Automated Quad-Scan Tool and Beam Emittance Measurement System Update and Results

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In partnership with:

Northern Illinois University

Outline

- Motivation
- PYTHON Quad-Scan Tool
- Python Emittance Tool
- FAST Experimental Results and Analysis
- Summary

Motivation

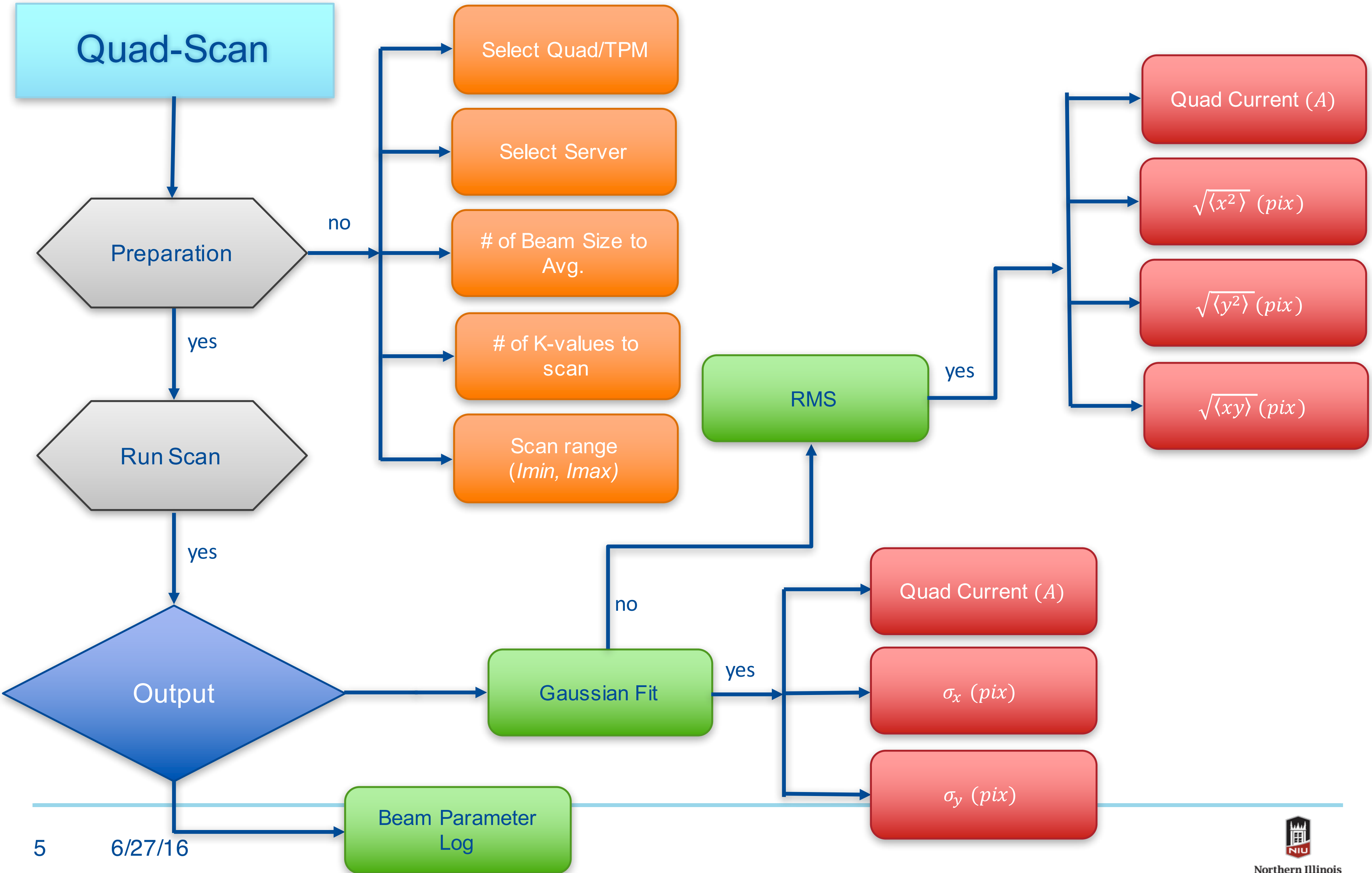
Motivation – there existed a need for a beam emittance measurements at FAST.

Proposal – deliver a quick and simple emittance measurement tool and “automated” quad-scan system.

Automated Quad-Scan

- PYTHON quad-scan tool for automated quad-scans.
- Functions and capabilities:
  - Record single or multiple beam size measurements per K-value.
  - Provide Gaussian and/or RMS measurements.
  - Saves images from each scan point for off-line analysis/fitting.
  - Depending on the desired settings, quad-scans take between 5 min and 30 min.

Automated Quad-Scan

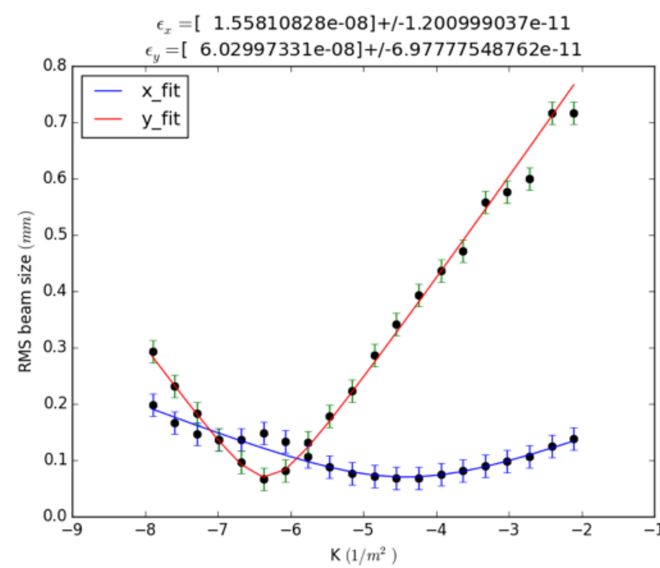


Emittance Calculator

- An emittance calculator was developed in PYTHON to compliment the automated quad-scan tool.

