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EUROPEAN PROJECTS IN HIGH-ENERGY PHYSICS

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ABSTRACT

The new high-energy facilities in Europe—either coming into operation, approved, or proposed—are reviewed here. Emphasis is placed not only on the more well-known big projects, such as the proton-antiproton collider, LEP, and HERA, but also on improvements to the CERN fixed-target program and to the DESY electron-positron colliders.

1. NEW NEUTRINO BEAMS AT CERN

In March 1982 a new facility will come into operation at CERN: the neutrino beam dump area. This area is located at the end of the tunnel where the Super Proton Synchrotron (SPS) neutrinos are produced. Fig. 1 shows a section of the now-completed civil engineering for this area. The target where the SPS protons will be dumped is about 400m from the neutrino detectors, whilst in the last beam-dump run the target was twice this distance away. The fourfold increase of the solid angle will

Fig. 1 Section of the new beam dump area at the CERN SPS: a is the surface building and the beam dump will be placed below d.

Fig. 2 A plan of the CERN site with the position of the 50 m decay tunnel where low-energy neutrinos will be produced for studying neutrino oscillations. The flight path to the SPS neutrino detectors is about 900 m.

allow a corresponding increase in the number of events seen by the three neutrino detectors [BEBC^{*)}, CDHS^{**)}, and CHARM^{***)}] and, hopefully, will lead to a better understanding of the various effects which were suggested by the results of the previous beam-dump runs¹.

A new low-energy neutrino beam will be derived from the Proton Synchrotron (PS) to study neutrino oscillations; Fig. 2 shows it superimposed on a map of CERN. The protons extracted from the PS along the beam line TT2, which injects them into the Intersecting Storage Rings (ISR), will be deflected into a new tunnel which points towards the SPS neutrino detectors. The pion decay path after the bare target is 59 m and, at about 130 m, a new experimental area will be excavated inside the building which houses the experiment mounted on intersection region I1 of the ISR. Two "close detectors" will be placed there by the CDHS and CHARM Collaborations, who will thus study the disappearance of ν_μ 's of 0.5–1.5 GeV over a path length of about 900 m. The appearance of ν_e 's in the beam will be studied experimentally by BEBC in a later run, during which the pion beam due to 18 GeV protons in the bare target will be replaced by a horn-focused pion beam produced by 12–14 GeV protons. The facility will be ready in September 1982, and it is foreseen to have a run before the end of that year.

2. THE CERN PROTON-ANTIPROTON COLLIDERS

Figure 3 shows the layout of the old and new accelerators involved in the CERN antiproton program. Antiprotons of 3.5 GeV/c are produced by the 26 GeV/c protons extracted from the PS. The

Fig. 3 The accelerators involved in the antiproton program. The heavy lines indicate the parts which have been built for the purpose.

^{*)} Big European Bubble Chamber

^{**)} CERN–Dortmund–Heidelberg–Saclay Collaboration

^{***)} CERN–Hamburg–Amsterdam–Rome–Moscow Collaboration

Fig. 4 Schematic drawing of the components of the device in the Antiproton Accumulator which cools the antiprotons in the transverse space.

antiprotons, stored and cooled in the Antiproton Accumulator (AA) with the technique invented by Simon Van der Meer, are extracted, and injected into the PS through the channel TTL2. In the PS they are accelerated from 3.5 to 26 GeV/c and then injected either into the ISR (channel TT6) or into the SPS (channel TT70). In 1983 they will also be injected into the Low-Energy Antiproton Ring (LEAR) and used to perform experiments with intense and monochromatic antiproton beams in the energy range 0.1–2 GeV.

The heart of the project is the cooling system of the AA. There are two main types of cooling devices². The transverse cooling is performed by a transverse kicker which is fed by the amplified signal coming from a pick-up (Fig. 4). The lateral deviation of a particle from the nominal position is felt by the transverse pick-up, and a correction signal is applied in phase after suitable

amplification by a wide-band amplifier. Figure 5 indicates how longitudinal cooling is obtained. A pick-up detects the longitudinal position of an antiproton with respect to the particles which have the nominal rotation frequency f_c . The feedback signal is filtered by a system (Fig. 5a) which has zero output when the particle is rotating with the correct frequency, but accelerates particles which are going too slowly and decelerates those which rotate too quickly (Fig. 5b).

