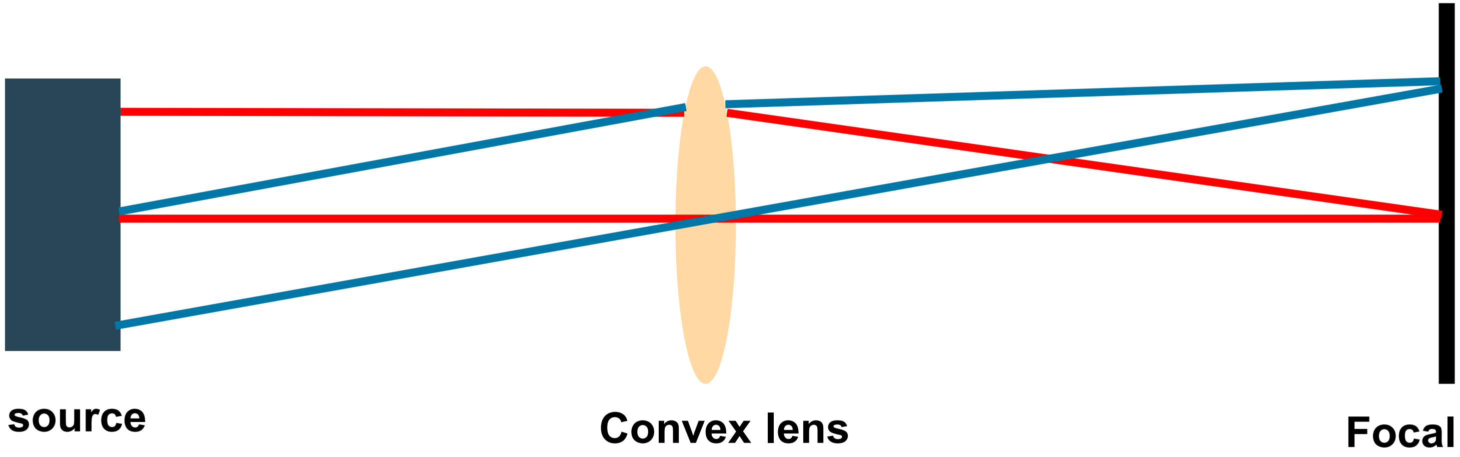
Single shot thermal momentum imaging: updated

Peng-Wei Huang, Zeuthen, 5. December

Imaging the momentum on the screen

Basic idea



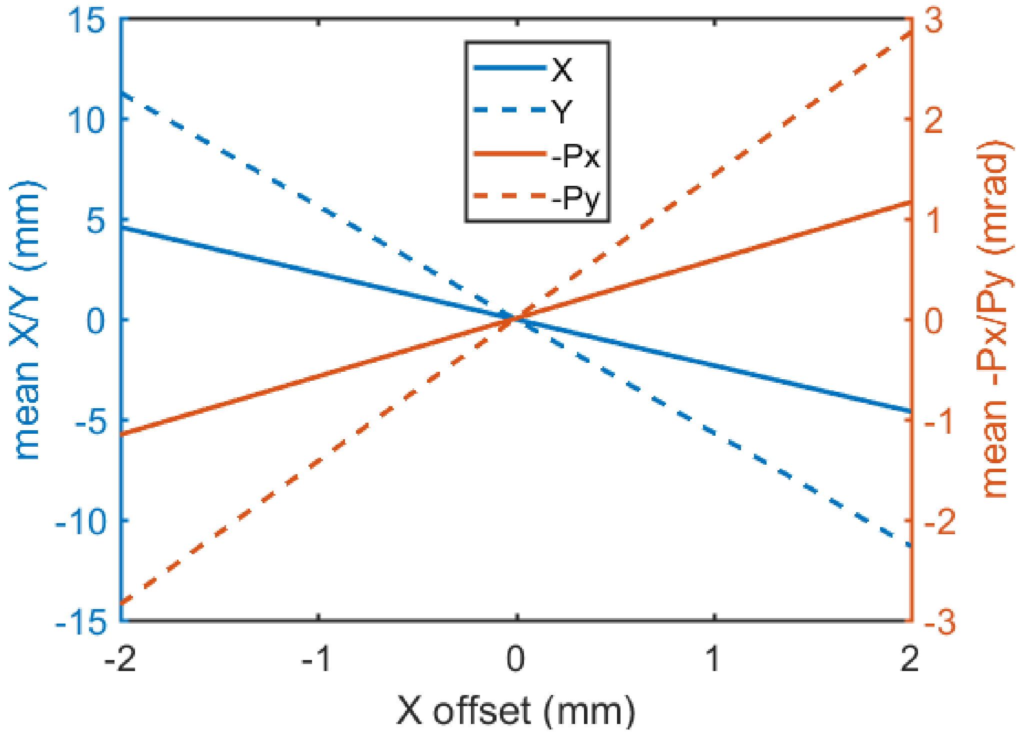
$$\begin{pmatrix} x \\ \frac{p_x}{m_0 c} \end{pmatrix} = \begin{bmatrix} 0 & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{pmatrix} x_0 \\ \frac{p_{x0}}{m_0 c} \end{pmatrix}$$

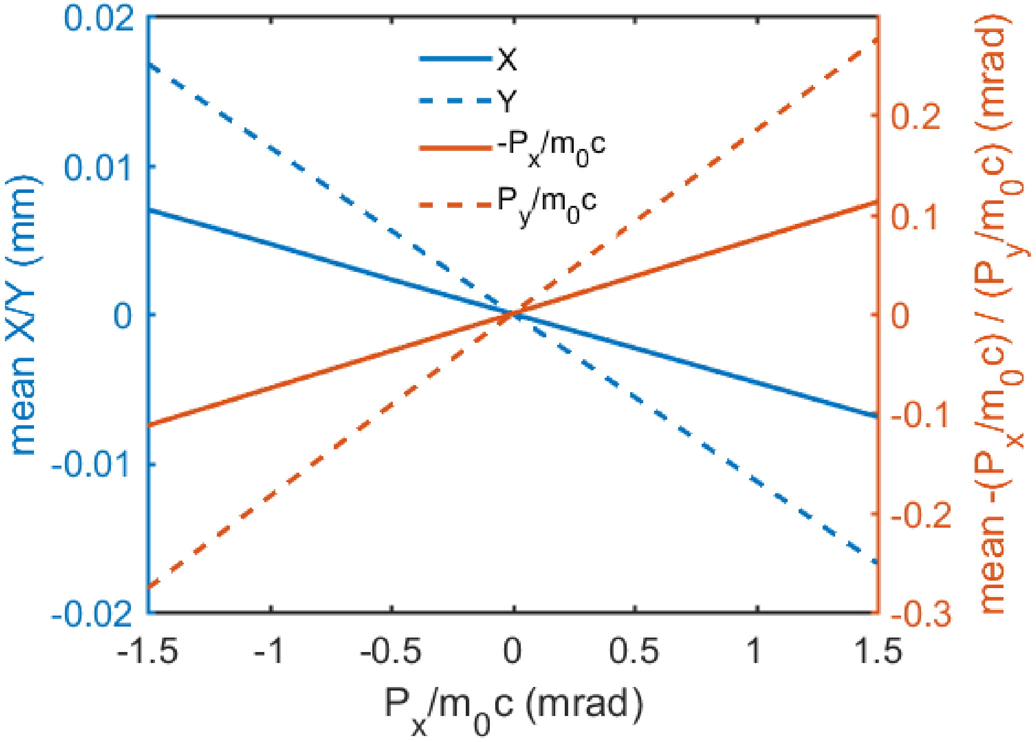
- ➢ A transport matrix exists
- ➢ M11 can be zero by tuning the solenoid.

