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FINDING BEAM LOSS LOCATIONS IN A LINAC WITH OSCILLATING DIPOLE CORRECTORS*

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Abstract

The paper proposes a method of finding the beam loss locations in a linac. If the beam is scraped at an aperture limitation, moving its centroid with two dipole correctors located upstream and oscillating in sync produces a line at the corresponding frequency in spectra of current-sensitive devices, loss monitors, and BPMs downstream of the loss point. The phase of this signal contains information about the location of the beam loss. Proof-of-principle measurements performed at the Fermilab Linac are presented.

INTRODUCTION

Transporting a beam with low losses is important requirement for beam lines or linear accelerators. While a large accidental loss can be detected by comparing the beam current in different parts of the linac [1], small chronic losses are usually identified using radiation monitors. An alternative solution proposed by V. Lebedev and used in CEBAF [2], employs that a beam loss caused by beam scraping on a physical aperture is typically associated with a sharp dependence of the loss signal on the beam position at that location. In this case, oscillating a dipole corrector current at the beginning of the linac produces a signal at that frequency in the beam current signal measured at the end of the linac. Such measurement does not provide an absolute value of the loss but rather the difference in the loss over the range of the beam oscillation. While the latter is lower than the total loss, the synchronous detection allows to greatly improve the overall sensitivity. For sufficiently long measurement time, the oscillations resulting in a detectable effect can be made small enough so that the emittance growth is negligible. What follows below is a development of this idea, with a more detailed derivation presented in [3].

FORMULAE

Trajectory deviation excited by a dipole kick turns zero in the locations where the betatron phase advance $\varphi(z)$ counted from the corrector is πn. Hence, a loss is such location remains unidentified. To address this, the procedure can be repeated with another corrector shifted from the first one by the betatron phase advance of $\varphi_x \neq \pi n$. To speed the process up, both correctors can be oscillated simultaneously with the same frequency ω and a phase difference in time of φ_t. Corresponding trajectory deviation downstream is

$$x_0(z,t) = \theta_1\sqrt{\beta_x(z)\beta_{x1}}\sin\varphi(z)\sin\omega t + \\ +\theta_2\sqrt{\beta_x(z)\beta_{x2}}\sin(\varphi(z)+\varphi_x)\sin(\omega t+\varphi_t), \quad (1)$$

where θ_i is the deflection amplitude, $\beta_x(z)$ and β_{xi} are the beta-functions along the line and in the location of i-th corrector, and i= 1, 2 is the corrector number. In all locations, the beam position oscillates at the same frequency but with amplitude and phase dependent on z:

$$x_0(z,t) = A(z)\sin(\omega t + \varphi_1(z)) \quad (2)$$

In the model where the aperture limitation is a flat-edge “scraper” separated from unperturbed central trajectory by the offset d, the current intercepted by the scraper is

$$I_s = \int_d^\infty j(x-x_0)dx = \int_d^\infty j(x)dx + j(d)x_0 - \frac{dj}{dx}(d)\frac{x_0{}^2}{2} + \cdots. \quad (3)$$

For the perturbations much smaller than the beam size, only first terms are significant. Using Eq. (2) and Eq. (3),

$$I_s \approx \int_d^\infty j(x)dx + j(d)A(z)\sin\big(\omega t+\varphi_1(z)\big) - \\ -\frac{dj}{dx}(d)\frac{1}{2}\Big(A(z)\sin\big(\omega t+\varphi_1(z)\big)\Big)^2 \equiv \\ \equiv I_{s0} + I_{s1}\sin(\omega t+\varphi_1(z)) + \\ +I_{s2}\Big(1-\cos\big(2\cdot(\omega t+\varphi_1(z))\big)\Big). \quad (4)$$

Let assume that the spatial current density distribution is scaled along the beam line as the beam rms size σ_b:

$$j(x) = \frac{I_0}{\sigma_b}J\left(\frac{x}{\sigma_b}\right), \ \sigma_b = \sqrt{\beta_x(z)\varepsilon_0}, \quad (5)$$

where ε_0 is the rms beam emittance, I_0 is the total beam current, and the dimensionless function $J\left(\frac{x}{\sigma_b}\right)$ does not change along the beam line. In this model, the loss linear component is determined by the scraper position and oscillation amplitude, both normalized by the rms beam size:

$$\frac{I_{s1}}{I_0} = \frac{A(z)}{\sigma_b}J\left(\frac{d}{\sigma_b}\right). \quad (6)$$

