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RD-17 Status Report
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**RD-17 STATUS REPORT**

# "Ultra fast Readout of Scintillating Fibres Using Upgraded Position-Sensitive Photomultipliers"

F.A.R.O.S. Collaboration

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## Abstract

This project is devoted to the research and development of a high space and time resolution detector based on simple and reliable technologies. During the period 1991 to 1992 major progress has been achieved in the following activities:

- Development of scintillating fibre (SciFi) detector prototypes and study of their performances using a test beam.
- Upgrades of position-sensitive photomultipliers (PSPM) based on new grid dynode configurations.

Experimental results obtained with an already existing position sensitive photomultiplier (PSPM) show promising performances: space resolution ≈ 200 μm, and time resolution ≈ 1.5ns with a detection efficiency higher than 90%.

Two PSPM prototypes have been newly constructed in the framework of RD-17. They have a gain of $5.10^5$ to $5.10^6$ at nominal voltages. A detailed study of the space resolution in a magnetic field is being prepared.

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## 1. Introduction

This R&D project was approved by the Research Board on April 4, 1991 after the recommendation of the DRDC in the March meeting. The Memorandum of Understanding was signed on January 17, 1992 by the CERN Directorate with the participating institutes on the basis of a R&D program for about 3 years.

The program consists of the following main activities;

- Upgrading of position-sensitive photomultipliers (PSPM)
- Usage of PSPMs for ultra fast readout of scintillating fibres
- Development of the necessary readout electronics

All of these activities are oriented toward future multi-TeV Collider experiments, in particular, a new scheme of "topological trigger" devices, which should play a unique role in a vertex detector in an LHC environment.

In the original proposal, DRDC/P-25, the major issues and milestones were defined as shown in Table 1.

We started a preliminary test in September 1991 of a SciFi detector in the T7-S beam with existing materials. This allowed us to achieve (in December of 1991) one of the first milestones, the space resolution of $\sigma$=150-200$\mu$m using a commercially available PSPM (R2486). Other relevant characteristics such as linearity and time resolution have been studied in detail during the runs of April through July of 1992.

In parallel with this study, the upgrade of the PSPM proceeded in two steps. First, modifications of the commercially available tubes were made, and second, construction of new PSPMs using extra-fine grid dynodes, designed and built within the framework of the RD-17 proposal. A R3941-Mod. (232 pad anodes), has already been tested, calibrated and mounted on a new SciFi detector prototype.

Two PSPM prototypes of the new design have been constructed; one by IHEP , the other by Hamamatsu Photonics. Evaluation of these tubes is in progress at IHEP and LAPP.

Concerning the associated electronics, major efforts have been devoted to a detailed simulation of a real time digitiser (RTD) in order to evaluate the capability of reconstructing multi-hit events (jets) by means of the delay-line method. In addition, part of our activities are oriented toward conceptual studies of a new real-time digitiser based on neural networks.

In this report we present in Section 2, a summary of experimental studies performed during 1991-1992. Some preliminary works in simulation of the front-end electronics are also briefly discussed. The program in the second year 92-93 is outlined, in Section 3, with its funding profile and manpower.

Table 1 . Major issues and milestones of RD-17.

| Year | PSPM | SciFi detector | Front-end electronics |
|---|---|---|---|
| 1991 | Test of R3941-Mod. calibration of the anode response etc..<br><br>First prototype of new PSPM (crossed-wire anodes), its evaluation.<br><br>Redesigning (if need be) and fabrication of new dynodes. | Design of SciFi arrays, Image converter etc..<br><br>Preliminary protos; lab test, beam test Goal: $\sigma \approx 150\ \mu m$. | Improvements of the real-time digitiser |
| 1992 | Start production of the 2nd series of new PSPM protos.<br><br>R3941-Mod. with "timing anodes".<br><br>2nd proto of new PSPM, evaluation. | Test of improved prototypes (with new RTD) on beam; Goal; two-hit resol. < 2 mm<br><br>Tests on a high intensity beam; Goal; rate capacity > 30 MHz/RTD.<br><br>Design of generic prototype. | Improved RTD<br><br>Generic prototype of the readout system (final version). |
| 1993 | 3rd series of new PSPM with pad anodes, application to SciFi detector. | Final test of the SciFi plus readout system based on R3941-Mod.. | |
| | Test of the whole system using new PSPM | | |

## 2. Progress in the year 1991-1992

### 2.1 Development of a "high space- and time-resolution" SciFi detector

The main activity of the collaboration in the year 1991-1992 has been devoted to the tests of prototypes using commercially available PSPMs (R2486) with crossed wire anodes.

In order to obtain the proposed spatial resolution of $\sigma \approx 150\mu m$, we have constructed a small prototype made of 0.5 mm diameter SciFis. The 28mm wide SciFi array (280 fibres) is split into 4 segments each 7mm wide. As illustrated in Figure 1, each segment consists of 5 consecutive layers with each layer staggered by 0.25 mm. At the opposite end of the array, the fibres are stretched over 35 mm on the photocathode so as to provide a magnification factor $\alpha$=5. The associated electronics are schematically shown in Figure 2. Apart from the auxiliary circuitry for "real-time monitoring" it is a very simple network for reading the time shift of the pulses coming out of the delay line ($t_R$ and $t_L$ to the TDC) and the number of the hit segment defined by a simple RTD ($Y_i$ to PU)

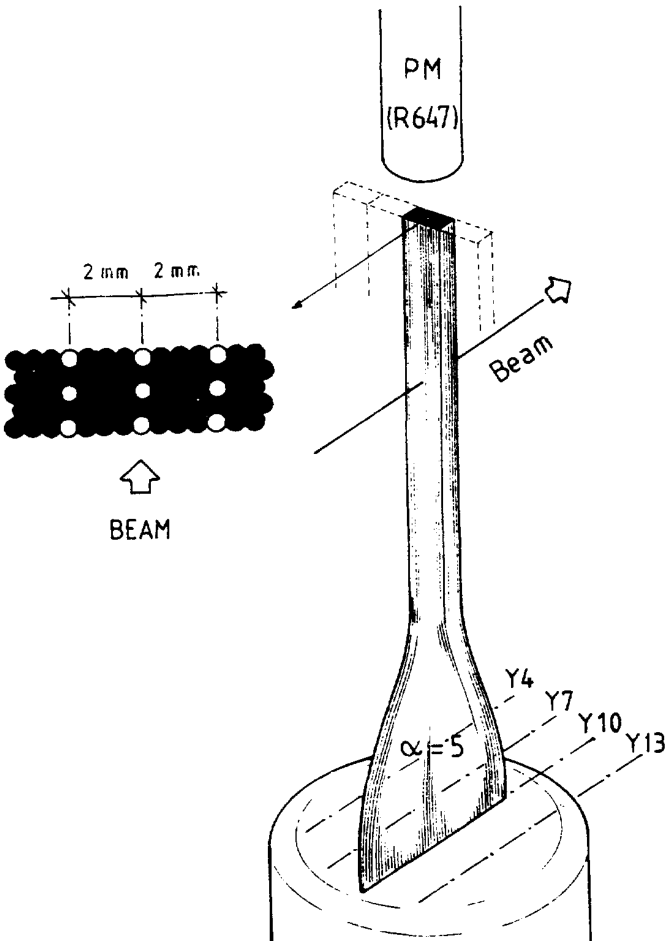



Figure 1. Set-up for the measurement of the space resolution (only one segment of the SciFi array shown). White circles in the SciFi array represent those fibres viewed by the R647 PMT (definition fibres).

