Multipass Beam Position, Profile, and Polarization Measurements Using Intense Photon Target

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Abstract

The Compton scattering of a circularly polarized laser beam condensed by an optical resonator can be used for multipass measurement of beam profile, position, and polarization in CEBAF's 250-m-long linac straight sections. The position and profile of the beam will be measured with an accuracy of $\sim$ 10 μm in about 200 seconds and beam polarization with 10% accuracy in 100 seconds when the lowest beam energy is 500 MeV and the beam current is 100 μA. For higher energies the times for measurement are much less. The photon target is within an optical resonator having a quality factor of 50. The Nd:Yag 5 W CW laser photon beam at wavelength λ = 0.532 nm will have a waist $\omega_0 \sim 30$ μm and a Rayleigh range of about 10 mm. Scanning the electron beams in the linac sections by this photon beam at a crossing angle of 0.1 rad will send to a proportional detector installed after the spreader magnet scattered photons with energies sharply correlated with the energy of the electrons.

1. INTRODUCTION

Linac straight sections of the multipass CEBAF accelerator accelerate beams of up to five different energies simultaneously, using superconducting rf accelerating cavities having a geometrical acceptance $\sim 1 \times 10^{-6}$ m·rad. Accuracy and stability of the coincidence of the beam axis of each pass with the optical axis of the linac are necessary for stability of the extracted beam energy and for protection of the linac system. Further, CEBAF will be equipped with a polarized gun. The polarized beams have to be transported through the two linacs and nine arc beamlines to the experiments. According to recent investigations, even small distortions of the vertical beam trajectory can significantly reduce polarization [1,2] and rotate the polarization vector (up to 20°) [3]. So the multipass measurement of beam polarization will permit high-accuracy orbit correction. Therefore precise and nondestructive multipass beam profile, position, and polarization measurements in linac straight sections are an important part of the CEBAF beam diagnostic program.

Different ideas are currently under investigation. Synchrotron radiation methods are limited by diffraction due to highly narrow angle of collimation ($\sim 10^{-4}$ rad) [4]. An optical transition radiation monitor cannot be used because of heating problems of the radiator [5].

This paper presents conceptually a solution using electron beam interactions with photon target. The main idea is to scan the multipass electron beam in a straight section by a laser beam focused by an optical resonator, as shown schematically in Figure 1. As is known [6,7], this interaction will produce high-energy photons in the direction of the electron path in solid angle $\Theta \sim 1/\gamma$, where γ is the Lorentz factor of the electron.

2. THE SCHEMATIC OF THE INSTALLATION

Figure 2 schematically presents the installation proposed for CEBAF. A circularly polarized laser beam (1), after focusing by a system of lenses (2) and an optical resonator (3), crosses the electron beam (4) in the straight section (after the recombiner). High-energy photons are counted by a proportional detector (5) located against the linac optical axis after the spreader magnet.

With scanning by a scanner mechanism (6), electron beams of different energies will send to a detector photons of corresponding spectral distribution. An amplitude analyzer (7) will distribute the pulses of absorbed photons correlated with the energy of the electron beam.

Electron beam profile and position can be determined by the scattered photon distribution for each energy versus the position of the scanning laser beam.

The polarization of the beam for each pass can be measured by the asymmetry of the intensity or by the spectral distribution of the high-energy scattered photons.

The described equipment, with a corresponding system of mirrors (8) permitting switching of the laser beam, can be installed in desirable points of the linac straight section.

3. CALCULATION OF THE FEASIBILITY

As is well known, an electron of energy E_e traveling through a photon flux having wavelength λ ($E_p \times \lambda$ = 1.24 μm·eV, where E_p is photon energy) radiates photons (Compton scattering) with maximal energy:

$$E_{\gamma\max} = E_e \frac{x}{1+x}, \qquad (1)$$

where:

$$x = \frac{4E_eE_p}{(m_0c^2)^2}. \qquad (2)$$

The energy of scattered photons is correlated with the angle of radiation θ as follows:

$$E_\gamma = \frac{E_{\gamma\max}}{1+(\theta/\theta_0)^2}, \tag{3}$$

where

$$\theta_0 = \frac{\sqrt{1+x}}{\gamma} \tag{4}$$

is the characteristic angle of the distribution. The angular distribution of radiated energy with arbitrary average polarization of electron beam Λ and laser photons P_c can be presented by the following equation:

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{d\theta^2} = \frac{2\sigma_0 y_m F(x, y(\theta))}{x\sigma_c\theta_0^2[1+(\theta/\theta_0)^2]^2}, \tag{5}$$

where

$$y_m = \frac{E_{\gamma\max}}{E_e} = \frac{x}{1+x}, \tag{6}$$

$$F(x,y(\theta)) = \frac{1}{1-y}+1-y-4r(1-r)-2\Lambda P_c xr(2r-1)(2-y), \tag{7}$$

$$r = \frac{y}{x(1-y)}, \tag{8}$$

$$y(\theta) = \frac{y_m}{1+(\theta/\theta_0)^2}, \tag{9}$$

$\sigma_0 = 2.5 \cdot 10^{-25}$ cm^2, and σ_c is the total cross section of Compton scattering.

The photon distribution can be found assuming that when $\theta \leq \theta_0$ all photons have maximal energy $y_{\max}$. According to (5) this distribution can be rewritten as:

$$dN_\gamma = \frac{\sigma_c \cdot L \cdot d\theta^2}{\theta_0^2[1+(\theta/\theta_0)^2]^2}, \tag{10}$$

where

$$L = \frac{n_p \cdot N_e}{S}, \tag{11}$$

n_p is the number of laser photons, and S is the interaction area.

After integration one can find the number of high-energy photons limited by the collimation angle $\Delta\theta$ as:

$$\Delta N_\gamma = N_\gamma \frac{\Delta\theta^2}{\theta_0^2}. \tag{12}$$

The total cross section of Compton scattering for a nonpolarized electron beam can be presented as follows:

$$\sigma_c = \frac{2\sigma_0}{x}\left[(1-\frac{4}{x}-\frac{8}{x^2})\ln(1+x)+\frac{1}{2}+\frac{8}{x}-\frac{1}{2(1+x)^2}\right]. \tag{13}$$

The polarization has a small (about 0.3%) contribution to σ_c, and polarization effects are described by (7). The total number (intensity) of scattered high-energy photons per second N_γ has been calculated as follows:

$$N_\gamma = \sigma_c \times \frac{n_p \times N_e}{S}, \tag{14}$$

where

$$n_p = \frac{P_{\text{laser}}\text{ (W)}}{E_p\text{ (eV)}} \times \frac{\Delta s}{c} \times Q, \tag{15}$$

Δs and S ($S = \sigma_e^2$) are accordingly the length and cross section of the interaction area, σ_e is the dispersion of electron distribution in the interaction point, Q is the quality factor of the optical resonator, N_e is the number of accelerated electrons in one second, and c is the speed of light.

A value of the Q factor equal to 50 is accessible. The crossing angle α between electron and photon beams can be about 0.1 rad and therefore the interaction length estimated as $\Delta s = 2\sigma_e/\tan\alpha$ is equal to 1 mm if $\sigma_e = 0.5 \cdot 10^{-4}$ m.

For calculation, 5 W CW power at wavelength $\lambda = 0.532$ nm was used as Nd:Yag laser parameters.

The waist of the photon distribution contour, 2 ω_0, in the optical resonator can be found from the following relation:

$$R_L = \frac{\pi\omega_0^2}{\lambda}, \tag{16}$$

where λ is the photon wavelength and R_L is the Rayleigh range, i.e. the length of the beam contour in the resonator where the waist increases by 40%. For the chosen wavelength λ and waist length $2R_L = 10$ mm this waist $\omega_0 = 29$ μm.

The calculation of the rate of scattered photons was performed for 100 μA electron beam current (which corresponds to $N_e = 6.25 \times 10^{14}$ electrons per second).

Total cross section of Compton scattering within energy bandwidth 0.5 GeV $\leq E_e \leq$ 4.0 Gev according to (13) is $\sim 6.65 \times 10^{-25}$ cm^2.

The scattered photons will travel to a detector installed after the spreader magnet. This photon flux will have an angular collimation $\theta_{\min} = 10^{-4}$ rad by the $\sim$ 250-m-long linac and the aperture of 25 mm.

The results of calculations of the rate of scattered photons N_γ versus the electron energy of different passes in the angle of collimation $\theta_{\min}$ are presented in Table 1. Also presented are the following important parameters: x, $E_{\gamma\max}$, $E_{\gamma\min}$, and θ_0. $E_{\gamma\min}$ according to (9) is the minimal energy of scattered photons limited by $\theta_{\min}$.

