Large Hadron Collider in the LEP Tunnel

A feasibility study of possible options

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1. Review of Possible Options

A wide range of possibilities exists for a Hadron Collider in the LEP tunnel, as shown in Fig. 1. The conceptually simplest option is a $p\bar{p}$ ring with a single beam channel which can either be built with superconducting magnets of present technology or with high-field magnets after a fair amount of research and development effort. The luminosity is relatively low because antiproton sources are not very intense. In order to make provision for bunch separation at unwanted beam crossings, the aperture must be somewhat enlarged with respect to a single beam machine.

Using two beam channels gives a more versatile collider. The rings can have either a common magnetic circuit, which couples both rings magnetically, or two independent circuits. For space reasons, the two beam channels will always be in one cryostat. The most interesting option is the one where the two beam channels are side by side allowing for high luminosity pp collisions with many bunches. Depending on the desired field level, the two apertures may be part of a common magnetic circuit or of separate circuits.

In the first case (common magnetic circuit) there is enough space in the LEP tunnel to install high-field magnets. At high field level, the field must be necessarily equal and opposite in the two apertures as required for pp operation. This precludes pp with the beams in two separate channels. At considerably lower field level, the magnets can be excited such that the field is the same in both apertures and $p\bar{p}$ operation in two channels becomes possible. Of course it would be possible to put both the proton and the antiproton beam in one of the apertures, and either work with a low number of bunches at low luminosity without separation or install separators.

In the second case (independent magnetic circuits), pp and $p\bar{p}$ operations are equally possible at nominal field but, for space reasons, only moderate fields (~ 5 T) can be obtained.

Having the two coupled channels on top of each other allows for a $p\bar{p}$ machine which can have as many bunches as required without being beset with the problem of bunch separation as the one channel $p\bar{p}$ option. However, since this configuration does not provide a pp option, it is not considered any further.

These arguments favour very clearly the side-by-side, two-channel pp collider with one magnetic circuit; it holds the promise of top pp performance while leaving the door open for $p\bar{p}$ physics. The machine study focused on this option because it also appears as the more demanding one from the technological point of view.

The other option which has received some attention is the one-channel, high field $p\bar{p}$ collider. These two options represent in a certain sense two extremes and, therefore, provide a good coverage of the total range of possibilities.

Before turning to the machine performance of these two options we cast first a glance at the detector performance. Fig. 2 shows a graph of luminosity L versus the time T_x elapsing between two bunch collisions in the detector. Also drawn are lines of constant $L.T_x$: along those lines the number of events <n> per bunch collision is constant for a given total proton-proton cross-section Σ. Since it is very difficult to handle more than one event per bunch collision, the line 1×10^{25} cm^{-2} therefore becomes an upper limit of the working region for a total cross-section of 100 mb. The maximum possible trigger-rate of the detector puts a lower limit on T_x providing a boundary on the left. One of the results of the March 1984 CERN-ECFA workshop was that values for T_x as low as 25 ns are conceivable without this being a too hard limit. Thus it can be seen that a luminosity of about 4.10^{32} can be obtained if the operating point of the machine is put at the top left corner of the region allowed for by the detector performance. For experiments which can accept a higher <n>, luminosities up to $\leq 1.5\times10^{33}$ $(cm^{-2}s^{-1})$ could possibly be reached.

From the machine point of view this high luminosity operation is indeed feasible with the pp option. The number of bunches k is between 3000 and 4000. In order to make the bunch-to-bunch distance a multiple of the RF wave-length in the LHC and in the SPS, only discrete values of k are permitted. The value of 3564 fulfils this requirement and was chosen as nominal value. The graph also indicates the total number of particles which does not appear to be excessive, since it corresponds to only a few SPS pulses at the present performance level. The stored energy in the beam remains acceptable in the range under consideration; it reaches 70 MJ at $N = 5\times10^{13}$. The beam-beam effect, imposing a limit on the number of particles per bunch, is of not much concern because it cannot become very strong as long as the constraint of one event per collision is respected. The bunch intensity also seems low enough such that beam instabilities are avoided or can be dealt with by feed-back systems. Table 1 (see section 2)gives a list of the main parameters.

If detectors with a higher trigger rate were developed, the operating point could move upwards along the line $L.T_x = 10^{25}$ cm^{-2} and eventually approach $L = 10^{33}$ $cm^{-2}s^{-1}$ for $T_x = 10$ ns. However, this implies an increase of the total number of particles N, which in turn means more stored energy in the beam. The increased number of bunches makes the beam also more prone to coupled-bunch instabilities. For this reason it is preferred to keep the nominal number of bunches at 3564 in agreement with the presently estimated detector performance, and to work out a consistent set of parameters on this basis, though it is not unreasonable to expect the eventual operating point somewhere in the shaded area of Fig. 2.

