Slice energy spread spatial correlation and slit filtering effect

H. Qian

17.03.2022

From one referee

Most important points

- On cutting the beam with slits. The authors mention that the charge is reduced from 250 pC to 25 pC when inserting slit 1 with 50 um opening. The authors do not say how much the charge is reduced when inserting slit 2, but I assume that it is in a similar value. Strangely, although the energy spread measurement is done for the cut beam with much lower charge, the authors seem to claim that the results correspond to the uncut beam with higher charge. In my view, this is not valid. The charge reduction significantly reduces the impact of collective effects (such as intra-beam scattering) that may reduce the energy spread of the beam. Moreover, in presence of beam correlations (energy or time vs transverse), cutting the beam would also reduce the energy spread. All this, in my view, partially invalids the conclusion reached by the authors: the existence of some mechanisms that deteriorate the energy spread at the high-energy section of the facility. Although it is true that the energy spread may increase at the high-energy part (e.g. intra-beam scattering grows with the distance), it is also true that the energy spread increase may come from having an uncut beam with higher charge. About this point, the authors should:

Slice energy spread measurement at PITZ

- Slice energy spread measurements

$$\sigma_{\text{total}}^2 = \sigma_{\text{scr}}^2 + \frac{\varepsilon_{n1}\beta_{\text{scr}}}{\gamma} + \left(D\frac{\sigma_\gamma}{\gamma}\right)^2 + \left(D\frac{\sigma_{\gamma,\text{TDS}}}{\gamma}\right)^2$$

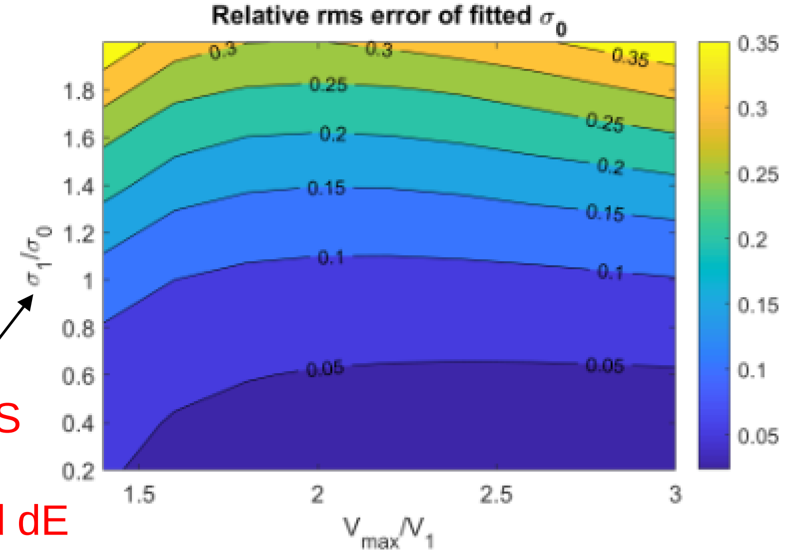
Scr x emittance true dE TDS dE

Dominating error

$$\sigma_t\sigma_{\gamma,\text{TDS}} = \frac{\varepsilon_{n2}}{c\sin(\psi)}$$

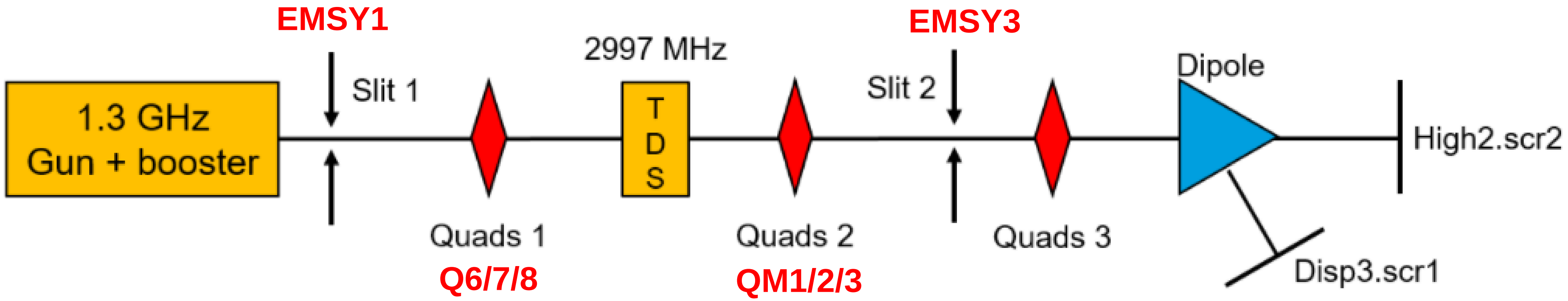
Y emittance

- How to do a reliable TDS voltage scan?



Min TDS voltage induced dE

Assuming 3% rms measurement error



Slice energy spread measurement at PITZ

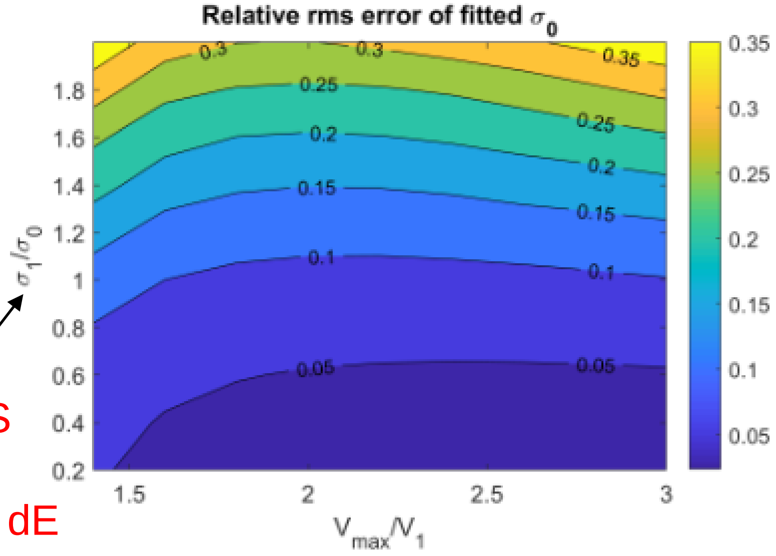
- Slice energy spread measurements

$$\sigma_t \sigma_{\gamma,\mathrm{TDS}} = \frac{\varepsilon_{n2}}{c \sin(\psi)}$$

← Y emittance

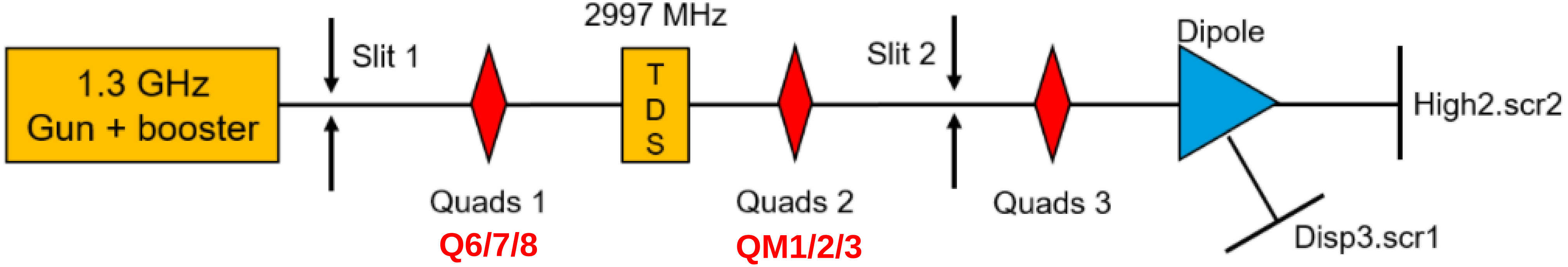
- Assuming 0.4 um.rad (optimum case, no EMSY1 cut)
  - Sigt ~0.25 ps → sigE ~2.7 keV→ 10% error ~0.3 keV rms
- Assuming 0.04 um.rad (optimum case, EMSY1 cut)
  - Sigt ~0.25 ps → sigE ~0.3 keV→ ~0.05 keV rms

- How to do a reliable TDS voltage scan?



Min TDS voltage induced dE

Assuming 3% rms measurement error



Slice energy spread measurement at PITZ

- Slice energy spread measurements

$$\sigma_t \sigma_{\gamma,\mathrm{TDS}} = \frac{\varepsilon_{n2}}{c \sin(\psi)}$$ ← Y emittance

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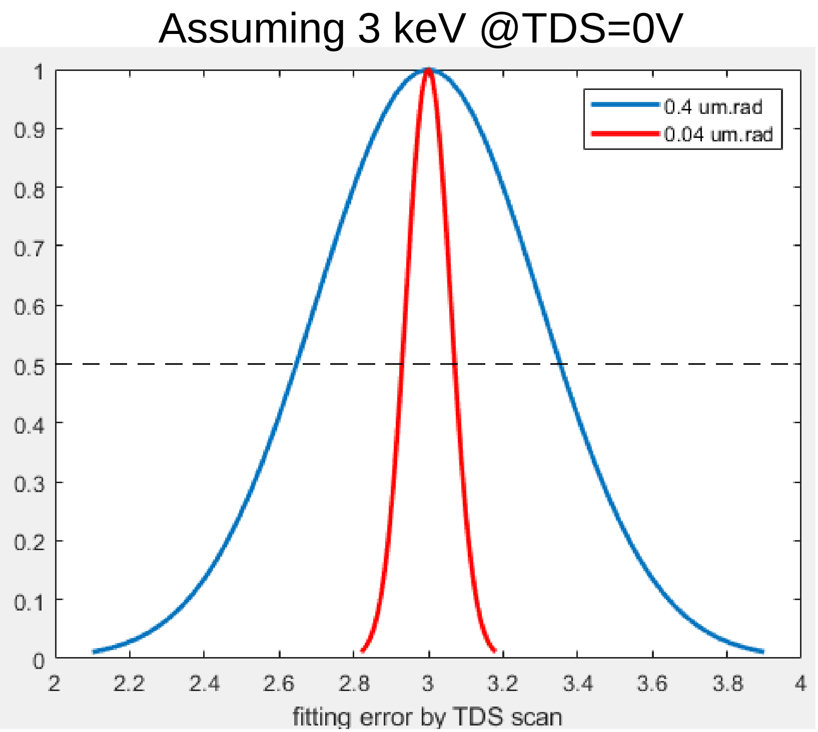
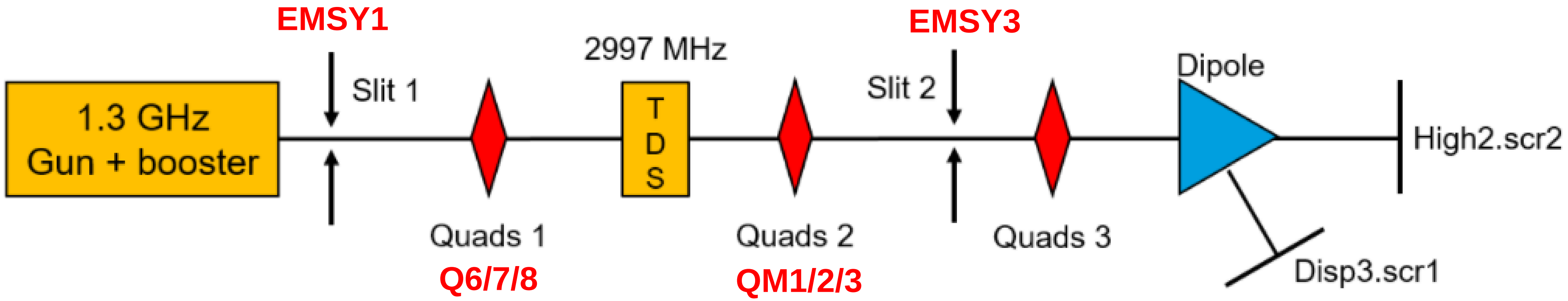
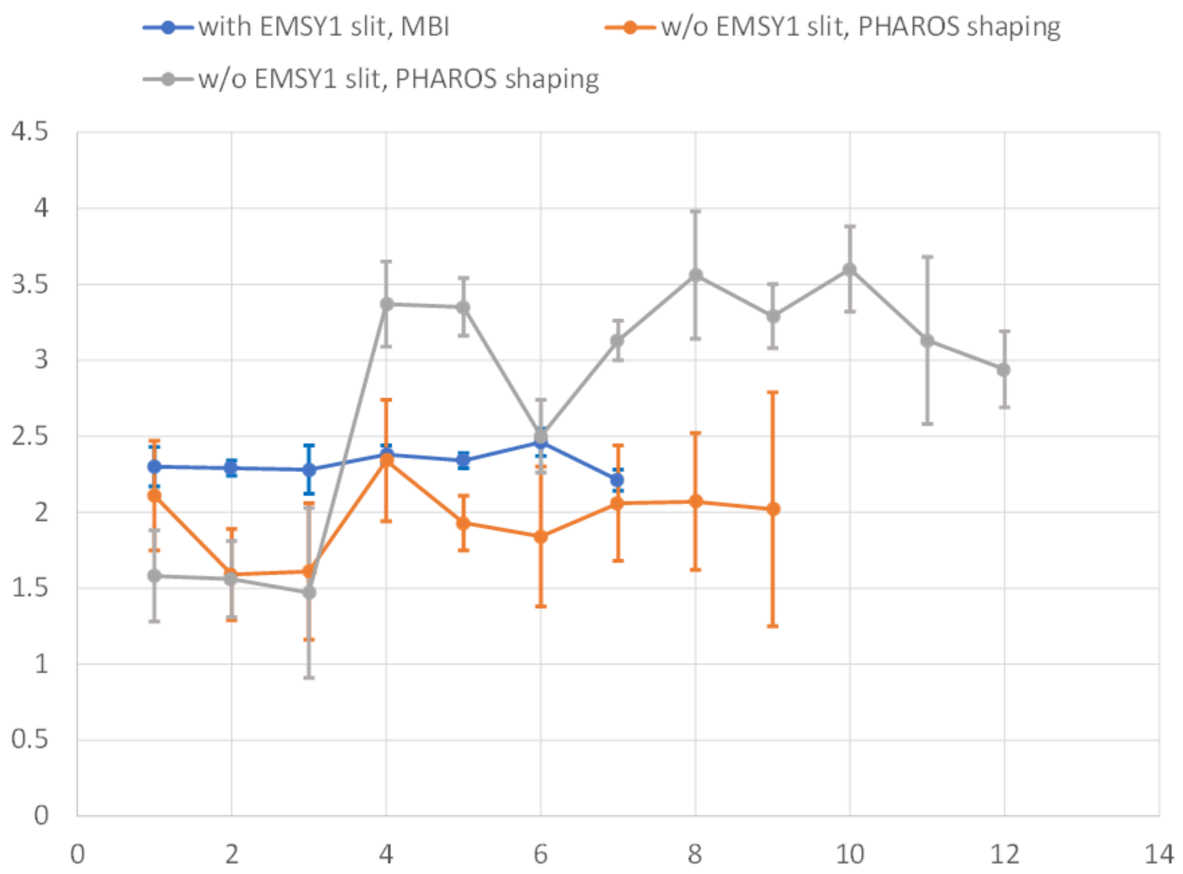




