# The DAΦNE Luminosity Monitor

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**Abstract.** DAΦNE, the Frascati Φ-factory, is an $e^+/e^-$ collider with 2 interaction points (IPs). The center of mass energy is 1020 MeV and the design luminosity $4.2 \times 10^{30}$ $cm^{-2}$ $s^{-1}$ in single bunch mode and $5 \times 10^{32}$ $cm^{-2}$ $s^{-1}$ in multibunch mode. Between the possible electromagnetic reactions at the interaction point, single bremsstrahlung (SB) has been selected for the luminosity measurement. The SB high counting rate allows real-time monitoring, which is very useful during machine tune-up and moreover the narrow peak of the SB angular distribution makes the counting rate almost independent from the beam position at the IP. A description of the experimental set-up, calibration results and luminosity measurements is presented.

## INTRODUCTION

DAΦNE, the Φ-factory under commissioning at Frascati (1), is an $e^+/e^-$ collider with the center of mass energy tuned to 1020 MeV for the production of Φ mesons. Two interaction regions allow two simultaneous experiments. One of these in particular, the detector KLOE (2), will start data acquisition at the end of this summer and will investigate the CP violation in the $K_0$ meson decay. High luminosity is needed to measure this rare event with good accuracy. DAΦNE has been designed to obtain a maximum luminosity of $5 \times 10^{32}$ $cm^{-2}$ $s^{-1}$. The design strategy used to achieve this performance is to store up to 5 A in 120 bunches in each ring. This multibunch, high-current approach allows one to maintain the single bunch luminosity value to $4.2 \times 10^{30}$ $cm^{-2}$ $s^{-1}$, permitting a relaxation of the requirements on related machine parameters. At the present time, the single-bunch luminosity commissioning is nearing completion.

Several luminosity measurement methods are possible in lepton colliders. Most of them use electromagnetic reactions at the interaction points (IPs) with well known theoretical cross sections. The most commonly used are:

Single bremsstrahlung (SB) (3):

$$e^+ + e^- \rightarrow e^+ + e^- + \gamma \tag{1}$$

Double bremsstrahlung (DB) (4):

$$e^+ + e^- \rightarrow e^+ + e^- + 2\gamma \tag{2}$$

Small-angle Bhabha scattering (SAS):

$$e^+ + e^- \rightarrow e^+ + e^- \tag{3}$$

Reaction (1) can be monitored by measuring the number of $\gamma$ photons emitted in the direction of one of the colliding beams. The counting rate is typically very high, allowing one to perform 'on-line' luminosity measurements. Moreover, the very sharp SB angular distribution significantly simplifies the geometry of the monitor at the interaction region and makes the measurement weakly dependent on the position and angle of the two beams at the IP. On the other hand, the measurement must be carefully extracted from the background, which is mainly due to gas bremsstrahlung (GB), the interaction of the stored beam particles with the residual gas molecules. The GB counting rate depends linearly on the distance between the IP and the $\gamma$ detector; for this reason the SB method is not used for large high-energy machines with very long interaction regions.

In reaction (2), two $\gamma$ photons are emitted simultaneously, one in the direction of the $e^-$ beam and the other in the direction of the $e^+$. The counting rate is much smaller than in the SB case and the angular distribution is broader. From the background point of view, GB contribution can be easily removed by measuring coincidence in the $\gamma$ detectors. Accidental counts of simultaneous emission of two SB or GB photons must be removed on a statistical basis by the delayed-coincidence technique.

In reaction (3), the background subtraction can be performed in a very efficient way, but the counting rate is the lowest and the dependence of the cross section on scattering angle is strong.

For the DAΦNE luminosity monitor the SB technique has been selected but the system layout also permits the possibility of DB luminosity measurements (5). Complete information on the SB luminosity measurement technique can be found in Ref. (6); in the final part of this introduction only the relevant features of the method are described.

