EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/86-63

28 May 1986

**A MUON SPECTROMETER WITH CALORIMETER DUMP
USED FOR THE BEAUTY SEARCH AT THE CERN SUPER PROTON SYNCHROTRON**

The WA78 Collaboration at CERN
Geneva, Switzerland

M.G. Catanesi, A. Clemente, L. Liberti, M.T. Muciaccia, S. Natali, S. Nuzzo and F. Ruggieri
Università di Bari and INFN, Bari, Italy

H. Cobbaert and R. Roosen
Inter-University Institute for High Energies, ULB-VUB, Brussels, Belgium

G. Carboni¹⁾, G. Crosetti²⁾, M. Fidecaro, C. Gerke³⁾, P. Musset^{*)}, G. Poulard,
M. Renevey and H. Sletten
CERN, Geneva, Switzerland

M. Coupland, I.G. Roberts and P.T. Trent
Birkbeck College, London, United Kingdom

J.H. Bartley, J. Conboy, B.G. Duff^{*)}, M.J. Esten, P. Fennel, P. Harrison,
F.F. Heymann and D.C. Imrie
University College, London, United Kingdom

F. Bronzini, M. De Vincenzi, S. Di Liberto, A. Frenkel, E. Lamanna, G. Marini, G. Martellotti,
A. Nigro, G. Pellizzoni, G. Penso, S. Petrerà, E. Petrolo, P. Pistilli, G. Romano,
G. Rosa and A. Sciubba
Università di Roma and INFN, Rome, Italy

B. Alessandro, W. Alpe, V. Bisi, D. Gamba, L. Ramello and L. Riccati,
Università di Torino and INFN, Turin, Italy

(Submitted to Nuclear Instruments and Methods in Physics Research A)

1) Now at INFN, Pisa, Italy.

2) Now at INFN, Genoa, Italy.

3) Now at DESY, Hamburg, Fed. Rep. Germany.

*) Deceased.

ABSTRACT

A detailed description is given of the apparatus, which combines a dump calorimeter and a muon spectrometer and is used to measure the cross-section for $B\bar{B}$ production by a high-intensity 320 GeV π^- beam. The performance of the various parts of the equipment is discussed. In particular, we consider all the problems related to the calorimetric measurement in high-rate conditions.

1. INTRODUCTION

The detector described in this paper has been developed to search for $B\bar{B}$ pairs produced by a π^- beam of 320 GeV. The signal is selected among events of the type

$$\pi^- N \rightarrow \mu^\pm \mu^\pm + X$$

and

$$\pi^- N \rightarrow 3(4)\mu + X$$

coming from $B\bar{B}$ semileptonic decay chains:

$$B \rightarrow \mu^- + D(\rightarrow \mu^+ + X) + X ,$$

$$\bar{B} \rightarrow \mu^+ + \bar{D}(\rightarrow \mu^- + X) + X .$$

For background rejection we required at least one high- p_T ($p_T \geq 1.5$ GeV/c) muon together with a large missing energy due to escaping neutrinos.

The apparatus comprises a dump calorimeter followed by a magnetic spectrometer (fig. 1). The directions and momenta of the muons filtered by the dump are measured by the magnetic spectrometer. The missing energy (E_{miss}) is calculated by comparing the beam energy (E_{beam}) with the sum of the hadronic energy measured in the dump calorimeter (E_{cal}) and the energies of the outgoing muons (E_μ) measured in the spectrometer:

$$E_{\text{miss}} = E_{\text{beam}} - E_{\text{cal}} - \sum E_\mu .$$

To obtain sufficient sensitivity (~ 300 pb to 1 nb, depending on the production mechanism) in the measurement of the $B\bar{B}$ cross-section, it is necessary to dump a large number of incident pions ($\sim 10^{12}$); this, in turn, requires an intense beam flux ($\sim 10^7$ π per burst). The whole apparatus—calorimeter, spectrometer, trigger, and data-acquisition system—therefore had to be optimized to work in such a high-rate condition.

A major background process arises from the association of one or more detected muons coming from Drell-Yan or $D\bar{D}$ production, with ‘non-prompt’ muons coming from π and K decay. The dump calorimeter was designed in such a way that it could be expanded in order to operate at different target densities. By extrapolating to infinite density it is then possible to obtain experimentally a separation between prompt and non-prompt muon contributions.

