Low emittance electron beam transportation from photocathode DC gun

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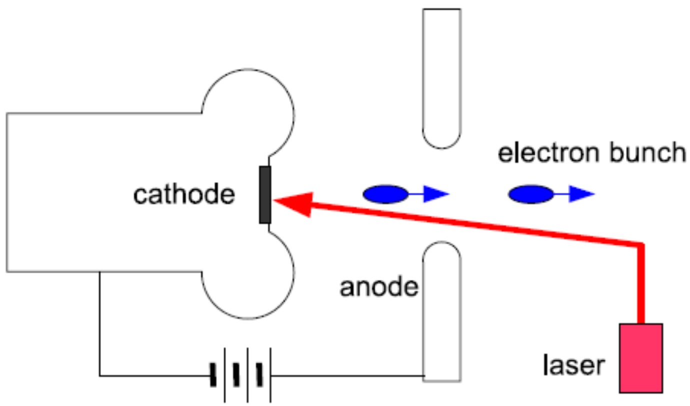
1. Introduction

- Photo cathode DC gun

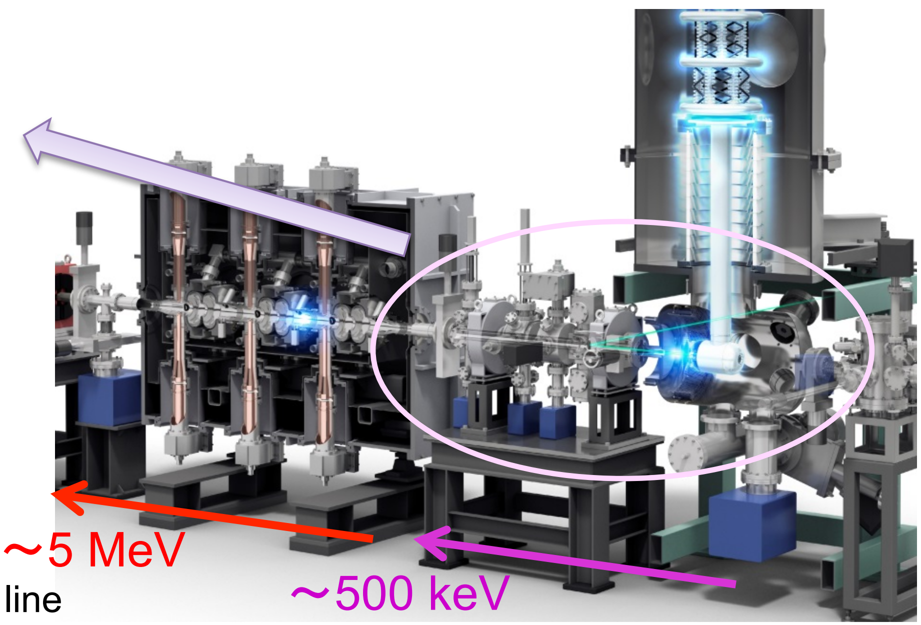


Property of electron beam from photo cathode DC gun

- Low emittance (∼0.1 mm mrad, normalized emittance)
- Short pulse length (few ps -)
- High bunch charge (∼77 pC/bunch)
- CW operation (∼ 1.3 GHz repetition rate)

Example: compact ERL (cERL) DC gun
Maximum beam energy: 500 keV ⇒ Space charge effect is dominant.

- To keep high quality, to understand beam optics from the gun is important.



compact ERL injector beam line

Motivation and Goal

- What dose affect beam optics around the gun?
  - Gun focusing effect due to transverse electric field
  - Initial condition of excitation laser (laser spot size, laser pulse width, laser power, …)
  - Focusing magnet (solenoid magnet)
  - Space charge effect (it depends on charge density)

- Motivation
  - To reproduce measured low emittance beam transportation from photo cathode DC gun by numerical model
  - Beam line: cERL injector beam line (Gun + solenoid magnets)

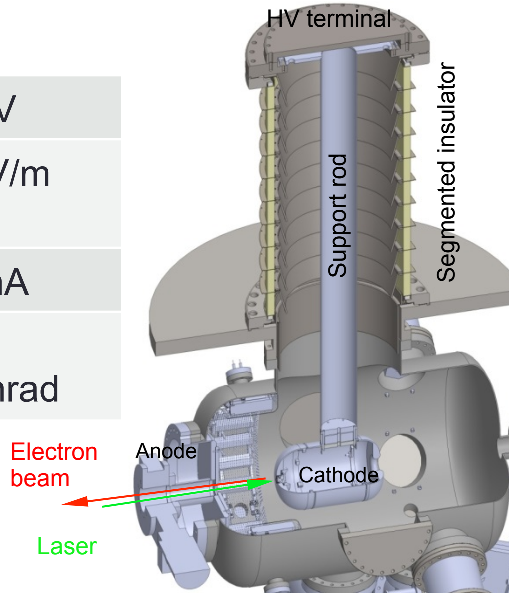
- Goal: to reproduce the following measurement results
  - Gun focusing effect (single particle model)
  - Beam profile without space charge effect (multi particle model)
  - Beam profile with space charge effect (multi particle model + SC effect)

2. Photo cathode DC gun in compact ERL (cERL)

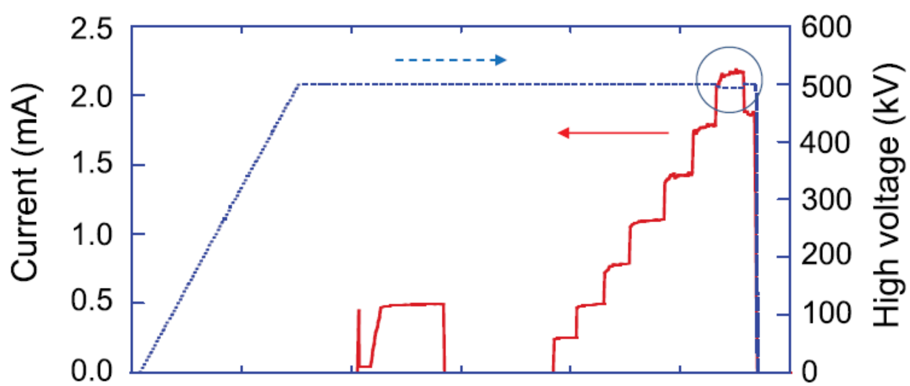
Photo cathode DC gun in cERL

Goals

High voltage	500 kV
Electric field on cathode	> 5MV/m
Beam current	100 mA
Normalized emittance	0.1-1 mm·mrad



Successful production of 500-keV, 1.8 mA beam



N. Nishimori et al., Appl. Phys. Lett. 102, 234103 (2013).

The cERL photocathode gun was developed by JAEA.

Performance at JAEA

- Successful production of 500-keV, 1.8-mA beams
- Electric field on cathode surface: 5.8 MV/m (@500 kV)

Performance at cERL

•Normalized emittance: 0.07 mm·mrad @10fC (at cERL, V=390 kV)

•Long term operation (~ 260 hours) at V=390 kV at cERL

Using this DC gun, we carried out experiments to measure the gun focusing and beam optics in the beam transportation line.

Bunch charge:

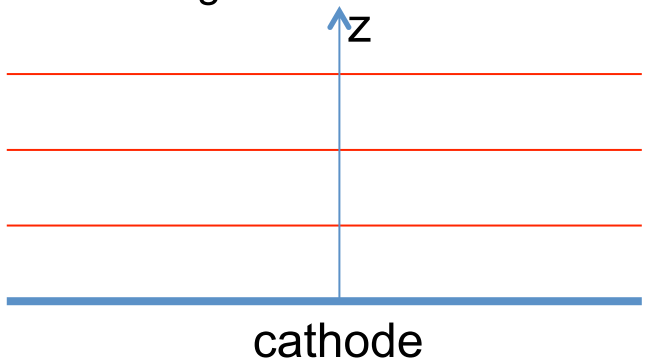
10 fC/bunch – 7.7 pC/bunch

3. How to adjust numerical model of gun focusing

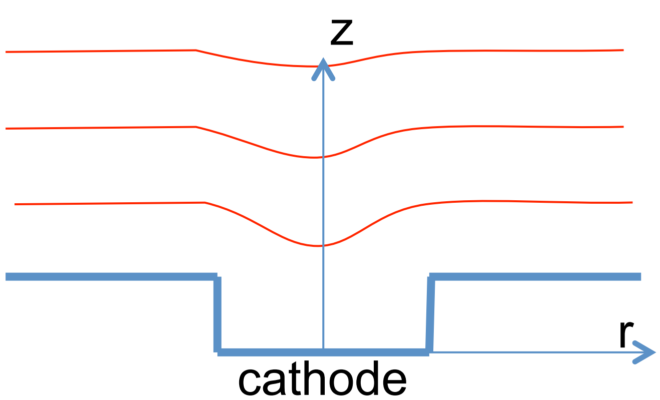
Focusing effect due to gun electric field

- Origin of gun focusing effect
  - Transverse electric field

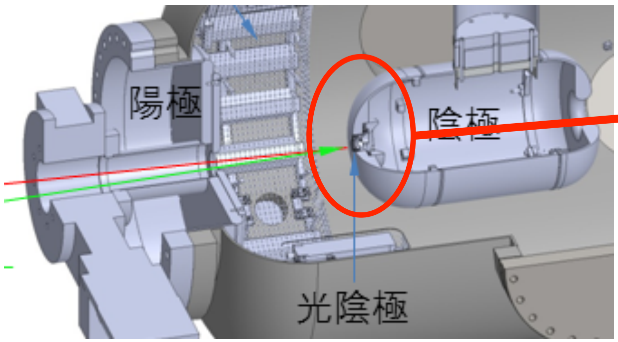
(1) Parallel plate cathode
Equipotential line is parallel to cathode surface.
Transverse electric field is zero.
No focusing effect.

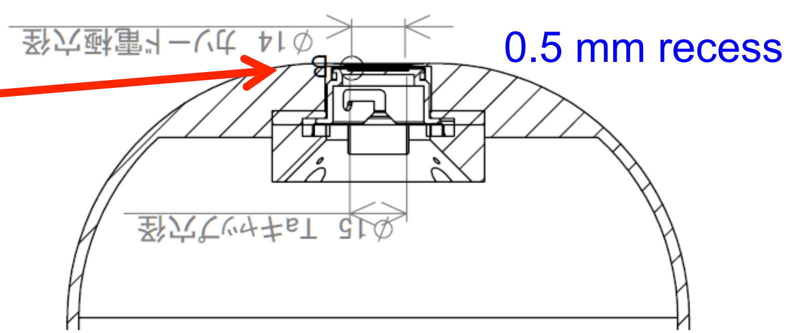


(2) Cathode with recess
Equipotential line is deformed around center.
Transverse electric field in non-zero.
It cause focusing effect.



