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

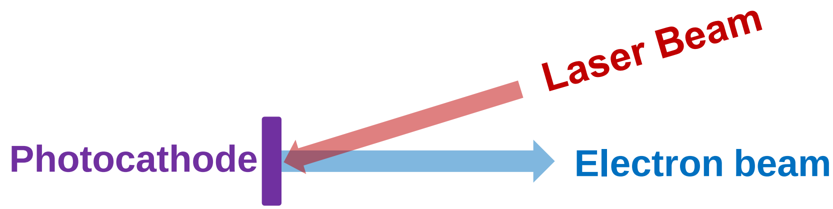
- Modern energy recovery linac (ERL) based applications (E-cooling of ion beams, high average power Free Electron Lasers and Terahertz Light Sources) need electron sources with:
  - High peak-current
  - High average-current
  - low emittance
  - long lifetime

- The MEIC project in JLab requires an electron source with:
  - High bunch charge (up to 2 nC)
  - Short bunch length (~ 2 cm)
  - High average current (above 100 mA)
  - High bunch repetition rate (up to 75 MHz)
  - Magnetization of ~ 590 µm.

- Existing sources cannot meet the needs.

Overview of Current Electron Source Technologies

Photocathode electron sources

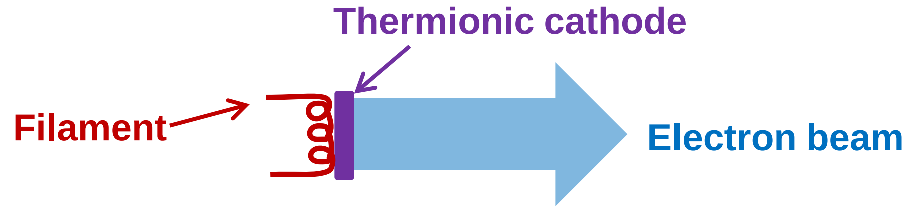


- **Advantages:**
  - Capable of generating high peak current beams in DC or RF guns.
  - Low emittance.

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

Overview of Current Electron Source Technologies

Thermionic electron sources



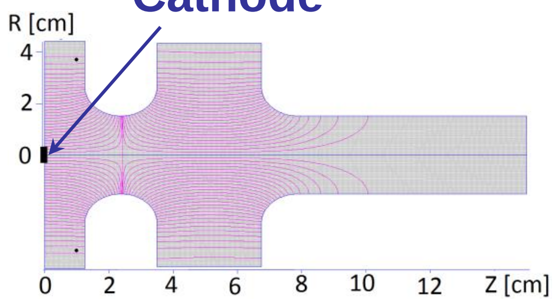
- **Advantages:**
  - High current (DC).
  - Low thermal emittance (thermal energy of ~0.12 eV).
  - Long lifetime (a few thousand hours for LaB_6 cathode).
  - Low cost. No UHV; No laser.

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

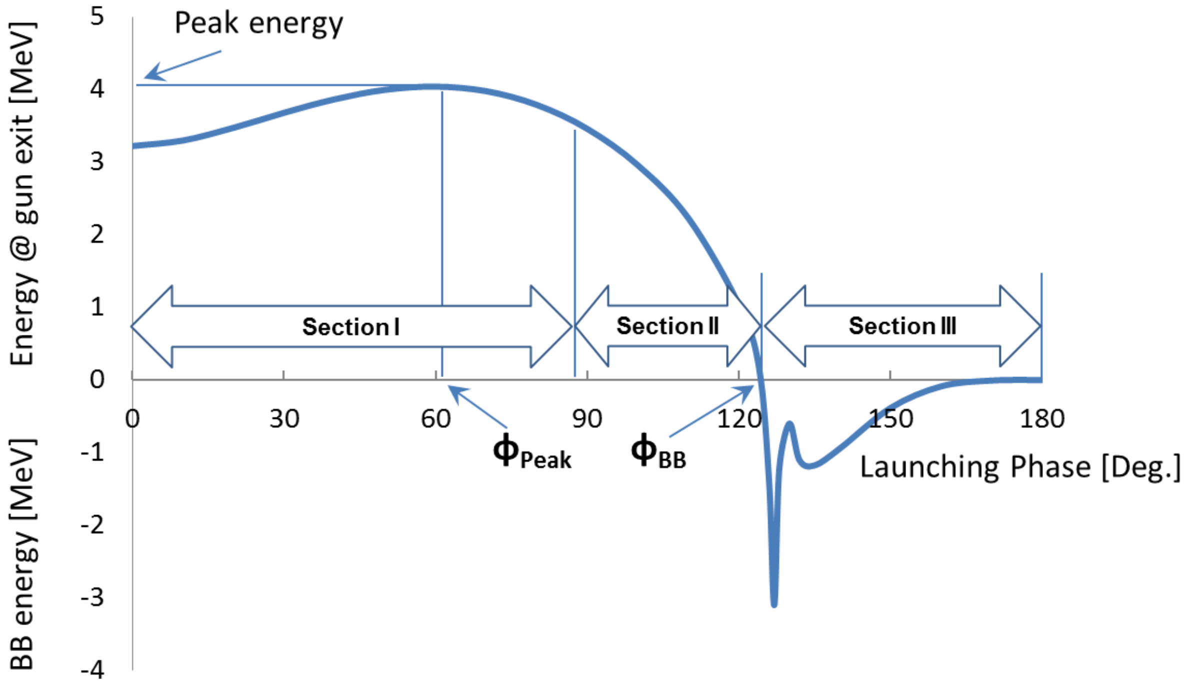
Field emitter sources and secondary emission sources.

- 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



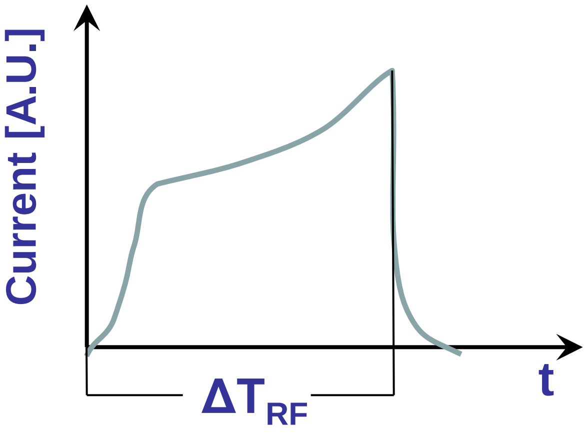
Electron energy at gun exit or back-bombardment (BB) energy vs. cathode launching phase (initial phase).