The space resolution was studied first by means of the so-called "self calibrating" method by selecting track definition fibres placed inside the SciFi array itself with a given spacing. Figure 3 presents an example of results obtained with 7 GeV/$c$ positive particles. After unfolding the effect of the width of the definition fibres, the resolution is estimated to be about 200μm, which is close to the expected value based on the limitations of the presently available PSPMs.

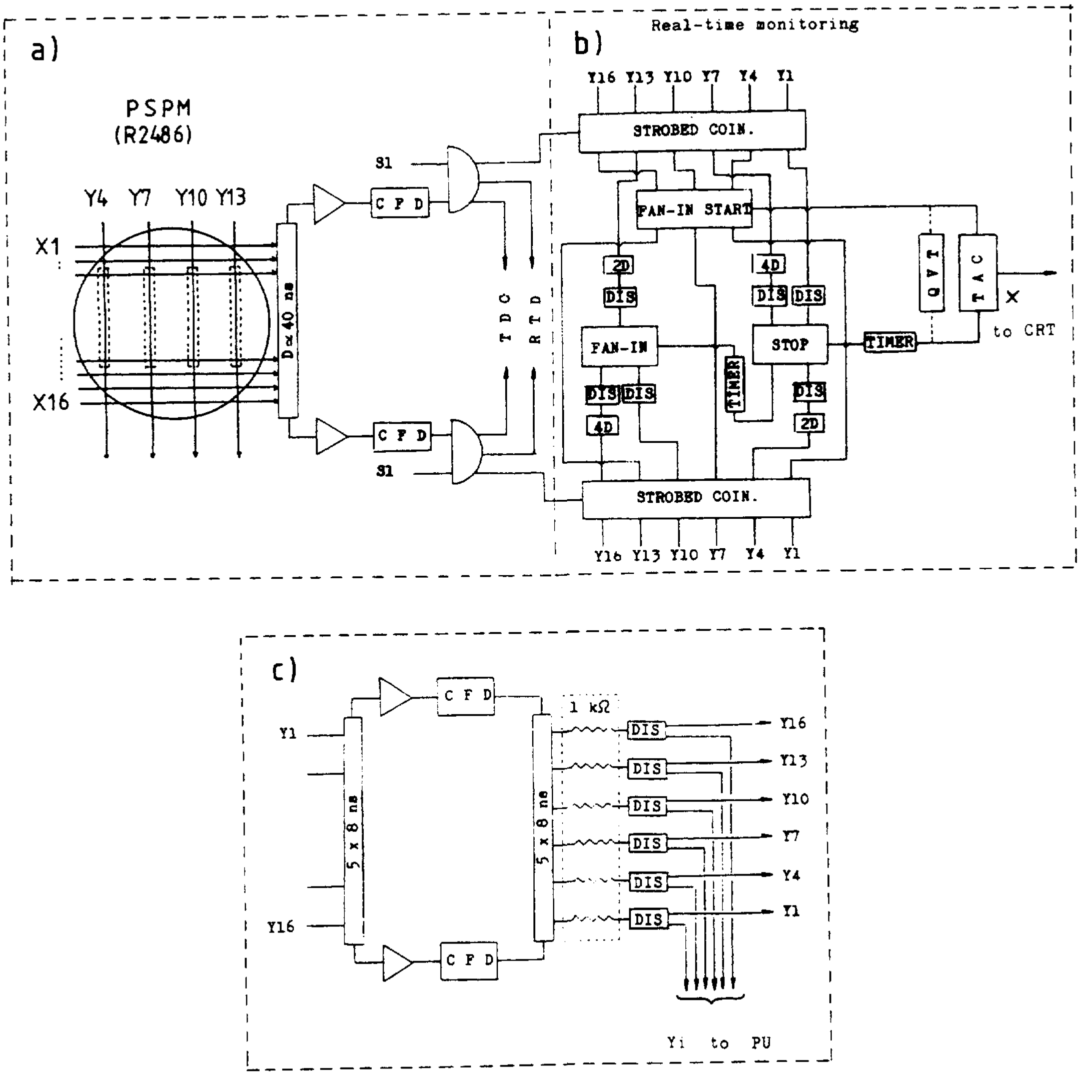



Figure 2. Block diagram of the readout electronics showing the PMT anode-X connections (top left), the real time monitoring circuit (top right), and the delay line circuit used for segment determination.

The above resolution has been independently confirmed by using 2 definition counters 0.5 mm wide placed up- and down-stream of the hodoscope. The attenuation of light along the scintillating fibres as well as the clear fibre light guides under realistic detector conditions* can be compensated by increasing the

* For example, LHC style detector will require a much longer SciFi (1m.) (DRDC/P-25).

thickness of SciFi array from ≈ 2mm (the effective thickness of 5 single layers) to ≈ 10 mm ( ≈ 0.025 $X_0$).

The linearity of the reconstructed position was measured by scanning the full width of the SciFi array with a finger counter, 0.5mm wide, in steps of 0.5mm. The results are presented in Figure 4.

The linearity within each segment is good over about 70% of the segment with non-linearities occurring near the edges. This edge effect can be explained by a shortness of effective anodes beyond the extremities. Note that the width of each segment (35 mm) is seen by 12 anodes separated by 3.75 mm. This configuration provides only one "guard" anode beyond each extremity.

