Geometric efficiency of a two-stage fully absorbing collimation system in single-pass linacs

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(Received 2 February 2010; published 12 May 2010)

Collimators are commonly used in particle accelerators to prevent particles traveling at large amplitudes from hitting the vacuum chamber. We derive here, for a single-pass linac, a one-dimensional analytical expression for the efficiency of a two-stage fully absorbing collimation system (CS), based on the CS geometrical and optical properties only. We show that, in the presence of physical space or optics constraints, the best betatron phase advance in between the first and the second collimation stage may differ from the usually prescribed $\pi/2$. The analytically computed collimation efficiency is then compared to particle tracking results.

DOI: 10.1103/PhysRevSTAB.13.052801

PACS numbers: 29.20.Ej, 29.27.Eg, 29.27.Bd

I. INTRODUCTION

Control of beam losses in particle accelerators is often mandatory to protect equipment. This includes preventing halo particles traveling at large amplitudes and eventually hitting the vacuum chamber creating secondary showers. The halo is usually intercepted by absorbing metal blocks called collimators; they locally restrict the vacuum chamber physical aperture without affecting the main beam. The main beam is defined as the ensemble of particles whose trajectory in the pseudocanonical transverse phase space (u, u') , with $u = x, y$, is contained in an ellipse of area ε_u , ε_u being the transverse geometrical emittance of the beam. By definition, the halo particles have betatron oscillation amplitudes larger than $\sqrt{\varepsilon_u \beta_u}$, β_u being the betatron function.

To intercept both large amplitude and large angle particles both a primary and a secondary collimator are needed. In the literature, a collimation system (CS) design usually includes a spoiler and an absorber; the purpose of the spoiler is to increase the transverse footprint of any unwanted particles before they are stopped in the absorber. The present scheme relies instead on a CS consisting of two fully absorbing apertures in the beam path, such as, e.g., a 20 cm long Cu block whose stopping power for proton beams up to the MeV range and electron beams up to the GeV range is high [1].

II. BACKGROUND

Collimation systems are used both on linear [2–7] and on circular accelerators [8–10] to minimize background in physics detectors, to avoid quench magnets in superconducting machines, and to limit the irradiation of equipment, possibly leading to demagnetization of undulator permanent magnets. The need of high luminosities in colliders and in linac-based free electron lasers (FELs) obtained with high beam intensities makes these problems even more serious.

1D and 2D detailed analytical studies and particle tracking simulations of CS for *circular* accelerators are available in the literature. The guiding principle for positioning the secondary collimators in circular accelerators is thought to have been first given in [11] and independently developed in [12,13]. More recent general principles for two-stage, spoiler plus absorber collimation in circular accelerators have been extensively examined in [14–16].

The optimization criteria of the CS contained in the mentioned references assume the quasiperiodic particle motion in a storage ring. The choice of the working point, normally clear of resonances in the tune diagram, justifies the assumption that particles touch the primary collimator at their outermost spatial extension. This is not necessarily true in a linac, since particles might reach the primary collimator with a small offset but still with a large angular divergence. The quasiperiodic motion also carries the requirement of a secondary collimator with a larger aperture than that of the first, because particles that do not interact with the primary collimator must not be affected by the secondary one. This is not the case when using full-absorption collimators that are therefore allowed to have the same aperture.

Before illustrating the novel features of this article, a brief review of how the collimation process is described in the literature is given. In [14] the phase advance $\Delta\mu$ between the primary and the secondary collimator is the critical quantity to be chosen in order to minimize the excursion of the particles scattered by the primary collimator:

$$\Delta\mu_{\text{opt}} = 2 \arcsin \sqrt{\frac{1}{2} \frac{H}{L+H}}, \quad (1)$$

where L is the normalized half aperture of the primary collimator and H is the normalized step back of the secondary one. In [15,16] the phase advance between the primary and the secondary collimator is derived by considering the minimum kick that a particle has to receive in

the primary collimator in order to be intercepted by the secondary one:

$$\cos \Delta \mu_{\text{opt}} = \frac{n_1}{n_2}, \quad (2)$$

where n_1 and n_2 are the half apertures (in the normalized phase space) of the primary and of the secondary collimator, respectively. By definition, $L > H$ in (1) and $n_2 > n_1$ in (2) to prevent particles from hitting the secondary collimator before hitting the primary one.

