

Beam halo from Touschek scattering in the KEK Accelerator Test Facility

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Beam halo is one of the most crucial issues limiting the machine performance and causing radioactivation in high-intensity accelerators. Understanding halo formation is vital for high-luminosity colliders, advanced light sources, and spallation neutron sources to effectively mitigate beam loss through machine optimizations and tailored collimation systems. This article details numerical and experimental investigations of transverse and longitudinal halos at the KEK Accelerator Test Facility. Halo distributions are modeled incorporating operational beam parameters, synchrotron radiation, beam-gas scattering, and Touschek-scattering processes. A newly developed yttrium aluminum garnet/optical transition radiation monitor, positioned at the extraction line, enables direct imaging of transverse and longitudinal halo distributions. The general consistency between predictions and observations in various conditions indicates that the Touschek scattering is the dominant mechanism forming the horizontal and momentum halos.

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I. INTRODUCTION

Beam halo is one of the most critical issues limiting the performance and potentially causing component activation of high-intensity accelerators, especially high-energy colliders at the luminosity frontier. However, a general definition of “halo” is complicated because it should be given in line with the requirements of machine operation and the primary concerns of beam loss. From the diagnostic point of view, one thing is undoubtedly clear—by definition, beam halo is of low density and difficult to measure. In some literature, the complete beam profile is divided into three parts referring to the beam center: core, tail, and halo [1]. However, the boundary between the tail and the halo is rather ambiguous. As a consequence, hereinafter, beam halo presents both tail and halo particles without additional specifications. The formation of beam halo is generally complex and associated with collective

effects, nonlinearities, optics errors, beam-beam interaction, secondary emission, and so on [2–11]. The collimation system has been a fundamental part of a high-intensity accelerator to mitigate the undesired background induced by halo-particle loss. To evaluate the collimation efficiencies and the residual backgrounds, knowledge of the primary driving mechanisms and beam halo modeling is vital. Moreover, a clear picture of halo formation can help to predict the detector background around sensitive regions, e.g., the injection area and the interaction point. To accomplish this task, both simulations with various physical processes and observations employing a powerful halo monitor with sufficient dynamic range are required. The dynamic range in the context of this article is the inverse ratio of the smallest resolvable fractions of a large quantity, in our case, the number of particles, to the maximum of that quantity. Massive tracking simulations in the presence of realistic machine imperfections and primary collective effects are typically necessary to provide a reasonable prediction of beam halo. Regarding the halo diagnostics, even though one can sample the halo regions using a sensitive monitor with a standard dynamic range, a complete profile imagined with a high-dynamic-range monitor is more desirable. In principle, many profile monitors could be adapted for direct observation of beam halo after necessary upgrades. For an electron accelerator, a halo diagnostic based on the optical method is typically

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favorable to obtain a satisfactory dynamic range of more than 10^5 .

The Accelerator Test Facility (ATF) at KEK was initially constructed to demonstrate the feasibility of producing low-emittance beams required at a future linear collider and supply high-quality beams for the R&D activities on beam dynamics, instrumentation, and control technology, which will be needed at future accelerator-based facilities [12–15]. ATF provides an excellent opportunity to investigate halo formation toward future high-energy accelerators. Compared with a high-energy collider with a high local chromaticity in the interaction region and strong nonlinear beam-beam interaction effects, the primary mechanisms driving particles into the halo region in a GeV-scale electron storage ring are more straightforward, involving mainly beam-gas scattering (BGS), Touschek scattering, and nonlinearities [16–18]. However, the verification of such plausible driving mechanisms from direct observations has been rarely reported. Precedent beam halo studies in ATF have concentrated on the development of high-dynamic-range halo monitors and analytical evaluations based upon Campbell’s theorem [19,20]. The later measurements using a diamond-sensor detector indicate that the vertical halo is dominated by the elastic BGS process [21]. The measured vertical halos over more than $\pm 10\sigma_y$, where σ_y is the vertical rms beam size, are in good agreement with predictions in the presence of multipoles, synchrotron radiation, and the BGS processes, and show clear dependence on the vacuum pressure. However, the observed horizontal halos are an order of magnitude higher than the predictions based solely on the BGS process and show little dependence on the vacuum pressure. Given the nonzero horizontal dispersion in the arc sections, these horizontal halos were suspected to arise from a scattering process such as Touschek scattering. However, a systematic check of this hypothesis was missing because of the lack of an adequate numerical simulation, including the necessary physical processes and a powerful monitor, for both transverse and longitudinal halos.

In this article, numerical simulations of halo generation, including a complete set of scattering processes in the presence of realistic machine parameters, are presented, followed by direct observations of transverse and longitudinal halos employing a combined yttrium aluminum garnet/optical transition radiation screen monitor. The reasonable agreement between simulation and measurement confirms the Touschek effect’s leading role in forming horizontal and momentum halos.

II. ACCELERATOR TEST FACILITY

The KEK-ATF consists of an electron source based on a Cs_2Te photocathode injector, a 1.3 GeV linac, a damping ring (DR), and an extended extraction line, based on which the ATF2 beamline was later built. The ATF DR is a racetrack-type storage ring with a circumference of

TABLE I. ATF main parameters [12,13].

Beam energy (GeV)	1.3
Circumference (m)	138.6
Bunch charge (nC)	0.16–1.6
Vertical emittance (pm)	> 4
Horizontal emittance (nm)	1.2
Energy spread (%)	0.056 (0.08)
Bunch length (mm)	5.3 (7) ^a
Damping time ($x/y/s$) (ms)	17/27/20
Number of bunches	1–20
Repetition rate (Hz)	3.12
rf frequency (MHz)	714

^aFor a bunch charge of 1.6 nC.

138.6 m. It was initially built to demonstrate the production of an ultra-small-emittance beam required for linear colliders. There are 36 FOBO cells in the arc sections, where B represents the combined-function bending magnet. The phase advances per FOBO cell are $\pi/2 - 5\pi/6$ and $\pi/6 - \pi/3$, horizontally and vertically, respectively, and can be controlled employing two individual quadrupoles. The smallest vertical emittance of 4 pm has been achieved at a low beam intensity of about 0.16 nC/bunch [13]. Tuning of the low-emittance beam was achieved through iterating a series of optics corrections: the closed-orbit-distortion correction, optics matching, dispersion correction, and global xy -coupling correction. Thanks to such well-developed tuning techniques, a vertical emittance of around 12 pm can be preserved for the daily operation of the ATF DR. The primary parameters of the ATF DR are listed in Table I.

ATF2 is an extended extraction line to the ATF damping ring, which supplies a high-quality electron beam with a vertical normalized emittance of about 30 nm, comparable to the requirement of the International Linear Collider (ILC) beam delivery system [22]. The primary goal of ATF2 is to achieve a nanometer beam size with beam orbit stabilization in nanometer precision in the vertical plane at the IP. ATF2 beamline contains three sections: the extraction line (EXT) for the beam extraction and manipulation, the matching section for the adjustment of the downstream optics, and the final focus section (FFS), as depicted in Fig. 1. The EXT section comprises a “dogleg” inflector with two skew quadrupoles adjacent to the two 10° bends for the vertical dispersion and xy -coupling corrections [23]. Six bipolar quadrupoles in the matching section are for optics matching between the EXT and FFS sections. The FFS compensates the chromaticity locally using two sextupoles adjacent to the final doublet (FD) with nonzero horizontal dispersion generated by upstream bends. Another three sextupoles are placed upstream of the FD in the proper phase with the FD sextupoles to cancel the higher order aberrations. For the nanometer beam size diagnostic at the interaction point (IP), a laser-interferometer beam size monitor has been built at ATF2. Thanks to the successful international collaboration, a capability for

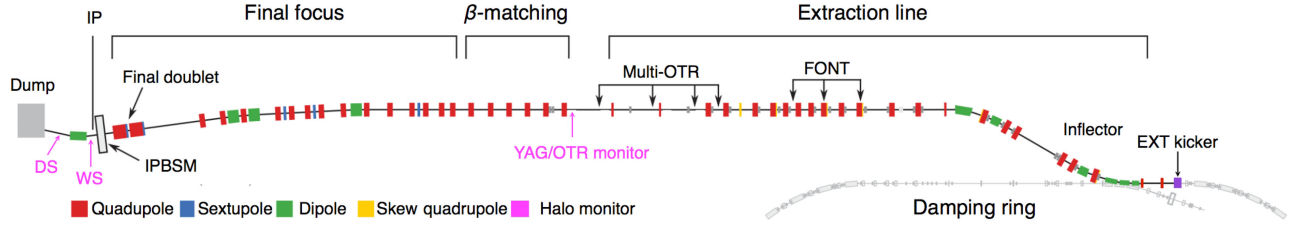


FIG. 1. Schematic layout of the ATF2 beamline.

repeatable tuning of a vertical beam size of less than 60 nm has been successfully demonstrated since 2013 [14,24].

