INTERPRETATION OF WIRE-SCANNER ASYMMETRIC PROFILES IN A LOW-ENERGY RING

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Abstract

In the CERN PS Booster, wire-scanner profile measurements performed at injection energy are affected by a strong asymmetry. The shape was reproduced with the code PyORBIT, assuming that the effect is due to the beam evolution during the scans, under the influence of space-charge forces and Multiple Coulomb Scattering at the wire itself. Reproducing the transverse profiles during beam evolution allows to use them reliably as input for simulation benchmarking.

INTRODUCTION

The PSB, the first circular accelerator in the CERN injector chain, is made of 4 rings stacked on top of each other. It operates on energy range from 50 MeV to 1.4 GeV. The acceleration cycle of the beam lasts 500 ms. PS Booster provides full beam range to various CERN users with beam intensities varying from 40e10 p+ to 800e10 p+ per ring and transverse normalized emittances between 1 mm.mrad and 15 mm.mrad.

One of the PSB goals is to provide to the LHC high quality beam in terms of high brightness, defined as the intensity divided by the transverse emittance.

Usually, emittance measurements are taken at the extraction energy flat top, however in order to perform some dedicated measurements explained later in the paper and benchmark them with simulations, we collected data at the beginning of the acceleration ramp. The beam profiles measured at the injection energy are asymmetric (Figure 1) and in this paper we try to explain this effect.

We assume that the asymmetry is due to two effects and their superposition.

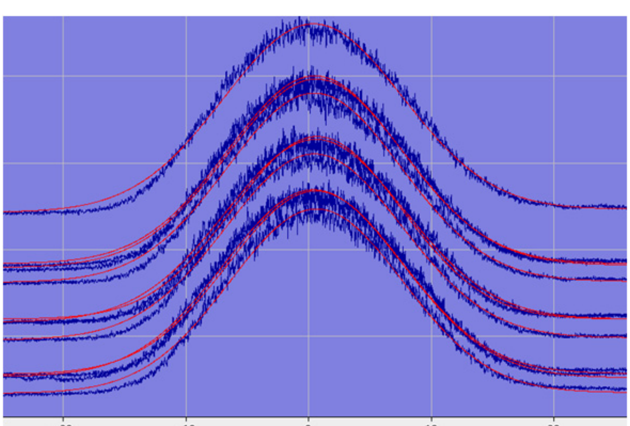

Figure 1: Example of an asymmetric measured vertical profile in PS Booster, at 60 MeV at C406.

The first effect is the Multiple Coulomb Scattering of the beam at the wire itself. Protons of the beam interacts with the atoms of the material of the wire scanner and due to electromagnetic interactions change theirs transverse momenta, which results in emittance growth. We measured this effect and we present the experimental results compared with the data from numerical simulations and analytical estimates. Thanks to this experiment, we defined an equivalent of the wire thickness used for further simulations.

The second effect is the space charge, which is very strong in the range of the PSB operation energies, and might induce emittance blow-up during the measurement time. Due to space-charge, the beam suffers from emittance blow up or losses, depending on the actual tune and the tune necktie which overlaps machine resonances. Moreover, for several beams like EAST-type beams and some special LHC beams, for which the final emittance is reached via transverse scraping [1], we observe tails repopulation due to the space charge itself.

An example of the reconstructed profile after transverse shaving is presented in this paper.

PS Booster Wire Scanners

The PSB is equipped with 8 independently operated, 25 μm-thick carbon wire scanners - one per plane for each of the 4 PSB rings. The user is able to measure the beam profile twice during one cycle: with the “IN” and the “OUT” scan indicating the direction of the wire move. The “IN” scan goes from negative values (-50 mm) to positive (+50 mm), according to the PSB convention, and the opposite for the “OUT” scan. Three speed of the wire are available: 10 m/s, 15 m/s and 20 m/s. Assuming 10 m/s wire speed, the measurement of a beam with an emittance of 2 mm mrad takes about 3 ms.

EMITTANCE BLOW UP DUE TO THE SCATTERING AT THE WIRE

The emittance blow up due to the scattering at the wire depends on the energy of the impacting beam which translates into a different scattering angle. We performed an experiment in which we swapped the wire scanner at low energy with a vertical “IN” scan in order to induce emittance blow up and then we measured the increase of emittance at extraction energy with a vertical “OUT” scan. As a reference, we considered measurements with the “OUT” scan, with the “IN” scan launched before injection, i.e. with no beam in the machine. The measured beam had a normalized emittance of ~ 2.2 mm mrad in both planes and an intensity of I = 160e10 p+. Data was

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collected as a function of the beam energy at the time of the "IN" scan, for two speeds of the wire scanner: 10 m/s and 15 m/s. For each point, we considered the average over 20 measurements.