Fig. 5 Schematic drawing of the momentum cooling device. Figure 5a shows the filter, which uses a delay line to produce the response indicated in Fig. 5b.

At present (October 1981), the AA has accumulated and cooled antiproton bunches of 10^{11} antiprotons. The accumulation rate is only five times smaller than the value which was aimed for. A factor of 2 is attributed to a smaller antiproton production cross-section than expected, whilst the rest is probably due to the acceptance of the AA ring. Antiprotons have been injected into the ISR, where physics results have already been obtained. In particular, first measurements of the total antiproton-proton cross-section at $\sqrt{s} = 53$ GeV, based on the Roman pots technique, have been published³.

The SPS experiment UA5 has already recorded in a streamer chamber several thousand events at $(270+270)$ GeV, while the very large magnetic detector of experiment UA1 (Fig. 6) has seen events

Fig. 6 The experiment UA1 (co-spokesmen: A. Astbury and C. Rubbia) has vertical coils which produce a magnetic field perpendicular to the beam direction.

and measured multiplicities and experiment UA4 has detected elastic scattering events⁴. The experiments find that the average multiplicity is much larger than the one predicted by simple $\ln s$ extrapolation. During these runs the luminosity was in the range $10^{25} - 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ because there was a single antiproton bunch and the low-beta quadrupoles were not on. Physics runs will start in November 1981.

3. THE LEP PROJECT

Phase 1 of LEP, a $50+50$ GeV e^+e^- storage ring, was approved by the 12 CERN Member States at the end of October 1981⁵. The main parameters, at the moment of approval, are listed in Table I. Note that in Phase 1 only four interaction regions will be equipped for physics.

Table I Main LEP parameters

Machine circumference	26.658.88 m
Average machine radius	4243 m
Bending radius	3104 m
Tunnel diameter	3.6 m
Number of intersection regions (IR)	8
Number of IR's equipped in Phase I	4
Number of bunches per beam	2-4
Horizontal betatron wave number	90.35
Vertical betatron wave number	94.20
RF frequency	352.21 MHz
Harmonic number	31320

The luminosity of LEP at about 50 GeV can be computed by using lower and upper bounds to the quantities appearing in the formula

$$L = (\gamma \Delta Q k_b / 2\pi r_e e) (I_b / \beta^*), \quad (1)$$

where γ is the relativistic factor of the electrons (positrons), r_e is the classical electron radius, e is the electron charge, k_b is the number of bunches per beam, ΔQ is the maximum beam-beam tune shift, I_b is the current per bunch, and β^* is the value of the vertical β -function at the interaction point. At the General Meeting on LEP held at Villars (Switzerland) in June 1981, E. Picasso gave the following list of limits

$$\begin{aligned} 0.025 &\leq \Delta Q \leq 0.04, \\ 2 &\leq I_b \leq 6 \text{ mA}, \\ 5 &\leq \beta^* \leq 10 \text{ cm}, \end{aligned} \quad (2)$$

which are derived from experience with existing machines and from simulation studies⁶. As a result, the LEP luminosity will lie in the range

$$6 \times 10^{30} \leq L \leq 6 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}. \quad (3)$$

Note that as far as we know, the lower limit is a very conservative estimate.

In Phase I, only 1/6 of the available space along the ring will be equipped with RF cavities. By adding other normal temperature cavities and increasing the RF power in steps from 16 to 96 MeV, LEP could reach 85 GeV per beam, as indicated in Table II. However, the technology of superconducting cavities is developing, and very probably Phase 2 will be based on this new technique. Table III shows the achievable energies as a function of the maximum accelerating gradient of the superconducting cavities. It has to be noted that at CERN, one superconducting cell has already reached voltages in excess of 3 MV/m at 500 MHz, and a four-cell structure has been tested at more than 2.5 MV/m.

