COMMISSIONING AND OPERATING EXPERIENCE WITH THE ELECTROSTATIC BEAM SEPARATION SYSTEM OF THE LEP e^+e^- COLLIDER

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ABSTRACT

Electrostatic separators are used in the LEP collider to separate the e^+ and e^- bunches in the eight collision points during injection and acceleration. The maximum operating field is 25 kV/cm across a gap of 11 cm between 4 m long stainless steel electrodes. The power of the higher order mode losses deposited on the electrodes is extracted by a closed loop cooling system in order to prevent an increased outgassing which would raise the electron background in the experiments. The overall system comprising 32 separators, 16 cooling stations, 40 HV generators, 8 inverters and 4 synchronous discharge switches is working very reliably. The HV performance of the complete system during the acceptance tests and the running-in of LEP has been excellent. The operational characteristics measured in commissioning experiments are reported and the implications of an upgrading for LEP200 are presented.

GENERAL FEATURES

Since the start-up of the LEP collider in July 1989 electrostatic separators are used to separate the four electron from the four positron bunches in the eight collision points during injection and acceleration. For colliding beams without using wiggler magnets the beam-beam strength parameter is inversely proportional to the cube of the energy. Therefore, it is necessary during injection and acceleration to separate the beams in order to accumulate sufficient current at the injection energy of 20 GeV, so as to reach the beam-beam limit only at top energy which for Z_0 physics is about 46 GeV.

The total system [1,2,3,4] comprises 32 separator tanks, each 4.5 m long with a vacuum of 10^{-8} Pa after bake-out at 300°C. The maximum operating field is 25 kV/cm across a vertical gap of 11 cm between 4 m long stainless steel electrodes.

Each of the eight collision points (CP) of LEP is equipped with four electrostatic separators creating a fully compensated local deformation of the vertical closed orbit. At top energy, the beams are brought into collision with a time constant of 15 ms by means of synchronous discharge switches in the centres of the four LEP detectors (CPs : 2,4,6,8), whereas they are kept separated in the high beta insertions (CPs : 1,3,5,7). Thereafter, the colliding beams are squeezed by tuning the four low-beta insertions. The collision of the bunches in the even CPs can be vertically adjusted over $\pm$ 90 µm at 46 GeV by vernier generators including a field reversal in the separators in order to optimize the luminosity.

Higher order mode losses cause heating of the electrodes and the increased outgassing may provoke a significant rise in pressure for high LEP currents. This could raise the electron background due to beam-gas interaction. In order to avoid this effect the separator electrodes which are near to the four LEP experiments are cooled, whereas in the odd collision points no direct cooling is applied.

The first year of operation has proven the sound design of all major components and in particular the high reliability of the entire system distributed over all eight collision points of LEP. Up to now practically no beam time has been lost due to hardware failures and only a few hours of down-time have been caused by control problems.

A severe limitation of electrostatic separators could be due to high voltage breakdowns across the electrode gap or the high voltage feedthrough, which cause the loss of the stored currents as observed in an experiment described below. Low breakdown rates can only be obtained with a careful high voltage design combined with ultra high vacuum and a thorough conditioning at an electric field of at least twice the operating field which cleans the high field surfaces in situ [1]. Such a performance can only be continued under beam operation if the separator electrodes could be perfectly screened against synchrotron radiation.

Due to the excellent high voltage behaviour of the electrostatic separators it was possible, without any performance loss, to augment the maximum operating field from the design value of 20 kV/cm to 25 kV/cm which allowed to increase the separation in the low-beta insertions by 25%.

The commissioning of the separation system has been carried out in a series of machine development experiments. First, the mea' red closed orbit bumps produced by the separators were compared with those calculated from the beam optics. Second, it was checked whether the beams collide head-on in the even collision points. For this purpose, vertical luminosity scans were carried out and closed orbit oscillations measured. Third, the strength of the beam-beam coupling was measured as a function of the vertical bunch separation and compared with a non-linear theory of the beam-beam forces [5]. From these measurements the required separation for the energy upgrade (LEP200) could be estimated. Fourth, measurements were carried out to explore the scope of performance and the limitations of the present separation system under various conditions. For this purpose the breakdown rate was measured as a function of the electric field and the electrode gap with and without beam. In view of a future energy upgrade of LEP this should answer the question, whether an operation with a reduced electrode gap of only 60 mm and at twice the actual field, i.e. at 50 kV/cm, would be feasible, since those parameters can be met without constructing any new hardware.