- 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.***



Output current signal from a thermionic RF gun

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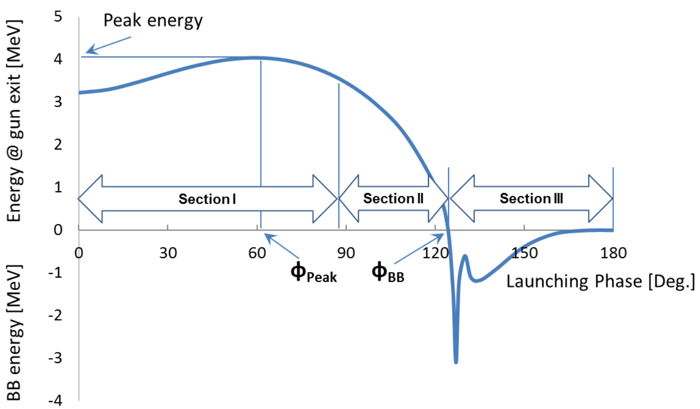
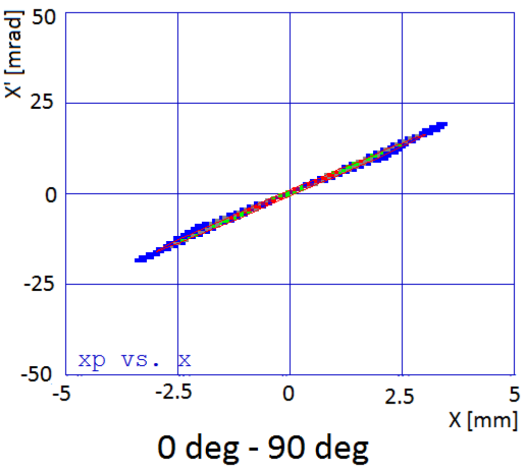
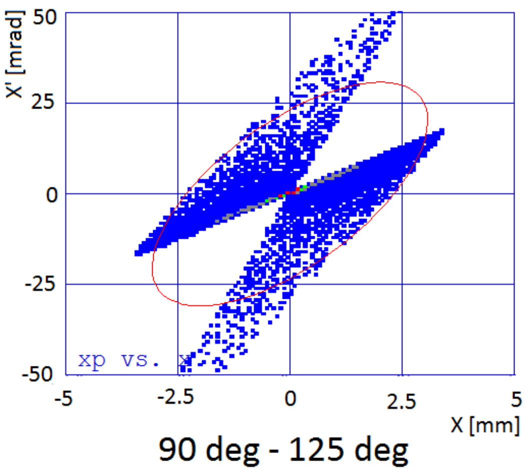
Thermionic RF Gun Issue: Emittance Growth





Phase space of section I beam



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

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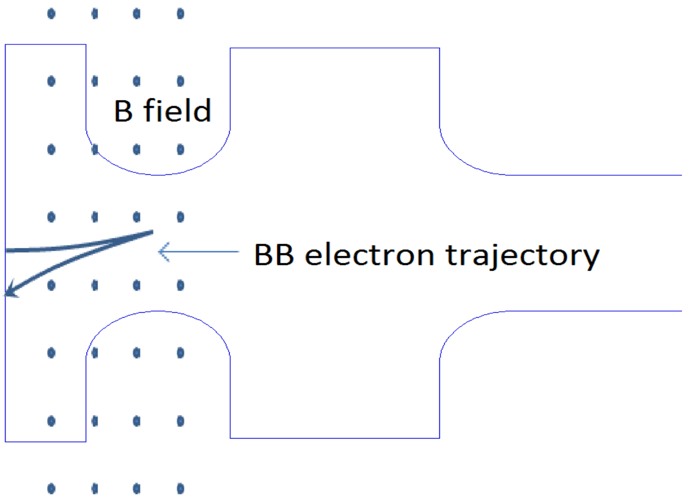
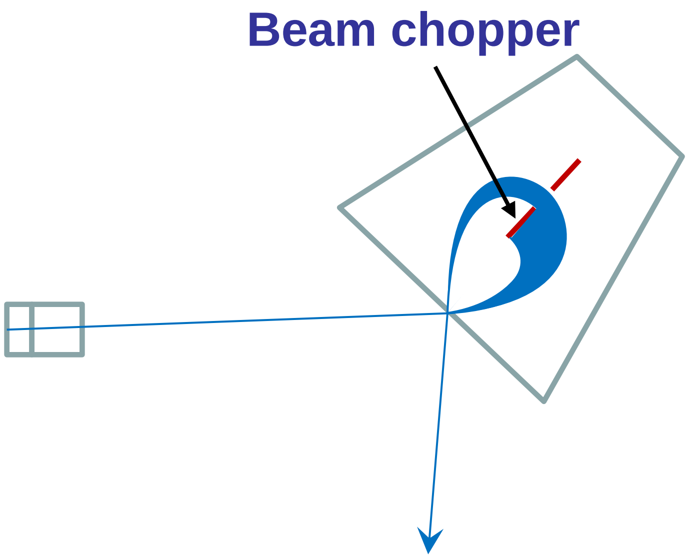
Suppressing BB & section II beam

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.

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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*