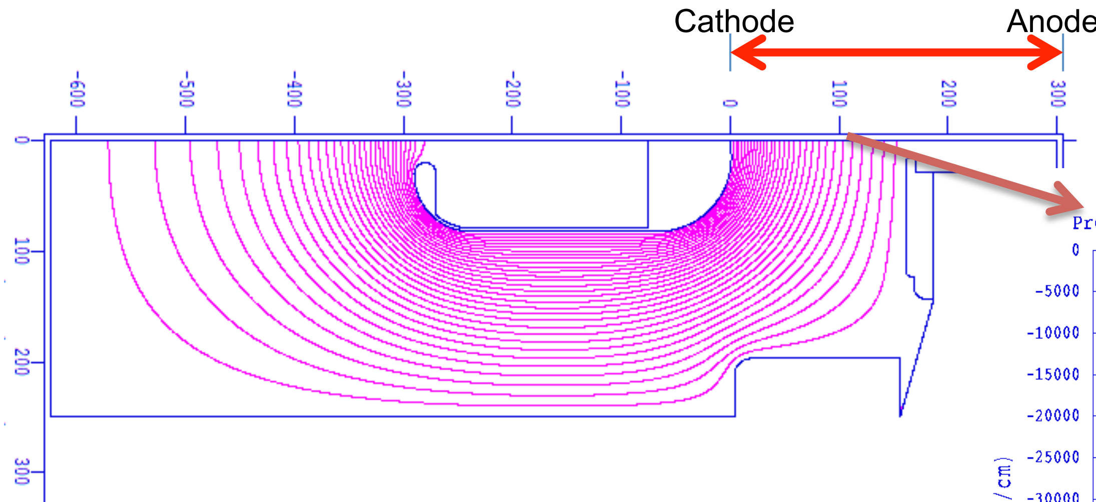
JAEA 500 kV photocathode DC gun
Cathode electrode has recess around center.



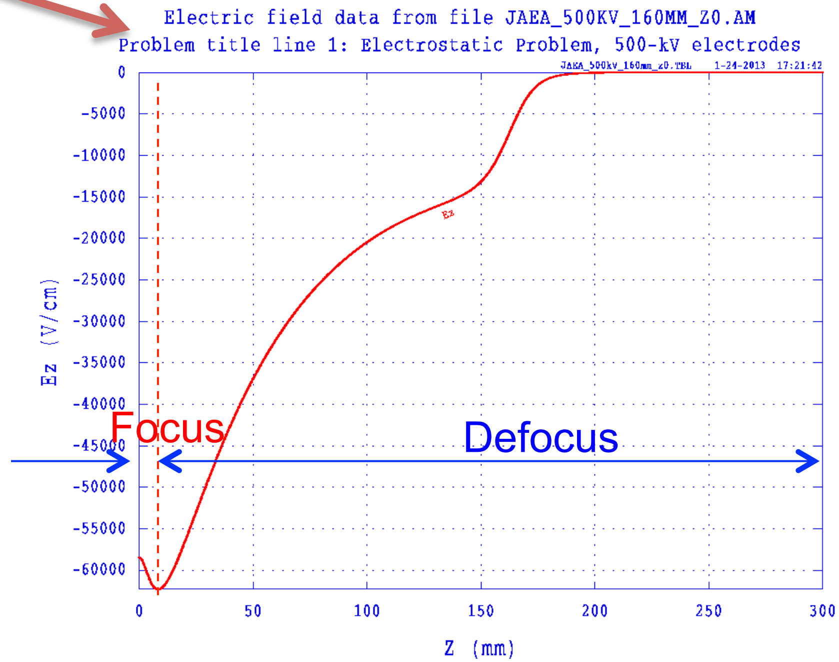


Gun focusing due to electric field with axial symmetry

<u>Calculated field map of photocathode DC gun</u>



Longitudinal electric field on beam axis
Ez vs. z



Paraxial approximation of transverse electric field

$$E_z(r,z) = E_{z0}(z) - \frac{1}{4} r^2 \frac{\partial^2 E_{z0}(z)}{\partial z^2}$$

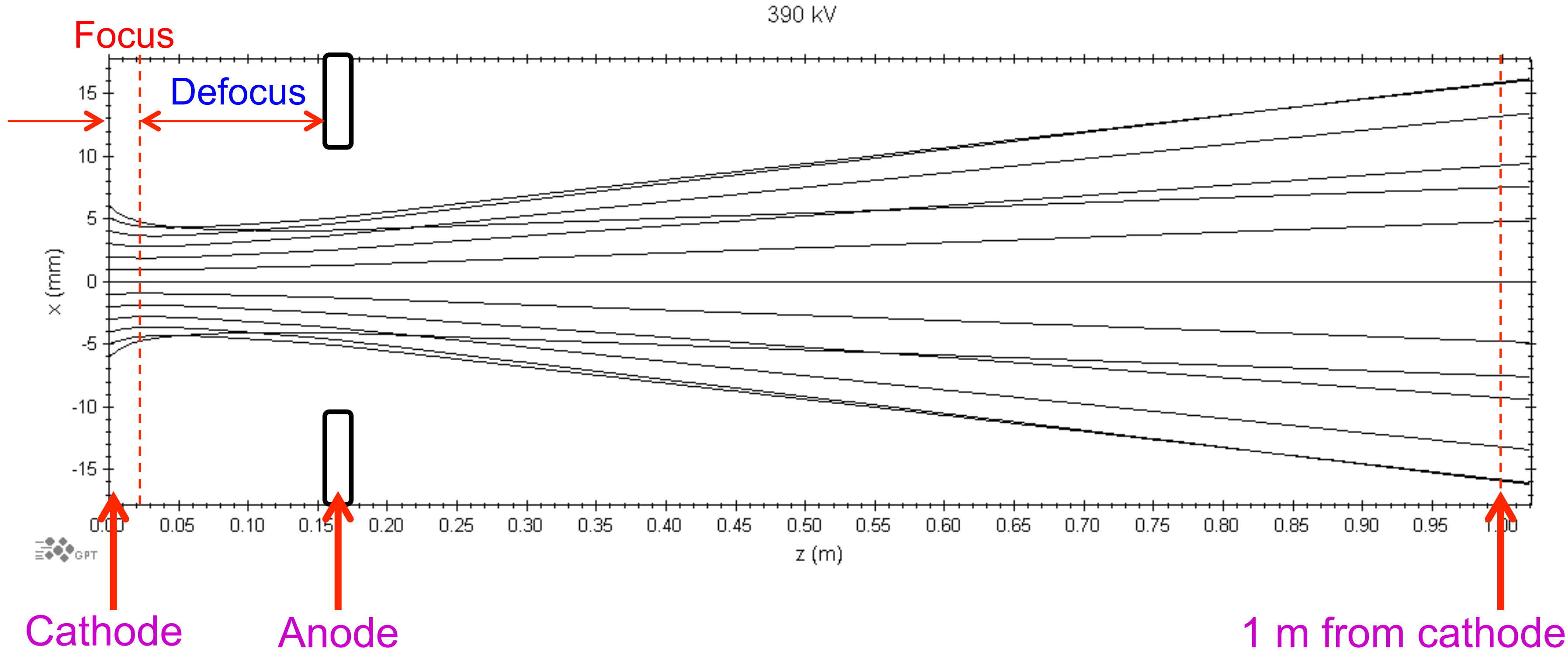
$$E_r(r,z) = -\frac{1}{2} r \frac{\partial E_{z0}(z)}{\partial z}$$

Transverse electric field depends on dEz/dz.

- Focusing force of JAEA 500 kV photocathode gun :
  - dEz/dz > 0 : Focus
  - dEz/dz < 0 : Defocus

Particle tracking simulation result

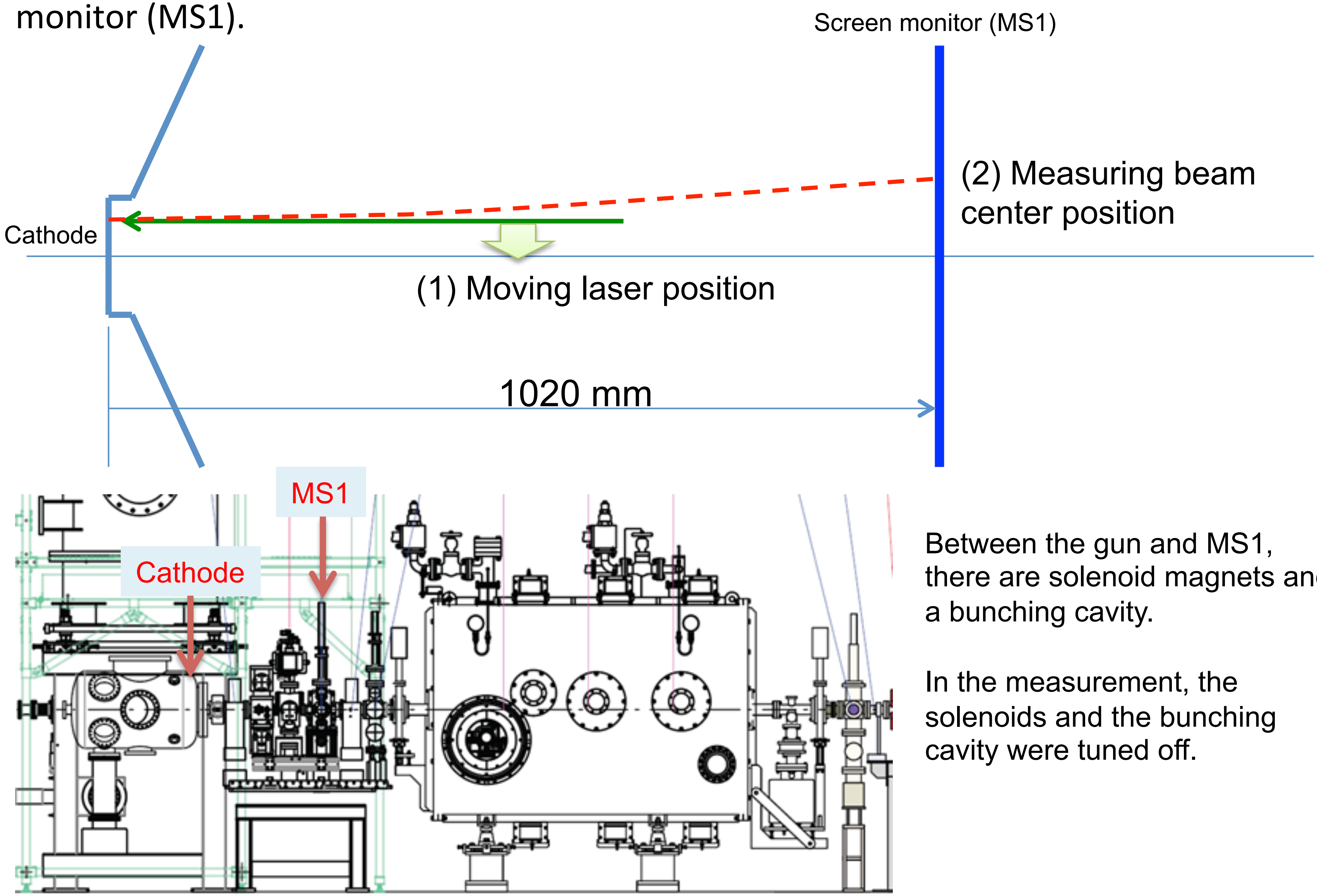
- Particle tracking simulation: GPT and 2D field map of the previous slide



- The focusing effect is very important to beam transportation.
- How to check the effect of the real photo cathode DC gun?

