200 mA Magnetized Beam for MEIC Electron Cooler

MEIC Collaboration Meeting

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Outline

- MEIC Magnetized Electron Beam Cooling Requirements
- Source Pros and Cons
- Gun Options:
  I. RF guns, warm and cold
  II. Thermionic gun
  III. Photogun
- Magnetized Beam
- Summary

Bunched Magnetized Electron Gun for Cooling

Bunch Length	100 ps (3 cm)
Repetition Rate	476 MHz
Bunch Charge	420 pC
Peak Current	4.2 A
Average Current	200 mA
Emitting Area	6 mm ϕ
Transverse Normalized Emittance	10s microns
Solenoid Field at Cathode	2 kG

Source Pros and Cons

- Warm RF gun: thermionic emitter or photocathode, the promise of high bunch charge, but long low-energy tail, managing heat load for CW operation (AES and LANL examples)

- SRF gun: huge potential, but also huge technical challenges including applied mag field (Rosendorf and BNL)

- RF-pulsed grid thermionic gun: simple, long lifetime, but also long pulse and worst emittance (TRIUMF and BINP's NovoFEL)

- DC high voltage photogun: good emittance, delicate photocathodes, high bunch charge demands high bias voltage (JLab and Cornell)

Source Dependencies

- Thermal Emittance: Intrinsic property of a cathode. Depends on work function, surface roughness, laser wavelength, temperature.

- Achievable Current: QE, laser wavelength, laser power, laser damage, heating, emitter size, temperature.

- Bunch Charge: laser peak power, repetition rate, active cathode area, bunch length.

- Cathode Lifetime: ion back bombardment, dark current, contamination by residual gas, evaporation, beam loss, halo beam.

What will applied magnetic field do?

Warm RF gun options

Example 1: Advanced Energy Systems, Inc., design…:

<u>Example 2:</u> LANL design…:

<u>Example 3:</u> MAX-LAB Thermionic – Photocathode RF Gun.
Thorin *et al*., NIM A **606**, 291 (2009):

- Thermionic: for storage ring injection
  - BaO: 6 mm diameter, 1100˚C
  - Bunch charge: 13 pC, 3 GHz
  - Bunch length: 1 ps after energy filter
  - Peak current: 13 A. Average beam current: 40 mA
  - Electrons kinetic energy after gun cavity: 1.6 MeV
  - Normalized emittance: 10 microns

To switch, reduce T=1100˚C to T=700˚C

- Photocathode: for FEL
  - Bunch charge: 0.2 nC
  - Laser: 9 ps, 10 Hz, 263 nm
  - Average beam current: 2 nA
  - Normalized emittance: 5.5 microns
  - QE: 1.1×10^{-4}

SRF Gun Options

Example 1: Rosendorf BESY:

Example 2: BNL:

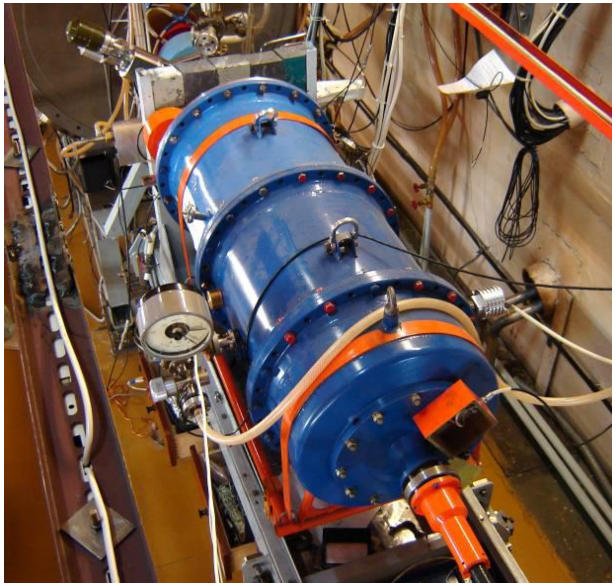
Thermionic Gun Options

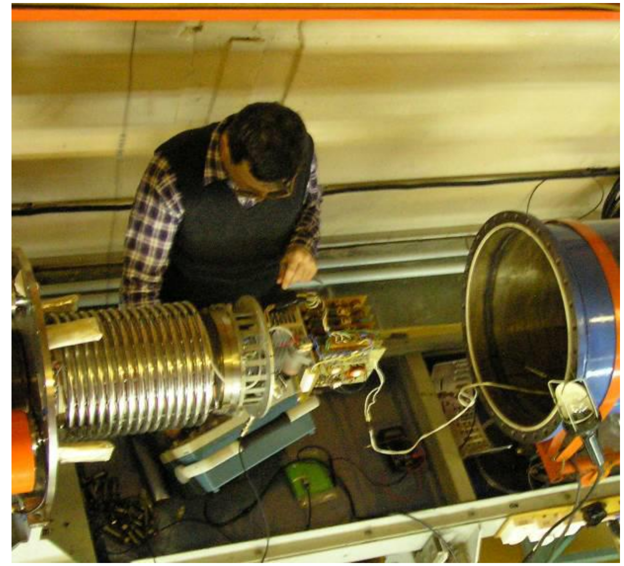
Example 1: TRIUMF e-Linac for photo-fission of actinide target materials to produce exotic isotopes:

- BaO: 6 mm diameter, 775˚C
- Grid at 650 MHz
- Gun HV: 300 kV
- Average beam current: 25 mA
- Bunch charge: 38 pC
- Normalized emittance: 30 microns. Emittance is dominated by the electric field distortion caused by the grid.

Production target sets no requirement on beam emittance

<u>Example 2:</u> Thermionic Gun and 1.5 MeV Injector of BINP's NovoFEL. B.A. Knyazev *et al*., Meas. Sci. Tech. **21**, 054017 (2010):



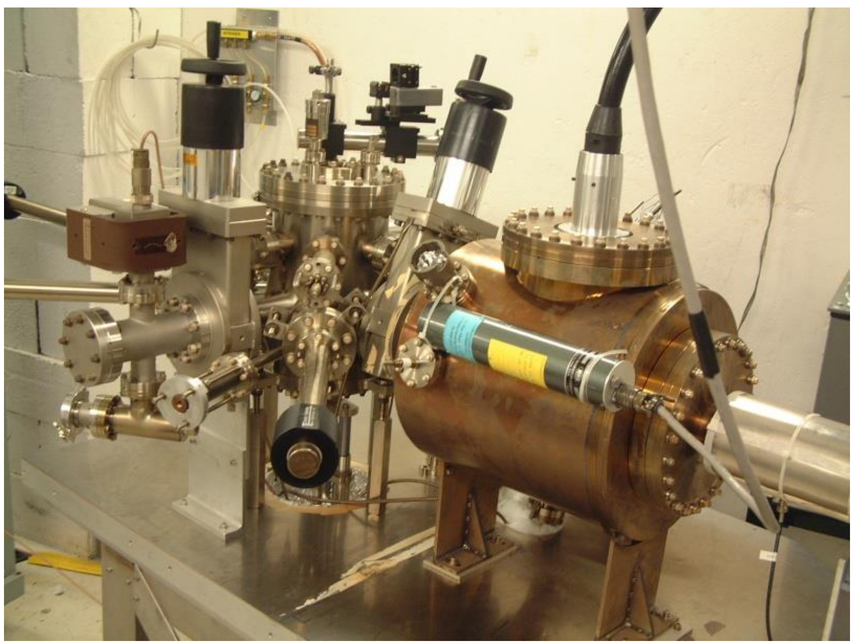


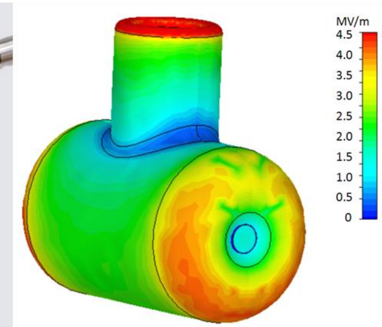
Gun HV	300 kV
Maximum peak current	1.8 A
Maximum average current	30 – 45 mA
Maximum bunch repetition rate	22.5 MHz
Bunch length	1.3 ns
Bunch charge	1.5 – 2 nC
Normalized emittance	10 microns

Photogun Options

<u>Example 1:</u> JLab 200 kV Inverted dc Gun with K_2CsSb photocathode:

- Average beam current: 10 mA
- Laser: 532 nm, dc
- Lifetime: very long (weeks)
- Thermal emittance: 0.7 microns/mm(rms)





Mammei *et al*., Phys. Rev. ST AB **16**, 033401 (2013)

