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TRANSVERSE BEAM PROFILE MEASUREMENTS FROM EXTRACTION LOSSES IN THE PS

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Abstract

During Multi-Turn Extraction (MTE) of continuous beams in the Proton Synchrotron (PS) at CERN, losses are generated on the blade of both the active and non-active septum during the rise time of the extraction kickers. Utilising pCVD diamond detectors, secondary signal generated from these losses is measured. The high time resolution of these devices allows for insight into the detail of the horizontal beam distribution during extraction, and hence useful information such as the horizontal beam emittance may be computed. In this contribution, FLUKA simulations to relate the detector response to the beam impact conditions on the blades of the two septa are presented. The dependence on the beam angle, magnetic fringe field, and positioning of the detector is explored. Finally, realistic beam distributions are used to determine expected signal profiles at each septum.

INTRODUCTION

By the end of 2015, the CERN PS Multi-Turn Extraction (MTE) [1, 2] has become operational [3]. Since then, this complex beam manipulation has been constantly developed to improve its performance [4–6] and make it ready for future challenges [7, 8]. Beam splitting due to resonance crossing is at the heart of MTE: by changing the horizontal tune, a fourth-order resonance is crossed and the beam is partly trapped in the four stable islands surrounding the origin. The beam can then be extracted over five turns: the beam in islands is extracted first and over four turns, while the beam left in the centre is extracted last and over a single turn.

The longitudinal beam structure just prior to extraction is continuous, so that during the extraction kickers rise-time beam losses are observed due to the beam sweeping through the blade of the dummy or extraction septum magnets (the first installed in the PS straight section (SS) 15 and the latter in SS16). The so-called dummy septum has been installed to shadow the extraction one and to create a location in which controlled beam losses are concentrated [9, 10].

The beam losses at extraction are a source of activation, but they could also be exploited to provide information on the transverse beam distribution. In [5] a possible method to reconstruct the transverse beam distribution starting from the accurate measurement of the losses as a function of time had been proposed. In this paper, the process of beam-matter interaction is simulated and this opens up the possibility to reconstruct the horizontal emittance of the beam.

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THE PROPOSED METHOD

In the PS ring, two diamond Beam Loss Monitors (BLMs) [11] have been installed on the main magnet units just downstream of SS15 and SS16 where the dummy and the extraction septa are installed. These devices are capable of providing the turn-by-turn losses with sub-turn sampling rate. Thus, they allow to distinguish between the losses generated by the islands and the core when they sweep through the blade of the dummy or extraction septa. An example of the raw signal recorded with BLM15 is shown in Fig. 1. The difference in peak height is due to the difference in rise-time of the extraction kickers for the island and the core [4].

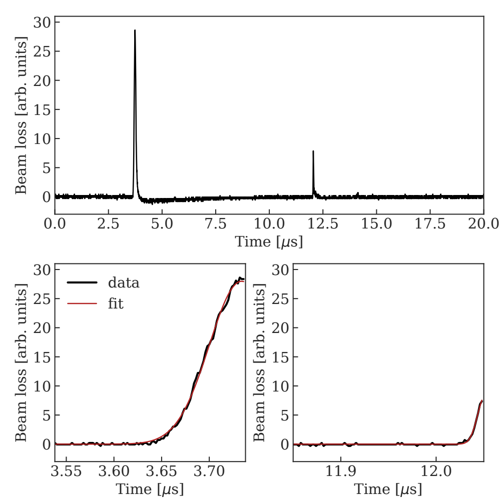

Figure 1: Top: Example of BLM15 signal $\ell_m(t)$ recorded in SS15. The losses generated by the island sweeping through the blade of the dummy septum cause the first spike, the second one represents the losses of the core. Bottom: detailed views of the island and core losses (left and right plot, respectively) together with a fitted Gaussian model (from [5]).