How to measure gun focusing?

- Moving laser position on cathode surface and measuring beam center position on screen monitor (MS1).



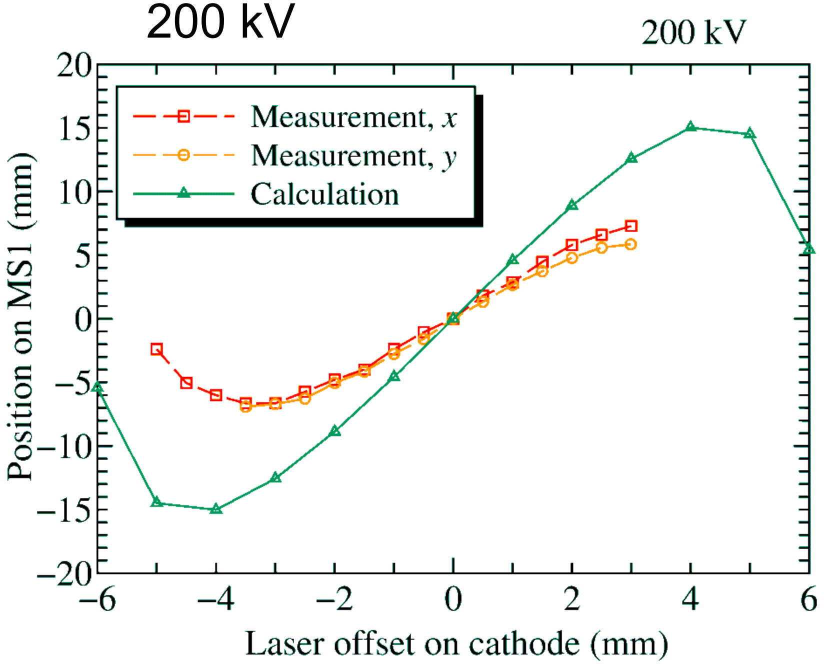
Between the gun and MS1, there are solenoid magnets and a bunching cavity.

In the measurement, the solenoids and the bunching cavity were tuned off.

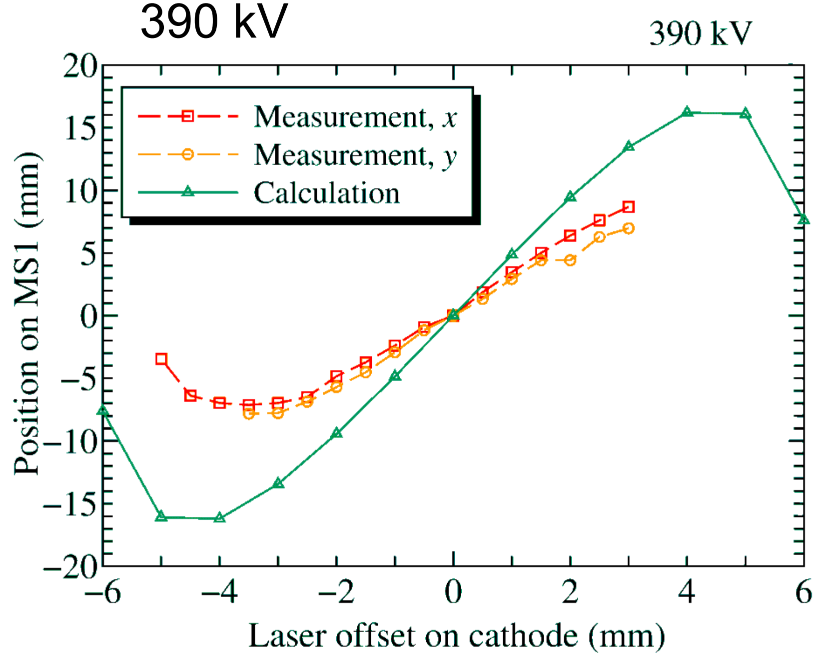
Measurement results

- Gun voltages in the measurements : 200 kV, and 390 kV

200 kV



390 kV



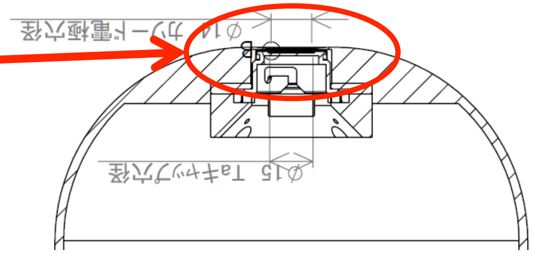
Horizontal and vertical responses are almost the same.
⇒ The electrode has axisymmetric shape.

The measurement result did not agree with the particle tracking result.

To reproduce the measurement result, we modified the cathode electrode shape for the particle tracking simulation, because the focusing effect is sensitive to it.

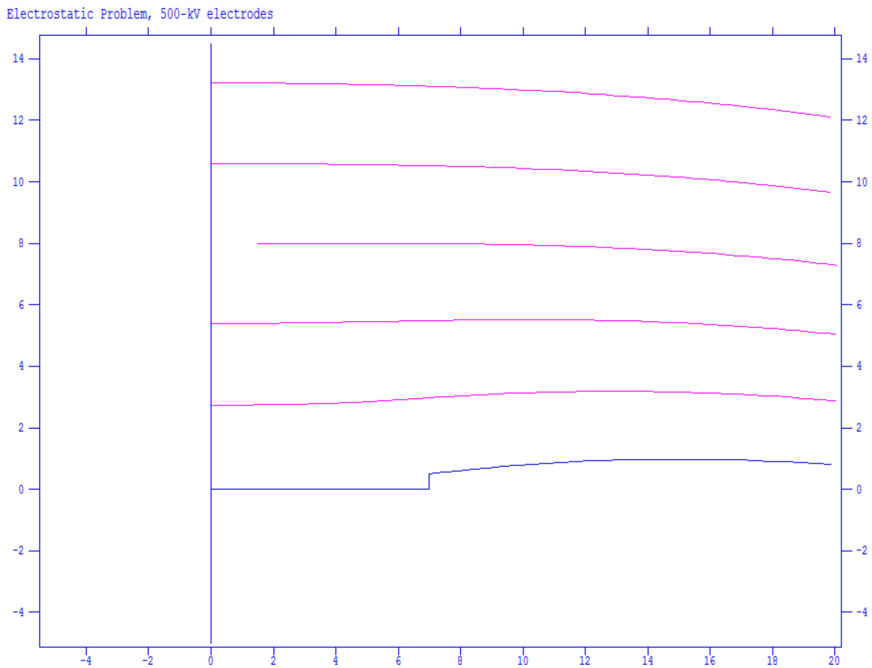
Correction of gun focusing

- The focusing effect is sensitive to the cathode shape.
- The cathode electrode has a margin to connect the cathode pack which hold GaAs material.
  - The recess may be different with original 0.5 mm recess.

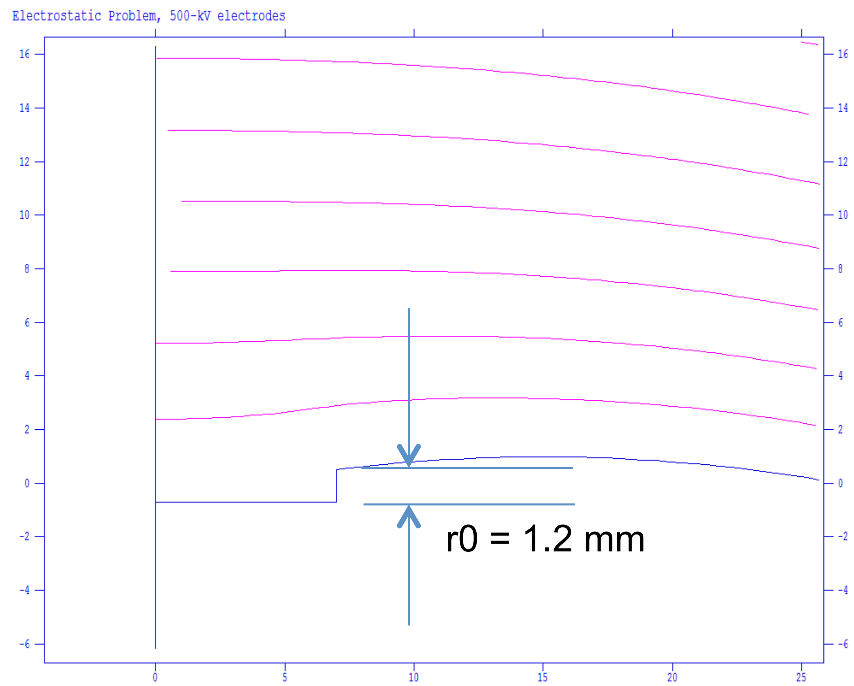


- We try to do particle tracking simulations with different recess（r0 = 0.9, 1.0, 1.2 mm）.