III. THEORETICAL EVALUATIONS

A. Perturbation by Touschek scattering

Coulomb scattering of particles in bunched beams generates an exchange of momenta between the transverse and longitudinal planes. The multiple small-angle Coulomb scattering, called intrabeam scattering (IBS), diffuses the beam-core distribution and leads to dilution of emittance, degrading the luminosity of the collider or the brightness of the modern synchrotron radiation light source. The large-angle Coulomb scattering, named Touschek scattering, transfers transverse momentum to the longitudinal and is boosted by a Lorentz factor for the relativistic beam. The resulting momentum perturbation might exceed some characteristic longitudinal momentum for a given emittance, thus causing beam halo and particle loss. The Touschek-scattering theories have been investigated as soon as the Touschek effect was observed for the first time in the Anello Di Accumulazione (AdA) electron storage ring [25]. Following Piwinski's derivations, the momentum exchange induced by Touschek scattering is rederived, as follows.

The momenta of particles before collision in the laboratory (LAB) coordinate system (s, x, y) are given by

$$\vec{p}_{1,2} = \begin{pmatrix} p_{s1,2} \\ p_{x1,2} \\ p_{y1,2} \end{pmatrix}_{\hat{s}, \hat{x}, \hat{y}}, \quad (1)$$

where $\hat{s}$, $\hat{x}$, and $\hat{y}$ represent the longitudinal, horizontal, and vertical unit vectors parallel to the s , x , and y coordinate axes. We then define a new coordinate system in the LAB frame with the unit vectors ($\hat{u}$, $\hat{v}$, and $\hat{w}$), which satisfies

$$\hat{u} = \frac{\vec{p}_1 + \vec{p}_2}{|\vec{p}_1 + \vec{p}_2|}, \quad \hat{v} = \frac{\vec{p}_1 \times \vec{p}_2}{|\vec{p}_1 \times \vec{p}_2|}, \quad \hat{w} = \hat{u} \times \hat{v} \quad (2)$$

and the momenta becomes

$$\vec{p}_{1,2} = p_{1,2} \begin{pmatrix} \cos \chi_{1,2} \\ 0 \\ \pm \sin \chi_{1,2} \end{pmatrix}_{\hat{u}, \hat{v}, \hat{w}}, \quad (3)$$

where $\chi_{1,2}$ is the angle between $\vec{p}_{1,2}$ and $\hat{u}$. Applying a Lorentz transformation parallel to $\hat{u}$, we obtain the expression of the momenta in the center-of-mass (c.m.) coordinate system ($\tilde{u}, \tilde{v}, \tilde{w}$) as

$$\vec{\tilde{p}}_{1,2} = p_{1,2} \begin{pmatrix} \gamma_t \left(\cos \chi_{1,2} - \frac{\beta_t}{\beta_{1,2}} \right) \\ 0 \\ \pm \sin \chi_{1,2} \end{pmatrix}_{\hat{\tilde{u}}, \hat{\tilde{v}}, \hat{\tilde{w}}}, \quad (4)$$

where β_t is the relative velocity of the ($\tilde{u}, \tilde{v}, \tilde{w}$) coordinate system and $\beta_{1,2}$ are the relative velocities of the two particles in the laboratory frame

$$\beta_t = \frac{|\vec{p}_1 + \vec{p}_2|c}{E_1 + E_2} = \frac{\beta_1 \gamma_1 \cos \chi_1 + \beta_2 \gamma_2 \cos \chi_2}{\gamma_1 + \gamma_2}, \quad (5)$$

and the Lorentz factor of the transformation is

$$\gamma_t^2 = \frac{1}{1 - \beta_t^2} \approx \frac{\gamma^2}{1 + \beta^2 \gamma^2 \chi^2}. \quad (6)$$

For the Touschek scattering, which induces a large momentum deviation larger than the momentum spread, we further assume that the initial longitudinal projection is small in the ($\tilde{u}, \tilde{v}, \tilde{w}$) coordinate system

$$\xi \sqrt{1 + \gamma^2 \chi^2} \ll 2\chi, \quad (7)$$

where ξ and χ are defined as

$$\xi = \frac{p_1 - p_2}{\gamma p}, \quad \chi^2 = \frac{(p_{x1} - p_{x2})^2 + (p_{y1} - p_{y2})^2}{4p^2}, \quad (8)$$

where p is the mean momenta, and the momenta in the c.m. frame are then approximated as

$$\vec{\tilde{p}}_{1,2} \approx \pm \frac{p}{2} \begin{pmatrix} 0 \\ 0 \\ 2\chi \end{pmatrix}_{\hat{\tilde{u}}, \hat{\tilde{v}}, \hat{\tilde{w}}}. \quad (9)$$

The relative velocity of the ($\tilde{u}, \tilde{v}, \tilde{w}$) coordinate system is given by

$$\beta_t = \beta \cos \chi, \quad (10)$$

where β is a function of the mean momenta p . The Touschek effect concerns mainly the amount of transverse

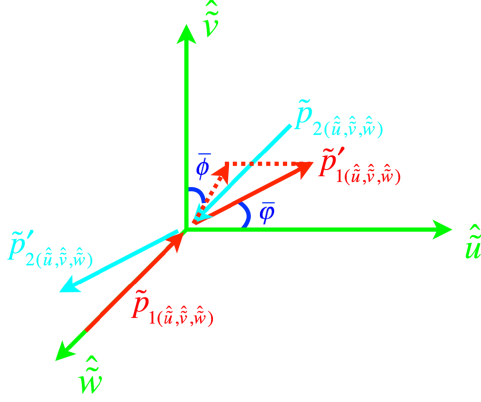


FIG. 2. Schematic of momenta transfer from the transverse plane to the longitudinal direction in the c.m. frame.

momentum coupled into the longitudinal direction. Therefore, we define two angles: the polar angle $\bar{\varphi}$ between $\vec{p}'_{1,2}$ and $\hat{u}$ axis, and the azimuthal angle $\bar{\phi}$ between the projection of $\vec{p}'_{1,2}$ on the $\hat{u}\hat{w}$ plane and the $\hat{v}$ -axis, as shown in Fig. 2. With such definitions, the calculation of the cross section, as well as the magnitude of the momentum transferred into the longitudinal direction, becomes easier. The momenta after a large-angle collision in the c.m. frame are

$$\vec{p}'_{1,2} = p\chi \begin{pmatrix} \cos \bar{\varphi} \\ \sin \bar{\varphi} \cos \bar{\phi} \\ \sin \bar{\varphi} \sin \bar{\phi} \end{pmatrix}_{\hat{u}, \hat{v}, \hat{w}}. \quad (11)$$

Then, in the (u, v, w) coordinate system, the momentum change because of a two-body collision is

$$\vec{p}'_{1,2} - \vec{p}_{1,2} = p\chi \begin{pmatrix} \gamma_t \cos \bar{\varphi} \\ \sin \bar{\varphi} \cos \bar{\phi} \\ \sin \bar{\varphi} \sin \bar{\phi} - 1 \end{pmatrix}_{\hat{u}, \hat{v}, \hat{w}}. \quad (12)$$

