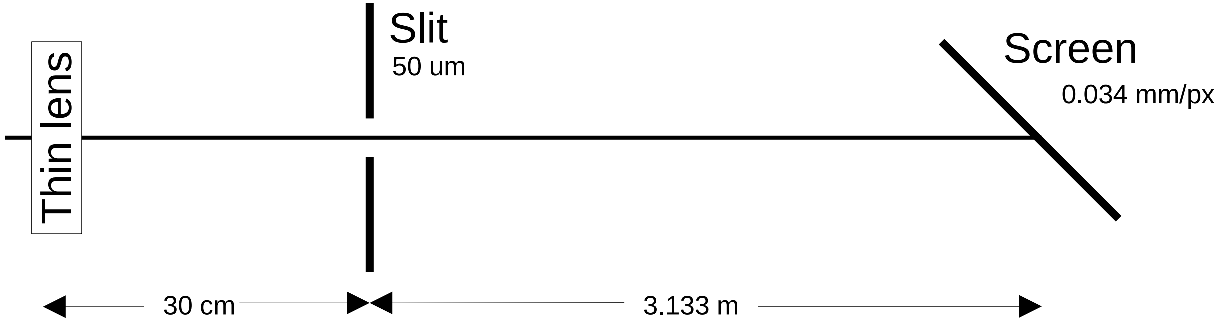
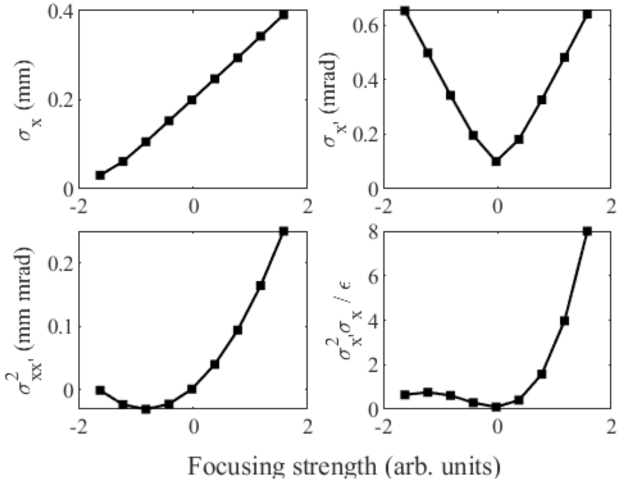
Slit and camera corrections for EMSY measurements

Chris Richard
PPS 06.09.2022

Linear EMSY model

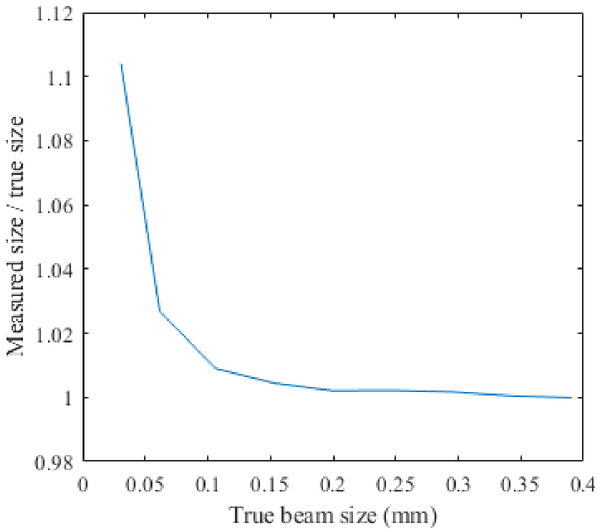
- To study effects on EMSY measurements a linear EMSY model was made in Matlab
  - Input 4D beam distribution of particles, slit size and step, slit-screen separation, and camera resolution
  - Separate particles into beamlets based on slit size and step
  - Propagate each beamlet to the screen location, x_f = x_i + Lx’_i
  - Generate beamlet density distribution images. Pixel size determined by camera resolution
  - Use images to determine angle profiles
- A Gaussian beam was used with geometric emittance = 0.02 mm mrad
  - To get a range of parameters, the beam is kicked with a thin lens, propagated 30 cm, then input into the EMSY model