The linearity of electrons

A transport matrix exists only when the dynamics is all linear with position and divergence. The ideal field of RF gun, solenoid and quadrupole plus paraxial assumption can satisfy this requirement.

Simulation proof: The linearity is preserved for the ideal field of PITZ gun, so a matrix exists.


Initial horizontal offset


Initial horizontal divergence offset

How to determine the matrix

Matrix comes from astra simulation.

$$x_0' = \frac{p_{x0}}{m_0 c} \qquad y_0' = \frac{p_{y0}}{m_0 c}$$

$$M = \begin{pmatrix} \frac{dx}{dx_0} & \frac{dx}{dx_0'} & \frac{dx}{dy_0} & \frac{dx}{dy_0'} \\ & \cdots & \cdots & \\ \frac{dy}{dx_0} & \frac{dy}{dx_0'} & \frac{dy}{dy_0} & \frac{dy}{dy_0'} \\ & \cdots & \cdots & \end{pmatrix}$$

$$x = M_{11}x_0 + M_{12}x_0' + M_{13}y_0 + M_{14}y_0'$$

We believe all the cross terms should be zero at the cathode.

$$\begin{aligned} \langle x^2 \rangle &= M_{11}^2\langle x_0^2\rangle + M_{12}^2\langle x_0'\rangle + M_{13}^2\langle y_0^2\rangle + M_{14}^2\langle y_0'\rangle \\ &= (M_{11}^2 + M_{13}^2)\langle x_0^2\rangle + (M_{12}^2 + M_{14}^2)\langle x_0'^2\rangle \\ &= (M_{11}^*)^2\langle x_0^2\rangle + (M_{12}^*)^2\langle x_0'^2\rangle \end{aligned}$$

The corresponding emittance: $\varepsilon = \sqrt{\langle x_0^2\rangle\langle x_0'^2\rangle}$

- When the M_{11}^* is zero, that is the situation for **thermal momentum imaging**.

$$\frac{\boldsymbol{\varepsilon_0}}{\boldsymbol{\sigma_{x_0}}} = \frac{\boldsymbol{\sigma_x(L)}}{\boldsymbol{M_{12}^*}}$$

- When the M_{11}^* is not restricted to zero and data on different solenoid current (means different M_{11}^* and M_{12}^*) and beam size are collected, emittance can be obtained by fitting and then linear fit against beam size to determine the thermal emittance. That is **solenoid scan**.

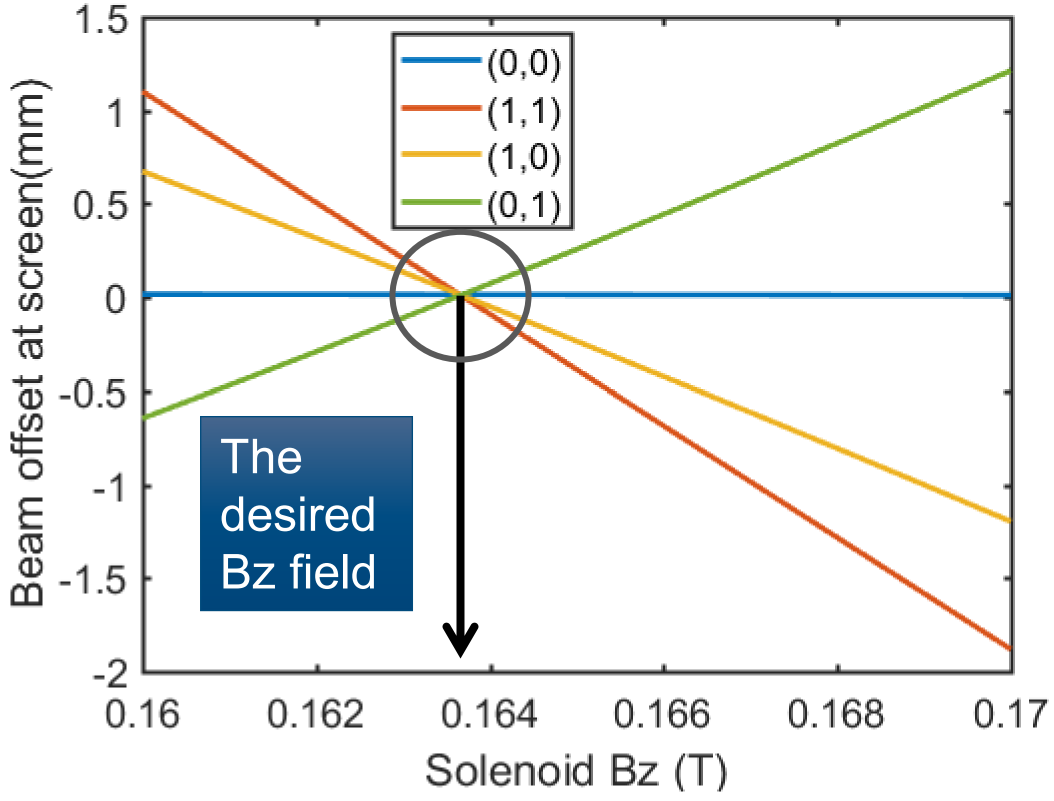
The simulation proof of thermal momentum imaging

$M_{11}, M_{13}=0$

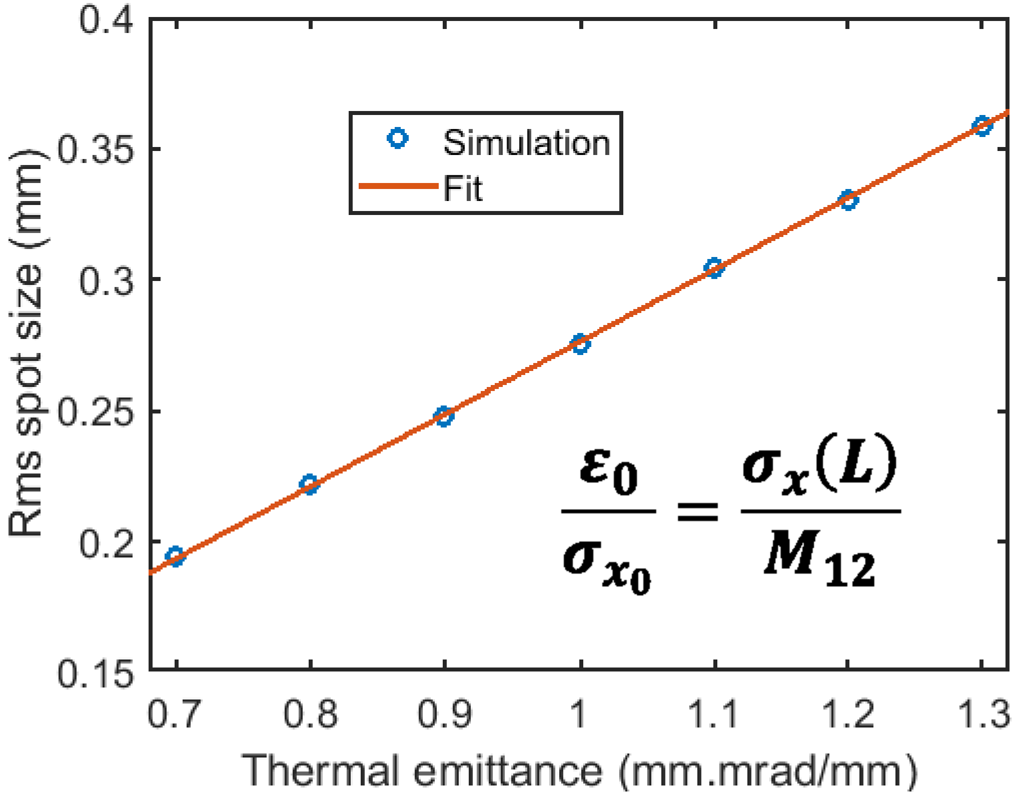
↓

The position at the observed screen should irrelevant to the initial point. This can be achieved by a proper solenoid setting.