In the $p\bar{p}$ option the luminosity is limited by the $\bar{p}$ accumulation rate, which determines the total number of particles $N_{\bar{p}}$ accumulated in a time comparable to the luminosity decay time in the LHC. As explained in section 3 we may expect $N_{\bar{p}} = 10^{12}$ with the new antiproton source under construction in CERN. This imposes an upper limit on the luminosity around 1.5×10^{31} $cm^{-2}s^{-1}$. In order to minimize the number of unwanted bunch crossings in the one-channel machine, this limited number of antiprotons is distributed over the minimum number of bunches compatible with the requirement of one event per bunch collision. This leads to the working point shown in Fig. 2 for $N_{\bar{p}} = 10^{12}$ and, taking into account the constraints by the RF system, to 108 bunches in the machine, corresponding to $T_x = 825$ ns.

If a ten times more intense antiproton source became available, the luminosity could be increased in principle to a level of about 1.5×10^{32}. However, as can be inferred from Fig. 2, this leads either to an elaborate system for bunch separation at about 2000 unwanted crossing points, which becomes especially tricky near the interaction points, or to many events per bunch collision in the detector, which is hardly acceptable. Obviously, a wide range of combinations in between these two extremes exists but all of them are beset with the problems of beam separation and of multiple events per bunch collision. Thus it seems to be difficult to exploit a more powerful source for peak luminosity. It should be noted, however, that the luminosity averaged over a run can be much improved by a better source because the machine filling can be more frequent. More details are given in section 3.

2. The pp Option

2.1. Layout, parameters and performance

Fig. 3 shows schematically the ring layout with the 8 interaction points. The two beam channels are separated horizontally by $\leq$ 180 mm, and the insertions are designed such that the beams cross with a small angle of 96 μrad in the interaction points. Detectors can be put over at least six intersection points. Two long straight sections are reserved for the dumping of the beams though it might be possible to put eventually both dump systems into one straight section. Fig. 4 gives a cross-section of the LEP tunnel with the dipole of the LHC above the LEP magnets. It is apparent that the space available for the Hadron Collider is adequate. The assumption of installing it in the LEP tunnel determines the circumference which should be equal to that of LEP, 26658 m, within a very small margin; the number and length of the straight insertions, eight insertions of about 490 m length; and the average radius of the arcs, R = 3494 m. Because of the fixed radius, the maximum energy in each beam becomes a function of the magnetic field in the dipoles and of the layout of the LHC periods. The study is based on a dipole field B = 10 T.

The two proton beams are assumed to be bunched. Collisions between the bunches occur only in the interaction regions. This is achieved by a small crossing angle between the two beams. Bunched beams are preferred over continuous beams because they hold the promise of a higher luminosity for a given circulating current, and also because the energy loss due to synchrotron radiation is automatically compensated by the RF system.

From the users' point of view, the most important parameters are the luminosity L, the bunch spacing T_x and the average number of events per bunch crossing <n> related by

$$\langle n \rangle = L \cdot T_x \cdot \Sigma$$

where Σ is the total proton-proton cross-section. At the CERN-ECFA workshop a consensus was reached that, in the most general case, <n> should not exceed unity. For a cross-section of 100 mb, this means that the product $L.T_x$ should not exceed a value of 10^{25} cm^{-2}. Given this constraint, the largest luminosity is obviously achieved with the smallest possible T_x which can be obtained by the machine and is still acceptable by the detector. The bunch spacing in time T_x cannot be varied continously because it must be a multiple of the RF wave-length in the LHC and in the SPS. However, the step-size is sufficiently small (5 ns) in the range between 5 and 35 ns such that the machine can produce the smallest bunch spacing the trigger of the detector can cope with. Since it seems that the detectors can handle bunch spacings as low as 25 ns, this spacing was adopted provisionally as nominal value in order to have a basis for one consistent set of parameters. However it should be noted that each of the possible bunch spacings needs a special small RF system in the PS. Thus the bunch spacing cannot be changed at a moment's notice.

It can be seen from Fig. 2, which gives a synopsis of all these limits based on the parameters given before, that the maximum luminosity is 4×10^{32} cm^{-2} s^{-1} for T_x = 25 ns and <n> = 1. Although the machine operation would become more difficult, it is not unconceivable that the luminosity could eventually approach or even exceed 10^{33} cm^{-2} s^{-1} provided a smaller T_x or a larger <n> is acceptable for the detector. This is indicated by the shaded area around the nominal working point in Fig. 2.

Table 1 gives the general parameters and performance.

