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(Submitted to "Lettere al Nuovo Cimento" for publication).

Two beam operation has recently been successfully achieved at Adone, the 1.5 GeV electron positron storage ring of the Laboratori Nazionali di Frascati del CNEN(1, 2, 3); the first results, which are in good agreement with the design aim, are reported here.

Measurements of the luminosity (defined as the interaction rate in a crossing region for an event having unitary cross section) have been performed observing the interaction rate of events with known cross section (e^+e^- single bremsstrahlung and e^+e^- scattering at small angles); the luminosity has also been computed from beam currents and transverse dimensions.

A luminosity of $(3.4 \pm 0.4) \times 10^{32}$ cm^{-2} hr^{-1} has been measured at 1.1 GeV, with 40 mA of positrons and 23 mA of electrons, in head-on collision; this has to be compared with the design value of 7.3×10^{32} cm^{-2} hr^{-1}, at the same energy, with two beams of 100 mA each crossing at an angle.

(x) - Now at the Laboratorio dei Gas Ionizzati del CNEN, Frascati.

We expect that operation of the storage ring at higher luminosity will be achieved within the next few months, when the two beam orbit separation, which leads to the crossing at an angle, will be available; it is to be noted that, when the beam can be made to cross at an angle, adjustable according to the circulating currents, the luminosity is proportional to the current of the weaker beam; the results so far achieved show, therefore, that with 100 mA beams we should obtain a luminosity somewhat higher than the design value.

In the following, after a brief account of the studies on the single beam behaviour, the present operation characteristics and the luminosity measurements are discussed.

1. - SINGLE BEAM BEHAVIOUR. -

The first electron beam was stored in ADONE in December 1967; parts of the ring still missing at that time have been installed during 1968, and the machine was completed in its present form by mid-1968.

The experimental study of the single beam instabilities has taken the major part of the ring operation until the beginning of 1969; the interpretation of the phenomena has allowed the development of suitable means of suppressing the instabilities.

The multiple bunch coherent phase oscillations have been cured separating the synchrotron oscillation frequency of the bunches by means of a low power radio frequency cavity operating on a harmonic of the revolution frequency, but not of the main radiofrequency system(4).

Transverse betatron instabilities with very low current threshold (about 200 μA per bunch at the injection energy, 300 MeV) were observed with a positron beam, or with an electron beam when the positive ions were swept out using transverse electric fields; these thresholds were much lower than expected on the basis of the current theories, and the dependence on the machine parameters indicated that the dynamics was not that of the resistive wall instability. It has been interpreted as being due to an interaction between the beam and rapidly decaying electromagnetic fields with frequencies extending in the GHz range induced by the beam in its environment(5); the theory has been found correct. All the elements in the vacuum chamber should therefore have been suitably terminated for frequencies in the GHz range, in order to reduce the forces acting on the beam, and increase the rise time of the instability, while previous theories on beam instabilities were concerned with frequencies in the 10 MHz range and the machine was built accordingly.

After removal of the electrodes, that were installed to obtain the crossing angle at the interaction region and to sweep the positive ions out of the electron beam, the threshold current at injection energy increased by an order of magnitude; at higher energies, 1 GeV or more, the threshold did not increase by the same amount, and is of about $5 \div 10$ mA/bunch. New electrodes that will allow to obtain separated beam orbits and the crossing angle without introducing strong antidamping terms, are now being prepared.

At the same time a fast feedback system has been successfully tested: the transverse displacement signal of a bunch is detected, amplified and fed back on the same bunch, preventing the onset of the instability. Technical difficulties have up to now prevented the installation of the fast feedback in its final form.

Stable currents higher than the threshold are obtained by increasing the beam transverse dimensions, and consequently the betatron frequency spread and the Landau damping; currents higher than 100 mA can easily be stored.

The enlargement is obtained by applying a transverse sinusoidal electric field, whose frequency is periodically swept over a range wide enough to excite all the particles in the beam, the sweeping period being short as compared to the radiation damping time constant. The same system is used in two beam operation to keep the transverse beam density below the incoherent space charge limit at injection and during acceleration.