With proper solenoid field setting, the simulation shows the beam size at the observed screen is linear with the predetermined thermal emittance of the input electron file.



The desired Bz field

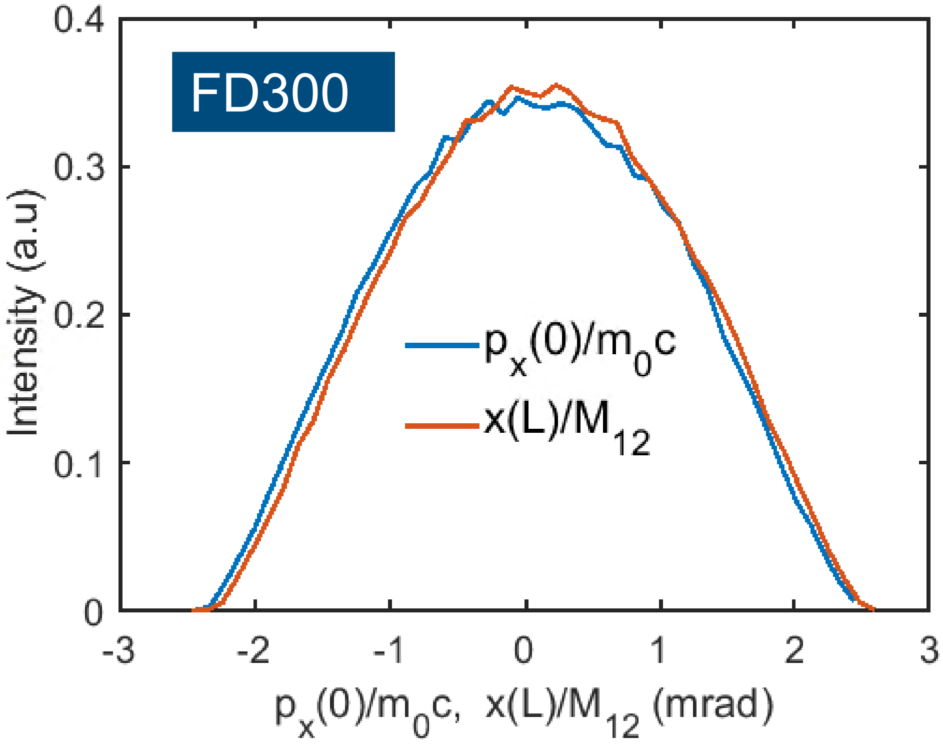


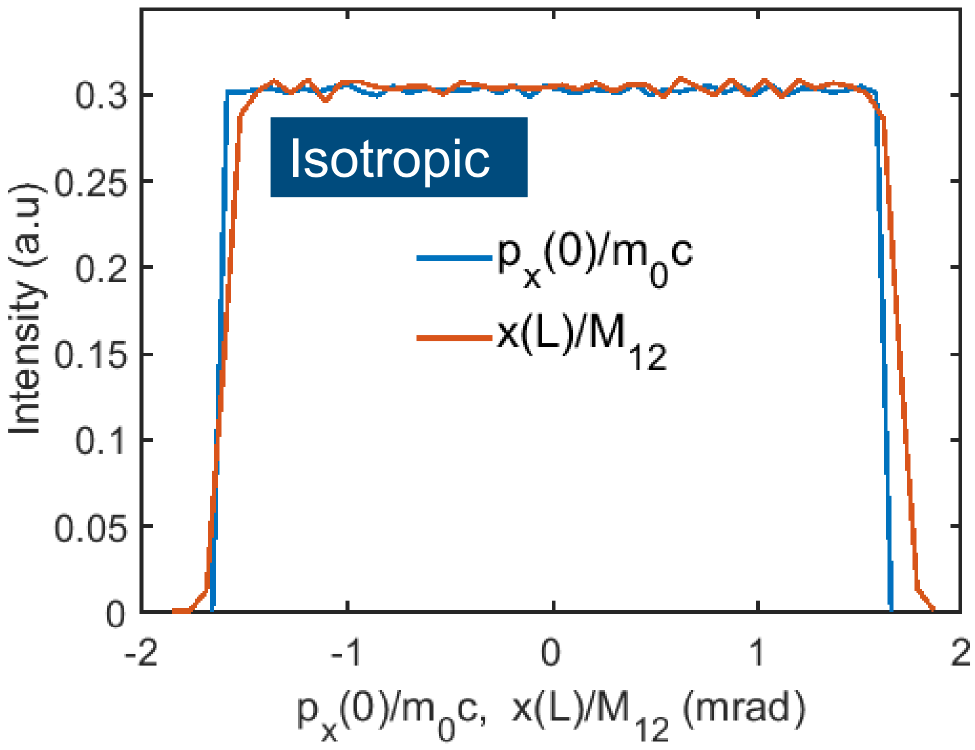
$$\frac{\varepsilon_0}{\sigma_{x_0}} = \frac{\sigma_x(L)}{M_{12}}$$

The simulation proof of momentum imaging

$$F_{p_x}\left(\frac{p_x}{m_0 c}, 0\right) = F_x\left(\frac{x}{M_{12}}, L\right)$$

In principle, the distribution in real space at the observed screen should be the imaging of momentum space at the cathode. The simulation shows the beam transverse distribution is consistent with the initial momentum under two different emission model, FD300 (typical for metal) and isotropic (used for Cs_2Te).





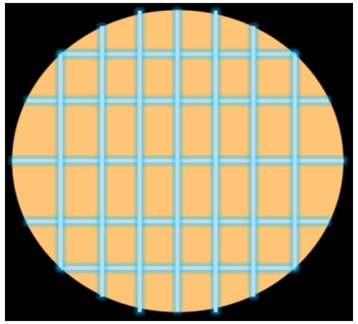
Application

- In principle, we can obtain the information about the initial momentum by analyze the spot on the screen placed at L **with one shot**. The rms divergence $\sigma_{x_0'}$ can be easily calculated through $\sigma_x(L)/M_{12}$. So the thermal emittance is

$$\frac{\varepsilon_{0,rms}}{\sigma_{x_0}} = \sigma_{x_0'} = \frac{\sigma_x(L)}{M_{12}}$$

