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

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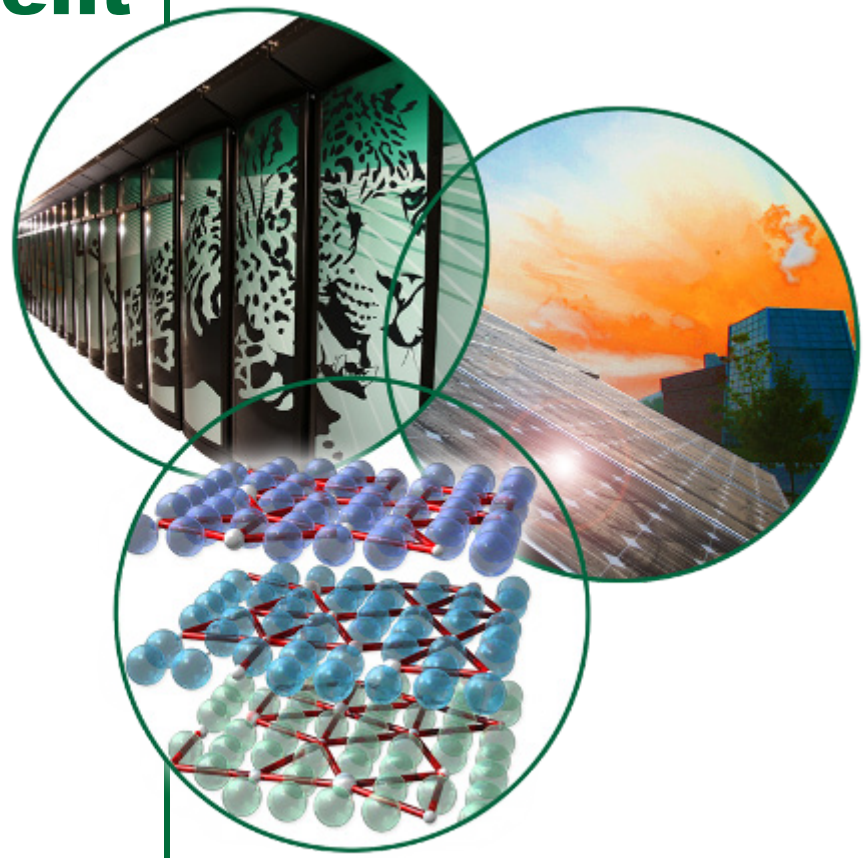

U.S. DEPARTMENT OF ENERGY

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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

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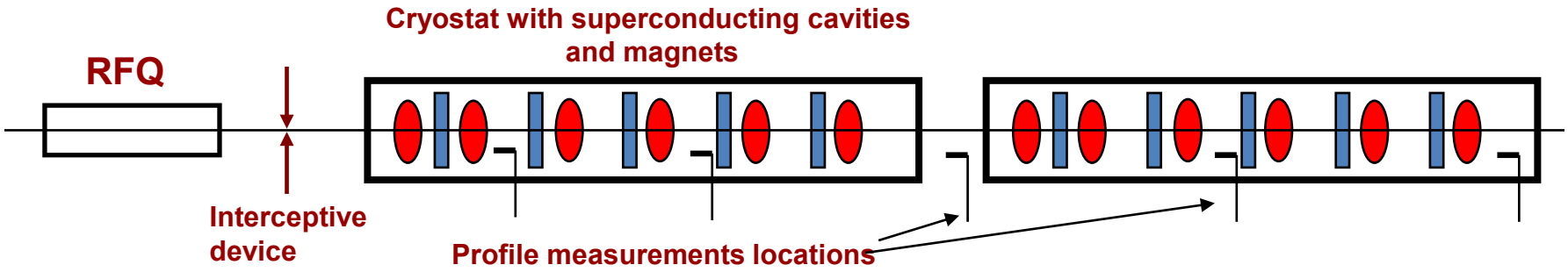
Quasi-non-interceptive measurements

