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Highly Efficient Field Emission Cathodes Using Carbon Nanotubes

by

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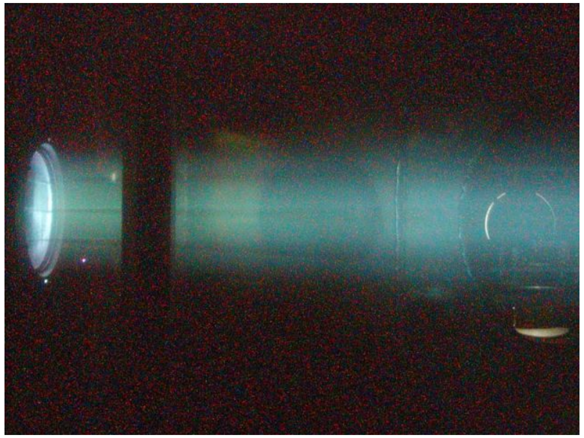
Presentation Outline

- Motivation
  - Demand for small & low-power electron sources
- Objective
  - To develop feasible small cathodes for space application
- Field Emission Cathode Using Carbon Nanotube
  - Fundamentals
  - Desirable characteristics for field emission cathode
- Experiments
  - Laboratory model cathode
  - Current-voltage characteristics
  - Influences of relative potential conditions
  - Long duration test
- Summary

Motivation and Objective

- Demand for small & low-power electron sources
  - Charging relaxation / control of satellites
  - Neutralizer for small electric propulsion
  - Electrodynamic tether (EDT) system
  - Electron sources for space science



Neutralizer for small Ion engines

Electron source for EDT

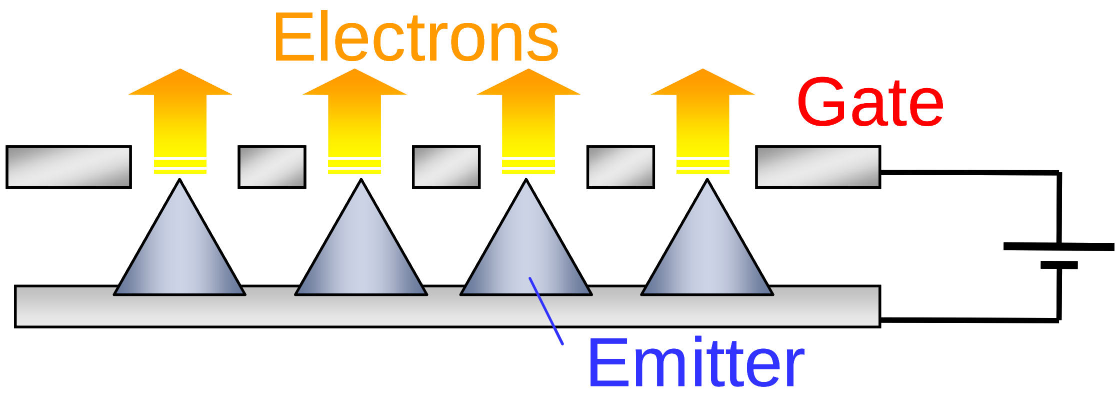
Goal

To develop feasible small cathodes for space applications

Field Emission Cathode (FEC)

- Field Emission
  - Electrons are extracted from emitter tips by applying a strong electric field
  - “Gate” is used for the extraction
  - Electron field on the tips is enhanced by its “sharpness”
- FEC needs neither heater power nor consumables

  ➡ *Small, Simple, Low-power*

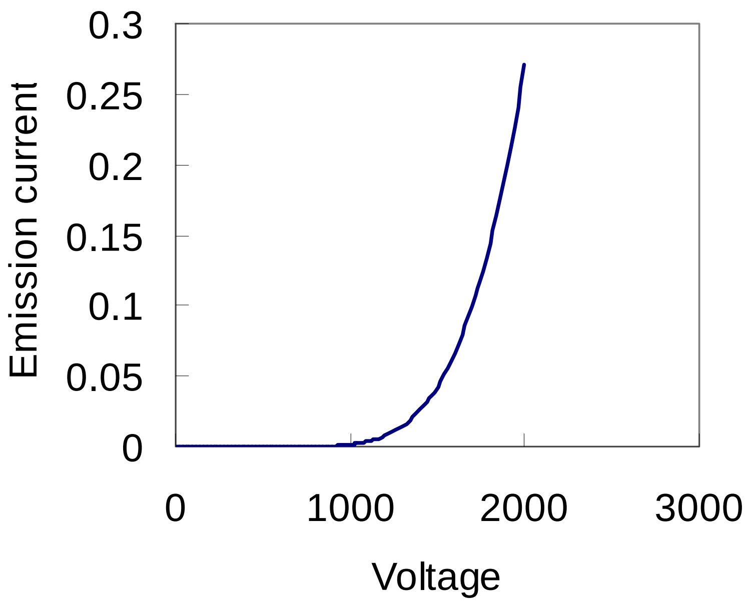


Fowler-Nordheim Equation

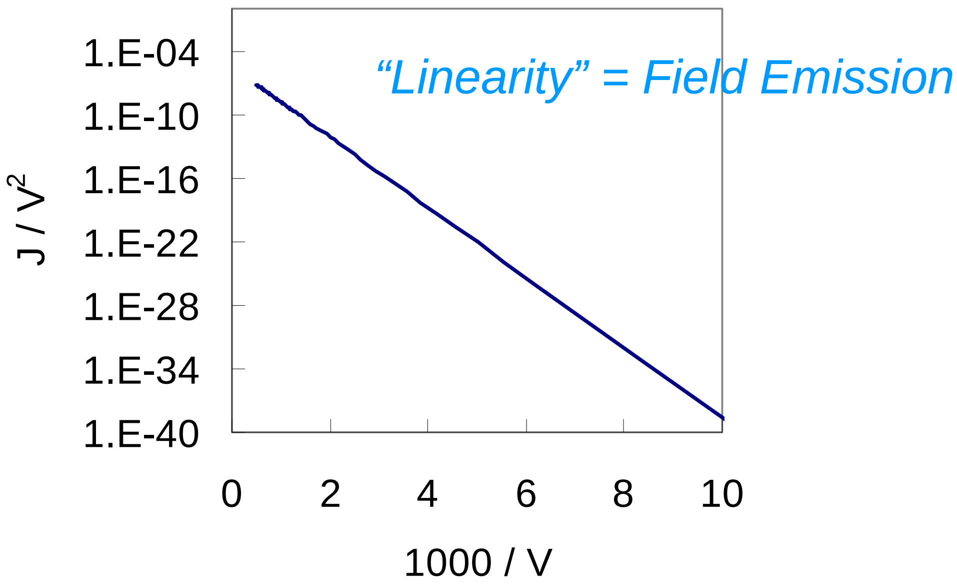
- Field emission current is described by the Fowler-Nordheim (F-N) equation:

$$j_e = \frac{e^3 F^2}{8\pi h \phi} \exp\left(-\frac{8\pi\sqrt{2m}}{3heF} \phi^{3/2} \right)$$

