ON THE POSSIBILITY OF PRECISE MEASUREMENT OF ELECTRON BEAM ENERGY USING RESONANCE ABSORPTION OF LASER LIGHT BY ELECTRONS IN A STATIC MAGNETIC FIELD

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Abstract

A method for measuring electron beam energy using resonance absorption of laser light by electrons in a static magnet field is proposed. The method permits measurement of the average electron beam energy for a wide range up to a few hundred GeV. The relative accuracy of the measurement can reach 10^{-4} – 10^{-5} if the arrangement is calibrated using an electron beam of known energy . The required typical laser power can be much less than 1 W/cm^2.

1. INTRODUCTION

The determination of the electron beam energy is an important requirement for some experimental programs requiring knowledge of electron beam energy with a relative accuracy of the order of 10^{-4} – 10^{-5} [1-3].

The Resonant Depolarization (RD) method, which provides the most accurate determination of the absolute electron beam energy, cannot be used at very high beam energies (above 55-60 GeV) because of stochastic depolarization [2,3]. Also, the RD method cannot be used for continuous electron energy monitoring during experiments using polarization or for beams in linear accelerators.

Here, we study the possibility of precisely measuring the electron beam energy using the Resonance Absorption (RA) of laser light by electrons in a static magnetic field. Because the energy of electrons in a magnetic field has a discrete spectrum the photons can be resonantly absorbed at transitions between electron energy levels. Then the energy of the electrons can be determined using the energy dependence of the RA frequency.

The RA method permits the measurement of the average electron beam energy for a wide range up to a a few hundred GeV and can be used for continuous monitoring of the electron beam energy during of an experiment.

RA can be detected by measuring the ratio of the number of absorbed photons to the number of incident laser photons during the time of interaction of the electron beam in an external field.

The relative accuracy of the electron beam energy measurement by the RA method can reach 10^{-4}-10^{-5} if the arrangement is calibrated with an electron beam of known energy.

2. THE FREQUENCY OF RESONANT ABSORPTION AND THE DETERMINATION OF THE ELECTRON ENERGY

We consider the absorption of laser photons by electrons in a static homogeneous magnetic field $\vec{B}$ directed along the longitudinal (z)–axis. Photons are injected at a small angle θ to the z-axis (Fig. 1). Using the discrete spectrum of electron energy in a magnetic field and the law of energy-momentum conservation for photon absorption, we can find the condition for resonant electron transitions. For the absorption of photons of the optical and lower frequencies of interest to us and in the approximation $\omega/\varepsilon_0 \ll 1$ the resonance condition can be written as (see also [4, 5]):

$$\omega = \frac{\omega_c (n' - n)}{\gamma_0 - \cos\varphi \cos\theta \sqrt{\gamma_0^2 - 1}}, \qquad (1)$$

where $\gamma_0 = \varepsilon_0/m$ is the electron relativistic factor, ε_0 is the electron energy before photon absorption, ω_c = eB/m is the cyclotron frequency of an electron, n = 0, 1, 2 … labels the electron energy levels, ω is the photon frequency, and φ is the angle between the electron velocity $\vec{V}_0$ and the z-axis (Fig.1). We use units for which $\hbar$ =c=1.

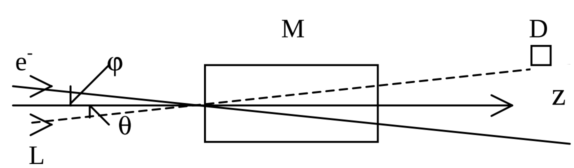

Fig. 1. Sketch of the arrangement. e$^-$ - electron beam, L – laser beam, M – magnet, D – detector.

Here we consider only transitions at the main harmonic n' - n = 1. Transitions at higher harmonics (at $\theta \neq 0$) permit the strength of the resonant magnetic field (contained in (1)) to be reduced.

If for an electron beam of unknown γ_0 resonant absorption of photons at some ω_c/ω for fixed angles φ and θ is observed, then γ_0 can be calculated using (1) with known values of φ, θ and ω_c/ω,:

$$\gamma_0 = \\ = \frac{\frac{\omega_c}{\omega} \pm \cos\varphi \cos\theta \sqrt{\left(\frac{\omega_c}{\omega}\right)^2 - 1 + \cos\varphi^2 \cos\theta^2}}{1 - \cos\varphi^2 \cos\theta^2} \quad (2)$$

The dependence of γ_0 on ω_c/ω for some fixed angles φ and θ is represented schematically on Fig.2.

