

Evaluation of wakefield effects caused by the orbit fluctuation on nanometer scale beams at the Accelerator Test Facility

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Future electron-positron linear colliders require extremely small beam sizes at the interaction point (IP) to achieve high luminosity. The Accelerator Test Facility (ATF) at KEK has been developed to demonstrate the required beam focusing scheme, achieving a vertical size of 37 nm at the virtual IP using a low-emittance beam generated in a damping ring. However, as nanometer scale focusing requires specialized optics, even small kicks in the beamline can lead to significant distortions at the IP. Transverse wakefield effects have previously been observed as beam size growth with increasing bunch intensity and have been primarily interpreted as static effects arising from orbit distortion and misalignment. Dynamic wakefield effects caused by pulse-by-pulse beam orbit fluctuations have also been suggested by previous measurements and investigated through numerical simulations; however, a direct experimental and quantitative evaluation has not been reported. In this paper, we present the first experimental and quantitative study of dynamic wakefield effects on nanometer scale beams at the ATF. Controlled orbit fluctuations were introduced using steering magnets, enabling systematic measurements over a wide range of fluctuation amplitudes without changing the beam optics configuration. The resulting beam size growth was quantitatively evaluated through both experiments and simulations incorporating all wakefield sources in the beamline. The results demonstrate that dynamic wakefield effects can significantly contribute to beam size growth and must therefore be taken into account to achieve stable nanometer scale beams in future linear colliders.

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I. INTRODUCTION

A wakefield is an electromagnetic field generated by charged particles passing through beamline structures with geometrical discontinuities and material properties, including contributions from resistive walls. The excited wakefield acts on subsequent particles in the beam, distorting their particle orbits and increasing the beam size. It is important to investigate the effects of wakefields on beams produced by advanced accelerators, such as the International Linear Collider (ILC) [1]. In these systems, low-emittance beams are focused to extremely small vertical sizes at the interaction point to maximize luminosity.

The final focus (FF) beamlines of such colliders have a special design requirement. To achieve an extremely small beta function at the final focal point, the beta function throughout most of the beamline must remain large.

Consequently, orbit fluctuations, even when small relative to the nominal beam size, can cause significant transverse orbit distortions and beam size growth at the final focal point. A detailed explanation is provided in Sec. II.

The final focus line of the Accelerator Test Facility (ATF) at KEK is designed as a prototype of the final focus of the ILC to focus the electron beam to 37 nm at the virtual interaction point (IP), utilizing the low-emittance beam (vertical emittance: 12 pm·rad) generated in a damping ring (DR). The ATF consists of a linear accelerator (LINAC), DR, extraction (EXT) beamline, and FF beamline [2,3]. Figure 1 shows the layout of the beamline after the DR. Table I shows the nominal beam parameters for a nanometer scale beam study. A low-emittance beam is generated at DR [4,5] and focused with the EXT and FF beamlines [6].

Significant beam size growth depending on the bunch intensity has been observed at the IP of the ATF. Numerous studies have investigated the effects of transverse wakefields on the beam size at the IP [7]. Wakefield effects have been primarily considered as “static wakefield effects,” defined as those arising from orbit distortion and misalignment. In addition, beam size growth has been reduced using a bunch-by-bunch feedback system that suppresses orbit fluctuation [8]. This suggests the presence of a

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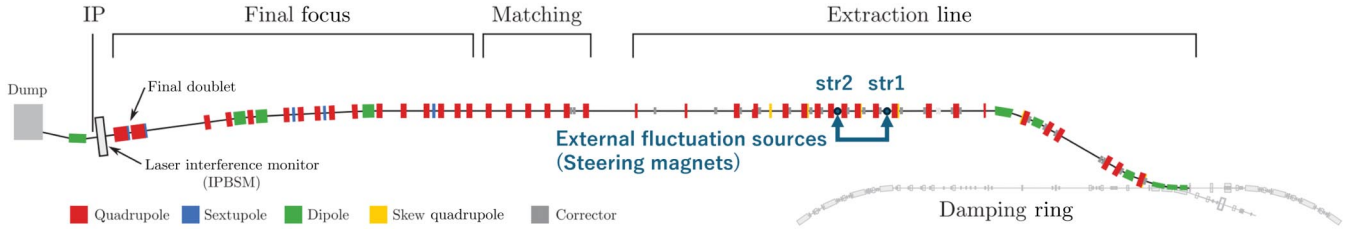


FIG. 1. Extraction and final focus beamlines after extraction from the damping ring.

“dynamic wakefield effect,” defined as the effect of wakefields excited by pulse-by-pulse beam orbit fluctuations. However, a direct quantitative evaluation of the effect has not been reported. Subsequently, both static and dynamic wakefield effects caused by major wakefield sources have been evaluated using simulations, and the impact of dynamic wakefield effects has been demonstrated at the simulation level [9]. However, these effects have not been experimentally verified. This study presents the first experimental and quantitative evaluation of dynamic wakefield effects on nanometer scale beams at the ATF. Controlled orbit fluctuations are introduced using steering magnets, enabling systematic measurements over a wide range of fluctuation amplitudes without changing the beam optics configuration. Experiments and simulations incorporating all wakefield sources in the ATF EXT and FF beamlines are conducted to quantitatively evaluate the beam size growth as a function of bunch intensity.

The remainder of this study is organized as follows. Section II formulates the wakefield effect with orbit fluctuations. Section III introduces the wakefield model and analytical estimation results. Section IV presents simulation results and evaluates the dynamic wakefield effect. Section V compares the experimental results with the simulations. Section VI concludes the study.