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

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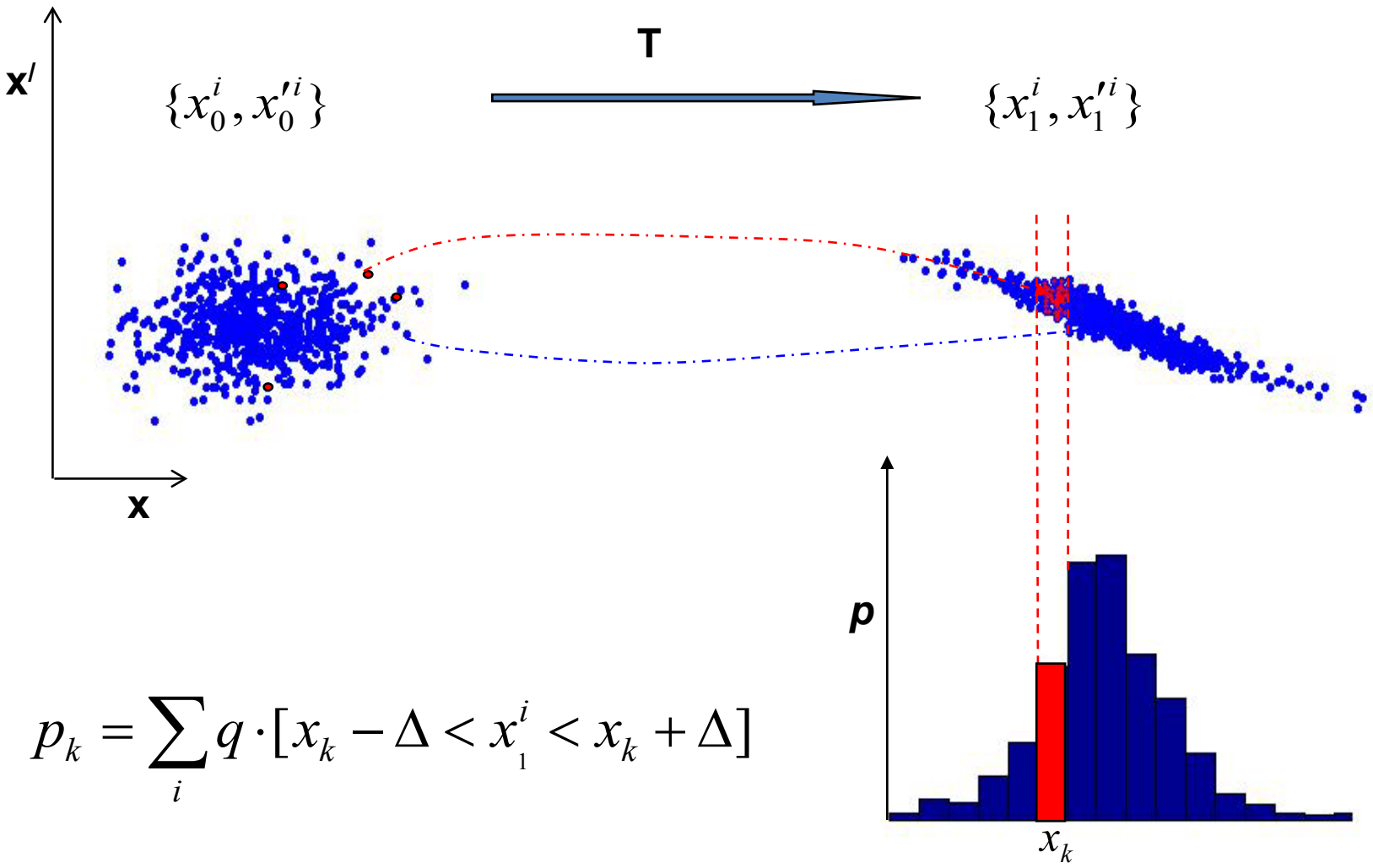
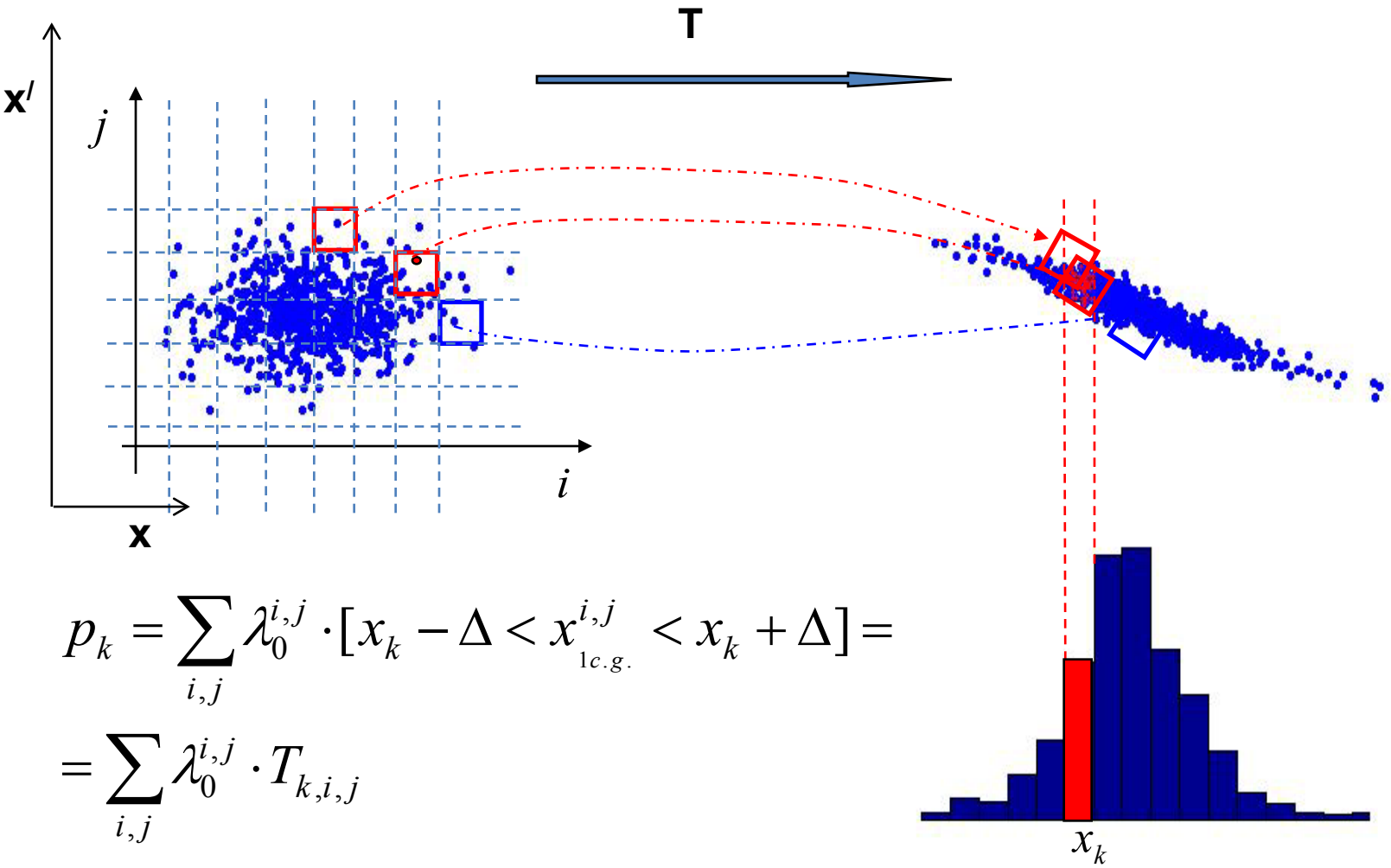
How we calculate beam profile in tracking codes



$$p_k = \sum_i q \cdot [x_k - \Delta < x_1^i < x_k + \Delta]$$

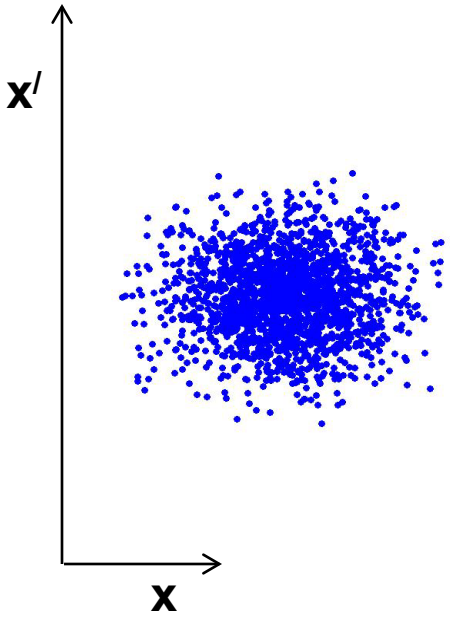
We can measure beam profile in similar way

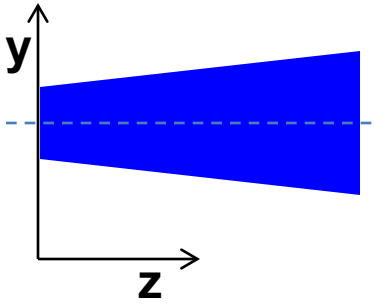


$$p_k = \sum_{i,j} \lambda_0^{i,j} \cdot [x_k - \Delta < x_{1c.g.}^{i,j} < x_k + \Delta] =$$

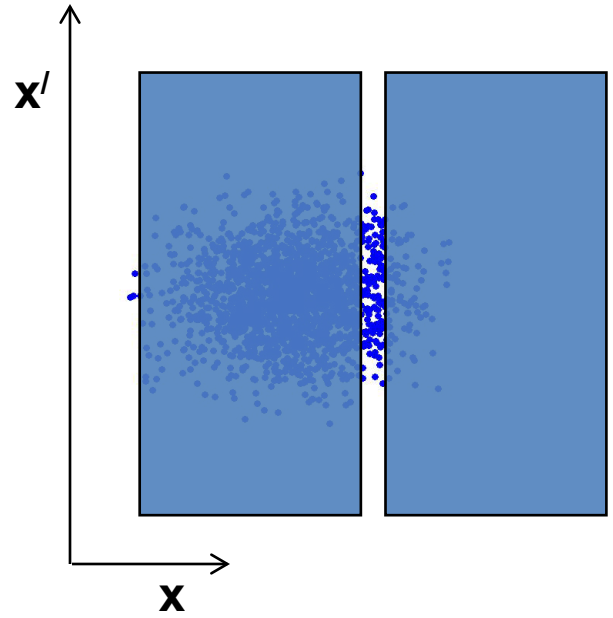
$$= \sum_{i,j} \lambda_0^{i,j} \cdot T_{k,i,j}$$