The optimum design of a two-stage, fully absorbing CS in a single-pass linac driving a FEL is presented in [4,5], where the largest clearance between the collimated beam and the undulator vacuum chamber is defined by a phase advance of $\pi/2$ between the primary and the secondary collimator.

A comparison of the CS performance for linac-based FELs is reported in [10], where the effectiveness of the collimation system is quantified by means of particle tracking results in terms of the fraction of initial halo particles that survive the CS. Particle tracking plays a role also in [7,8,17] where the *inefficiency* η_c is defined as the ratio of the number $N_i(A_{\text{cut}})$ of particles traveling at amplitudes larger than the cut amplitude A_{cut} over the number N_{imp} of particles impacting the collimator; A_{cut} is given by the vacuum chamber aperture downstream of the CS:

$$\eta_c = \frac{N_i(A_{\text{cut}})}{N_{\text{imp}}}. \quad (3)$$

As mentioned before, the above criteria are not necessarily always appropriate to motion in single-pass accelerators, in which angular divergence rather than offset is the primary cause for far-out halo buildup. The present study has produced a one-dimensional analytical expression for the efficiency of a fully absorbing, two-stage collimation system in a single-pass linac that is independent of the number of particles impacting the CS and of their transverse distribution. The expression is a function of the collimators' aperture, the vacuum chamber aperture downstream of the CS, and the optical functions.

Unlike the definition given in (3), the efficiency is proportional to the number of particles *stopped* by the real CS over those stopped by the ideal CS and, unlike the prescriptions of (1) and (2), the efficiency depends not only on the phase advance between the primary and the secondary collimator but also explicitly on the collimator aperture and the betatron function value. As a result, for some optics and aperture settings, the predicted optimum phase advance in between the primary and the secondary collimator differs from $\pi/2$. Finally, a more general collimation index is defined that also describes the case of a real CS with an acceptance smaller (bigger cleaning capability) than the ideal one.

FIG. 1. Schematic of a two-stage CS with low- β symmetric optics.

The analytical approach assumes linear, uncoupled, non-chromatic optics. The case study of low- β symmetric optics defined over a drift space as shown in Fig. 1 is considered. The aim is, given an arbitrary halo particle distribution, to minimize the fraction of halo particles surviving the CS. The result of the analytical approach is then checked against particle tracking with the ELEGANT code [18].

III. COLLIMATION EFFICIENCY AS FUNCTION OF THE RELATIVE PHASE ADVANCE

The collimation acceptance is defined in the normalized transverse phase space with particle coordinates:

$$X(\mu) = \sqrt{\varepsilon} \cos(\mu + \phi) = \frac{x}{\sqrt{\beta}} \quad (4)$$

$$X'(\mu) = \frac{dX}{d\mu} = -\sqrt{\varepsilon} \sin(\mu + \phi) = \left(\sqrt{\beta} \frac{dx}{ds} + \alpha \frac{x}{\sqrt{\beta}} \right),$$

where X will be replaced by Y when appropriate. The notation refers to the usual Twiss functions (α, β), betatron phase advance (μ), and particle invariant (ε) for the plane of interest. This transformation reduces the betatron oscillations to a simple harmonic motion.

The simple geometric considerations depicted in Fig. 2 show that, for a given collimation half aperture g , a phase advance $\Delta\mu = \pi/2$ between the primary (C1) and the secondary (C2) collimator maximizes the probability of intercepting particles having large betatron amplitude. The circular phase space described by (4) is represented at the C2 location and limited in spatial position by the collimator half aperture $g/\sqrt{\beta} = |\overline{IO}|$. For a generic phase advance $\Delta\mu$ in between the collimators, the shadow of C1 at the location of C2 is represented by the inclined lines $|\overline{EF}|$, $|\overline{GH}|$ tangent to the circumference. The area $a(\Delta\mu)$ of the parallelogram EFGH is the CS acceptance. By geometric considerations (see Fig. 2) we can infer that

$$\begin{aligned} E\hat{L}M &= (\pi/2 - \Delta\mu); & |\overline{EM}| &= g/\sqrt{\beta} \tan \Delta\mu; \\ O\hat{L}F &= \Delta\mu; & |\overline{FM}| &= g/\sqrt{\beta} \sin \Delta\mu; \\ I\hat{O}H &= \Delta\mu/2; & |\overline{HI}| &= g \cdot \tan(\Delta\mu/2)/\sqrt{\beta}. \end{aligned} \quad (5)$$

