Low-Emittance Compact RF Electron Gun with a Gridded Thermionic Cathode

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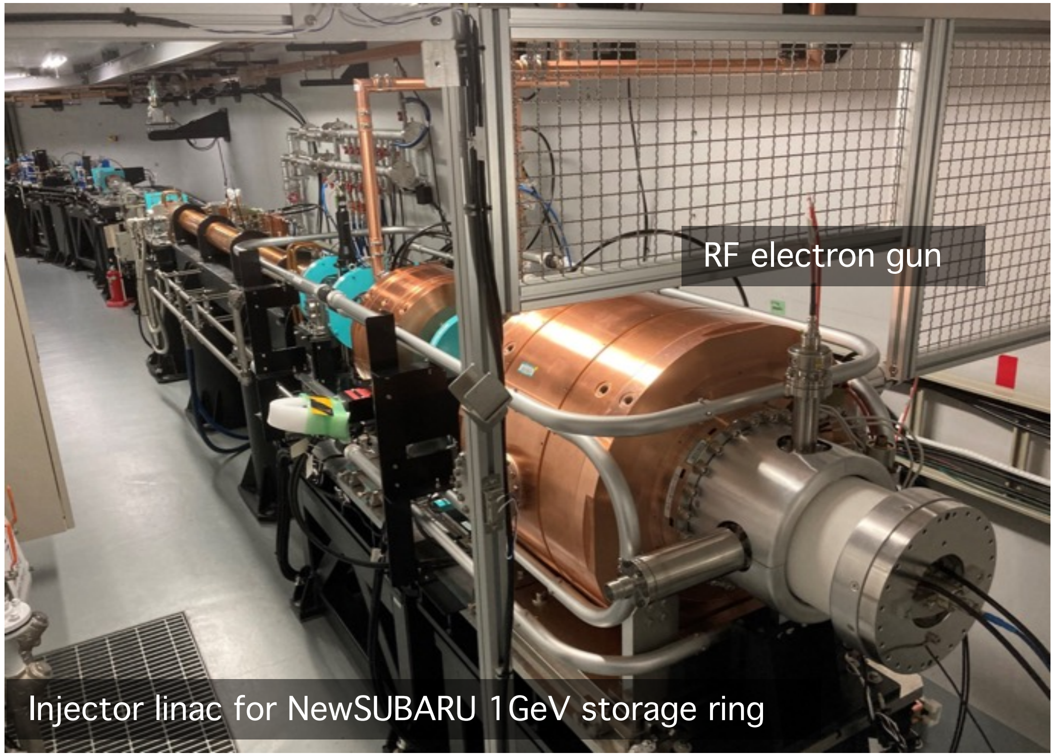
Outline

- Introduction and Motivation
- Design strategy of the rf electron gun with gridded thermionic cathode
- Beam emittance due to the lens effect in the grid mesh
- Design of the 50 kV electron gun and rf cavity
- Simulation results
- Characteristics of rf electron gun system
- Electron gun test stand to demonstrate beam performance
- Summary



Introduction and Motivation

- Gridded thermionic guns are widely used as electron sources for accelerator facilities.
  - ✓ Reliability, easy maintainability, and long lifetime
- Commercially available gridded thermionic cathodes (with a radius of 4 mm)
  - ✓ Normalized emittance of larger than 10 mm mrad

Requirements for electron guns

- X-ray and soft x-ray free-electron lasers require smaller emittance of roughly 1 mm mrad.
- Linac for low-emittance storage rings requires smaller emittance of 10 mm mrad or less.

Gridded thermionic cathodes have been considered unsuitable for low-emittance electron guns.

Distortion of the electric field caused by the grid mesh

➡ Emittance degradation

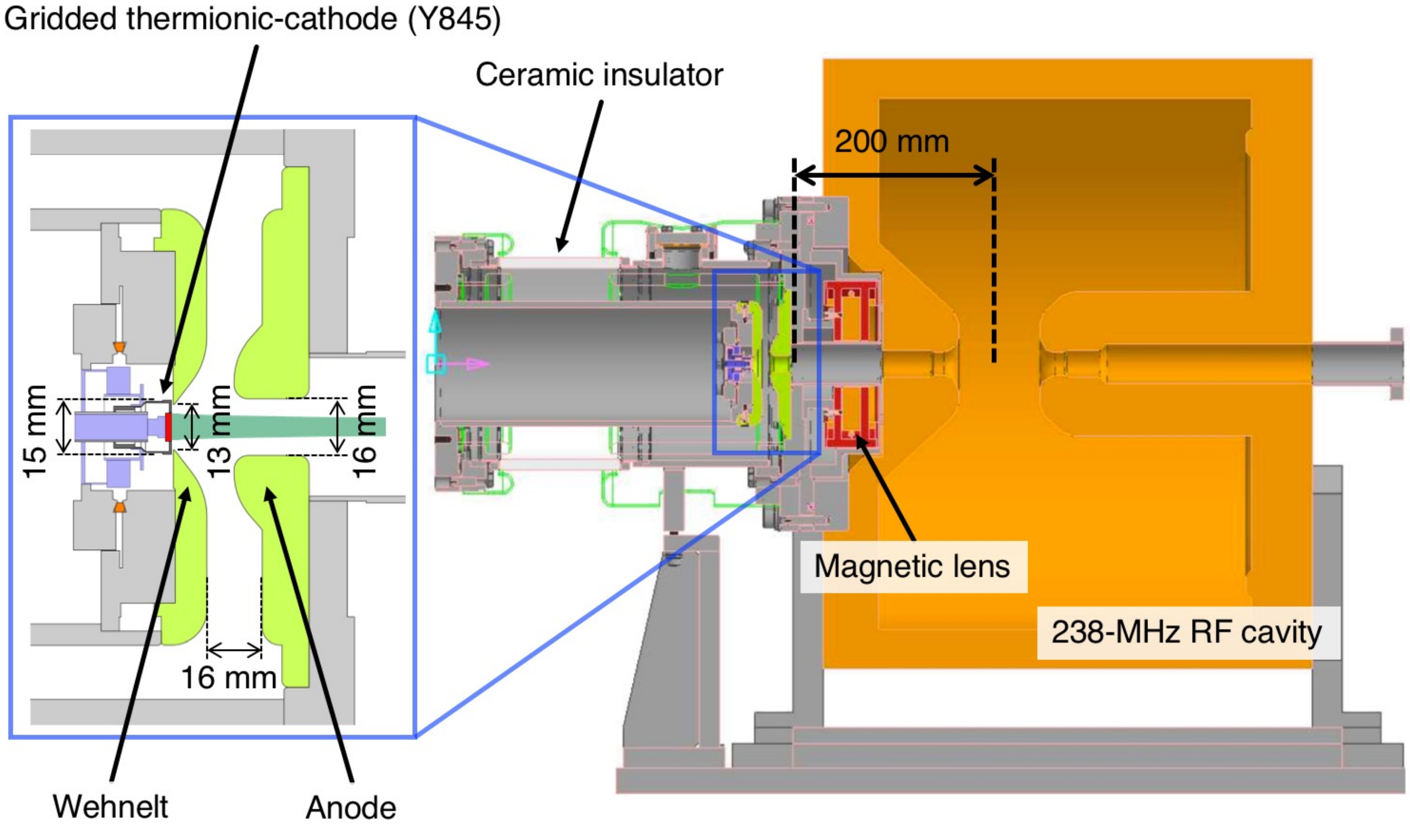
Introduction and Motivation (cont'd)

Two types of low-emittance electron guns（0.5 ~ 1 nC / < 2 mm mrad）

- Photocathode RF gun（1.6 cell BNL type, ...）
  - ✓ Use of complex drive laser system at ultraviolet wavelength
  - ✓ Resident laser specialists to maintain stable and reliable operation
- 500 kV gridless thermionic electron gun equipped with a single-crystal CeB6 cathode
  - ✓ Use of large oil-filled high voltage pulse modulator
  - ✓ Use of electromagnetic chopper system

Introduction and Motivation (cont'd)

- As a third type of low-emittance electron gun, ➡ rf gun using a gridded thermionic cathode
- Concept of rf electron gun
  - ✓ 50 kV gun connected with 238 MHz acceleration cavity
  - ✓ rf electron gun offers the prime advantage of the thermionic gun while not requiring the large equipment.



Design strategy for rf electron gun system

Commercially available gridded thermionic cathode

➡ EIMAC Y845 produced by CPI Inc.

- Thermal emittance

$$\varepsilon_{n,T} = \frac{r_b}{2}\sqrt{\frac{k_B\,T_c}{mc^2}} \approx 0.92\; mm\; mrad$$

- Magnetic emittance

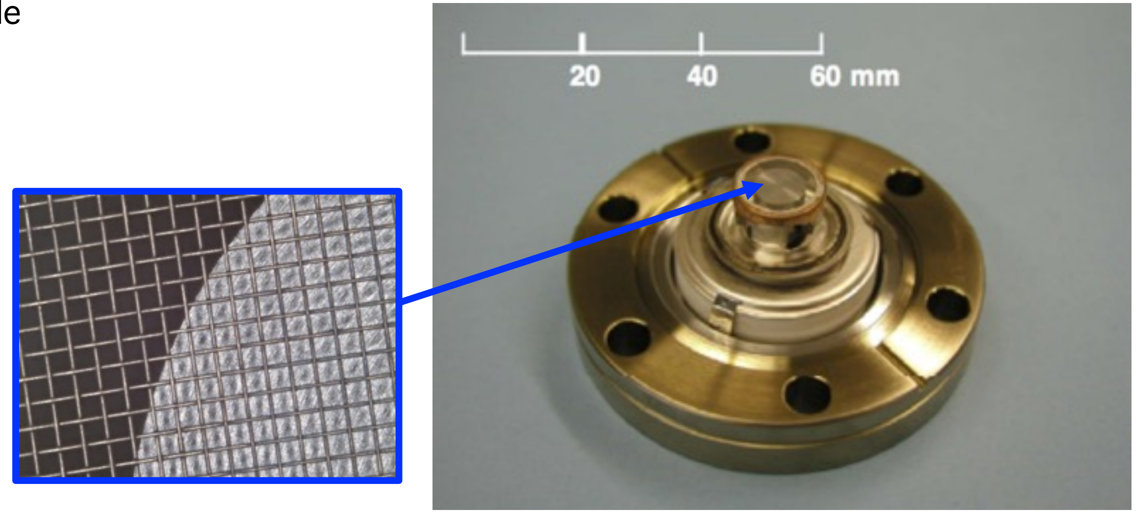
$$\varepsilon_{n,B} = \frac{eB_0 r_b^2}{2mc} \approx 0.23\; mm\; mrad$$

