Ion Back-Bombardment in RF Guns

Eduard Pozdeyev

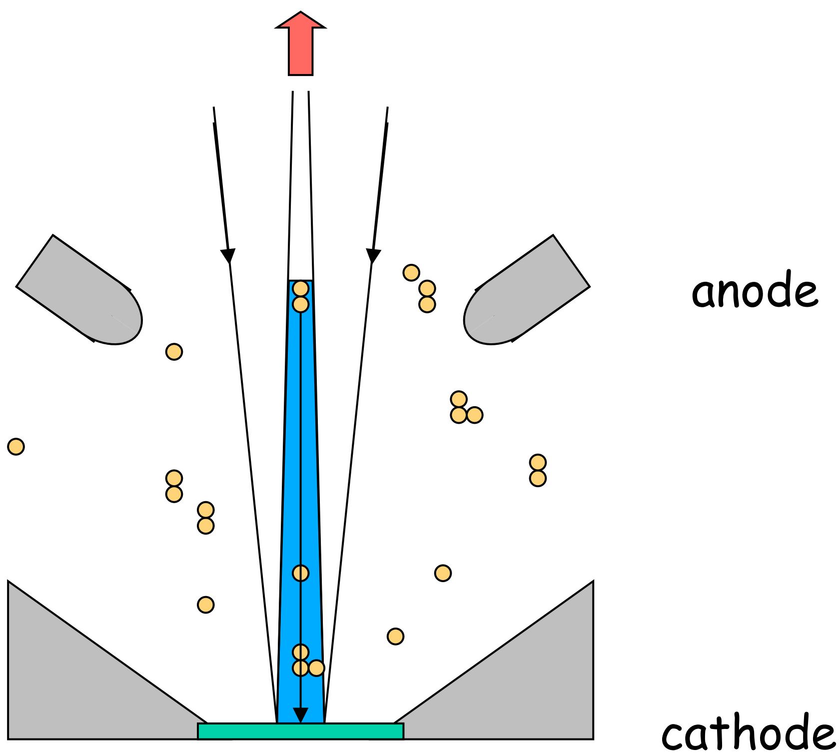
with contributions from
D. Kayran, V. Litvinenko, I. Ben-Zvi

Photoguns

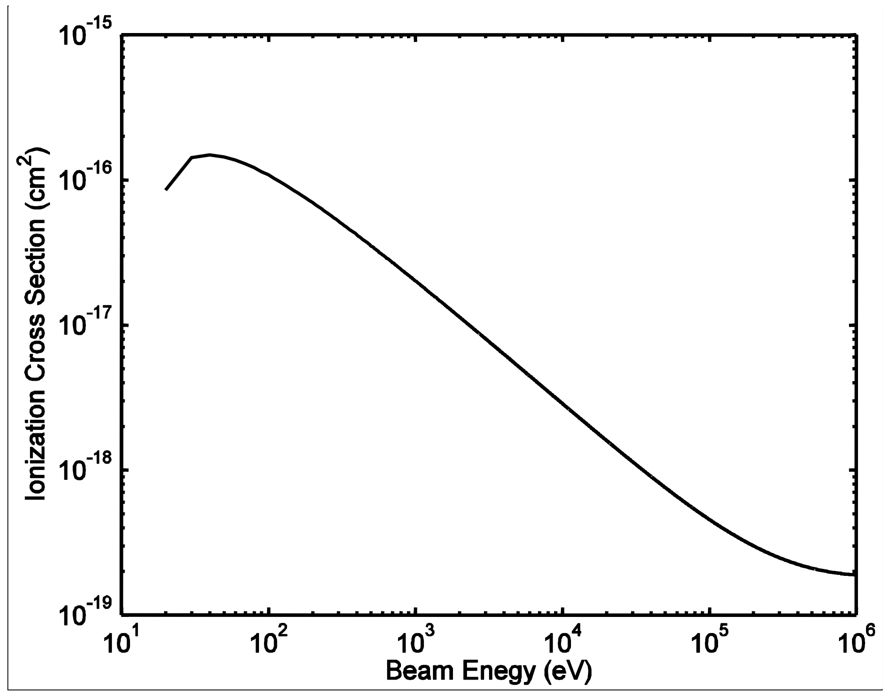
- Photoguns allow for
  - Short bunches
  - Good beam quality
  - Polarized beam
- Linac/ERL based accelerator drivers:
  - eRHIC and other Linac/ERL based colliders
  - Electron coolers, conventional high(er) energy and coherent
  - Light Sources and FELs
- Achieved operational current and life time:
  - DC, unpolarized: ~5 - 10 mA, ~500 C (?) (~10 h)
  - DC, polarized: <500 μA, ~500-1000 C
  - SRF Rosendorf, unpolarized: ~ 1 mA (was not routinely operated)
  - Cu RF ? No CW.
- More current (>100 mA) => longer cathode life time needed

Ion Bombardment in DC photoguns

Ion back-bombardment is believed to be the main cause of degradation of quantum efficiency (QE) of photocathodes in DC photoguns.