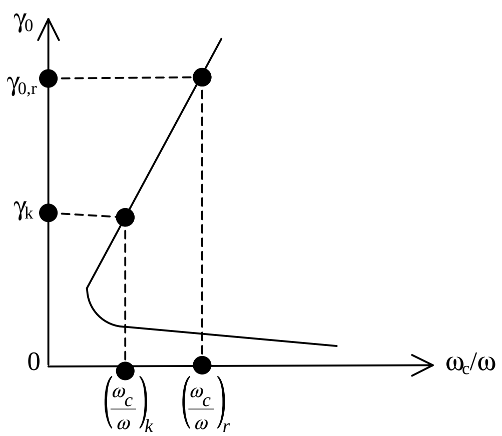

Fig. 2. Dependence of the γ-factor on ω_c/ω for some fixed angles φ and θ. Determination of the unknown $\gamma_{0,r}$ relative to the calibrated value of γ_k.

The precise determination of the absolute value of γ_0 according to (2) is difficult because it is difficult in practice to know the angles φ and θ with the necessary accuracy. However, an unknown $\gamma_{0,r}$ can be determined with high accuracy relative to a calibrated γ_k at some known $(\omega_c/\omega)_k$ (Fig.2). In fact, for fixed angles φ and θ from (1) we have:

$$\frac{\gamma_{0,r} - \left(\frac{\omega_c}{\omega}\right)_r}{\sqrt{\gamma_{0,r}^2 - 1}} = \frac{\gamma_k - \left(\frac{\omega_c}{\omega}\right)_k}{\sqrt{\gamma_k^2 - 1}}. \quad (3)$$

Now, if the quantities γ_k and $(\omega_c/\omega)_k$, are known precisely then by measuring $(\omega_c/\omega)_r$ at resonance absorption we can calculate $\gamma_{0,r.}$ precisely using (3). This method enables the electron beam energy to be measured for a wide range up to a few hundred GeV.

3. THE MOTION OF ELECTRONS AND THE INTENSITY OF RESONANCE ABSORPTION

The number n_γ of photons absorbed by an electron during the time of interaction with the external field, t_i, can be estimated from the increase of the electron energy due to photon absorption using energy - momentum conservation. In fact using the equations of electron motion to get the rate of energy increase near resonance we find (see also [6]):

$$\frac{d\gamma}{dt} = \frac{\xi\omega}{\gamma}\sqrt{\frac{2\omega_c}{\omega}(\gamma - F)}, \quad (4)$$

where

$$F = \gamma_0 \sin\theta_{c,0}^2 + \left(\frac{\omega_c}{2\omega} + \frac{\omega}{2\omega_c}\right)\cos\theta_{c,0}^2,$$

$\theta_{c,0}$ is the initial phase of cyclotron rotation and $\xi = eE/m\omega$ describes the laser intensity.

Taking into account that for the practical parameters of interest to us, $\theta = 0$, $\xi \ll 1$ and $\omega/2\omega_c \ll \gamma_0$, then near to resonance the growth of the electron energy obtained from (4) is approximately

$$\varepsilon - \varepsilon_0 = n_\gamma \omega \cong m\xi\omega t_i \sqrt{\frac{2\omega_c}{\omega\gamma_0}} \cong m\xi\omega t_i \varphi. \quad (5)$$

Now the number of photons N_γ absorbed by an electron beam of pulse length T can be estimated. If N_e is the number of electrons in the beam, $T \gg t_i$ and each electron passes the interaction region only once, then $N_\gamma = N_e n_\gamma$.

To observe the resonance absorption we suppose that in (5) the parameters are chosen so that $n_\gamma \geq 1$. Then for known ξ the required values of E and the laser power W can be determined. The required power W determines the required number of incident laser photons $N_{l,ph}$ on an area S in time T

$$N_{l,ph} = \frac{W}{\omega} ST \quad (6)$$

Resonance absorption is observed by measuring and establishing the maximum value of the ratio $N_\gamma / N_{l,ph}$. Near to resonance the ratio $N_\gamma / N_{l,ph}$ can be changed by optimizing ξ, t_i and ω_c at fixed values of the other parameters to give a measurable $N_\gamma / N_{l,ph}$..