Table 1 : GENERAL PARAMETERS AND PERFORMANCE

GENERAL PARAMETERS

COLLIDER TYPE IN LEP	PROTON-PROTON	
SEPARATION BETWEEN ORBITS (mm)	165-180	
NUMBER OF BUNCHES	3564	
BUNCH SPACING (ns)	25	
NUMBER OF CROSSING POINTS	8	
BETA VALUE AT CROSSING POINT (m)	1	
NORMALIZED EMITTANCE $4\pi\gamma\sigma^2/\beta$ (μm)	5 π	
FULL BUNCH LENGTH (m)	0.31	
FULL CROSSING ANGLE (μrad)	96	
LATTICE PERIOD LENGTH (m)	79	158
LATTICE PHASE ADVANCE	π/3	π/2
DIPOLE MAGNETIC FIELD (T)	10	10
OPERATING BEAM ENERGY (TeV)	8.14	8.99

PERFORMANCE

$\langle n \rangle$ at $\Sigma = 100$ (mb)	1	4
LUMINOSITY ($cm^{-2}s^{-1}$)	4×10^{32}	1.5×10^{33}
NUMBER OF PARTICLES/BUNCH	1.34×10^{10}	2.6×10^{10}
CIRCULATING CURRENT (mA)	86	167
BEAM-BEAM TUNE SHIFT	0.0013	0.0025
BEAM STORED ENERGY (MJ)	63	121
RMS BEAM RADIUS (μm) *	12	
BEAM LIFE-TIME (h) **	42	21

* at interaction point for $\beta^* = 1$ m

** particle loss due to beam-beam collisions

The lattice consists of modules similar to the LEP lattice with arcs containing regular lattice cells, low-β insertions for collisions and dispersion suppressors for matching.

The LEP arcs and their support and supply systems are built in modules of length corresponding to half a cell, i.e. 39.5 m. We have limited the choice of LHC cell lengths to 79 and 158 m, associated respectively with 60° and 90° betatron phase advance. Fig. 5 shows the layout of the magnetic elements in a cell.

Fig. 6 shows a schematic layout and the optical functions. The quadrupole gradients are 250 T/m, the same value as in the standard lattice period. The value β^* can be increased by a factor 3 in order to overcome aperture restrictions and chromaticity problems during injection and energy ramping. The free space for the experiment between the quadrupoles is $\pm$ 10 m.

Two different inner diameters of the dipole coils were assumed for the study. The larger one (50 mm) allows for 40 mm inner diameter of the vacuum chamber; the smaller one (35 mm) leaves only 30 mm as inner pipe diameter, which precludes the use of the 90°, higher energy lattice as the injected beam diameter is 18 mm in this case.

The dominant field error effect is due to the persistent currents; it is a large sextupole component in the field of the dipoles. In any given magnet, this component is reproducible from cycle to cycle. However, between dipoles there is a random variation. The resulting chromaticity is compensated by appropriately exciting the sextupoles next to the quadrupoles in the LHC periods.

The widths of non-linear resonance stop-bands due mainly to the position tolerances of the superconducting wires are comparable to those in operating machines.

Intra-beam scattering imposes a minimum longitudinal emittance of the order of 2.5 eVs. This value is also sufficient to stabilize the beam via Landau damping against most of the presently known collective effects.

Most of the intensity dependent effects of importance in the LHC arise from the interaction of the beam with the vacuum chamber surrounding it. Therefore the relevant properties of the vacuum chamber must be carefully considered. Beam induced wall currents will heat the vacuum chamber, and together with the synchrotron radiation, contribute to the heat load of the cryogenic system. Table 2 shows the heat losses per unit length from the two counter-rotating beams averaged over the arcs.

Table 2

	Heat-loss Wm^{-1}
Resistive wall	.014
Broad-band	.09
Bellows	.026
Synchrotron Radiation *	.24
Total	.37

* emitted power per unit length

All intensity dependent effects discussed above are evaluated in the most difficult case of the 79 m long cell and a vacuum chamber radius of 15 mm. It was found that all collective phenomena could be handled in this lattice, with the help of appropriate feedback systems where required.

With the assumed parameters, a crossing angle of 96 μrad is large enough to ensure a sufficient separation at the first near-crossing. The long range beam-beam tune shift is only a fraction of the beam-beam tune shift at the interaction point and should pose no problems. Because of the short bunch-length involved, the loss of luminosity compared to head-on collisions is only 4%.

Eventually, a choice will have to be made. The arguments entering the choice are the maximum energy, the good field region of the magnets, field errors due to persistent currents and coil position errors in the dipoles, and collective phenomena. The advantages and disadvantages of the two period lengths, and the two vacuum chamber diameters are shown in Table 3.