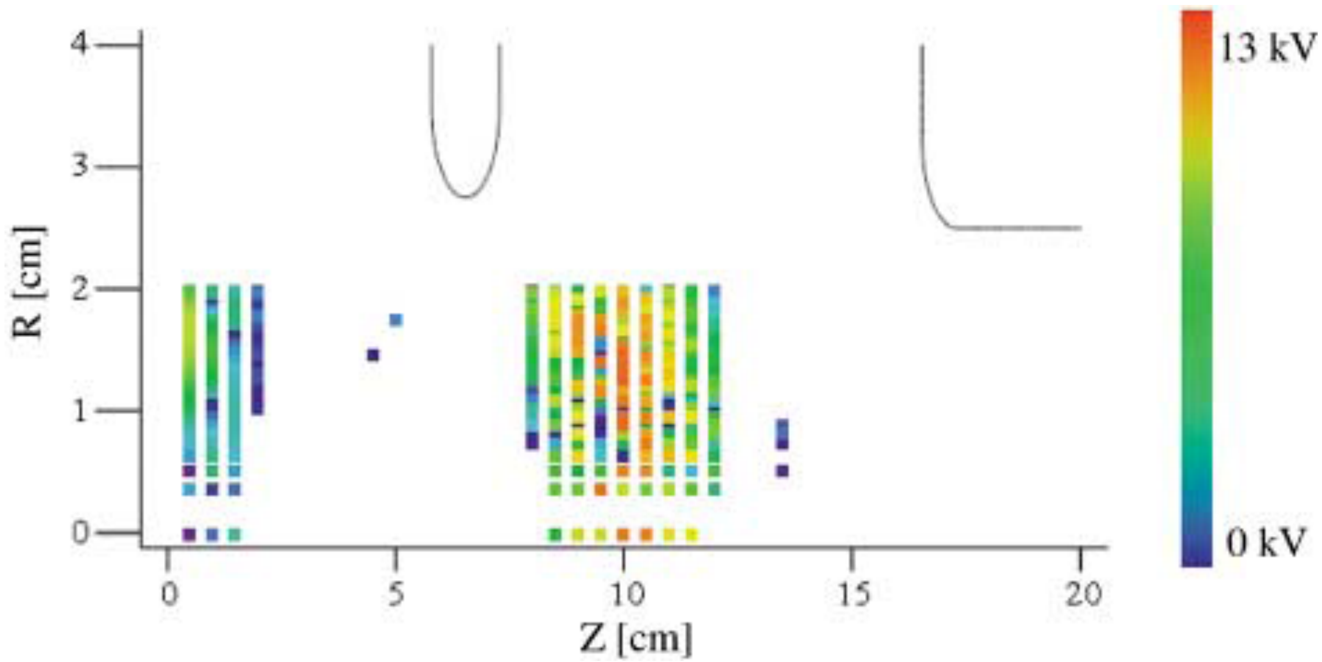


Ionized residual gas strikes photocathode



A large portion of ions comes from the first few mm's of the beam path. This problem is hard to overcome.

Simulation of ion bombardment in RF guns: Lewellen, 2002



Lewellen, PRST-AB 5, 020101 (2002)

Simulation results indicated that cathode ion bombardment in RF guns is possible. Results are hard to interpret and extrapolate to other guns.

Analytical model is needed for better insight!

Analytical Model:
Slow Ion in fast oscillating RF field

Proposed by Kapitza (1951), Landau+Lifshitz (Mechanics, 1957), A. V. Gaponov and M. A. Miller (1958) – applied to EM Fields

1) $$m\ddot{\vec{r}} = \vec{f}, \quad \vec{f} = q\vec{E} + \frac{q}{c}\vec{v}\times\vec{B}$$

Method works if oscillations are small comparatively to the size of field variations:

2) $$(\vec{\xi}\cdot\nabla)\vec{E} << \vec{E} \quad \Leftrightarrow \quad |\vec{\xi}\,|/L << 1$$ $L \sim$ a few cm's, $\xi \sim$ 10-100 μm

$$\text{Assuming:} \quad \vec{E}(r,t) = \vec{E}_0(r)\cos(\omega t+\phi),$$

3) $$\nabla\times\vec{E} = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t} \quad \Rightarrow \quad \vec{B} = -ƛ(\nabla\times\vec{E}_0)\sin(\omega t+\phi)$$

4) $$\left|\frac{\vec{v}\times\vec{B}}{c}\right| \sim \left|\frac{\vec{\xi}}{ƛ}\times(ƛ\nabla\times\vec{E}_0)\right| \sim \frac{\xi}{L}|\vec{E}| << |\vec{E}|$$

To the first order in ξ/L and using slow and fast components, r_0 and ξ:

5) $$m(\ddot{\vec{r}}_0 + \ddot{\vec{\xi}}) = q\vec{E}(r_0,t) + q(\vec{\xi}\cdot\nabla)_{r_0}\vec{E} + \frac{q}{c}\vec{v}\times\vec{B}(\vec{r}_0,t)$$

Analytical model: Effective potential energy

0th-order approximation: $m\ddot{\vec{\xi}} = q\vec{E}_0\cos(\omega t + \phi) \quad \Rightarrow$

