FAR-TECH

A high-peak and high-average current, low emittance, long lifetime electron source* for ERL applications

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* Patent applied for.

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New Electron Source Needed

- Modern energy recovery linac (ERL) based applications (E-cooling of ion beams, high average power Free Electron Lasers and Terahertz Light Sources) need electron sources with:
  - High peak-current
  - High average-current
  - low emittance
  - long lifetime

- The MEIC project in JLab requires ultimately an electron source with:
  - High bunch charge (3.2 nC)
  - Short bunch length (~ 2 cm)
  - High average current (1.5 A)
  - High bunch repetition rate (476 MHz)
  - Magnetization of ~ 590 μm.

- Existing sources cannot meet the needs.

Overview of Current Electron Source Technologies

Photocathode electron sources

- **Advantages:**
  - Capable of generating high peak current beams in DC or RF guns.
  - Low emittance.

- **Disadvantages:**
  - Hard to obtain high average current beams (state-of-the-art: ~75 mA).
    - Metal photocathodes have low QE ($<10^{-3}$).
    - Multi-alkali cathodes and semiconductor cathodes:
      - Require UHV
      - Short lifetime
  - Expensive. Require UHV, cathode preparation system and laser system.
  - Metal photocathodes have higher thermal emittance (~0.4 eV) than thermionic cathodes.

Overview of Current Electron Source Technologies

Thermionic electron sources

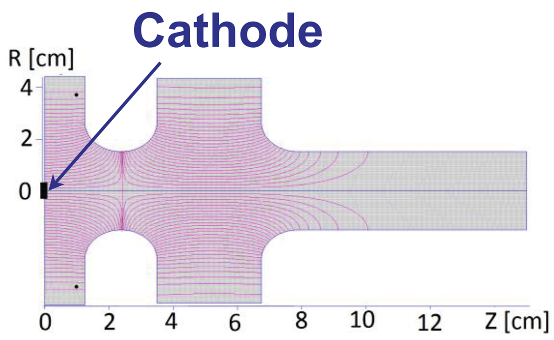
- **Advantages:**
  - High current (DC).
  - Low thermal emittance (thermal energy of ~0.12 eV).
  - Long lifetime (a few thousand hours for LaB_6 cathode).
  - Low cost. No UHV; No laser.

- **Disadvantages:**
  - DC beam can not be directly used in linac systems.
  - Can not generate high-average current, high-brightness beam in RF guns.

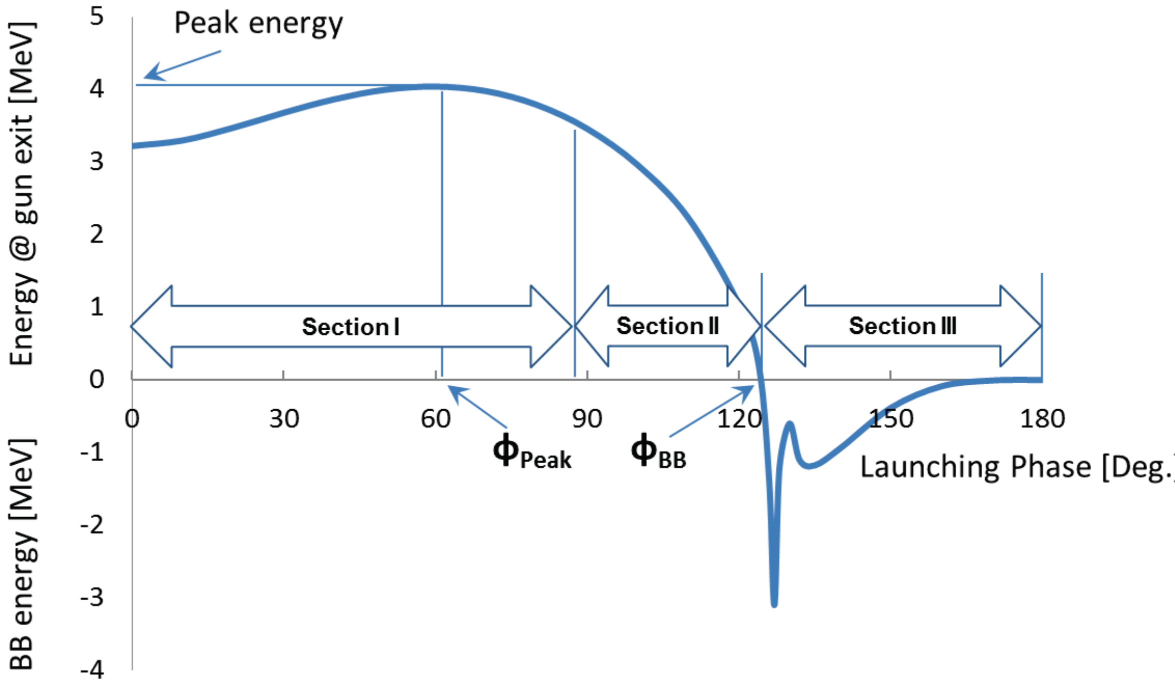
Field emitter sources and secondary emission sources.

  - Hard to obtain high average current beam or operation in RF guns not yet demonstrated

Thermionic RF Gun Issue: Back-bombardment



A typical RF gun (BNL/SLAC/UCLA 1.5 cell gun). f=2856 MHz, E_{peak}=100 MV/m



Electron energy at gun exit or back-bombardment (BB) energy vs. cathode launching phase (initial phase).

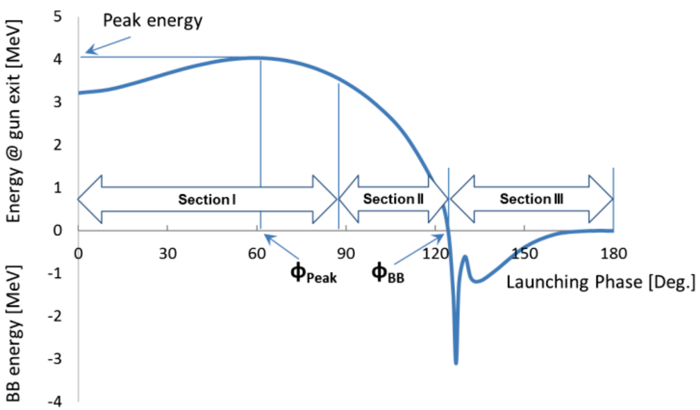
- **Electrons from section I and section II can escape from the cavity.**
- **Electrons from section III strike back on cathode (back-bombardment) under decelerating field.**

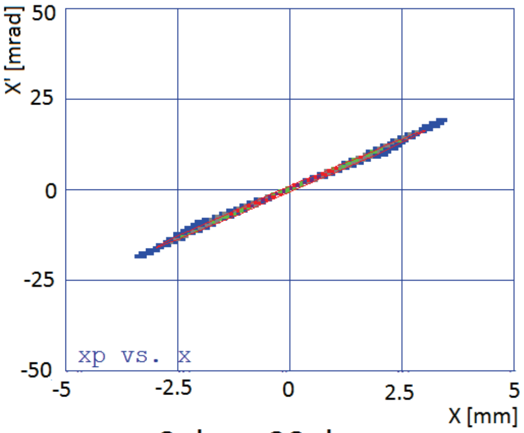
Thermionic RF Gun Issue: Back-bombardment

Back-bombardment power density is large (a few - tens kW/mm^2) and is directly on cathode surface.