II. WAKEFIELD EFFECTS ON BEAMS

A. Beam size growth caused by wakefield

This study assumes no horizontal-vertical coupling in the beam motions; it considers only the vertical direction (y). The vertical wake potential is defined as the integrated fields experienced by a particle at a longitudinal position z

relative to the bunch center, which is expressed as [10]

$$W_y(y_m, z) = \frac{1}{q} \int_{s_1}^{s_2} [E_y(0, y_m, s, t) + cB_x(0, y_m, s, t)] ds, \quad (1)$$

where q is the total bunch charge; y_m is the transverse position of the bunch that excites the wakefield; z is the relative longitudinal position with respect to the center of the bunch; and $E_y(x, y, s, t)$ and $B_x(x, y, s, t)$ are the vertical electric field strength and horizontal magnetic field strength, respectively, at position (x, y, s) at time t , where $ct = s + z$. We assume an ultrarelativistic beam with a velocity equal to the speed of light, c . Here, all the particles go through the transverse position $x = 0$ and $y = y_m$ parallel to the design beamline. This is a good approximation for cases wherein the beam size and the orbit distortion are considerably smaller than the typical size of the beamline components (wakefield sources). The integration is from the entrance, s_1 , to the exit, s_2 , of a wakefield source.

The vertical angle change of a particle at a longitudinal position z with respect to the center of a bunch is expressed as

$$\Delta y'(z) = \frac{eq}{E} W_y(y_m, z), \quad (2)$$

where e is the electron charge and E is the beam energy. When the effects of all wakefield sources (index i) on the particle position at the IP are summed, the vertical position change at the IP can be expressed as

$$\Delta y_{\text{IP}}(z) = \frac{eq}{E} \sum_i W_{y,i}(y_{m,i}, z), \sqrt{\beta_{y,i}\beta_{y,\text{IP}}} \sin \Delta\phi_i, \quad (3)$$

where $W_{y,i}$ is the wake potential of the i -th wakefield source, $y_{m,i}$ is the vertical position of the bunch at the i -th wakefield source, $\beta_{y,i}$ is the beta function at the i -th wakefield source, $\beta_{y,\text{IP}}$ is the beta function at the IP, and $\Delta\phi_i$ is the phase advance from the i -th wakefield source to the IP.

The position change at the IP, $\Delta y_{\text{IP}}(z)$, depends on the relative longitudinal position of particles, z . Therefore, the wakefield effect on the beam size of a bunch at the IP can

TABLE I. Nominal beam parameters for nanometer scale beam study.

Parameter	Symbol	Unit	Value
Beam energy	E	GeV	1.3
Max. bunch population	Q	$10^9 e^-/\text{bunch}$	20
Bunch length	σ_z	mm	7
Energy spread	σ_E	%	0.08
Emittance	ε_y	pm·rad	12
Beta function at IP	β_y	mm	0.1

e^-/bunch corresponds to electrons per bunch.

be expressed as a variance of $\Delta y_{\text{IP}}(z)$ as [11]

$$\begin{aligned} \Delta \sigma_y^2 = & \left(\frac{eq}{E} \sqrt{\beta_{y,\text{IP}}} \right)^2 \\ & \times \left[\int_{-\infty}^{\infty} \left\{ \sum_i W_{y,i}(y_{m,i}, z) \sqrt{\beta_{y,i}} \sin \Delta \phi_i \right\}^2 \lambda(z) dz \right. \\ & \left. - \left\{ \int_{-\infty}^{\infty} \sum_i W_{y,i}(y_{m,i}, z) \sqrt{\beta_{y,i}} \sin \Delta \phi_i \lambda(z) dz \right\}^2 \right], \end{aligned} \quad (4)$$

where $\lambda(z)$ is the normalized longitudinal electron density of the bunch ($\int \lambda(z) dz = 1$).

B. Wakefield effects caused by the orbit fluctuation

This section describes the wakefield effects that occur with pulse-by-pulse beam orbit fluctuations. The beam orbit can be expressed as a summation of two phase components. The vertical position at an arbitrary location (index i) is expressed as

$$y_i = \sqrt{\beta_{y,i} \beta_{y,\text{IP}}} \left(\frac{A_{\text{posi}}}{\beta_{y,\text{IP}}} \cos \Delta \phi_i - A_{\text{angl}} \sin \Delta \phi_i \right), \quad (5)$$

where A_{posi} is the “position at IP” phase orbit, A_{angl} is the “angle at IP” phase, and ϕ_i is the phase advance from location i to the IP.

For cylindrically symmetric structures, the wake potential $W_y(y_m, z)$ is approximately proportional to the beam offset y_m when y_m is small relative to the structure size. Thus, we introduce the normalized wake potential $V_y(z)$ and use an approximation,

$$W_{y,i}(y_{m,i}, z) \approx y_{m,i} V_{y,i}(z). \quad (6)$$

Substituting Eq. (5) into $y_{m,i}$ of Eq. (3) and using this approximation, we obtain

$$\begin{aligned} \Delta y_{\text{IP}}(z) = & \frac{eq}{E} \beta_{y,\text{IP}} \sum_i V_{y,i}(z) \beta_{y,i} \\ & \times \left(\frac{A_{\text{posi}}}{\beta_{y,\text{IP}}} \cos \Delta \phi_i \sin \Delta \phi_i - A_{\text{angl}} \sin^2 \Delta \phi_i \right). \end{aligned} \quad (7)$$

The contribution of each wakefield source is proportional to the beta function at its location. To achieve an extremely small beam size, as shown in Fig. 2, regions with very large beta functions are introduced, and the phase advance from these regions to the IP is approximately $(n + 1/2)\pi$. Therefore, the approximations $\cos \Delta \phi_i \approx 0$ and $\sin \Delta \phi_i \approx \pm 1$ can be applied. Consequently, the term proportional to A_{posi} becomes negligibly small and

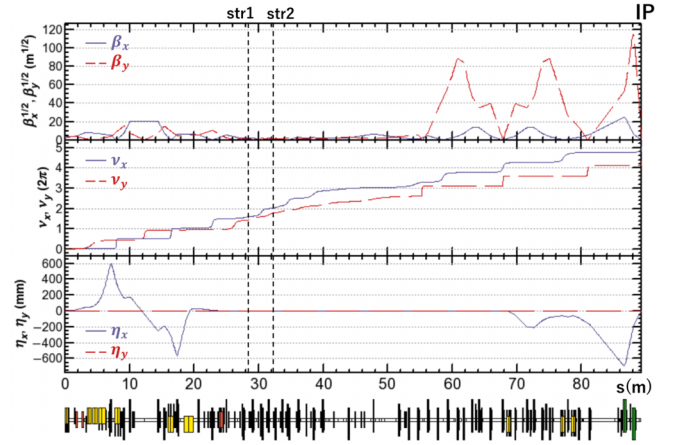


FIG. 2. ATF nominal optics of EXT and FF beamlines for nanometer scale beam study, where $(\beta_x, \beta_y) = (40, 0.1)$ mm.

