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TOLERANCES OF TTF-2 FIRST BUNCH COMPRESSOR

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Abstract

In bunch compressors for SASE-FEL facilities, the projected transverse emittance can be diluted by magnetic multipole component errors in dipoles and dipole misalignments as well as by coherent synchrotron radiation (CSR). In this paper, we describe the multipole field tolerances and the misalignment tolerances of the first bunch compressor (BC2) for the TESLA Test Facility Phase-2 (TTF-2).

INTRODUCTION

In SASE-FEL and linear collider projects such as TTF-2, TESLA X-ray FEL, and TESLA linear collider, a high quality beam with small transverse emittance and high peak current should be supplied in order to achieve a saturation and a high brightness of SASE sources and a high luminosity of colliding beams. Generally, CSR is the main source of the transverse emittance growth in a bunch compressor (BC). However we can control the emittance growth due to CSR by several methods [1]. Since bending magnets may have magnetic multipole components as well as the dipole component, the transverse beam emittance can be diluted in a high dispersion region such as the magnetic chicane. Besides the multipole components, the transverse emittance can be diluted by the dipole field strength error and magnet misalignment errors. To control the emittance growth in the BC, bending magnets should be fabricated and aligned within their tolerances. We have used ELEGANT code to consider CSR induced emittance growth in investigating the multipole field, misalignment, and rotational tolerances of the TTF-2 first bunch compressor (BC2) [2].

TOLERANCES INVESTIGATION

Multipole Component Tolerances with CSR

The vertical magnetic field of a bending magnet in the horizontal middle plane can be expanded in a series of multipoles, which is given by

$$\begin{aligned} B_y(x,0) &= \sum_{n=0}^{\infty} B_n \frac{x^n}{n!} = (B_0\rho)\sum_{n=0}^{\infty} K_n \frac{x^n}{n!}\,, \\ &= \sum_{n=0}^{\infty} b_n \frac{(x+iy)^n}{a^n}\Big|_{y=0}\,, \\ &= B_0 + (B_0\rho)K_1 x + \frac{1}{2!}(B_0\rho)K_2 x^2 + \dots\,, \\ &= b_0 + b_1\frac{x}{a} + b_2\frac{x^2}{a^2} + b_3\frac{x^3}{a^3} + \dots\,, \end{aligned} \tag{1}$$

where x and y are the horizontal and vertical coordinates whose origin is the center of the bending magnet, a is the reference radius of expansion, and ρ is the bending radius [3]. Here $B_0 = b_0 = B_y(x,y)|_{x=0,y=0}$ is the magnetic field at the origin, and it is also given by $p_0/\rho q$ where p_0 is the momentum of the reference particle, and q is the particle charge. The momentum-normalized multipole component K_n is given by

$$K_n = \frac{B_n}{B_0\rho} = \frac{1}{B_0\rho}\,\frac{\partial^n B_y}{\partial x^n}\Big|_{x=y=0} = \frac{1}{B_0\rho}\frac{n!}{a^n}b_n\,. \tag{2}$$

If we choose that a is the half gap height between the magnet poles and estimate the field error at a horizontal middle point with $x = a$ and $y = 0$, $B_y(x = a, 0)$ is given by

$$B_y(a,0) = b_0 + b_1 + b_2 + b_3 + b_4 + \dots\,. \tag{3}$$

At the estimation point $(a, 0)$, the quadrupole, sextupole, octupole, and decapole component errors with respect to the dipole component b_0 are defined as

$$\frac{QM}{BM}\Big|_{x=a,y=0} = \frac{b_1}{b_0} = \rho K_1 a\,, \tag{4}$$

$$\frac{SM}{BM}\Big|_{x=a,y=0} = \frac{b_2}{b_0} = \frac{1}{2!}\rho K_2 a^2\,, \tag{5}$$

$$\frac{OM}{BM}\Big|_{x=a,y=0} = \frac{b_3}{b_0} = \frac{1}{3!}\rho K_3 a^3\,, \tag{6}$$

$$\frac{DM}{BM}\Big|_{x=a,y=0} = \frac{b_4}{b_0} = \frac{1}{4!}\rho K_4 a^4\,. \tag{7}$$

We have swept K_n for each dipole with ELEGANT including CSR wakefields while monitoring the projected transverse normalized emittance growth at the end of the bunch compressor. From Eqs. (4), (5), (6), and (7), the tolerance of the multipole strength error can be determined by a K_n which gives 2% emittance growth [2].