The horizontal beam distribution is described as

$$\rho(x,t) = \frac{N_p}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{1}{2}\left(\frac{x-\mu(t)}{\sigma}\right)^2\right], \quad (1)$$

where N_p is the total beam intensity, σ the beam size, and $\mu(t)$ the displacement during the rise time of the kickers, i.e.

$$\mu(t) = \frac{A}{2}\left\{\sin\left[2\left(t-\frac{\pi}{4}\zeta\right)\frac{1}{\zeta}\right]+1\right\},\ 0 \le t \le \frac{\pi}{2}\zeta, \quad (2)$$

where A is the maximum horizontal beam displacement at the location where the losses are measured and

$$\zeta = \frac{\tau_\alpha}{\arcsin(1-2\alpha)}, \quad (3)$$

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where τ_α is the time during which the kicker sweeps particles through the amplitude interval $[\alpha A, (1-\alpha)A]$. Typically, we use $\alpha = 0.1$ and $\tau_{0.1}$ is 350 ns for the kickers extracting the islands [12].

The measured losses $\ell(t)$ can be obtained as

$$\ell(t) = \frac{N_p/5}{\sqrt{2\pi}\,\sigma}\frac{\tau}{\tau_{\text{rev}}}\int_{x_s^-}^{x_s^+} \exp\left[-\frac{1}{2}\left(\frac{x-\mu(t)}{\sigma}\right)^2\right] \mathrm{d}x, \quad (4)$$

where $x_s^\pm = x_s \pm \Delta/2$ and x_s and Δ_s are the central position and width, respectively, of the dummy septum (or magnetic septum) blade, τ_{rev} is the revolution time, i.e. 2.1 µs at 14 GeV/c, τ is a given time interval used to normalise the measured losses, and N_p is the total beam intensity.

Note that $x_s = \hat{x}_s - \hat{x}_b - \hat{x}_{co}$, where $\hat{x}_s$, $\hat{x}_b$, and $\hat{x}_{co}$ represent the dummy septum position with respect to the zero closed orbit, the amplitude of the slow bump, and the value of the closed orbit, respectively. These quantities depend on the location along the ring and on whether the island or the core are considered. Therefore, from Eq. (4) σ can be evaluated from the knowledge of $\ell(t)$ (obtained from beam measurements), and $\mu(t)$ (obtained from the characteristics of the kicker magnets and of the ring optics). This approach can be used to determine emittance of the core and island, assuming the knowledge of the optical functions of core and island and of dispersion function.

NUMERICAL SIMULATIONS

The MAD-X [13] model of the PS ring, including the settings needed to simulate the beam splitting performed with MTE, has been used to generate the initial beam distribution in the horizontal phase space. The vertical beam distribution has been added as a standard Gaussian with typical one sigma normalised beam emittance $\epsilon_V^* = 4.08$ µm, as the dependence of the simulations' results on the actual value of ϵ_V^* should be negligible. This is justified by the fact that the two transverse planes are, to a large extent, decoupled.

An initial beam distribution filling the island that is extracted first has been generated by starting from a set of Gaussian-distributed particles, corresponding to a value of ϵ_H^* of 7.31 µm, centred in the fixed point located inside the island. These initial particles are then tracked for $N_{\text{fil}} = 2048$ turns, so that they can filament and adapt to the shape of the island and only those that are still inside the island at N_{fil} are used to simulate the interaction with the septum blade. The horizontal beam distribution is built including the closed-orbit deformation generated by the slow bumpers installed in the extraction region and that are used to push the beam close to the blade of the dummy and extraction septum magnets [12]. In a second stage, the displacement of the centre of the island and of the beam core generated by the extraction kickers is computed, using the function (2) and the nominal strength of the kicker magnets.

Detailed geometry of the region around the dummy and extraction septa was implemented in FLUKA [14–16], with the aid of Python program Line Builder [17] to place elements along the curved trajectory, s, based on the existing MAD-X model. The geometry includes the tanks enclosing both septa, concrete shielding around the dummy septum, the main ring combined-function magnets MU15 and MU16 and models for the (B2-type) pCVD diamond detectors positioned above the magnets. 3D field maps in the combined-function magnets were included, as well as a constant field set to give a nominal 30 mrad kick within the extraction magnet. Successful bench-marking studies to confirm accurate tracking of beam protons over an extended (13 main magnets) version of the geometry were carried out.

