MPS/BR/LIN/Note 75-12
10.4.1975.

MAGNETIC POSITION MONITORS FOR THE NEW LINAC [*] AND THE PSB INJECTION LINE

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1. Introduction

There is an operational need for beam position information in the line between the Linac and the PSB. For the new Linac project, it is intended to install monitors that depend on measuring the magnetic flux from the proton beam linking the detector. Such monitors are in use at BNL[1].

During the construction of the PSB, a prototype of an electrostatic position monitor was built and a series started but discontinued because of its poor performance. These monitors, which responded to the 200 MHz structure of the Linac beam, appeared to work properly in the laboratory when exposed to an antenna supplying 200 MHz radiation but failed to give comprehensible results when installed in the beam line. In particular, the sum signal often had a strong amplitude modulation, not related to beam intensity, over the 100 μs of the Linac pulse but which seemed to be related to the adjustment of the Linac r.f. system. It was never clear whether this effect was due solely to the beam properties or was related to the electronics for obtaining the position information from the 200 MHz signal.

Because of the difficulties in investigating further, the impossibility of having a calibration facility and the limited operating range of these devices, the series was discontinued and a prototype for a magnetic position monitor was constructed. This type of monitor is simple, robust, and does not have any component inside the vacuum system.
It can also be supplied with a calibration pulse. Its chief disadvantages are sensitivity to pulsed low-level magnetic fields and the lack of an inherent beam current measurement to normalize the observed signal.

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[*] PS Project No. 0040 approved at MAC meeting No. 75-15.

The first drawback can be overcome by magnetic shielding together with electronic subtraction of any residual background while the second is countered by using signals from nearby beam current transformers already installed.

2. Description of the monitor

An assembly drawing is shown in Fig. 1. The unit, which houses separate detection loops for horizontal and vertical displacements, fits in a 600 mm length of the injection line. A rectangular ferrite frame surrounds each loop which has a length of 14 cm along the beam direction. Each loop is threaded through a toroidal current transformer. This double assembly is enclosed in various shielding boxes, two of mu-metal, one of mild steel and one of aluminium. A ceramic vacuum pipe, with attached bellows and flanges, completes the monitor.

3. Principle of operation

To understand the operation of the monitor, one starts by considering two infinite conductor sheets shown in Fig. 2a. Assume that the proton beam is an infinite sheet parallel to and between the conductors.

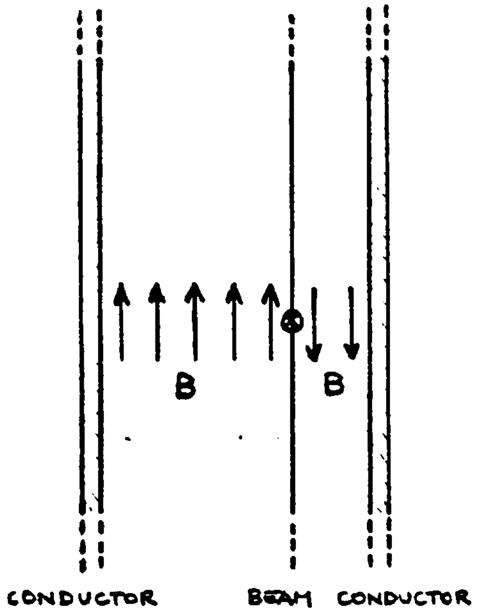


Fig. 2a.

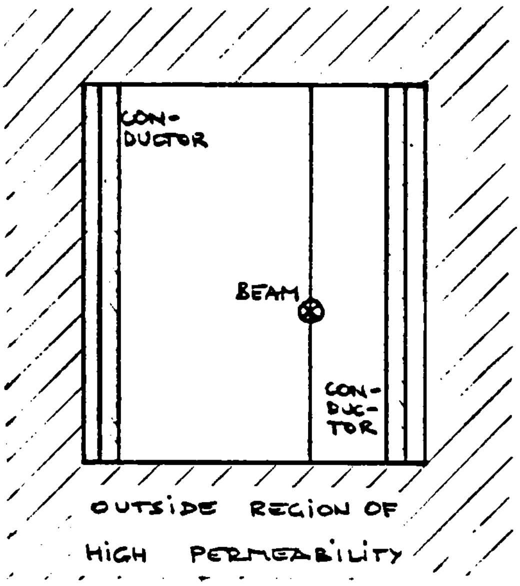


Fig. 2b.

