A novel scheme for quasi-non-interceptive beam profile measurement in a linac.

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Outline

• Motivation
• Method
• Hardware requirements
• Advantages
• Limitations
• Experimental data from SNS linac
Why non-interceptive profile diagnostics is desirable?

1. Can measure during productive operation
2. Not limited by intercepted beam power and losses
3. No risk of contaminating nearby structures
   - E.g. superconducting RF cavities

All this is very attractive but difficult to achieve

Our goal is to device a method which:

- Fulfills at least some of the above requirements
- Allows simultaneous measurements at multiple locations
- Is practical = relatively inexpensive
Quasi-non-interceptive measurements

1. Beam is not intercepted at locations of profile measurement
   • no risk of contaminating nearby structures

2. Beam is intercepted at low energy (in injector)
   • Intercepted beam power and radiation is low

3. Measurement disrupts productive operation

example: Facility for Rare Isotope Beams (FRIB)
   • CW superconducting linac, heavy ions, 400kW
   • long cryo-modules with focusing solenoids inside
   • high intensity but no space charge
How we calculate beam profile in tracking codes

\[ p_k = \sum_i q \cdot [x_k - \Delta < x^i_1 < x_k + \Delta] \]
We can measure beam profile in similar way

\[ p_k = \sum_{i,j} \lambda_{0,i,j} \cdot [x_k - \Delta < x_{1e.g.}^{i,j} < x_k + \Delta] = \]

\[ = \sum_{i,j} \lambda_{0,i,j} \cdot T_{k,i,j} \]
Practical implementation
Practical implementation

Slit 1
Practical implementation
Practical implementation

1. Define \((x_0, x'_0)\) with 2 slits in front end
2. Measure position \(x\) with BPMs
3. Repeat 1. and 2. to cover whole phase space
4. Calculate profiles for all BPMs (simultaneously)
Hardware requirements - slits

Slit size is 100-200 µm for a typical rms beam size of 1mm x 1mrad
Hardware requirements - BPMs

- Resolution and accuracy
  - No special requirements, but good mapping is essential

- Beam current dynamic range
  - Major concern
  \[ I_{slit} = \frac{I_0}{2\pi} \frac{\Delta x}{\sigma_x} \frac{\Delta x'}{\sigma_{x'}} \approx \frac{I_0}{2\pi} \cdot \frac{0.1}{1} \cdot \frac{0.2}{1} = \frac{1.6}{6.4 \cdot 10^{-3}} \cdot I_0 \]

- No higher dynamic range for measuring beam tails is required

\[ p_k = \sum_{i,j} \lambda_{i,j}^0 \cdot T_{k,i,j} \]

*measure charge distribution using sensitive Faraday Cup (emittance measurement)*

*measure transport coefficients using BPMs.*

*keep beam centered on the slits during measurement with upstream correctors*
Potential advantages of the method vs. usual profile scan (I)

Direct measurement of transport matrix coefficients

\[ x_{1(1)} = t_{11} \cdot x_{0(1)} + t_{12} \cdot x'_{0(1)} + t_{111} \cdot x_{0(1)}^2 + t_{112} \cdot x_{0(1)} \cdot x'_{0(1)} + \cdots \]

\[ x_{1(2)} = t_{11} \cdot x_{0(2)} + t_{12} \cdot x'_{0(2)} + t_{111} \cdot x_{0(2)}^2 + t_{112} \cdot x_{0(2)} \cdot x'_{0(2)} + \cdots \]

\[ \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \]

\[ x_{1(N)} = t_{11} \cdot x_{0(N)} + t_{12} \cdot x'_{0(N)} + t_{111} \cdot x_{0(N)}^2 + t_{112} \cdot x_{0(N)} \cdot x'_{0(N)} + \cdots \]

\[ \overrightarrow{x_1} = X_0 \cdot \overrightarrow{t} \quad \rightarrow \quad \overrightarrow{t} = X_0^{-1} \cdot \overrightarrow{x_1} \]

Accuracy depends on properties of matrix \( X_0 \)

- Hard to predict in general case
- Simulation for SNS linac sho good results up to 3\textsuperscript{d} order
Potential advantages of the method vs. usual profile scan (II)

