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WIDE ANGLE SPECTROMETERS FOR INTERMEDIATE ENERGY ELECTRON ACCELERATORS

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1. Introduction

Convinced by the advantage of the electromagnetic probe as a tool in nuclear physics, many people are now trying to develop new high energy electron accelerators with a main emphasis on very high duty cycle. Such efforts must be matched by equivalent improvements in detection efficiency. Increases in solid angle and momentum bite of spectrometers have therefore been discussed in great detail during recent workshops at Mainz [1] and Argonne [2].

In this talk, I will show that improvements of the detector acceptances (in solid angle and momentum bite) is as important as increased duty cycle for coincidence experiments. I will point out also that they open the way to new possibilities for experiments : out-of-plane experiments and multiple coincidences, which are out of the reach of present facilities.

To have a maximum efficiency and thus to reduce the cost of experiments, it is imperative to develop maximum solid angle systems. This implies an axial symmetry with respect to the incoming beam. At Saclay, we have investigated some of the properties of specific detectors covering up to 90 % of 4π steradians for a high energy, 100 % duty cycle electron accelerator. The techniques of wide angle spectrometers have already been explored on a large scale in high energy physics. However, in the case of charged particles, such detectors, compared to classical iron dipole spectrometers, present a smaller resolving power and a rather low background rejection. The choice of which of these two solutions is to be used depends on the conditions of the specific experiment.

2. Basic conditions for standard coincidence experiments

At the heart of any coincidence experiment is the problem of the ratio of real to accidental counts, as shown in the classical time diagram of Fig. 1. At the beginning of a given experiment, this ratio, R, and the number, N_R, of coincidences to be counted, can be fixed as a requirement on the quality of the data. This will fix the maximum instantaneous luminosity (defined as the product of target thickness by beam intensity) to which the experiment can be performed. Then, an interesting expression for the lowest measurable cross section can be derived. Let be the singles counting rates $\hat{\tau}_1$ and $\hat{\tau}_2$ in the acceptances $\Delta\Omega_1\ \Delta p_1$ and $\Delta\Omega_2\ \Delta p_2$ respectively, with a peak current $\hat{I}$ and a target thickness t. By defining properly the differential cross sections σ_{S_1} and σ_{S_2}, one can write :

$$\hat{\tau}_i = \sigma_{S_i}\ \Delta\Omega_i\ \Delta p_i\ \hat{I}\ t. \qquad (1)$$

The real coincidence counting rate is then :

$$\hat{\tau}_R = \sigma_R \, \Delta\Omega_1 \, \Delta p_1 \, \Delta\Omega_2 \, \Delta p_2 \, \hat{I} \, t \tag{2}$$

and the accidental counting rate, which depends on the time resolution ΔT, is

$$\hat{\tau}_A = \sigma_{S_1} \, \sigma_{S_2} \, \Delta\Omega_1 \, \Delta p_1 \, \Delta\Omega_2 \, \Delta p_2 \, (\hat{I} \, t)^2 \, \Delta T. \tag{3}$$

The ratio R of trues to accidentals is :

$$R = \frac{\sigma_R}{\sigma_{S_1} \, \sigma_{S_2} \, \hat{I} \, t \, \Delta T}. \tag{4}$$

This fixes the luminosity $\hat{I}$ t.

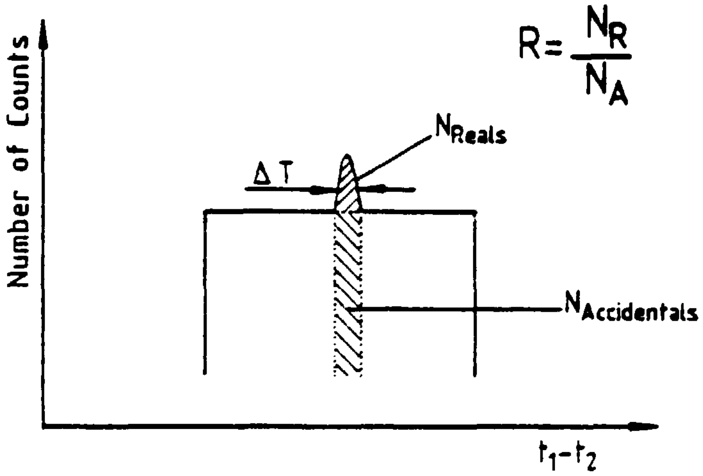


Fig. 1 – A diagram showing the differential time distribution of a coincidence experiment.