$$F = \beta E = \beta \frac{V}{d}$$



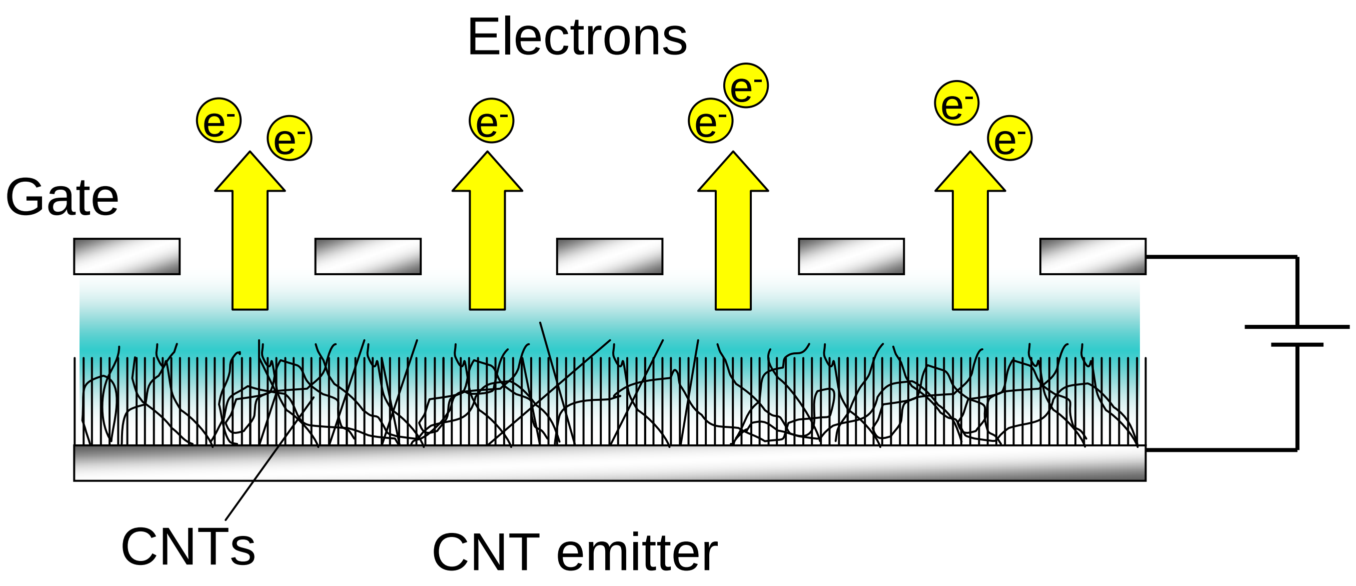
I-V Characteristics



Fowler-Nordheim (F-N) plot

Carbon Nanotube Cathode

- Carbon nanotube (CNT) cathode is a type of field emission cathode
  - CNTs are used as “emitter tips”
  - CNT has Nanometer-scale tube-diameter
  - High β (field enhancement factor) can be expected
  - CNT is tolerable to ion impingement
  - Low-cost manufacturing

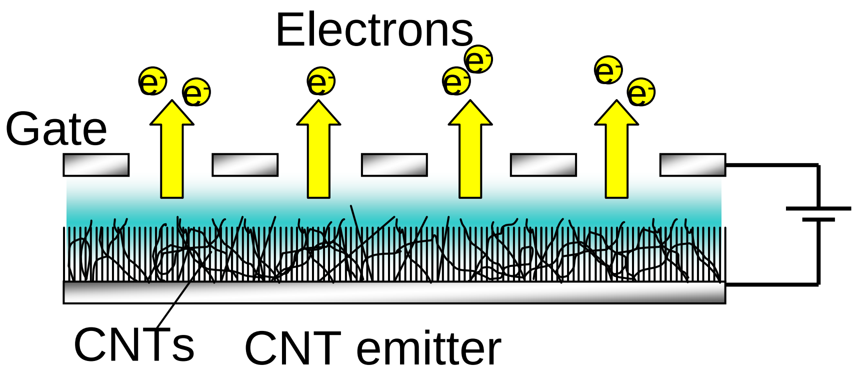


Desirable Characteristics for FECs

- Low extraction voltage
- High extraction efficiency
- Low contact voltage
- High durability

Low extraction voltage

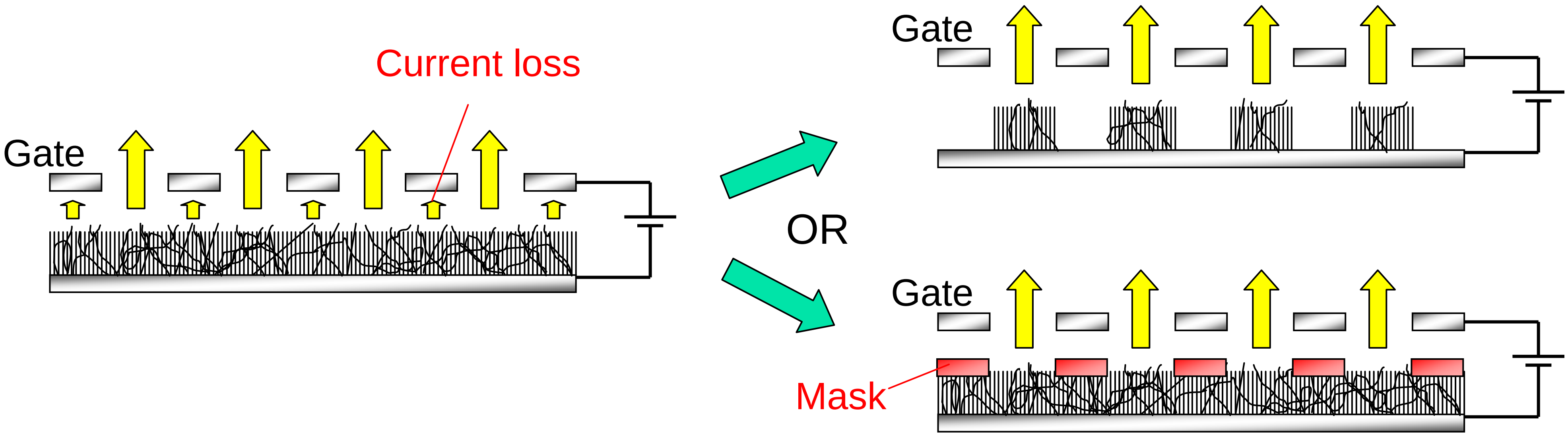
- It is good for
  - Reducing power consumption
  - Avoiding high-voltage-breakdowns
- It requires
  - Decreasing emitter-gate distance
  - Using high "β" emitter tips
  - Using low "ϕ" emitter material



Desirable Characteristics for FECs

High extraction efficiency

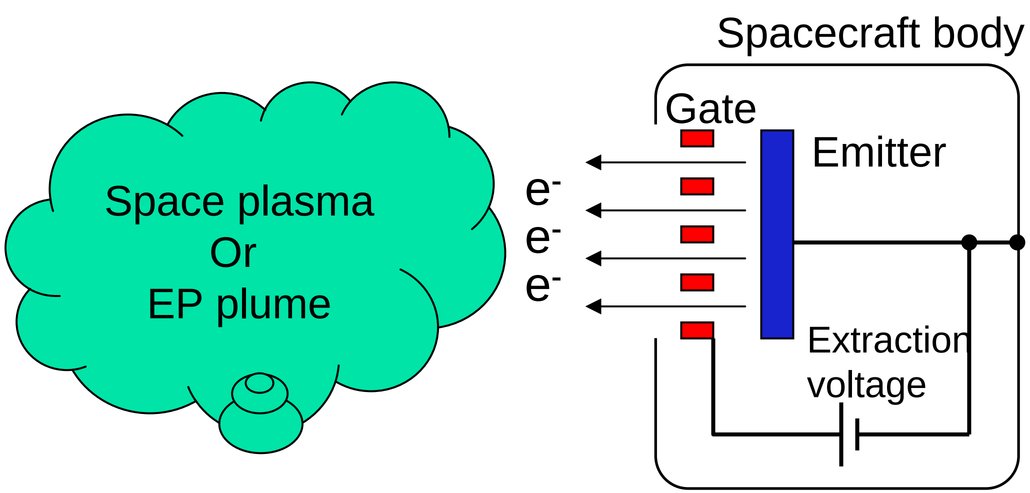
- It is good for
  - Reducing power consumption
  - Suppressing thermal load
- It requires
  - Geometrical treatment for decreasing electron flow to gate



Desirable Characteristics for FECs

Low Contact Voltage

- It is good for
  - Operational at various potential conditions
  - Reducing acceleration loss of EP
  - Reducing voltage loss in EDT