$$\Delta y_{\text{IP}}(z) \approx -A_{\text{angl}} \frac{eq}{E} \beta_{y,\text{IP}} \sum_i V_{y,i}(z) \beta_{y,i}. \quad (8)$$

The beam size is measured as a projection of many pulses, as described in Sec. IV B; hence, the effect of wakefield on the beam size is evaluated as the variance of the position changes of all particles at the IP with different z values over multiple pulses. If random orbit fluctuations are assumed, A_{angl} follows a Gaussian distribution with the root-mean-square (rms) of σ_A :

$$\Delta \sigma_y^2 \approx \left(\frac{eq}{E} \beta_{y,\text{IP}} \right)^2 \sigma_A^2 \int_{-\infty}^{\infty} \left\{ \sum_i V_{y,i}(z) \beta_{y,i} \right\}^2 \lambda(z) dz. \quad (9)$$

In this section, we described the dynamic wakefield effect and showed the following: (i) Only the beam angle at IP phase orbit fluctuation is important; the beam position at IP phase is not significant. (ii) The effect is estimated by the sum of products of the normalized wake potentials and the beta functions at the wakefield sources, i.e., $\sum_i V_{y,i}(z) \beta_{y,i}$.

III. EVALUATION OF WAKEFIELD SOURCES IN EXT AND FF BEAMLINES

A. Wakefield sources at ATF beamline and wakefield calculation using 3D models

Table II lists wakefield sources, such as vacuum components, beam position monitors (BPMs), and collimators, in the EXT and FF beamlines and the number of installations for each.

Figure 3 shows the internal structure (vacuum region) of the bellows. The bellows comprise pipes with a diameter of 23.9 mm, matching the inner diameters of the beam pipe on both sides, and 40 steps with an outer diameter of 38 mm. Shielding parts are inserted in some components in

TABLE II. Wakefield sources in ATF EXT and FF beamlines.

Name	Location	Amount
Vacuum port	EXT	15
Bellows	EXT	34
Optical transition radiation monitor	EXT	4
Septum magnet chamber	EXT	3
Stripline BPM	EXT	12
Stripline kicker	EXT	2
Rectangular chambers	EXT	4
Vacuum flange (ICF70)	EXT, FF	223
Reference cavity	EXT, FF	2
Cavity BPM (CBPM)	EXT, FF	25
Gate valve	EXT, FF	3
Stripline BPM	FF	1
Shielded vacuum flange (ICF70)	FF	20
Shielded bellows	FF	34
Shielded vacuum port	FF	13
Manual gate valve	FF	1
Collimator	FF	1
Wakefield corrector	FF	1
Wakefield Study chamber	FF	1
Vacuum flange (ICF114)	FF	12
Vacuum port (ICF114)	FF	2

EXT: Extraction beamline; FF: Final focus beamline.

the FF beamline that are identified as strong wakefield sources. For example, a radio frequency (rf) shield, which is in contact with the inner wall of the bellows, is inserted into bellows, as shown in Fig. 3, to shield the steps from the traveling electron beam.

We calculated the wake potential of each wakefield source using GdfidL, an electromagnetic field simulation

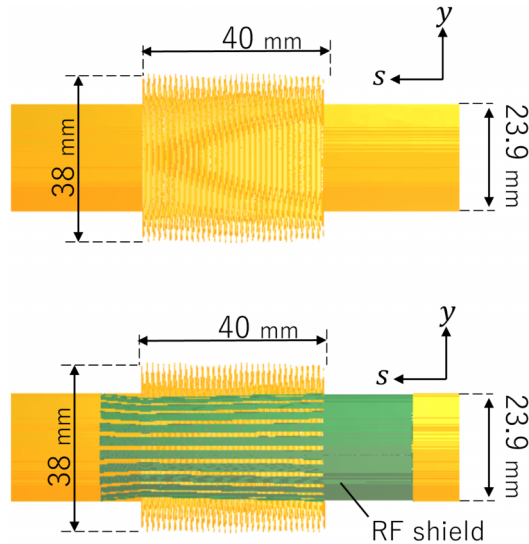


FIG. 3. Inside structure (vacuum region) of “bellows with/without rf shield.” The boundary between the vacuum region and outer conductor is assumed to be a perfect conductor; the rf shield is also assumed to be a perfect conductor.

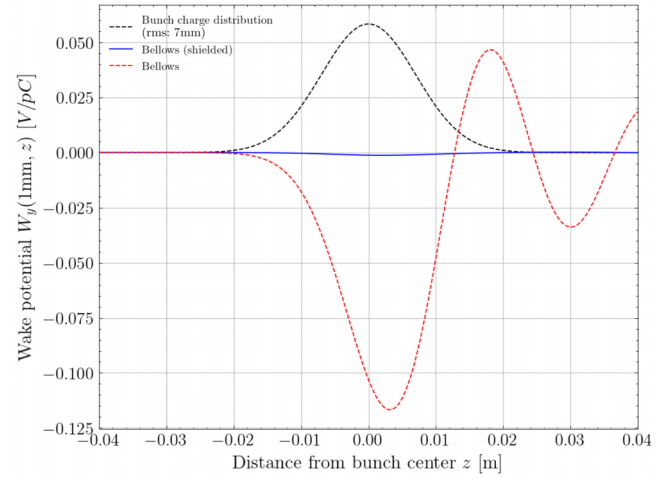


FIG. 4. Comparison of the transverse wake potentials of the bellows with/without the rf shield. The vertical offset between the center of the structure and the beam is 1 mm. The horizontal axis denotes the relative longitudinal position in a bunch.

code [12]. The 3D models were constructed to reproduce the actual geometrical shapes of the wakefield sources, as shown in Fig. 3. Figure 4 shows the calculated wake potentials of the bellows (with and without rf shielding) with offsets between the center of the structure and the beam ranging from 1 mm. For the traveling beam, we set a line charge following a Gaussian distribution with an rms length of 7 mm. The strength of the wakefield kick depends on the relative longitudinal position within the bunch and the offset of the center of the structure and the beam, as shown in Eq. (1). Once the rf shield is inserted, the excited wakefield is reduced to approximately 1/100 of its original value.