FIG. 2. Collimator acceptance in the normalized phase space.

and finally, in normalized phase space one has

$$a(\Delta\mu) = 2g(\overline{EM} + \overline{IM} + \overline{HI})/\sqrt{\beta} = 4g^2/\beta |\sin\Delta\mu|. \quad (6)$$

The parallelogram base $|\overline{EH}|$ increases monotonically from $2g/\sqrt{\beta}$ to $+\infty$ as $\Delta\mu$ goes from $\pi/2$ to 0 (while its height remains $2g/\sqrt{\beta}$). The minimum acceptance for a given collimator half aperture is therefore the area ABCD corresponding to $\Delta\mu = \pi/2$, $a_{\min} = 4g^2/\beta$.

For any $g \neq 0$, $a(\Delta\mu) \geq a_{\min} > 0$ and $\Delta\mu = \pi/2$ allows one to obtain the same acceptance but with the largest half aperture. This is usually a major goal in order not to restrict the accelerator vacuum chamber and, for this reason, we can set $a_{\text{opt}} \equiv a_{\min} = 4g^2/\beta$. We propose to define the “collimation efficiency as function of the relative phase advance” between the primary and the secondary collimator as follows:

$$\xi_{\text{coll}}(\Delta\mu) = \frac{1/a(\Delta\mu)}{1/a_{\min}} = |\sin\Delta\mu|, \quad (7)$$

where the symbol ξ is used for the collimation efficiency instead of η , in the literature usually referred to signify the collimation inefficiency. For any given incoming beam, the quantity $1/a_{\min}$ is supposed to define the optimum number N_{opt} of particles stopped by the CS. Hence, $\xi_{\text{coll}}(\Delta\mu)$ can be interpreted as the ratio of the number N_{real} of particles stopped by the real CS over the optimum number N_{opt} .

IV. COLLIMATION EFFICIENCY AS FUNCTION OF THE COLLIMATOR HALF APERTURE

The CS acceptance has to be fixed according to the area in the transverse plane (x, y) to be protected from stray particles. Inside the vacuum chamber, for simplicity as-

FIG. 3. Cross section of the vacuum chamber downstream of the CS. $R = \overline{OA}$ is the chamber radius; $r = \overline{OC}$ is the “beam stay clear” radius; a clearance ring of width $\Delta = \overline{BC}$ prevents particles from hitting the vacuum chamber surface. The collimator half aperture footprint $g = \overline{OD}$ is also projected on the (x, y) plane (not to scale).

sumed as cylindrical, a safety clearance area of width $\Delta = R - r \geq 0$ is defined. The main goal of the CS is to prevent particles traveling through the real space in the shaded region $(R - r)$ of Fig. 3.

With reference to Fig. 3, the optimum collimator acceptance a_{opt} can be defined for any $\Delta_{\text{opt}} > 0$ as follows [4,5]:

$$a_{\text{opt}} = \frac{(R - \Delta_{\text{opt}})^2}{2\beta_0} = \frac{r_{\text{opt}}^2}{2\beta_0}, \quad (8)$$

where β_0 is the maximum betatron function over the layout region to be protected by particle hits. The optimum collimator half aperture is then calculated for a given betatron function β_{coll} at the collimator. One has

$$g_{\text{opt}} = \sqrt{a_{\text{opt}} \cdot \beta_{\text{coll}}}. \quad (9)$$

Once a_{opt} is fixed by (8), then g_{opt} is univocally specified. However, the practical lower limit of the collimator half aperture is usually determined by the effect of the transverse wakefield in the collimator on the main beam dynamics [19,20] and the real half aperture g may happen to become larger than g_{opt} .

