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FIRST PROTOTYPE OF A CORONAGRAPH-BASED HALO MONITOR FOR bERLinPro*

Ji-Gwang Hwang † and Jens Kuszynski,
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (HZB), Berlin, Germany

Abstract

Since particle losses by beam halo induced by space charge force and scattering of trapped ions are critical issues for superconducting-linac based high power machines such as bERLinPro, a halo monitor is demanded to monitor and control particle distribution at the level of $10^{-4} \sim 10^{-5}$ of the core intensity. A coronagraph-based halo monitor was adopted and the first prototype has been designed as a demonstrator system aimed at resolving a halo-core contrast in the 10^{-3} to 10^{-4} range. This monitor was tested at BESSY II with various operation modes such as Transverse Resonance Island Buckets (TRIBs) and Pulse-Picking by Resonant Excitation (PPRE). We show our design parameters, experimental criterion, and experimental results.

INTRODUCTION

The Berlin Energy Recovery Linac Prototype (bERLinPro) project was launched at the Helmholtz-Zentrum Berlin (HZB) to demonstrate and establish technologies for energy recovery linac (ERL) based accelerators for a future light source [1, 2]. The bERLinPro will provide electron beams up to 50 MeV in the recirculation loop with several operation modes such as a single pulse mode with various repetition rates, bursting mode, and 50 MHz and 1.3 GHz continuous waves (CW) modes [3]. The bERLinPro injector, consisting of a photocathode 1.4-cell superconducting radio frequency (SRF) gun, followed by three 2-cell booster SRF cavities, generates high-quality electron beams with an energy of 6.5 MeV. The beam is transported to the main linac module and accelerated by three 7-cell SRF cavities up to 50 MeV energy [4]. The design layout is shown in Fig. 1.

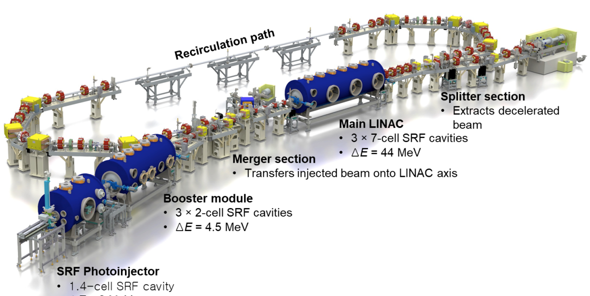

Figure 1: Layout of bERLinPro having accelerating structures of 1.4-cell SRF gun, three 2-cell SRF booster cavities, and three 7-cell SRF cavities for generation of high-quality and high-power electron beams [5].

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† ji-gwang.hwang@helmholtz-berlin.de

The construction of a building and basic infrastructure was completed in 2017 so that the installation of accelerator components has begun. As the first stage, the installation of the vacuum system of a "Banana" section, which includes the entire low energy beam path from the gun to the high power beam dump. The 5 mA SRF gun (Gun1) and the cryomodule of the booster cavities as well as a diagnostics line, is ongoing [6].

HALO MONITOR TEST SETUP

A total of five synchrotron light based electron beam diagnostics for measuring a beam halo distribution, and temporal and spatial distribution will be installed in the recirculator of the bERLinPro. Due to the heat capacity of a cryogenics, it is not allowed to provide an additional power load of more than 50 W on the cryomodule for main SRF cavities by small beam losses from halo particles, which corresponds to 10^{-5} level of maximum beam power. Since a halo monitor is a crucial diagnostic for minimizing uncontrolled beam losses by halo particles by adjusting the optics at the upstream of the first arc section, it stimulates the development of the beam halo monitor with the contrast ratio of 10^{-5}.

For the observation of the halo distribution with the contrast of 10^{-5} to the beam core, various monitors such as a wire-scanner monitor, diamond detector, the optical monitor based on a digital micromirror device (DMD), and coronagraph-based halo monitor were compared and analyzed. Finally, the coronagraph-based halo monitor is preferred since this technique can observe the full 2-D halo distribution without any disturbance to the beam and it has already been demonstrated at the KEK Photon Factory to achieve a 6×10^{-7} ratio for the background to peak intensity [7, 8]. The design study of the coronagraph-based halo monitor with a Lyot-stop technique, which produces the image of a entrance pupil using re-diffraction optics to remove the majority of diffraction fringes, is performed using a Fourier-optics interpretation which is equivalent to the classical optics approach using Fourier transforms, in which the waveform is regarded as made up of a superposition of plane waves [9].

The beam-halo monitor will be installed on the first dipole of the first arc section because this dipole has a relatively small dispersion, which does not disturb the horizontal beam distribution. Since the full energy operation of the bERLinPro is scheduled for 2020, a preliminary test is performed at a diagnostics beam line of BESSY II. The diagnostics beam line of BESSY II provides multi-platform for research and development of various synchrotron light based monitors [10, 11]. The beam line has a distance of 15.5 ± 0.5 m

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from a source point. The picture of the coronagraph-based halo monitor installed at the BESSY II diagnostics beam line is shown in Fig. 2.