In the next paragraph we present the measured increase in the normalized emittance $\Delta\varepsilon_{norm}$ with respect to the energy when the IN scan was performed. The outcome of the experiment was then compared to the results of the numerical simulations and the expected values calculated with analytical formulae.

SIMULATION OF MULTIPLE COULOMB SCATTERING AT THE WIRE

The Multiple Coulomb Scattering at the wire has been simulated using the code PyORBIT [2] code (with PTC [3] tracking), which includes space charge calculations and a particle-matter interaction module. The wire moving through the beam has been modelled as a moving scattering foil. We profited from the fact that the Foil class in PyORBIT has a dedicated routine using a simple Multiple Coulomb Scattering implementation. The foil is defined by its transverse dimensions and its thickness (in $\mu m/cm^2$).

The moving wire was modelled as a foil of vertical size equal to the wire diameter and a time dependent transverse position. The initial position of $y_{min} = -0.025$ m (instead of the -0.050 m) was chosen in order to shorten the time needed for each simulation. The 3 sigma beam size is much smaller than 25 mm, so this assumption is valid.

Simulations were performed in order to find the equivalent foil thickness which will allow us to simulate a flying wire and reproduce the measured profiles. The initial foil thickness has been defined as:

$$thickness\ (foil) = \rho * d_{eq}$$

Where:

ρ – density of the Carbon, i.e. 2.26 g/cm3 [4]

d_{eq} – equivalent of the foil (wire) thickness. The real wire diameter is d = 25 μm [5]

We made a scan in the energy range of interest, i.e. from the current PS Booster injection energy of 50 MeV up to 260 MeV. For each energy, we launched the simulations of the wire going through the beam in the vertical plane and we measured the increase of normalized vertical r.m.s. emittance.

In the simulations the space charge module was switched off in order to separate the space charge related effects from the scattering at the wire. The simulated particle herd had an initial Gaussian distribution with the normalized reference emittance of 2.2 mm mrad, comparable to the one measured in the machine. In order to ensure that there was no additional blow up due to other factors, we launched in parallel a simulation without the moving wire scanner. In this case, we obtained the $\Delta\varepsilon_{norm} = 10^{-4}$ mm mrad, which proved that the interaction with the wire was the only source of emittance increase.

The data from simulations and from measurements were then compared to the analytical predictions based on the formulae [5]:

$$\Delta\varepsilon_n^{x,y} = \frac{\pi\, d\, f_r}{4\, v}\,\frac{1}{2}\,\beta_{x,y} < \Theta_{rms}^2 > (\beta\gamma)$$

Where:

πd/4 – wire diameter equivalent

fr – revolution frequency

v – wire speed

βx,y – beta function in x/y plane

βγ – relativistic factors

The average scattering angle has been calculated using the formula [6]:

$$< \Theta_{rms}^2 > = \left(\frac{13.6MeV}{pv}\right)^2 \frac{d}{L_{rad}} \left[1 + 0.038ln\frac{d}{L_{rad}}\right]^2$$

Where:

L_{rad} – radiation length of carbon = 18.9 cm [4]

p – momentum of the impacting particles

v – speed of the particles

Figures 2 and 3 present the comparison of the theoretical, simulated and measured data of the normalized r.m.s. emittance blow up as a function of the beam energy during the scan, for the two speeds of the wire scanner: 10 m/s and 15 m/s. In Fig. 2 and 3, we also included the points of a scan of the simulated emittance blow up as a function of the equivalent wire thickness, for the current and future PSB injection energy: 50 MeV (β = 0.314) and 160 MeV (β = 0.52). We tested a wire equivalent thickness d_{eq} of 1.0d, πd/4, 0.5d and 0.25d.

Based on the presented data we conclude that for purposes of further simulations, the wire thickness can be approximated with a thickness equivalent of 0.5d. This value seems to be a very good fit for both wire speeds, for the energy range above ~80 MeV (β = 0.39). We observe a difference between the measurements and the simulated values for the energies of 50 MeV to 80 MeV.

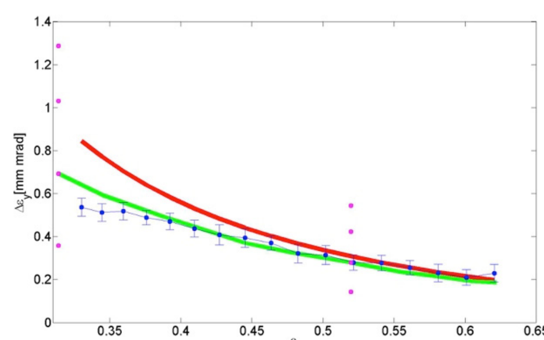

Figure 2: Theoretical (in red), simulated (in green) and measured (in blue) normalized rms emittance blow up as a function of the beam relativistic beta. Wire speed 10 m/s, assuming 99% confidence interval. The magenta points are a scan over the wire equivalent thickness.