Now, assume $r = \sqrt{2\beta_0 a} = \sqrt{(2\beta_0)/\beta_{\text{coll}}} g$ the radius of the CS defined by the real acceptance a or, equivalently, by the real gap g , is different from the optimum value r_{opt} in (8). For any $0 \leq \Delta \leq \Delta_{\text{opt}}$, one can define the “collimation efficiency as function of the collimator half aperture” as follows:

$$\xi_{\text{coll}}(r) = \frac{R^2 - r^2}{R^2 - r_{\text{opt}}^2}. \quad (10)$$

By definition, $0 \leq \xi_{\text{coll}}(r) \leq 1$ and it describes the ratio of the clearance area defined by the real CS over its nominal value. The optimum case of unity efficiency is given by $r = r_{\text{opt}}$, when particles are stopped exactly at the desired amplitude r_{opt} . When $r = R$, the CS does not shadow the downstream vacuum chamber, all particles

are allowed to hit the chamber and therefore the efficiency is zero.

V. COLLIMATION INDEX

In order to characterize the expected CS performance both in terms of the phase advance between the primary and the secondary collimator and of their half aperture, we propose the following definition of “collimation index” as the product of the two efficiencies (7) and (10):

$$\chi_{\text{coll}} = \frac{R^2 - r^2}{R^2 - r_{\text{opt}}^2} |\sin(\Delta\mu)|. \quad (11)$$

The physical meaning of (11) is the following.

(i) For any width of the clearance area $0 \leq \Delta \leq \Delta_{\text{opt}}$, $0 \leq \chi_{\text{coll}} \leq 1$ and it can be interpreted as general collimation efficiency. In this case, the relative phase advance that gives the (local) maximum of collimation efficiency is $\pi/2$. Alternatively, if the phase advance is fixed, the collimation efficiency is maximum for $\Delta = \Delta_{\text{opt}}$.

(ii) For any width of the clearance area $\Delta_{\text{opt}} < \Delta \leq R$, χ_{coll} can be greater than 1, in which case it describes a CS that, for the same incoming beam, is stopping more particles than in the ideal case.

(iii) A null phase advance leads to zero efficiency because it implies that one collimator only is active; thus, for any finite collimator half aperture there is no cleaning of particle angular divergence. Alternatively, a clearance area of width $\Delta = 0$ leads to zero efficiency because, for any phase advance between the collimators, it allows particles to travel at amplitudes as large as R in the downstream vacuum chamber.

Equation (11) can be made more explicit by substituting (8) into (9) and then by giving the explicit dependence of β_{coll} on the lattice geometry. A simple case is given by the two-stage CS in the presence of low- β symmetric optics, as shown in Fig. 1. If $\check{\beta}$ is the betatron function at the waist and Δs is the CS half length, then we have

$$\begin{cases} \beta(\Delta s) = \check{\beta} + \frac{\Delta s^2}{\check{\beta}} \\ \Delta\mu(\Delta s) = 2 \arctg\left(\frac{\Delta s}{\check{\beta}}\right) \end{cases} \Rightarrow \begin{cases} \Delta s = \sqrt{\check{\beta}(\beta(\Delta s) - \check{\beta})} \\ \Delta\mu(\Delta s) = 2 \arctg\left(\sqrt{\frac{\beta(\Delta s) - \check{\beta}}{\check{\beta}}}\right) \end{cases} \Rightarrow \beta(\Delta s) = \beta_{\text{coll}} = \check{\beta} \left[1 + \tg^2\left(\frac{\Delta\mu}{2}\right) \right], \quad (12)$$

where $0 \leq \Delta\mu < \pi$. Substituting (8), (9), and (11) into (12), we obtain

$$\chi_{\text{coll}} = \frac{[R^2 - g^2 \frac{\beta_0}{\check{\beta}} (1 + \cos\Delta\mu)]}{R^2 - r_{\text{opt}}^2} \sin\Delta\mu. \quad (13)$$

FIG. 4. (Color) Collimation index χ_{coll} as a function of the phase advance between C1 and C2. The solid curve refers to the optimum set of parameters (nominal collimator half-aperture = 1.4 mm): $\chi_{\text{coll}} = 1$ at 90 deg. The dotted curve and the dashed curve refer to a smaller (1.2 mm) and a bigger (1.6 mm) collimator half aperture, respectively. In these cases, χ_{coll} can be restored to 1 at 71.4 deg and at 104.4 deg phase advance, respectively. The bottom line shows the betatron function at the collimators' location.