- Measurement of 2-D phase space at BPMs locations
  - If there is a pair of BPMs separated by a free space

\[ x'_1 = \frac{x_2 - x_1}{L} \]

- Measurements of \((x, x', y, y')\) correlations in 4-D phase space
  - By using 2 pairs of slits in horizontal and vertical planes simultaneously
  - Can be problematic due to BPM dynamic range and measurement time constraints
Simulation example

Why we measure beam profiles:

To characterize beam
To characterize beam transport line

Amplitude [a.u.] vs. x [mm]

BPM readout [mm] vs. slit position [mm]
Limitations of the method

• Collective effects
  – space charge, wake fields
  – method is still useful for measuring zero-current transport

• Diffusion (phase space density is not conserved)
  – multiple scattering, synchrotron radiation, strong filamentation
  – needs study

• Coupling between planes
  – OK for linear coupling
  – needs study for non-linear coupling
  – 4D scan will work
SNS hardware for proof-of-principle experiment

- **Emittance device in MEBT**
  - 100µm slit and 32-wire harp
  - No second slit

- **85 BPMs in linac and HEBT**
  - 100µm resolution
  - 5 ÷ 50mA dynamic range

Have been planning to install a second slit

.......... still waiting for an opportunity
What can be done with single slit?

\[ x_1 = m_{11} \cdot x_0 + m_{12} x'_0 + \ldots \]

for each particle

\[ < x_1 > = m_{11} \cdot < x_0 > + m_{12} < x'_0 > + \ldots \]

for an ensemble

\[ x_{BPM} = m_{11} \cdot s + m_{12} < x'_0 >_s + \ldots \]

BPM readout when slit is at position \( s \)

\[ \frac{dx_{BPM}}{ds} = m_{11} + m_{12} \frac{d < x'_0 >_s}{ds} + \ldots \]

Measure with BPMs

Measure with emittance scanner
Emittance scans

\[ \frac{dx_{BPM}}{ds} = m_{11} - 1.3 \cdot m_{12} \]

\[ \frac{dy_{BPM}}{ds} = m_{11} + 0.9 \cdot m_{12} \]

\[ \frac{dy_{BPM}}{ds} = m_{11} \]
Experimental slit scans - horizontal

\[ x_{BPM} = \frac{u_l - u_r}{u_l + u_r} \]
Dynamic range limitation

Simple model of slit scan with offset in BPM electronics

\[ x_{\text{beam}} = a \cdot S \]

\[ x_{\text{BPM}} = \frac{u_t - u_b}{u_t + u_b} \approx g \frac{I \cdot x_{\text{beam}} + \delta_1}{I + \delta_2} = g \frac{I(s) \cdot a \cdot s + \delta_1}{I(s) + \delta_2} \]

Slope determination error:

\[ \delta a \approx \frac{\delta_{1,2}}{I_0} \]

Simple model fit to measured data:

- Typical slope error of 5%-10%
- Maybe sufficient for linear transport
- Not feasible for non-linear transport (too many model parameters: offsets, BPM nonlinearity, transport non-linearity)
Experimental slit scans - vertical
Experimental slit scans -vertical

\[ \frac{dy_{BPM}}{ds} = m_{11} \]
Experimental slit scans -vertical

We have to conclude that base line SNS linac BPMs do not have dynamic range sufficient for these measurements

Do better BPMs exist?
SNS RTBT transport line measurements

- SNS accumulator ring and RTBT BPMs have dynamic range of $\sim 10^4$
  - Switchable gain
- Have been used for 2D beam cross-section measurement at 1GeV
  - Idea is similar to what we presented above: sampling of phase space
  - Manipulation of ring injection/extraction parameters instead of slits

Figures are reproduced from:
S. Cousineau, T. Pelaia, M. A. Plum, “APPLICATIONS OF A BPM-BASED TECHNIQUE FOR MEASURING REAL SPACE DISTRIBUTIONS IN THE SPALLATION NEUTRON SOURCE RING AND TRANSPORT LINES”, Proceedings of EPAC08, Genoa, Italy
Summary and future plans

- We propose a method of measuring beam transport parameters using set of slits and BPMs
- 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 full demonstration is to be done yet
  - Will install an additional slit in the MEBT
  - Will replace one set of SNS linac BPM electronics with a higher gain version