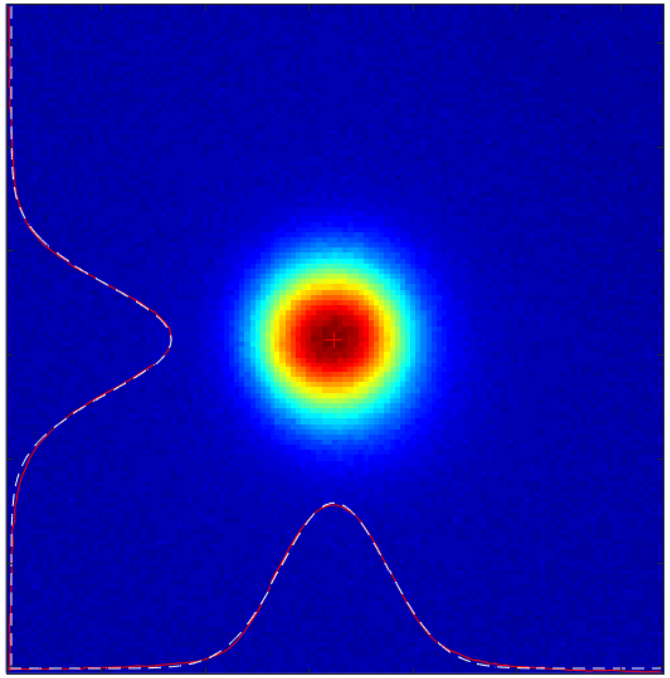
Teaching: single shot thermal emittance measurement



H. Qian, 2.06.2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

- Introduction to the technique
- Proof of principle experiment
- Application to cathode study
- Summary

Thermal emittance

Definition and traditional measurements

- Electron source already carries emittance from their emission mechanism
  - $\varepsilon_{thermal} = \sigma_{beam} * \frac{\sigma_{px}}{m_0 c}$

Transverse rms beam size at cathode

RMS Transverse momentum spread at cathode

  - Traditional measurement: laser rms size scan

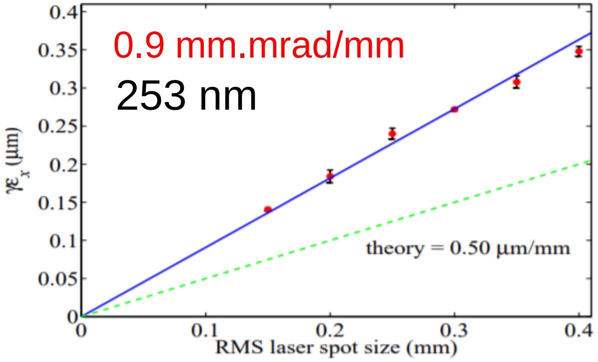
$$\frac{\sigma_{px}}{m_0 c} = \frac{\varepsilon_{thermal}}{\sigma_{beam}} \quad \text{(mm.mrad/mm)}$$

LCLS/SwissFEL use core slice emittance (<20 pC)
PITZ uses solenoid scan (<0.1 pC)

Difficulties:

1) More measurements, >3 laser diameters
2) Assumption: beam size equals laser size, needs good QE uniformity

