EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

COMMENTS ON CHARGED PARTICLE DETECTORS FOR THE $\bar{p}p$ LARGE SOLID ANGLE DETECTOR

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1. Introduction

The transformation of the CERN SPS into a $\bar{p}p$ storage ring will open a new field of research at very high energy and it is generally agreed that a very large solid angle detector should be installed in one interaction region both for the observation of expected phenomena such as the production of W's, large p_T jets etc. and for the study of unexpected surprises.

An essential part of this apparatus will be the charged particle detector which could have three functions:

- Pattern recognition
- Measurement of the momentum of individual tracks
- If feasible, measurement of the mass of some particles through dE/dx.

In this note, we comment on the various methods to build such a detector. In particular we study in detail the concept of projection chambers, which is quite appealing for our application, and try to point out the important developments necessary before adopting this method.

We consider both the cases of a dipole field and of a solenoidal field (Ref. 1). In order to be more specific, we consider a magnetic field volume which is in a cylinder, with its axis parallel to the beam, a length of 6 m and a radius of 1 m. We assume a magnetic field of the order of 1.5 Tesla. We do not consider the 'lever arm' chambers which could be outside this volume.

Let us just outline the physics requirements:

1.1. Pattern recognition

The density of information should be as high as possible. There are many reasons for this:

- Multiplicities are in general high (> 20 charged).
- Particles may be highly correlated for instance in jets.
- Low momentum tracks can spiral in the detector.
- Tracks can have a small angle with respect to the beam pipe and therefore be fairly short (on one projection).
- We would like to see newsemi-stable particles signed by V^o and charged V's.
- Finally the background may be high and confusing (see section 1.4).

More generally, since our detector will be an exploratory device, it should give, as a bubble chamber, the maximum amount of information.

Two details of construction may be important for the easiness of reconstruction:

- The density of the charged particle detector should be kept as small as possible in order to limit the number of γ ray conversions.
- If possible chambers should give directly space points in order to limit pairing ambiguities.

1.2. Momentum measurement

The spatial accuracy should be as good as possible, in order to allow to shrink the detector: this decreases the cost of the magnet and of the surrounding equipment, limits the π-μ and K-μ decays and reduces sensitivity to background. A r.m.s. error on the sagitta of 100 μ seems a reasonable target in agreement with the mechanical tolerances which could be achieved on large dimensions.

Two-particle resolution also should be maximised. In a two-jet decay of a W (Ref. 2), there will be about 10 particles per jet with a mean opening angle of 80 mrad. For more quantitative statement, one could look at figures 1a) and 1b) (taken from Ref. 3b). They consider two-jets at lower energy (2 x 15 GeV) for which the mean opening angle is 160 mrad. Two particle resolution of 0.5 cm or so is very much desirable especially

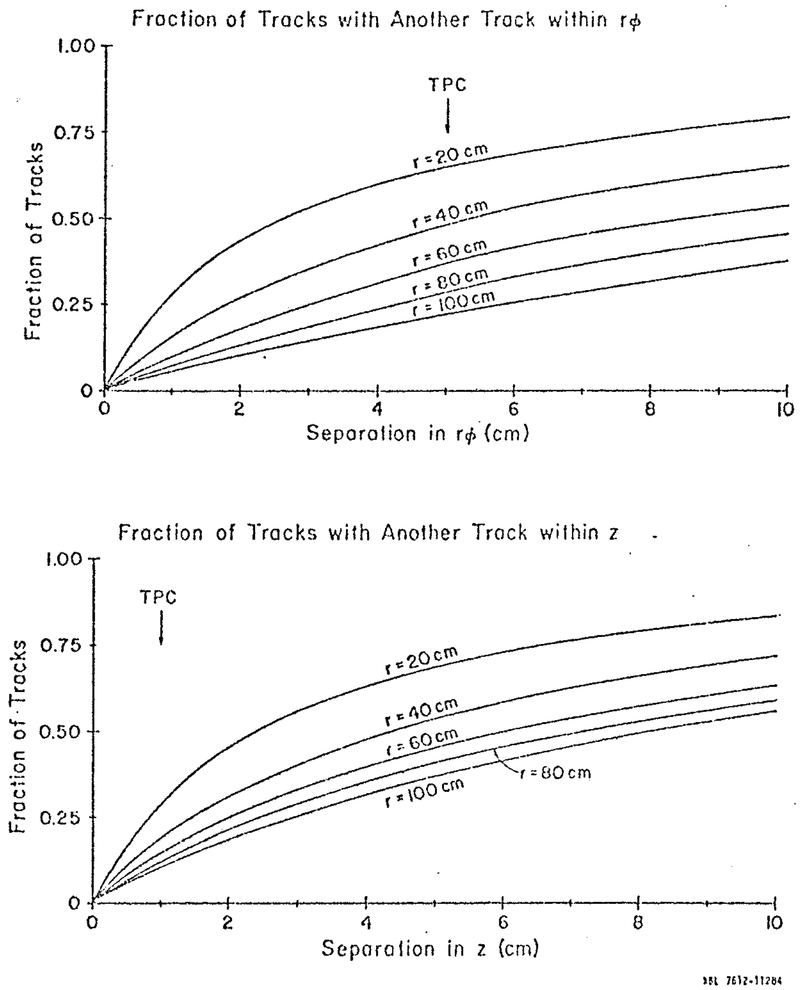


Fig. 1. Fraction of tracks with another track within:
a) rφ (Direction perpendicular to beam
b) z (Direction parallel to beam).

in the projection where the momentum is measured.

1.3. Measurement of dE/dx

We have seen in point 1.1 that it is necessary, in order to reconstruct complex events, to have a large density of points. This large number of samples could be advantageously used for ionisation loss measurement. This will allow us to identify quarks or very heavy particles, help in e identification at low energy and allow some π to K separation through the use of relativistic rise.

The dependence of the resolution, on the number of cells and thickness have been studied by many groups (Ref. 4 and 3b). Fig. 2 shows the expected behaviour for Argon according to Aderholz et al.

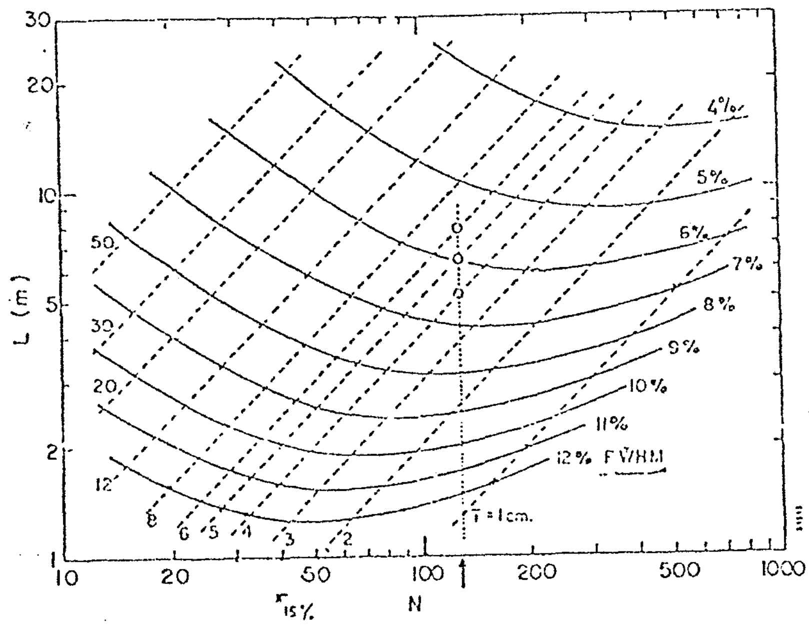


Fig. 2. Expected behaviour of $\frac{dE}{dx}$ resolution as a function of the number of samples N, the thickness T of each sample and the total length L.