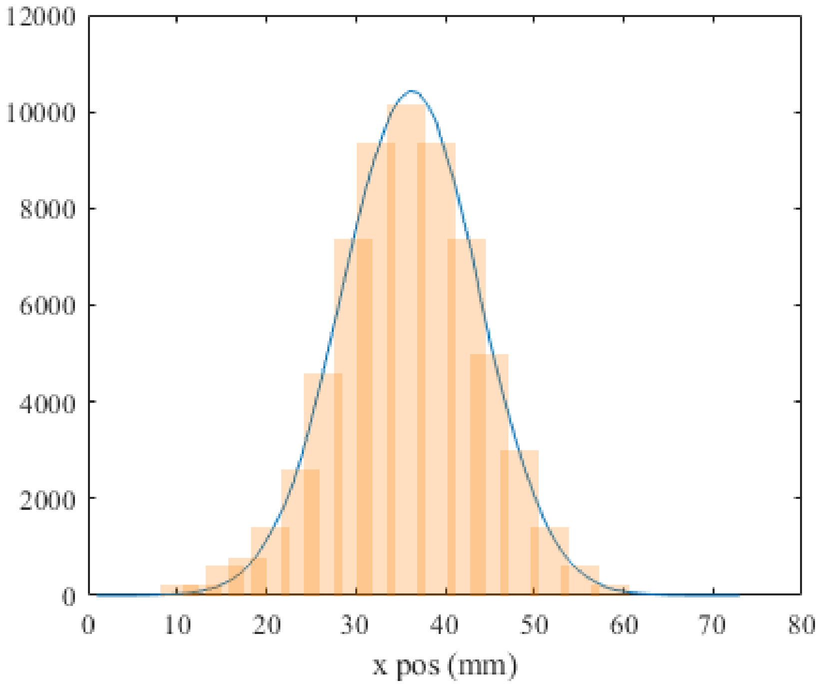




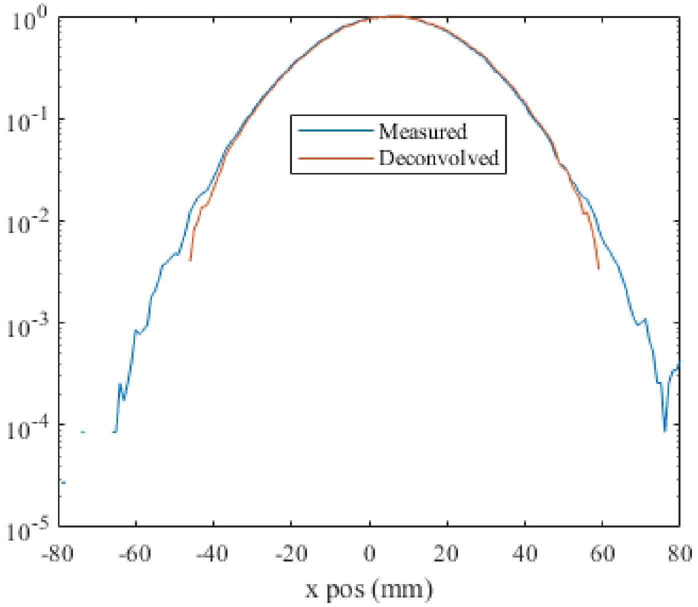
Effect of slit on measured distribution

- The measured position profile is a 1D convolution of the true profile with the slit profile
  - Rectangular opening stepping through the beam and measure the passed intensity at each step. This is a physical representation of a convolution
  - The measured beam size will be $\sigma^2_{meas} = \sigma^2_{true} + \sigma^2_{slit}$
- This is true regardless of step size: the finite step is subsampling the 'true' convolved result
  - Each measurement is still the average intensity over the slit opening