In Section 2 we give a description of the calorimeter and discuss its performance, with emphasis on the problems connected with the high rate. In Sections 3 and 4 we describe the spectrometer and the multilevel trigger, respectively. Section 5 is devoted to the data-acquisition system. In Section 6 we give a short description of the off-line data-analysis system.

2. HADRON CALORIMETER

The parameters chosen for the hadron calorimeter were such as to obtain an energy resolution $\sigma/E \approx 0.65/\sqrt{E}$, useful for a strong background rejection, together with high density necessary for minimizing the ‘non-prompt’ muon yield.

We used rather thick uranium layers alternating with thin scintillator plates in order to combine the maximum available effective density with good energy resolution in comparison with other materials at fixed sampling thickness.

An extensive study of the performance of this calorimeter with different absorber materials and sampling thicknesses was carried out, and the results are reported in ref. [1]. As discussed in subsection 2.2, special care was taken in the choice of photomultipliers (PM) and in the development of the linear chain in order to keep the energy resolution constant up to a beam flux of $\sim 10^7$ particles per burst (1 burst ~ 2.4 s).

2.1 Mechanics

The hadronic calorimeter consists of an absorber-scintillator (NE110)^{*)} sandwich, 60×60 cm² in cross-section. The calorimeter is divided into two parts: an upstream expandable part, and a downstream fixed part (fig. 2). The first part consists of 52 scintillator plates, 0.5 cm thick, alternating with uranium absorber, 1 cm thick for the first 20 layers and 1.5 cm thick for the remaining 32 layers. The total length of the calorimeter is 125 cm. The uranium is placed inside iron boxes closed at each end by a thin (1 mm) iron foil. Each box fits inside a U-shaped iron frame, which is placed on two small carriages and can be moved along rails fixed to the calorimeter support. The light-guides use an arrangement of optical fibres, gathering the light outputs of four scintillators to a single PM. Both the support for the fibre optics at the scintillator edge and the scintillator itself are held by the U-shaped frame (fig. 3). Thus each module, made up of four elements of scintillator and absorber seen by a single PM, can be expanded up to 50 cm, which is within the limit imposed by the optical-fibre length (~ 90 cm). Each module can be displaced along the calorimeter support (about 4 m long) independently of the others. In this way, altering the target density by expanding the calorimeter is a simple operation. Moreover, since the absorber plates are not connected to the scintillator and light-guide system, they can be removed from the frame and easily replaced.

The downstream fixed part of the calorimeter consists of a sandwich of iron and scintillator, 2.5 cm and 0.5 cm respectively, placed on another horizontal support. The light-guides are the same as those of the upstream part.

2.2 Photomultipliers + linear chain

In addition to the usual problems connected with any calorimetric measurement when a linear response and a good resolution are required, we have to cope with the specific problems of high-rate conditions.

The main problems are:

- i) the gain variation of the PMs at high average anode current ('rate effect');
- ii) the 'pile-up' of spurious pulses entering in the time window of the ADC gates.

We will discuss these points in some detail together with the solutions adopted. In general the gain of a given PM (defined as the ratio between the anode and the cathode current) at 'high' average current does not depend only on the inter-dynode potential; it also depends on the average current itself. We have studied this 'rate effect' extensively [3] and the conclusions can be summarized as follows:

- i) the 'rate effect' turns out to be a gain variation between $\sim 1\%$ and 10% , depending on the type of PMs, at an average anode current $I_a \approx 10 \mu\text{A}$. In the interval $I_a = 10 - 100 \mu\text{A}$ the increase of the 'rate effect' shows a $\sqrt{I_a}$ proportionality.
- ii) The 'rate effect' depends mainly on the material and the geometry of the dynodes; SbCs dynodes produce a smaller effect than CuBe ones at the same average current.

*) This type of scintillator was found [2] to be one of those least sensitive to radiation-damage effects.

We have therefore used special tubes (THORN-EMI D254A) with six SbCs dynodes, bi-alkali cathode circularly focused. These PMs show an average rate effect of $\approx 1-2\%$ at $10\ \mu\text{A}$ and have a fast time-response (2.5 ns). The venetian-blind type PMs have been discarded, despite a smaller 'rate effect', because of their slow time-response.