In our case, we will have typically 1 m of track, and could expect in Argon, resolution of the order of 13% FWHM, with a number of cells between 50 (2 cm samples) and 120 (1 cm sample). Since the relativistic rise is about 1.54 (Ref. 4b), this will allow separation of a proton of 60 GeV and a K of 30 GeV from a relativistic π (1 FWHM i.e. poor separation).

It would be interesting, as suggested by Sauli during the workshop to use Xenon for two reasons:

- The relativistic rise is significantly higher (1.73 compared to 1.54 see Fig. 3).
- It has a much higher number of non-electron pairs produced per unit length (a factor 3.3). Naively, at least, this should be equivalent to an increase of pressure by the same factor and allow a significant gain in resolution. 100 samples of 1 cm would give, with this simplifying hypothesis, 8% FWHM.

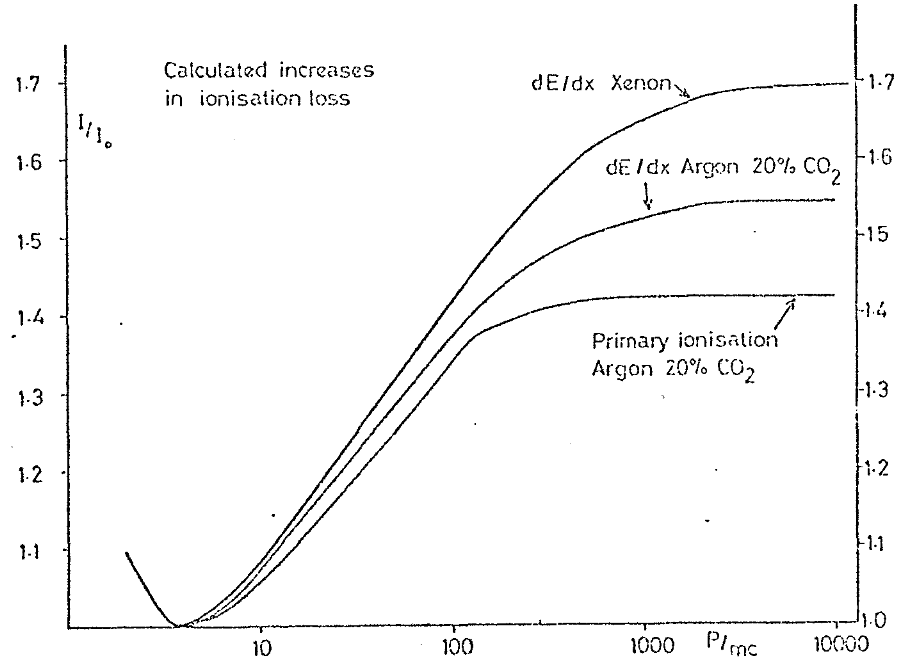


Fig. 3. Relativistic rise according to Cobb et al.

The combination of both effects may allow to have π to K separation up to 120 GeV/c (1 FWHM) and may justify the complication of a recirculating gas system. As a warning to this optimism, we should however mention the theoretical result of Cobb et al. which for their condition (5m, 1.5 cm sample) do not predict any increase in resolution.

1.4. Rates

In order to estimate expected rates in the detector, we should take into account both the interaction rate and the background.

Assuming σ_{TOT} = 100 mb as the total cross-section and $L = 10^{30} cm^{-2} s^{-1}$ as luminosity, we will have 10^5 interactions per sec.

A cylinder of 1 m radius and 6 m length, covering therefore 4 units of rapidity, will receive about 8 charged particles per interaction. Therefore, on the periphery of the detector, the rate will be:

$$\frac{8 \times 10^5}{2\pi\, r\ell} \simeq 2\ 10^4 \text{ part./s/m}^2$$

At 10 cm however the rapidity range is about 8 and the rate:

$$\frac{16 \times 10^5}{2\pi\, r\ell} \simeq 4\ 10^5 \text{ part./s/m}^2$$

For the background evaluation, let us assume a beam lifetime of 24 hours (we expect a luminosity lifetime of this order). With $2 \times 1.5\ 10^{12}$ p + $\bar{p}$ this lead to a loss of 10^7 part/s over the whole circumference of the SPS or if the loss is constant around the machine, to 10^5 part/s in the ± 35 metres surrounding the interaction region. It can be safely assumed that the remaining of the straight section can be shielded properly. Therefore, if we can prevent the lost particles to begin to shower, the rate induced by the background will be smaller than the one due to interaction. If, on the other hand, we assume that particles produced at more than 10m indeed shower and produce individually 300 particles in a cone of 0.3 radian (approximate condition at shower maximum, therefore a gross upper limit), the density of particles will be at the detector:

$$\int_{10}^{\infty} \frac{10^5\, dx}{70\, x^2} \times \frac{300}{2\pi \left[1-\cos(.3)\right]} \sim 2\ 10^5 \text{ part/s/m}^2$$

In conclusion, for safe operation, the charged particle detector should be able to accomodate rates of the order of 10^6 part/s/m^2.

1.5. Bunched beams

For some details of implementation, it is important to note that the zero time is known with accuracy. This means also that the background has the same timing as the interactions.

The revolution period in the SPS is 23 μs, and it is likely that we will have a maximum of 6 bunches. There is therefore a minor advantage to have devices with memory time smaller than 3.8 μs.

1.6. Why proportional chambers?

The rates we have just given are not very high and would in principle, be taken by relatively slow devices such as spark chambers and streamer chambers. However, we will not consider these types of detector in this note, because of their drawbacks with respect to proportional chambers:

- They have to be triggered with external devices.
- The triggering has to be fairly elaborated because the repetition rate is limited to few times a second (10-20) while with proportional counters, we could have a multi-level trigger allowing the selection of very specific configurations.
- Their performances depend quite sensitively on the angle of the particle (double sparking, flares).
- The accuracy of spark chambers may not be as good as some drift chamber or bidimensional chambers.
- Finally spark chambers may have problems with large number of close-by particles.

However, for a first stage at low luminosity, a streamer chamber could be very well adapted to a first look at a typical event.

2. Discrete chambers

The 'traditional' way of equipping a charged particle detector is to fill the magnetic field volume with discrete proportional or drift chambers with a total gap typically of 2 cm. However, with frames, supports, connectors, electronics, cables, it is difficult to pack more than 20 to 30 chambers per metre. This implies that for most tracks we will have only 40 samples of 2 cm and according to Fig. 2, this gives

$\frac{\Delta E}{E}$ = 15% FWHM.

A possible arrangement of chambers in a solenoidal or a dipole field is sketched in Fig. 4a) and b) respectively. Among the many possibilities, we have looked more specifically into two methods:

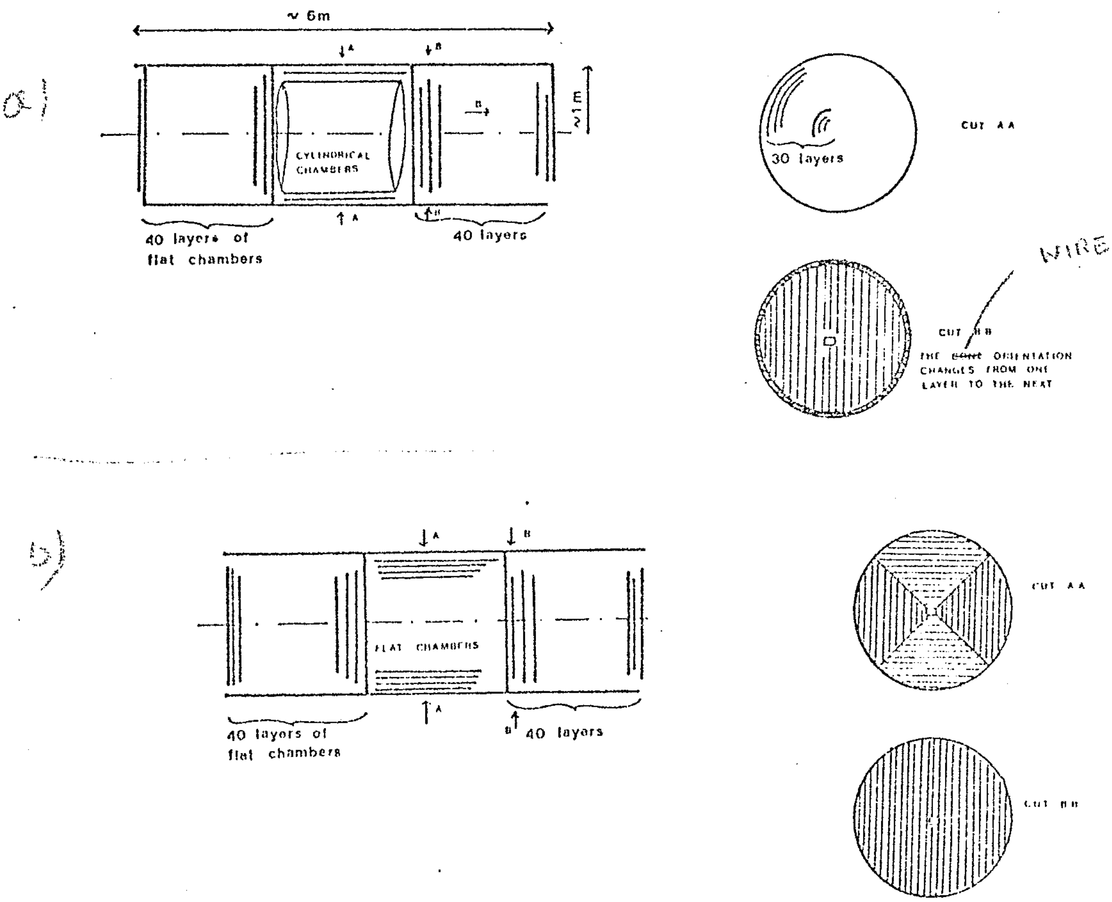


Fig. 4. a) Possible arrangement of discrete chambers in a solenoid.
b) Possible arrangement of discrete chambers in a dipole.

a) Use of traditional drift chambers without field shaping and with measurement of the longitudinal coordinate through cathod strip read-out. The pairing can be done by time measurement on the strips. With 2 cm wire spacing, 1 cm cathode strips, 30 layers in the central region and 40 in the forward direction, we compute 12 500 sense wires and about 25 000 strips for a solenoid. For a dipole we obtain a very similar number of channel (40 000).

The advantage of such technique is that it uses by now standard electronics and has been demonstrated to achieve 100 μ r.m.s. resolution even on large dimensions (Ref. 5).

b) Use of 'bidimensional proportional chambers' proposed by Charpak, Sauli and coworkers (Ref. 6). Very high accuracy (50μ r.m.s.) can in principle be achieved by analysing the signal on the cathode strips (Fig. 5).

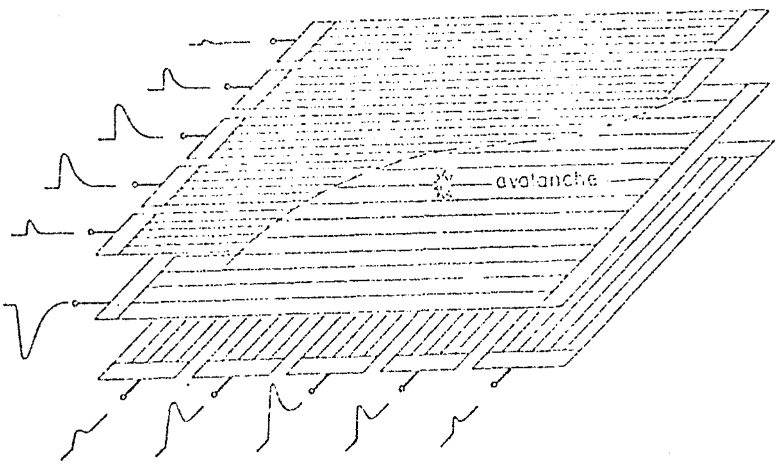


Fig. 5. Principle of bidimensional proportional chambers from Ref. 6.

However at least with the chamber parameters chosen by Charpak et al., this method leads to a very large number of channels (∿ 200 000 with 2 mm wire spacing and 4 mm strips). Some reduction to about 100 000 could be achieved at the price of some loss of resolution in the direction across the wires. It should therefore be realised that this device relies on the availability of low cost ADC (with no multihit capability). Taking the present price of 150 SF per channel[7] 100 000 channels lead to 15 MSF which is out of question.

Finally the method does not seem to be well adapted for cylindrical chambers in the central region of a solenoid since the resolution in the azimuth is determined by the wire spacing and is not so good.

From a mechanical point of view the use of discrete chambers is cumbersome. In particular two problems are difficult to solve economically:

a) The construction of cylindrical chambers: Self supporting styrofoam chambers (CCDR, or Ref. 5) are quite expensive and introduce a significant amount of matter (with a maximum of precaution, 0.6% of a radiation length for 2 gaps ,Ref. 6).
Threading wires across two end plates as done at SLAC for 'Mark II', is elegant but does not practically allow cathode read-out. It is also somewhat worrying to have to build and debug the complete detector in one go and a broken wire could make the entire set-up unoperational.
The solution proposed by U. Gastaldi at the workshop (and used at Brookhaven) to sketch a mylar foil into a cylinder does not have these problems but is more complicated mechanically (especially if stand offs in the way of particles are not wanted).

b) A second difficult problem is to achieve a high density of chambers (flat or cylindrical).

3. Projection chambers

For a large detector,it is therefore quite useful to find ways of simplifying the mechanical construction of the chambers, transferring onto the electronics the burden of dividing the space into a large number of cells.

D. Nygren made an important step into this direction with his proposal of 'time projection chambers'(Ref. 3). And we would like here to generalise his approach. The main idea is to 'project' the tracks onto a bidimensional measuring device exactly in the same way as a bubble chambers picture is projected onto a film. However in the case of an electronic detector, the projection could be made through the drift in an electric field of the electrons generated along the track and the reception could be a proportional chamber with one of the usual bidimensional reading tricks (induction on cathode pads or strips, current division, stereo, delay lines).The 'depth' of each point is measured by the drift time of electrons. It has been shown by Charpak-Sauli and coworkers (Ref. 8) that a sense wire can see successive avalanches if they are separated by about 50 ns that is 2.5 mm in space. One could therefore consider with this principle a subdivision of the space into more or less cubic cell of a few millimetre size.

Note that one can project from left and right onto the same plane. The resulting left right ambiguity is not a serious problem since it can be solved at specific points by couples of wires or by staggering of sense wires.

Once this principle of 'projection' is accepted, a subsidiary question is to decide whether one should drift along the magnetic field or perpendicularly. For a more detailed study, we have to distinguish between the two types.

3.1. Longitudinal projection chambers, where the electric field is parallel to the magnetic field: in other words the original time projection chamber (Fig. 6).

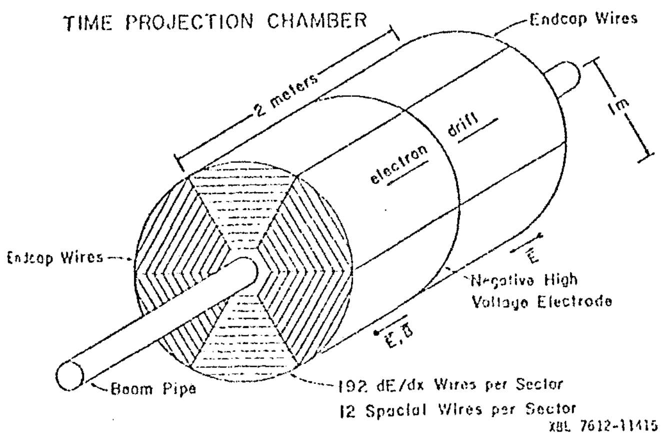


Fig. 6. The time projection chamber of D Nygren.

