PROCEEDINGS OF SCIENCE

Compton transmission polarimetry of laser-plasma accelerated electron beams

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Polarised particle beams are indispensable for the study of spin-dependent processes . The LEAP (Laser Electron Acceleration with Polarisation) project at DESY aims to demonstrate the acceleration of polarised electrons in the extremely high fields enabled by laser plasma accelerators to create high energy electron beams in ultra-compact footprint. In this proof of principle experiment, spin-polarised electron beams with energies of tens of MeV will be generated in a sub- millimetre long plasma source. For electron beams of such energies, Compton transmission polarimetry is the ideal method to measure the polarisation. Gamma rays produced by bremsstrahlung are transmitted through an iron absorber core magnetised by a surrounding solenoid, with rate and energy spectrum depending on the relative orientation of the gamma spin and the magnetisation direction of the iron. The transmission asymmetry with respect to the direction of the magnetisation is proportional to the initial electron polarisation.

In this contribution, an overview of the LEAP project is presented, detailing the setup of the polarimeter as well as its implementation and commissioning status.

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1. Introduction

Spin-polarised electron beams are a key tool for many experiments in particle and nuclear physics. They facilitate, for example, the investigation of the spin structure of nucleons [1] or enhance our capability to test the standard model [2]. Conventional sources, quite often GaAs photo-cathodes within DC high voltage photo-guns [3], require radio frequency (RF) resonators for further acceleration, but are limited by the RF breakdown at very high acceleration gradients. This already excludes some applications for reasons of space. Plasma accelerators, on the other hand, are not restricted by this limit, allow acceleration gradients of more than three orders of magnitude higher [4] and hold great potential for compact sources of polarised electron beams.
Theory predicts that the electron beam polarisation can be maintained during plasma acceleration [5]. Concepts for generation using Laser Plasma Acceleration (LPA) were developed by means of simulations [6, 7]. The LEAP project at DESY aims to experimentally demonstrate the LPA of polarized electron beams.
This paper gives a brief overview of the LEAP project and describes the design and implementation of the employed Compton transmission polarimeter.

2. The LEAP Project at DESY

The project itself is divided into two parts: the generation and acceleration of polarised electron beams, where polarisation will be introduced via a prepolarised plasma target [8], and their polarimetry.
The FLARE facility at DESY accommodates a robust and reliable LPA source with a 10 Hz, 25 TW Ti:Sapphire laser system and stable acceleration of electron bunches over several hours has been demonstrated [9]. The adjustments required for polarised LPA are still in preparation. However, based on previous measurements and particle in cell simulations using FBPIC [10] the following beam parameters are expected with the above described, currently employed, system: A tunable central energy between 30 and 80 MeV, a bunch charge of 1-10 pC and a polarisation of about 10 %. More than 90 % polarisation are possible assuming a completely prepolarised plasma target and tens of pC of charge are possible with nowadays available 100 TW laser systems [11].
Because of the expected electron energy range of a few 10 MeV, Compton transmission polarimetry is going to be used to measure the degree of polarization. Common methods such as Mott-, Møller- or laser-Compton-polarimetry are rather difficult at this range due to impractical scattering angles, very high backgrounds, or very small signal rates, respectively [12].

3. Compton Transmission Polarimetry

Compton transmission polarimetry works in two steps:

1. Electrons are converted to photons via bremsstrahlung. During this process the photons inherit the polarisation of the electrons, so that the photons are circularly polarised. The photons then traverse through a magnetised iron absorber. The likelihood of their transmission is dependent on their polarisation and proportional to $\exp(-nL_B\sigma_{pol}P_\gamma P_{Fe})$, where n is the number density of atoms in the absorber, L_B the absorber length, σ_{pol} the polarisation

