Proof-of-principle experiment for single-shot transverse phase space measurement

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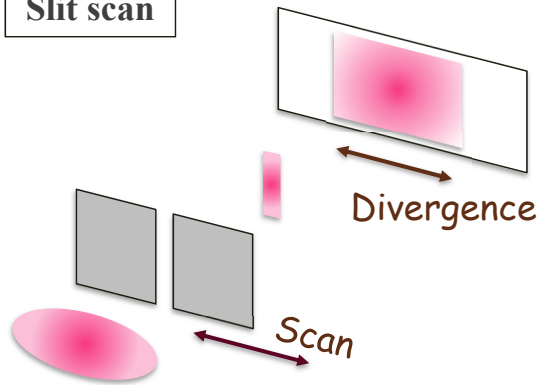
Content

- Introduction of new method
- Demonstration using beam dynamics simulation
- Limiting factors
- Applications
- Experimental demonstration

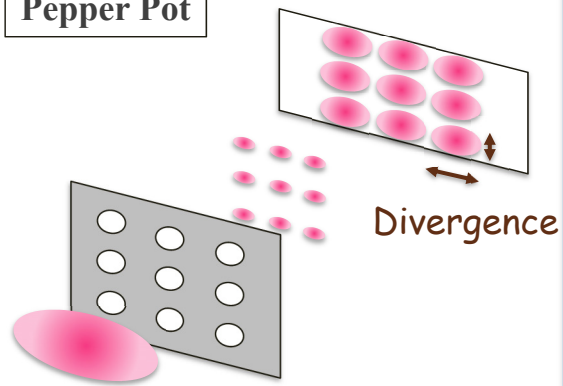
How do we measure transverse phase space?

Slit scan



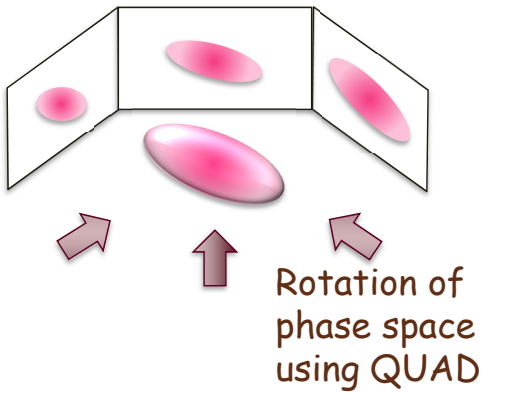
- Full image of phase space
- Averaged image only
- Long data taking time
- Inadequate for high E / low divergence

Pepper Pot



- Partial image of phase space
- Single shot / average
- Short data taking time
- Inadequate for high E / low divergence

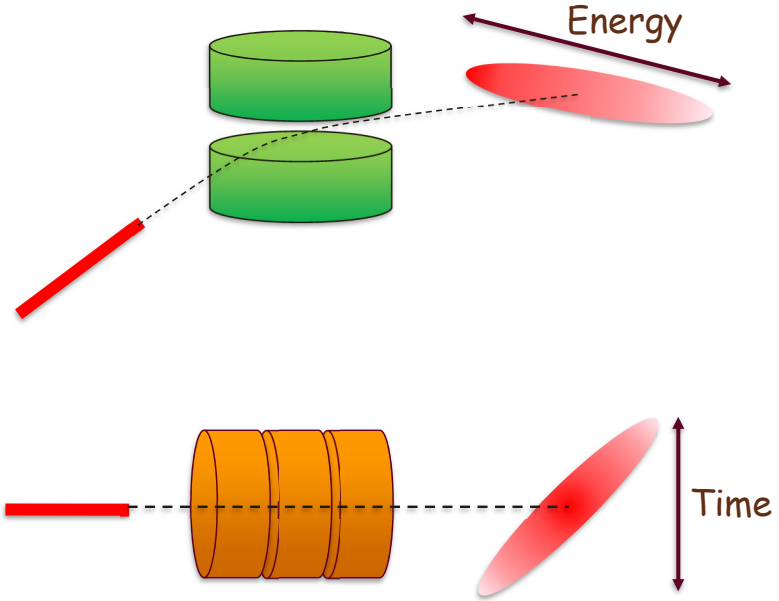
Tomography



- Full image of phase space
- Averaged image only
- Long data taking time
- Adequate for high E / low divergence

Can we use PROJECTION scheme for transverse phase space?

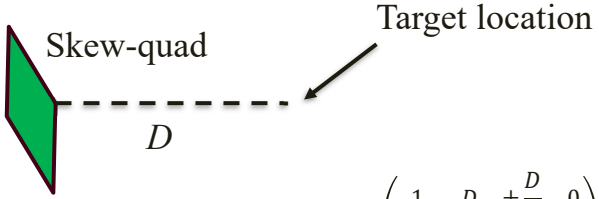
We already do projection of an interested coordinate to an easy-to-measure coordinate!!!



How to project (x,x′) to (x,y)?

Step1

We need x-y coupling



$$\begin{pmatrix} 1 & D & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & D \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \pm\frac{1}{f} & 0 \\ 0 & 0 & 1 & 0 \\ \pm\frac{1}{f} & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & D & \pm\frac{D}{f} & 0 \\ 0 & 1 & \pm\frac{1}{f} & 0 \\ \pm\frac{D}{f} & 0 & 1 & D \\ \pm\frac{1}{f} & 0 & 0 & 1 \end{pmatrix}$$

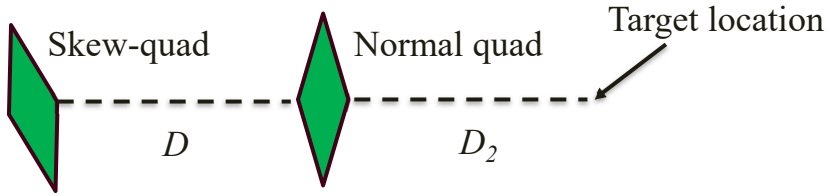
$$x_f = x_0 + \boldsymbol{D x'_0} \pm \frac{D}{f} y_0$$

$$y_f = \pm\frac{\boldsymbol{D}}{\boldsymbol{f}} \boldsymbol{x_0} + y_0 + D y'_0$$