The ADCs used were the FERA type (LeCroy 4300) with a dynamic range 0–512 pC and a precision of 11 bits. With a rate of $5 \times 10^6\ \text{Hz}$ and with the limitation on the I_a of $\approx 10\ \mu\text{A}$, we need an extra amplification stage with a current gain $A \approx 44$ after each PM to fit the ADC dynamic range. The amplification was achieved by using LeCroy VV100BTB preamplifiers, placed in the bases of the PMs. At the present high rate they exhibit a variation of the output d.c. level comparable to the PM 'rate effect'. The overall effect of the order of a few percent is monitored and recorded for the off-line analysis.

Figure 4 shows the voltage divider and amplifier scheme. The connection between the amplifier output and the ADC was made by 100 m of (50 Ω) low attenuation cable (type Suhner S12272-4) in order to maintain the time profile of the signal.

With respect to pile-up problems at a rate of $\approx 5 \times 10^6\ \text{Hz}$ (i.e. mean time-interval between two beam particles of $\approx 200\ \text{ns}$), the probability that a fraction of a spurious pulse enters within the 75 ns gate that is necessary for the charge integration of the pulse is not negligible, and could result in a deterioration of the energy resolution.

To deal with this effect, we split the output of each PM to two ADCs with different gate lengths (75 and 100 ns). Moreover, using a TDC (LeCroy 4208) connected to the beam counter BC2, we record the arrival times of any particle around $\pm 400\ \text{ns}$ with respect to the particle that triggers the system and gives an ADC gate. In such a way the combined information of the two sets of ADCs and the time distance between the pulses permits a correction of the pile-up effect (fig. 5). The energies associated with the measurements of the two sets of ADCs will be referred to as E_L (100 ns gate) and E_S (75 ns gate).

2.3 Monitoring of the calorimeter: the LED system

The absolute calibration of the calorimeter is performed continuously during the data-taking, using the monochromatic incident beam. Therefore only the relative gain of all PMs and their linear chain need to be monitored. This monitoring was performed by sending to each PM, through an optical fibre, a light-pulse coming from a light-emitting diode (LED) system. In order to obtain light-pulses of the required intensity, an array of 50 Siemens CQV 55-L LEDs was used, arranged as shown in fig. 6.

The light coming from each LED is collected by a Crofon optical fibre (1.5 mm in diameter). A Perspex cylinder (14 mm in diameter, 125 mm in length) mixes the light coming from these fibres and shares it amongst those going to each PM. This system allows the monitoring of all the PMs with the same light source. Each LED is driven by a LED-driver with an avalanche output stage. The light-pulses delivered by this system are $\approx 50\ \text{ns}$ wide (FWHM). The LED-driver pulse amplitude is regulated in such a way as to give light-pulses which correspond roughly to half the ADC full scale. Owing to the optical mixer, any variation in the light output (e.g. temperature dependence) of one or more LEDs will affect all the PMs in the same way.

The LEDs are fired continuously during data-taking, and those which do not arrive within $\pm 100\ \text{ns}$ of an incident pion are accepted. In this way, one LED trigger is recorded just before the start of the burst, and ≈ 7 LED triggers are recorded during the burst. The pedestals of the linear chains are measured with a similar logic. The pedestals and LED values are stored in dedicated hardware processor memories.

With such a system, it is possible to check the relative short-term and long-term stability of each calorimeter channel. Any possible overall gain instability is monitored by the incident monochromatic beam itself, by taking data, during one burst in every twenty, without any trigger bias.

The observed short-term gain variation (of a few percent) is mainly due to 'rate effects' on PM gain and preamplifier offset instability.

2.4 Calibration

Equalization between modules was performed by looking at the average shower energy profile for interactions starting at different depths. By selecting a shower which starts in the j^{th} module and defining A_i^j ($i \geq j$) to be the average amplitude deposited in the i^{th} module, one can write:

$$\alpha_i A_i^j = \alpha_{n-j} A_{n-j}^{n-i},$$

obtaining a system of equations that fixes the relative calibration constants. The absolute calibration is obtained by comparing the total energy $\sum \alpha A$ with the beam energy. The energy distribution obtained in such a way is corrected by a weighting procedure in order to minimize the difference between the responses to the electromagnetic and the hadronic showers. The algorithm used (similar to that discussed in ref. [1]) is:

$$E'_{\text{tot}} = E_{\text{tot}} - c'(E) \times \sum_i a_i, \quad c'(E) = c/\sqrt{E_{\text{tot}}},$$

where a_i are the ADC outputs (in channels) after calibration, E_{tot} is the total unweighted energy, and c (a constant value obtained by optimization of the energy resolution) turns out to be $c = -0.01 \text{ ch}^{-1/2}$. The negative value of c reflects the 'overcompensation' of the uranium, i.e. the response of the calorimeter is higher for hadrons than for electrons [1]. After this calibration and correction procedure, we obtain a resolution $\sigma/E \approx 0.65/\sqrt{E}$, approximately constant in the energy range between 135–320 GeV. The equalization constants α_i can be quickly obtained by minimization of the standard deviation of the distribution $\sum \alpha_i A_i$ with respect to α_i , considered as free parameters.

Using this method we get a resolution $\sigma/E \approx 4\%$ at 320 GeV, slightly worse than that obtained with the complete procedure. Nevertheless it has been used for the preliminary analysis because of its simplicity.

In the high-rate condition the α_i have been computed using the complete procedure, selecting events satisfying the following criteria:

- i) no extra particle within a time of ± 200 ns with respect to the triggering particle, as given by the TDC;
- ii) $(E_L - E_S) < 30$ GeV, where E_L is the energy measured in the long gate ADC (100 ns) and E_S is the energy measured in the short gate ADC (75 ns).

These two requirements eliminate pile-up effects from the calibration procedure.

In fig. 7 we show the energy distribution E_S obtained at $10^7 \pi$ per burst without any event selection. The shape of the distribution shows an asymmetric high-energy tail and a second smaller peak at ≈ 600 GeV. This is due to pile-up, inside the short-gate length, producing an increase in the energy value. The peak around 600 GeV is due to events in which two particles enter almost completely within the 75 ns gate.

The phenomenon is even clearer in fig. 8, where the scatter plot $(E_L - E_S)$ versus E_S is given. One can see the increase of $(E_L - E_S)$ for the higher values of E_S , whilst the second peak at ≈ 600 GeV corresponds, as expected, to small $(E_L - E_S)$ values.

2.5 Event selection and correction

A first selection is made by requiring $E_S < 450$ GeV; the effects of pile-up in events with higher E_S values are too big to be corrected. This corresponds to a rejection of $\approx 15\%$ of the events at an intensity of $\sim 10^7 \pi$ per burst.

The correction for signal pile-up is performed using the TDC information and the $(E_L - E_S)$ values. The first correction is given by

$$E_{\text{cor}} = E_S - \epsilon \sum e^{-\beta t_i} ,$$

where t_i are the times of arrival of the particles before the triggering ones, n is the number of these particles, and ϵ and β are parameters to be fitted.

Owing to the exponential law approximation in the previous correction and to counter inefficiency, a correlation between E_{cor} and $(E_L - E_S)$ is still present. The final value of the energy will be given by

$$E'_{\text{cor}} = E_{\text{cor}} - \gamma(E_L - E_S) ,$$

where γ is a constant obtained by optimizing the resolution.

In fig. 9 the energy resolution is shown as a function of rate, with and without correction, for selected events ($E_S < 450$ GeV).

3. SPECTROMETER

The detectors and equipment of the spectrometer provide information for the event trigger logic and for precise measurement, by off-line analysis, of the trajectories of the muons filtered by the dump. The spectrometer is, with minor changes, the same as that used by experiment WA75 [4]. Here we summarize its principal characteristics and discuss the performance of the detectors under high-rate conditions.

The muon spectrometer consists of a bipolar superconducting magnet equipped with a system of drift chambers and multiwire proportional chambers (MWPCs), as indicated in fig. 1.

The scintillation counter system used for the first-level trigger is described in section 4.

3.1 Spectrometer magnet

The two superconducting coils of the magnet have an internal diameter of 2 m and are 1 m apart. The horizontal entrance and the exit apertures are limited to a width of 2.8 m by the iron return yoke and the vertical aperture is given by the coil separation. The field is 1.5 T for a current of 5000 A. The current in a precision shunt is continuously monitored, and a feedback system stabilizes the current within 1‰ of the nominal value.

3.2 Chamber system

The upstream part of the spectrometer consists of three small MWPCs and four drift chambers, followed by one MWPC in front of the magnet; another chamber has been placed at the centre of the magnet. The downstream part consists of four large MWPCs. The position of the chambers is shown in fig. 1.