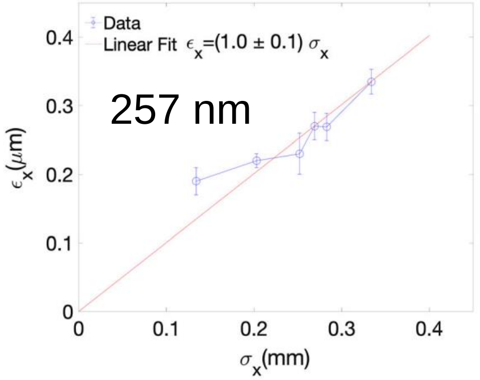
LCLS Cu measurement



0.9 mm.mrad/mm

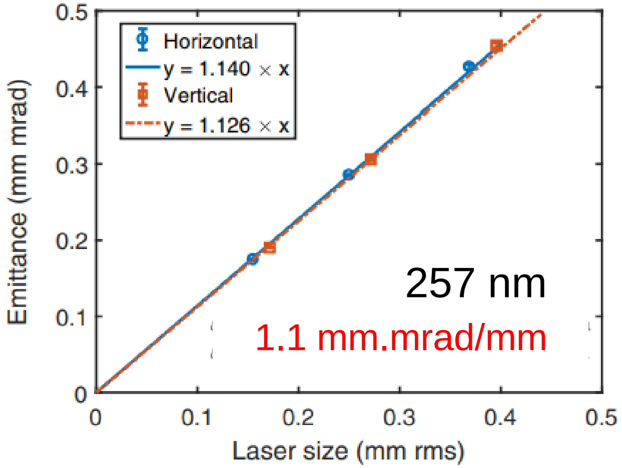
253 nm

LCLS-II Cs2Te



257 nm

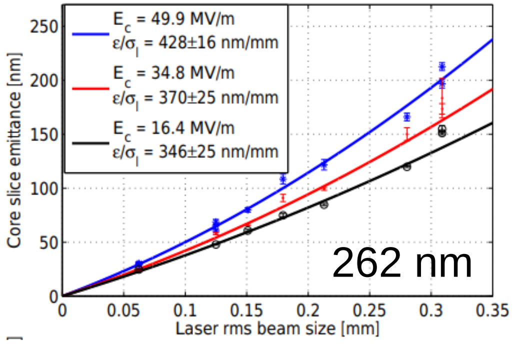
PITZ measurement #661.1



257 nm

1.1 mm.mrad/mm

SwissFEL Cu/Cs2Te

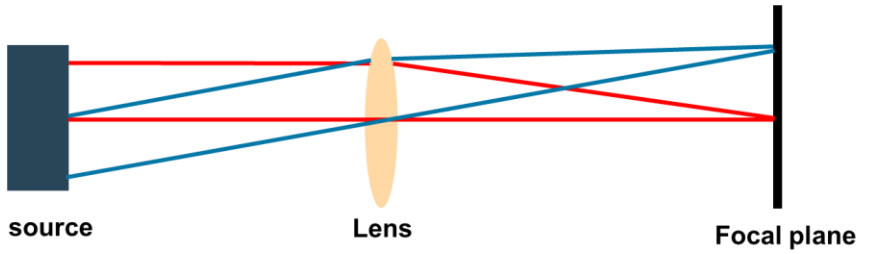


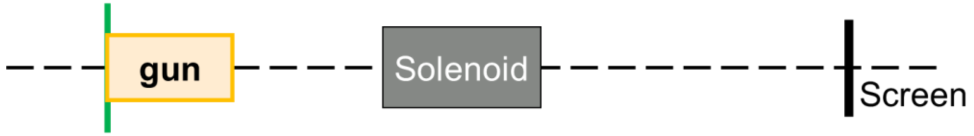
262 nm

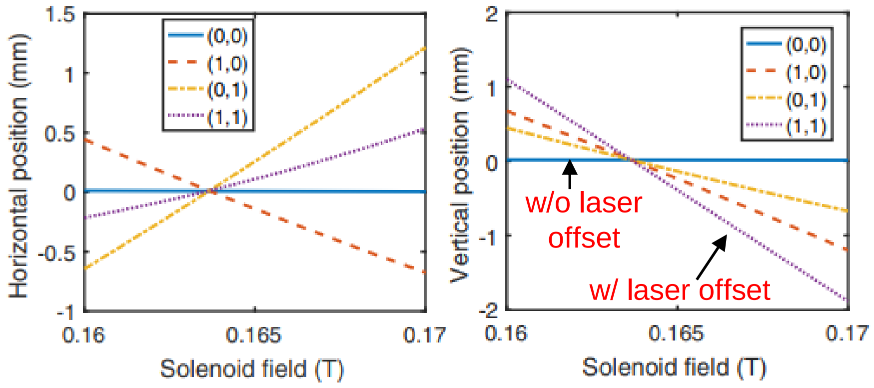
Single shot cathode transverse momentum measurement

Basic idea

- Imaging transverse momentum to position
  - Linear dynamics at low charge
    - $x_2 = R_{11}x_1 + R_{12}x_1'$
    - When R11=0, $\sigma_{scr} = M_{12}\frac{\sigma_{px}}{m_0 c}$ (Momentum imaging)
  - Advantage vs traditional method
    - Single shot, does not involve laser size variation, reduces time
- How to find the solenoid setting & M12 in simulation?
  - Set up gun (gradient & phase) and screen in ASTRA
  - Single particle tracking in ASTRA
  - Offset the particle on cathode (e.g. by laser radius or rms size)
  - Scan solenoid vs beam position (on measurement screen)
  - Solenoid setting → beam offset on screen back to zero
  - Fix solenoid to that value, full beam tracking w/o space charge, record rms beam size
  - M12 equals beam size (mm) divided by assumed thermal emittance (mm.mrad/mm) in ASTRA



