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INVESTIGATION OF POLARIZATION DEPENDENT THOMSON SCATTERING IN AN ENERGY-RECOVERING LINEAR ACCELERATOR ON THE EXAMPLE OF MESA*

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Abstract

At the Johannes Gutenberg University (JGU) in Mainz, a new accelerator is currently under construction in order to deliver electron beams of up to 155 MeV to two experiments. The Mainz Energy-recovering Superconducting Accelerator (MESA) will offer two modes of operation, one of which is an energy-recovering (ER) mode. As an ERL, MESA, with it's high brightness electron beam, is a promising accelerator for supplying a Thomson back scattering based Gamma source. Furthermore, at MESA, the polarization of the electron beam can be set by the injector. The aim of this work is to provide a concept and comprehensive analysis of the merit and practical feasibility of a Thomson backscattering source at MESA under consideration of beam polarization and transversal effects. In this paper, an overview and results of our semi analytical approach to calculate various Thomson back scattering light source scenarios at MESA will be given. Furthermore we will discuss the benefits of using polarized electrons in combination with a polarized laser beam.

INTRODUCTION

The Mainz Energy-recovering Superconducting Accelerator (MESA) at the Institute for Nuclear Physics (KPH) of the JGU Mainz is being built for two modes of operation for two respective experiments. In the external beam (EB) mode, in which an electron beam of 150 μA current will be accelerated to an energy of 155 MeV, the accelerated particle bunches will be dumped after interaction with the target. In the energy-recovery (ER) mode, a beam current of 1-10 mA will be accelerated to an energy of 105 MeV. After the experiment, the spent electron bunches re-enter the accelerating cavities with a phase shift of 180° with respect to the RF field. Now synchronized to the cavity RF in deceleration phase, the electrons transfer the energy back to the RF field, allowing for an elegant way to recover the energy stored within the electron bunches before dumping the beam. The acceleration takes place in two superconducting MESA Enhanced Elbe Cryomodule (MEEC) cavities, a modified version of ELBE style cryomodules. Each pass through a cryomodule increases the electron energy by 25 MeV. [1]
In the MESA injection system [2], the electron beam spin polarization can be set via 2 solenoids and 2 Wien filters in both ER and EB mode, albeit at a lower beam current of 150 μA instead of 10 mA (numbers are potentially subject to change in development). [3] It is known that the spin polarization of both photon and electron beam affects the scattering cross section and energy spectrum both [4]. Ways to potentially make use of the polarization dependent properties are to be explored.
Implementation via dedicated Thomson scattering arc into the MESA layout was discussed in last year's IPAC paper [5] and will omitted from this year's. Due to the low impact on the electron beam, another option is to implement a Thomson scattering experiment parasitically into an existing MESA beam line. In this scenario, the Thomson scattering experiment can only be conducted during another MESA mode activity, but the necessary changes to the overall MESA layout would be reduced.
This report is structured as follows:
Sections 1, polarized Thomson scattering with recoil, summarizes the mathematical foundation of our calculations and introduces the aspect of polarization. In section 2, the results of our calculations for an example scenario are discussed. Lastly, section 3 gives a brief outlook on future tasks.

POLARIZED THOMSON SCATTERING WITH RECOIL

The term Thomson scattering, or Thomson back scattering, is used to describe the process in which photons scatter quasi-elastically on free electrons. It is the low incidence photon energy limit of Compton scattering. While in literature we find definitions in which the recoil experienced by the electron is zero, others are writing about a process in which the recoil is merely low. In this release, we are following the latter. As we are expecting relativistic electrons, our calculations are taking place in Lorentz boosted reference frames using four-vector algebra. The Lorentz factor γ^* of the boosted system is defined by the relation between the overall energy contained in the laboratory frame E_{lab} to that contained in the center of mass frame E_{cm}:

$$\gamma_{cm} = \gamma^* = \frac{E_{lab}}{E_{cm}} = \frac{E_e + h\nu}{m_e c^2\sqrt{1+\Delta}} \simeq \frac{\gamma}{\sqrt{1+\Delta}} \quad (1)$$

While E_{lab} is the sum of the initial electron E_e and photon energy $h\nu$, E_{cm} can be expressed for unpolarized beams via relativistic recoil factor $\Delta \equiv \frac{2h\nu\gamma}{E_0} + \frac{2\hbar c^2}{E_0^2}(k_x P_x + k_y P_y + k_z P_z)$ where k_i & P_i ($i = (x, y, z)$) are the photon respectively electron momenta in 3D and E_0 is the electron rest energy.
Transforming the reference frame and with it each four-