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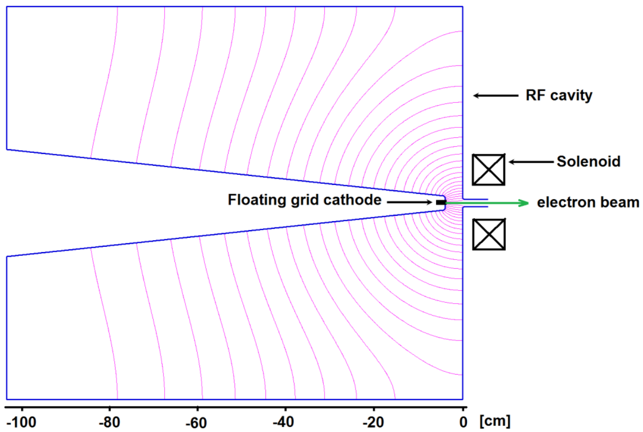
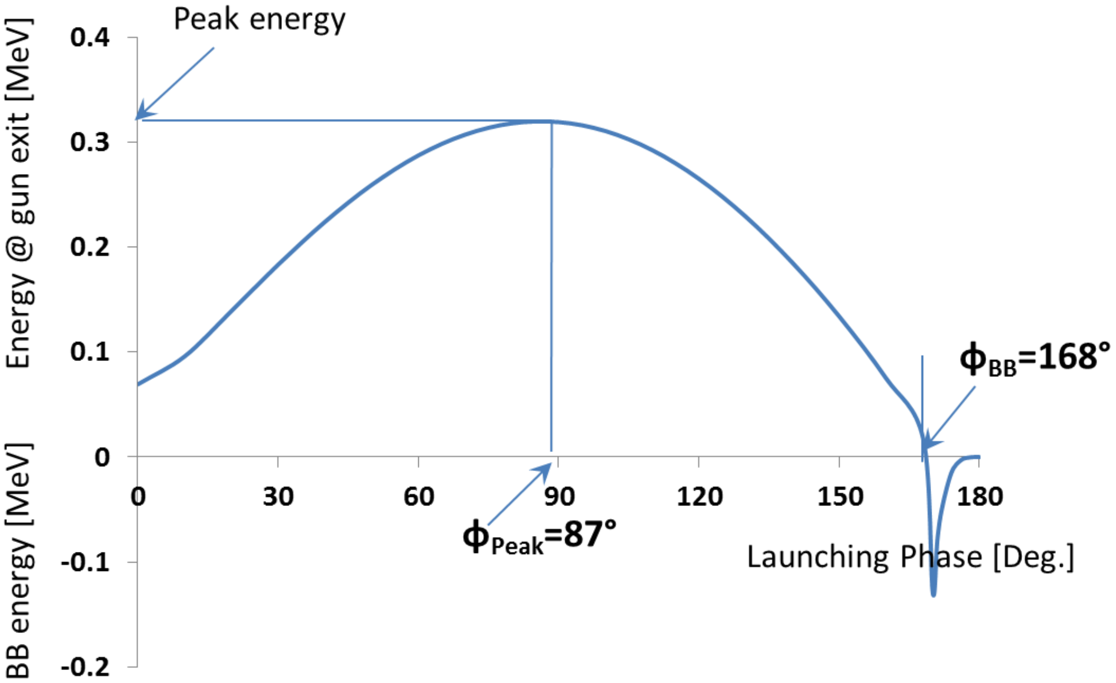
FAR-TECH's Proposed Thermionic RF Gun Without BB & Section II Beam: Step I

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

- Pushes ϕ_{Peak} close to 90° (87°) and ϕ_{BB} close to 180° (168°).
- Still has considerable back-bombardment power.



A short accelerating gap 75 MHz RF gun



Energy at gun exit vs. initial phase

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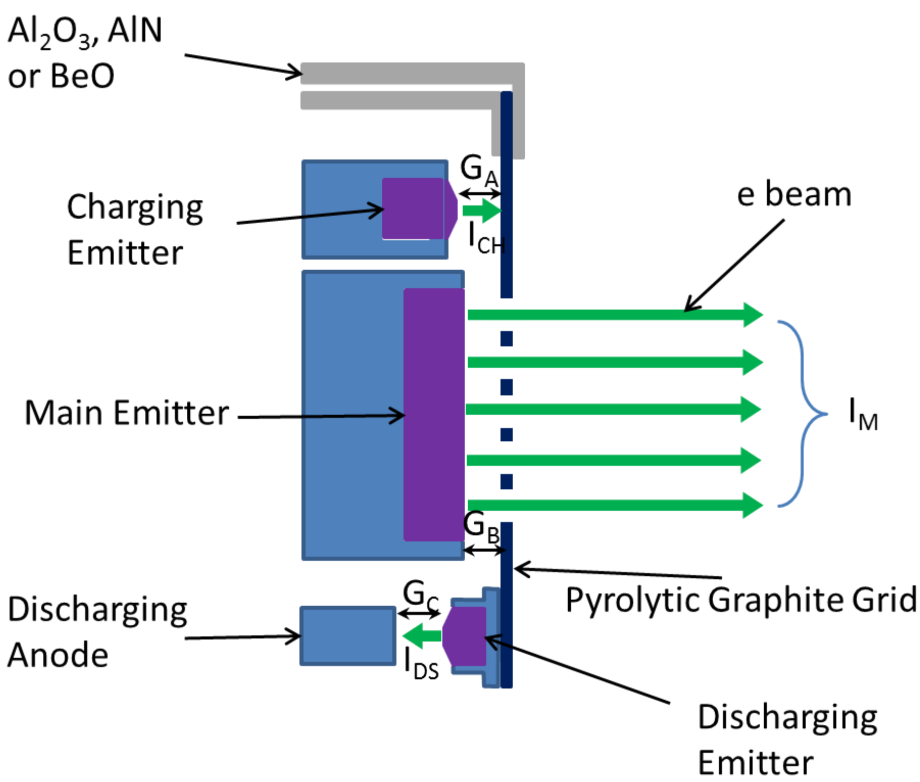
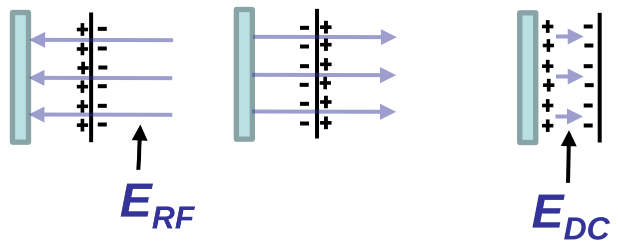
FAR-TECH's Proposed Thermionic RF Gun Without BB & Section II Beam: Step II

Step II, use a <u>floating grid cathode.</u>



A floating grid thermionic cathode



$$E_{Grid-Main\ Emitter} = E_{RF} + E_{DC}$$

- E_{DC} is determined by the geometry of the floating grid and the net charge on it.
- The floating grid net charge can be adjusted by changing the emission of the charging and discharging emitters:
  - Temperature
  - Gap
  - DC bias

