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DETECTORS FOR HIGH RATE COLLIDING BEAM EXPERIMENTS

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SUMMARY

An analysis of the performance of large solid angle detectors to be used at colliding beam facilities is attempted, with a view of reducing the overall dimensions, yet keeping a satisfactory quality of the data. Special attention is given to position measurements and particle identification and to high event rates.

1. INTRODUCTION

Most general purpose detectors with large solid angle coverage used at colliders have grown spectacular in size and complexity. A natural extrapolation to higher centre of mass energies brings about an additional growth which approaches the limits of what is considered to be feasible, at least on financial grounds.

It is therefore appropriate to analyze the parameters which enter in the design of a general purpose detector and single out the most promising improvements which allow a size reduction or at least a slow growth with centre of mass energy. Such an analysis cannot be done in too general terms appropriate for all types of physics and detector design. The considerations which follow are based on a physics goal of detecting jets of particles originating from the collision in a set-up constructed around a solenoid with its axis along the beam direction. Special attention is given to the rate capability of the detector, either to cope with the wealth of events available at hadron machines (ISR, ISABELLE) or to master the background in e-p machines (HERA, TRISTAN).

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A hypothetical detector for neutral current events proposed for the HERA e-p collider¹⁾, is used to fix the ideas (fig. 1). It contains all the usual components, namely

- a central detector to determine position of charged particles and measure their energy loss in a gas;
- a solenoid producing a magnetic field along the beams direction;
- an electromagnetic shower counter;
- a hadron calorimeter, imbedded in the magnet return yoke;
- forward detectors for the scattered electron and the proton fragments.

The heart of the set-up is the central detector based on gaseous amplification. Its design and performance have a primordial impact on the overall size of the set-up built around it. Therefore the considerations which follow refer to the central detector: electromagnetic and hadronic calorimetry is left to the review of Fabjan²⁾ where only fast detection and readout methods (scintillation, solid state etc.) should be retained for high rate machines.

Other detector layouts with different magnetic field geometry have been studied in the past, leading to considerations similar to the ones outlined in this report. See for instance^{3,4)} for a dipole field.

2. CHARGED PARTICLES MOMENTUM MEASUREMENT

The requirements on particle momentum measurements vary widely according to the type of experiment. They range from a minimum of recognizing the sign of the particles of highest momentum to the precise measurement of the momenta of all particles in order to detect, for instance, missing energy by neutrinos when photons and neutral hadrons are also detected. In all cases the momentum resolution of a particle $\delta p/p$ can be expressed in terms of an average magnetic field strength along the track B , a track length where the measurement is possible L and an error on the individual measurement ϵ :

$$\delta p/p^2 \propto B^{-1} L^{-2} \epsilon.$$

The two handles to reduce L are obviously an increase of the magnetic field strength and a reduction of the error of each measurement along the track. A further modest improvement could be obtained by increasing the number of independent measurements.

Fig. 1 Schematic drawing of a HERA detector designed primarily for detection of neutral current events¹⁾.

2.1 Magnetic Field Strength

In addition to the straightforward improvement in momentum resolution an increase of the magnetic field has a number of side effects.

Particles tightly bunched in a jet benefit in separation from one another by an increase of the field. However the effect is sizeable only for the lower momentum particles which represent the majority (fig. 2) but carry only a modest fraction of the total energy. Nearby particles of high momentum are unappreciably separated by the magnetic field (fig. 3).

Fig. 2 Momentum distribution of charged particles in two jet events for e^+e^- collisions at a c.m. energy of 140 GeV (solid line)⁵⁾. Distorted spectrum, when particles originating from photon conversion in .2 radiation length of material around the intersection are added (dashed line).

Fig. 3 Track length of well separated tracks vs. particle momentum for different magnetic field strengths⁵⁾.

The number of primary particles per jetlike event curling up repeatedly in the central detector is of the order of 1% for $B.L \approx 1\text{ T.m}$. More serious is the background of curling particles originating from the materialization of photons from π^0 s into the vacuum chamber or central detector walls, which are often crossed at a small angle. Fig. 2 displays the charged particle spectrum distorted by photon conversion through an average wall thickness of .2 radiation lengthy.