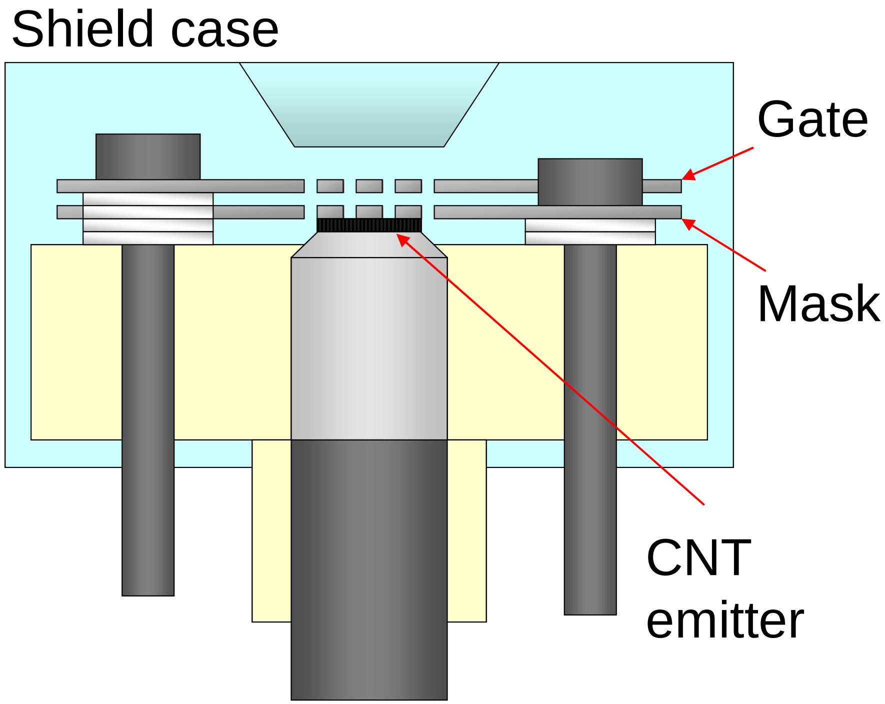
- Spacecraft potential = Emitter potential (Vs/c = Ve)
- Vs/c should be lower than plasma space potential (or EP plume potential)
- This potential difference depends on sheath condition around spacecraft
- This potential difference is better to be small

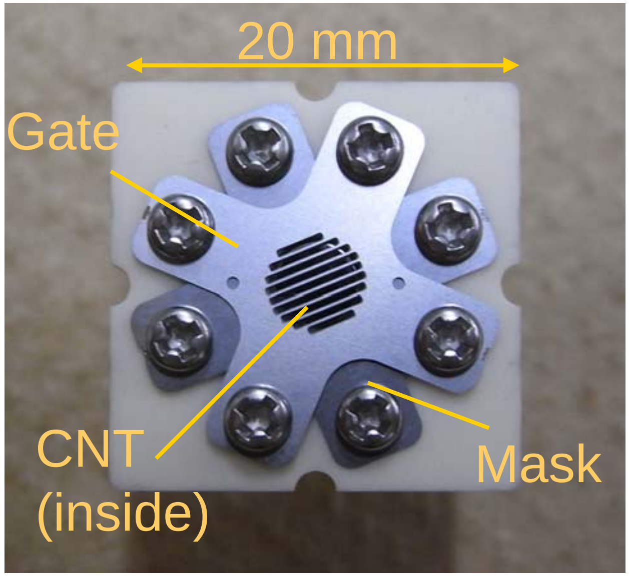
Desirable Characteristics for FECs

High Durability

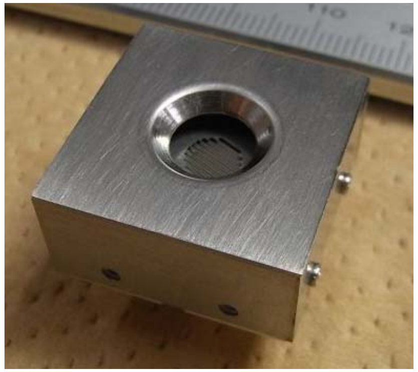
- It is good for
  - Long term operation
- It requires
  - Tolerable emitter material against space environment
    - Ion impingement, atomic oxygen, uv, …

Laboratory-Model Cathode 1 (LM1)





w/o shield case



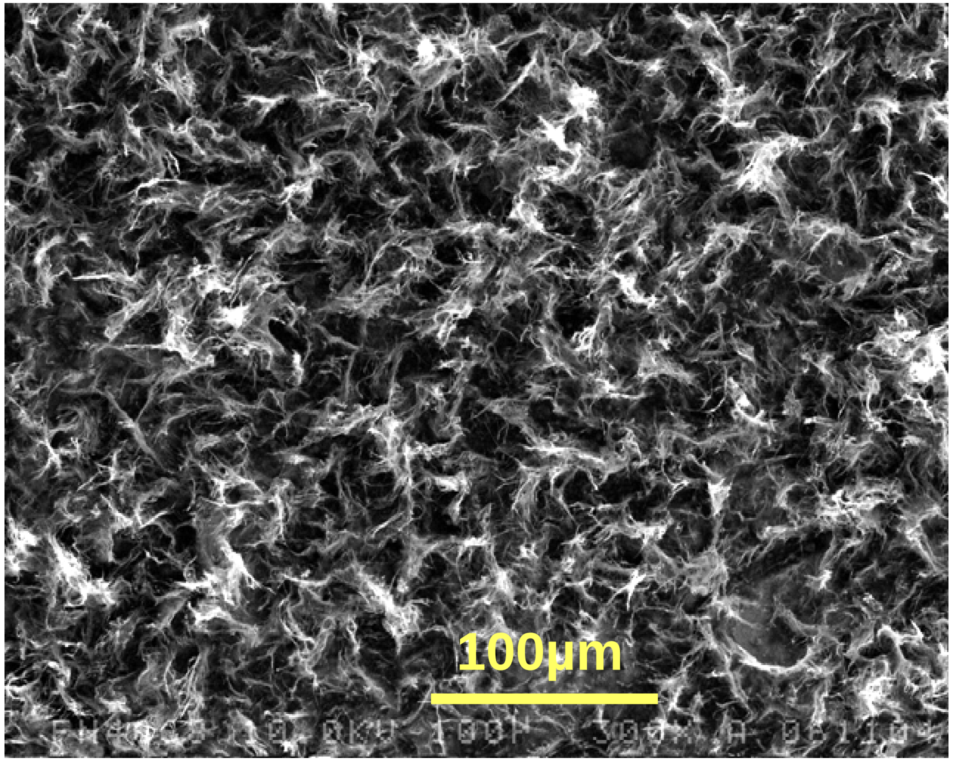
w/ shield case

Size: 20 x 20 x 30 mm
Mass: 24 g

CNT Emitter

- Multi-wall nanotubes by arc discharge method
- Fluffy nanotubes are complexly intertwined
- Many emission sites (tube tips) are distributed randomly

CNT emitter
(JFE Engineering Corp)



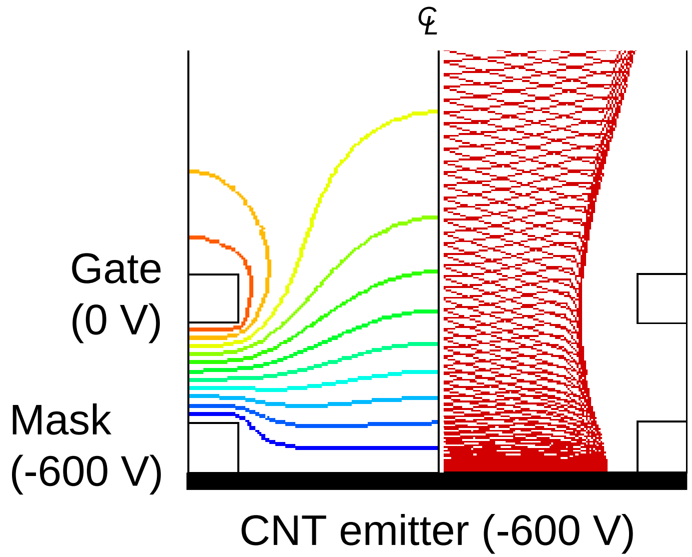
SEM image of emitter surface

Role of Mask Electrode

- Mask electrode is placed on emitter surface
- Role of the mask
  - To cover unnecessary emitter area
  - To make electron trajectories converge by distorting the field