Then, if T_a is the accepted length of time devoted to acquisition of data, and C the duty cycle, one counts a total number of real coincidences N_R :

$$N_R = \hat{\tau}_R \, T_a \, C. \tag{5}$$

Then, in term of these parameters, the lowest cross section that can be reached is :

$$\sigma_{R_{min}} = \sqrt{R \, N_R \, \frac{\Delta T}{C \, T_a} \, \frac{\sigma_{S_1}}{\Delta\Omega_1 \, \Delta p_1} \, \frac{\sigma_{S_2}}{\Delta\Omega_2 \, \Delta p_2}} \, . \tag{6}$$

This formula shows that, for a certain ratio, R, and a total number of coincidences, N_R, the minimum cross section varies only as the square root of the different phase space factors in contrast to single arm experiments where it is proportional to them. As we are interested in measuring very small cross sections at lowest cost, all relevant parameters must be increased : solid angles as well as duty factor and time resolution.

3. A larger solid angle does not always improve the experimental efficiency

Equation (6) shows that the benefit of a larger solid angle can be restricted by the associated variation of the singles cross sections. This can happen on two ways :

1) By a large variation of σ_{S_i} within the angular acceptance.

In that case, Eq.(6) remains true only if we take σ_{S_i} to be an average over angles :

$$\overline{\sigma_{S_i}} = \frac{\iint_{\Delta\Omega_i} \sigma_{S_i}(\theta,\phi)\, d\theta d\phi}{\Delta\Omega_i} \tag{7}$$

where θ and ϕ are, respectively, the scattering angle and the azimuthal angle. However, axial symmetry with respect to the incident beam removes ϕ from the equation (7), so that :

$$\overline{\sigma_{S_i}} = \frac{\int_{\Delta\theta} \sigma_{S_i}(\theta)\, d\theta}{\Delta\theta} . \tag{8}$$

If this averaged differential cross section happens to vary as fast as $\Delta\theta$, the experimental efficiency will not be improved by a larger acceptance in the *scattering* angle. On the other hand, since we have an axial symmetry of the beam target system (and thus σ_{S_i} is independent of ϕ), any benefit in the azimuthal aperture is always effective. This is why the most effective detector should be built with an axial symmetry with respect to the incident beam.

2) By the increase of the number of different particles contributing to σ_{S_i}.

In all classical designs, some kinds of particles emerging from the target are stopped by shielding. If, in a new design presenting a larger aperture, these particles are now able to trigger the detection system, they must be taken into account in the expression for σ_{S_i}. This reduces the benefit from the increase in solid angle.

These two limitations, 1) and 2), must always be kept in mind when designing wide angle spectrometers. Quantitative estimates of the particle flux have to be performed under the specific conditions of the experiment.

4. New possibilities presented by spectrometers with very large solid angle

1) When the solid angle of the detection system is a substantial fraction of the full 4π steradians (as opposed to currently available solid

angles which are of the order or 5×10^{-3} steradian) an experiment can be performed in a very different manner : instead of looking successively at different kinematical settings, one can investigate in one shot the full spatial distribution. This requires, however, a more complex detection system, as all angles within the angular acceptance must be measured.

2) A new class of experiments, that I will call "out-of-plane" experiments, can also be investigated. It consists of detecting in coincidence the particles that are emitted out of the scattering plane (defined by the incident and outgoing electrons). Such measurements are needed to perform a kinematically complete experiment and to map out the whole set of the four nuclear structure functions describing the reaction (see ref. [3]).

3) One of the most promising fields opened by a high duty cycle machine is the study of (e,e'NN) reaction requiring triple coincidences measurements. The equivalent of equation (6) then contains three $\Delta\Omega$'s in the denominator. A gain in solid angle would be the most effective improvement.

In these three situations, a very large solid angle facility having an axial symmetry seems to be the most promising solution.

5. Wide angle detectors with axial symmetry

In principle, such an instrument could be made by covering the surface of a cylinder (with axis along the incident beam) with position and energy sensitive detectors. These detectors must be segmented in as many independent parts as is necessary to avoid pile-up. Other layers of detectors, such as plastics, Čerenkov counters, and calorimeters can provide particle recognition and energy determination. The inclusion of a magnetic field is essential to obtain high momentum resolution and effective low energy cut-off of charged particles. Momentum is measured by tracking their trajectories as they are modified by the magnetic field. This means that the particles have to be detected several times by position sensitive detectors. Apart from the effect of limited spatial resolution, accuracy in momentum determination will be restricted by multiple Coulomb scattering through the earliest detectors.