- The calculator takes the raw data file output by the quad-scan tool and quickly produces:
  - Emittance (Thick Lens)
  - Courant-Snyder parameters
  - Beam matrices
  - Estimated errors on all parameters
  - Plots:
    - Squared beam size (m) vs. $K\ (m^{-2})$
    - Beam size (mm) vs. $K\ (m^{-2})$

```
Enter the beam energy (MeV): 42.3
Enter the quadrupole magnet: q120
Enter the TPM: x121
Drift Length (m) =  1.052537
Beam size in x, y (m):
[ 0.00028724] +/- 1.25667538179e-06 ,
[ 0.00097728] +/- 3.26203618743e-06
4D beam matrix:
[[  8.25064638e-08  -1.18969284e-07              nan              nan]
 [ -1.18969284e-07   1.74488881e-07              nan              nan]
 [             nan              nan   9.55076687e-07   1.41983247e-07]
 [             nan              nan   1.41983247e-07   2.49145440e-08]]
Geometrical Emittance in x, y (m*rad):
[  1.55810828e-08] +\- 1.43363373263e-13 ,
[  6.02997331e-08] +\- 8.3293774679e-13
Normalized Emittance (x, y) (m*rad):
[  1.30527519e-06] +/- 1.200999037e-11 ,
[  5.05149396e-06] +/- 6.97777548762e-11
4D Emittance:
nan
Twiss parameters:
alpha in x, y:
[ 7.63549526] +\- 0.000123759331367 ,
[-2.35462479] +\- 4.06996594185e-05
beta in x, y (m):
[ 5.29529719] +\- 8.37703872867e-05 ,
[ 15.83882111] +\- 0.000262683725156
```



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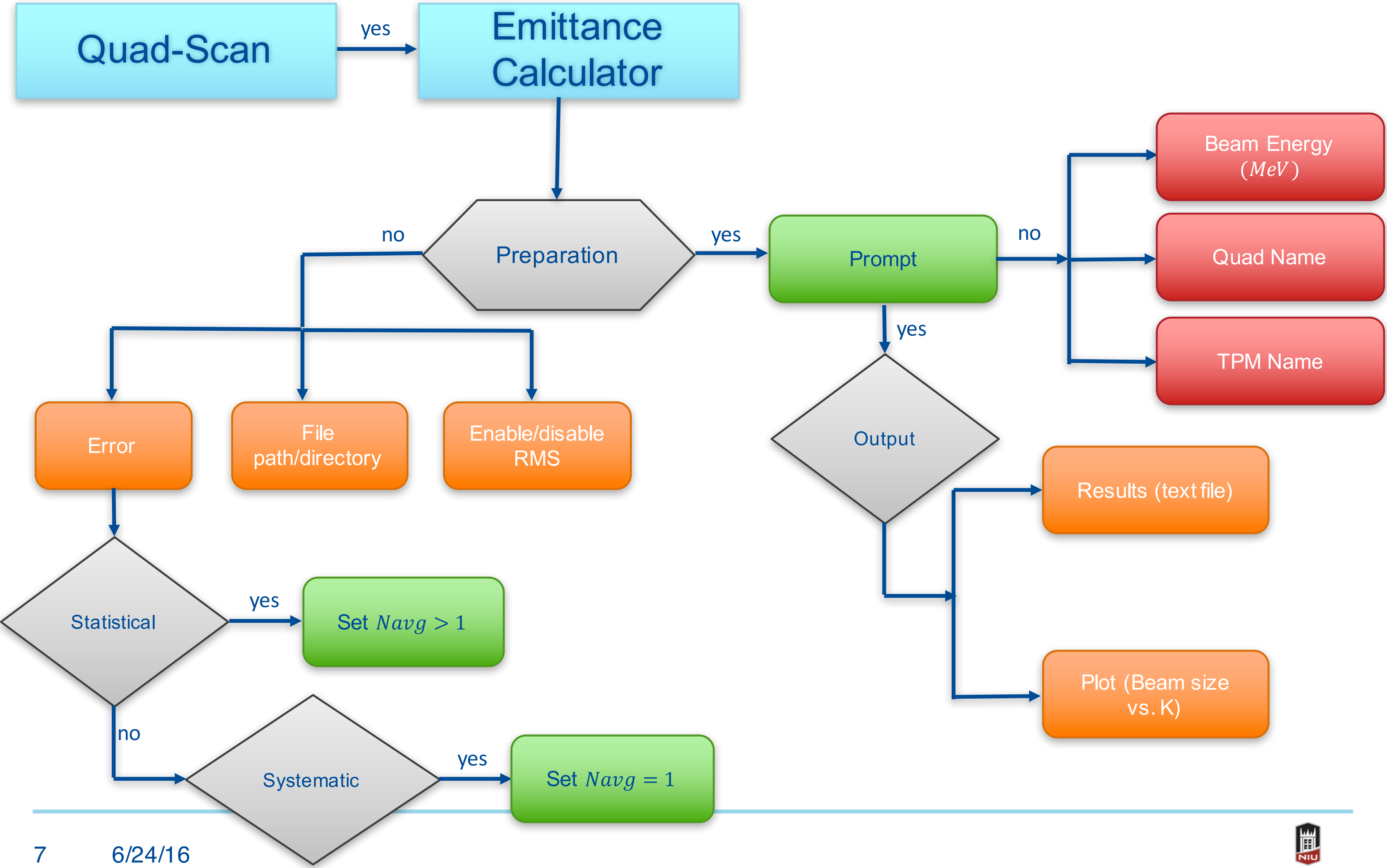
Emittance Calculator



ELEGANT simulation

- A snippet of the full ELEGANT lattice file for the FAST beamline was used to benchmark the PYTHON emittance calculator.