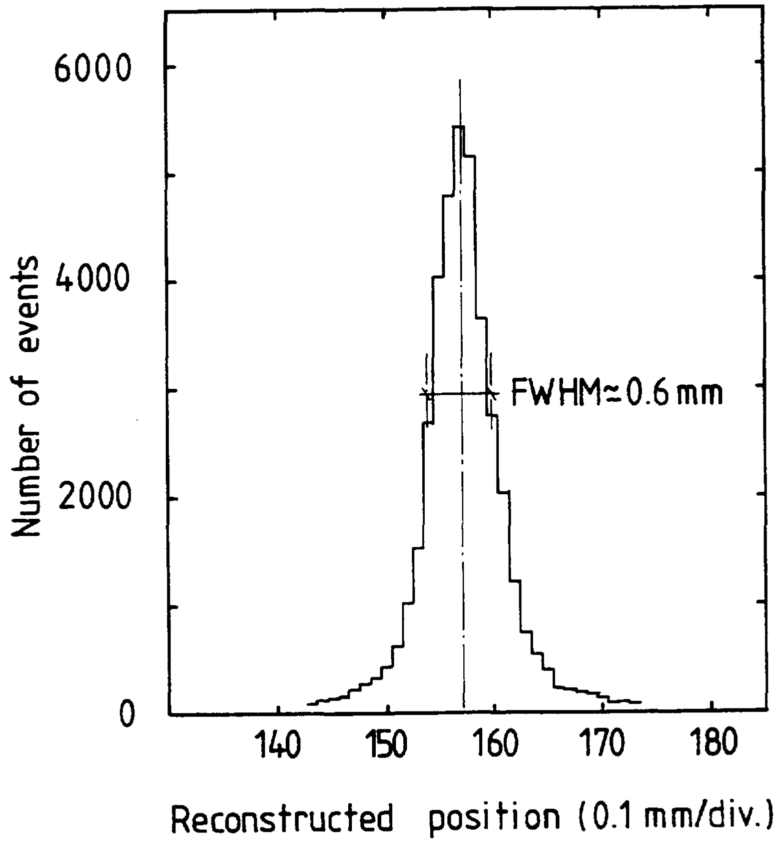



Figure 3. Space resolution before unfolding the width of the definition fibres (0.5 mm $\phi$)

The local detection efficiency was also studied by normalising the number of events detected by the last dynode of the PSPM with respect to the incident flux defined by the finger counter. This "raw" efficiency, not including any loss of RTD, is plotted in Figure 5 over the full range of the SciFi array. It is higher than 90 % almost everywhere, except at the boundaries of the SciFi segments located at -14, -7, 0, +7 and +14 mm on the plot.

Note that these low efficiency regions correspond to a periphery of r ≈2.5 cm on the photocathode of roughly 6 cm diameter. This efficiency was attainable only after increasing the luminosity by means of a reflector on the opposite edge of the SciFi, and by making an optical contact between the SciFi and the photocathode with silicon grease. In this connection it is worthwhile to mention that the quality of SciFi as well as the actual array structure are well tailored to this problem. For example, the stacking of 5 single layers locally provides only 2 fibres traversed by incident particles. Assuming the thickness of the cladding is ≈ 3 % of the fibre diameter (≈ 15 μm for 0.5 mm fibres) the portion of such a "weak" region presents ≈ 6 % of the array surface. The fine structure often seen in the local efficiency could be explained by this effect.

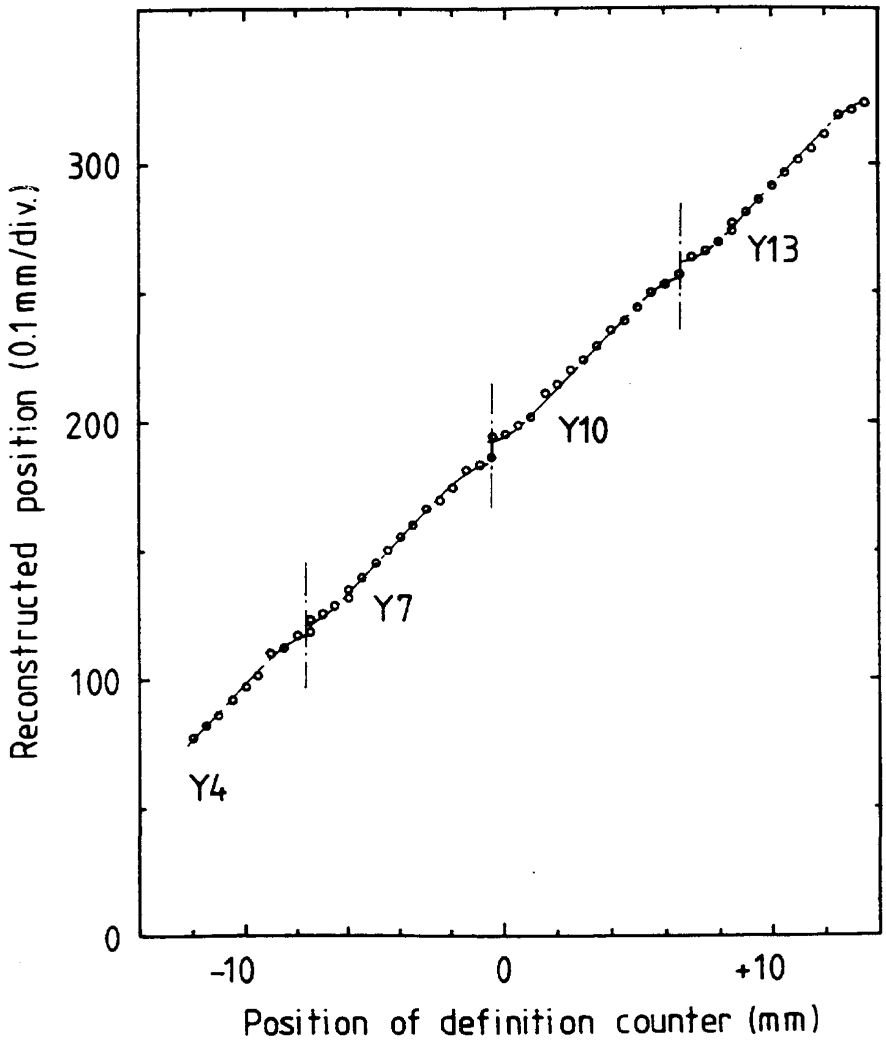



Figure 4. Linearity of the reconstructed position.

Another important issue concerns the time characteristics of the readout system based on the delay-line method. The time characteristics were studied by computing the sum, $t_L + t_R$, where $t_L$ and $t_R$ are the TDC contents corresponding to the arrival times of the left and right propagating signals coming out of the delay line with respect to a reference time $t_0$. Figure 6 presents a $(t_L+t_R)$ distribution with $t_0$ defined by the last dynode signal of the PSPM. Two peaks were obtained by shifting the signal 10 ns in $t_0$ thus providing a calibration of the time scale.