Another effect of increasing the magnetic field strength is on the drift angle in the gas, when the magnetic field is not parallel to the electric drift field. This spoils indirectly the precision by demanding a close and difficult monitoring of the drift velocity in inhomogeneous fields and adds some burden on pattern recognition and momentum fit. On the other hand, when the magnetic field is parallel to the electric drift field, a reduction of transverse diffusion of the drifting electron occurs leading to an improvement of space resolution (sec. 2.2).

Last but not least the financial implication of an increased magnetic field strength should be mentioned. They come from the large forces on the coil which must be properly balanced and from power consumption. If a superconductor is chosen to limit the latter, design complications have to be mastered, which usually mean cost and longer timescale.

2.2 Precision of Position Measurements

The second parameter which makes an improvement of momentum resolution possible is a reduction of the error on each individual position measurement. The factors affecting spacial resolution in a gaseous detector have been analyzed in the literature⁶⁻⁸⁾. They are primarily

- δ -ray production along the particle trajectory, making the track to appear "fatter";
- diffusion of ionization electrons between the times of generation and detection;
- intrinsic limitations of measuring techniques based on electron multiplication by avalanche.

Pressurization of the detector can provide an improvement subject to some conditions. A pressurized detector presents more material to the particles originating from the collision, both in the walls of the enclosure and in the gas itself. The higher density of the gas is detrimental to curvature measurements because of multiple Coulomb scattering at low momenta. The increased amount of matter around the interaction region has two counteracting effects: it produces more background, mainly by photon conversion, but in turn is more efficient in absorbing spiralling particles, hence it helps confining the background in space.

The mechanism by which pressure reduces the apparent size of the track can be understood by interpreting fig. 4: the yield of δ -rays emitted above a given energy E_0 depends only on the number of atoms seen by the primary particle (number of g.cm^{-2} or pressure.thickness) whilst the range of the same δ -rays, which determines the "size" of the track, is depressed by density (pressure) alone. Thus pressurisation works in the direction of improving precision only if increased pressure is associated with correspondingly smaller sampling intervals.

Diffusion follows an inverse square root dependence with pressure in the absence of external electric and magnetic fields. When an electric drift field is present, longitudinal diffusion still follows an inverse square root dependence if the ratio of electric drift field to gas density is kept constant^{10,11)} (this condition keeps also the drift velocity unchanged). A magnetic field component perpendicular to the electric drift field has no first order effect on diffusion¹⁰⁾, whereas a parallel one reduces the transverse diffusion

Fig. 4 Probability of obtaining a δ -ray with a range equal to or larger than R_0 , in the detection of minimum ionizing tracks in the indicated gas mixture, sample length and pressure⁶⁾.

coefficient¹²⁾. The overall improvement on resolution by the influence of magnetic fields on diffusion is therefore negligible as far as the coordinate measured by drift time is concerned but can be sizable in the plane normal to the drift detection.

Multiplication by avalanche in gaseous detectors is reduced by increasing pressure if both anode voltage and wire diameter are unchanged. The reduction of gaseous amplification can be compensated by:

- higher electronic amplification, limited by noise and complexity;
- smaller wire diameter, becoming rapidly unpractical;
- higher anode voltage, which adds some high voltage engineering problems.

A smaller gaseous amplification has the unpleasant effect of a slower movement of the ions close to the wires, resulting in a longer pulse: this affects the rate or multi-hit capability of the system. On the other hand, a smaller gaseous amplification makes the effect of positive ion space charge back into the drift region more manageable.

To conclude, pressurization of the detector helps to improve precision of the coordinate measurements but reduces somewhat the maximum acceptable rate. The last difficulty is overcome by adding more anode wires per unit volume, which gives the extra benefit of reducing the positive ion space charge effect.

Two remarks are appropriate before leaving this section. The mechanical complication required by a pressurized detector leads to more engineered solutions which by their stability supply a favourable framework for precise positioning of the wires and careful calibration and alignment. All what has been said about pressure is actually related to gas density. Therefore also temperature, in as much as it affects density, can be used to improve precision, although this may sound awkward. In this perspective pressure and temperature control and monitoring are equally vital for ensuring a stable operation of the detector.

3. PARTICLE IDENTIFICATION BY IONIZATION ENERGY LOSS

A gaseous detector with fine sampling appears to be the most attractive means of particle identification through measurement of the energy lost by ionization by charged particles in the gas. The momentum range of particles of interest spans over the relativistic rise into the plateau. The difference of energy loss for different particles has to be matched to the attainable precision in the detector.