TDS scan vs EMSY1 slit, vs different lasers

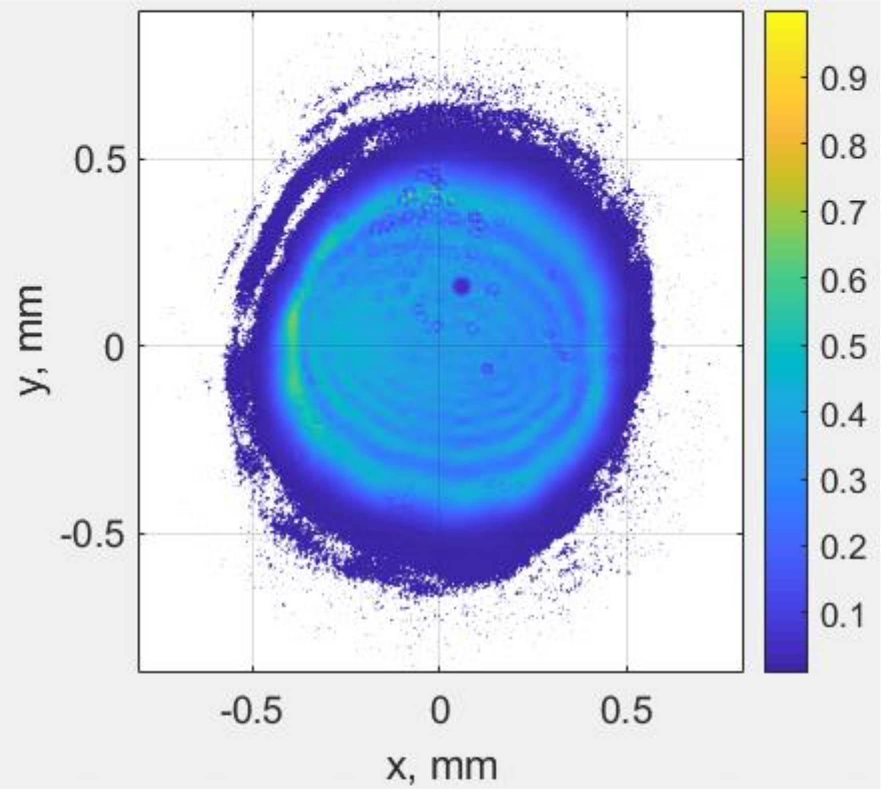
Repeat the same measurements for stability check



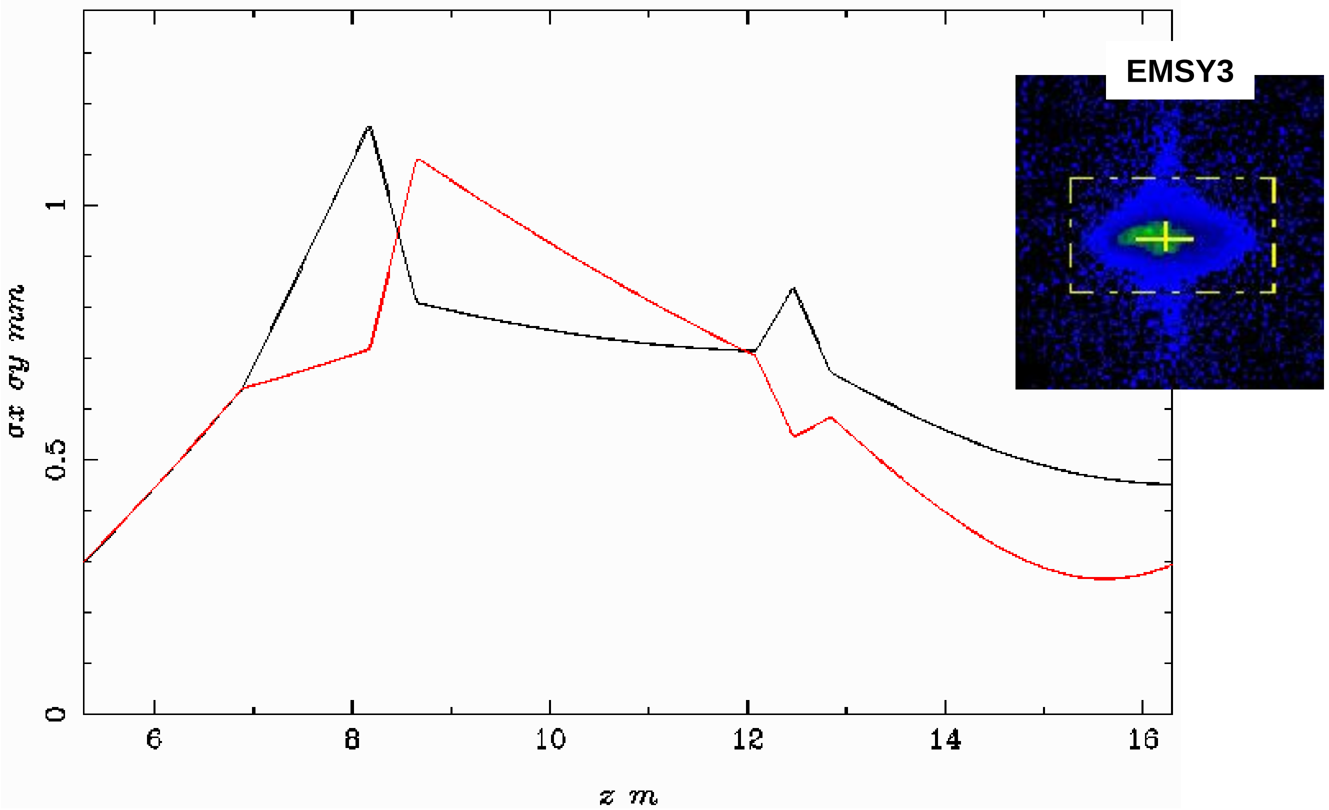
- With EMSY1 slit cut (MBI laser)
  - Stable result around 2.3 keV @TDS=0 V
  - Consistent small error bar ~0.05 keV
- W/o EMSY1 slit cut (PHAROS laser)
  - Large error bar >0.3 keV (expected)
  - Large fluctuation of fitting results beyond statistical error bar
    - Partially due to large error bar
    - SLM shaping not stable?

Beam distribution at EMSY1

- VC2 → ASTRA distribution
  - BSA1mm, uniform distribution (22.04.2021, 7 ps)
  - Azimuthal uniform distribution in ASTRA
  - Thermal emittance 1 mm.mrad/mm

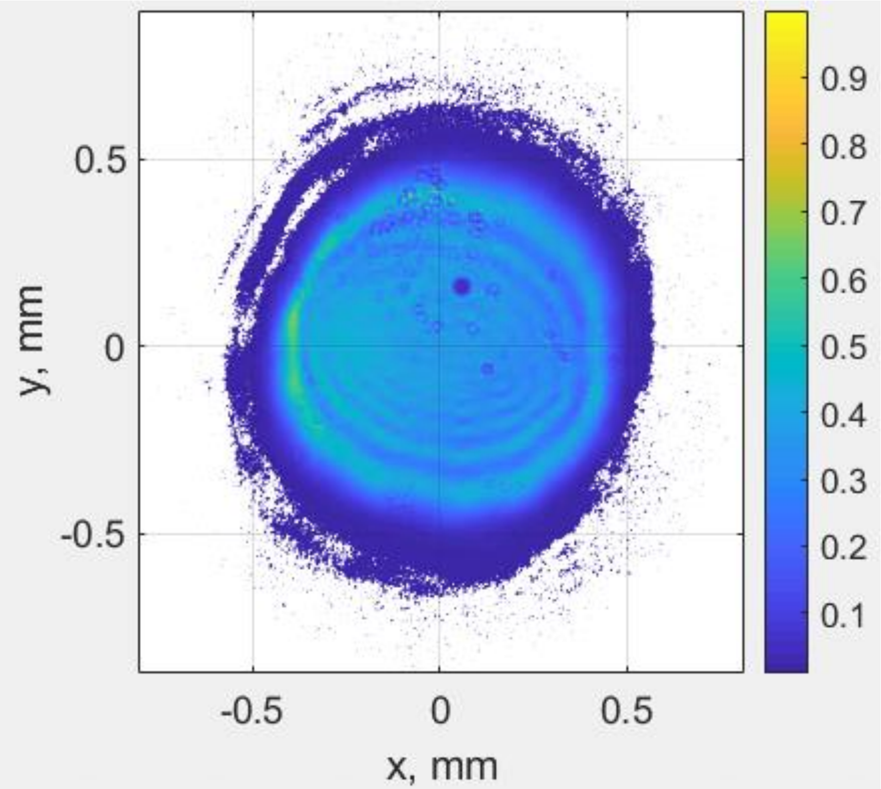


- EMSY1 → EMSY3 (no slit cut, 250 pC)

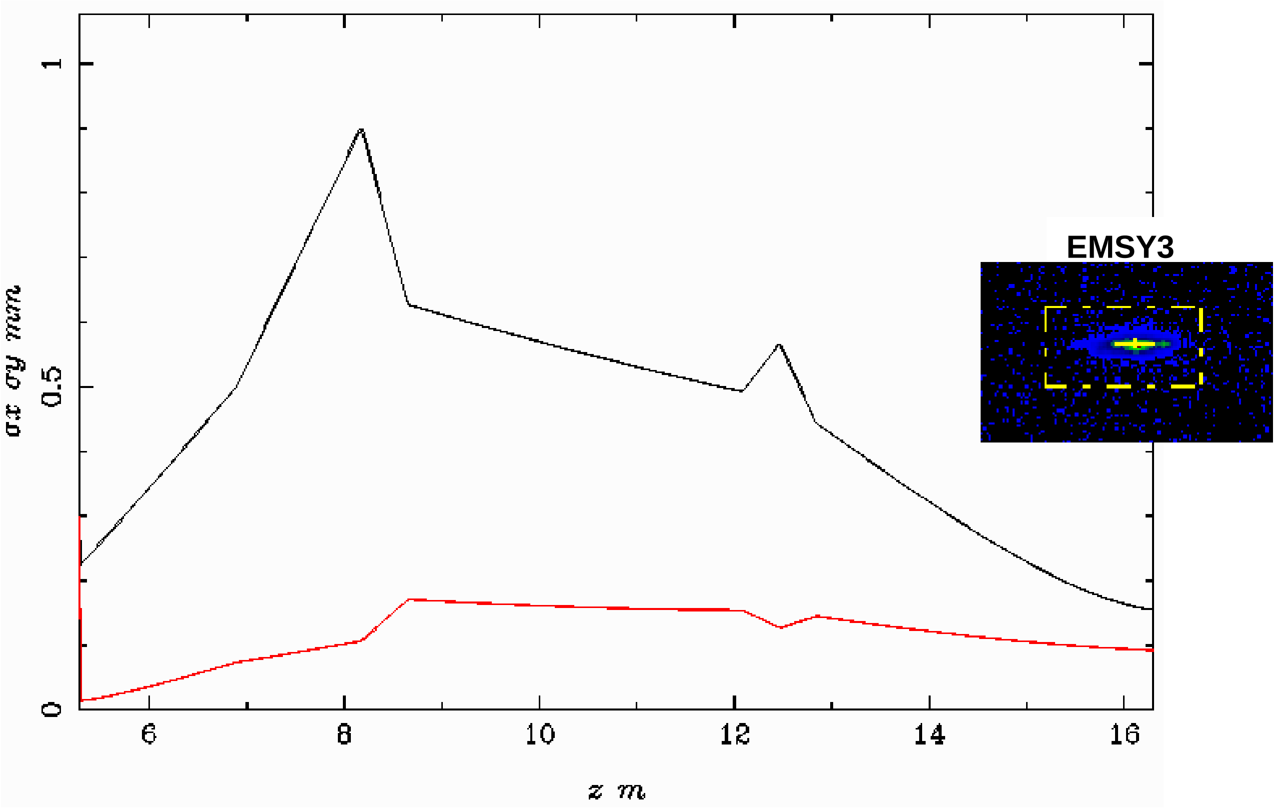


Beam distribution at EMSY1

- VC2 → ASTRA distribution
  - BSA1mm, uniform distribution (22.04.2021)
  - Azimuthal uniform distribution in ASTRA
  - Best emittance point



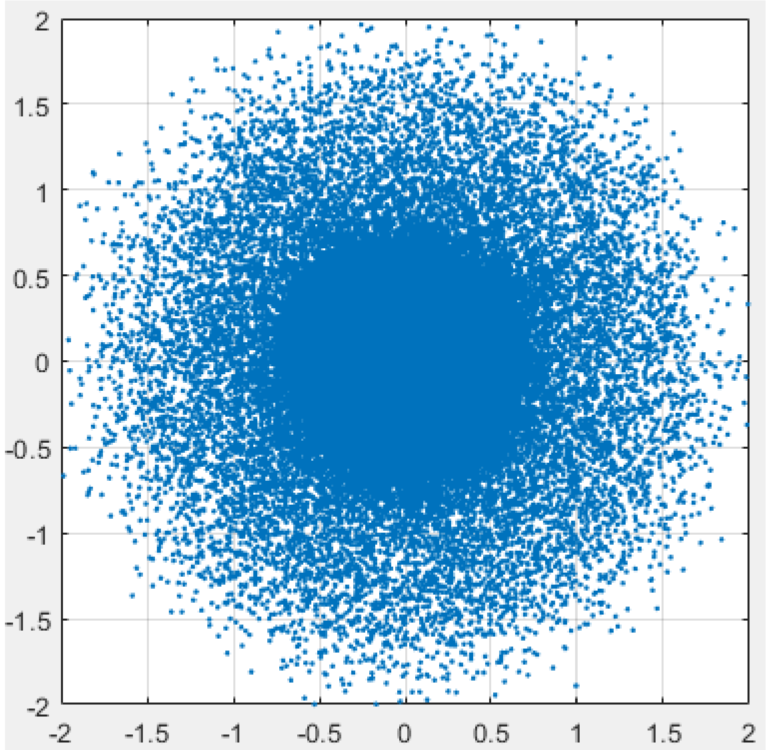
- EMSY1 → EMSY3 (EMSY1 Y slit cut, 25 pC)
  - Same magnet settings