- Cathode surface roughness

$$\varepsilon_{n,R} = \frac{\pi h}{2l} r_b \sqrt{\frac{eE_C h}{2mc^2}} \approx 0.34\; mm\; mrad$$

Cathode emittance

$$\sqrt{\varepsilon_{n,T}^2 + \varepsilon_{n,B}^2 + \varepsilon_{n,R}^2} \approx 1\; mm\; mrad$$



Parameter of Y845		
Cathode type	Dispenser cathode	
Cathode radius	r_b	4 mm
Cathode temperature	T_C	1270 K
Geomagnetism	B_0	0.5 G
Cathode surface roughness (depth)	h	1 μm
Cathode surface roughness (period)	l	20 μm
Cathode – anode field	E_C	-1.2 MV/m

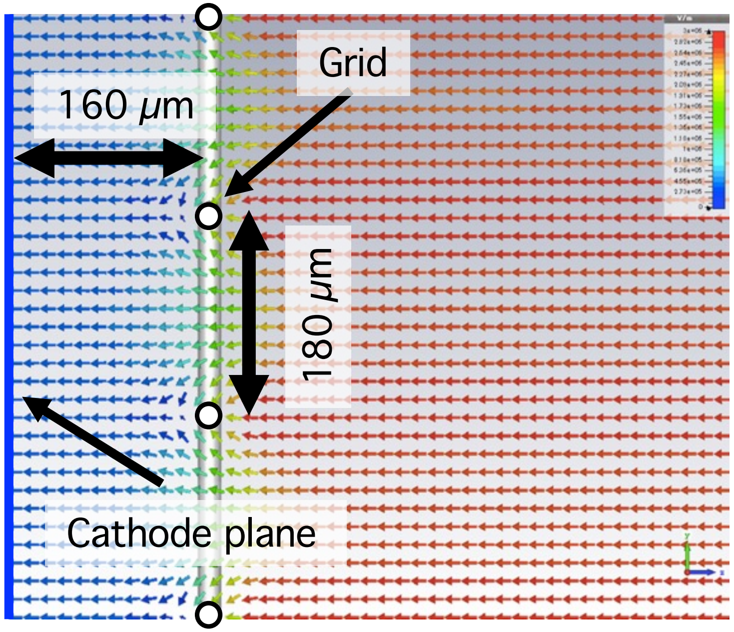
Design strategy for rf electron gun system (cont'd)

An initial concern about our schema is how to suppress the emittance growth that resulted from the distorted electric potential near the grid mesh next to the cathode.

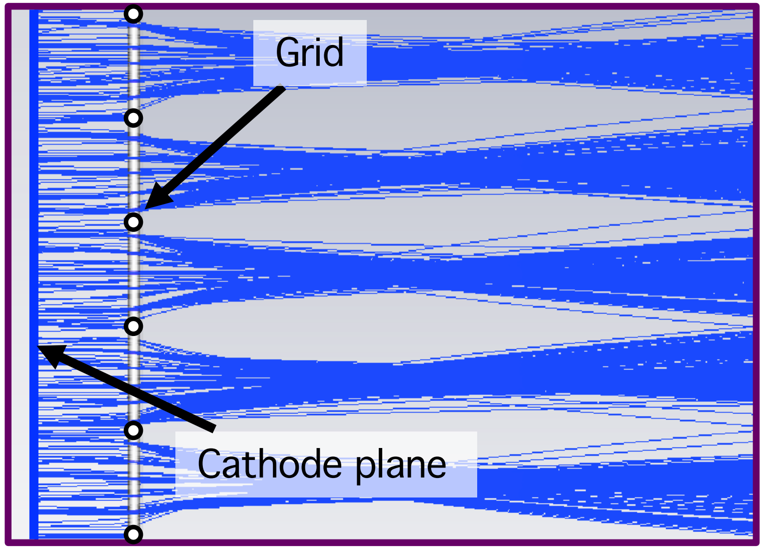
➡ Lens effect

The lens effect originates from a mismatch between grid and gun high voltages, which forms the unnecessary electric field to transversally kick the electrons passing the grid.

Electric field near grid



Beam trajectory near grid



Design strategy for rf electron gun system (cont’d)

- Three key development points.
  - ✓ To obtain the parallel beam after the grid, we optimize the grid voltage to compensate for the electric potential distortion near the grid.

    ➡ Transparent-grid scheme

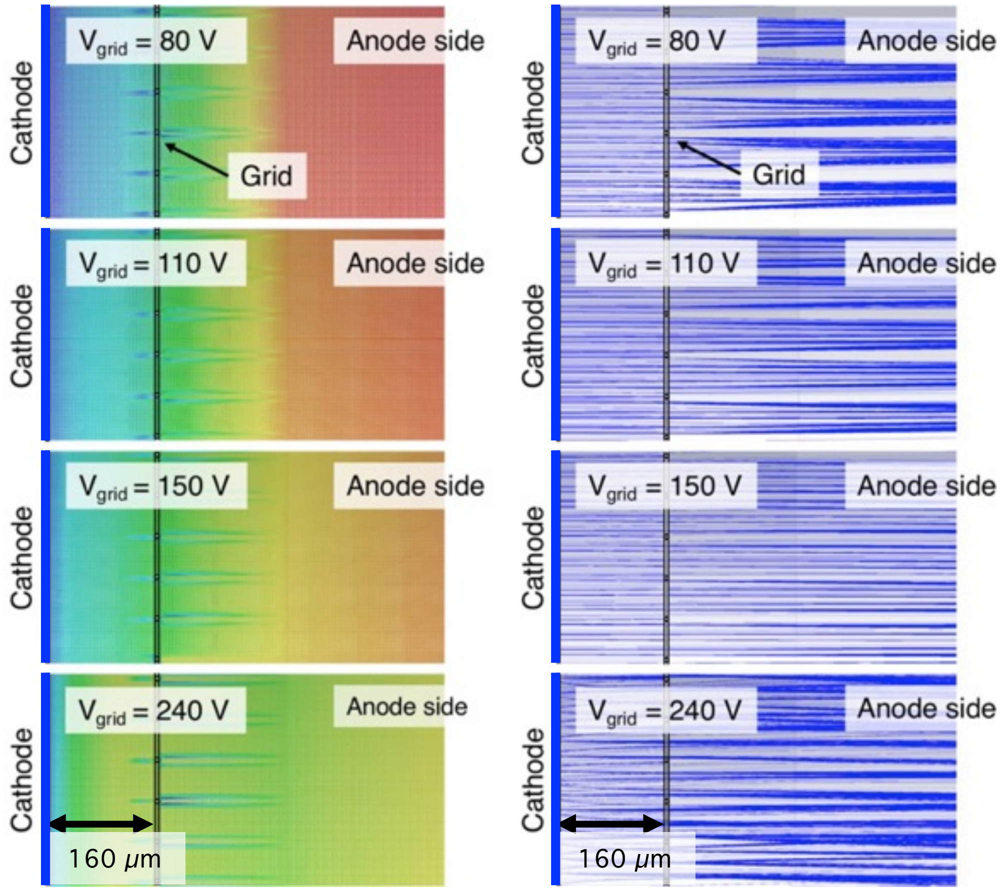
  - ✓ To avoid emittance growth due to the space charge effect at low energy regions, the 50 kV gun was connected to a 238 MHz rf cavity with a minimum distance, which immediately accelerated the beam energy to 500 keV.

  - ✓ In order to maintain the homogeneous beam in the beam transport, a symmetric magnetic lens is embedded in the rf cavity.

Beam trajectory due to lens effect

- Transverse kick near grid depends on voltage between cathode and grid.
- There is condition under which parallel beam can be generated.

➡ ”Transparent-grid scheme” ➡ “Minimized emittance（Homogeneous cylindrical beam）”