MAIN PARAMETERS

The main parameters of the separation system are given in Table 1.

Table 1 : Main parameters of the separation system

Separator length	4.5 m
Inner diameter of separator tank	540 mm
Electrode length	4.0 m
Electrode width	260 mm
Standard operating gap	110 mm
Deflection per separator at 25 kV/cm for 20 GeV	500 µrad
Maximum voltage of main generators	$\pm$ 160 kV
Maximum possible field strength	29 kV/cm
Maximum voltage of vernier generators	$\pm$ 35 kV
Vacuum pressure with beam	10^{-8} Pa
Number of separators per CP	4
Total number of separators	32
Low Beta Insertions (CPs 2, 4, 6, 8) :	
Maximum operating field strength	25 kV/cm
Maximum operating voltage	$\pm$ 137.5 kV
Standard separation at 20 GeV	1.7 mm
Standard separation at 46 GeV	0.74 mm
Tuned beta values at CP : β_x	1.75 m
β_y	0.07 m
Horizontal beam size σ_x at 46 GeV	250 µm
Vertical beam size σ_y at 46 GeV	25 µm
Separation at 46 GeV in units of σ_x	3.0
High Beta Insertions (CPs 1, 3, 5, 7) :	
Maximum operating field strength	16.4 kV/cm
Maximum operating voltage	$\pm$ 90 kV
Standard separation at 20 GeV	5.0 mm
Standard separation at 46 GeV	2.2 mm
Tuned beta values at CP : β_x x β_y	20m x .8m
Horizontal beam size σ_x at 46 GeV	850 µm
Vertical beam size σ_y at 46 GeV	85 µm
Separation at 46 GeV in units of σ_x	2.6

ELECTRODE COOLING IN THE LOW BETA INSERTIONS

The cooling of the electrodes is the main sub-system which has not been described earlier [1-4]. The design specifications of the cooling stations were based on a maximum possible current of 5.5 mA per beam corresponding to 230 W of higher order mode losses per electrode [1]. Therefore, each cooling station should be capable to cool away at least 460 W. Due to large uncertainties in the estimated power, a cooling station is designed for about twice this capacity, i.e. 1000 W. However, up to now, LEP has reached a current of about 2 mA per beam and at the corresponding loss per electrode of only about 30 W no thermal effect due to higher order mode losses could be observed.

The power deposited on the electrodes due to higher order mode losses is extracted by a closed loop cooling system. The primary electrode cooling circuit comprises a circulation pump running at 12 l/min, a heat exchanger, a bellows expansion vessel and various probes to monitor and control flow, pressure and temperature. The cooling liquid must be an excellent insulator ; therefore, FREON 113 (boiling point : 47.6°C) is currently being used which will be replaced for higher LEP currents by FLUOROINERT FC77 (boiling point 97 °C). The secondary cooling circuit uses raw water at a flow rate of about 10 l/min. The circuit elements are mainly constructed from stainless steel. A cooling station has the following size (length 800 mm, width 550 mm, height 450 mm) ; 16 units are operated since the start-up of LEP with good reliability. The nominal cooling capacity, including the power of about 800 W dissipated by the circulation pump, is about 2000 W for a maximum temperature increase in the primary circuit of 5°C.

CHECK-OUT OF CLOSED ORBIT BUMPS

The vertical closed orbit (c.o.) bumps, each created by a set of four separators, are measured with the beam pick-ups for the even (fig. 1) and the odd collision points. Each separator bump shows the required symmetry with respect to the CP and furthermore the amplitudes agree well with the required values calculated from beam optics.

A more sensitive tool to study whether the separator settings are optimized, is to measure the vertical c.o. oscillations created by a non-compensated separator bump. For this purpose the kick ratio of the two independent separator pairs has been varied in each of the eight CPs for the different insertion optics and energies. It results in a clear minimum of the vertical c.o. amplitudes at the nominal kick ratio (fig. 2).

MEASUREMENT OF THE VERTICAL MIS-CROSSING IN THE EVEN COLLISION POINTS

A possible mis-crossing of the bunches in the even CPs could result from the combined effect of the discontinuous replacement of the radiated beam energy and alignment errors [6] and, furthermore, from non-closed separator bumps in the odd CPs.

