# High-rate Precision Experiments

E. Chudakov[a] *

[a]Thomas Jefferson National Accelerator Facility,
12000 Jefferson avenue, Newport News, VA 23606, USA

A new generation of experiments for studies of the nucleon structure with electromagnetic probes is under consideration by the physics community interested in hadron physics. One of the main goals of these projects is studying the Generalized Parton Distributions (GPD), which typically requires detecting several particles in the final state, high luminosity, large acceptance and good missing mass resolution of the spectrometers. The combination of these requirements is challenging and pushes the detectors involved to the limits. In this paper a review of the proposed experiments is presented and their feasibility is evaluated taking into account the recent progress of the detector technique.

## 1. Introduction

Electromagnetic probes have played a major role in studying the nucleon structure, by measuring, for example, the electromagnetic form-factors in elastic scattering and the structure functions in deep inelastic scattering. Typically, the most important experiments in DIS detected one particle - the scattered lepton in the final state. Presently, the physics community is considering a new generation of experiments, more demanding to the accelerators and detectors than the present facilities. Such tasks as studying the "transversity" and Generalized Parton Distributions (GPD), typically require detecting several particles in the final state at high luminosity, by a spectrometer with a large acceptance and a good missing mass resolution. These conditions require high duty cycle accelerators and very fast detectors. In this paper a review of the proposed experiments is presented and their feasibility is evaluated taking into account the recent progress the detector technique.

## 2. Recent Progress in Detector Technique

Several kinds of detectors are essential for the new generation of spectrometers, namely the coordinate detectors, detectors for particle identification and electromagnetic calorimeters for detecting photons and identifying electrons. The general requirements include a good time resolution, low dead time and radiation hardness. Additionally, the spatial resolution of the coordinate detectors and the energy resolution of the calorimeters are

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important because of the requirement for a good missing mass resolution of the spectrometer. Additionally, the coordinate detectors should contain as little material as possible in order to minimize the multiple scattering at the energies of secondary particles of a few GeV, typical for ELFE-type projects and to reduce the conversion of low energy photons, abundant in the experiments with electron beams.

### 2.1. Coordinate Detectors

Several type of coordinate detectors are considered for high rate experiments, namely various gaseous detectors, solid state detectors like silicon microstrips and scintillating fibers. The main detector parameters are summarized in Table 1, a more detailed description is given here.

Up to now large magnetic spectrometers used various types of drift chambers for the main coordinate detector, covering large apertures. In order to reduce the number of accidental hits per event the drift time has to be minimized. An example of the fastest drift detector of a large scale is the Transition Radiation Tracker (TRT) of ATLAS[1], utilizing carbon plated kapton straw tubes 4 mm diameter with a 30 $\mu$m wire, filled with a $Xe/CF_4/CO_2$ gas mixture, The detector, consisting of about 0.5M tubes is designed to operate under extremely high radiation levels of the LHC, serving both for tracking and particle identification. The maximum drift time is about 40 ns. At low counting rates the spatial accuracy is about 110 $\mu$m and the tube efficiency is 88%, while at a very high rate of 18 MHz per tube, the resolution is reduced to 140$\mu$m and the efficiency to 60%. This relatively low efficiency is compensated by a large number of detectors on the track. The straws add about 0.06%$X_0$ of material per layer and two layers are needed to measure one coordinate. Additionally, there are carbon fibers glued to the straws for reinforcement, which amounts in total to about 0.2%$X_0$ for one coordinate measured.