Projection of transverse phase space

Step2

We don't want x-x relation



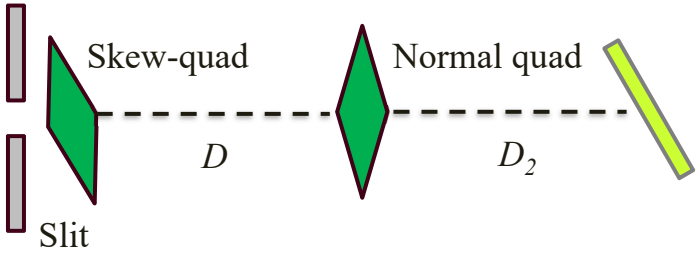
$$\begin{pmatrix} 0 & D_2 & 0 & 0 \\ -\frac{1}{D_2} & 1 & 0 & 0 \\ 0 & 0 & 2 & D_2 \\ 0 & 0 & \frac{1}{D_2} & 1 \end{pmatrix} \begin{pmatrix} 1 & D & \pm\frac{D}{f} & 0 \\ 0 & 1 & \pm\frac{1}{f} & 0 \\ \pm\frac{D}{f} & 0 & 1 & D \\ \pm\frac{1}{f} & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & D_2 & \pm\frac{D_2}{f} & 0 \\ -\frac{1}{D_2} & 1-\frac{D}{D_2} & \pm\frac{1}{f}\left(1-\frac{D}{D_2}\right) & 0 \\ \pm\frac{2D+D_2}{f} & 0 & 2 & 2D+D_2 \\ \pm\frac{1}{f}\left(1+\frac{D}{D_2}\right) & 0 & \frac{1}{D_2} & 1+\frac{D}{D_2} \end{pmatrix}$$

$$\Rightarrow \quad x_f = (\boldsymbol{D_2})\boldsymbol{x'_0} \pm \frac{D_2}{f} y_0$$

$$y_f = \pm\frac{\boldsymbol{2D + D_2}}{\boldsymbol{f}} \boldsymbol{x_0} + 2y_0 + (2D + D_2)y'_0$$

Step3

We don't want vertical contribution



$$\boldsymbol{x_f} \cong (\boldsymbol{D_2})\boldsymbol{x'_0}$$

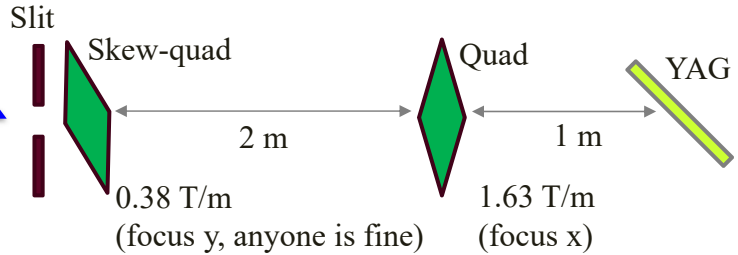
$$\boldsymbol{y_f} \cong \pm\frac{\boldsymbol{2D + D_2}}{\boldsymbol{f}} \boldsymbol{x_0}$$

when $\quad \sigma_{x'_0} \times f_{SQ} \gg \sigma_{y_0}$

$$\left(\frac{\sigma_{x_0}}{f_{SQ}}\right)^2 \gg \sigma_{y'_0}^2 + \frac{4\sigma_{y_0}^2}{(2D + D_2)^2} + \frac{4\sigma_{yy'}}{(2D + D_2)}$$

Test with realistic quadrupoles

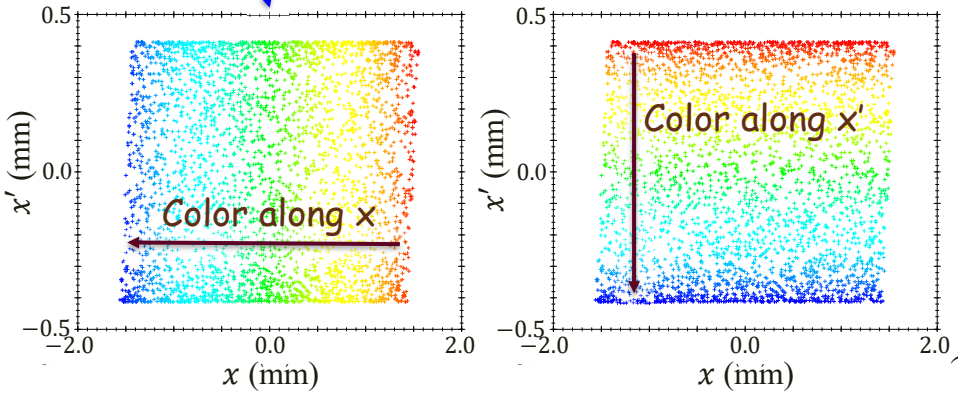
Set this configuration in beam dynamics code



Transfer matrix

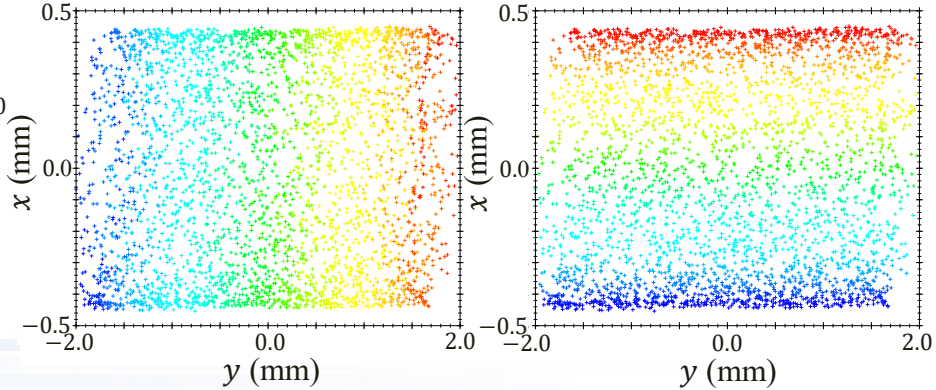
$$\begin{pmatrix} 0.00 & \mathbf{1.05} & -0.24 & -0.04 \\ -0.95 & -1.14 & 0.23 & 0.03 \\ \mathbf{-1.20} & -0.18 & 2.04 & 5.62 \\ -0.69 & -0.10 & 0.99 & 3.21 \end{pmatrix}$$