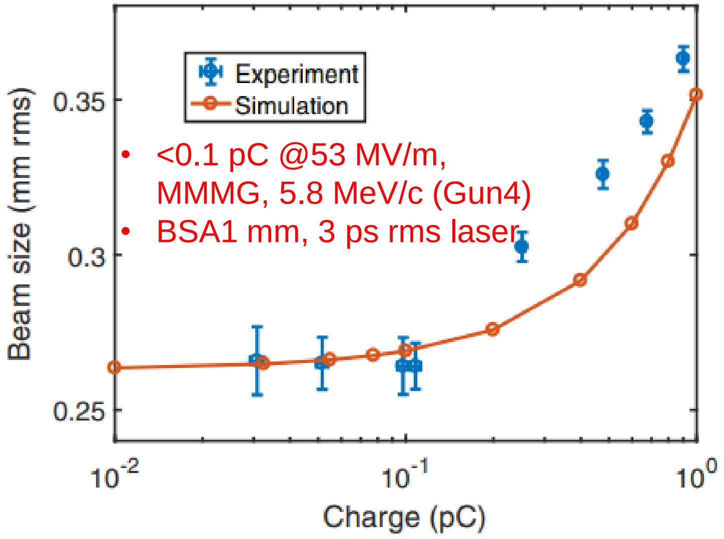




Single shot cathode transverse momentum measurement

Other effects

- Space charge effect @momentum imaging
  - Scan bunch charge (simulation, or experiment)
  - Take that beam size when variation becomes negligible
- How to reduce space charge effect
  - Longer laser pulse length (PITZ, 3 ps rms)
  - Larger BSA (0.5-1.5 mm)
  - Reference charge <0.1 pC (for 5.8 MeV/c)



- <0.1 pC @53 MV/m, MMMG, 5.8 MeV/c (Gun4)
- BSA1 mm, 3 ps rms laser

- Dark current effect
  - Reduces SNR of low charge beam size measurements
  - Limits gun gradient for thermal emittance measurement
  - Beam collimator at low.scr2 helps.
  - Good news: gun5.1 has low dark current
- Gun phase (pitz operation phase, not astra phase)
  - MMMG-9: the only phase for thermal emittance mapping
  - Don’t go beyond MMMG-10: energy spread effect will contribute to beam size increase
- SNR
  - Use LYSO or GAGG screen
  - Use camera imaging very close to view port to increase photon collection efficiency
  - Reduce dark current by collimator or lower gradient
  - Use at least 30 pulses, match camera exposure time to pulse number

Single shot cathode transverse momentum measurement

Other effects

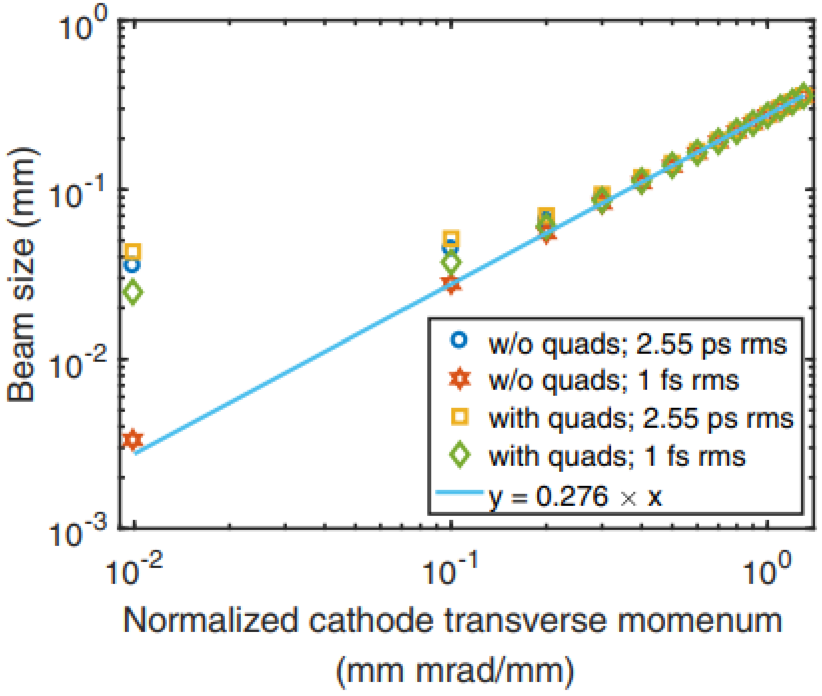
- RF emittance and solenoid quadrupole error effects
  - No quads error, ~3 ps laser
    - Reliable until 0.2 mm.mrad/mm
    - Enough for most cathodes at PITZ
    - reduce laser pulse length can help measure even lower thermal emittance
    - MMMG-9 can also minize RF emittance contribution
  - With solenoid quads error field
    - Difficult to find round beam
    - Difficult to find imaging solenoid current
      - Contributes beam size errors
    - Use gun quads to compensate
  - Screen station
    - Use to be EMSY1/LYSO
    - Wish: move it to High1.scr2 (install LYSO or YAP screen), put EMSY1 back to standard setup
      - Compatible with e window test?