In order to simulate the extraction process, the transverse outer island distribution was sampled from as a continuous function of time, over the kicker rise-time period of ≈600 ns. The nonlinear horizontal offset and corresponding angular changes applied to particles associated with Eq. (2) were computed and included in sampling. Scoring of energy deposition in the sensitive material of the diamond detectors due to secondary particles generated in beam-septum interactions was then collected cumulatively in 10 ns bins to allow for sufficient statistics per time slice.

Analysis of primary protons arriving downstream from the dummy septum during the extraction process provided κ_{FLUKA}, the fraction of protons lost in interactions with the blade from the beginning of the kicker rise to the peak of the signal. The corresponding energy deposition in the sensitive material of the diamond detector in SS15 has been computed in preparation to provide an additional scaling factor between simulation data and measured signal, pending calibration data for the specific device installed. Simulations performed whilst neglecting the angular change due to the kicker rise confirmed that further complications arising from this additional time dependence do not need to be considered in this analysis.

A comparison between data obtained from these simulations and measurements performed with a beam with $N_p = 1.9 \times 10^{13}$ can be seen in Fig. 2. Note that in the data analysis only the rising front of the signal will be used, since discrepancies arising after the peak associated with electronics readout are expected.

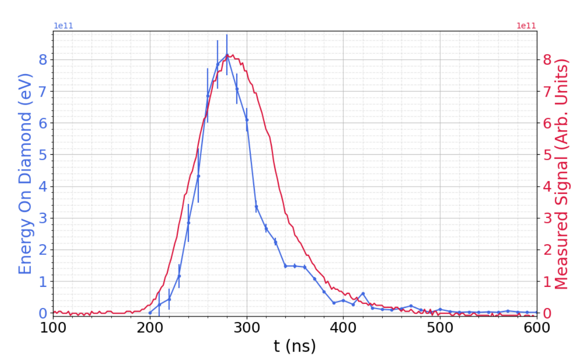

Figure 2: Expected energy deposition on the active material of the SS15 diamond detector from simulations (blue), overlaid with measured data (red).

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BEAM-EMITTANCE RECONSTRUCTION

The FLUKA simulations described in the previous section are essential for the calibration of the measured signals provided by the diamond BLMs. Indeed, $\ell_{\mathrm{m}}(t)$ as given in Fig. 1 should be normalised and this has been done according to

$$\ell(t) = \kappa_{\mathrm{FLUKA}} \frac{N_{\mathrm{p}}}{5} \frac{\ell_{\mathrm{m}}(t)}{\int_0^\tau \ell_{\mathrm{m}}(t)\mathrm{d}t} = \hat{\kappa} \frac{N_{\mathrm{p}}}{5} \ell_{\mathrm{m}}(t), \tag{5}$$

where $\hat{\kappa} = \kappa_{\mathrm{FLUKA}} / \int_0^\tau \ell_{\mathrm{m}}(t)\mathrm{d}t$, $\tau = 270\,\mathrm{ns}$, $\kappa_{\mathrm{FLUKA}} \approx 3.87 \times 10^{-2}$, and only the part of the loss signal up to the peak, which is assumed to be at $t = 270\,\mathrm{ns}$, is used in our analyses as already stated. Therefore, the model (4) becomes

$$\ell_{\mathrm{m}}(t) = \frac{1/\hat{\kappa}}{\sqrt{2\pi}\,\sigma} \frac{\tau}{\tau_{\mathrm{rev}}} \int_{x_s^-}^{x_s^+} \exp\left[-\frac{1}{2}\left(\frac{x-\mu(t)}{\sigma}\right)^2\right] \mathrm{d}x, \tag{6}$$

and $\tau/(\kappa_{\mathrm{FLUKA}}\, \tau_{\mathrm{rev}}) \approx 3.32$.

It can be observed that each of the loss peaks in $\ell_{\mathrm{m}}(t)$ can be represented as a Gaussian of the form

$$\ell_{\mathrm{m}}(t) = \frac{a}{\sqrt{2\pi}\,\sigma_t} \exp\left[-\frac{1}{2}\left(\frac{t-t^*}{\sigma_t}\right)^2\right], \tag{7}$$

where it is immediate to observe that $\mu(t^*) = x_{\mathrm{s}}$, i.e. the loss peak occurs when the beam centre crosses the septum blade.

