REQUIREMENTS ON THE PULSED MAGNETS FOR THE BEST INJECTOR PERFORMANCE*

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Abstract
Instabilities in the booster extraction system may compromise the extracted beam quality deteriorating value of high-performance injector design. Here we discuss requirements and tolerances for the extraction system components and methods of increasing its performance.

INTRODUCTION

Modern injectors for synchrotron light sources are designed to produce electron beams with low emittance. Size and complexity of a low-emittance injector-accelerator strongly depend on the beam emittance value. However successful design of the accelerator lattice does not yet guarantee the same high quality of the beam delivered to the storage ring entrance. The emittance can be compromised during the beam extraction or transport, which would waste the cost and reduce the benefits of a high-performance accelerator design.

Pulsed magnets are essential part of any light source injector including these in the booster extraction and storage ring. Always a pulsed magnet waveform is far less reproducible as compared with a constant DC level of a static magnet. Amplitude jitter of the waveform results in the jitter of the trajectory of the beam after passing through the pulsed magnet. Similarly time-dependent waveform ripples dilute emittance of the bunch train where single bunches pass the magnet at different times and "see" different fields in it. These effects increase the phase space area occupied by the beam and reduce the beam quality.

In this paper we estimate effects from the pulsed magnet ripples and amplitude jitter on the beam emittance. We then discuss methods of reducing these detrimental effects on the beam emittance.

EMITTANCE DILUTION OF THE BEAM PASSING THROUGH A KICKER

Let us consider a simple but general case of the bunch train passing through a kicker with a sinusoidal modulation of the waveform (fig. 1). We assume that the every other bunch will be "flying" through the magnet at the moments corresponding to the opposite peaks $\pm\Delta$ of the waveform ripple. This would lead to the same situation as when the waveform changes shot-to-shot by 2Δ peak-to-peak. The overall phase space area covered by the particles will increase either on the same shot in the case of the waveform ripples or over a number of shots if there is amplitude irreproducibility of the waveform between the shots.

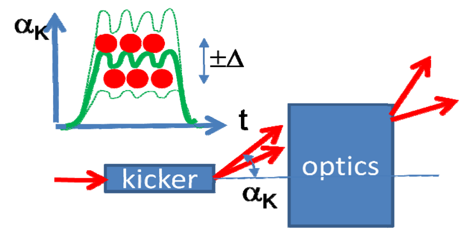

Fig. 1: Cartoon showing the train bunches passing through a kicker and receiving different deflections due to the waveform ripples.

We consider two particle distributions, which are shifted by $\pm\Delta$ in the phase space and calculate equivalent ellipses to evaluate the emittance dilution. For clarity we use the normalised coordinates $\tilde{X} = x\beta^{-0.5}, \tilde{PX} = (\alpha \cdot x + \beta \cdot px)\beta^{-0.5}$, where the Twiss parameters are taken at the kicker location (Fig. 2).

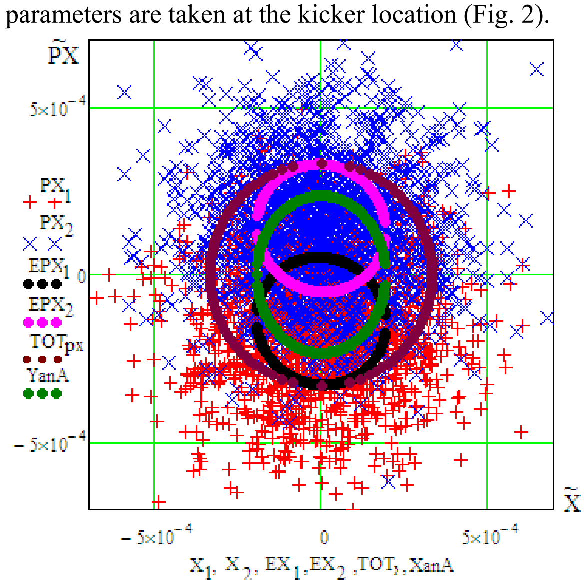

Fig. 2: Phase space of the beam disturbed by a pulsed magnet. (X_1 PX_1) and (X_2 PX_2) are phase spaces of two sets of bunches in the bunch train shifted in angle after passing through the kicker, (EX EPX) are equivalent circles corresponding to 1 rms size. (TOT_x TOT_{px}) is an equivalent circle for the disturbed beam distribution. (XanA, YanA) is the mismatched ellipse describing the 1 rms dimensions of the disturbed beam distribution.