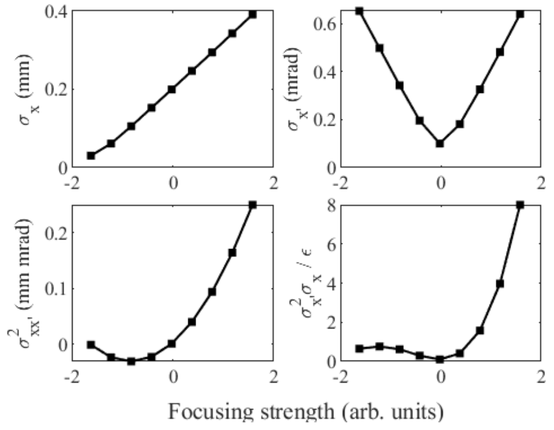


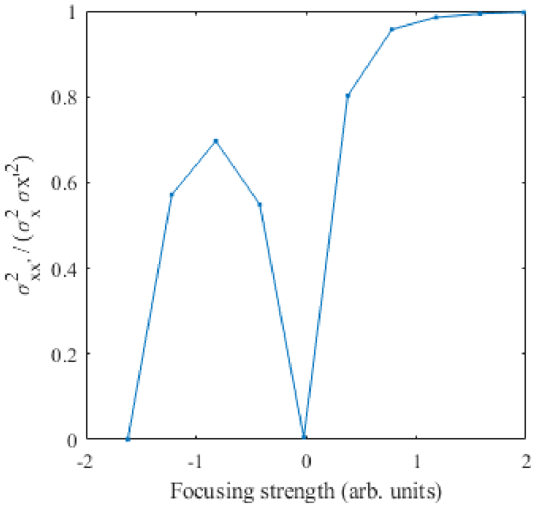


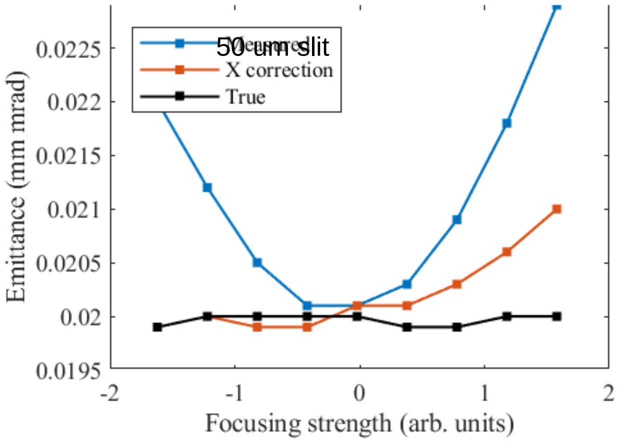
Correcting for slit effect

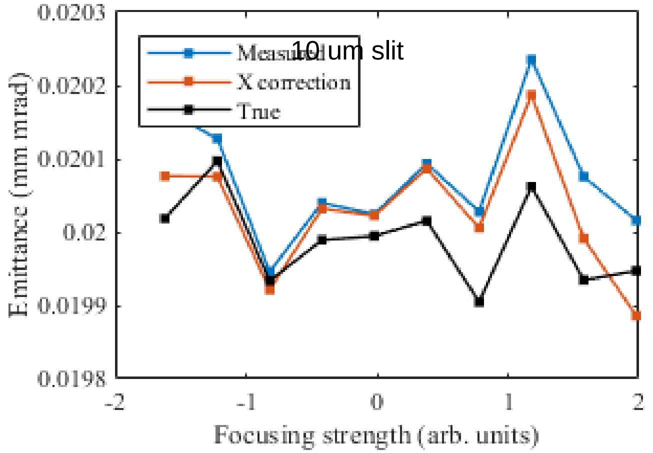


- The measured beam size will be $\sigma^2_{meas} = \sigma^2_{true} + \sigma^2_{slit}$
- This causes the measured emittance to increase for small beams and strongly x-x’ coupled beams $\epsilon = \sqrt{\sigma_x^2 \sigma_{x'}^2 - \sigma_{xx'}^2}$
- Correct by deconvolving the measured profile with the slit profile
  - Deconvolving can lead to issues with noise and singularities due to the zeros in sinc(x). Requires further cuts to remove artifacts
  - Instead can correct the measured rms size with above equation $\epsilon_m = \sqrt{\left(\sigma^2_{x,m} - \sigma^2_{slit}\right) \sigma^2_{x',m} - \sigma^2_{xx',m}}$



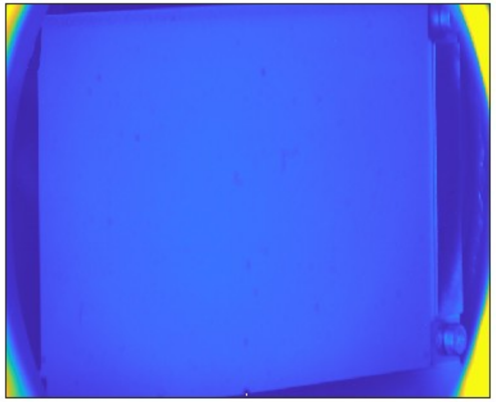




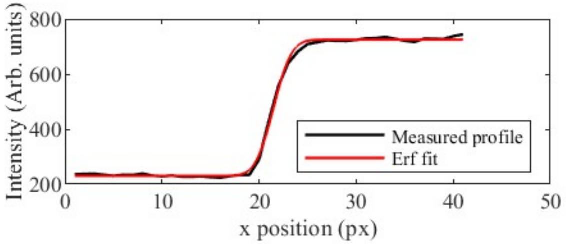


Determining point spread function (PSF)