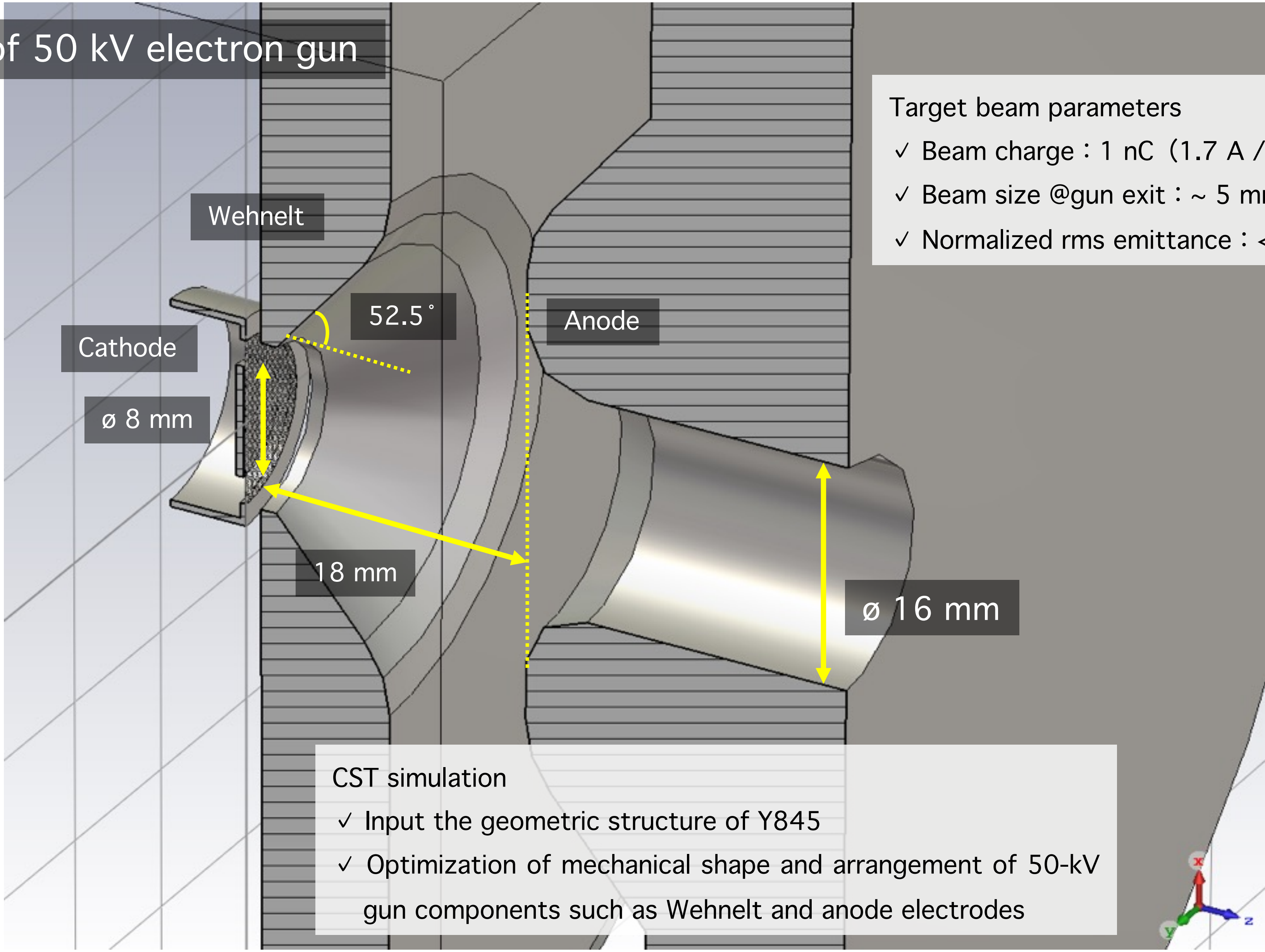
✓ Beam focusing due to electric field distortion near the grid.

✓ Decrease in beam focusing.

✓ Parallel beam is obtained after the grid.

✓ Beam divergence due to electric field distortion near the grid.

Design of 50 kV electron gun



Target beam parameters

✓ Beam charge : 1 nC（1.7 A / 0.6 ns)

✓ Beam size @gun exit : ~ 5 mm

✓ Normalized rms emittance : < 2 mm mrad

CST simulation

✓ Input the geometric structure of Y845

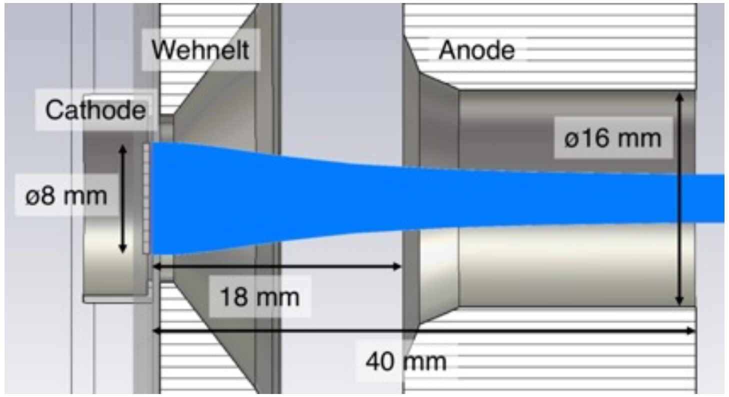
✓ Optimization of mechanical shape and arrangement of 50-kV gun components such as Wehnelt and anode electrodes

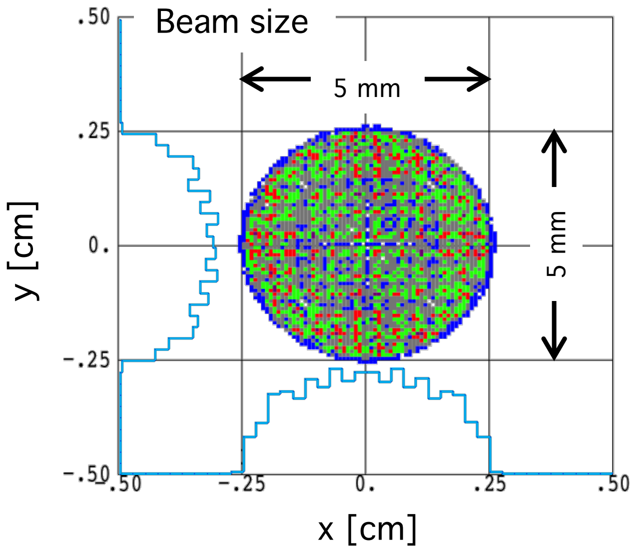
Simulation results of 50 kV electron gun

Anode exit (40 mm from the cathode)

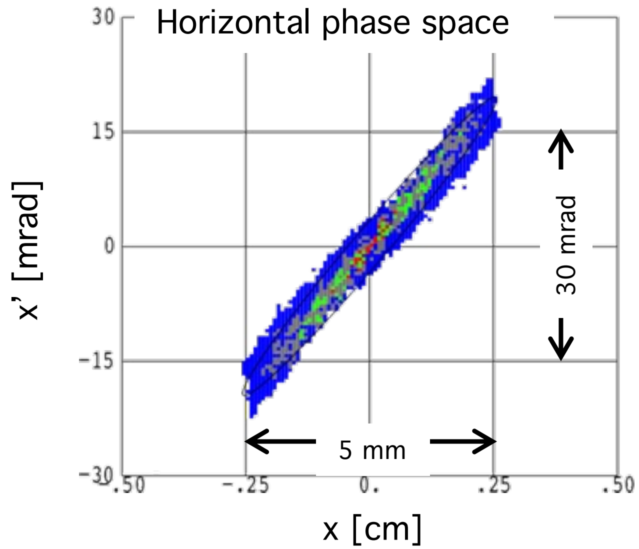
Beam parameter	
Energy	50 keV
Beam charge	1 nC (1.7 A / 600ps)
Beam size	ϕ5 mm
Nor. emittance	1.3 mm mrad

Electrode cross section and beam envelop



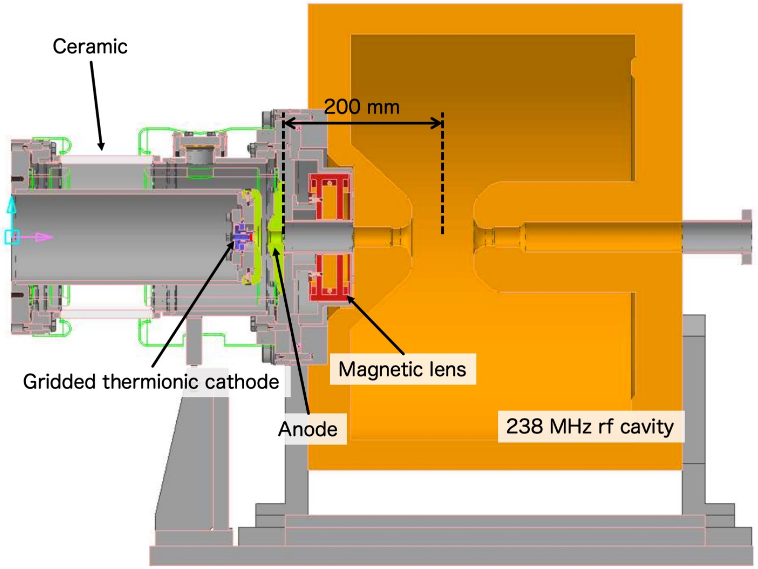


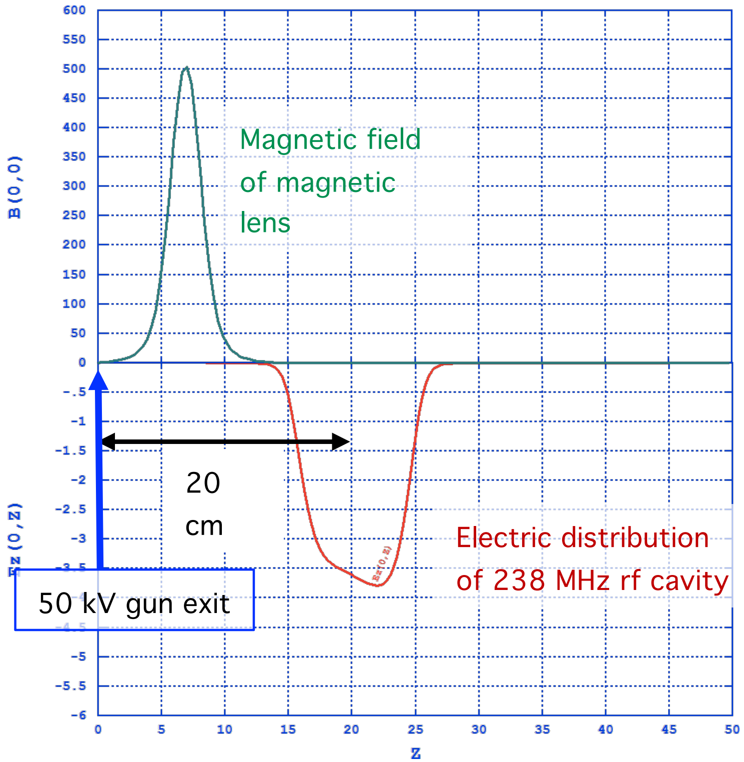
Generation of homogeneous beam.



Feasibility of the transparent grid scheme.