- Thermal emittance **VS** Positions – Thermal emittance mapping

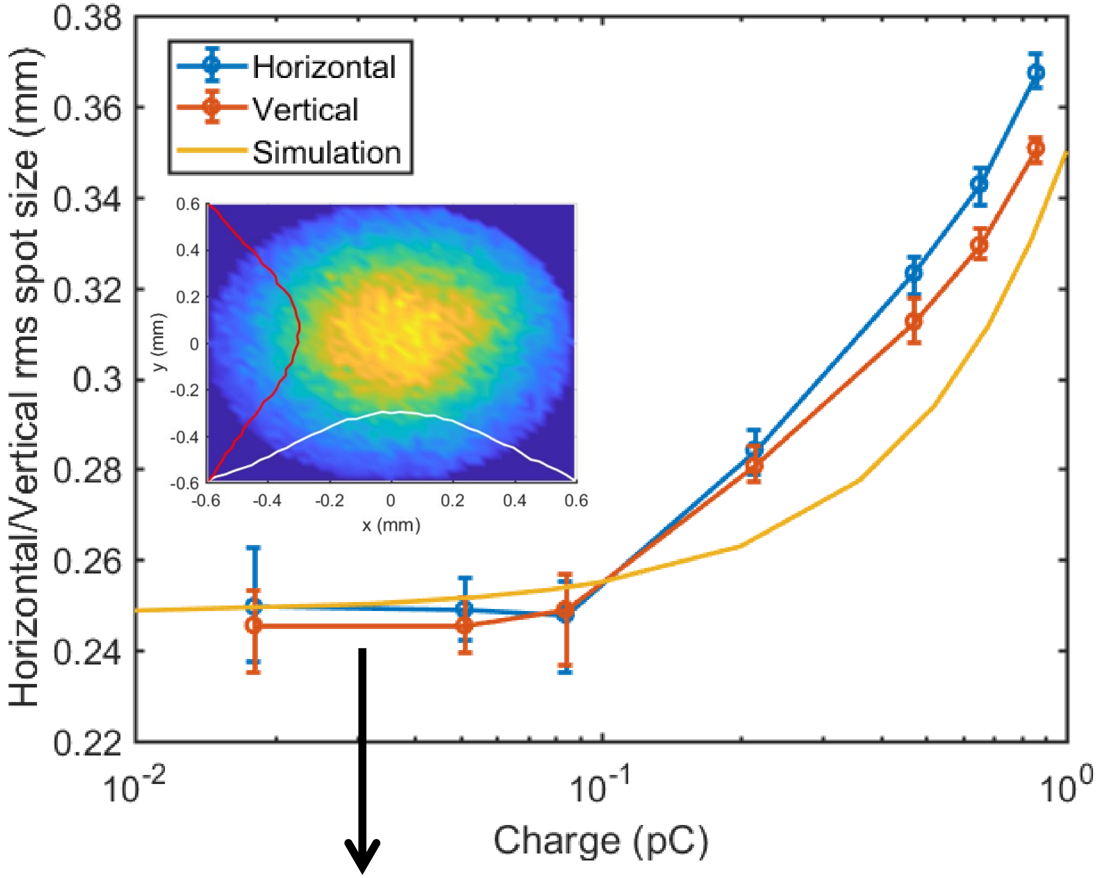
It is possible to combine with QE map to figure out their correlation without the interference of slightly different deposition among samples.



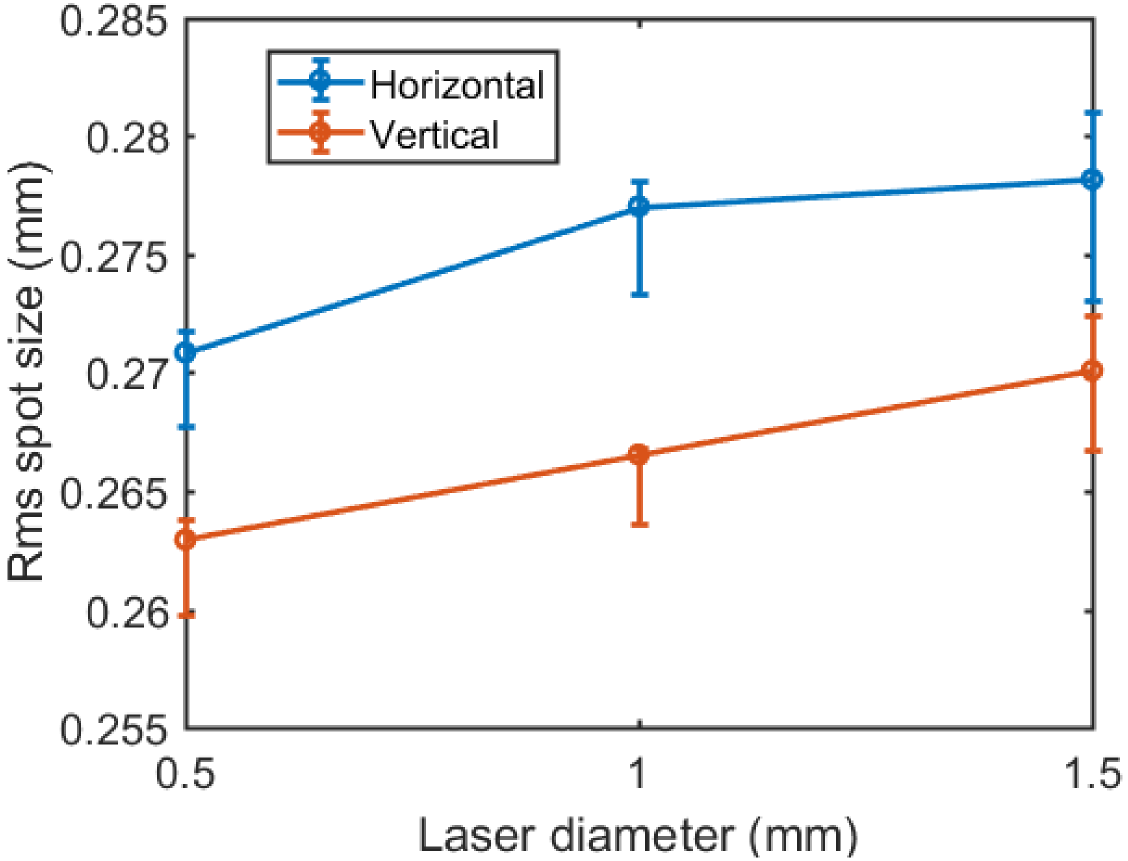
- Thermal emittance **VS** Electric field

It may provide a reference to the design of high brightness photoinjectors.