Send artificial beam to the beamline

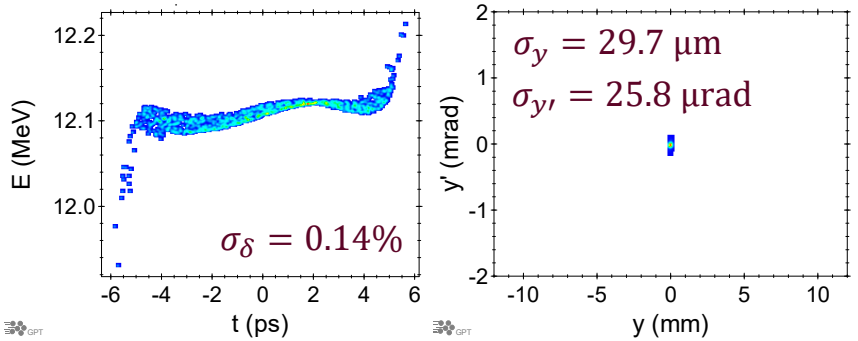


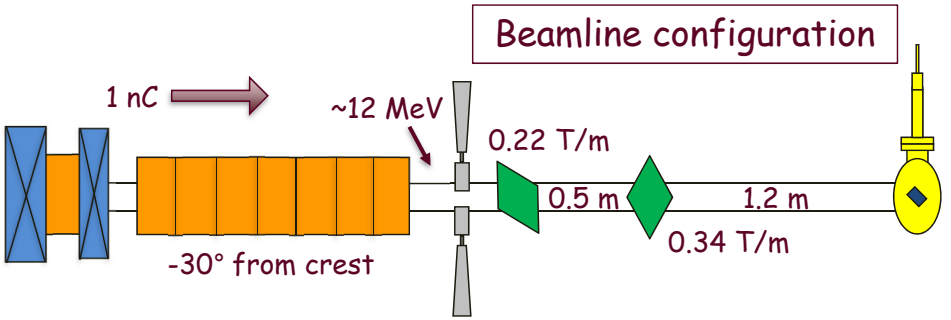
Horizontal phase space after slit

YAG image

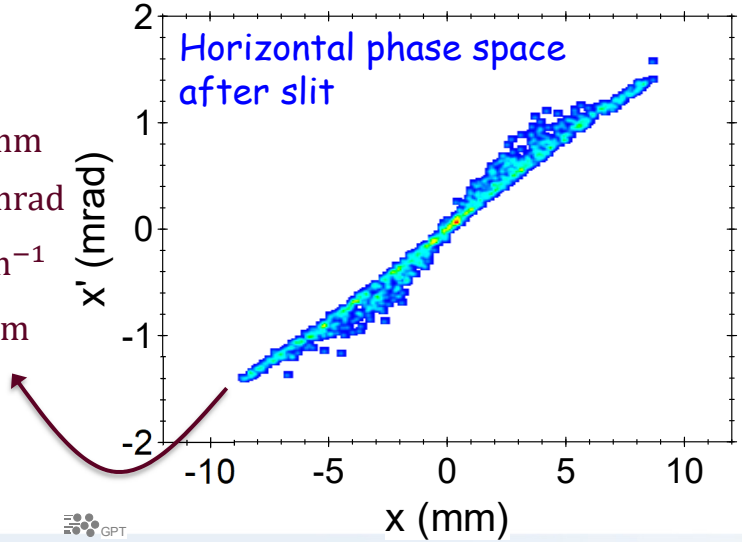


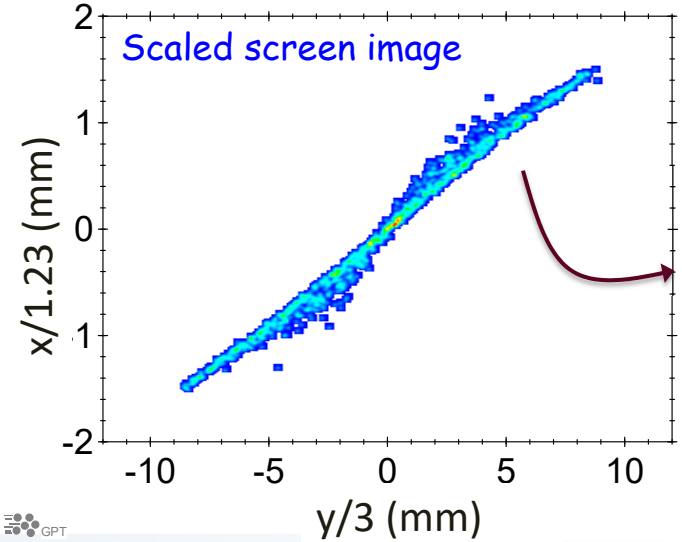
Is it working with realistic beam?





$\sigma_x = 4.08$ mm
$\sigma_x = 0.74$ mrad
$S_x = 0.18\ \mathrm{m}^{-1}$
$\varepsilon_x = 9.46$ µm





$\sigma_x = 4.08$ mm
$\sigma_x = 0.73$ mrad
$S_x = 0.18\ \mathrm{m}^{-1}$
$\varepsilon_x = 9.72$ µm

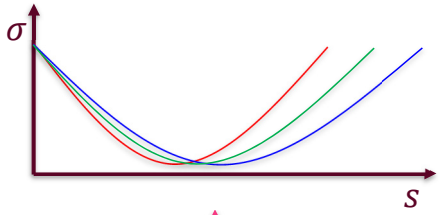
Limiting factors

Limiting factors

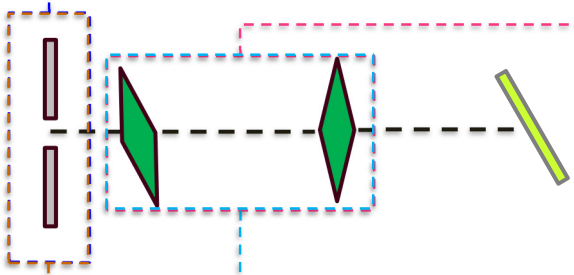
$$x_f = (D_2)x_0' \pm \frac{\boldsymbol{D_2}}{\boldsymbol{f}}\boldsymbol{y_0}$$

$$y_f = \pm\frac{2D + D_2}{f}x_0 + \boldsymbol{2y_0} + \boldsymbol{(2D + D_2)y'_0}$$

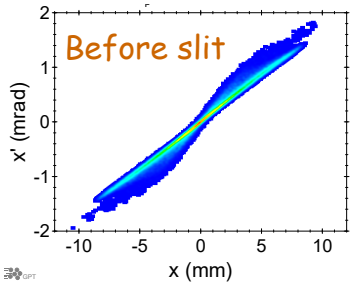
Remained extra transverse components → Gap size?

