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**Fast measurement of luminosity at LEP by detecting
the single bremsstrahlung photons.**

C. Bini, G. De Zorzi, G. D'Ambrini Palazzi, G. Di Cosimo,
A. Di Domenico, P. Gauzzi and D. Zanello

Dipartimento di Fisica, Università "La Sapienza", Roma
and INFN Sezione di Roma, Italy

ABSTRACT

Luminosity and beam angular divergence have been measured at LEP with a fast monitor based on the single bremsstrahlung process $e^+ e^- \rightarrow e^+ e^- \gamma$. The photons emitted at the interaction point 1 are detected by an e.m. calorimeter: both the photon energy and impact point are measured. The beam angular divergence and the luminosity are determined in few minutes with a statistical error of 1%. With the present experimental lay-out the systematic error is of few percent; it would be reduced by performing the measurement on an experimental interaction point.

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1. - INTRODUCTION

Since many years the luminosity at electron-positron colliders is commonly measured and monitored by detecting the QED process $e^+ e^- \rightarrow e^+ e^-$, namely the Bhabha scattering (BS).

At LEP energies however the QED process $e^+ e^- \rightarrow e^+ e^- \gamma$, i. e. the single bremsstrahlung (SB), also called radiative Bhabha scattering, can be used as a faster "monitor process" than BS, mainly due to its cross section dependence on the total c.m. energy.

We recall that BS cross section decreases as the inverse of the total c.m. energy squared, and that it depends on the $e^\pm$ scattering angle θ as θ^{-4} . The SB cross section slowly increases with s (logarithmic dependence) and almost all SB photons are emitted at very small angle ($< 10 \mu\text{rad}$ at LEP energies) over the whole photon energy spectrum.

Two requirements in a luminosity monitoring system are essential:

- a) precision: high precision in absolute luminosity determination is required for experiments that measure cross sections;
- b) speed: a short measurement time is needed in order to check and to optimize continuously the machine operating conditions.

The most important SB feature at 50 GeV beam energy (the maximum energy at LEP phase 1), is the very high rate: $\sim 10^2$ photons/crossing or 4×10^6 photons/sec, at a luminosity of $1.6 \times 10^{31} \text{cm}^{-2} \text{sec}^{-1}$. This value has to be compared with $\sim 0.1\text{--}5.0$ Hz expected for the standard and very small angle (respectively) luminosity monitors employed in LEP experiments.

In this paper the experiment LEP-5 is described [1]. It has been performed at the interaction point 1 of LEP in 1990.

Finally we recall that the SB method had been used in 1973 at ADONE in Frascati [2], and in Novosibirsk (VEPP colliders) [3], and the analogous process $e^- p \rightarrow e^- p \gamma$ will be utilized at HERA [4].

2.- SINGLE BREMSSTRAHLUNG METHOD AT LEP

The forward SB photons emitted at an interaction point (IP) of LEP must pass through a window in the vacuum pipe, placed just after the first dipole magnet at the straight section end, and reach the photon detector. In Fig.1 a sketch of a LEP half straight section from the IP-

1 to the arc is shown; the detector, facing the incoming positron beam, is located at ~350 m from IP-1.

In order to minimize the absorbing material traversed by SB photons, some modifications of the machine were done near the arc: (i) the vacuum pipe inside the QL12 quadrupole* has a thin window of 2 cm (vertical) x 5 cm (horizontal); (ii) the coils of the QL13 quadrupole are modified; (iii) the B4/2 dipole is reversed.

Two main features are peculiar of SB method at LEP: (a) the SB photons acceptance is not 100%; (b) the average number of SB photons per beam-crossing is larger than one (except for very low luminosity values).

Due to the window size the acceptance for SB photons is limited as shown by the Fig.2, and is evaluated to be 41%. The beam angular divergence σ_D is estimated to be 55 μ rad in IP-1, much larger than the intrinsic angular spread of SB photons of the order of 10 μ rad. The accepted photons "beam" profile has to be measured in order to determine the whole spatial distribution of SB photons.