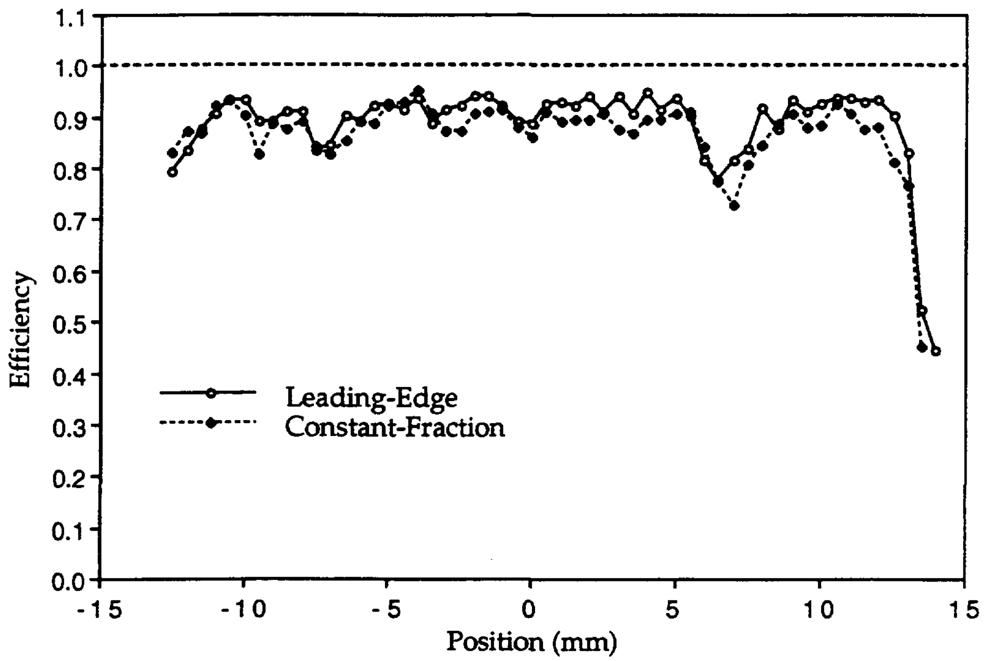



Figure 5. "Raw" detection efficiency measured with the last dynode signals of the PSPM using a leading edge discriminator, and a constant fraction discriminator.

The resolving time of ≈0.7 ns can be interpreted mainly as an "internal" time spread of the last dynode signals with respect to the corresponding anode signals. Such a good time resolution will allow a fast strobe coincidence at the level of the RTD as foreseen in our proposal for reconstruction of multi-hit events.

Figure 7 presents a similar result obtained with $t_0$ defined by an external counter. Assuming that the resolving time of the external counter is roughly comparable with that of the PSPM the total resolving time of the hodoscope is estimated to be ≈ 1.5 ns.

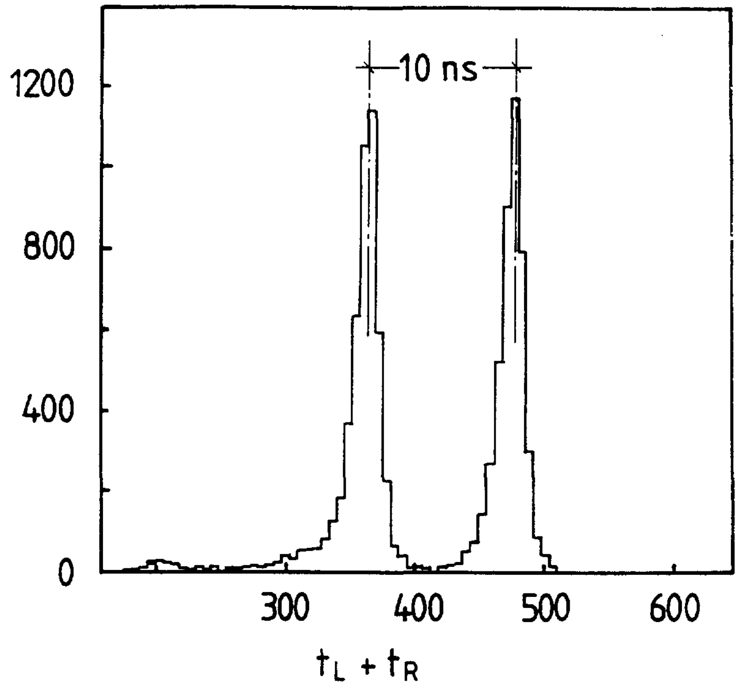



Figure 6. "Internal" time resolution. Two peaks were obtained by shifting the signal 10 ns in $t_0$ thus providing a calibration of the time scale.

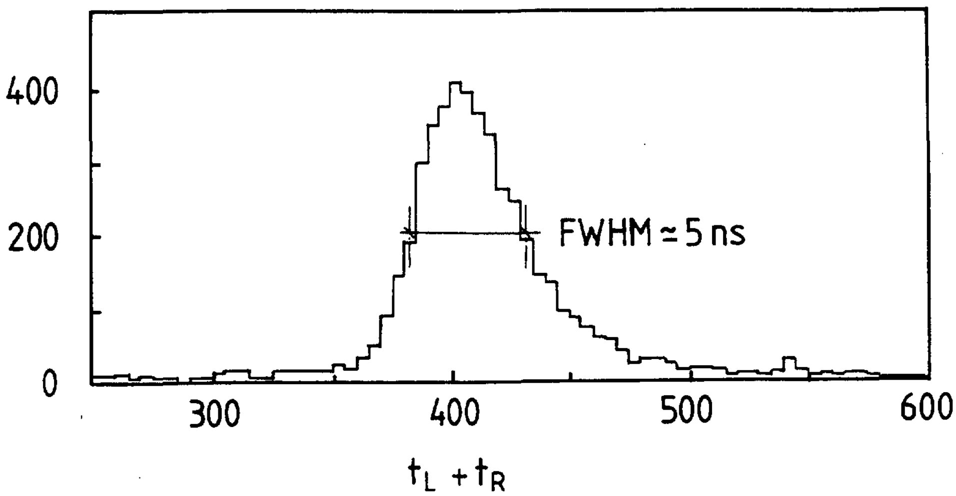



Figure 7. Time sum ($t_L + t_R$) distribution obtained with the reference time $t_0$ defined by an external counter.

In Figure 8 is shown an example of two-dimensional images obtained in real time with 2 planes of such a type of hodoscope. The letters, defined by short SciFi segments are viewed by an ordinary PMT and extend over an ≈ 8 x 20 $mm^2$ area.

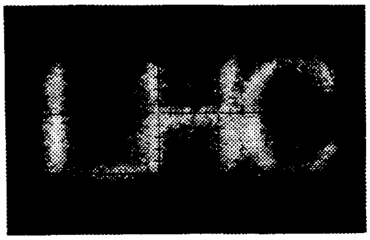


Figure 8 An example of two-dimensional images obtained in real time with 2 planes of hodoscope. The letters extend over an ≈ 8 x 20 $mm^2$ area.

From these results we can conclude that the present study using the commercially available PSPM constitutes a promising step toward designing a "high space & time resolution" detector.

## 2.2 Upgrade of the PSPM

As described in our proposal, the PSPM upgrade consists of improving commercially available PSPMs, such as R3941 produced by Hamamatsu Photonics, and of developing new PSPMs with finer grid dynodes built in the Mechanical Technology Division of CERN.

In order to meet the demands of high performance at high counting rates as well as in multi-hit detection, a modification of R3941 (3" x 3" square) has been done by replacing the crossed-wire anodes by 8 rows of 29 pad anodes. Two prototypes were delivered, and one was mounted in a new hodoscope for the study of two-hit resolution. The gain is ≈ 5 x $10^6$ at H.V. = 1.4 kV with a quantum efficiency of ≈ 18 % at 420 nm. The response curves of the anodes were measured by scanning the full range of the photocathode with a point-like source (LED). The results are shown in Figure 9. The uniformity of gain is about ± 30 %, except for the outer rows (1 and 8). The FWHM of the response curves is ≈ 8 mm as typically observed in this type of PSPM.

