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Development of a transmittance monitor for high-intensity photon beams

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ABSTRACT

A transmittance monitor has been developed for the second tagged-photon beamline at the Research Center for Electron Photon Science, Tohoku University, Japan. In this beamline, an internal radiator is employed to produce the bremsstrahlung photon beam out of circulating electrons in a synchrotron. The transmittance, which is defined as the probability of finding a photon coming to the target position when an electron is detected with a photon-tagging counter, should be determined to deduce cross sections for photo-induced reactions. The developed monitor consists of a telescope of thin plastic scintillators with a positron and electron converter, and a dedicated circuit implemented in a field-programmable gate array chip. The transmittance can be measured with this monitor for high-intensity photon beams corresponding to 20 MHz tagging signals. The measured transmittance is found to be constant with respect to the photon intensity for each photon-tagging channel.

1. Introduction

Photo-induced reactions with the incident energy ranging from several hundred MeV to a few GeV are important to study the structure of hadrons in detail. A hadron is a color-neutral object, and described in principle by quark and gluon dynamics as a solution of the fundamental theory of the strong interaction, quantum chromodynamics (QCD). At low energies, little is known for the solution owing to the large running QCD coupling constant. What are the effective degrees of freedom describing hadrons is a subject of interest associated with the color confinement problem. Meson photoproduction experiments have been conducted [1–5] to give information on the subject with an electromagnetic-calorimeter (EMC) system, FOREST [6], on the second photon beamline [7] at the Research Center for Electron Photon Science (ELPH), Tohoku University, Japan. Fig. 1 shows a schematic view of the second photon beamline at ELPH.

Bremsstrahlung photons are generated by inserting a thin carbon fiber (radiator) with a diameter of 11 μm into circulating electrons [7] in the electron synchrotron called Booster STorage (BST) ring (previously known as the STB ring) [8]. The energy of each photon is determined by measuring the momentum of its corresponding post-bremsstrahlung electron with a tagging detector system, STB-Tagger II [7], having 116 photon-tagging channels. Each tagging signal is produced from a telescope of two scintillating fibers with a cross section of 4×4 mm^2, covering a photon energy with a width of 0.5–2.8 MeV (σ). The tagging signal does not always correspond to a photon arriving at the target. Some of the tagged photons may be converted into a positron and electron (e^+e^-) pair owing to the material on the photon beamline. These undesirable e^+e^- pairs are swept out with a dipole magnet, $\mathcal{R}$TAGX [9], which is placed in front of FOREST. Furthermore, a photon is not generated when Møller scattering or Coulomb multiple scattering takes place at the radiator, but the scattered electron might hit a tagging detector. Therefore, the photon transmittance (so called the tagging efficiency), which is defined as the probability of finding a photon coming to the target position when an electron is detected with a tagging detector, should be determined to deduce cross sections for photo-induced reactions. The transmittance is experimentally measured since it is difficult to incorporate all the conditions of circulating electrons in the calculation.

So far, we have measured the transmittance, T_γ, using an EMC module on the photon beamline. The energy of a photon is measured with the module in response to the tagging signal. The singles rate of the module should be reduced so that it could work, namely the photon-beam intensity should be much lowered. Thus, we make the circulating current in the BST ring very low during the transmittance measurement. We describe a photon beam in this condition as a faint beam. To deduce

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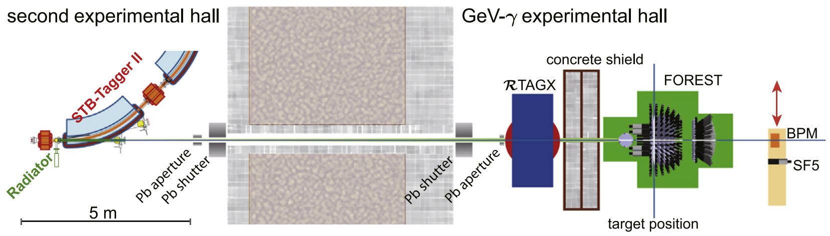

Fig. 1. Schematic view of the second photon beamline at ELPH. An electron synchrotron called Booster STorage (BST) ring [8] (previously known as the STB ring) and a photon-tagging detector, STB-Tagger II [7], are located in the second experimental hall. A charge sweeping magnet, ℛTAGX [9], and a detector system, FOREST [6], are placed in the GeV-γ experimental hall. The photon-beam profile monitor with scintillating-fiber hodoscopes (BPM) [10] and an SF5 lead-glass Cherenkov counter for the photon-transmittance measurement can be inserted into the beamline by moving a stage horizontally. The diameters of the two lead apertures located in the second and GeV-γ experimental halls were 20 and 25 mm in the present work, respectively.

