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A SECOND COLLIDER IN THE CERN LEP TUNNEL FOR pp ($p\bar{p}$) AND ep PHYSICS IN THE MULTITEV ENERGY RANGE

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Abstract and Introduction

The LEP collider at present under construction at CERN will provide e^+e^- collisions in four large detectors, initially at a centre of mass energy of 110 GeV to be gradually increased to ~ 200 GeV by means of superconducting r.f. cavities. First beam is planned for the end of 1988. The tunnel has a circumference of ~ 27 km and can house a second collider on top of the present one, designated as Large Hadron Collider (LHC)[1] (Figs. 1 and 2).

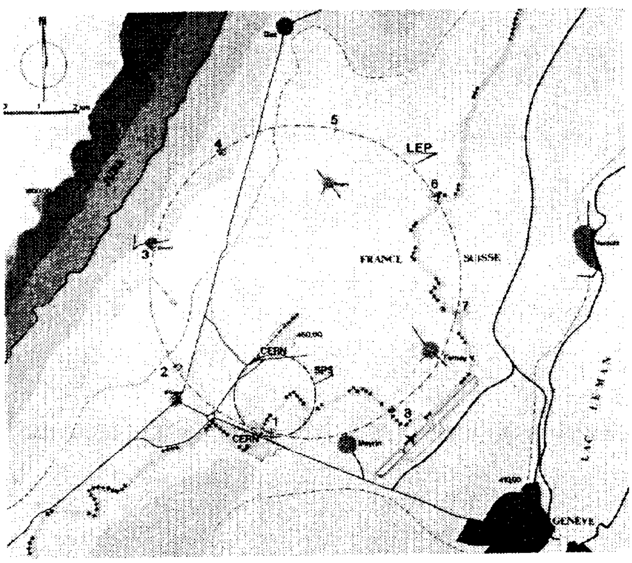

Fig. 1 : LEP in the Geneva area.

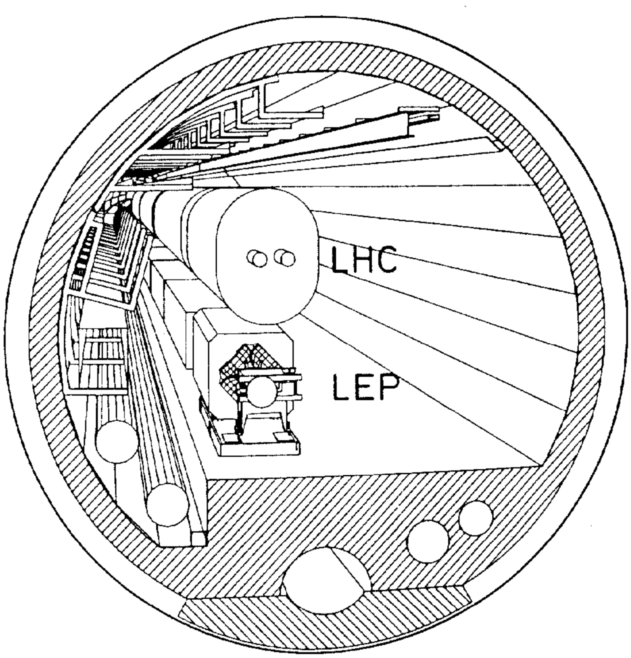

Fig. 2 : Large Hadron Collider in the LEP Tunnel (perspective view in the LEP tunnel)

The LHC can be constructed with either one or two magnetic channels. The former allows collisions of protons with antiprotons circulating in the new channel in up to eight points, while protons can be made to collide with the electrons of LEP in the odd collision points, which are free from r.f. cavities. An LHC with two channels can of course provide pp collisions of high luminosity and the same ep possibilites as already indicated by using only one of the proton beams. Concerning hadronic collisions, the two-channel machine should produce a larger luminosity and be more reliable (ease of refill with protons, which are abundant) than the single channel one ($p\bar{p}$) but will be more expensive due to the double magnets. It should be noted that the CERN $\bar{p}$ source, as being developed for higher intensity[2], would be perfectly suited for this application.