B. Analytical estimation of wakefield effects caused by orbit fluctuations on the beam

Figure 5 shows the calculated wake potentials of all wakefield sources in the ATF EXT and FF beamlines. The wake potential of each component is shown for a beam passing through the vertical offset $y = 1$ mm.

The beam size growth due to the wakefield effects induced by the orbit fluctuations was expressed as Eq. (9). The effects depend on the number of wakefield sources, the β function at the locations, and the strength of the induced wakefield (wake potential). We estimate the relative wakefield effects of each type (index j) of the wakefield source to be

$$\Delta\sigma_{y,j} \propto V_{y,j}(z) \sum_i \beta_{y,j,i}, \quad (10)$$

where $V_{y,j}(z)$ is the transverse wake potential, normalized by the vertical beam offset, of the j -th-type wakefield source, and i goes through all of the j -th-type wakefield

sources in the beamline. Figure 6 shows the result, suggesting that the wakefield corrector, ICF70 flanges, collimator with a 3 mm half gap, and CBPMs significantly impact the beam size because they are located in the larger-beta-function sections of the FF beamline. The wakefield corrector consists of unshielded bellows and two cavity BPMs mounted on a vertical mover, which was originally introduced to compensate for static wakefield effects by independently adjusting its vertical position. It is located near the maximum vertical beta-function location in the FF

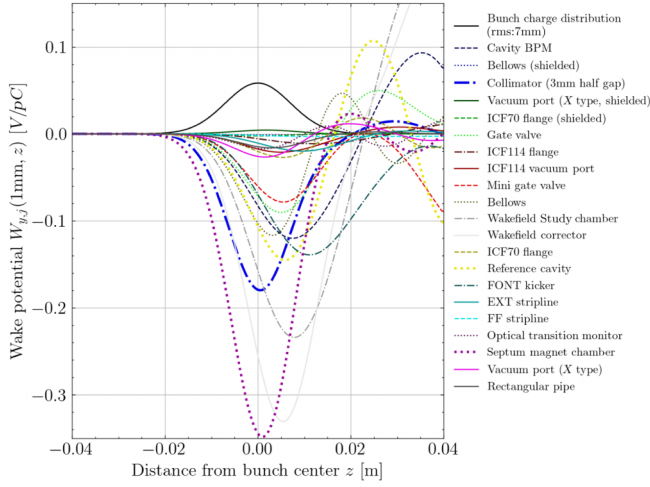


FIG. 5. Calculated wake potential for each type of wakefield source with a 1 mm vertical offset between the center of the structure and the bunch for a traveling beam based on a line charge following a Gaussian distribution with an rms length of 7 mm. Horizontal axis: Relative longitudinal position in bunch.

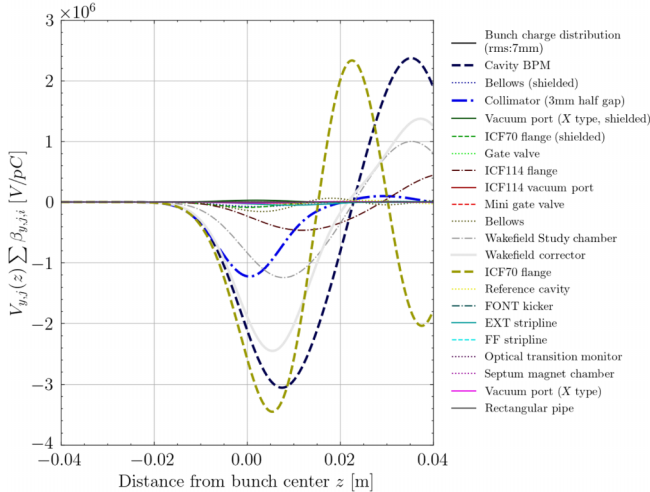


FIG. 6. Analytical estimation of wakefield effects of each type of wakefield source with orbit fluctuation on the beam size. Horizontal axis: Distance from bunch center. Vertical axis: Impact of the wakefield kick on beam size, defined by $V_{y,j}(z) \sum_i \beta_{y,j,i}$.

beamline to maximize the effectiveness of the static wakefield correction.

IV. ESTIMATION OF WAKEFIELD EFFECTS CAUSED BY DYNAMIC CHANGES IN BEAM ORBIT

A. Wakefield model in tracking simulation

We estimated the effects of wakefields caused by orbit fluctuation by performing tracking simulations using the computer program Strategic Accelerator Design (SAD) [13]. Macroparticles with initial Gaussian distributions in six-dimensional phase space were tracked from the entrance EXT to the IP.

The wakefield effect at each wakefield source is introduced as an angular change of the macroparticles, as expressed in Eq. (2). Here, the average of the vertical positions of the macroparticles in a bunch is denoted as y_m . In addition, the relative longitudinal position of a macroparticle with respect to the bunch center is denoted as z . The strength of the wake potential for the bunch position y_m and particle position z is derived using the calculated wake potentials for 11 vertical offsets from -5 mm to $+5$ mm at an interval of 1 mm. To account for the nonlinear dependence on y_m , the wake potential for arbitrary y_m is evaluated as a third-order polynomial via least-squares fitting using the 11 data points.

Tracking simulations were performed using 1000 macroparticles per bunch, with the initial orbit of the angle at IP phase (orbit angle at IP is 1 mrad) for different bunch populations (0 , 4 , and 10×10^9 electrons/bunch). Figure 7 shows the distributions of vertical positions at the IP. Beam shape distortions become stronger for higher bunch intensities owing to the wakefield.