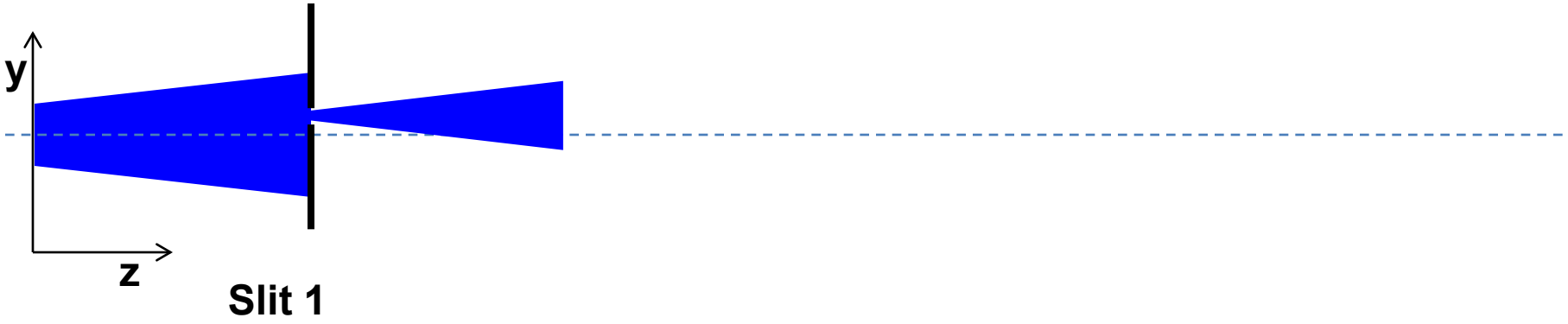
Practical implementation



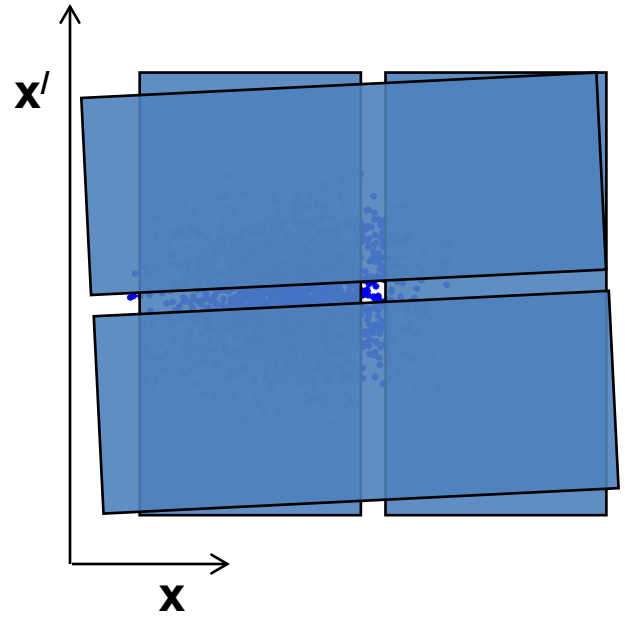


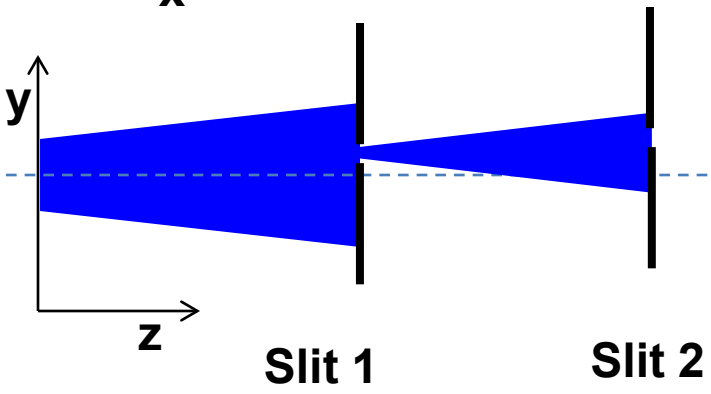
Practical implementation



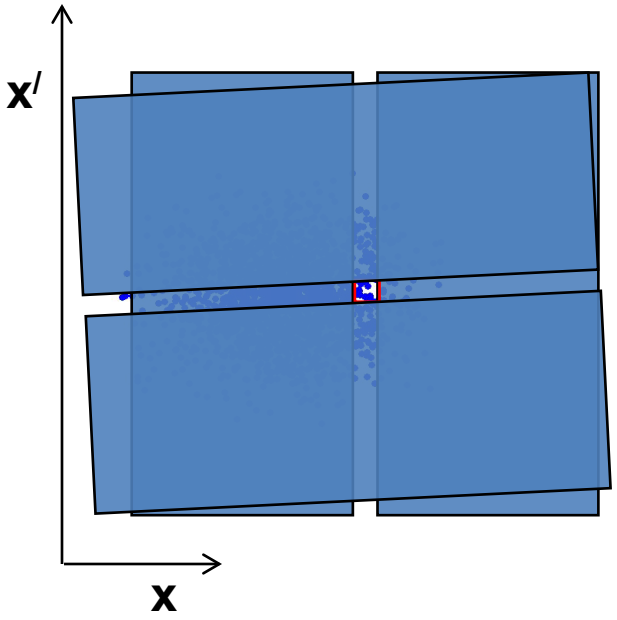


Practical implementation

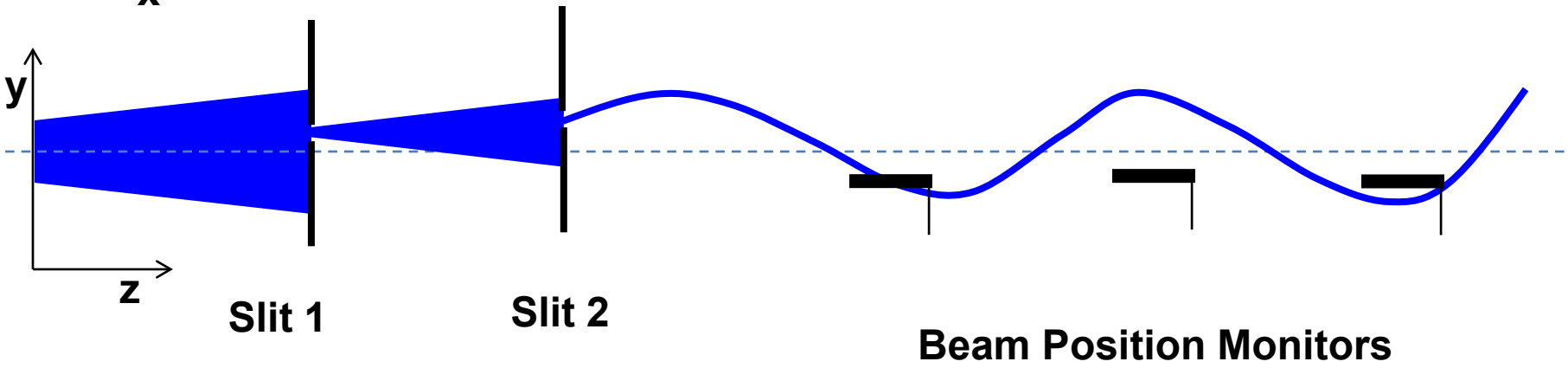




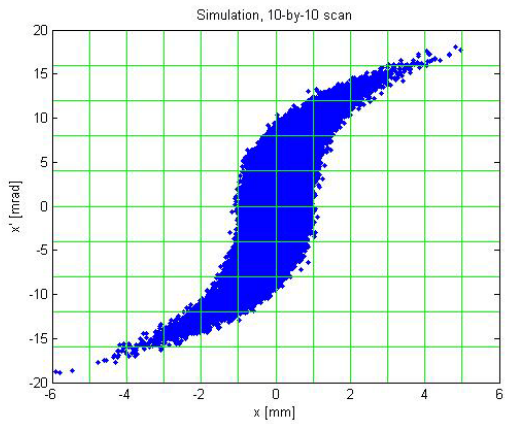
Practical implementation

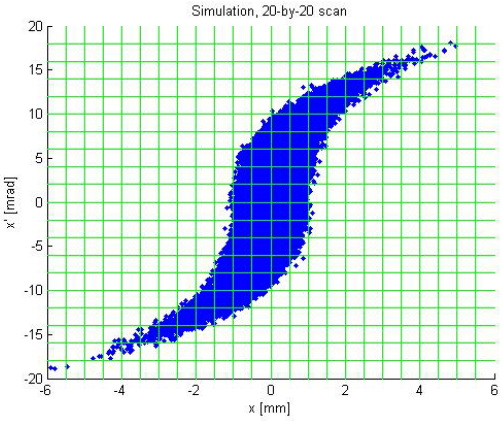


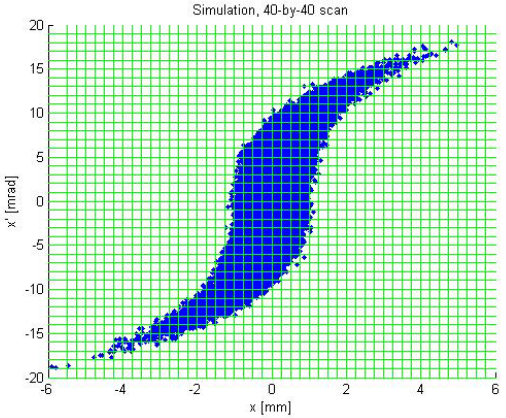
1. Define (x_0, x'_0) with 2 slits in front end
2. Measure position x with BPMs
3. Repeat 1. and 2. to cover whole phase space
4. Calculate profiles for all BPMs (simultaneously)

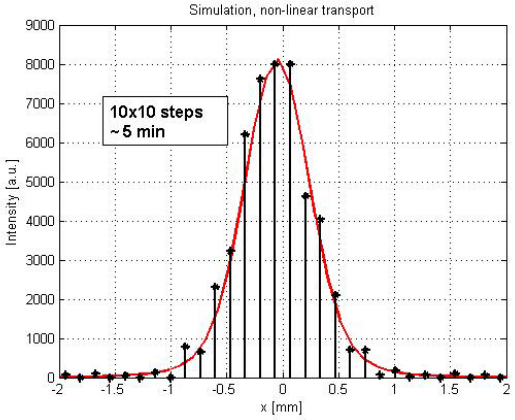


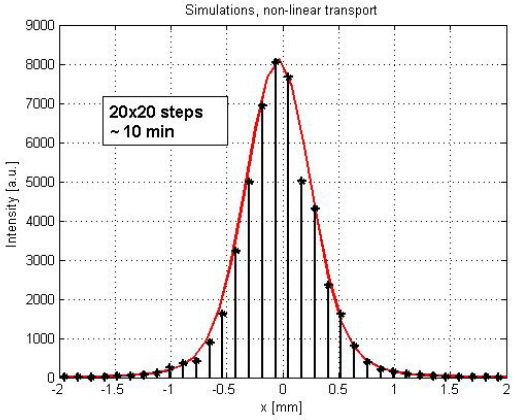
Hardware requirements - slits

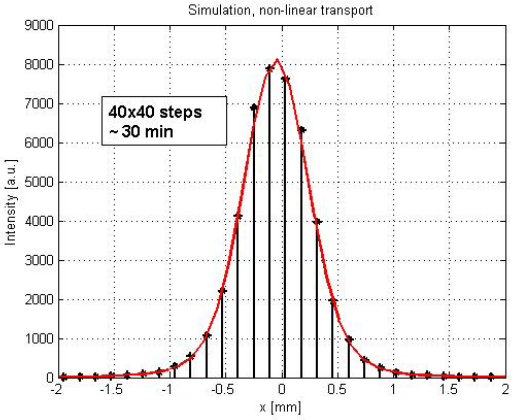












Slit size is 100-200 μm for a typical rms beam size of 1mm x 1mrad

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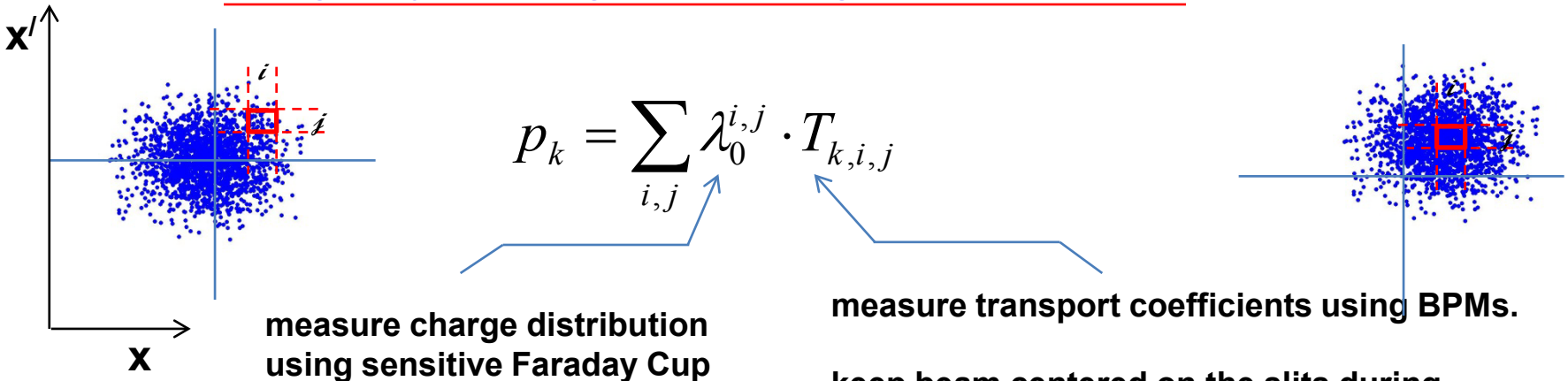
Hardware requirements - BPMs