When considering the global economic balance it should be stressed that, in the case a of one-channel ring, proton and antiproton beams must be separated everywhere except than at the wanted collision points and hence electrostatic separators must be added to the hardware list.

Concerning the proton beam energy obtainable, the lattice studies conducted so far indicate that the beam energy E relates to the dipole field B through :

$$E\ (\mathrm{TeV}) = K\ B(\mathrm{T}) \qquad (1)$$

with K being in the range 0.814 to 0.899 depending on the cell length to be chosen (79 or 158 m).

It is being demonstrated for the SSC that, with present technology (NbTi conductors at ~ 4.5°K), dipoles with fields in excess of 6 T can be obtained.

Given the fixed tunnel circumference, it would be interesting to increase the field. This could be obtained either by cooling NbTi conductors down to 1.8°K (superfluid He), or by using Nb_3Sn conductors.

It is currently assumed that a maximum field of ~ 10 T could be considered in the environment of the LEP tunnel. A European collaboration among a dozen laboratories is being set up to achieve this goal[3]. It should be noted that recently a field of ~ 10 T has been obtained in a one-metre model of 60 mm aperture at KEK - Japan (NbTi at 1.8°K).

Therefore, according to (1) the range of proton beam energies to be considered is 5 to 8 or 9 TeV, with corresponding centre of mass energies of 10 to 16 or 18 TeV.

Possible Performance

The luminosity obtainable with pp and $p\bar{p}$ collisions are indicated in Fig. 3 as function of T_x, time 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

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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 workshop[1] 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} (cm^{-2} s^{-1}) 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 $\langle n \rangle$, luminosities up to $\leq 1.5\times10^{33}$ 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 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 $L = 10^{33}$ $T_x \simeq 10$ 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. 3.

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. 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 in Fig. 3 for $N_{\bar{p}} = 10^{12}$ and taking account the constraints by the RF system, to 108 bunches in the machine, corresponding to T_x = 825 ns.

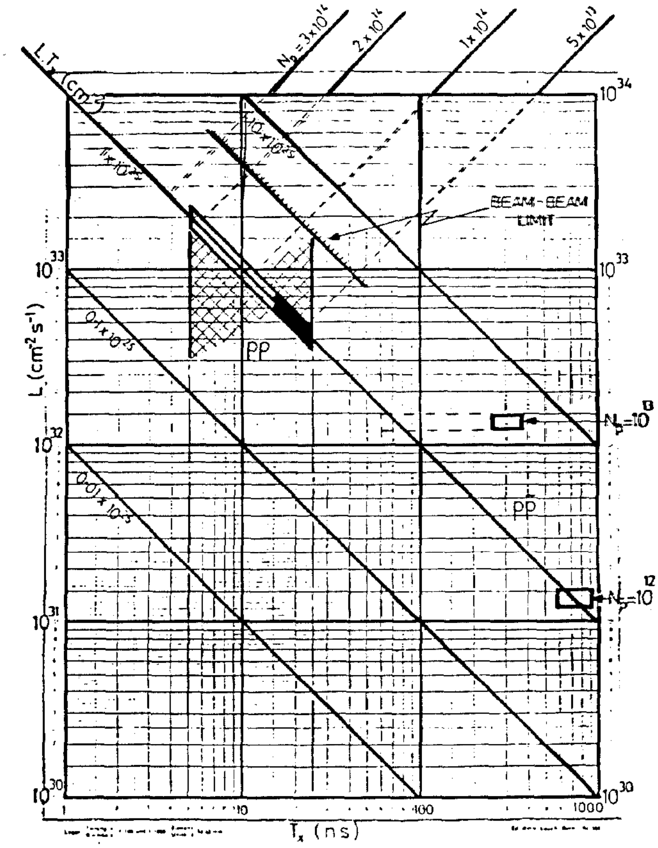


Fig. 3 : Performance of pp and $p\bar{p}$ colliders

When a ten times more intense antiproton source becomes available, the luminosity could be increased in principle to a level of about 1.5×10^{32}. However, as can be inferred from Fig. 3, 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

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

COLLIDER TYPE IN LEP	PROTON-PROTON	
$\langle n \rangle$ at Σ = 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