Example 2: JLab 350/500 kV Inverted dc Gun:

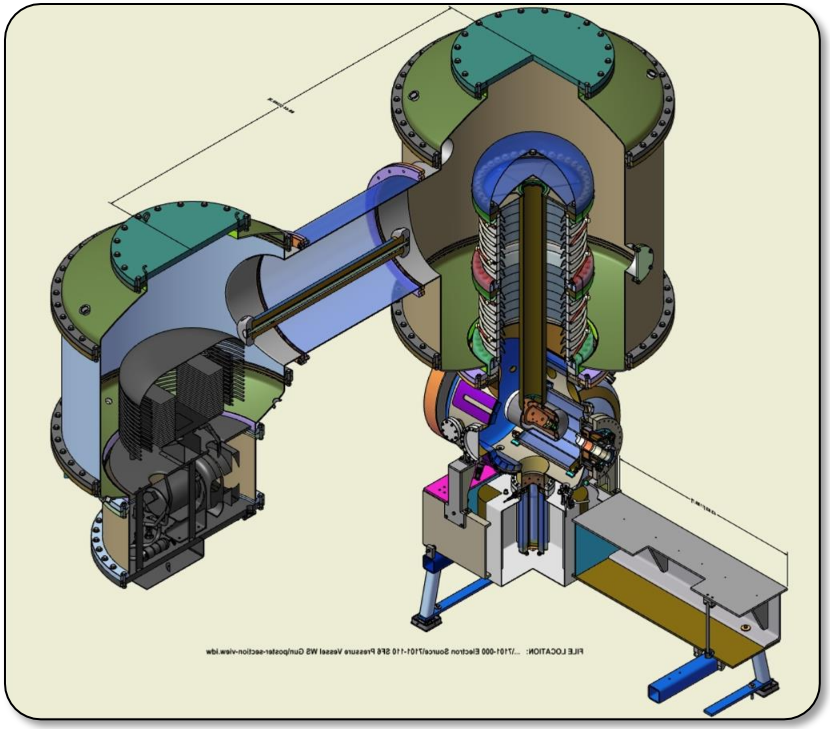
	200 kV Gun	350/500 kV Gun
Chamber	14” ϕ	18’’ ϕ
Cathode	2.5” T-shaped	6” ϕ Ball
Cathode Gap	6.3 cm	6.3 cm
Inverted Ceramic	4” long	7” long
HV Cable	R28	R30
HV Supply	Spellman 225 kV, 30 mA	Glassman 600 kV, 5 mA
Maximum Gradient	4 MV/M	7 (10) MV/m

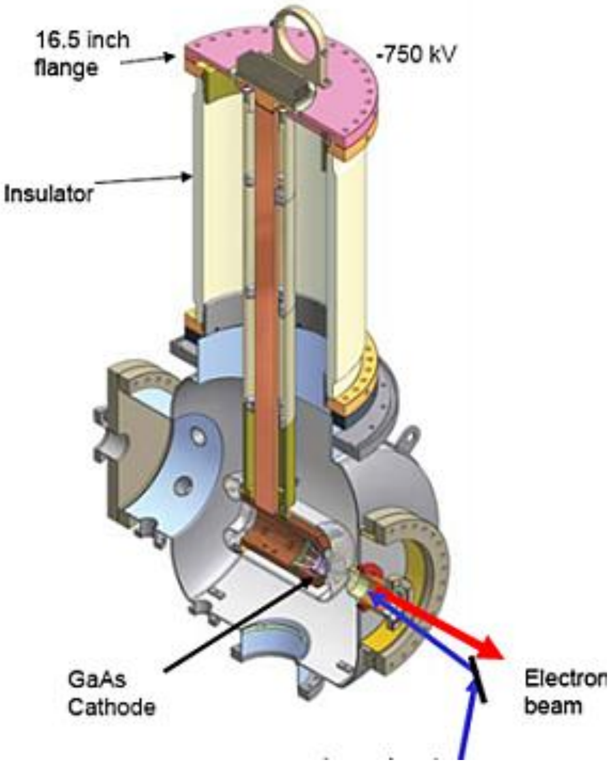
Achieved 350 kV with no FE, next:

- Keep pushing to reach 500 kV
- Run beam with K_2CsSb photocathode

Example 3: Cornell dc Gun with K_2CsSb photocathode:

- Gun HV: currently operating at 350 kV (designed 500-600 kV)
- Average beam current: 60 mA for X hours….
- Bunch charge: 77 pC
- Bunch length: 10 ps, 1.3 GHz
- Normalized emittance: <0.5 microns



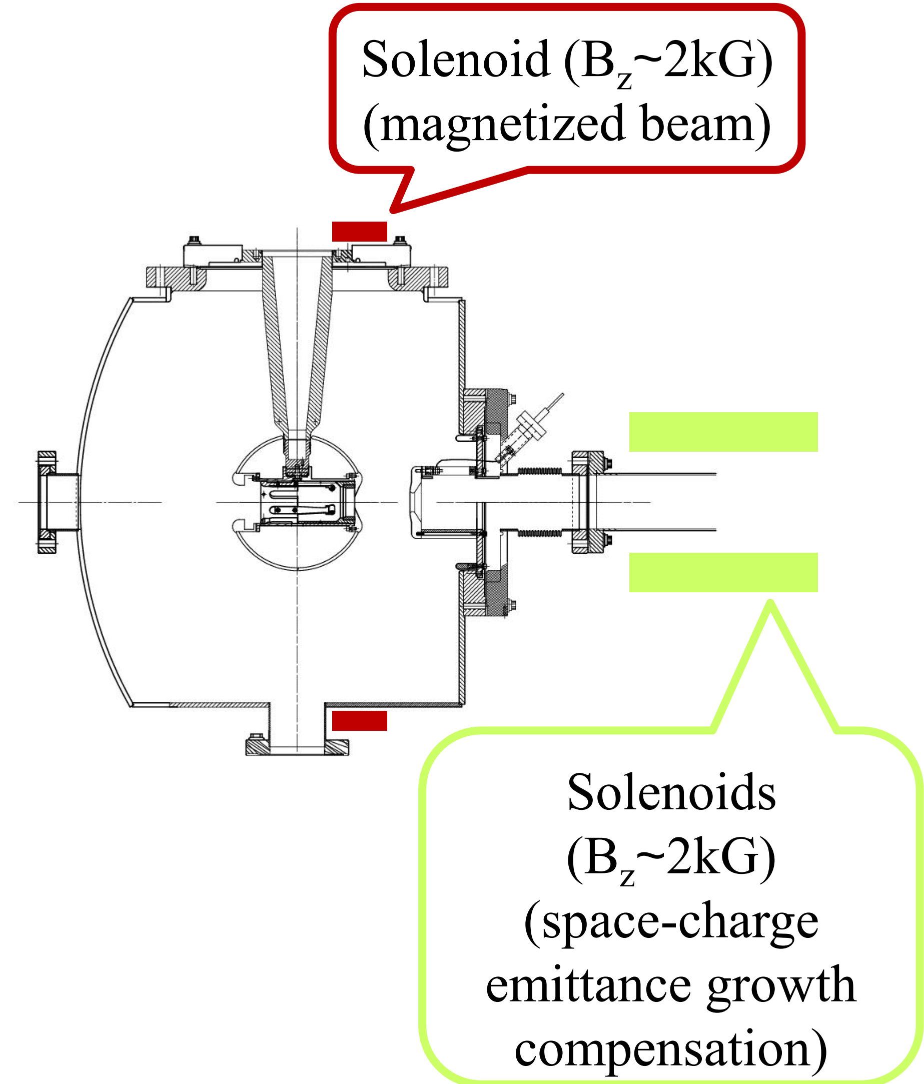


Magnetized Beam and Emittance Compensation

I. Magnetized Cathode:
  - ➢ To produce magnetized (angular-momentum-dominated) electron beam to ensure zero angular momentum inside cooling-solenoid section)

II. Injector Solenoids:
  - ➢ To compensate space-charge emittance growth

III. Will be easier to implement with compact gun (inverted photogun or thermionic gun)



Summary

I. Thermionic gun would be our first choice (less maintenance but may need complicated injector):

   - **TRIUMF/BINP Gun with <u>Inverted Ceramic</u>**

II. For better emittance, a dc HV photogun is good option:

   - **JLab 350/500 kV Inverted Gun and JLab multi-alkai photocathode (Na_2KSb or K_2CsSb)**