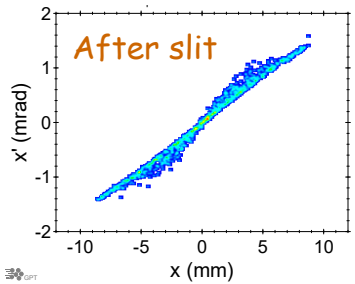


Chromatic effect due to energy spread



Beam selection from slit

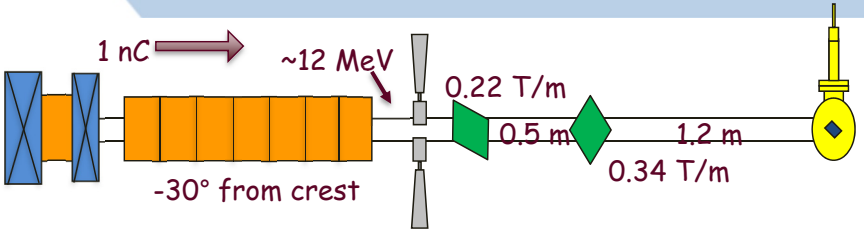




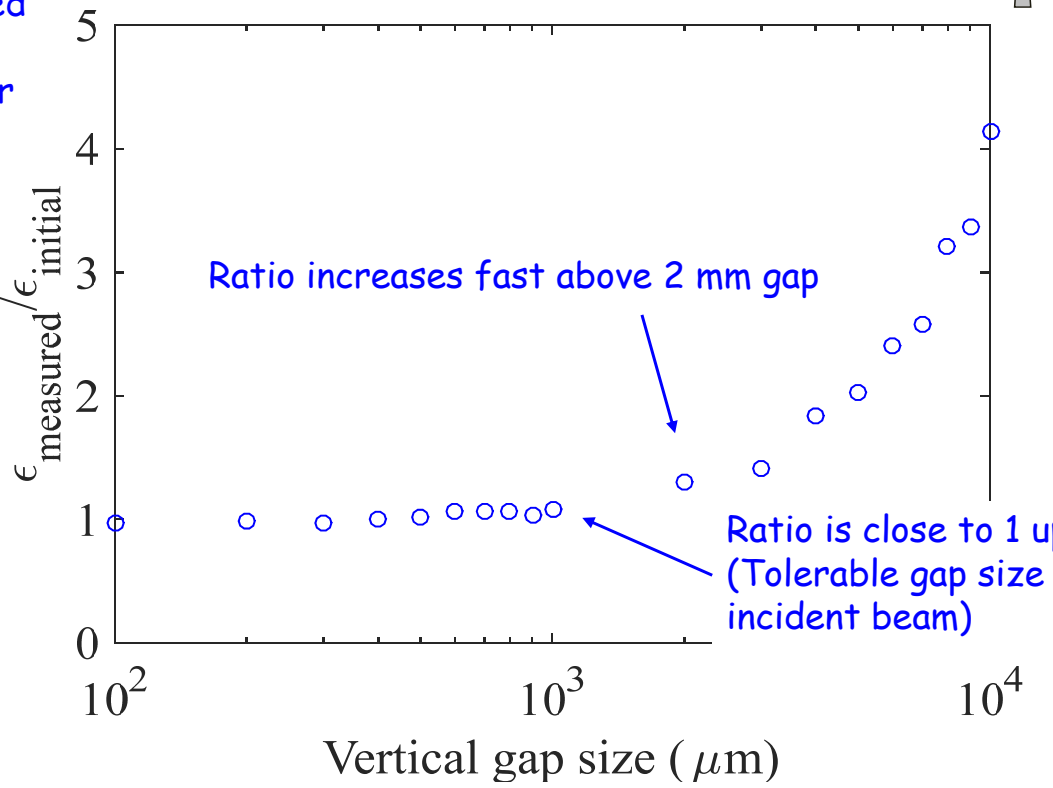
Quadrupole strength error

$$\begin{pmatrix} x_f \\ y_f \end{pmatrix} = \begin{pmatrix} 0 \to R'_{11} & R_{12} \to R'_{12} \\ R_{31} \to R'_{31} & R_{32} \to R'_{32} \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}$$

What gap size we can use?



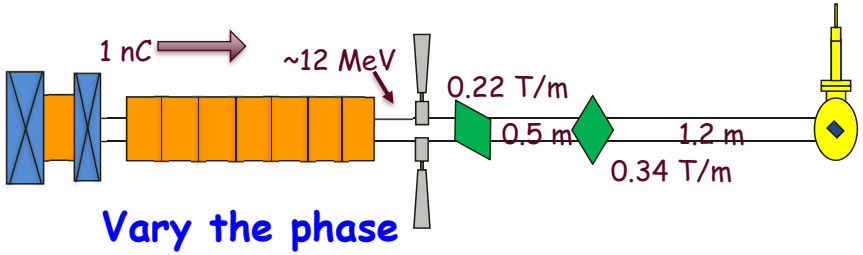
Use the ratio of measured emittance to emittance after the slit as indicator