- ***Rapid temperature increase of the cathode during the RF macro pulse causes the current to increase and the beam energy to decrease***
- ***Typical macro-pulse width is a few μs with low duty cycle.***

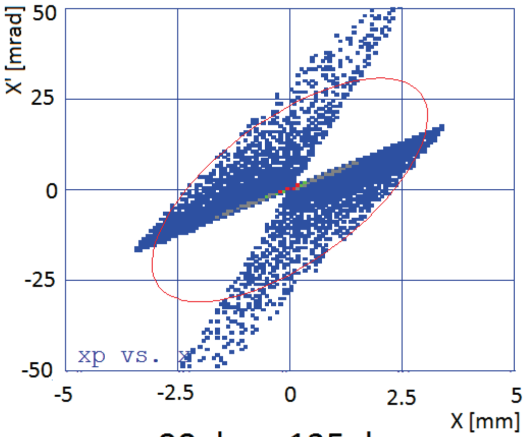
Thermionic RF Gun Issue: Emittance Growth





0 deg - 90 deg

Phase space of section I beam



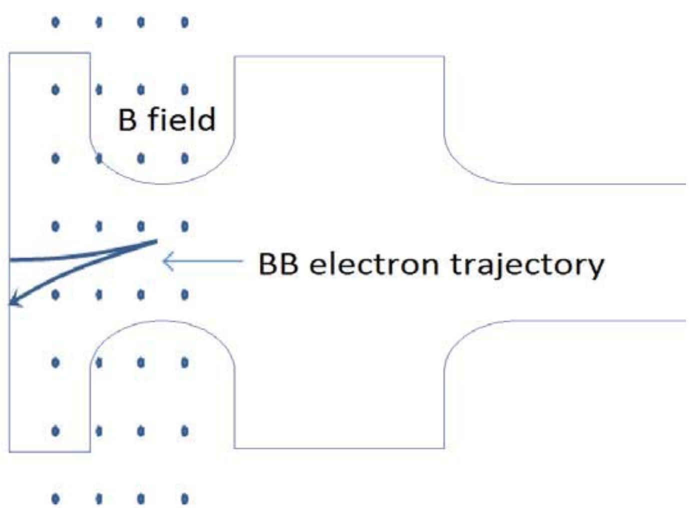
90 deg - 125 deg

Phase space of section II beam

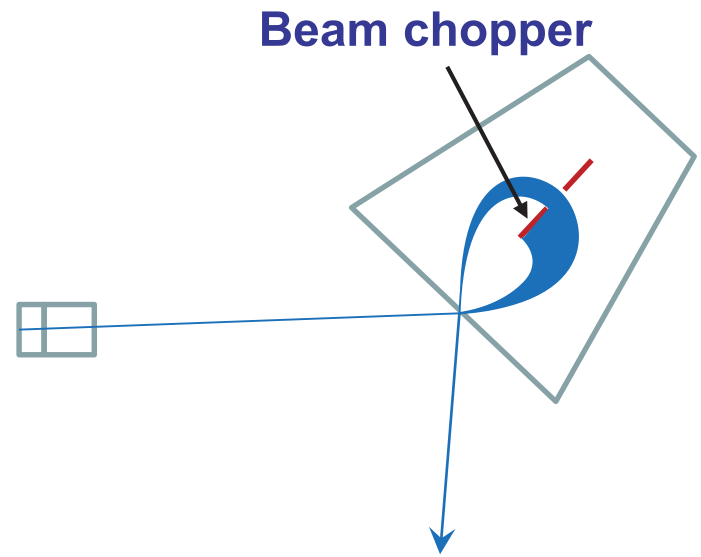
- **Section I beam (from 0° to somewhere after ϕ_{Peak}) has small emittance**
- **Section II beam has large emittance**

Suppressing BB & section II beam

Conventional way suppressing BB beam include applying deflecting magnetic field on cavity which has finite effect. Alpha magnet is used suppressing the section II beam.



Deflecting magnet for reducing BB beam.



α magnet for suppressing section II beam.