Table 3 : COMPARISON OF CHOICES

Period length	79	79	158	158	m
Chamber radius	15	20	15	20	mm
Energy	8.136	8.136	8.993	8.993	TeV
RF voltage	16	16	28	28	MV
Tune spread	0.026	0.004	0.676	0.088	
Required good field radius	8.5	8.5	12	12	mm
Dynamic aperture due to					
- persistent currents	9	13	4	11	mm
- coil position	8	14	7	14	mm

2.2. Magnet system

According to present knowledge, the design and construction of accelerator magnets with field, say up to 6 or 7 T can be based on existing superconductors and on technologies already developped in Fermilab for the Tevatron and further tested in Desy for Hera, in BNL for CBA, in Serpukhov for UNK, and in KEK for Tristan.

The pioneering work done in various other laboratories (LBL-USA, CEA-Saclay, KfK-Karlsruhe, NIKHEF-Amsterdam, Rutherford Appelton Lab., CERN, etc.) can also serve as a very good base for future work.

Of course, before launching such an important project, several alternative designs should be considered with the prime aim of reducing production costs, and their features should be tested in an adequate number of prototypes. However, no fundamentally new development would be required. This is not true for magnets of higher field level up to 10 T.

Indeed, the purpose of the studies described in this section is to make a first assessment of the electromagnetic, cryogenic and mechanical problems which have to be faced for the design and construction of LHC magnets with a field as high as 10 T, would a suitable superconductor be available in time.

The development of such a superconductor, which can be industrially produced, is an absolutely necessary prerequisite to the final design and construction of such magnets. Small quantities of superconductors almost suitable for this application have already been made in industry.

Another important ingredient is the availability of insulation materials and techniques suitable for winding the coils according to the "wind and react" method.

Therefore all what is indicated below should be considered as a first assessment of the situation and as a guide-line for the indispensable development.

Dipoles and quadrupoles of the two rings are combined into "two in one" units, each having a common yoke and cryostat. The two rings are, therefore, magnetically coupled, especially at high field, which imposes the same energy for the two beams. Focusing quadrupoles in one ring are paired to defocusing quadrupoles in the other. Sextupole and dipole corrector pairs need to be magnetically uncoupled and can indeed be made so by means of independent cores. Horizontal dipole correctors in one ring are paired with vertical correctors in the other ring. The complete set of quadrupoles, sextupoles and dipole correctors will be contained in a common cryostat.

The dipole magnets should be made in units as long as possible, both because the bending length loss at each end reduces the attainable energy and in order to minimize the number of ends, which are the most difficult part of the magnet to fabricate. An upper limit to the unit length is, however, given by the access facilities (shafts, service tunnels, etc.) to the LEP tunnel, which are designed to allow installation of single components up to 12 m long. Another limitation to unit length is given by safety at a quench. It is estimated that 12 m long magnet plus cryostat units can be built, handled and operated without excessive difficulties and risks.

Existing evidence, gathered from experiments at the ISR and from the Tevatron, confirms the feasilibity of a cold vacuum chamber. Accordingly, no space for thermal insulation needs to be reserved in the magnet coil bore. For the sake of the present study it is assumed that the final choice for the inner diameter of the coil will fall in the range between 35 mm and 50 mm. Most of the work was therefore done on a version corresponding to the upper limit of 50 mm, which is more demanding in magnet size, excitation and structure. A possible dipole design is given in Fig. 7 with parameters in Table 4. One has also established that scaling to 35 mm is feasible from the magnetic point of view and probably acceptable for beam dynamics.

Table 4 : DIPOLE PARAMETERS

Nominal field		10 T
Peak field in windings	<	11 T
Average overall current density		300 $A.mm^{-2}$
Excitation (per dipole)		1300 kA-turns
Maximum current	~	10 kA
Stored energy (full "2 in 1" magnet)		730 kJ/m
Coil inner diameter		50 mm
Distance between gap centerlines		180 mm
Transverse size of active part		
width	~	600 m
height	~	500 mm
Transverse size of the cryostat		
width		750 mm
height		900 mm
Magnetic length		10.23 m
Cold mass per unit length	~	1.5 t/m

2.3. Cryogenics

The production, transport and distribution of the cryogenic fluids (He and N), are compatible with the space in the LEP tunnel. One refrigerator per octant should be installed in the interaction regions.

2.4. Vacuum

Profiting from the magnet cryostats, cold bore will be used, which intrinsically provides a very low pressure.

2.5. Radio-frequency

Only 30 m of active cavity structure are in total needed for both rings. To allow a large number of bunches in the Hadron Collider, the frequency should be ~ 400 MHz, namely the double of the SPS frequency.

2.6. Injection, beam transfers and dumps

At least two alternative layouts of transfer tunnels are possible between SPS and LEP (Figs. 8 and 9). Beam dumps are feasible with present technology.

2.7. Radiation protection

It has been established that there are no problems for the environment. Beam losses must however be controlled very well to avoid quenches of the superconducting magnets.