- **Resolution and accuracy**
  - No special requirements, but good mapping is essential
- **Beam current dynamic range**
  - Major concern

$$I_{slit} = \frac{I_0}{2\pi}\frac{\Delta_x}{\sigma_x}\frac{\Delta_{x\prime}}{\sigma_{x\prime}} \cong \frac{I_0}{2\pi}\cdot\frac{0.1\div0.2}{1.}\cdot\frac{0.1\div0.2}{1.} = 1.6\div6.4\cdot10^{-3}\cdot I_0$$

  - No higher dynamic range for measuring beam tails is required



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Potential advantages of the method vs. usual profile scan (I)

Direct measurement of transport matrix coefficients

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

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

$$\cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots .$$

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

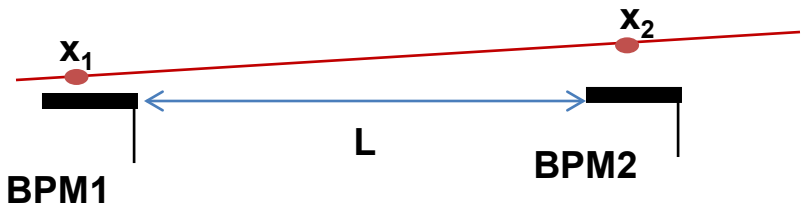
$$\overrightarrow{x_1} = X_0 \cdot \vec{t} \quad \rightarrow \boxed{\vec{t} = X_0{}^{-1} \cdot \overrightarrow{x_1}}$$