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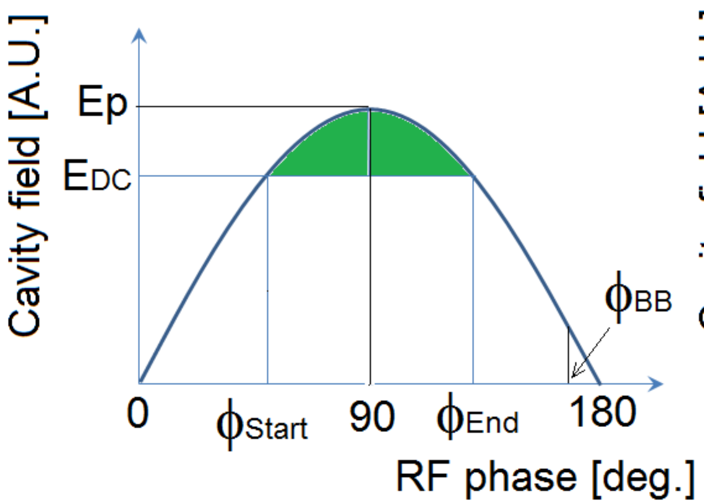
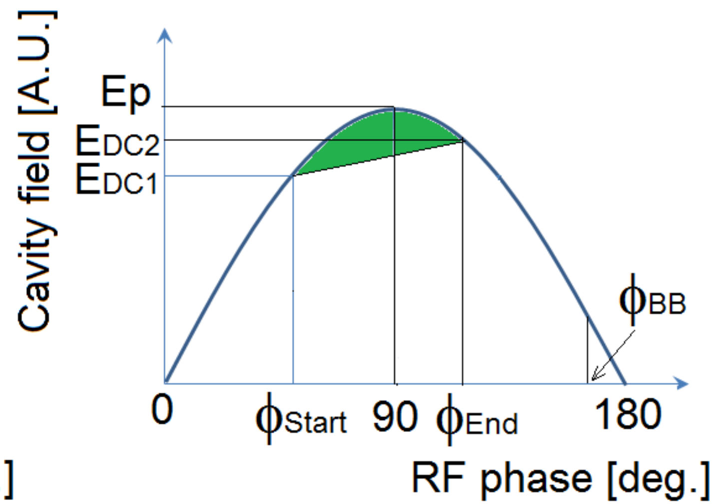
Emission Window of A Floating Grid Cathode



Small I_{CH} (I_{DS})

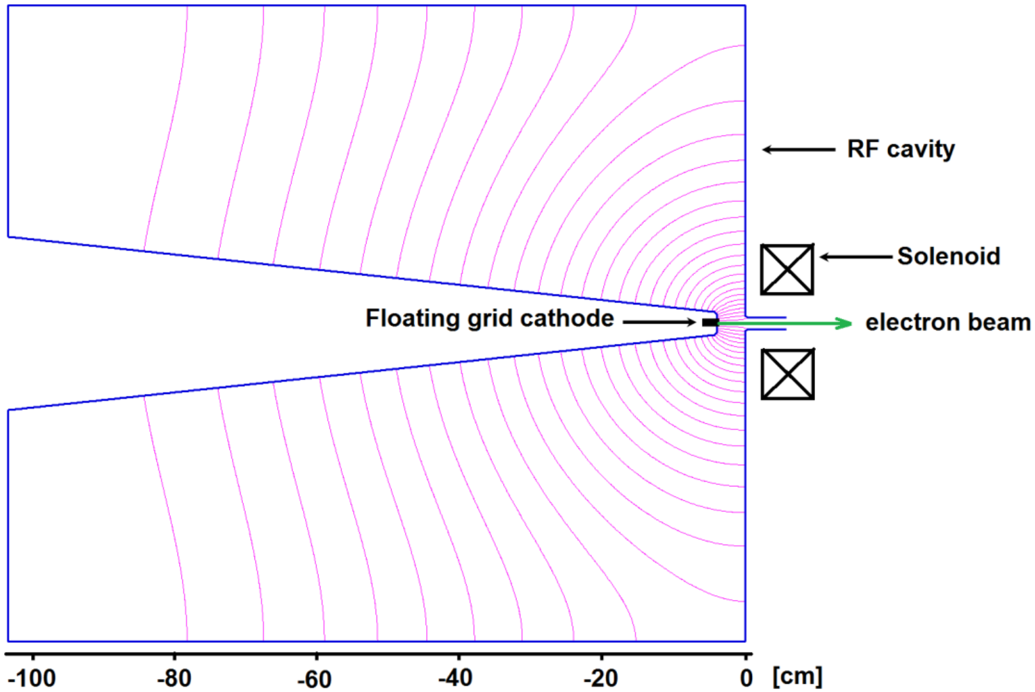


Large I_{CH} (I_{DS})

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

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

- 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.
- Cath. size: 6 mm
- Solenoid for magnetization and beam focusing.



RF cavity (Cu)

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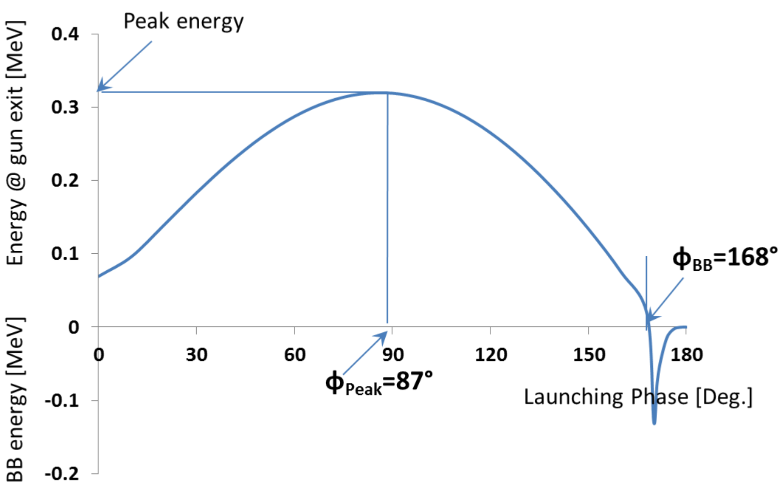
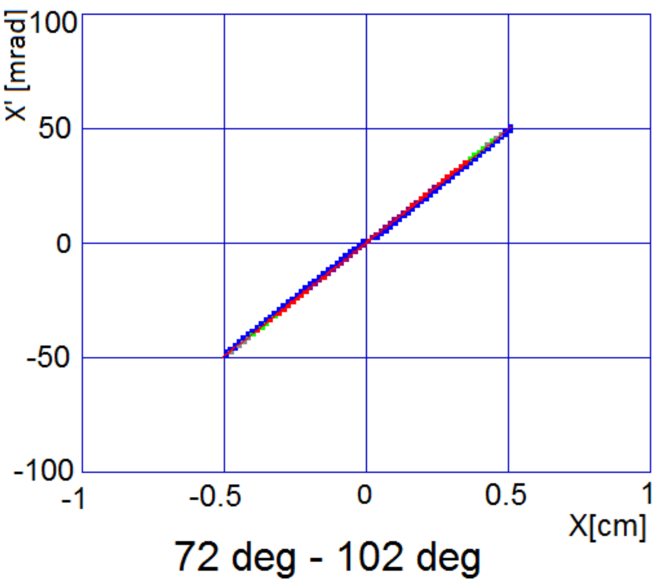
Example: JLab's Magnetized Beam for MEIC e-cooling





