extending further the construction time of LEP. Also the model demonstrates very well the advantages to be gained in further reducing the costs of LEP and in seeking ways of further reducing operating costs.

The Constraint of Energy Consumption

20. In addition to the constraints of budgets and manpower, which have always limited the activities of CERN, another one has arisen in recent times which promises to become more serious in the years ahead. This is a possible constraint on the permissible or acceptable consumption of electrical energy of a laboratory like CERN. The present electrical energy consumption of CERN is about 660 GWh per year and when LEP comes into operation at the Stage $^{1}/3$, at a beam energy of about 60 GeV per beam, the electrical energy consumption of CERN would increase by about 30% above the present figure. If the current policies to reduce electrical energy consumption now being pursued in the CERN Member States continue and perhaps intensify in the future the consumption of CERN is unlikely to go unchallenged.

21. For several years now CERN has conducted a campaign to reduce its electrical consumption without which it is estimated that the consumption today would be more than 100 GWh per year above the present level of 660 GWh. These savings have mainly resulted from the use of superconducting magnets for the large spectrometers and bubble chambers, and from pulsing the beam lines of the SPS machine. During the last year, the design of the LEP machine has been strongly influenced by the need to reduce its power consumption.

22. Although at the Stage $^{1}/3$ of LEP operation the increase in electrical energy by CERN is not excessive, the rise in energy consumption in going to the next Stage of LEP operation with beam energies of about 86 GeV per beam is appreciable. The electrical power input to LEP will rise from just under 100 MW to about 250 MW if this next stage is achieved with copper cavities for the RF accelerator system. The expectation is that superconducting cavities will be available by this time, which is about 10 years from now, and CERN has launched a vigorous programme of development of this new technology in collaboration with several national laboratories in the Member States. It is considered that a good and reasonable research programme can be carried out at CERN in the 1980's based on LEP and the PS/SPS machines within a total electrical energy consumption of about 1000 GWh per year.

23. In considering the question of energy consumption by CERN it is important to use the appropriate frame of reference. CERN is the only international laboratory for high-energy physics in Europe. Even on the national level, after the closure of many of the large accelerators in the Member States, only DESY is now operating large accelerators for high-energy physics. The electricity consumption of CERN should therefore be viewed in relation to the consumption of the twelve Member States of CERN. The ratio works out to be 1 to 2000.

Concluding Remarks

24. This note has attempted to explain the consequences of the LEP project by constructing a model of CERN activities during the LEP construction period. The model is based on assumptions concerning CERN total budgets, which the Directors-General put forward previously, and on the manpower available which follows from the present staffing policies of CERN.

25. The model shows that LEP could be constructed at CERN on a time-scale somewhat longer than the technical time-table given in the Pink Book by making some reductions in the present operational level of the PS and SPS research activities and by operating the SC machine only for the ISOLDE facility.

26. Total budgets and available manpower are the main constraints on the model. Within these constraints, a balance has to be reached between the duration of LEP construction and the reductions to be made in the SC, PS and SPS research activities during the construction period.

27. The model clearly points to the lines along which future work must progress. These are to further reduce the initial costs of LEP construction up to the time that the first research experiments can start, since it is this time which is of paramount importance to the European physics community, and to explore all possible ways of reducing the material operation costs of the research activities during the LEP construction period without affecting the quality of the research output, so that more material money can be allocated to LEP to reduce its construction time. In regard to decreasing LEP construction costs up to the time of first operation for physics it is possible to imagine that the seven-year construction time could be achieved if LEP is constructed up to Stage $^{1}/6$ (49 GeV per beam), only four experimental areas and four experiments are constructed instead of eight, and the present West Hall is closed down for SPS research and used as an assembly hall for LEP. This is a matter which will be studied further and discussed with the Scientific Policy Committee early next year.

28. The model does not attempt to look further than the completion of LEP at Stage $^{1}/3$. In other words, it does not extend further in time than the next 10 years. However, a check has been made that both LEP and the PS/SPS research activities could be operated within the same financial and manpower constraints after the initial LEP construction period. Once LEP is in operation at Stage $^{1}/3$, at the end of the 1980's, there are several options open for the Management of CERN. It would be possible to extend the beam energies of LEP to 86 GeV per beam by adding more copper RF cavities or, preferably, to change over to superconducting RF cavities if they are available at that time. It can also be envisaged that the research trends may indicate a preference for colliding together the electron beam of LEP with the proton beam of the SPS or, in the longer term, for constructing a proton-antiproton collider in the LEP tunnel. The options are many but the decision which way to go is best left to the future.

29. It is pointed out that the electrical energy consumption of CERN in the future may become a more serious constraint on the operation of the Laboratory than it is at present.

30. Finally, it must be emphasized that this note has only presented a possible model of the years of LEP construction. Its main utility is to show that LEP can be built even within the financial and manpower constraints that have been assumed. The model is also useful for pointing out where the main difficulties will lie during this period and hence the lines of attack for future studies. And since the period of time in question is so long and planning is not an exact science, it is salutary to end with the quotation:

> "Prediction is always uncertain, especially when it concerns the future."

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