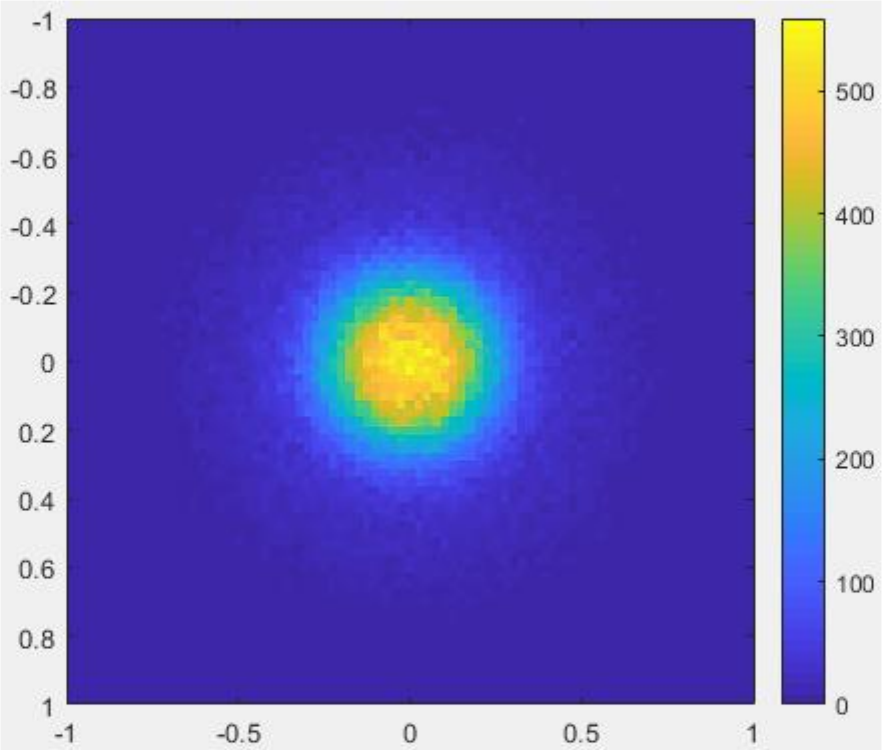


Beam distribution at EMSY1

- EMSY1 distribution
  - RMS size 0.3 mm, Gauss fit 0.188 mm
  - Experiment 0.2-0.25 mm, 0.18 mm

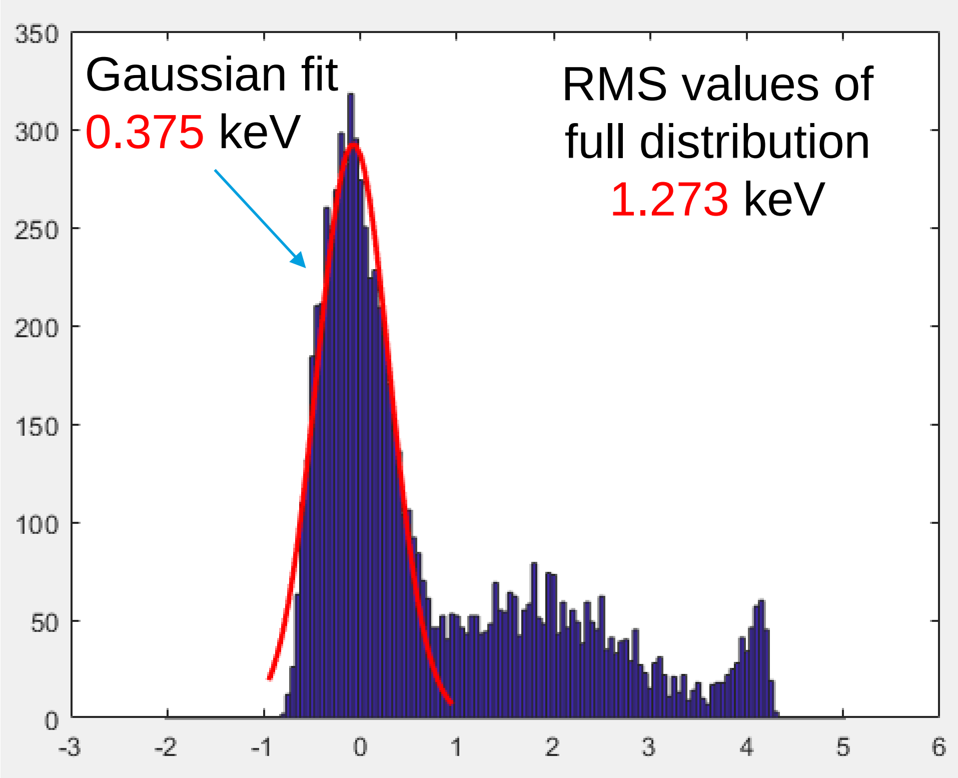
- EMSY1 distribution
  - 0.85 mm.mrad (100% emittance)
  - 0.46 mm.mrad (95% emittance)



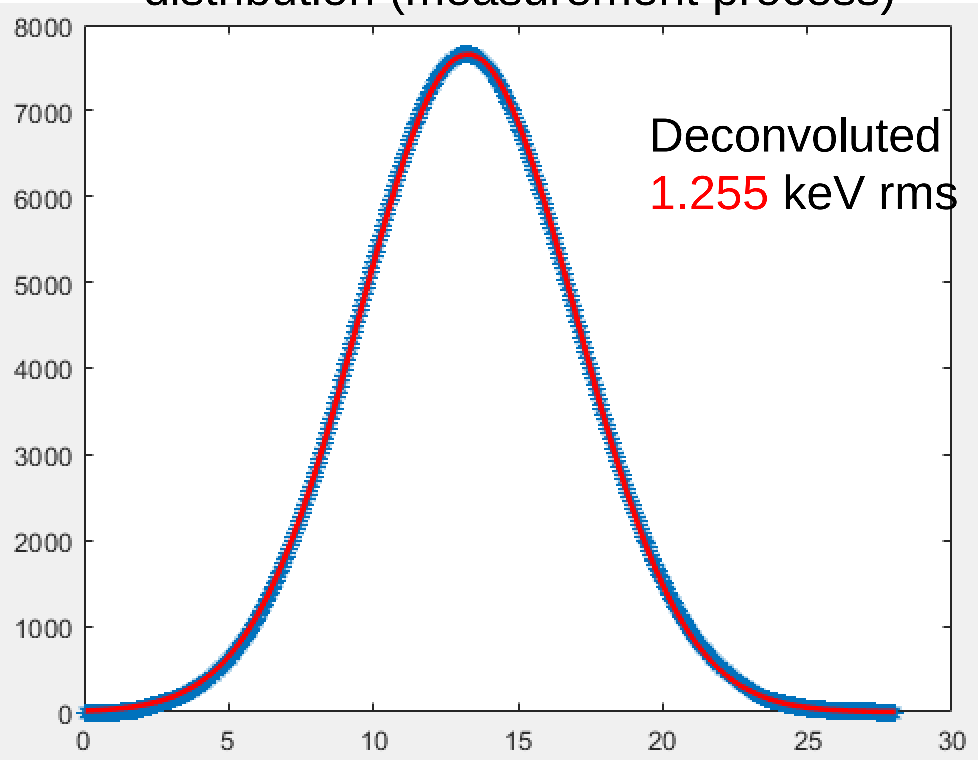


Slice energy spread @EMSY1, no slit

Slice energy spread distribution (0.5 ps width)



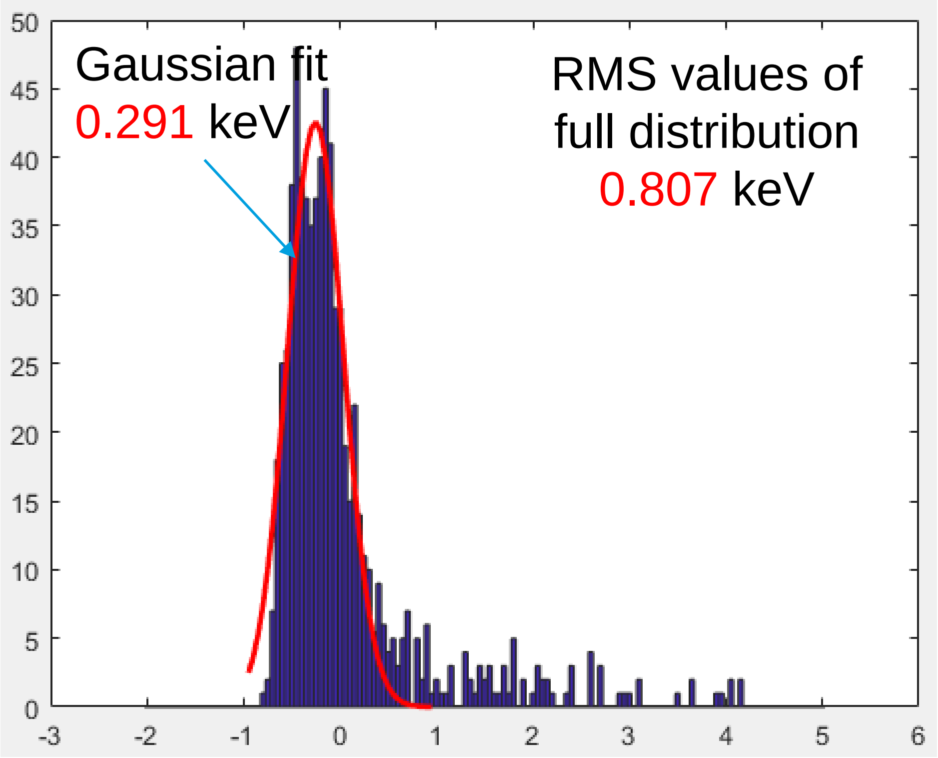
Slice energy spread convolution with a 3.5 keV rms Gaussian distribution (measurement process)



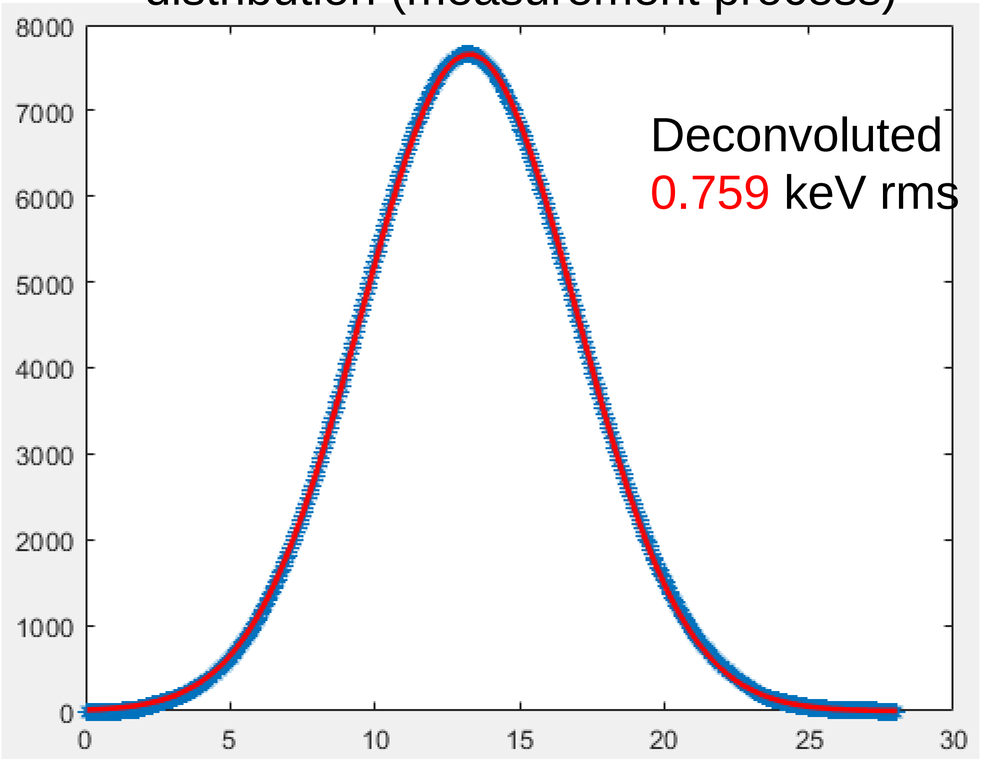
The detailed distribution of beam energy spread is lost, but rms value can be calculated.