III. If one gun cannot provide 200 mA, then use two or three guns and combine beams using RF combiner or dipole magnet

LDRD: 200 mA Magnetized Beam

I. Use JLab 350/500 kV Inverted Gun and K_2CsSb photocathode

II. Design and build Cathode Solenoid

III. Generate magnetized beam

IV. Measure beam magnetization:
   i. Measure beam emittance vs. beam size
   ii. Measure directly using slit and screen

V. Study transportation of magnetized beam (must preserve magnetization)

VI. Measure magnetized photocathode lifetime at high currents

VII. Repeat with 100 kV thermionic gun loaned to TRIUMF

Backup Slides

Magnetized Electron Cooling

Busch's Theorem

- On entering or exiting solenoid, beam acquires a kick that makes beam to rotate

- Busch's Theorem: Canonical angular momentums is conserved,

$$mr^2 \dot{\theta} + \frac{e}{2\pi}\Phi = P_\theta = Const.$$

- Canonical angular momentum:

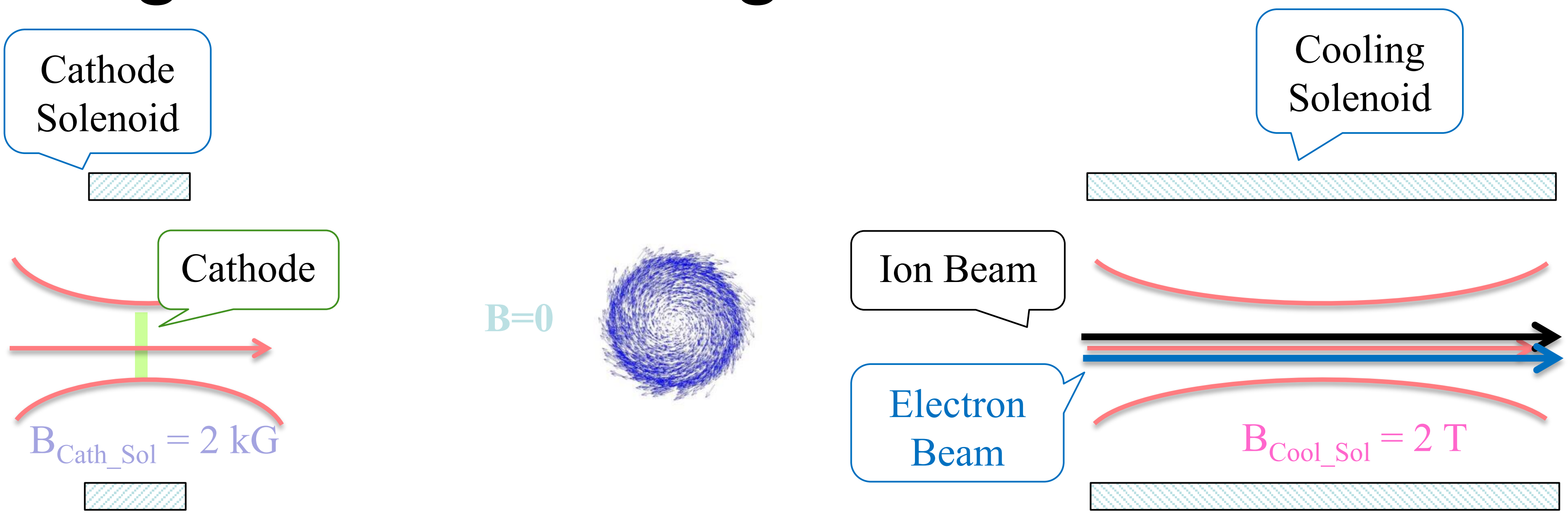
$$P_\theta = \frac{1}{2} e B_z \sigma_e^2$$

- Magnetic emittance:

$$\varepsilon_{mag} = \frac{e B_z \sigma_e^2}{2 m_e c}$$

ε_{mag}[microns] ~ 30 B[kG] σ_e[mm]^2

Magnetized Cooling



Electrons born in uniform B_z

$$\varepsilon_{n,total} = \varepsilon_{th} R = R\sqrt{\frac{k_B T}{m_e c^2}}$$

$\sigma_e = R_{laser} = 3$ mm

Upon exit of Cathode Solenoid

$$\varepsilon_{n,total} = \sigma_e \sqrt{\varepsilon_{th}^2 + \varepsilon_{mag}^2 + \varepsilon_{SC}^2}$$

$$\varepsilon_{mag} = \frac{e B_{Cath\_Sol} \sigma_e^2}{2 m_e c}$$

Upon entering Cooling Solenoid

$$P_\theta = P_{Cath\_Sol} - P_{Cool\_Sol} \approx 0$$

$$\varepsilon_{mag} \approx 0$$

$$\frac{B_{Cool\_Sol}}{B_{Cath\_Sol}} = \frac{R^2}{\sigma_e^2}$$

$\sigma_e = 1$ mm

Why: Magnetized beam?