The magnetic induction, between the conductors, due to the beam must be everywhere parallel to the current sheet and therefore uniform. The flux linking the circuit (closed at infinity) can be seen by inspection to be proportional to the product of the beam's intensity and its displacement from the mid-line of the two conductors. By placing a magnetic material around the region of interest, we arrive at the configuration shown in Fig. 2b. Exactly the same argument as before is valid in the air region inside the magnetic material. Slabs of high-resistivity ferrite are used in practice for this purpose.

If one replaces the current sheet by a line, it is not obvious that the relation given above holds because now one has no simple way of calculating the flux threading the loop although it is to be expected that the induced current depends on the displacement. However one can show, using the reciprocity theorem that the same result holds:

Consider the two circuits below.

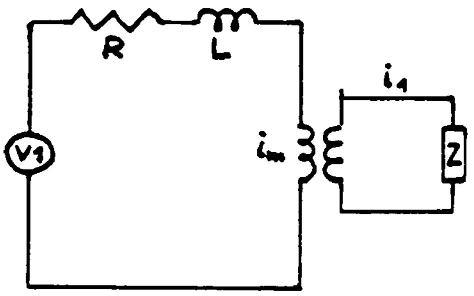


Fig. 3a.

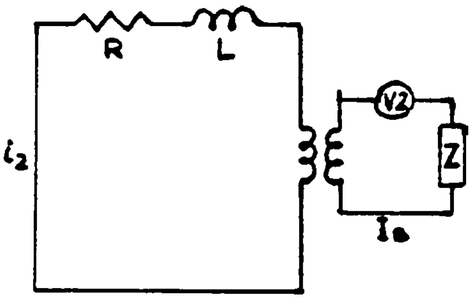


Fig. 3b.

Circuit b (Fig. 3b) is a model in which the proton beam ($I_B = V_2/Z$) is coupled to the detector which has an inductance, L, and resistance, R. In circuit a (Fig. 3a) one has the same circuit except voltage V_1 causes a current i_1 in the circuit modelling the beam (Z, we will see, can be arbitrarily high).

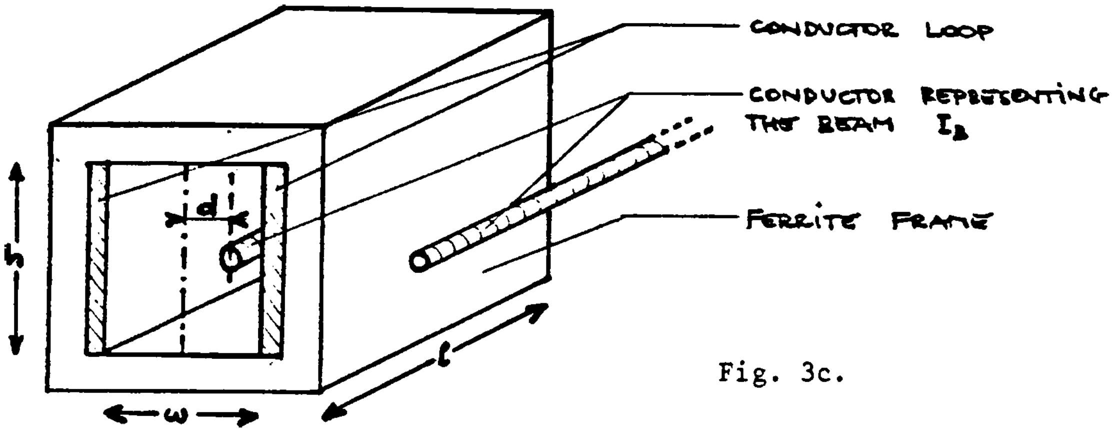


Fig. 3c.