- Point spread function: finite sized camera response to a infinitesimal input
- All images taken by a camera are convolution of true image with PSF
- Theoretical PSF definition
  - Assume the PSF is Gaussian $p(x) = \frac{1}{\sqrt{2\pi}\sigma_p} e^{-\frac{x^2}{2\sigma_p^2}}$
  - Take Fourier transform to get modular transfer function $z(\omega) = \int_{-\infty}^{\infty} p(x) e^{-i\omega x} dx = e^{-\frac{1}{2}\sigma_p^2 \omega^2}$
    - ω is camera resolution (px/mm)
  - Set z=0.1 and solve => $\sigma_p \approx 2.14\omega_0 \text{ mm}$



- PSF measurement
  - Record image of screen with light on it. Edges should be hard edges from screen holders
  - Measure profile across edge. Profile is the convolution of Gaussian PSF with hard edge i.e. error function
  - Fit to profile to error function to get PSF size, $\sigma_p = 2.01 \pm 0.11 \text{ px}$



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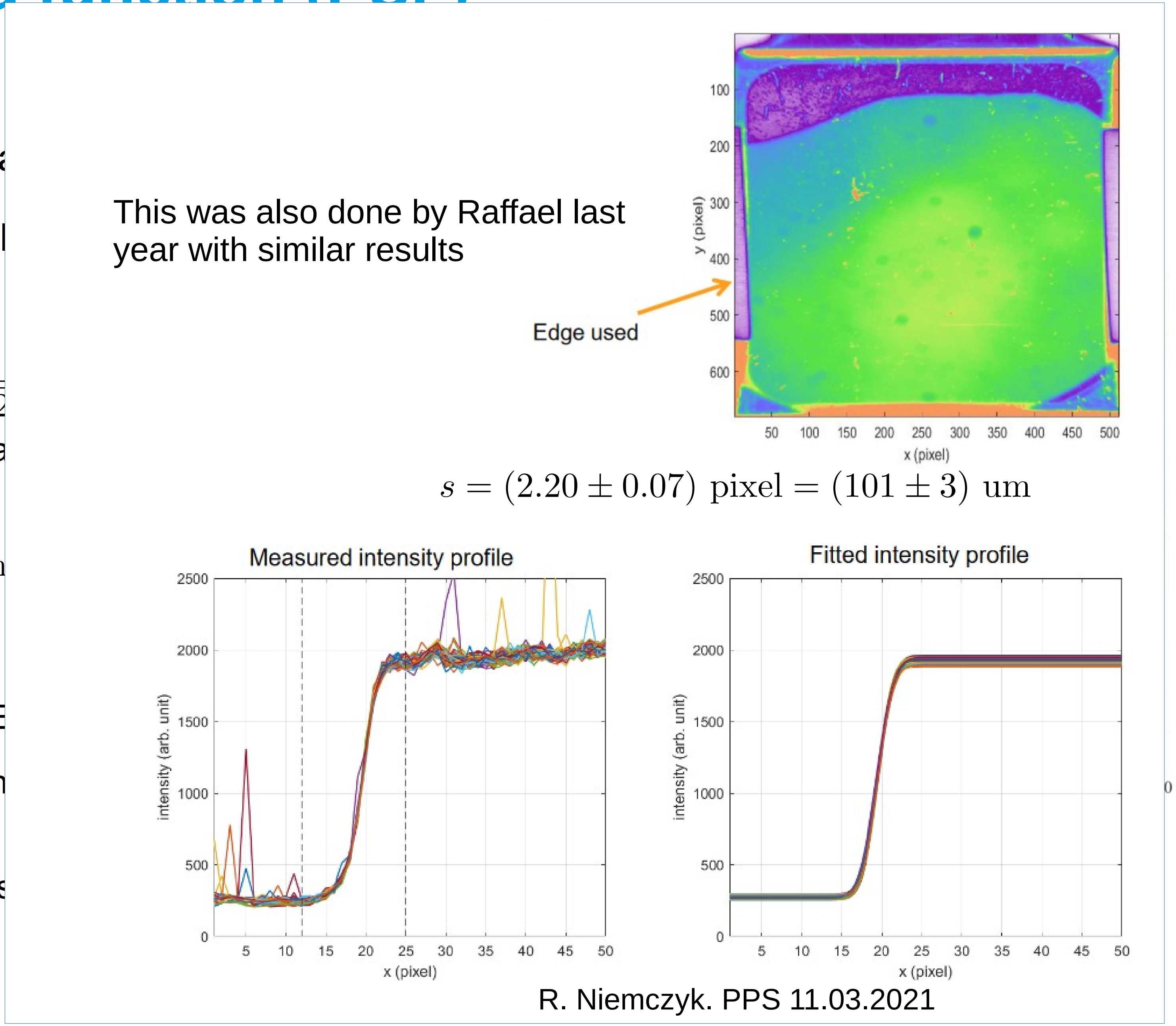