The first prototype of PSPM with a new dynode structure was delivered in May 1992. It consists of 10 dynode stages, each composed of 2 layers of fine grids staggered by a full width of the grid bars (each grid 0.2 mm wide) as shown in Figures 10 and 11-a. For simplicity, the prototype has 16 crossed-wire anodes in both the x and y directions aligned with interval of 2 mm.

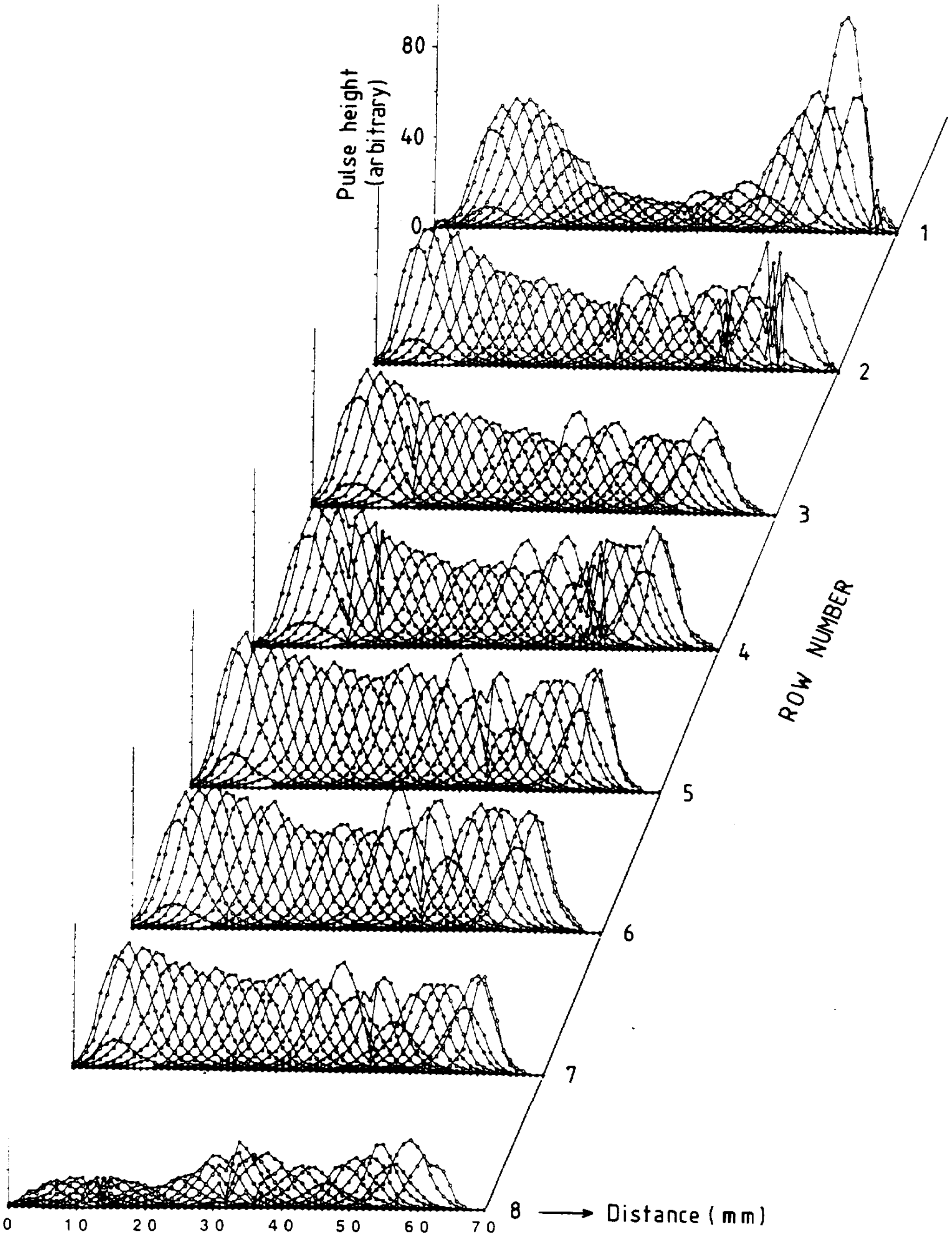



Figure 9. Curves of anode response vs. LED position for the R3941-Mod. PMT (8 x 29 pad anodes).

The PSPM quantum efficiency is $\approx$ 18 % at 400 nm. The gain with the proportional H.V. distribution, i.e. the potentials proportional to the distances between the grids, is at least the order of $10^5$ at 1.3 kV. We studied the variation of gain as a function of the potential difference between the 2 grid layers of the same dynode stage. Defining a factor $k$ as the deviation due to the potential difference from the proportional H.V. distribution (see Figure 11a), the total gain increases as shown in Figure 11b by a factor of 3 with respect to that with the proportional H.V. distribution. Figure 11-b shows also the variation of the relative gain per stage, $\delta g$. Such a variation of gain was expected from a Monte Carlo simulation carried out by us in 1988 [1].