The polarization can be measured due to the asymmetry of N_γ by changing the spin direction ($\Lambda = \pm 1$). For a small value of x the function of the photon distribution can be presented as:

$$F(x,y) = 2(1-2x\Lambda P_c), \tag{17}$$

which for the lowest energy ($\gamma = 10^3$ and $x = 1.86 \times 10^{-2}$) creates asymmetry equal to 3.62%. Using integration within $\theta = 10^{-3}$ rad, polarization measurement accuracy of about 10% can be achieved during $\sim$ 100 seconds.

4. BACKGROUND CONSIDERATIONS

The background will consist of two components: gas bremsstrahlung and synchrotron radiation.

The rate of bremsstrahlung photons for average pressure equal to 5×10^{-9} Torr along the linac straight section (250 m) calculated according to [8] is of the order of 0.2 photons per second.

The intensity of synchrotron radiation photons, N_{sr}, having energy equal to minimal energy of the scattered photons (to 9.3 MeV) from a 100 μA and 4 GeV electron beam within a collimating angle θ_{min} equal to 5×10^{-5} rad and with a magnetic field intensity in the spreader magnet $\sim 5 \times 10^3$ Gauss calculated according to [9] is less than one photon per second.

5. ACCURACIES AND MEASURING TIME

According to the calculations the background coming from gas bremsstrahlung and synchrotron radiation can be neglected. Therefore the main limitation of the accuracy of beam size measurement is quantum fluctuations of flux intensity, N_γ, of Compton scattered γ-photons.

Beam size d here is limited as a distance, Δx, between two scanning points where measured intensities are accordingly N_{max} and 0.1 N_{max}. Therefore for a desired accuracy of the measurement $\frac{\Delta d}{d}$, one can write:

$$\sqrt{N_{max} \times t} = 0.1\ N_{max} \times t \times \frac{\Delta d}{d}, \qquad (18)$$

where t is the time (in seconds) necessary to reach the given accuracy.

According to (18) for energy $E = 500$ MeV ($N_{max} = 91$ ph/sec), beam size can be measured with 10% accuracy in ~ 220 sec (two measurements each during 110 sec). For 4 GeV this time is about 2 sec.

6. ACKNOWLEDGMENTS

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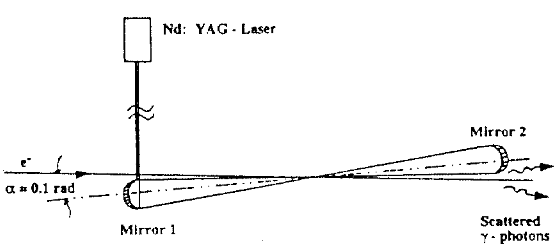

FIGURE 1.

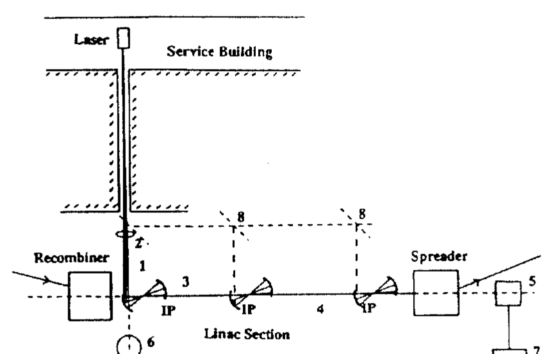

FIGURE 2.

Table 1. The Results of the Calculations

E_e (GeV)	x	$E_{\gamma max}$ (MeV)	θ_0 (rad)	N_γ in $\theta_{min} = 10^{-4}$ rad photons/sec	$E_{\gamma min}$ in $\theta_{min} = 10^{-4}$ (MeV)
0.5	1.86×10^{-2}	9.3	10^{-3}	91.0	9.28
1.0	3.72×10^{-2}	37.2	5.1×10^{-4}	3.5×10^2	36.83
2.0	7.45×10^{-2}	149.0	2.55×10^{-4}	1.39×10^3	143.3
3.0	1.12×10^{-1}	336.0	1.75×10^{-4}	2.97×10^3	308.25
4.0	1.86×10^{-1}	740.0	1.28×10^{-4}	5.54×10^3	638.0