In a multi-photon regime the total energy per crossing is measured rather than the single photon energy. Hence the measurement of the luminosity integrated over a time interval is based on the relation:

$$E_{\text{meas}} - E_{\text{bckg}} = A L \int_0^{E_{\text{beam}}} \varepsilon(k) k \frac{d\Sigma}{dk} dk \quad (1)$$

where: k is the photon energy, L is the integrated luminosity (pb^{-1}), E_{meas} the total measured energy (GeV) in the time interval, E_{bckg} the background measured energy (GeV), E_{beam} the beam energy (GeV), A the acceptance, $\varepsilon(k)$ the energy detection efficiency and threshold function, and $d\Sigma/dk$ the differential SB cross section (pb/GeV).

E_{meas} is the measured amount of energy deposited in the e.m. calorimeter. $E_{\text{bckg}} = (E_{\text{SBR}} + E_{\text{noise}})$ represents the background energy to be subtracted and is the sum of two terms. E_{SBR} , which is measured in condition of no beam-crossing in IP-1, is the sum of beam-gas bremsstrahlung plus Compton scattered thermal photons [5] plus minor contributions. E_{noise} is due to an e.m. noise induced in the cables connecting the apparatus to the read-out system.

* Corrected to: B4/1 magnet

The acceptance A is obtained by measuring the spatial distribution of the energy in the calorimeter modules (see Appendix). In the same way the beam angular divergence is also determined.

The function ε is evaluated by the calorimeter calibration on test beams (≥ 5 GeV). The fit of the low energy part of the photon spectrum at LEP requires an effective threshold of 200 MeV. It should be noted that the integral value I_V of Eq.(1) is affected by less than 1.5 % if the energy threshold changes from 0 to 0.5 GeV (see Fig. 3).

The SB differential cross section $d\Sigma/dk$ has to be evaluated taking into account the finite transverse size of the beams (σ_X and σ_Y), due to the large value of the impact parameter for the emission of SB photons at the LEP energy [3]. The uncertainty on the σ_X and σ_Y values propagates to the cross section value hence to I_V , as shown in Fig.4. A 20 % change on σ_Y corresponds to less than 1 % change on I_V . The SB photons rate evaluated by the formulas of Ref.3 turns out to be $\sim 25\%$ lower with respect to the standard QED calculations. Finally, in case of LEP, the radiative corrections are less than 1%.

3.- EXPERIMENTAL APPARATUS

The LEP-5 experimental apparatus mainly consists of a modular e.m. calorimeter capable to measure energy and impact point of SB photons.

A low-Z absorber of about 2 R.L. made of LiH is placed in front to the calorimeter and it strongly reduces the huge flux of synchrotron radiation photons. A careful estimate of the synchrotron radiation background is reported in Ref.6, taking into account the magnetic structure of the straight section 1 of LEP and the size of the window. The estimated energy going through the window at the maximum nominal luminosity turns out to be 3×10^6 GeV/crossing. After the absorber it represents only 1.2 % of the total energy deposited into the active part of the calorimeter, according to a careful Montecarlo calculation of the absorber-calorimeter system [7].

The e.m. calorimeter consists of 42 modules made of scintillating fibres [8] embedded in lead with a filling ratio of 18%. Each module has 35 cm length and 2.5×2.5 cm² section. The fibres have a 1 mm diameter, and are longitudinal, i.e. parallel to module axis and nearly parallel to the incoming particles trajectory. The light signal collected by each fibre bundle is seen, via a square-shaped light guide, by a photomultiplier tube (PMT) XP1911 and the PMT signal

sent to an ADC LeCroy FERA 4300. Each of six central modules is divided in four read-out channels to further improve the reconstruction of the photons impact point.

The calorimeter response is monitored by means of a system including both light emitting diodes and an Am^{241} source.

The whole detector (absorber + calorimeter) has been calibrated on the CERN-SPS test beams X5 and X7, with electrons of energy ranging from 5 to 50 GeV.

The calorimeter is installed in LEP tunnel on a movable and remote controlled platform, in order to allow for a vertical scan of the detected "beam" of photons.

Some problems are caused by the large distance between the detector (in the LEP tunnel, beyond the arc) and the LEP-5 counting room (in SU-15, i.e. near the interaction point 1): some electromagnetic noise affects the signals travelling from the PMTs to the ADCs along the 420 m long cables connecting the detector to the electronics (see Sect.5). Further details on the experimental apparatus and its performances will be given in Ref.9.

