Perspectives for a Next-Generation Electron-Nucleon Scattering Facility in Europe

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Abstract. This paper discusses perspectives for a future fixed-target electron-nucleon scattering facility in Europe. Based on the intended measurements the requirements on accelerator, target and spectrometer are presented and their possible realisation is discussed.

INTRODUCTION

With the advent of Generalised Parton Distributions (GPDs)[1, 2, 3] a unified approach to the description of nucleon structure has become possible. Formerly separate aspects, such as form factors and (forward) parton distribution functions, can now be described in a common framework. An investigation of the currently approved experiments [4] shows that the study of the momentum and spin structure of the nucleon cannot be completed with the current generation of accelerators and spectrometers.

In a European context a next-generation facility is being discussed in the form of a fixed-target experiment, combining a linear accelerator with a large acceptance spectrometer. Two related proposals (ELFE@DESY [5], TESLA-N [6]) have been included in the appendix of the TESLA technical design report. The ‘Declaration of Ferrara’¹, outlining the need for a next-generation facility, has already been signed by more than 160 European scientists and a European network is being formed. The alternative idea, a colliding beam facility, has also originally been discussed in Europe [7] and may now be realised in North-America in the form of the Electron Ion Collider (EIC) [8]. A collider and a fixed-target facility would complement each other in an ideal way, as the different kinematics would allow better access to gluon or quark distributions, respectively.

This paper outlines the main physics questions and the resulting requirements of a next-generation facility. Possible accelerator options are discussed and the basic design parameters for a fixed-target spectrometer are presented.

¹ http://www.fe.infn.it/qcd-n02/
PHYSICS AND RESULTING REQUIREMENTS

The complete set of GPDs consists of eight distributions for each parton species \( f = u, d, s, g \). These distributions are classified according to whether they they flip parton helicity (subscript \( T \)) or not, if they conserve nucleon helicity (\( H \)) or not (\( E \)) and if they are unpolarised or polarised (marked with \( \sim \)) [9, 10]. When all currently planned experiments will be completed and analysed, some information will be available on the unpolarised u-quark GPD \( H_u \). All other GPDs will remain completely unmeasured [11].

The limiting cases of GPDs, parton distributions and form factors, have been studied for some time and will mostly be well known after the completion of the current or currently planned experiments. Notable exceptions are the transversity distributions and the polarized gluon distribution \( \Delta g \) - they will be measured, but still lack in precision. An overview of the experimental status of the relevant quantities is given in [4].

Generalised Parton Distributions can be accessed through measurements of exclusive reactions, e.g. Deeply Virtual Compton Scattering (DVCS), while transversity and \( \Delta g \) require semi-inclusive measurements. A common requirement for both types of measurement is the increase of the available luminosity by two orders of magnitude compared to present facilities to \( 10^{35} \text{cm}^{-2}\text{s}^{-1} \). The following sections will give a short overview of the requirements on the different parts of a future facility (accelerator, target, spectrometer) and review the available options.

ACCELERATOR OPTIONS

The present beam energy at HERMES can be seen as the lower limit for a future facility, while the energy available at TESLA-N has been shown to be sufficient for the semi-inclusive measurements. The technically feasible spectrometer resolution (see below) limits exclusive measurements to beam energies below about 50 GeV. The accelerator for a next-generation fixed-target facility should therefore ideally have a variable beam energy from 30-250 GeV.

As beam charge asymmetries are part of the measurement program for GPDs, both beam charges are required. The necessary beam intensity to achieve the desired luminosity of \( 10^{35} \text{cm}^{-2}\text{s}^{-1} \) can only be reached with electrons/positrons. The luminosity also leads to the requirement of a large duty factor > 10% to avoid pile-up. The condition of exclusivity implies that the energy spread of the beam should be of the order of only 1/3 of the pion mass or less.

Up to now three proposals for an accelerator have been made:

- ELFE@DESY [5]: use part of TESLA as injector and HERA as stretcher ring
- TESLA-N [6]: fill \( e^- \) into ‘empty buckets’ in the \( e^+ \)-arm of TESLA
- EVELIN [12]: use TESLA cavities to put a 4.5 km linac into the HERA tunnel

All of these proposals fulfill some, but not all requirements: TESLA-N has a low duty factor of 0.5 % and delivers only electrons, the beam energy is limited to 27 GeV at ELFE@DESY and to 75 GeV at EVELIN. The duty factor of TESLA-N could perhaps be improved to 12.5% if two different RF sources could be used in TESLA.
TARGETS

Beam currents of the order of 1 A would be necessary to achieve a luminosity of $10^{35} \text{cm}^{-2}\text{s}^{-1}$ with gas targets. This does not appear to be feasible and therefore it is unavoidable to use solid polarised and solid or liquid unpolarised targets. A liquid $H_2$ ‘spaghetti’ could be used as unpolarised target, while $\text{NH}_3$, $\text{ND}_3$ or $6\text{LiD}$ would be suitable materials for polarised targets [5, 6, 13]. While there is no problem in principle, a series of technical problems must be solved, especially concerning the heat load from the beam and the design of a target geometry that allows for the combination with a recoil detector.

