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A PROTON-ANTIPROTON VERSION OF THE LARGE HADRON COLLIDER IN THE LEP TUNNEL

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1. INTRODUCTION

inside the same tunnel.

In this paper an antiproton-proton version of the LHC as an alternative to the proton-proton version is discussed.

A proton-proton collider can achieve a luminosity of more than 10^{33} s⁻¹ cm⁻² if two beams with many bunches are circulating in separated magnetic channels which only intersect at specific interaction points.

A proton-antiproton collider holds the promise of reduced cost, especially at CERN where a powerful antiproton source already exists. However, to achieve a high luminosity many bunches have to be used because the mean number of events per crossing should not exceed one. The beams have to be separated by electrostatic separators to keep the strength of the beam-beam effect below a certain limit. With this technique, already applied in the SPS proton antiproton collider /1/, a luminosity of 1.8×10^{-2} s⁻¹ can be achieved

2. The pp version versus the ppbar version of the LHC

A proton-proton collider in the LEP tunnel can deliver a luminosity of more than 10 s cm⁻². However for those experiments which require an average number of events per crossing $\langle n \rangle = 1$, the luminosity is limited to 4×10^{-2} s⁻¹ cm⁻² if the beam is made up of 3564 bunches. With the same constraints the useful luminosity of a proton-antiproton collider is :

Number of bunches per beam * L _____ppbar = If the beams are not separated the number of bunches in each beam is limited by the strength of the beam-beam effect which increases with the number of crossing points. The beam-beam effect leads to a betatron tune spread and produces higher order resonances. From the SPS ppbar collider it is known that the maximum linear tune shift should not exceed 0.02-0.03 if both beams have the same emittances

In order to produce one event per bunch crossing the number of particles per bunch must be 2.2*10¹⁰ (with a normalized emittance $E = 4\sigma^2 + \gamma / \beta = 15 \pi$ mm mrad and an energy of 9 TeV). This yields a tune shift of 0.00072 per crossing point. Assuming that the total linear tune shift is the sum of the tune shifts of each crossing, this limits the number of crossings to 40. The number of bunches is limited to 20 per beam which gives a total luminosity of 2.2×10^{30} cm⁻² sec⁻¹.

The CERN antiproton source is currently being upgraded to produce about 1.22×10^{12} antiprotons per day, much more than is needed for 20 antiproton bunches in the LHC. By separating the beams with electrostatic separators it is possible to use up to 120 bunches per



Fig. 1: Collision points in the straight sections assuming 120 bunches perham

beam which considerably increases the luminosity. The cost of the system of electrostatic separators needed The LHC is a hadron collider to be located on top of LEP to achieve this can be minimized by a suitable choice of the properties of the lattice.

3. The global machine layout

The essential geometrical parameters are already fixed by the LEP-tunnel : An 8-fold symmentry, the total length of 26658.883 m, arcs with a length of 2449 m. The harmonic number of the RF-system is 35640. It is assumed that the beams should meet in at least experimental regions.

In order to have equidistant bunches, the harmonic number should be a multiple of the number of bunches. This yields for the bunch number N :

N = 35640 / k , k...any integer

To get interactions at all symmetric crossing points equipped with a physics experiment we must have :

> N = 4 * k , k...any integer

These two equations lead to the following possible values for N: 20,24,36,40,44,60,72,80,108,120,132,....

To work with more than 120 bunches seems to be unrealistic due to

the limitation in the antiproton production rate.

- the time needed to inject a bunch in the presence of the other beam. The injection of a bunch has to be done between the passage of two bunches of the counter-rotating beam.

- the necessity for the beams to be separated at all unwanted crossing points. This becomes more difficult to achieve the closer the crossing points are.

With 120 bunches per beam the beams meet at 240 positions with 111.078 m separation between two adjacent crossing points, 6 unwanted crossings occur in each of the insertions (see fig. 1), and 192 crossings in the arcs.

The arcs are composed of an integer number of regular cells. The length of each cell is chosen in such a way the crossing points are located at similar that positions in each cell. With 22 cells, each with a length of 111.318 m, this condition is fulfilled : The crossing points are always within 2 m of the end of each cell.

In the SPS, the beams are separated in the horizontal plane because of the constraints coming from the already existing lattice. However, in the LHC, the orbit excursion necessary to separate the beam by 6σ (σ is the rms beam size) is minized in the case of vertical separation because of the absence of vertical dispersion. The minimization of orbit excursions is important to keep the beam bore as small as possible.

The beam size shrinks proportionaly to 1 / J E. At injection energy of 450 GeV the orbit excursions are maximum and determine the size of the magnetic bore. In order to keep the beams separated by 60 the field strength in the separators has to be increased proportionally to $\int E$.