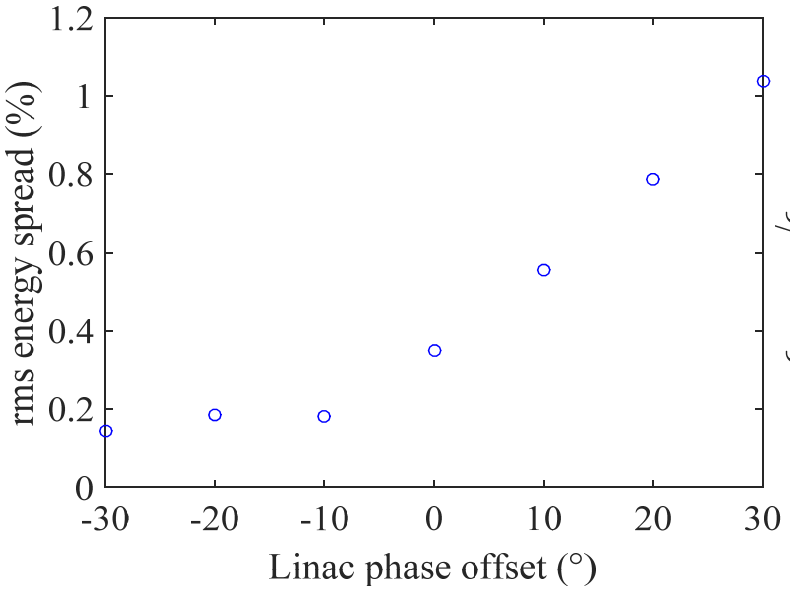


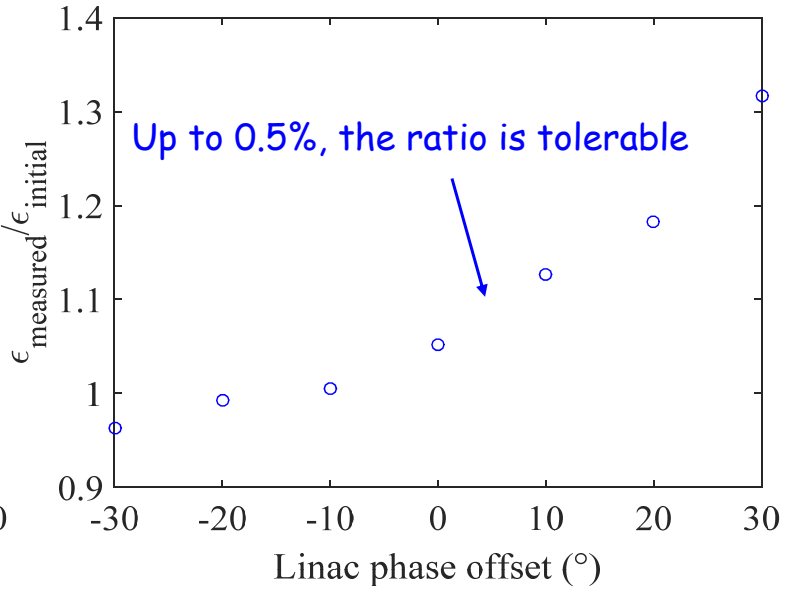
Ratio increases fast above 2 mm gap

Ratio is close to 1 up to 1 mm gap (Tolerable gap size will depend on the incident beam)

What energy spread we can tolerate?



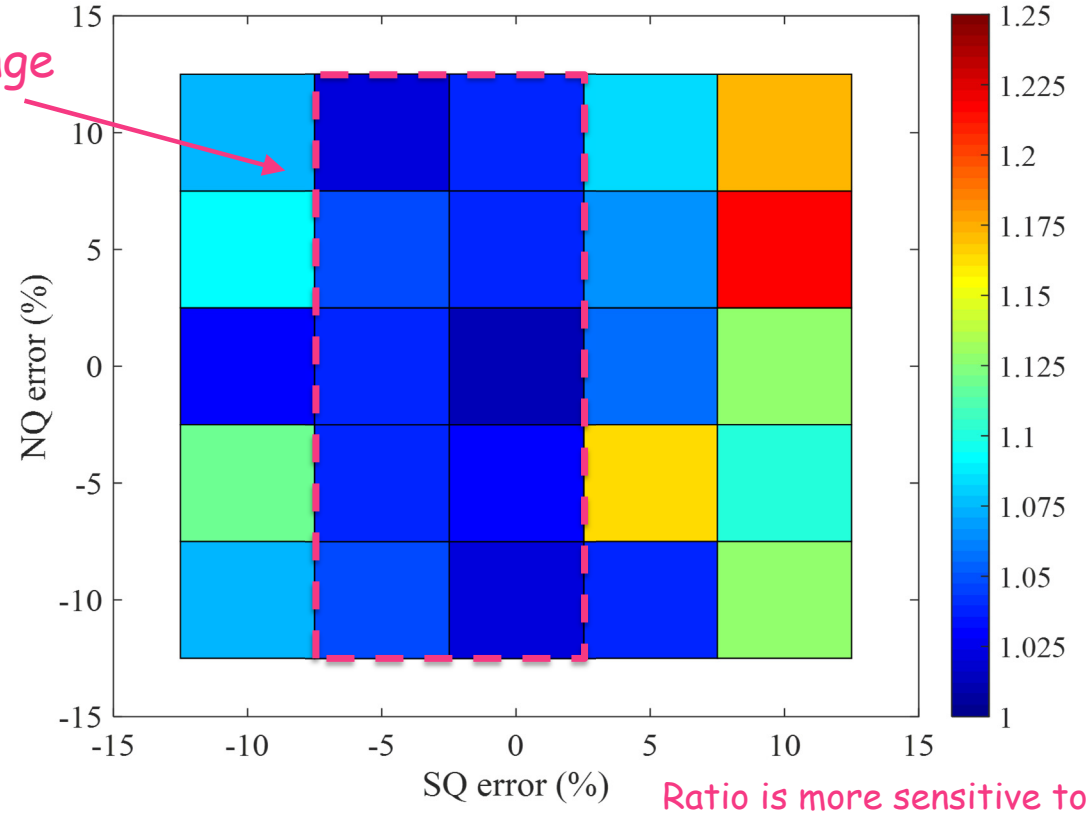




What quadrupole error we can tolerate?

Colors are $\frac{\varepsilon_{measure}}{\varepsilon_{real}}$

Tolerable range

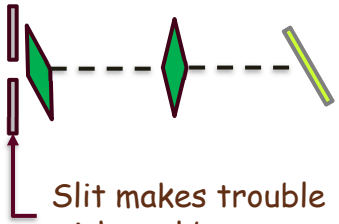


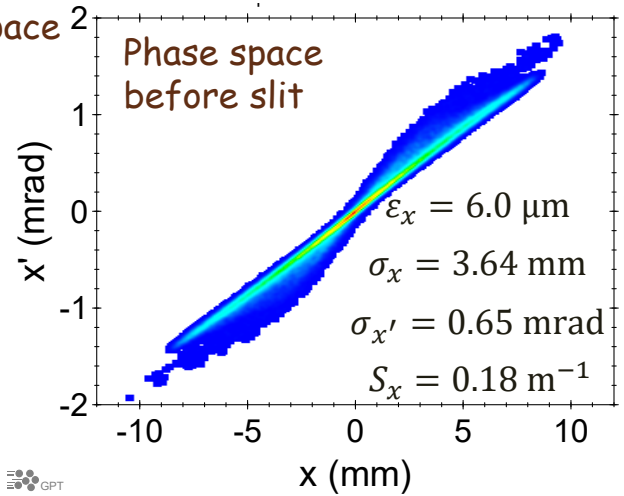
Ratio is more sensitive to the skew quad since it generates x-y coupling