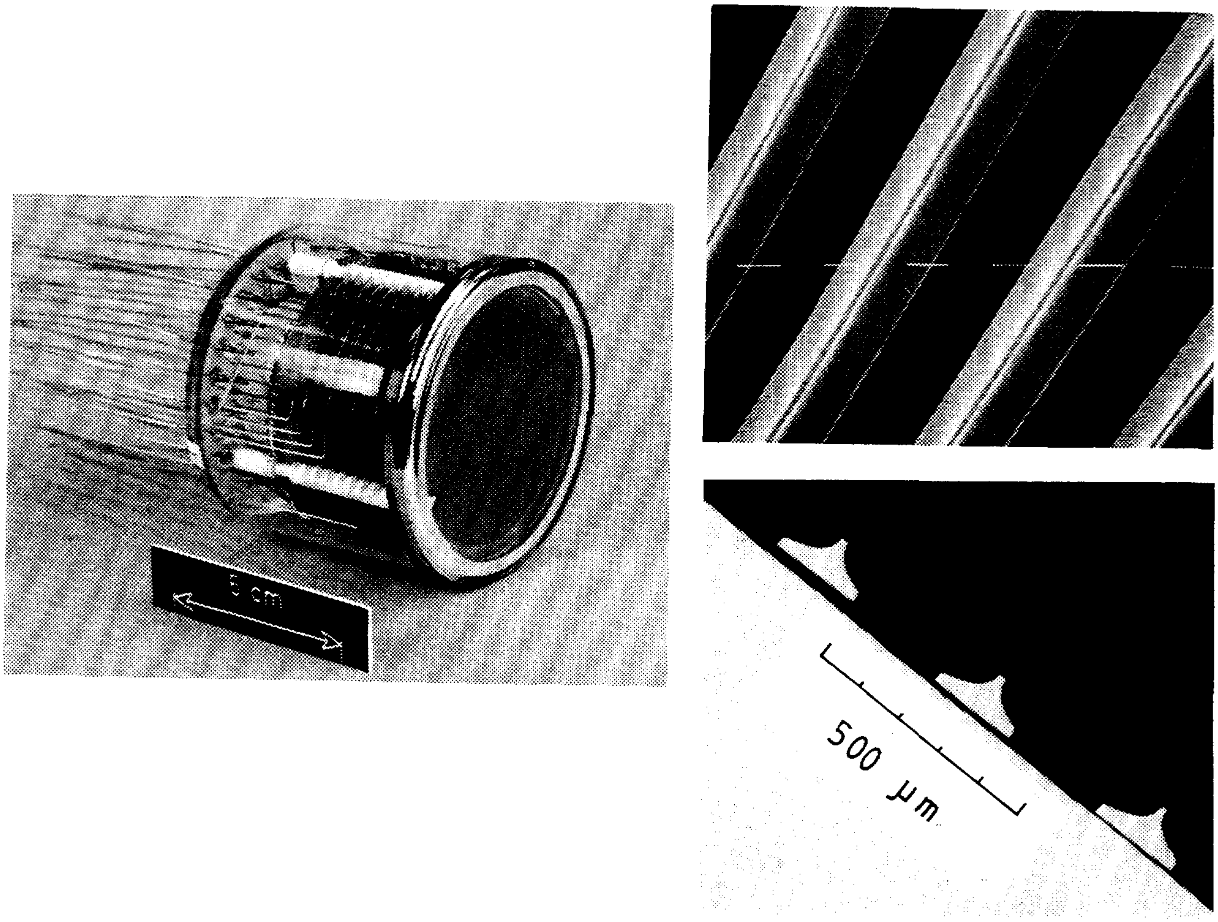



Figure 10. Geometry of the prototype PSPM (left), Plan view of the grid dynode. (upper right), and dynodes cross section (lower right).

Note also that the second prototype constructed by the IHEP collaborators has a gain of $\approx 5 \times 10^6$ at 1.8 kV.

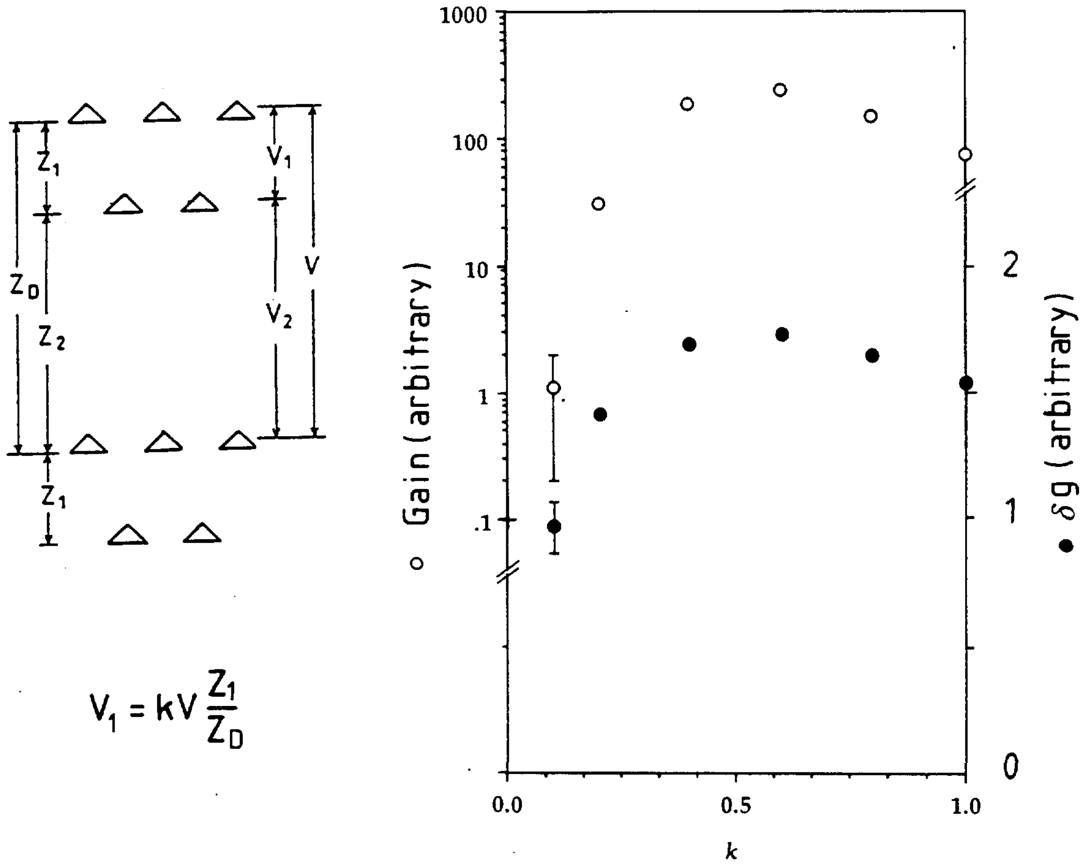



Figure 11. a) Cross section showing the bias potential between two grid layers of dynode stage: $k = 1$ proportional H.V. distribution, $k = 0$ short circuit between the layers.
b) Variation of the total gain, G, and of the gain per stage, $\delta g$, as a function of the bias factor $k$. (arbitrary scale).

## 2.3 Readout electronics

Our activity in this area has been organised in two ways: detailed studies of the delay-line RTD by means of a Monte Carlo simulation, and of a new type of digitiser based upon parallel readout.

a) Delay-line digitiser

Until now, a readout based on a delay line has been used for real-time digitisation. A delay line of less than 50 ns is well suited to the moderate intrinsic spatial resolution of the PSPM and the use of this purely passive element makes its readout simple, inexpensive, very fast and reliable. So far a rough estimation makes us think that the RTD based on the delay line is fully usable in the very high rate environment of the LHC. To check in more detail the applicability of this method to the LHC detectors, and to pinpoint the possible technical difficulties, we have started making a simulation study of the whole detector system.

Events are generated by ISAJET, and number of photons as well as the timing of those photons arriving at the photocathode of the PSPMs. A program already exists which simulates the electron multiplication inside the PSPM, which is known to be reliable, and reproduces well the measurement. This program permits us to calculate the response of each anode, and the current in the delay line as a function of time. Simulating the constant-fraction discriminator, and the rest of the logical chain, we can see how well the whole system can handle high rates, and how spurious combinations of hits are produced and can be excluded, and especially what the optimum length of the delay line.

The software is presently in the debugging stage, and will be operational by the end of this year.

b) Study of a new type of RTD

In addition to the above method, the possibility of a parallel read-out of all the anodes is being studied. This read-out system is required to be fast, having minimum dead time, and also must be easily integrable into a fast-trigger system. An electronic circuit based on the idea of the neural network is now being tried-out. Anode signals go through one or two hidden layers of artificial neurons, and then the hit points on the photo-cathode are determined from the sum of the non-linear responses of the last hidden layer.