Slice energy spread @EMSY1, 50 um slit

Slice energy spread distribution (0.5 ps width)

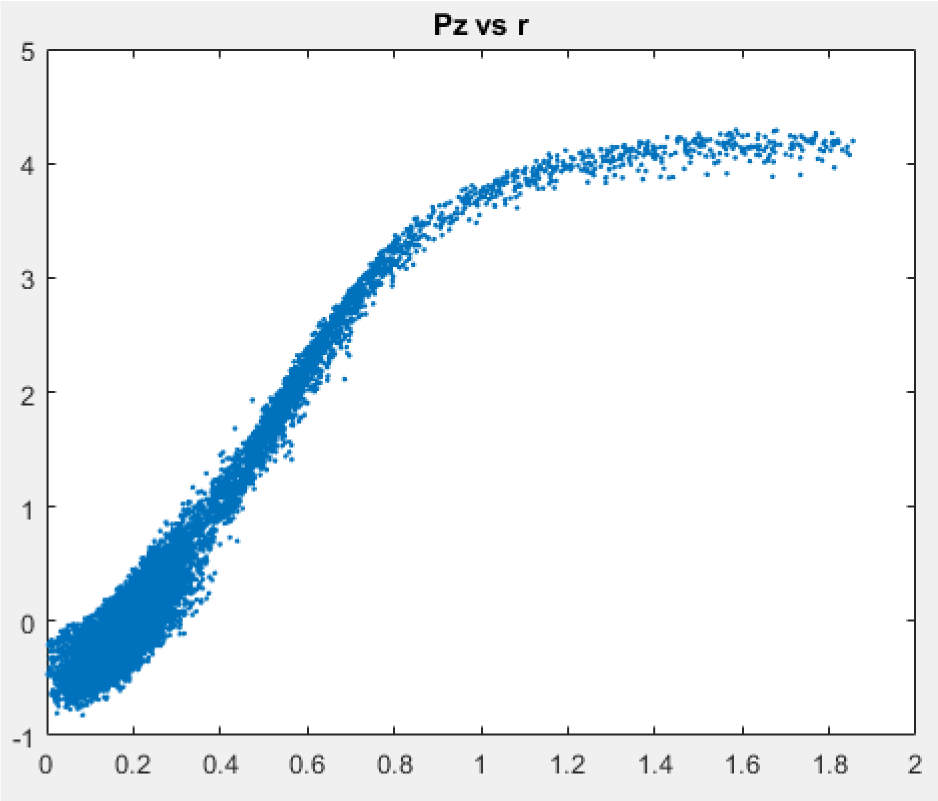


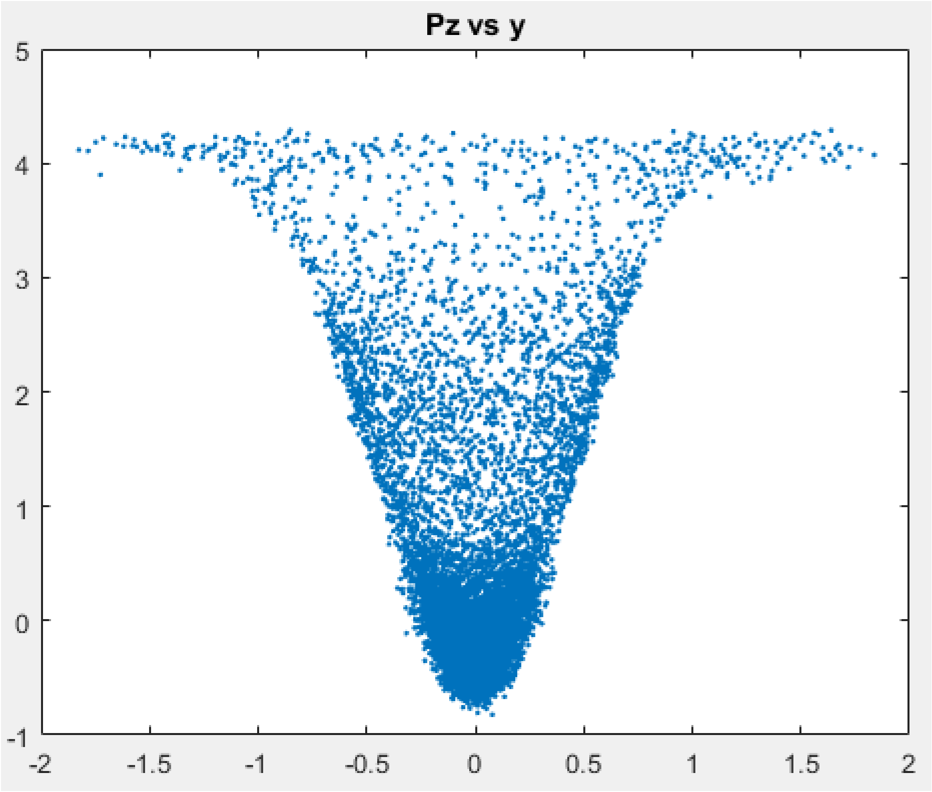
Slice energy spread convolution with a 3.5 keV rms Gaussian distribution (measurement process)



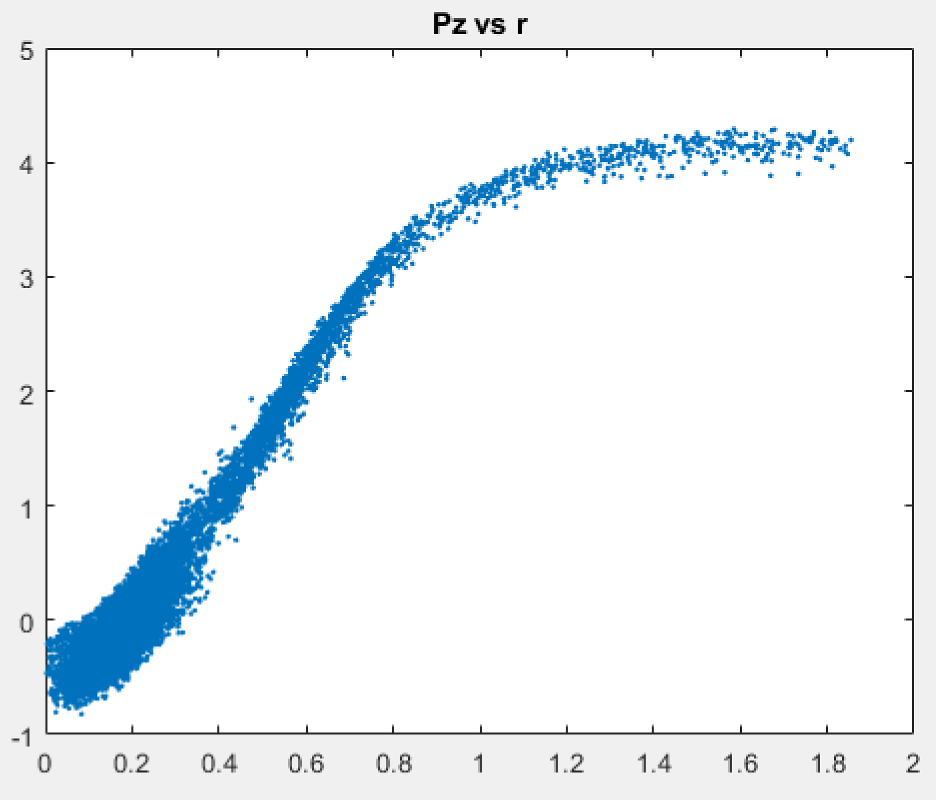
The detailed distribution of beam energy spread is lost, but rms value can be calculated.

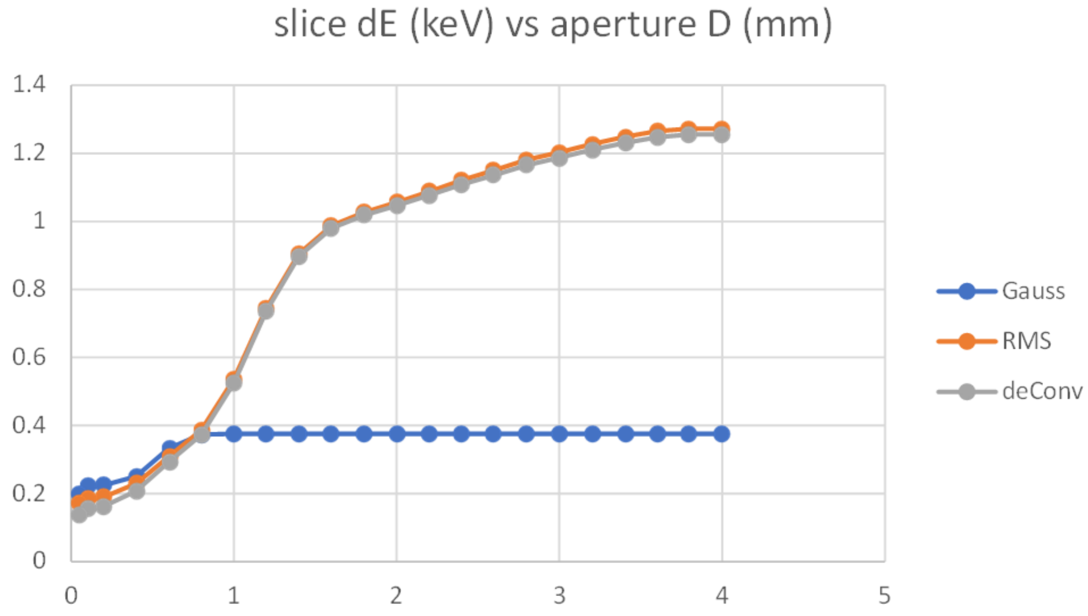
Central slice: slice energy spread spatial correlation @EMSY1





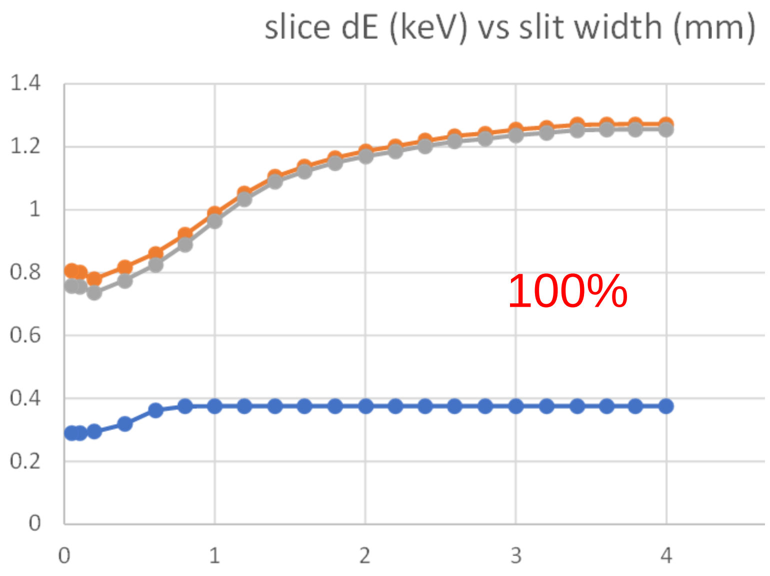
Central slice: slice energy spread spatial correlation @EMSY1

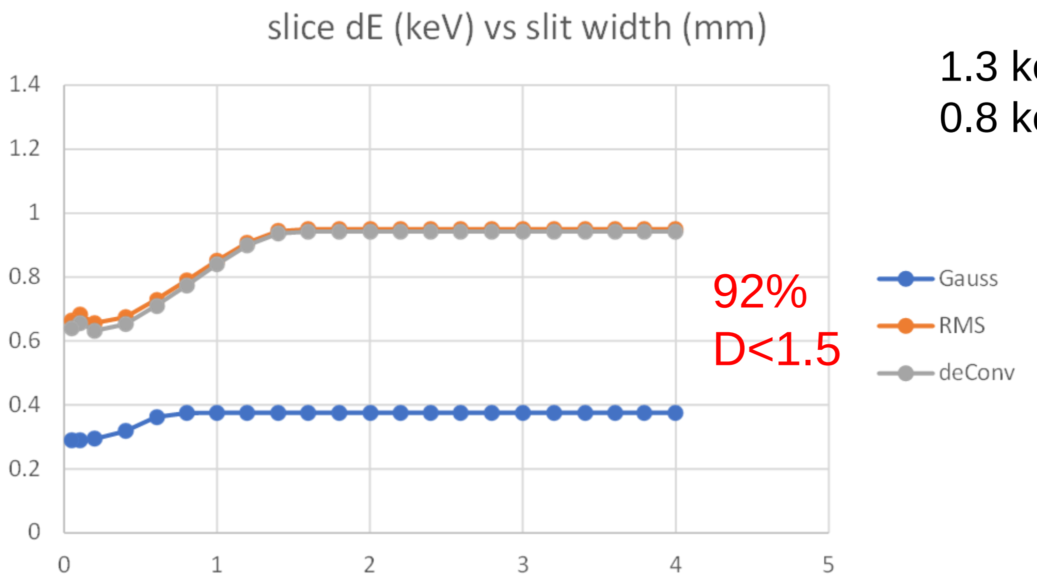


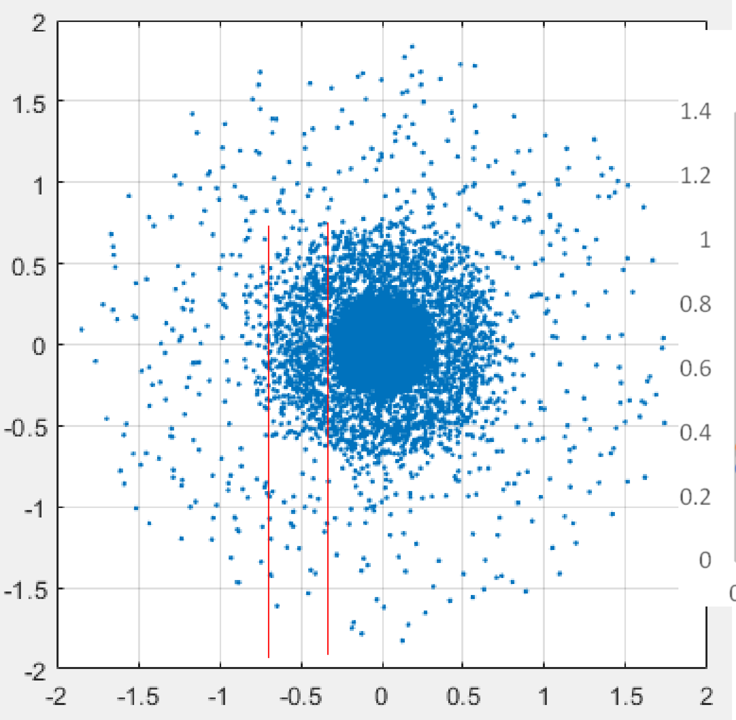


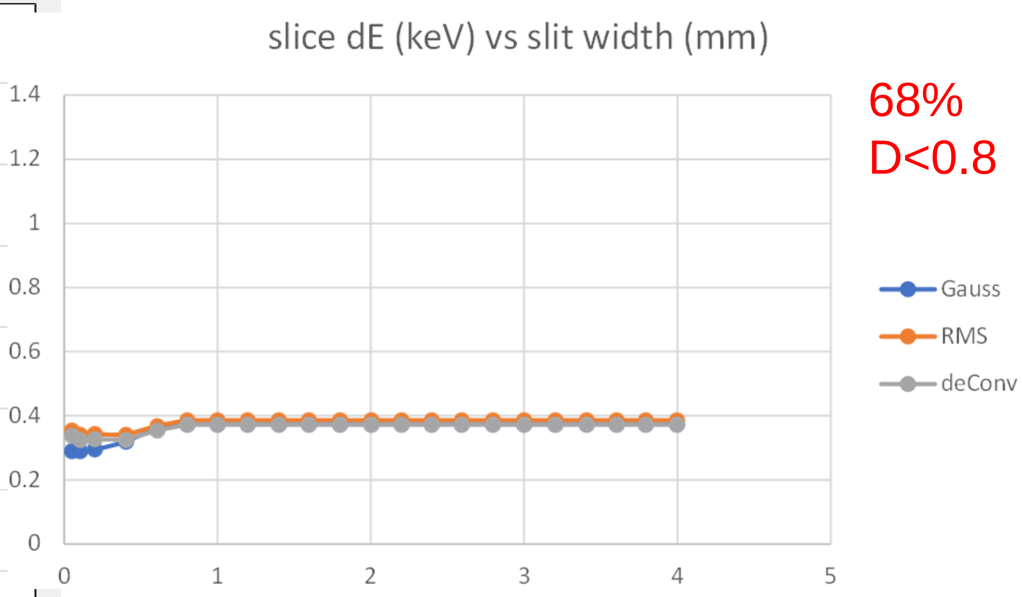
Central slice energy spread vs EMSY slit width