Beam transport from 50 kV gun exit to rf cavity, beam acceleration

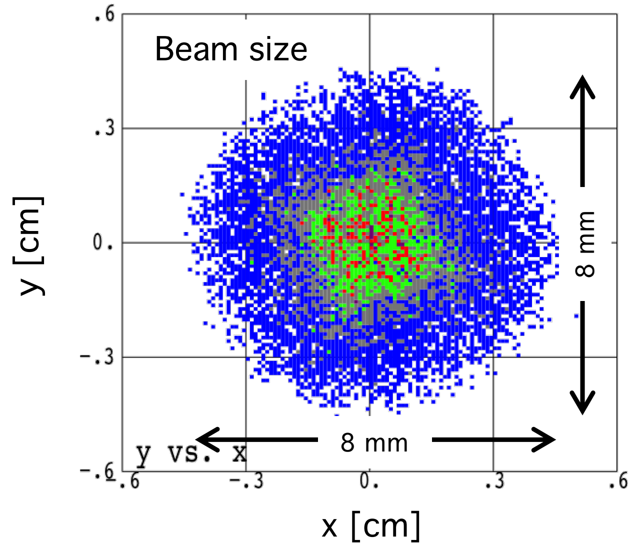




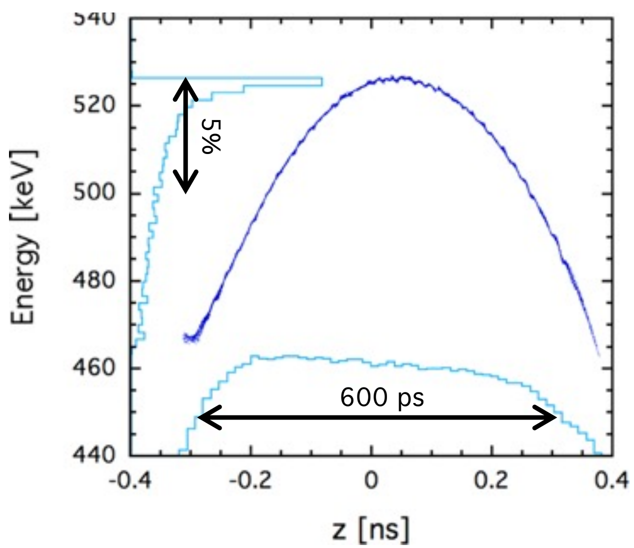
- Magnetic lens is embedded in the rf cavity.
- The distance from the gun exit to the center of the rf cavity gap is shortened to 200 mm.
- Independence of the magnetic field of magnetic lens and the electric field of rf cavity.
- The 50 keV beam arriving at the gap of rf cavity is accelerated to 500 keV to avoid emittance growth.

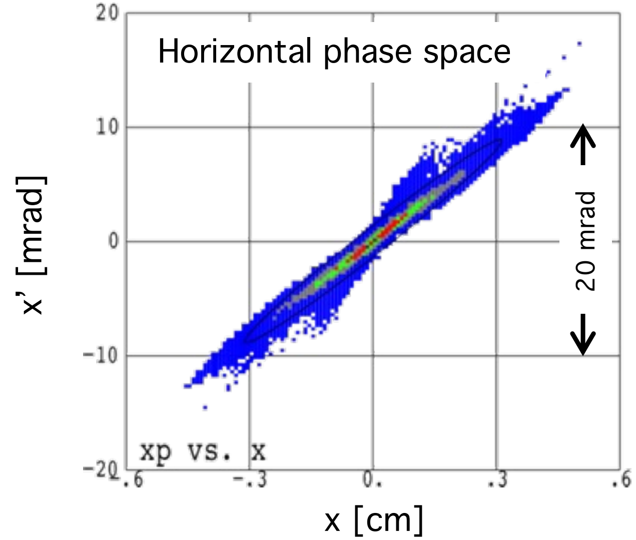
Simulation results of 238 MHz rf cavity exit

Beam parameters	
Energy	500 keV
Energy spread	10% 5% (60% core part)
Transmission	100% (1 nC)
Beam size	ϕ8 mm
Nor. emittance	2.5 mm mrad（100%) 2 mm mrad（60%)



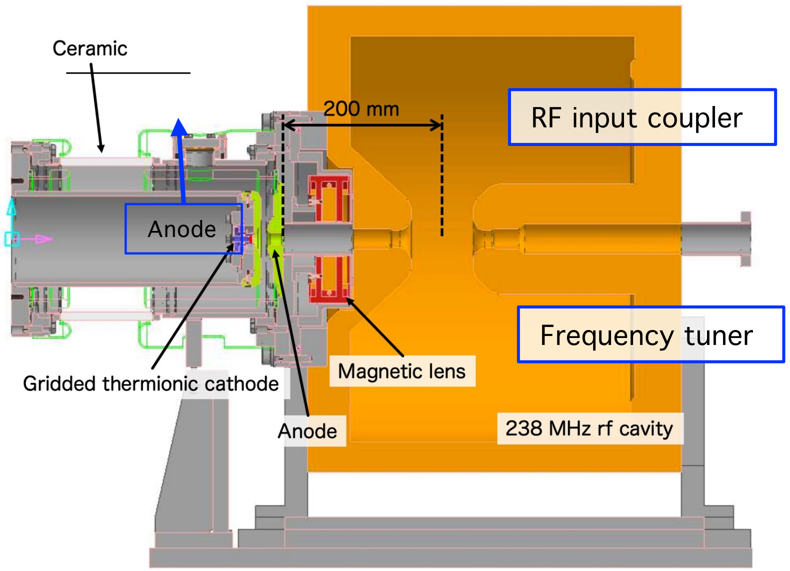
Beam pulse length and energy profile



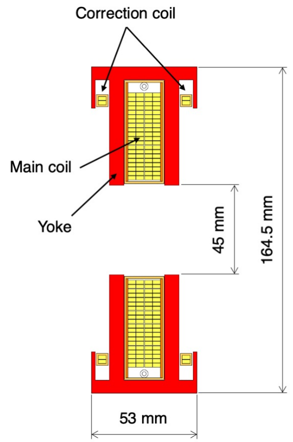


Characteristics of each component of rf electron gun system

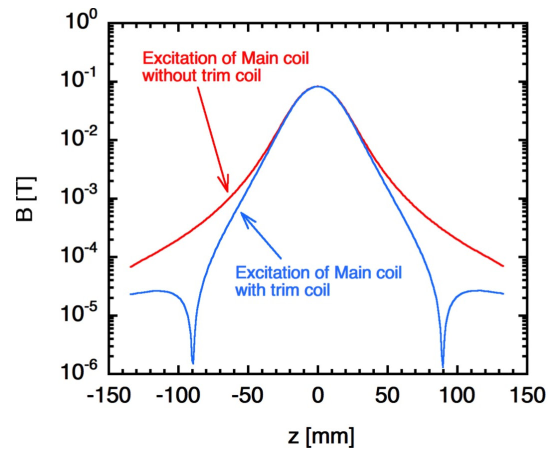
- <u>50 kV electron gun</u>
  - ✓ Electric field strength : < 8 MV/m
- <u>Magnetic lens</u>
  - ✓ Correction coils to reduce leakage field
  - ✓ Metal casing enclosing the magnetic lens
- <u>238 MHz rf cavity</u>
  - ✓ Re-entrant type
  - ✓ Shunt impedance of 6 MΩ
  - ✓ Axially symmetric acceleration field distribution