This was also done by Raffael last year with similar results

Edge used

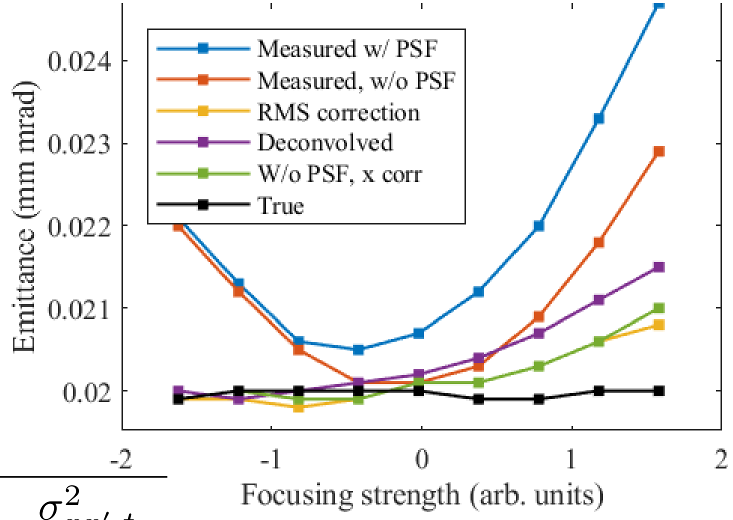
$$s = (2.20 \pm 0.07)\ \text{pixel} = (101 \pm 3)\ \text{um}$$