An impressive progress occurred during the last several years with gaseous micro-pattern detectors. In these detectors the gas amplification happens in a narrow parallel plate gap. The fast removal of positive ions in combination with the high granularity of the detector allows to obtain a very good time and spatial resolutions with minimal dead time. These detectors have a much higher rate capabilities than the wire detectors, where the space charge effects limit the performance. Two competitive technologies have been developed, both look robust and are already used in physics experiments. Both detectors have a conversion gap about 3 mm thick providing the initial gas ionization by the crossing particle, with a drift field of about 1 kV/cm, and a gas amplification gap with a field of about 50 kV/cm. In a detector called MICROMEGAS[2] the amplification happens between a metal micro-mesh several $\mu$m thick and a printed circuit board with metal strips about 0.2 mm apart, used to collect the signal. The signal is induced by both electron and ion motion in the amplification gap, the ion motion takes about 100 ns for a typical gap of 0.1 mm. The electron component of the signal has the rise time of about 1 ns. The concept was developed and described in a number of papers[3–7].

Another detector, called Gas Electron Multiplier (GEM)[8] has separate amplification and induction gaps. The key element is the GEM electrode, consisting of a polymer film about 0.1 mm thick, metallized on both sides, with holes about 70 $\mu$m diameter spaced

100 μm apart. A voltage is applied to the opposite sides of GEM, providing a strong field inside the holes, where the gas amplification happens. The secondary electrons pass through the hole and are pulled to the next electrode, while the ions go back and are absorbed on the negative side of the same GEM. Stacking several GEMs serially provides very high total gains. Finally, the electrons produced cross the induction gap and induce a fast signal on a printed circuit board. Since the ions drift outside of the induction gap they do not contribute to the signal at all. Two-dimension readout has been used. The detector performance has been thoroughly studied[9–17].

An intrinsic problem of the gaseous micro-pattern detectors, limiting the particle flux the detector can stand at a certain gain, is occurrence of discharges caused by strongly ionizning particles, which make the whole detector dead for a few milliseconds and may damage the electronics attached to the detector. Since GEM detectors allows to distribute the gain between two or three GEM electrodes, they are more stable than MICROMEGAS by 4-5 orders of magnitude and can give only one discharge for $\sim 10^{11}$ incident hadrons. Apart from this feature, the parameters of GEM detectors and MICROMEGAS are very similar (see Table 1). No significant drop of the gas gain was observed at high particle fluxes up to $10^5$ mm$^{-2}$.

Table 1
Parameters of the coordinate detectors. The best time resolution of the scintillating fibers of 0.4 ns was achieved using a PMT readout, while the VLPC readout at 6K° provided a resolution of 3 ns. The radiation hardness for the gaseous detectors refers to non-aging gas mixtures. The time resolution of the straw tubes refers to the drift time. A stack of several planes provides a much better resolution of about 5 ns for tracks. The drift time of straw tubes depends on the diameter and can be as low as about 40 ns for 4 mm diameter tubes.

| Detector | $X_0$/ coord % | $\sigma_X$ $\mu m$ | $\sigma_t$ $ns$ | Rad. hardness | | size of a unit $cm^2$ | full size in use $m^2$ |
|---|---|---|---|---|---|---|---|
| | | | | $Mrad$ | MIPs/$cm^2$ | | |
| Scint. fibers | 0.9 | $\sim 100$ | 0.4-3. | 1 | $3 \cdot 10^{13}$ | $\ell \sim 3\ m$ | $\sim 10$ |
| Si μ-strips | 0.15-0.3 | $\sim 10$ | <100 | 30 | $10^{15}$ | $6 \times 6$ | $\sim 3$ |
| GEM | 0.15 | $\sim 80$ | <18 | >10 | $> 3 \cdot 10^{14}$ | $30 \times 30$ | $< 2$ |
| MICROMEGAS | 0.3 | $\sim 70$ | 8 | >10 | $> 3 \cdot 10^{14}$ | $40 \times 40$ | $< 2$ |
| Straw tubes | 0.2 | $\sim 100$ | $\sim 100$ | >10 | $> 3 \cdot 10^{14}$ | $\ell \sim 3\ m$ | $\sim 20$ |

Another type of detectors to be considered includes the silicon micro-strip or micro-pad detectors. These are the detectors of choice for the LHC experiments ATLAS and CMS. The detectors[18] provide the best spatial accuracy and also are radiation hard, if kept at low temperatures of about 250 K. The time properties of these detectors are limited by the signal to noise ratio, preventing using a faster electronic amplifiers. The pad detectors, with a much lower capacitance per pad than the strip capacitance, provide a very good signal to noise ratio, which helps to improve both the timing and the radiation hardness. The disadvantages of these detectors include a relatively small size of one unit and their relative large thickness.