Peak energy:	**330 keV**
ϕ_{Peak}:	**87°**
ϕ_{BB}:	**168°**

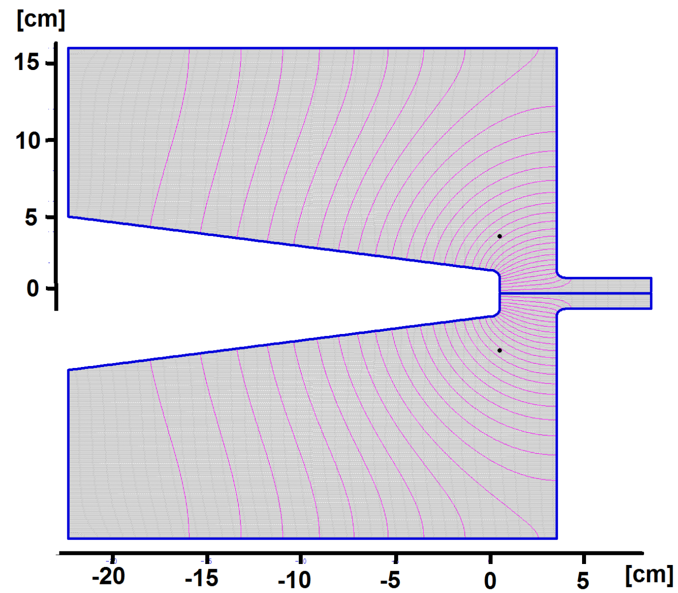
Phase space @ gun exit

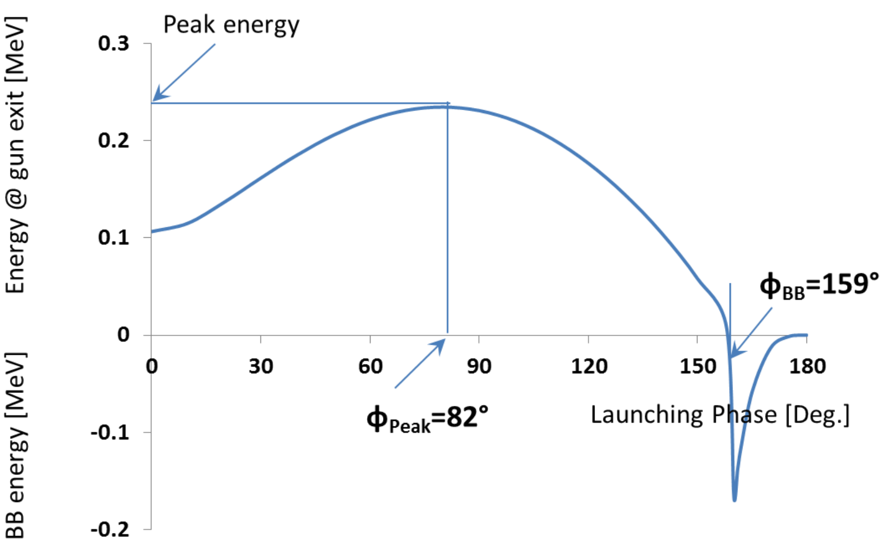
RF field induced emittance: 0.4 μm

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/cm²

- Beam energy: 235 keV





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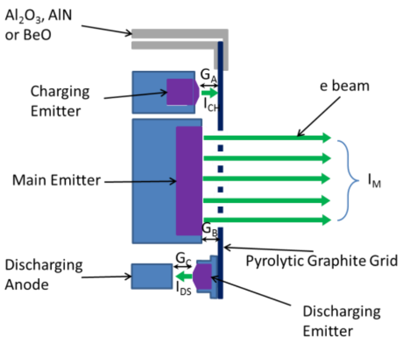
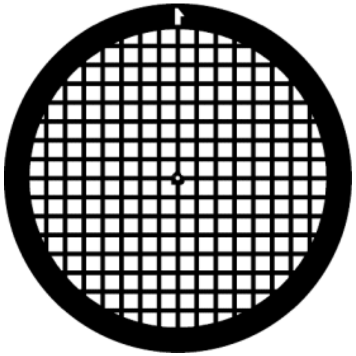
Floating Grid Structure





Floating grid

Material: Pyrolytic graphite (>3000°C)
Diameter: 6 mm

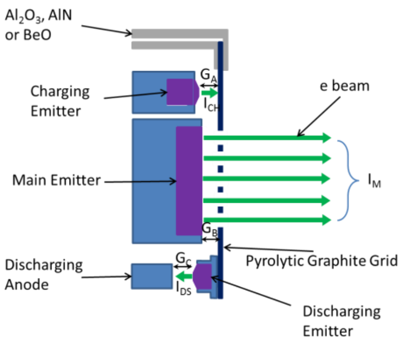
RF heating power: Negligible

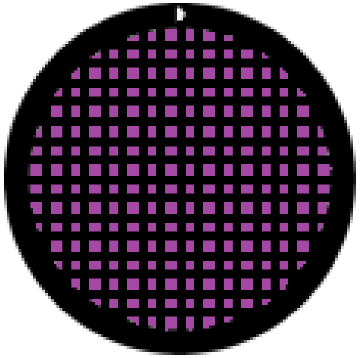
Heating/dissipating:

- Radiation
- Conduction
- Charging current

Temperature: ~ 1500 K

Main Emitter





Main emitter

Material: LaB_6(2.65 eV)/CeB_6 dispenser, FEA, etc.
Diameter: 6 mm
Temperature: 1800 K
Current density: 15 A/cm^2 (100 A/cm^2)

Assume emission window is ±15°(±30°)

- **Bunch charge is <u>2.3 nC (4.6 nC)</u>**
- **Average current of <u>175 mA (350 mA)</u>.**

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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

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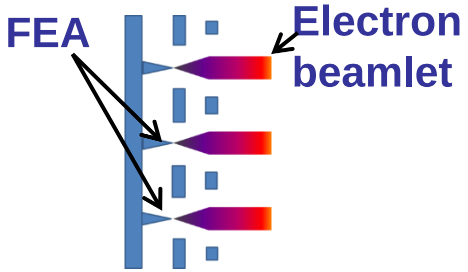
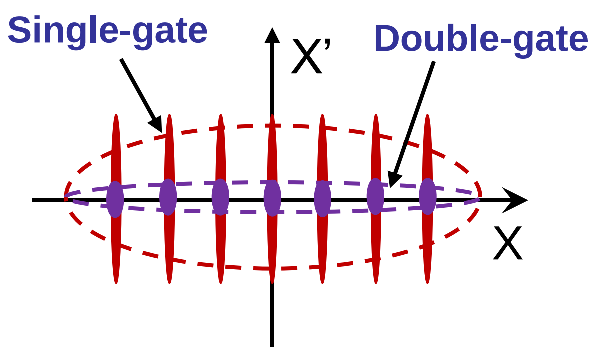
Emittance of Multiple Beamlets