From the reciprocity theorem

$$V_2 i_1 = V_1 i_2 \tag{1}$$

To calculate i_2 without this relationship we would need the detailed magnetic field due to the beam in the detector. However, to calculate i_1 is relatively easy. We have simply the configuration of a "window frame" dipole.

$$i_1 = (1/Z).d\phi/dt$$

$$B = \mu_o H = (\mu_o i_m n)/h$$

assuming a uniform field formed by a winding of n turns. A step-function V_1 applied to the dipole results in

$$i_m = (V_1/R).\left[1 - \exp(-t/t_o)\right]$$

where $$t_o = L/R$$

For a "window frame" magnet;

$$L = (\mu_o \ell w n^2)/h = n^2 L_o$$

$$R = n\, R_o$$

where R_o and L_o are the resistance and inductance for a single turn.

$$d\phi/dt = (Ld/n\omega).di_m/dt$$

$$= (V_1 d/n\omega).\exp(-t/t_o)$$

From (1)

$$V_2 i_1 = (I_B Z).\left[(V_1 d/n\omega).\exp(-t/t_o\right]/Z$$

$$= V_1 i_2$$

$$i_2 = (I_B d).(1/\omega n).\exp(-t/t_o)$$

where i_2 is the detector response to a step function beam current I_B displaced from the center by d.

The initial output voltage is

$$V_{det} = n\ R_o\ (I_B d).(1/\omega)$$

and the time constant

$$t_o = n\ L_o/R_o$$

Clearly there is an advantage in having many turns, but this leads to a difficult construction. A more practical approach is to make a single turn loop linked to a current transformer. Using a commercially available transformer we get effectively 500 turns as far as the output voltage is concerned with the time constant remaining within usable limits (400 - 500 µs).

Because we require the monitor to fit in a length of 600 mm, we have a ratio of aperture to length for the ferrite frame ≈ 1. Just as a "window frame" magnet with these dimensions would have end-effects causing a deviation from a pure dipole, so the monitor has a slightly non-linear response and a small dependence on the displacement in the orthogonal direction.

4. Performance specification, signal treatment

We aim to be able to detect a shift of beam position of 0.1 mm for a 50 mA beam. The absolute beam position accuracy is set by the construction and alignment tolerances. We think that ± 0,25 mm is sufficient for all applications in the 50 MeV line.

The first requirement leads to a minimum detectable signal of 2 μV. This then is the noise level to be achieved referred to the input of the amplifier. We do not require a very large bandwidth; 3 MHz should be adequate. If the amplifier gain is 1000, we get a minimum signal of 2 mV for observation on an oscilloscope or the current to an A/D converter. For the new Linac project a maximum signal of 5.12 volts is to be used giving a range of 1:2560 for the output signal e.g. the maximum displacement for a 200 mA beam will be 38 mm before the capacity of the A/D converter will be exceeded. This is also a reasonable level for linear treatment of the analogue signal.

A section must also be included in the amplifier to correct for the decay of the response to a step function. This can be done with an active filter using an operational amplifier. The analysis of the previous section assumes that the decay is exponential i.e. L_o and R_o are constant. In fact this is not true for R_o. For the monitor as now proposed, the appropriate value of R_o depends on the insertion loss of the current transformer (0.0002 Ω) in series with the resistance of the loop. Because of the finite time required for the current to diffuse into the copper sheet, we find that this term changes appreciably. We can approximate the decay to the sum of two exponential decays and make the required filter network to correct for this.