The ADC channels are read-out via CAMAC by a MICROVAX 3300. Thus the acquisition rate is limited to less than 10^2 Hz, so that only a small fraction of beam crossing events is collected by our present system [10]. Nevertheless this rate is much higher than in the conventional luminometers at LEP.

4.- DATA ANALYSIS AND RESULTS

Data taking has been performed at IP-1 of LEP in 1990, both in separate beams and in crossing beams conditions.

In a LEP beam fill (usually 10÷12 hours time) the regime of running in IP-1 is normally with separate beams. Beam crossing was set-up in IP-1 for this experiment when the sum of the two beam currents was as low as ~ 1.7 mA, corresponding to the last 1÷4 hours time of a fill.

The single beam radiation (i.e. beam gas bremsstrahlung plus Compton scattered thermal photons) background is measured in the first part of a run, while the whole photon spectrum (beam-beam + single beam radiation) is measured in the last hours of run.

In the following we discuss, as an example, the results obtained during the LEP fill 409 (August 1990) at 46.1 GeV.

Fig.5 shows the energy detected by the calorimeter per ADC gate time as a function of positrons current in separate beams regime. A parabolic fit is in good agreement with the data, as expected, since

the residual gas pressure in the vacuum pipe is also proportional to the current so that the single beam radiation has a dependence like a $I^2 + b I$.

The data plot of the energy per gate deposited in the calorimeter versus the o'clock running time is shown in Fig.6. In the first part (no beam crossing) the typical behaviour due to the decreasing of the single beam radiation is shown ; the energy jump, just after the crossing was established, shows very clearly the additional contribution of the beam-beam bremsstrahlung. The last three points were taken soon after the beam separation and are again due only to the single beam radiation. It can be seen that the energy jump is of the same order as the background level produced by the single beam radiation.

It is then possible to subtract this background contribution E_{bckg} from the total energy measured E_{meas} in order to evaluate the first term of eq (1). We obtain: $E_{meas} - E_{bckg} \sim 4 \text{ GeV/gate}$, and $R = E_{bckg}/E_{meas} = 0.5$. Concerning the ratio R , notice that the low beta focusing system is not operating in IP-1, but only in IP-even where the main experiments are installed. Also the residual gas pressure in these intersections is lower than in IP-1 hence if our monitor were installed in one of the experimental IP even, one should expect R to be of the order of few percent.

In order to determine the absolute luminosity value L the acceptance A of our monitor must be evaluated. As explained in Sect.2 and Appendix, this can be accomplished by measuring the space distribution of the energy deposited in the calorimeter modules. In Fig.7 this distribution is shown in a 3-dimensional plot.

Assuming a gaussian distribution, we can deduce through a fitting procedure the width value σ_D , and the coordinates x_c , y_c of the gaussian center. Then the acceptance A and finally the luminosity value L can be obtained as explained in Sect.2.

In Fig.8 the coordinates of the gaussian maximum x_c and y_c relative to the window centre, are given versus time. The same in Fig.9 for σ_D . Finally in Fig.10a the luminosity values are shown, while in Fig.10b the specific luminosity L_{sp} values are plotted versus time.

Here we define $L_{sp} = L / \sum_{i=1,4} I_i^+ I_i^-$, where the sum is extended to the 4 bunches, and $I_i^+ I_i^-$ is the product of the e^+ and e^- currents corresponding to the i -th bunch pair. The raise of L between 16:00 and 16:30 o'clock corresponds to the beam crossing setting-up in IP-1. During this fill, a special scanning was performed in IP-6 (the so called 'beta waist scanning'), in order to maximize the luminosity. Its

effect in IP-1 is just the variations of the L_{sp} value shown in the Fig.10b, and it agrees with the general change of L as measured by the Bhabha scattering luminometers in the IP-even [11].

Each point has a statistical error of 1% corresponding to 2×10^4 events which were collected in about 10 min, because the read-out system utilized had an acquisition time of the order of 10 msec. With the faster read-out system in preparation [10], the same statistical error will be reached in few seconds of collection time.