- Simulations were performed with a beam energy of $50\ MeV$ with two quadrupole magnets at two different TPMs and reasonable agreement between the PYTHON algorithm and simulation was found:

Q106 at X109

	ELEGANT	PYTHON	% Difference
ϵ_{x_g}	$1.00\times10^{-8}\ m\cdot rad$	$9.56\times10^{-9}\ m\cdot rad$	$< 5\%$
ϵ_{y_g}	$1.50\times10^{-8}\ m\cdot rad$	$1.43\times10^{-8}\ m\cdot rad$	$< 5\%$

Q108 at X111

	ELEGANT	PYTHON	% Difference
ϵ_{x_g}	$1.50\times10^{-8}\ m\cdot rad$	$1.46\times10^{-8}\ m\cdot rad$	$< 3\%$
ϵ_{y_g}	$1.75\times10^{-8}\ m\cdot rad$	$1.70\times10^{-8}\ m\cdot rad$	$< 3\%$

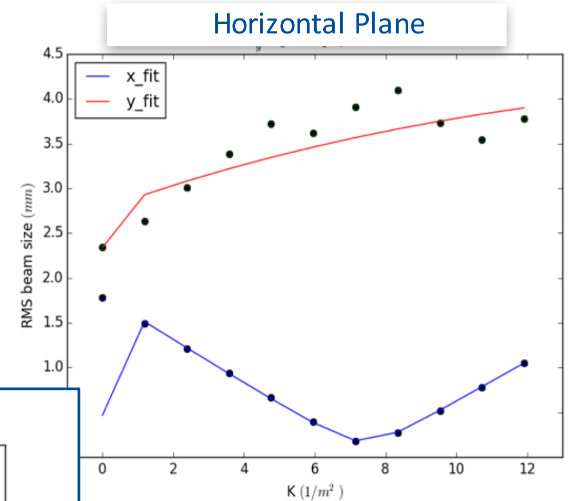
Experimental Results

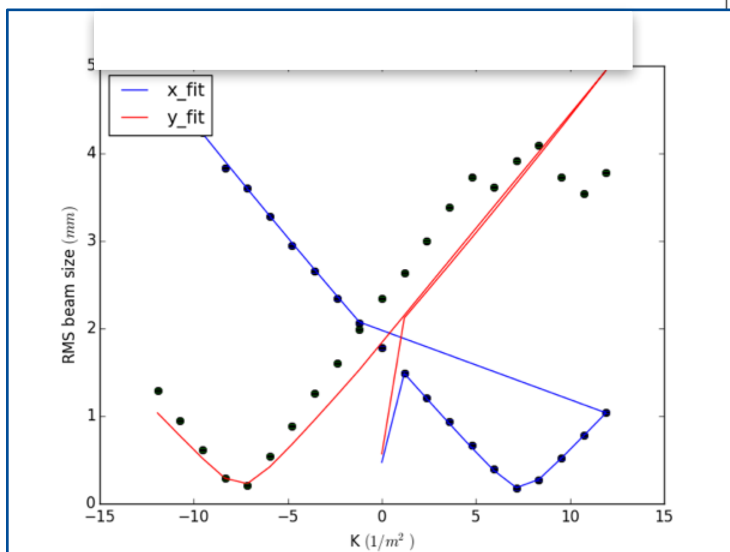
- Early results:

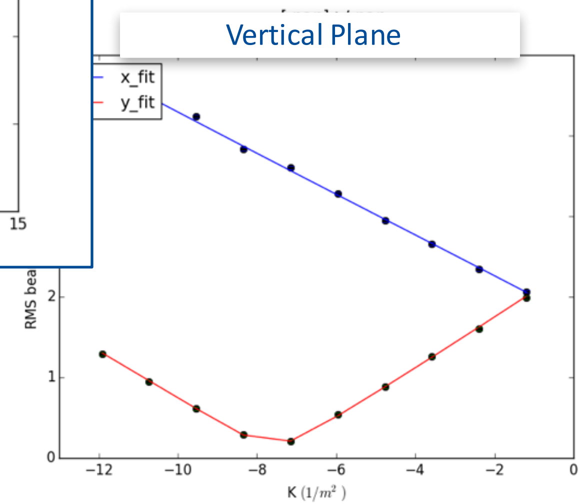
  $20-30\ mm \cdot mrad$

- Best emittance (nominal settings):

  $5-6\ mm \cdot mrad$







Beam parameters:

- Energy = $\sim 40\ MeV$
- Bunch charge = $200\ pC$
- # of bunches = $50-100$
- Main solenoid = $310\ A$
- Bucking solenoid = $70\ A$