6) $$\vec{\xi} = -ƛ^2 \frac{q\vec{E}_0\cos(\omega t+\phi)}{mc^2}, \quad \dot{\vec{\xi}} = ƛc\frac{q\vec{E}_0\sin(\omega t+\phi)}{mc^2}$$

1st-order approximations with averaging:

7) $$\ddot{\vec{r}}_0 = -ƛ^2c^2\left(\frac{q}{mc^2}\right)^2\left((\vec{E}_0\cdot\nabla)\vec{E}_0\overline{\cos^2(\ldots)} + \vec{E}_0\times(\nabla\times\vec{E}_0)\overline{\sin^2(\ldots)}\right) =$$
$$-\frac{ƛ^2c^2}{2}\left(\frac{q}{mc^2}\right)^2\left((\vec{E}_0\cdot\nabla)\vec{E}_0 + \vec{E}_0\times(\nabla\times\vec{E}_0)\right) = -\frac{ƛ^2c^2}{4}\left(\frac{q}{mc^2}\right)^2\nabla|\vec{E}_0|^2$$

Effect of oscillating field is the effective potential energy, which is just averaged kinetic energy of oscillations **(Isn't it cool!)**:

8) $$U_{eff} = m\frac{\overline{|\dot{\vec{\xi}}|^2}}{2} = \frac{ƛ^2mc^2}{4}\left(\frac{q|\vec{E}_0|}{mc^2}\right)^2 = \frac{Z^2}{A}\frac{ƛ^2m_uc^2}{4}\left(\frac{q|\vec{E}_0|}{m_uc^2}\right)^2$$

Analytical model: Initial Conditions and Effective Kinetic Energy

Ions originate with thermal (almost zero) energy and velocity only when and where electrons are present

General solution of the 0[th]-order equation is

$$m\ddot{\vec{\xi}} = q\vec{E}_0 \cos(\omega t + \phi) \quad \Rightarrow$$

$$0 = \lambdabar c \frac{q\vec{E}_0 \sin(\omega t + \phi)}{mc^2} + \vec{v}_0 \quad \Rightarrow \quad \vec{v}_0 = -\lambdabar c \frac{q\vec{E}_0 \sin(\omega t + \phi)}{mc^2},$$

$$T_{eff} = m\frac{|\vec{v}_0|^2}{2} = \frac{\lambdabar^2 mc^2}{2}\left(\frac{q|\vec{E}_0|}{mc^2}\right)^2 \sin^2(\omega t + \phi) =$$

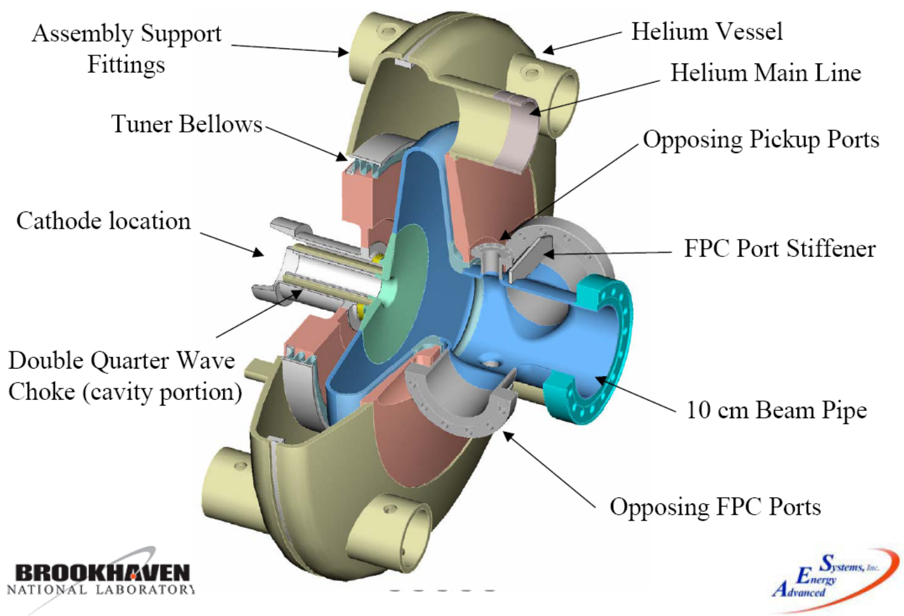
$$\frac{Z^2}{A}\frac{\lambdabar^2 m_u c^2}{2}\left(\frac{q|\vec{E}_0|}{m_u c^2}\right)^2 \sin^2(\omega t + \phi) =$$

