A NOVEL METHOD FOR QUASI-NON-INTERCEPTIVE BEAM PROFILE MEASUREMENT IN A LINAC

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Abstract

Beam profile diagnostics is an important tool for understanding beam dynamics in accelerators. Non-interceptive diagnostics have many great advantages but often are difficult in implementation. We suggest a method of measuring beam profiles that is not truly non-interceptive, because beam has to be intercepted at some point, preferably in the beginning of the linac. But significant difference from a conventional interceptive measurement is that beam is not intercepted at any of the points of measurement along the linac. One important application is measuring beam profiles within cryostats of a super-conducting linac. The equipment required for implementing this diagnostic is simple: a set of slits in the beginning of the accelerator, and a Beam Position Monitor (BPM) in the point of measurement. Beam profiles can be measured simultaneously at every BPM along the linac. In this paper we will discuss details of the method, its limitations, and effect of non-linearity, coupling and space charge. Results of a demonstration experiment at SNS will be presented and discussed.

INTRODUCTION

Non-interceptive beam profile diagnostics are desirable for several reasons:

1. The ability to do measurements at any time without changing beam parameters and not disrupting the productive operation
2. The power density of the beam with the nominal operational parameters can be too high for any interceptive device to withstand the thermal or mechanical stress.
3. There is no risk of contaminating of the nearby structures (e.g. super conducting cavities) with particulates in the case of an interceptive device disintegration under the beam

Unfortunately, non-interceptive diagnostics are usually more complicated and expensive than more traditional interceptive devices. This is an especially important consideration for a linac, where multiple points of measurement are desirable.

Our goal was to find a method for measuring beam profiles satisfying at least some of the above three conditions. In addition it should be inexpensive and allow simultaneous measurements at multiple locations along a linac. The quasi-non-interceptive method described in this paper does not require intercepting beam at the points of measurement, so the condition #3 is fully satisfied. Beam is intercepted so the condition #1 is not met, but at low energy, therefore the condition #2 is significantly relaxed. A general scheme of the measurement arrangement is shown in Fig.1

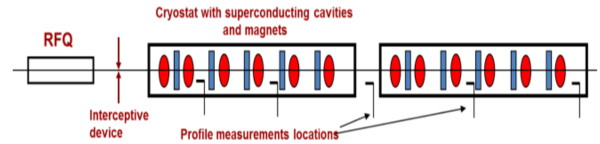

Figure 1: A layout of the measurement arrangement.

We should note that an ideologically similar scheme was successfully used for measuring beam profile in the SNS accumulator ring [1].

METHOD FOR QUASI-NON-INTERCEPTIVE BEAM PROFILE MEASUREMENT

Description of the Method

The measuring procedure is the following (see Fig.2):

1. Define a small cell in the beam phase space $\Delta x_{0i} \times \Delta x_{0j}'$ at the beginning of the linac
2. Measure electrical charge in that cell $\lambda_0^{i,j}$
3. Measure the average position of the particles in the cell at a point of interest along the linac $x_1^{i,j}$
4. Repeat steps 1-3 to cover the whole phase space
5. The beam profile is calculated as a histogram p of the measured positions with weight $\lambda_0^{i,j}$:

$$p_k = \sum_{i,j} \lambda_0^{i,j} \cdot [x_k - \Delta < x_1^{i,j} < x_k + \Delta] = = \sum_{i,j} \lambda_0^{i,j} \cdot T_{k,i,j} \quad (1)$$

where [..] is the Iverson bracket ([P]=1 if P is true; [P]=0 otherwise), and Δ is the histogram bin size.

Implementation of the Method

A pair of slits of width w separated by a distance d can be used to define a phase space area of size $w \times \frac{w}{d}$. The two terms inside $\sum$ in Equation (1) can be measured using two separate scans. A charge sensitive device, e.g. a Faraday cup, is used to measure the charge $\lambda_0^{i,j}$ passing through the slits during the first scan. This measurement is identical to beam a emittance measurement.

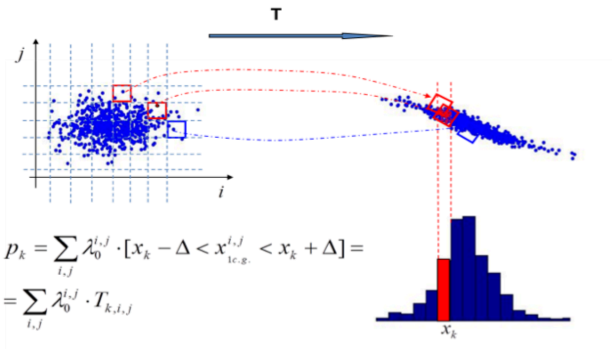

Figure 2: An illustration of the method idea.