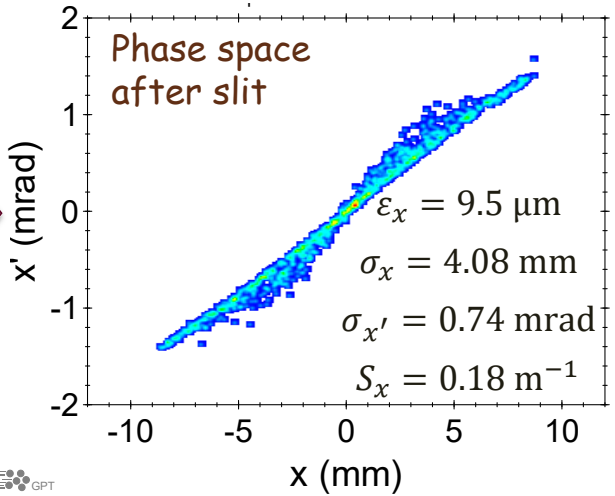
Limitation of method…

*GPT S2E simulation result

Slit does not change the phase space if the beam is perfect Gaussian







Due to the slit…

- Beam loses more particle in the core than halo
- Beam size and divergence has error ≤10%
- Slope error is ≤1% since the shape of phase space is preserved
- Emittance has error ~ 50%

We are working on

*There should be way to retrieve the phase space from two or more averaged images without slit

** There should be way to minimize the vertical contribution without slit

Is this method still usable? YES

Application examples

- Alternative option of existing methods
- Slice emittance measurement
- Diagnose beam/beamline status
- Investigation of beam degradation source

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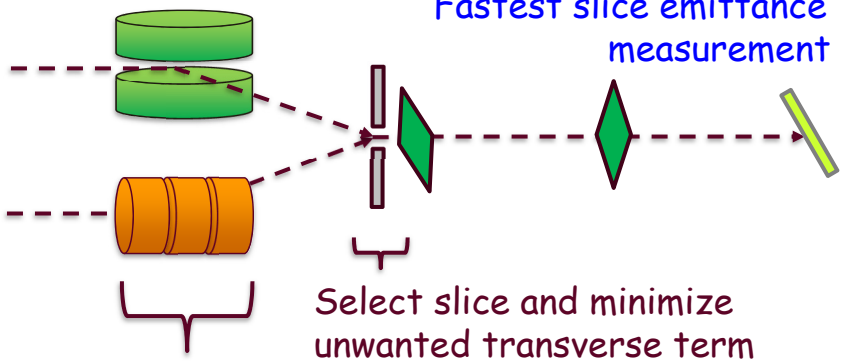
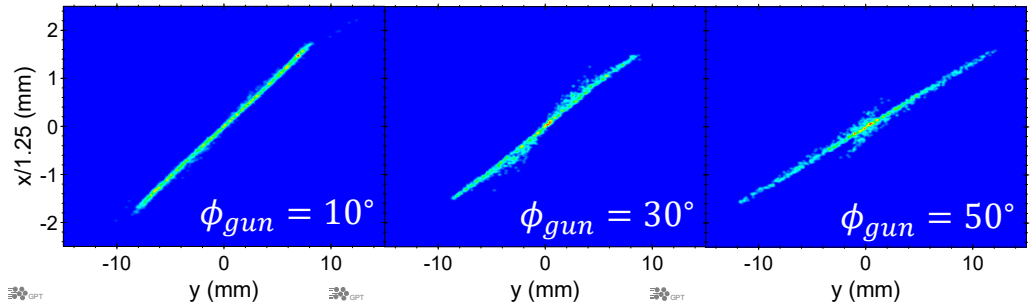
Alternative of existing methods

Full image	○		○		○
Data taking time	**S**	**>**	**P**	**<**	**T**
High-E availability	×		○		○
Space charge effect	**S**	**~**	**P**	**<**	**T**

S: slit-scan P: projection+scan T: tomography



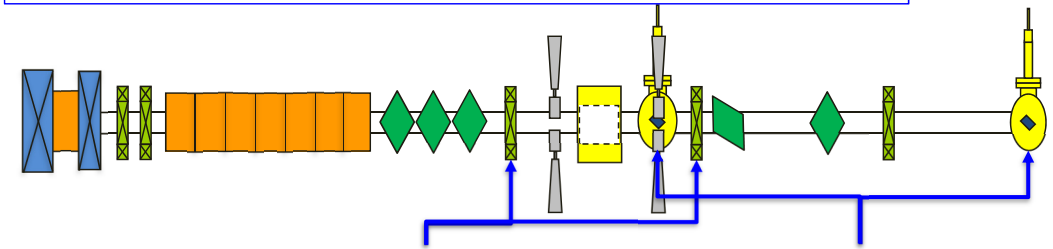
Online space charge compensation



Experiment

Transport matrix measurement and inverse mapping

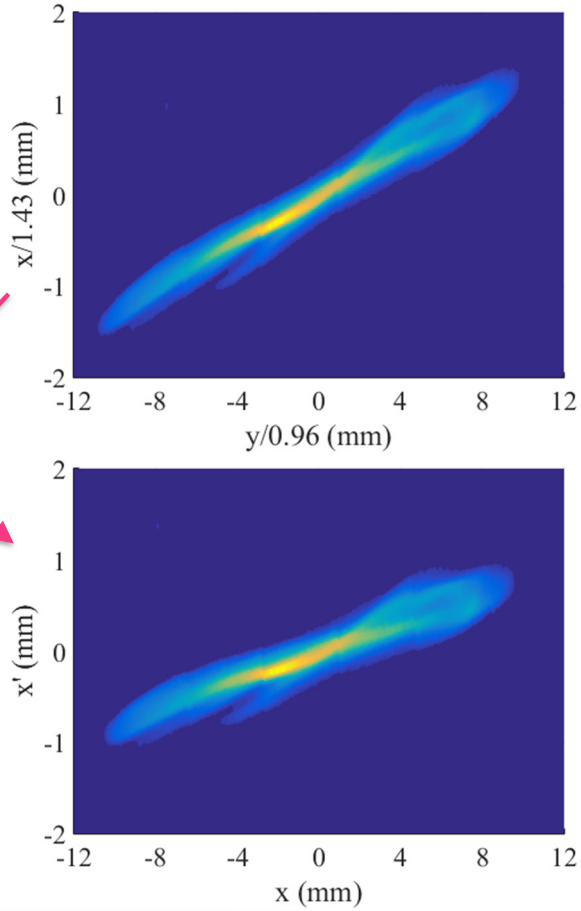
Argonne Wakefield Accelerator – Witness beamline