2. - PRESENT STATUS OF THE RING. -

As a consequence of the work on single beam instabilities the ring operation is not yet, in some aspect, that foreseen.

The maximum beam energy is temporarily limited to about $1.2 \div 1.3$ GeV, as one of the two radiofrequency cavities has not yet been installed; the beam crossing is only head-on, and, as a consequence, the interaction region has a longitudinal r.m.s. dimension of 25 cm, at 1 GeV; the overall pumping speed of the vacuum system has been reduced by about a factor of two and will be brought back to the original value the first time that the system will be let down to air: the residual gas pressure is correspondigly higher.

The positron injection rate is satisfactory: to achieve the desired flexibility in the ring operation, the linac beam is usually modulated at the revolution frequency and the injection is made on one bunch at a time; in this condition positron injection rates of 10 mA/minute.

per bunch at 300 MeV are obtained, and a rate of 5 mA/minute per bunch is usual.

The static vacuum after the vacuum chamber bake-out is everywhere in the 10^{-10} torr range, with minima of 2×10^{-10} torr; the pressure rise caused by synchrotron radiation is, at 1 GeV, about 10^{-10} torr/mA. The beam lifetime at 1 GeV (3 to 5 hours depending on beam intensity) is in fairly good agreement with the measured pressure and gas composition, assuming that the loss process is bremsstrahlung on the residual gas. When the pumping speed of the vacuum system will be restored to the original value, the beam lifetime is expected to improve by at least a factor of two; continuous operation tends to decrease the outgassing rate due to synchrotron radiation, with a consequent improvement of the lifetime.

The two beam operation proceeds, at present, as follows: the positron beam is stored at 300 MeV and kept enlarged with the sweeping oscillator; the electron beam is then injected at the same energy; at the end of the injection the energy of the two beams is raised to the desired value, increasing at the same time the amplitude of the sweeping oscillator excitation to keep the beam density below the beam-beam incoherent interaction limit; at the final energy, where the oscillator is not effective as a beam dimension control, use is made of a linear coupling resonance (equal betatron wave numbers for radial and vertical oscillation modes) to keep the beam density at the limit for optimum luminosity.

The time required to store two beams of about 30 mA each, injecting one bunch at a time, and to raise their energy to 1 GeV is about 15 minutes; injection on three bunches at the same time, beam orbit separation during injection and a more complete automatization of the injection procedure will certainly allow a reduction of this time, which nevertheless is already within the foreseen limits.

3. - LUMINOSITY MEASUREMENTS. -

Luminosity was measured by independent observation of two different reactions:

single beam-beam bremsstrahlung

1) $e^+ + e^- \rightarrow e^+ + e^- + \gamma$

and small angle elastic scattering

2) $e^+ + e^- \rightarrow e^+ + e^-$

The first method was conceived as a machine control monitor(6); due to our present vacuum it only works with one bunch out of three in one beam and two out three in the other since a simple background subtraction procedure is then available as discussed below.

The second method was designed as a precise monitor by the group who will investigate the $e^+e^- \to \mu^+\mu^-$ process(7). The counting rate is much lower than for reaction (1), but,because of the coincidence method used(8), it is virtually unaffected by beam interactions with the residual gas: measurements can therefore be performed with any number of bunches. The measurements have been mostly carried out by G. Barbiellini, A. Nicoletti, M. Preger, R. Santonico(9); we refer to the μ-pair group for the discussion of the results quoted here.

The main background to reaction (1) is due to single bremsstrahlung on the residual gas. In our present situation the signal to background ratio is of the order of 10%. The background subtraction procedure therefore requires special care and a brief discussion of our method is given.