Measured intensity profile

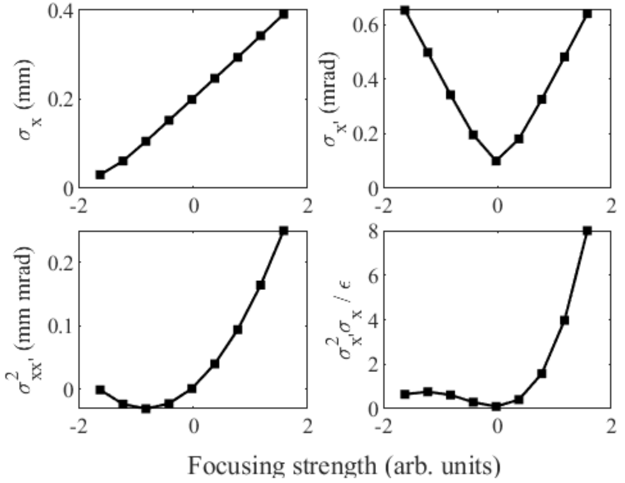
Fitted intensity profile

R. Niemczyk. PPS 11.03.2021

PSF affect on beamlet images

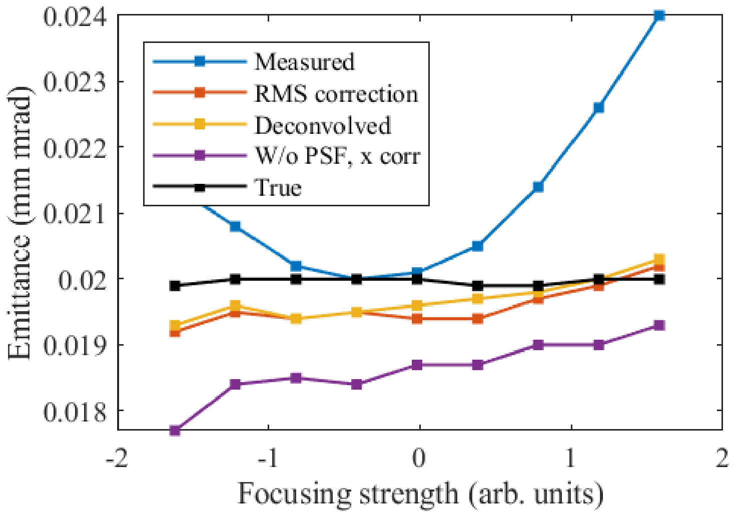


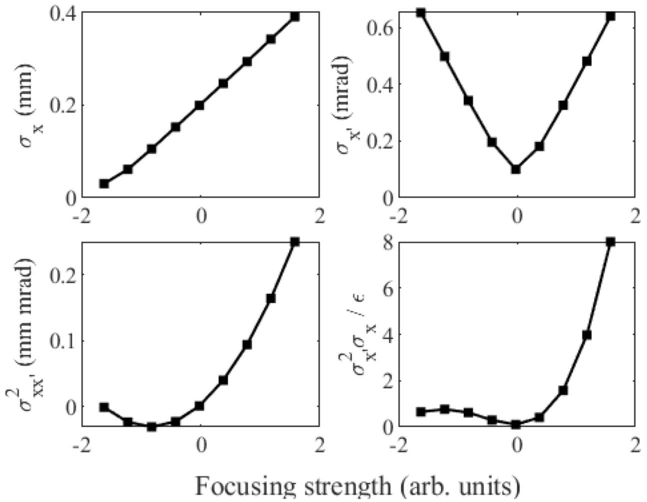
- Beamlet images are 2D convolution of true screen response with the PSF
  - Measured beamlet size $\sigma^2_{bl,m} = \sigma^2_{bl,t} + \sigma^2_p$
  - (may not be strictly true for non-Gaussian beams, but rule of thumb)
- Beamlet size for Gaussian beam assuming infinitesimally thin slit
  - Beamlet size is small when $\sigma_{x'}$ is small or $\sigma_{xx'}$ is large $\sigma_{bl,t} = \frac{\epsilon_t}{\sigma_{x,t}} L = L\sigma_{x',t}\sqrt{1 - \frac{\sigma^2_{xx',t}}{\sigma^2_{x,t}\sigma^2_{x',t}}}$
- Requires 2D deconvolution of beamlet images with PSF
  - Used method: Richardson-Lucy with 5 iterations and regularization parameters of 0.1
  - Significantly improves measured emittance
  - Cons: slow, 2D deconvolutions are difficult (ill posed problems, noisy) and artifacts must be cleaned
- RMS parameter correction: assume $\sigma^2_{x',m} = \sigma^2_{x',t} + \sigma^2_p / L^2$ is true
  - Only need to correct $\sigma_{x'}$. $\sigma_{xx'}$ is unaffected by convolutions to x and x' for a Gaussian distribution