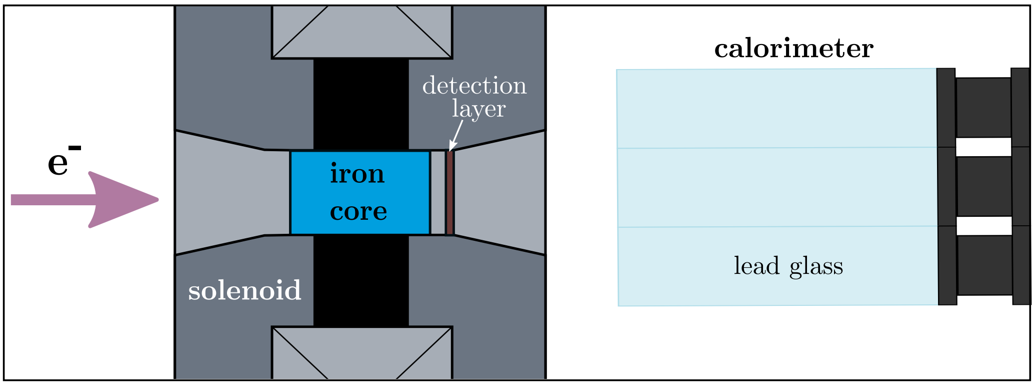

Figure 1: Schematic of GEANT4 detector geometry. Not to scale.

dependent part of the cross-section for Compton scattering, P_γ the photon polarisation and P_{Fe} the polarisation of the free electrons inside the iron.

2. The amount of transmitted photons, or rather the photon energy sum, is measured with a calorimeter.

When the direction of the magnetic field is changed, P_{Fe} changes accordingly. This leads to a difference in measured photon energy sum. Given that other properties of the electron beam (such as energy distribution and number of particles) are kept constant when changing the polarisation state, one can define an asymmetry between parallel and antiparallel polarisation configurations as follows:

$$\delta = \frac{E_{AP} - E_P}{E_{AP} + E_P} \tag{1}$$

To find the polarisation of the LPA accelerated electrons P_{e^-}, one must first determine the analysing power $\mathcal{A} \equiv \delta(P_{e^-} = 1, P_{Fe} = 1)$ using simulation, then measure the different photon energy sum distributions in an experiment to calculate the measured asymmetry δ_m. P_{e^-} can then be obtained as

$$P_{e^-} = \frac{\delta_m}{P_{Fe}\mathcal{A}} \tag{2}$$

This type of polarimetry has for example already been demonstrated for positrons at the E166 experiment [13]. The positrons had energies between 4 and 8 MeV. A polarisation of about 80 % was measured with a relative measurement error of 10-15 %.

4. Parameter Study

The key parameters of the polarimeter need to be adjusted to the experimental conditions at LEAP. Therefore, a Monte Carlo design study was performed employing GEANT4 [14].

A schematic of the geometry simulated is displayed in figure 1. As a first step a mono-energetic electron point source was simulated and GEANT4 physics-lists were used that include polarised electromagnetic physics. To obtain the analysing power $\mathcal{A}$, the polarisation of the beam electrons was set to 1 and that of the iron core of the solenoid to +/- 1. The transmitted energy sum was extracted from an ideal detector volume placed behind the core. The mean energy sum $E_{AP/P}$ was calculated over 1000 individual runs per polarisation configuration.

Figure 2a) shows the dependence of the analysing power on the electron beam energy for three different solenoid core lengths L_B. $\mathcal{A}$ decreases with E_{beam} because the cross section for Compton scattering does. At 30 MeV and L_B = 150 mm $\mathcal{A}$ is 20.73 ± 0.03%, where the error on $\mathcal{A}$ is the statistical error arising from the Monte Carlo simulation. At 80 MeV it has reduced to 11.75 ± 0.02%. However, it is less dependent on E_{beam} at higher values. The analysing power increases with increasing core thickness L_B, so does the statistical error due to reduced transmission rates at higher L_B. At 30 MeV it increases from 9.27 ± 0.01% with L_B = 75 mm to 43.92 ± 0.02% with L_B = 300 mm. It can be seen from figure 2b) that with E_{beam} = 30 MeV and L_B = 150 mm, 20 shots would suffice to achieve a statistical error below 1 %.

Using the same parameters an estimate of the measured asymmetry would be $\delta_m = \mathcal{A} \times P_{e^-} \times P_{Fe}$ = 20.73% × 10% × 7% = 0.15%. Simulations with realistic beam conditions and including the beam line to get as accurate an $\mathcal{A}$ for the experimental conditions as possible are in progress.