The length of the separators is determined by the required beam deflection at the maximum energy of 9 TeV.

It is suggested to install separators at only 4 locations in the machine (see fig.2). The beams are separated over each half of the machine and the bunches collide at the experimental interaction points (IP) at a small crossing angle. Higher order effects such as coupling and tune shifts induced by orbit deviations in the sextupoles are cancelling out if the sign of the two separation orbits are chosen in the appropriate way.



1P.....experimental interaction points

Fig 2: Schematical layout of the separation orbit of one of the beams



4. Layout of the cell

The suggested length of the cell is 111.318 m with a phase advance of 90 per cell. The crossing points are 90° apart (see fig. 3).

For an emittance E = $4\sigma^2 \star \gamma / \beta$ = 15 m $\star mm \star mrad$ the maximum orbit excursion in the cells is 3.6 mm at injection energy.

5. The insertions

The beam optics in the insertions with physics experiments must meet the following requirements :

- the beams must be separated at the 6 unwanted crossing points in each insertion and must meet at the experimental IPs (see fig.1).

- the dispersion must be zero at the experimental interaction points (IP), this is achieved by a dispersion surpressor.

- β values at the IP of 1 m * 1 m are desired.

- The vertical betatron phase advance between the IPs and the first crossing point in the arc must be given by $\Delta\phi$ = n * 180 0 + 45 0 .

First insertion :

A beam optics fulfilling all these constraints with a phase advance of 1.375 (in units of 360^{0}) is shown in fig.4. Fig. 5 illustrates the phase advance for each crossing point in the insertion: the beams are well separated if the phase advance is 90^{0} or 270^{0} and not separated if the phase advance is 0^{0} or 180^{0} . For a reasonable separation the phase advance at the crossing points has to fall into the non-shaded area.

The geometry of the dispersion surpresser is taken from the design for the pp-version of the LHC /2/. The quadrupoles in the last cell of the arc have slightly different field strengths than those in the regular arcs. Between the dispersion surpresser and the quadrupole triplet focusing the beams into the IP, some additional quadrupoles are installed for phase matching.



Second insertion :

The phase advance for the vertical betatron oscillation between two experimental interaction points must be a multiple of 180° :

 ϕ_{-} = n * 0.5 , with n any integer

The 22 cells in the arc contribute a phase advance of 5.5. The above described insertion has a phase advance of 1.375. In order to get the required phase advance between two interaction points, a beam optics with a phase advance of 1.625 was developed for the second insertion.

<u>Third insertion : The separator insertion :</u> A third type of beam optics is needed for the insertions with the separators :

- The beams must meet at the <u>Crossing Point CPO</u> (see fig. 6). At CP1 they should already be separated. The separators should be installed as close as possible to CP1 in order to maximize the space available for the installation of quadrupoles between the crossing points CP1 and CPO. With these quadrupoles tune corrections can be done.

- Between the first separators and CP1 the phase advance must be about 90^{0} . Furthermore it is desirable to have a high vertical beta at the separators because the kick needed to produce a certain orbit change is inversely proportional to the square root of the beta function.

A way to fulfill these constraints is to setup the quadrupoles as for a low-beta insertion (see, fig. 6). The separators are installed close to the highest beta value. At the minimum beta value the two beams are already separated by the first two separators. An additional deflection is produced by separator 3 and 4. They can also be used to make small trims on the orbit bump.

The length of the 4 separators required to separate the beams by 6σ at the maximum energy is about 15 - 20 meters. A set of 4 separators is needed at 4 positions in the machine (see fig. 2) resulting in a total length of about 80 meters.

A total phase advance close to multiples of 8 should be avoided. In the beam optics described here the total tune is given by 69.7. To achieve this goal the separator insertion was matched to give a phase advance of 1.8.

6. Summary

A solution for the optics of the proton-antiproton version of the LHC was found which allows operation of the machine with up to 120 bunches per beam. The beams are separated by electrostatic separators at all crossing points apart from the experimental collision points. A luminosity of 1.8×10^{31} cm⁻² s⁻¹ can be achieved. The machine consists out of 8 arcs and three different types of insertions (see fig.7).

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8. <u>References</u>

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Crossing point at the end of the arc





FIG.6 INSERTION FOR THE SEPERATORS



- A... Insertion for experimental IP with $\Psi z = 1.375$ B... Insertion for experimental IP with $\Psi z = 1.625$
- C... Separator insertion

<u>Fig.7</u> : The $p\bar{p}$ _version of the LHC: the different insertions