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INVESTIGATION OF THE THOMSON SCATTERING INFLUENCE ON ELECTRON BEAM PARAMETERS IN AN ENERGY-RECOVERING LINEAR ACCELERATOR ON THE EXAMPLE OF MESA

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Abstract

At the Johannes Gutenberg University (JGU) in Mainz, the Mainz Energy-recovering Superconducting Accelerator (MESA) is currently under construction. It is designed to deliver electron beams of up to 155 MeV. As it can be operated in an energy-recovery (ER) mode thus allowing for high repetition rate, it is a promising candidate for a high flux Thomson scattering based gamma source. This paper will provide a status update on the study of the impact of Thomson scattering on electron beam parameters and the underlying mechanics. Further, the implementation into a simulation code will be discussed.

INTRODUCTION

The Mainz Energy-recovering Superconducting Accelerator (MESA) at the Institute for Nuclear Physics of the JGU Mainz is being built to run in 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 °C with respect to the RF field. Now synchronized to the cavity RF in deceleration phase, the electron beam energy transfers back to the RF fields, leaving only 5 MeV to be disposed at beam dump. The acceleration takes place in two superconducting MESA Enhanced Elbe Cryomodule (MEEC) cavities, a modified version of ELBE style cryomodules, themselves an enhanced version of TESLA-Type 9-cell cavities. Each pass through a cryomodule increases or decreases the electron energy by 25 MeV [1].

The electron beam accelerated in EB mode is used in the P2 experiment where high-precision measurements of the Weinberg mixing angle are taken by detecting parity violations (PV) of electron-proton scattering in the elastic regime. Afterwards, the EB mode path leads the electron beam into the beam dump.

In the ER mode, the path diverges from the EB mode after acceleration to 105 MeV. Here, the beam line leads through the MESA Gas Internal Target Experiment (MAGIX) where electron bunches interact with a gas jet of customizable makeup ranging from hydrogen up to xenon to investigate proton radii and search for particles beyond the standard model. The MAGIX section of the beam line leads back into the recirculation but introduces a 180 °C phase shift. Now, electron bunches pass through the cryomodules in deceleration phase, transferring their kinetic energy to the cavity RF fields in steps of 25 MeV. That way, energy-recovering accelerators can be a good economic solution if bunch quality degradation is low enough to safely reuse post experiment particles.

A key challenge of Thomson scattering is the very low interaction cross section of $\sigma_T = \frac{8\pi}{3} r_e^2 \simeq 6.6525 \cdot 10^{-29}\ \mathrm{m}^2$. To provide a bright gamma source under these conditions requires a brilliant laser and high brightness electron beam. Here, ERLs with high repetition rates in the GHz range such as MESA (1.3 GHz) are promising candidates for delivering electron beam. Therefore, we are investigating the merit of a Thomson scattering based gamma source at MESA.

This report is structured as follows: In Section 1, an early investigation of practical realization options within the MESA hall will be discussed. Section 2 focuses on the merit of a Thomson scattering gamma source through analysis of possible input and output parameters in the context of MESA. Finally, in Section 3, an outlook of the activities over the next couple of years will be provided.

IMPLEMENTATION IN MESA LAYOUT

When colliding electrons with laser beams, head-on collisions provide the highest photon energies and intensities of scattered Thomson radiation. They are thus preferable to high incident angle configurations. To avoid undesired incidents of laser radiation within the sensitive accelerator cavities, the Thomson scattering interaction point has to be on or parallel to the recirculation arcs. As displayed in Fig. 1 the area around the left recirculation arc close to the MAGIX and P2 experiments is already densely accounted for, yet on the opposite side, above the DarkMESA experiment, space for experiments, diagnostics and measurement stations exists. Furthermore, the right hand recirculation arc leaves room for modifications. An expansion to a fully featured third operational mode providing a Thomson scattering gamma source would require a source of incident photons, a beam collision chamber, a multitude of photon detectors installed at different observation angles and diagnostic systems all within a third 130 MeV recirculation arc introducing an accumulated RF phase shift of 180 °C. As MESA RF cavities are designed for operation at 1.3 GHz, this constitutes a path length difference of $(2n + 1) \times (c/\ (2 \times 1.3\ \mathrm{GHz}))$ for $n = 0, 1, 2, \ldots$ between the standard recirculation arc and the Thomson path. This needs to be taken into account by the design of the Thomson scattering arc. Please note that the fifth cryomodule pass through allowing for a beam energy

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of 130 MeV and thus higher gamma-ray energies is enabled by the suggested experiment location around the right hand recirculation arc.