The SB $\gamma$ photons are collected by a proportional counter situated near the IP. The integral of the signal coming from this detector is proportional to the energy of the $\gamma$ photon. An energy analysis and counting system (Figure 1), counts and makes the energy spectrum of all the signals having an amplitude greater than a tunable threshold, fixed by a discriminator. The typical system also allows coincidence measurements with a selected rf bucket, very helpful for background subtraction, as explained later, and anticoincidence measurements of counts generated by charged particles on a scintillator plate placed in front of the proportional counter. This last feature allows one to filter undesired counts due to lost beam particles, pairs produced by the electromagnetic showers generated by $\gamma$, beam particles hitting the vacuum chamber, etc.

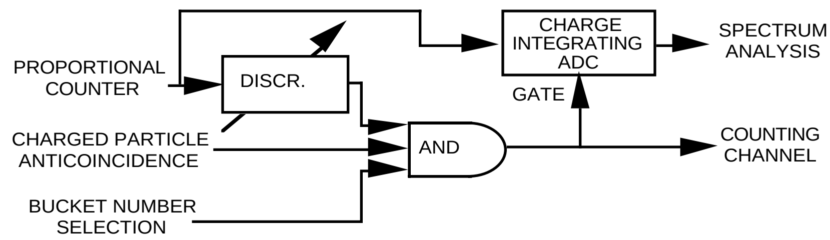


**FIGURE 1.** SB Measurement Typical Diagram.

The $\gamma$ counting rate includes both SB and background photons. After background subtraction, as explained later, the SB counting rate $N_{SB}$ can be obtained and used for calculating the luminosity value:

$$L = \dot{N}_{SB} \Big/ \int_{E_T}^{E_{MAX}} dE \int_{\Omega_T} d\Omega \frac{\partial^2 \sigma_{SB}}{\partial E \partial \Omega} \tag{4}$$

where $E_{MAX}$ is the maximum energy a $\gamma$ photon can have. (For relativistic particles it is practically half the center-of-mass energy of the beam.) $\sigma_{SB}$ is the SB theoretical cross section, $\Omega_T$ is the solid angle viewed by the detector, as defined by a collimator placed in front of the proportional counter, and $E_T$ is the minimum photon energy accepted by the system. The value of $E_T$ is fixed by the discriminator threshold voltage level. In order to evaluate $E_T$, a calibration procedure is necessary. This is performed by using the GB spectra obtainable by the energy analysis system when only one beam is stored in the machine. The comparison between the well known GB theoretical spectrum shape and the experimental one allows $E_T$ to be evaluated.

# EXPERIMENTAL SETUP

## Interaction Region Layout

DAΦNE is a ~100 m long collider with two independent vacuum chambers. Only at the two interaction regions (IRs) do the beams have a common chamber. Each IR, whose length is about 10 m, has splitter magnets at the extremes where the beams are horizontally separated into the different vacuum chambers. The beams collide at the IP with a horizontal angle tunable from 10 mrad to 15 mrad; standard operations are performed with 12.5 mrad. Figure 2 shows the splitter area and the position of the proportional counter. The layout allows the placement of two detectors in each of the IRs, but at the present time, only the one on the positron beam direction is installed.

The distance of the detector from the IP is ~6 m. At the splitter output, a 1.5 mm thick aluminum window allows the $\gamma$ photons to come out of the vacuum chamber and to enter the detector. Between the thin window and the proportional counter, a 10-radiation-length thick lead collimator with a 10 mm radius circular aperture is used to fix the accepted solid angle within a cone of 1.6 mrad semi-aperture, centered on the crossing angle of 12.5 mrad. By integrating the SB cross section within this solid angle, it has been determined that 70% of the SB $\gamma$ photons are accepted.