The fastest tracking detector, also providing a good spatial resolution is a hodoscope of scintillating fibers (see for example [20–23]). The typical diameter of the fiber core is 0.5 mm and 5-8 of them are positioned one after another to provide a coordinate measurement with a good efficiency. Two types of readout have been widely used - multichannel photo-multiplier tubes (MPMT) and semiconductor Visual Light Photon Counters (VLPC) which have to operate at temperatures of about 6 K. The MPMT solution, being more expensive, provides the superb time resolution of ~0.5 ns, while the VLPC provide a resolution of ~3 ns. Building large detectors of several $m^2$ is possible although expensive. Another disadvantages of this detector are a relatively large amount of material it contains per one measured point and a medium radiation hardness.

From the discussion above and Table 1 one may conclude that the best performance detector for large acceptance, high rate experiments at high energies would be the scintillating fiber hodoscope, while at low energies, with the secondary particles being in the energy range of a few GeV, other solutions might be better, as a combination of GEM detectors with drift tubes.

### 2.2. Particle Identification

Separation of electrons from hadrons is mainly done with calorimeters. For separation of different hadrons in the energy range of ~1-100 GeV Ring Image Cherenkov (RICH) detectors are typically considered. The problem with the RICH is how to build a two-dimensional photon detector with a time resolution better than ~50 ns and a good angular resolution. The latter depends on the detector granularity and the thickness of the optical photo-sensor. The most popular solution for the moment is using photo-multiplier tubes or their derivatives So far, the fastest RICH detectors have been built using photo-multiplier tubes[24–27] with the number of detector pads (tubes) ranging from 700 to 4000, and also multi-anode photo-multiplier tubes with about 20k pads[28]. New hybrid multi-pixel phototubes have been designed, which might be used in future experiments[29–31].

### 2.3. Electromagnetic Calorimeters

A number of future experiments require a good energy resolution of the photon detector, as, for example, the Deeply Virtual Compton Scattering (DVCS) experiments. Here, we consider only non-sampling calorimeters with optical readout as the most popular high resolution detectors. The main parameters of the materials used in such calorimeters are compared in Table 2. The requirements for the energy resolution and radiation hardness are not met by lead glass. $CeF_3$ is not massively produced, at least at the moment. It leaves three types of crystals[32–35] to consider. CsI has a slow radiation component and is second in radiation hardness, though it provides the best energy resolution. The most interesting option seems the $PbF_2$[35] one. This material is radiation hard, has a short radiation length, provides a reasonably good energy resolution and, since it is not a scintillator, it is not sensitive to low energy particles.

Table 2
Parameters of materials for non-sampling calorimeters with optical readout.

| Material | CsI | $CeF_3$ | $PbWO_4$ | SF-5 LG | $PbF_2$ |
|---|---|---|---|---|---|
| Density $g/cm^3$ | 4.5 | 6.2 | 8.3 | 4.08 | 7.77 |
| $X_0$ cm | 1.85 | 1.68 | 0.9 | 2.54 | 0.93 |
| Molière radius cm | 3.5 | 2.6 | 2.0 | 4.3 | 2.22 |
| $\lambda_I$ cm | 37 | 26 | 18 | 21.4 | |
| Hygroscopicity | slight | none | none | none | none |
| $\tau_1$ ns / Yield/NaI | 6 / 2.3% | 9 / 2.0% | 5 / 0.005% | Cher | Cher |
| $\tau_2$ ns / Yield/NaI | 35 / 5.6% | 30 / 6.6% | 15/ 0.008% | | |
| $\tau_3$ ns / Yield/NaI | ~1000 | | 100/ $10^{-4}$ | | |
| d(Yield)/dT %/C° | -0.6 | 0.14 | -1.9 | 0 | |
| Stochas. term $GeV^{0.5}$ | 1-2% | 1-2% | 2-3% | 5% | 3.5% |
| Rad. hardness rad | $10^5$ | $10^6$ | $10^6$ | $10^3$ | $10^6$ |