$$2U_{eff}\sin^2(\omega t + \phi)$$

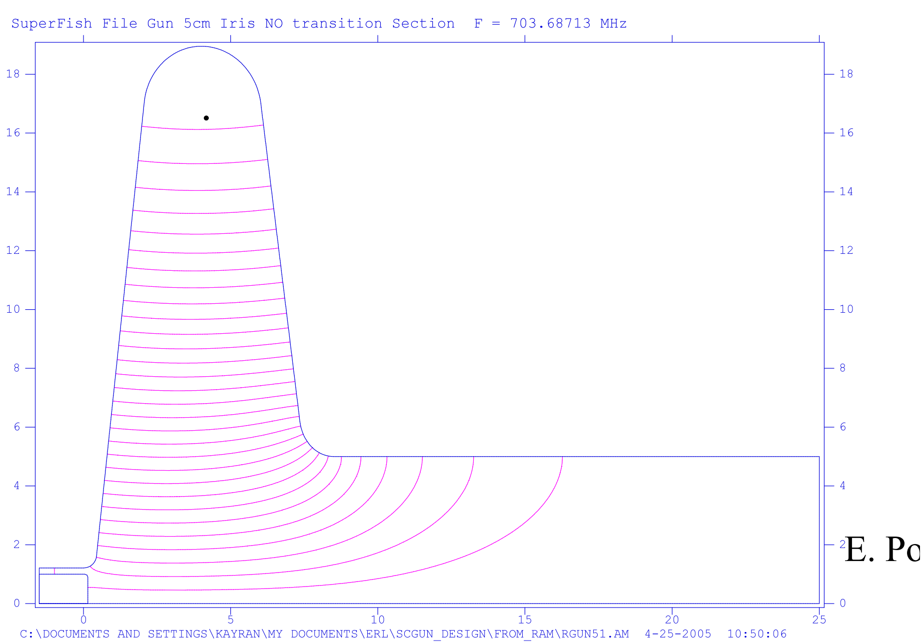
Now we can solve the problem without solving equations of motion.

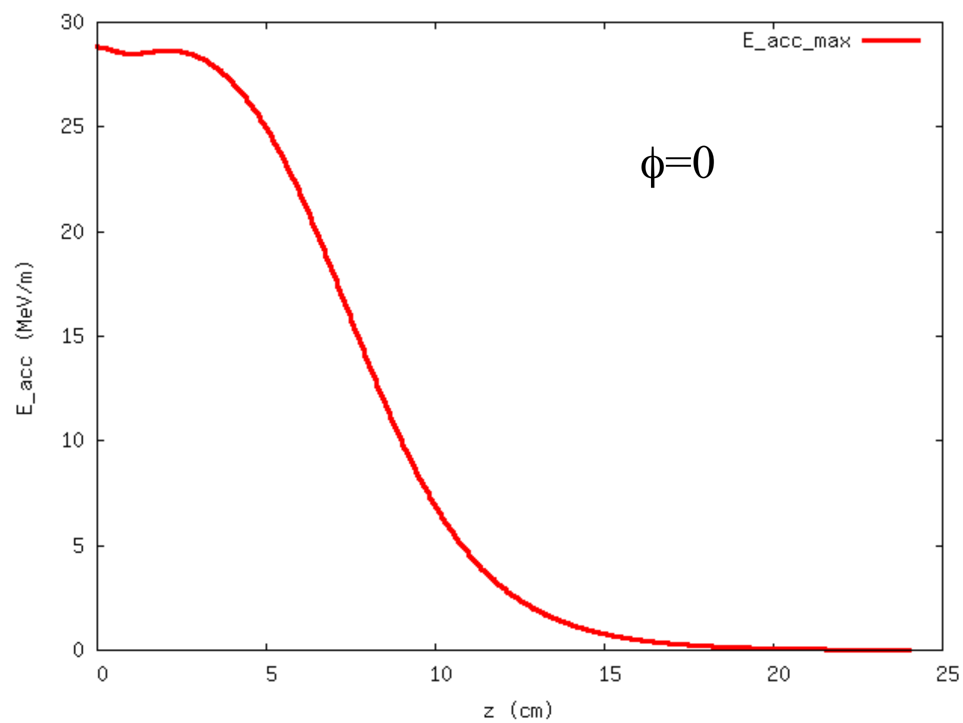
Important: $\boldsymbol{v_0}$ depends on the RF phase when ionization happens.