Recess：r0 = 0.5 mm (original)

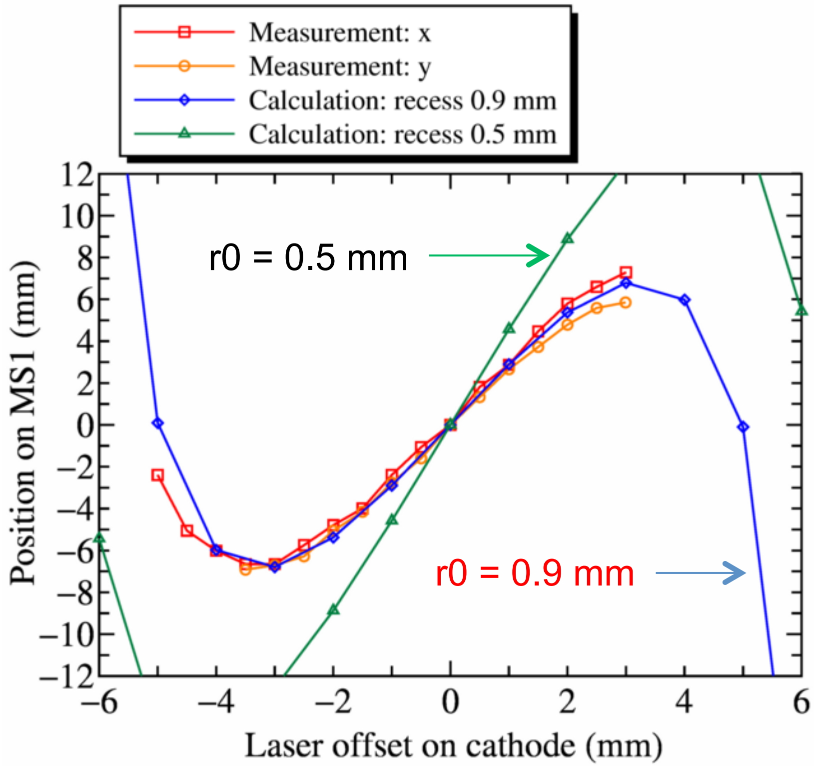


Recess：r0 = 1.2 mm

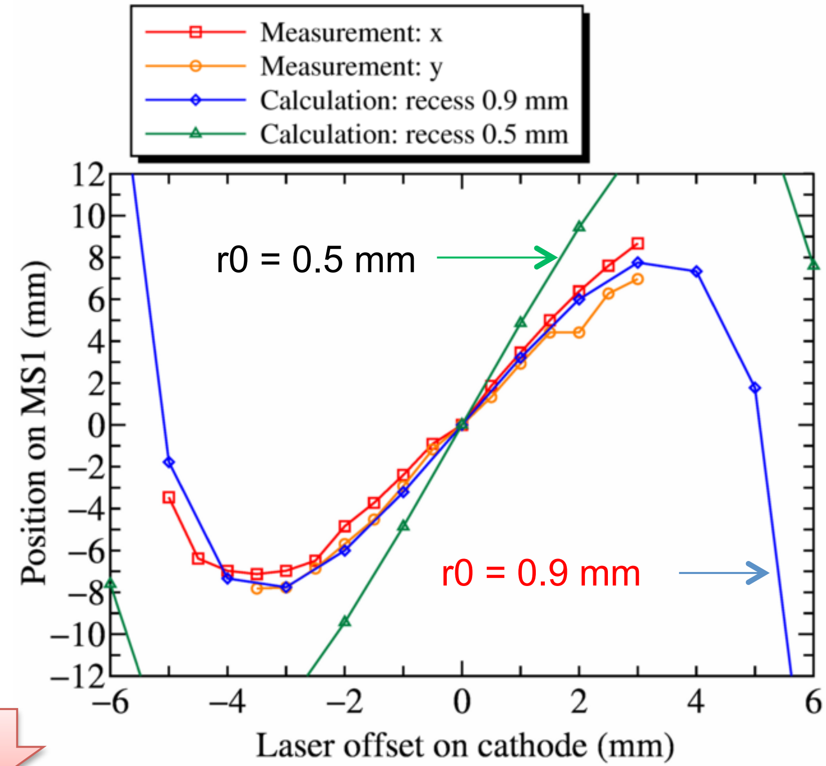


Corrected model with recess of 0.9 mm

200 kV



390 kV



The recess of 0.9 mm reproduced the measurement results for both voltages.

From the results, we decided the cathode shape for the particle tracking simulation as the recess of 0.9 mm.

So far, we think single particle dynamics. The next step is to check the multi particle dynamics (particle distribution).

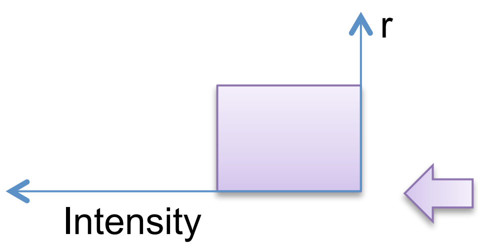
4. Beam transportation without space charge effect

Initial laser condition

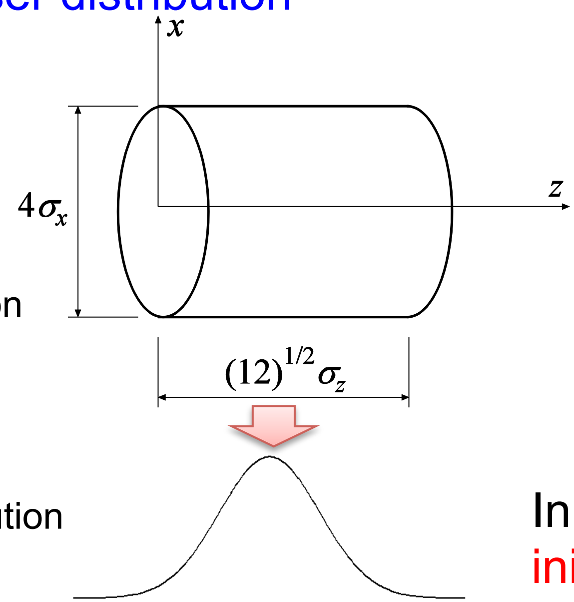
- Photo electron is emitted from a photo cathode when laser is applied on it.
- Emitted electron beam from the cathode strongly depends on initial laser condition.

Initial laser condition	Emitted electron beam
Laser spot size, *d*	Transverse beam size
Laser pulse width	Bunch length
Laser power	Bunch charge
Laser wave length	Initial emittance ($k_B T$)

Laser distribution



Transverse profile: uniform distribution
d = 1.2 mm (design)



Longitudinal profile: gaussian distribution
σ_z = 3 ps (design)

Initial emittance

$$\epsilon_n = \frac{d}{4}\sqrt{\frac{k_B T}{mc^2}}$$

Measured $k_B T$ is 120 meV [1].

In the next step, we estimate the initial laser spot size using experimental method.

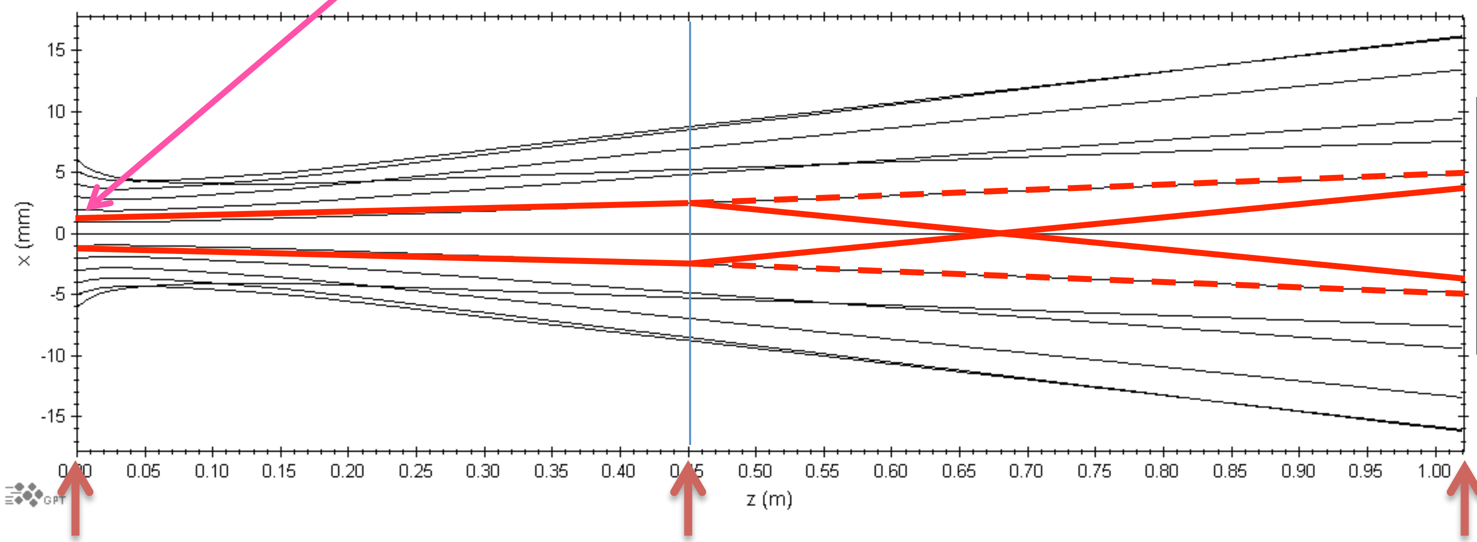
[1] S. Matsuba et. al, Japanese Journal of Applied Physics 51 046402 (2012).

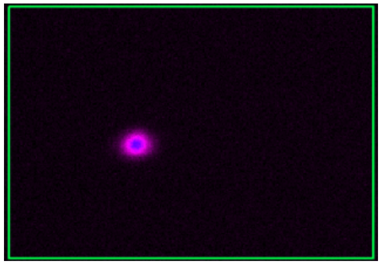
How to measure beam optics?

- We can estimate the initial laser spot size by measurement of the beam size on the screen.
- Bunch charge : - 10 fC (to avoid space charge effect)

- To increase measurement accuracy, we carried out solenoid scan.
- Important points in the solenoid scan:
  - Positions of gun , solenoid and screen <- we checked them by laser tracker.
  - Excitation curve of solenoid magnet <- we carried out the magnetic field measurement.
  - Gun focusing <- we checked it in the previous section.

Initial transverse beam size depends on initial laser spot size.