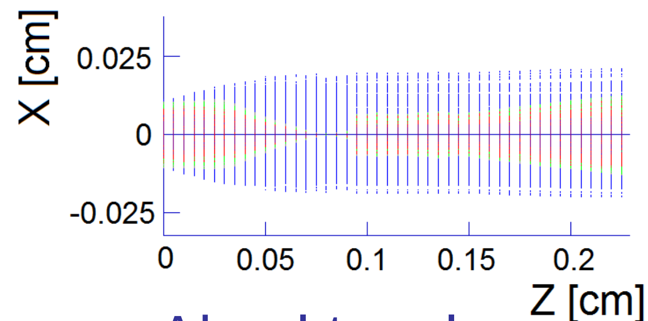
- **Space charge is strong near cathode (∝ $1/(\beta\gamma)^3$.**
- **A focusing near cathode helps suppress emittance growth, like a double-gate FEA (~0.2 μm/mm) compared to a single-gate FEA (~2μm/mm).**
- **Negative biased floating grid also provides a focusing (like in an Einzel lens), provides the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

<u>Cathode diameter: ϕ=6mm</u>

Single-gate FEA	Double-gate FEA	Normal grid	Floating grid
12μm	1.2μm	6μm	**<u>3μm</u>**

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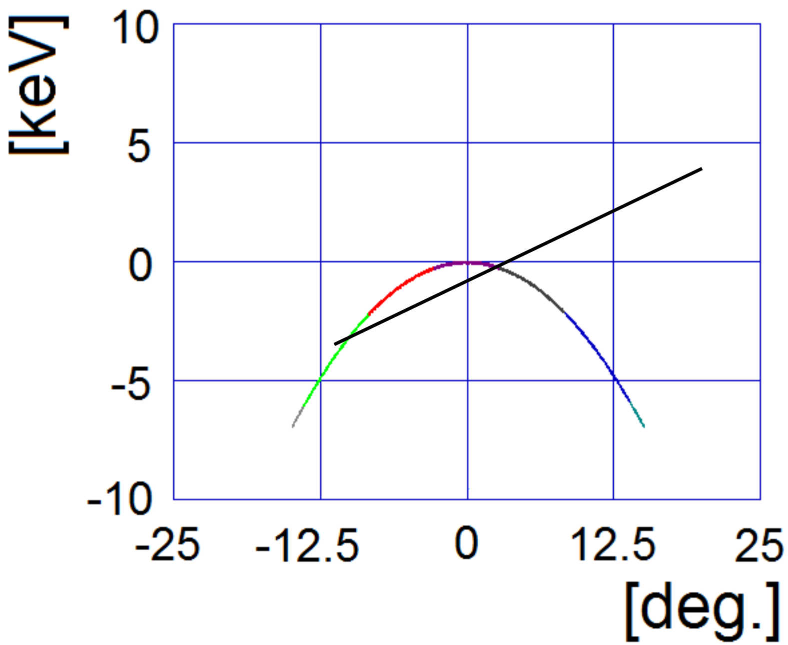
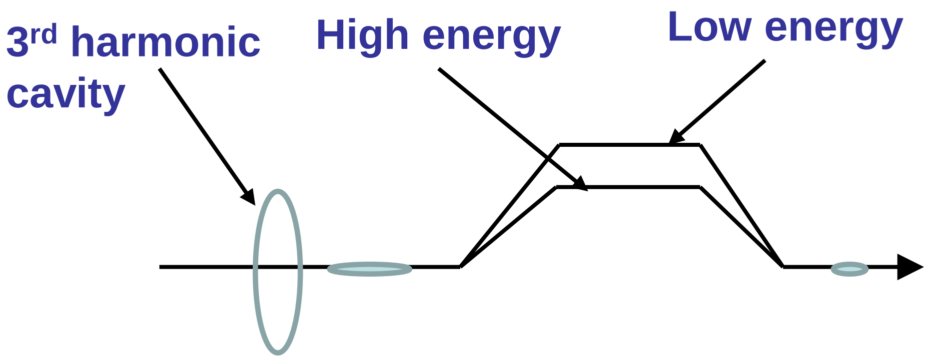
Longitudinal Phase Space





Bunch compression system

- **Dominated by sinusoidal RF component.**
- **RMS bunch length: 7.5 cm, need compression. 3rd harmonic frequency cavity + Chicane.**
- **Higher frequency cavity can have shorter bunch and higher average current.**

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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 **1,500 hours**.

- Lowering operating temperature can increase lifetime dramatically, for example, at 1700 K, lifetime becomes **15,000 hours**. 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.

Flexible Design

Current design parameters can be improved!

	Current design	Up to
Bunch charge	*>2.3 nC*	*> 10 nC*
Average current	*>175 mA*	*> 1 A*
Beam energy	*330 keV*	*> 1 MeV*
Thermal emittance (of multiple beamlets)	*~ 3μm*	*< 1 μm*
RMS bunch length	*~ 7.5 cm*	*< 1 cm*
Cathode lifetime	*1,500 hours*	*> 15,000 hours*