During the tests with the prototype it was seen that it is difficult to shield against the fields from nearby pulsed magnets. Improved magnetic shielding is planned for the series but it was felt that a further solution would be required to meet all eventualities both expected and unexpected. The magnetic fields from the pulsed magnets change relatively slowly during the Linac beam time. Consequently, a circuit has been proposed and developed which detects the amplitude and slope of the background signal before the Linac beam is due and uses these values to make a subtraction during the Linac pulse. The results for the prototype are shown in Fig. 5.

5. Prototype performance with and without beam

A series of experiments have been carried out with two different position monitor prototypes. The monitor is not sensitive to high frequency components (i.e. 200 MHz bunch structure), therefore beam simulation in the laboratory is straightforward: put a wire through the monitor, send a current pulse through it and look at the output signal as a function of wire displacement.

A spare PSB injection line steering dipole - pulsed with half-sine wave of 4 msec length - was used in the laboratory experiment in order to study the pick-up of time varying magnetic stray fields. Even with shielding (1 layer μ-metal, one layer of mild steel and one layer Al) the pick-up was of the same order as the beam signal. This stray field induced signal depends on

i) distance r between dipole and monitor ($\sim \frac{1}{r3}$ was measured as expected for a dipole field),

ii) the extent of the μ-metal shield along the vacuum chamber (extension to diameter ratio of 0,7 seemed to be adequate). Main results of these laboratory tests are summarized in the following table.

Parameter	Prototype 1		Prototype 2
Simulation beam pulse		100 mA/100 µsec	
Monitor length (mm)	250		130
width (mm) = height		170	
Current transformer (V/A)		.1	
Theor. sensitivity (µV/mA mm)		.588	
Measured sensitivity (µV/mA mm)	.412		.397
Noise level after amplifier		~10 mV	
Corresponds to		~25 (mA*mm)	
Linearity within ± 50 mm	Better than 1%		~1%

Table 4.1. Summary of laboratory test results of prototype position monitors.

Note that the performance of both monitors is sensibly the same. The calibration line output signal vs wire position for horizontal prototype monitor 2 is given in Fig. 4. Linearity has been measured also by vertical displacement of the test wire in a horizontal monitor.

Is there any cross-coupling if one wants to combine horizontal and vertical monitor into one unit? Putting 2 monitors (galvanically isolated) together (as planned for the operational device) did not result in any mutual influence.

During the last running period 1974 prototype 1 was put into the PSB 50 MeV injection line in a particulary "noisy" place: 1 m up-stream the vertical distributor and adjacent to a pulsed steering dipole. The monitor was shielded by a µ-metal screen, an Al-screen and a screen of mild steel. (Note: inadequate end shielding, known beforehand) Results:

i) High frequency (a few MHz) stray fields created by vertical distributor well visible,

ii) Pick-up induced by pulsed steering coil is indeed of the order of the beam induced signal. However, as the beam duration (100 µsec) is short compared to the steering coil pulse length (4 msec), the latter generates a "base line" distortion of more or less constant slope during signal time (see Fig. 6).

iii) The sensitivity of the monitor was checked by displacing a 50 mA beam and controlling its position on a TV screen. Within the precision of this measurement (± 5%), the sensitivity corresponds well to the figure given in Table 4.1 for prototype 1 (see Fig. 7).

6. Operational aspects for the PSB

In what follows we discuss positioning, diameter and utilization of the monitor for the PSB Injection line.

At present, the beam is steered through the line essentially by looking at the television screens. These lack precision and destroy the beam. Electrostatic pick-up monitors are installed at present in four locations between I-BH2 and I-DIS (I-U4 to I-U7, see Fig. 8), all of them near steering coils (the idea being that a given steering dipole is used for adjusting the beam position in the next monitor down-stream). Two monitors per level downstream I-Q12 were planned, but never installed for reasons discussed in chapter 1. They would allow determining position and angle in both planes of the incoming beam at PSB injection: In the vertical phase plane for minimizing ε_v of the circulating beam, in the horizontal phase plane for optimizing the multiturn injection efficiency which is particularly sensitive on steering. On top of this, proper centering of the beam would allow for modifying the matching conditions at the injection point without changing the steering, which is impossible for the time being.