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The radius of the circle that defines the new beam distribution is a combination of the radius for the "undisturbed" beam distribution and the angular amplitude error Δ. The phase space area covered by the circle TOT (Fig.2) is A_2:

$$\sqrt{A_2} = \sqrt{A_1} + \Delta\sqrt{\beta} \qquad (1)$$

or

$$A_2 = A_1 + \beta\Delta^2 + 2\Delta\sqrt{\beta A_1}$$

This area gives an estimate for reduction of the beam quality as a result of the errors in the kicker waveform.

Another way to estimate this effect is to use the "usual" emittance definition:

$$\varepsilon^2 = \langle x^2\rangle\langle px^2\rangle - \langle x\,px\rangle^2 \qquad (2)$$

In this case we get the following expression:

$$\varepsilon_2 = \varepsilon_1\sqrt{1+\beta\cdot\Delta^2/\varepsilon_1} \qquad (3)$$

Under the assumption that $\beta\cdot\Delta^2 << \varepsilon_1$, which is true for small Δ, the beam emittance is

$$\varepsilon_2 \approx \varepsilon_1(1+\beta\cdot\Delta^2/2\varepsilon_1) \qquad (4)$$

This emittance covers the equivalent particles phase space, but does not include the phase space ("beta") mismatch. The beta mismatch induces emittance increase by a factor of B_{mag}, which is

$$B_{mag} = (\beta_*\cdot\gamma + \beta\cdot\gamma_* - 2\alpha\cdot\alpha_*)/2 = \frac{\varepsilon_1}{\varepsilon_2}(1+\beta\cdot\Delta^2/2\varepsilon_1) \qquad (5)$$

$$= (1+\beta\cdot\Delta^2/2\varepsilon_1)/\sqrt{1+\beta\cdot\Delta^2/\varepsilon_1}$$

Subscripts * denote mismatched parameters describing the beam. Again assuming Δ to be small, the equation 5 becomes:

$$B_{mag} \approx 1 + (\beta\cdot\Delta^2/2\varepsilon_1)^2/2 \qquad (6)$$

Comparing equation 4 and 6, we can see that the beta mismatch effect is a second order effect, therefore it can be neglected.

Including the beta mismatch, the new effective emittance is ((XanA, YanA) in Fig. 2):

$$\varepsilon_3 = \varepsilon_2 B_{mag} = \varepsilon_1(1+\beta\cdot\Delta^2/2\varepsilon_1)B_{mag} \qquad (7)$$

Equation 7 includes the emittance increase due to the waveform error and beta-mismatch. It is the same as the small approximation beam emittance. Comparing with the equation 1 definition, this way gives the emittance is the second order effect.

The above equations only apply to the effects caused by the beam angle deviations. To be more general, the beam position and angle deviation are x_c and x'_c. By substituting $\beta\Delta^2/2\varepsilon_1$ with $(\beta x'^2 + 2\alpha\cdot x\cdot x' + \gamma x^2)/2\varepsilon_1$, the above expressions apply to the general case of the emittance dilution through instability of the beam angle and coordinate due to the pulsed magnet errors.

As an example we take parameters of the extraction kicker in the NSLS-II booster [1] (ε_1=40 nm rad, β_x=8.5 m, α_x=0.4). Taking the error Δ=0.4% of the kicker angle 5 mrad we obtain 67% error in emittance as estimated using (1) as compared with 4% by using (3) or (7). This significant discrepancy in the calculated emittance comes from (1) being a gross overestimate of the phase space area due to assumptions: a) disturbed beam emittance is defined by the phase space dimensions of the undisturbed beam and b) that the beam is still matched, i.e. that the beam Twiss parameters are the same as for the kicker without errors.

The code ELEGANT [2] was used to simulate the emittance dilution due to extraction kicker error by tracking 100 bunches, which is comparable with the design bunch number in a bunch train. Table 1 compares the tracking result with the analytical estimates. With small error, they agree with each other well.

Table 1. Relative emittance increase through estimates and tracking.