3. The $p\bar{p}$ Option

Only a one-channel machine is considered as stated in the introduction. The layout of this single ring is shown schematically in Fig. 10. In order to make the bunches collide only in the eight interaction points, the orbits of protons and antiprotons outside the collision regions are kept apart by electrostatic separators which are positioned downstream and upstream of each interaction point.

The transfer of protons and antiprotons seems easier following Variant 2 (Fig. 9) since both types of particles circulate in the SPS in their normal dirrection. Using Variant 1 (Fig. 8) would combine the longer transfer lines with the disadvantage of polarity reversal of the SPS (for $\bar{p}$) and the construction of a new beam line linking the PS/SPS antiproton transfer line TT70 with TT10. Also TT10, the injection system in LSS1 and the extraction in LSS4 must be able to operate at reversed polarity.

Since there is only one channel in the ring, the magnets are simpler than for the pp collider, but the aperture possibly larger to accomodate the separation of the orbits. The stored energy in the beam is lower, and the beam is likely to be more stable because the number of bunches is reduced by more than an order of magnitude compared to the pp option. Unfortunately, these advantages have to be paid for by a lower luminosity and by the necessity of having separators. The separators deflect the beams in opposite directions electrostatically; their length is about 40 m per station. The operation of $p\bar{p}$ rings is also more complicated and the limited accumulation rate has adverse effects on the luminosity, especially when averaged over time.

As explained before, the peak luminosity is limited by the total number of antiprotons available at the beginning of a run. With the new CERN antiproton source approximately 10^{12} particles can be expected, resulting in a peak luminosity around 10^{31} cm^{-2} s^{-1} (see Fig. 2). Respecting $\langle n \rangle < 1$ and selecting a bunch spacing compatible with the RF yields 108 bunches as nominal number corresponding to T_x = 825 ns. The separators are installed behind the low-β quadrupoles but before the first unwanted crossing occuring at 124 m from the interaction point. The most promising scheme of beam separation makes the orbits spiral around each other by means of a set of vertically deflecting plates and a set of horizontally deflecting plates. Hence, the bunches always circulate off-centre in the arc, which might adversely influence their stability.

If the number of available antiprotons could be increased, say, to 10^{13} a higher peak luminosity could in principle be reached. If the number of bunches were not changed the number of events per bunch collision would become inadmissibly high as can be seen on Fig. 2 . Increasing the number of bunches k would help in this respect but quickly trouble arises if k approaches 300, corresponding to T_x = 300 ns. At this point the unwanted crossing has approached the low-β quadrupoles leaving no space for the long separators. Another serious problem arises during injection. The separation is not sufficient to prevent deflection of the already stored beam by the kicker magnet when the second beam is injected. Thus the injection kicker must be positioned between two unwanted crossings and its field must rise and fall within T_x. This is already difficult for 108 bunches but becomes nearly impossible once k reaches 200 to 300, at least with present technology. The possibility remains to separate the orbits by such an amount that the beam is not disturbed by the kicker field acting on the other beam. Such a scheme has not yet been worked out.

In order to obtain a resonable luminosity averaged over time, the duration of a run should be approximatley equal to the initial luminosity decay time τ_L. Taking this as a guide the necessary $\bar{p}$ acculation rate becomes :

$$A \gtrsim N_{\bar{p}} / \tau_L$$

For our parameters $\tau_L \sim 20$ h yielding for $N_{\bar{p}} = 10^{12}$ $A \gtrsim 5 \times 10^{10}$ h^{-1} and for $N_{\bar{p}} = 10^{13}$ $A \gtrsim 5 \times 10^{11}$ h^{-1}. The rate 5×10^{10} h^{-1} is the design aim of the new CERN antiproton source and the FNAL source under construction, while 5×10^{11} h^{-1} could possibly be reached with a sophisticated multi-ring source.

It is apparent that even with a very advanced $\bar{p}$ source the maximum expected peak $p\bar{p}$ luminosity is inferior to the peak pp luminosity by about one order of magnitude. The machine becomes technically rather difficult for luminosities approaching 10^{32} cm^{-2} s^{-1}. Moreover, the ratio of average to peak luminosity will certainly suffer from the operational complications and will be lower than for the pp, which will profit from the powerful proton sources at hand.

4. Final Remarks and Conclusions

In this report we have considered mainly a proton-proton collider, as the most promising tool for extending the present energy range for research at constituent level into the TeV region.

The basic machine structure can of course be used for other possibilities, for instance for collisions of the electrons of LEP with the protons of the hadron collider, up to a centre-of-mass energy of about

2 TeV. Collisions of ions would also be possible, with beam energy per nucleon of about one half of the proton energy. However, no work has yet been done on these other possibilities.