$$\varepsilon_{RF} \approx \frac{eE_0}{2m_0c^2}\sigma_x\sigma_\phi \cos\phi_f \sqrt{\sigma_x^2 + x_0^2}$$

Beam size

Bunch length

Beam offset



$$\varepsilon_{\text{coupled}} = \beta\gamma\frac{\sigma_{x,\text{sol}}\sigma_{y,\text{sol}}}{f_a}\left|\sin 2(KL+\alpha_a)\right|$$

Focal length of quad error

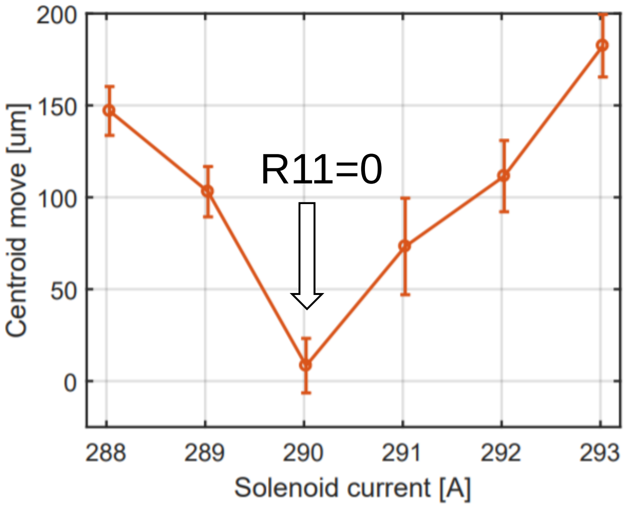
Larmor angle

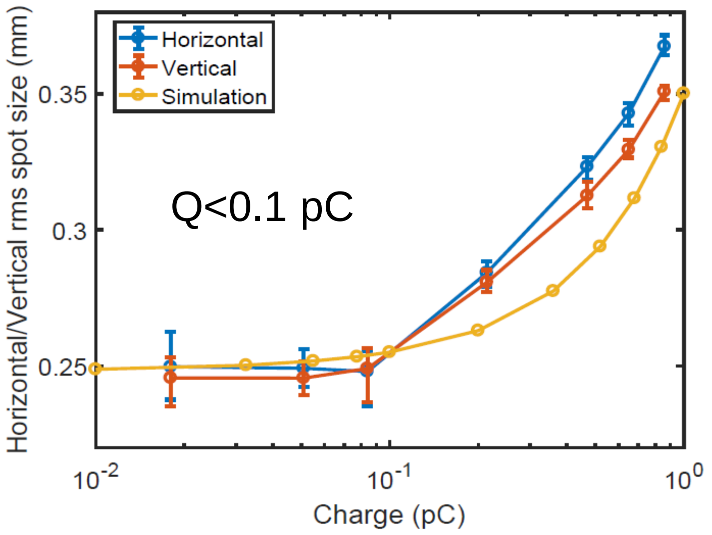
Effective angle of the rotated quadrupole