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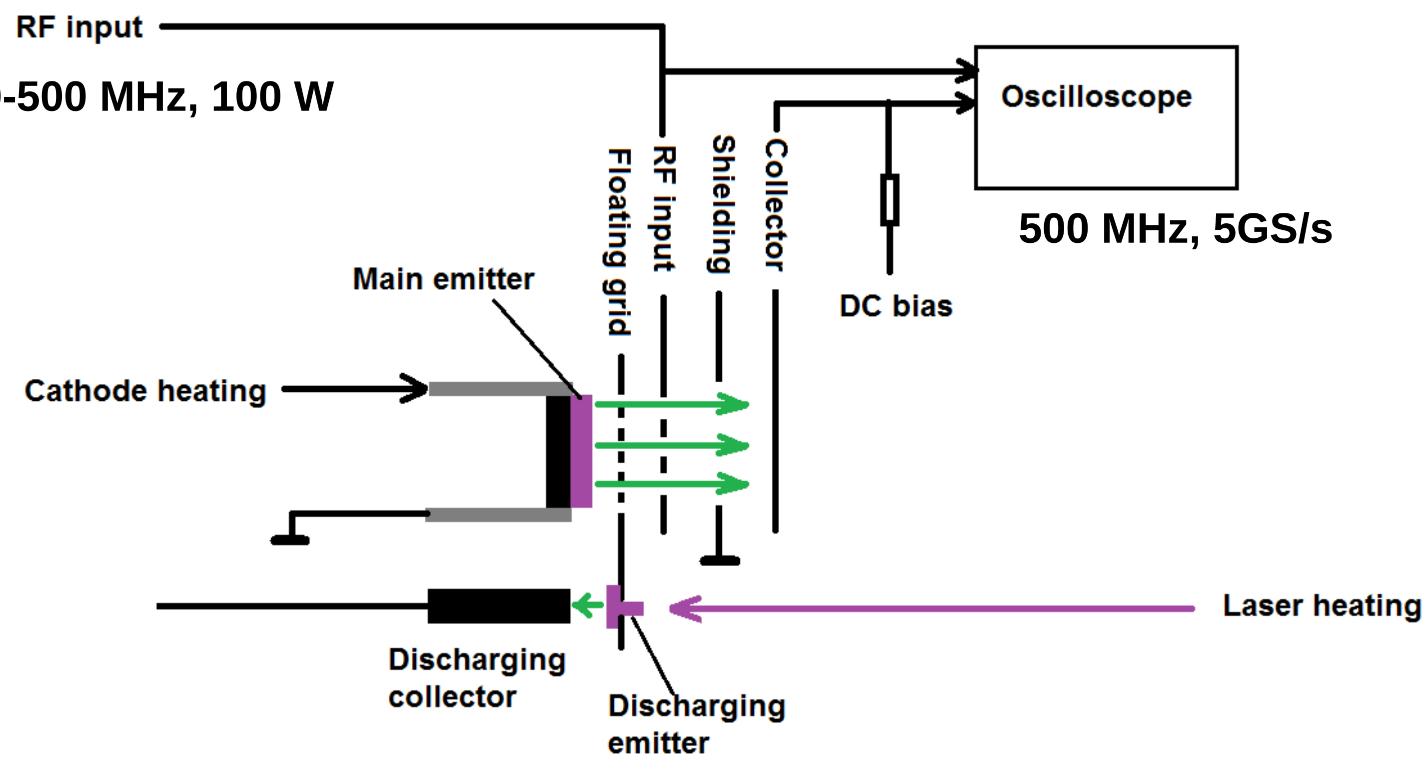
Advantages

- Simple. No additional RF source needed.
- Reliable.
- Cheap to fabricate (single cell Cu).
- Easy operation. (bunch charge / current, bunch length).
- High average current capability.
- Potentially good quality beam.

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

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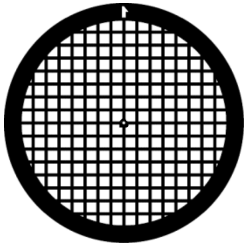
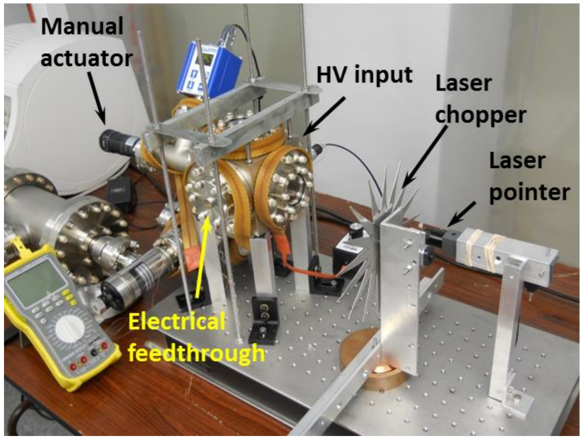
Proof of Principle Experiment

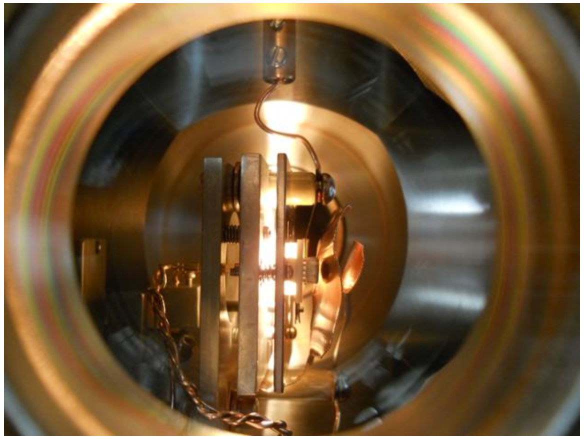
Main emitter &
discharging emitter



Floating grid:
TEM grid



Experimental setup



Vacuum chamber
during conditioning

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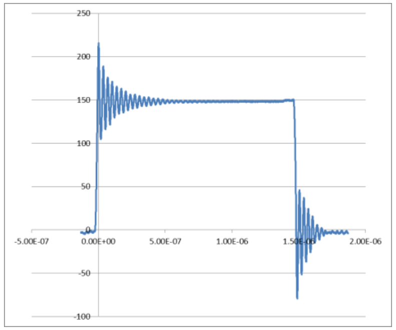
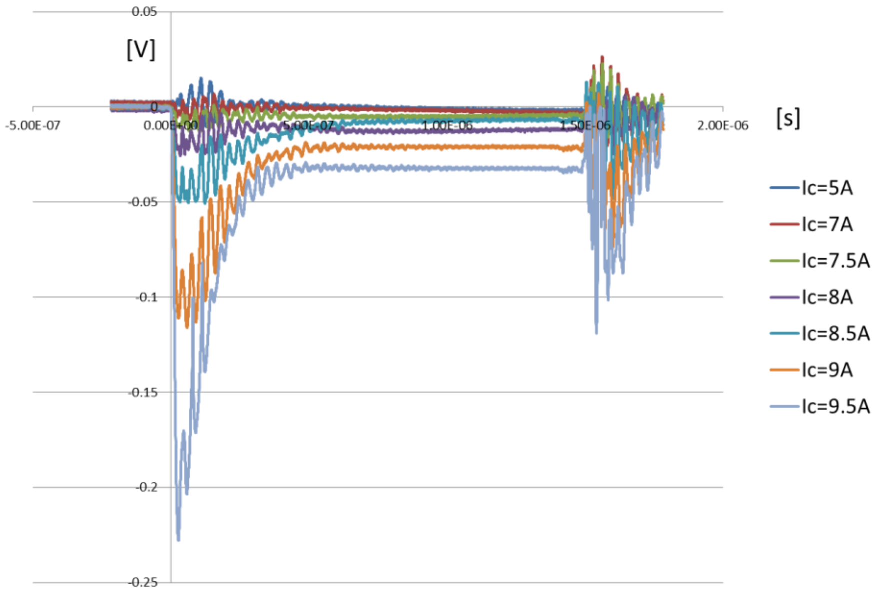
Voltage Pulser Test



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**
- **Laser heating effect.**

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Summary

- This research is to develop a phase controlled thermionic source that eliminates the electron back-bombardment and the poor quality beam associated with the normal use of thermionic sources in RF guns.
  - Allows CW operation for high average current.
  - Small emittance.
  - Long lifetime (a few thousand hours).
  - Robust, can be assembled in air and operate at vacuum as low as 10^{-7} Torr.
  - Stable current.
  - No expensive laser or load lock / preparation chamber required.