Δ	0.4%	0.8%
Δε/ε (beam emittance, Eq. 4)	4.25%	17%
Δε/ε (beta mismatch, Eq.6)	0.090%	1.45%
Δε/ε (beam emittance, tracking)	4.25%	16.25%
Δε/ε (beta mismatch, tracking)	0.091%	1.13%

NSLS-II BOOSTER EXTRACTION KICKER

Similar to the ASP booster [3] the NSLS-II booster extraction system consists of four slow orbit bumpers, pulsed and DC septa and extraction kicker as shown in Figure 3. The orbit of the circulating bunch train is moved out toward the extraction septum over several hundred turns by the slow orbit bumps and is kicked into the extraction septum by the extraction kicker.

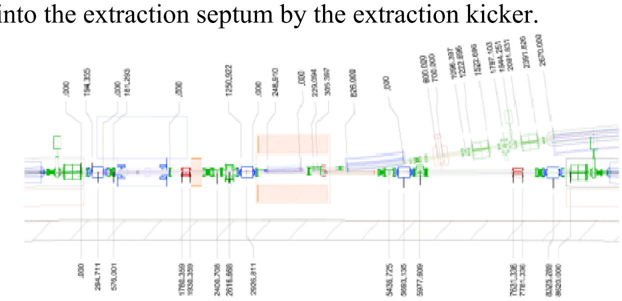

Fig.3: Booster extraction layout

To extract the bunch train from booster during one turn, the extraction kicker needs to build up field fast and maintain a wide flat top waveform. This is a challenging task for 200 ns rise time and 300 ns flat-top.

NSLS-II Pulsed Magnet lab has succeeded in achieving the required quality of the waveform. The recent experimental result, shown in figure 4, using 4 parallel pulse forming lines (PFLs) achieves 0.7% ripple and droop. We are planning in future to use 4 parallel pulse forming networks (PFNs) with 12 cells each to further reduce ripple and droop on the flat top of current pulse.

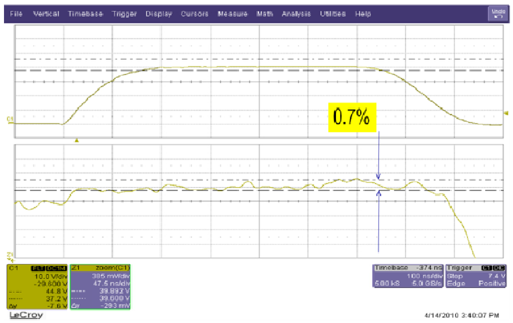

Fig. 4: Measured pulse waveform using 4 parallel PFLs.

ERRORS AND MINIMIZATION OF THEIR IMPACT ON THE BEAM EMITTANCE

In order to reduce the impact of the pulsed magnets on the beam emittance it is obviously useful to reduce their strength, so that the angular or coordinate jitter induced by a pulsed magnet is much less than the beam natural divergence or the beam size respectively.

Technical methods of reducing errors in the pulsed magnet waveforms are: a) to use multi-cell PFNs with the large number of cells, so the ripple wavelength becomes short and ripple amplitude becomes small and b) to use a high-quality charging power supply with the small jitter of the output voltage shot-to-shot. We also note that the coating of the ceramic vacuum chamber reduces ripples in the waveform due to the skin effect that leads to efficient attenuation of the high frequency content in the waveform.

More advanced ideas can be explored. One is to use the stripe line kicker at the BSR transport line to compensate the extraction kicker droop, as shown in Figure 4. The optimal phase advance between them is 180+360*n degree, where n is integer. In the booster to storage ring transport line, the optimal position is after Q4 quadrupole [1]. Initial design of the stripe line can compensate up to 1% droop, 50 μrad. It is a 0.6m long stripline magnet with 1.25 kV power supply. In order to compensate the extraction kicker field droop within 300 ns, the stripline driver must be wideband, with frequency bandwidth up to 250MHz.

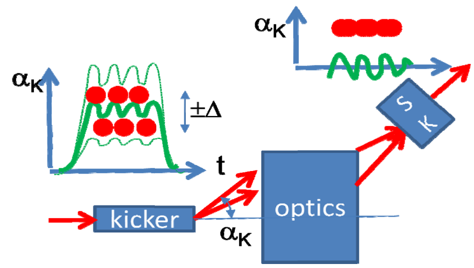

Fig. 5: Extraction kicker droop compensation with a stripline.

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