Experiment – Space charge and BSA



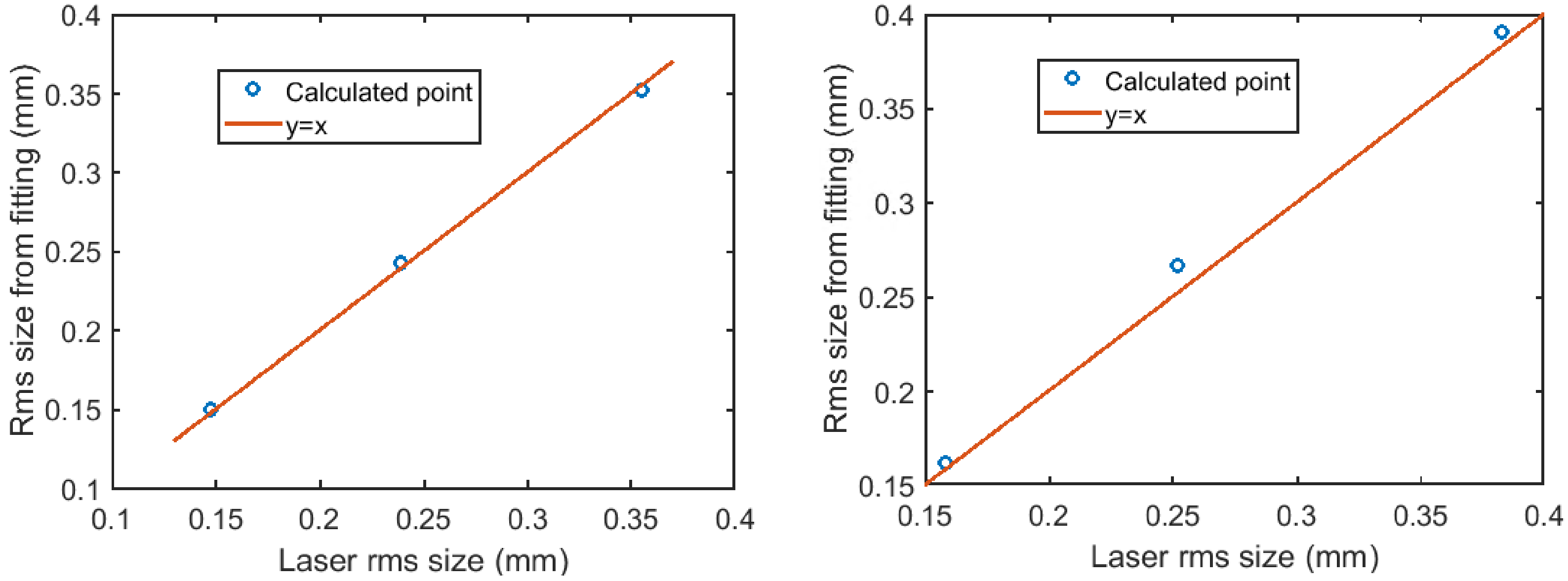
The space charge effect has negligible influence on the bunch size at screen under **0.1 pC**.

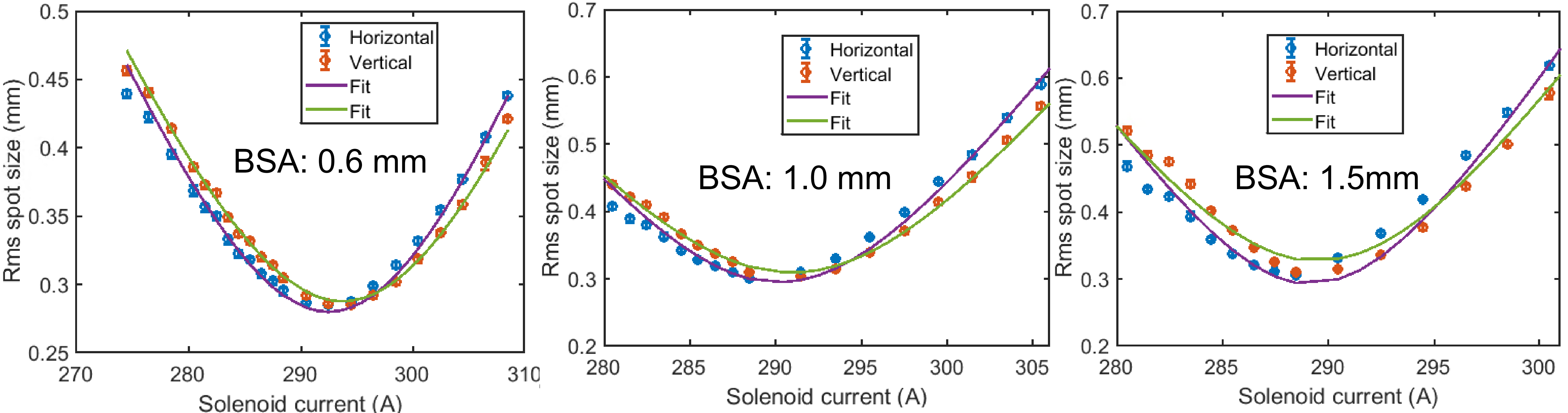


The beam size is not related to the laser diameter. It is a support to real thermal momentum imaging.

Solenoid scan measurement

The rms size from fitting is consistent to the size of laser image, a support to the reliability of our measurement and data processing.



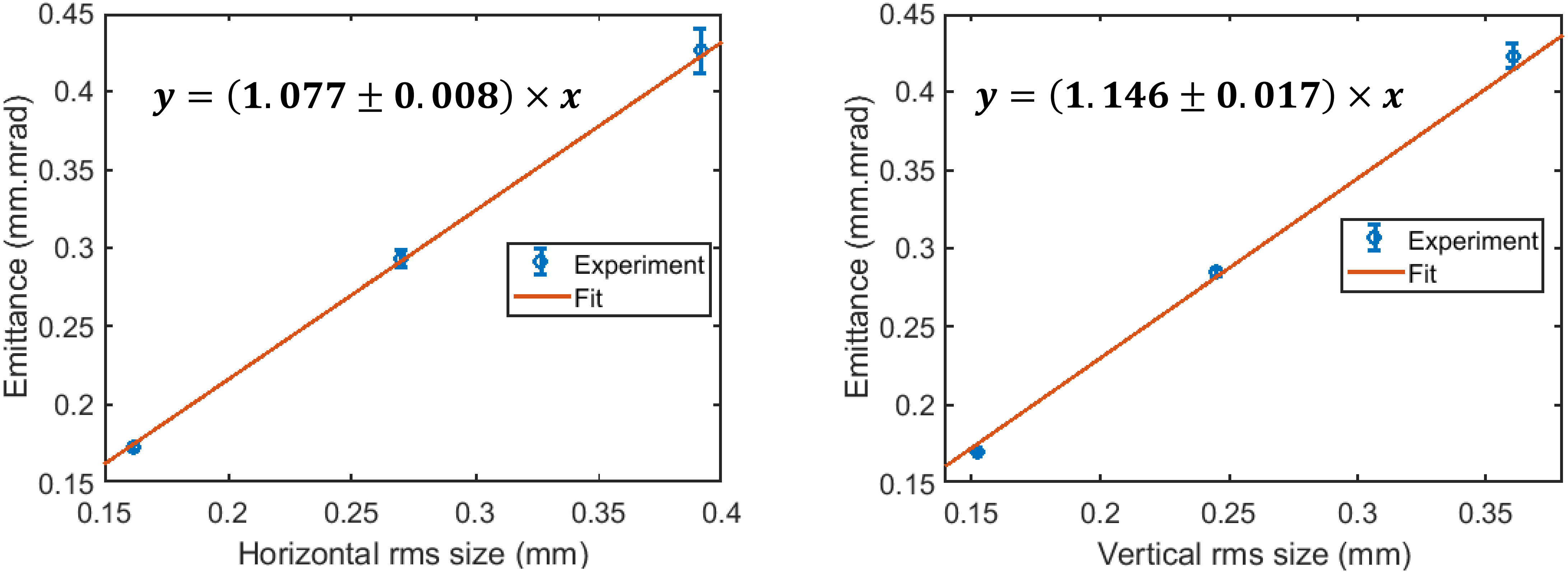


Cross check between two methods

As a comparison, the thermal momentum imaging gives the results:
Horizontal : $\mathbf{1.084 \pm 0.007}$ Vertical : $\mathbf{1.118 \pm 0.009}$