The conclusions which can be drawn from the study are :

i) A proton-proton collider can be installed in the tunnel above LEP. A center-of-mass energy of about 18 TeV could be reached with superconducting magnets of 10 T.

ii) In order to achieve this goal, it is necessary to launch in Europe a vigourous programme of development of materials and techniques necessary for the construction of such magnets.
Several European Laboratories and Institutions express a great interest to participate in such a programme.

iii) According to present knowledge, magnets with smaller field, say 6 or 7 T (centre-of-mass energy between 10 and 13 TeV), could be built after a shorter programme of technological development.

iv) All other machine components and systems appear to be feasible with the present technology.

Acknowledgements

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We were also greatly helped by accelerator physicists and experts of superconducting magnets and cryogenics from various other laboratories, who took part in the preparatory meetings and in the Workshop.

Their advice and contributions are thankfully acknowledged.

References

Details of the design of the magnet and other major accelerator systems together with a full list of references are given in the Proceedings of the CERN-ECFA Workshop on the feasibility of a large hadron collider in the LEP tunnel held at Lausanne and CERN in March 1984.

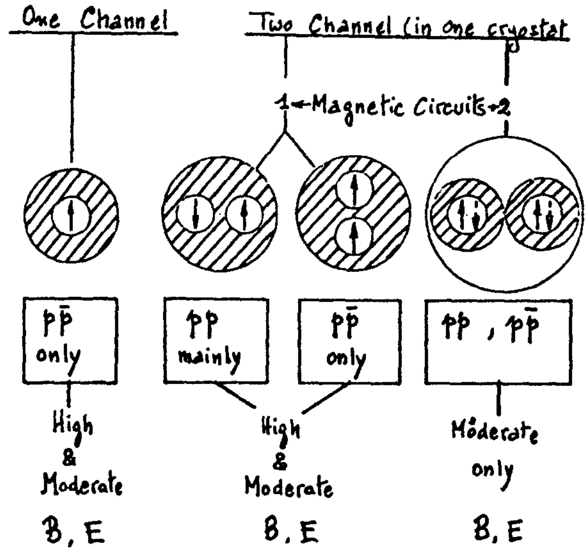


Fig. 1 : Synopsis of Hadron Collider Options for LEP Tunnel

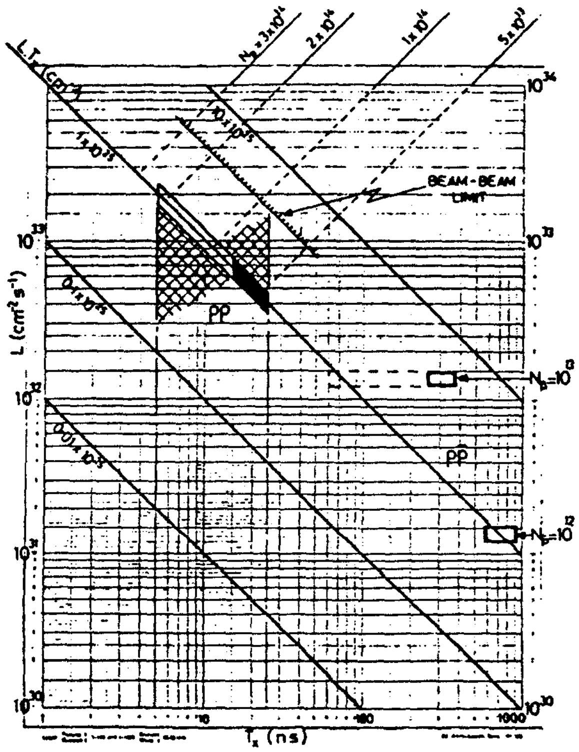
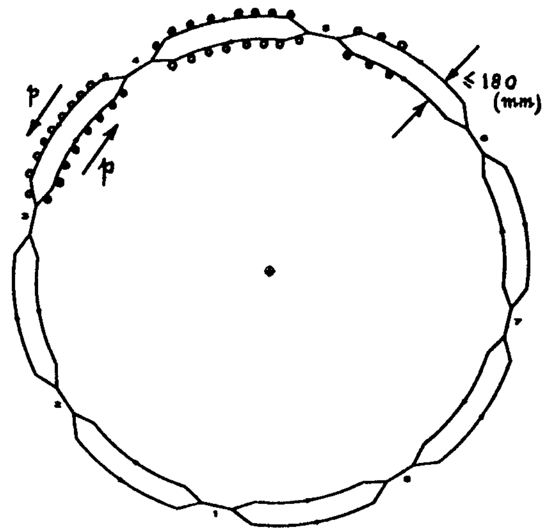


Fig. 2 : Performance of pp and $p\bar{p}$ Colliders

PROTON-PROTON COLLIDER

(TWO MAGNETIC CHANNELS)