At the specific choice of deflection amplitudes and the time delay between correctors waveforms,

$$\theta_2\sqrt{\beta_{x2}} = \theta_1\sqrt{\beta_{x1}}\,, \quad \varphi_t = \pi \pm \varphi_x, \quad (7)$$

Eq. (2) is simplified [3] to

$$x_0(z,t) = \theta_1\sqrt{\beta_x(z)\beta_{x1}}\sin\varphi_x\sin\big(\omega t+\varphi_1(z)\big) \quad (8)$$

with the phase changing linearly with the betatron phase:

$$\varphi_1(z) = \pm(\varphi(z)+\varphi_x). \quad (9)$$

The amplitude of the current first harmonic becomes dependent only on the relative penetration of the scraper:

$$\frac{I_{s1}}{I_0} = \frac{\theta_1\sqrt{\beta_{x1}}}{\sqrt{\varepsilon_0}}J\left(\frac{d}{\sigma_b}\right). \quad (10)$$

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The phase of the beam current first harmonic measured anywhere downstream carries information, through Eq. (9), about the betatron phase at the loss location (if the scraper is on the negative side of the trajectory, the only difference is the shift of the phase in Eq. (10) by π).

The procedure discussed above assumes that the optics is known, the initial Twiss functions are defined according to the beam phase space distribution in that location ("matched beam"), and the relationship between correctors' signals is set by Eq. (7) with optical functions defined for the matched beam. If the latter is not the case (e.g. the optics is not measured accurately), the signals reported by the Beam Position Monitors (BPMs) can be still interpreted through Eq. (8) and (9) but with the different meaning of Eq. (7): now it defines the initial Twiss functions. Since the beam is not matched anymore, $\sigma_b \neq \sqrt{\beta_x(z)\varepsilon_0}$, different locations will not be probed evenly. However, for not dramatic deviations from the matched case, most of losses still would be identified. Importantly, phases of the BPM position signals measure the betatron phase advance in this optics, creating a "reference system" that maps the phases against known physical BPM locations. Therefore, comparing the first-harmonic phases of the loss signal in current-measuring devices or radiation monitors with the BPM position phases might help to locate the loss more accurately.

Note that recording the BPM responses to the deflection by two dipole correctors is equivalent to the differential trajectory analysis. The advantage is that they can be made parasitically (because the oscillation amplitude is low), and, if made with the matched-beam settings, deliver immediately the values of the β-function and phase advance.

TEST

The proof-of-principle test was performed at Fermilab 400 MeV H^- Linac [4]. The Linac front end, consisting of the ion source, 750 keV RFQ, and Medium Energy Beam Transport (MEBT) supplies the 25 mA, 30 µs H^- beam pulses to the Drift Tube Linac (DTL). Five DTL tanks accelerate the beam to 116 MeV, followed by the Side-Coupled Linac (SCL). Seven SCL RF modules, with 4 section in each, increase the energy to 400 MeV. BPMs, toroids, and Beam Loss (radiation) Monitors (BLMs) are located between the tanks and sections. In these measurements, the sum signal from the BPM plates ("BPM intensity") is used as an indicator of the beam intensity as well.

Currents of two horizontal dipole correctors in the MEBT were modulated at the frequency of about 0.5 Hz. The changes in the correctors' currents were made by the program [5] at each beam pulse. While the Linac RF pulses followed at 15 Hz, beam pulsing was periodically interrupted at the time of manipulations in the downstream machines, so that the average beam pulse frequency was 13 Hz. Correspondingly, the corrector currents were sinusoidal with respect to the pulse number rather than in time, but for brevity we will refer to the signals as 0.5 Hz lines.

The amplitudes and phase difference between correctors' oscillations were set according to Eq. (7) with the optical functions reconstructed according to simulations presented in Ref. [6]. The test was performed during regular operation in a parasitic mode, and no changes in the average beam losses or transmissions were observed. In the total acquisition time of 11.5 minutes, 300 oscillation periods with 29.99 points per period were recorded. The signals included readings of the corrector currents, 8 toroids, 31 BPM positions, 22 BPM intensities, and 19 BLMs.