BNL 1/2-cell SRF Gun



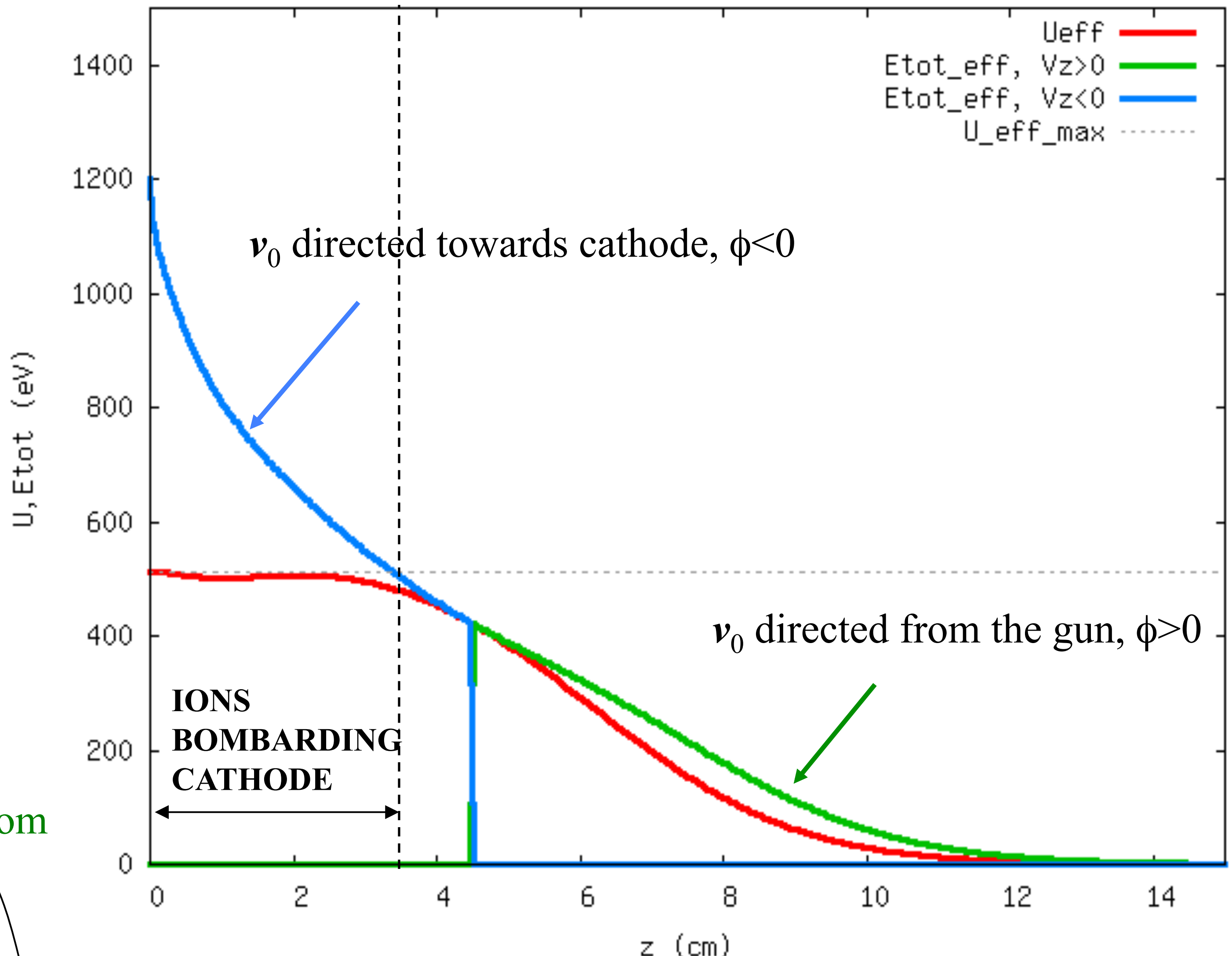
f_{RF} = 703.75 MHz
E_{max} = 30 MeV/m (on axis)
Energy = 2 - 2.5 MeV
I_{av} = 7-50 mA (0.5 A)
q_b = 0.7-5 nC
f_b = 10 MHz (up to 700 MHz)

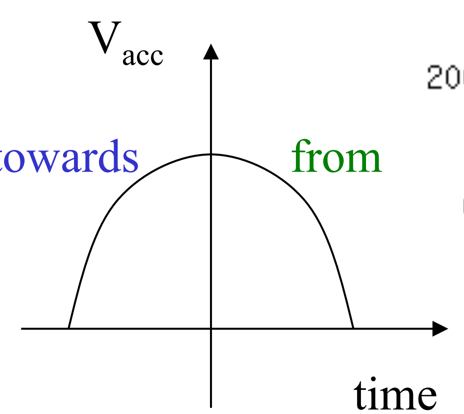




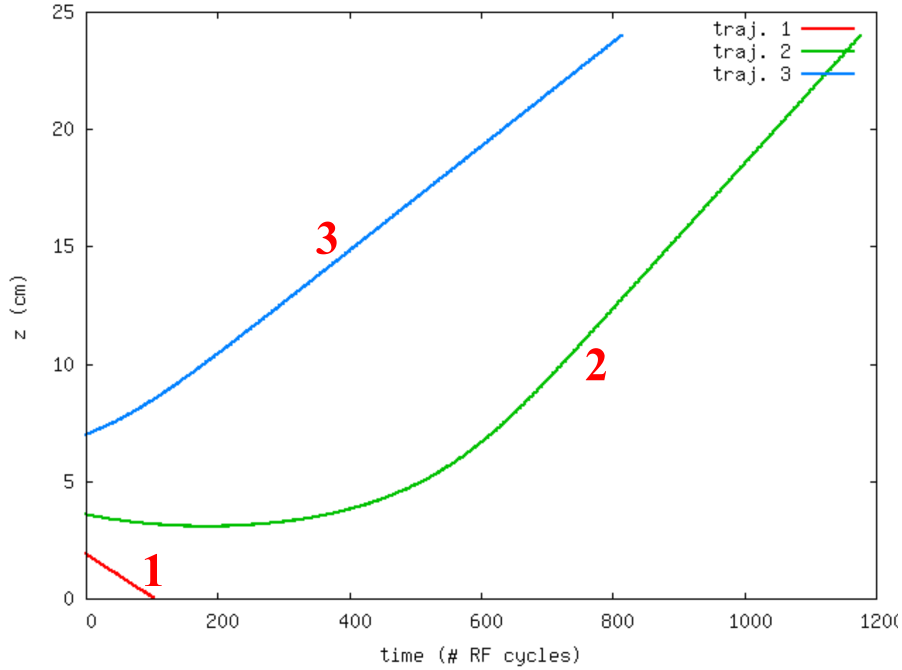
Ion Bombardment in the BNL Gun: 1D case

Beam phase was obtained using Parmela.