Misalignment Tolerances

With the help of the method described in the previous section, we can determine the multipole component tolerances. For the misalignment tolerance investigation, we have assumed that all dipoles have multipole component errors about 60% of the tightest tolerances. Under those

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Table 1: Parameters of TTF-2 BC2.

Parameter	Unit	Value
initial beam energy E	MeV	121
initial projected energy spread σ_δ	%	1.0
initial uncorrelated energy spread $\sigma_{\delta u}$	10^{-5}	5.0
initial horizontal emittance $\epsilon_{nx,i}$	μm	1.32
initial vertical emittance $\epsilon_{ny,i}$	μm	1.32
final horizontal emittance $\epsilon_{nx,f}$	μm	2.18
final vertical emittance $\epsilon_{ny,f}$	μm	1.34
bunch charge Q	nC	1.0
initial rms bunch length $\sigma_{z,i}$	mm	2.1
final rms bunch length $\sigma_{z,f}$	mm	0.3
momentum compaction factor R_{56}	mm	180.6
bending angle θ	deg.	18.0
maximum horizontal dispersion η_x	mm	346.1
maximum horizontal beam size σ_x	mm	3.47
bending radius ρ	m	1.62
pole width	mm	200
vacuum chamber width	mm	135
dipole geometric length	mm	500
half gap height between poles a	mm	12.5

artificial multipole component errors, we have tracked an electron bunch in the bunch compressor. By increasing the horizontal misalignment error Δx, vertical misalignment error Δy, or the rotational misalignment error $\Delta\phi$ while monitoring the projected transverse emittance growth, we can determine the misalignment tolerances. If we can use the real measured multipole component errors instead of our assumed 60% magnitude, the misalignment tolerances will be estimated more precisely.

TOLERANCES OF TTF-2 BC2

BC2 Beamline for Tolerance Investigation

We have investigated the tolerances of TTF-2 BC2 for its nominal operation conditions. Since the 3rd harmonic cavity will be turned on for the nonlinearity compensation in the longitudinal phase space during the nominal operation, the beam is decelerated from 136 MeV to 121 MeV [1], [4]. The main parameters of BC2 used in this investigation are summarized in Table 1. Here all energy spreads are the rms relative values, and all emittances are the projected transverse normalized rms values. For the tolerance investigations, we have used an optimized BC2 lattice shown in Fig. 1, where β-functions are asymmetric around the chicane, and α-functions are close to zero at the fourth dipole magnet (DM4). This asymmetric lattice helps in reducing the CSR induced projected horizontal emittance growth in the bunch compressor [1]. Although we have optimized the chicane beamline, ϵ_{nx} is increased to 2.18 μm at the end of the bunch compressor. However ϵ_{ny} is not significantly increased because the vertical CSR force is weak enough under the condition that the vertical dispersion η_y is zero.

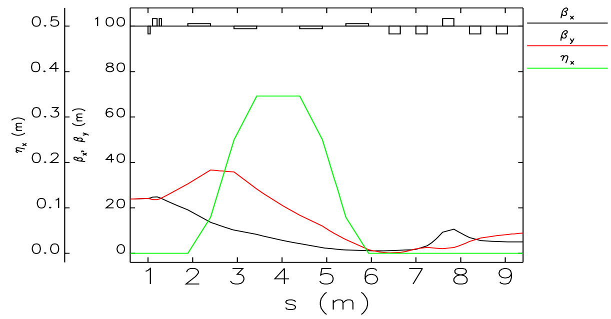

Figure 1: Beamline of TTF-2 BC2.