- Current loss to gate is suppressed
- High extraction efficiency

-550 to 50 V @ 50 V interval

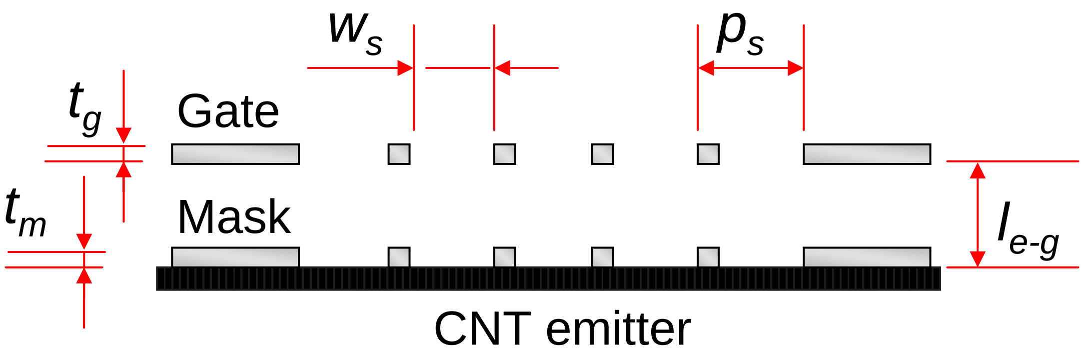


Trajectory calculation

Left: Electrical potential contours

Right: Electron trajectories

Geometrical Parameters of Electrodes

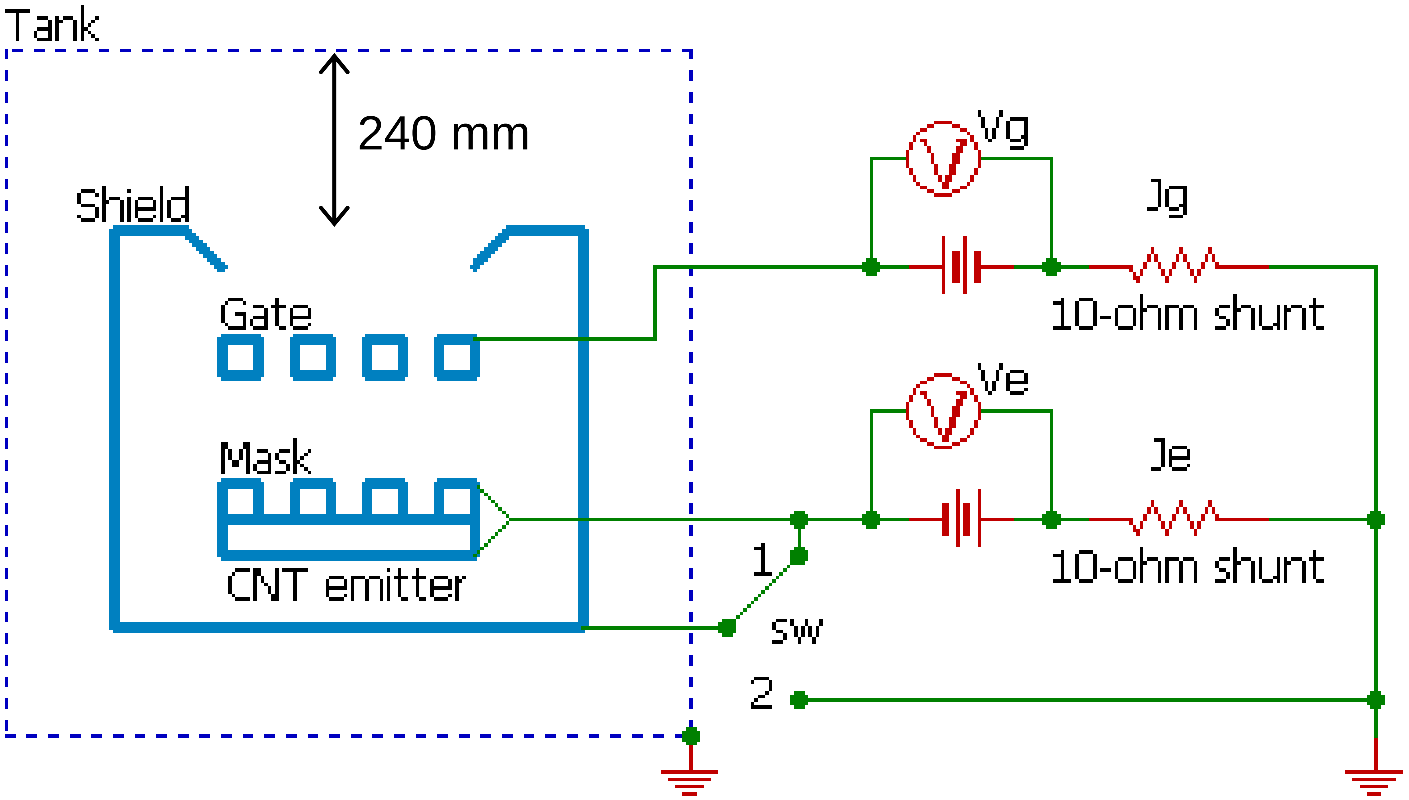


[μm]

Gate thickness, t_g	50
Mask thickness, t_m	50
Emitter-gate distance, $l_{e\text{-}g}$	160
Slit pitch, p_s	500
Slit width, w_s	400

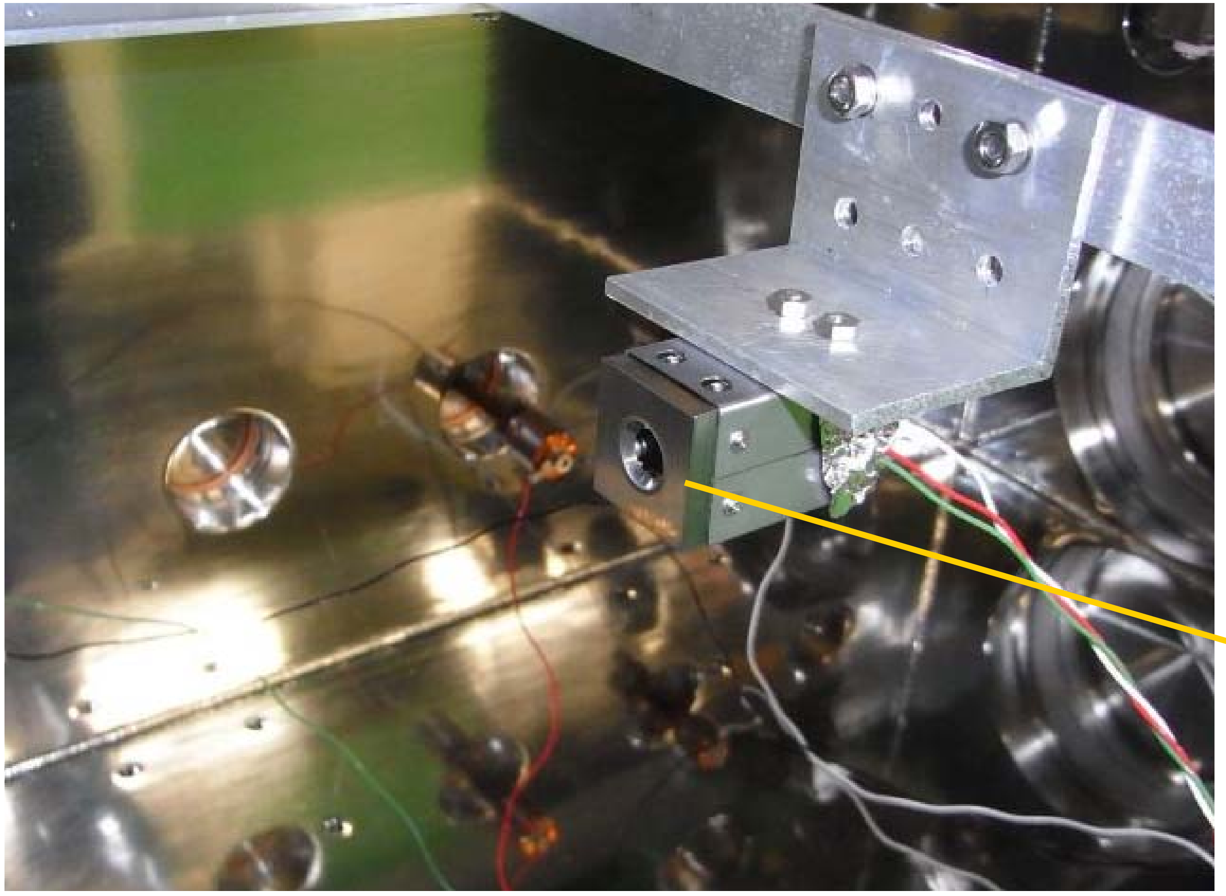
Circuit for Cathode Operation

- Vacuum tank simulates ambient plasma (or EP plume)
- Shield case simulates spacecraft body
- Various potential conditions are simulated by two power conditioners