The error bars shown in the plots include systematic contributions as explained in the following.

5.- DISCUSSION ON THE SYSTEMATIC ERRORS.

The main sources of systematic errors are the following. First an electromagnetic noise is induced in the LEP tunnel on the 420 m long cables, connecting the monitor to the counting room. The noise can be measured and subtracted, but its fluctuation contributes to the error by a 2 % in IP-1, while in a low beta IP-even it would be negligible, due to the higher luminosity value.

Two other contributions come from the evaluation of the acceptance A and from the knowledge of the cross section value Σ .

The acceptance error is a function of the accuracy in the determination of the photon distribution width, σ_D , and on the maximum position coordinates x_C and y_C . These accuracies turn out to be dependent on the error in the determination of the relative values of the monitor calibration constants and on the induced e.m. noise fluctuation, quoted above. In this fill we obtained $\Delta\sigma_D/\sigma_D \sim \Delta A/A = 1.5 \%$, after averaging σ_D and A values over the four hours of beam-crossing.

Finally the error in the evaluation of the cross section value to be adopted in our measurements, has three components. The first one is the theoretical uncertainty, due to the unknown higher order corrections, which can be estimated to be $\leq 1\%$. The second one is connected with the transverse bunch dimensions, giving lower cuts to the momentum transfer, and so reducing the cross section value. Therefore its error depends on the accuracy on the knowledge of the bunch dimensions (see Fig.4). The third one is due to the uncertainty in the lower energy threshold in the bremsstrahlung spectrum (see Fig.3). Each of these contributions is of the order of 1 %; therefore $\Delta\Sigma/\Sigma \sim 1.7 \%$, and the overall systematic error on luminosity,

including single beam radiation subtraction, is in the range $3.1\% < \Delta L/L < 4.6\%$ (depending on the absolute luminosity value).

6.- CONCLUSIONS

A new luminometer based on the single bremsstrahlung process has been tested in the IP-1 of LEP. We have shown that this monitor is able to collect 2×10^4 events in 10 min with the present read-out system. This collection time will be reduced down to few seconds by using a fast processor, expected to be ready for the next LEP run. Due to his fast response this monitor, if installed in one or more IP-even, could contribute in a unique way to optimize both the LEP collider and the physics performance.

At present the systematic error is less than 5%. If the monitor were to be installed in an IP-even (experimental straight sections) the systematic error could be reduced down to 2 % .

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APPENDIX

The window acceptance A is depending on the value of the beam divergence and of the beam tilt. Divergence and tilt are respectively described by the r.m.s. widths σ_{Dx} and σ_{Dy} and by the central values x_c and y_c of the angular bi-gaussian distribution of the primary photons.

In the multi-photon regime, σ_{Dx} , σ_{Dy} , x_c and y_c can be measured by fitting the experimental distribution of the energy deposited in the calorimeter modules with the function

$$I(x,y) = \int_0^{E_b} dk \int_{-x_w}^{x_w} dx' \int_{-y_w}^{y_w} dy' k \varepsilon(k) \frac{d\Sigma}{dk} G(x', y', \sigma_{Dx}, \sigma_{Dy}, x_c, y_c) M(x'-x, y'-y, k)$$

obtained by folding the angular distribution G of the primary photons and the transverse spatial distribution M of the shower; x_w and y_w are defined by the horizontal and vertical dimension of the window; E_b is the beam energy. In this function σ_{Dx} , σ_{Dy} , x_c and y_c are free parameters. Since in normal conditions of the machine $\sigma_{Dx} = \sigma_{Dy}$, only one divergence σ_D can be used as free parameter in the fitting procedure. A sum of two gaussian distributions has been used as parametrization of the transverse structure M of the shower [12]. By application of a fitting procedure on GEANT simulated showers, this parametrization is found to hold in the energy range 1-50 GeV.