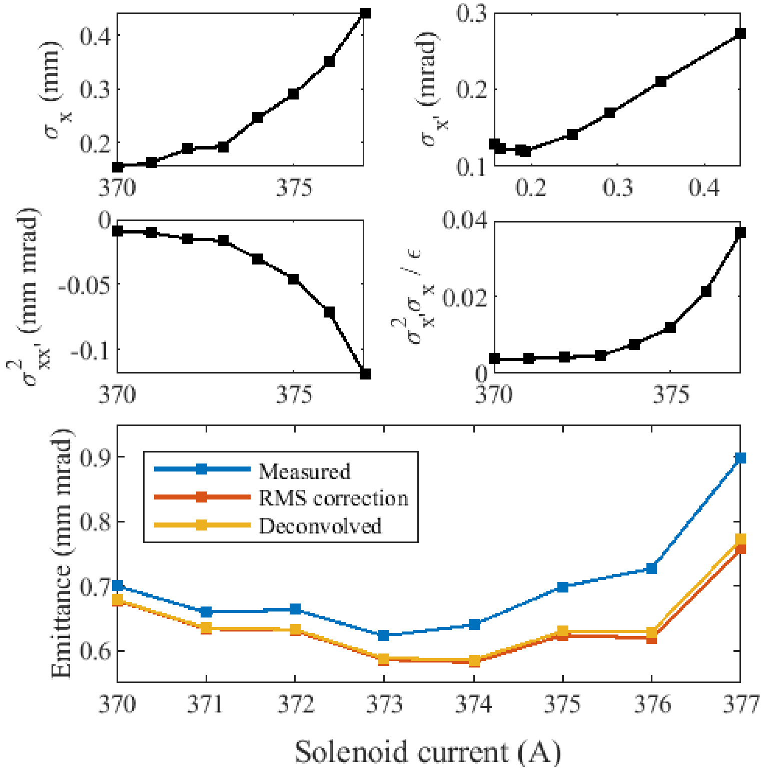
Correcting for the PSF – with noise

- Create true beamlet images, convolve with PSF, add noise, apply noise removal algorithm to the images.
  - Added Gaussian noise with rms level = 1% of peak intensity of all beamlets
  - Typical level of EMSY measurements ~0.5%
- With slit and PSF effects, the measured emittance > true, 100% emittance
- With corrections, the emittance isn't flat and the PSF still causes ~10% increase in the emittance compared to the case without the PSF
- How to estimate systematic error for a given measurement?





Correcting measured results

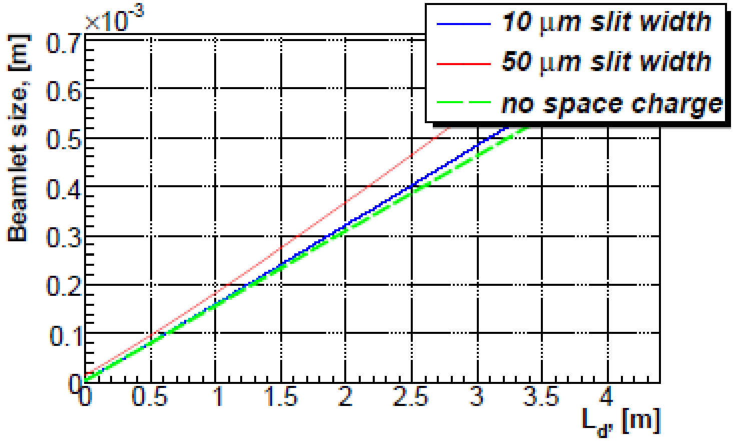


- Slit and PSF corrects were applied to measured solenoid scans at EMSY1
- Correction for the PSF with deconvolution and with rms correction agree within 2%
  - This gives some credibility to the rms correction method
- Results in a 5-15% reduction in the measured emittance
  - Largest corrections when x-x’ coupling is the largest
- The corrections can shift solenoid current for minimal emittance

Summary

- The slit size and camera PSF must be accounted for in emittance calculations
  - These can cause >10% increase in measured emittance based on the Twiss parameters
  - Corrections can shift the minimum emittance solenoid settings
- Avoid taking EMSY measurements of strongly x-x' coupled beams. The emittance becomes very sensitive to changes in the rms parameters

- Next steps
  - Characterize effects for non-Gaussian beamlets (started)
  - Develop corrections for space charge effects
    - Space charge will increase the beamlet sizes resulting in larger measured emittance
  - Study effects the of scintillator screen response (started)
    - Quantify effects of non-uniformities and non-linear response