A number of such instruments have been built. Some of the most sophisticated ones have been developed in connection with intersecting or collision rings. They have been reviewed recently in ref. [4]. Other developments have been investigated on an even larger scale for Isabelle [5] and for LEP [6].

A detector such as "Cello" [7] built for DESY at Hamburg presents properties which could satisfy many requirements of an electron scattering facility at intermediate energies. It is optimized for electron and photon detection. It tracks charged particles by proportional counters and drift chambers inside a solenoidal field of 1.3 T created by an extremely thin superconducting coil (0.5 radiation length) in a length of 1.6 m. Photons are detected by liquid argon scintillators. Around the flux return iron yoke, 200 m^2 of wire chambers detect muons. A very sophisticated trigger system reduces the data flow to specific coincidence events. Its momentum resolution for charged particles is limited to the transverse component of the momentum (solenoidal field). It is given by

$$\frac{\Delta P_T}{P_T} = 0.08\ P_T\ (\mathrm{GeV})\ . \tag{9}$$

The effect of multiple Coulomb scattering, negligible for the energies that are considered in the case of "Cello", is not included in this formula. Equation (9) can be understood from the way the momentum is deduced. Projected in a plane perpendicular to the axis of the field, the trajectory is a circle whose radius R can be deduced from the sagitta s over a certain length ℓ (see Fig. 2a) :

$$R = \frac{\ell^2}{8\ s}\ . \tag{10}$$

Then the momentum resolution depends on the spatial resolution ds

$$\frac{dP_T}{P_T} = \frac{8\ P_T\ ds}{e\ B\ \ell^2}\ , \tag{11}$$

where B is the field induction and e the unit charge. This shows that in a constant field the absolute resolution varies as the square of the momentum.

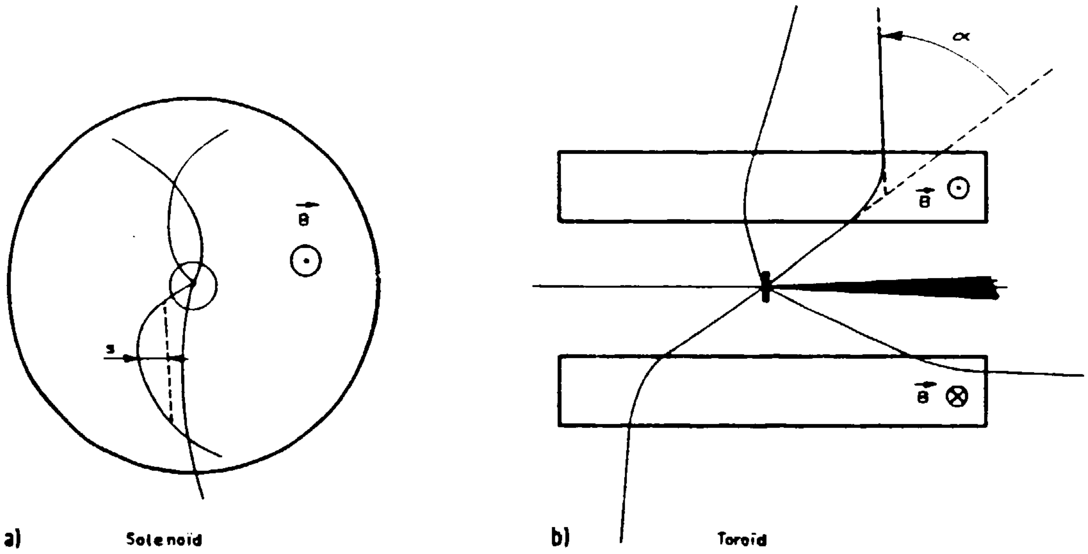
6. Axially symmetric magnetic field with a toroidal distribution

Although most of the present set-ups have been developed with a solenoidal field, there is one and only one other possible distribution which respects axial symmetry. It corresponds to field lines forming circles around the beam axis, i.e. a toroidal field (Fig. 2b). It can be produced by current sheets going back and forth along two cylindrical surfaces of different radii. The magnetic field is confined between them. However, the coil supporting those currents would interfere with the trajectory of the particles coming out of the target and penetrating into the field. The coil must then be segmented and restricted to limited portions of the space. These lumped coils intercept a part of the azimuthal acceptance and create only an approximation of a perfect toroidal field distribution. No iron flux return yoke is required as the field is automatically closed. This toroidal solution has been investigated [8] for very large angular acceptance detectors because it presents several advantages over the solenoidal one :

- The particles remain at fixed azimuthal angle and therefore, this quantity can be measured directly. A very effective segmentation of the detectors can be realised.