The experimental layout is sketched in Fig. 1. Two cylindrical lead glass Čerenkov counters ($\check{C}_1, \check{C}_2$) shielded by two anticoincidence scintillator counters (S_1, S_2) are positioned at two contiguous interaction straight sections. Thin steel windows are provided in the vacuum chamber, on the γ-ray beam path. Both counters face the same beam (either e^+ or e^-).

A pulse, synchronous with the RF, defines the time interval during which one bunch goes through the interaction section of interest. Calling this pulse RF a γ-ray event is defined by $\check{C} \cdot RF \cdot \bar{S}$.

Amplitude discrimination on the $\check{C}$ pulse provides the energy threshold. The logic of the experiment allows for separately counting events due to different bunches.

Let us assume one has two bunches containing N_1^- and N_2^- electrons respectively in the e^- beam, and one positron bunch, N^+, in the e^+ beam. Also assume the counters are facing the e^- beam. By suitable choice of the injected bunches the following counting rates in straight sections 1 and 2 are obtained:

$$\dot{n}_1^{(1)} = G^{(1)} N_1^- + BL(N_1^-, N^+) \qquad \dot{n}_1^{(2)} = G^{(2)} N_1^-$$

$$\dot{n}_2^{(1)} = G^{(1)} N_2^- \qquad \dot{n}_2^{(2)} = G^{(2)} N_2^-$$

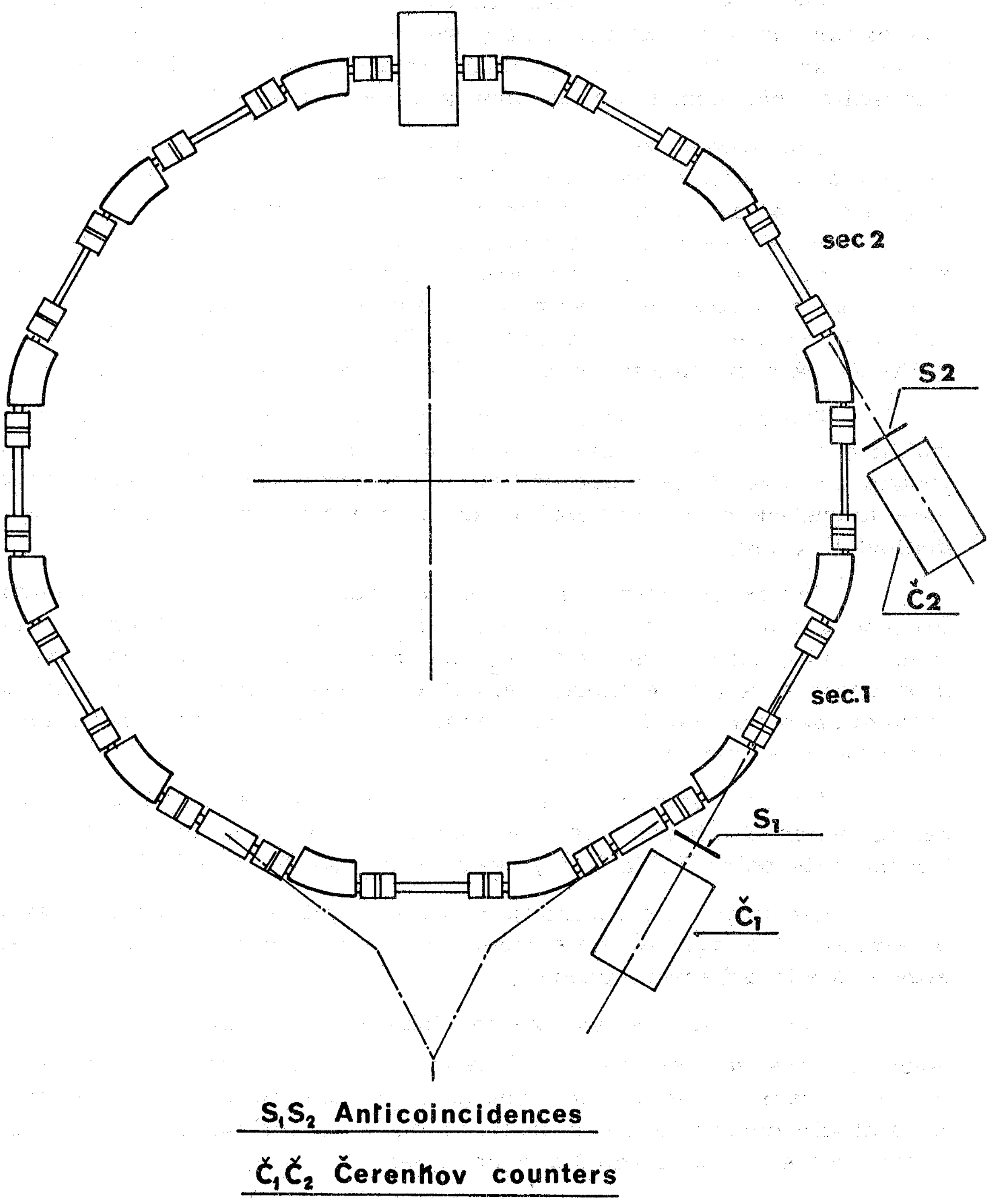

FIG. 1 - Experimental apparatus for single bremsstrahlung detection.

By $n_i^{(j)}$ we indicate the counting rate in section j, due to bunch i. The terms proportional to $G^{(1)}$ and $G^{(2)}$ describe the background, and are essentially due to gas bremsstrahlung. The coefficient B is proportional to the cross section of reaction (1), and $L(N_1^-, N^+)$ is the luminosity produced by the crossing of N_1^- and N^+.

The one to one bunch luminosity is then given by

$$L(N_1^-, N^+) = \left[\dot{n}_1^{(1)} - \dot{n}_2^{(1)} \frac{\dot{n}_1^{(2)}}{\dot{n}_2^{(2)}} \right] \frac{1}{B}$$

Different procedures could of course be adopted. The choice of this particular setup was essentially determined by the present location of our thin windows.