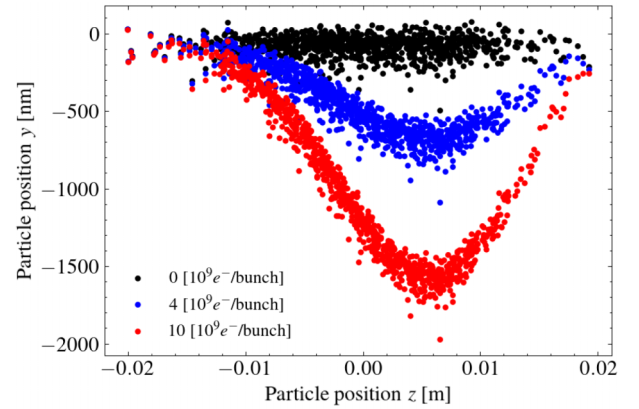


FIG. 7. $z-y$ distribution of tracked 1000 macroparticles from the entrance of the ATF beamline to the IP for different bunch populations (0 , 4 , and 10×10^9 e^- /bunch) and an IP angle of approximately 1 mrad.

B. Simulation of beam size measurement

The vertical beam size at the IP of the ATF is measured using the IP beam size monitor (IPBSM), which uses interference fringes of laser beams [14,15]. The electron beam is made to collide with the laser fringes, and the intensities of the created gamma rays are measured as a function of the phase of the interference fringes. The fringe phase (ψ) is scanned, and the relative gamma-ray intensity is expressed as

$$\begin{aligned} G(\psi) &\propto 1 + C \int \cos(2ky + \psi) \rho(y) dy \\ &= 1 + C(P \cos \psi - S \sin \psi), \end{aligned} \quad (11)$$

with

$$P = \int \cos(2ky) \rho(y) dy, \quad (12)$$

$$S = \int \sin(2ky) \rho(y) dy, \quad (13)$$

where C ($0 < C \leq 1$) is the contrast of the fringe, $k = \pi/d$ (d is the pitch of the fringe), and $\rho(y)$ is the normalized vertically projected electron density at the IP ($\int \rho(y) dy = 1$). The maximum and minimum intensities occur at phases satisfying $\tan \psi = -S/P$ and are expressed by

$$N_{\max, \min} = 1 \pm C\sqrt{P^2 + S^2}. \quad (14)$$

The modulation depth is defined by

$$M \equiv \frac{N_{\max} - N_{\min}}{N_{\max} + N_{\min}} = C\sqrt{P^2 + S^2}. \quad (15)$$

For a bunch following a Gaussian distribution with rms σ_y^* ,

$$M = Ce^{-2k^2\sigma_y^{*2}}, \quad (16)$$

$$\sigma_y^* = \frac{1}{2k} \sqrt{2 \ln\left(\frac{C}{M}\right)} = \frac{1}{2k} \sqrt{2 \ln\left(\frac{1}{\sqrt{P^2 + S^2}}\right)}. \quad (17)$$

In our tracking simulations, modulation depth M is calculated from the vertical positions of all macroparticles as

$$M = C \frac{\sqrt{\{\sum_j \cos(2ky_j)\}^2 + \{\sum_j \sin(2ky_j)\}^2}}{N}, \quad (18)$$

where N is the total number of macroparticles, and the index j is from 1 to N . Next, the beam size is evaluated assuming a Gaussian distribution using Eq. (17).

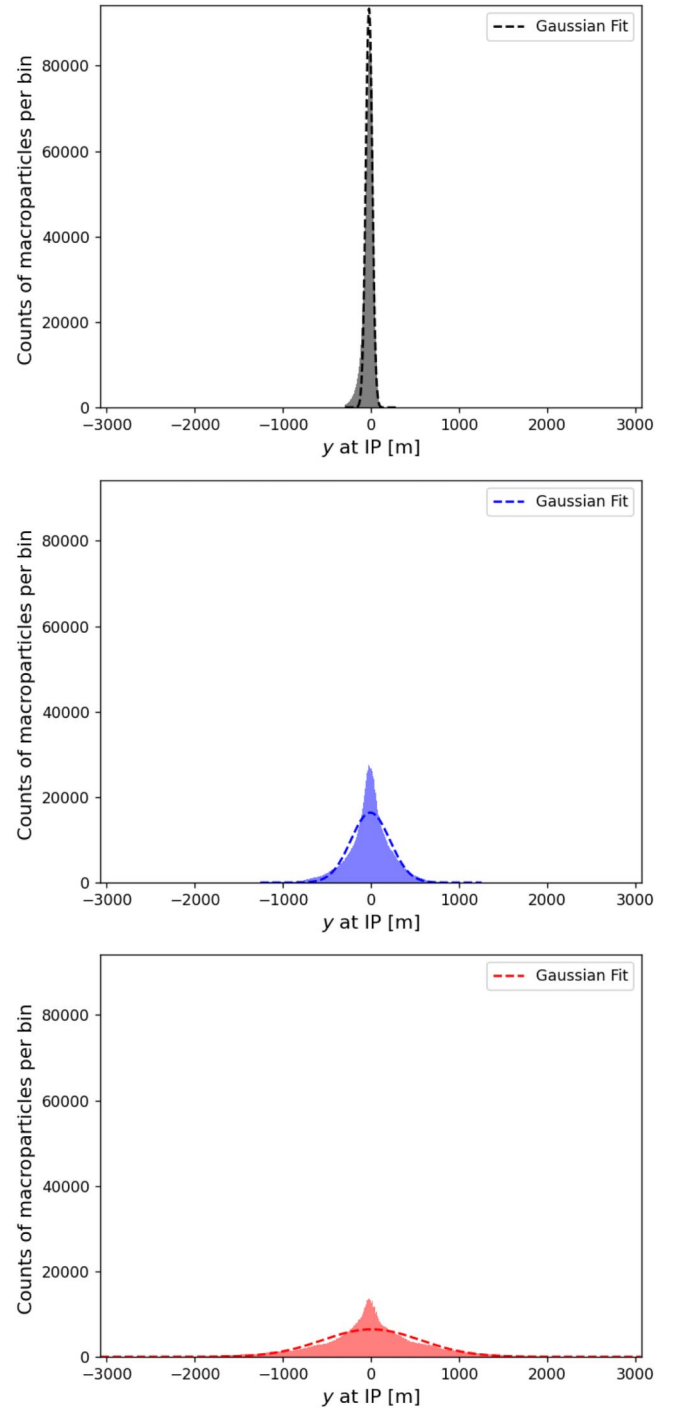


FIG. 8. Projected y distribution of multiple bunches of macroparticles with different bunch populations (0, 4, and $10 \times 10^9 e^-$ /bunch) for an IP angle fluctuation of approximately $600 \mu\text{rad}$. The distributions are obtained from tracking simulations using 1000 bunches, with 1000 macroparticles per bunch. The vertical axis represents the number of macroparticles per bin.