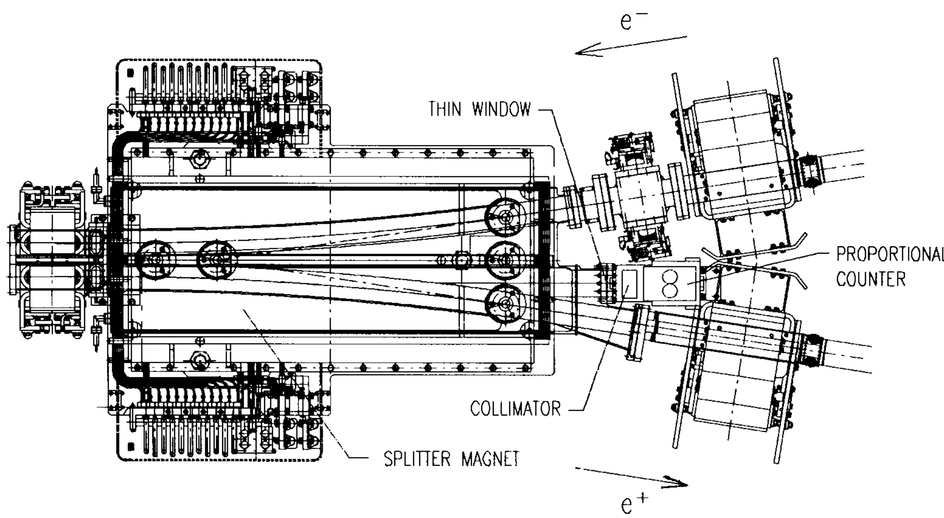


**FIGURE 2.** SB Luminosity Monitor layout at splitter area.

Special care has been used in shielding the monitor photomultipliers from the stray magnetic fields from nearby machine magnets.

## Proportional Counter

The DAΦNE luminosity monitor proportional counter is a very fine-sampling lead-scintillating fiber calorimeter with photomultiplier read-out. The sampling structure is the same as the one used for the KLOE electromagnetic calorimeter (7).

The calorimetric module is built up by gluing 1 mm diameter blue scintillating fibers between thin-grooved lead plates, obtained by passing 0.5 mm thick lead foils through rollers of a proper shape. The grooves in the two sides of the lead are displaced by one half of the pitch so that fibers are located at the corners of adjacent, quasi-equilateral triangles, resulting in optimal uniformity of the final stack. The grooves are just big enough to insure that the lead does not apply direct pressure on the fibers. The blue-green scintillating fibers (Pol.Hi.Tech-46) provide high light yield, short scintillation decay time, and long attenuation length (8). The selected fiber pitch of 1.35 mm results in a structure which has a fiber:lead:glue volume ratio of 48:42:10 and a sampling fraction of ~15% for a minimum ionizing particle. The final composite has a density of ~5g/cm$^3$ and a radiation length of ~1.6 cm. It is self-supporting and can be easily machined. The resulting structure is quasi-homogeneous and has high efficiency for low-energy photons.

This kind of sampling calorimeter has been extensively tested (9) and has an excellent linearity and energy resolution for fully contained e.m. showers induced by photons, given by:

$$\frac{\sigma_E}{E} = \frac{4.4\%}{\sqrt{E_{(GeV)}}} \qquad (5)$$

Each of the luminosity monitor calorimeters has a squared face ($122 \times 122$ mm$^2$) and is 184 mm long, corresponding to a 11.5 radiation length. Fibers are vertically positioned and are read on one side by two plastic light guides, each covering half the width (61 mm), but the whole length. Each light guide is equipped with a 2-inch photomulti-plier tube (EMI 9814B).

## Energy Analysis and Counting System

Each of the IRs has a completely independent energy analysis and counting system (EACS). Figure 3 shows a diagram of this system.