## 3. Future High Rate Experiments and Their Limitations

A number of proposals have been discussed for future electron machines. Their parameters and the physics goals are summarized in Table 3.

Table 3
The energies and luminosity limits of the new accelerators being considered, along with some of the main physics goals. The column "SM" marks tests of Standard Model, the column "Tr." marks studies of transversity. The upper part presents the fixed target projects and the lower part presents colliders.

| project | interaction | $E_{CM}$ GeV | $\mathcal{L}$ $cm^{-2}s^{-1}$ | Physics Highlights SM | $F_2$ | $g_1$ | GPD | $\frac{\Delta G}{G}$ | Tr. | other |
|---|---|---|---|---|---|---|---|---|---|---|
| JLab[36] | $\vec{e}$p,A | 4.8 | $10^{38}$ | | | + | + | | | hybrids |
| ELFE[37–41] | $\vec{e}$p,A | 7.0 | $10^{38}$ | | | + | + | | + | |
| NLC-N[42,43] | $\vec{e}$p,A | 20.0 | $10^{38}$ | + | | | | | | GDH |
| TESLA-N[44] | $\vec{e}$p,A | 20.0 | $10^{36}$ | | | + | + | + | + | |
| ELIC[45] | $\vec{e}$p,A | 31.0 | $6 \cdot 10^{34}$ | | | + | + | + | + | |
| eRHIC[46,47] | $\vec{e}$p,A | 150.0 | $2 \cdot 10^{32}$ | | | + | + | + | + | |
| THERA[48] | $\vec{e}$p | 1000.0 | $4 \cdot 10^{30}$ | + | + | | | | | |

Here, we consider only the experiments requiring large aperture, high resolution multi-particle spectrometers, aiming at studying the GPD, transversity or $\frac{\Delta G}{G}$. Some of the proposals, like TESLA-N, NLC-N, THERA are based on the projects of accelerators (linear colliders), being developed for the high-energy physics program, and are limited by the design parameters of these accelerators. The ELFE project, requiring a relatively low beam energy of ~25 GeV can be potentially built as a machine dedicated to the physics of eN interactions.

The duty cycle of the NLC-N is certainly too low to make coincidence measurements with a high sensitivity. In the TESLA-N project a way to increase the duty cycle was developed to 0.5% and it is considered potentially possible to provide a 2% duty cycle. The new projects for large acceptance experiments are summarized and compared to the existing experiments in Table 4.

Table 4
Running and considered accelerator facilities and large aperture experiments. The second column indicates the experiment's status, with the question mark indicating the projects under discussion inside the community. The luminosity for TESLA-N project is the conservative limit from the proposal[44].