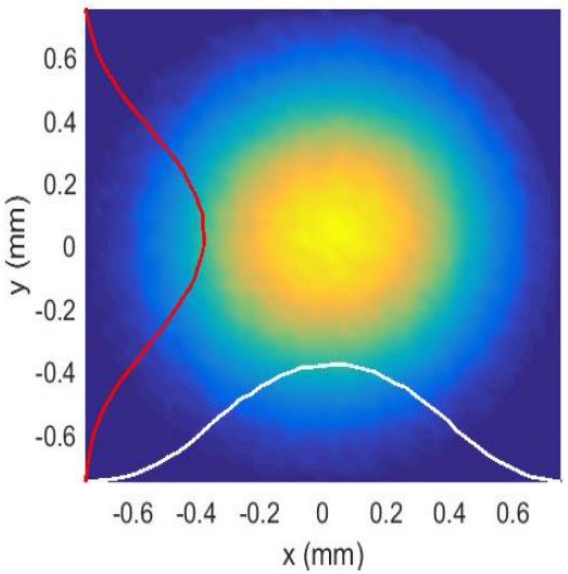
Proof of principle experiment at PITZ

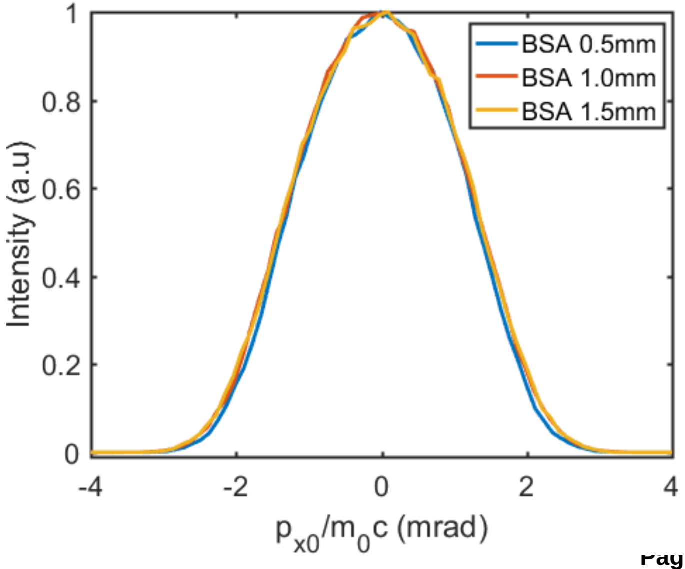
Step by step

- Experiment settings
  - Gun: 5.8 MeV/c
  - Laser: 6-7 ps FWHM, 1 mm diameter
  - Screen: ~5 meter from cathode
- Tune $R_{11} = \frac{dX_{scr}}{dX_{laser}} = 0$
  - Laser BBA
  - Beam position vs solenoid
  - Move the laser on cathode (~0.5 mm)
  - Beam position vs solenoid
  - Calculate beam movement on screen
  - Find Solenoid current for R11=0
- Beam size vs laser size at R11=0
  - Laser diameter 0.5/1.0/1.5 mm
  - Beam size does not change on screen





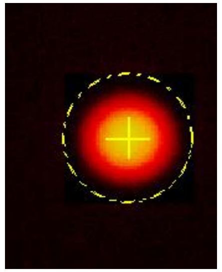




Procedure for measuring thermal emittance

For gun4

- Laser BBA (record laser beam position on VC2, print to logbook)
- Laser BSA1mm, ~3 ps rms, 10-30 pulses, try to have a good profile on VC2
- Gun 5.8 MeV/c, set RF reflection to ~3% reflection
- LEDA scan, set gun phase to MMMG (emission field ~35 MV/m for gun4)
  - Use low charge <5 pC
  - if you want to measure thermal emittance off the cathode center, set phase to MMMG-9 degree
- Find beam on high1.scr1, LYSO screen (use ‘LV gradient’ color mode in VC)
  - If later high1.scr2 is later used for thermal emittance measurement, set it to high1.scr2
  - Camera has to be very close to view port for high signal



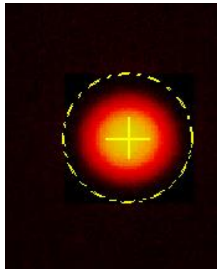
Beam with LV
color mode

Procedure for measuring thermal emittance

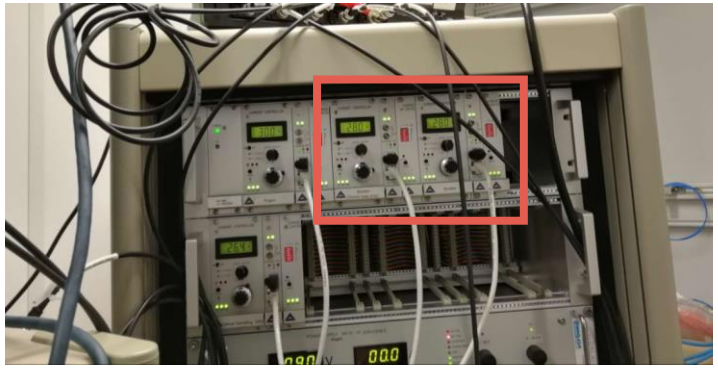
For gun4

- Setup up bunch charge to <0.1 pC
  - Low.FC1 can’t measure 0.1 pC directly
  - Tune down the pump current to have smaller charge. (~20 A)
  - Measure charge Q (by FC1) vs sum of pixel intensity (by high1.scr1 LYSO), start from 2 pC beam
  - Scale from sum of pixel intensity to find 0.1 pC, 0.05 pC
    - 10 pulses, ~3 points from 2 pC to 1 pC (Q vs sum of pixel)
    - Scale it to 0.1 pC and 0.05 pC
  - Set up ~0.1 pC, 30 pulses for later measurements