* For "two-in-one" magnets
** at interaction point for $\beta^* = 1$ m
*** particle loss due to beam-beam collisions

Table 2 : EXAMPLE OF AN ep INSERTION (MAX. LUMINOSITY)

Proton beam			Electron beam		
Number of protons/bunch		3.10^{11}	Total e-current	(mA)	28
Number of bunches		870	Number of bunches		870
Beta-X at crossing	(m)	34	Beta-X at crossing	(m)	0.7
Beta-Z at crossing	(m)	2.8	Beta-Z at crossing	(m)	0.2
Beam energy	(TeV)	8	Beam energy	(GeV)	65
Luminosity		$1.23 \cdot 10^{32}$ cm^{-2} s^{-1}			
Centre of mass energy		1.44 TeV			

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.

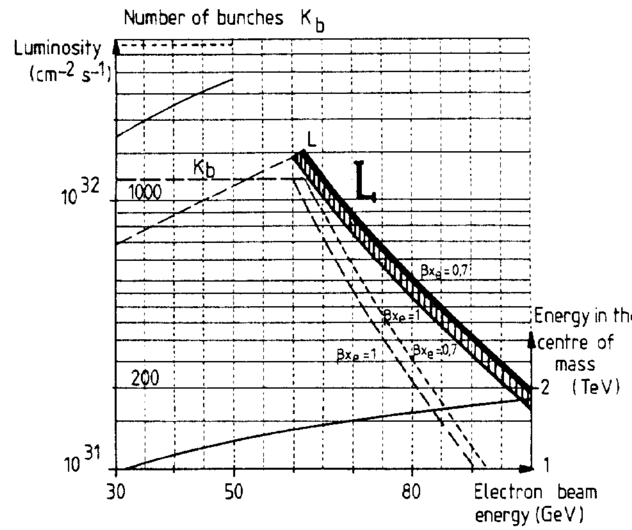
The optimization of the average luminosity for the $p\bar{p}$ case is presented in this conference[4]. Results of beam separation experiments are also presented[5].

Recently work has been directed toward workable solutions for ep collisions[6]. In the most promising configuration the electron beam is deviated upward and made to collide head-on with the proton beam which is located ~ 1 m above the present LEP beam level.

A feature of ep collisions in LEP is that the considerable r.f. power installed can be used either to maintain the electron beam at its highest energy and hence obtain the highest centre of mass energy, or to increase the e-beam current at lower energies, therefore sacrifizing centre of mass energy ($\sqrt{s} \propto E_{ec}^{1/2}$) but increasing considerably the luminosity. Fig. 4 illustrates this. It is seen that ep insertions in the LEP tunnel would provide a unique opportunity to obtain this type of collisions at energies of five times those achievable at Hera.

Table 2 gives an example of a possible ep insertions optimized for maximum luminosity[6]. One should however note that to achieve these performances, the LHC should be equipped with a second HF system working at the same frequency as LEP.

Various other beam dynamics effects have also been studied and are reported separately[7].



βx_e = 1.0 (0,7) βx_p = 50

βz_e = 0.2 βz_p = 2.8

Fig. 4 : Luminosity for head-on ep collisions

Magnets and cryogenics

As already indicated in the introduction, dipoles with a field of ~ 6 T appear to be completely feasible according to the present technology, while higher fields, say 8 to 10 T, require development either of a cryogenic system at low temperature (2°K) in order to use NbTi conductors or of high current density Nb_3Sn conductors to be used at the normal liquid He temperature (~ 4.5°K).

Since one of the problems in the LEP tunnel may be space, an assessment has been made of electromagnetic, cryogenic and mechanical problems which have to be faced for the design and construction of dipoles with a field as high as 10 T, would suitable materials and technologies be available in time.

Two types of double magnets suitable for the most demanding case of proton-proton collisions (Fig. 5) are being considered, namely "two-in-one" (A in the figure) and "dual" (B in the figure). In the former case the two channels are combined into a common yoke and cryostat, with the consequence that the fields in the two apertures are coupled for most of the field range. In the latter case the fields are (almost) independent.