Each of the three small MWPCs (32×32 cm²) consists of four planes with y , z , u , and v coordinates (the wire planes are rotated by 0° , 90° , 45° and 135° , respectively; altogether 12 planes).

The drift chamber^{*)} system consists of one chamber of $130 \times 90 \text{ cm}^2$ and three chambers of $190 \times 137 \text{ cm}^2$, the first one with three planes (zyz) and the others with two planes (u/v and y). We have investigated the performance of the chambers at 320 GeV as a function of the beam intensity up to $10^7 \pi$ per burst. This rate corresponds to about 10^5 particles per burst emerging from the dump and traversing the upstream part of the spectrometer. Comparing the results obtained at $10^5 \pi$ per burst with those at $10^7 \pi$ per burst, we do not see any substantial difference in the chamber efficiency or resolution.

In order to cope with higher multiplicity events, two new chambers have been added to the WA75 spectrometer, one in front of the magnet and one inside it. Each chamber has external dimensions of $280 \times 90 \text{ cm}^2$ to fit the gap of the magnet, and is made of four independent planes, each with two graphited Mylar cathodes and one anode wire plane. The gap between the cathode and the wire plane is 0.8 cm, and the separation between the $20 \mu\text{m}$ tungsten wires is 0.2 cm. The efficiency was 98% during all the data-taking period.

In the downstream part of the spectrometer we have used four large MWPCs^{**)}. Each chamber ($232 \times 232 \text{ cm}^2$ sensitive area) includes four planes of sense wires. The position of chambers 2 and 3 was chosen to allow a 60 cm wire superposition in the central region, where the particle flux is maximum. Only a fraction of the sense wires were used in experiments WA75/WA78 to cover the spectrometer acceptance (4352 for chambers 1 and 4; 3840 for chambers 2 and 3).

The average computed efficiency of the single planes in each chamber is 0.92 ± 0.02 . As expected, no difference in the efficiency of the chambers has been observed in the high-rate condition.

4. TRIGGER

The trigger was designed to accept events with a large missing energy, as measured in the calorimeter, and two or more muons in the spectrometer, at least one of which had a high p_T . The system was designed to reduce several sources of background, and the rate of multi-muon triggers was thereby reduced to levels not incompatible with conventional data-acquisition systems for beam intensities of up to $\approx 10^7$ particles per burst.

Single-muon triggers were, however, also needed to complete the experimental programme, and under these conditions the far higher trigger rate was limited by the dead-time of the data-acquisition system. The use of a PDP-11 emulator [MICE^{***)}] as a high-speed interface reduced the dead-time to an acceptable level.

The event selection was organized on two levels of trigger processing:

- i) The first level (referred to as T1) required a predetermined muon multiplicity and configuration in conjunction with certain veto requirements designed to reduce background. It was essential that the details of the selection criteria for the muon(s) could be varied easily, in particular between single-muon and multi-muon candidates.
- ii) The second level (referred to as T2) required that the energy deposited by the hadronic shower (E_{had}) in the target calorimeter should be less than some threshold value.

These levels of trigger processing together with the data-acquisition system, were organized as shown in fig. 10. A feature of this organization is that each level could easily be switched out of the trigger processing under programme control (via enables E1, E2, and E3), either for every burst in a run, or

*) The first chamber was developed by the FRAMM Collaboration, the other chambers for the Omega spectrometer.

**) The four MWPCs described in ref. [5] have been designed and built by the WA7 Collaboration.

***) MICroprogrammable filtering 'Engine'.

for one burst every predetermined number of bursts. Thus during normal running, for reasons of calibration the first-level trigger dropped the requirement on muons every $1/N_1$ bursts (thus becoming a 'beam' trigger), and the second-level trigger (cutting on E_{had}) was bypassed every $1/N_2$ bursts.

4.1 Top-level trigger and control

The first-level trigger combined signals from the various scintillator subsystems indicated in fig. 1, together with the various control signals indicated in fig. 10. The characteristics of the scintillators which composed this part of the trigger are summarized in table 1.

The control information available to the top-level trigger included that from the Master Gate (MG), which used the OR of all 'Busies' around the system in order to inhibit trigger processing when closed.