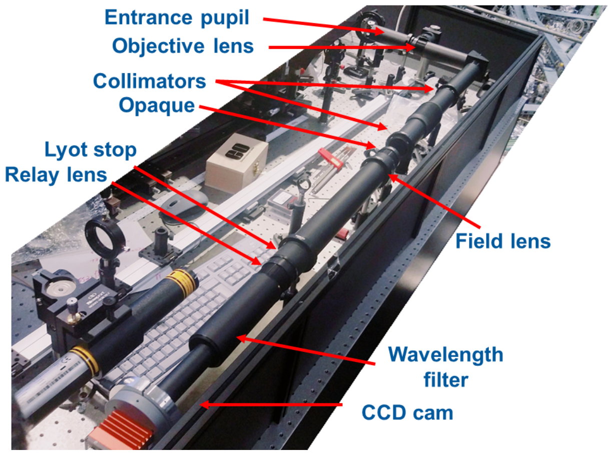

Figure 2: Picture of coronagraph-based halo monitor setup at BESSY II diagnostics beamline.

The coronagraph-based halo monitor consists of an objective lens (first lens) to produce a real beam image, several intermediate collimators, opaque disk to block a high-intensity core, field lens (second lens) to produce re-diffraction fringes, Lyot stop to remove the majority of diffraction fringes, and relay lens (third lens) to make the image for a charge-coupled device (CCD) camera. The square entrance pupil with the opening of 25 mm was adopted. The opaques were printed by a 3D printer with an irregular reflection surface, for various size from 150 µm to 580 µm with a fabrication error of 0.1 mm. All the lenses have a diameter of 2 inches with a quality of 40-20 (scratch-dig) and all elements such as an entrance pupil, lenses, and collimators are installed in 2-inch lens tube to prevent ambient light. The CCD camera used for imaging is a Prosilica GT1920 from Allied Vision. Since the strong distortion of the front-end mirror of the beam line is recognized in the vertical direction from other experiments, all measurements are performed in the horizontal plane.

PRELIMINARY TEST AT BESSY II

Since July 2015 the BESSY II storage ring has been providing a new bunch filling pattern in Top-Up mode, namely, standard user mode. This consists of a Hybrid (Chopper) bunch of 4 mA in the center of a 200 ns wide dark gap, followed by a pulse-picking by resonant excitation (PPRE) bunch for the single bunch science driven user community, the standard multibunch mode each of 1 mA current separated by 2 ns, and slicing bunches deliver photons daily to the ultrafast experiments at the Femtoslicing facility [12, 13]. In addition to the standard user mode, the BESSY II storage ring provides various sophisticated filling patterns such as a high current single bunch mode, a few bunch mode of 4 bunches, and low-alpha multibunch hybrid mode for time-resolved studies. The low-alpha mode is modified a momentum compaction factor to smaller values by a special setting of the electron optics of the storage ring. Since the beam size in the low-alpha mode is larger than the standard mode and the beam distribution is expected to be close to the Gaussian distribution, the measurement with various opaque sizes was carried out. The result is shown in Fig. 3.

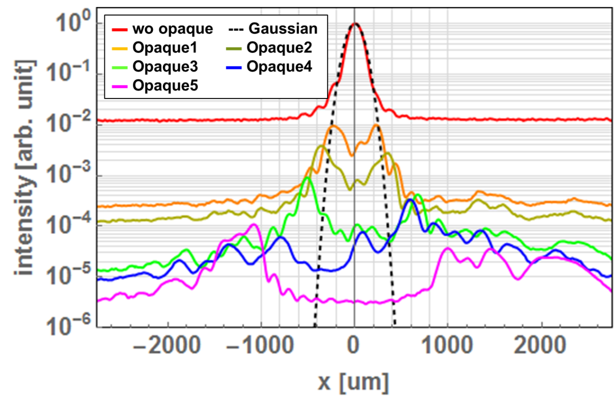

Figure 3: Measured result of beam halo with various opaque disks in the low-alpha mode of BESSY II. Transverse magnification is about 1/14.5 and all data normalized by the exposure time of CCD camera.

As shown in Fig. 3, the measured beam halo distribution is qualitatively close to Gaussian distribution up to 10^{-3} contrast to the beam core. Due to diffraction noise, it is difficult to measure the practical halo distribution at 10^{-4} contrast to the beam core. The polishing quality of the objective lens limits the measurement because the background noise from the Mie-scattering effect due to the dig and scratch on the lens surface is 3×10^{-4} for a 200 µm dig [14].