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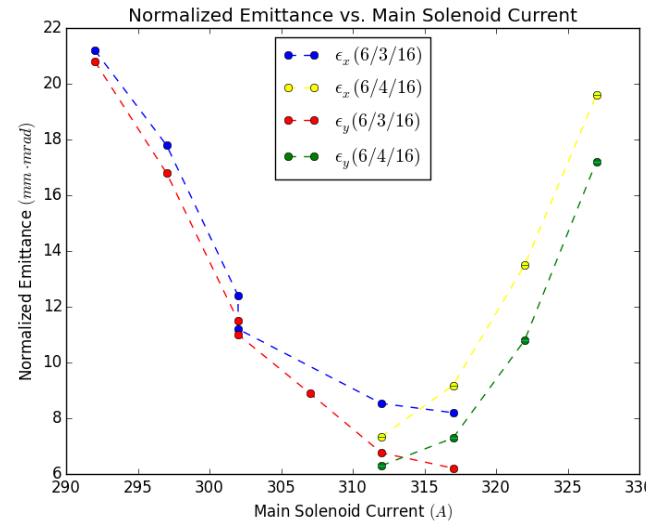
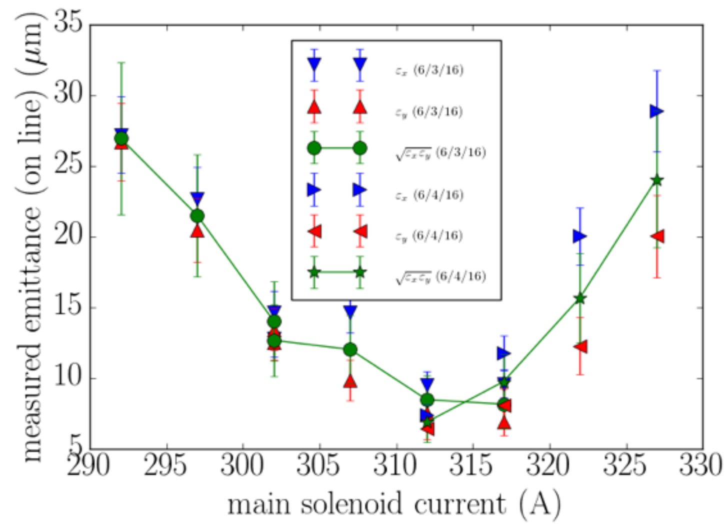
Main Solenoid Scans

- After tuning of the beamline quad-scans were performed with Q108/X111 as a function of the main solenoid current.
- This was done in order to find the optimum solenoid setting.
- Beginning with $292\ A$, the main solenoid was scanned in $5\ A$ increments up to $327\ A$.
- It was discovered that the optimum solenoid setting was around $312\ A$, dropping the emittance by a factor of 3, or $6 - 7\ mm \cdot mrad$.

PYTHON



ELEGANT

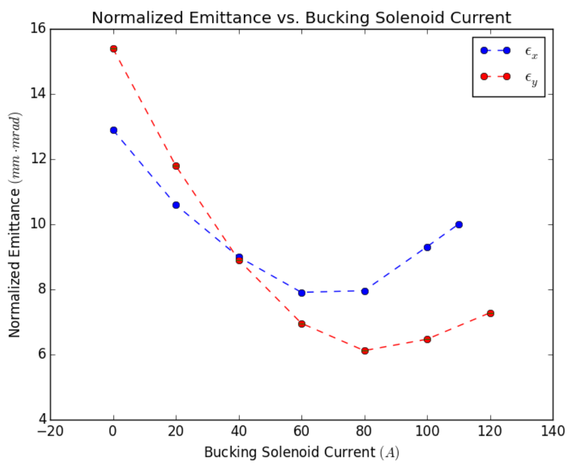


Bucking Solenoid Scans

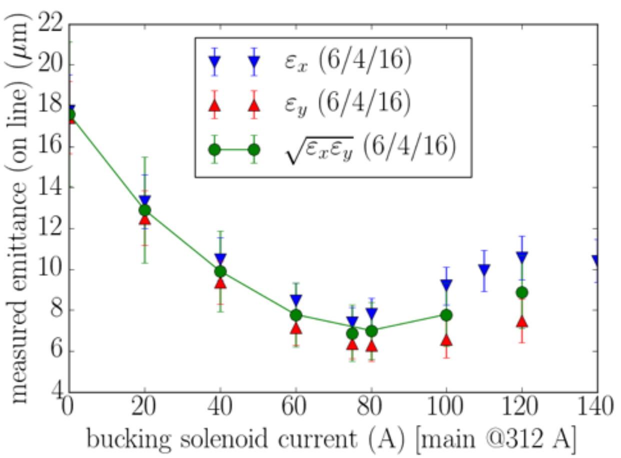
Following the main solenoid scans, attempts at lowering the emittance further were continued and the same procedure was applied to the bucking solenoid.

- The main solenoid was set to the optimal setting $(312\ A)$ and the bucking solenoid was scanned from $20\ A - 140\ A$ in $20\ A$ increments.
- From the analyzed data it appears that the nominal setting of $70\ A - 75\ A$ was indeed the optimal setting for low emittance.

PYTHON



ELEGANT



Summary and Conclusion

- The goal of this project was to deliver an ”automated” quad-scan tool and emittance calculator using PYTHON computing language.
  - These tools have been tested and offer users the ability to quickly perform quadrupole scans using the PYTHON quad-scan tool.
  - Working in tandem, the PYTHON emittance calculator allows users to quickly calculate the emittance, Courant-Snyder parameters, and various other parameters using the “Thick Lens” model with error analysis.
- By tuning the accelerator during the ongoing commissioning of the $50\ MeV$ beamline, a decrease in the normalized emittance by a factor of 4 has been calculated.
- As compared to simulation, the emittance is still a factor of 2 larger (experimentally).
- Coupling between the transverse planes or the space charge force could explain the larger emittance.
- More studies need to be performed as well as comparisons with other emittance measurement methods.