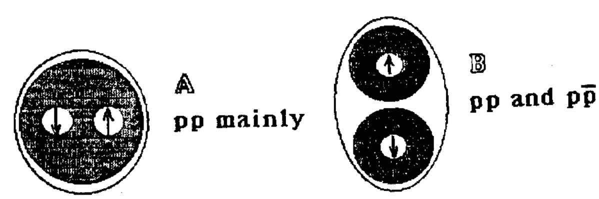


Fig. 5 : Configurations of a pp collider
A - Two-channel, magnet. coupled, 1 cryostat
B - Two-channel, magnet.independ., 1 cryostat

The advantage of "two-in-one" magnets (Fig. 6) is clearly a saving in space and materials (iron yoke, superconductor and cryostat), but the energies of the two beams must be equal over most of the range because of the strong coupling of the two machines. However, depending on the exact spacing between the two beams, it might still be possible to accelerate one of the beams to an intermediate energy before injecting the second one. Such an operation would be advantageous if the beam lifetime at injection energy would be too small. However, it should be stressed that the CERN injectors PS and SPS allow a fast filling sequence (less than 100 s) which should minimize this potential difficulty. A preliminary design for a one aperture 10 T model which is being thoroughly investigated is shown in Fig. 7. Such an aperture package can be used as a model either for a "two-in-one" or for a "dual" configuration. The advantage of "dual" magnets is the independance of the magnetic fields in the two apertures, which allows separate manipulation of the two beams.

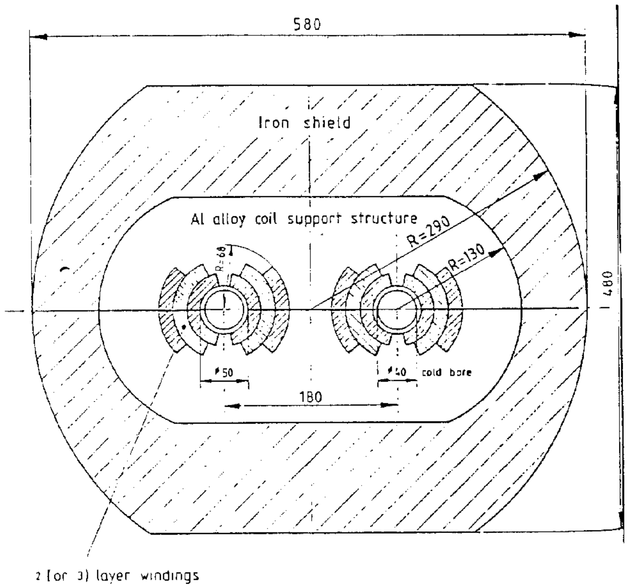


Fig. 6 : Twin bore (2 in 1) magnet

Since, however, such magnets occupy more space it is necessary to determine if such a configuration would still be possible in the LEP tunnel. Fig. 8 gives the evaluation of the horizontal and vertical extensions of dual magnets as a function of field. It has been determined that vertically superposed magnets with fields between 9 and 10 T could still be installed in the LEP tunnel.

A preliminary configuration of quadrupoles, sextupoles and correcting magnetic elements can be found in Ref. 1.

A feasibility study of a 4.5°K cryogenic system has already been made[1]. A study is underway for a 2°K cryogenic system and its first results indicate that such a system would be feasible in the LEP tunnel.

Vacuum system

The beam chamber is a 40 mm stainless steel tube of circular cross-section ("cold-bore").

Because of possible beam instabilities and of the heating produced by the image current circulating on the surface of the vacuum chamber, the latter must be coated internally with a material with low electrical resistivity at 4.5 K and at a field of 10 T. A good choice for the such a low resistivity material is copper, because stainless steel can easily be coated with it and because it reduces the risk of multipactoring processes, thanks to its low yield of secondary electrons[8].

Interaction with residual gas molecules via nuclear scattering and multiple Coulomb scattering results in loss of circulating protons and decay of circulating beam intensity. Theoretical estimates and past experience with the operation of the CERN SPS as proton storage ring[8] show that an average hydrogen pressure of 6×10^{-10} Torr would be quite tolerable, which is not difficult to achieve.