Accuracy depends on properties of matrix X_0

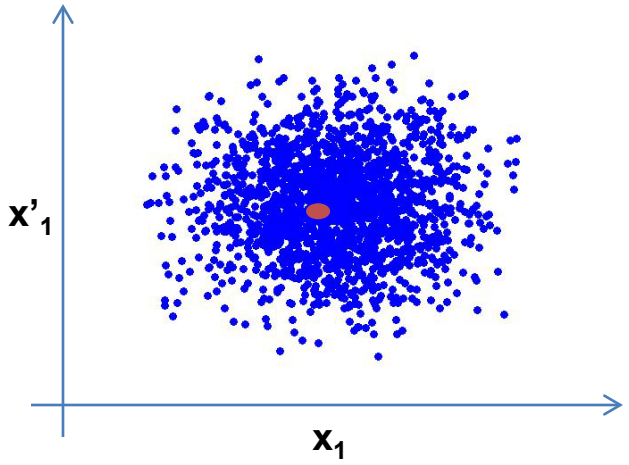
- Hard to predict in general case
- Simulation for SNS linac sho good results up to 3^d order

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

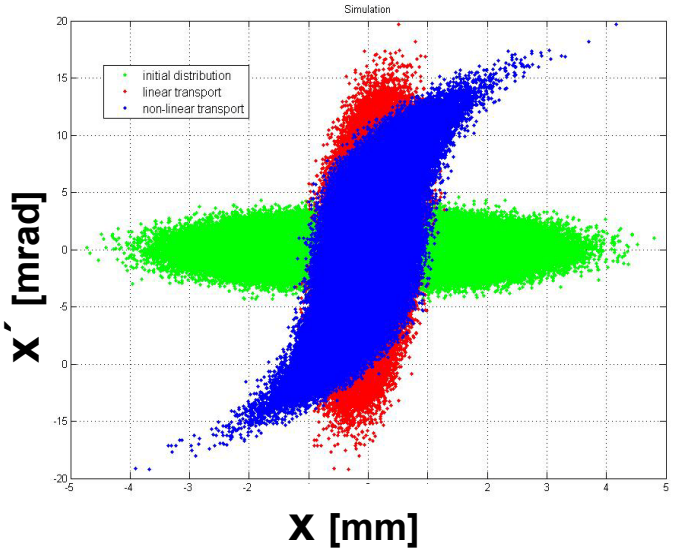


$$x'_1 = \frac{x_2 - x_1}{L}$$



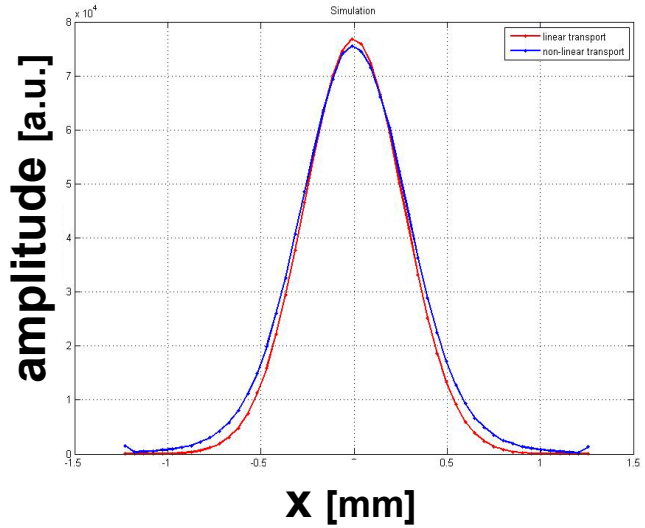
- Measurements of (x, x', y, y') correlations in 4-D phase space
  - By using 2 pairs of slits in horizontal and vertical planes simultaneously
  - Can be problematic due to BPM dynamic range and measurement time constraints

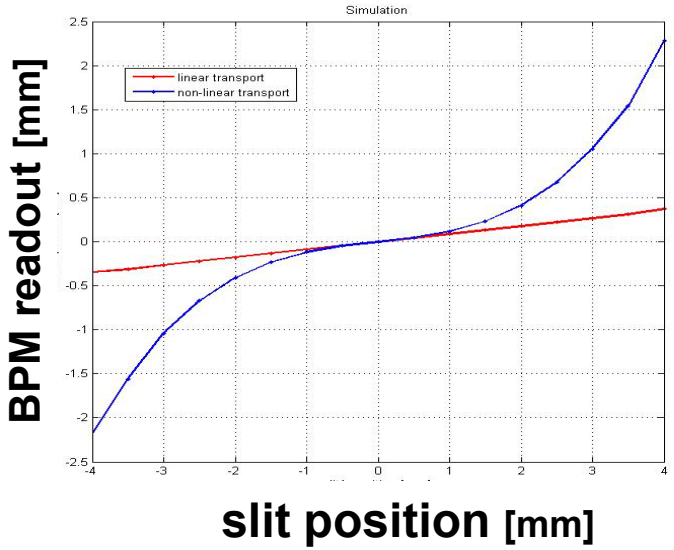
Simulation example



Why we measure beam profiles :

- **To characterize beam**
- **To characterize beam transport line**





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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

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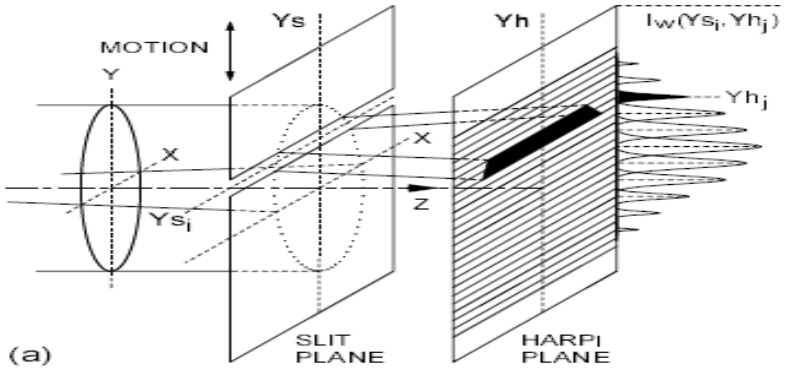
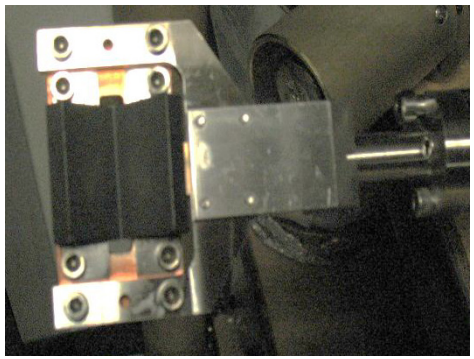
SNS hardware for proof-of-principle experiment

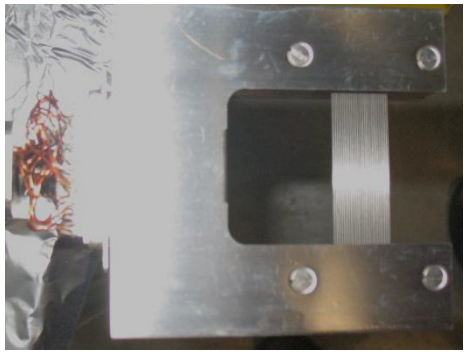
- Emittance device in MEBT
  - 100μm slit and 32-wire harp
  - No second slit