Acknowledgements

I would like to say thank you to the following members of the FAST/NIU group for guidance and technical support as well as for the opportunity to be a part of this group and for beam time to perform these experiments:

D. Broemmelsiek , K. Carlson, D. Crawford, D. Edstrom, A. Halavanau, J. Hyun, A. Lumpkin, D. Mihalcea, P. Piot, A. Romanov, J. Ruan, J. Santucci, G. Stancari, Y.M. Shin, C. Thangaraj, and A. Valishev

Extra Slides

FAST Experimental Results and Analysis

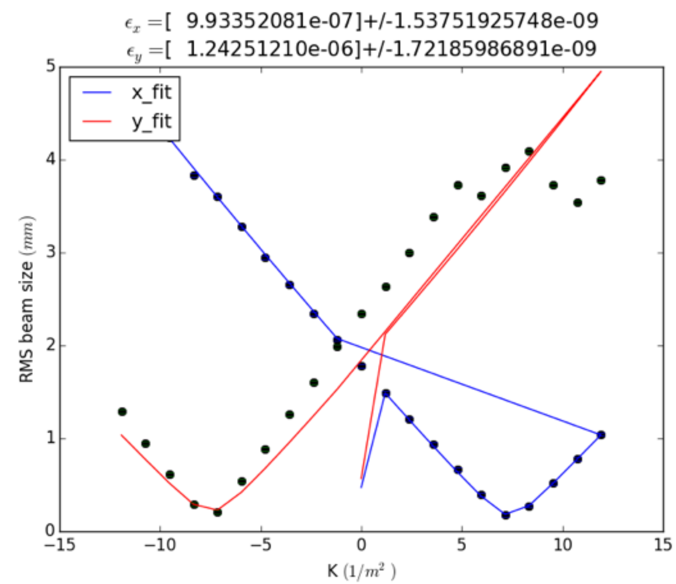
Experimental Results – Preliminary Quad-Scans

- The first quad-scans were performed with Q110/X111.

```
Drift Length (m) = 0.42133
Beam size in x (m) = 0.00310948358479 +/- 9.78021881425e-06
Geom. emittance in x (m*rad) = 9.93352080752e-07 +/- 1.88827457781e-11
Norm. emittance in x (m*rad) = 8.08832556219e-05 +/- 1.53751925748e-09
alpha_x = 7.13201823895 +/- 0.000145117266514
beta_x (m) = 9.73359632643 +/- 0.000199381830572
Beam size in y (m) = 0.00314000634171 +/- 1.03365092632e-05
Geom. emittance in y (m*rad) = 1.2425121007e-06 +/- 2.11466893907e-11
Norm. emittance in y (m*rad) = 0.000101171000496 +/- 1.72185986891e-09
alpha_y = 5.72149808355 +/- 0.000105632214854
beta_y (m) = 7.93524652225 +/- 0.000145251649412
```

```
Gun phase (deg)     = 30.0
Gun Field (MV/m)     = 42.0
CC1 phase (deg)    = 72.0
CC1 Field (MV/m)     = 21.0
CC2 phase (deg)    = 108.0
CC2 Field (MV/m)     = 14.0
# of pulse          = 50.0
UV waveplate (%)    = 3.0
UV COB iris  (%)    = 80.0
UV photodiode (uJ) = 0.1446743
Gun Main soleno(A) = 295.0
Gun Buck soleno(A) = 70.0
Spectro. D122(G)    = 925.6
bunch charge (pC)   = 0.2122
```

Should be nC



- Full scan performed through both beam waists.
- Poor fits – it was decided to narrow the scan range over each beam waist and perform individual scans for each plane.

FAST Experimental Results and Analysis

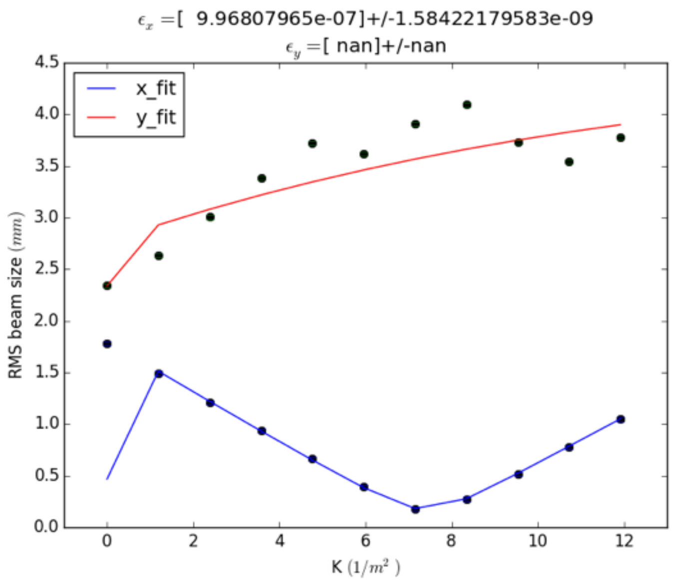
Experimental Results – Preliminary Quad-Scans