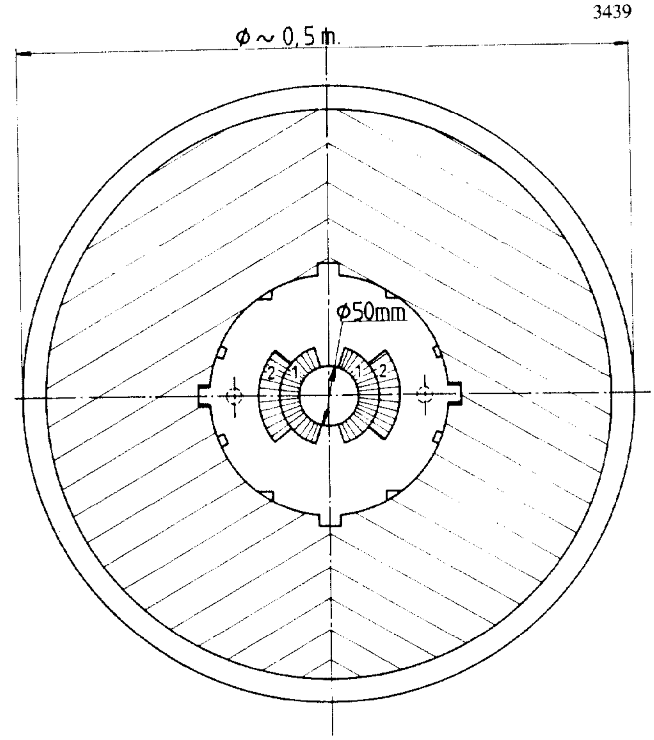


Fig. 7 : Configuration of a one aperture model magnet

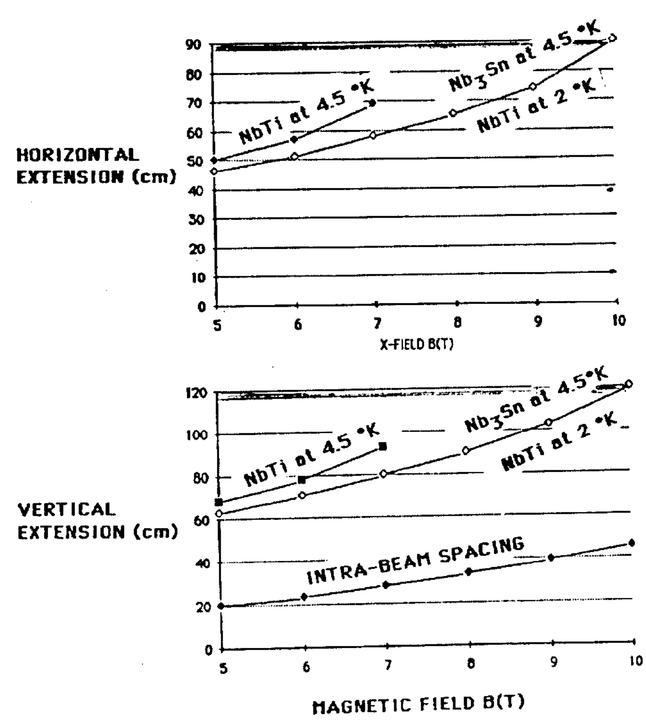


Fig. 8 : Space required by magnetically decoupled magnets

The synchrotron radiation will deposit 0.25 $W.m^{-1}$ at 8.1 TeV with a critical energy of 70 eV. Assuming that the induced gas desorption rate from unbaked surfaces is proportional to the radiation power it can be shown that the radiation induced pressure rise is negligible. Experience with the ISR cold-bore test section indicates that ion induced desorption of H_2 and He is also negligible.

RF system

In a $p\bar{p}$ single ring collider an RF system common to both beams would be used. In pp twin rings this is undesirable. Firstly, coupling the beams, which are exposed to separate magnetic field perturbations, via a common RF may lead to additional RF noise problems. Secondly, threading separated beams off-centre through a common cavity exposes them to deflecting forces, beam-driven and inherent. For these reasons we propose the use of completely separate acceleration systems for the two beams. At the assumed beam separation of 180 mm or less, this requires specially designed cavities, as shown below, at not too low a frequency.