- A completely open space without return yoke provides more room to implement large detectors for particle identification.

- The magnetic field is used in a more efficient way because it is always perpendicular to the trajectory. As a result, higher resolving power can be achieved.



a) Solenoid b) Toroid

Fig. 2 - Principles of axially symmetric magnetic field for wide angle spectrometers.

One can evaluate the analysing properties of such a field in a simplified way, valid in the limit of the small bending angles. Out of the magnetic field, the trajectories are straight lines (Fig. 2b). Consequently, their respective directions can be measured before and after the field area and the total angle by which the trajectory has been bent is, in first approximation, proportional to the inverse of the momentum :

$$P = \frac{e\int B\,d\ell}{\alpha}\ . \tag{12}$$

The momentum resolution which can be expected from such an instrument depends on the accuracy that can be obtained in the angle determination. The latter is limited by the spatial resolution, ds, of the detectors over a given arm length ℓ. It is also limited by multiple Coulomb scattering ; its contribution to the resolution is inversely proportional to the momentum P as : $\langle\theta\rangle = k/P$. The quadratic combination of the two effects gives

$$d\alpha = \sqrt{4\left(\frac{ds}{\ell}\right)^2 + 2\left(\frac{k}{P}\right)^2} \tag{13}$$

and

$$\frac{dP}{P} = \frac{\sqrt{4\left(\frac{ds}{\ell}\right)^2 P^2 + 2\,k^2}}{e\int B\,d\ell}\ . \tag{14}$$

To give a numerical estimate of the momentum resolution, we assume the performance of currently available wire chambers : a thickness of 0.002 radiation length and a spatial resolution of 0.2 mm. We assume further a geometry of the coils such that $\int B\,d\ell = 0.8$ T.m and lever arms of 1 m. With these assumptions, we find a resolution of about half a percent at 2 GeV/c. It varies with P as shown in Fig. 3 : at low momentum, multiple Coulomb scattering predominates, whereas at high energy, the bending angle becomes too small and the spatial resolution terms predominate.

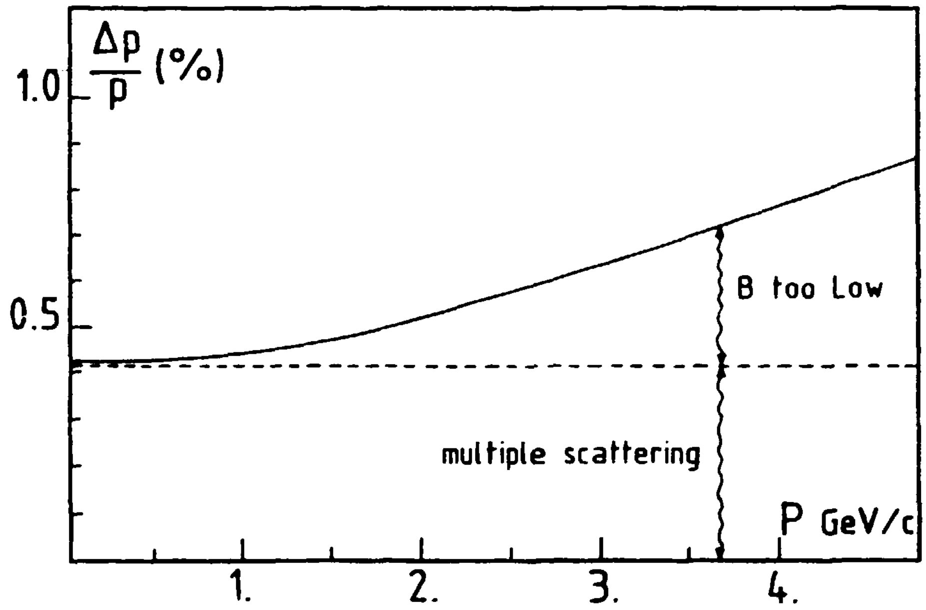


Fig. 3 - Variation of the resolution of a typical toroidal detector with the momentum.