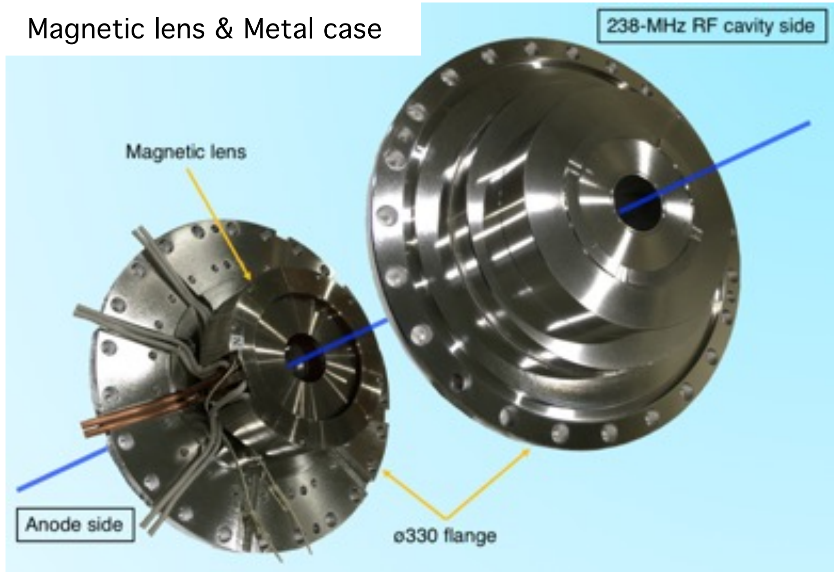
Cross section of magnetic lens



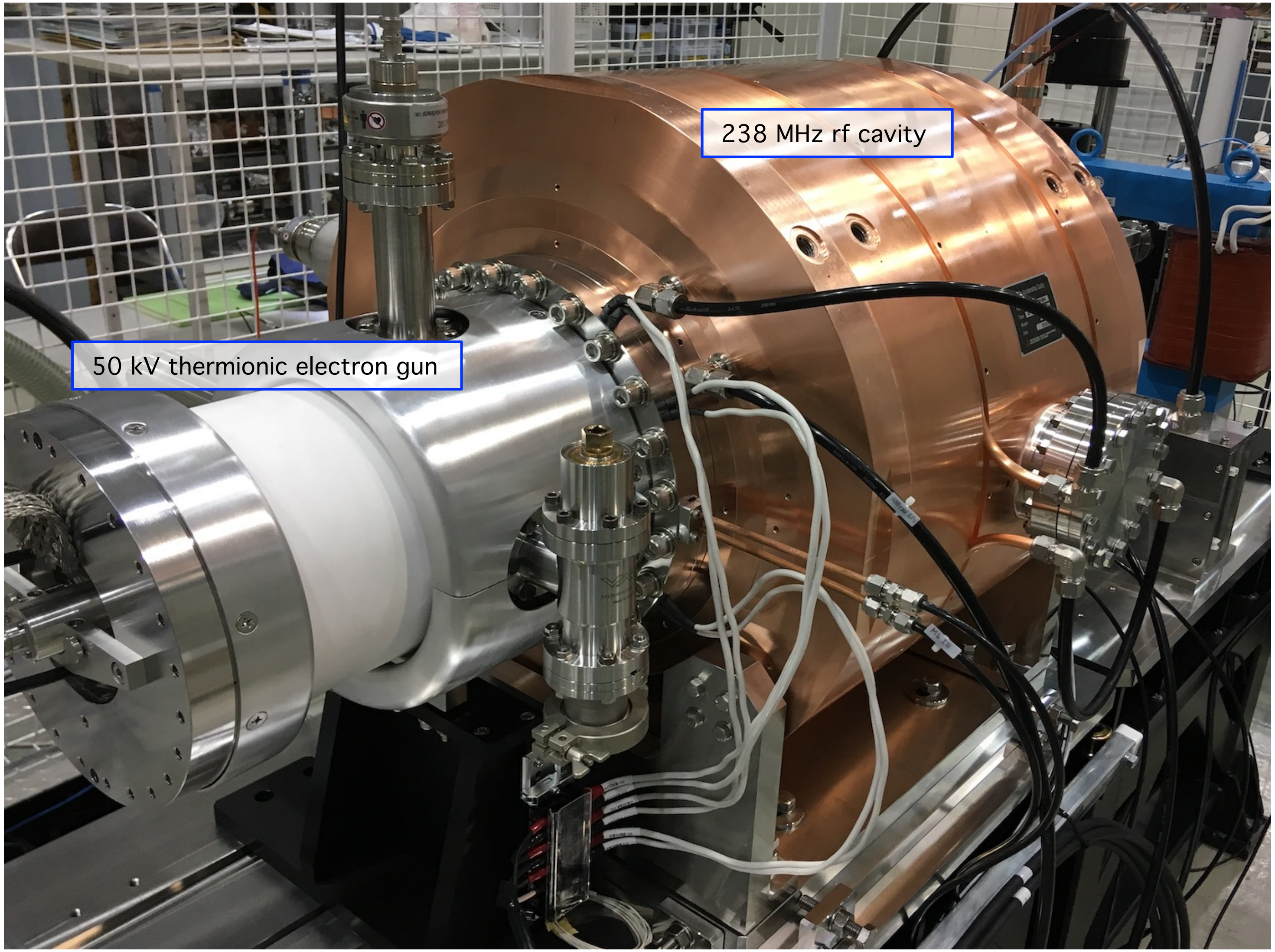
Magnetic field distribution



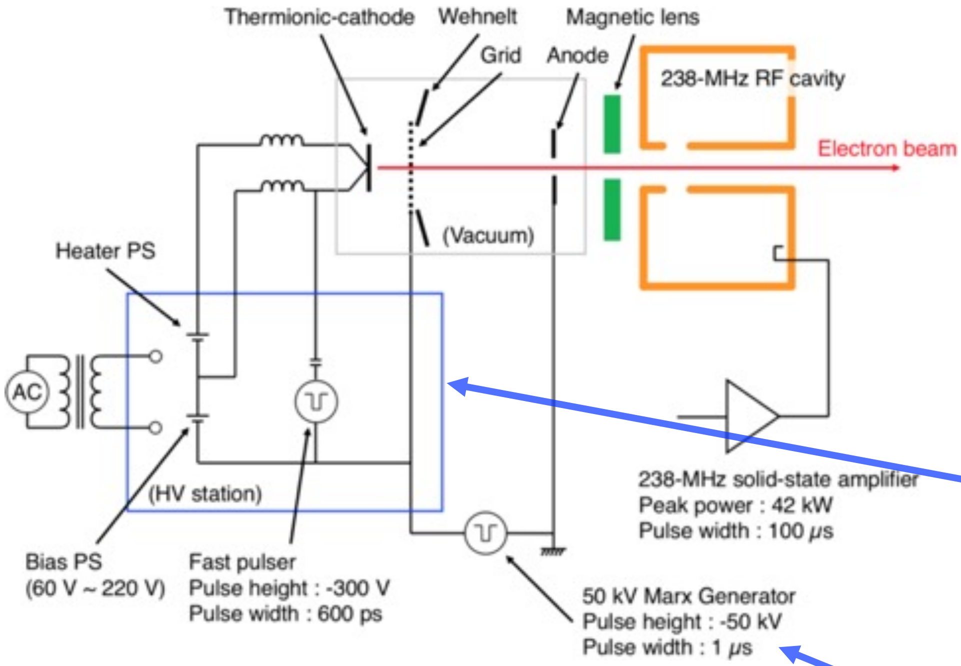
Magnetic lens & Metal case



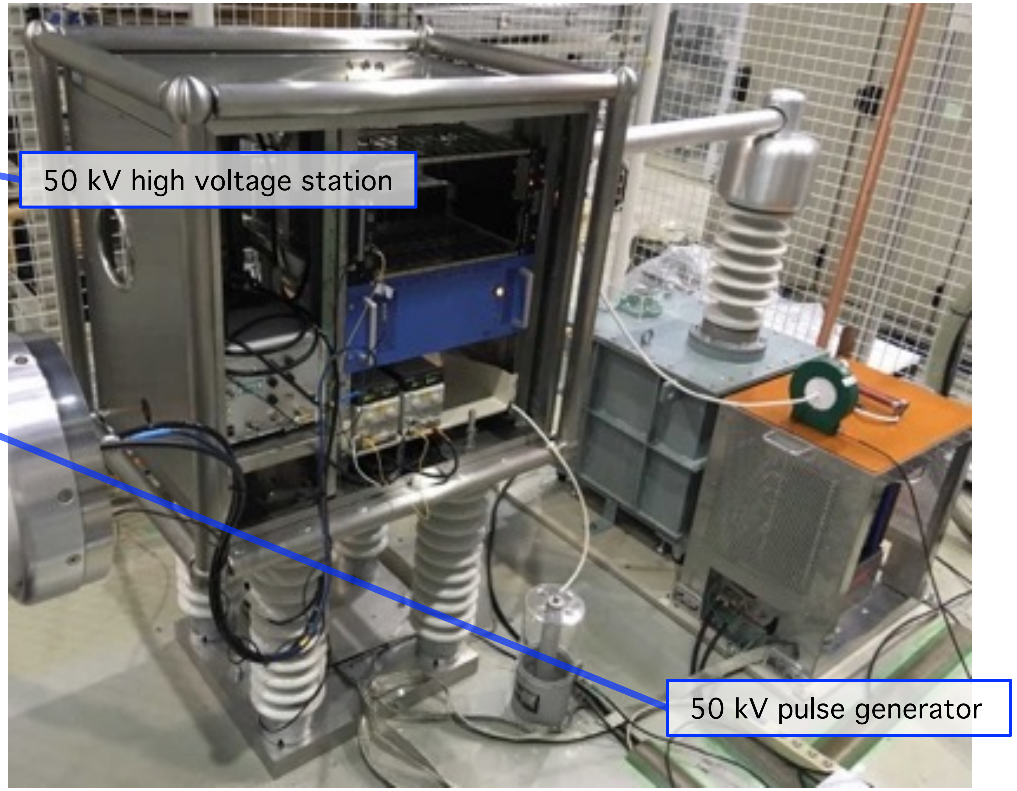
Characteristics of each component of rf electron gun system (cont'd)



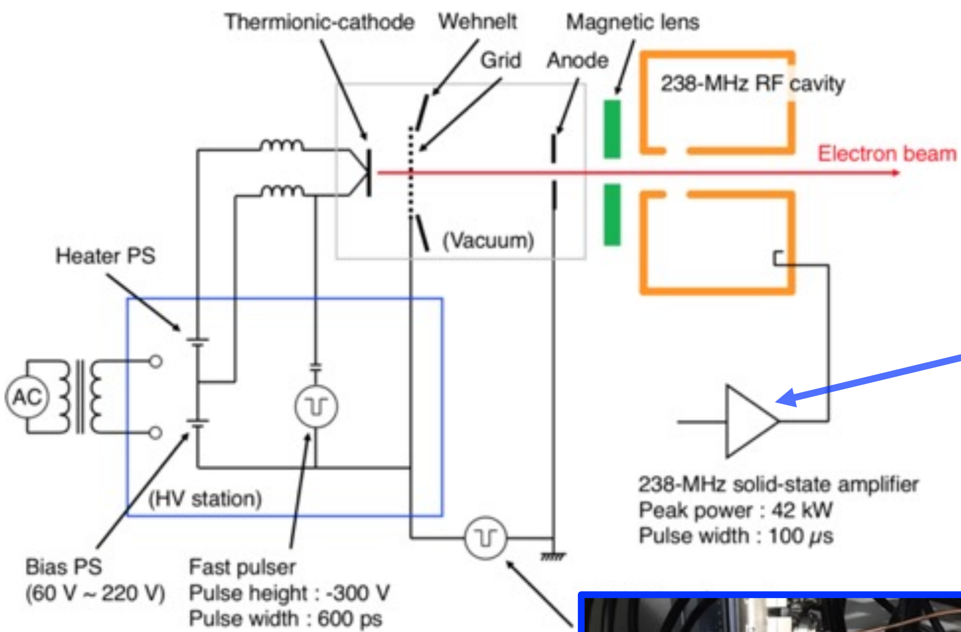
Characteristics of each component of rf electron gun system (cont'd)