The IPBSM measures the beam size as a projected beam size of multishot bunches; hence, the apparent beam size includes the bunch-by-bunch fluctuations. The projected beam size for 1000 bunches with orbit fluctuation is

TABLE III. Beam size evaluation results based on (1) rms beam size, (2) beam size by Gaussian fitting, and (3) modulation reproduction from y distribution of macroparticles based on Eqs. (17) and (18). IP angle fluctuation of approximately 600 μrad is assumed.

Bunch population ($10^9 e^-/\text{bunch}$)	(1) (nm)	(2) (nm)	(3) (nm)
0	59	37	59
4	252	221	248
10	613	557	567

evaluated via simulation. Figure 8 shows the projected beam distribution in the vertical direction at the IP for 1000 bunches $\times$ 1000 macroparticles with three different beam intensities and an angle at IP orbit fluctuation of rms 600 μrad . Table III shows the beam size evaluation results for three different methods: rms of the distribution, Gaussian fitting, and evaluation based on Eqs. (17) and (18). Although minor differences were observed among the results of these methods, indicating deviation from a Gaussian distribution, the method based on using the modulation depth yields reasonable results.

C. Estimation of wakefield effects on beam size with orbit fluctuation

In this section, based on the tracking simulations described in Sec. IV A and the beam size evaluation method introduced in Sec. IV B, we evaluate the beam size growth caused by the dynamic wakefield effect using tracking simulations with pulse-by-pulse orbit fluctuations. The simulation includes all wakefield sources described in Sec. III A. Next, we extract the intensity dependence parameter by fitting the simulated beam size as a function of bunch intensity.

Tracking simulations were performed for various bunch intensities with several amplitudes of angle at IP orbit fluctuation (randomly varied following a Gaussian distribution with rms, $\sigma_A = 0, 25, 50, 100, 200, 400$, and 600 μrad). Figure 9 shows the results. For each IP angle fluctuation setting, the intensity dependence parameter ω is extracted by fitting the simulated beam size as a function of bunch population using the following expression:

$$\sigma_y^2 = \sigma_{y0}^2 + (\omega Q)^2, \quad (19)$$

where σ_y is the simulated beam size, Q is the bunch intensity, and σ_{y0} and ω are the fittings. Here, σ_{y0} denotes the beam size at zero intensity, while ω represents the intensity dependence parameter. Moreover, this characterizes the strength of the beam size growth as a function of bunch intensity. A larger value of ω indicates a stronger increase in beam size with increasing bunch intensity. The

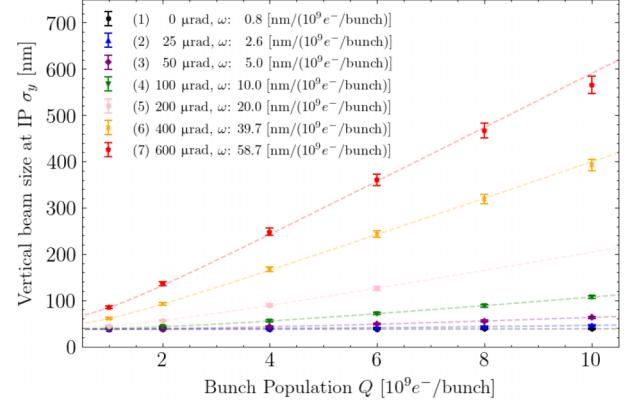


FIG. 9. SAD tracking simulation results for effects of incoming orbit fluctuation related to IP angle fluctuation, with different bunch intensities (0, 1, 2, 4, 6, 8, and $10 \times 10^9 e^-/\text{bunch}$) and different IP angle fluctuations (0, 25, 50, 100, 200, 400, and 600 μrad). The dashed lines show fitting results based on Eq. (19). The values of ω correspond to the fitted results for each IP angle fluctuation.

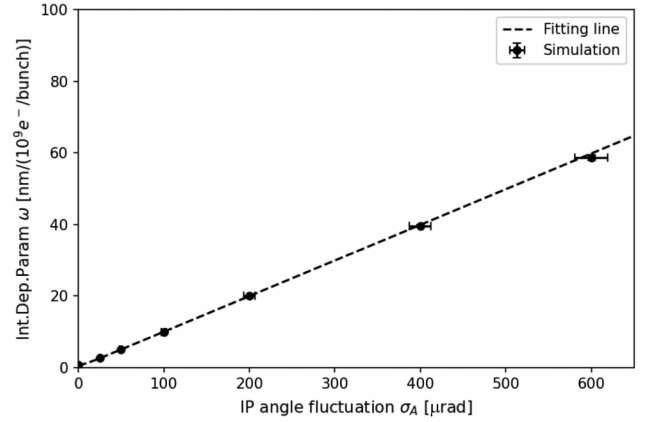


FIG. 10. Bunch intensity dependence of the vertical beam size, quantified by the intensity dependence parameter, as a function of IP angle fluctuation.

results show the strong intensity dependence of the beam size with a large angle at IP phase orbit fluctuation. The beam size at zero intensity is slightly increased with angle at IP phase orbit fluctuation due to nonlinear magnetic fields in the beamline.

Figure 10 shows the intensity dependence parameter ω as a function of the amplitude of the angle at IP phase orbit fluctuation σ_A . The line is from a fitting with free parameters ω_0 and ω_1 where

$$\omega^2 = \omega_0^2 + (\omega_1 \sigma_A)^2. \quad (20)$$

The static intensity dependence parameter ω_0 denotes static wakefield effects, i.e., effects of a wakefield excited by the misalignment of structures in the beamlines or beam

orbit distortion. The dynamic intensity dependence parameter ω_1 denotes dynamic wakefield effects, i.e., effects of a wakefield excited by beam orbit fluctuations.