In order to make a more accurate estimate of the possible properties of this kind of instrument by ray-tracing calculations, we have sketched a typical detector (Fig. 4). The field is created by 8 lumped coils. They are supposed to be made thin enough to occupy only 30 % of the total azimuthal acceptance. The field is not perfectly toroidal and tends to blow out of its "electrical jail" as can be seen in Fig. 5. In spite of this lack of cylindrical symmetry, the field path integral $\int B\, d\ell$ is almost constant in all possible azimuthal directions and out-of-plane deflections remain small thanks to compensations between the entrance and exit fields. In Fig. 4, the first superconductor layer is at 1 m from the beam axis and the field is spread radially over 0.5 m and longitudinally over 6m.

Performed at Saclay [9] in this specific frame, complete ray-tracing calculations have given the results shown on Fig. 6. It gives absolute resolution for all possible sets of angles and momenta accepted by the instrument. One can recognize the expected 0.5 % momentum resolution at 2 GeV/c predicted by equation (14). The angular acceptance is not symmetric because particles of a given charge are always bent in the same direction, whether they are emitted forward or backward. If the charge of the particle is changed or the direction of the field reversed, this asymmetric angular acceptance will be inverted with respect to the 90 degrees axis. Depending on a specific experiment, larger acceptance in the forward direction can be set for protons or electrons by simply reversing the field direction. This effect can be enhanced, as proposed by Blomquist [1], by moving the target along the beam axis.

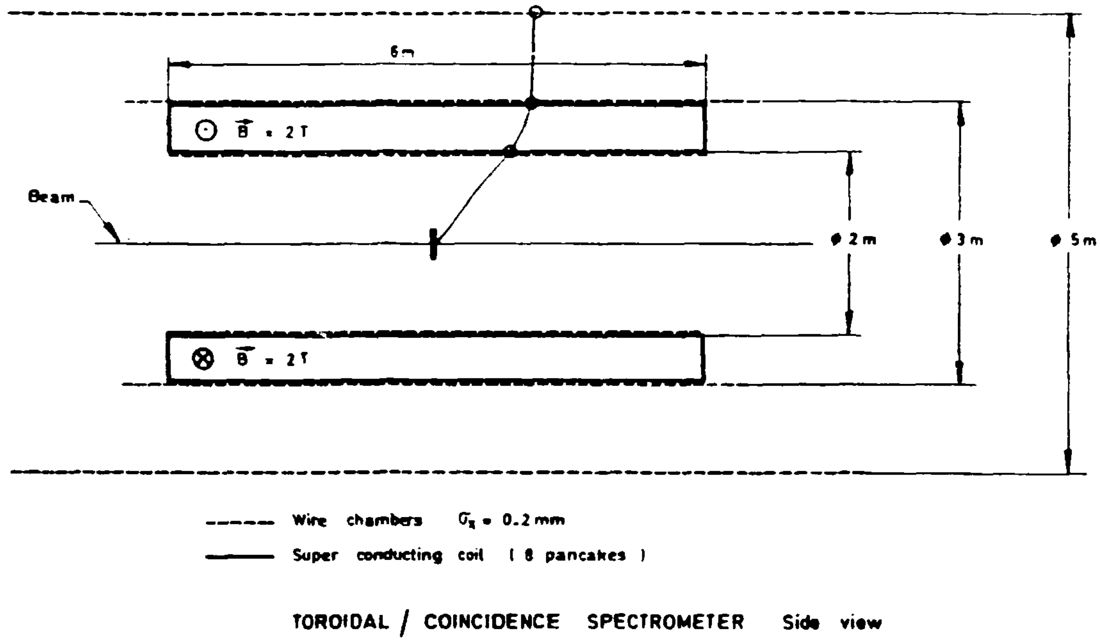


Fig. 4 - A possible toroidal spectrometer for high energy electrons coincidence experiments.