For a luminosity scan the rate of Bhabha pairs is monitored [7] as a function of the vertical beam separation by using the vernier adjustment facility. From the scans (fig. 3) carried out so far it can be concluded that the beams collide head-on in all four experiments with a possible mis-crossing of < 6 µm or < 1/4 σ_y, which could reduce the luminosity by a negligible 2%.

The contribution of the separators to this effect can be evaluated by using the arcs of LEP as a microscope for viewing a possible vertical mis-crossing in the even CPs. Since the beams remain separated in the odd CPs during physics runs, a non-compensated separator bump can produce closed orbit oscillations, and their amplitudes in the arcs are enlarged by the square root of beta ratios with respect to the amplitudes in the even CPs. Taking from fig. 2 the maximum r.m.s. value of the vertical c.o. amplitude of 0.1 mm and doubling it for the effect of the independent contributions of the e^+ and e^- bunches, an upper limit for the vertical mis-crossing of < 5 µm is obtained.

This means that the observed small mis-crossings could be explained by this effect.

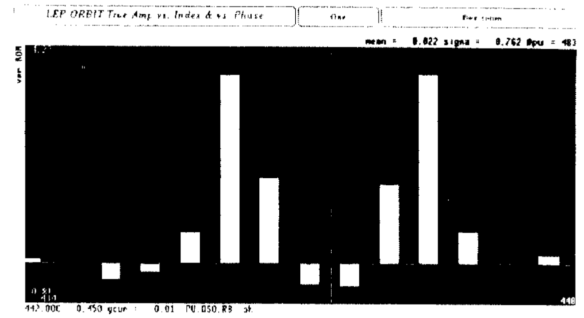

fig. 1 : Vertical c. o. bump (e+) for a detuned low beta insertion in CP8 5.25m x 0.21m at 20 GeV

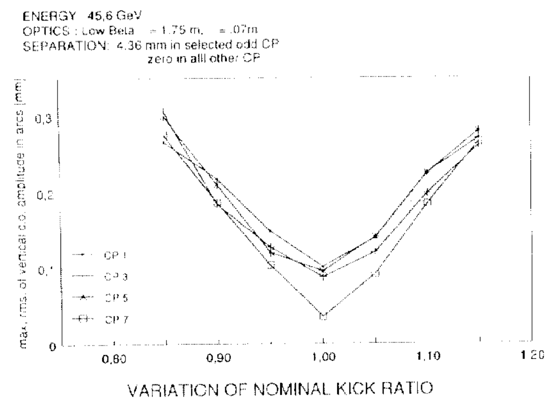

fig 2 : Dependence of vertical c. o. rms outside separator bump from the kick ratio for odd CPs

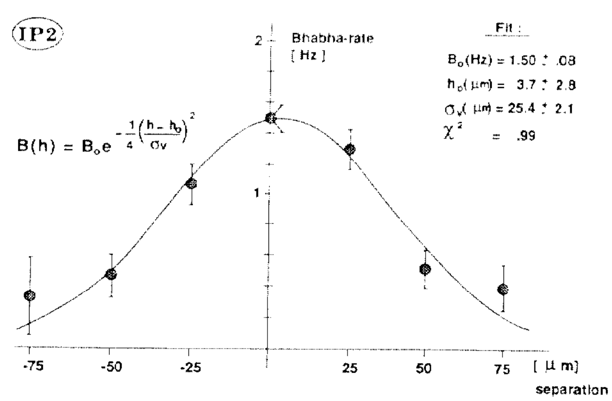

fig. 3 : Vertical luminosity scan in point 2

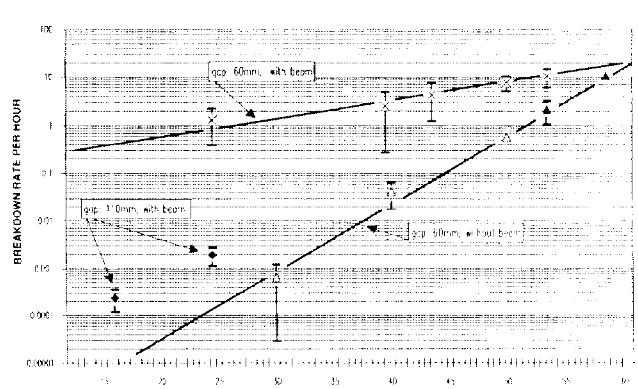

fig. 4 : Breakdown rate per separator unit as a function of mean electric field strength

MEASUREMENT OF THE BEAM-BEAM COUPLING

The strength of the beam-beam coupling was measured as a function of the separation and the results are presented elsewhere at this conference [5].