The assumption made is that G is the same for all bunches present in each straight section. The errors on relative luminosity measurements are then only due to statistics or to the performance of the electronics. The absolute value of L is also affected by the errors on B and on the corrections made.

The performance of the apparatus can be checked by working with one beam only. At 1000 MeV, over a period of several days, with thresholds varying between $\mathcal{E} = .5$ and $\mathcal{E} = .85$, where $\mathcal{E}$ is the ratio of Čerenkov threshold energy to maximum energy, the ratios $n_1^{(1)}/n_2^{(1)}$ and $n_1^{(2)}/n_2^{(2)}$ were identical to within, at most, $\pm\, 5 \cdot 10^{-3}$. With a signal to background ratio of the order of .1, this leads to an error of ± 5% on the measurement of luminosity. The error on the absolute value of L is estimated to be of the order of ± 20%.

Many runs were taken measuring luminosity by both single bremsstrahlung and scattering. Scattering alone was used to measure luminosity with three bunches per beam.

4. - RESULTS. -

The luminosity measurements have been mostly carried out at energies between 1 and 1.1 GeV; operation at lower energy is difficult, partly because the beam dimensions at the coupling resonance are smaller, and therefore the incoherent beam-beam interaction limit is lower, and partly because the coherent instabilities have lower thresholds. The beam equivalent dimension control through the crossing angle and an improved fast feedback system should allow normal operation at energies from 400 MeV upward.

Measurements at 1 GeV with one bunch per beam, and currents per bunch ranging from 2.2 mA to 8.5 mA in the weak beam and from 6 mA to 16 mA in the strong beam, have given luminosities ranging from $(1.6\pm.3)\times10^{31}$ cm^{-2} hr^{-1} to $(1.2\pm.2)\times10^{32}$ cm^{-2} hr^{-1}. The luminosity divided by the current of the weak beam, i_w, can be taken as a parameter of the crossing, and it should be a constant for a given energy, at the space charge limit, if the transverse charge distribution shape stays constant. Practical limits of operation in Adone lead to differences in beam shape that allow for ~ 30% variations of this ratio.