Finally, the momentum change in the (s, x, y) coordinate system can be derived as

$$\frac{\delta \vec{p}_{1,2}}{p} = \begin{pmatrix} \chi \gamma_t \cos \bar{\varphi} \\ \frac{\zeta}{2\chi} \sin \bar{\varphi} \cos \bar{\phi} + \frac{\theta}{2\chi} (\sin \bar{\varphi} \sin \bar{\phi} - 1) \\ -\frac{\theta}{2\chi} \sin \bar{\varphi} \cos \bar{\phi} + \frac{\zeta}{2\chi} (\sin \bar{\varphi} \sin \bar{\phi} - 1) \end{pmatrix}_{\hat{s}, \hat{x}, \hat{y}}, \quad (13)$$

where $\bar{\varphi} \in (0, \bar{\varphi}_m)$ and $\bar{\phi} \in (0, 2\pi)$. $\bar{\varphi}_m$ are functions of the momentum acceptance δ_m

$$\bar{\varphi}_m = \cos^{-1}(\delta_m / \gamma_t \chi). \quad (14)$$

Assuming linear synchrotron motion, the perturbations to the kinetic invariant in a dispersive region ($\mathcal{H}_x \neq 0, \mathcal{H}_y = 0$) are

$$\begin{aligned} \delta J_x &= (\alpha_x x_\beta + \beta_x x'_\beta) \frac{\delta p_x}{p} + \frac{\beta_x}{2} \left(\frac{\delta p_x}{p} \right)^2 \\ &\quad - \tilde{\eta}_x \frac{\delta p_x}{p} \frac{\delta p}{p} - [\gamma_x x_\beta \eta_x + \alpha_x \eta'_x + x'_\beta \tilde{\eta}_x] \frac{\delta p}{p} \\ &\quad + \frac{\mathcal{H}_x}{2} \left(\frac{\delta p}{p} \right)^2 \\ \delta J_y &= (\alpha_y y_\beta + \beta_y y'_\beta) \frac{\delta p_y}{p} + \frac{\beta_y}{2} \left(\frac{\delta p_y}{p} \right)^2 \\ \delta J_s &= \frac{h\eta_c}{2Q_s} \left[2 \frac{\delta p}{p} \frac{\Delta p}{p} + \left(\frac{\delta p}{p} \right)^2 \right] \end{aligned} \quad (15)$$

with

$$\mathcal{H}_{x,y} = \eta_{x,y}^2 + \tilde{\eta}_{x,y}^2, \quad \tilde{\eta}_{x,y} = \alpha_{x,y} \eta_{x,y} + \beta_{x,y} \eta'_{x,y}, \quad (16)$$

where $\beta_{x,y}$, $\alpha_{x,y}$, and $\gamma_{x,y}$ are the Twiss parameters, $\eta_{x,y}$ is the dispersion function, $\eta'_{x,y} = d\eta_{x,y}/ds$, $\Delta p/p$ is the off-momentum coordinate, $\delta p/p$ is the momentum change, $\mathcal{H}_{x,y}$ is the dispersion invariant, h is the harmonic number, η_c is the phase-slip factor, and Q_s is the synchrotron tune. In the presence of the nonzero horizontal dispersion and zero xy coupling, the vertical invariant J_y is only affected via the transverse heating, while the horizontal invariant J_x could be enlarged because of the transverse heating and the diffusion coupled through a nonzero $\mathcal{H}_x$. The transverse heating is the analog of the transverse kicks because of the synchrotron radiation emitted at a small angle to the forward direction. It typically does not result in a large oscillation amplitude.

B. Simulations

The simulation includes three main parts: mimicking realistic beam parameters, generating halo particles from stochastic processes, and particle tracking. The halo

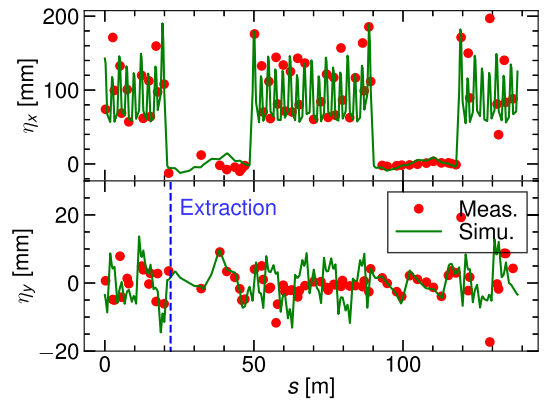


FIG. 3. Reproduction of horizontal and vertical dispersions of the ATF DR via local dispersion bump. The equilibrium vertical emittance is about 12 pm in the presence of intrabeam scattering with a bunch charge of 0.16 nC.

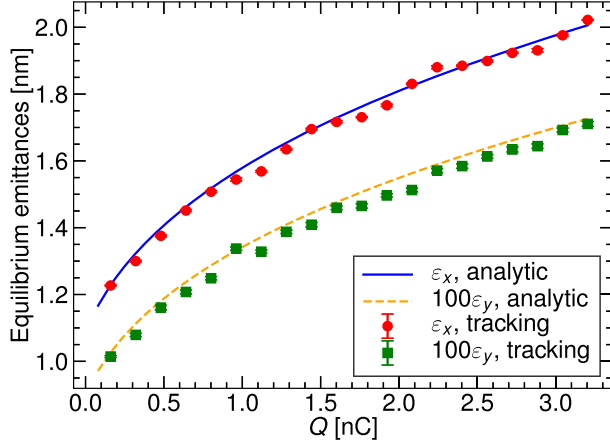


FIG. 4. Equilibrium emittances evaluated by numerical calculation in the presence of synchrotron radiation and IBS and tracking with one-turn damping and excitation matrices.

generator was developed based on selective area diffraction (SAD) [26]. It initially included only the BGS process [21,27] and has now been expanded to treat also Touschek scattering.

In contrast to the BGS process, Touschek scattering depends on the local particle density inside the beam volume. To reproduce the operational emittances, vertical dispersion and xy coupling are deliberately introduced through local-dispersion bumps and rotations of quadrupoles in the straight sections, respectively, as depicted in Fig. 3. The corresponding sextupole families control chromaticity, while the beta-beat and horizontal-dispersion errors are ignored. For a high-intensity beam, the equilibrium emittance could be significantly diluted because of the intrabeam scattering process and is numerically approached through the beam-envelope method [28,29], as shown in Fig. 4.

Both elastic and inelastic scatterings between particles and nuclei of the residual gas have been included, as described in Refs. [21,27]. For the sake of simplicity, a uniform gas pressure with CO as the major gas component was assumed. For the Touschek effect, the theory established by Piwinski [30] has been employed to evaluate momentum transformations concerning two-dimensional (2D) particle distributions and variations of beam envelopes in the presence of nonzero dispersion. Piwinski's formulas determine the probability of collisions that result in relative longitudinal momentum changes larger than a minimum acceptance using a Moller scattering cross section. In the LAB frame, the total cross section is given by

$$\sigma = \frac{\pi\gamma_e r_e^2}{2\gamma^2} \left[\left(3 - \frac{2}{\beta^2} - \frac{1}{\beta^4} \right) \log \left(\frac{\gamma\chi}{\delta_m} \right) + \left(1 + \frac{1}{\beta^2} \right)^2 \frac{\gamma^2 \chi^2 - \delta_m^2}{\delta_m^2} - \frac{\delta_m}{\gamma\chi} + 1 \right], \quad (17)$$

where r_e is the classic electron radius, δ_m the minimum momentum perturbation, and $\tilde{\beta}$ is the relative velocity defined as

$$\tilde{\beta} = \beta\gamma\chi. \quad (18)$$

For a bunched beam with Gaussian phase-space distributions, the rate of Coulomb scattering leading to a relative longitudinal momentum perturbation of $[\Delta\delta_{\min}, \Delta\delta_{\max}]$ can be expressed as

$$R(\Delta\delta_{\min}, \Delta\delta_{\max}) = R(\Delta\delta_{\min}, \infty) - R(\Delta\delta_{\max}, \infty) \quad (19)$$

with

$$R(\Delta\delta, \infty) = \frac{r_e^2 c N_p^2}{8\pi\gamma^2 \sigma_z \sqrt{\sigma_x^2 \sigma_y^2 - \eta_x^2 \eta_y^2 \sigma_\delta^4} \tau_m} F(\tau_m), \quad (20)$$

where c is the velocity of light in vacuum, N_p is the bunch population, γ is the Lorentz factor, $\sigma_{x,y}$ is the transverse beam size, σ_δ is the energy spread, σ_z is the bunch length, and $\tau_m = \beta^2 (\Delta\delta)^2 F(\tau_m)$ is an integration over the whole beam column, as