Nevertheless, using the simulations above, one can make an estimate of requirements for the calorimeter. Simulations show that with a bunch charge of 3 pC and each electron having an energy of 30 MeV, about 550,000 bremsstrahlung photons are transmitted through the iron core of the solenoid. This leads to a deposited energy in the order of 2 TeV. In figure 2c) the relative statistical precision of δ_m is shown for different electron beam energies and calorimeter energy resolutions σ_{calo}. With 20 electron bunches and an electron beam energy of 50 MeV it ranges between 4 and 11 % for a σ_{calo} between 1 and 2.5 %. This emphasises the need to reach a resolution as close as 1 % as possible and is the reason why a crystal calorimeter is going to be employed.

5. Experimental status

To understand the experimental limitations of the LEAP Compton transmission polarimeter and the associated uncertainties, zero polarisation measurements are performed with the beam line currently implemented in FLARE as described above in section 2. The polarimeter has been set up in its designated beam area. It comprises a solenoid with an iron core of 150 mm length and 50 mm radius, and a crystal calorimeter.The latter has been chosen as crystal calorimeters are generally known for their high energy resolution. Here, nine lead glass crystals are wrapped in reflective coating, stacked in a 3x3 grid and equipped with PMTs. Their charge is read out via a VME charge to digital converter.

The calorimeter was tested with single electrons between 1.6 and 6 GeV at the DESY II test beam [15]. Figure 2d) provides the experimental data on the energy resolution of the LEAP calorimeter. The graph shows the RMS-90 of the charge measured with the PMTs divided by the mean-90 over electron beam energy. A fit with the function

$$\frac{\sigma_E}{E} = \sqrt{\frac{a^2}{E} + \frac{b^2}{E^2} + c^2} \tag{3}$$

results in a constant term c that lies with a probability of 95 % below 1.2 %.

At the time of writing polarimeter measurements with an unpolarised beam are ongoing. The setup is depicted in figure 3. An integrating current transformer is used to measure the bunch charge that makes it through a collimator and into the polarimeter's solenoid. The calorimeter is placed 100 mm behind the latter.