The values obtained at $1\div1.1$ GeV are in the following range:

$$\frac{L}{i_w} = (0.75\div1.5)\times10^{31}\ \mathrm{cm}^{-2}\ \mathrm{hr}^{-1}\ \mathrm{mA}^{-1}$$

that should be compared with the design value of 0.67×10^{31} cm^{-2} hr^{-1} mA^{-1} at 1 GeV.

The small amplitude betatron frequency shift per crossing comes out to be about 0.04, and, in most cases, is of the same order of magnitude for radial and vertical modes.

The beam-beam single bremsstrahlung luminosity measurements agree with the small angle scattering ones to within the experimental errors, whenever the comparison can be made, namely with one bunch in one beam and two in the other.

Operation with three bunches per beam, and correspondingly higher currents, has resulted, as foreseen, in a proportional increase of the luminosity: with currents in the weak beam of 22 to 23 mA and currents ranging from 33 mA to 51 mA in the strong beam, luminosities from $(2.9\pm0.3)\times10^{32}$ cm^{-2} hr^{-1} to $(3.4\pm0.4)\times10^{32}$ cm^{-2} hr^{-1} have been measured at energies between 1 and 1.1 GeV. The ratio L/i_w turns out to be $(1.3\div1.5)\times10^{31}$ cm^{-2} hr^{-1} mA^{-1}. This result shows that the incoherent beam-beam interaction limit does not depend on the number of crossings in the ring, but only on the transverse charge density per bunch, as the beam dimensions in the two cases, of one bunch per beam and of three bunches per beam, were essentially the same.

The results of several measurements during two runs are shown in Figg. 2, 3. The mean luminosity decay time is in the range of one to four hours and agrees with the mean life of the product of the currents. This should be so since beam dimensions are constant.

A few one to one bunch luminosity measurements at energies from 500 to 800 MeV have been made with weak beam currents ranging from 0.6 to 4 mA; the luminosity obtained ranges from $2\cdot10^{30}$ to