$$F(\tau_m) = \sqrt{\pi(B_1^2 - B_2^2)} \tau_m \int_{\tau_m}^{\infty} \left[\left(2 + \frac{1}{\tau} \right)^2 \left(\frac{\tau/\tau_m}{1+\tau} - 1 \right) + 1 - \sqrt{\frac{1+\tau}{\tau/\tau_m}} - \frac{1}{2\tau} \left(4 + \frac{1}{\tau} \right) \log \left(\frac{\tau/\tau_m}{1+\tau} \right) \right] \times e^{-B_1 \tau} I_0(B_2 \tau) \frac{\sqrt{\tau} d\tau}{\sqrt{1+\tau}} \quad (21)$$

with

$$B_1 = \frac{\beta_x^2}{2\beta^2 \gamma^2 \sigma_{x\beta}^2} \left(1 - \frac{\sigma_h^2 \eta_x^2}{\sigma_{x\beta}^2} \right) + \frac{\beta_y^2}{2\beta^2 \gamma^2 \sigma_{y\beta}^2} \left(1 - \frac{\sigma_h^2 \eta_y^2}{\sigma_{y\beta}^2} \right),$$

$$B_2^2 = B_1^2 - \frac{\beta_x^2 \beta_y^2 \sigma_h^2}{\beta^4 \gamma^4 \sigma_{x\beta}^4 \sigma_{y\beta}^4 \sigma_\delta^2} (\sigma_x^2 \sigma_y^2 - \eta_x^2 \eta_y^2 \sigma_\delta^4),$$

$$\frac{1}{\sigma_h^2} = \frac{1}{\sigma_\delta^2} + \frac{\beta_x \mathcal{H}_x}{\sigma_{x\beta}^2} + \frac{\beta_y \mathcal{H}_y}{\sigma_{y\beta}^2},$$

$$\tau = \beta^2 \gamma^2 \chi^2, \quad (22)$$

where I_0 is the modified Bessel function, and $\sigma_{x\beta, y\beta}$ the horizontal and vertical betatron beam sizes. The resulting momentum perturbations are applied to the core particles, generated randomly based on the equilibrium beam matrices. The local scattering rate is determined considering both the local beam parameters and the distance to the closest upstream element. It should be noted that these calculations assume a significant longitudinal momentum change, and as such, it is important to choose the value of $\Delta\delta$ carefully.

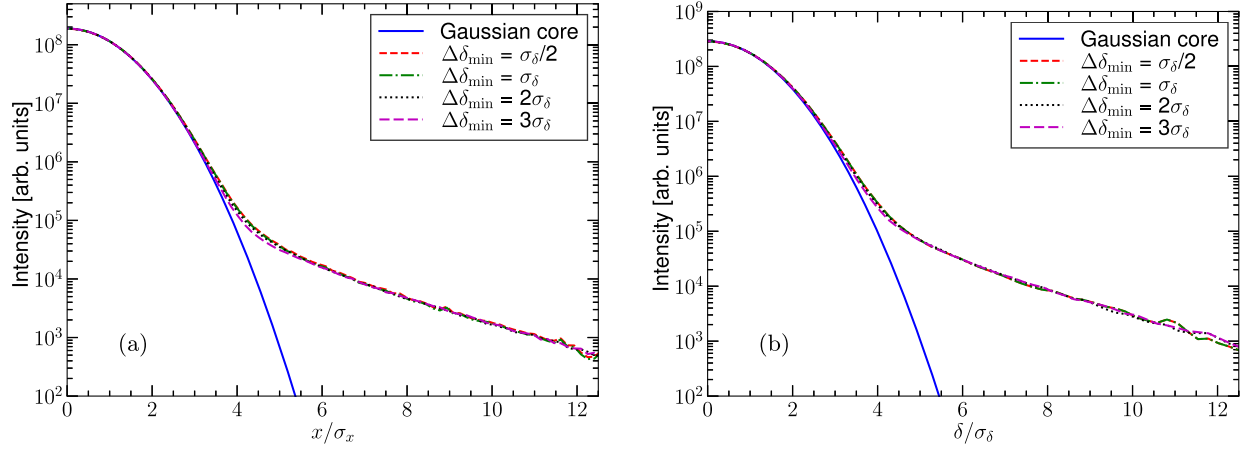


FIG. 5. Evaluations of horizontal (a) and momentum (b) halos versus the bottom limit of the momentum change ($\Delta\delta_{\min}$) in the Touschek-scattering process.

The one-dimensional (1D) halo distributions for different minimum momentum changes ($\Delta\delta_{\min}$), from $\sigma_\delta/2$ to $3\sigma_\delta$, have been evaluated and compared, as shown in Fig. 5. The choice of $\Delta\delta_{\min}$ mainly affects the non-Gaussian tails in the

$3 - 6\sigma_{x,\delta}$ region, where $\sigma_{x,\delta}$ denotes the horizontal beam size or the energy spread. Here, the minimum momentum change has been set as $1\sigma_\delta$ for the following concerns: the horizontal and longitudinal tails in the $3 - 6\sigma_{x,\delta}$ region

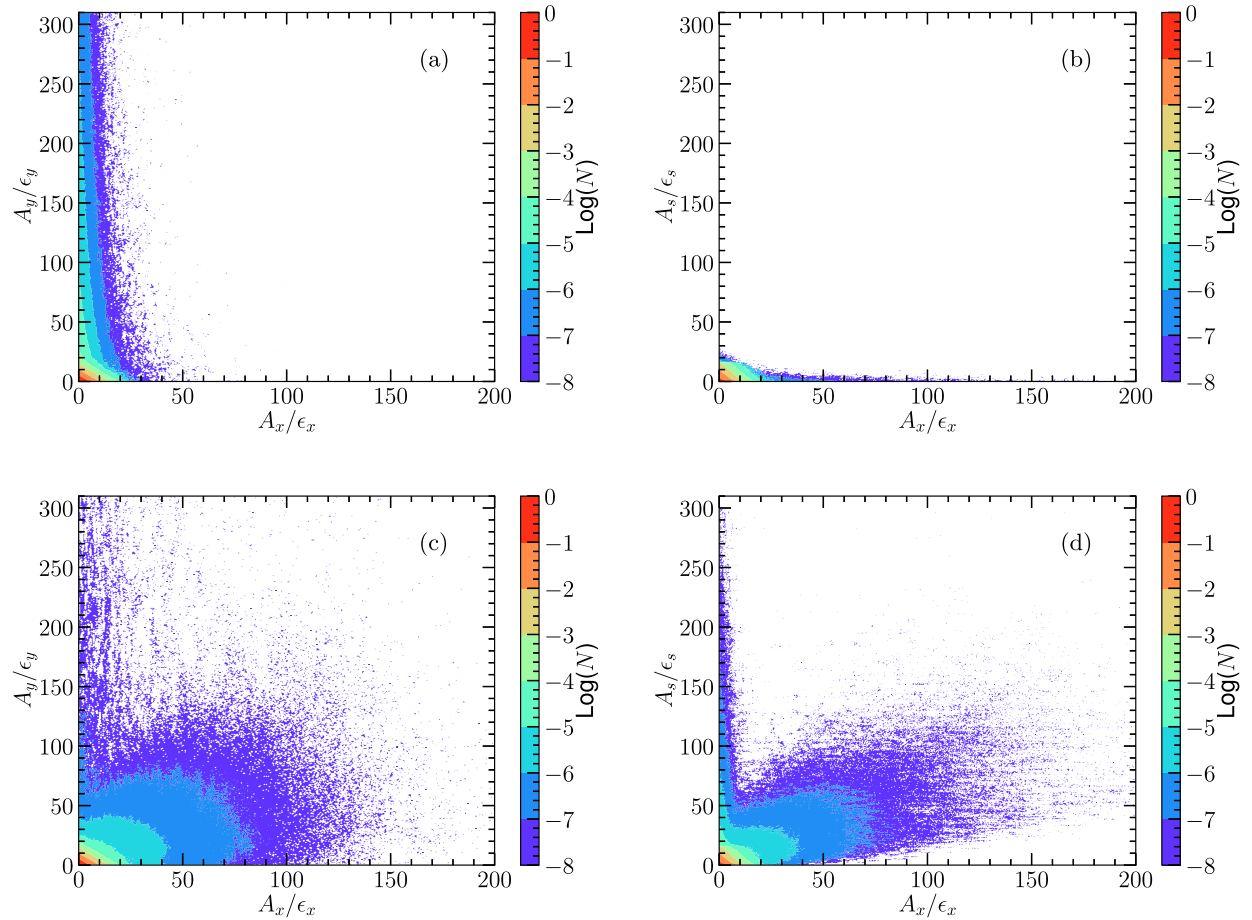


FIG. 6. Two-dimensional beam halos in the presence of different scattering processes: beam-gas scattering (a),(b) and Touschek scattering (c),(d). The equilibrium vertical, horizontal, and longitudinal emittances are 14.0 pm, 1.4 nm and 4.1 μm , respectively, for a bunch charge of 0.48 nC. Moreover, a uniform gas pressure of 2×10^{-7} Pa has been assumed for the BGS process.