From the measurements it can be concluded that the current separation system, designed for a maximum energy of 55 GeV, cannot provide, without upgrading, sufficient beam-beam separation in the four low beta insertions for energies up to about 93 GeV necessary for W^+W^- physics. For LEP200, the required upgrading of the separation by a factor of two could be achieved without difficulties by adding those eight separator units which were already included in the initial design [1]. A second possibility is investigated below.

SEPARATOR PERFORMANCE FOR STANDARD AND MINIMUM GAP WITH AND WITHOUT BEAM

The electrode gap of the separators can be manually adjusted in the range from 160 mm to 60 mm. This facility is vital for their excellent high voltage performance, since it allows to condition the separators during shut-down periods at higher fields of up to 53 kV/cm with the same high voltage generators as used for the operation [1].

In view of this facility, it was tested whether the required upgrading of the separation system in the even CPs for LEP200 could also be achieved by reducing the electrode gap from 110 mm to 60 mm and thus increasing the field to about 50 kV/cm. Under these conditions the breakdown rate per unit is raised to about 0.6 per hour even without beam.

For this experiment, in four of the eight separators which normally are operated at 25 kV/cm the gap height was reduced to 60 mm. When beams were injected (20 GeV) the accumulated currents were completely lost whenever a limiting current per bunch of typically 0.2 mA was reached which is less than 30% of the LEP design figure. With the present accumulation rate these losses occurred about every two minutes. Each beam loss could accurately be related with the help of the spark monitors to an electrical breakdown in one of the four reduced electrode gaps. The beam loss is due to an uncompensated separator bump of up to 1 mrad and not caused by beam-beam effects, since the same result is obtained by a single particle beam too. The dramatic increase in the breakdown rate can only be explained by synchrotron radiation hitting the separator electrodes. Any attempt of screening the electrodes from synchrotron light with vertical collimators installed next to the separators failed, because these collimators could not be closed enough to create the required shadow against synchrotron radiation without reducing considerably the beam lifetime.

The performance of the separators as a function of the field under these conditions is shown in fig. 4 (upper curve). It is striking that under the heavy impact of direct or scattered synchrotron radiation from the low beta quadrupoles the breakdown rate is only slowly decreasing with diminishing field. This is in sharp contrast to the performance without beam (lower curve), from which a rule of thumb can be derived that for lowering the field by 10 kV/cm the breakdown rate is reduced by about one order of magnitude. An interesting observation is that both curves cross at about 60 kV/cm where pure high voltage effects start to play a more important role than the synchrotron radiation.

For comparison, the breakdown rates with the standard operating gap of 110 mm under present beam operation are also indicated. In the even CPs the unit breakdown rate is $1.5 * 10^{-3}$ per hour at a field of 25 kV/cm, and in the odd CPs it is $2.5 * 10^{-4}$ per hour at a field of 16 kV/cm. Taking into account that the 16 separators in the odd CPs operate practically continuously, whereas in the even CPs only 8 units operate at a high field of 25 kV/cm but only approximately 2 hours per day, we shall expect a beam loss due to a breakdown in the odd CPs once every 10 days and in the even CPs once every 41 days. It is important to note that these rates with beam are only about a factor of 10 higher than those extrapolated for the same fields without beam, proving that electrodes set at the standard gap are well screened from synchrotron radiation.

CONCLUSION

The LEP separating system has worked from the LEP start-up according to its design specifications and is operating with a high reliability ; its high voltage performance is excellent. The observed low breakdown rates are achieved by a careful high voltage design, the use of ultra high vacuum techniques and an efficient screening of the electrodes from synchrotron radiation. For the coming energy upgrade for W^+W^- physics eight additional separators will be needed in the low beta insertions.

ACKNOWLEDGEMENTS

The authors are pleased to acknowledge the important contributions of X. Altuna, G. Boch, R. Bonvin, B. Dedieu, J.P. Deluen, R. Ducret, D. Gélard, R. Guinand, R.L. Keizer, R. Oberli, A. Rizzo, Y. Sillanoli, J. Soubeyran, J. Stirnimann (fabrication, assembly, installation and maintenance), O. Gröbner, L. Hernberg, F. Le Normand, H. Schuhbäck, H. Wahl (vacuum and bake-out), H. Rieder (cooling), J.H. Dieperink, R. Finiel, M. Ninet, D. Perrin (controls), and F. Hedman (application software).

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