The information from all sources mentioned above was presented to a cascaded array of 13 programmable logic units (model CAEN 85 [6]), each having eight inputs and six outputs. The top-level trigger (T1) was available from this array about 150 ns after the information from the beam counters reached the control room. The system also provided a pretrigger (T0) at 50 ns in order to gate the wire chambers, hodoscope bit-registers, etc. A Fast-Clear and Abort-Trigger processing ($T0 \cdot \bar{T1}$) was issued at 175 ns if the pretrigger T0 did not eventually result in a first-level trigger T1. For normal multi-muon trigger programmes, this pretrigger was

$$BC1 \cdot BC2 \cdot \overline{VW} \cdot (H1Y \geq 1) \cdot (H1Z1 \geq 1) .$$

The pretrigger T0 was used to close the Master Gate and inhibit further trigger processing until either a Fast-Clear and Reset was issued from a further level of trigger processing (such as $T0 \cdot \bar{T1}$ or $T1 \cdot \bar{T2}$) or the data-acquisition system had completed readout.

The programmable logic was supported by a software system enabling easy generation of different triggers, automatic re-reading of the memories at regular intervals (typically 30 min) via CAMAC, and error logging. Any one of a variety of programmes ('triggers') could be loaded prior to the start of a run, and its identification recorded by the data-acquisition system.

A detailed study of the trigger rates shows that the dimuon trigger is reasonably clean up to the highest beam rates, the true dimuon rate constituting about 65% of the total observed trigger rate. Most of the residual rate arises from spurious hits in the hodoscopes H2 and H3, due to general background in the experimental area.

4.2 The hadronic energy trigger

The second-level trigger is realized by feeding the calorimeter data, converted by the FERA ADC system, into a hardware processor especially designed for this high-rate experiment (for a complete description of the processor, see ref. [7]). The energy deposited in the calorimeter is computed as

$$E = \sum \alpha_i (A_i - P_i) ,$$

where α_i are the calibration constants, P_i are the pedestal values, and A_i are the amplitudes of the 25 PM signals. A special trigger module compares the E values with two thresholds (upper and lower values). If $E_{low} < E < E_{up}$, then the T2 trigger is generated.

The hardware processor computes the energy deposited in the calorimeter in 15 μ s. The on-line energy resolution is 6% at 320 GeV. The possibility of loading the calibration constants via CAMAC permits correction for any long-term shift of the gain of the PMs and the linear chain, and to conversion of the processor to different calorimeter configurations (absorber and density change).

During data-taking requiring at least two muons in the first-level trigger, the typical cut in energy was $E_{\text{cal}} < 280 \text{ GeV}$. Under such conditions the trigger rate T2 is reduced to $\approx 15\%$ of the T1 rate. Figure 11 shows the calorimeter energy distribution as computed on-line for the events selected by the first-level 'beam' trigger. A comparison of the energy deposited in the calorimeter, computed on-line by the hardware processor and off-line for the events selected by the second-level trigger, is given in fig 12.

5. THE DATA-ACQUISITION SYSTEM

The readout system was based upon the REMUS [8] variant of CAMAC, and the various detector systems each occupied their own branch (i.e. calorimeter, drift chambers, and hodoscopes). The MWPCs were read out using the receive memory hybrid (RMH) system [9], which formed a separate branch and which, for reasons of interfacing to MICE, did not form part of the rest of the data-acquisition tree structure.

Dependent upon the enable E3 (fig. 10), the generation of a second-level trigger T2 caused either the main data-acquisition computer (a PDP 11/44) or a MICE emulator to read the event data. The MICE [10, 11] is a PDP-11 emulator with special DMA interfaces to REMUS and to the wire chamber readout system RMH. It has an execution speed typically an order of magnitude faster than that of the PDP 11/44. The MICE ran a special-purpose interrupt-driven software system [12], which generated blocks of events of variable length for presentation to the PDP. The interrupt handling and DMA channel opening time of the MICE was about $40 \mu\text{s}$ (cf. about 2 ms for the PDP). REMUS reading proceeded at the usual speed for such systems (about $1.6 \mu\text{s}$ per word), whereas RMH was read at about $0.2 \mu\text{s}$ per word which, in our case, was limited by the length of cable along which handshaking was performed between MICE and the RMH system interface.