Quadrupole components in a bending magnets dilute the horizontal emittance because the horizontal dispersion is changed. Without consideration of CSR, the analytical formula of the quadrupole component tolerance is given by

$$\left|\frac{b_1}{b_0}\right| < \frac{1}{|\theta|}\frac{a}{\eta_x\sigma_\delta}\sqrt{\frac{2\epsilon_{x0}}{\beta_x}\left(\frac{\Delta\epsilon_x}{\epsilon_{x0}}\right)}, \tag{8}$$

where ϵ_{x0} is the initial projected horizontal emittance and $\Delta\epsilon_x$ is the projected horizontal emittance growth [5]. From Fig. 1 and Eq. (8), we can expect that the quadrupole component tolerances of the second and third dipoles (DM2 and DM3) will be tighter than those of the first and fourth dipoles (DM1 and DM4) because η_x is highest at DM2 and DM3. And the quadrupole component tolerance of DM1 will be tighter than that of the DM4 because β_x is higher at DM1 although the horizontal dispersion is the same at DM1 and DM4.

Sextupole components in bending magnets dilute the transverse emittance due to chromaticity and second order dispersion. Without consideration of CSR, the analytical formula of the sextupole component tolerance for the horizontal emittance growth is given by

$$\left|\frac{b_2}{b_0}\right| < \frac{1}{|\theta|}\frac{a^2}{\eta_x^2\sigma_\delta^2}\sqrt{\frac{\epsilon_{x0}}{\beta_x}\left(\frac{\Delta\epsilon_x}{\epsilon_{x0}}\right)}. \tag{9}$$

From Fig. 1 and Eq. (9), we can expect that the behavior of the sextupole component tolerance will be similar to that of the quadrupole component tolerance.

When a dipole magnet has a rotational error $\Delta\phi$, the horizontal magnetic field in the horizontal middle plane can be given by $|B_y(x,0)\sin\Delta\phi|$ which generates a nonzero vertical dispersion η_y and a vertical emittance growth in the chicane. Without consideration of CSR, the analytical formula of the rotational error tolerance is given by

$$\Delta\phi < \frac{1}{|\theta|}\frac{1}{\sigma_\delta}\sqrt{\frac{2\epsilon_{y0}}{\beta_y}\left(\frac{\Delta\epsilon_y}{\epsilon_{y0}}\right)}, \tag{10}$$

where ϵ_{y0} is the initial projected vertical emittance and $\Delta\epsilon_y$ is the projected vertical emittance growth [5]. Under CSR wakefields, the vertical CSR force becomes strong because

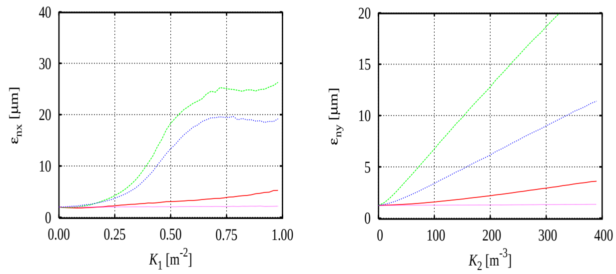

Figure 2: ELEGANT simulation results at the TTF-2 BC2: (left) quadrupole component error versus ϵ_{nx}, (right) sextupole component error versus ϵ_{ny}. Here red, green, blue, and magenta lines mean the projected transverse emittances at DM1, DM2, DM3, and DM4, respectively.

η_y is not zero. Hence the projected vertical emittance is significantly increased when a dipole in the bunch compressor has a rotational error. From Fig. 1 and Eq. (10), we can expect that DM1 has the tightest rotational error tolerance because β_y is highest at DM1.

Estimated Tolerances

From Fig. 2, we have determined K_1 and K_2 which give 2% projected transverse emittance growth ($\Delta\epsilon_{nx} = 0.0436$ μm, $\Delta\epsilon_{ny} = 0.0264$ μm). Hence the quadrupole and sextupole component tolerances are determined from Eqs. (4) and (5). Other multipole component tolerances can be obtained by the same method and are summarized in Table 2 where left and right values in a column mean the tolerances for the horizontal and vertical planes, respectively, and smaller bold-faced numbers mean the tightest tolerances of them.