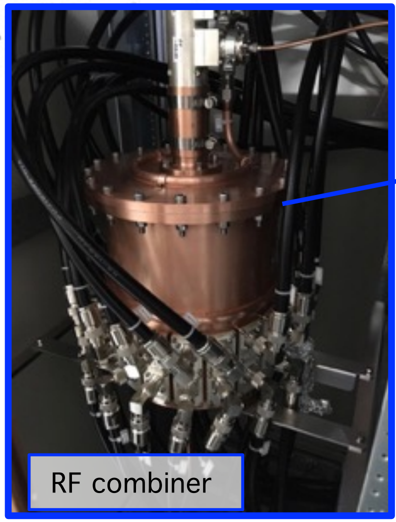
- 50 kV pulse generator
  - ✓ Marx generator using ultra-high voltage SiC MOSFETs.
  - ✓ Voltage fluctuation : < 0.05%

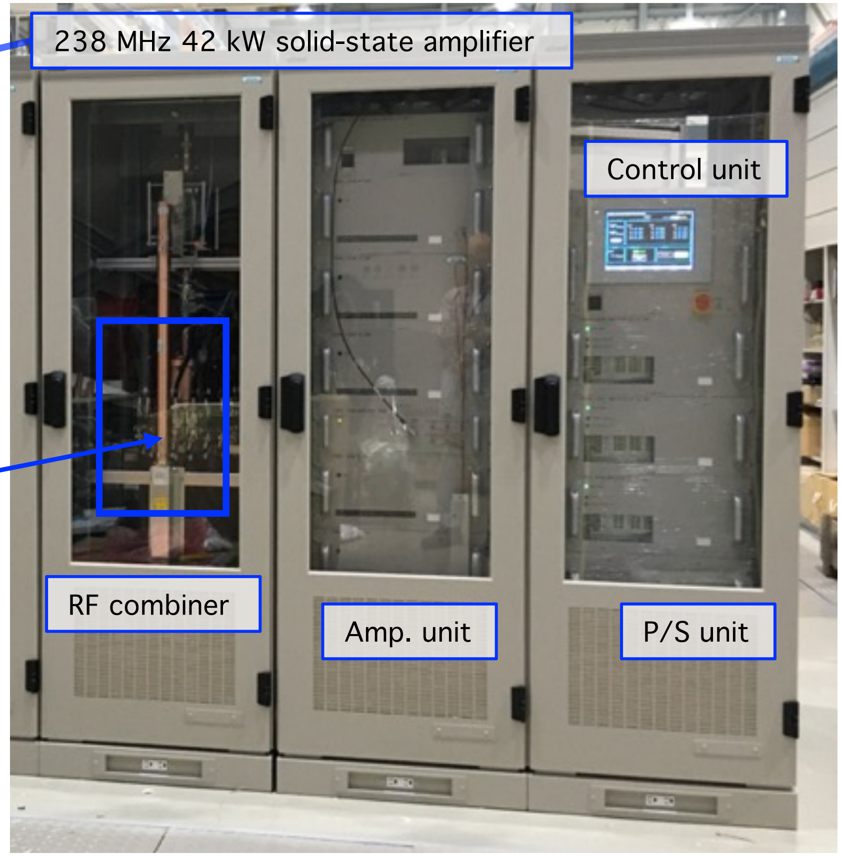


Characteristics of each component of rf electron gun system (cont'd)



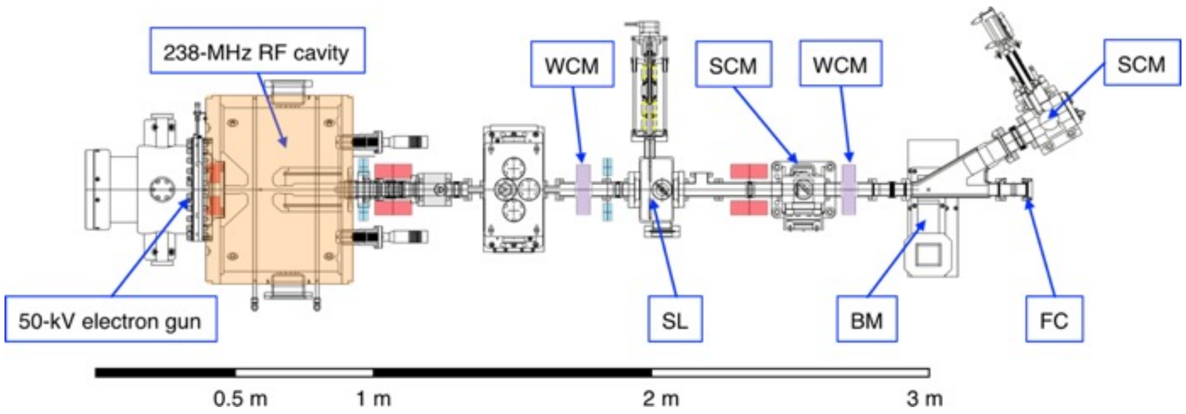
- <u>238 MHz 42kW sold-state amplifier</u>
  - ✓ Power stability : 0.01% (rms)
  - ✓ Phase stability : 0.02° (rms)



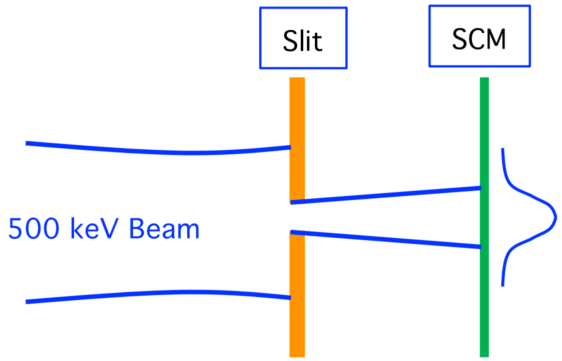


Layout of rf electron gun test stand, beam measurement item

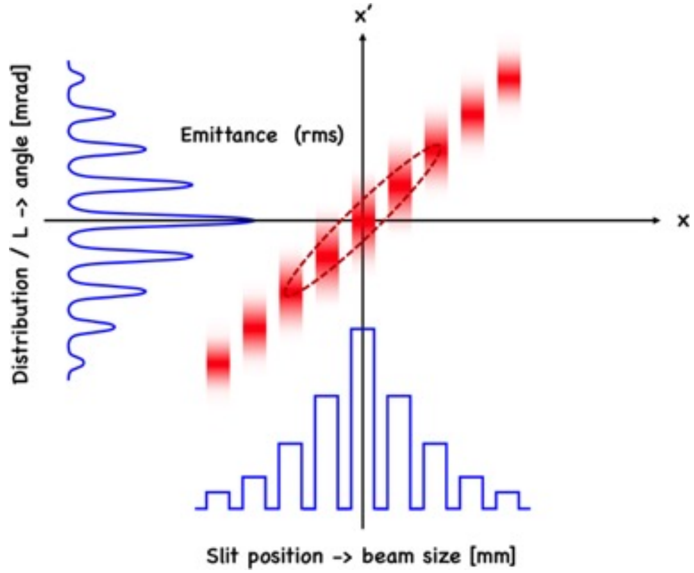
- Energy at the gun exit is measured by TOF between two wall current monitors.
- Beam charge is measured by Faraday cup.
- Beam size is observed by screen monitor.



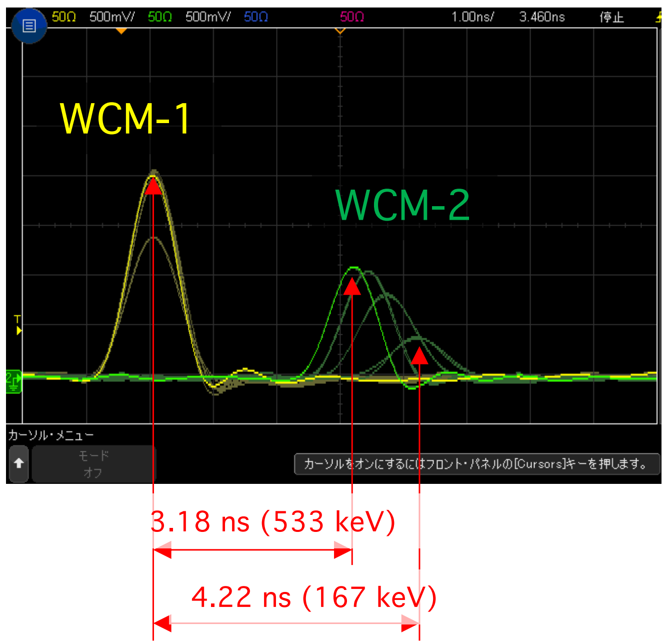
- Emittance is measured by slit scan.