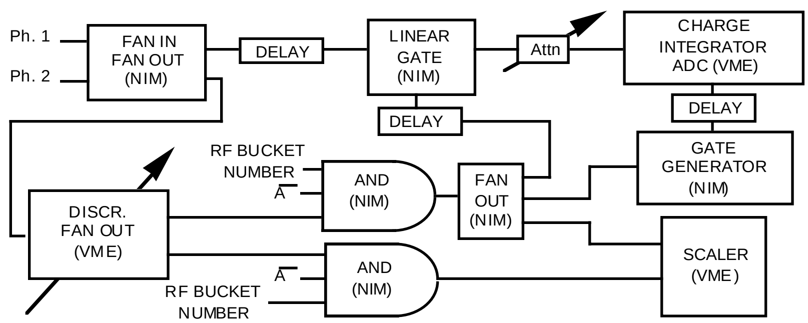


**FIGURE 3.** Energy Analysis and Counting System diagram.

The signals coming from the two proportional counter photomultipliers are summed at the EACS front end and then split into an analog channel for pulse integral analyses and into a logic channel for pulse counting and for shaping the system gates.

The charge integrating ADC needs a relatively long gate pulse, 120 ns FWHM. Most of the gate duration is needed for setting up the electronics. With such a gate, the rate of accidental counts gives a non-negligible contribution to the error in the energy spectrum acquisition. The 20 ns window of the linear gate upstream the ADC reduces this effect by a factor of six.

The EACS front end dynamic range accepts photomultiplier pulses with voltages down to –2.5 V, without saturating. The attenuator downstream of the linear gate permits matching the dynamic range of the ADC to this signal range. Figure 4 shows a linearity measurement of the EACS.

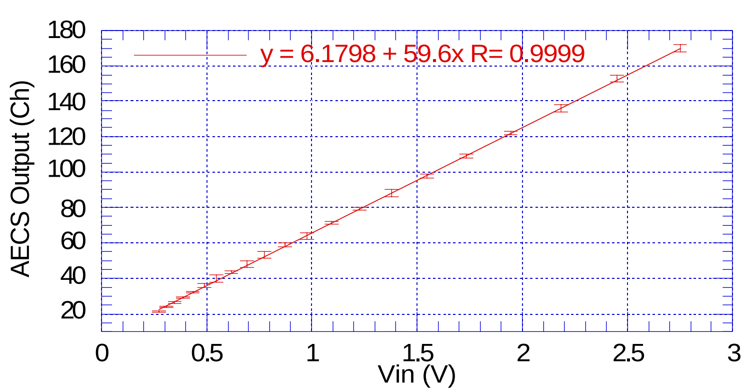


**FIGURE 4.** Energy Analysis System linearity.

The logic channel allows coincidence measurements with two different rf buckets, a feature used in one of the background subtraction schemes. The photomultiplier output pulse length at the pedestal is about 17 ns. In order to permit complete integration of the pulse, the linear gate ENABLE signal has been set with a duration of 20 ns FWHM. The distance between two contiguous buckets is 2.7 ns. This means that in measuring the coincidence with two different rf buckets, special attention must be paid to selecting and filling the two buckets at least 20 ns distant from each other.

The luminosity measurement in the multibunch mode must be performed without any coincidence with the rf. The 20 ns photomultiplier pulse length limits the counting system bandwidth to 50 MHz. At the maximum luminosity, $5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$, the expected SB counting rate, with a threshold set to 0.7 times the beam energy, is 4 MHz, while the background rate is one order of magnitude lower. In this situation an underestimation of the counting rate of about 8% is expected. In order to improve this figure, photomultipliers with shorter output pulses must be used.

The two EACS are fully integrated in the DAΦNE control system. The components in Figure 3 labeled with “VME” are remotely controlled. The HV power supplies for the proportional counter photomultipliers are programmable VME boards. It is therefore possible to switch off one of the photomultipliers and perform the energy analysis of the signals coming from the other under computer control.

## Background Subtraction Schemes

In the DAΦNE luminosity monitor, two background subtraction methods can be used: single counting channel pedestal subtraction (SCPS) and missing bunch background subtraction (MBBS).