- The first quad-scans were performed with Q110/X111.

```
Drift Length (m) = 0.42133
Beam size in x (m) = 0.00315740867435 +/- 1.23377126634e-05
Geom. emittance in x (m*rad) = 9.96807964936e-07 +/- 1.94563139819e-11
Norm. emittance in x (m*rad) = 8.11646494693e-05 +/- 1.58422179583e-09
alpha_x = 7.31866550049 +/- 0.000168933319989
beta_x (m) = 10.0011535697 +/- 0.000234800929638
Beam size in y (m) = nan +/- 2.28754588382e-05
Geom. emittance in y (m*rad) = nan +/- nan
Norm. emittance in y (m*rad) = nan +/- nan
alpha_y = nan +/- nan
beta_y (m) = nan +/- nan
```

```
Gun phase (deg)     = 30.0
Gun Field (MV/m)     = 42.0
CC1 phase (deg)    = 72.0
CC1 Field (MV/m)     = 21.0
CC2 phase (deg)    = 108.0
CC2 Field (MV/m)     = 14.0
# of pulse          = 50.0
UV waveplate (%)    = 3.0
UV COB iris  (%)    = 80.0
UV photodiode (uJ) = 0.1446743
Gun Main soleno(A) = 295.0
Gun Buck soleno(A) = 70.0
Spectro. D122(G)    = 925.6
bunch charge (pC)   = 0.2122
```

Should be nC



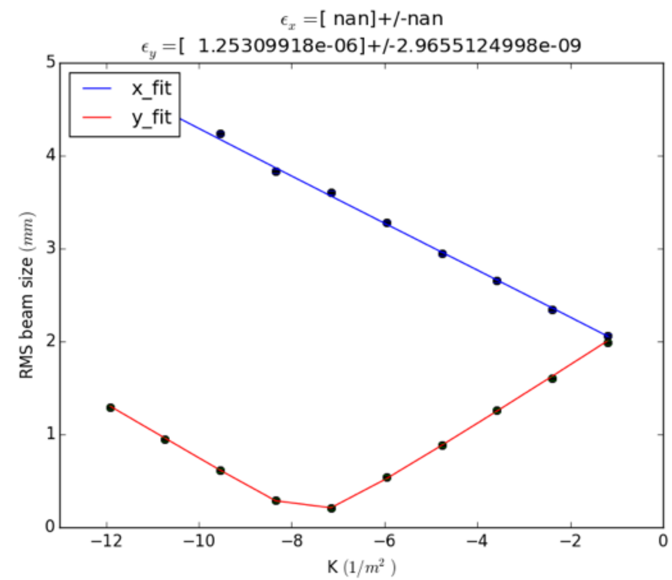
- Scan performed over a narrow range over the beam waist in x.

FAST Experimental Results and Analysis

Experimental Results – Preliminary Quad-Scans

- The first quad-scans were performed with Q110/X111.

```
Drift Length (m) = 0.42133
Beam size in x (m) = 0.00285681426962 +/- 4.98456011337e-05
Geom. emittance in x (m*rad) = nan +/- nan
Norm. emittance in x (m*rad) = nan +/- nan
alpha_x = nan +/- nan
beta_x (m) = nan +/- nan
Beam size in y (m) = 0.00409166122264 +/- 1.58856566474e-05
Geom. emittance in y (m*rad) = 1.25309917522e-06 +/- 3.64203689567e-11
Norm. emittance in y (m*rad) = 0.000102033048375 +/- 2.9655124998e-09
alpha_y = 9.47025848442 +/- 0.000317323980871
beta_y (m) = 13.3602286969 +/- 0.000456683487269
```




```
Gun phase (deg)     = 30.0
Gun Field (MV/m)     = 42.0
CC1 phase (deg)    = 72.0
CC1 Field (MV/m)     = 21.0
CC2 phase (deg)    = 108.0
CC2 Field (MV/m)     = 14.0
# of pulse         = 50.0
UV waveplate (%)   = 3.0
UV COB iris  (%)   = 80.0
UV photodiode (uJ) = 0.1446743
Gun Main soleno(A) = 295.0
Gun Buck soleno(A) = 70.0
Spectro. D122(G)   = 925.6
bunch charge (pC)  = 0.2122
```

Should be nC

- Scan performed over a narrow range over the beam waist in y.

FAST Experimental Results and Analysis

Experimental Results – Preliminary Quad-Scans

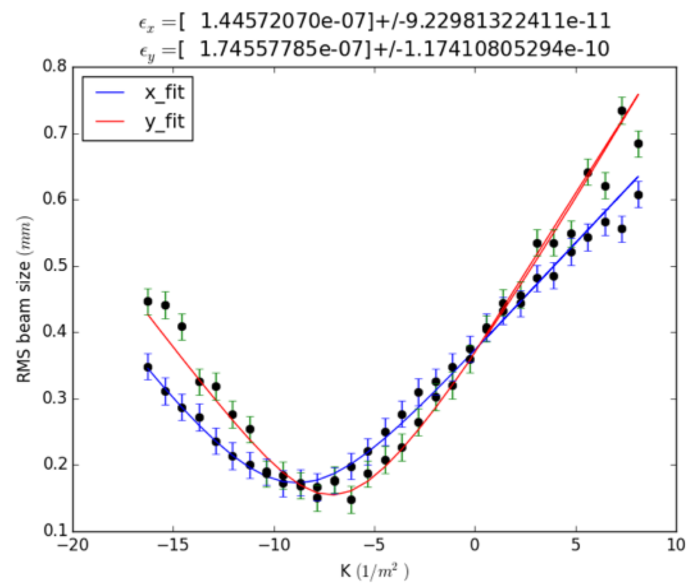
- From the last two scans one can see that the fits in their respective planes improved.
- Beginning with the first few experiments-on, it was decided to scan individual planes in most cases to achieve the best results.
- The emittance was larger than the simulated results of $\sim 3\ mm \cdot mrad$ normalized emittance.
- For scans up to 35 K-values, the time it took to perform a quad-scan was around 5 minutes.
- The emittances measured in the early tests ranged $12\ mm \cdot mrad - 15\ mm \cdot mrad$ (normalized).