High Current, Low Emittance Thermionic RF Gun Requires

1. *CW mode for high average current by eliminating the back-bombardment*

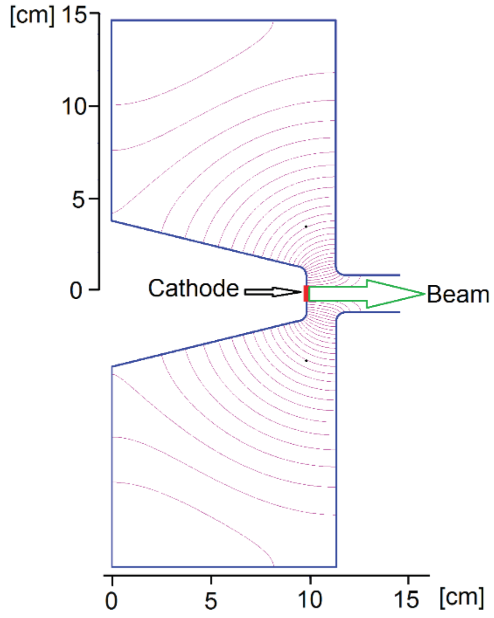
and

2. *Improved beam quality by suppressing the section II beam*

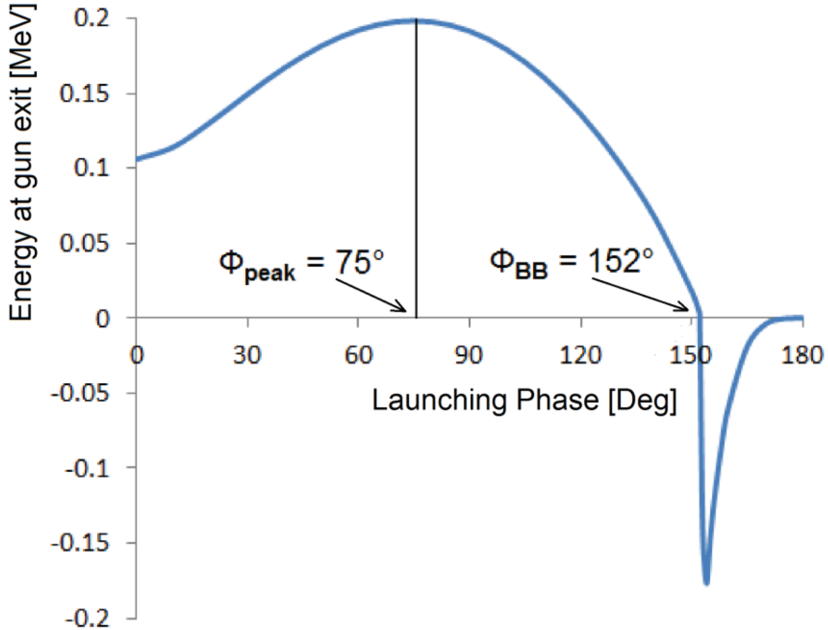
FAR-TECH's Proposed Thermionic RF Gun Without BB & Section II Beam: Step I

Step I, a <u>short accelerating gap</u> RF cavity

- Pushes ϕ_{Peak} close to 90° (75°) and ϕ_{BB} close to 180° (152°).
- Still has considerable back-bombardment power.



A short accelerating gap 476 MHz RF gun



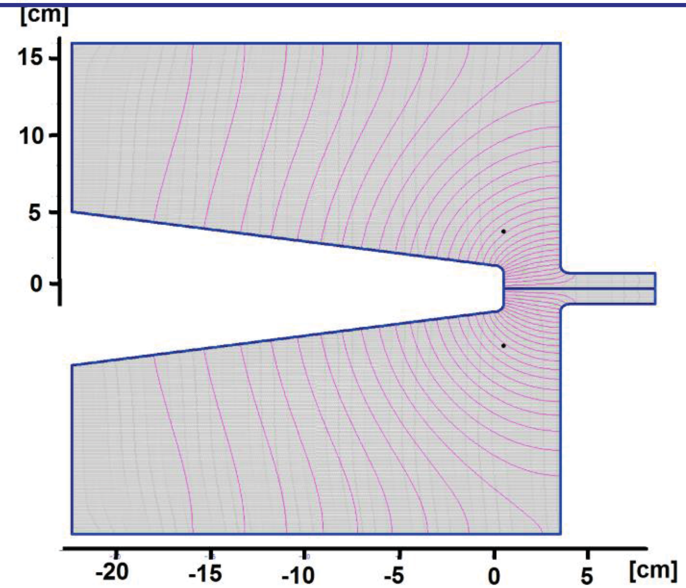
Energy at gun exit vs. initial phase

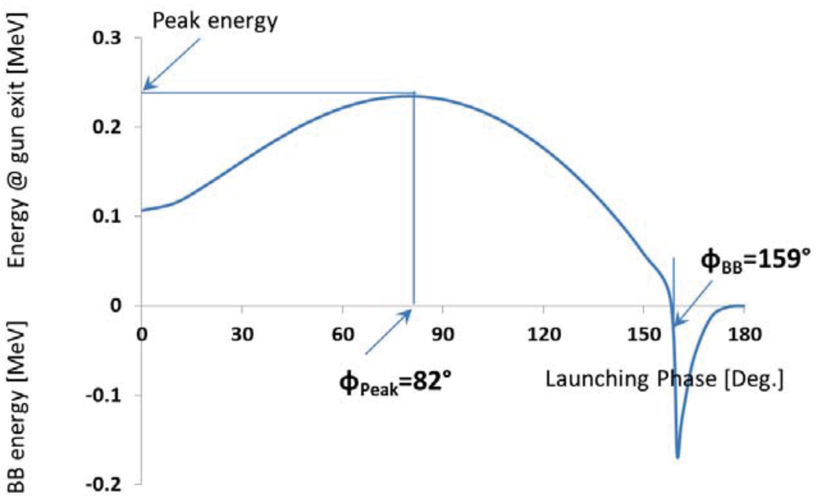
300 MHz cavity

- Frequency: 300 MHz
- Acc. gap: 3 cm
- Aperture: 2 cm
- $E_{Cathode}$: 12 MV/m
- E_{Peak}: 21 MV/m
- r/Q: 180 Ω
- P_{Total}: 10 kW
- Peak power density: 18 W/cm^2