LEP TUNNEL

CIRCUMFERENCE	26659 M
ARC RADIUS	3494 M
REVOLUTION TIME	89 uS

Fig. 3

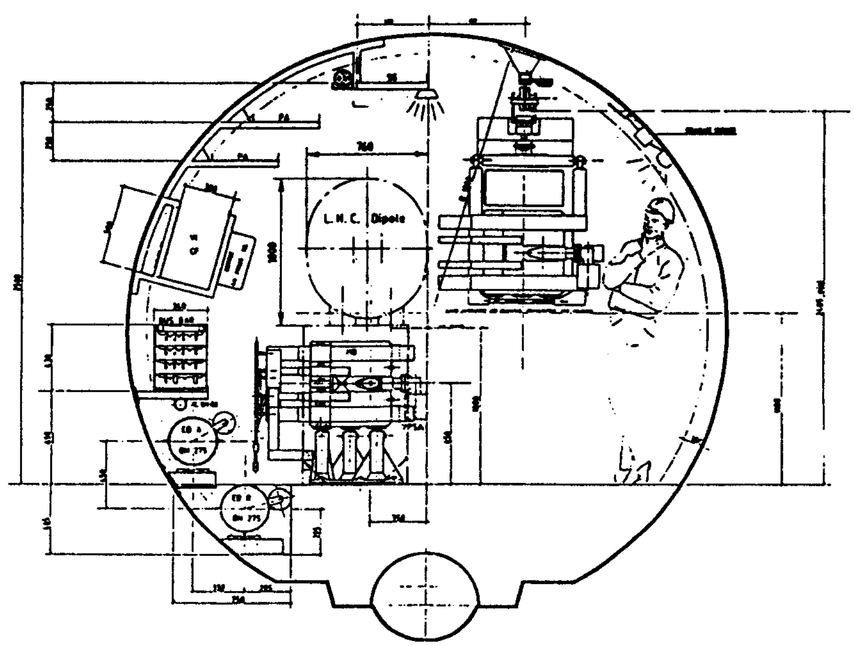


Fig. 4 : LEP Tunnel with LHC magnets above LEP dipoles

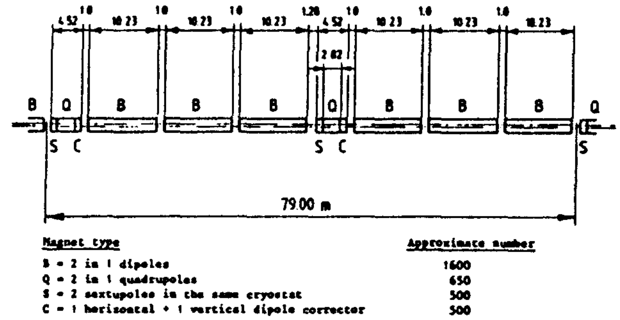


Fig. 5 : LHC Typical Cell (magnetic lengths)

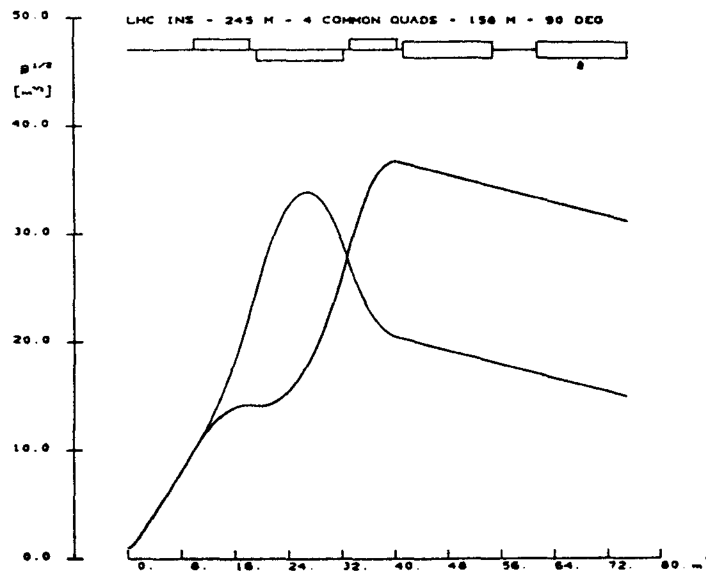
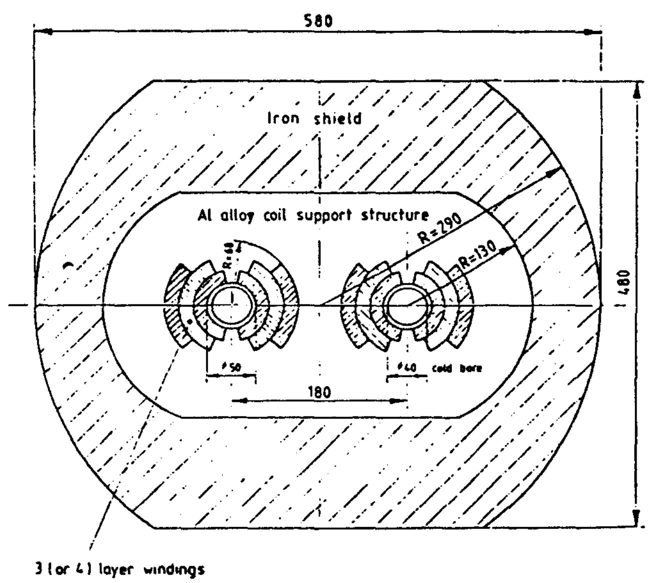