Cathode

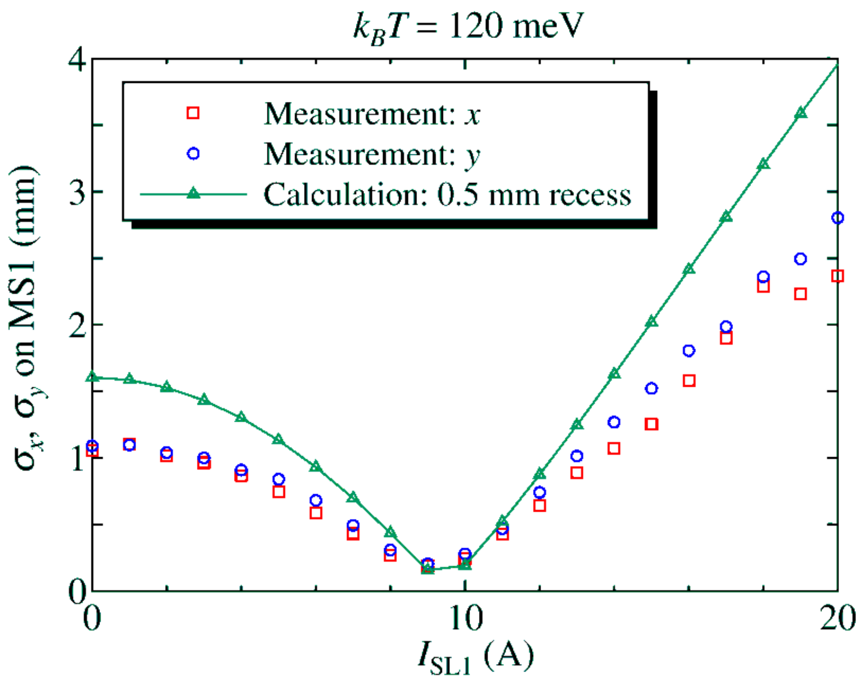
Solenoid (SL1)

Screen (MS1)

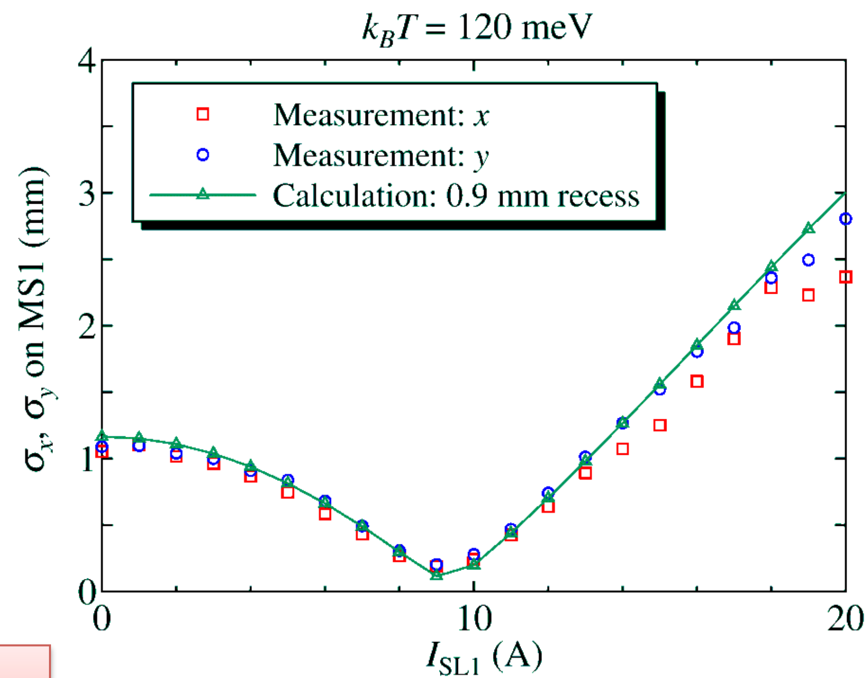
Results of solenoid scan

- We carried out the solenoid scan with very low charge beam to avoid space charge effect.
- Initial laser spot size in simulations: d = 1.2 mm (original)

Recess of 0.5 mm (original)



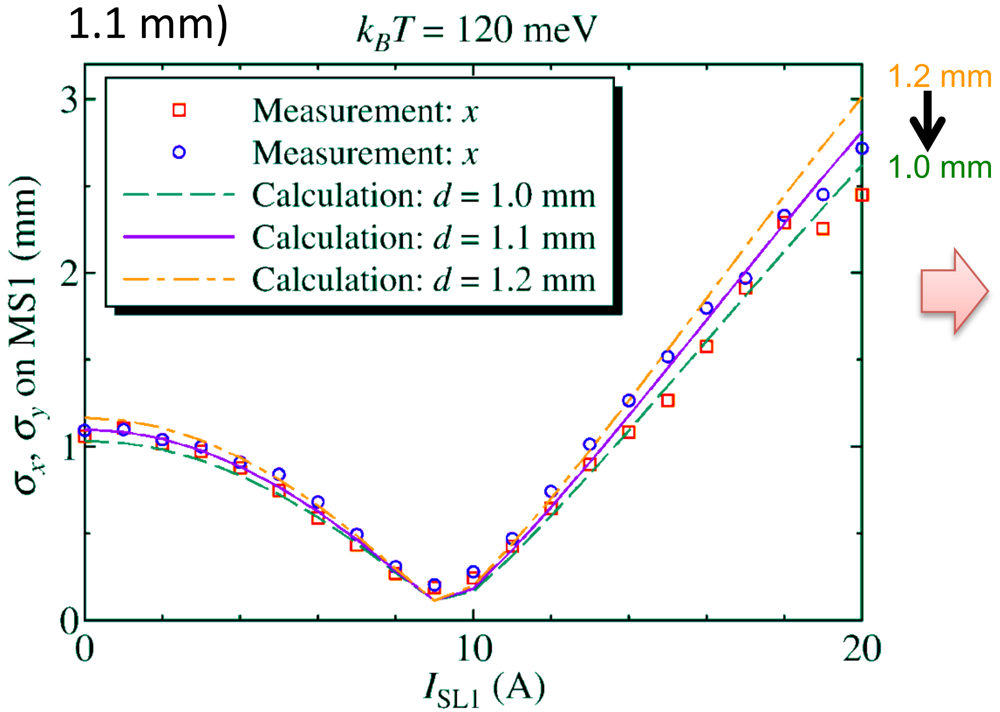
Recess of 0.9 mm (corrected gun shape)



- Calculation result with corrected gun shape almost agreed with the measurement.
- However, the slight difference remains.
- To improve the agreement, we carried out the fine tuning of the initial laser spot size.

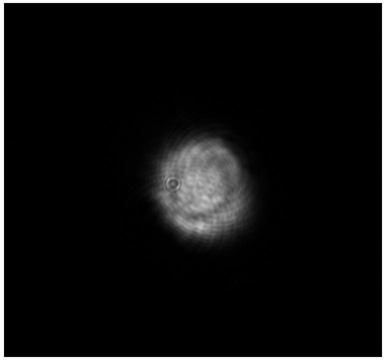
Correction of laser spot size

- We try to do particle tracking simulations with different initial laser spot size (d = 1.0, and 1.1 mm)



The calculation result with d = 1.1 mm reproduced the measurement results.

<u>Measurement result of laser profile on a virtual cathode</u>



Vertical size : 1.09 mm
Horizontal size : 1.02 mm

Average size : 1.06 mm

The measured laser spot size agreed with the above corrected size of 1.1 mm.
Form the correction, we decided the initial laser spot size as 1.1 mm.

The next step is to check space charge effect for high bunch charge beam.

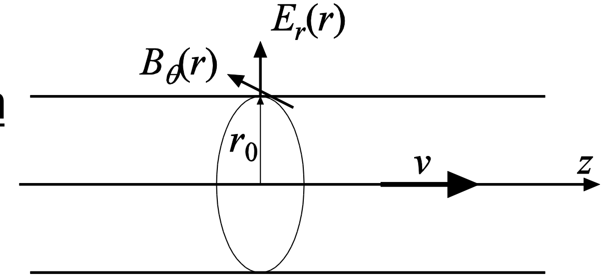
5. Beam transportation with space charge effect

Space charge effect

- For high bunch charge beam, we have to include space charge effect in beam transportation.

Space charge effect for cylindrical continuous beam

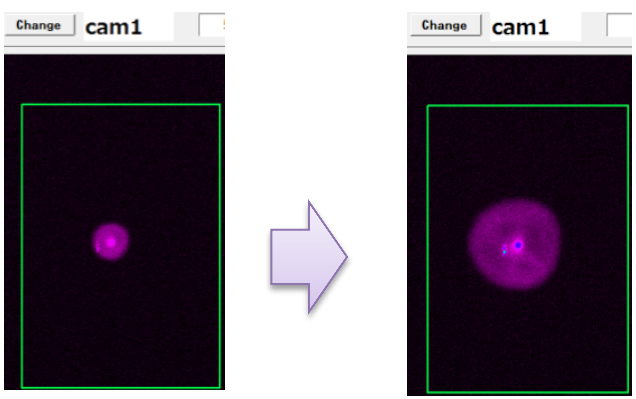
$$F_r = e(E_r - vB_\theta) = \frac{1}{2}\frac{e}{\varepsilon_0}\frac{\rho_0}{\gamma^2}r$$

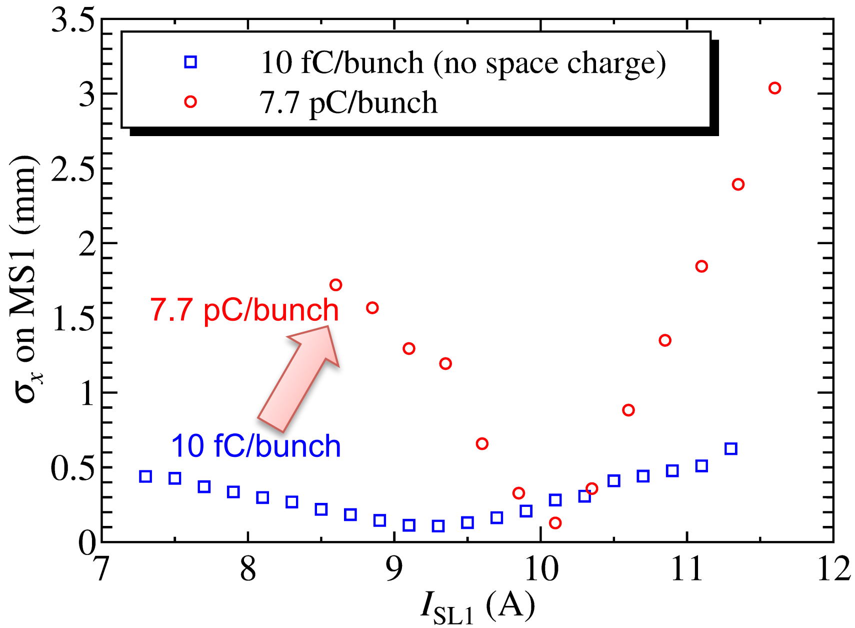


- In order to check space charge effect, we carried out solenoid scan with 7.7 pC/bunch.