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



slit



harp

Have been planning to install a second slit
……. still waiting for an opportunity

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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

$$x_{BPM} = m_{11} \cdot s + m_{12} < x_0^{/} >_s + \ldots$$

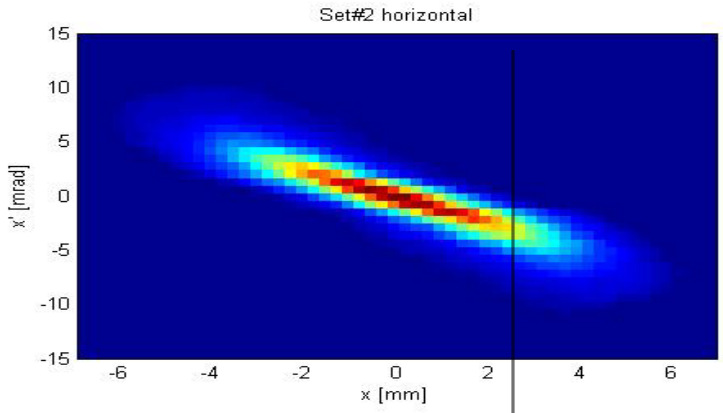
BPM readout when slit is at position s

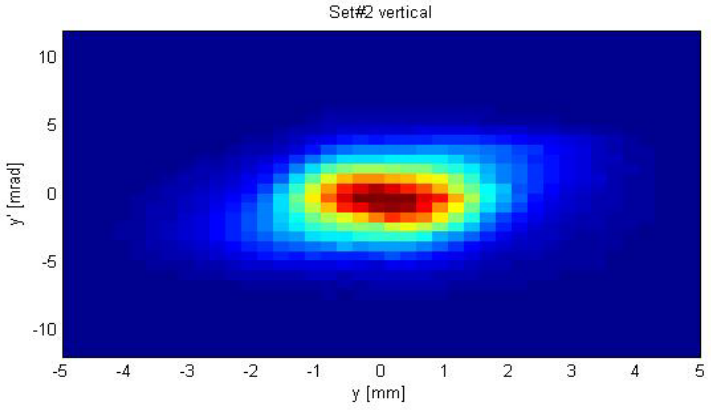
$$\frac{dx_{BPM}}{ds} = m_{11} + m_{12} \frac{d < x_0^{/} >_s}{ds} + \ldots$$

Measure with BPMs

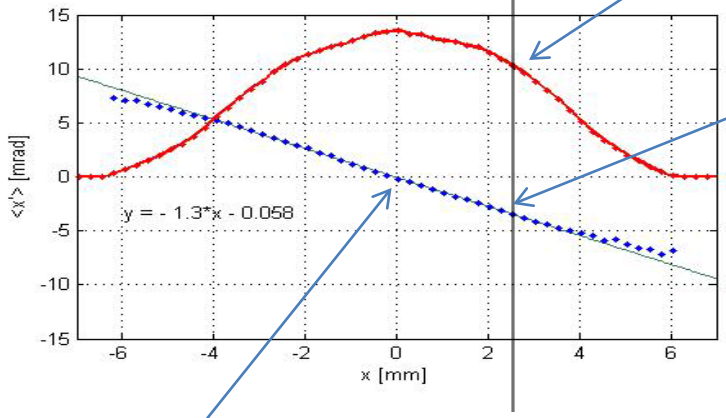
Measure with emittance scanner

Emittance scans

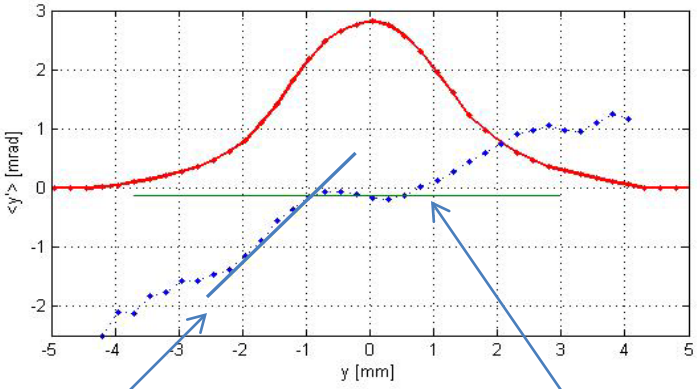




Current through slit



<x'>

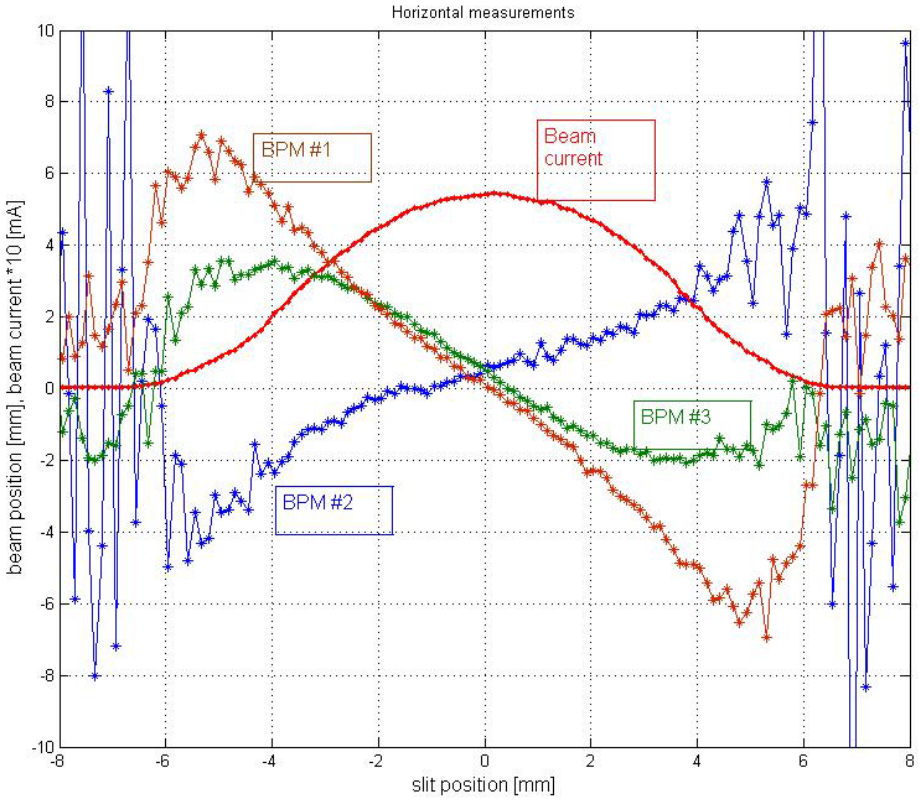


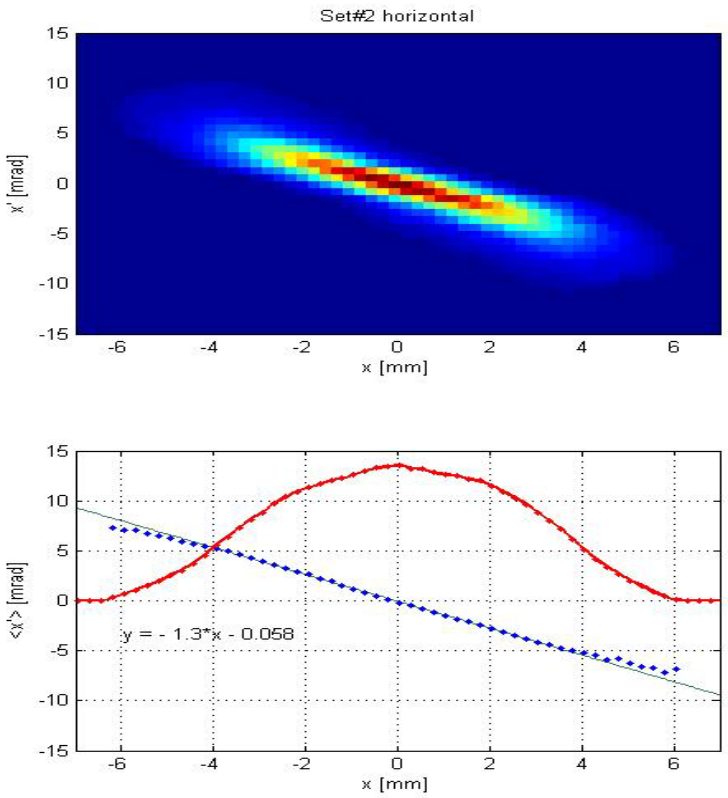
$$\frac{dx_{BPM}}{ds} = m_{11} - 1.3 \cdot m_{12}$$