REFERENCES

- 1 - G. Diambrini-Palazzi, contribution presented at the Workshop on Polarization at LEP, CERN 9-11 November 1987. G. De Zorzi and G. Diambrini Palazzi, Letter of intent LEPC 88-7/I 8, and subsequent Addenda: C. Bini et al., CERN/LEPC 89-5 (22-2-89) and CERN/LEPC 89-12 (1-6-89). See also: M. Chen, G. Coignet, G. De Zorzi, G. Diambrini Palazzi and A. Di Domenico, CERN 88-06 Vol. 2, p. 89.
- 2 - H.C. Dehne, M.A. Preger, S. Tazzari and G. Vignola, Nucl. Instr. and Meth. 116 (1974) 345.
- 3 - A.E. Blinov et al., Nucl. Instr. and Meth. A273 (1988) 31, and references therein.

- 4 - See e.g. : ZEUS Collaboration, Technical Proposal; DESY Int. Rep. (March 1986).
- 5 - C. Bini et al., Measurement of the Compton scattered thermal photons by a 45 GeV positron beam at LEP, (1991) to be published. B. Dehning et al. Phys. Lett. B 249 (1990) 145.
- 6 - C. Fischer and G. von Holtey, LEP Note 618 (14-2-1989).
- 7 - A. Di Domenico, Thesis, Universita' di Roma "La Sapienza" (1990), unpublished.
- 8 - Optectron, Z.A. Courtaboeuf, B.P 535, Av. du Quebec, F-91946 Les Ulis, France.
- 9 - C. Bini et al., in preparation.
- 10 - A fast processor will be installed in the next future. Its design and realization is due to D. De Pedis, who has joined our experiment in a later stage. See: C.Bini et al., CERN/LEPC 89-12 (1-6-89).
- 11 - G. von Holtey, private communication.
- 12 - G. Abshire et al. ,Nucl. Instr. and Meth. 164 (1979) 67.
- 13 - M. Caffo, R. Gatto, E. Remiddi and F. Semeria, Nucl. Phys.B32(1989)93.

FIGURE CAPTIONS

- 1 - A sketch of LEP half straight section from IP-1 to SB photons detector. Notice that photons go out of LEP vacuum pipe at about 300 m from IP-1.
- 2 - Distribution of SB photons emitted around zero degree due to a beam divergence of $55 \mu\text{rad}$ in IP-1. ϕ is the angle between the photon and the beam axis. Acceptances are shown separately for the horizontal ($-x_w, x_w$) and the vertical ($-y_w, y_w$) direction, and correspond to a window of 5 cm (horizontal) x 2 cm (vertical). The much narrower SB emission angular spread at 10, 20 and 45 GeV is also shown.

- 3 - Integral value I_V of Eq.1, from a threshold energy E_t as a function of E_t , for $E_{\text{beam}}=50$ GeV.
- 4 - Dependence of the integral value I_V of Eq.(1) on the transverse size of beam σ_y (dependence on σ_x is negligible).
- 5 - Energy E deposited in the calorimeter, during a gate-time of 1 μsec , as a function of the positrons current I^+ in LEP fill 409. Data are collected in "separate beams" condition.
- 6 - Energy E deposited in the calorimeter as a function of o'clock running time T of LEP (Fill 409, August 1990).
- 7 - A "lego plot" showing an example of the spatial distribution of the energy deposited in the 24 central channels of the e.m. calorimeter.
- 8 - Central value x_c (a) and y_c (b) of the spatial distribution of energy detected by the e.m. calorimeter as a function of o'clock running time T .
- 9 - Beam angular divergence σ_D in IP-1 as a function of o'clock running time T (Fill 409, August 1990).
- 10 -(a) Luminosity L and (b) specific luminosity L_{sp} in IP-1 of LEP as a function of o'clock running time T (Fill 409, August 1990).

1. The first part of the diagram shows a series of vertical bars representing a sequence of events or data points. The bars are labeled from QL1 to QL13, with a '7-beam' label at the top and a '7-detector' label at the bottom. The bars are arranged in a way that suggests a progression from left to right.

- Figure 1 -

- Figure 2 -

- Figure 3 -

- Figure 4 -

I^+ (mA)

- Figure 5 -

T (hours)

- Figure 6 -

- Figure 7 -

$T \text{ (hours)}$

- Figure 8a -

- Figure 8b -

T (hours)

- Figure 9 -

- Figure 10a -

- Figure 10b -