Fig. 6 : Schematic Layout of the low-β insertions



$B_0 = 10$ T

$J_{av} = 300$ A mm^{-2}

Fig. 7 : Twin Bore (2 in 1) Magnet, Cross-Section Type A

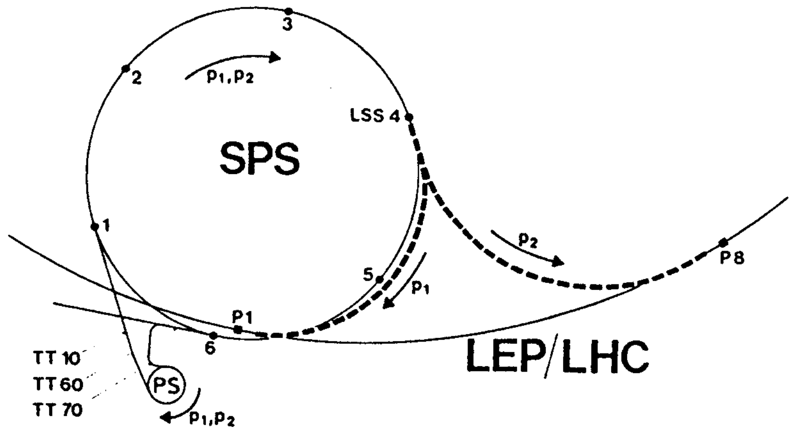


Fig. 8 : Beam Transfer through Injector Chain; Variant 1

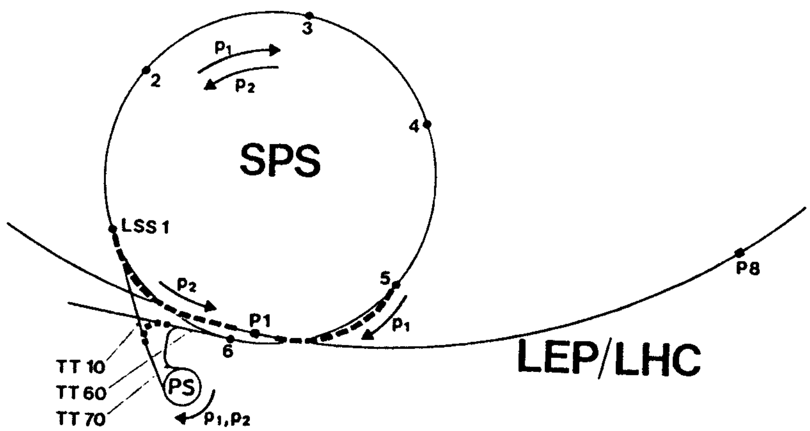


Fig. 9 : Beam Transfer through Injector Chain; Variant 2

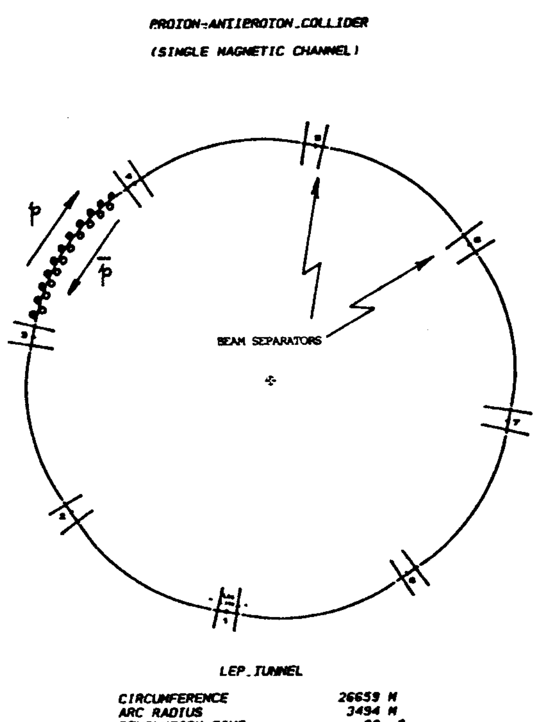


Fig. 10