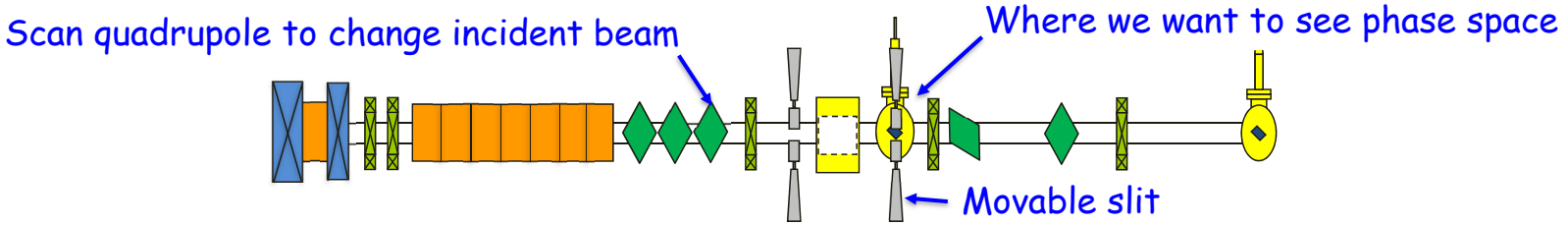
Coefficients of projection

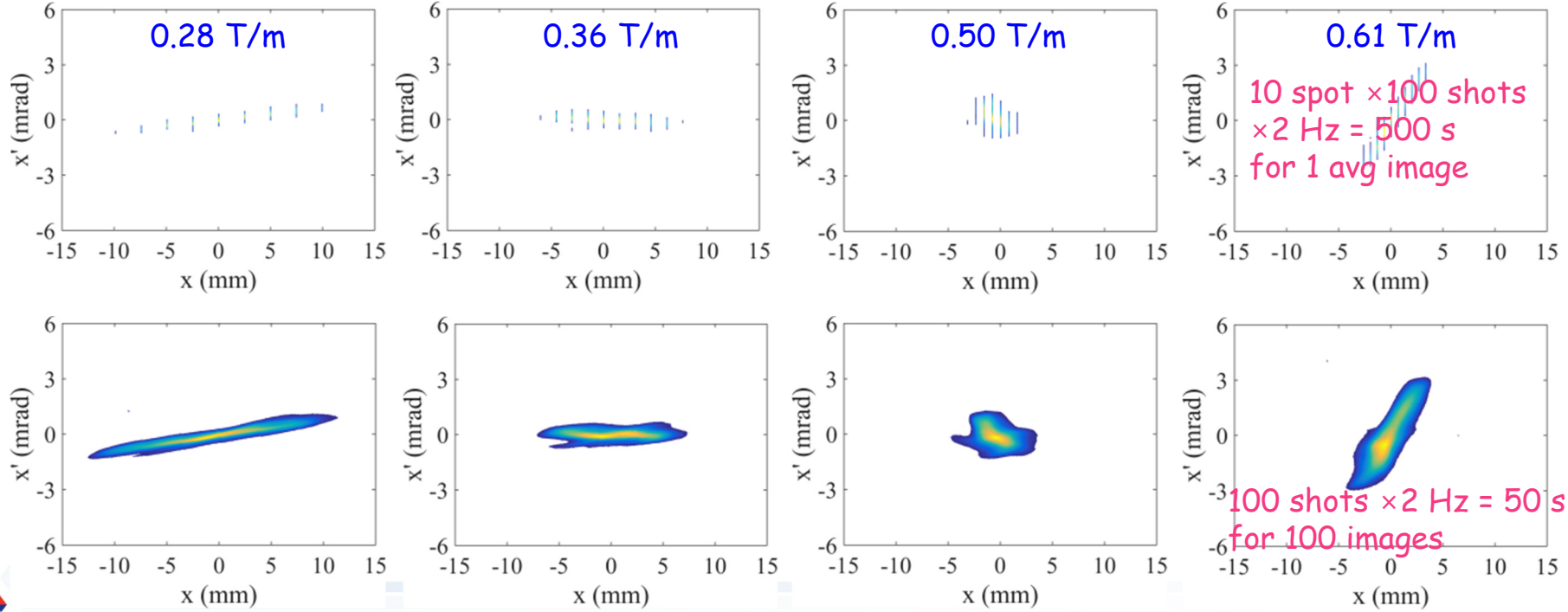
	Designed	Measured
$C_{x_0 \to x_2}$	0.00	0.07±0.05
$C_{x'_0 \to x_2}$	1.32	1.43±0.06
$C_{x_0 \to y_2}$	1.04	0.96±0.12
$C_{x'_0 \to y_2}$	0.33	0.31±0.15

Need rotation too



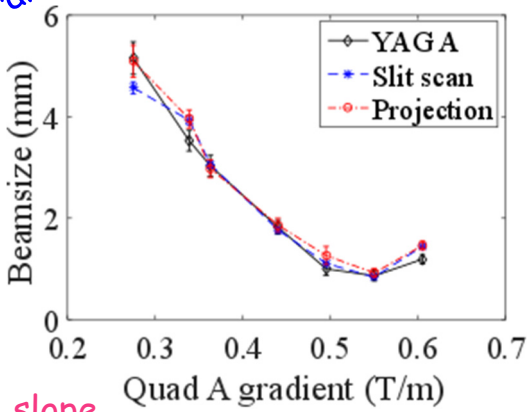
Comparison of slit scan and projection method

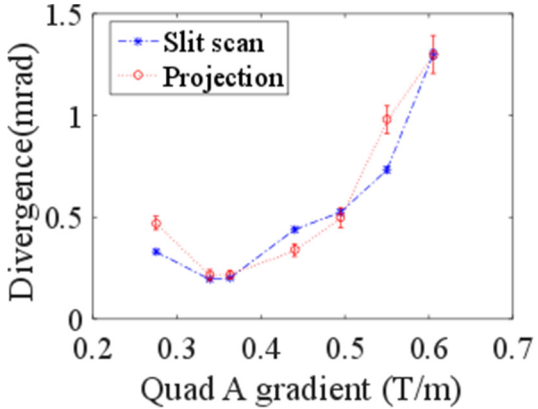




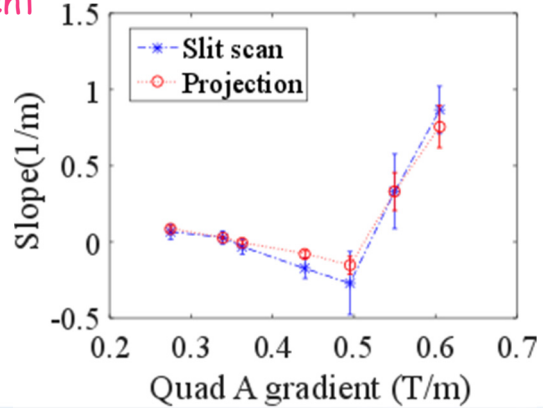
Comparison of slit scan and projection method