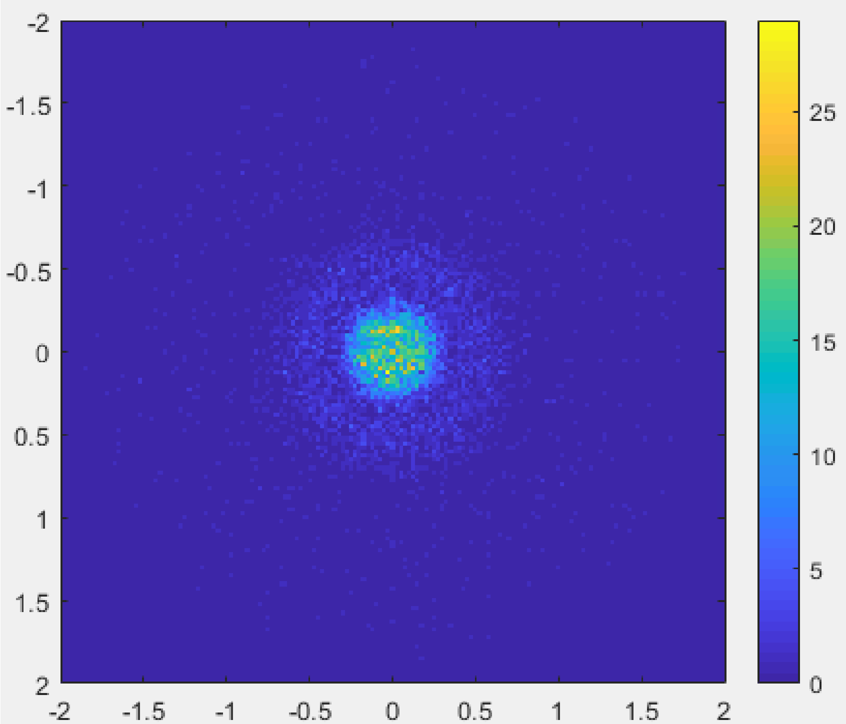
1.3 keV (full central slice)
0.8 keV (central slice with 50 um slit)