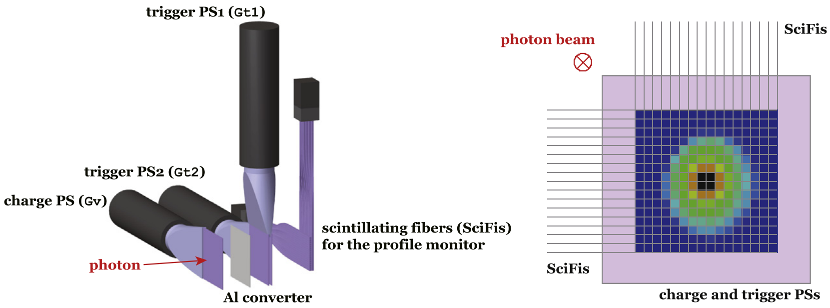

Fig. 2. Schematic view (left) of the detector system for the transmittance measurement together with its front view (right). It consists of three PSs with a thickness of 1 mm and an area of 70 × 70 mm^2. A 0.5 mm-thick aluminum plate is used as an e^+e^- converter. Additional two scintillating-fiber hodoscopes to give the intensity map of the photon beam at the target position are not used. A measured photon-beam profile taken from Fig. 11 in Ref. [10] is overlaid in the front view.

the differential and total cross sections for meson-photoproduction reactions measured with the high-intensity photon beams, the number of incident photons are given by the number of tagging signals and transmittance for each tagging channel. The values of the transmittance between the faint and high-intensity beams have been assumed to be the same so far. We have developed a transmittance monitor for high-intensity photon beams at normal operation (circulating current of ∼ 20 mA and photon-tagging rate of ∼ 20 MHz), and confirmed the transmittance is the same between the faint and high-intensity photon beams for each tagging channel.

2. Developed transmittance monitor

We used the same detector system for the photon-beam profile monitor with scintillating-fiber hodoscopes (BPM) [10]. BPM consisted of a plastic scintillator (PS) for charge veto (`Gv`), an aluminum-plate converter with a thickness of 0.5 mm, and two trigger PSs (`Gt1` and `Gt2`). The thicknesses of the three PSs measured 1 mm each, and the number of trigger PSs was different from that in Ref. [10]. Each PS was covered by a Tyvek-1073D sheet (reflector) with a thickness of 0.19 mm, and a black sheet (light shielding) with a thickness of ∼ 0.2 mm. The coverage of each PS with an area of 70 × 70 mm^2 was sufficient since the width of the delivered photon beam was ∼ 8 mm (σ) [10]. Additional two layers of scintillating-fiber hodoscopes to give the intensity map of the photon beam at the target position were not used for the developed transmittance monitor. Fig. 2 shows the schematic view of the detector system for the transmittance measurement. The condition of finding a photon by this detector system (BPM trigger) was described as

$$\mathtt{Tr} = \overline{\mathtt{Gv}} \otimes \mathtt{Gt1} \otimes \mathtt{Gt2}, \tag{1}$$

where ⊗ stands for coincidence of signals. The `Gv` signal rejected the events in which charged particles were produced upstream, and the `Gt1` and `Gt2` signals required the events having an e^+e^- pair before passing through the two trigger PSs. The discriminator thresholds for producing logic signals of `Gv`, `Gt1`, and `Gt2` were set to $0.5V_{\mathrm{mip}}$, $1.5V_{\mathrm{mip}}$, and $1.5V_{\mathrm{mip}}$, respectively. Here V_{mip} denotes the pulse height in response to the minimum ionizing particles. Only a fraction of the incident photon beam was converted in the aluminum plate into e^+e^- pairs. Since the BPM detector itself is sensitive only to charged particles (e^+e^- pairs) produced downstream of `Gv`, this fraction (sampling ratio), η_γ, affects the probability of finding a photon in the BPM detector corresponding to a tagging signal (BPM-response probability), R_γ. The actual photon transmittance, T_γ, can be determined from R_γ and η_γ:

$$T_\gamma = \frac{R_\gamma}{\eta_\gamma}. \tag{2}$$

Since T_γ is directly measured for a faint beam with an EMC module on the beamline, η_γ can be determined from the measured T_γ and R_γ values in the same condition. The determination of η_γ will be discussed in Section 3.

A circuit to give R_γ^i for each tagging channel i has been implemented into a developed NIM module called MPLM4. MPLM4 is a prototype of MPLM4X in Ref. [10] containing a field-programmable gate array (FPGA) chip, Xilinx Spartan-6 [11]. MPLM4 (MPLM4X) accepts and produces NIM standard signals through 36 (38) input and 18 output channels. The logical circuit has been designed using edge-aligned signals with an internal 200-MHz clock signal. The R_γ^i is determined by the numbers, Ns, of three signals for each tagging channel $\mathtt{Tc}i$:

$$R_\gamma^i = \frac{N(\mathtt{Tc}i \otimes \mathtt{Tr}) - N(\mathtt{Tc}i \otimes \mathtt{Tr}')}{N(\mathtt{Tc}i)}, \tag{3}$$

where `Tr'` denotes the 165-ns delayed signal for `Tr`, and the coincidence widths are the same between $\mathtt{Tc}i \otimes \mathtt{Tr}$ and $\mathtt{Tc}i \otimes \mathtt{Tr}'$. The harmonic number of the BST ring with an RF frequency of 500.14 MHz is 83 [8]. The 165-ns delay approximately corresponds to the time of a revolution in the BST ring. Fig. 3 shows the diagram describing the operation of the transmittance monitor. The logic signals of `Gv`, `Gt1`, and `Gt2` from the BPM detector, and those of 32 tagging channels out of 116 [7] are delivered to MPLM4.

The `Tr` signal is generated in the trigger generator component from `Gv`, `Gt1`, and `Gt2` signals. The signal width is 8 clock cycles (40 ns)