VI. OPTIMIZATION

Let us now assume that the geometrical or optical parameters of the CS might not be free parameters because of wakefield effect, space limitations, costs, or specific optics set for diagnostic purposes. Owing to the trigonometric functions in (13) and for any $r_{\text{opt}} \leq r \leq R$, the maximum of collimation efficiency does not necessarily occur at the $\pi/2$ phase advance. For example, if the collimator is defined with a half aperture larger than its optimum value, a wider phase advance could be adopted to obtain larger betatron functions at the collimators.

Figure 4 shows the collimation index χ_{coll} as defined in (13) as a function of the CS phase advance $\Delta\mu$. The three curves are for different collimator half apertures. The betatron function in the CS is also shown. Table I lists the fixed parameters used for the calculation: the vacuum chamber radius and the clearance aperture downstream of the CS, the betatron function at the waist and at its maximum downstream of the CS. Table II summarizes the parameters that vary when different curves are considered.

TABLE I. CS fixed parameters.

Parameter	Value	Unit
R	3.5	mm
Δ/R	0.2	
β_0	12	m
β_{waist}	3	m

TABLE II. CS optics parameters for different half apertures needed to restore the unity collimation index.

Collimator half aperture [mm]	Optimum phase advance [deg]	Δs [m]	β_{coll} [m]
1.4	90	3.0	6.0
1.2	71.4	2.16	4.6
1.6	104.4	3.87	7.98

VII. PARTICLE TRACKING

The validity of the analytical results shown in Fig. 4 and in Table II has been checked by particle tracking. As mentioned before, (11) and (13) have been defined, for any given incoming beam, as the ratio of quantities proportional to the number of particles stopped by the real CS over the design value. Similarly, the collimation performance extracted from simulation results is here determined by the ratio of the number of particles stopped by the real CS over the number of particles stopped by the nominal layout, both evaluated at the downstream location where $\beta = \beta_0$:

$$\chi_{\text{sim}}(\beta_0) = \frac{N_{\text{real}}}{N_{\text{opt}}}. \quad (14)$$

The beam at the entrance of the CS is modeled as follows. The main beam has a symmetric Gaussian particle distribution in (x, x') and (y, y') with a 3-sigma cutoff in phase space. Its geometric rms emittance is 0.91×10^{-8} mrad, so that it nominally extends up to 0.700 mm from the axis (in both planes) at the C1 location. The total charge is approximately 0.7 nC.

The halo beam is depicted by a Gaussian tail of the main beam. It has a symmetric Gaussian particle distribution in (x, x') and (y, y') , centered on the main beam axis and extending at radii from 0.700 to 1.465 mm in the physical transverse plane. Its charge is approximately 0.3 nC.

The main and the halo beam as a whole is represented by a Gaussian centered on the main beam axis with a 5-sigma cutoff in phase space, with geometric rms emittance of 1.43×10^{-8} mrad and total charge of 1 nC. It has a mean energy of 250 MeV and rms energy spread of 0.1%; no energy chirp is considered. The whole beam is represented by 10^5 particle self-generated by ELEGANT and matched to the lattice optics.

Figure 5 shows the particle distribution in the transverse plane after horizontal collimation, at the location where $\beta = \beta_0 = 12$ m.

The optimum cleaning is defined by the two-stage CS as described by the geometrical parameters listed in Table I and in Table II, for a nominal collimator half aperture of 1.4 mm and a relative phase advance of 90 deg. The two collimators C1 and C2 are identical, rectangular and perfectly absorbing. In this ideal case, the percentage of stopped particles is $N_{\text{opt}} = 3.3\%$ and this defines the unity collimation efficiency (in other words, it is supposed the user wants to stop exactly this amount of particles).

We now assume that the installed collimators have a half aperture different from the nominal. If the magnetic lattice cannot be changed—for example, due to stronger constraints on the optics or if there is no space available for a different configuration of the CS—the collimation efficiency changes.