I. Magnetic field limits transverse motion of electrons; cooling rate is determined by longitudinal velocity spread:

$$\lambda = \tau^{-1} \approx \frac{\rho}{v - v_{e\parallel}}$$

II. Cooling rate for non-magnetized beam:

$$\lambda = \tau^{-1} \approx \frac{\rho}{v_{e\perp}}$$

Cooling Solenoid

I. Cooling solenoid: 30 m long and 2 T field

II. Electron and ion are moving at same speed in cooling section (solenoid)

III. Inside cooling solenoid, electron beam is *calm:* not to have any angular motion

IV. Cooling solenoid must have high parallelism of magnetic field lines:

$$\frac{\Delta B_{\perp}}{B_z} < 10^{-5} (?)$$

Cooling Rate: Dependencies on Electron Beam Properties

I. Proportional to average beam current (does not depend on peak current)
II. Independent of ion beam intensity
III. Proportional to cooler length
IV. Magnetized cooling is less dependent on electron beam transverse emittance
V. Cooling rates with magnetized electron beam are ultimately determined by electron longitudinal energy spread only
VI. Non-magnetized beam depends on transverse electron velocity (a weak field may be used for focusing – i.e., FNAL dc cooler, 100 G)
VII. Bunched electron (from SRF gun) cooling planned at BNL – without any magnetization, shield magnetic field < 0.2 mG

Electron – ion Recombination Suppression

I. Suppresses ion-electron recombination in cooling section if loss of luminosity is not negligible
   - No suppression is planned at BNL. Future upgrade to use undulator field, 3 G and 8 cm period
   - For magnetized beam, large transverse temperature in cooling section suppresses recombination

Paraxial Beam Envelope Equation

$$\sigma''+\frac{\gamma'}{\beta^2\gamma}\sigma'+\left(\frac{eB_z}{2mc\beta\gamma}\right)^2\sigma-\frac{2I}{I_0\beta^3\gamma^3}\frac{1}{\sigma}-\left(\frac{P_\theta}{mc\beta\gamma}\right)^2\frac{1}{\sigma^3}-\left(\frac{\varepsilon_n}{\beta\gamma}\right)^2\frac{1}{\sigma^3}=0$$

Acceleration Damping

Injector Solenoids (for space-charge emittance growth compensation)