We propose to install magnetic position monitors (for both planes) in all locations U3 to U9 (Fig. 8), i.e. 12 monitors. TV8 would be replaced by U8. As a minimum requirement, we think one could live with 2 monitors only (I-U4 and U7) up-stream I-DIS, but U8 and U9 should be maintained (10 monitors). Although the lever arm between U8 and U9 is short (~2,6 m), determining the beam angle with a precision of 0,1 mrad should be feasible.

For the PSB injection line, the policy was adopted to stream-line all apertures to a 40 π beam in both planes. A monitor with circular aperture of 120 mm may be put into any location of the line without violating this requirement for the various PSB matching conditions.

The output signal of the monitor is proportional to the product (current * position), therefore we have to know the beam current in order to determine its position. Instead of including a beam transformer proper into the device, we think it is sufficient to compare the detector signal given by the monitor to the signal of the beam transformers nearby: I-TR3 as current measure for U4 to U7 and I-TR4 for U8 and U9. Each monitor will be equipped with a calibration wire, corresponding to a certain beam position. A pulse will be sent through this wire prior to beam arrival, in order to check electronics and signal treatment.

Analog observation of all 24 signals in MCR Booster will be available via the injection line multiplexer, which is also used for beam transformers. This device is going to be modified anyway in order to cope with a larger number of signals, to extend its bandwidth to ~5 MHz as well as to improve linearity up to ± 2.5 V signals.

7. Computer acquisition, installation and maintenance for the PSB

Computer acquisition of the PSB injection line current transformers I-TR3 and I-TR4 is operational, giving the total number of protons in each PSB level prior to injection. Since these will be used as "Σ-signal", the same technique is proposed for the position monitors: digital acquisition of the signal integrated over the pulse length ("Δ signal"). The controls computer evaluates the mean beam position Δ/Σ. However, detailed design of the acquisition electronics will be possible only after the decisions on the new PS-PSB control system have been taken.

Installation of the monitors will be eased by the fact that vacuum chamber pieces of 600 mm length are installed in the locations foreseen for these monitors. Cables of sufficient quality (RG216) are laid, as well as cables for the calibration pulse. Two single units or one stack may be installed during a short shut-down.

The overall responsibility for (i) the computer acquisition, (ii) the installation, (iii) the mechanical and electronics maintenance will be taken over by the BR Electronics Team (G. Gelato).

7. Price estimate, time scale, manpower

Prices per unit

Item	Price (SFr.)	Company	Delivery
Ceramic	2000.-	English Glass	16 - 18 weeks
Flanges, bellows, transition pieces	760.-	Calorstat + CERN	3 months
Coil	1000.-	CERN	<5 months
Support + alignment gabarit	2850.-	CERN	<5 months
Outer screens + substructure	2000.-	CERN	<5 months
Transformers	1500.-	Pearson	<5 months
Ferrites	750.-		5 - 6 months
Amplifier + signal treatment + calibration circuit	1500.-	CERN	<5 months
Price per unit	12360.-		

Supports

a) For stacked units

Support for 4 stacked units	3500.-
Feet + alignment facility with target	900.-
(For 4 units)	4400.-