Example of measured beam profiles

1.5 pC/bunch 7.7 pC/bunch





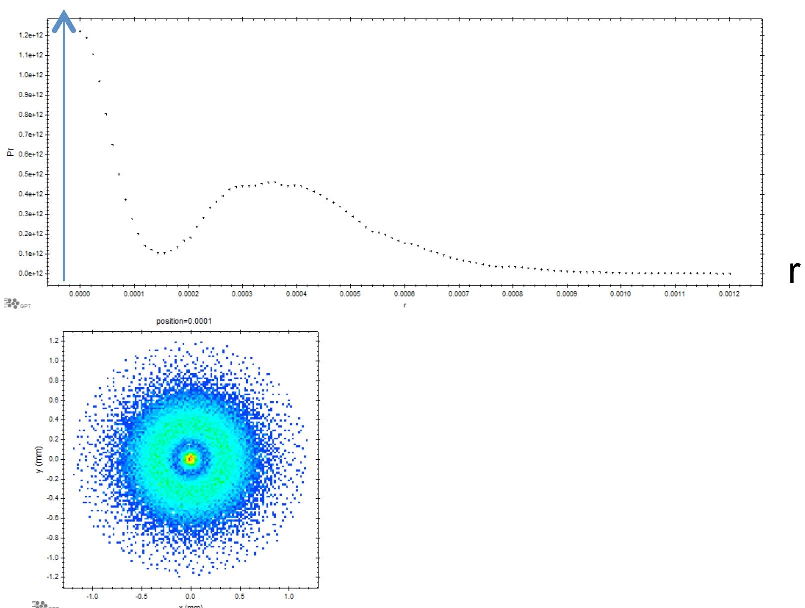
- The solenoid response for 7.7 pC/bunch is different from no space charge case.
- Can we reproduce the measurement result by numerical simulation?
- Important point: charge density (it depends on distribution and bunch charge)

Effect of transverse distribution

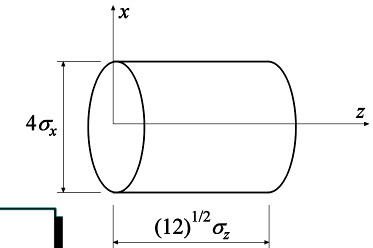
- Alignment error of laser optics may change initial laser distribution on cathode surface.

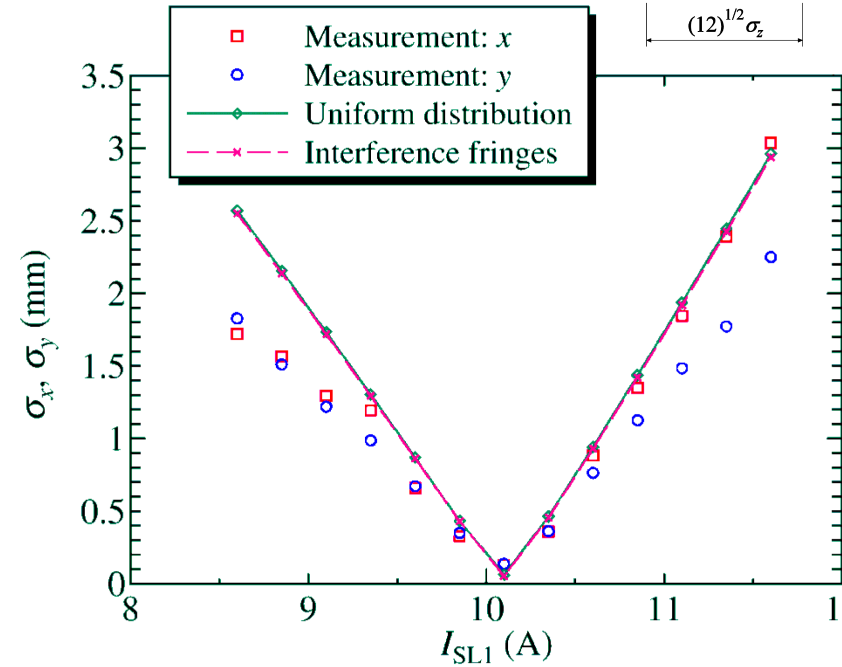
1. Uniform distribution (design)

2. Radial distribution with interference fringes



Transverse distribution with same rms size.

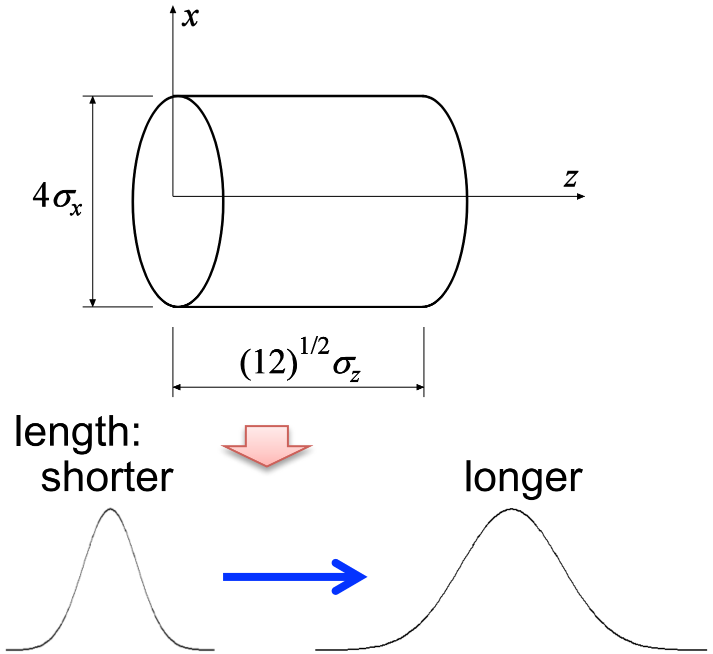


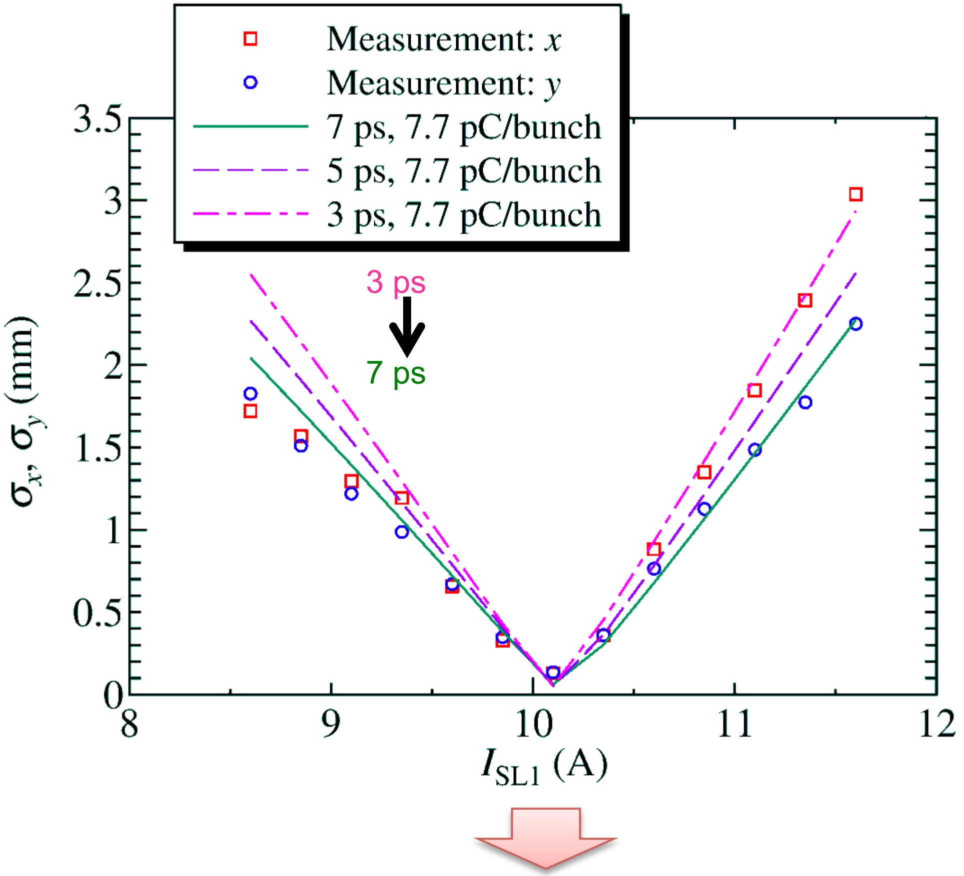


In this case, the effect of transverse distribution is not so large.
The calculation result has difference from the measurement result.

Effect of bunch length

- We carried numerical simulations with different initial laser temporal widths.





The calculation result with the bunch length of 7 ps is close to the measurement result.

It suggests that the charge density may be lower.

Measurement of space charge effect

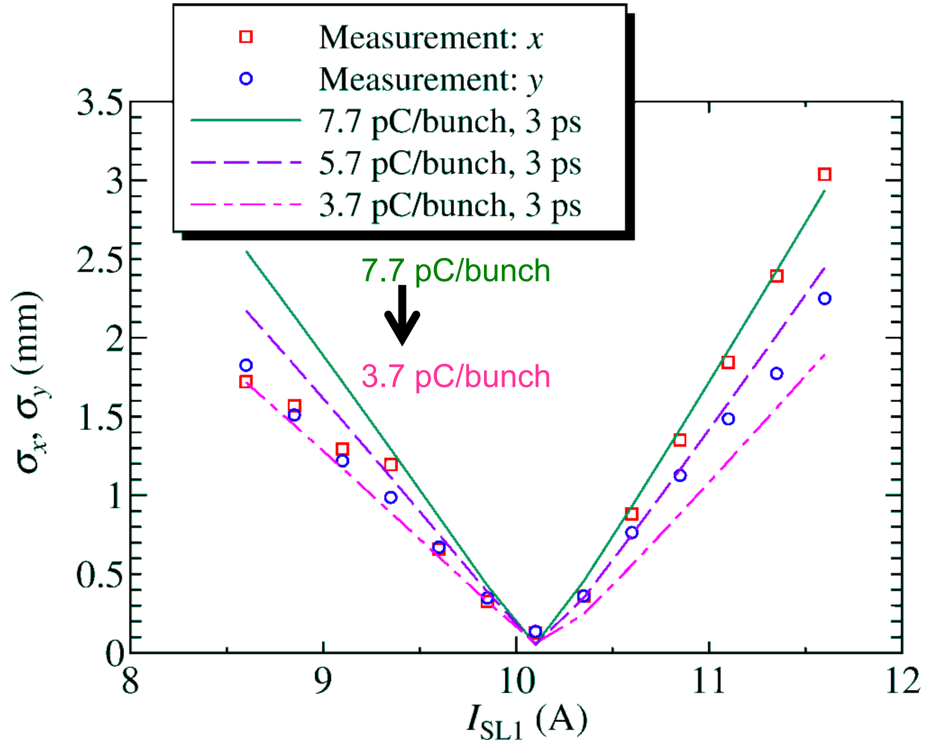
- We carried numerical simulations with different bunch charges.

<u>Space charge effect for cylindrical continuous beam</u>

$$F_r = e(E_r - vB_\theta) = \frac{1}{2}\frac{e}{\varepsilon_0}\frac{\rho_0}{\gamma^2}r$$

Bunch charge:
$Q = \rho_0 V$
V: bunch volume

In this simulation, initial bunch volume is constant.



The calculation result with the bunch charge of 3.7 pC/bunch is close to the measurement result.
It also suggests that the charge density may be lower.

So far, slight difference between the numerical model and the measurement remains.

6. Summary

Summary

- To reproduce measured low emittance beam transportation from the photo cathode DC gun for the cERL by numerical model, we measured the gun focusing effect, and carried out solenoid scans with and without space charge effect.