EMSY1 lyso



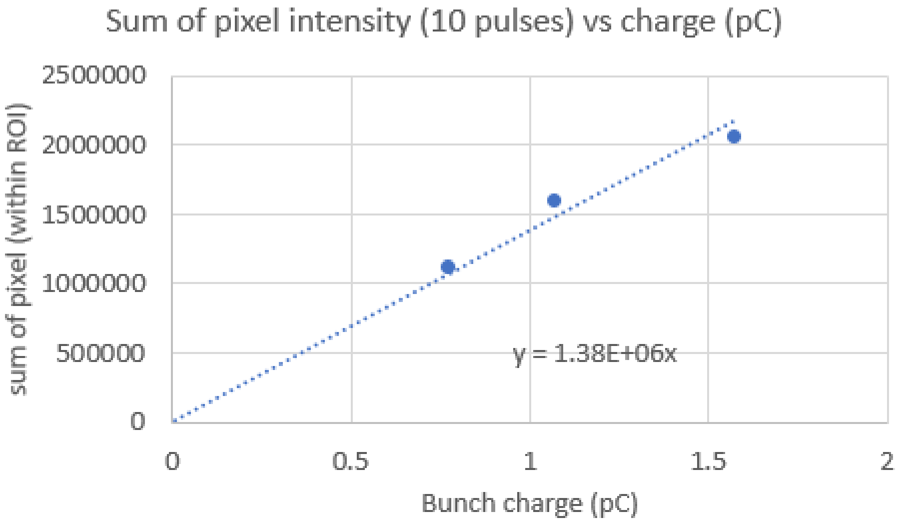
Beam with LV
color mode



Laser pump current reduce from nominal value (>26 A) to ~20 A;

After the experiment, restore the nominal value for high charge operation.

Background subtracted

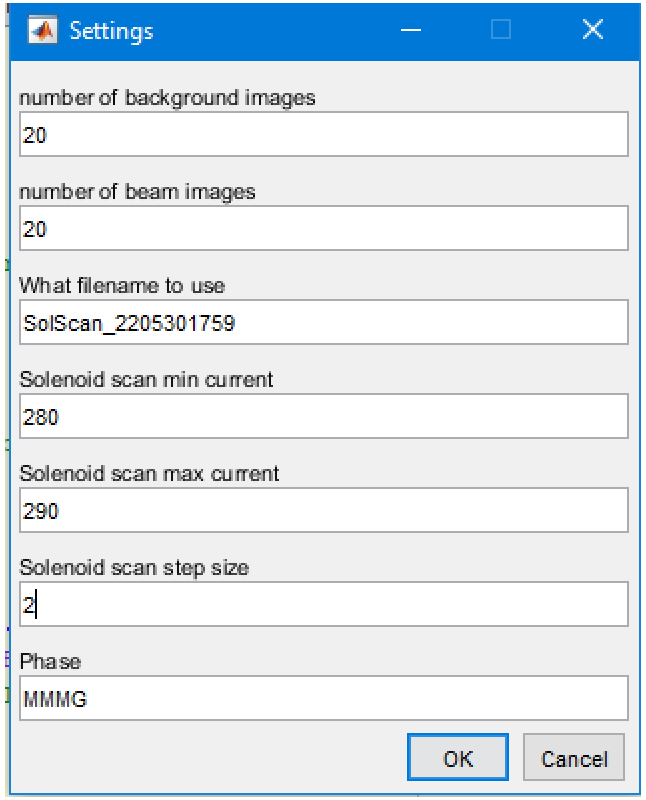


Procedure for measuring thermal emittance

For gun4

- Use gun quad optimizer to optimize beam symmetry on measurement screen
  - Set up solenoid to 288A (for MMMG)
  - Solenoid depends gun phase, screen location, and gun model (gun4/5)
  - Right table can be a reference, use it as a starting point
- Solenoid scan to find R11=0 (charge can be ~0.1 pC)
  - Script:\\win.desy.de\group\zn\4groups\zn_pitz\NFS\Measure\scripts\Development\Thermal_emittance\solenoid_scan_noVC2.m
  - Scan solenoid around the starting point solenoid current (+/-5 A or bigger)
    - The scan range can be bigger with 2 A step size for the 1st round
    - Then use 1 A step size for 2nd round with a smaller range when the solenoid values is found
    - Use M5/6 to move Laser by 0.5 mm (open in another matlab window)
    - Choose solenoid with minimum beam offset (<100 um)

w.r.t. MMMG	Pz (MeV/c)	Emission (MV/m)	sol (A)	M12 (m)
37	5.39	4.6	222	0.507
31	5.45	10.1	232	0.470
20	5.62	19.8	256	0.390
8	5.77	29.5	278	0.320
0	5.80	35.3	288	0.277
-9	5.75	41.0	289	0.251