Under artificial multipole component errors which are 60% of the tightest tolerances, we have investigated the misalignment tolerances by tracking with consideration of CSR. From Fig. 3, we have determined misalignment tolerances Δx, Δy, Δz, and $\Delta\phi$ which give 2% projected transverse emittance growth ($\Delta\epsilon_{nx} = 0.0421$ μm, $\Delta\epsilon_{ny} = 0.0278$ μm). Their tolerances are summarized at the bottom of Table 2. Here transverse misalignment tolerances are tight at DM2 and DM3 because the multipole component tolerances are tight at those dipoles, and the longitudinal misalignment tolerance is large at DM4 because α_x is close to zero at DM4.

To determine the tolerance of the magnet power supply ripple $\Delta I/I$, we have linked all four dipoles and applied the same error to them simultaneously. We should keep the magnetic power supply ripple smaller than 0.12% to control the emittance growth within 2%.

SUMMARY

We have investigated the magnetic multipole component tolerances and misalignment tolerances of dipole magnets for the TTF-2 first bunch compressor including the effect of CSR. The second and third dipoles have the tightest multipole component tolerances because they are located at the highest horizontal dispersion. The first dipole has the tightest rotational error tolerance due to the combined actions of the vertical CSR force under nonzero η_y and the highest β_y. We expect that those tolerances can be achievable by the current magnet fabrication and alignment technologies.

Table 2: Tolerances of TTF-2 BC2 for $a = 12.5$ mm.

	Unit	DM1	DM2	DM3	DM4
$\Delta b/b_0$	%	0.26	0.8	0.8	1.8
b_1/b_0	%	**0.38**, 0.55	**0.18**, 0.71	**0.06**, 1.94	**0.57**, ∞
b_2/b_0	%	1.01, **0.25**	0.04, **0.03**	0.14, **0.06**	5.70, **2.03**
b_3/b_0	%	16.9, **6.33**	0.39, **0.18**	**0.14**, 0.36	70.3, **60.6**
b_4/b_0	%	128, **52.7**	0.25, **0.12**	0.85, **0.24**	∞, **250**
$\Delta\phi$	deg.	0.07	0.18	1.65	3.21
Δx	mm	11.2	1.8	5.6	12
Δy	mm	2.9	1.4	1.4	12
Δz	mm	1.6	5	6	12
$\Delta I/I$	%	0.12			

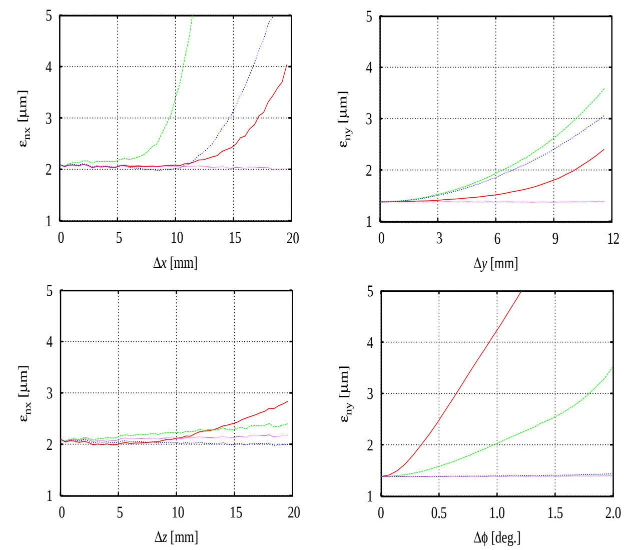

Figure 3: ELEGANT simulation results at the TTF-2 BC2: (upper left) horizontal misalignment error versus ϵ_{nx}, (upper right) vertical misalignment error versus ϵ_{ny}, (lower left) longitudinal misalignment error versus ϵ_{nx}, (lower right) rotational misalignment error versus ϵ_{ny}. Here color lines have the same meanings of Fig. 2.

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