increase by 5.1% and 1.8% as maximum, respectively, when further reducing $\Delta\delta_{\min}$ from $1\sigma_\delta$ to $\sigma_\delta/2$ that, on the other hand, requires 2 times more computing time. Moreover, the maximum perturbation should be larger than the momentum acceptance ($\sim 1.2\%$) since some large off-momentum particles might survive for a few turns and slip into the adjacent rf bucket. For simplicity, the transverse heating because of momentum transfers is not included, and therefore, the transverse diffusion takes place only in the dispersive regions.

Scattered particles are tracked element-by-element using the default symplectic tracking routine of SAD. Radiation damping and diffusion from quantum excitation and IBS are applied on a turn-by-turn basis using the corresponding 6×6 excitation matrices. In the ATF damping ring, transverse emittances evaluated analytically are in agreement with the tracking results applying the common excitation matrices, as shown in Fig. 4. The scattered particles are typically generated and tracked for about 40 ms ($\sim 10^5$ turns) to reach equilibrium. At beam extraction, the particles are then transported to the diagnostic location through the ATF2 extraction line. Besides, the randomness of quantum and IBS fluctuation allows one to accumulate halo particles over the last few turns for sufficient statistics with a reasonable computing time. The complete distributions are combinations of the scattered particles (more than 1×10^9) and the core particles obtained through tracking in parallel.

The distribution of halo particles in 2D in the presence of both BGS and Touschek-scattering processes has been evaluated and is illustrated in Fig. 6. The simulations demonstrate significant horizontal and momentum halos resulting from the Touschek process, while the BGS process mainly governs the formation of the vertical halo. The beam-gas scattering process is primarily elastic, leading to significant vertical halos compared to the horizontal and longitudinal dimensions, as depicted in Figs. 6(a) and 6(b). Touschek-scattering events in the dispersive region contribute to the transverse halos, while those in the dispersion-free region form only longitudinal halos. Because of the nonzero horizontal and vertical dispersions in the arcs, transverse halos induced by the Touschek process are correlated, as shown in Fig. 6(c). In the straight sections, the horizontal dispersion is small, and some longitudinal halos are not coupled into the horizontal plane, as depicted in Fig. 6(d). Moreover, both 1D and 2D distributions show visible halos up to $10\sigma_{x,\delta}$, demanding an instrumentation capable of detecting halos at the level of 10^{-5} of the peak core intensity for the experimental observations.

IV. MEASUREMENTS

A. Experimental setup

There are three types of halo monitors along the ATF2 beamline: wire scanner (WS), *in-vacuum* diamond-sensor

(DS) scanner, and combined yttrium aluminum garnet (YAG)/optical transition radiation (OTR) monitor. The transverse profiles measured by a carbon wire have been extended with varying voltage of the photomultiplier tube. Experiments performed at ATF2 have established a dynamic range of about 10^4 , limited by the remaining background because of beam loss along the ATF2 beamline. The DS scanner has four chemical-vapor-deposition single-crystal strips on a ceramic printed circuit board. Aiming to obtain a higher dynamic range, two narrow strips of $0.1 \times 4 \text{ mm}^2$ and two broad ones of $1.5 \times 4 \text{ mm}^2$ for the core and halo measurements, respectively, have been designed. Because of the space-charge effect inside the diamond crystal bulk and the instantaneous voltage drop at the resistor, the readout signal can be significantly distorted when the diamond strip travels into the core region. To overcome such issues, a rescaling scheme based on additional calibration using an adjacent wire scanner has been implemented to reconstruct the core profile. In addition, an effective dynamic range of 10^5 has been eventually obtained [21]. Halo diagnostics using the DS scanner is time-consuming (about 30 min) to meet the required resolution and accuracy.

For fast halo diagnostics, a combined YAG/OTR monitor has been developed and installed in the extraction line of ATF [31]. The favorable scintillating properties of cerium-doped YAG, for instance, the high photon yield (about $2 \times 10^4 \text{ ph/MeV}$), fast emission decay (decay time constants of 88 and 300 ns), mechanical rigidity, and radiation hardness, have made it one popular scintillator for two-dimensional imaging of energetic charged particles and photons, especially low-density particle distributions. On the other hand, the scintillation saturation of Ce:YAG from more densely populated incident beams must be avoided or compensated for by supplementary diagnostics. Following these considerations, four 0.5 mol% Ce:YAG screens with a central rectangular opening for visualizing core and halo

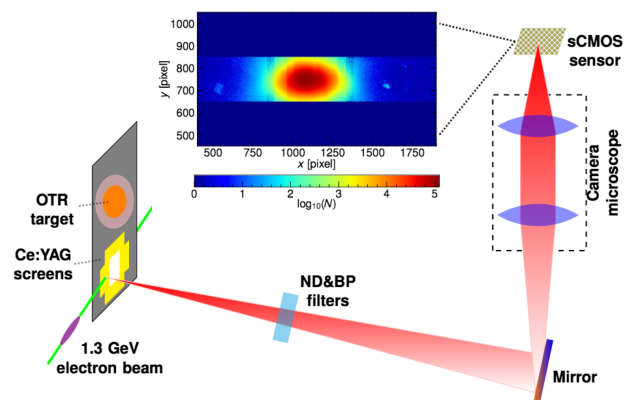


FIG. 7. Schematic of the YAG/OTR monitor, including a 2D core-halo image obtained through horizontal scanning of the left and right YAG pads. The glare in the halo region is from dust on the screen.

profiles and an OTR target providing supplementary visualization of the dense beam core have been constructed. Scintillation light and transition radiation can be alternately collected through a fused silica viewport and focused on the camera sensor, as depicted in Fig. 7. The YAG pads and rectangular opening sizes are $4 \times 6 \times 0.1 \text{ mm}^3$ and $4 \times 2.4 \text{ mm}^2$, respectively. The OTR target consists of an aluminum kapton of $2 \text{ }\mu\text{m}$ thickness seated in a titanium conical receptacle, leaving an exposed area of 7 mm diameter. The screens are placed on a holder actuated by an automatic manipulator. For halo imaging, one must adjust the YAG pads to allow core particles to pass through the central opening. In this way, the diffraction fringe surrounding the bright beam-core image, approximately $10^{-3} - 10^{-2}$ of the peak of the image, could be avoided. The YAG and OTR screens are at 45° and 67.5° to the beam trajectory, respectively, to collect scintillating and backward OTR light with a common optical system comprising neutral-density filters, a microscope lens, and a 16-bit cooled complementary metal-oxide-semiconductor (sCMOS) camera. The optical system is -45° to the beam direction and perpendicular to the YAG screen. In the sequence, the depth-of-field limitation of the microscope is loosened to 0.13 mm . Considering the size of the camera sensor ($13.3 \times 13.3 \text{ mm}^2$) and the required field of view ($10\sigma_{x,y}$), the magnification factor of the microscope lens was set at $2.5-3$, which is determined by correlating the observed holder edge movement versus the manipulator position readout. The backlash and readout accuracy of the four-dimensional manipulator ($\vec{x}$, $\vec{y}$, $\vec{z}$, and rotation around $\vec{z}$ axis) were found to be about $13.5 \text{ }\mu\text{m}$ and less than $0.2 \text{ }\mu\text{m}$, respectively, which allows precise determination of the magnification factor. Besides, an interface has been developed in Python for data acquisition and remote control.