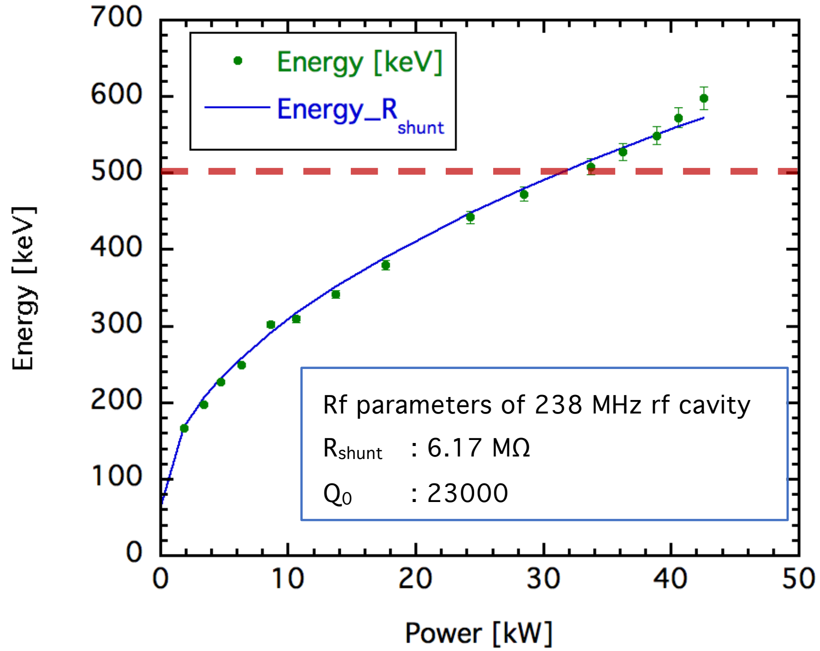


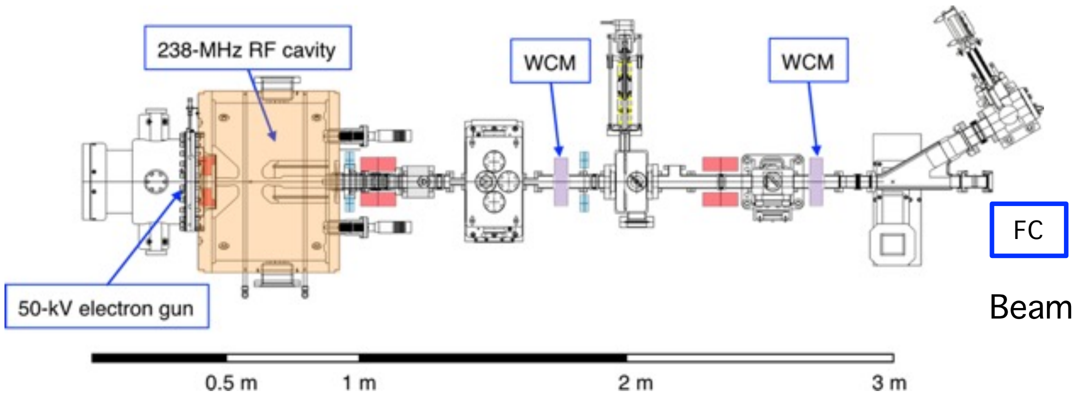
Slit width : 100 µm
Moving step : 250 µm



Energy measurement





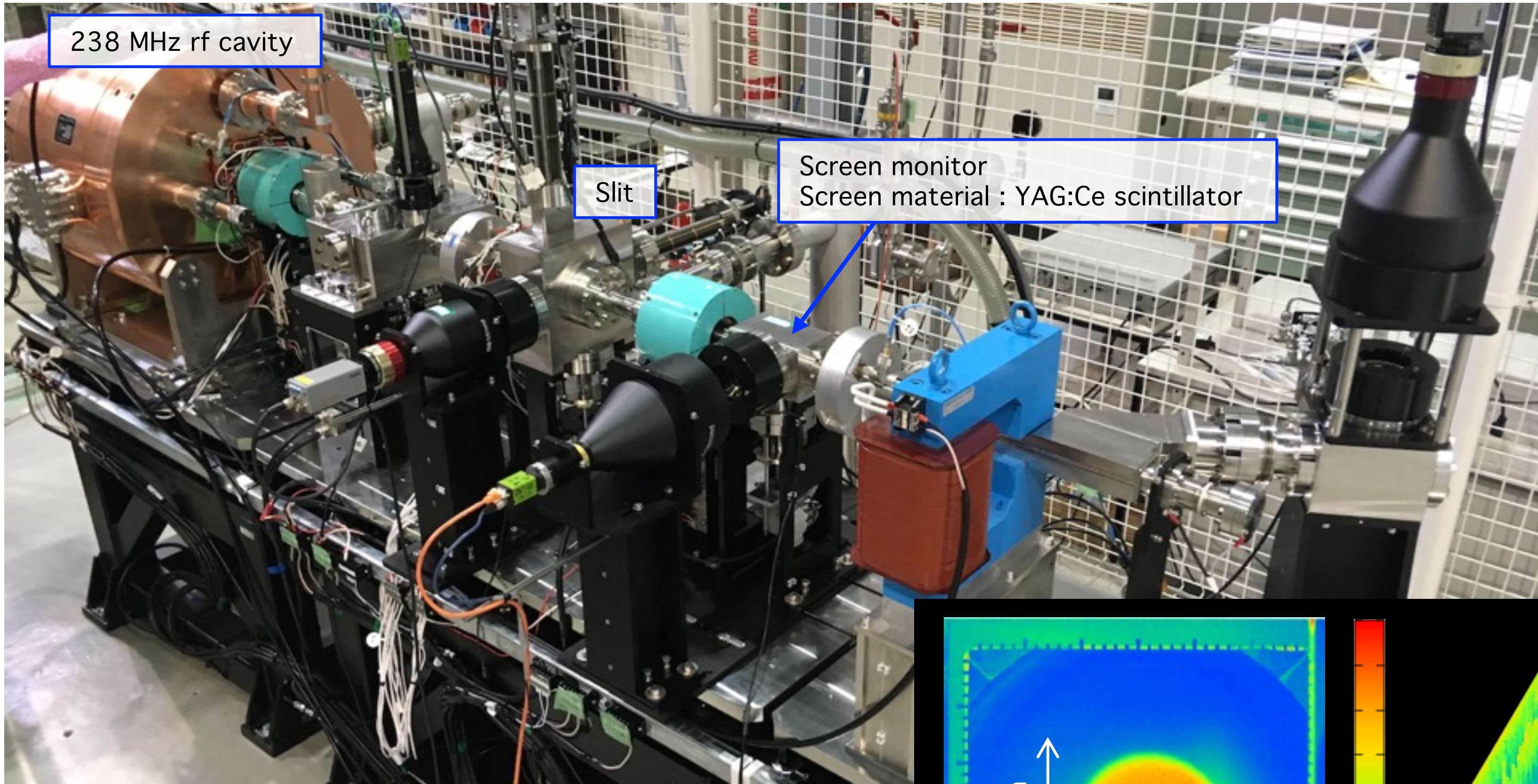


Beam charge : 1 nC

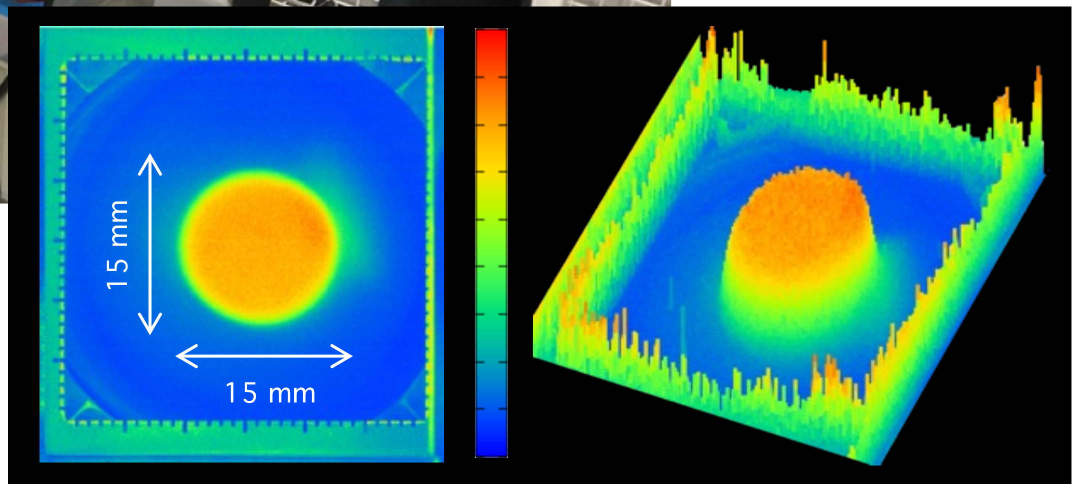
$$\beta = \frac{v}{c} = \frac{l}{\Delta t}\frac{1}{c}$$

$$E = \frac{0.511}{\sqrt{1-\beta^2}} - 0.511$$

Beam size measurement

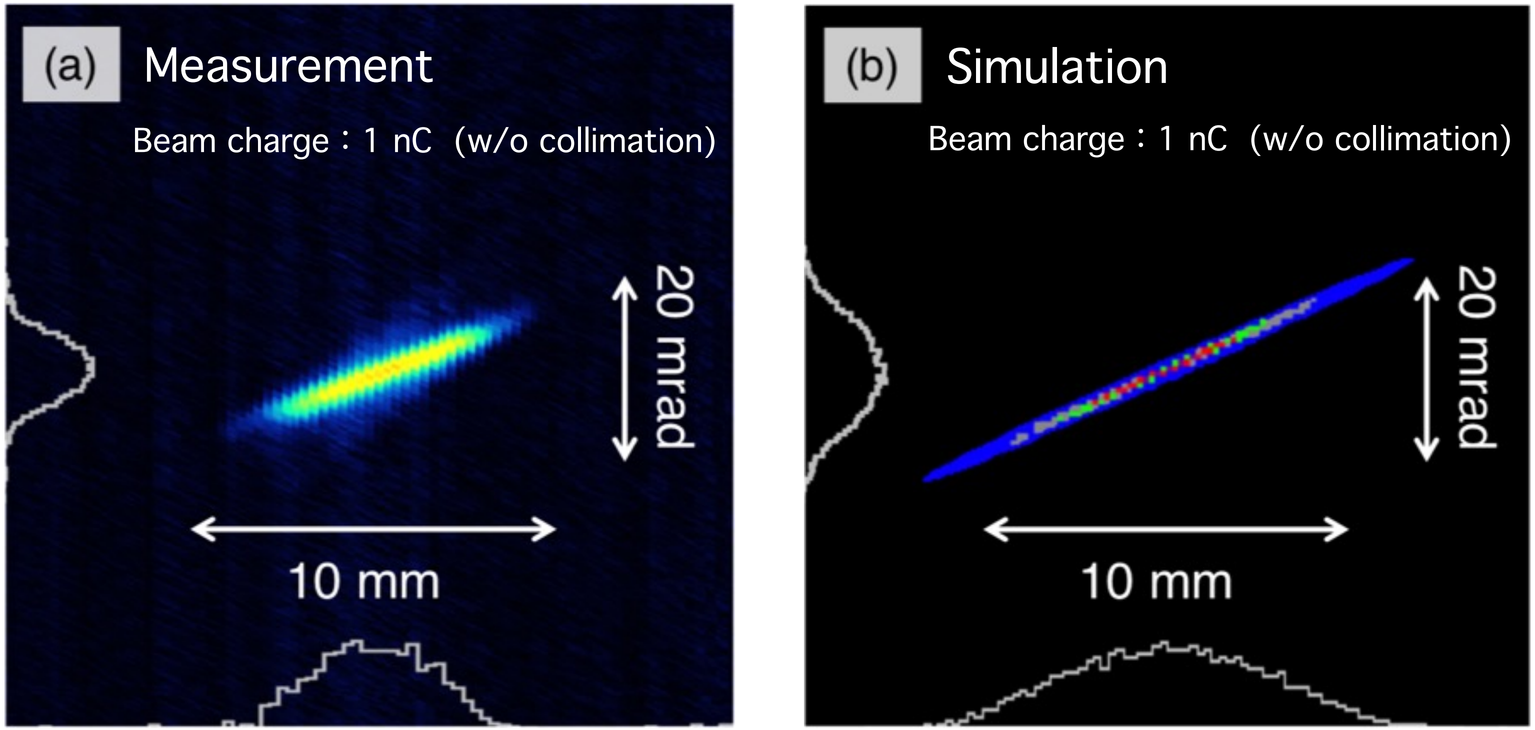


500 keV homogeneous beam is formed.