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

$$\frac{dy_{BPM}}{ds} = m_{11}$$

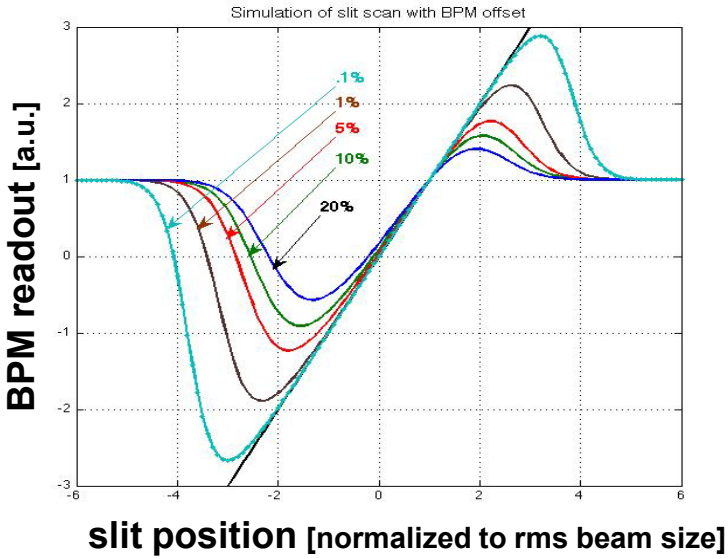
Experimental slit scans -horizontal





$$x_{BPM} = \frac{u_l - u_r}{u_l + u_r}$$

Dynamic range limitation



Simple model of slit scan with offset in BPM electronics

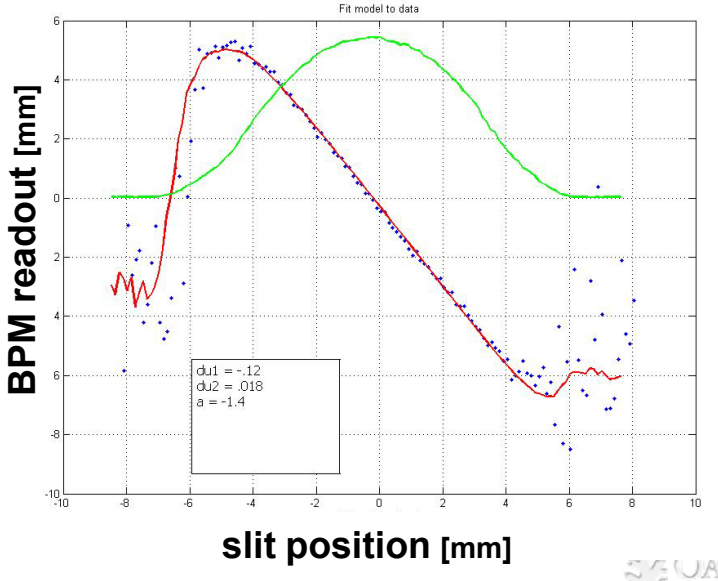
$$x_{beam} = a \cdot s$$

$$x_{BPM} = \frac{u_t - u_b}{u_t + u_b} \cong g \frac{I \cdot x_{beam} + \delta_1}{I + \delta_2} = g \frac{I(s) \cdot a \cdot s + \delta_1}{I(s) + \delta_2}$$

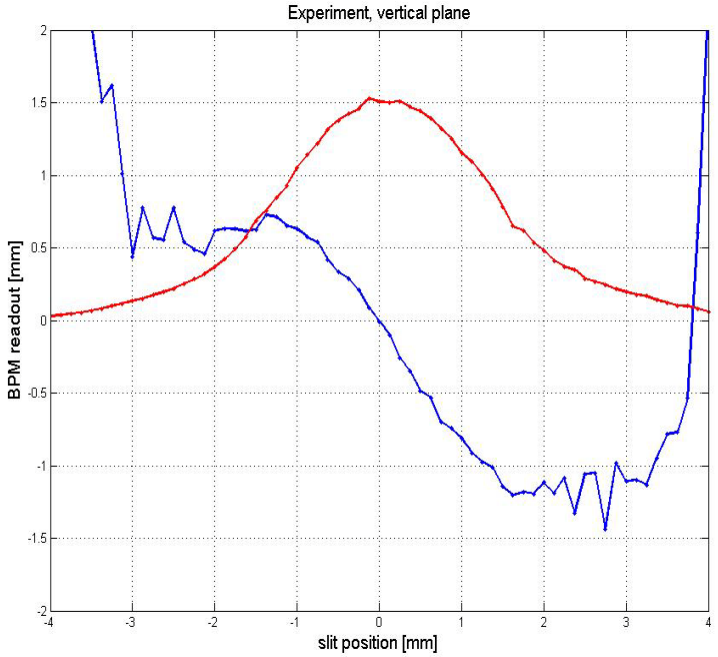
Slope determination error: $\delta a \approx \frac{\delta_{1,2}}{I_0}$

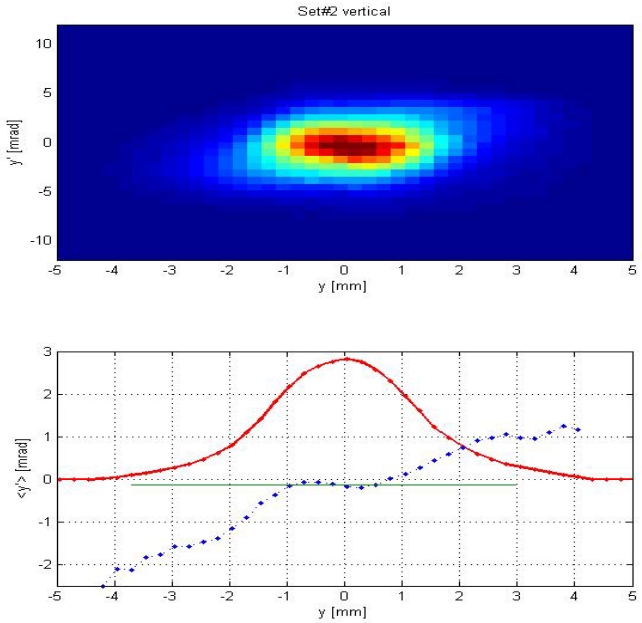
Simple model fit to measured data:

- Typical slope error of 5%-10%
- Maybe sufficient for linear transport
- Not feasible for non-linear transport (to many model parameters: offsets, BPM nonlinearity, transport non-linearity