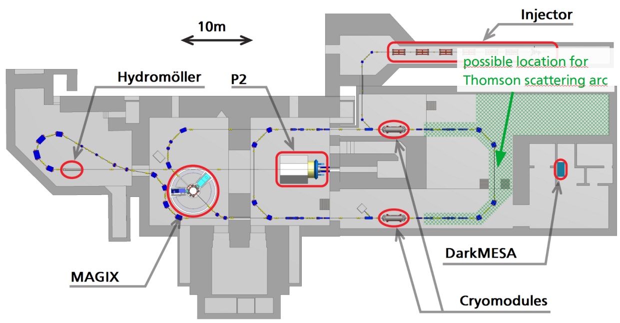

Figure 1: MESA layout as currently proposed. The green hatched area designates the components that would require modifications and areas that are likely candidates for diagnostics and measurement stations due to being currently unassigned. Image is an edited version of Fig. 1.2 in [1].

GAMMA SOURCE POTENTIAL OF MESA

In Thomson scattering, photons scatter elastically on free electrons. It is the low incidence photon energy limit of Compton scattering. For small scattering angles, the maximum fundamental energy of the scattered photons can be approximated by [2]

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1+\gamma^2\theta^2+\frac{1}{2}a_0^2}(1-\Delta), \qquad (1)$$

where γ_0 is the Lorentz factor of incident electrons, θ the observation angle, E_{ph} the laser photon energy before scattering and a_0 the normalized laser vector amplitude

$$a_0 \equiv e^2 A/(m_e c^2) = 8.5\times 10^{-10}\sqrt{I\lambda_0^2}, \qquad (2)$$

where I is the peak intensity in W/cm^2 and λ_0 the wavelength in µm. As we calculate the collision in the center of mass (CM) frame, recoil parameter Δ is a convenient definition [3]:

$$\Delta \equiv \frac{2h\nu\gamma}{m_e c^2} + \frac{2\hbar c^2}{m_e^2 c^4}\left(k_x P_x + k_y P_y + k_z P_z\right), \qquad (3)$$

where $k_i\hbar$ is the photon momentum, P_i the electron momentum and ν the photon frequency $\left(E_{ph} = h\nu\right)$. The invariant mass can be expressed as

$$E_{cm} = E_e^* + h\nu^* = m_e c^2\sqrt{1+\Delta}, \qquad (4)$$

with $E_e^* = m_e c^2 \frac{2+\Delta}{2\sqrt{1+\Delta}}$ and $h\nu^* = m_e c^2 \frac{\Delta}{2\sqrt{1+\Delta}}$ being the respective particle energies in CM reference system after scattering. The scattered electron momentum in CM can be expressed as:

$$\begin{pmatrix} p_x^* \\ p_y^* \\ p_z^* \end{pmatrix} = \begin{pmatrix} m_e c \frac{\Delta \sin\theta^* \cos\phi^*}{2\sqrt{1+\Delta}} \\ m_e c \frac{\Delta \sin\theta^* \sin\phi^*}{2\sqrt{1+\Delta}} \\ m_e c \frac{\Delta \cos\theta^*}{2\sqrt{1+\Delta}} \end{pmatrix}, \qquad (5)$$

with scattering angles θ^* and ϕ^* in reference to the z-axis in CM. Transformation to and from CM to lab system is done via Lorentz transformation using $\gamma_{cm} \simeq \frac{\gamma}{\sqrt{1+\Delta}}$.

At MESA, with a beam energy of 130 MeV, electrons possess a Lorentz factor of $\gamma_0 \simeq 255.4$. For 130 MeV electrons from MESA and a small a_0, the required incident photon energy for a 1 MeV gamma ray is ≈4.29 eV for an observation angle of $\theta = \frac{1}{3\gamma}$ in a head-on collision scenario. The photon energy is equivalent to the fourth harmonics of a 1 132 nm fibre laser and corresponds to around $\lambda_0 = 283$nm, and thus a realistic proposition for realization [4].