The main advantage is clear. In absence of space charge, the electrons are not deflected by the magnetic field. There is also some reduction of transverse diffusion by a factor

$$\frac{1}{1+\omega^2\tau^2} \simeq \frac{1}{1+\frac{3}{2}\frac{B^2}{E^2}w^2} \qquad \text{(Ref.3 and 9)}$$

where ω is the cyclotron frequency , τ is the mean time between collision, w is the electron drift velocity, B and E are the magnetic and electric field. However for a normal gas with saturated drift velocity, $w \sim 5\,10^4$ m/s for $E = 1.5\ 10^5$ V/m , B = 1.5T, the factor is only 0.73 which is practically negligible. Moreover the reading method chosen with pads gives an accuracy which is practically independent of the diffucion and therefore this point is not very relevant.

The main drawback, as we will see in section 5, is the necessity to measure the curvature of the trajectory in projection.

3.2. Transversal projection chambers

Another possibility is to drift transversally to the magnetic field. The main advantage of such a solution is that the sagitta is given directly by time measurement which is relatively easy to implement. The two particle resolution for momentum measurement is excellent (2.5 mm). The ultimate resolution which could be achieved is limited by the diffusion. Taking the results of Tsiganov et al.(Ref.10) which give roughly 45 μm r.m.s. after 10 mm of drift, a drift of 20 cm will give σ= 200 μ. This relatively large value is, however, compensated by the fact that in a projection chamber, there are many measurements along the track. Calling this number N, and assuming that these measurements are equidistant, we can deduce the error σ_s on the sagitta:

$$\sigma = \frac{1}{8}\sqrt{\frac{720}{N}}\,\sigma = \frac{3.35\sigma}{\sqrt{N}} \quad \left(\frac{p}{p} = \sqrt{\frac{720}{N}}\ \frac{p\,\sigma}{3\ BL^2}\right) \qquad 3.2.1.$$

With σ = 300 μ (including the electronics), we get:

$$\sigma_s \simeq 100\ \mu m$$

Note that for the electronics, an equivalent frequency of 75 Mhz (giving an r.m.s. of $\frac{0.66}{\sqrt{12}}$ = 190 μm, since we know the time zero) will be well adapted to the accuracy needed. Verweij described at the workshop (Ref. 7) a low cost solution using fast MCM 10145 memories which can provide speed of this order of magnitude (typical access time 10 ns).

The major drawback of transversal projection chamber is that the electrons are drifting at an angle α with respect to the electric field (Fig. 7a). A rough estimate (Ref. 9) is

$$tg\ \alpha = \frac{w_M B}{E} \sim \frac{w B}{E}$$

where by definition w_M is the 'magnetic' drift velocity which is roughly equal to the normal drift velocity w. With $w = 510^4$ m/s (Argon-Isobutane), B = 1.5 T, E = 1.5 kV/cm

$$tg\ \alpha = 0.5 \qquad \alpha \simeq 26^o$$

This is not very important, however, for projection chambers since it only changes the direction of projection. In a solenoidal configuration

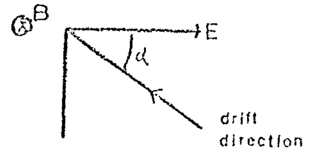
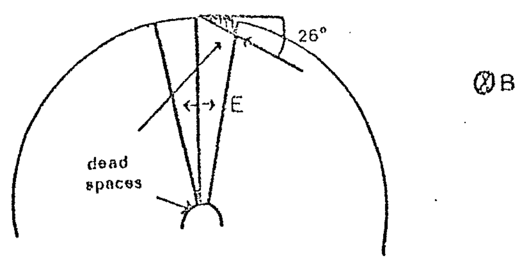


Fig. 7. a) In a transversal projection chamber electrons drift at an angle with respect to electric field E.

this results into a negligible loss of measuring length (Fig. 7b). This angle can be decreased with the use of Xenon mixtures such as the one proposed by C. Fabjan and collaborators ($w = 3 10^4$ m/s).



b) Dead region for a transversal projection chamber in cylindrical geometry (r = 1 m, max drift 20 cm, α = 20°).

We have sketched in Fig. 8 a possible design of a transversal proportional chamber for a cylindrical geometry in a solenoid. It looks like a 'bicycle wheel' , the spokes of which (broken lines) are made with sense wires running parallel to the axis. They delimit a small number of projections cells (2 x 16 in the case shown). The sense wire planes are equipotentials while the field wires around the cylinder and at the separation region between 2 cells (dotted lines on Fig. 8, see also Fig. 9) are at potential such that the electric field is uniform and perpendicular to the sense wire planes in each projection cell. With a maximum drift length of ∿ 20 cm, a radius of 1m, there will be 16 sense wire spokes of 128 wires each. Therefore with 2048 sense wires we could equip a region of 1 m radius and 2 to 3 metre length.

For simplicity on Fig. 8 and 9, we have not shown cathode wires which have to surround the sense wire plane in order to decrease the leakage of positive ions in the drift region (see next section). We have shown also the projection chamber surrounded by a conventional drift chambers which may be useful in order to get a fast trigger

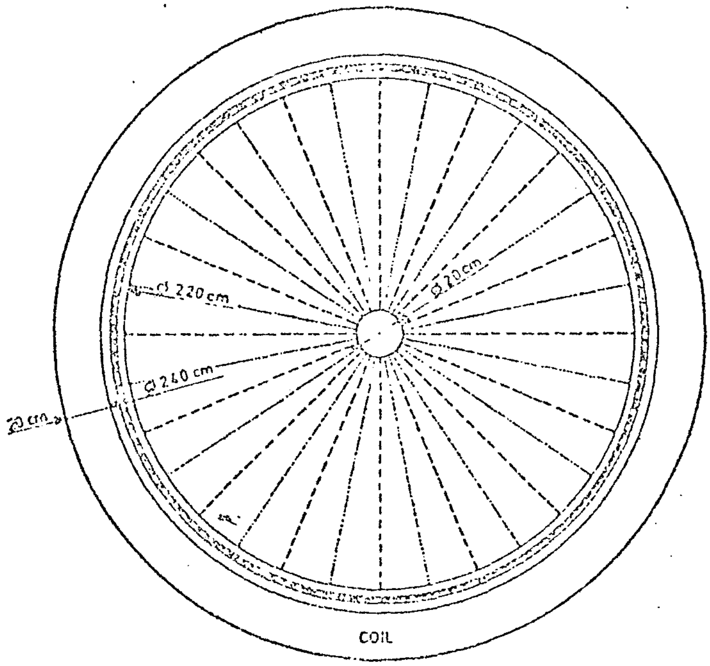


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Fig. 8. The 'bicycle wheel' transverse projection chamber in a solenoid.

information, to reduce the effect of the dead space sketched in Fig. 7b and to monitor the behaviour of the projection chamber (see section 3.3.).

The longitudinal coordinate can be measured either by grouping the cathode wires mentioned above into cathode strips or by current division (see section 6).

3.3. Calibration and monitoring of projection chambers

A projection chamber is fundamentally an analog device and will be exposed to distorsions.