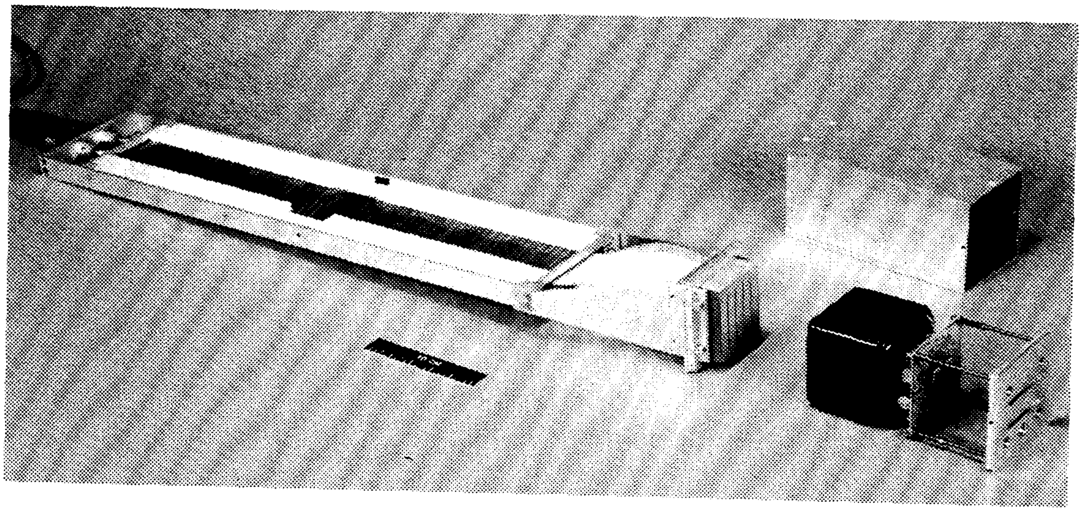
This method can easily take care of the irregularities in the anode responses, namely unequal anode gains and the edge effects. The result of a simulation study is promising. A prototype circuit with one hidden layer of 15 neurons with 5 anodes per neuron is under fabrication. The prototype is expected to produce hit positions each 10 ns. Further studies on the robustness of the system against noise, fluctuations and accidentals are under way.

## 3. Program in the year 1992-1993

The program in the second year is concentrated on improving the time characteristics of the whole readout system. This is necessary not only for high rate performance, but also for good reconstruction efficiency of multi-hit events in real time.

## 3.1 Study of new SciFi detector prototypes

Recently we have constructed two new prototypes using 3" x 3" square tubes (R3941 and R3941-Mod.). As shown in Figure 12 the first one, (designated type A) has a large sensitive area (60 x 500 $mm^2$) which allows us to extend the study on the basic characteristics such as the space resolution and the linearity of reconstructed position for a more realistic detector size. In particular, the dependence of the space and time resolutions on the light attenuation along the fibre length can be studied. Due to the larger surface of the photocathode, the edge effects mentioned in Section 2.1 are also minimised.



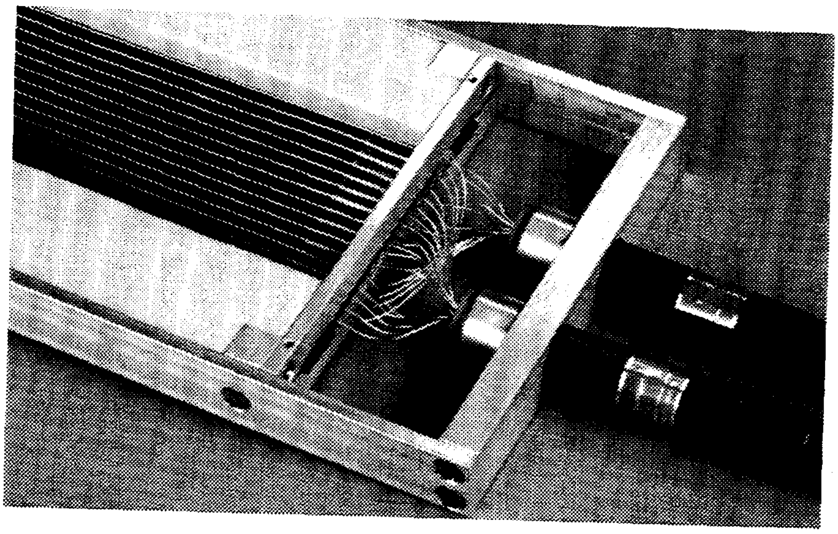


Figure 12. "Type A" hodoscope with large SciFi array (60 x 500 $mm^2$). The lower picture shows details of the definition fibres.

The second prototype (type B), will be used to study two particle hit resolutions. As illustrated in Figure 13, two-hit events can be simulated by a double array structure with one of the arrays movable with respect to the other. Both arrays are viewed by the same rows of pad anodes of the R3941-Mod.

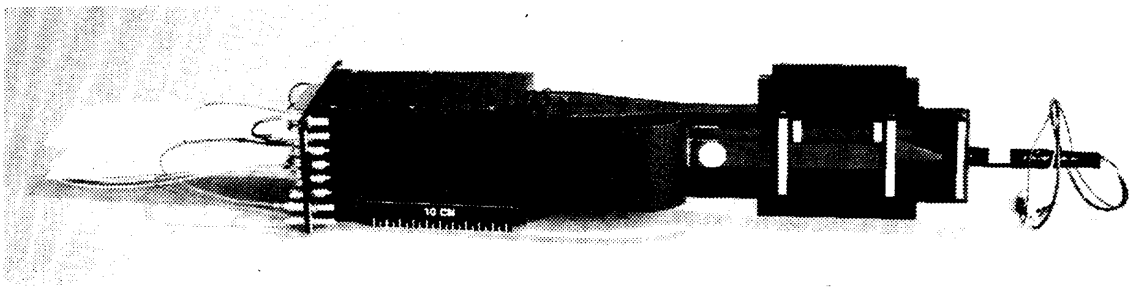


Figure 13. "Type B" hodoscope showing the two movable layers used to study two-hit resolution questions.

Both prototypes are already in the final stage of assembly. A systematic study of the two-hit resolution will start in the coming runs. Parallel efforts for improving the quality of the SciFi arrays as well as the time characteristics of the front-end electronics will be carried out.

### 3.2 Development of new PSPM

For the first prototype of new PSPM we plan to carry out an extensive study of the space resolution in a magnetic field. As a matter of fact, the dynode structure of this tube has been designed by scaling down by a factor of 2.5 the structure of the first generation PSPM (Multi-PM) working inside an axial magnetic field of 350 Gauss. Following the invariant property of the Lorentz equation under transformation of the space and time variables [2] this prototype should provide the intrinsic resolution of $\approx$ 1.2 mm (FWHM) in an axial magnetic field of $\approx$ 900 G.