The start of the losses occurs when the rise of the kickers is in the linear part of the sine function (2), hence, it is justified to approximate the sine with its argument and Eq. (6) becomes

$$\ell_{\mathrm{m}}(t) \approx \frac{\Gamma\, \Delta_{\mathrm{s}}}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{1}{2}\frac{A^2}{\zeta^2}\left(\frac{t-t^*}{\sigma}\right)^2\right], \quad \Gamma = \frac{\tau}{\hat{\kappa}\, \tau_{\mathrm{rev}}}, \tag{8}$$

where it has been assumed that with an appropriate time shift defined as $\Delta t = x_{\mathrm{co}}\, \zeta / A$ it is possible to get rid of the contribution of the closed orbit and integral in Eq. (6) has been computed trivially. At this point, Eqs. (7) and (8) can be used to establish a link between σ and σ_t, namely

$$\sigma = \frac{A}{\zeta} \sigma_t. \tag{9}$$

Note that to ensure the identity between the Gaussians in Eqs. (7) and (8), an additional scaling parameter b needs be used as global factor in Eq. (8), and it has the value

$$b = \frac{a}{\Gamma\, \Delta_{\mathrm{s}}} \frac{A}{\zeta}. \tag{10}$$

The data collected during an intense measurement campaign aimed at studying the behaviour of MTE beam as a function of total beam intensity [5] have been used to probe the performance of the proposed method to reconstruct the transverse beam sigma in the horizontal phase space.

A subset of the data collected has been considered and treated. This includes a fitting of the loss peaks corresponding to the island and the core (see Fig. 1) with a Gaussian model as in Eq. (7). Then, the beam sigma has been derived by applying Eq. (9) and the results are

$$\sigma_{\mathrm{isl}} \approx 2.76\ \mathrm{mm} \qquad \sigma_{\mathrm{core}} \approx 2.76\ \mathrm{mm}. \tag{11}$$

Note that the core deserved a special treatment. In fact, the value of τ_α is not the same for the two kickers used to extract the core, as one features $\tau_{0.1} = 86\,\mathrm{ns}$ and the second one $\tau_{0.1} = 56\,\mathrm{ns}$. Most of the displacement of the beam core is generated by the kicker with $\tau_{0.1} = 56\,\mathrm{ns}$. For this reason, the shape of the position change during extraction of the beam core has been fitted using the function (2) to derive an equivalent rise time, which resulted in $\tau_{0.1} = 56\,\mathrm{ns}$, confirming the observation made.

The knowledge of the beta-function and of the dispersion for the core, obtained by using MAD-X [13], allows reconstructing the value of the normalised emittance in the horizontal plane that reads $\epsilon^*_{\mathrm{H,core}} \approx 3.66\,\mathrm{\mu m}$, where $\sigma_p = 0.5 \times 10^{-3}$ has been used for the momentum spread.

No attempt is made to reconstruct the emittance for the island, as, in this case, the beam dynamics is fully nonlinear, and the definition of a beam emittance, i.e. a concept suitable for linear beam dynamics, is of little use.

CONCLUSIONS AND OUTLOOK

In this paper, a method to reconstruct the transverse beam parameters in the horizontal plane based on extraction losses measured by diamond detectors has been presented and discussed in detail. Indeed, these detectors have the nice feature of providing an excellent time resolution of the beam loss measurements, which is paramount for this application.

This method has been applied to the CERN PS MTE case, in which the extracted beam has a continuous longitudinal structure and, during the rise time of the extraction kickers, unavoidable losses are detected by the dedicated monitors installed in the extraction region, when the beam sweeps through the blades of the dummy or extraction septa.

The blade of the dummy septum can be used as a diagnostic device that allows reconstructing the transverse beam distribution and hence its sigma. It is worth noting that the peculiar non-Gaussian transverse structure of the MTE beam, which is split by crossing the horizontal fourth-order resonance, prevents the beam properties to be inspected.

The analysis of part of the data collected during dedicated measurement campaigns confirmed the devised approach and allowed computing the beam sigma for both the island and the core, and for the latter the beam emittance has been computed, too. In the near future, the proposed method will be applied to the complete data set to study the dependence of the horizontal emittance for island and core as a function of the total beam intensity.

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