Table III shows that the collimation performance simulated by ELEGANT agrees with its analytical prediction both for a smaller and a larger half aperture than the nominal, with a discrepancy of 6% and 20%, respectively. Several runs with different seeding numbers generating the initial particle distribution show fluctuations within 10% of χ_{sim} that are intrinsic to the tracking procedure; this uncertainty reduces the discrepancy between χ_{sim} and χ_{coll} .

As a final check, the optics is rematched in ELEGANT for the 1.2 and 1.6 mm half apertures to reestablish the unity collimation efficiency according to the analytical prescrip-

FIG. 5. (Color) Particle distribution after horizontal collimation for the CS parameters listed in Tables I and II, half aperture = 1.4 mm. From left to right: physical transverse plane (x, y) observed downstream of the CS, where $\beta = \beta_0 = 12$ m; vertical particle distribution with $\sigma_y = 0.415$ mm; horizontal particle distribution with $\sigma_x = 0.388$ mm. The absorbing coefficient is 3.3%. ELEGANT code output for 10^5 initial particles.

TABLE III. Comparison of the simulated and the analytical collimation performance for fixed C1-C2 phase advance and different collimator half apertures. The numbers in parentheses refer to the 2D collimation performed with rectangular jaws; in this case, the 2D collimation index is calculated as the product of the two 1D ones.

Collimator half aperture [mm]	$\Delta\mu_{C1-C2}$ [deg]	Particles stopped [%]	$\sigma(\beta_0)$ [μm]	χ_{sim} [Eq. (14)]	χ_{coll} [Eq. (13)]
1.4	90	3.3 (6.7)	391	1.0 (1.0)	1.0 (1.0)
1.2	90	7.9 (15.3)	369	1.4 (2.3)	1.5 (2.3)
1.6	90	1.3 (2.5)	404	0.6 (0.4)	0.5 (0.3)

TABLE IV. Comparison of the simulated and the analytical collimation performance for C1-C2 phase advance as prescribed by Table II and different collimator half apertures. The numbers in parentheses refer to the 2D collimation performed with rectangular jaws; in this case, the 2D collimation index is calculated as the product of the two 1D ones.

Collimator half aperture [mm]	$\Delta\mu_{C1-C2}$ [deg]	Particles stopped [%]	$\sigma(\beta_0)$ [μm]	χ_{sim} [Eq. (14)]	χ_{coll} [Eq. (13)]
1.4	90	3.3 (6.7)	391	1.0 (1.0)	1.0 (1.0)
1.2	71.4	3.6 (7.5)	395	1.09 (1.12)	1.0 (1.0)
1.6	104.4	3.5 (6.9)	388	1.06 (1.03)	1.0 (1.0)

tions in Table II (see also Fig. 4). The resulting collimation efficiencies are listed in Table IV; they converge towards the (nominal) unity value with a discrepancy smaller than 9%.

VIII. CONCLUSION

A one-dimensional analytical description of a two-stage, fully absorbing collimation system in a single-pass linac is given. The explicit dependence of the collimation efficiency on the geometrical and the optical parameters of the CS for low- β symmetric optics is also given. Since the expression for the efficiency relies on pure geometrical and optical properties of the CS, this analysis allows a first attempt at a CS design without the need for particle tracking.

In contrast with the usual prescription of a $\pi/2$ betatron phase advance between the first and the second stage of collimation, this study points out that, when some limiting space or optics constraints are present, a different phase advance should be chosen in order to maximize the number of undesired particles stopped by the CS.

The concept of collimation efficiency is also extended to the case of a CS with a bigger stopping power than the nominal one (i.e., smaller collimator half aperture or bigger betatron function at the collimator).

In conclusion, the proposed analytical model allows one to design the CS so as to maximize the collimation efficiency according to the possible constraints on the collimator's hardware (aperture limited by wakefield considerations), optics, and available space. Since the aim of this study is, given an arbitrary halo particle distribution, to minimize the fraction of halo particles surviving the CS, the predicted collimation performance has been directly evaluated from particle tracking, before and after the optimization procedure. The collimation performances (simulated and analytical) agree well and finally converge to the optimum unity value as expected.

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