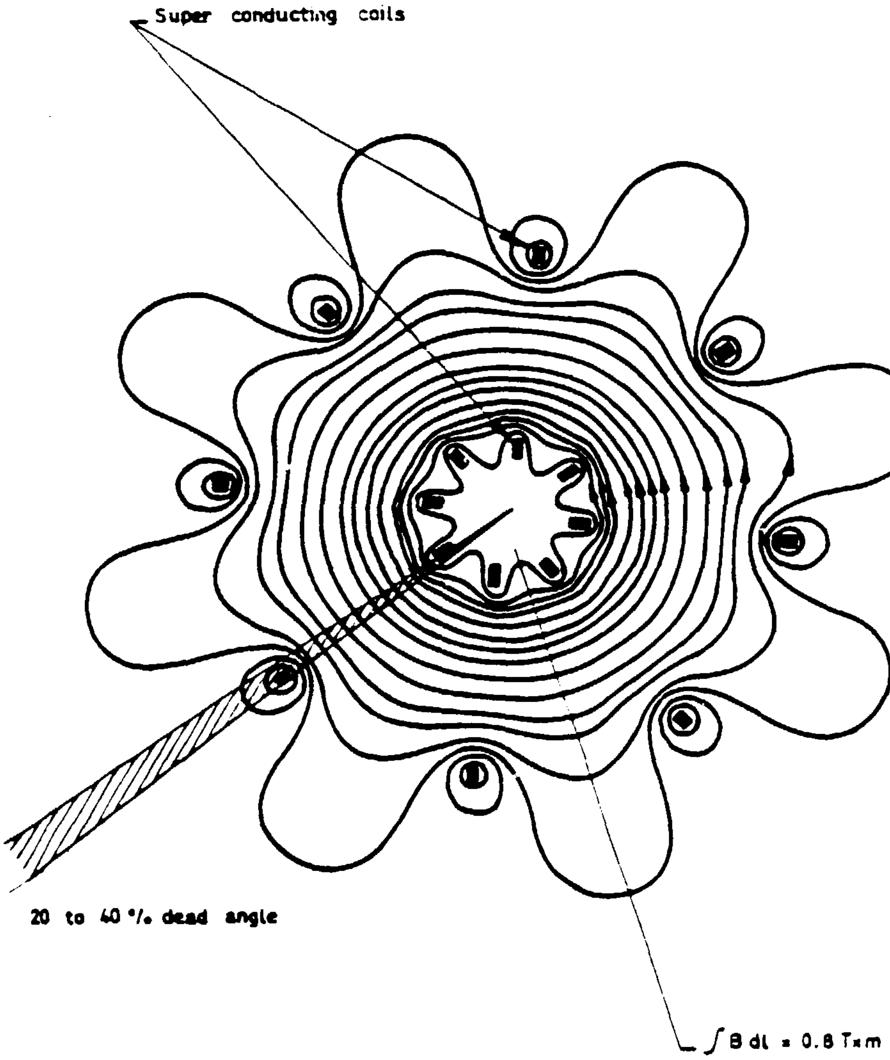
7. Comparison of axially symmetric magnetic field with classical dipole iron spectrometers

As seen above, although angular and momentum acceptances of such an axially symmetric detector are incomparably higher, other characteristics are far from surpassing those of classical dipole iron spectrometers. The latter have, in particular, two excellent characteristics :

1) They can be built with an accurately predictable field pattern allowing sophisticated optics. This provides high resolution with the use of only one single detection. A double detection in the area of a focal region can also provide high resolution within a fairly large angular acceptance with the help of software corrections. The location around the focal region is essential to minimize the effect of multiple Coulomb scattering.

2) They provide a complete separation of particles that are either neutral or having a charge opposite to that which is analysed. As a result, one obtains an extremely high background rejection with the help of shielding and direction sensitive detectors. Thus, cross sections as low as 10^{-37} cm^2/steradian have been measured in a single arm electron scattering experiment [10].

A chronological list of such classical spectrometers used in intermediate energy physics is presented in Table 1. The most recent ones are only projects. Almost all of them are provided with multiple detection and software corrections. Impressive improvements can be seen. However, they fill an enormous amount of space with respect to the rather small solid angle they are covering. Consequently, they interfere with other spectrometers looking at the same target, thus creating large respective dead angles. They are so bulky that it is difficult to imagine how to move them out of the horizontal plane, to perform out-of-plane experiments.



FRONT VIEW OF A LUMPED COIL TOROID

Fig. 5 - Distribution of the magnetic field in a lumped coil toroid spectrometer.