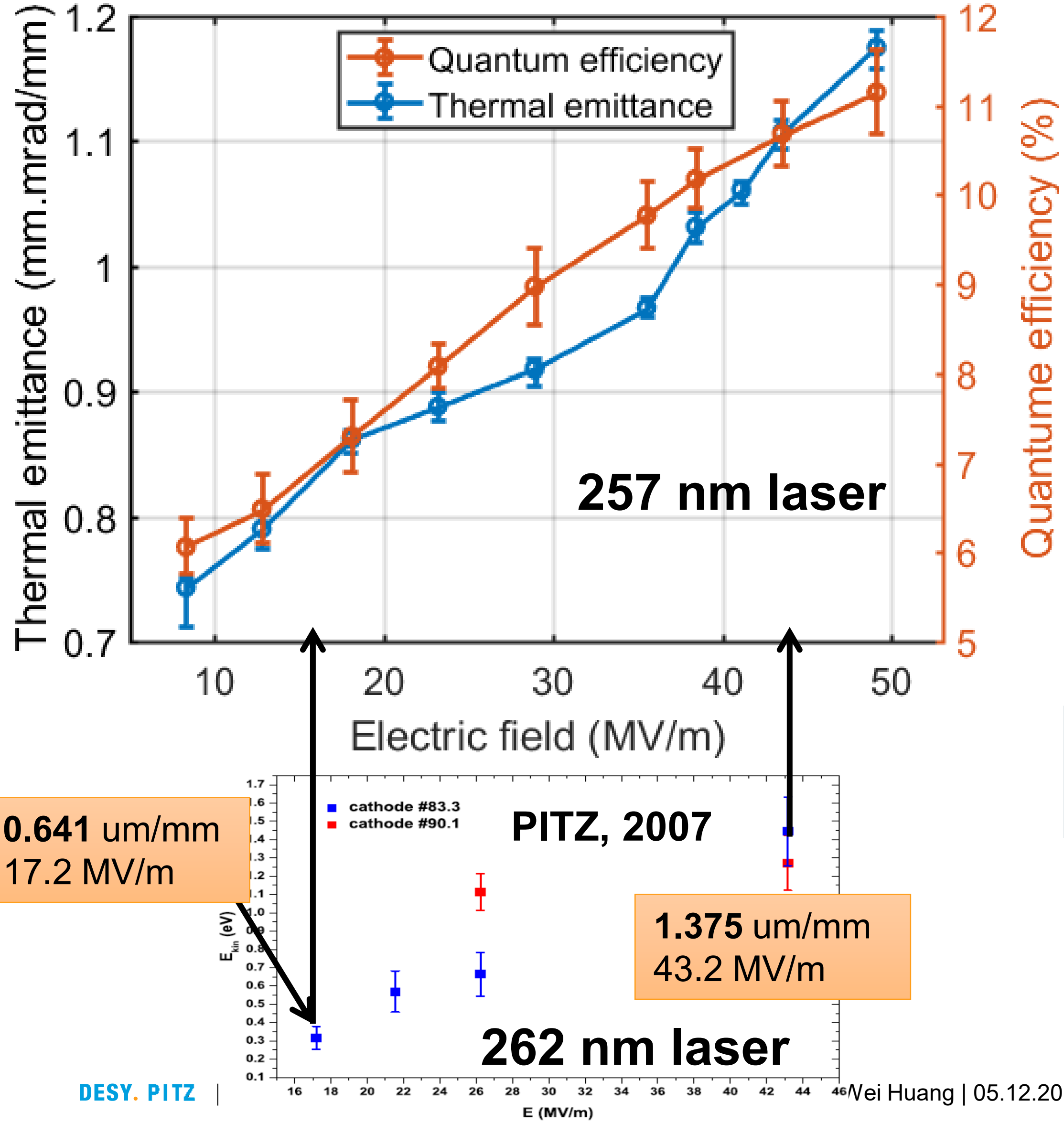
The cross check is successful. The results from thermal momentum imaging turn out to be convincing.

The asymmetry between x and y may be due to the gun quadrupole effect.



Experiment – Electric field and thermal emittance

Large electric field lead to large emittance



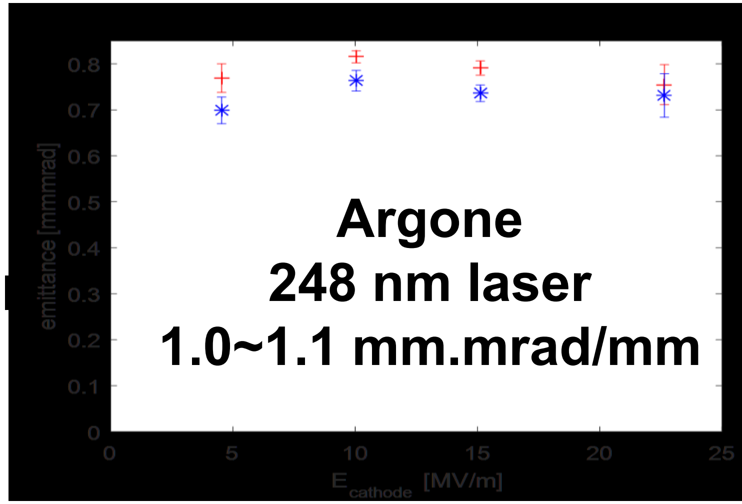
0.641 um/mm
17.2 MV/m

1.375 um/mm
43.2 MV/m

The thermal emittance increase dramatically with electric filed.

- ❖ Schottky effect
- ❖ Surface roughness

As a comparison, Cs2Te in Argone shows an insensitive relation with electric field. PSI manage to obtain a low thermal emittance 0.549 mm.mrad/mm at very high field.



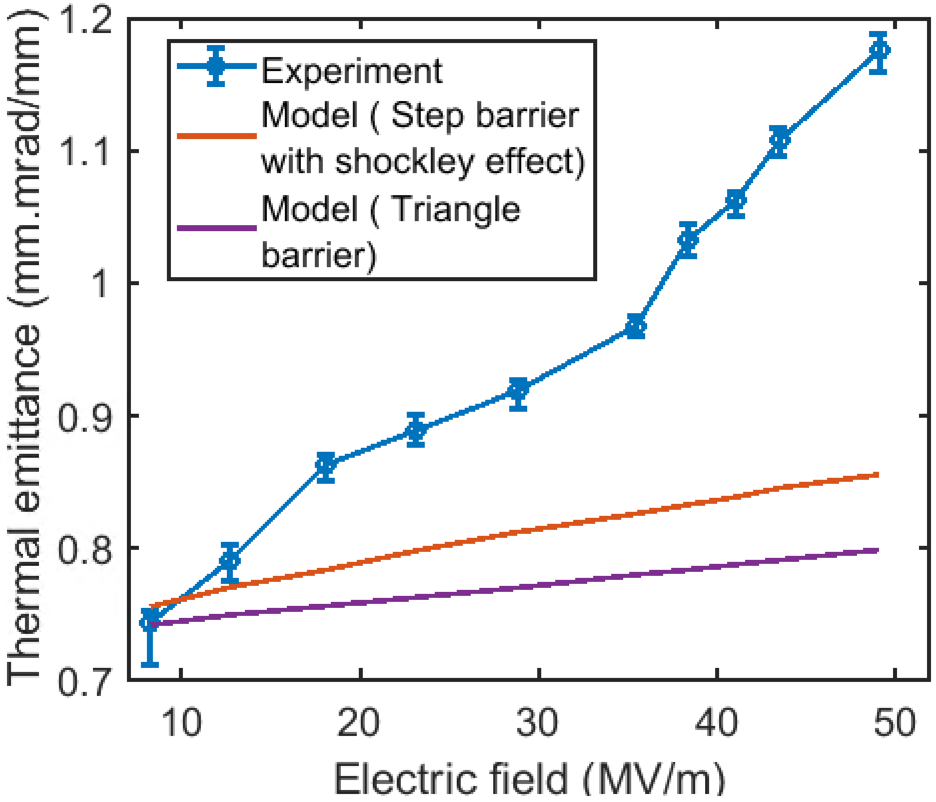
Argone
248 nm laser
1.0~1.1 mm.mrad/mm

The fabrication process has a dramatic effect on the cathodes' performance.