Beam position monitors (BPMs) are used to measure the beamlet position $x_1^{i,j}$ during the second scan, as illustrated in Fig.3.

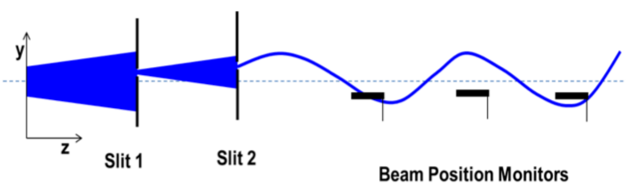

Figure 3: An illustration of the method implementation.

The data from these two scans allows the calculation of the beam profiles simultaneously at all BPM locations downstream of the slits

The Hardware Requirements

The slit size and the distance between the slits is determined by the beam transverse and angular size. For a typical beam ellipse size of 1mm by 1mrad, 100μm slits 500mm apart are a good choice.

There is no special demand to the BPM accuracy and resolution. Accuracy of the position measurement will determine accuracy of the profiles. The beam current dynamic range of the BPMs is of major importance. The fraction of the beam current coming through the slits, when the beam is centered on the slits is

$$I_{slit} = \frac{I_0}{2\pi} \frac{\Delta_x}{\sigma_x} \frac{\Delta_{x'}}{\sigma_{x'}} \approx \frac{I_0}{2\pi} \cdot \frac{.1}{1.} \cdot \frac{.1}{1.} = 1.6 \cdot 10^{-3} \cdot I_0, \quad (2)$$

The BPMs should be capable of measuring the position of this low current beam with a reasonable accuracy.

It is very important to note that the dynamic range of the order of the estimate from Equation (2) is sufficient for measuring the tails of the beam profile as well as the core. The achievable resolution in the tails is determined by the sensitivity of the Faraday cup during the first scan, when $\lambda_0^{i,j}$ is measured. The BPMs are only used during the second scan, when $T_{k,i,j}$ is measured. The beam can be kept centered on the slits, using upstream correctors, during this measurement so that the beam current through the slit is always close to estimate in Equation (2).

Potential Advantages of the Method

The method described above can have several potential advantages over a direct profile measurement.

1. It is possible to derive the transport matrix coefficients directly. For each position of the slits $x_0^{(k)}, x'^{(k)}_0$ one can write:

$$x_1^{(1)} = t_{11} \cdot x_0^{(1)} + t_{12} \cdot x'^{(1)}_0 + t_{111} \cdot x_0^{2(1)} + t_{112} \cdot x_0^{(1)} \cdot x'^{(1)}_0 + \ldots$$
$$x_1^{(2)} = t_{11} \cdot x_0^{(2)} + t_{12} \cdot x'^{(2)}_0 + t_{111} \cdot x_0^{2(2)} + t_{112} \cdot x_0^{(2)} \cdot x'^{(2)}_0 + \ldots$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$x_1^{(N)} = t_{11} \cdot x_0^{(N)} + t_{12} \cdot x'^{(N)}_0 + t_{111} \cdot x_0^{2(N)} + t_{112} \cdot x_0^{(N)} \cdot x'^{(N)}_0 + ..$$

Or, in matrix form,

$$\vec{x_1} = X_0 \cdot \vec{t},$$

The vector of the transport matrix coefficients can be found after inverting the matrix of initial positions:

$$\vec{t} = X_0^{-1} \cdot \vec{x_1}$$

2. The 2-D phase space footprint can be calculated (emittance) if there is a pair of BPMs separated by a drift of length L. The position x_1 of each beamlet is measured by the first BPM and the angle is calculated as $x_1^{/} = \dfrac{x_2 - x_1}{L}$ from measurements of both BPMs.

3. Direct measurements of correlations in 4-D phase space and coupling coefficients are possible by using 2 pairs of slits (horizontal and vertical) simultaneously. The main limitation is another three orders of magnitude reduction in the beam current and significant time required for a 4-D scan.

Limitations of the Method

The biggest limitation of the method comes from collective effects in the transport line, e.g. space charge force and wake fields. The method can be still useful for measuring zero-current transport parameters.

If significant diffusion-like processes take place in the transport line than phase space density is not conserved and Equation (1) cannot be used for calculating the profiles. Examples of such processes are multiple scattering, synchrotron radiation, and strong non-linearity, causing filamentation in phase space.

In case of a linear coupling between the horizontal and vertical plane, the profiles can still be calculated and coupling coefficients found. In case of a non-linear coupling a 2-D scan is not sufficient and a 4-D scan with two pairs of slits should be used.