FAST Experimental Results and Analysis

Experimental Results – Preliminary Quad-Scans

- After tuning the beamline (Q110/X111):

```
Drift Length (m) = 0.42133
Beam size in x (m) = 0.000543231609255 +/- 1.96611230055e-06
Geom. emittance in x (m*rad) = 1.44572070196e-07 +/- 1.13354168309e-12
Norm. emittance in x (m*rad) = 1.17717171344e-05 +/- 9.22981322411e-11
alpha_x = 5.63216329324 +/- 6.49276496838e-05
beta_x (m) = 2.04120049533 +/- 2.44084028258e-05
Beam size in y (m) = 0.000612162063125 +/- 2.10811222696e-06
Geom. emittance in y (m*rad) = 1.74557785275e-07 +/- 1.4419581265e-12
Norm. emittance in y (m*rad) = 1.42132907765e-05 +/- 1.17410805294e-10
alpha_y = 1.6928921399 +/- 2.56493194106e-05
beta_y (m) = 2.14680995717 +/- 2.71642414947e-05
```




```
Gun phase (deg)     = 30.0
Gun Field (MV/m)     = 42.0
CC1 phase (deg)    = 72.0
CC1 Field (MV/m)     = 21.0
CC2 phase (deg)    = 108.0
CC2 Field (MV/m)     = 14.0
# of pulse          = 100.0
UV waveplate (%)    = 3.0
UV COB iris  (%)    = 80.0
UV photodiode (uJ) = 0.16829461
Gun Main soleno(A) = 300.0
Gun Buck soleno(A) = 75.0
Spectro. D122(G)    = 925.6
bunch charge (pC)   = 0.2271
```

Should be nC

- Full scan performed through both beam waists after tuning the beamline.

FAST Experimental Results and Analysis

Experimental Results – Main Solenoid Scans

- Since the calculated emittance from quad-scan simulations were larger than the experimental results by factor of 3 or 4, a method for further tuning the beamline and reducing the emittance was needed.

- One such method was scanning the main solenoid and performing quad-scans for each solenoid current setting.

- There are two solenoids immediately after the gun – a main solenoid and a bucking solenoid.

- The nominal settings for the main and bucking solenoids since the $20\ MeV$ beamline had been commissioned was $290 - 295\ A$ and $70 - 75\ A$, respectively.

FAST Experimental Results and Analysis

Experimental Results – Main Solenoid Scans

- Relative agreement was found between results calculated from both PYTHON and ELEGANT, however more studies are needed to uncover the small discrepancies between the two codes.

- One such discrepancy, which was previously an issue when comparing to ELEGANT, was error analysis.

- The only source of error considered for these scans in PYTHON was the systematic error coming from the camera resolution limit of $20\ \mu m$.

- There are indeed error bars being displayed in the PYTHON plot, but the errors are four orders of magnitude smaller than the emittance, which are therefore unseen unless each data point is zoomed in on.

- These quad/solenoid scans were performed over the course of two days – on the second day quad-scans resumed at $312\ A$ main solenoid setting (the optimum setting). The saved lattice settings show repeatable results (showing consistency within the accelerator).

FAST Experimental Results and Analysis

Experimental Results – Emittance as a Function of Charge

- Studying emittance as a function of bunch charge was also of interest as the various planned experiments will not necessarily use the same charge throughout.

- Knowing the optimum main solenoid setting was $\sim 310\ A$, quad-scans as a function of both the bunch charge and main solenoid setting were performed.

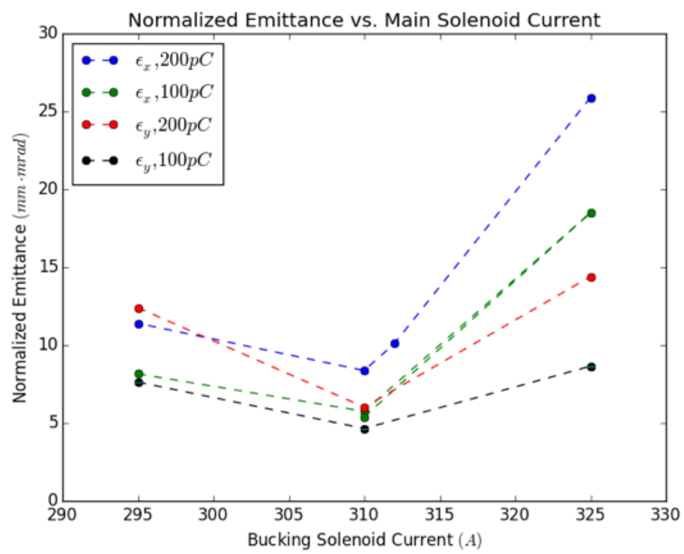
- The solenoid was scanned over $295\ A$, $310\ A$, and $325\ A$ for $100\ pC$ and $200\ pC$ bunch charge.

- As expected, the emittance was lower at lower charge.

- These quad-scans were performed with a beam energy of $42.3\ MeV$ and $50\ bunches$ in the macro-pulse, again with Q108 at X111.

- It was noticed from the individual quad-scans that some coupling was occurring and the fits began to degrade, particular in the horizontal plane.

- Possible sources of the large emittance could be coupling induced by the laser or possibly instabilities in the capture cavities.