number of background images: 20

number of beam images: 20

What filename to use: SolScan_2205301759

Solenoid scan min current: 280

Solenoid scan max current: 290

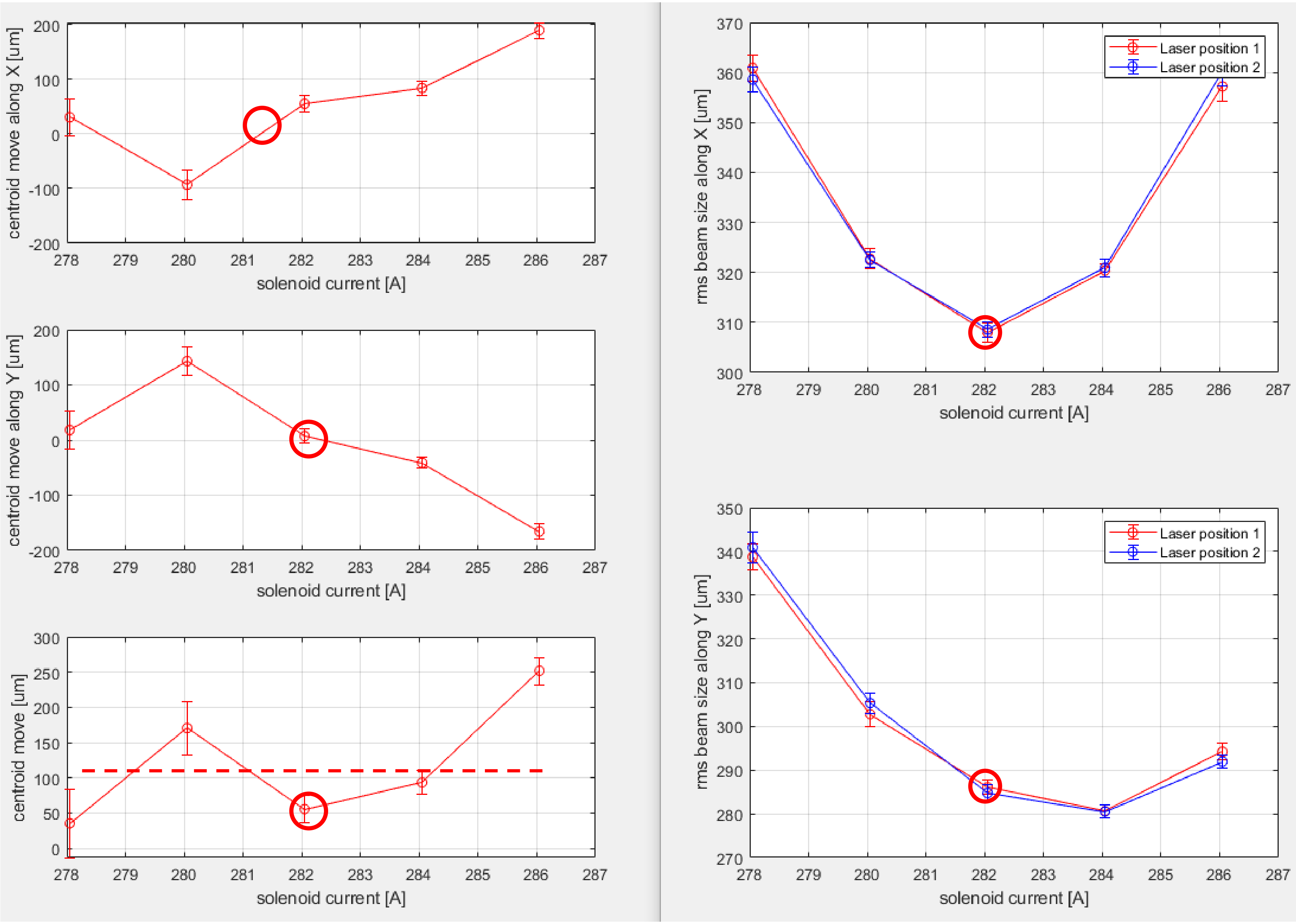
Solenoid scan step size: 2

Phase: MMMG

Solenoid scan output

Script:\\win.desy.de\group\zn\4groups\zn_pitz\NFS\Measure\scripts\Development\Thermal_emittance\solenoid_scan_results.m   can reload the old data