Emittance measurement

T. Asaka et al., Phys. Rev. Accel. Beams **23**, 063401 (2020)

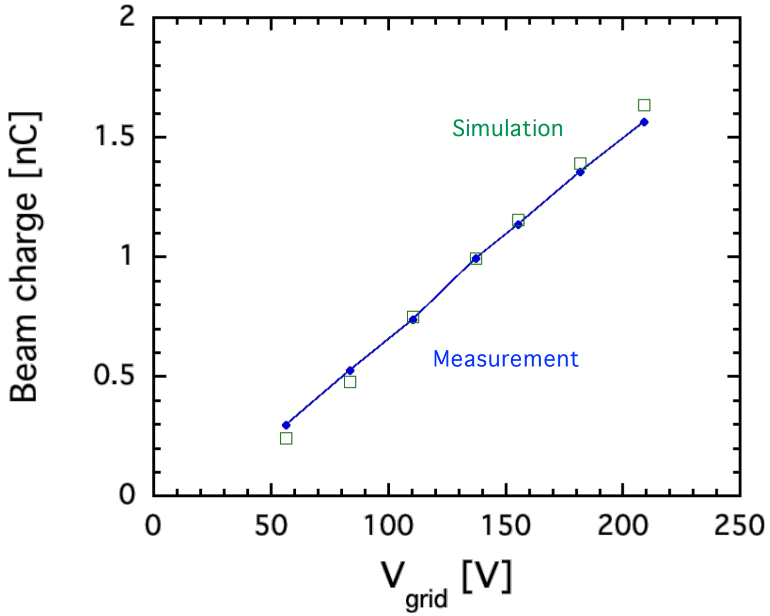


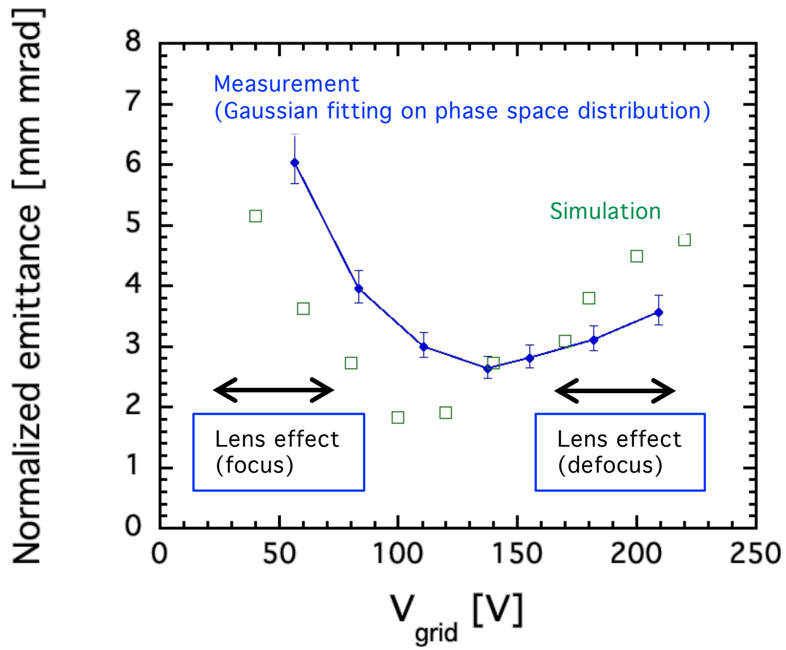
- Normalized ε_x : 3.1 mm mrad (Gaussian fitting)
  : 1.7 mm mrad (rms, 60%)

- Normalized ε_x : 2.0 mm mrad (rms, 60%)

$$\varepsilon_{n,\,rms} = \overline{\beta\gamma}\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x\cdot x'\rangle^2}$$

Cathode-grid voltage vs beam charge, emittance

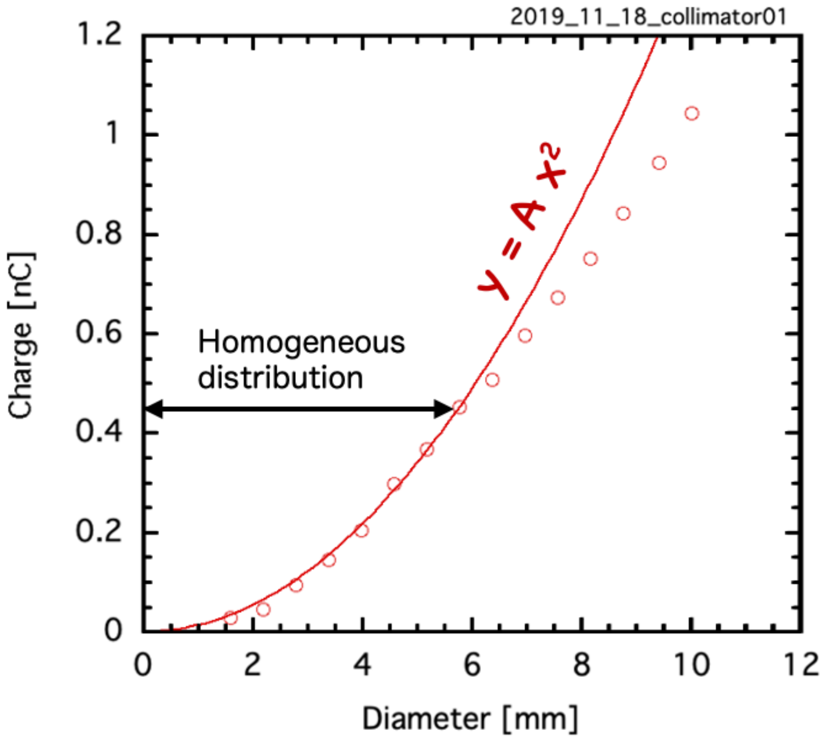




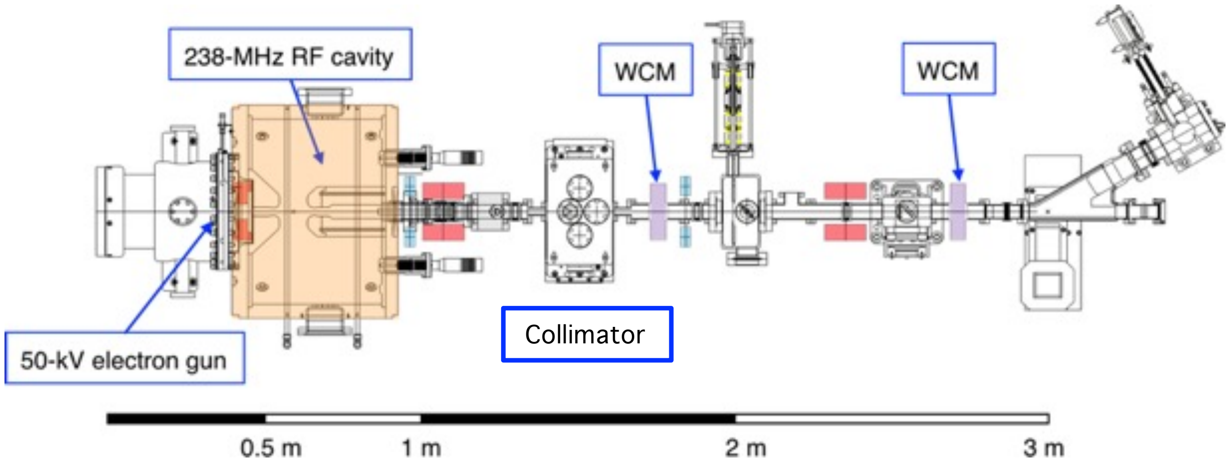
- With increasing the cathode-grid voltage,
  - ✓ Beam charge increases.
  - ✓ Emittance deterioration caused by the lens effect.

- Measurement results show the same trend as the simulation results.
- There is cathode grid voltage at which emittance is at minimum.

Adjustment of beam charge



- In the beam intensity distribution from the rf electron gun, agreement with the quadratic function means the homogeneous beam generation.



Summary

- We developed a low emittance rf electron gun using a commercially available gridded thermionic cathode.
- 50 kV electron gun does not require a large equipment.
- The design takes into account emittance growth due to lens effect near the grid.

  “Transparent grid scheme” ➡ “Homogeneous beam” ➡ “Low emittance beam”
- 50 kV thermionic gun connected to the rf cavity in order to immediately increase the beam energy to 500 keV.
- Our proof of performance experiments were consistent with CST and PARMELA simulations.
- In the beam measurement, normalized emittance of 1.7 mm mrad (60% core part of the whole electrons) was obtained with beam energy of 500 keV and beam charge of 1nC.
- This rf electron gun system is installed in the injector linac of the 1 GeV storage ring “NewSUBARU” at the SPring-8 site to stable operation.
- In addition, this rf electron gun is used for the linear accelerator of the 3 GeV next-generation synchrotron radiation facility currently under construction in Tohoku.
- This rf electron gun system can be used as a practical electron source for soft x-ray free electron laser system.

Thank you for your attention.