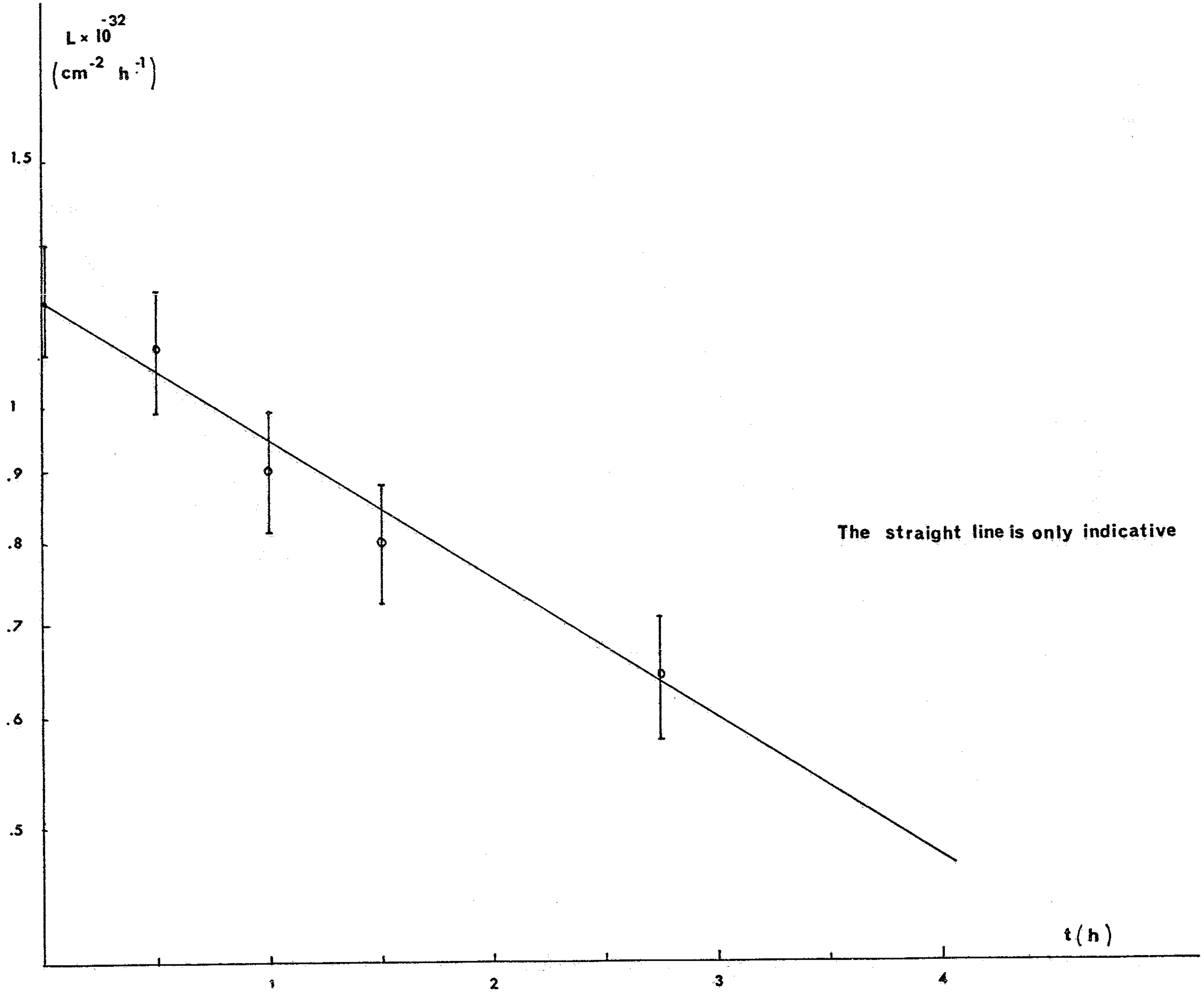

FIG. 2 - Luminosity (L) measurements with the bremsstrahlung apparatus at 1 GeV. The luminosity is due to one bunch crossing.