At a normal dimuon trigger rate of ≈ 150 triggers per burst the input dead-time of the experiment without the MICE was $\approx 24\%$. Using the MICE merely as an interface, it fell to $\approx 13\%$.

When operating under saturation conditions with a one-muon trigger, the maximum number of events which could be read by the PDP without MICE was about 400, and was input dead-time limited. When MICE was on-line, this number rose to about 1100 events per burst, and the limitation was the tape-drive speed on the PDP.

6. OFF-LINE ANALYSIS

The design of the off-line analysis program is as modular as possible in order for it to be run in different conditions. The program uses the HYDRA memory management system, and each important function is carried out by an independent processor which creates the necessary banks for pursuing the analysis. These main functions are as follows:

6.1 Decoding of raw data tape

Data are read from the raw PDP tape. Each event is individually extracted from the MICE super-event record and the event structure is created. In addition, data for each piece of hardware equipment are identified and stored in an 'equipment' bank.

6.2 Decoding of equipment

The data of each piece of equipment are decoded and stored in the appropriate detector bank after some preliminary treatment, such as pedestal subtraction for the calorimeter, drift-time determination, or cluster-size analysis for the MWPC. Geometrical information is also added at this stage.

6.3 Calorimeter analysis

As reported in subsection 2.6, several cuts are applied at the calorimeter analysis level. These are

- i) no extra particles between -200 ns and $+80$ ns with respect to the triggering particle (TDC cut);
- ii) the number of the module in which the shower starts must be below 7 in order to discard events beginning deep within the calorimeter (energy leakage);
- iii) $(E_L - E_S) < 30$ GeV;
- iv) $E_S < 400$ GeV.

Altogether, these cuts reduced the raw data by $\approx 20\%$.

6.4 Segment reconstruction

A segment is defined by at least two space points reconstructed in the large MWPCs plus at least one associated hit in the downstream hodoscope.

The space-point reconstruction was done in the normal manner, independently for each of the four chambers. A space point is defined either by the intersection of four wires (75% of the reconstructed points), or of 3 wires (20%), or, in some particular cases, of only two wires (5%). Several passes were made in the same reconstruction routines, with increased tolerances to take into account possible tilt effects.

Then the space points and hodoscope hits were associated to form the segment, whose parameters are determined by a space fit which uses the wire coordinates directly.

6.5 Line reconstruction

Three different algorithms are used successively to reconstruct the space lines in the front part of the spectrometer in order to cover the maximum of geometrical cases, taking into account the large differences in acceptance of the two detectors involved.

The first algorithm is a set of three MWPCs, each having four planes 32×32 cm², the second is a set of four drift chambers of three or two planes each, whose acceptance is larger than that for the MWPCs.

In the first algorithm, Y and Z projections are reconstructed independently, then combined to form a line in space using the other projections. In the second algorithm the unused Y projections found previously are combined with 'pseudo' Z projections defined by two hits in the drift chambers plus one hit in the Z hodoscope, and an attempt is made to find an association with the other projections.

Finally, a last iteration is done using only the drift chambers to find the remaining tracks.

6.6 Track association and muon momentum determination

The association between lines and segments is made in two steps:

- i) all possible candidates for a track are accepted, without taking into account any possible ambiguities;
- ii) these ambiguities are sorted out, using the quality parameter of the candidate.

In the first step we accept any line-segment pairs which survive raw cuts on the difference in slope z, slope y, and the z-coordinate. At the same time, a quality parameter of the candidate is defined, using the slope z, the z-coordinate in the centre of the magnet, and the perpendicular distance of the track from the centre of the magnet.

In the second step, ambiguous candidates are rejected, using the quality parameter in the following way. The candidates are ordered according to this parameter, and the first one is kept as a good track. The second one is only accepted if it has no ambiguities with the first track. For the next candidate the algorithm is the same, and it is only kept if no ambiguities are found with the already

accepted tracks. With such method we get the maximum possible number of tracks, and also select the best candidate for the track.

6.7 Performances

With the algorithms discussed above, we have a muon reconstruction efficiency of $\approx 80\%$. The momentum resolution turns out to be $\Delta p/p \approx 6 \times 10^{-4}$ (GeV). The p_T resolution, dominated by the multiple scattering in the dump calorimeter, is of the order of $\Delta p_T \approx 100$ MeV/c. Figure 13 shows the invariant-mass distribution for the events with two muons with $p_T \geq 1.1$ GeV/c. The J/ψ peak width gives the mass resolution (720 MeV FWHM). Selecting the J/ψ events, we have studied the p_T acceptance of the spectrometer. The results are given in fig. 14.