Cathode Setup

P = 5 x 10^{-5} Pa



FEC

Experimental Results

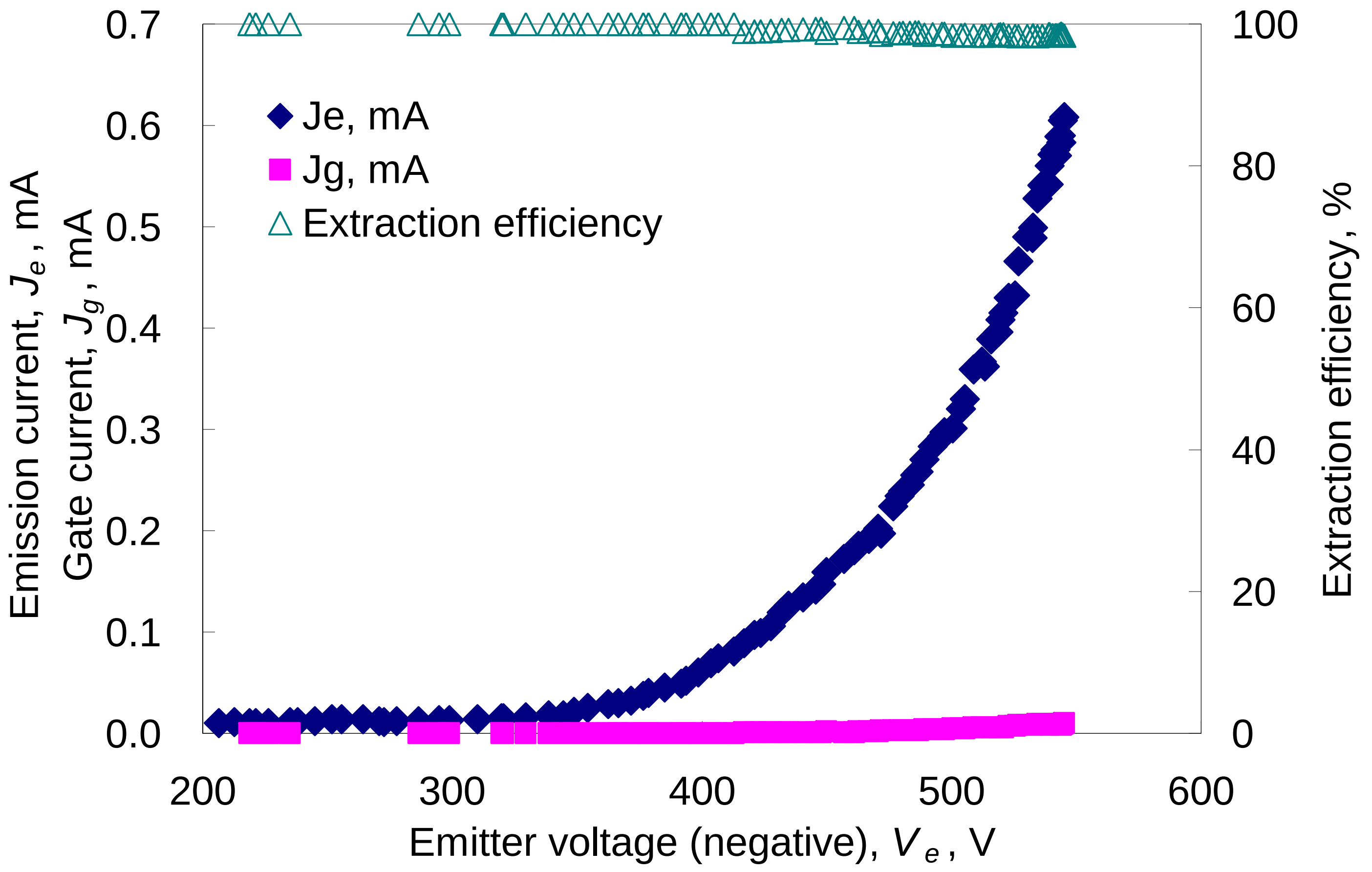
- Current-Voltage characteristics

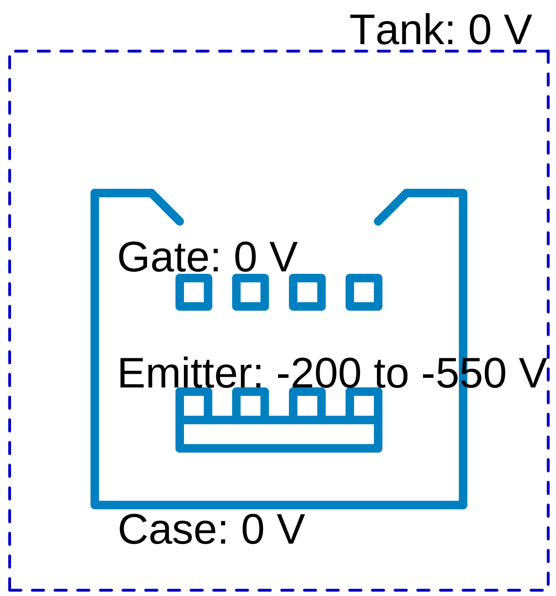
- Influences of relative potential conditions