The oscillation line was clearly observed in the Fourier spectra of all signals (see example in Fig. 1). The signal-to-noise (S/N) of a response was characterized by the ratio of the 0.5 Hz harmonic amplitude to the mean value of all amplitudes in the recorded spectrum.

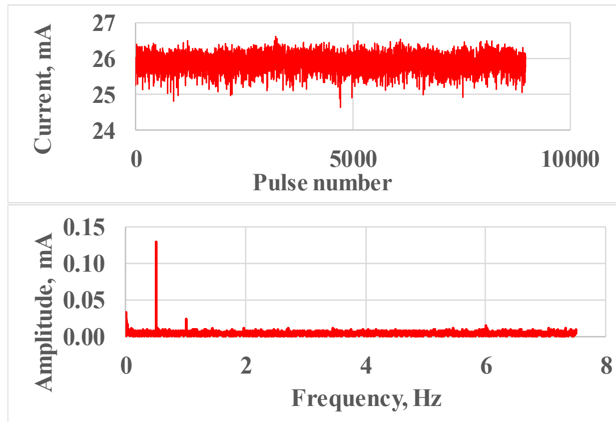

Figure 1: Signal of the first toroid in time (top) and frequency (bottom) domains. S/N=36. Z=30.7 m.

The oscillation amplitudes in the BPM positions varied from 0.04 mm to 0.39 mm (Fig. 2), with S/N ranging from 54 to 383.

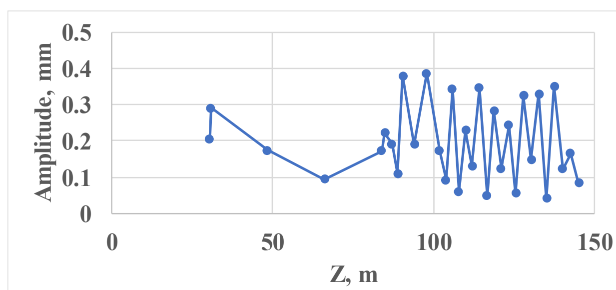

Figure 2: Oscillation amplitudes in the BPM position along the Linac. Z=0 corresponds to the ion source.

The growth of the time-average emittance caused by the oscillations can be estimated as

$$\frac{\delta\varepsilon}{\varepsilon} \approx \frac{A^2}{2\sigma_b{}^2}\,. \tag{11}$$

Estimation made with the maximum value in Fig. 2 and the typical rms beam size measured in the Linac, 3 mm, predicts the emittance dilution about 1%.

All current-measuring devices exhibited the 0.5 Hz line with the S/N ratio of 17-36 for toroids and 4-30 for BPM

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intensities. Relative amplitudes (i.e. an oscillation amplitude divided by the average value of the signal) are shown in Fig. 3, and phases of the signals are in Fig. 4.

The first toroid shows the highest relative amplitude (0.5%), indicating that the first loss point is immediately at the Linac entrance, where the beam is known to be intentionally collimated. The first harmonic amplitude is by 6 times higher than the one of the second harmonic, indicating an asymmetrical scraping.

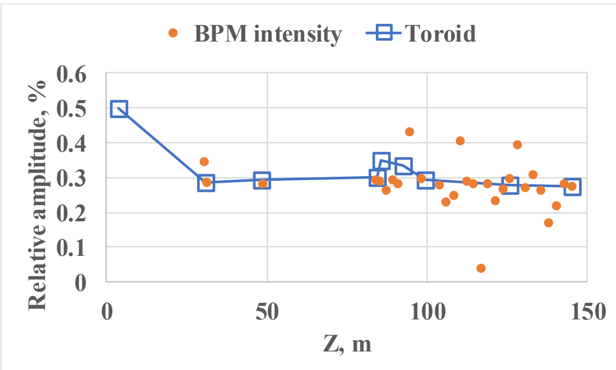

Figure 3: Relative amplitudes of the toroids and BPM intensities along the Linac.