Scan data saved to transverse emittance folder:
e.g. folder name …\02A_thermal

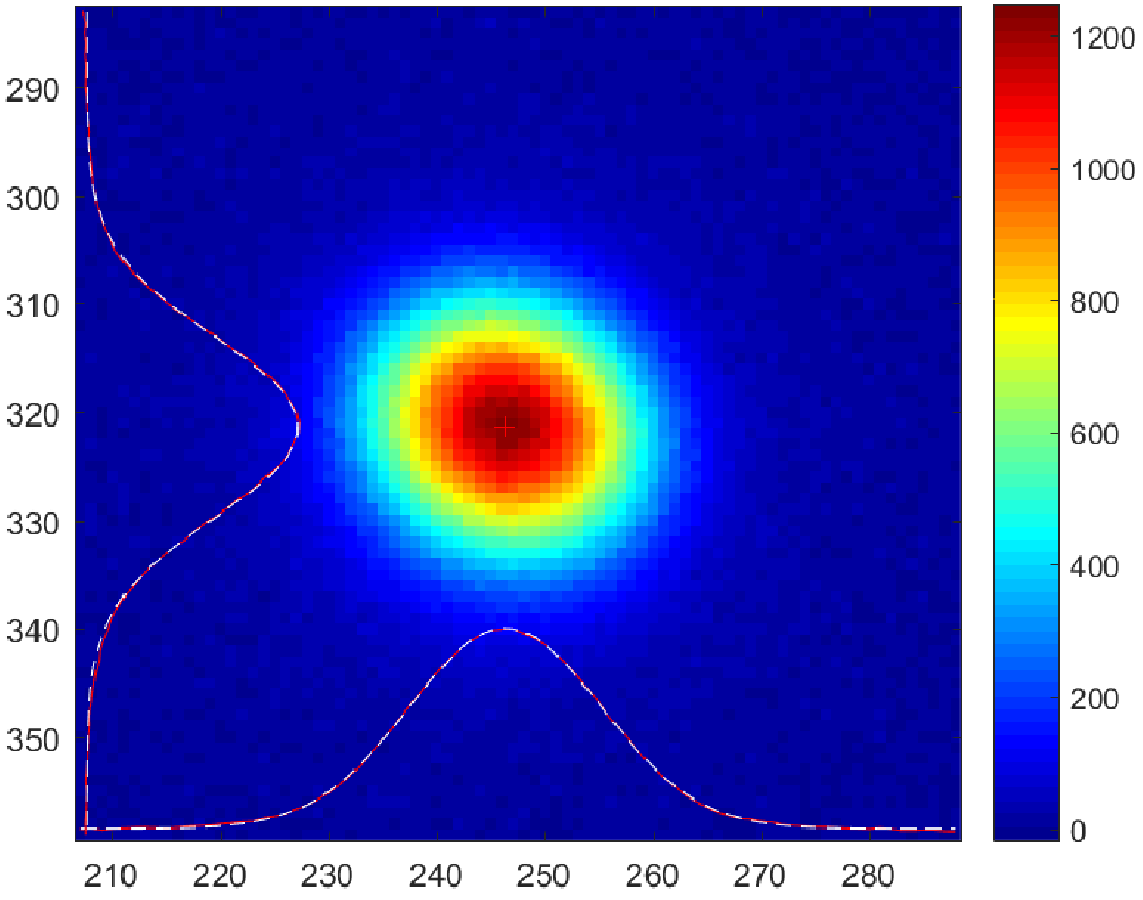


Take thermal moementum imaging at R11=0 solenoid current

\\win.desy.de\group\zn\4groups\zn_pitz\NFS\Measure\scripts\Development\Thermal_emittance\save_images.m

- Typically use 0.1 pC, 30 pulses, lyso screen with camera close to view port
  - If signal not enough (sum of pixel >300000), use more pulses
- Script will take images and provide beam size in the output of matlab
- XY_rms (mm)/M12(m) equals thermal emittance (mm.mrad/mm)
  - E.g. XY_rms=0.298 mm
  - M12=0.28 m
  - → 1.07 mm.mrad/mm
- Save data to the same folder for solenoid scan
- Script to reload the data
  - \\win.desy.de\group\zn\4groups\zn_pitz\NFS\Measure\scripts\Development\Thermal_emittance\save_images_results.m

~1.07 mm.mrad/mm (298 um rms)



Confirm thermal momentum imaging

- Space charge effect
  - Reduce charge to 0.05 pC, use more pulses to get the similar intensity
  - Measure the beam size again by script save_images.m
  - Beams size should be similar, otherwise space charge effect is still not negligible
  - For 5.8 MeV/c, MMMG, ~0.1 pC or lower is enough
  - For lower emission field, check it vs bunch charge
- BSA effect
  - Change BSA from 1 mm to 1.5 mm
  - Keep the same bunch charge with negligible effect
  - Keep the similar sum of pixel intensity by adjusting number of laser pulses
  - Measure the beam size again
  - If the solenoid is close to thermal momentum imaging, the beam size is not dependent on laser size