b) For single units

Standard quadrupole table	750.-

Common costs

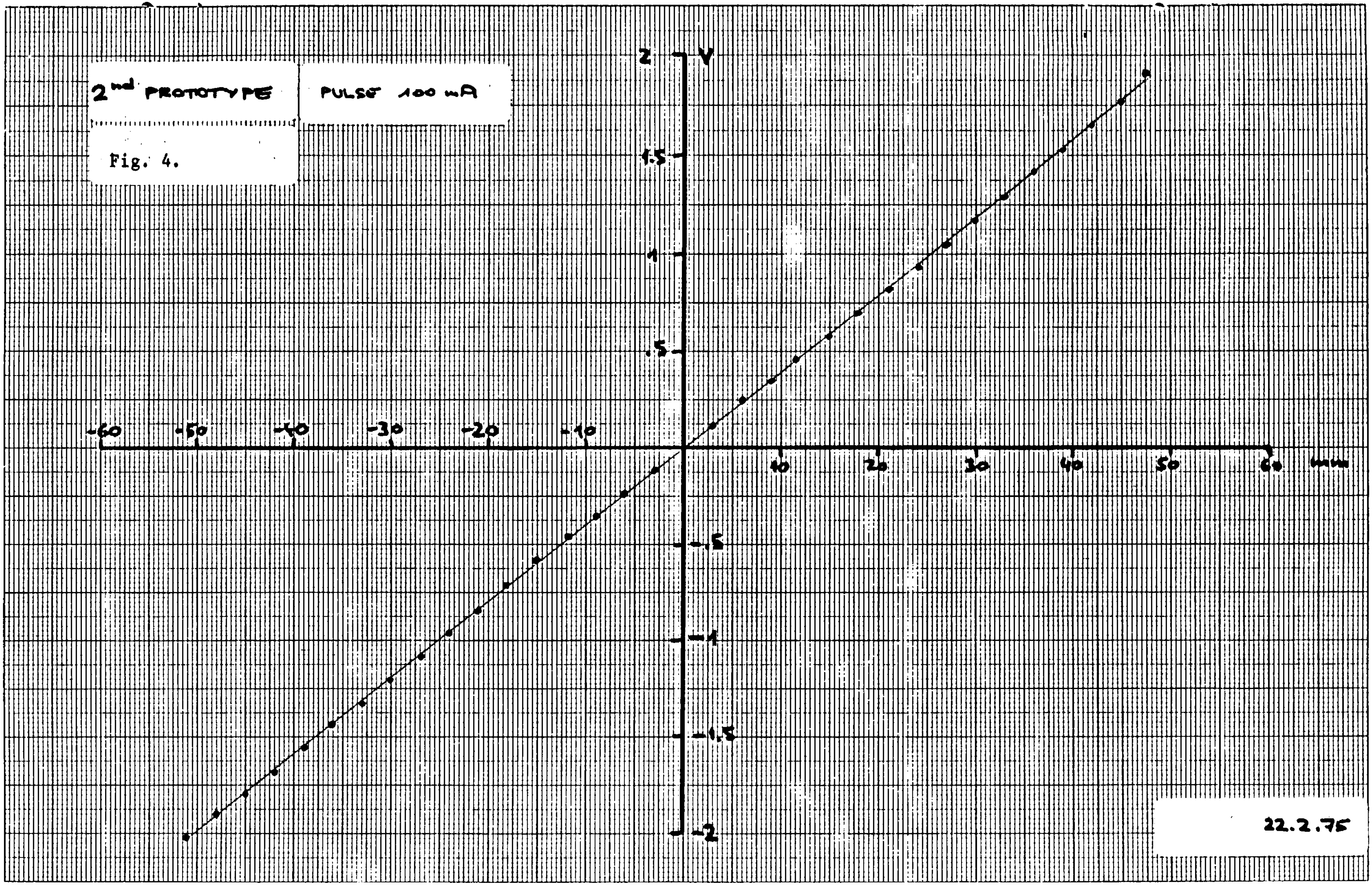
Mech. design, detail drawing 1 month regie labour	5000.-
Assembly of 20 units assuming all components delivered completely finished.	
1 month regie labour	5000.-
Contribution to improvement of signal transmission BCER-MCR	5000.-
Computer acquisition (conversion electronics + CAMAC, rough estimation) for 12 PSB units	40000.-

Reference

1. J. Claus, A magnetic beam position monitor, IEEE Vol. NS-20, No. 3 (1973), p. 590.

Distribution (open)

List PS/9



2nd PROTOTYPE

PULSE 100 mA

Fig. 4.