A large effort should be invested in the stability of various components. The drift velocity should be as stable as possible (saturation region), the electron attachment coefficient of the gas kept as low as possible, the orientation between the electric field and the magnetic field well known, and the electronic gain should be

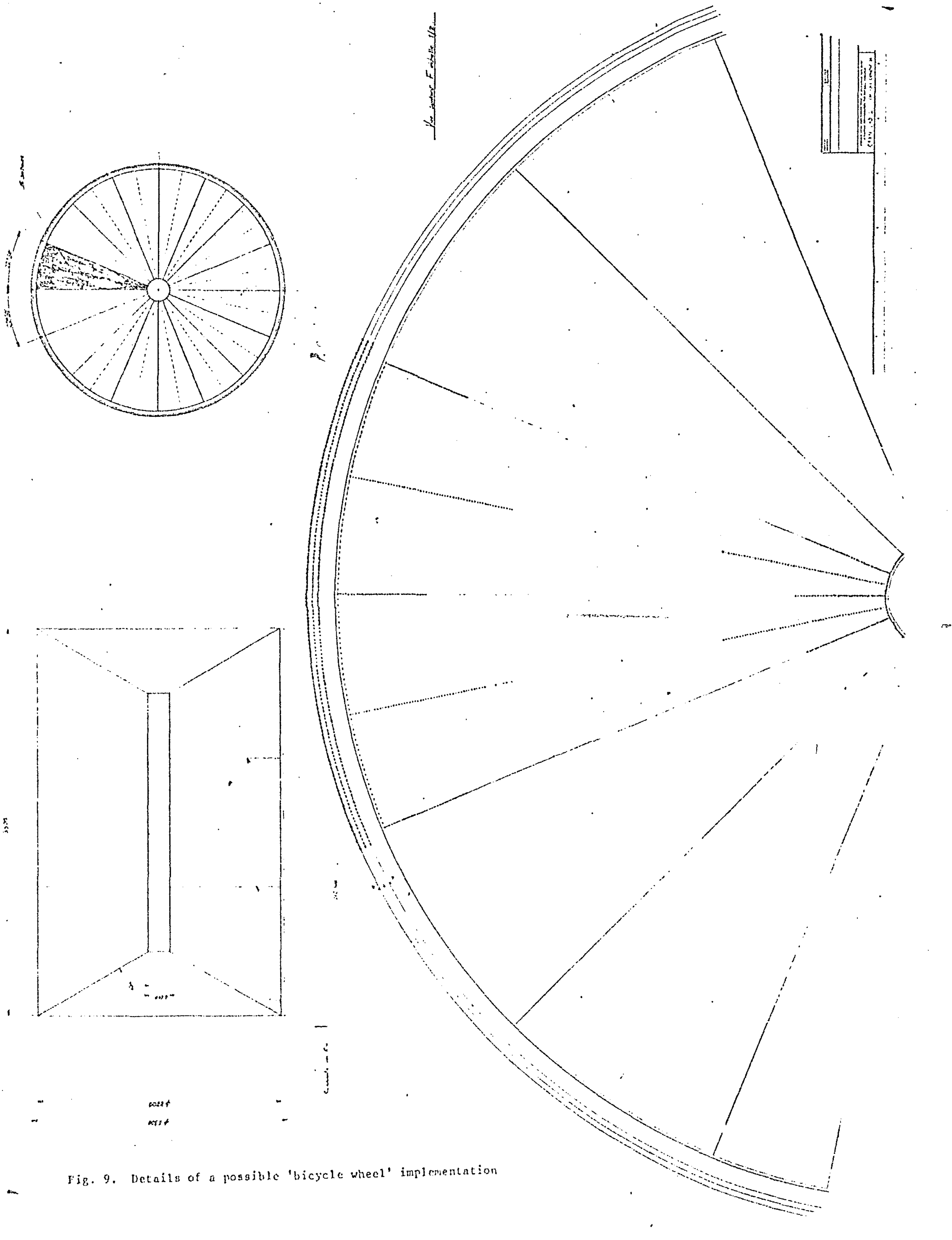


Fig. 9. Details of a possible 'bicycle wheel' implementation

constant.
However in spite of these efforts, and because of some effects which are fundamentally dependent on operating conditions such as space charge build up (see section 4), it will be necessary to have 'fiducial marks' in the measuring space. They could be of three natures:

- ^{55}Fe sources painted at suitable places will give information on the gain of the entire system and on the direction of drift of electrons at various places. This calibration requires to be able to gate out $p\bar{p}$ interactions.
- Artificial induced signals for time measurement, current division, amplitude analysis calibration.
- Some information can be extracted from normal (simple) events or cosmic ray through the use of, for instance, maximum drift time, correlation between several cells of the projection chamber or between the projection chamber and some other more finely fragmented device.

4. Space charge effects in projection chambers

An important problem with large gap chambers is the space charge build up by the positive ions created in the avalanches. They at the same time, reduce the electric field (affecting therefore the drift velocity) and modify its orientation, producing then a distorsion of the trajectory.

In order to compute the positive ion charge density ρ, let us consider n particles per second and m^2, entering normally a detector of section $\ell \times g$ and thickness t. Let us assume first that the ions drifting along the direction g (Fig. 10a) and let us call q e the primary charge deposited per unit length ($\sim 1.6 \cdot 10^{-19} \times 10^4\ m^{-1}$), A the amplification ($\sim 10^5$) and $w^+ = \mu^+ E$ the drift velocity of positive ions ($\mu^+ \sim 1.6\ 10^{-4}\ m^2/s/v$ in Argon, $E \sim 1.5 10^5$ V/m). If f is the fraction of positive ions escaping into the gap ($\sim 10^{-1}$ if the sense wires are surrounded by cathodes wires), we can equate the input and output of charge per unit of time and area in the drift region:

$$\frac{f\ q\ e\ A\ t\ n\ lg}{\ell t} = \rho\ w^+$$

or

$$\frac{f\ q\ e\ A\ g\ n}{w^+} \sim 0.7 10^{-12} \quad g\ n \qquad \text{(MKSA)} \qquad (4.1)$$

If the ions are drifting in the same direction as the particles (Fig. 10b), one has still the same formula where g is also the drift length of the ions.

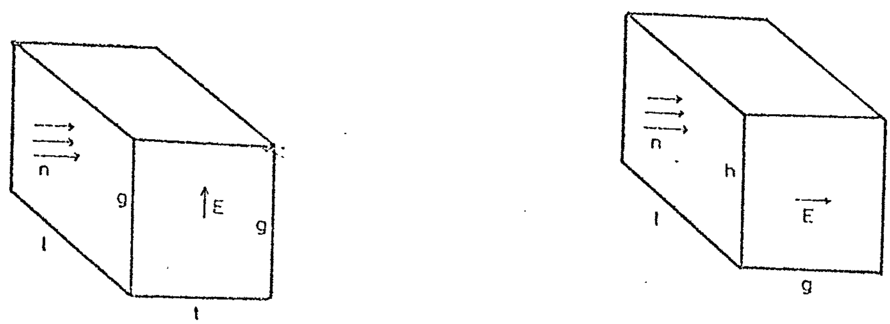


Fig. 10. Computation of the space charge effect.
a) Ions drift normally to the direction of particles.
b) Ions drift along the direction of particles.

Let us study first the reduction of elastic field in the gap. We have

$$\text{div } E = \frac{\rho}{\varepsilon o}$$

This reduces the elastic field along the g direction over the whole gap by

$$\Delta E = \frac{\rho}{\varepsilon o} \quad g \quad \sim \quad 0.075\ g^2\ n \quad V/m \qquad (4.2)$$

with $g \simeq 1$ m, $n = 10^6$ part/s/m^2

$$\Delta E = 0.74\ 10^5 \qquad V/m$$

that is half the original field.