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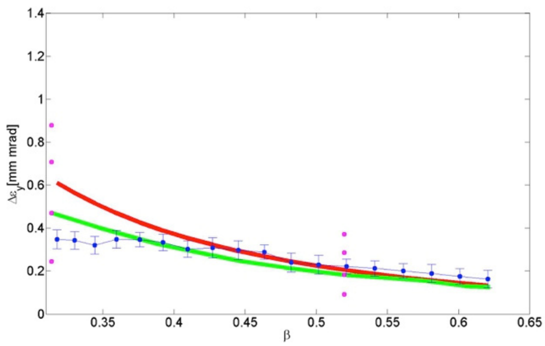

Figure 3: Theoretical (in red), simulated (in green) and measured (in blue) normalized rms emittance blow up as a function of the beam relativistic beta. Wire speed 15 m/s, assuming 99% confidence interval. The magenta points are a scan over the wire equivalent thickness.

EMITTANCE BLOW UP DUE TO SPACE CHARGE EFFECTS

The low intensity beams in the PSB are shaped with a process called "shaving" consisting in reducing the beam intensity and beam transverse emittances by scraping the beam on the PSB aperture restriction [1]. When the shaving is finished, we observe tail repopulation driven by space charge, which we suspected might be one reason of the asymmetry of the measured profile.

In the experiment, we set up a dedicated cycle in PSB with the flat top energy of 60 MeV, where we performed the shaving and we measured the profiles of the shaved beam every 1 ms to see its evolution in time. We observed rms emittance increase in time as well as changes in the shape of the measured profiles.

Figure 4 presents a profile taken with the wire scanner, measured right after shaving, while the beam experience tails repopulation. Our hypothesis here is that since the wire scan lasts a few ms, it captures the evolution of the tails, resulting in an asymmetric profile. The left side of the beam profile was registered much earlier that the right side. In other words the left tail of the beam had less time to evolve than the right side.

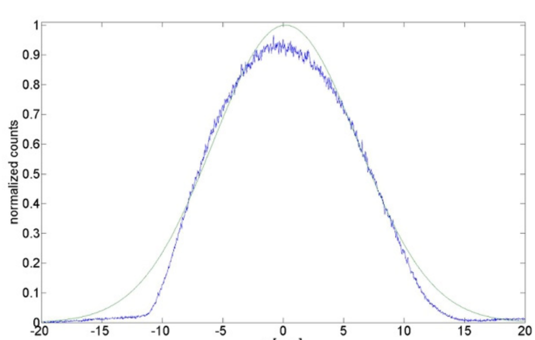

Figure 4: Measured profiles after the shaving process in PSB. Time C433.

SPACE CHARGE SIMULATIONS

We wanted to reproduce this measured beam profile numerically, so we simulated the vertical shaving in PyORBIT. After the shaving process is finished we let the beam evolve under space charge and we observed the tails repopulation. We added to the simulation also a moving wire, as described in the previous section, to combine the blow up due to the space charge with the blow up coming from the Multiple Coulomb Scattering.

Figure 5 shows the r.m.s. emittance evolution during the motion of the wire scanner, under space-charge forces and Multipole Coulomb Scattering. When the wire scanner starts interacting with the tail of the beam, the beam starts experiencing a strong emittance growth, much larger than the one associated with space-charge. For illustration, we also run a case with 1.5 times larger beam intensity (black, dashed curve on Fig.5), to see the effect of space charge. This was a purely academic exercise, the simulations are not self-consistent and one can notice a large mismatch.

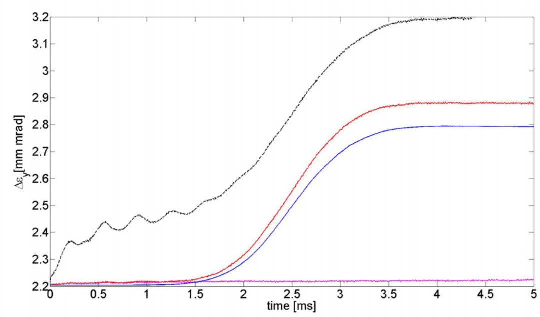

Figure 5: Simulated emittance increase versus time. In red: space charge and scattering, in blue: only scattering, in magenta: only space charge. The case with a 1.5 larger intensity is marked with a black dashed line.

RECONSTRUCTION OF THE ASYMMETRIC PROFILE

In order to reconstruct the measured beam profile we needed multiple samples of the beam at different time stamps. We dumped the beam profiles every 0.1 ms, simulating the sampling coming from the flying wire scanner. Assuming the wire moving with the speed of 10 m/s and measuring from -50 mm to +50 mm in vertical plane, the time needed to fly through the beam is 10 ms, corresponding to ~6600 turns of the simulation and 100 profiles in total.