22.2.75

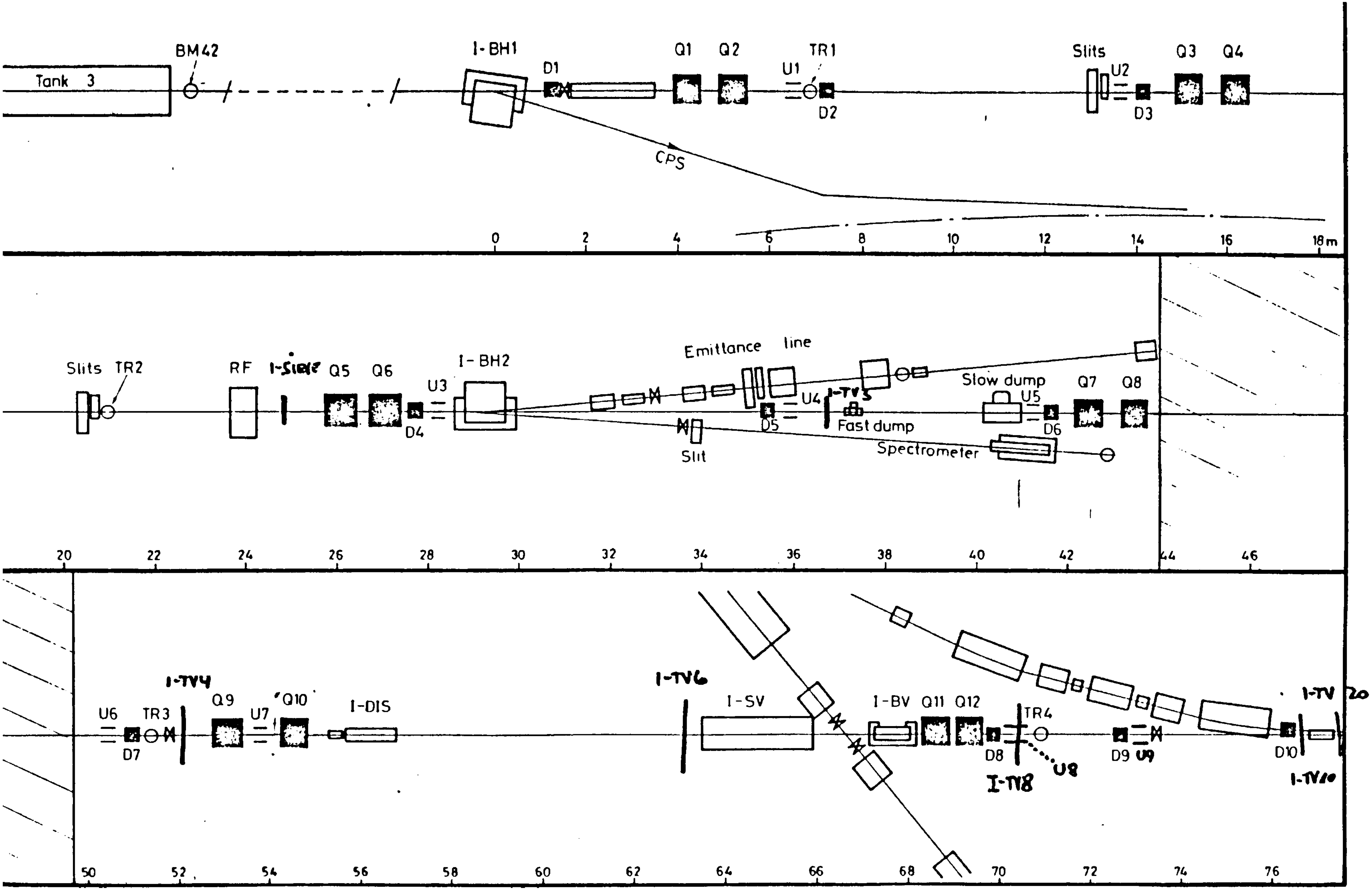


Fig. 8. LAYOUT OF COMPONENTS IN P.S.B. INJECTION LINE

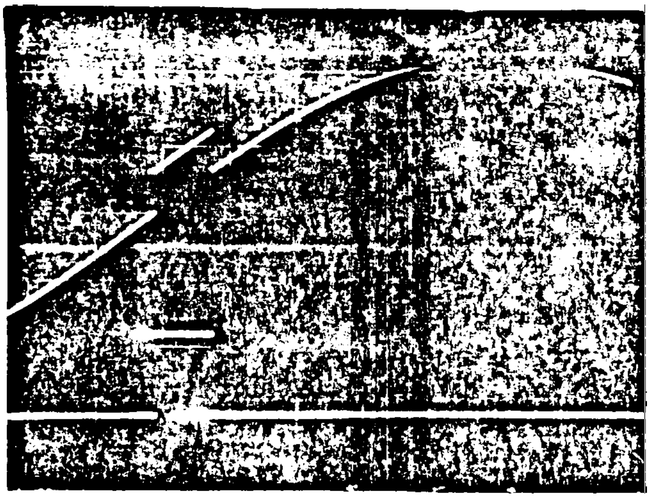


Fig. 5. Effect of circuit for background suppression during beam pulse.

Upper trace: beam signal + background.

Lower trace: beam signal, background subtracted. 100 µsec/DIV

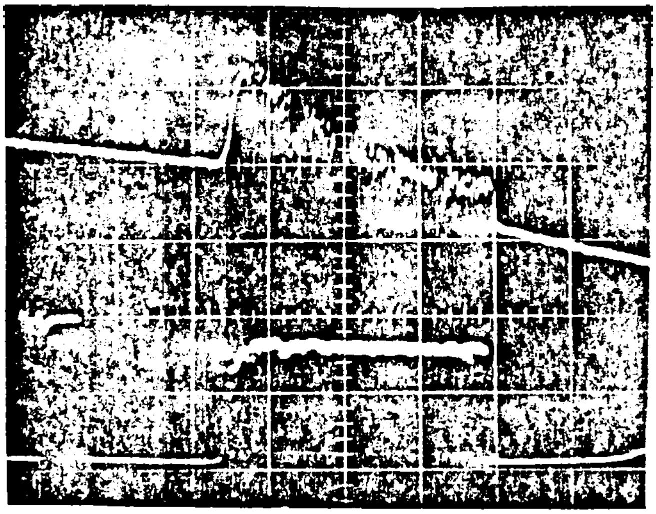