With the standard user mode, which has the PPRE bunch, the measurement of beam halo was performed to verify the performance of the monitor. Because the PPRE bunch has a 1.2 % (3/250 mA) of total beam current in the ring as well as relatively larger beam size than the 1 mA standard multibunch, so it has the same characteristics as beam halo. The result is shown in Fig. 4.

As shown in Fig. 4, the measured beam size is smaller than the beam size in the low-alpha mode, and the particle distribution deviates greatly from the Gaussian distribution at 10^{-2} contrast to the beam core. Furthermore, the result of numerical simulation using Elegant code show qualitative agreement with the measurement [15, 16].

In order to ensure the performance limitation of the beam halo monitor, it is worthwhile to measure the beam located off the section of strong diffraction noise area. Since 2017 BESSY II provides a special setting of the magnetic lattice generating a second stable orbit using transverse resonance island buckets (TRIBs) [17, 18]. This special operation mode allows the beam separation in the horizontal plane as well as the manipulation option of bunch filling in the second orbit. The outer laying TRIBs bunch is beyond the diffraction noise. By using the halo monitor, we observed coincidentally the diffused particles from a core orbit to the second stable

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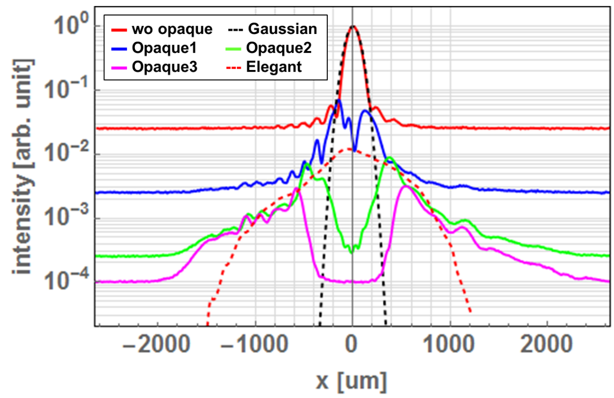

Figure 4: Measured result of beam halo with various opaque disks in the standard user mode of BESSY II. Transverse magnification is same as in Fig. 3 and all data normalized by the exposure time of CCD camera.

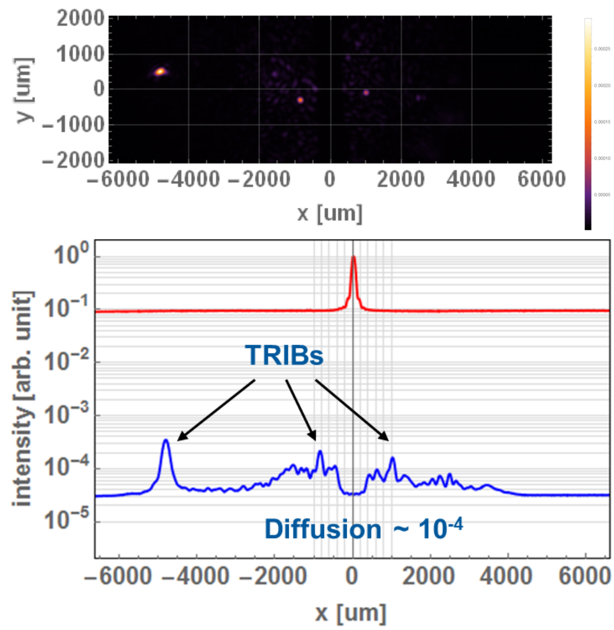

Figure 5: Image of the diffused beam at the second stable orbit measured in the TRIBs operation with the opaque disk. Transverse magnification is same as in Fig. 3.

orbit during the commissioning of TRIBs. The measurement result of the diffused beam at the second stable orbit is shown in Fig. 5.

As shown in Fig. 5, the three TRIBs bunches are clearly distinguishable and the beam intensity is in good agreement with the values measured in the user beam line with comparable detectors. From this measurement, the halo monitor can be used potentially for continuous monitoring of the bunch in the second stable orbit during TRIBs operation.

SUMMARY

The halo monitor is one of the most crucial diagnostics for high power accelerators such as the bERLinPro to control uncontrolled beam losses in the machine. The preliminary test of the coronagraph-based halo monitor is performed at the diagnostics beam line of BESSY II with various operation modes. The measurement results show that the monitor can measure the halo at the contrast ratio of $10^{-3} \sim 10^{-4}$. The halo monitor can be used potentially for continuous monitoring of the bunch in the second stable orbit during TRIBs operation. The performance to date is limited by the polishing quality of the objective lens since the background noise from the Mie-scattering effect due to the dig and scratch on the lens surface is 3×10^{-4} for a 200 µm dig [14]. We will purchase a high-quality lens to improve the performance of the monitor. The preparation of the mechanical design will be performed to install the monitor into the bERLinPro diagnostics line.

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