Figures 2a and 3a show the expected spectral distribution for an observation angle range from 0 to $3/\gamma$ and incident photon energies of 1.10 eV and 4.38 eV. The laser intensity is assumed to be low, so that the respective a_0 for the two different photon energies are $a_0 = 7.2740\cdot 10^{-4}$ for 1.10 eV and $a_0 = 1.8185\cdot 10^{-4}$ for 4.38 eV. Due to low intensity related to the small a_0 value, only the fundamental harmonics are generated. The longitudinal phase space distribution of the electrons are presented in Figs. 2b and 3b. The observation angle for the scattered photon beam was $1/3\gamma$. The scattered electrons have lost a noticeable amount of energy. Dependent on optics of the Thomson arc and energy acceptance of MESA, these outlier particles could get lost. In severe cases, outlier particles become halo particles upon pass through of dipole elements. At high energies, they constitute a potential risk for the beam line.

Assuming low intensity laser radiation the number of scattered photons is around 2000 per bunch. Thus in the above configuration with a repetition rate of 5 MHz a photon flux of about 10^{10} [photons / s] for up to 1 MeV photons can be expected. The high repetition for incident laser can be provided via a Fabry-Pérot cavity. Aside from the conventional laser approach, another potential solution is a magic mirror or optical cavity type dipole radiation refraction and focus system as proposed [5] by M. Shimada and R. Hajima. Here, inevitable dipole radiation emitted in electron bunch curve deflection is collected around and collimated back onto the electron beam axis. In this elegant solution incident photon pulses and electron bunches are inherently synchronized if the construction is set up correctly. It would constitute another method to make use of post collision electron bunches.

OUTLOOK ON FUTURE TASKS

The goal of this work is a concept for the realization of a Thomson Scattering Gamma Source at MESA. For this, the python code based on the formulas briefly outlined in this paper will provide a swift tool for beam parameter and gamma radiation calculations. As opposed to more generalized solutions, does not require computationally expensive numerical simulations. As a next next step, a beam lattice for the proposed Thomson scattering arc will be designed. It needs to adhere to both spatial and beam dynamics requirements at MESA. In short, the Thomson arc and connected diagnostic devices must not exceed the space available in the MESA hall while keeping the electron beam within MESA