Fig. 6: Position monitor signal in beam (upper trace, 50 mV/DIV) and beam transformer signal I-TR1 (100 mA calibration pulse in front of the signal). 20 µsec/DIV. Distributor on, adjacent dipole pulsing.

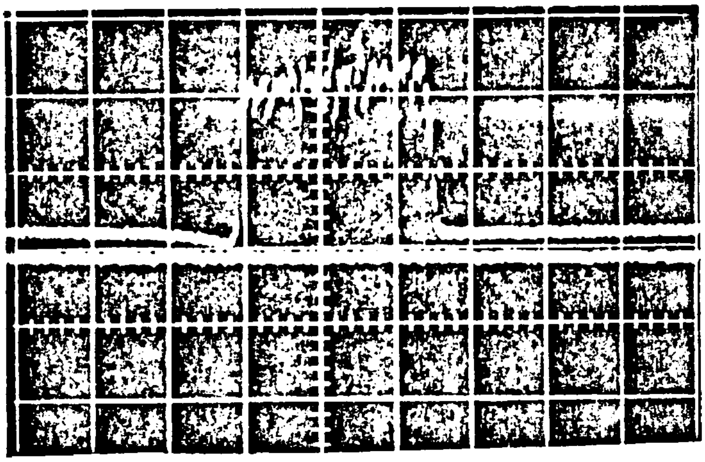


Fig. 7: Position monitor signal of a 50 mA beam displaced by 30 mm. 50 mV/DIV, 20 µsec/DIV. Distributor off, adjacent dipole pulsing.