Experimental slit scans -vertical





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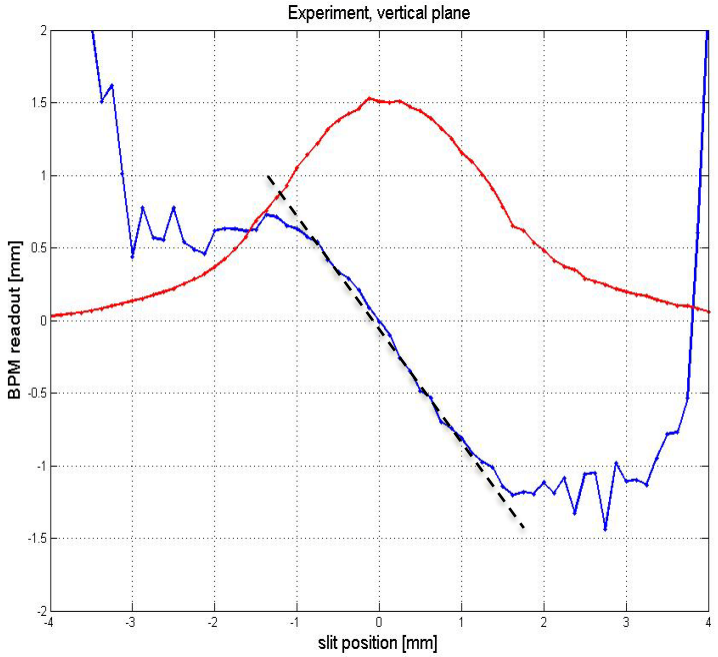
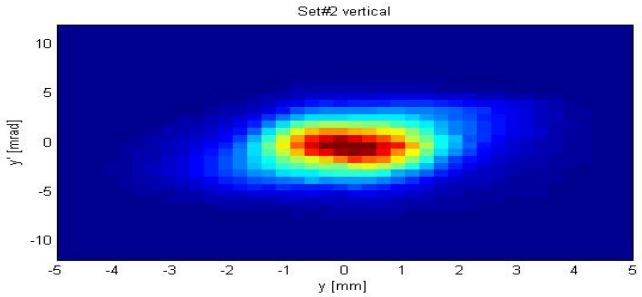
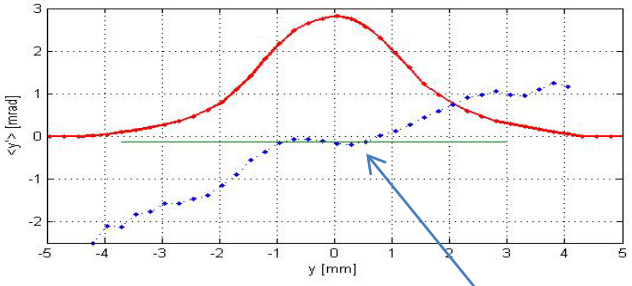
Experimental slit scans -vertical

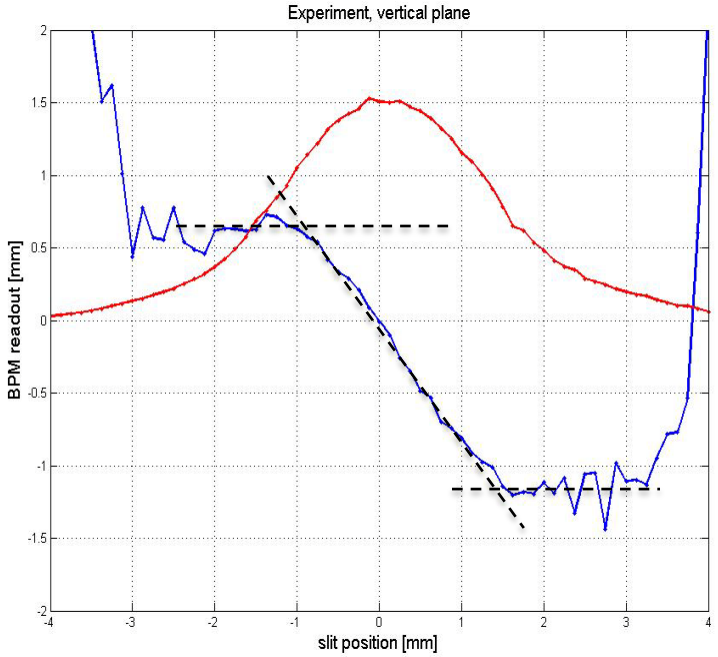


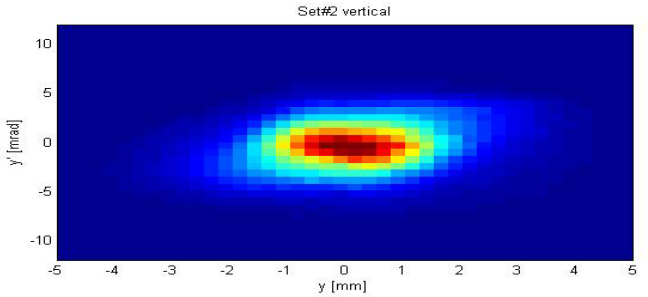


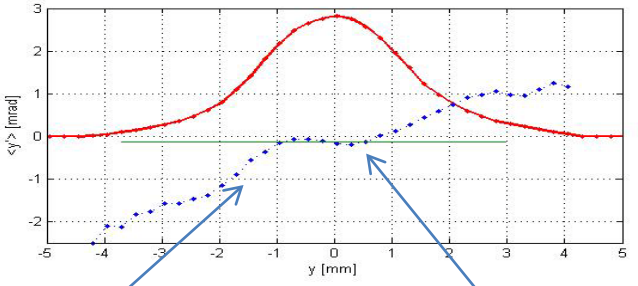


$$\frac{dy_{BPM}}{ds} = m_{11}$$

Experimental slit scans -vertical







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

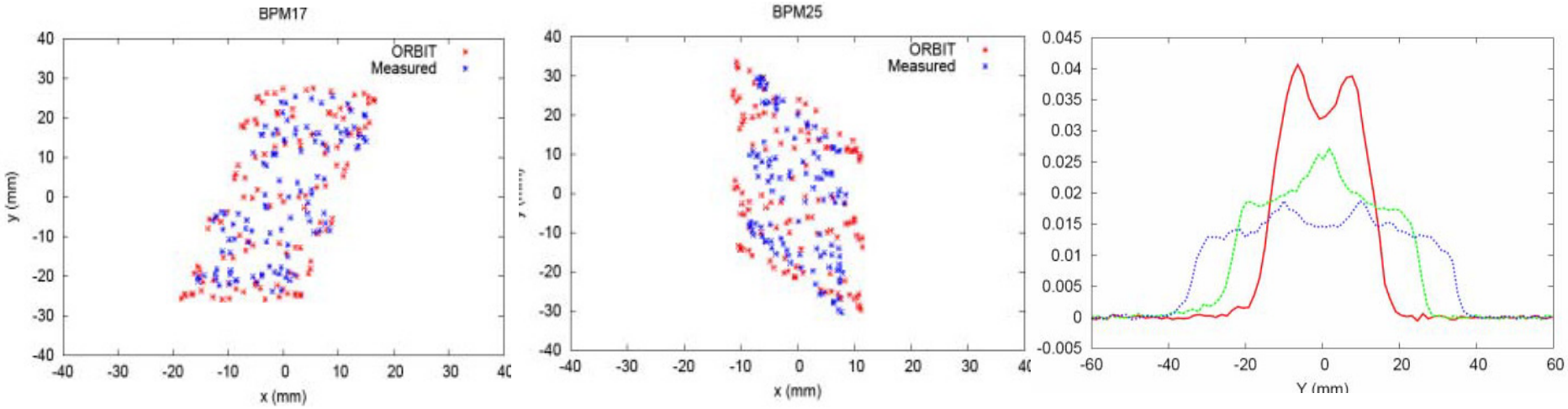
$$\frac{dy_{BPM}}{ds} = m_{11}$$

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 ~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

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