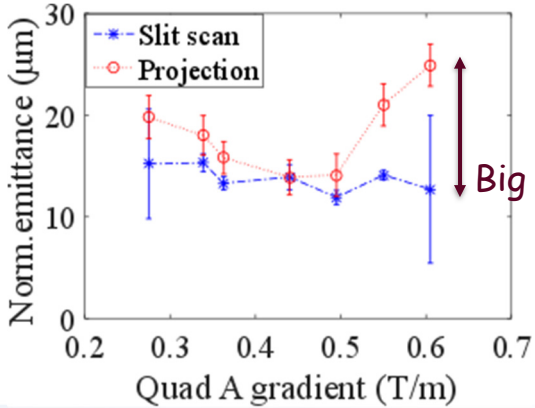
Beam statistical parameters



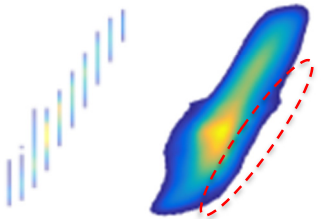


Beam size, divergence, slope shows good agreement





Due to charge density at screen



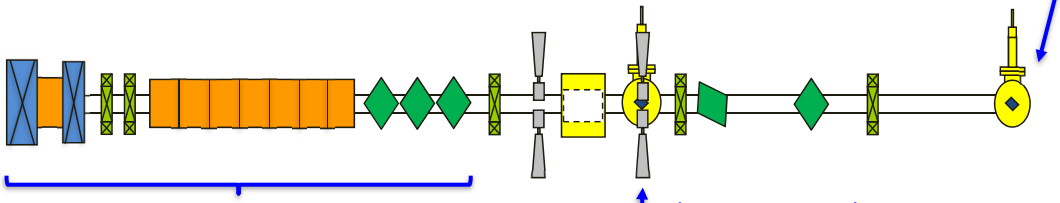
Slit-scan miss outer low density particles

Big difference on emittance

Application to inspect injector

Shot-to-shot phase space check

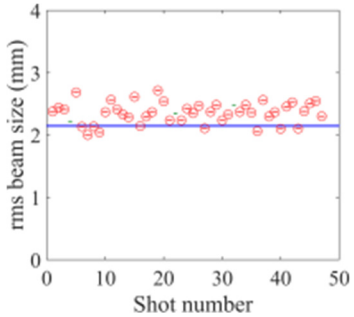
Tracking of all jitter sources with phase space would help to find the source of emittance jitter

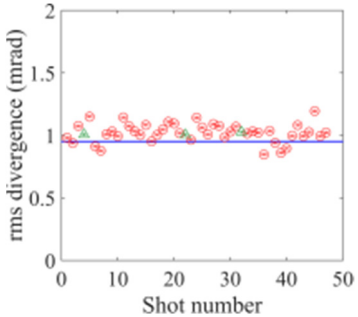


Emittance degradation sources

Change on phase space

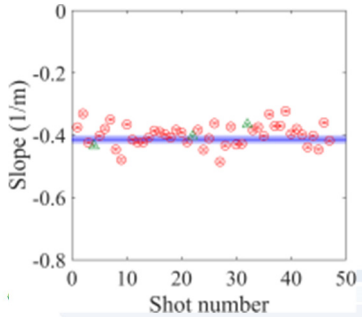
Cathode QE map, Laser profile jitter may be the source

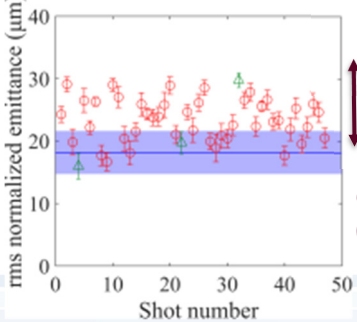




Charge jitter does not explain emittance jitter

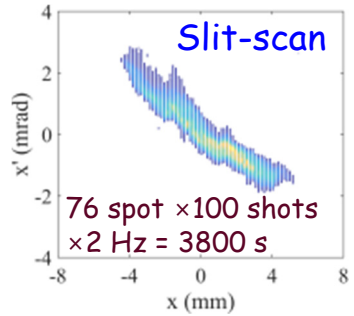
Charge window ±5% of mean value

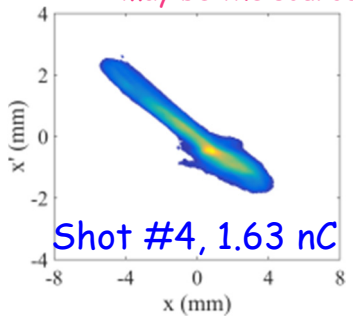


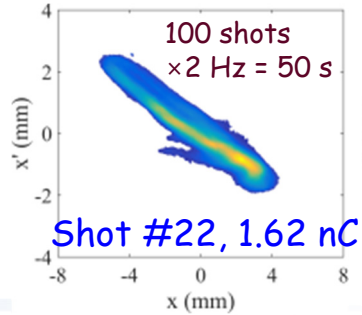


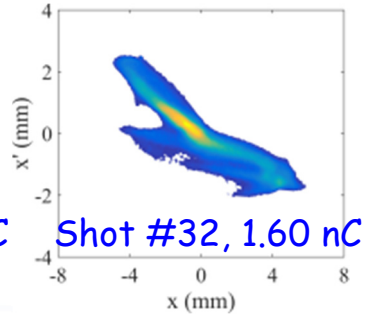
~30%

Other sources…
(e.g. laser spot, solenoid etc)









Conclusion

- The projection scheme is used to project transverse phase space to screen.
- The method is quite resistive to error sources (gap size, energy spread, strength).
- The method is not appropriate for emittance measurement due to the slit effect.
- The method has a limitation due to slit, but it can be applied many applications.
- The method is successfully demonstrated by comparison with slit-scan.
- AWA is working on finding advanced method to accurately calculate the emittance or phase space without slit.

Thank you for your attention