8. Conclusion

Axially symmetric spectrometers offer significant possibilities in view of their extremely large angular acceptance. However, because of their limited performance in resolution and background rejection, they can not be considered as substitutes for classical dipole spec-

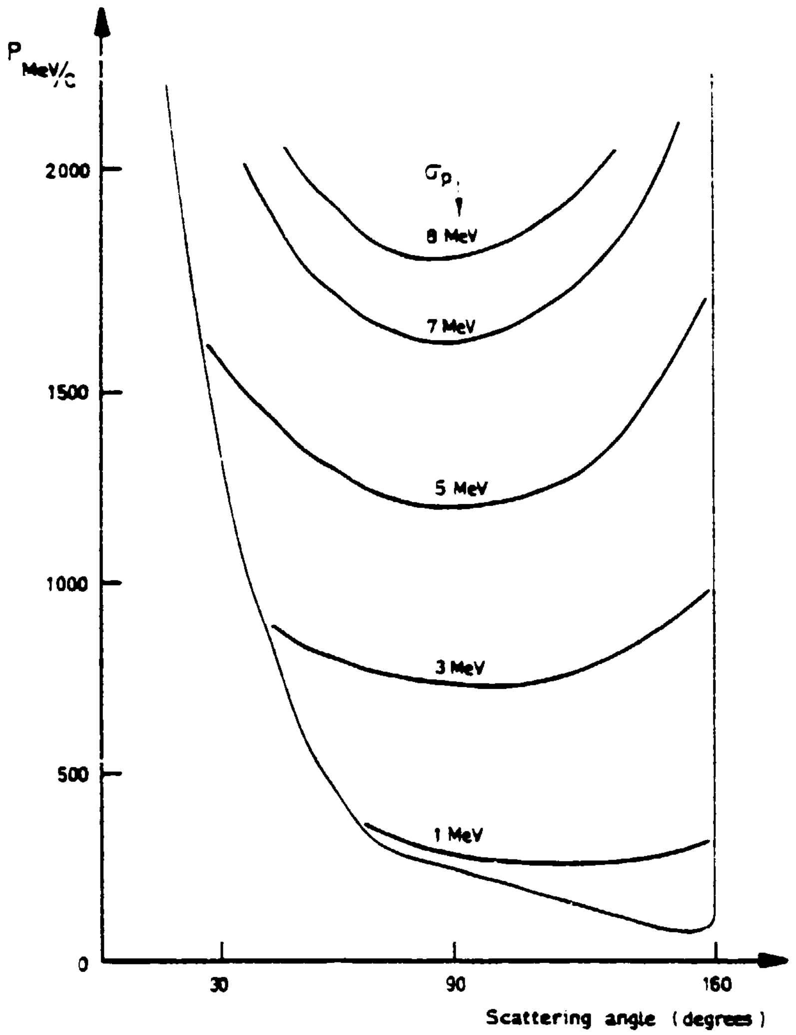


Fig. 6 - Calculated resolution, acceptance in solide angle, and momentum bite of the spectrometer described in Fig. 4.

trometers. More detailed investigations should be made in the light of specific experiments for which these last features may be of lesser importance. As an example, resolution is not fundamental for reactions presenting no sharp structure in momentum space.

Important questions remain about the flux of the different particles emerging from a target struck by a high energy electron beam. They are presently being studied at Saclay. Among them, the most important are :

- What is the behaviour of the full angular distribution of electrons in the momentum acceptance considered ? It is well known that elastic and low excitation level inelastic scattering show an extremely steep angular distribution. Other processes, however, present a much smoother behaviour. What is their relative importance?

- What is the general aspect of the angular distribution of hadrons? It is a rather smooth one, due to the Fermi motion, but aren't most of the

Table 1

List of performances of spectrometers for intermediate energy physics

Spectrometer		σ_p/p 10^{-4}	Δp %	Ω msr
600	Saclay	5	36	6.8
900	Saclay	1.	10	5.6
900 MeV/c	MIT	1.	10	5.4
SPES I	Saclay	1.	8	3.8
HRS	Los Alamos	0.25	2	3
SPES II	Saclay	10	36	20
QDD	Amsterdam	1.	10	5.6
QDQ	Amsterdam	10	10	17
SPES III	Saclay	4-10	80	10
RPI	MIT	5	15-20	35
1.2 GeV/c	MSU	0.5	5	20
(QDD)'s	Mainz	2	20	30
Clamshell	Los Alamos	5	30-60	40

hadrons correlated with electrons scattered at very small, forward angles, due to the Mott cross section?

- What are the angular and momentum distributions of photons, soft photons, soft electrons, muons?

- How should one cope with accidentals, dead-time, overflow of information, beam transport and beam dump background?

- How should one perform neutron and photon detection?

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