Figure 7 shows a schematic drawing of the path followed by the electron and the positron bunches before being injected into LEP. The 600 MeV bunches produced by a Linac are accumulated in a ring (the ACR) and accelerated by the CERN PS to 3.5 GeV/c. They are transferred successively to the

Table II Energies and luminosity of LEP as a function of the installed RF power

	Phase I RF/6	RF/4	RF/2	RF/1
PW power (MW)	16	24	48	96
Installed in:	Part of 2 IR	2 IR	4 IR	8 IR
Max. energy (GeV) for $L = 0$	59	66	78	93
I_b (mA)	2.8	3.1	3.8	4.7
$L_{\max} (\Delta Q = 0.03)$ in $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$	0.9	1.3	1.8	2.7
Energy for $L_{\max}$ in GeV	51.5	59	70	85

Table III Maximum LEP energies for various superconducting cavity lengths L_c

Maximum accelerating gradient (MV m^{-1})	2 IR with RF $L_c = 407 \text{ m}$	4 IR with RF $L_c = 814 \text{ m}$	8 IR with RF $L_c = 1628 \text{ m}$
2.0	70.3	83.6	99.4
3.0	77.8	92.5	110.0
4.0	83.6	99.4	118.2
5.0	88.4	105.2	125.0

Fig. 7 The complex of accelerators used as injectors for LEP. The positrons will be produced by 200 MeV electrons and then accumulated at 600 MeV together with the electron bunches in the accumulator ring (ACR). The CERN Proton Synchrotron (PS) will accelerate the electron and positron bunches to 3.5 GeV and the Super Proton Synchrotron (SPS) to 22 GeV.

SPS, where they are accelerated to 22 GeV/c and eventually injected into LEP. The 3.5 GeV/c cycle of the PS lasts about 0.6 s, and fits in very well amongst the two or three cycles used for injecting 10 GeV protons into the SPS. To accelerate electrons to 22 GeV/c the SPS needs 1.4 s, and this can be inserted between the 11 s cycles needed to accelerate protons to 450 GeV. In summary, LEP can be injected in parallel with the normal acceleration of protons in the SPS, so that the SPS fixed-target physics is not disturbed. Of course, while injecting into LEP, the SPS cannot be used as a proton-antiproton collider.

Most LEP components have been built and tested at the prototype level. As examples, we would like to mention here three interesting new developments.

A few years ago, W. Schnell proposed the use of low-loss storage cavities to reduce the RF power consumption⁷. Figure 8 shows two such spherical cavities coupled to two five-cell structures used to accelerate positron and electron bunches. The coupling is such that the electromagnetic energy is present in the accelerating cavities only when needed, i.e. when the bunches pass through it. For roughly half of the time the energy is stored in the spherical cavity, which has smaller losses. In this way, power savings of the order of 40% can be achieved.

The magnetic field needed to curve the electrons and positrons is very weak: less than 200 G. To save iron (and money), the LEP bending magnets are made of laminated steel 1.5 mm thick, separated by 4.1 mm of concrete⁸. Small indentations in the foils define the spacing between consecutive steel laminations. These steel/concrete magnets are mechanically stronger than normal iron magnets and have very good magnetic properties.

As a last example of a new technological development⁹, we mention the LEP pumps, which are based on Non-Evaporable Getters (NEG), substances which form stable chemical compounds with the active gases such as O₂, CO, N₂, CO₂, H₂O, etc. The activation of the NEG strips is obtained by

Fig. 8 Spherical storage cavities connected to two LEP accelerating five-cell structures. The 350 MHz waveguides are also shown.

heating them in vacuum at 700° C for about 30 minutes. Their lifetime is extremely long and they do not need magnetic fields to work.