The lower limit of the dynamic range is primarily determined by three factors: the photon yield (PhY) of the Ce:YAG, the photon collection efficiency, and the background noise. The YAG scintillation saturation sets an upper limit to the dynamic range, which the OTR screen can further improve. Monte Carlo simulations in MCNPX predict that energy deposition inside the YAG pad is about $0.1-0.12 \text{ MeV/e}$ for a beam energy of 1.3 GeV . Assuming a PhY of $2 \times 10^4 \text{ ph/MeV}$, the photon emission is estimated at $2000-2500 \text{ ph/e}$, and the photon collection is evaluated as $0.32-4 \text{ ph/e}$. This estimation considers a light transmission of around 85% in the optical observation system and an effective observation angle of 6.2 mrad . Notice that the refraction of light exiting the YAG screen induces a smaller observation angle, which can be evaluated as [32]

$$\theta' = \arcsin(n_1/n_2 \sin \theta), \quad (23)$$

where n_1 and n_2 are the refractive indices of vacuum and YAG, respectively, and θ is the acceptable angle of the observation system. The sCMOS camera was placed at

300 mm above the beamline to reduce the beam-induced background. However, noise from the camera sensor is unavoidable, dependent on its temperature (10°C with the cooling system), the exposure mode, and the exposure time. Typically, the camera was operated in the rolling shutter mode with an exposure time of 10 ms . A nonuniform noise level for each pixel has been observed with a noise level of less than one digital count, as shown in Fig. 8. Subtracting a constant noise level, the residual background level was found to be less than 0.5 count/pixel , i.e., 0.33 ph/pixel in terms of the nominal quantum efficiency of 70% and the A/D conversion of 0.46 e/count . To obtain a signal-to-noise ratio larger than 3, at least one incident photon on a single pixel, i.e., a minimum particle density of 4 electrons over one pixel-equivalent size on the YAG screen, is required. The maximum particle density in the absence of scintillation saturation is characterized by the saturation threshold, which is challenging to quantify analytically. Therefore, experimental measurements of the saturation threshold have been conducted at KEK-ATF. During quadrupole scanning, beam sizes and fluxes of scintillation light were measured to determine the saturation threshold by the

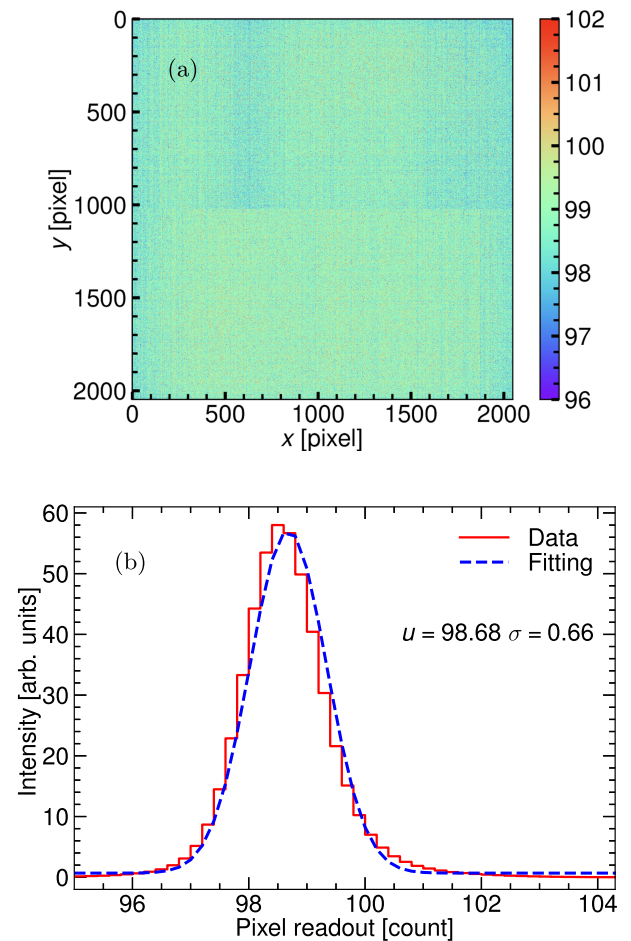


FIG. 8. A background image (a) and the histogram of dark count (b) in the rolling shutter mode with an exposure time of 10 ms .

maximum local particle density (at the beam center) at the transition between saturation and no saturation. Here, the beam core is always assumed to be distributed according to a Gaussian function. For a beam intensity of 3×10^9 e/pulse, the flux of collected scintillating light tends to remain constant (around 1.2×10^9 photons) when the vertical beam size is large. Then, it decreases because of scintillation saturation when focusing the vertical beam size down to $40 \mu\text{m}$, as shown in Fig. 9. The saturation threshold is therefore found to be $16\text{--}18 \text{ fC}/\mu\text{m}^2$. Correspondingly, for a magnification factor of 2.5, the effective particle density is expected to be about 4.8×10^5 e/pixel without saturation, which implies a dynamic range of approximately 1×10^5 imaging with YAG screens.

To avoid blooming effects, halo distributions are measured through one-dimensional scans of the YAG pads. After taking a picture of the halo far from the beam core, the YAG pads are moved toward the beam core step by step, and images are captured with light attenuation at each step. Then, sliced halo images at different distances to the center are cut out by trimming the parts near the inner edge of the

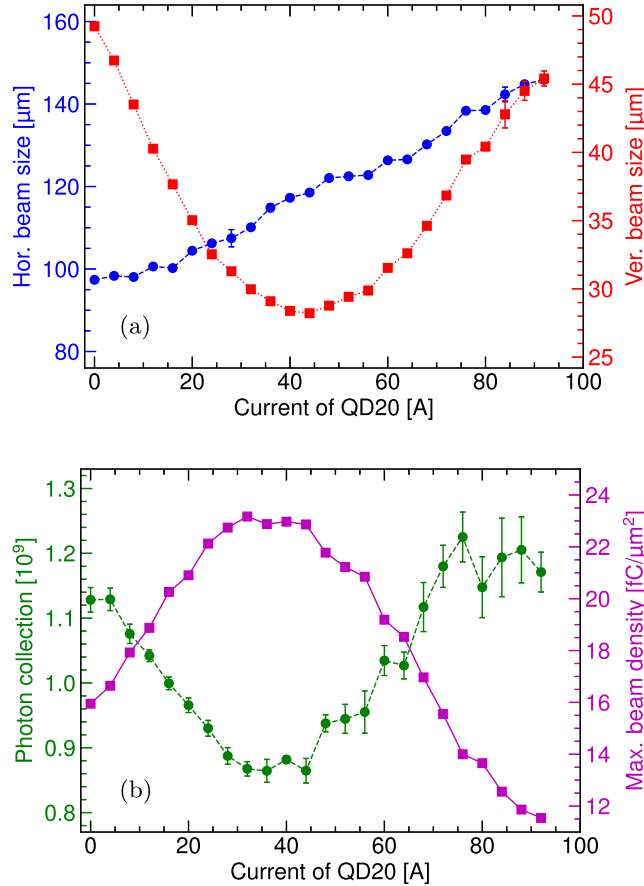


FIG. 9. Evolution of vertical and horizontal beam sizes (a), number of collected photons and maximum beam density (b) as a function of the upstream quadrupole (QD20) current. Notice that the saturation threshold is given by the maximum particle density at 75 A.

YAG, overlapping with preceding images. Eventually, a complete core-halo distribution is obtained by combining the core and the sliced halo images of the two sides, as illustrated in Fig. 7. Owing to this scanning procedure, vertical and horizontal profiles have to be captured individually. Using solely the YAG screens, a dynamic range of about 1×10^5 , limited by the photon-yield efficiency of the scintillator, background noise, and scintillation saturation, has been demonstrated.