- Beam energy: 235 keV

- $\phi_{Peak} = 82°$
- $\phi_{BB} = 159°$

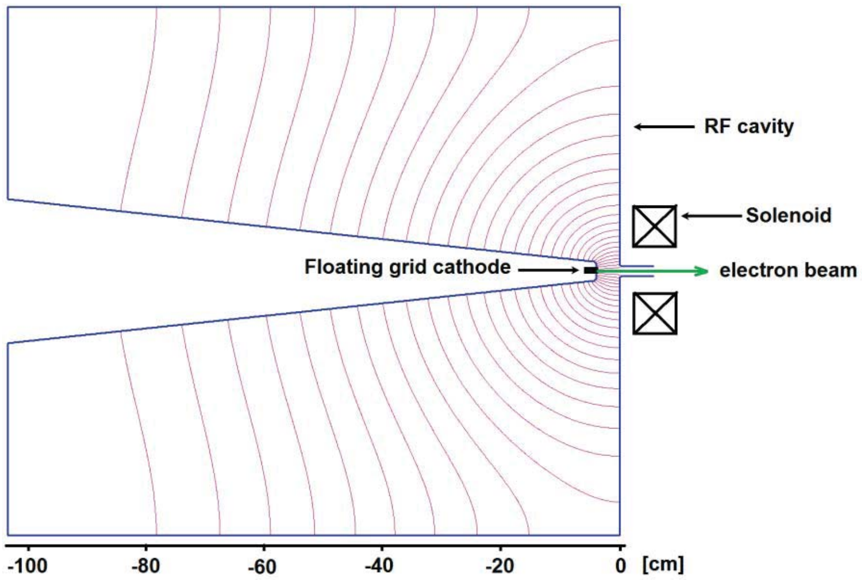


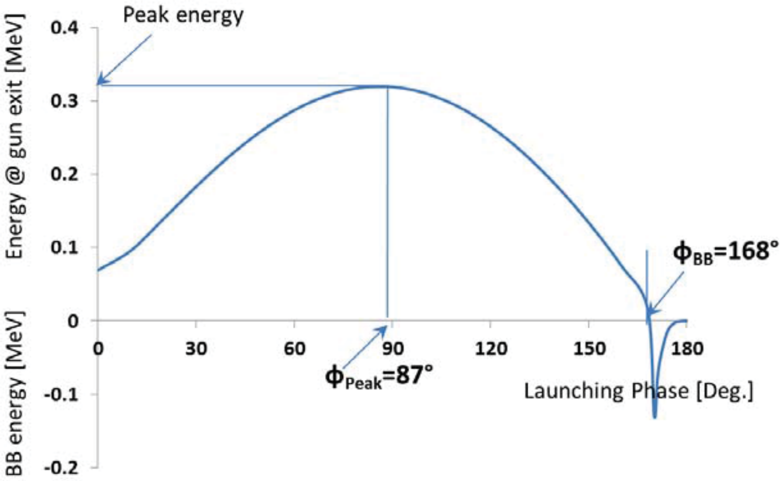


75 MHz cavity

- Frequency: 75 MHz
- Acc. gap: 4 cm
- Aperture: 2 cm
- $E_{Cathode}$: 11 MV/m
- E_{Peak}: 20 MV/m
- r/Q: 200 Ω
- P_{Total}: 8 kW
- Peak power density: 1.5 W/cm^2
- Beam energy: 330 keV

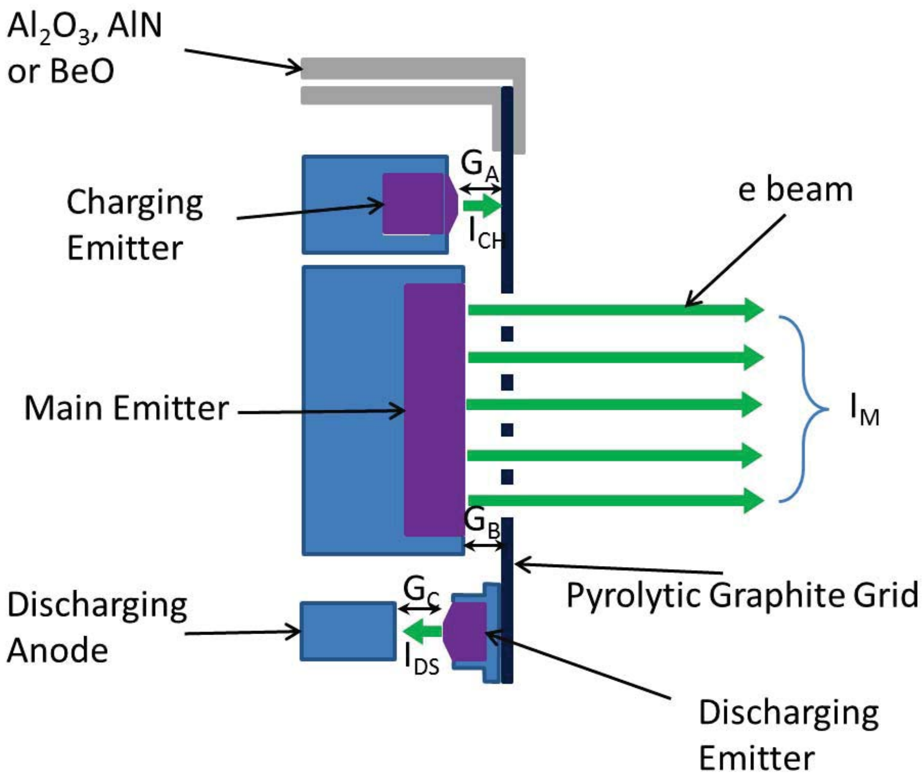
- $\phi_{Peak} = 87°$
- $\phi_{BB} = 168°$





FAR-TECH's Proposed Thermionic RF Gun Without BB & Section II Beam: Step II

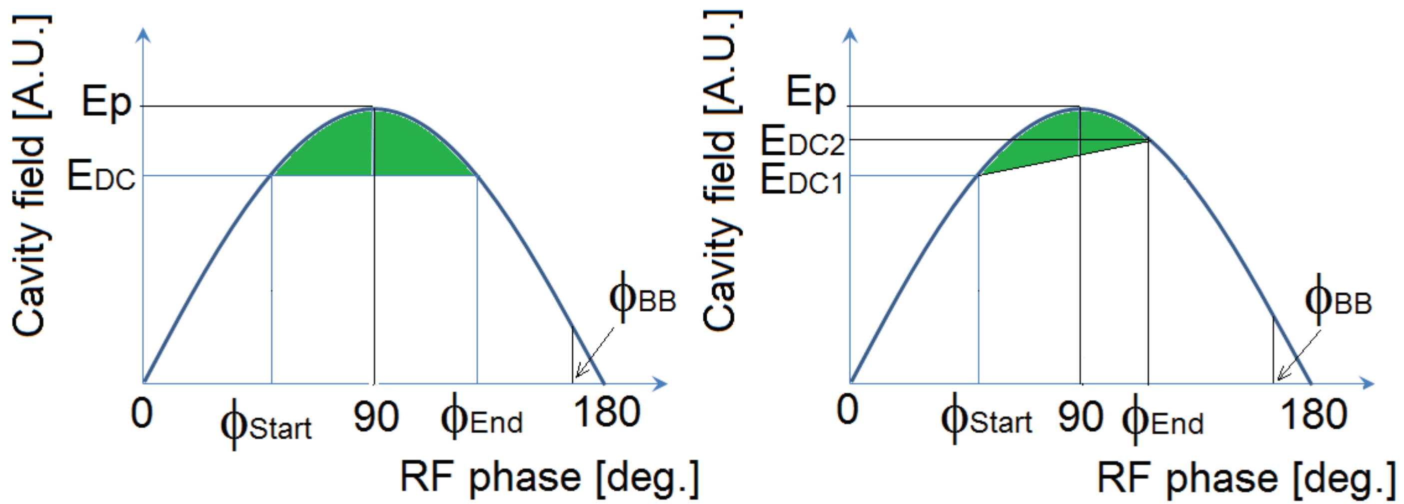
Step II, use a floating grid cathode.



A floating grid thermionic cathode

- $E_{grid\text{-}Main\ Emitter} = E_{DC} + E_{RF}$
- E_{DC} is determined by the geometry of the floating grid and net charge on it.
- The floating grid net charge can be adjusted by changing the emission of charging / discharging emitters through changing their operating temperatures or apply bias fields.