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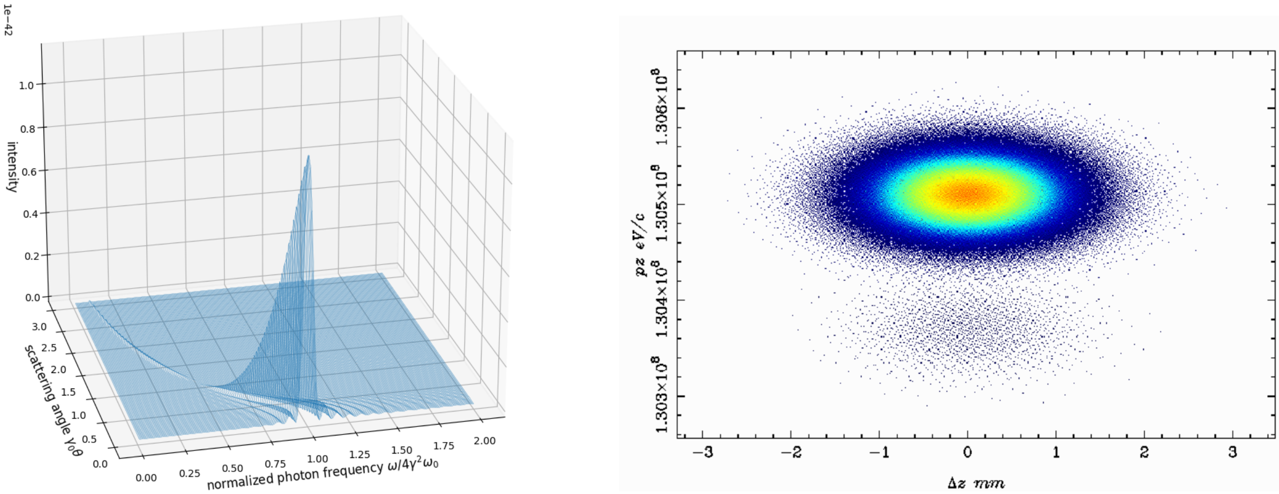
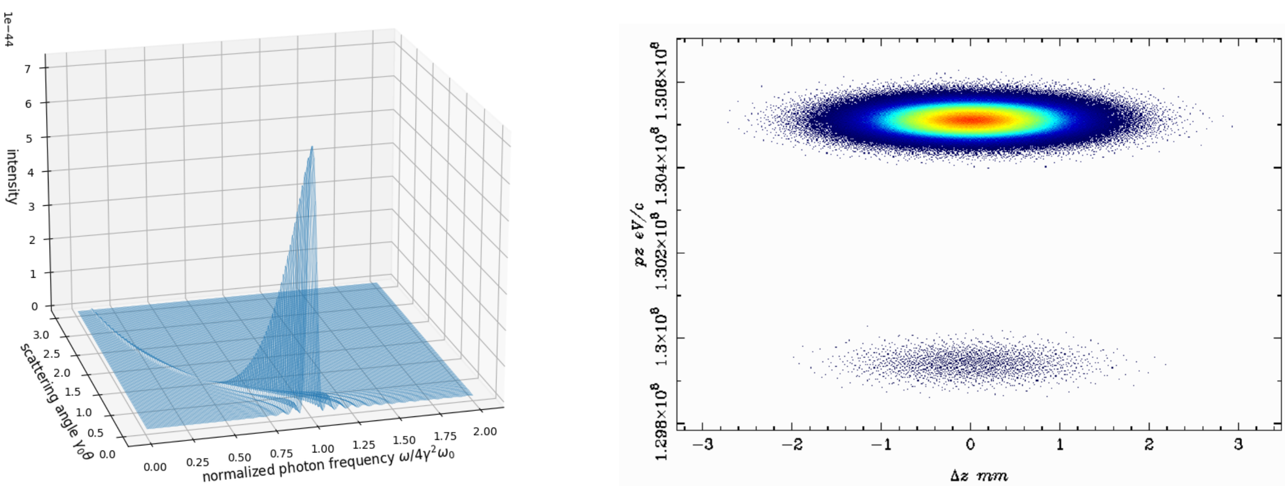


(a) Relative intensity distribution for λ =1 132 nm

(b) Longitudinal phase space $\Delta z/pz$ for 1 132 nm

Figure 2: (a) Intensity of scattered Thomson radiation emitted during the collision process between 2000 linearly polarized 1 132 nm laser photons and 2000 electrons accelerated by 130 MeV. This electron distribution is generated with Astra-generator [6] for an rms electron beam cross section of $\sigma_{e,rms} = 1.205 \cdot 10^{-4}$ m, rms energy spread $\sigma_{E_{kin},rms} = 26$ keV and normalized transverse emittance $\epsilon_{n,rms} = 0.3\ \pi$ mrad mm. The laser intensity within the same cross section is $I_0 \approx 5.7170 \cdot 10^{11}$ W/ cm^2 and the resulting normalized vector amplitude of a laser is $a_0 \approx 7.2740 \cdot 10^{-4}$. Intensity is calculated dependent on scattered photon frequency ω and observation angle θ for the first 2 harmonics. (b) Longitudinal phase space $\Delta z/pz$ of electron beam post collision under scattering angle $\theta \to 0$. Other parameters as in (a).



(a) Relative intensity distribution for λ =283 nm

(b) Longitudinal phase space $\Delta z/pz$ for 1 132 nm

Figure 3: Parameters analogue to 2 but for incident photons of λ =283 nm i.e. $E_{ph} \approx 4.38$ eV. As a result, the normalized laser vector amplitude is now even lower at $a_0 = 1.8185 \cdot 10^{-4}$.

target parameters and introducing a 180 °C phase shift in order to properly re-enter the currently planned MESA ER beamline in deceleration phase. Additionally, effects and merits of beam polarization on the Thomson scattering experiment will be investigated, as MESA is being constructed with electron beam polarization capabilities. Finally, a full front to end simulation of the Thomson scattering arc will be conducted.

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