The profile presented in Fig. 6 is therefore a reconstructed profile with the y-position correlated to the movement of the wire, such that the bins around a given position are taken from the profile dumped at the corresponding time. There is a strong, visible asymmetry in the reconstructed profile, to be compared with the experimental data of Fig. 4.

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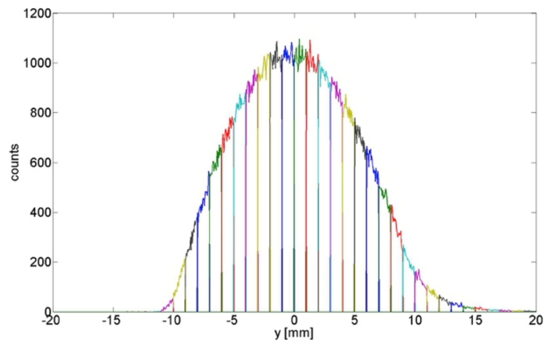

Figure 6: Reconstructed profile of the beam undergoing tails repopulation and multiple scattering at the wire scanner, to be compared with Fig.4. Time C433.

In order to identify the different contributions to the profile asymmetry, we simulated four different cases: with/without space charge and with/without Multipole Coulomb Scattering. The reconstructed profiles are reported in Fig. 7. The dominating phenomena is the scattering at the wire, however the space charge also contributes slightly to its asymmetry. We reconstructed the profile also for the artificial case where we increased the beam intensity by 50% to see whether a strong space charge also leads to the profile asymmetries. This case is marked with a black line in Fig. 7, but also in this case we observed little asymmetry coming from space charge. The reason is, as one can see from Fig. 5, that the simulated space-charge blow-up is occurring in a much shorter timescale as compared to the wire passage.

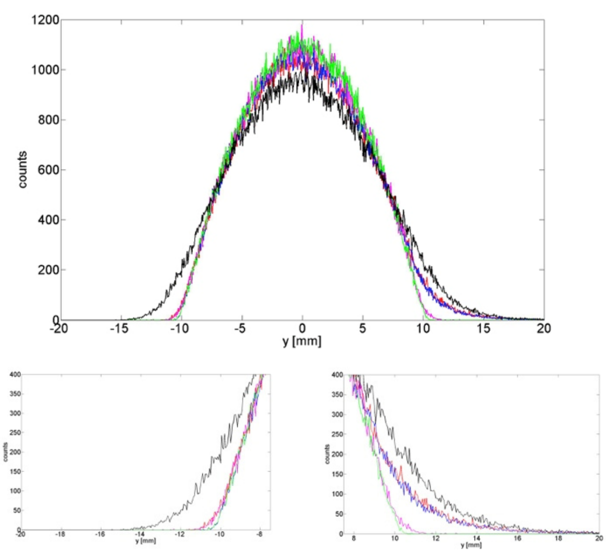

Figure 7: Reconstructed profile of the beam at C433. In red: space charge + the wire scanner, in blue: only wire scanner, in magenta: only space charge, in green: none of the effects. The case with an increased intensity is marked with a black line. The left and right tails are zoomed at the lower plot.

CONCLUSIONS

We have modelled in PyOrbit a wire scanner flying through the beam and we have developed a routine to post-process the data and reconstruct the profiles taking into account the time needed to perform a measurement, i.e. a few ms for a 2 mm mrad beam. With our recipe, we successfully managed to reproduce the asymmetry observed in the measured profiles at low energies in the CERN PS Booster.

First of all, we have measured the emittance blow-up due to Multiple Coulomb Scattering at the wire, as a function of the beam energy, we have compared it with analytical formula and simulations and we have obtained an equivalent thickness to be used in our further simulations.

We have focused our analysis on the profiles measured after beam scraping, during the “shaving” process in the PSB, occurring at around 60 MeV and after which we expect tail repopulation.

Our hypothesis was that the Multiple Coulomb Scattering together with the space charge are be two main sources of the emittance blow up, and that this increase of beam size is captured by the wire scanner while it is flying through the beam.

The conclusion, for this particular case, was that the Multipole Coulomb Scattering at the wire was the dominant phenomenon, while the tail repopulation driven by space charge had a negligible effect on the measured profile asymmetry. Improvements in the PSB optics model, which is presently ongoing [7], and/or different case study might put in evidence a larger contribution from space charge.

In any cases and for any mechanism driving beam blow-up or losses, the ability to reproduce the transverse profiles measured with the wire scanners while the beam is evolving, allows using them reliably as input for simulation benchmarking.

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