PSI

Label	Material	Meas. day	Norm. thermal emittance [nm/mm]	Laser wavelength [nm]	Field on the cathode [MV/m]
13	Cs_2Te	28-10-2013	713±88	262.0	49.9
8	Cs_2Te	04-04-2014	549±29	262.0	49.9

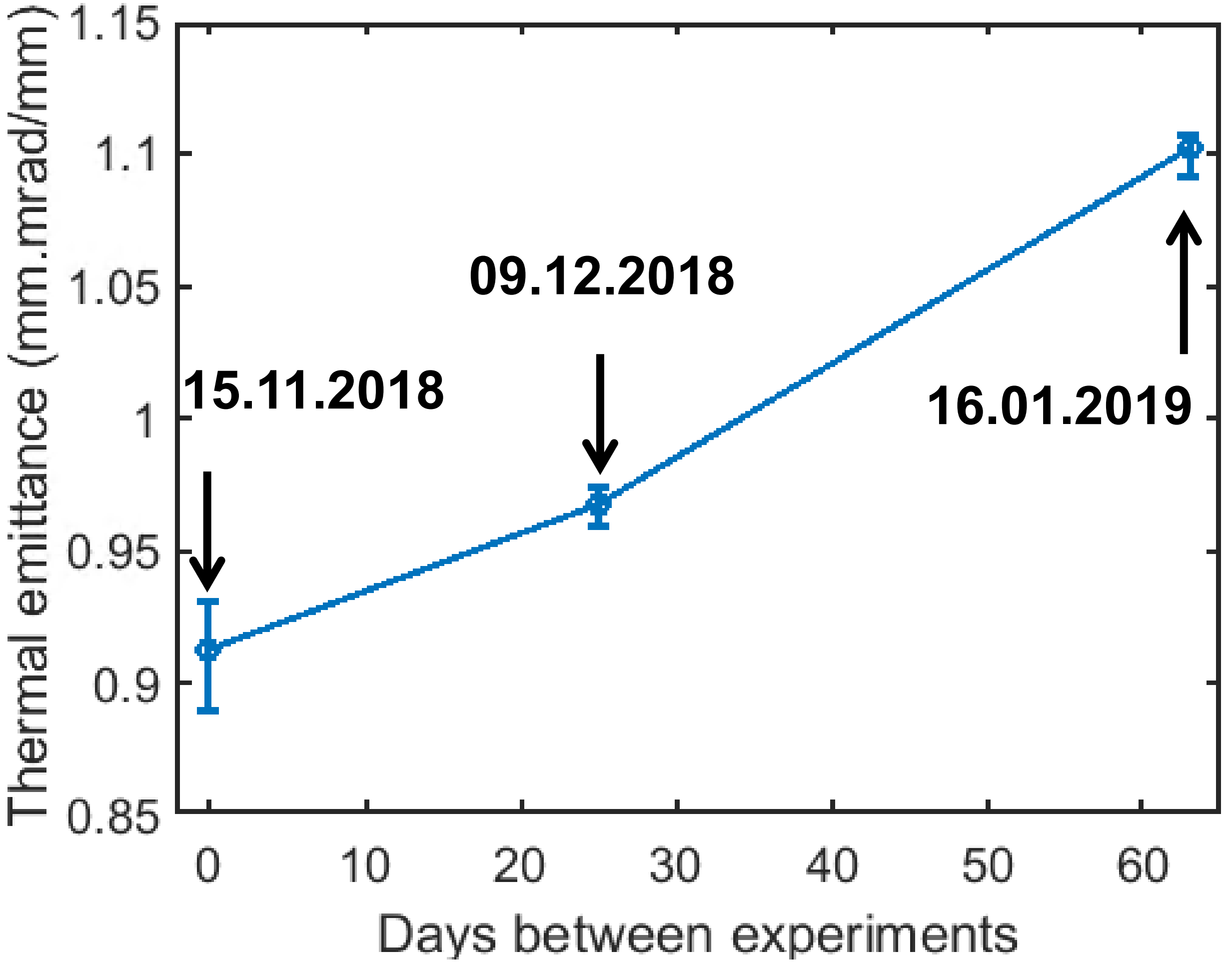
Comparison between experiment and model prediction



The model can not explain the large change of thermal emittance against electric field. The model have considered the effect brought by the penetration of electric field. But the surface roughness has not been considered maybe it is the reason resulting in such dramatic growth.

Long term evolution of thermal emittance

The thermal emittance has a significant growth



- After the first 24 days, the thermal emittance has grown by 6 %.
- After another 38 days, the thermal emittance grows by 14%, totally 20.9% growth compared with the very beginning value.

The thermal emittance has a significant growth while the QE is almost the same

Residue gases?
Ion back bombardment?
Surface break down?
……
The surface might need to be checked to explore the reason.

Future plan

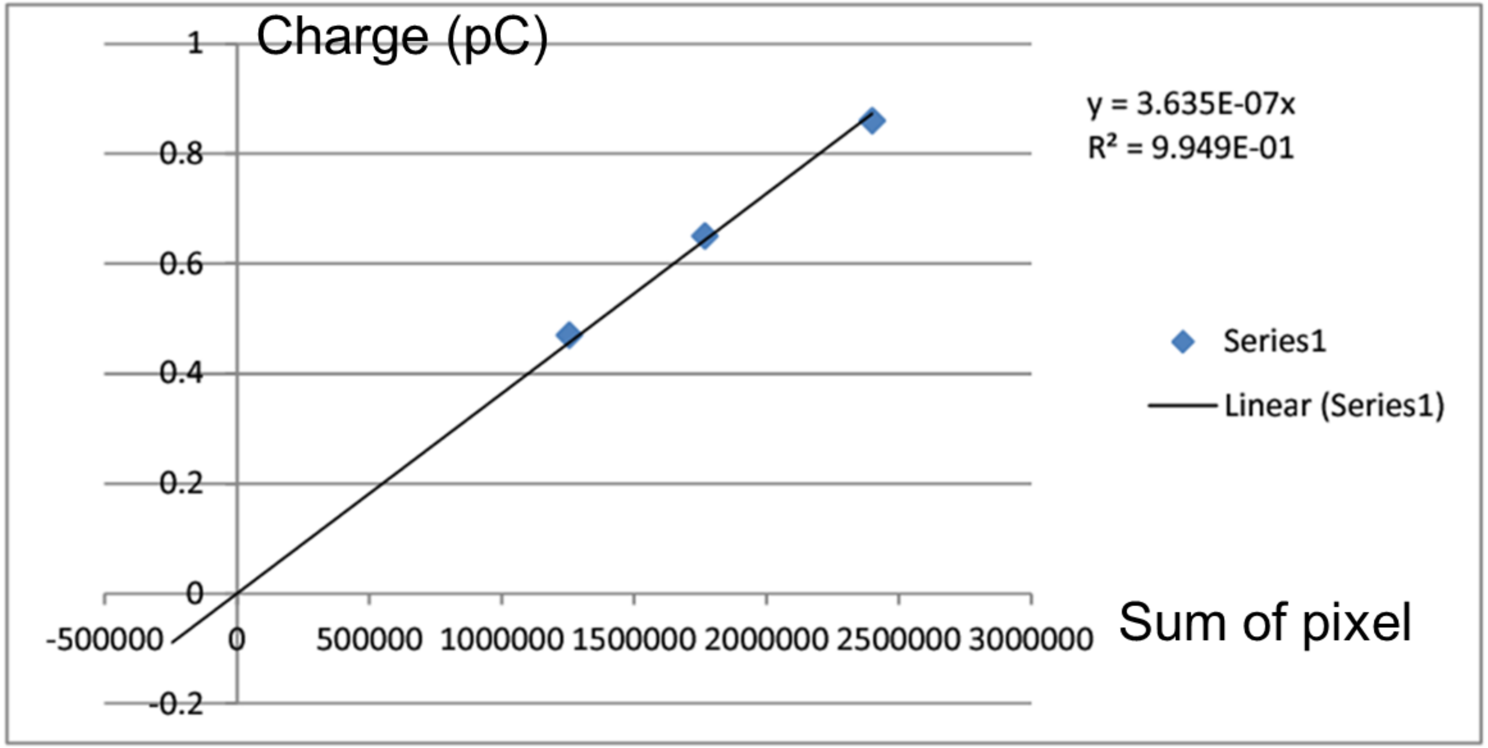
- Experiments on thermal momentum imaging with different RF power but the same surface electric field by tuning the phase. It would be another good way test the validity of the method and also the RF effect on the method.
- Thermal emittance map with a finer resolution (i.e. smaller BSA 0.5 mm).
- The evolution of thermal emittance in the pulse train study
- Long term track of thermal emittance evolution with time (over several months)