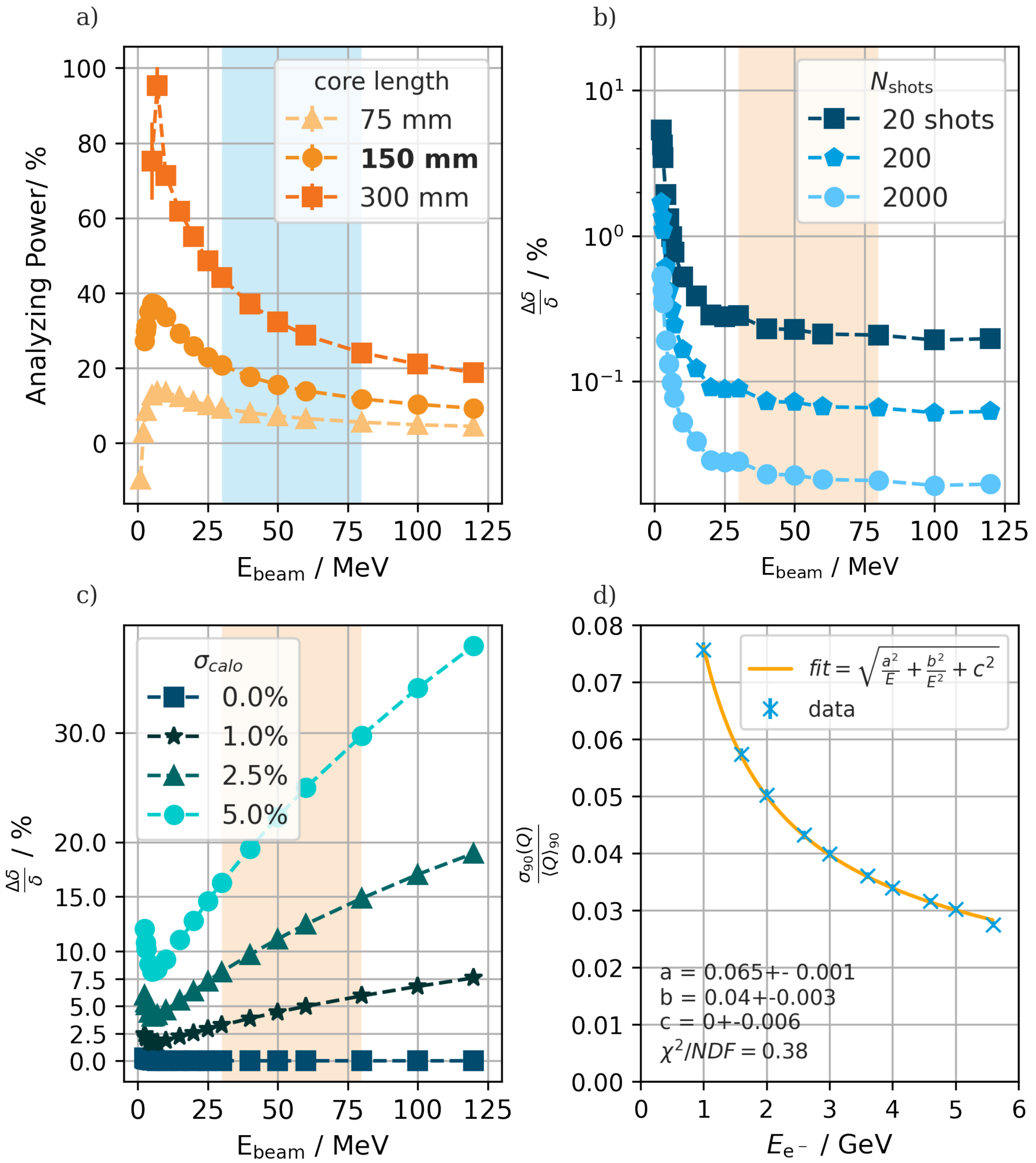

Figure 2: a) Analysing power over electron beam energy for different absorber thicknesses. $P_{e_-} = 1$, $P_{Fe} = \pm 1$. b) relative statistical precision of the expected asymmetry for different numbers of laser shots. $N_{e^-}^{sim}$/bunch = 5×10^5, core = 150 mm, $d_{conv} = 1.75$ mm, $Q_{\text{expected}} = 3$ pC, $P_{e_-} = 1$, $P_{Fe} = \pm 1$, $\sigma_{\text{calo}} = 0$. c) relative statistical uncertainty of the expected asymmetry including different energy resolutions of the calorimeter. d) Energy resolution of the LEAP calorimeter. RMS-90 of the measured charge divided by the mean-90 over electron beam energy.

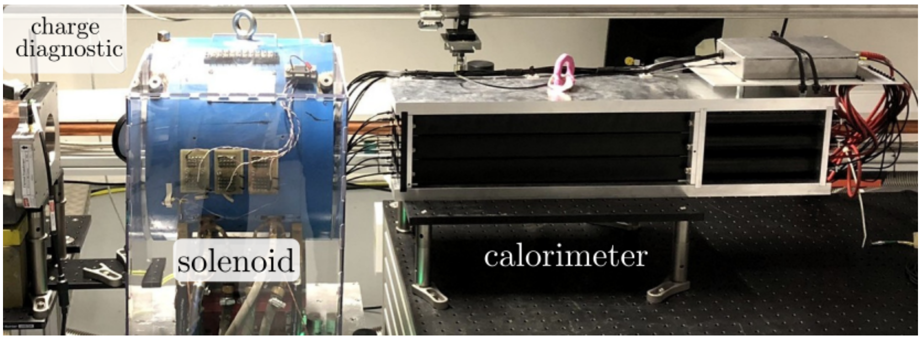

Figure 3: Image of the polarimeter in the beam area. From left to right: Integrating current transformer used as charge diagnostic, solenoid with 150 mm iron core, lead glass crystal calorimeter.

6. Summary and Outlook

LEAP is a proof of principle experiment at DESY aiming to demonstrate the creation of spin-polarised electron beams from LPA. With the current setup ~10% polarisation is expected for 3pC bunches at 30 MeV. Because of the expected energy range of a few ten MeV Compton transmission polarimetery was chosen. Transmitted photon energy sums of ~TeV are expected with an observable asymmetry of 0.2%. With 20 electron bunches a relative statistical precision of 4-11% is expected on the observable δ for a calorimeter resolution of 1-2.5%. The polarimeter setup has been tested and is in its designated beam area. First $P_{e^-} = 0$ measurements are ongoing at the time of writing. With advances in laser technology pre-polarised plasma sources using pure hydrogen are expected to become possible. This enables close to 100 % prepolarisation allowing for more than 90 % polarised accelerated electron beams.

Acknowledgments

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