We would have preferred to use for the LHC the same frequency - 352 MHz - as for electrons and positrons in LEP. This would have limited the maximum number of bunches in LHC to 540. In order to allow for a substantially larger number of bunches, a frequency of 400.8 MHz has been chosen, twice the present SPS frequency. This frequency provides a wide choice of number of bunches in LHC compatible with the transfer requirements.

The voltage is determined by the bucket area of 7.5 eVs which is required to hold a bunch of 2.5 eVs with a good lifetime in the presence of RF noise. The peak RF voltage required per revolution is 15.8 MV.

Placing cavities side by side at 180 mm spacing seems excluded and so are common cavities at the E_{11} mode. However, if the cavities for the two beams are staggered along the circumference, "septum cavities", as shown in Fig. 9, become possible. Computations give a shunt impedance of 7.0 MΩ per cell.

A tentative choice may be eight five-cell π-mode cavities per beam, giving 1.05 MV/m accelerating gradient and a dissipation of 22 kW per cell. Two klystrons of the LEP type (1 MW nominal output, 1.1 MW test power at present) per beam are more than sufficient and the grand total for both beams is 30 m of active structure length and four klystrons.

Other aspects of the r.f. system are discussed in Ref. 1.

Injection and Beam Transfers

The existing CERN 450 GeV Superproton-synchrotron (SPS) will be used as injector of LHC. It can provide proton bunches containing more than 10^{11} particles and it can cope with a total number of particles of about 3×10^{13} per pulse. Its typical repetition time is about 10 s which makes it easy to provide in about 100 s the 5×10^{13} particles required for each ring of the Hadron Collider. The same injector can also provide electrons for the ep options as it is the injector of LEP.

There are two possible variants to transfer the beam from the SPS to LHC. The preferred one uses longer tunnels but does not need polarity reversal of the SPS nor superconducting magnets. No polarity reversal is needed for the PS, but a simple junction between TT10 and TT60 existing tunnels.

Since the circumference ratio LHC/SPS is 27/7, LHC can be filled by four SPS pulses. Each SPS pulse consists of a bunch train which is added behind the preceding one already circulating in LHC ("box-car" stacking). The bunch train is ejected from the SPS and injected into LHC using fast deflecting kicker magnets. The bunch-to-bunch distance is too small for the kicker field to rise between two bunches at this energy. It is proposed to leave an azimuthal gap of 0.5 to 1 μs in

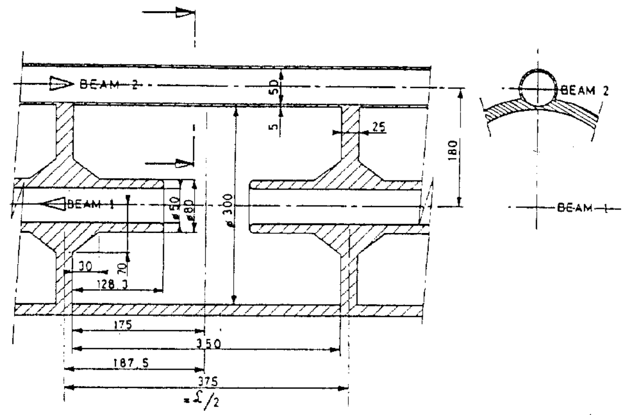


Fig. 9 : Septum cavity for 180 mm beam spacing

the SPS beam so that the kicker field (ejection SPS, injection LHC) can rise in this gap without disturbing the preceding bunch and providing full field for the first bunch to be deflected.

The spacing between two bunches collisions T_x can be adjusted in the interesting range between 5 and 35 ns with the sufficiently fine stepsize of 5 ns. Higher values 50, 60, 75, 100 ns etc. are also possible.

Interaction Insertions

The interaction regions for both the pp ($p\bar{p}$) and the ep options have been studied with some details and are reported separately[6]. It is therefore enough to summarize briefly their main features.

The pp Insertions[9]

They have been designed assuming the two in one magnet solution (two beams in the horizontal plane 1 m above LEP).

The two rings are of equal length with crossing at every intersection (change over from inner to outer arc at every intersection).