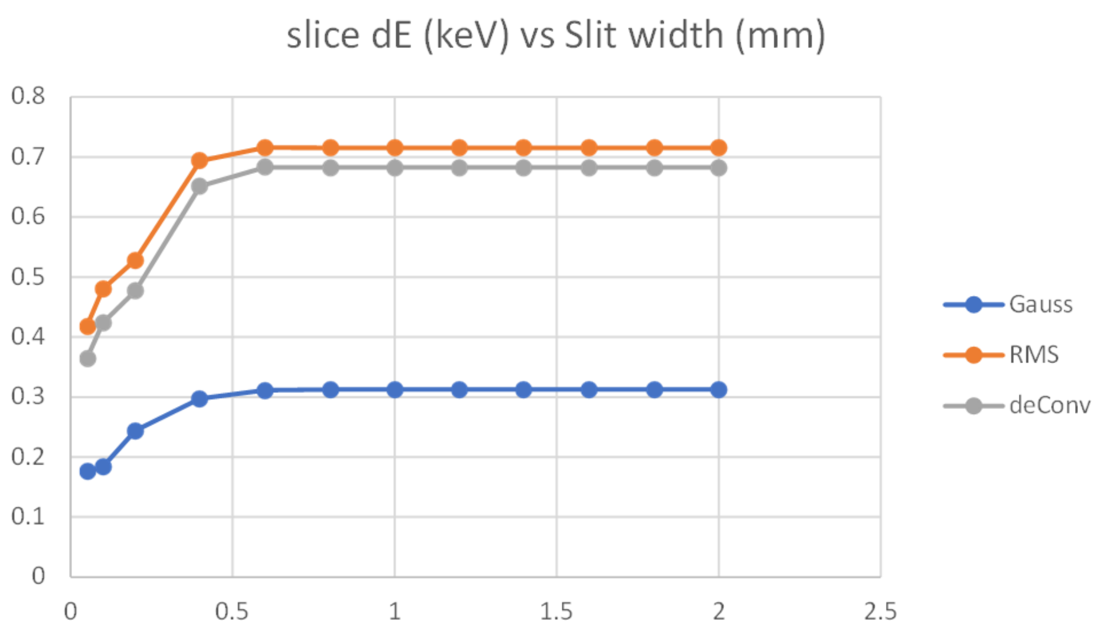




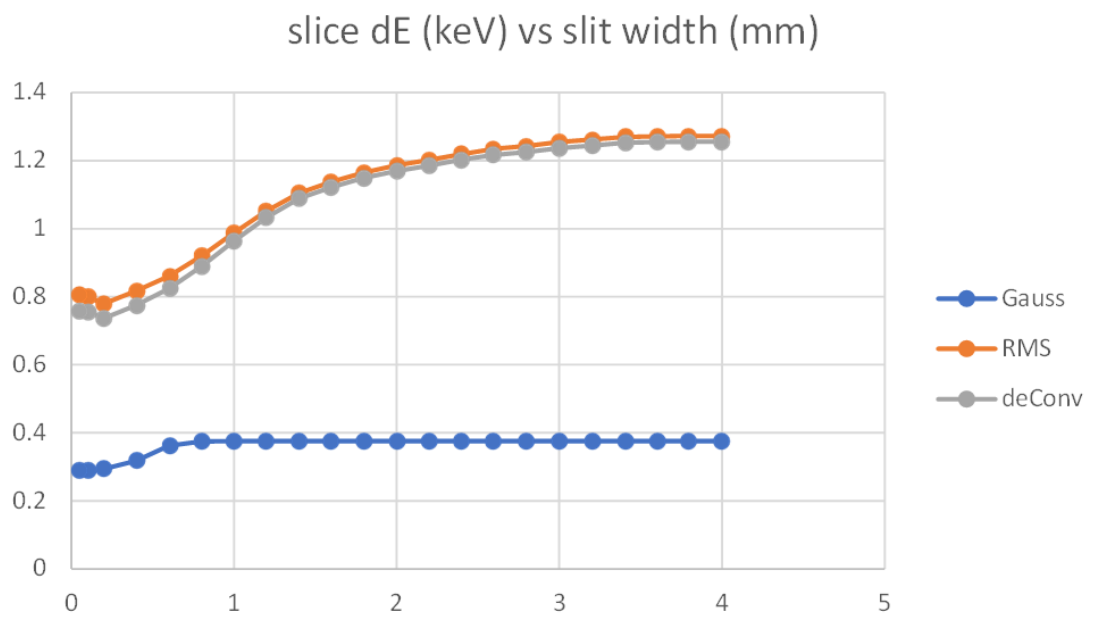


EMSY1 Y cut + EMSY3 X cut

EMSY3 X cut:0.7 keV → 0.4 keV

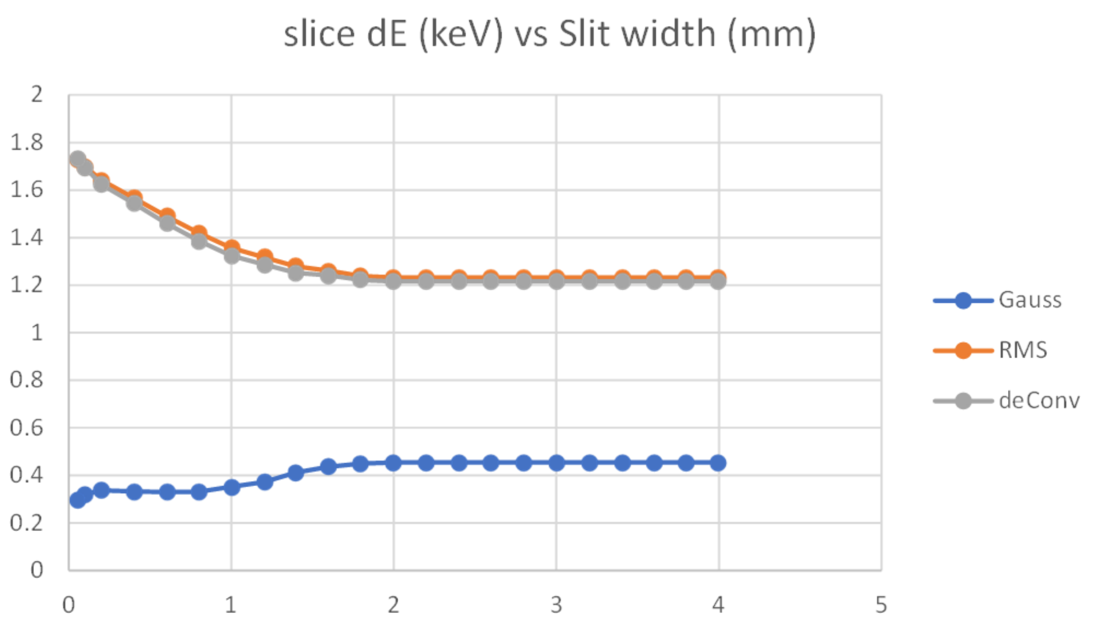


EMSY1 Y cut:1.3 → 0.8 keV

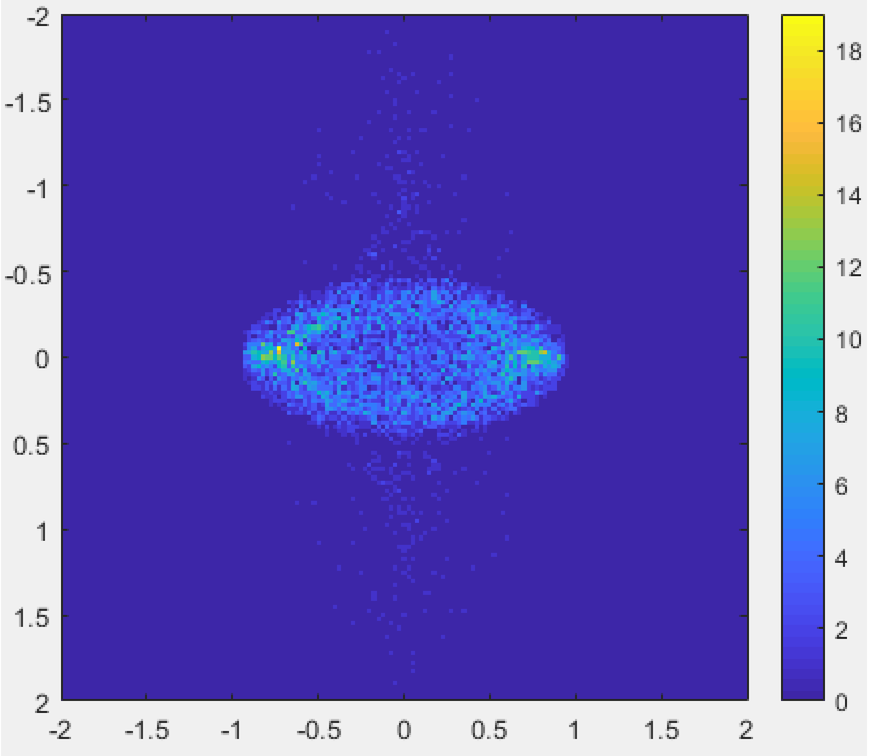


EMSY3, w/o EMSY1 slit

Central slice：1.2 keV → 1.7 keV

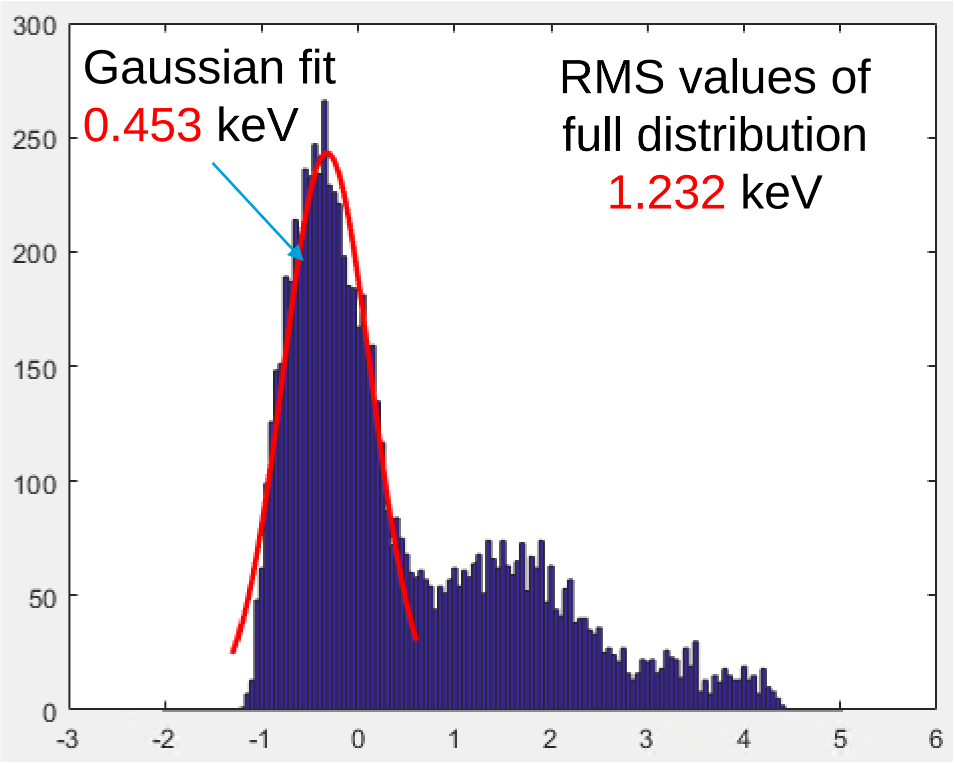


Central time slice

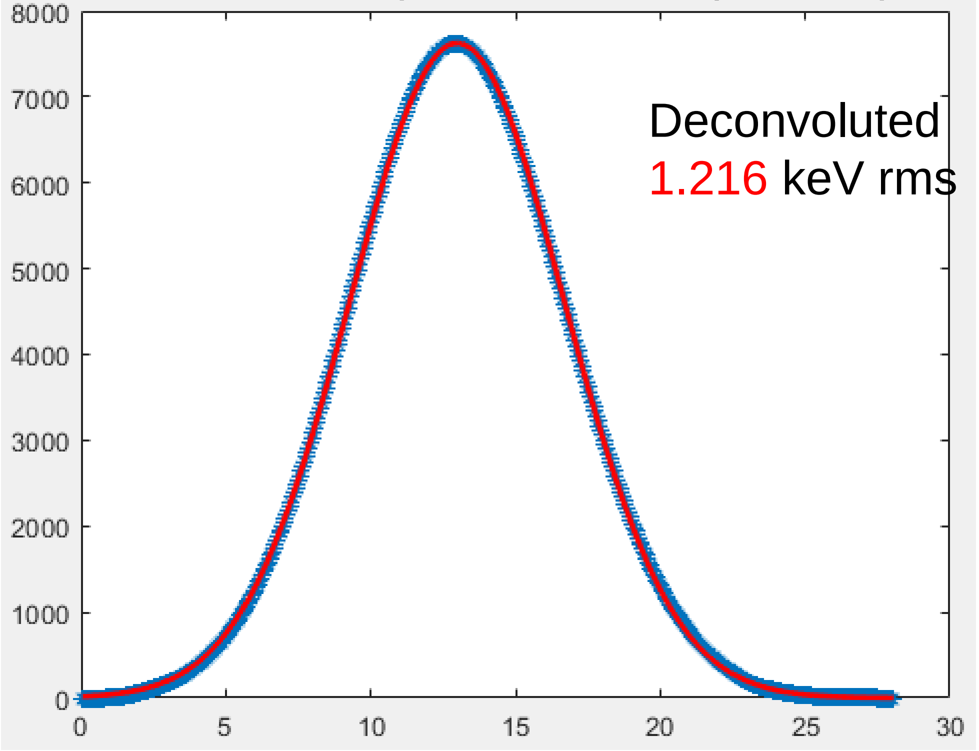


Slice energy spread @EMSY3, no slit

Slice energy spread distribution (0.5 ps width)



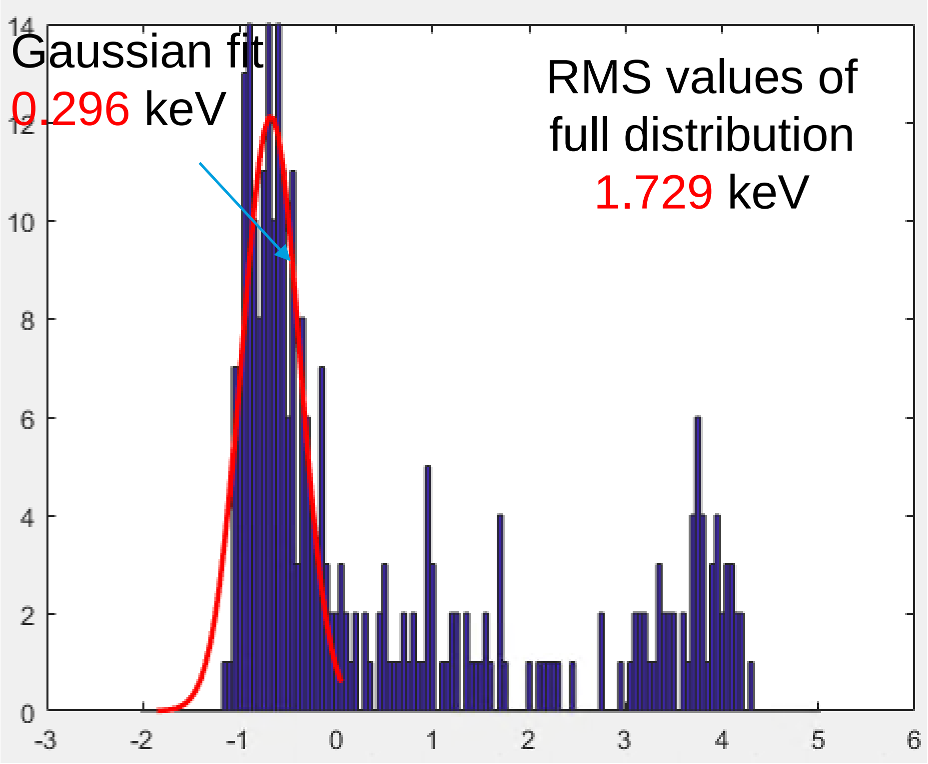
Slice energy spread convolution with a 3.5 keV rms Gaussian distribution (measurement process)



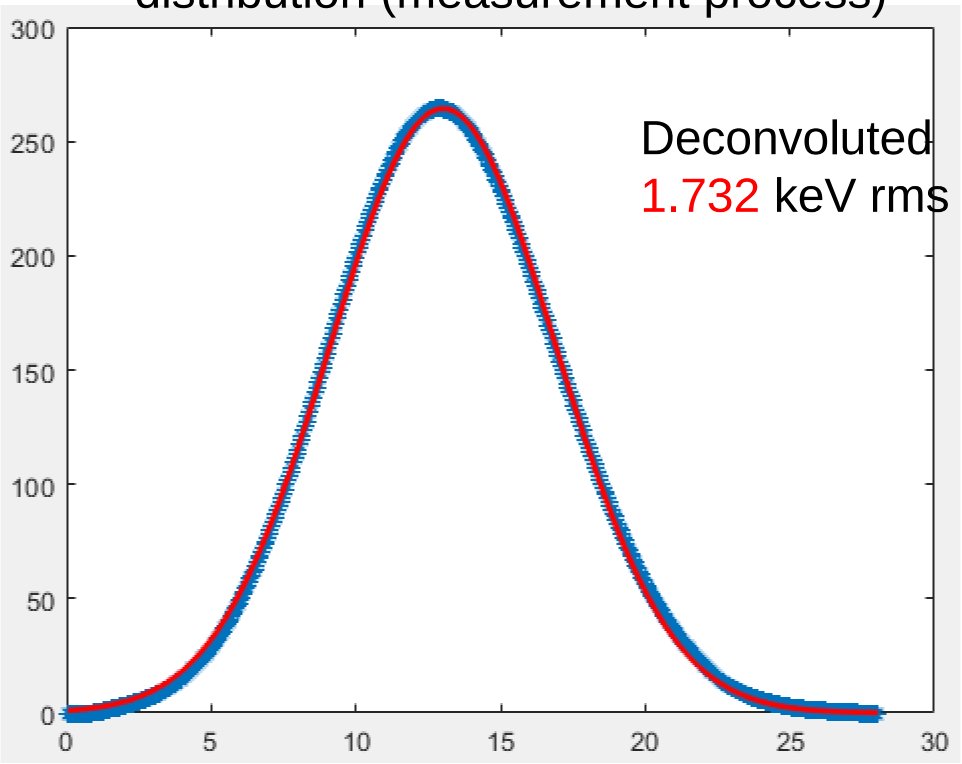
The detailed distribution of beam energy spread is lost, but rms value can be calculated.

Slice energy spread @EMSY3, 50 um slit

Slice energy spread distribution (0.5 ps width)



Slice energy spread convolution with a 3.5 keV rms Gaussian distribution (measurement process)



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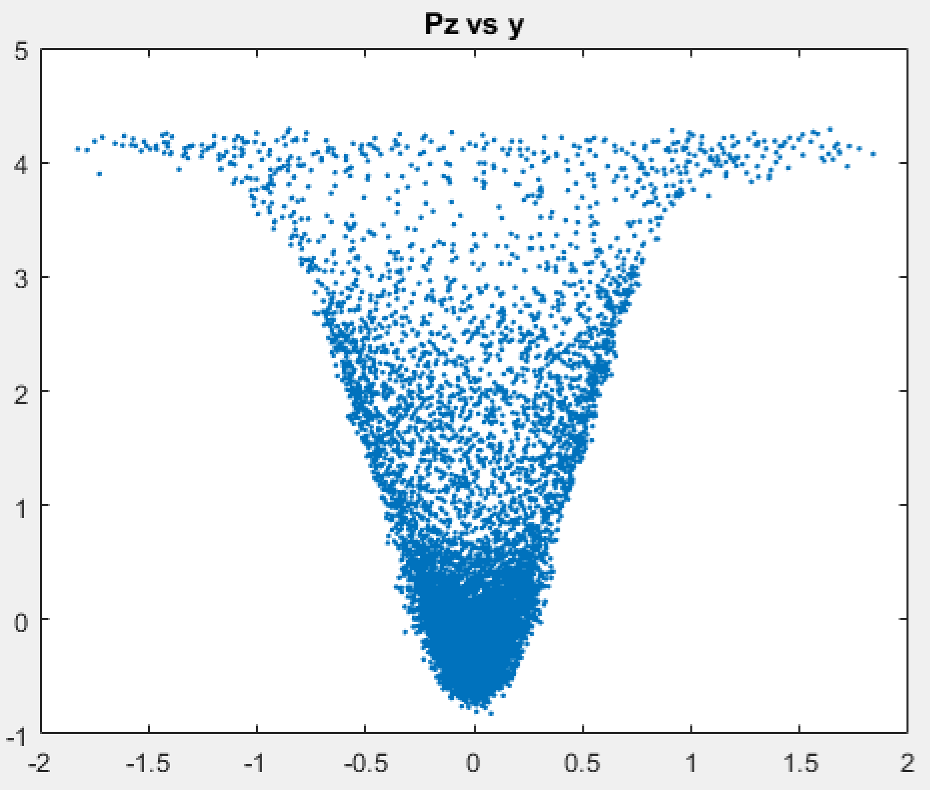
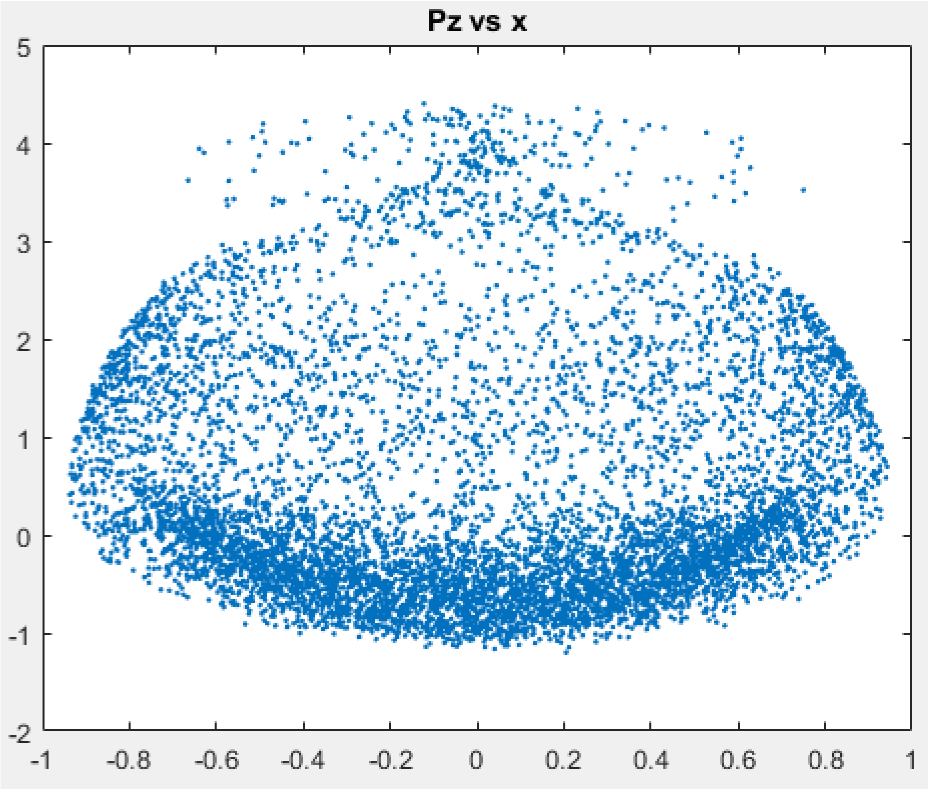
Pz spatial correlation