- Long duration test

Current-Voltage Characteristics

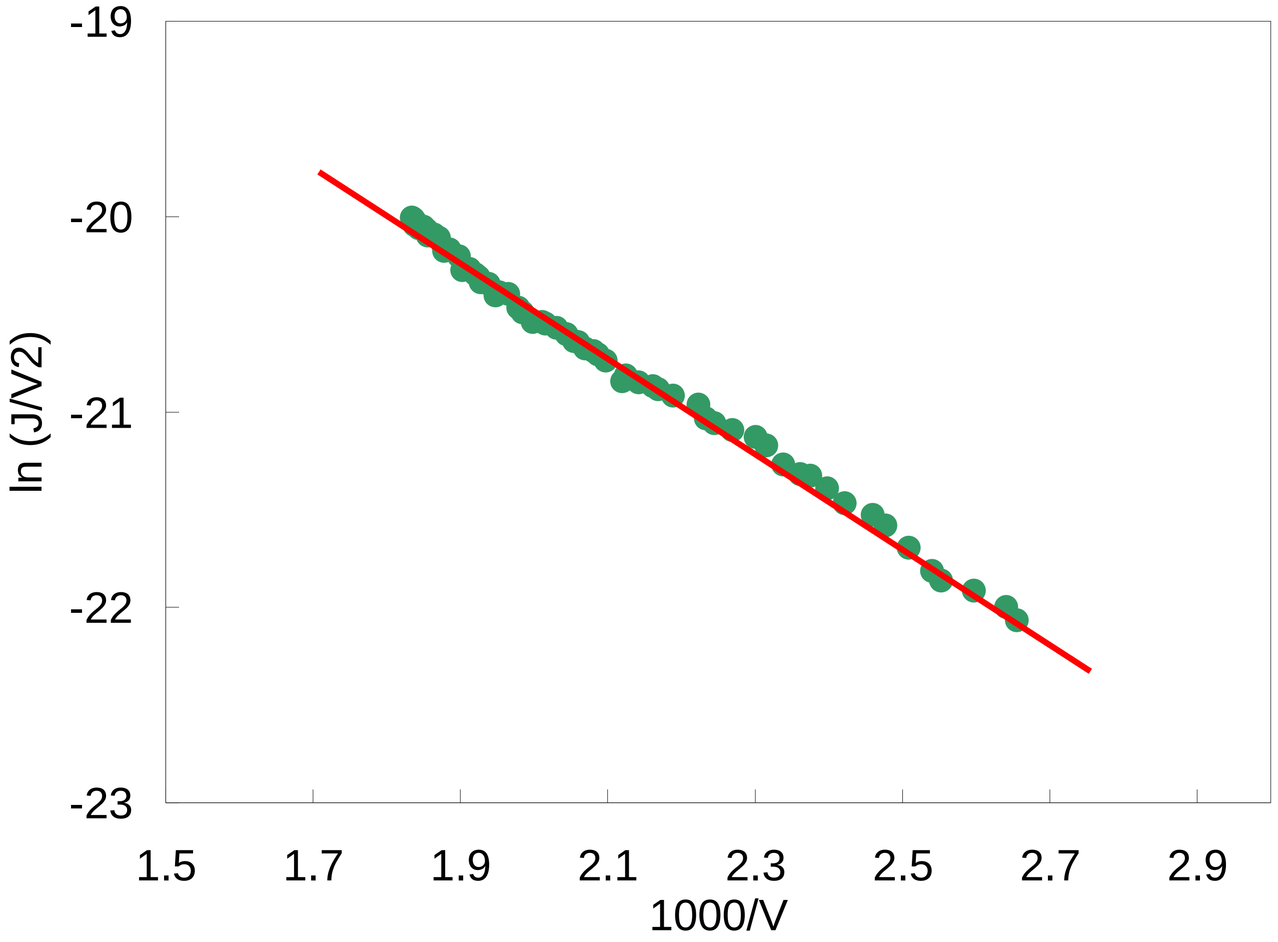
- Ve = -200 to -550 V
- Vg = Vs = 0 V





Current-Voltage Characteristics

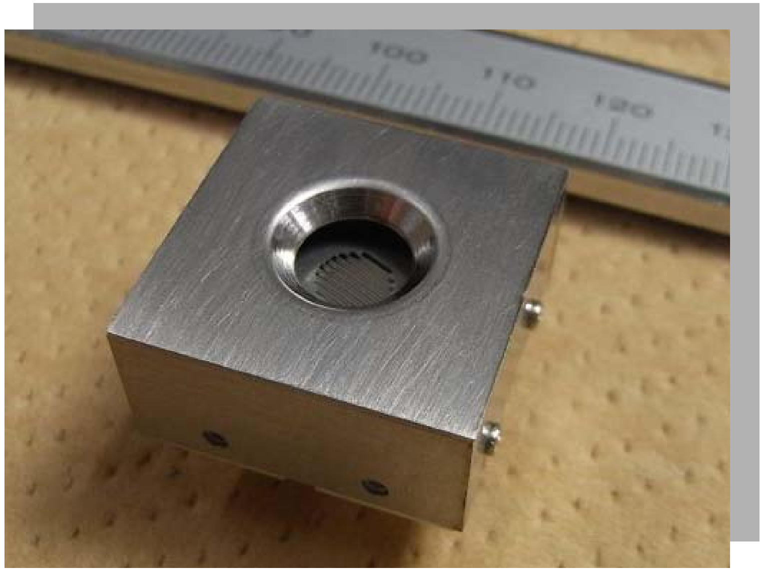
- Fowler-Nordheim plot



High linearity is a good indication that the current is attributable to “field emission”.

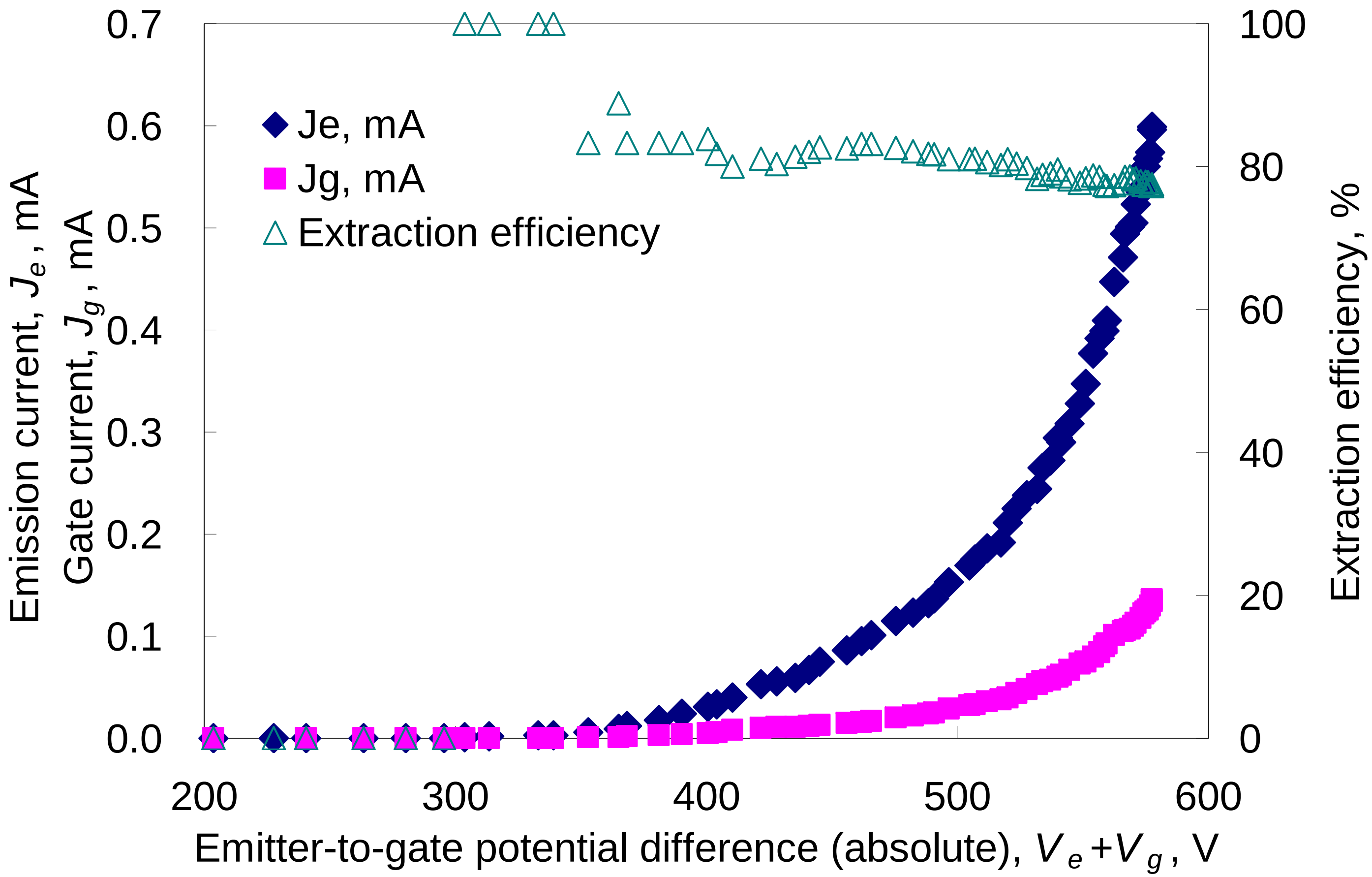
Specs of LM1 Cathode

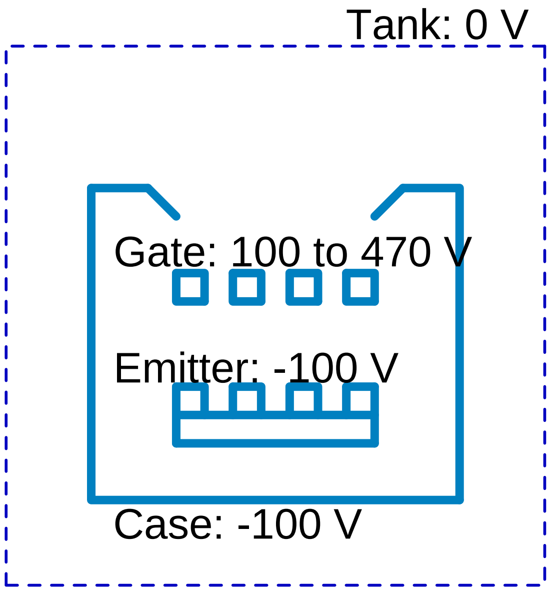
- Size: 20 x 20 x 30 mm
- Mass: 24 g
- Emission current: 0.6 mA
- Diameter of emitter: 4 mm
- Required voltage (BOL): 550 V
- Extraction efficiency: 98%