| Experiment | status | $E_{CM}$ GeV | $\mathcal{L}$ $cm^{-2}s^{-1}$ | Repet. rate | Pulse length | Spill structure |
|---|---|---|---|---|---|---|
| CLAS JLab@6GeV | old | 3.3 | $1.0 \cdot 10^{34}$ | 0.5 GHz | 2 ps | 1 |
| CLAS JLab@12GeV | developed | 4.5 | $1.0 \cdot 10^{35}$ | 0.5 GHz | 2 ps | 1 |
| ELFE (pol) | ? | 7 | $5.0 \cdot 10^{35}$ | 0.5 GHz | 20 ps | 1 |
| HERMES (pol) | old | 7.2 | $2.0 \cdot 10^{31}$ | 10 MHz | 600 ps | 1 |
| HERMES (unpol) | old | 7.2 | $4.0 \cdot 10^{33}$ | 10 MHz | 600 ps | 1 |
| COMPASS | old | 20 | $5.0 \cdot 10^{32}$ | - | - | 18% |
| TESLA-N | ? | 22 | $1.2 \cdot 10^{34}$ | 1.3 GHz | 20 ps | 0.5% |
| TESLA-N (20Hz) | ? | 22 | $5.0 \cdot 10^{34}$ | 1.3 GHz | 20 ps | 2.0% |

Let us consider the experiment at ELFE. The main purpose is studying semi-exclusive reactions, like DVCS. Several important conditions should be met by the detector: a) it should operate at the designed luminosity; b) the missing mass resolution must be much better than the pion mass, therefore the momentum resolution of the spectrometer should be $\sigma p/p$ <0.1%; c) the spectrometer should have a large acceptance for the useful kinematics range of $Q^2$ <25 GeV$^2$ and detect particles with $p > 1 - 2$ GeV/c. The main sources of background for these type of experiments are low energy Møller electrons, produced by the electron beam and the pions coming from decays of vector mesons produced by quasi-real photons. A very good filter for the Møller electrons is a solenoid magnetic field. This approach was exploited in an early ELFE project MEMUS[38], designed to run at $\mathcal{L} < 10^{36}\ cm^{-2}s^{-1}$. Unfortunately, the designed momentum resolution of MEMUS of ~1% is difficult to improve. A new proposal[41] considers a spectrometer (see Figure 1) with a large dipole magnet with $\int Bdl \sim 5$ T·m and an acceptance of $|\theta_X| < 25^\circ$, $0.3^\circ < |\theta_Y| < 10^\circ$. The central area $|\theta_Y| < 0.3^\circ$ ("the sheet of flame") is excluded, and also a wider "Møller parabola" is excluded from the acceptance, depending on the coordinates in X and Z.

The acceptance angle with respect to the beam angle is limited to $|\theta| > 1^\circ$. Due to the high background it is not possible to place any detector in front of the dipole, the first tracking detector is positioned after the dipole. The calculated background rates in the first detector are shown in Table 5. The total background rate is about 30MHz per plane, which is a reasonably comfortable for all the detectors mentioned in Table 1. The momentum resolution requirements impose important constrains on