Space Charge

Cathode Solenoid Cooling Solenoid

Cathode Emission

$$P_\theta = P_{Cath\_Sol} - P_{Cool\_Sol} \approx 0$$

$$P_{Cath\_Sol} = \frac{1}{2}eB_zR^2$$

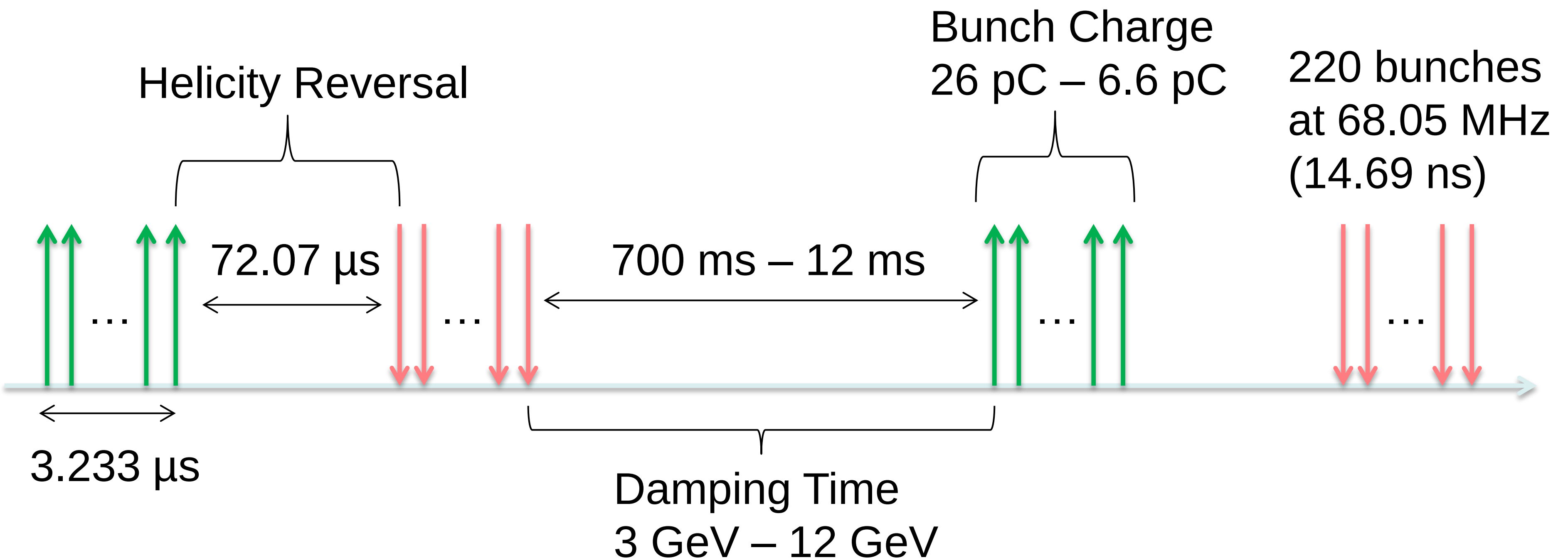
B_z=2 kG

$$P_{Cool\_Sol} = \frac{1}{2}eB_z\sigma_e^2$$

B_z=20 kG

MEIC Polarized Electron Source

MEIC Polarized Source



- Pockels cell switching time at CEBAF today ~70 us. Planned for Moller Exp. ~10 us
- Bunch charge 72 x larger than typical CEBAF, 20 x greater than G0 – Expect to use a gun operating at higher voltage
- 68.05 MHz pulse repetition rate not be a problem for gun, maybe for LINACs
- We are not considering simultaneous beam delivery to fixed target halls, using typical CEBAF beam
- Message: MEIC polarized source requirements do not pose significant challenges

Source Parameter Comparison

Parameter	JLab/FEL	CEBAF	EIC MEIC	EIC eRHIC	Cornell ERL	LHeC	CLIC	ILC
Polarization	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Photocathode	Bulk GaAs	GaAs / GaAsP			K_2CsSb			
Width of microbunch (ps)	35	50	50	100	2	100	100	1000
Time between microbunches (ns)	13	2	14.69	106	0.77	25	0.5002	337
Microbunch rep rate (MHz)	75	499	68.05	9.4	1300	40	1999	3
Width of macropulse	-	-	3.233 µs	-	-	-	156 ns	1 ms
Macropulse repetition rate (Hz)	-	-	2x83	-	-	-	50	5
Charge per microbunch (pC)	133	0.36	26	5300	77	640	960	4800
Peak current of microbunch (A)	3.8	0.008	0.52	53	38.5	6.4	9.6	4.8
Laser Spot Size (cm, diameter)	0.5	0.1	0.3	0.6	0.3	0.5	1	1
Peak current density (A/cm^2)	19	1	7.4	188	500	32	12	6
Average current from gun (mA)	10	0.2	0.001	50	100	25	0.015	0.072

Proposed

* Unpolarized: Bulk GaAs (Cs,F), K_2CsSb, Na_2KSb, …
Polarized: GaAs/GaAsP (Cs,F).