B. Vertical dispersion bump

For the observation of the momentum halo, the optical dispersion at the diagnostic point must be modulated to dominate the transverse beam profile. To characterize the resolution of the momentum visualization, the least distinguishable energy spread can be roughly assessed as

$$\delta_{\min} = 2\sqrt{\varepsilon_{x,y}\beta_{x,y}/\eta_{x,y}}, \quad (24)$$

where $\varepsilon_{x,y}$ is the transverse emittance. Apparently, a small $\sqrt{\beta}/\eta$ ratio, which can be realized through careful tuning of linear beam optics, will be necessary to improve the momentum resolution. For the ATF2 beam, the vertical emittance is typically only 1% of the horizontal emittance, and the visualizations in the “vertical” plane will be favored. As a result, the YAG/OTR monitor has been placed downstream of a dogleg inflector in the extraction line. A large vertical dispersion ($> 200 \text{ mm}$) can be easily generated using two skew-quadrupoles, named QS1X and QS2X, located in the dogleg where the horizontal dispersion reaches its largest absolute values ($\sim 0.6 \text{ m}$) but with opposite signs, as shown in Fig. 10. Thanks to the appropriate phase advances between the two skew-quadrupoles (2π and π for the horizontal and vertical planes, respectively), a small β -function ($\sim 4 \text{ m}$) at the

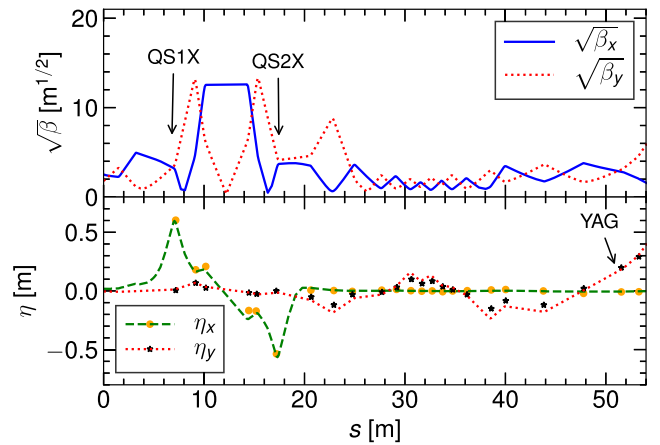


FIG. 10. Beta-function and dispersion along the extraction line. The colored marks represent the experimental data, and the lines denote the model optics. QS1X and QS2X are the skew-quadrupoles for vertical-dispersion control.

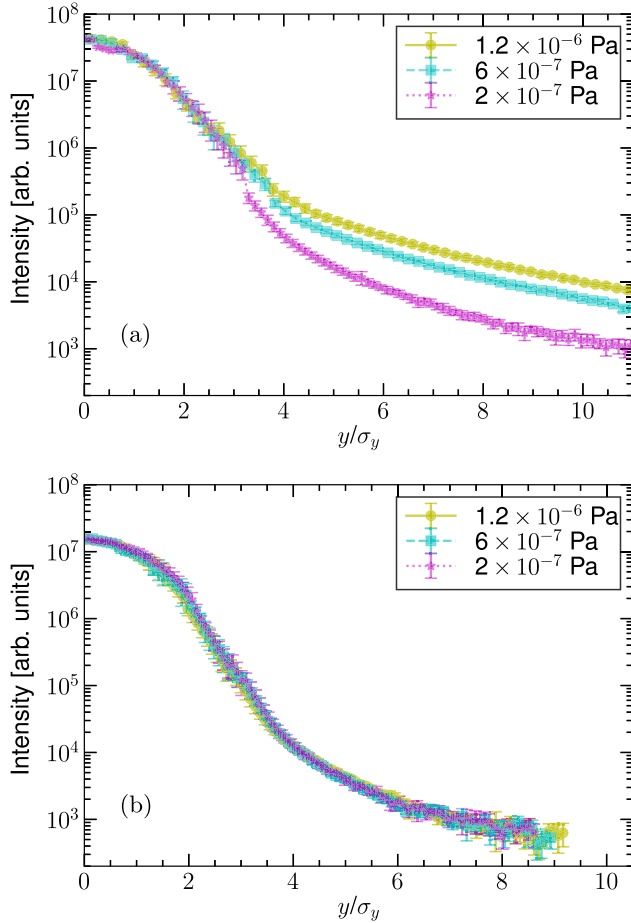


FIG. 11. The normalized vertical distribution at the YAG/OTR monitor for a vertical dispersion of 50 mm (a) and 200 mm (b).

observation point can be well preserved while manipulating the downstream vertical dispersion. Regarding the typical ATF2 beam parameters, tracking simulations have suggested a vertical dispersion of more than 160 mm for picturing the momentum spectrum. In reality, through the comparisons of the “vertical” profiles predicted by the tracking simulation and observed by the YAG/OTR monitor, especially the observations of vacuum dependency with different vertical dispersions, we have concluded that a vertical dispersion of above 200 mm would offer the expected representation of the momentum spectrum. As shown in Fig. 11, the halo levels are almost proportional to the vacuum pressure for a vertical dispersion of about 50 mm and show insignificant vacuum dependence when the vertical dispersion is increased to about 200 mm.

C. Transverse and longitudinal halos

The vertical halo was already shown in a previous study to be primarily driven by the elastic BGS process [21]. Therefore, only the horizontal and momentum halo measurements are presented here.

As shown in Figs. 12(a) and 12(b), the measured horizontal halos are in reasonable agreement with the simulations for varying gas pressures ($2 \times 10^{-7} - 1.2 \times 10^{-6}$ Pa) and bunch charges (0.16–0.96 nC). Although the DR vacuum level has a negligible impact on horizontal halos, a higher bunch charge significantly enhances them. The measurements only extend to $8-10\sigma$ because of background noise near the edges of the camera sensor. It is apparent that measurements away from the beam core are already noisy, especially for low bunch charges. The relative residuals of horizontal halos have also been evaluated, and the average of relative residuals for horizontal halos in the $4-8\sigma_x$ region is below 11%, as indicated in Table II. Notice that the relative residual is the ratio of the deviation of the observed value to the expected value.

The momentum halos are imaged in the vertical plane with a vertical dispersion of about 200 mm at the YAG/OTR monitor. The potential impact of the vertical betatron halo requires a thorough evaluation. The observations at two different gas pressures (2×10^{-7} and 1.2×10^{-6} Pa) show good agreement with numerical simulations and insignificant correlation with the gas pressure, as shown in Fig. 12(c). The averages of relative residuals over the $4-8\sigma_\delta$ region are 2% and 31% for the two gas pressures, respectively, as shown in Table III. These presences indicate a negligible contribution from the vertical betatron halo that has been verified to be proportional to the DR gas pressure. Although the observations suggest a weaker intensity dependence than the numerical predictions, but the observed trends are consistent, as shown in Fig. 12(d). The averages of relative residuals over the $4-8\sigma_\delta$ region are -11% , -30% , and -24% for bunch charges of 0.32, 0.64, and 1.12 nC, respectively, as shown in Table III. Because of a limited sensitivity of the YAG/OTR monitor, the obtained momentum halos at low bunch charges (< 0.32 nC) exhibit visible fluctuations.

The congruence between measurements and simulations, along with the anticipated dependencies on gas pressure and bunch charge, strongly indicates Touschek scattering as the predominant factor contributing to the formation of horizontal and momentum halos. Because of the intrinsic differences between real machines and their corresponding lattice models, perfect consistency between experimental measurements and simulation predictions may not be directly achieved on the real machine. The residual discrepancies between predictions and observations might be attributed to the systematic uncertainty related to the instrumentation and the modeling of the particle beam. The instrumentation-related uncertainty can plainly be seen in the observed halos far from the beam center, especially at a low bunch charge. In addition, the numerical predictions could be influenced by other factors, such as the modeling of the high-order multipoles in the ring lattice, uncertainties in vertical emittance measurements, and ambiguities in mimicking the realistic machine parameters. To assess the