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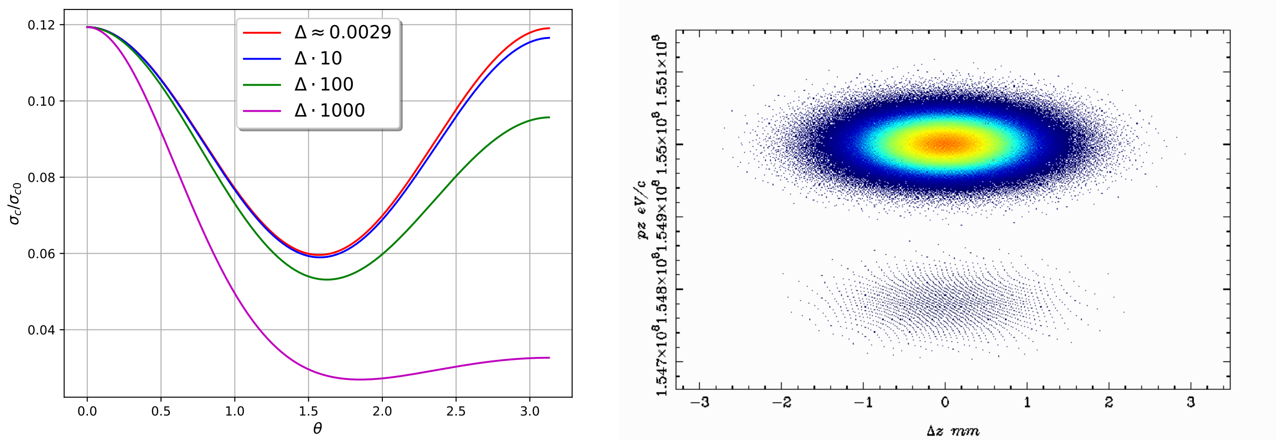

(a) normalized unpolarized cross section

(b) longitudinal phase space $\Delta z/pz$ for 1030 nm

Figure 1: a) Normalized unpolarized interaction cross section dependent on observation angle θ for different magnitudes of recoil Δ. With increasing observation or scattering angle θ, the electron recoil factor Δ, a parameter of initial photon and electron energy, has a growing impact on the Thomson cross section. b) Longitudinal phase space $\Delta z/pz$ of electron beam post collision under a small scattering angle $\theta \to 0$. This scenario assumes a collision between 2000 linearly polarized 1030 nm laser photons and 2000 electrons accelerated by 155 MeV as part of a $4.81 \cdot 10^6$ electrons bunch. The group of scattered electrons with reduced energy is visibly found wholly outside of the unscattered phase space. The energy transfer from electrons to photons results in a scattered gamma radiation of $E^{'}_{ph} \approx 310.66$ keV or $\lambda^{'} \approx 0.004$ nm.

vector into the center of mass (cm) or rest frame allows for the calculation of the electron to photon energy transfer using elastic collision energy conservation. The electron four-vector in the center of mass frame depends on recoil factor Δ and scattering angles θ^*_e, ϕ^*:

$$\begin{pmatrix} E^*_e \\ p^*_x \\ p^*_y \\ p^*_z \end{pmatrix} = \begin{pmatrix} m_e c^2 \frac{2+\Delta}{2\sqrt{1+\Delta}} \\ m_e c \frac{\Delta \sin\theta^*_e \cos\phi^*}{2\sqrt{1+\Delta}} \\ m_e c \frac{\Delta \sin\theta^*_e \sin\phi^*}{2\sqrt{1+\Delta}} \\ m_e c \frac{\Delta \cos\theta^*_e}{2\sqrt{1+\Delta}} \end{pmatrix} \tag{2}$$

The final result of the calculations needs to be transformed back into the laboratory frame to make meaningful statements about a Thomson backscattering experiment. Accordingly, for the scattered photons in the laboratory frame, we arrive at eq.3.

$$\begin{bmatrix} E_{ph} \\ k_x \hbar c \\ k_y \hbar c \\ k_z \hbar c \end{bmatrix} = \begin{bmatrix} \gamma^* \left(E^*_{ph} + k^*_x \beta^*_x + k^*_y \beta_y + k^*_z \beta^*_z \right) \\ \gamma^* \beta^*_x E^*_{ph} + \left(1 + \frac{\gamma^{*2}}{\gamma^*+1} \beta^{*2}_x \right) k^*_x + \frac{\gamma^{*2}}{\gamma^*+1} \beta^*_x \beta^*_y k^*_y + \frac{\gamma^{*2}}{\gamma^*+1} \beta^*_x \beta^*_z k^*_z \\ \gamma^* \beta^*_y E^*_{ph} + \frac{\gamma^{*2}}{\gamma^*+1} \beta^*_y \beta^*_x k^*_x + \left(1 + \frac{\gamma^{*2}}{\gamma^*+1} \beta^{*2}_y \right) k^*_y + \frac{\gamma^{*2}}{\gamma^*+1} \beta^*_y \beta^*_z k^*_z \\ \gamma^* \beta^*_z E^*_{ph} + \frac{\gamma^{*2}}{\gamma^*+1} \beta^*_z \beta^*_x k^*_x + \frac{\gamma^{*2}}{\gamma^*+1} \beta^*_z \beta^*_y k^*_y + \left(1 + \frac{\gamma^{*2}}{\gamma^*+1} \beta^{*2}_z \right) k^*_z \end{bmatrix} \tag{3}$$