Four of the eight interaction regions will be equipped with experiments for Phase 1 of LEP. Three of them are about 50 m below ground and are accessible from the surface. The fourth one is deep inside the Jura mountains and will be accessible through a 4 km tunnel. The cross-section of the foreseen tunnel is such that equipment not larger than $(1 \times 2) \text{ m}^2$ can be transported through it. Figure 9 shows a sketch of one of the large interaction regions. Close to the crossing point the machine tunnel is paralleled by a klystron gallery, which can be accessed through a big vertical shaft and two access tunnels, so that equipment can be moved whilst the machine is working. The experimental cave is foreseen to have a diameter of about 20 m and a secondary access shaft for people and small components. The details of the experimental areas and of the accesses were discussed at the Villars Meeting and are now being frozen in preparation for the tenders.

Before closing this section it is interesting to answer a question which is often posed: Why a large radius for LEP? LEP has been optimized for $\sim 90 \text{ GeV}$ per beam, an energy much larger than the predicted mass of the Z^0 . The optimized radius of an electron-positron storage ring increases proportionally to the square of the beam energy, and the cost follows the same scaling law¹⁰. Thus the cost of LEP Phase 1, which will accelerate beams up to 51 GeV, is higher than the minimum needed to study the expected Z^0 peak. However, by increasing the accelerating voltage it will be possible later on, with LEP Phase 2, to reach the W^+W^- threshold.

In my opinion the possibility of reaching the W^+W^- threshold is the first but not the only reason for which it was wise to choose a large circumference for LEP (about 25 km). At least two other reasons are worth mentioning here. On the one hand, a ring of superconducting magnets can be placed in the same tunnel to accelerate protons and antiprotons to an energy which is proportional to the length of the LEP circumference. With the present choice and a magnetic field of 5 T it will be possible to reach

Fig. 9 Sketch of the layout of one of the large interaction regions. The experimental area is connected to the surface by two vertical shafts. The U-shaped tunnels allow access to the klystron galleries during operation.

Fig. 10 This figure, taken from Ref. 12, compares the cost of electron-positron storage rings with the cost of colliding linacs. The comparison is made both for accelerators based on conventional room temperature cavities (a) and those based on superconducting cavities (b).

about 5 TeV per beam, definitely larger than the 3 TeV aimed at by the UNK project in the USSR. On the other hand, a colliding ring of about (200+200) GeV appears at present to be technically the largest circular electron-positron collider than can be built¹¹. By getting as close as possible to this limit, LEP will not only be the largest but also the final e^+e^- storage ring. This argument is strengthened by considering the foreseeable development in the field of electron-positron colliders. Figure 10 is taken from a review talk given at the 1979 Electron-Photon Conference¹² and compares the costs of colliding linacs with the cost of storage rings. Such a comparison is very delicate and depends upon the many assumptions discussed in detail in Ref. 10. The qualitative conclusions which can be drawn from Fig. 10 are, however, clear: the linear dependence of cost upon the energy of colliding linacs (both normal and superconducting) is such as to make these devices competitive with storage rings at beam energies larger than about 130 GeV. This figure fits well with the upper limit of the energy range in which storage rings seem to be technically feasible¹¹ and supports the point made above: an electron-positron collider such as LEP, which in Phase 2 with superconducting cavities will reach 100 GeV per beam, will probably be the largest circular e^+e^- collider to be built.

The cost of LEP has been estimated to be 910 MFS at 1981 prices. Since LEP will be part of the CERN basic program, the money will come from the normal budget. Because of the difficult economic situation in Europe, the CERN management has taken the engagement not to request increases in the budget during the whole LEP construction period, except for compensation of the inflation rate. It is foreseen to pay the cost of LEP on the budgets of the years 1982-89, but it is envisaged that the construction will not take so long: the first beams are expected for the end of 1987, or the beginning of 1988. In the present design, about 8 km of tunnel have to be excavated under the Jura mountain in a rock that is not well known. Since caverns and water could cause unforeseen delays, the final

positioning of the ring is at the moment (October 1981) under careful reconsideration. In concluding the Villars meeting, H. Schopper gave the following time scale for approval of LEP experiments. Letters of intent are due for 31 January 1982. The LEP Experiments Committee will be set up during 1982, so that proposals will be called for in the second half of 1982 and the first approvals will be given towards the middle of 1983.