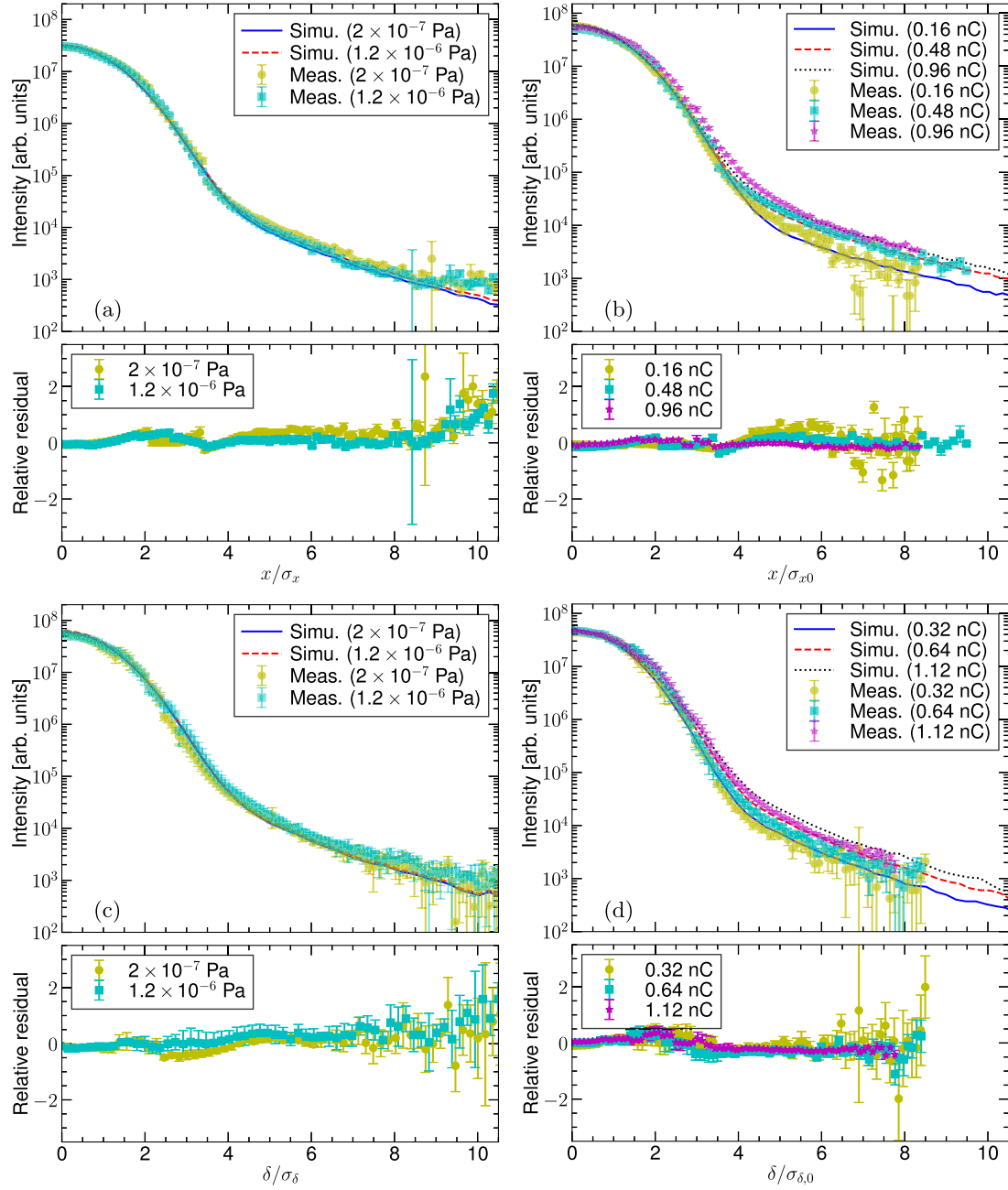


FIG. 12. Normalized horizontal (a),(b) and momentum (c),(d) halos for different gas pressures and bunch charges. Notice that a bunch charge of 0.48 nC is used for the vacuum-dependence studies. $\sigma_{x,0}$ represents horizontal beam size for a bunch charge of 0.48 nC and $\sigma_{\delta,0}$ is the energy spread at a bunch charge of 0.32 nC.

TABLE II. Averaged relative residual of the observed horizontal halos over the 4–8 σ_x region.

Pressure (Pa)	Bunch charge (nC)	Averaged relative residual (%)
2×10^{-7}	0.16	11
	0.48	8
	0.96	–10
1.2×10^{-6}	0.48	4

TABLE III. Averaged relative residual of the observed momentum halos over the 4–8 σ_δ region.

Pressure (Pa)	Bunch charge (nC)	Averaged relative residual (%)
2×10^{-7}	0.32	–11
	0.64	–30
	1.12	–24
1.2×10^{-6}	0.48	31

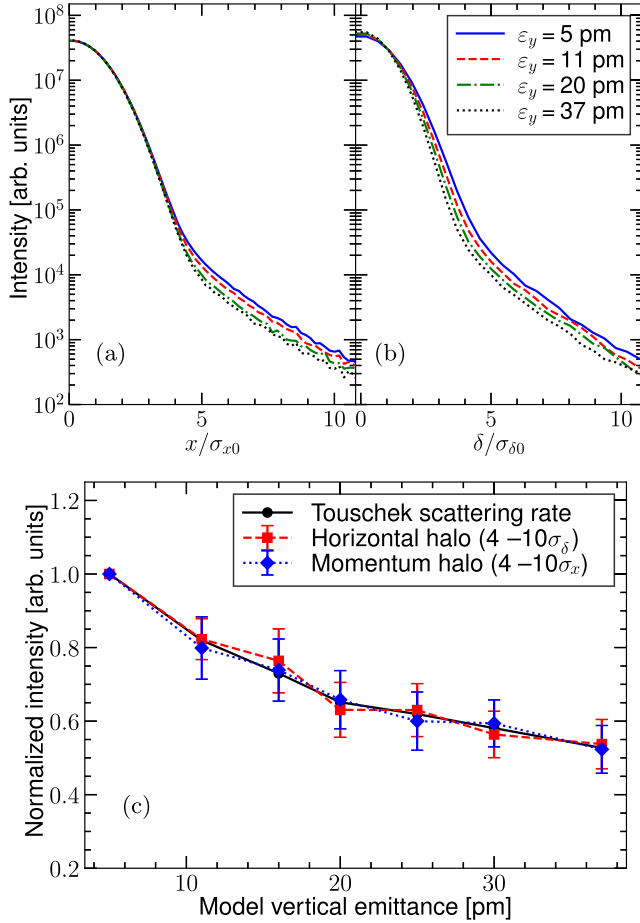


FIG. 13. Horizontal and momentum halos (a),(b), and summed halo intensity over the $4-10\sigma$ region (c) versus the model vertical emittances for a bunch charge of 0.96 nC. σ_{x0} and $\sigma_{\delta 0}$ are horizontal beam size and momentum spread, respectively, for a vertical emittance of 11 pm.

influence of the vertical emittance measurement error, the horizontal and momentum halos are simulated for the equilibrium vertical emittances ranging from 5 to 40 pm. Here, the model vertical emittance was approached by adjusting the xy coupling. For an equilibrium emittance of 10–20 pm, the horizontal and momentum halos in the $4-10\sigma_x$ and $4-10\sigma_\delta$ regions fluctuate by about 10% for an emittance measurement error of 5 pm, as shown in Fig. 13. The relative halo level change is coincident with the variance of Touschek-scattering rate ($\Delta\delta_{\min} \approx 0.2\%$), as shown in Fig. 13(c). More comprehensive measurements of emittances, bunch length, and energy spread are needed as input to the simulations to improve the comparisons with the measurements.

V. CONCLUSION

The distribution and origin of the horizontal and momentum halos have been theoretically and experimentally studied for the KEK-ATF. To this end, a halo generator

containing diffusions, BGS, and Touschek-scattering processes has been developed in a simulation approach based on realistic operational beam parameters. Moreover, a combined YAG/OTR monitor has been designed and installed to measure the vertical, horizontal, and momentum halos with a dynamic range of 10^5 . The momentum spectrum is imaged in the vertical plane, where a vertical dispersion of about 200 mm is introduced by paired skew quadrupoles located in the dogleg and exhibits an unprecedented dynamic range of 10^5 . The reasonable consistencies between observations and simulations for various gas pressures and bunch charges indicate that the Touschek scattering dominates horizontal and momentum halos. These observations provide a reliable benchmark of the halo generator and validate its applicability to future lepton colliders and modern synchrotron radiation light sources. Some observed residual discrepancies might be attributed to the systematic uncertainty related to the instrumentation and the modeling of the particle beam. Further simultaneous measurements of emittances and beam halos employing an improved monitor with a higher dynamic range at the controlled vertical emittance would be suggested. Recommendations for the future enhancement of the YAG/OTR monitors include the replacement of the sCMOS camera with an ultrasensitive qCMOS camera, optimization of the dark room, and the subtraction of the background noise using machine-learning-based techniques.

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