(a) $\vec{P}_{mean} = 15\ MeV/c$

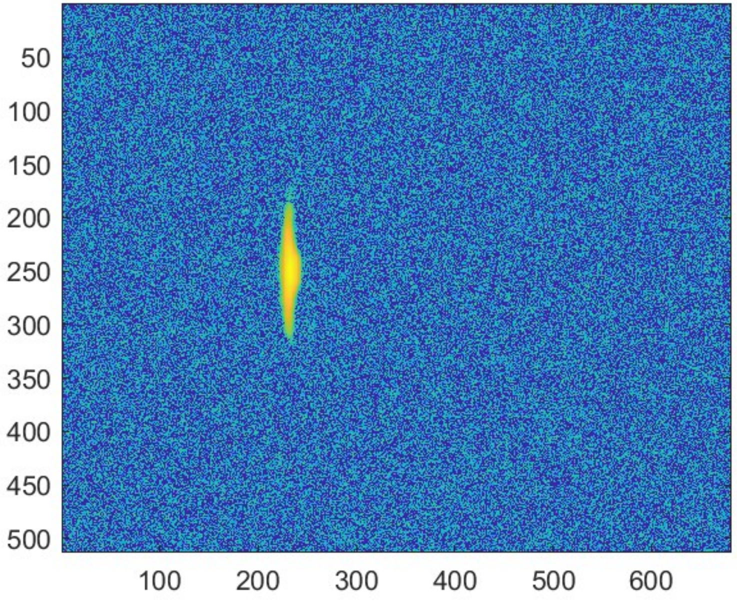
Staykov, thesis

Noise removal process

Note: log color scale on all plots

Step 1: Apply ROI filter to original image to remove large non-beam signals

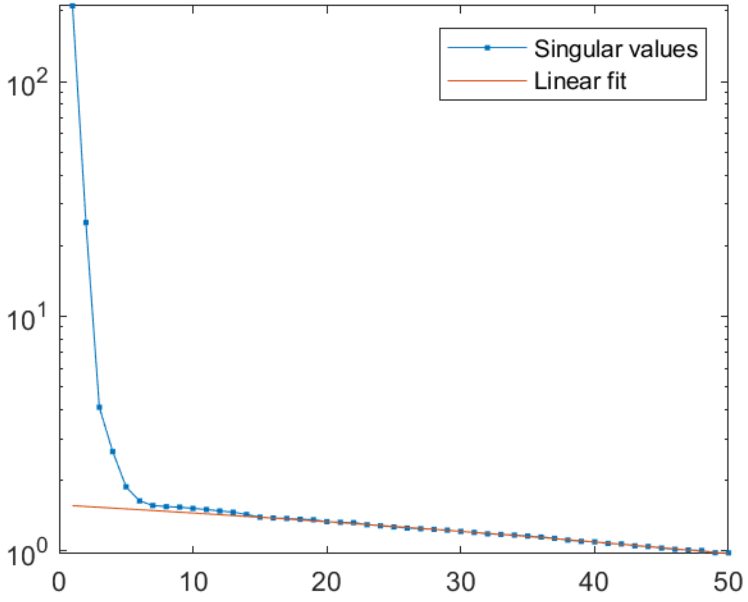
ROI filter: Create bininary mask. 1 if I_n > 0.5*I_max, 0 else. Apply median filter to remove salt and pepper noise. Dilate mask to increase size. Apply mask to image



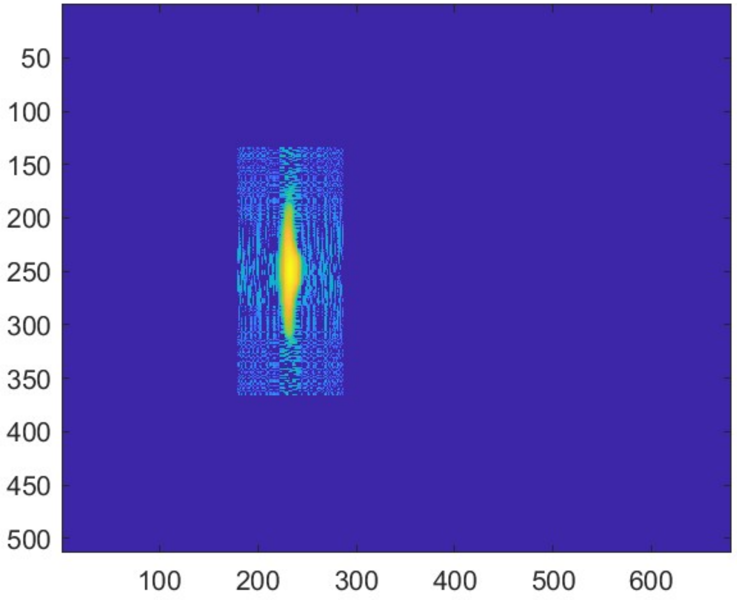
Step 2: Take SVD and fit noise-dominated singular values to a line.

Set all singular values < A*(fit line) to 0

Cut optimized with Pareto analysis. A=1.2



Step 3: Reconstruct image with modified singular values



Step 4: Create and apply a mask to remove artifacts from cleaning.

Same method as ROI filter, but using a smaller cut. Cut size optimized with Pareto analysis