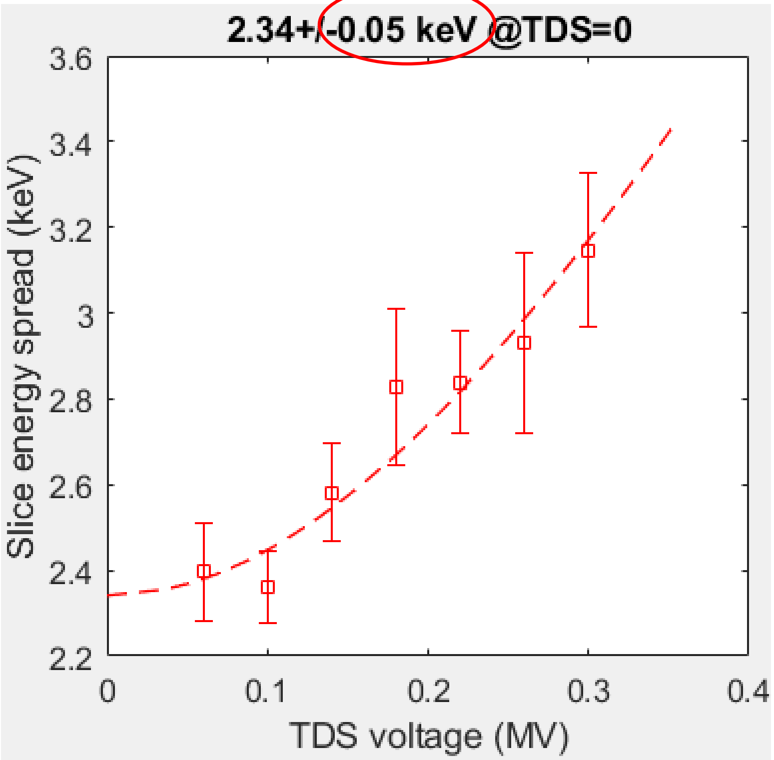
EMSY1



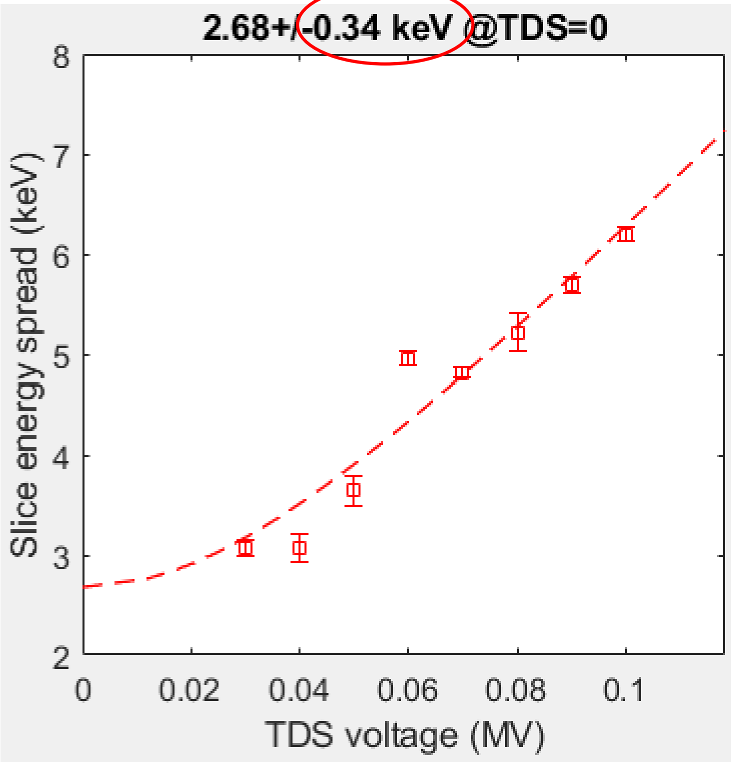
EMSY3

Experiment: 250 pC

- With EMSY1 cut (6.6.2021M, in paper)



- Without EMSY1 cut (25.4.2021N)

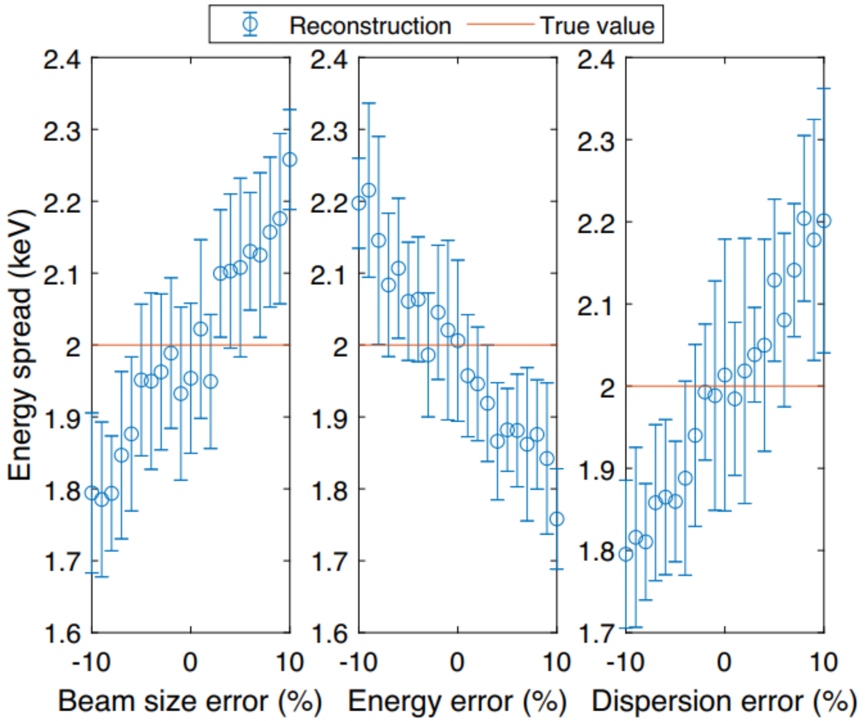


keV	Total	scr	emittance	true slice dE
EMSY1 out	2.68+/-0.34	1.5+/-0.02	0.56+/-0.02	2.16+/-0.34
EMSY1 in	2.34+/-0.05	1.5+/-0.02	0.65+/-0.02	1.65+/-0.06

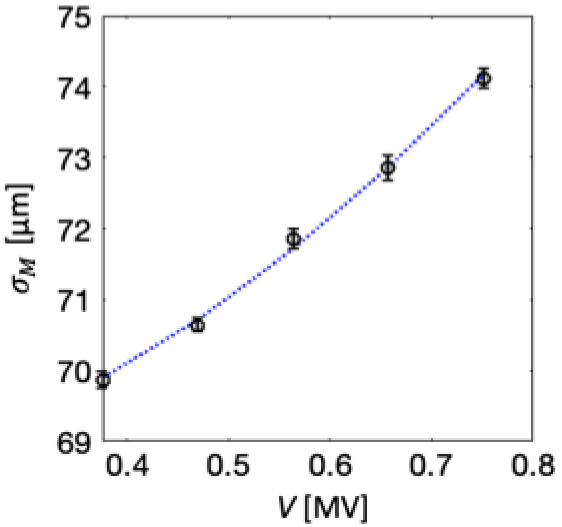
Other experiments

- PSI
  - 200 pC, 15+/-0.3 keV (**2% rms uncertainty**)
  - Beam size measurement error assumed in simulation 2.5%

5% error



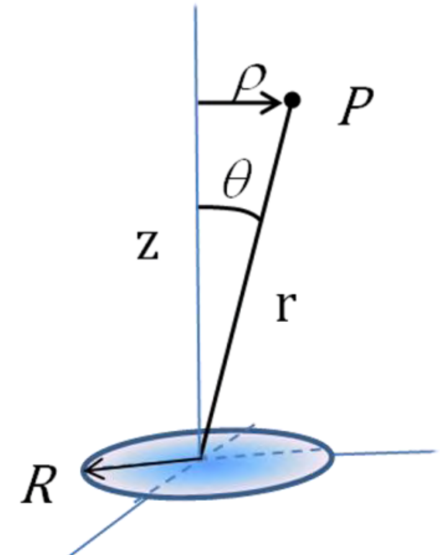
- XFEL
  - 250 pC, 5.95+/-0.06 keV (**1% rms uncertainty**)
  - Beam size measurement error assumed 2% in simulation
    - **~0.1% level** from experiment



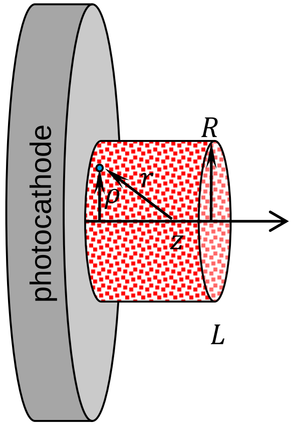
Space charge force during emission

D. Dowell, J. Lewellen “Photoinjector theory” in “An engineering guide to photoinjectors”, Edited by T. Rao and D. Dowell, 2013, ISBN-13: 978-1481943222 ISBN-10: 1481943227

$$V_0(\theta,r) = \frac{\sigma_0}{2\varepsilon_0}\left[R - rP_1(\cos(\theta)) + \frac{1}{2}\frac{r^2}{R}P_2(\cos(\theta)) - \frac{1}{8}\frac{r^4}{R^3}P_4(\cos(\theta)) + \ldots\right]$$



the off-axis electric field of a uniform charged disk



Space charge Ez field at the cathode:

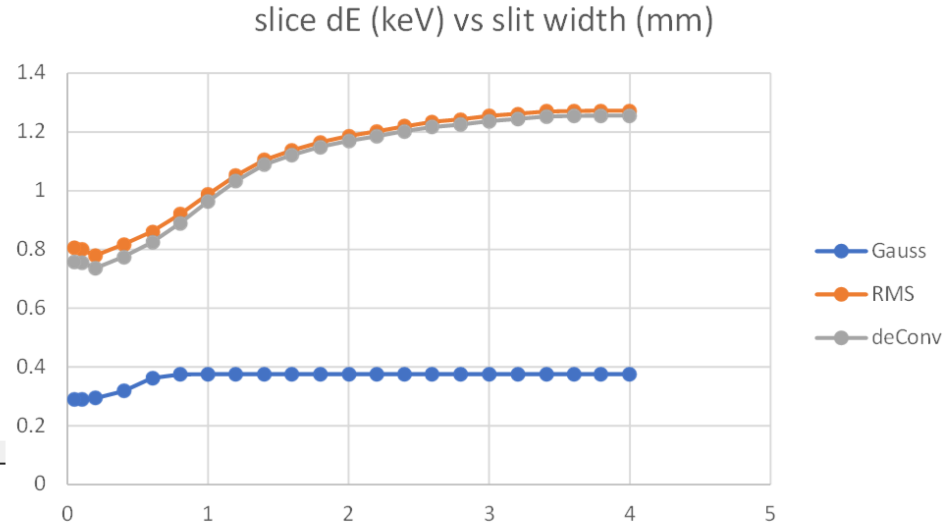
$$E_z(\rho) = -2\int_0^L \frac{\partial V_o(\rho,z)}{\partial z}dz \approx$$

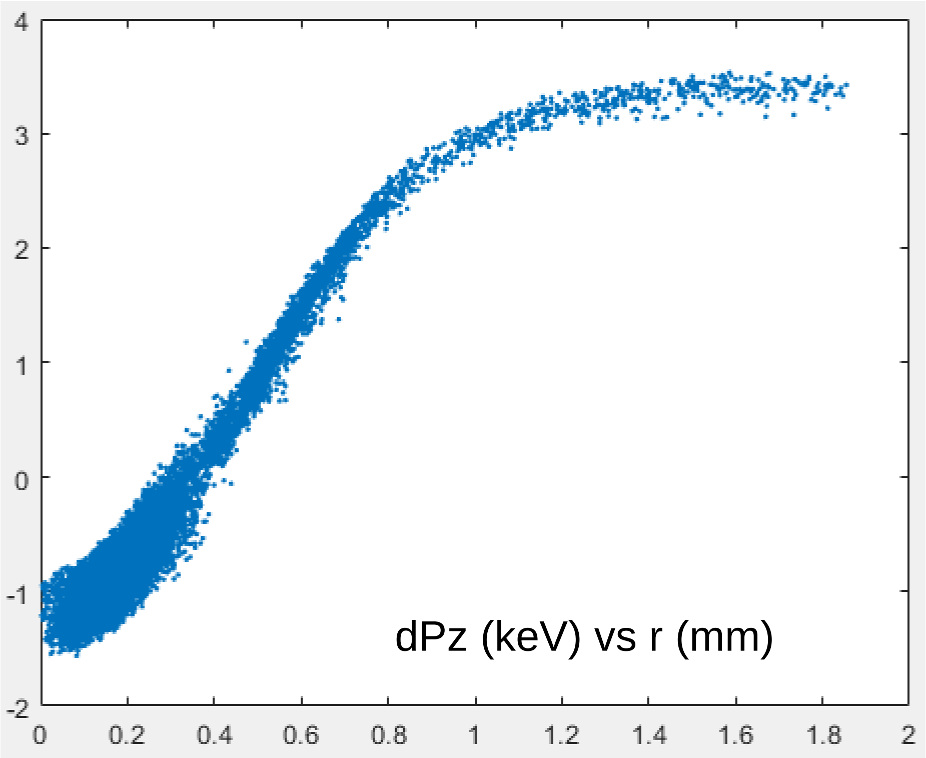
$$\approx \frac{Q}{\pi R}\cdot\left\{\frac{L^4 - 4L^2R^2 + 8LR^3}{4R^4} - \frac{3L^2}{4R^2}\cdot\left(\frac{\rho}{R}\right)^2\right\} \propto 1 - a\cdot\left(\frac{\rho}{R}\right)^2$$