The former uses a single counting channel of the EACS for getting the different counting rates when the two beams at the IP are in collision or separated. First the beams are separated and the background counting rate is recorded; then the rate with the beams again in collision is measured. The difference between these two values gives the SB counting rate that, when divided by the SB integrated cross section, gives the luminosity value. The DAΦNE IR has a low vertical beta configuration; the dimensions of the beam at the IP, at 1% coupling, are 20 μm rms and 2 mm rms in the vertical and horizontal planes respectively. This geometry makes the horizontal separation of the two beams impractical and longitudinal separation usable only with very low stored-current values. On the contrary, in the vertical plane, where bumps as high as ten sigmas can be obtained, the separation of the beams at the IP can be performed efficiently. Because of the finite lifetime of the beams, the background level must be periodically measured in order to maintain errors within an acceptable range. The SCPS method also allows luminosity measurements in the multibunch mode.

The MBBS method uses the following configuration. A single bunch is injected and stored into the electron beam. Two bunches are injected into the positron ring, one in the bucket colliding with the stored electron bunch and the other, usually with a smaller current, in a bucket not in collision. Assuming that the residual gas pressure does not change between the passage of the two positron beams and assuming that the background is due to the GB contribution only, it is possible to write:

$$\dot{N}_C = \dot{N}_{SB} + a_{GB} I_C^+ \qquad (6)$$

$$\dot{N}_{NC} = a_{GB} I_{NC}^+ \qquad (7)$$

where $\dot{N}_C$ and $\dot{N}_{NC}$ are the counting rates relative to the colliding and noncolliding bunches respectively, $\dot{N}_{SB}$ is the counting rate due to SB photons, $a_{GB}$ is the GB coefficient and $I_C^+$ and $I_{NC}^+$ are the currents of the colliding and noncolliding positron bunches. It is straightforward to derive from expressions (6) and (7) the relation:

$$\dot{N}_{SB} = \dot{N}_C - \frac{I_C^+}{I_{NC}^+}\dot{N}_{NC} \tag{8}$$

By using formula (8) and knowing the current ratio of the positron bunches, it is possible to measure the SB counting rate independently of other machine parameters. Special attention must be paid in checking that the background contribution is being dominated by the GB term. For example, if the lifetime of one of the beams is short, then the e.m. showers generated by the beam particles hitting the vacuum chamber will give a significant contribution to the background. In this situation, formula (8) cannot be applied. The MBBS method does not allows luminosity measurements in the multibunch mode.

## EXPERIMENTAL RESULTS

### Gas Bremsstrahlung Threshold Calibration

The complete description of this threshold calibration method can be found in Reference (6). The principle is to analyze a measured GB spectrum by using results of the well known related theory. By multiplying the value of the spectrum at a channel by the channel number and repeating this operation for all the channels, the $1/x$ dependence of the spectrum can be removed (see an example in Fig. 5). In this modified spectrum, some properties are enhanced. First of all, for a relativistic beam, the maximum energy that a GB photon can have is practically the energy of the stored beam. The sharpness of this high energy limit of the GB spectrum is mitigated by the calorimeter resolution. In the modified version of the spectrum, the channel relative to this limit can be analytically derived. The knowledge of this channel and of the one related to zero energy, derivable from the linear fit of the energy analysis system response (see Figure 4), allows one to calibrate the value $E_T$ of the low-energy threshold fixed by the discriminator. In the case of Figure 5, the high energy limit is 510 MeV at channel 142, the zero channel is 6, and $E_T$ is 94 MeV at channel 25. The spectrum includes 1.5 Msamples.