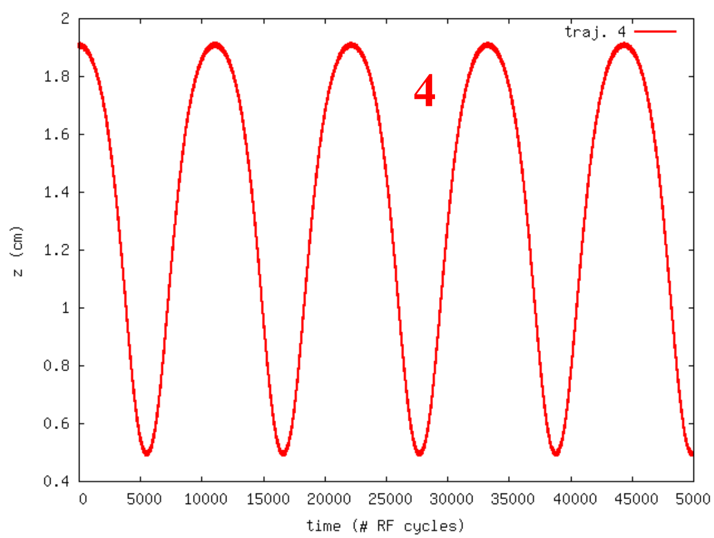
Validation by tracking



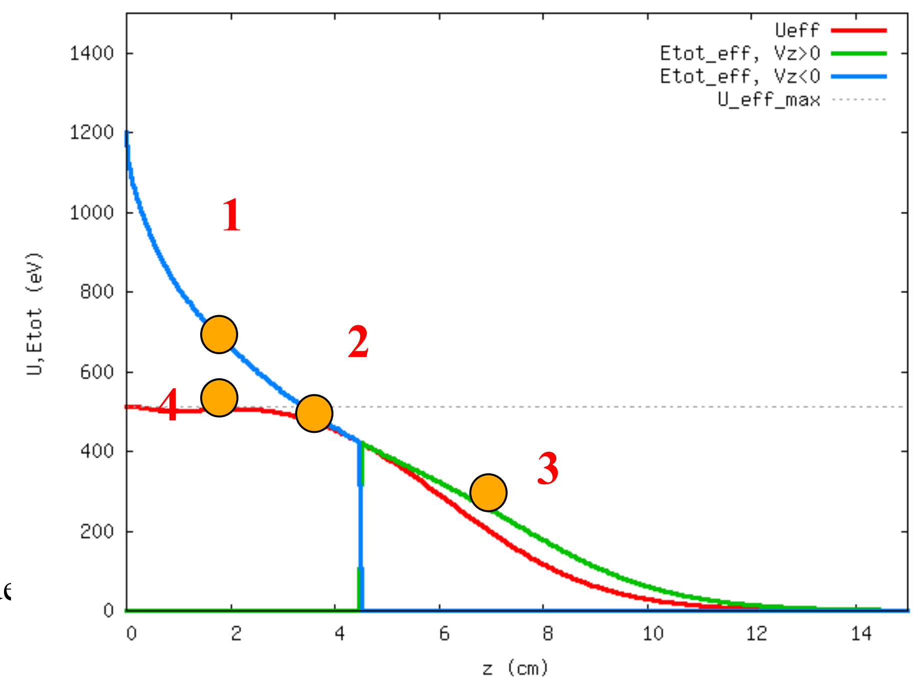
Trajectories 1,2,3 correspond to ions created by the beam.

Trajectory 4 corresponds to ϕ=0. The effective kinetic energy is 0.

(Initial velocity of ions is 0.)