4. DESY IMPROVEMENT PROGRAMS

In Hamburg both DORIS and PETRA have an important improvement program¹³. Starting in November 1981 the two rings of DORIS will be dismantled and rebuilt as a single ring for DORIS-II. With more RF voltage the maximum energy will go from 2×5.1 GeV to 2×5.6 GeV, whilst the power consumption will be halved by rebuilding the dipole and quadrupole magnets. The luminosity will be increased from $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ to more than $2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ by a mini-beta scheme similar to the one installed at PETRA. The injection channel will be rebuilt to allow injection at any required energy below 5.6 GeV. Moreover, a smoother vacuum pipe will be installed. It is foreseen to have the improvement program finished by April 1982. Two experiments will run on DORIS-II in the next years: the new magnetic detector ARGUS and the Crystal Ball, which will be shipped from SPEAR to Europe in 1982.

After the installation of the mini-beta insertions, PETRA reached a maximum energy for colliding beam physics of 2×18.4 GeV. At 17 GeV the maximum luminosity is $1.7 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ and is current limited. The approved PETRA improvement program foresees three steps. By the fall of 1981 a 1000 MHz RF system will be installed for lengthening the bunches and suppressing longitudinal instabilities. The luminosity may go up by a factor of two. By spring 1982 the RF power will be doubled, passing from 4.8 MW to 9.6 MW, so that the energy will increase to 2×20.5 GeV. In 1982-83, with twice the number of a new type of seven-cell cavity, the energy will go up to 2×23 GeV.

Further improvements for the later years foresee the installation of superconducting micro-beta quadrupoles to increase the luminosity by a factor of ~ 3 . Finally, with 200 m of superconducting cavities having a gradient of 3 MV m^{-1} , PETRA could reach, around 1985, a peak energy of 2×30 GeV.

5. THE HERA PROJECT

Figure 11 shows a schematic layout of the Hadron Electron Ring Accelerator in which 30 GeV electrons will collide with 920 GeV protons. Electron-proton collisions have been under consideration at DESY since 1972¹⁴. Studies have been conducted in collaboration with ECFA in 1979 and 1980¹⁵ and a detailed technical proposal was submitted to the German authorities in June 1981¹⁶. Since this document is very recent, in the following we shall describe its contents in some detail.

The underground tunnel is 6.3 km long and has a diameter of 3.2 m (Fig. 12). The superconducting ring for protons is installed above the electron ring. The general parameters of HERA are listed in Table IV. The electron ring is similar to the PETRA machine with some simplifications. For instance, the dipole magnet is excited by a single-turn conductor embracing the entire ring, and the vacuum chamber is made of copper instead of aluminium. Figure 13 shows a vertical cut through a superconducting dipole magnet of the proton ring. As in the FNAL design, the iron is warm and the bore is cold. Note the suspension rods that will allow the alignment of the magnet to ± 0.2 mm during the test stage.

As shown in Fig. 14, the interaction region is very complicated because it must not only bring the two different beams to collide at a small angle and with low beta-functions, but also turn the electron (or positron) spin either parallel or antiparallel to the beam direction. The beams cross in the horizontal

Fig. 11 Layout of HERA and of PETRA used as injector.

Fig. 12 Cross-section of the HERA tunnel.

Table IV Main HERA parameters

Machine circumference (m)	6336	
Tunnel diameter (m)	3.2	
Number of intersection regions (IR)	4	
Luminosity ($\text{cm}^{-2} \text{s}^{-1}$)	0.6×10^{32}	
	p-ring	e-ring
Bending radius (m)	603.8	540.9
Magnetic field (T)	4.53	0.1849
Nominal energy (GeV)	820	30
Energy range (GeV)	200 → 820	10 → 33
Particles per bunch	3×10^{11}	3.6×10^{10}
Number of bunches	210	210
Horizontal betatron wave number	32.14	48.3
Vertical betatron wave number	35.14	48.2
RF frequency (MHz)	208.189	499.667
Circulating current (mA)	480	58
Horizontal beta function (m)	3.0	3.0
Vertical beta function (m)	0.3	0.15
Polarization time (min)	—	20

Fig. 13 Cut through a HERA superconducting magnet: 1—Cryostat. 2—Coils. 3—Iron yoke. 4—50 K shield. 5—Two-phase helium. 6—One-phase helium. 7—Clamping collars. 8—Vacuum chamber. 9—Suspension rods. 10—Steel girder. 11—Sextupole correction.