This effect is however much smaller than the distorsion of the trajectory due to the presence of additional E x B terms. In order to be specific, let us consider a solenoidal field of value B (with a dipole the effect will be twice as big). Let us also neglect the effect of electrodes which will in fact reduce effects when the distance considered are comparable to their spacing. The positive ion density ρ creates a radial electric field

$$E_r = \frac{r\rho}{2\varepsilon_o} \sim 0.035\ g\ r\ n \quad \text{V/m} \qquad r \lesssim g \tag{4.3}$$

We consider first a time projection chamber (Fig. 11a). Instead of drifting along magnetic field lines, the electrons will drift at an angle

$$d\phi \simeq \frac{w\ E_r\ B}{E_o^2}$$

where w is the electron drift velocity, supposed to be saturated at the normal electric field E_o ($E_o \sim 1.5\ 10^5$ v/m, w = $5 10^4$ m/s) and the shift of azimuthal position of electrons after a drift length g is (B = 1.5 T)

$$d\ s = g\ d\phi \sim 10^{-7}\ g^2\ r\ n \qquad \text{(MKSA)} \tag{4.4}$$

If we want this shift to be smaller than the measuring accuracy ($\sim 10^{-4}$ m) for $g \sim r \sim 1$ m, n should be as small as $n = 10^3$ part/m^2/s. For $g \ll r$ (4.4) should be replaced by:

$$ds \sim 10^{-7}\ g^3\ n \tag{4.5}$$

(roughly! We have not done any complete calculation). By decreasing g to 20 cm, n can be increased to $1.2\ 10^5$ part/m^2/s and with 10 cm to 10^6.

Let us now study the same effect in a transversal projection chamber (Fig. 11b). The effect is to change the direction of the electric field by

$$d\alpha = \frac{E_r}{E_o}$$

This corresponds to a maximum error on the measured distance of the track

$$ds = g \; tg \; \alpha \; d\alpha$$

$$\sim 0.3 \; g \frac{E_r}{E_o} \sim 10^{-7} \; g^2 \; r \; n$$

which is the same of (4.4). For $g \lesssim r$, 4.5 is applicable. Note that for

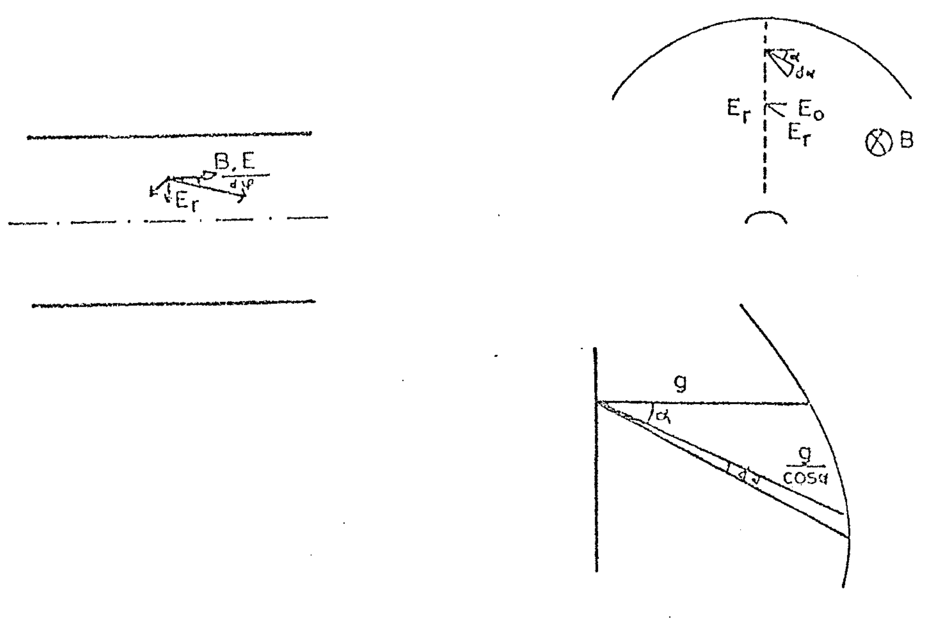


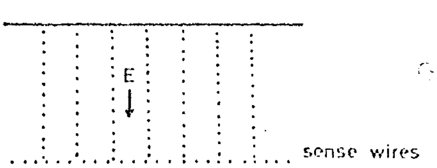
Fig. 11. Distortion of the trajectory by space charge effects.
a) In a time projection chamber
b) In transversal projection chamber.

a 'bicycle wheel' transversal projection chamber, the gap width is small in the region of high particle flux.

In conclusion, the main space charge effect goes as the cube of the gap width and, in order to absorb the relatively high rate expected in a $p\bar{p}$ detector, projection chambers should have a projection length limited to 20 cm (may be 10 cm close to the beam pipe).

Note that there are other tools to limit space charge effects:

- It is of primordial importance to reduce the number of ions escaping into the drift region.
- One may attempt to decrease the electron drift velocity (Xe gas) if possible without decreasing the positive ion drift velocity.
- In formula (4.4) and (4.5) a E_o^3 factor is buried in the denominator therefore the electric field in the drift region has to be high.
- One may attempt to decrease slightly the amplification. Our value $A = 10^5$ corresponds, in Argon, to a mean pulse height of 5 mV on 1 kΩ or 10 μA at low impedance.
- Finally, along a line suggested by C. Rubbia, suitable field wire arrangement limiting the width of the drift region will decrease space charge effect (quadratically) (Fig. 12a). This is better than decreasing the effective length of the drift region (Fig. 12b) since each grid plane will absorb electrons (Sauli, private communication). This method is not significantly simpler than decreasing the projection length which have as an additional advantage the decrease of memory time. 20 cm is quite well adapted to the repetition rate of the machine (with 6 bunches).



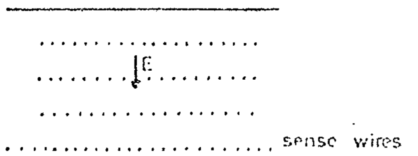


Fig. 12. Systems of field wire to limit space charge.

5. Measurement of sagitta in time projection chambers (longitudinal projection chamber)

5.1. Pads

The simplest method conceptually, is to use the induced signals on cathode pads as proposed by D. Nygren (Ref. 3). The measurement of the amplitudes allows to extrapolate between pads (Ref. 6). However in a high rate detector, the number of projection chambers has to be large (see last section) and the necessary number of pads becomes extremely large. For instance in the solenoid example of Fig. 13a, we need 3000 pads per chamber (8 rows of 8 x 8 pads). With 32 chambers (2 x 16) this is about 100 000 pads. For a dipole, similar numbers are reached. This jeopardizes one of the main advantage of projection chambers which is supposed to be its mechanical simplicity and the relatively small number of channels. The electronics price will be very big (see section 2). Moreover the only practical way to make pads is to print them on aluminium (or copper) mylar sandwich. This requires twice as many chambers and pads since a wire plane cannot be used for two adjacent projection regions.

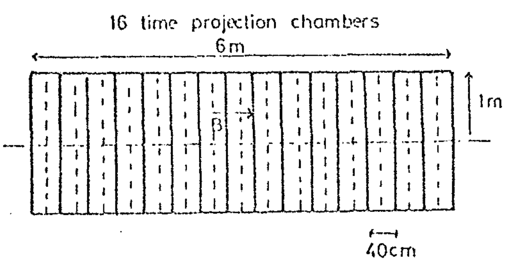


Fig. 13a)
T.P.C. in a solenoid

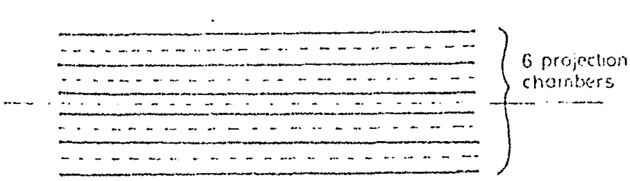


Fig 13b)
Projection chambers in a dipole

Fig. 13. Sketches of projection chambers in 2 magnetic field configurations.
a) Time projection chamber in a solenoid (For transversal projection chamber see Fig. 8 and 9.)
b) Projection chamber (of any type) on a dipole.

5.2. Cathode strips

One could then attempt to simplify the idea and use cathode strips instead of cathode pads. They could be made by grouping electrically the cathode wires which are necessary in order to reduce positive ions escape into the projection region and a single chamber could then be used for left and right projection. In the exemplified geometry the number of strips could be about 500/chamber (8 mm strips on both sides) that is for 16 chambers 8 000 strips, which is quite a reasonable number.