Emission Window of A Floating Grid Cathode

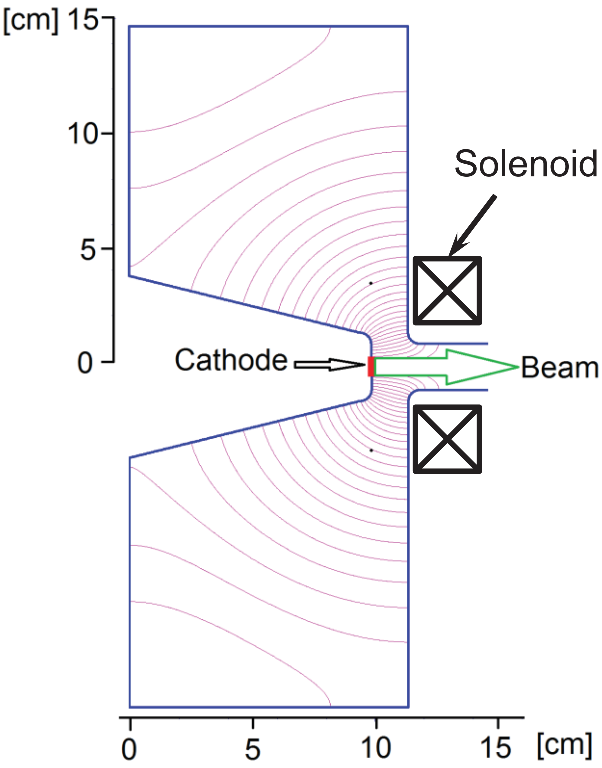


Small I_{CH} (I_{DS}) Large I_{CH} (I_{DS})

- At sufficient high E_{DC}, $\phi_{End} < \phi_{BB}$, the **back-bombardment beam is eliminated and section II beam is suppressed**.
- Allows CW operation, every RF bucket filled, high average current.
- Small emittance.

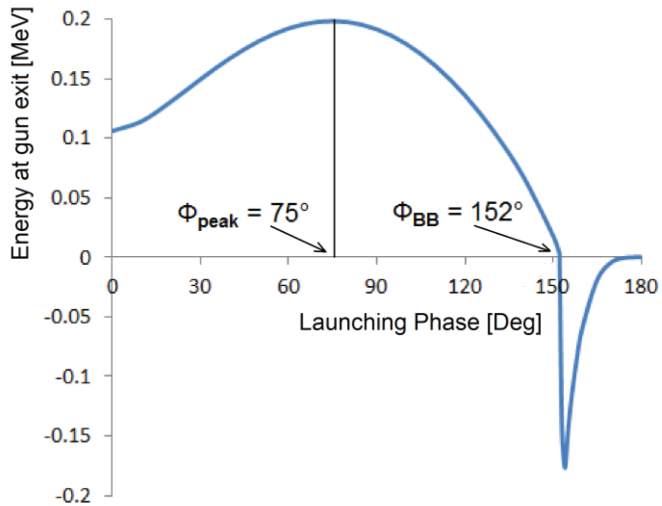
Example: JLab's Magnetized Beam for MEIC e-cooling

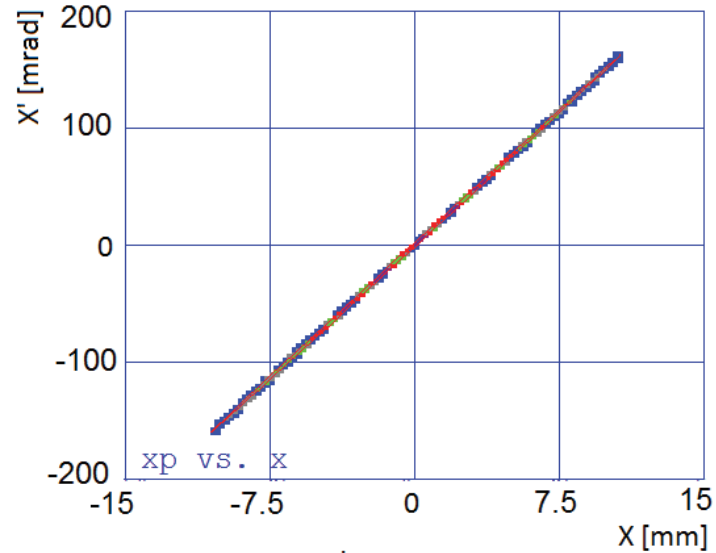
- Frequency: 476 MHz
- Acc. gap: 1.5 cm
- Aperture: 2 cm
- $E_{Cathode}$: 13.6 MV/m
- E_{Peak}: 24.2 MV/m
- r/Q: 135 Ω
- P_{Total}: 9.4 kW
- Peak power density: 22 W/cm^2.
- Cath. size: 1.2 cm
- Solenoid for magnetization and beam focusing.



RF cavity

Example: JLab's Magnetized Beam for MEIC e-cooling





70 deg < ϕ_{Ini} < 110 deg

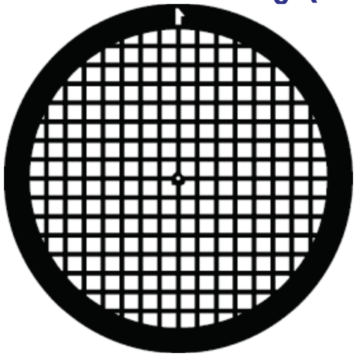
Phase space @ gun exit

Peak energy:	**200 keV**
ϕ_{Peak}:	**75°**
ϕ_{BB}:	**152°**

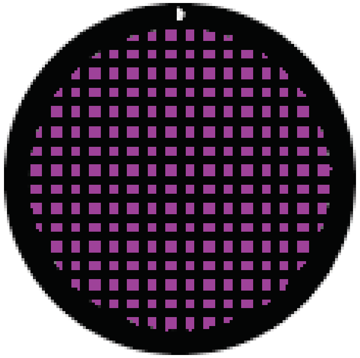
RF field induced emittance: 13 μm

Floating Grid Structure

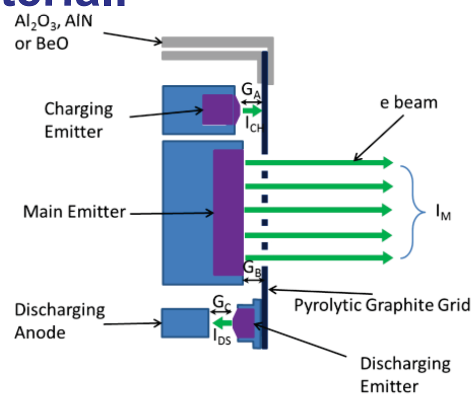
We choose LaB_6 (2.65 eV, >100A/cm^2) as the emitter material.



Floating grid



Main emitter



Material: Pyrolytic graphite (>3000°C)

Diameter: 12 mm

RF heating power: Negligible

Heating/dissipating:
- Radiation
- Conduction
- Charging current

Temperature: ~ 1500 K

Material: LaB_6/CeB_6, dispenser, FEA, etc.