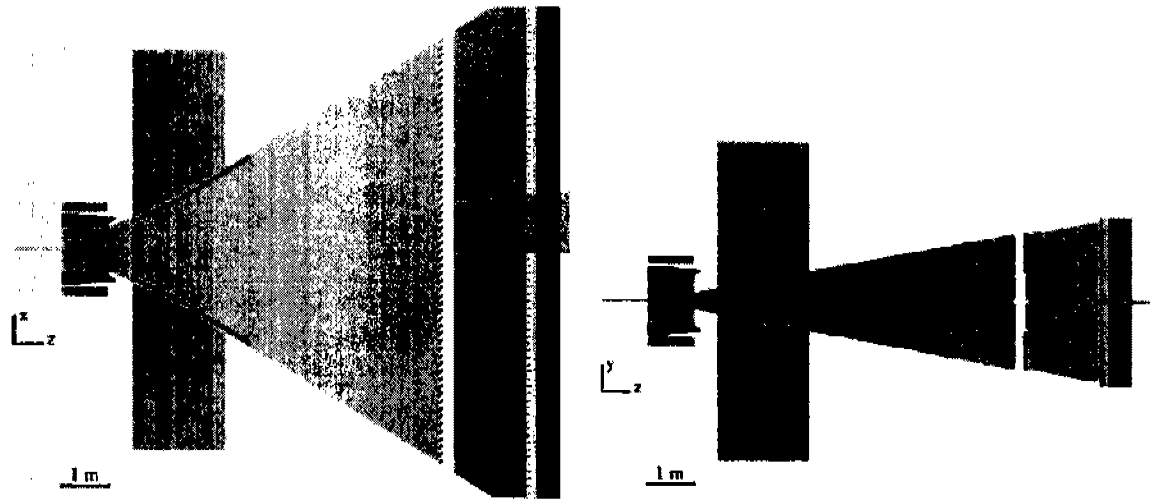

Figure 1. High resolution spectrometer for ELFE[41], top and side views

the longitudinal dimensions of the spectrometer and requires no air between the main coordinate detectors. It is proposed[41] to place the detectors in a vacuum tank. This would exclude the gaseous detectors from consideration and, because of a large surface of the detector planes, leaves the only option of scintillating fiber detectors. With the time resolution of 0.5 ns an effective gate of $\pm 3\sigma \sim 3$ ns for the tracking detectors can be considered. This leaves $\sim$ 0.01 background pions and $\sim$ 0.06 Møller electrons per one event. The Møller electrons can be efficiently suppressed kinematically, while the pion constitute an important background. The level of 0.01 per event is considered still comfortable[44].

Table 5
Rates and pileup

| Machine | Acceptance | | $\mathcal{L}$ | Per pulse | | | Per second | | per |
|---|---|---|---|---|---|---|---|---|---|
| | $\theta_{min}$ | $P_{min}$ GeV | $cm^{-2}s^{-1}$ | $N_{beam}$ | $N_{Moller}$ | $N_\pi$ | $N_{BG}$ | spill $N_{BG}$ | 3 ns $N_{BG}$ |
| ELFE | 0.02 | 2 | $5.0 \cdot 10^{35}$ | $1.6 \cdot 10^3$ | 0.05 | 0.01 | $3 \cdot 10^7$ | $3 \cdot 10^7$ | 0.08 |
| TESLA-N | 0.005 | 5 | $1.2 \cdot 10^{34}$ | $0.8 \cdot 10^3$ | 0.04 | 0.01 | $1 \cdot 10^6$ | $5 \cdot 10^7$ | 0.16 |

At least two planes of scintillating fibers are needed for tracking, and at least one additional plane downstream of the vacuum vessel. The other detectors foreseen for this spectrometer are a RICH detector and an EM calorimeter. The main challenge comes from the transverse sizes of these detectors, the calorimeter being 10×3 $m^2$. For the calorimeter a good energy resolution is essential, therefore the options with crystals are considered. The rate capacity of the RICH detectors and calorimeters discussed above is adequate. The radiation hardness of the detectors proposed is sufficient for the project.

Similar calculations, done for the TESLA-N[44] project with a 2% duty cycle (see Table 5) establish a limit of $\mathcal{L} \sim 1.2 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$. The setup proposed is similar to the one proposed for ELFE, but contains several dipole magnets in order to cover a wide energy range. Also, the multiple scattering is less important than in case of ELFE. The detector choice may be different, but again, the main parameter is the time resolution and at least one fast detector for the track segment is essential.

### 3.1. Conclusion

The future fixed target experiments for measuring GPD, transversity, $\Delta G/G$ etc, look technically challenging. The requirements for a good missing mass resolution favor the design of large aperture spectrometers with strong dipole magnets. No tracking would be possible between the target and the first dipole, while after the dipole the particle density is low enough for several types of tracking detectors. The limiting background comes from pion production by quasi-real photons and the crucial parameter is the time resolution of the detectors. Scintillating fibers is the fastest tracking detector, also providing a very good spatial resolution. The proposed spectrometer for ELFE should be able to operate at the designed luminosity of $5 \cdot 10^{35}$ cm$^{-2}$s$^{-1}$, while the similar limit for TESLA-N with a 2% duty cycle is $1.2 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$.

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