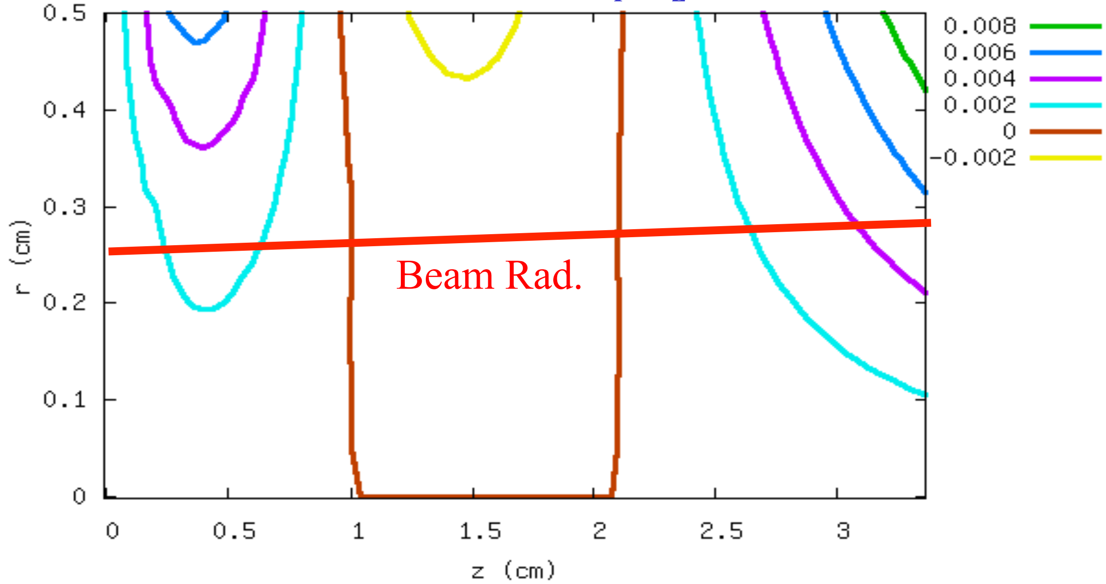


E. Pozde



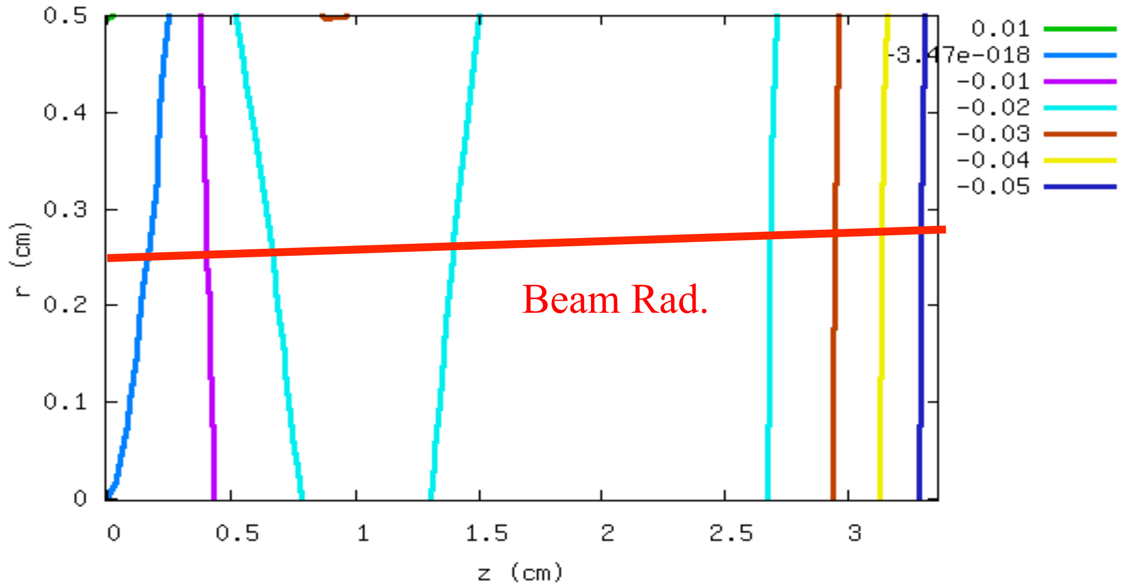
Ions originating off-axis: 2D aspects

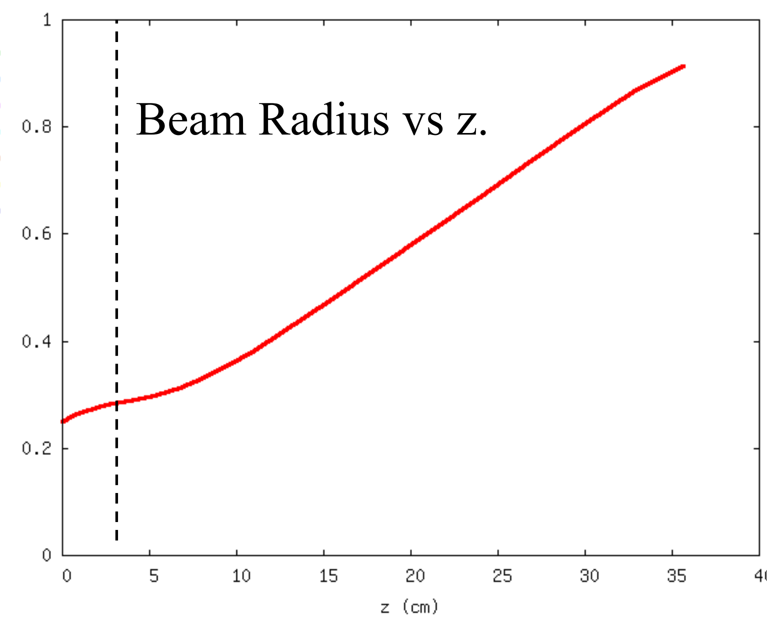
contour plot of E_r/E_z



Because the $\boldsymbol{v}_0$ points almost directly towards the cathode and ∇U_{eff} is almost parallel to the gun axis, <u>the problem can be treated as 1D</u>

contour plot of dU/U





Effect of the electron beam on ions

To calculate the effect of the e-beam along z, the beam can considered as DC with average local charge density ρ=I/(Ave). Because the beam diverges slowly, the potential along z changes slowly too, except the very near to the cathode.