The estimated ω_0 was small because the misalignment of structures in the beamlines or fixed beam orbit errors were not included in the simulation. The estimated ω_1 from the simulation was $0.100 \text{ nm}/10^9 e^-/\text{bunch}/\mu\text{rad}$. This value shows the overall wakefield effects of the beamline.

Depending on machine operating conditions, such as beam stability in the injector and damping ring, as well as phase and timing fluctuations in the upstream beam transport, orbit fluctuations of approximately 10%–30% of the nominal beam size are typically observed in the FF beamline of the ATF. The nominal beam divergence at the IP is approximately $350 \mu\text{rad}$, corresponding to a vertical emittance of $12 \text{ pm}\cdot\text{rad}$ and a beta function of 0.1 mm at the IP. An angle fluctuation of 10%–30% of the nominal divergence corresponds to $35\text{--}100 \mu\text{rad}$ at the IP. These angle range fluctuations correspond to a beam size increase of approximately $12\text{--}74 \text{ nm}$ at a bunch intensity of $10 \times 10^9 e^-/\text{bunch}$ from the nominal beam size 37 nm . Conversely, a position fluctuation of 10%–30% of the nominal beam size corresponds to a beam size growth of only $0.2\text{--}1.6 \text{ nm}$. Therefore, wakefield effects induced by angle at IP orbit fluctuations are significantly larger than those caused by position fluctuations of the bunch at the IP.

V. EXPERIMENTAL EVALUATION OF WAKEFIELD EFFECTS CAUSED BY DYNAMIC CHANGES IN BEAM ORBIT

A. Method of generation and measurement of IP angle fluctuation

We used two steering magnets installed in the EXT beamline to create external pulse-by-pulse orbit fluctuations. Figure 1 shows the location where the steering magnets were installed. We used two steering magnets to generate angle fluctuations without position fluctuations at the IP. We defined the kick angles using the steering magnets. The amplitudes of the kick angles must maintain a ratio of $-R_{34,\text{str1} \rightarrow \text{IP}}/R_{34,\text{str2} \rightarrow \text{IP}}$ to induce angle fluctuations at the IP without creating position fluctuations. $R_{34,\text{str} \rightarrow \text{IP}}$ denotes the transfer matrix element from the steering magnet to the IP.

For the IP angle fluctuation measurement, 38 BPMs were used to estimate the bunch position and angle at the IP. For each beam pulse (pulse number i), the orbit position and angular displacement at the IP ($\Delta y_{\text{IP},i}$ and $\Delta y'_{\text{IP},i}$) are evaluated via the least-squares method, minimizing

$$\chi_i^2 = \sum_l \left(\frac{\Delta y_{\text{meas},l,i} - \Delta y_{\text{calc},l,i}}{\sigma_l} \right)^2, \quad (21)$$

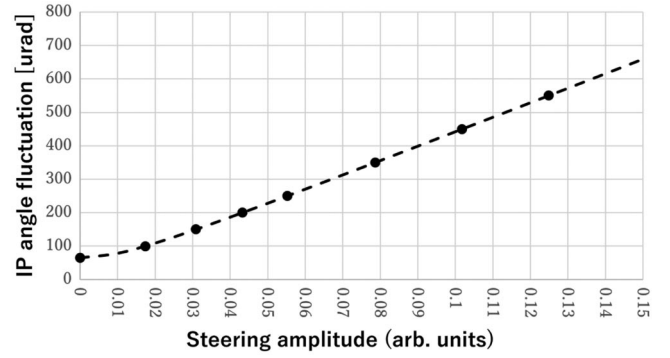


FIG. 11. Observed IP angular fluctuations at different amplitudes for a pair of air-core steering magnets used to generate external fluctuations. IP angular fluctuations are quantified as rms of the IP angle for 500 bunches. Dots indicate measured values. Dashed line indicates a fitting line.

where σ_l is the BPM resolution; $\Delta y_{\text{meas},l,i}$ is the beam position deviation from the average measured at the l -th BPM. The transfer matrix is symplectic; hence, the beam position and angle at each BPM location are related to those at the IP through the inverse transfer matrix given by

$$\begin{pmatrix} y_l \\ y'_l \end{pmatrix} = \begin{pmatrix} R_{44,l} & -R_{34,l} \\ -R_{43,l} & R_{33,l} \end{pmatrix} \begin{pmatrix} y_{\text{IP}} \\ y'_{\text{IP}} \end{pmatrix}. \quad (22)$$

$R_{34,l}$ denotes the transfer matrix element from the l -th BPM to the IP. Therefore, the position deviation at each BPM ($\Delta y_{\text{calc},l,i}$) is expressed in terms of the position and angle deviations at the IP ($\Delta y_{\text{IP},i}$ and $\Delta y'_{\text{IP},i}$) as

$$\Delta y_{\text{calc},l,i} = R_{44,l} \Delta y_{\text{IP},i} - R_{34,l} \Delta y'_{\text{IP},i}, \quad (23)$$

The fluctuations are derived as the rms of the calculated bunch position and angle at the IP for 500 shots. Figure 11 shows the measured IP angle fluctuations for 500 shots of the bunches. The amplitudes of the steering magnets were randomly varied pulse by pulse, indicating that the IP angle fluctuations were changed by the pair of steering magnets.

B. Evaluation of wakefield effects caused by orbit fluctuation

To quantify the effects of wakefields caused by pulse-by-pulse orbit fluctuations, we evaluate the relationship between the IP angle fluctuation and the intensity dependence parameter ω , as defined in Eqs. (19) and (20). The beam size was measured using the IPBSM while varying the bunch intensity. Moreover, the IP angle fluctuation was controlled by adjusting the amplitudes of a pair of steering magnets.