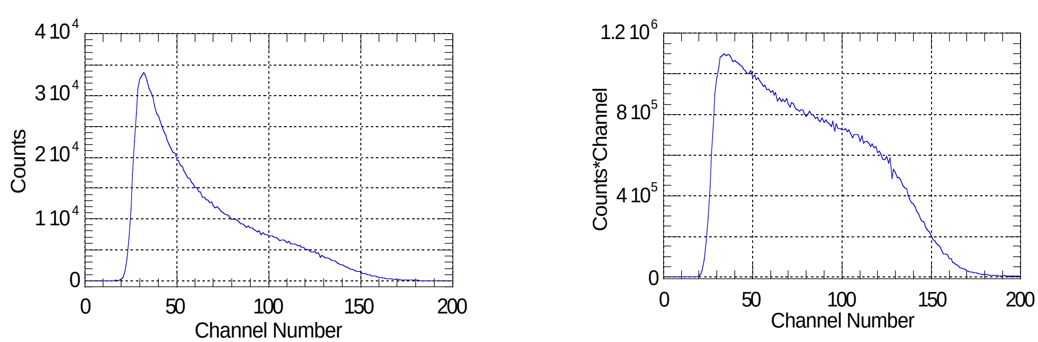


**FIGURE 5.** Gas bremsstrahlung measured spectra: raw and modified.

The rms resolution of the EACS is 1-2 channels out of 256. The resolution of the proportional counter at 510 MeV is about 6%; that corresponds, in the case of Figure 5, to about 8.2 channels. Thus in this case the global rms resolution of the monitor is about 8.4 channels and it is dominated by the calorimeter term. The total width of the spectrum is about 150 channels; assuming for a rough estimate a standard deviation of the GB modified spectrum of about 37.5 channels (150/4), then the contribution to the error in the threshold calibration can be estimated to be about 2.5%. In the measurement of the Figure 5, the energy 'width' of a channel is 3.75 MeV. This generates an additional indeterminacy on the threshold value of about 2%. Special care must be also taken in the determination of the zero energy channel. In the case of Figure 4 an error of 0.5 channels generates an indeterminacy of 2% on the threshold. The statistical error on the single channel counts must be kept lower than 1% so that the indeterminacy of the high-energy limit channel is negligible. This requires an average sampling per channel of at least $10^4$ samples. The sampling rate of the EACS in the 256 channels scale is 1.1 kHz, permitting the acquisition of a 2 Msamples spectrum in half an hour. By summing all the contributions a total indeterminacy of ±6.5% of the threshold is obtained, generating an indeterminacy of ±5% on the SB integrated cross section and thus on the luminosity.

The above indeterminacy estimate has been done assuming that the gains of both the calorimeter photomultipliers are identical. The gain-equalizing procedure consists of measuring the GB spectrum of the individual tube and in regulating the gain in order to obtain the same high-energy threshold channel in both the photomultipliers. A bad equalization degrades the calorimeter resolution.

## Luminosity Measurements

In Figure 6, a set of luminosity measurements performed with the SCPS method are shown. The typical accuracy is ±15%, with a 10% contribution coming from the threshold calibration due to the fact that the calorimeter photomultipliers were not well equalized. Other contributions are background evaluation (4%) and statistical fluctuations and accidental counts (1%). The measurements in Figure 6 were performed with different values of the positron beam coupling.

At the present time, luminosity measurements with the MBBS method are affected by larger errors. The main reason is that the necessary real-time measurement of the positron bunch current ratio has not yet been implemented.

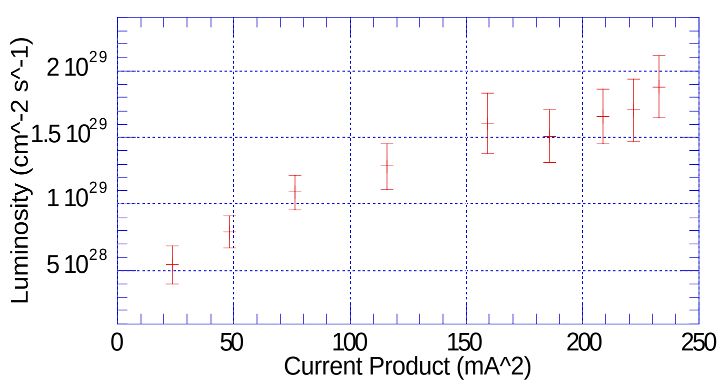


**FIGURE 6.** Example of luminosity measurements on DAΦNE.

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