7. CONCLUSIONS

We have described an experiment using a dump calorimeter, followed by a magnetic spectrometer, to search for multi-muon events associated with a large missing energy.

The set-up is capable of working up to a rate of 10^7 particles per burst, with negligible deterioration of the calorimeter energy resolution.

In such conditions, the trigger and the data-acquisition system allow an event selection based on the requirements of at least two muons and a missing energy cut of ≈ 50 GeV, with a dead-time of the order of $\approx 10\%$.

REFERENCES

- [1] M. De Vincenzi et al., Nucl. Instrum. Methods **A243** (1986) 348.
- [2] G. Marini et al., CERN 85-08 (1985).
- [3] M. De Vincenzi et al., Nucl. Instrum. Methods **225** (1984) 104.
- [4] WA75 Collaboration, Description of the experimental apparatus, in preparation, to be submitted to Nucl. Instrum. Methods.
- [5] M. Bozzo et al., Nucl. Instrum. Methods **178** (1980) 77.
- [6] A. Fucci et al., Nucl. Instrum. Methods **147** (1977) 587.
- [7] A. Frenkel et al., Nucl. Instrum. Methods **A245** (1986) 45.
- [8] C. Jacobs and L. McCulloch, CERN CAMAC Notes 63 and 64 (1976).
- [9] J.B. Lindsay et al., Nucl. Instrum. Methods **156** (1978) 329.
- [10] C. Halatsis et al., Proc. 7th Annual Symp. on Computer Architecture, La Baule (1980); CERN-DD 79-7.
- [11] J. Anthonioz Blanc et al., Proc. Topical Conf. on the Application of Microprocessors to High-Energy Physics Experiments, Geneva, 1981 (CERN 81-07, Geneva, 1981), p. 266.
- [12] J.P. Dufey and A. Vascotto, CERN Mini- and Micro-Computer Newsletter, 1 Oct. 1983, 25.

Table 1

Counter	Name	Extent Y (cm)	Extent Z (cm)	Diameter (cm)	Remarks
Beam counters	BC1	1	5	4	5 channels ^{a)}
	BC2			5	
	BH				
Veto wall	VW	240	120	5 (hole)	
Interaction counter	IC	40	40		Inserted in the calorimeter after 3λ
Hodoscopes	H1Y	120	50		24 channels
	H1Z	120	50		10 channels
	H2	380	150		84 channels
	H3	490	165		92 channels
Diaphragm counter	DC	120	40		Square hole of variable diagonal (10–15 cm)

a) The beam hodoscope (BH) was not used in the trigger, but its information was recorded on tape.

Figure captions

- Fig. 1** General layout of the experiment.
- Fig. 2** Sketch of the calorimeter.
- Fig. 3** Calorimeter module (artist's view).
- Fig. 4** Schema of the voltage divider and amplifier.
- Fig. 5** Timing of the two sets of ADCs of the experiment. Solid and dashed lines represent the 75 ns and 100 ns gates, respectively. The A signal is 'in time', B is a spurious signal.
- Fig. 6** The LED layout.
- Fig. 7** The E_S distribution at $10^7 \pi$ per burst, without event selection.
- Fig. 8** Scatter plot of $(E_L - E_S)$ versus E_S .
- Fig. 9** Resolution (FWHM) as a function of the rate, a) with and b) without corrections, for selected events with $E_S < 450$ GeV.
- Fig. 10** Trigger logic layout.
- Fig. 11** On-line energy distributions obtained with 'beam' trigger: solid line with calibration constants, dotted line without calibration constants.
- Fig. 12** On-line (dotted line) and off-line (solid line) energy distributions for the events selected by first- and second-level triggers.
- Fig. 13** Invariant mass distribution for the $\mu^+ \mu^-$ events with $p_T \geq 1.1$ GeV/c. The solid line represents the Monte Carlo prediction.
- Fig. 14** Acceptance (trigger + reconstruction) for the $J/\psi \rightarrow \mu^+ \mu^-$ events, with $p_T^{\max} \geq p_T^{\text{cut}}$. The solid line represents the Monte Carlo prediction.

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14