- Possible applications:
  - High average current ERL based applications:
    - E-cooling of ion beams.
    - High average power Free Electron Lasers and Terahertz Light Sources
  - High-power high-efficiency RF amplifiers, such as the Inductive Output Tubes

- Our design and calculations indicate that this technique could be used to generate JLab's magnetized beam for ion beam electron cooling and even beyond.

- Some preliminary proof of principle experiment results support our concept.

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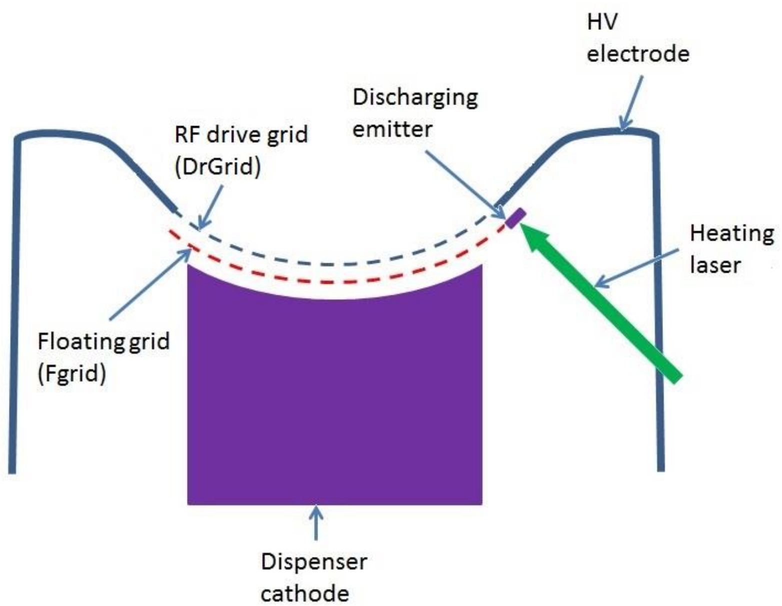
Thank you!

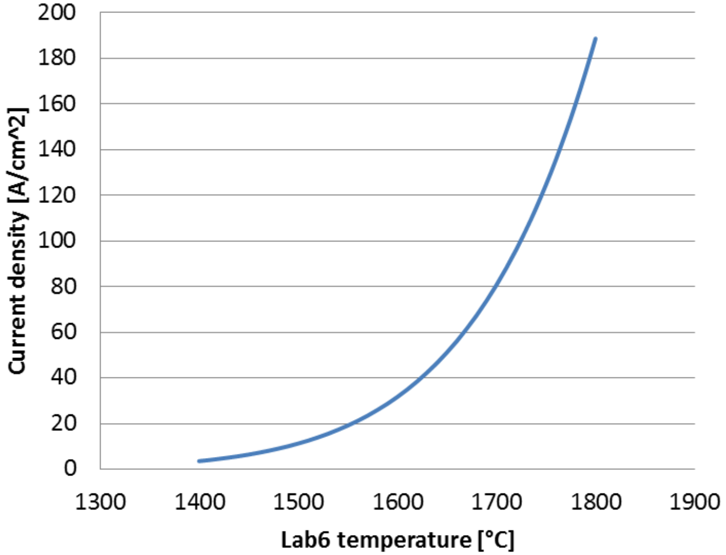
Emittance of a strongly magnetized beam

- 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.
- e-cooling beam also requires high bunch charge, high temperature cathode.
- 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).

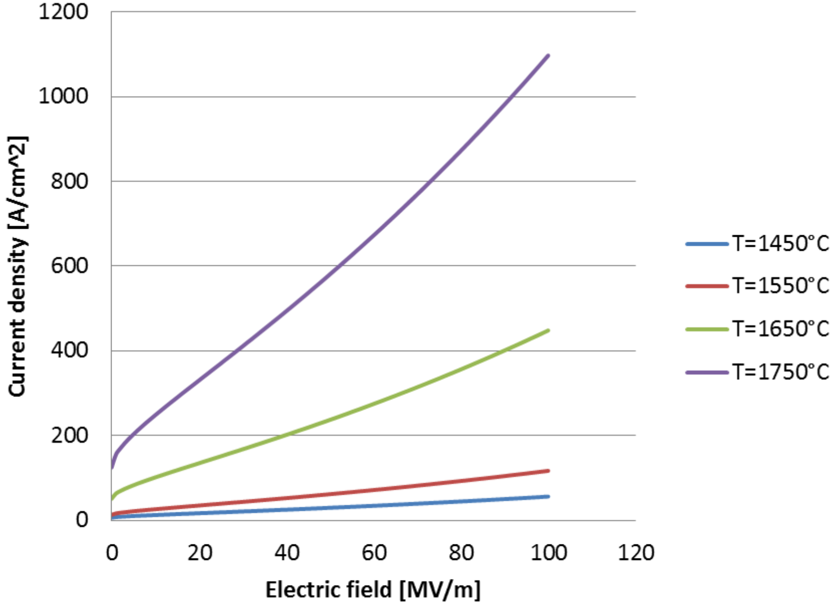
A floating grid in an inductive output tube



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

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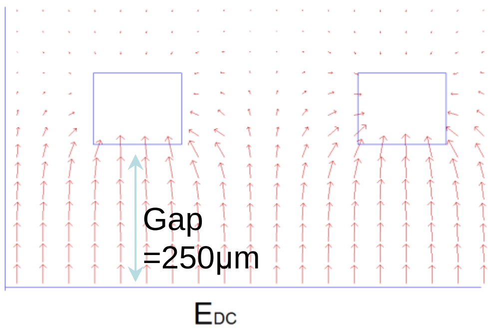

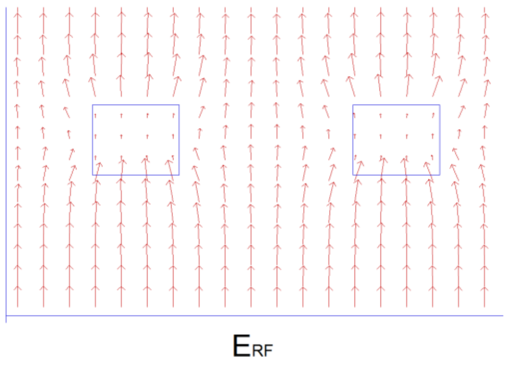

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