However, the situation is much more complex than in a discrete chamber, where a limited amount of wires and strips are hitted and where combination of stereo and comparison of pulse height allow an easy pairing of strips and wires (Ref. 6). In a projection chamber each track induces signal on a large number of wires and strips and the relevant pair of coordinates will be more difficult to extract:

- Contrary to a pad, each strip 'sees' many sense wires and, in general, two neighbouring strips will see signals such as shown on Fig. 14a. The time difference δt between the successive peak can be estimated:

$$\delta t = \frac{d \text{ tg } \lambda}{w \sin\psi} \sim 200 \text{ ns tg}\lambda \quad \text{for } \sin\psi \text{ close to 1}$$

where (Fig. 14b) d is the distance between 2 sense wires ($\sim$ 1 cm), λ the dip angle of the track with respect to the projection

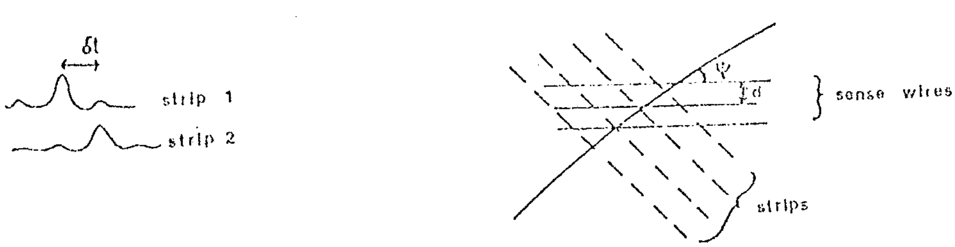


Fig. 14. Signals induced on strips in a projection chamber.

plane, ψ the prjected angle between the track and the sense wire and w the drift velocity (5 cm/μs). For small ψ the pulse width will increase rapidly and the gain on δt will be useless.

Interpolation will have to rely on fast analog sampling devices (CCD) and will be practically impossible if tg $\lambda < \frac{1}{4}$ that is if the particle is too parallel to the cone plane.

- In principle, pairing can be done with time but here again if the track is too parallel to the wire plane, all strip signals occur at the same time, and pairing has to rely on pulse height. This is complicated by the fact that each avalanche will induce signals on several strips.
- Finally it is important to minimise the occupation time of each strip amplifies since any dead time projects a 'shadow' in the whole depth of the chambers (100 ns would give 5 mm).

Therefore, apart from this shadow, the information for sagitta reconstruction through pairing is available with cathode strips. And given an accurate model for cathode induction, it would be possible to predict from a set of tracks, the pattern they should produce in a chamber and therefore fit the parameters of the tracks to a measured pattern. The main problem may be to recognise a given pattern and to find a close enough approximation to the event for the fit to converge. The reconstruction efficiency and the computer time cost of such a procedure will have to be tested in detail with Monte Carlo, before deciding to use strips in time projection chambers. For financial reasons (the cost of ADC) this may be a crucial element.

6. Dip measurement in transversal projection chambers

What we have said for sagitta measurement in time (longitudinal) projection chambers is valid for transversal projections with an important modification. The measurement of the trajectory dip has not to be very precise and the pattern to recognise in projection is much simpler since it is made of straight tracks. These observations open many more possibilities.

6.1. Pads are not presumably worth while since it is absurd to spend much more money for dip measurement than for momentum measurement.

6.2. Strips can be used. However interpolation between strips may not be necessary, saving the connection of most of the strips to analog memory. The time of individual hits on the strips will have to be measured for pairing purposes. The difficulties mentioned in the preceding section with track parallel to the wire plane can be solved in two ways:

- Without additional hardware,the dip of a track parallel to projection plane is known roughly by the point at which it enters and exits from the projection region.
- It would be possible, if the analog information is acquired for the sense wires, to add on a few strips pulse height measurement which would help in the pairing.

6.3. Current division . Since the coordinate along the wire does not need to be measured to better than a cm or so current division can be also used. The necessary multihit capability of this method be demonstrated, it would be nearly ideal since it gives directly points in space and is a natural extension of dE/dx measurement.

6.4. Other methods . Wires could be tilted for stereoscopic projections. The necessity of not distorting the electric field appreciably requires that the wire displacement remains a small fraction of the drift length. The stereo angle will be quite small (∿ 20 mrd for 2 cm on 1 m) giving typical resolution of 50 cm along each wire This may be not good enough and may lead to many ambiguities.

Simple delay lines suffer from the same defect because of the large width of the signal at the end of the line (several hundred ns) and any compensation which could decrease the signal width will introduce too much matter in the way of particles.

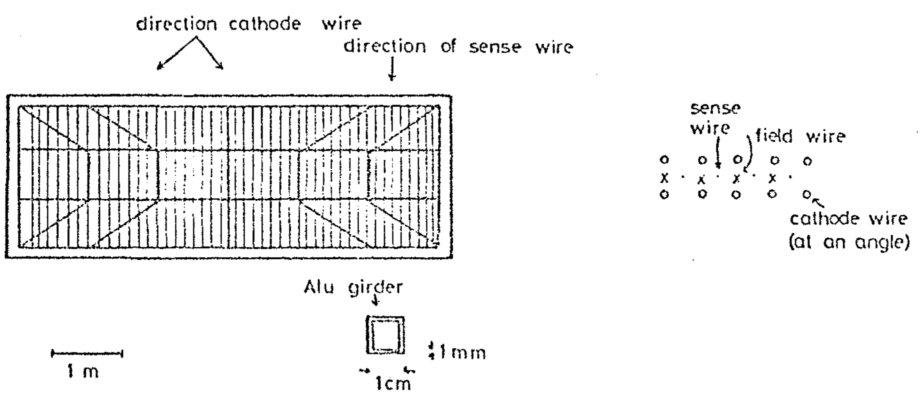
7. Mechanics of projection chambers

One of the main motivation of projection chambers is to simplify the mechanical construction of the detector. We have therefore to show that is indeed simple to build projection chambers.

7.1. Dipolar field. This is most readily seen in the dipole field configuration in which projection chambers are simply made of flat chambers parallel to the beam and either perpendicular or parallel to the magnetic field (Fig. 15b).

A particularly simple configuration is obtained if cathode strips or current division read-out is used since one plane can be used both for left and right projection.

The use of a long dipole requires very large frames (typically 6 m x 2 m). In order to limit the size of frame edges, it is necessary to include intermediate girders (Fig. 15a). However they can be quite light as we will show in the forthcoming calculation.



DIPOLE PROJECTION CHAMBER

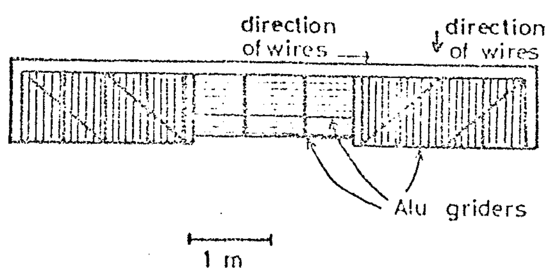


Fig. 15. Frame for projection chambers.
a) Dipole field (any type).
b) 'Bicycle wheel' transversal projection chamber in a solenoid.

A beam which cannot rotate at its extremities will support a maximum force (Ref. 13)

$$F = \frac{4\pi^2}{\ell^2} EI$$

where E is the elasticity modulus, I is the moment of inertia and ℓ is the length of the beam. With a square aluminium profile of thickness 1 mm and section 1 cm

$$I = 6.6\ 10^{-10} m$$
$$E = 6700\ Kg/mm = 6.7\ 10^{9}\ Kg/m$$
$$\ell \sim 1\ m$$
$$F_{max} \simeq 175\ Kg$$

A safety factor of 4 gives a maximum load of 40 Kg that is 400 cathode wires of tension 100g or with a 5 mm spacing 1 m of cathode (on both sides). Of course in a realistic design, the two extremities can rotate somewhat and the above numbers may be divided by a factor 2 (Ref. 13).