Eq.3 has been re-derived and corrected of printing errors encountered in published literature ([6], [7]). Aside from scattered radiation energy, flux is also of high interest for the evaluation of a potential gamma source:

$$F = \frac{N_e N_L r}{4\pi\sigma^2_L} \sigma_T \tag{4}$$

This is a function of the number of electrons and photons N_e, N_L per 2D interaction area $4\pi\sigma_L$ multiplied by repetition rate r and Thomson cross-section σ_T. The latter is a key factor of high variation depending on circumstances. The classical Thomson cross section is given by

$$\sigma_{c,clas.} = \frac{8\pi r^2_e}{3} \tag{5}$$

with r_e being the electron radius. For a more detailed spatial distribution of cross section values, we use the Klein-Nishina cross section for the scattering of photons and electrons, which depends on the scattering angle and initial particle energies eq. 6. The angular differential form expressed with Δ is:

$$\frac{d\sigma}{d\theta' d\phi'} = r^2_e \left(\frac{2}{2+\Delta(1-\cos\theta')} \right)^2 \left(\frac{1+\cos^2\theta'}{2} \right) \left(1 + \frac{\Delta^2 (1-\cos\theta')^2}{2(1+\cos^2\theta')(2+\Delta(1-\cos\theta'))} \right) \sin\theta' \tag{6}$$

Results of this approach for unpolarized particle beams can be found Fig. 1a and 1b.

It is known that electron and photon beams are influenced in their interaction by their spin polarization qualities [4]. For example, the helicity dependent cross section [8] can be expressed as

$$\sigma_c = \sigma^{np}_{c,clas.} + 2\lambda_e P_c \sigma_1 \tag{7}$$

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where $\lambda_e P_c$ is the mean helicity of the photon and electron beam and σ_1 the helicity influenced part of the overall cross section

$$\sigma_1 = \frac{2\sigma_0}{x}\left[\left(1+\frac{2}{x}\right)\ln(x+1) - \frac{5}{2} + \frac{1}{x+1} - \frac{1}{2(x+1)^2}\right] \quad (8)$$

We can see a strong divergence of the energy dependent

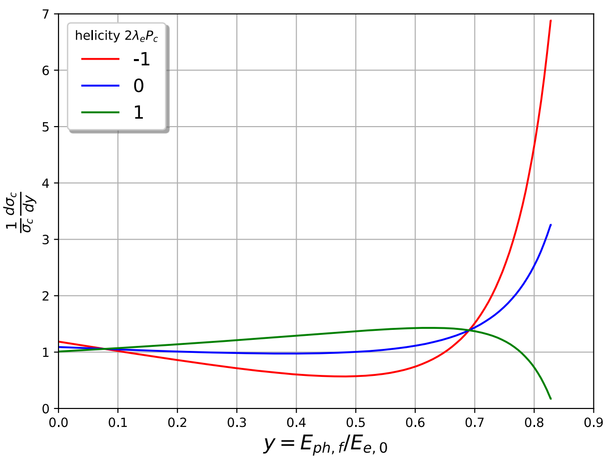

Figure 2: Dependence of the interaction cross section on the initial photon energy normalized by the classic Compton cross section for 3 helicity combinations. Clearly observable are considerable differences in intensity behaviour for different mean photon and electron helicities $2\lambda_e P_c$. The Figure was created for an electron recoil of $\Delta = 4.8$. Recoil values in the range expected for MESA, $\Delta < 1$, do not result in significant differences between the 3 helicity cases.

cross section for different helicities in Fig.2. For a more granular calculation of the polarized Thomson cross section that encompasses not only helicity but precise photon and electron polarisation, we're introducing Stokes parameters into our four-vector calculation. This part of our work is still ongoing, as the behavior of the spatial Stokes parameter distribution is complex. The polarisation of incoming and outgoing photons and electrons influences the Thomson cross section and in return, the Thomson scattering process changes the Stokes parameters of the particles involved. [9] These steps are implemented in a python code created to quickly iterate various scenarios. This code can use simulated or real particle distributions and beam parameters.

Outlook

While the scattering and observation angle influence on both recoil and Thomson cross-section is understood and a polarization sensitive cross-section is formulated, work yet remains. For instance, so far calculations assume a perfectly parallel laser of constant power density. We are working with colleagues of TU Darmstadt as part of the RTG 2128 AccelencE to describe a realistic photon distribution. This will allow us to further improve the accuracy of our calculations and investigate the feasibility of alternative incident laser solutions such as Magic Mirror or Optical Cavity schemes. [10] As this PhD work will conclude with the presentation of several scattering scenarios for MESA and a connected feasibility study, knowing the limitations and possible improvements on the laser side is valuable. For this, we also aim to include the impact of polarization on the recoil strength in our code.

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