FAST Experimental Results and Analysis

Experimental Results – Emittance at the Goniometer

- A goniometer has been installed near the end of the low-energy beamline.
- One of the planned experiments at FAST is a crystal channeling radiation experiment.
- There is a crystal within the goniometer and for this experiment a small emittance is needed ($\sim 1\, mm \cdot mrad$).
- It was therefore necessary to measure the emittance at a location near the goniometer to assure the accelerator was capable of achieving the required emittance.
- Conveniently, there exists a quadrupole and TPM in the low energy beamline near the goniometer: Q120 and X121.
- It was intended to lower the charge, and thus the emittance, and so such low charge should not have adverse effects on the beam measurement.
- Reducing the bunch charge to $50\, pC$ and 50 bunches, the emittance was measured to be $\sim 1\, mm \cdot mrad$.

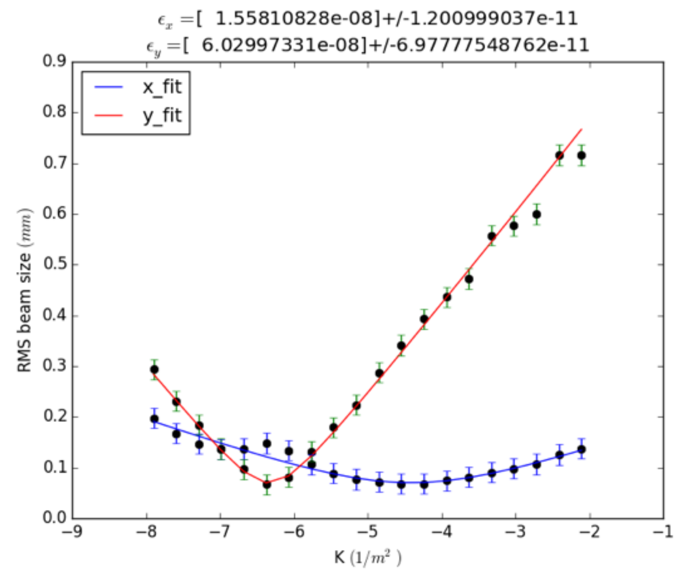
FAST Experimental Results and Analysis

Experimental Results – Emittance at the Goniometer

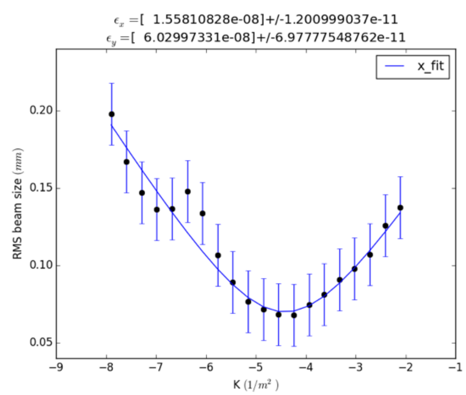
- These quad-scans were performed with Q120/X121.

```
Drift Length (m) = 1.052537
Beam size in x (m) = 0.000287239384162 +/- 1.25667538179e-06
Geom. emittance in x (m*rad) = 1.55810827689e-08 +/- 1.43363373263e-13
Norm. emittance in x (m*rad) = 1.30527518814e-06 +/- 1.200999037e-11
alpha_x = 7.6354952582 +/- 0.000123759331367
beta_x (m) = 5.29529719068 +/- 8.37703872867e-05
Beam size in y (m) = 0.000977280249732 +/- 3.26203618743e-06
Geom. emittance in y (m*rad) = 6.02997331457e-08 +/- 8.3293774679e-13
Norm. emittance in y (m*rad) = 5.05149396189e-06 +/- 6.97777548762e-11
alpha_y = -2.35462479055 +/- 4.06996594185e-05
beta_y (m) = 15.838821114 +/- 0.000262683725156
```

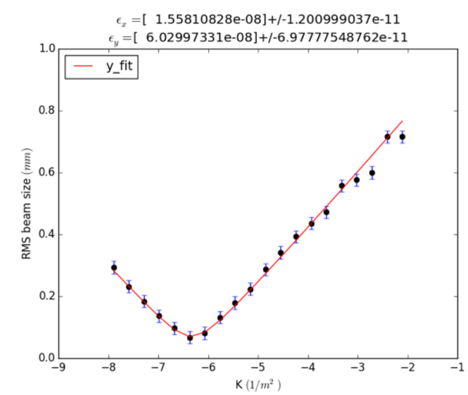
```
Gun phase (deg)     = 32.0
Gun Field (MV/m)     = 42.0
CC1 phase (deg)    = 52.0
CC1 Field (MV/m)     = 21.0
CC2 phase (deg)    = 110.0
CC2 Field (MV/m)     = 14.0
# of pulse           = 100.0
UV waveplate (%)     = 0.6034
UV COB iris  (%)     = 30.0
UV photodiode (uJ) = 0.16238953
Gun Main soleno(A) SP = 310.0
Gun Buck soleno(A) SP = 74.834
Gun Main soleno(A) = 310.0
Gun Buck soleno(A) = 75.0
Spectro. D122(G)    = 1996.0
bunch charge (nC)   = 0.0486
```



Same plot (in x only)



Same plot (in y only)



FAST Experimental Results and Analysis

Experimental Results – Emittance at the Goniometer

- While $1.3\ mm \cdot mrad$ was achieved in x, the normalized emittance in the y-plane was $5.1\ mm \cdot mrad$.
- Additionally, the fitting was again of poor quality at these low charges.
- When examining the data from this scan in the individual planes and the poor fits, these results are likely misleading.