- Gun focusing effect
  - From the measurement results, we decided the cathode shape for the particle tracking simulation as the recess of 0.9 mm for the corrected numerical model.

- Initial laser spot size
  - Form the solenoid scan result without space charge effect, we decided the initial laser spot size as 1.1 mm for the corrected numerical model.

- Space charge effect
  - The solenoid scan results suggest that the charge density may be lower.
  - So far, slight difference between the numerical model and the measurement still remains.

- We are analyzing the other measurement results with respect to charge density effect to improve the numerical model.

Back slides

ERL collaboration team

- A) High Energy Accelerator Research Organization (KEK)
  - 坂中章悟A), 足立伸一A), 明本光生A), 荒川大A), 浅岡聖二A), 江並和宏A), 遠藤有聲A), 福田茂樹A), 古屋貴章A), 芳賀開一A), 原和文A), 原田健太郎A), 本田融A), 本田洋介A), 本間博幸A), 本間輝也A), 細山謙二A), 穂積憲一A), 石井篤A), 加古永治A), 神谷幸秀A), 片桐広明A), 河田洋A), 小林幸則A), 小島裕二A), 近藤良也A), 久米達哉A), 松本利広A), 松村宏A), 松下英樹A), 道園真一郎A), 三浦孝子A), 宮島司A), 長橋進也A), 仲井浩孝A), 中島啓光A), 中村典雄A), 中西功太A), 中尾克己A), 濁川和幸A), 野上隆史A), 野口修一A), 野澤俊介A), 帯名崇A), 尾崎俊幸A), ﾁｭｳﾌｧﾝA), 阪井寛志A), 佐々木慎一A), 下ヶ橋秀典A), 佐藤康太郎A), 佐藤昌史A), 設楽哲夫A), 島田美帆A), 篠江憲治A), 塩屋達郎A), 宍戸寿郎A), 多田野幹人A), 高橋毅A), 高井良太A), 竹中たてるA), 谷本育律A), 飛山真理A), 土屋公央A), 内山隆司A), 上田明A), 梅森健成A), 渡邉謙A), 山本将博A), 山本康史A), 矢野喜治A), 吉田光宏A)
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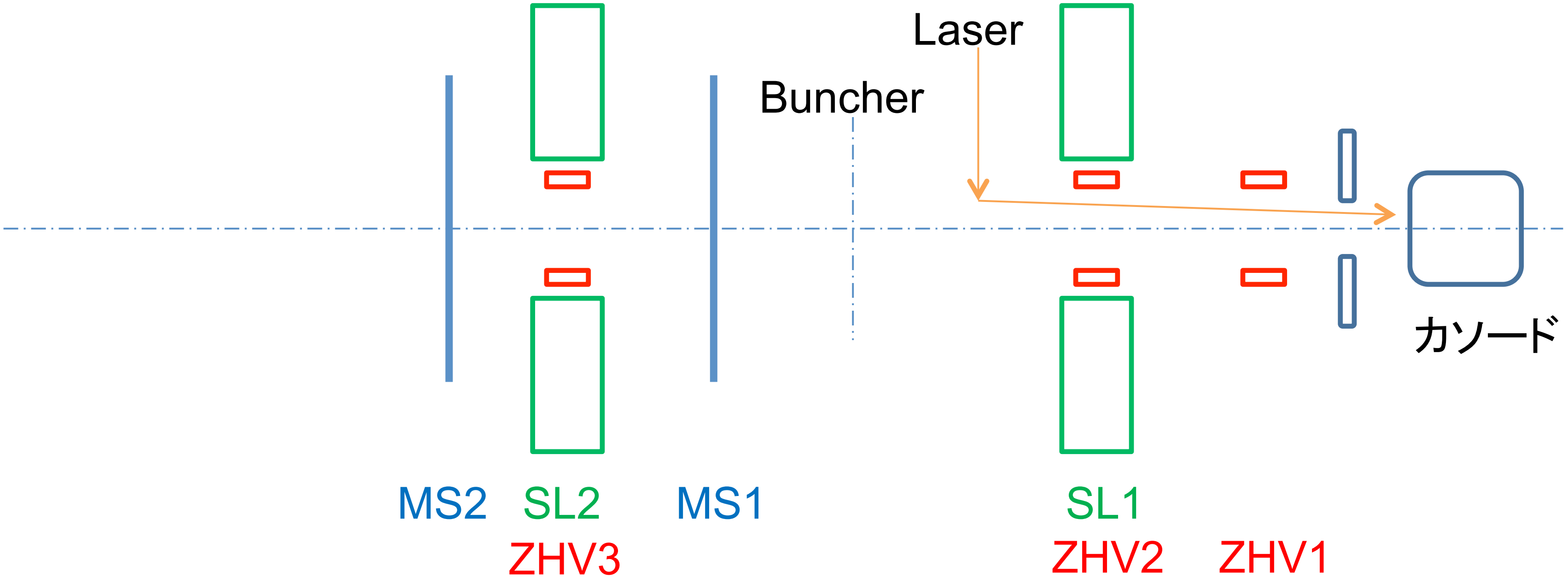
  - 栗木雅夫E), 飯島北斗E)
- F) Kyungpook National University, Department of Physics
  - Ji-Gwang Hwang D), Eun-san Kim D)

ビームラインレイアウト（入射部近傍配置）



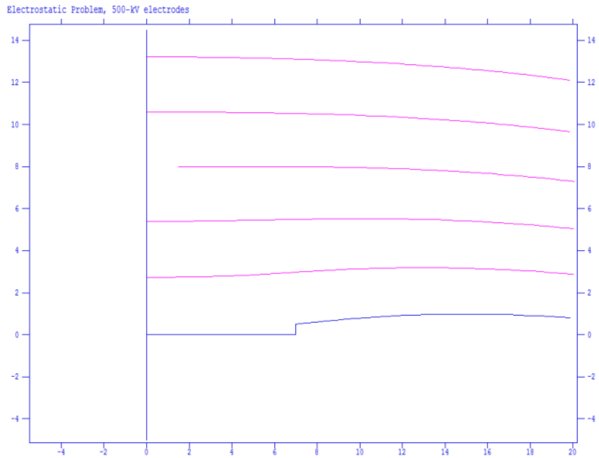
名称		距離(カソード面から※)	測量の差	測量位置
第1ステアリングコイル	ZHV01	233		
第1ソレノイド電磁石	SLGA01, PMGA01, ZHV02	448.791	−3.626	445.165
レーザー導入チェンバー		626.791		
バンチャー	CBGA01	809.291		
第1スクリーンチェンバー	MSGA01	1020.741		
第2ソレノイド電磁石	SLGA02, PMGA02, ZHV03	1219.791	−2.089	1217.702
第2スクリーンチェンバー	MSGA02	1372.228		

レーザートラッカーによる測量結果から、計算用入力ファイルを作っている。
実際、SL1, SL2の応答測定結果を比較すると、位置はほぼ合っているといえる。

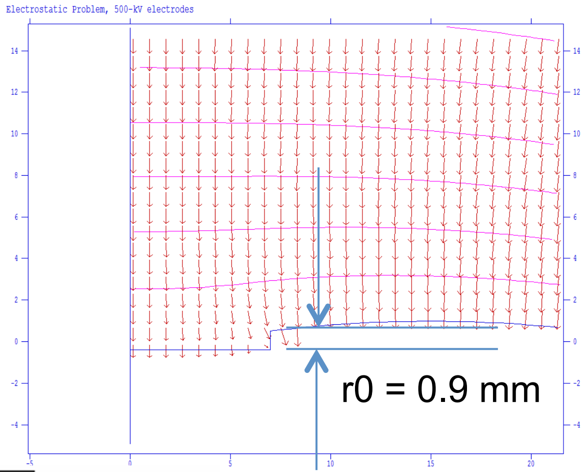
電子銃収束力の影響

- 5月22日の測定で、カソード電極凹みを当初想定していた0.5 mmから、0.9mmにするとほぼ測定結果が再現されることがわかった。

凹み : r0 = 0.5 mm

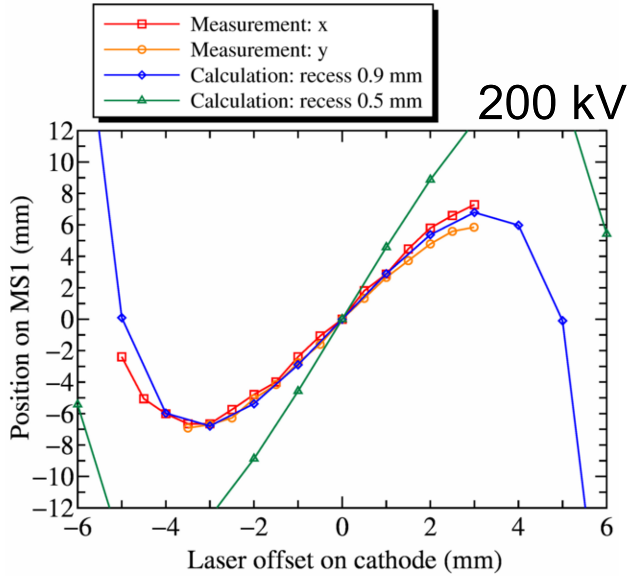


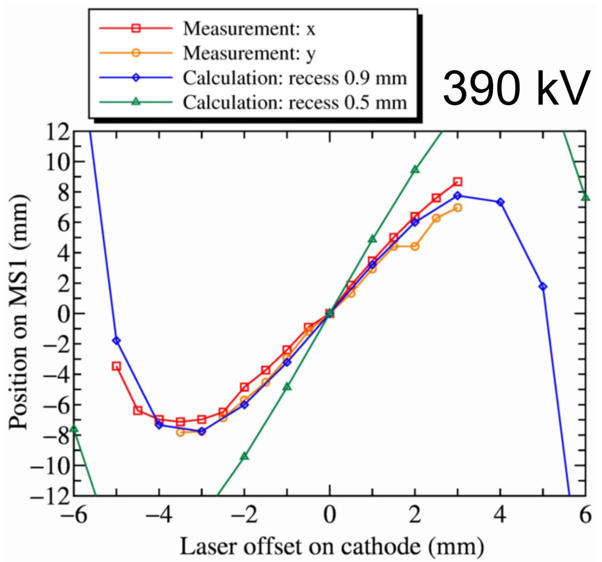
凹み : r0 = 0.9 mm



r0 = 0.9 mmとすることで、電子銃収束力測定結果をどちらの加速電圧でも再現できた。

これを用いて、再度ソレノイド応答測定データの再現を試みる。





Summary of gun focusing measurement

- 電子銃の電場による収束・発散力を実験的に測定するために、レーザー位置を変えながらMS1上でのビーム位置変化の応答を測定した。

- この結果、これまでシミュレーションで使用していた電極形状では、測定結果を再現できないことがわかった。

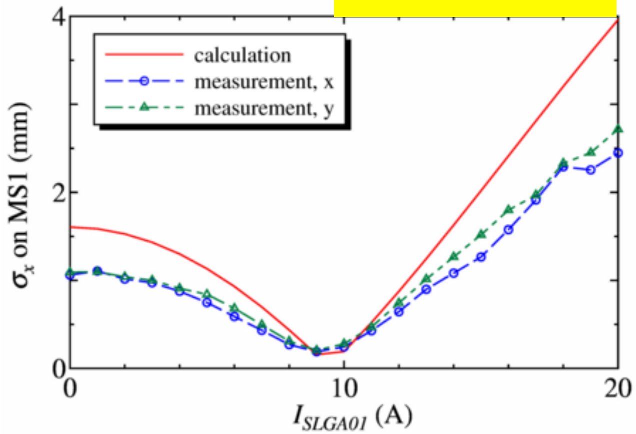
- カソード付近のわずかな電極形状の違いでも、下流では大きく見えるため、カソード部分の凹みをわずかに変えながら、電場分布を計算して、トラッキングを実施した。
- カソード部分の凹みが0.9 mmのときに最もよく測定結果を再現することがわかった。