There is equal but opposite focussing in adjacent quadrupoles of the rings. The horizontal and vertical beta values at the crossing points are 1 m. The two proton beams are brought together and separated after the crossing by a doublet of dipoles of opposite field leaving ± 10 m of free space for the experiments. Matching of the regular arcs with the insertions is achieved by dispersion suppressor regions. Energy loss is avoided in these regions by tolerating a small transverse offset between the axis of LEP and LHC and by eliminating the weak dipole (BW of LEP) and having only four groups of equal length dipoles.

The ep Insertions[6]

For the ep insertions it is assumed (because of limitation in space and deflection) that they are only in a straight section between two arcs which do no contain r.f. cavities, namely in odd sections (as the 4 even sections will be fully filled with r.f. when the LEP energy is upgraded). The stiffer proton beam will be left in its plane and the electron beam deflected vertically and made to achieve head-on collisions which gives the highest luminosity. There is a path common to both beams between the LEP low-β quadrupoles, which are used for separating the two beams outside this region. The vertical dispersion is made to vanish with the insertion quadrupoles. Under these conditions a luminosity of 10^{32} cm^{-2} s^{-1} can be reached and synchrotron radiation background limited with collimators and masks.

An obvious question directly related to the proposal of installing an LHC in the LEP tunnel is the *compatibility of the two programmes. In a preliminary* way one could imagine the following scenario:

- The present four LEP experiments installed in the even regions (2, 4, 6 and 8) are still active.
- These even regions have been filled with superconducting r.f. cavities to increase the centre of mass energy of LEP to ~ 200 GeV.
- In connection with LHC two or three new areas would be opened up (for instance 1 and 5) for new experiments based on pp ($p\bar{p}$) and/or ep collisions.

The running conditions would be :

i) When e^+e^- is on, the LEP experiments are in their normal data taking position. The new experiments *in 1 and 5 are withdrawn from the beam.*

ii) When pp ($p\bar{p}$) or ep is on, the experiments 1 and 5 are of course in the data taking position. The LEP experiments are withdrawn and the p beams pass the even areas in removable vacuum pipes.

The evolutions with time could be that some or all of the present LEP experiments are transformed for pp ($p\bar{p}$) collisions and work in their present area, possibly adapted for this new use. In such a case pp collisions can be produced in the even points, but at a level of 1 m above the present LEP level.

Conclusions

The simultaneous existence on the CERN site of powerful high quality particle injectors with record performance and of the LEP tunnel opens up a wide range of possibilities.

It has been demonstrated that a variety of collisions of pp, $p\bar{p}$, ep,.. are feasible and would constitute a unique and unequalled facility.

References

1 M. Jacob (Editor). Proceedings of the ECFA-CERN Workshop on a Large Hadron Collider in the LEP Tunnel. ECFA 84/85, CERN 84-10. March 1984. G. Brianti, K. Hübner (Editors). Large Hadron Collider in the LEP tunnel. A feasibility study of possible options. DIR-TECH/84-01. May 1984.

2 E.J.N. Wilson (Editor). Design Study of an Antiproton Collector for the Antiproton Accumulator (ACOL). CERN 83-10.

3 CEN Saclay and Grenoble, CEN Mol, DESY, ECN Petten, ENEA, INFN, KfK Karlsruhe, NIKHEF, RAL, SIN, Tech. University Wien, and CERN.

4 K. Hübner, E. Keil. Optimization of $p\bar{p}$ Luminosity in the LHC. This Conference.

5 L.R. Evans, A. Faugier, R. Schmidt. Beam separation at the CERN SPS Collider. This Conference.

6 G. Guignard, K. Potter and A. Verdier. Interaction regions for ep and pp collisions in the LEP tunnel. This Conference.

7 M. Bassetti, W. Scandale. Limiting effects of the parasiting sextupoles in the CERN Large Hadron Collider. This Conference.

8 L. Vos. Beam vacuum chamber effects in the CERN Large Hadron Collider. This Conference.

9 M. Bassetti, W. Scandale. Linear optics of the Large Hadron Collider for pp and $p\bar{p}$ options. This Conference.