Thanks for your attention

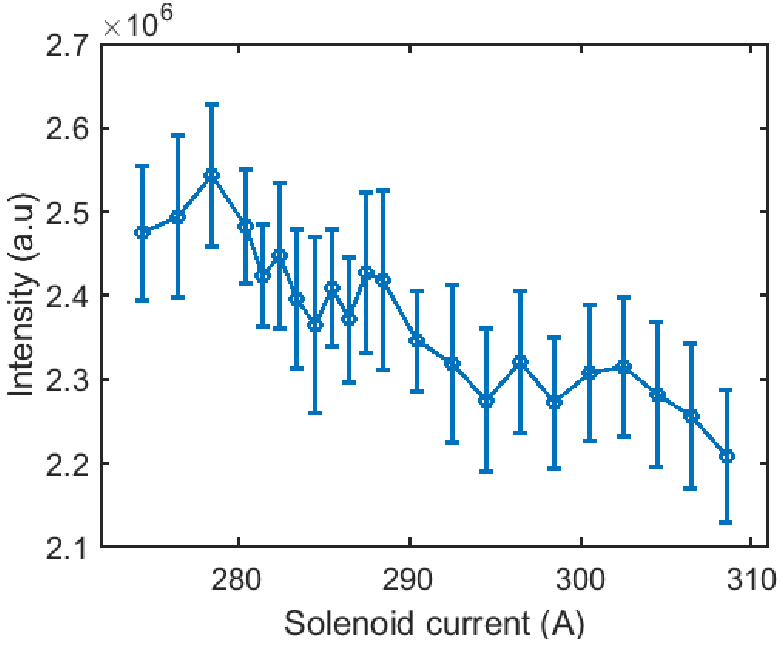
Back up slides

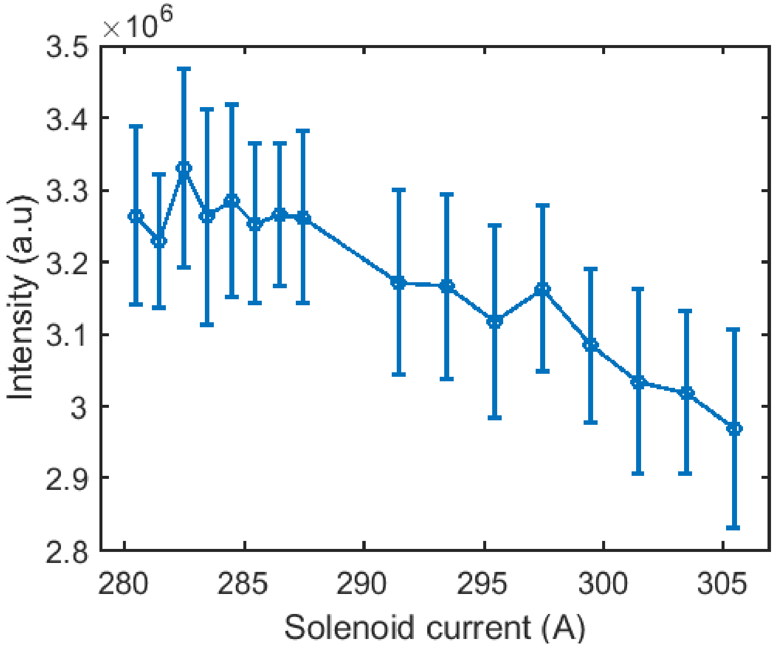
Sum of Pixel	Charge (pC)
2399883	0.86
1768532	0.65
1255767	0.47

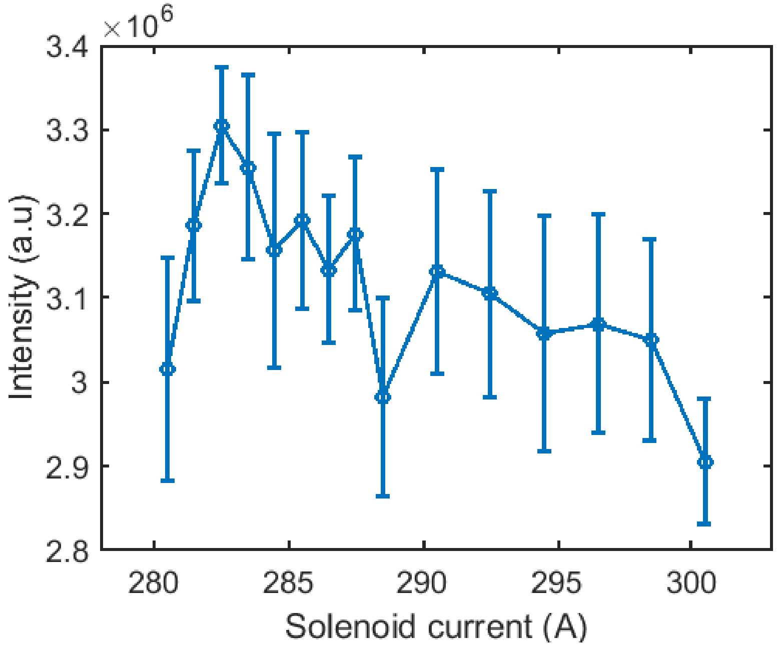
→ Measured by the Faraday cup



We use the sum of pixel of the signal to calibrate the electron charge, assuming they have linear relationship.


×10^6
2.7
2.6
2.5
2.4
2.3
2.2
2.1
Intensity (a.u)
280
290
300
310
Solenoid current (A)


×10^6
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
Intensity (a.u)
280
285
290
295
300
305
Solenoid current (A)


×10^6
3.4
3.3
3.2
3.1
3
2.9
2.8
Intensity (a.u)
280
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290
295
300
Solenoid current (A)