Fig. 14 Layout of the magnets in one interaction region of HERA.

plane at an angle of 20 mrad, while the spin is turned by an 80 m long rotator installed at the end of the arc, and restored to the transverse direction by a similar rotator positioned at the entrance of the next arc. The rotator is optimized at a fixed energy of (27.5 ± 0.5) GeV and will provide a 57% longitudinal polarization.

The HERA luminosity at the nominal energy is presumably not limited by the beam-beam interaction but rather by the currents in the two beams and the available RF power. Indeed the beam-beam tune shifts are less than $\Delta Q = 0.0004$ and $\Delta Q = 0.014$ for protons and electrons, respectively, which is smaller than the accepted limits. At lower energies the luminosity will instead be limited by the tune shifts, as shown in Fig. 15.

The largest part of the injection system is based on existing accelerators. The electrons will be accelerated to 500 MeV by the DESY LINAC II, transferred to the DESY synchrotron where they will be accelerated to 7 GeV, and then to PETRA to be brought to an energy intermediate between 7 and 14 GeV. Positrons produced in an intermediate target of the Linac are injected into the damping ring PIA and then extracted and transferred to PETRA. The filling times of HERA are expected to be 15 min (25 min) for electrons and positrons, respectively. The protons will be accelerated through the following sequence: Proton Linac (50 MeV) $\rightarrow$ DESY (7.6 GeV) $\rightarrow$ PETRA (40 GeV) $\rightarrow$ HERA. With the exception of the proton linear accelerator, also the proton injection system is based on existing accelerators.

The total capital cost of HERA is 650 MDM, of which 260 MDM are needed for site buildings, power, and cooling. 112 MDM cover the components of the electron ring, and 278 MDM are foreseen for the proton ring. Figure 16 shows the time schedule of the prototype development, which is already

Fig. 15 Predicted HERA luminosity as a function of the proton energy E_p for different values of the electron energy E_e . Listed in the brackets are the phase advances per cell ϕ , together with the parameters which limit the luminosity. The number of protons per bunch was assumed to be $N_p \leq 3 \times 10^{11}$, while $RF \leq 12$ MW, and the maximum beam-beam tune shifts were taken to be $\Delta Q_p \leq 2.5 \times 10^{-3}$ and $\Delta Q_e \leq 2.5 \times 10^{-2}$.

TASK	1980	1981	1982	1983
<u>Site and Buildings</u>				
<u>Superconducting Magnet</u>				
Short Prototypes				
Prototypes, Dipole				
Prototypes, Quadrupole				
Refrigeration System				
<u>Conventional Component</u>				
Prototype Magnets				
Prototype Vacuum Chamber (with pumps)				
Other Components				

Fig. 16 Time schedule of the preparation of the HERA components and of developments of prototypes.

Fig. 17 Time schedule for the construction of HERA.

under way. The schedule for the construction of HERA appears in Fig. 17, and is such that, if started in 1983, it would give e^+e^- collisions at (35+35) GeV in 1987 and electron-proton collisions in 1989. In January 1981 the project was endorsed by the Pinkau Committee, set up by the Federal Government to study the very large projects in fundamental research in which Germany is involved. The Committee recommended the construction of HERA, but did not encourage the start of construction before 1984 in the light of the exploitation and upgrading of PETRA, although prototype work and planning should go on. The Committee emphasized the desirability of having a second international high-energy physics laboratory in Europe and urged international participation not only in the use but also in the construction of the new facility.

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