Such a profile represents only 1.1 g/cm^2, that is 4.5% of a radiation length, so particle could go through it without too much damage. In addition the girders could be arranged so they are not too close to the interaction region and cover a small amount of solid angle.

Undoubtledly more sophisticated techniques (honeycomb, styrofoam, use of better materials) can be used to decrease still the amount of matter in each beam. We can therefore safely conclude that the frame can be subdivided as shown in Fig. 15a) into subcells about 1 m x 1 m with very light beams.

7.2. Solenoidal Field. In that case we have to distinguish between time projection chambers and transversed projection chambers and consider separately the central detector ($45^{o} < \theta < 145^{o}$) and the forward detectors.

a) Time projection chambers: They will be essentially disks positioned every 40 cm (Fig. 13a). In the forward direction, the wire orientation have to change for each successive layer so particles are never parallel in projections to all the wires. In the central region where the particles do not cross a large number of T.P.C., each wire plane has to be arranged in a way similar to the one proposed for end caps in the PEP time projection proposal Fig. 16 (Ref. 3b). The main drawback is that each side of the represents a dead region of the order of 2 cm which for fast tracks, obscuring partially $\frac{6 \times 2}{2 \times 20 \, r\pi} = 10\%$ of the azimuth and totally 2%. We have therefore to conclude that T.P.C. with small gaps are not very well suited to solenoidal field.

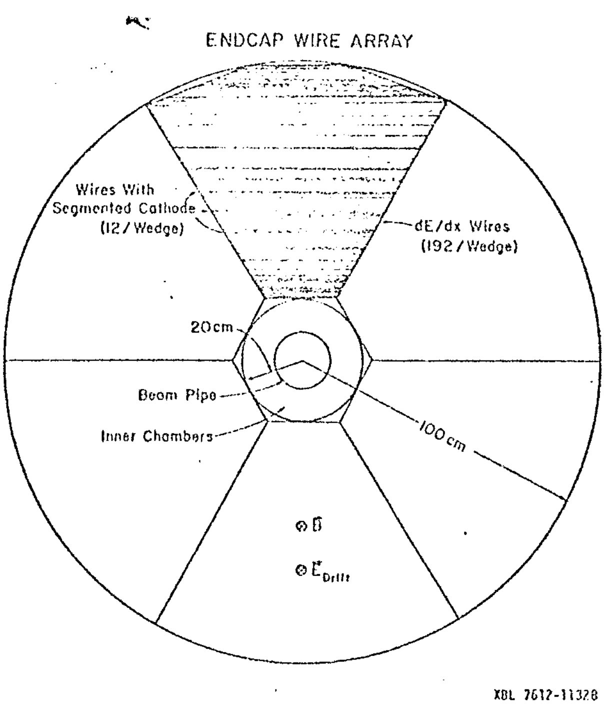


Fig. 16. End caps in the PEP time projection proposal.

b) Transversal projection chamber: In the central region, the most convenient arrangement is the 'bicycle wheel' proposed in section 3.2.

Two methods of construction could be considered. Either as we have proposed at the first $p\bar{p}$ study week (Fig. 9) we could use the SLAC technique of threading directly the wires in a prebuilt cylinder with end plates (which could be conical for rigidity).

The main problems are maintenance, safety of operational and longitudinal read-out which is then limited to current division and stereo. Or we could make each spoke as a frame with the amount of matter in any beam close to the interaction region reduced to its minimum (typically the 1 x 1 x 0.1 cm^3 Aluminium profile discussed above at 30 cm from the beam). This solution has several advantages:

- All the spokes are easily dismountable and interchangeable. You have 16 identical chambers and can afford to have only a few spare.
- In addition to current division, you can use cathode strip read-out, which decreases the dependancy of the project on technics yet to be developed.
- The field wire plane can be designed similarly and can be made of printed mylar separatins mechanically the chambers into several sectors, increasing therefore the safety of operation.

For the forward part, one could use the same system of frame but now with sense wires along the radii in order to be more perpendicular to particle trajectories.

Therefore contrary to what is commonly believed, for solenoidal geometry, simple solutions indeed exists ,especially with transversal projection chambers.

8. Data Reduction with ~~time~~ projection chambers

In order to estimate the amount of information generated by a projection chamber, let us take the example of a system of transversal projection chambers with 7000 wires, 2 μs mean maximum drift time, 75 Mhz shift register for time measurement and 20 Mhz 8 bit resolution CCD's with two of them attached to each wire for current division.

If empty cells are not suppressed we arrive to 7000 x (15o+40x2x8) $\sim 6\ 10^6$ per event. If zeroes are taken out, we are left typically with $20 \times 100 \times (2 \times 8 + 8 \times 2 \times 3) \simeq 1.5\ 10^5$ bits where we have assumed 20 tracks, that we sampled the tracks 100 times, that we kept two 8 bit time information per sample and that the pulse height has been measured 3 times per pulse.

But a typical Camac speed is $1.5\ 10^5 \times 16$ bits/s (although 1.4 μs is the specified maximum data way cycle time). So without any further data reduction we are limited to 16 events per s.

We conclude therefore, that some data reduction should be done at a very early level (even before Camac), for instance identifying unambiguous segments of tracks. A natural extension will lead to multilevel triggers.

9. Conclusions

What we have attempted to show in this study can be summarised as follows:

0) For a large angle $p\bar{p}$ device with the expected event complexity, there is no other choice than to have a very large density of information. dE/dx measurement is then a natural extension which could be very productive.

1) Discrete chambers lead to a very large number of channels (in the example taken 40 000 for drift chambers, 100 000 for 'bidimensional read-out' chambers) even with a somewhat reduced density of information. The cost of mechanics and electronics is worrying and the amount of matter may be quite large adding to the complexity of the events.

2) Projection chambers are an elegant way of simultaneously increasing the density of information and decreasing at the same time the mechanics complexity. The main problem comes from space charge effects. It seems possible to reach a particle density of 10^6 part/m^2/s with small projection length of the order of 20 cm. We propose that the $p\bar{p}$ detector group investigate actively this approach.

3) It is a separate issue to decide whether the projection should be done parallel to the magnetic field (longitudinal or time projection chambers) or perpendicularly (transversal projection chambers).

It is the author's opinion that momentum measurement, after all the main mission of a charged particle detector, is far easier with transverse projection chambers than with time projection chambers. The former type relies on already standard electronics while the latter requires either a large number of pads (100 000) which may be unrealistic price wise or a sophisticated analysis of the pattern induced on cathode strips. The point has to be investigated by Monte Carlo before a decision is taken in that direction.

For transversal projection chambers the longitudinal coordinate can be measured with cathode strips or with current division. The latter method seems very attractive but deserves a detailed study since nobody has used it in the multihit mode.

4) Mechanically projection chambers are very simple. This is obvious for dipolar field and time also for solenoid at least for transversal projection chambers. Detailed designs should check these statements.

5) The quality of projection chambers depends, in a large part, on the sophistication of the electronics. Two areas seem to be worth detailed investigation:
   - Low cost, multihit time to digital convertors, 50 to 100 Mhz with multihit capability. A solution seems to exist base of fast MECL memories.
   - Low cost analog memories or fast ADC (20 Mhz 8 bits). The most attractive devices seem to be the CCD's although performances of off-the-shelf items are not optimal for our kind of application. We think that this study should be given very high priority since many choices rely on the availability of a low cost solution. (The projection chamber and multihit charge division in particular).

6) We should be fully aware of the large amount of information generated by projection chambers. It is basically of 2 types:
   - Calibration data. It would be necessary to have 'fiducial marks' on the measuring space. It is essential to incorporate the calibration procedure into the system design so it is to a large degree automatic.
   - Measurement data. Some fast data reduction technique at a very early level in the chain should be developed, with its natural spill over: a sophisticated multilevel trigger.

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