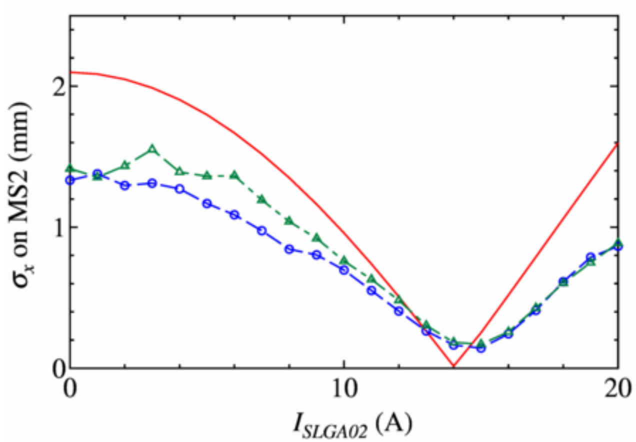
- この測定以降では、cERL phase1 コミッショニング用の計算では、カソード凹み 0.9 mm の電極形状を用いて計算を行っている。

Results of solenoid scan

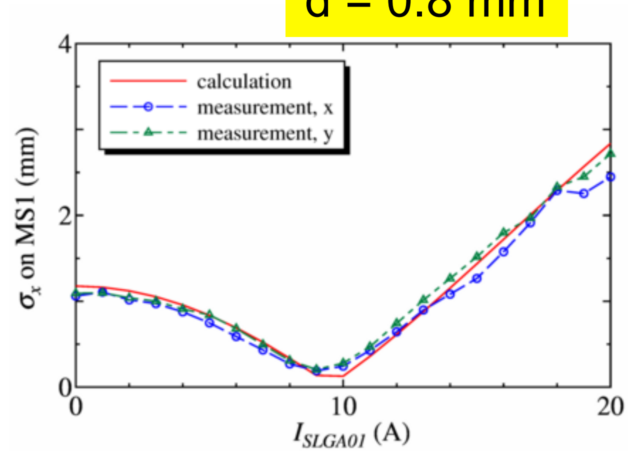
- 4月22日（月）にソレノイド１、２の応答測定を行った
- シミュレーションと比較したところ、ずれが大きかった
- 計算で、初期レーザー直径を1.2 mm から 0.8 mmとすると良く一致することがわかった
- レーザー輸送路の距離の精度で、カソード面での直径が小さくなる可能性はあるとのことなので、今後確認する

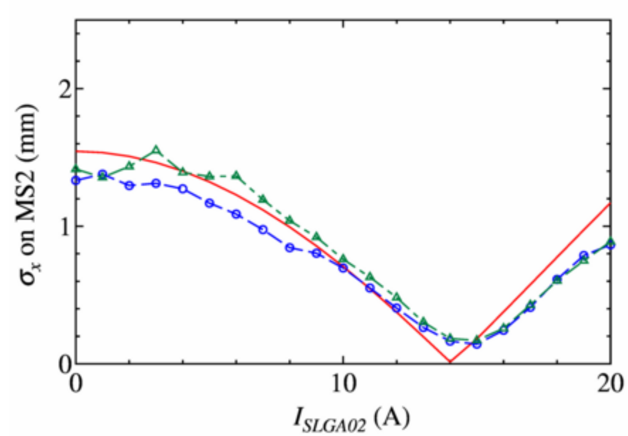
d = 1.2 mm





d = 0.8 mm





最小値を結ぶ位置はほぼ合っているので、電流と磁場の変換は合っている。
初期スポット直径を変えると計算と測定結果がほぼ一致。

<u>本当に、d = 0.8 mmという小さい値なのか？</u>
ここで考慮していないのは、
- ビームラインレイアウト
- 電子銃収束力

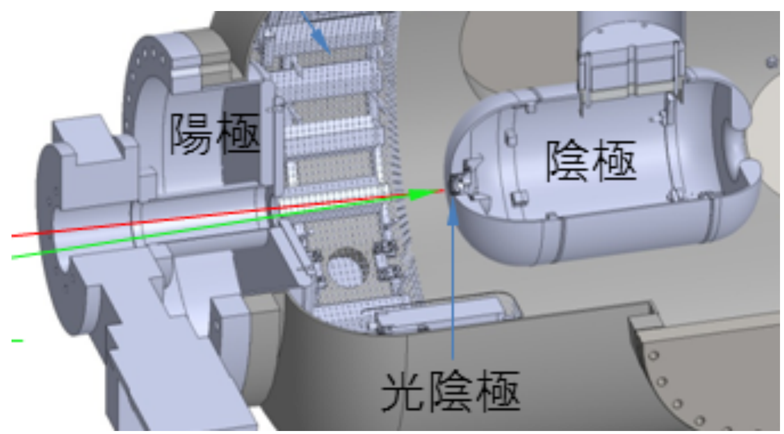
Beam optics in transportation line

- 光陰極DC電子銃では、レーザーを光陰極面に当てて、電子ビームを取り出している。
- 光陰極から取り出されるビームは、照射するレーザースポット径によって決まる。
- 下流でのオプティクスは初期ビームサイズに依存するため、初期レーザースポットサイズを実験的に押さえておくことが重要

- 初期レーザースポットサイズの影響
  - 初期電子ビームサイズ: d
  - 初期エミッタンス $\epsilon_n = \frac{d}{4}\sqrt{\frac{k_B T}{mc^2}}$

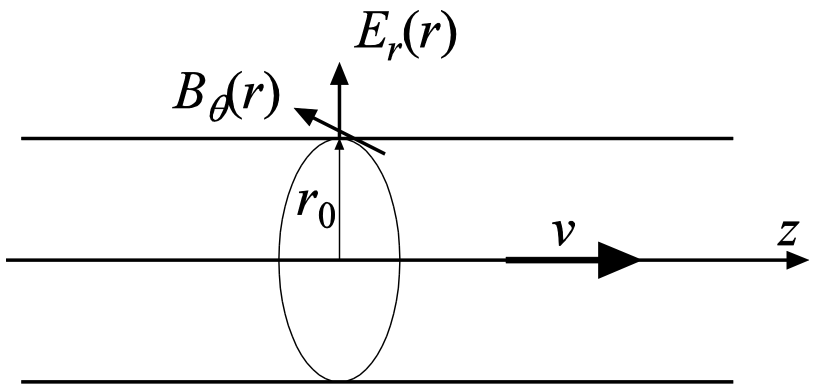
- ここでは、
  - 実験的にレーザースポット直径を推定する方法
  - 最初の測定結果
  - 電子銃収束力確定後の再測定

  について紹介する



Space Charge effect (simple case)

- There is continuous beam for z direction with velocity, v.
- Cross-section of beam: radius r
- Charge density is uniform. ($\rho_0 = \text{const.}$)
- Electromagnetic field caused by beam has cylindrical symmetry.
- z-components of electromagnetic field are zero.
- E_r, B_θ are nonzero.



Force from the E_r, B_θ is

$$F_r = e(E_r - vB_\theta) = \frac{1}{2}\frac{e}{\varepsilon_0}\frac{\rho_0}{\gamma^2}r$$

Radial electric field（Gauss's law）

$$E_r(r) = \frac{1}{2\varepsilon_0}\rho_0 r$$

Charge density is uniform. $j = \rho_0 v$

From Ampere's law,

$$B_\theta = \frac{1}{2}\mu_0\rho_0 v r$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}, \quad \beta = v/c,$$

$$c^2 = 1/(\varepsilon_0\mu_0)$$

■The electron is affected by space charge effect, and diverge to radial direction.
■It is proportional to $1/\gamma^2$.

Space Charge Effect (simple case)

Space charge effect for cylindrical continuous beam

$$F_r = e(E_r - vB_\theta) = \frac{1}{2}\frac{e}{\varepsilon_0}\frac{\rho_0}{\gamma^2}r$$

- For high energy beam with high γ, we can ignore the space charge effect
- For kinetic energy of beam E_0, γ is described by

$$\gamma = 1 + \frac{E_0}{mc^2}$$

$E_0 = 2.5\ \mathrm{GeV}$

$$\gamma = 4893$$

$$\frac{1}{\gamma^2} = 4.2\times10^{-8}$$

$E_0 = 10\ \mathrm{MeV}$

$$\gamma = 20.6$$

$$\frac{1}{\gamma^2} = 2.4\times10^{-3}$$

- For $E_0 = 2.5\ \mathrm{GeV}$, $1/\gamma^2$ is very small and we can ignore the space charge effect. For high energy accelerator, we treat the beam as a single particle.
- For $E_0 = 10\ \mathrm{MeV}$, we can not ignore space charge effect.

To treat low energy beam, we use particle tracking code with space charge effect.

Summary

- 電子銃光陰極面に照射しているレーザースポット直径（初期ビームサイズ）を決めるために、電子銃から出たビームのソレノイド応答測定を行った。

- 電子銃電極形状を最初の値（凹み0.5 mm）とすると、レーザースポット直径0.8 mmと推定された
- 電子銃電極形状較正後に再解析を行うと、レーザースポット直径d = 1.1 mmでほぼ測定結果を再現できた

- レーザー輸送路上に設置された仮想カソード面で測定したレーザースポット直径は1.06 mmであった。
- ピンホール直径は1.2 mmであり、ほぼ近い値となった。

- 電極形状較正後の解析と、仮想カソード面での測定結果から、レーザースポット直径を1.1 mm と定めた
- 現在、この値を使って、数値計算と測定結果の比較を進めている。