Addressing MEIC Bunch Charge

20 to 72 times larger than CEBAF

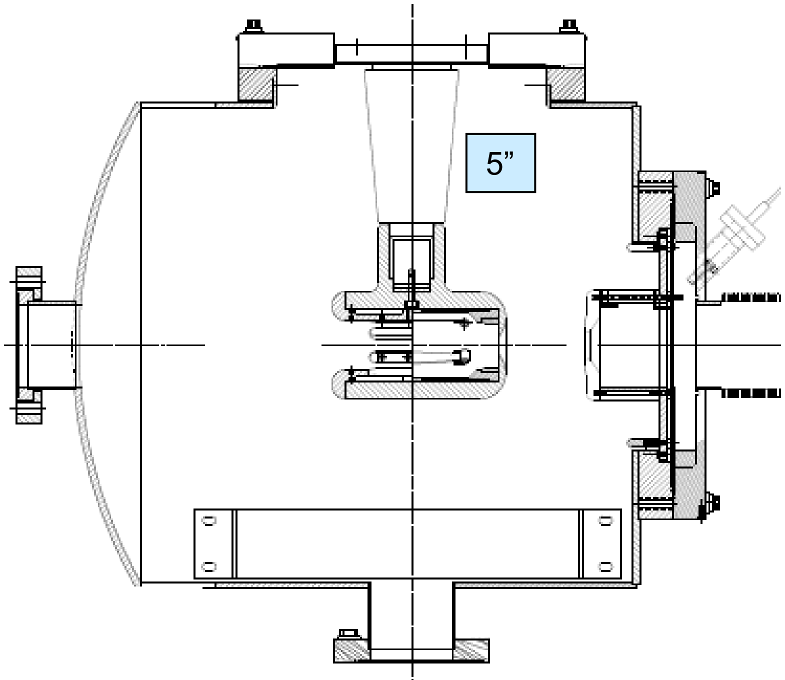
I. Larger Laser Size (reduces space-charge emittance growth and suppresses surface charge limit)

II. Higher Gun Voltage:

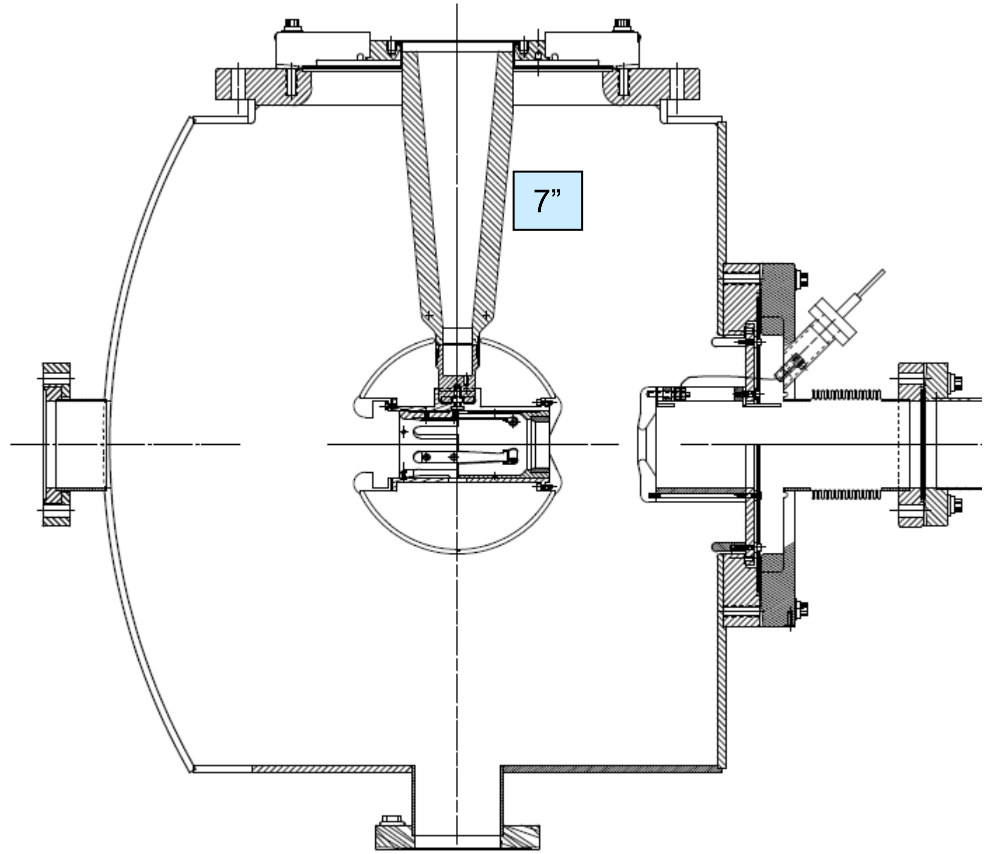
- Reduce space-charge emittance growth, maintain small transverse beam profile and short bunch-length; clean beam transport
- Compact, less-complicated injector

III. To accelerate large bunch charge in CEBAF: use RF feedforward system for C100 cryomodules

JLab 500 kV Inverted Gun



200 kV Inverted Gun



- Longer insulator
- Spherical electrode