For example if $\gamma = 10^5$, λ = 10,6 micro-meter (CO_2 laser) and $\varphi = 2 \cdot 10^{-4}$, then according to (2) the field strength B near to resonance is B = 20,2 kGs. For $n_\gamma = 1$ and $t_i = 3 \cdot 10^{-9}$ sec from (5) we have $\xi = 2 \cdot 10^{-9}$, E = 6,4 V /cm, W = 0,1 W/cm^2. If S = 0,1cm^2 and T = 0,64 msec (TESLA), then from (6) we find $N_{l,ph} = 3,7 \cdot 10^{14}$ photon/pulse. For $N_e = 4,1 \cdot 10^{13}$ e/pulse we find $N_\gamma / N_{l,ph} \approx 0,1$.

So the number of absorbed photons near to resonance does suffice to measure the ratio $N_\gamma / N_{l,ph}$. Because the resonance absorption of photons can be observed quickly, the RA method is suitable for monitoring the electron beam energy during experiments.

4. THE WIDTH OF THE RESONANCE ABSORPTION INTENSITY AND THE ACCURACY OF THE ELECTRON BEAM ENERGY MEASUREMENT

The time of resonance absorption $t_{r.a.}$ of a photon by an electron can be estimated from (5) as:

$$t_{r.a.} = \frac{\omega}{m}\frac{1}{\xi\omega\varphi}. \qquad (7)$$

Then the width $\delta\omega$ of the resonance absorption intensity $I(\omega)$ is determined by

$$\delta\omega = \frac{1}{t_{r.a.}} = \frac{m}{\omega}\xi\,\omega\,\varphi \qquad (8)$$

For example for the parameters mentioned above and using (8) we have $\delta\omega/\omega \approx 1{,}8 \cdot 10^{-6}$. In the case θ=0, $(\omega_c/\omega)_r >> \sin\varphi$ of interest to us, the relative accuracy for the measurement of the absolute electron beam energy is from (3) approximately:

$$\frac{\Delta\gamma}{\gamma} \cong \left[\left(\frac{\Delta\Omega_r}{\Omega_r}\right)^2 + 4\left(\frac{\Delta\varphi}{\varphi}\right)^2\right]^{1/2}. \qquad (9)$$

When measuring the unknown electron beam energy γ relative to the calibrated energy γ_k we have from (2) approximately

$$\frac{\Delta\gamma}{\gamma} \cong \left[\left(\frac{\Delta\Omega_r}{\Omega_r}\right)^2 + \left(\frac{\Delta\gamma_k}{\gamma_k}\right)^2 + \left(\frac{\Delta\Omega_k}{\Omega_k}\right)^2\right]^{1/2} \qquad (10)$$

if $\delta\omega/\omega << \Delta\gamma/\gamma$. For brevity we have defined $\Omega_r = (\omega_c/\omega)_r$ and $\Omega_k = (\omega_c/\omega)_k$. So according to (10) the precision of the electron beam energy measurement is determined by the precision of γ, Ω_k and Ω_r. For example if $\Delta\Omega_r/\Omega = \Delta\Omega_k/\Omega_k = \Delta\gamma_k/\gamma_k = 10^{-5}$ then $\Delta\gamma/\gamma \approx 3^{1/2}\cdot 10^{-5}$.

5. SUMMARY

The possibility of determining electron beam energy using resonance absorption of laser light by electrons in a static and homogeneous magnetic field is proposed.

Laser photons can be resonantly absorbed by electrons when condition (1) is satisfied. The energy of the electrons can be determined using (2) or (3) and the dependence of the γ-factor on ω_c/ω at some fixed angles φ and θ.

The error on the electron beam energy relative to some calibrated energy can reach down to 10^{-4} - 10^{-5}.

The RA method enables the average electron beam energy to be measured for a wide range up to a few hundred GeV and can be used for continuous energy monitoring.

The typical required laser power is much less than 1 W/cm^2.

6. REFERENCES

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