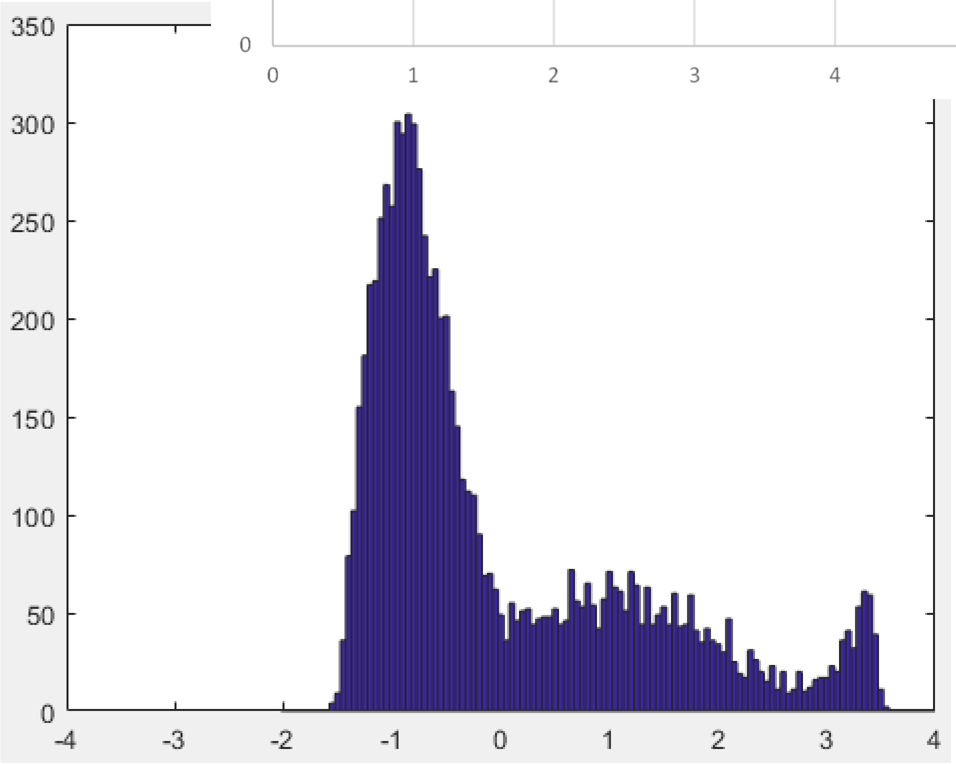
~“attenuation” of the accelerating field (quadratic in ρ)

z=5.28m

1.27 keV



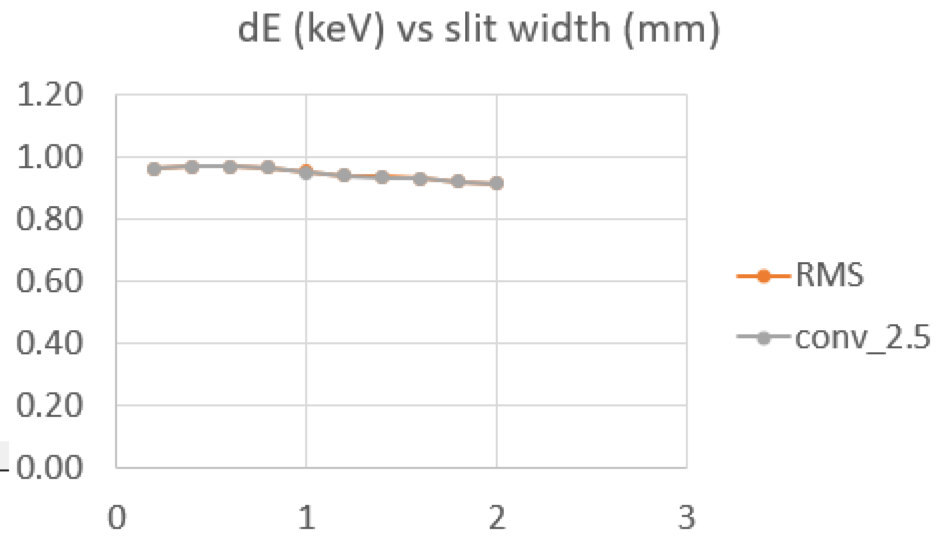


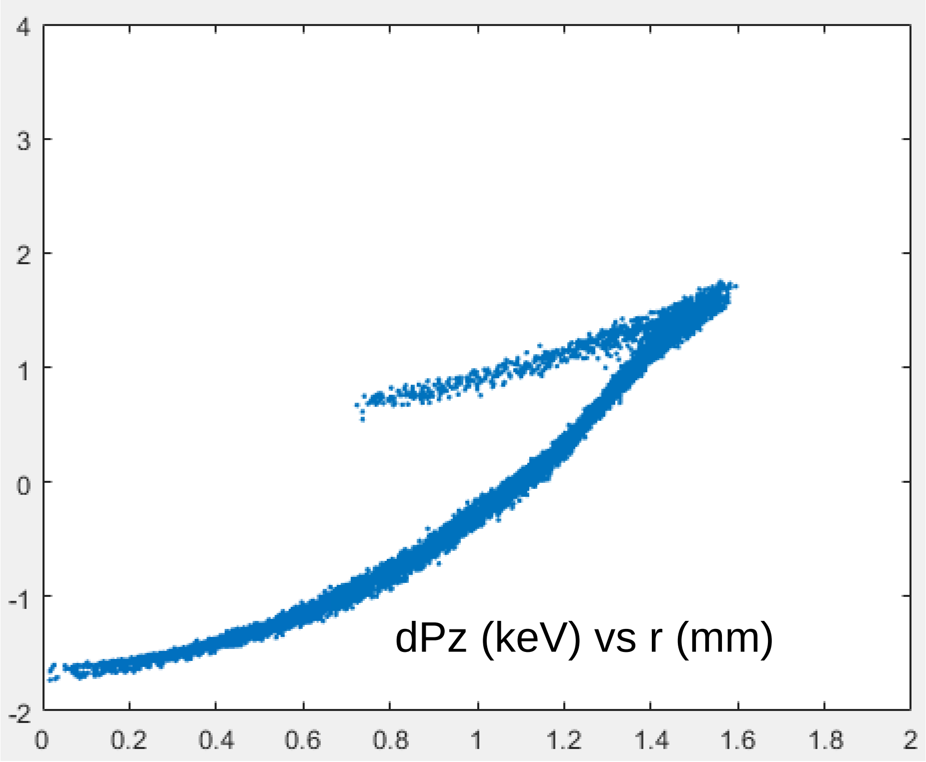


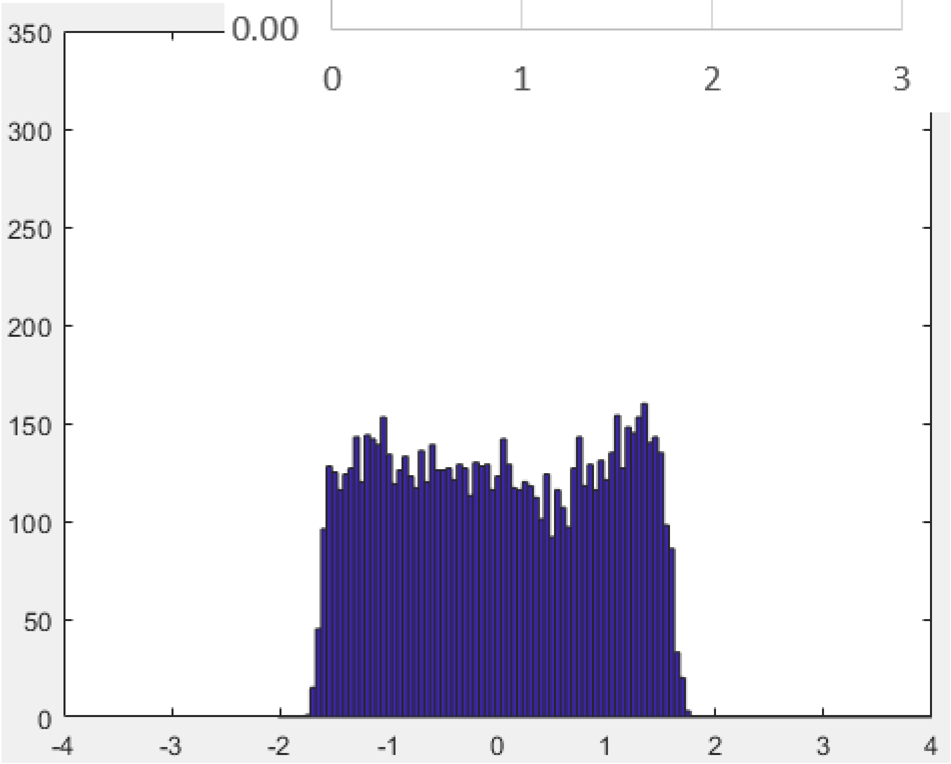
dPz (keV)

z=2.5m

0.95 keV



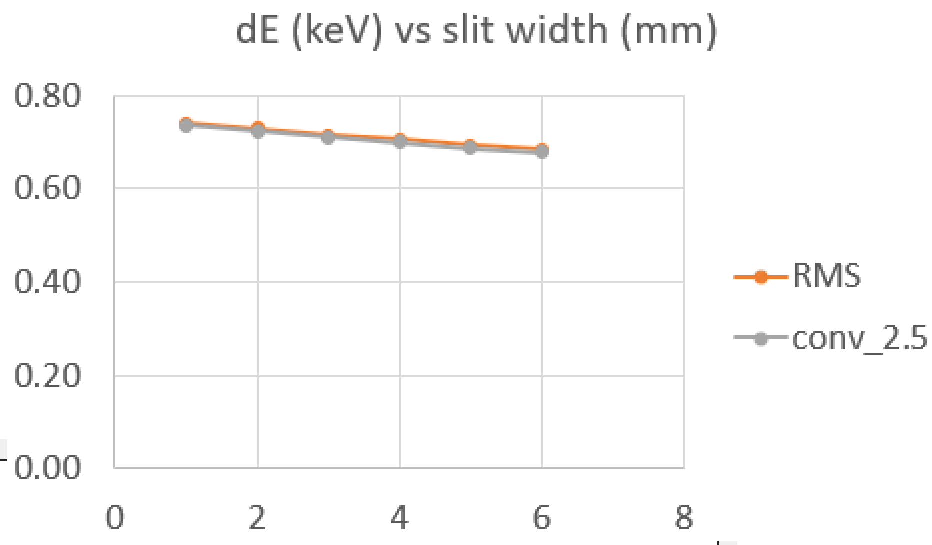


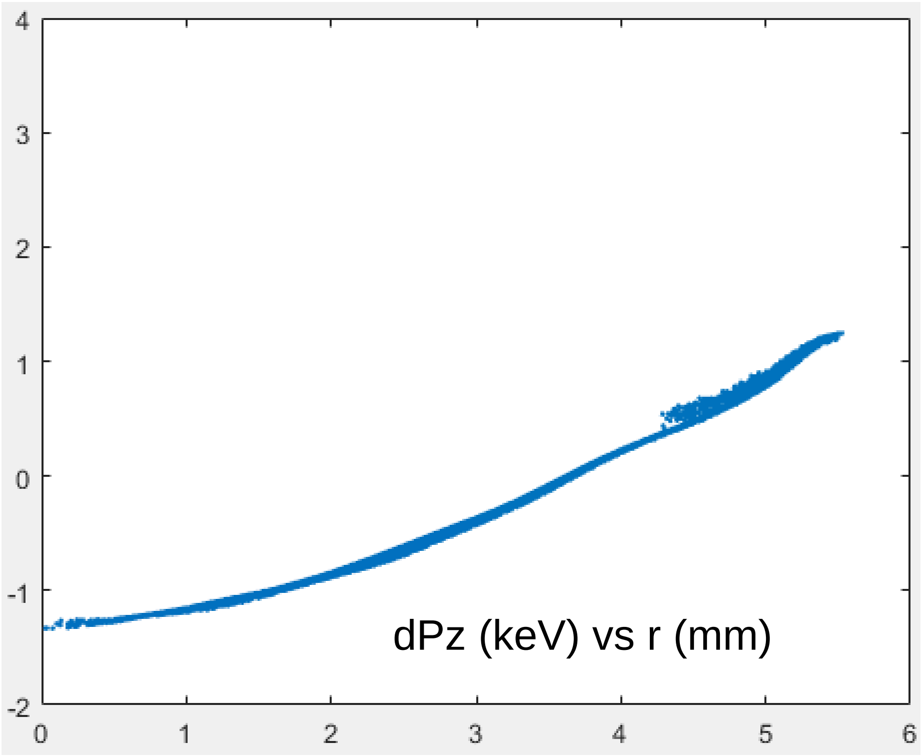


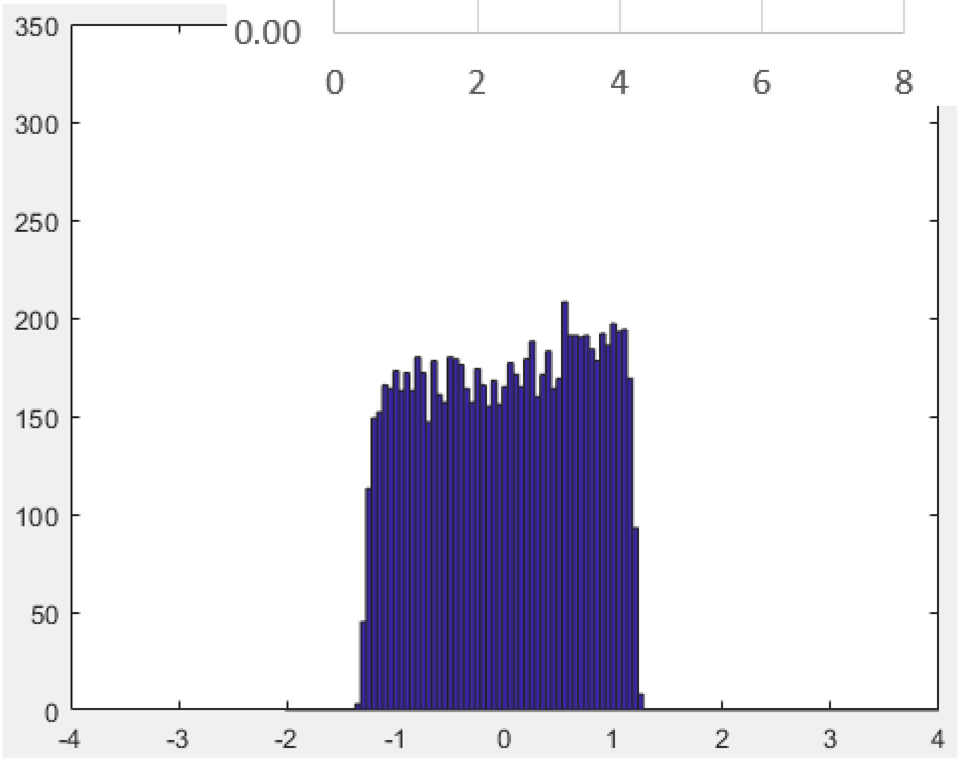
dPz (keV)

z=0.3m

0.72 keV







dPz (keV)

Conclusion

- Conclusion change from original draft
  - Can’t use slit to measure slice energy spread with good resolution
    - First slit will cut slice energy spread
    - Use only 2nd slit will be more proper to have a close measurement, but uncertainty is larger
  - Still valid: energy spread upper limit is still much lower than high energy injector, there is slice energy spread growth in high energy injector