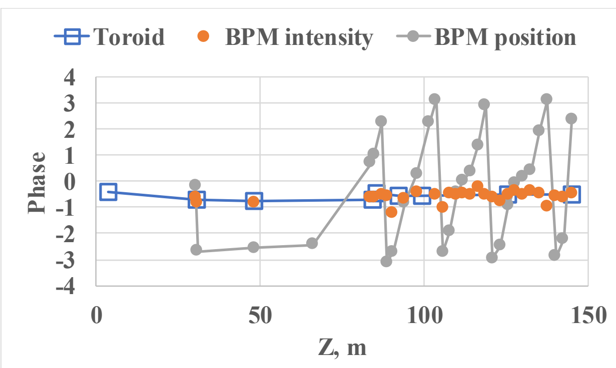

Figure 4: Phases of 0.5 Hz signal in toroids, BPM intensities and positions along the Linac.

In the next measurement location, around Z=30 m, both amplitude and phase of the 0.5 Hz line differ from the first point. Therefore, there is at least one loss point in between. To analyse it, the signal of the first toroid is subtracted from the second one (both relative). The amplitude of the difference is 0.24%, and the phase is shifted by ~π from the first toroid's phase. Unfortunately, due to lack of dipole correctors in the DTL at Z<30 m, one cannot use this information to decrease losses in both locations simultaneously. In the downstream DTL locations (Z < 80 m), the signals stay constant and equal for both toroids and BPM intensity signals, indicating no losses.

In the SCL (Z= 80-145 m), the toroids signals are also mainly stable both in amplitude and phase, which may be interpreted as losses in SCL being significantly lower than in the two DTL locations.

The phase of the BPM position signals in SCL (Fig. 5) increases monotonically (within (-π, +π)) along the Linac as expected from Eq. (9).

Most of BLMs located in the SCL exhibit clear 0.5 Hz line (S/N > 4), and typically those with S/N < 4 have low average level of radiation as well. In distinction to toroids and BPM intensities, the BLMs are sensitive to a local loss, and, therefore, the phase of the BLM signal should correlate with phases of the neighbouring BPM positions or those phases shifted by π if the loss occurs on the negative side of the horizontal plane (dotted line in Fig. 5). While majority of BLM signals do follow this prediction, we do not have an explanation for a handful of points that are too far from the phase of nearby BPMs' position lines.

Contrary to the toroid signals, the amplitudes of the BPM intensities vary significantly in SCL. However, they do not change in average, that would be more natural in the case of actual beam losses, and the phase stays almost constant as well. As an additional check, the 0.5 Hz line was analysed in the differences between the BPM intensity signals in neighbouring BPMs. The phases of these differential amplitudes, also shown in Fig. 5, do not correlate with the BPM position phases. Likely the BPM intensity signals in SCL do not represent correctly the beam intensity at the sub-percent level. It could be because of peculiarities of BPMs or, for example, the signals might be affected by the secondary electron produced by scattered fast ions.

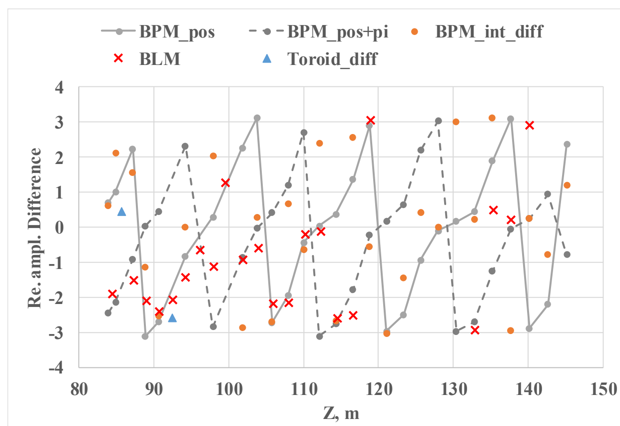

Figure 5: Comparison of phases observed in signals of BPM positions, BLMs, and differences between relative intensity signals of neighbouring BPMs. Note that +π and -π phase is the same, so that the lines on the plot connecting such points do not represent an interpolation.

CONCLUSION

Two dipole correctors oscillating with the properly chosen amplitudes and phase delay generate a signal at the corresponding frequency in the BPM positions and in current-measuring devices downstream of a beam loss location. Such signals were experimentally observed in the first test at the Fermilab Linac, indicating that majority of the beam loss downstream of the MEBT occurs in two upstream Linac locations.

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