In principle, one would rescale the electric field along with the physical grid dimensions, however, this is not possible due to voltage break down limitations (nominal voltage < 1.3 kV instead of < 4 kV for the Multi-PM). Even under these conditions, the optimum operation can be expected with a magnetic field of $\approx$ 500 G*, still promising the intrinsic resolution of $\approx$ 2 mm in FWHM.

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* This value simply comes from the quadratic relation between the electric field E, and magnetic field B, $B \sim E^{1/2}$, for the helicoidal focusing of electrons at a given distance.

For use in future prototypes with large photocathodes a new design of grid dynodes has recently been completed (see Figure 14). The preparation of dynode samples is in progress at the Mechanical Technology Division of CERN. First, 200 μm grids will be fitted inside a square 3"x 3" tube. Next we are planning to construct finer grids (100 μm) in order to further improve the space and time resolution of the PSPM.

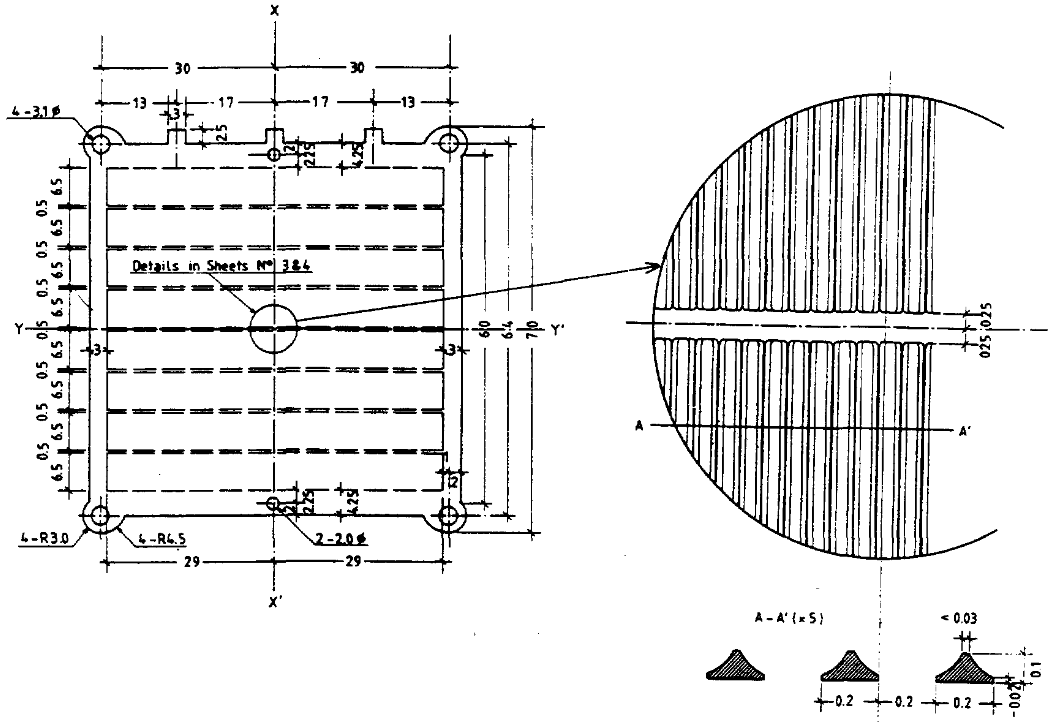


Figure 14. The new design of grid dynodes for 3" x 3" square tubes showing the layout of the dynode structure together with an expanded view of the grid structure.

The Kyoto-Sangyo University group has expressed a strong interest in the time characteristics of such an upgraded PSPM and a systematic study of this matter is being planned at their laboratory.

### 3.3 Readout electronics

a) Delay line method

Success in the performance of the two hit resolution relies upon the improvement of the front-end electronics. For example, the gain of the PSPM is presently rather low, $10^5$ -$10^6$, which requires an additional amplification of a factor ≈ 100. This means that the two-hit resolution strongly depends on the upper limit of the bandwidth. The major limitation in the pulse pair resolution is due to the shaping time constant of our linear amplifier (≈ 30 ns). In addition, the ORTEC module 934 constant-fraction discriminator (CFD) is limited to ≈ 10 ns between pulses. For this reason we intend to carry out a detailed study on the time characteristics of all the components of the RTD. In this connection, a promising advance has recently been developed with an amplifier developed at CRN/Strasbourg. Combination of such an amplifier with a faster CFD will be used in the coming runs. This study will be undertaken aided by the simulation program mentioned in Section 2.3a.

b) "Neuron" type digitiser

A full study of this digitiser is in progress. A prototype for 5 anodes interconnected to 15 cells (with one hidden layer) is presently under construction at LAPP. The first laboratory test is foreseen at the beginning of 1993. Preceding the Laboratory test, a simulation of such a digitiser will be completed under realistic conditions by using anode pulses from the PSPM, which are treated by a simulation program. The spatial resolution as well as the two hit separation will be studied in this way as a function of luminosity.

### 3.4 Funding profile and manpower in 1992-1993

The total equipment budget in 1991 and 1992 was about 260 kSF. As of July 1992 roughly 90 % of the budget had been spent or committed, half of which was for PSPM purchases.

For 1993 we request a global budget of 270 kSF, in which 20 kSF from CERN corresponds to the second part of the CERN contribution approved by the Research Board in April 1991. As shown in Table 2 the major expenses are dedicated to the upgrade of the second generation PSPM, and the fast electronic devices, which are of great importance to achieve our next milestones, high performance in two-hit position resolution as well as in high counting rate.

Table 2 . The 1993 budget.

| Description | Cost (kSF) |
|---|---|
| PSPM upgrade: 4 prototypes (from IHEP/H.Ph.) | 80 |
| Data Acquisition System | 40 |
| Front-end Electronics, Fast amp, CFD etc. | 50 |
| Test Instr., Fast electronics , MWPC etc. | 50 |
| SciFi detector prototypes | 30 |
| Consumables | 20 |
| **Total** | **270** |

Our activity in the year 91-92 consisted of the beam tests of the SciFi detectors and a certain number of "home tasks", such as R&D on the front-end electronics, tests of the luminosity and the light transmission of fibres and calibration of the PSPM prototypes. The main activity at CERN has been supported by a group of physicists (5) staying quasi-permanently at CERN, plus short-term but frequent visitors (5-6 per year) from the participating institutions. A similar situation is foreseen in the year 1992-1993 with new visitors from IHEP of 1 man-year. In addition, the collaboration extends to include a group from CRN-Strasbourg, who have already contributed not only to the beam runs, but also in their home institution.

Concerning the installation of RD-17 at CERN we have already profited from laboratory space of $\approx 28\ m^2$ and an office for 3 people allocated February 1992. However, taking into account the increasing number of visitors, and their corresponding needs, we request an expansion of our laboratory space to $\sim 50\ m^2$, and an additional office for 3 people.

Our request concerning the test-beam and computer time for 1993 is similar to that of 1992, that is about 8 weeks of T7-S beam time starting immediately after the next shutdown, and a computing time of 1000 CERN units.

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