Influences of Relative Potential Conditions

- Ve = Vs = -100 V
- Vg = 100 to 470 V

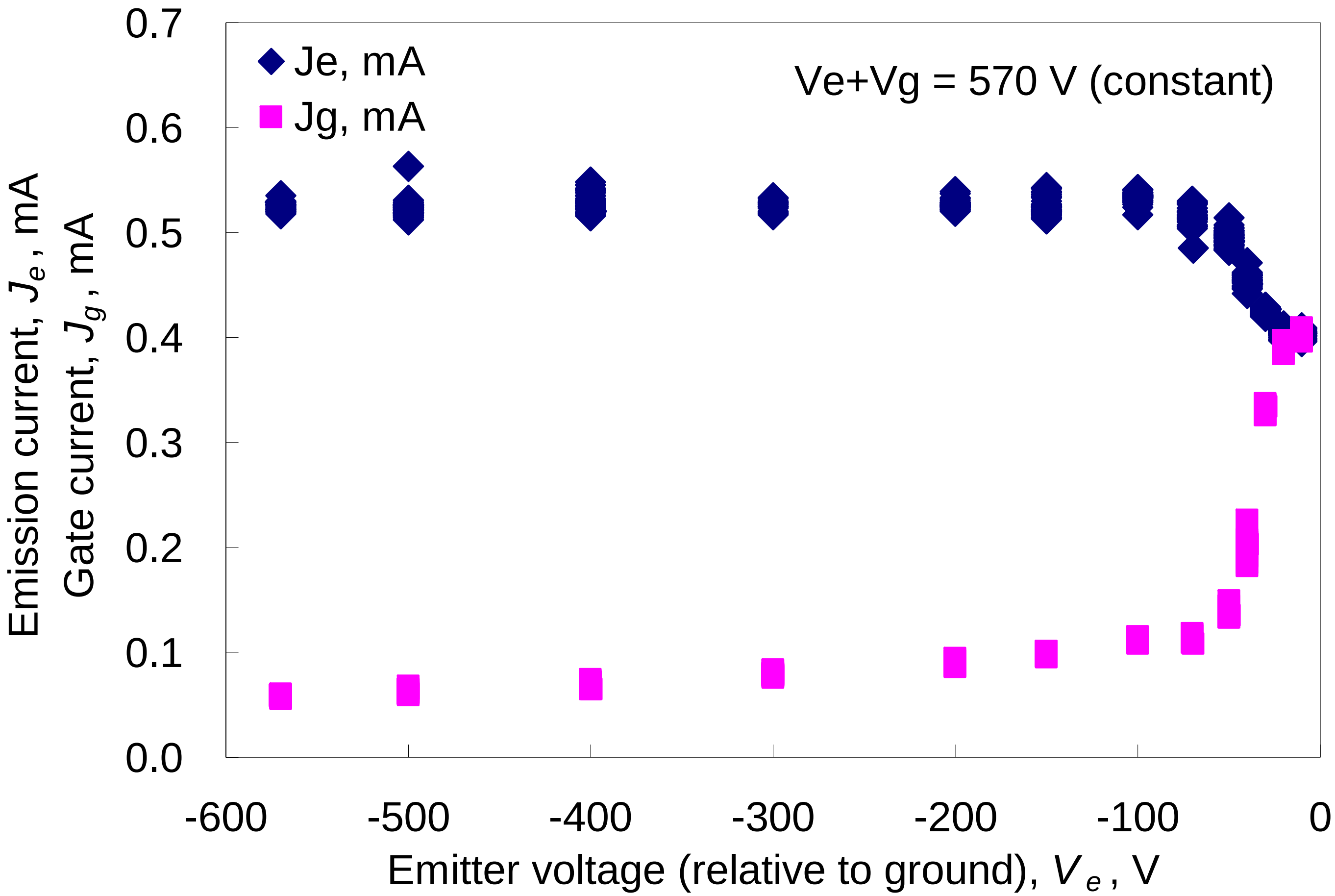


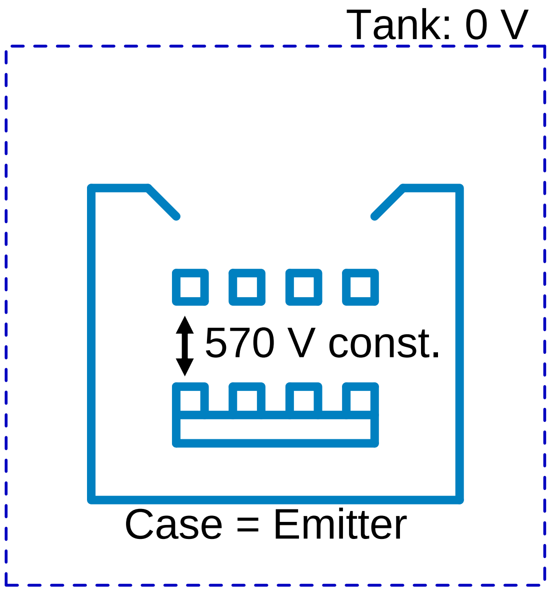


Influences of Relative Potential Conditions

Emission current and Gate current

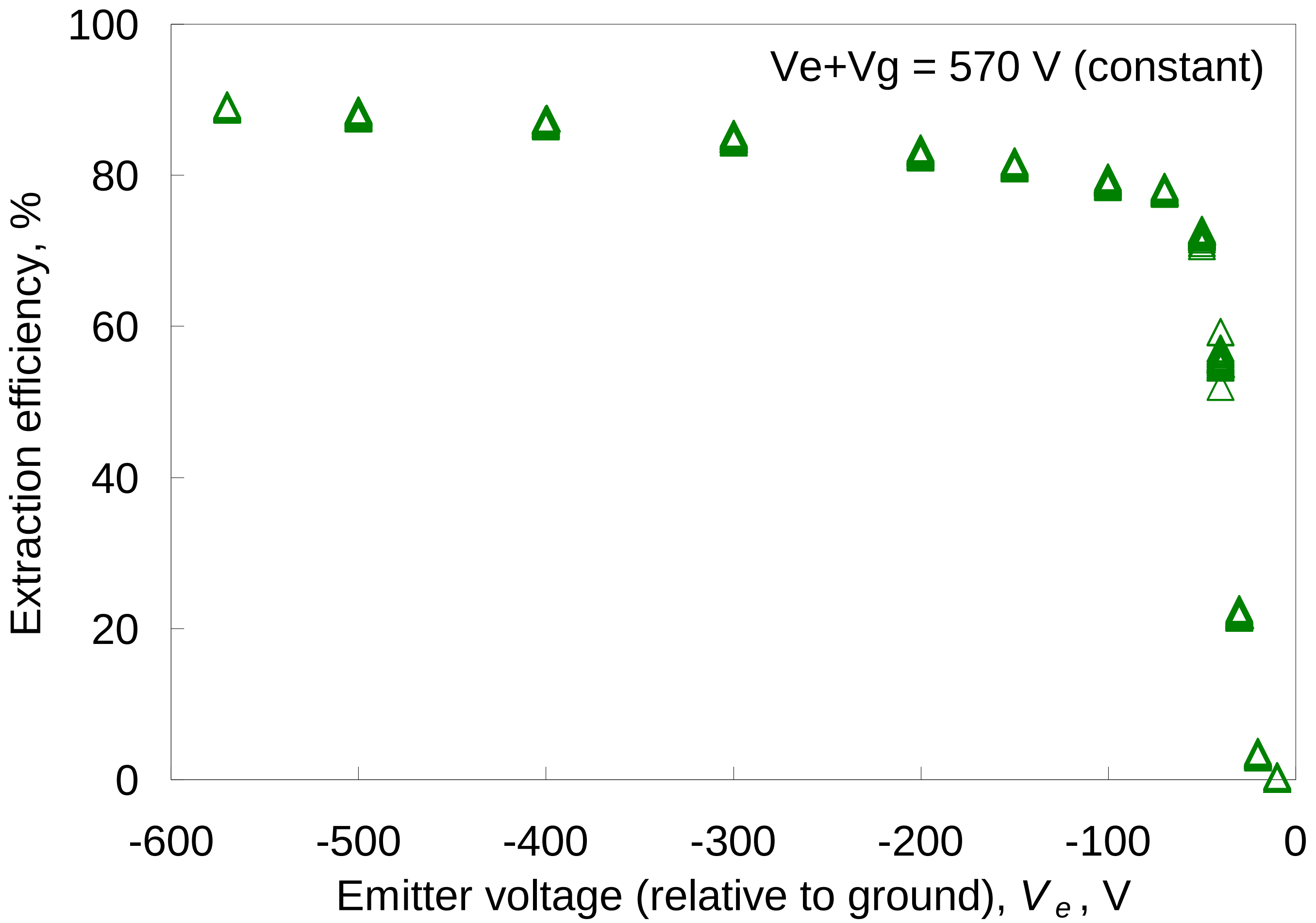
■ Ve = Vs

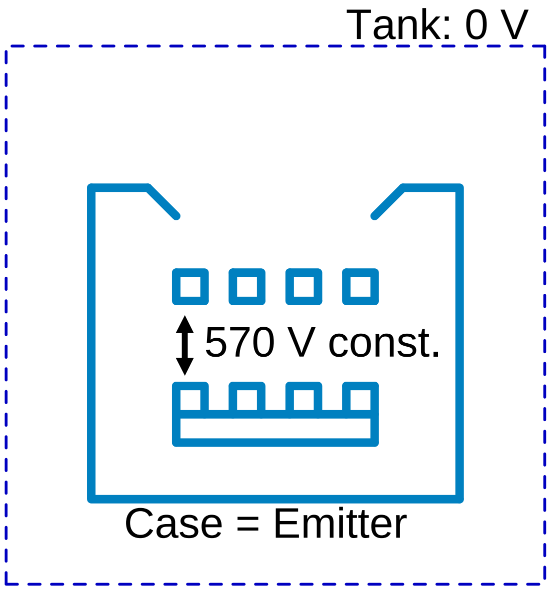




Influences of Relative Potential Conditions

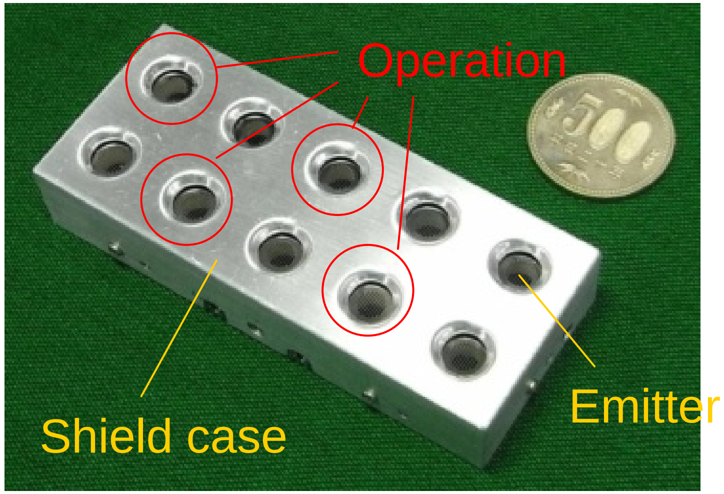
Extraction efficiency

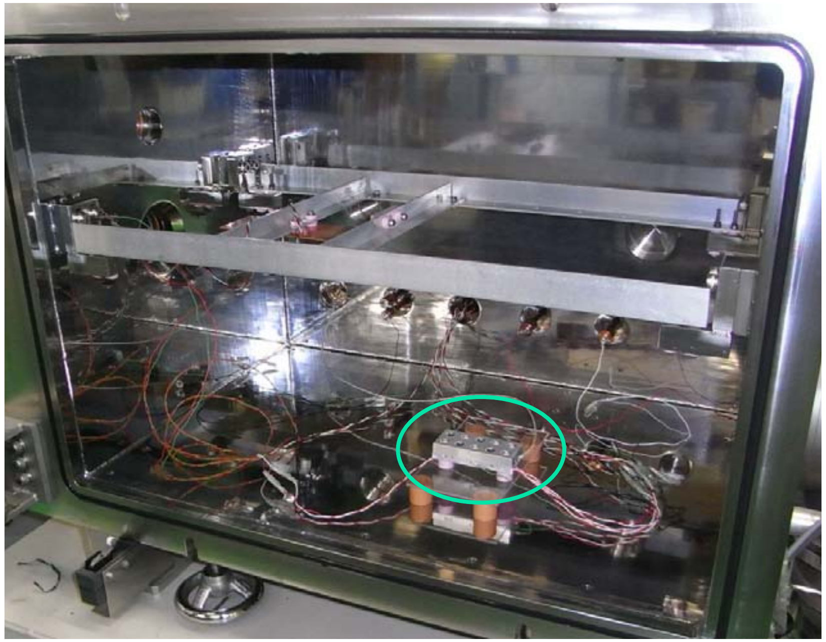




1000-Hour Operation

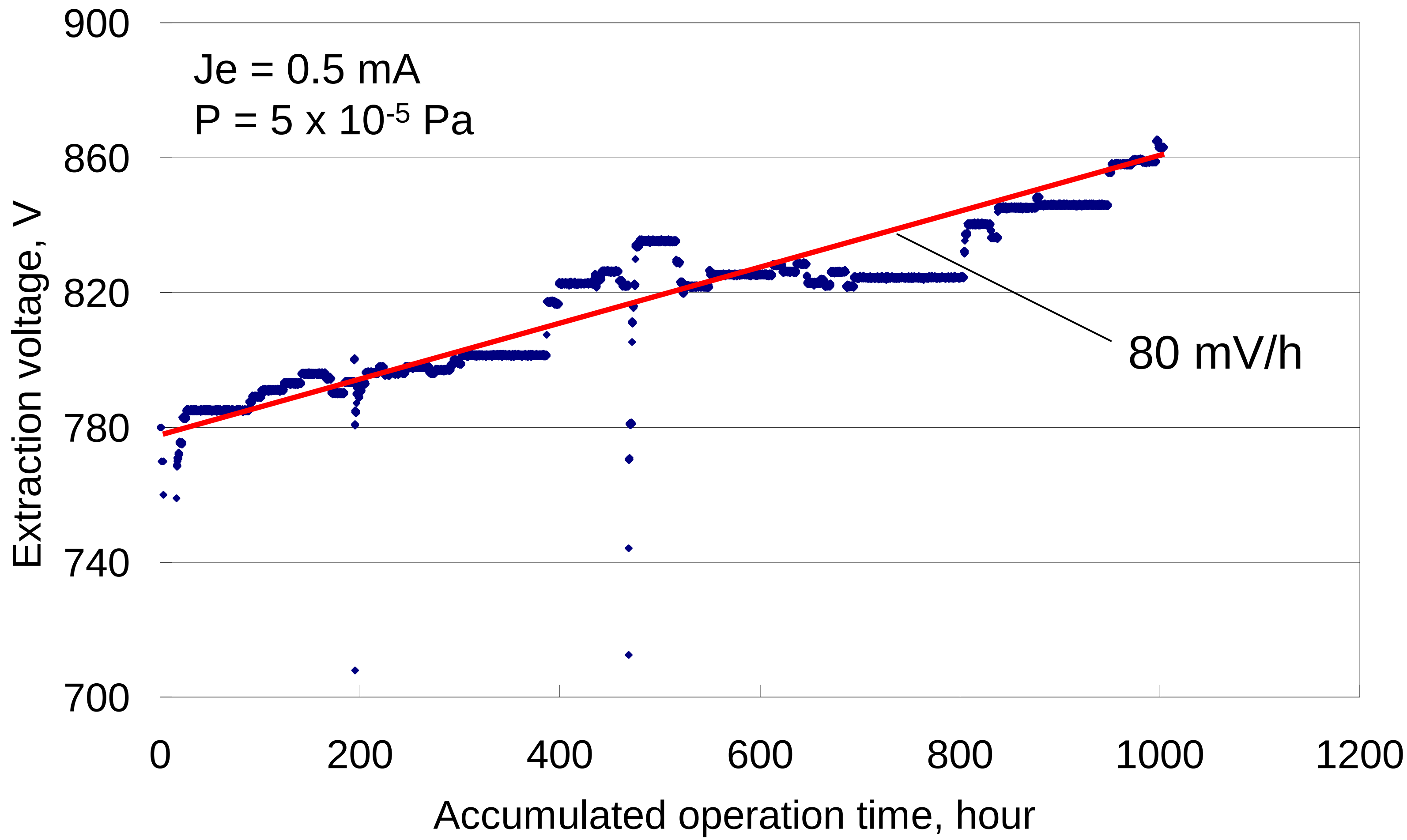
- 10-emitter-arrayed FEC was used
- 4 of 10 emitters were operated
- Total emission current was around 0.5 mA (manually controlled)
- 4 emitters were operated by one power conditioner
- Background pressure: 5 x 10^{-5} Pa





1000-Hour Operation

Extraction voltage required for 0.5-mA-emission



- *No fatal trouble in 1000-hour operation*
- *Extraction voltage increased from 780 to 860 V during 1000-hour operation*
- *Higher durability is expected in lower pressure conditions*

Summary

- Laboratory models of carbon nanotube cathode were designed, fabricated, and tested
- Feasible performance was obtained
  - Emission current: 0.6 mA
  - Required voltage (BOL): 550 V
  - Extraction efficiency: 98%
  - Size: 20 x 20 x 30 mm
  - Mass: 24 g
- Influences of relative potential conditions were evaluated
- 1000-hour-operation was conducted without fatal trouble

Future works

- Simulating practical FEC-plasma interaction
- Developing appropriate control algorism
- Coupling operation with electric propulsion