Three main sources contribute to the resolution:

- the statistical fluctuation of the ionization loss;
- the statistical fluctuation of the gas amplification near the wires;
- systematic errors.

Energetic δ -rays are responsible for the asymmetric statistical fluctuations in the energy loss distribution measured in a thin sample. The need of a proper statistical treatment is the basis of the methods of repeated sampling along the track

which has been successfully used so far¹³⁾. The question has been fiercely debated whether in a pressurized detector one can trade track length against pressure and still obtain the same dE/dx resolution at fixed number of samples¹⁴⁾. Most arguments favour this conclusion. However, experimental results are in contradiction with expectation (fig. 5), in particular for detectors operated at high pressure. The discrepancy can be ascribed to intrinsic properties connected to the pressure itself or to systematic errors.

Fig. 5 FWHM resolution W over most probable energy loss E vs. reduced absorber thickness $\alpha t/I$ for various detectors normalized as if they consisted of a single sample¹⁴⁾. The reduced absorber length $\alpha t/I$ is defined by the mean ionization potential I [MeV] and $\alpha t = 0.153(Z/A)\rho t$ [MeV], where Z = number of protons in the nucleus, A = number of nucleons in the nucleus, ρ = gas density [$\text{g}\cdot\text{cm}^{-3}$], t = sample thickness [cm]. Solid line and lower scale (atm.cm) refer to measurements in pure Argon¹⁴⁾.

The statistical fluctuations in the gas gain around the wires represent a small contribution to the error for some commonly used gases¹⁴⁾. This contribution is supposed to become even smaller when pressure is increased if the ratio of the electric field around the anode wire to pressure is kept constant, a condition discussed in sec. 2.2. Such an expectation awaits experimental proof for most gases over an appreciable pressure range¹⁵⁾.

The improvement due to an increased number of samples within a constant pressure length is weaker in particle identification than in momentum measurement due to the nature of the statistical distribution of the measurements in each layer. Nevertheless it represents the only hope to improve the method, subject of course to experimental verification¹⁶⁾.

It should be stressed here again that a pressure increase brings about an enhancement of background in the detector and may reduce the track length useful for measurement depending on event topology and details of detector design.

4. CONCLUSIONS

The analysis of the preceding sections has shown that a reduction of the central detector size in a large acceptance set-up is possible without compromising on momentum resolution. This is achieved by an increased magnetic field strength and an improved space resolution through pressurization.

The performance of the same detector for particle identification by energy loss is either constant or slightly degraded when pressure is increased as track length is reduced.

APPENDIX - THE PROTON FRAGMENTS JET IN e-p COLLISIONS

As an example of an application where miniaturization of detectors opens a new field of research one can suggest the study of the proton fragments jet in e-p collisions¹⁾ (fig. 6).

Models assume that the proton fragments carry globally no transverse momentum. In neutral current events this hypothesis can be checked by a careful measurement of the scattered electron and the current jet. In charged current events all kinematics is determined by the measurement of the current jet with the assumption that the undetected proton fragments jet has no transverse momentum.

Fig. 6 Two hadronic jets structure expected to be dominant in deep inelastic scattering.

A measurement of particles in the proton jet could provide not only a constraint on energy and momentum balance, but also on flavour. Such a programme requires a careful design of the proton forward arm of fig. 1 as well as a beam pipe spectrometer¹⁷⁾, allowing charged particle momentum measurement, particle identification and calorimetry.

The experimental conditions are severe, since the rate of interesting events is in the 1 Hz range, while background due to proton beam gas interactions makes a halo of 10^5 particles per second around the proton beam. Moreover, event associated background is enhanced by the centre of mass motion, with many particles at a grazing angle with respect to vacuum pipe, drift chamber walls, shower counter and calorimeter edges.

The problem is challenging, unsolved so far. It involves high precision in position measurements of many high momentum charged particles. It requires particle identification in a momentum range where ionization loss techniques may well be complemented by transition radiation. It puts great emphasis on fine grained calorimeters at such a cell size not tried so far, possibly based on novel techniques like solid state detecting elements or the high density projection chamber¹⁸⁾. Pattern recognition in the forward calorimeters is of particular concern in this very confined and crowded geometry.

All of the techniques required to attack this problem are available today, yet unproven for large scale application in a difficult environment.

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