Diameter: 12 mm

Temperature: ~1800 K

Current density: ~20 A/cm^2

Effective emission area: ~60%

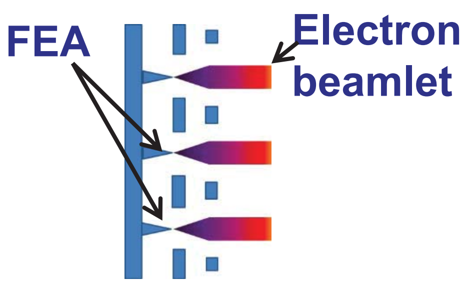
G_B ~ 250 μm.

Equivalent thermal energy of the beamlets at virtual cathode position (beamlet waist after floating grid) is < 0.3 eV.

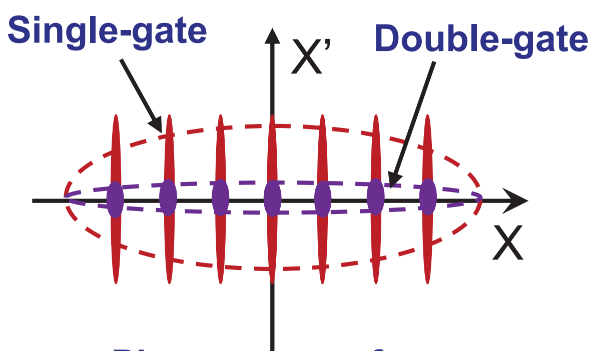
Cathode lifetime > 1,500 hrs.

Emittance of Multiple Beamlets

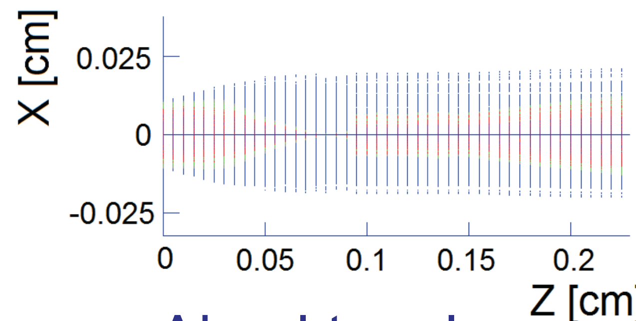
- Space charge is strong near cathode ($\propto 1/(\beta\gamma)^3$.
- A focusing near cathode helps suppress emittance growth, like a double-gate FEA (~0.2 μm/mm) compared to a single-gate FEA (~2μm/mm).
- Negative biased floating grid also provides a focusing (like in an Einzel lens), provides the beamlets collimation like in the double-gate FEA.



A double-gate FEA



Phase space of a double-gate FEA



A beamlet envelope near cathode and grid.

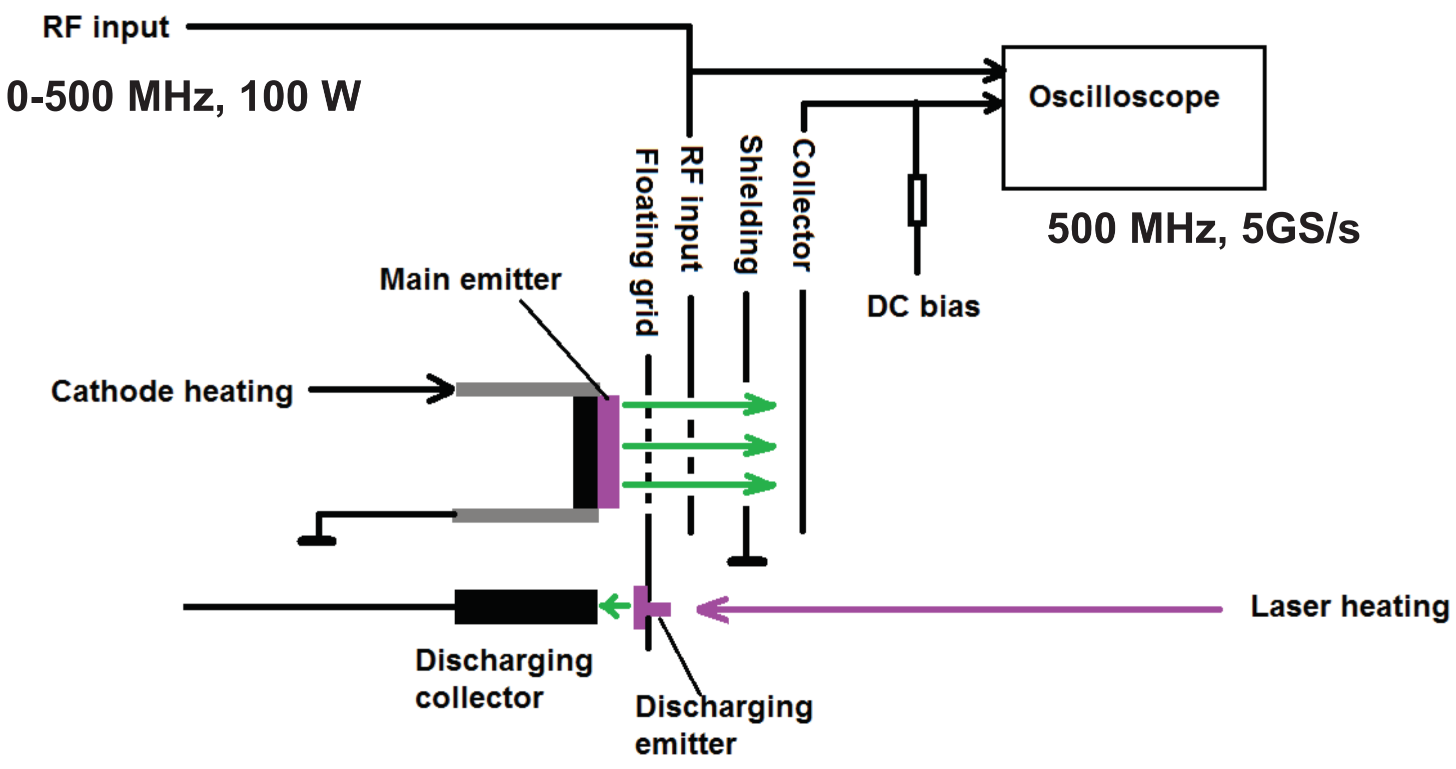
- $\varepsilon_{@z=0.08cm}$=150% X $\varepsilon_{@z=0}$, beam divergence @ z=0.08cm is o (virtual cathode position).
- Equivalent beam thermal energy of <0.3eV, better than many metal photocathode.

Current design parameters can be improved!