For each IP angle fluctuation setting, the beam size was measured as a function of bunch intensity. In addition, the

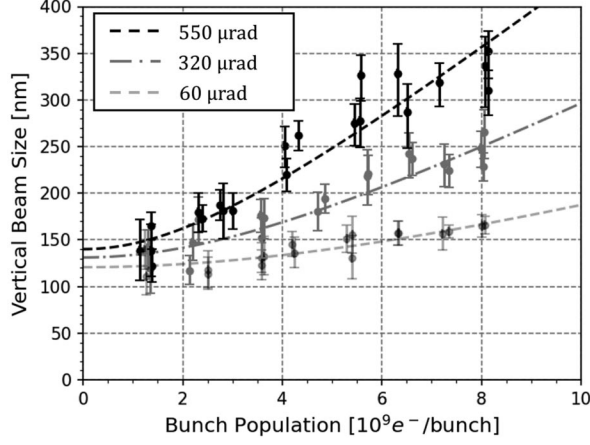


FIG. 12. Beam size growth as a function of bunch intensity with different IP angle fluctuations (without external fluctuation: approximately 60 μrad , with external fluctuation: approximately 320 and 550 μrad). Vertical axis: Vertical beam size at IP. Horizontal axis: Bunch intensity.

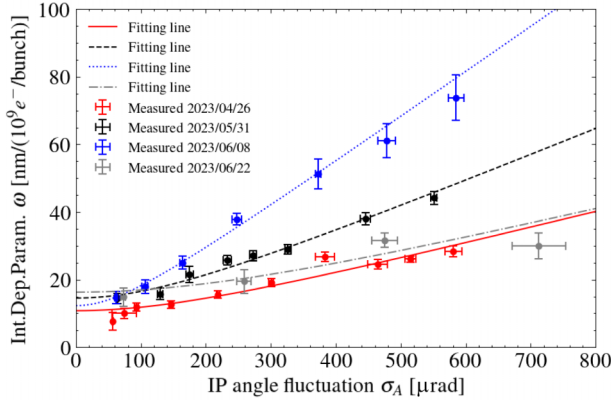


FIG. 13. Intensity dependence parameter ω as a function of IP angular fluctuations, obtained from several measurements. Vertical axis: Intensity dependence parameter ω . Horizontal axis: IP angle fluctuation σ_A .

intensity dependence parameter ω was extracted by fitting the measured beam size using Eq. (19). Figure 12 shows the measured beam size as a function of bunch intensity for different IP angle fluctuation settings. Here, the intensity-dependent beam size growth becomes stronger with increasing IP angle fluctuation.

Next, the extracted ω values are analyzed as a function of the rms amplitude of the IP angle fluctuation σ_A . In addition, the parameters ω_0 and ω_1 are obtained by fitting the relation in Eq. (20). As defined in Sec. IV C, the dependence of ω on σ_A is used to separate the fluctuation-independent (static) and fluctuation-dependent (dynamic) components, denoted by ω_0 and ω_1 , respectively. Figure 13 shows multiple experimental results obtained under various IP angle fluctuation settings. The horizontal error bars

TABLE IV. Comparison between tracking simulation and experimental results. All experimental data were obtained in 2023. ω_0 and ω_1 are the static and dynamic intensity dependence parameters.

	Not dependent on orbit fluctuation ω_0 [nm/($10^9 e^-/\text{bunch}$)]	Depends on orbit fluctuation ω_1 [nm/($10^9 e^-/\text{bunch}$)/ μrad]
Exp. 04/26	10.8	0.048
Exp. 05/31	14.6	0.079
Exp. 06/08	12.3	0.134
Exp. 06/22	16.3	0.047
Exp. average	13.5	0.077
Simulation	...	0.100

represent the standard error of the measured IP angle jitter, whereas the vertical error bars represent the fitting uncertainty of the intensity dependence parameter. Although some variations are observed among independent measurements obtained under similar experimental conditions, all results consistently show that the intensity-dependent beam size growth becomes stronger with increasing IP angle fluctuations.

Table IV summarizes multiple experimental results obtained under various IP angle fluctuation settings. The static intensity dependence parameter is 13.5 nm/($10^9 e^-/\text{bunch}$) and the dynamic intensity dependence parameter is 0.077 nm/($10^9 e^-/\text{bunch}$)/ μrad , both averaged over the four independent experimental results. Using a typical orbit angle fluctuation of 60 μrad observed under normal operating conditions without external excitation, the dynamic contribution corresponds to an effective intensity dependence of 4.6 nm/($10^9 e^-/\text{bunch}$). At a bunch intensity of $10 \times 10^9 e^-/\text{bunch}$, the static contribution corresponds to a beam size growth from the nominal beam size of 37 to 140 nm at the IP. The dynamic contribution leads to a beam size increase from the nominal 37 nm to approximately 59 nm. Although the static contribution is dominant in absolute beam size growth, the dynamic contribution can still lead to a significant increase even under typical orbit fluctuation conditions. Therefore, the dynamic contribution cannot be neglected in achieving stable nanometer scale beams.

VI. CONCLUSION

Transverse wakefields in accelerators had been considered mainly to be a static wakefield effect, wherein the excitation is due to the misalignment of structures in beamlines or fixed beam orbit errors. This study presents the first experimental and quantitative evaluation of

dynamic wakefield effects, in which the excitation arises from phase pulse-by-pulse beam orbit fluctuations, for nanometer scale beams at the ATF. Controlled orbit fluctuations were introduced using steering magnets, and the resulting beam size growth was quantitatively evaluated through simulations and experiments. A wakefield model including all wakefield sources was constructed, and the dynamic wakefield effect on nanometer scale beams was evaluated. For final focus optics, only angle at IP phase pulse-by-pulse beam orbit fluctuations are crucial for the dynamic wakefield effects. The simulation indicates that the dynamic wakefield effect can significantly impact the beam size growth.

Experimentally, the magnitude of orbit fluctuations was controlled using steering magnets to generate angle fluctuations at the IP. The dynamic wakefield effect was quantified as the relationship between the IP angle fluctuation and beam size growth. Although some variations are observed among independent measurements taken under similar experimental conditions, the results demonstrate that the intensity-dependent beam size growth becomes stronger as the IP angle fluctuation increases. The dynamic wakefield effect of $0.077 \text{ nm}/(10^9 e^-/\text{bunch})/\mu\text{rad}$ corresponds to a beam size growth to 59 nm at the same bunch intensity with an IP angle fluctuation of $60 \mu\text{rad}$. These results demonstrate that the dynamic component of transverse wakefield effects can significantly affect nanometer scale beams. This study elucidates the role of pulse-by-pulse orbit fluctuations in beam size growth and provides novel insights for achieving stable nanometer scale beams in future linear colliders, based on simulations and experiments.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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