EXPERIMENTAL STUDY

There is an emittance measuring station in the SNS MEBT, which has a slit and a multi-wire harp. This equipment allows the measurement of the beam phase space density $\lambda_{i,j}$ term in Equation (1). We have been planning to install a second slit on the harp actuator to be able to measure the $T_{k,i,j}$ term. Unfortunately these plans have not materialized by the time of writing this paper. We had to resort to a single slit scan, which does not allow a full implementation of the method but can be used to find linear coefficients of the transport matrix.

Single Slit Scan

Equation of a single particle motion is

$$x_1 = m_{11} \cdot x_0 + m_{12} \cdot x_0^{/} + n.l.t.$$

For simplicity, we will neglect the non-linear terms in the right hand side of the equation. Then the average position of an ensemble of particles can be calculated:

$$< x_1 >= m_{11} \cdot < x_0 > + m_{12} \cdot < x_0^{/} > . \quad (2)$$

$< x_1 >= x_{BPM}$ is measured by BPM, $< x_0 >= s$ is defined by the slit position:

$$x_{BPM} = m_{11} \cdot s + m_{12} \cdot < x_0^{/} > . \quad (3)$$

This linear equation allows finding unknown m_{11}, m_{12} if one can measure x_{BPM} vs. s for two different sets of initial beam parameters with different $< x_0^{/} >$.

A typical measured phase space footprint and the corresponding $< x_0^{/} >$ are shown in Fig.4. The dependence of $< x_0^{/} >$ upon the slit position is close to a linear function for slit position in the range of ±5mm.

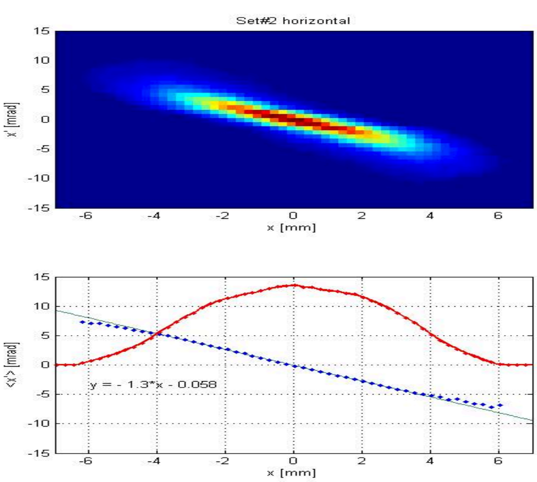

Figure 4: The measured horizontal emittance in the SNS MEBT (top). Beam current through the slit (bottom, red), and <x'> (bottom, blue) vs. slit position.

The dependence of beamlet position vs. slit position for three different BPMs in the SNS linac is shown in Fig. 5. The curve for BPM #3 deviates from a linear function starting from about ±3mm, which can indicate a non-linearity in the beam transport. But more plausible explanation is the effect of electrical offset in the BPM electronics. The linear part of the curve can be used for calculating linear terms in transport matrix, which can be used for validation of simulation codes. This work is ongoing.

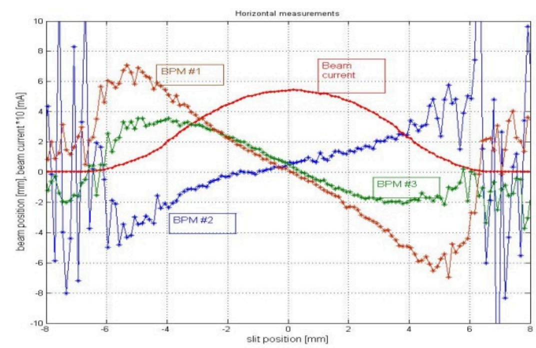

Figure 5: The measured dependence of the beamlet position vs. the slit position at three BPMs and the beam current through the slit.

CONCLUSION

We propose a method of measuring beam transport parameters using a set of slits and BPMs. The beam is not intercepted at the points of measurement; therefore the method can be suitable for superconducting RF linacs. In absence of collective effects, the method provides as much information as direct profile measurements and, potentially, more. The main hardware requirement is sufficient dynamic range of BPMs. Tails of the distribution can be measured as well.

Preliminary experiments at SNS linac show expected results but absence of the second slit and insufficient dynamic range of the BPM have not allowed for full implementation of the method yet.

ACKNOWLEDGEMENT

Author is grateful to A. Shishlo for help with the simulations and useful discussions, and to A. Zhukov for help in collecting the experimental data.

ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

REFERENCES

[1] S. Cousineau, T. Pelaia, M.A. Plum, “Applications of a BPM-based Tehnique for Measuring Real Space Distributions in the Spallation Neutron Source Ring and Transport Lines”, Proceedings of EPAC08, Genoa, Italy