	Current design	Up to
Bunch charge	*3.2 nC*	*> 10 nC*
Average current	*1.5 A*	*> 1.5 A*
Beam energy	*200 keV*	*> 1 MeV*
Thermal emittance (of multiple beamlets)	*~ 3μm*	*< 1μm*
RMS bunch length	*~ 2 cm*	*< 1 cm*
Cathode lifetime	*1,500 hours*	*> 15,000 hours*

Proof of Principle Experiment

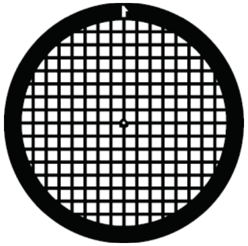
Objective: to demonstrate that the floating grid DC bias can be adjusted and the electron emission phase window is therefore controlled.



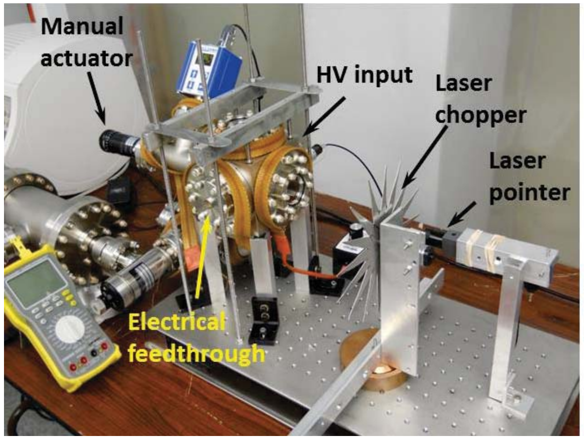
Schematic diagram of the POP experiment

Proof of Principle Experiment

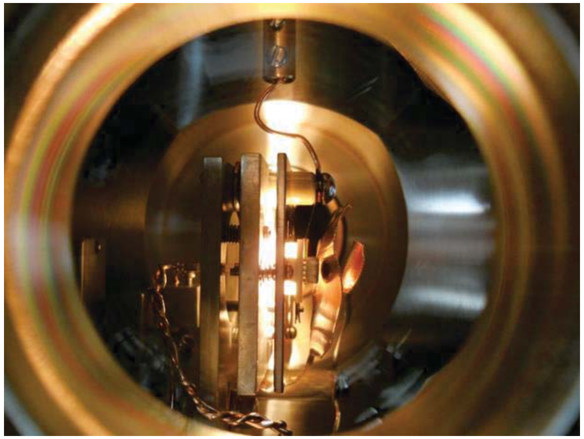
Main emitter &
discharging emitter



Floating grid:
TEM grid

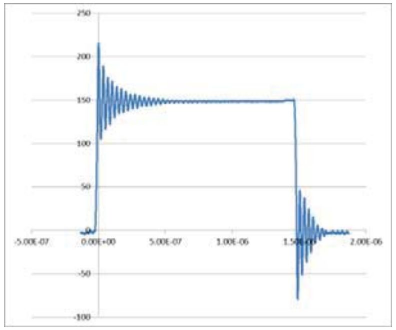


Experimental setup

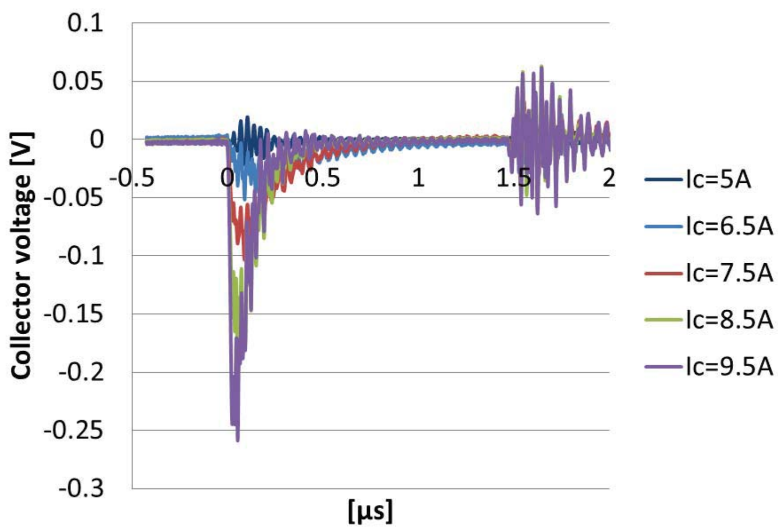


Vacuum chamber
during conditioning

Voltage Pulser Test



Voltage pulse on RF input



Emission current on collector

We've observed qualitatively in the pulser test:

- The electron emission from a floating grid structure.
- Emission suppression by the floating grid due to its charging. No emission current without discharging of the floating grid

Summary

- This research is to develop a thermionic RF gun (cathode can also be other cathode like field emitter array) without back-bombardment and suppressed poor quality beam.
  - Allows CW operation for high average current.
  - Small emittance.
  - Long lifetime (a few thousand hours).
  - Simple, robust and reliable. Assemble in air and operate at 10^{-7} Torr.
  - Current is stable.
  - Cheap. No expensive laser or load lock / preparation chamber required.

- This technique makes it possible to generate the 1.5 A average current bunched beam required by JLab's MEIC project.

- Our initial proof of principle test results support of model.

- Flexible design for various applications. This technique could also be applied to other accelerator based applications requiring high average current, such as the high average power free electron lasers and terahertz sources.

- Limitations:
  - Not suitable for initially short bunch beams.
  - Not suitable for polarized electron beam
  - Not suitable for high frequency RF cavities.

Thank you!

Charging / Discharging Emitters

	Charging emitter	Discharging emitter	Discharging anode
Material	LaB_6/CeB_6, dispenser, FEA, etc	LaB_6/CeB_6, dispenser, FEA, etc	Carbon tube, other high temperature martials.
Size	~ 1 mm diameter	~ 2 mm diameter	~ 2 mm diameter
Operating temperature	~ 1600 K	~ 1450 K	
Current density	~ 1.4 A/cm^2	~ 0.16 A/cm^2	
Current	~ 1 mA (I_{CH})	$I_{DS} = I_{CH}$	~ 1 mA
Current control methods	• Ohmic heating • Laser heating • Adjusting gap • Applying bias	• Radiation heating • Laser heating • Adjusting gap • Applying bias	
Beam heating power	~ 0.06 W (on floating grid)	~ 2.6 W (on carbon tube)	~ 2.6 W