It is instructive to compare the luminosity of polarised experiments with solid state targets and of experiments at a collider or with a pure target. In such a comparison an effective polarised luminosity $L_{\text{eff}}$ should be used that includes an appropriate correction factor. Assuming a $\text{NH}_3$ target with 80% polarisation and a purity of 0.176 and a proton beam/target with 70% polarisation and purity 1.0 this correction factor is about 25. Figure 1 shows the effective luminosity versus the center-of-mass energy for present and future high-energy $e\text{N}$-scattering facilities.

![Figure 1](image_url)

**FIGURE 1.** Effective Luminosity $L_{\text{eff}}$ for present and future high-energy $e\text{N}$-scattering facilities. Shaded (yellow) areas mark the anticipated regions of ELFE/TESLA-N and EIC, future projects are labeled in tilted font. The point for HERMES (unpolarised) appears within the area of ELFE/TESLA-N (polarised).

SPECTROMETER

In the absence of perfect hermeticity and detector efficiency, exclusivity can only be guaranteed through a missing mass resolution that is small compared to the pion mass. An even stronger condition arises if also excited intermediate states should be detected.
(\Delta M_{\text{min}} = M_{\Sigma} - M_{\Lambda} = 77 \text{ MeV}). The key issue of the spectrometer is therefore the momentum resolution \( \frac{\sigma_p}{p} \), which can be approximated as [5]

\[
\frac{\sigma_p}{p} \approx \frac{0.0138 \sqrt{\delta/X_0}}{0.3} \cdot \frac{z_1}{z_m} \tag{1}
\]

where \( \int B \, dl \) is the integrated field strength, \( \sqrt{\delta/X_0} \) is the thickness of material in front of the second tracking detector and \( \frac{z_1}{z_m} \) the ratio of the position of the first tracking detector to that of the magnet center. For a sufficient missing mass resolution (\( \leq 40 \text{ MeV} \)) a momentum resolution of \( \leq 0.1\% \) is required at a beam energy of 50 GeV.

While factors like the maximisation of the integrated magnetic field over a short distance are important, the main technical challenge arises from the requirement to keep the material between target and the second tracking detector as thin as possible. This implies the necessity of a large vacuum vessel reaching from the target to the second tracking detector. Detector 1 is therefore located inside the vacuum (see fig. 2). One technical solution is the use of scintillating fibres: 5 layers of 500 µm fibres with a pitch of 340 nm offer 80 µm resolution, 99% efficiency and a thickness of only 0.6% of a radiation length. However, to measure both coordinates the thickness must be doubled and this is already crossing the limits of the thickness allowed for the required resolution. A possible alternative could be the use of a large area double sided silicon detector: 200 µm silicon plus Kapton foils with printed copper lines add up to only about 0.5% of a radiation length. Such a detector would have the problem of acceptance gaps while the size of this detector (about 7 m²) would still be small compared to the largest silicon detectors (CMS silicon tracking detector, 206 m² [14]).

![FIGURE 2. Schematic view of the ELFE spectrometer [5].](image)

The conceptual layout of a forward spectrometer has already been studied for the ELFE proposal [5] at a beam energy of 25 GeV. It is shown in figure 2. This layout needs to be extended to allow for higher beam energies and to include flexibility towards a pos-
sible second stage. Besides the previously discussed tracking detectors the spectrometer should consist of a transition radiation detector (TRD), ring imaging Cherenkov (RICH) detector and electromagnetic calorimeter for particle identification. The set-up is completed by a recoil detector. For each component detectors exist or are currently being developed that can serve as models: the HERMES TRD [15] or ALICE TRD [16], the LHCb RICH [17] or the COMPASS RICH2 [18], the CMS [19] or ALICE calorimeters [20] and the HERMES Recoil Detector [21]. A detailed discussion of some of these choices can be found in [22].

CONCLUSION

In principle, it appears to be feasible to realise a next-generation electron-nucleon scattering facility with luminosities of \( \geq 10^{35} \text{cm}^{-2}\text{s}^{-1} \) as a (polarised) fixed-target experiment. However, further research into experimental technologies is necessary, especially concerning the accelerator design, the combination of targets and recoil detectors and the realisation of ultra-thin large area tracking detectors operating in vacuum.

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