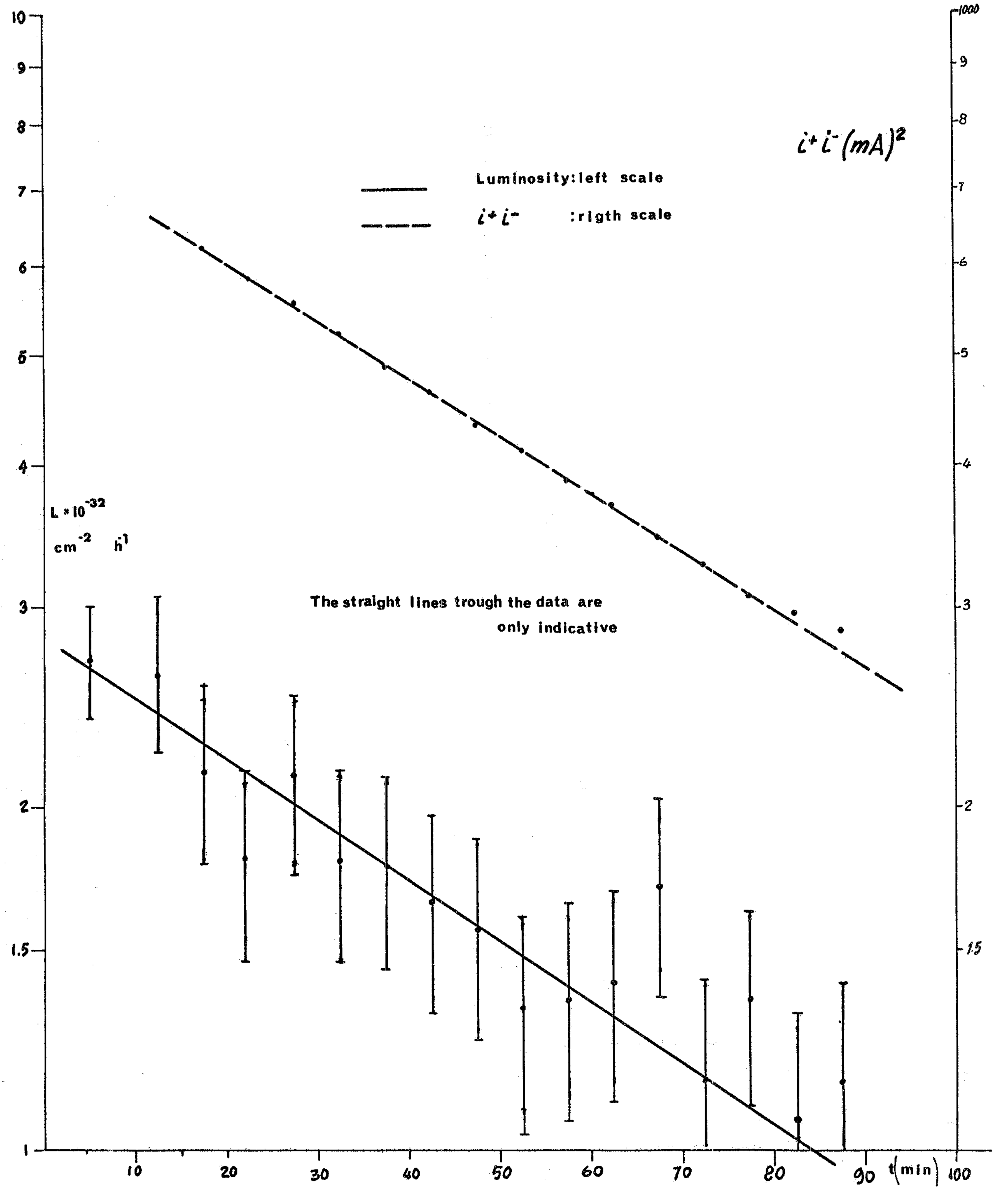

FIG. 3 - Luminosity (L) measurements with the scattering apparatus and three bunches per beam (full curve) at 1 GeV. The product of beam currents is also shown as a function of time (dotted curve). Errors are statistical.

1.5×10^{31} cm^{-2} hr^{-1}, and the ratio L/i_w is in agreement with the design value of $(0.33 \div 0.53) \times 10^{31}$ cm^{-2} hr^{-1} mA^{-1}, depending on energy. No special effort has been made so far to improve these results, as the crossing angle is expected to make operation easier in this range of energy.

The luminosity value as computed using the circulating current and the measured beam dimensions, tends to be systematically lower than the directly measured one; the ratio between the two fluctuates between 1 and 0.5.

We feel though that the reliability of the dimension monitor, the fact that it gives an average over time and all bunches of one beam while luminosity is defined as the integral of the density product of interacting bunches, and errors in the measurement of currents, are enough to account for our results.

It follows that the directly measured values of luminosity are considered the correct ones.

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It was a pleasure the presence of Dr. H.C. Dehne, on leave of absence from Hamburg Univ. - DESY since the end of 1966, whose help was indispensable in the preparation of the single bremsstrahlung monitor.

We are grateful for helpful discussions with many physicists of Frascati Laboratory and of other laboratories; we are especially grateful to Prof. C. Bernardini, whose contribution has been very important in the design stage, and to Prof. B.Touschek for his brillant ideas and for suffering with us through the instability problems.

The achievement presented here has been made possible by the active work and the intelligent partecipation of the engineers and technicians of the Adone group and by the cooperation of the whole of the Laboratory staff (especially of the Civil Engineering group, led by Dr. R. Cerchia) during the many years of design and construction of the storage ring.

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