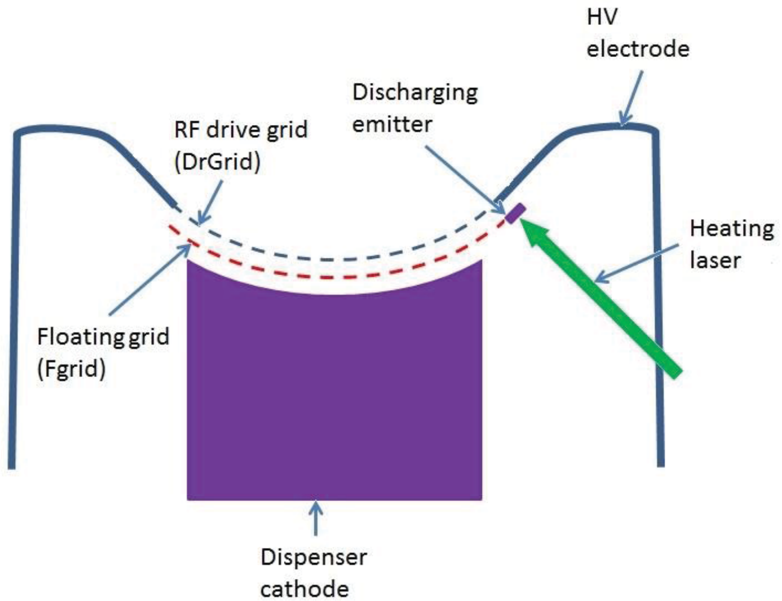
Cathode Lifetime

- **Cathode lifetime is primarily determined by the evaporation of the LaB_6 material. We define the lifetime of the emitter as a thickness decrease of 25 μm (1/10th of the main emitter gap). At 1800 K operating temperature, the evaporation rate is 2.2 X 10^{-9} g/cm^{2}s, and the lifetime is <u>1,500 hours</u>.**

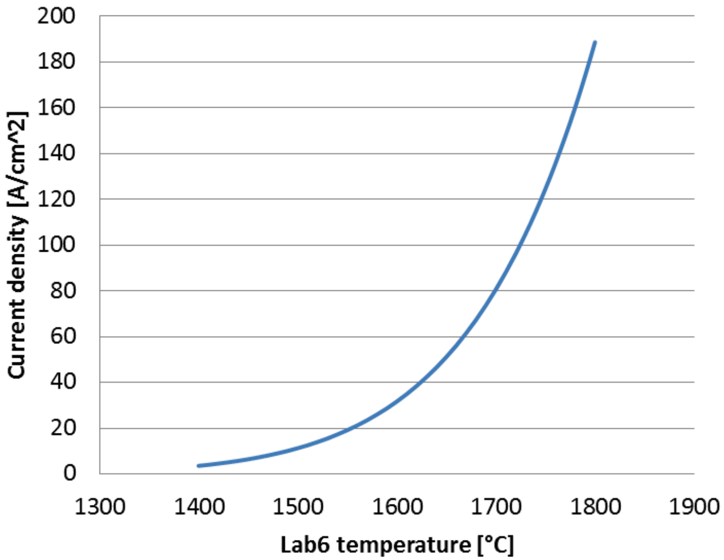
- **Lowering operating temperature can increase lifetime dramatically, for example, at 1700 K, lifetime becomes <u>15,000 hours</u>. Meanwhile the current density drops to 1/3 that of 1800 K, which requires 73% diameter increase to have the same charge.**

- **Charging and discharging emitter operate at much lower temperature than that of the main emitter, their lifetimes are not critical.**

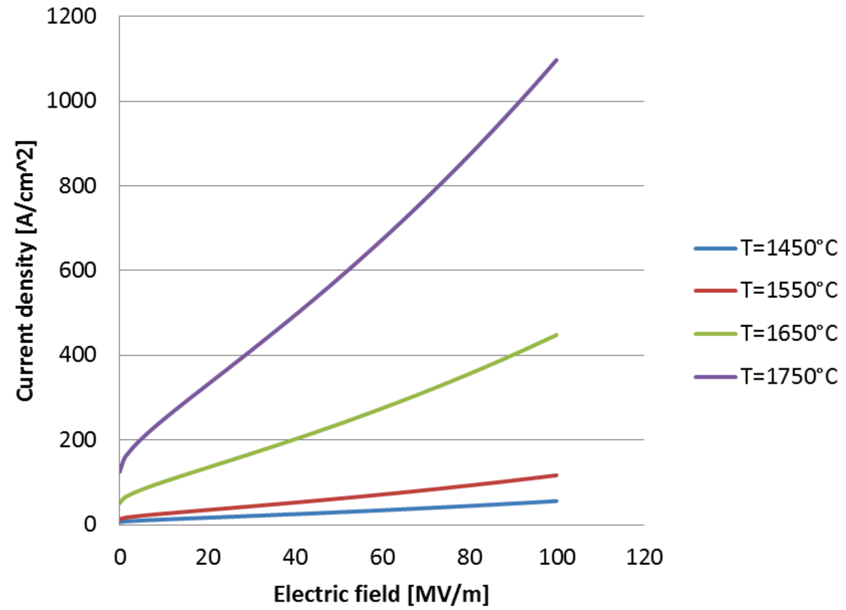
A floating grid in an inductive output tube



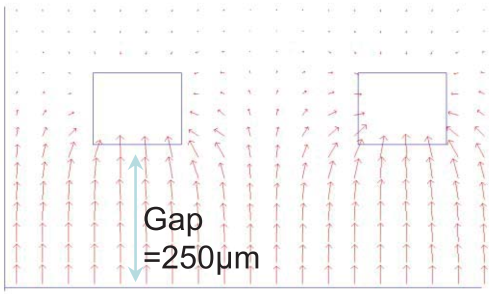
The floating grid can aid in the suppression of cathode arcing in the vacuum electron device.



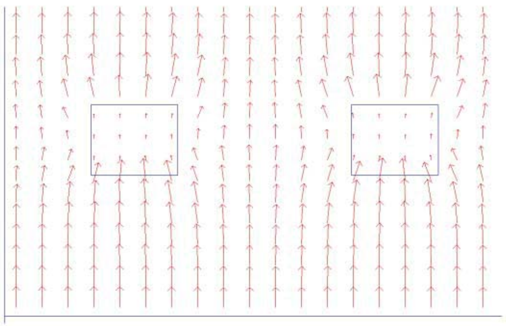
Current density
vs. temperature



Current density
enhancement by field



E_{DC}



E_{RF}

Emittance compensation of a strongly magnetized beam

- Electron cooling prefers electron beam with small Lamor radius in cooling section.
- If a beam is strongly dominated by magnetization, the Lamor radius is determined by the B field and electron thermal energy (instead of emittance).
- A strongly magnetized beam like Jlab's magnetized e-cooling beam (590 µm), prefers a large size, low temperature cathode, which also benefit the cathode lifetime.
- Although emittance compensation of a magnetization dominated beam is less effective than that of a space charge dominated beam, it is still doable (keep beam envelope large).