Transverse effect of electron beam can be represented, in time, by a series of linear focusing lenses and drifts. Motion and stability analysis is straight forward:

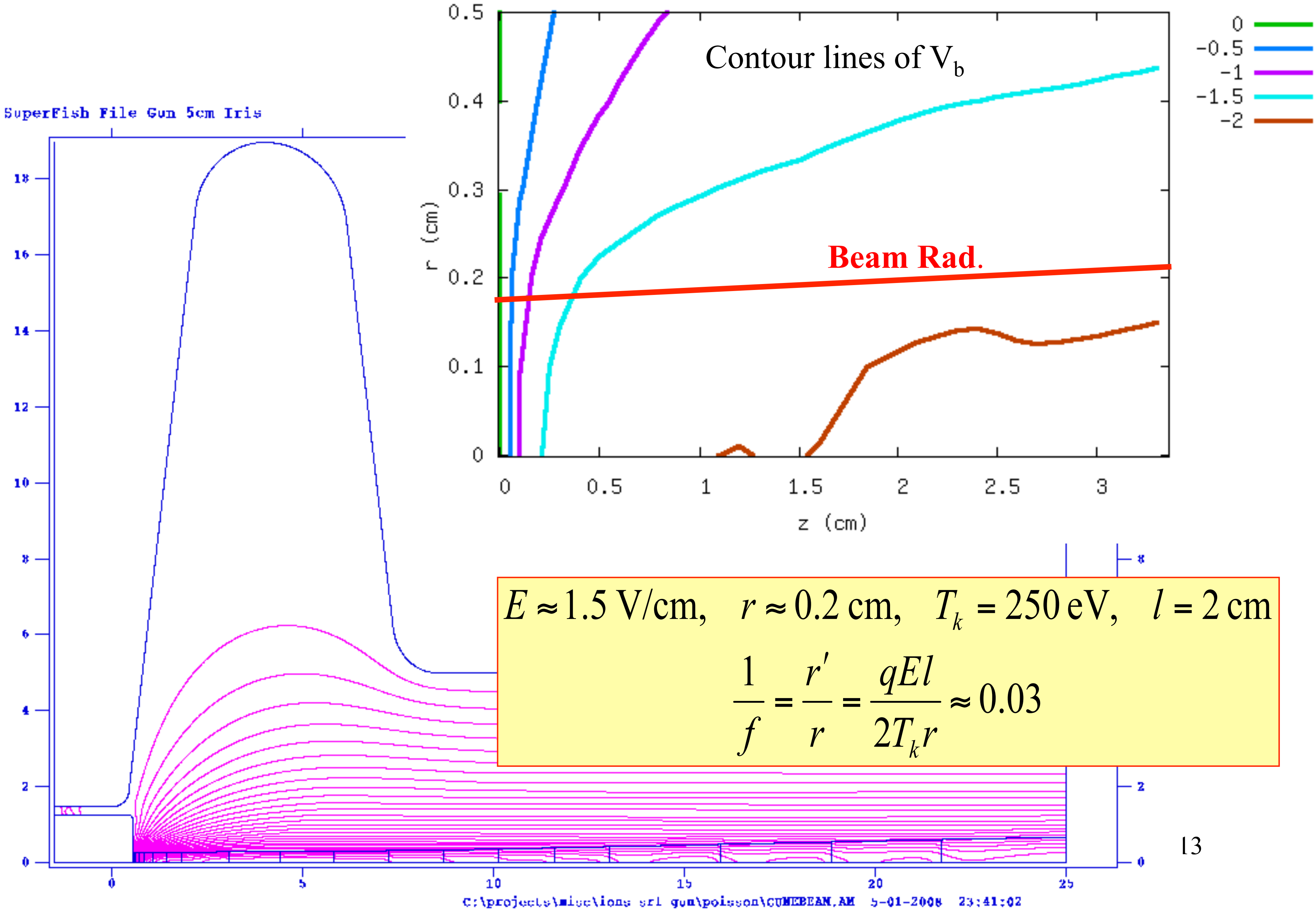
$$\cos\mu = \frac{\mathrm{Tr}(M)}{2} \quad \Leftrightarrow \quad \left|\frac{\mathrm{Tr}(M)}{2}\right| \le 1$$

At 10 MHz, rb=2.7 cm, β=0.5, $I_s = \frac{\beta}{0.55}\left(\frac{a}{2\mathrm{mm}}\right)^2\left(\frac{f_b}{10\mathrm{MHz}}\right)^2 \cdot 0.3\mathrm{A} \approx 0.4 - 0.5\mathrm{A}$

If electron current is well below I_s, the beam can considered as DC with $\rho = I/(Av_e)$.

Let's use: f_b=10 MHz, q_b=1.0 nC, I=10 mA.
Frequency of ions oscillations $f_i \approx$ 500 kHz => μ ≈ 15º - 20º. Time it takes for an ion with E=250 eV reach the cathode is ~ 100 nsec.

Effect of the electron beam: Cont'd



$$E \approx 1.5\ \text{V/cm}, \quad r \approx 0.2\ \text{cm}, \quad T_k = 250\ \text{eV}, \quad l = 2\ \text{cm}$$

$$\frac{1}{f} = \frac{r'}{r} = \frac{qEl}{2T_k r} \approx 0.03$$

Comparison to a DC gun

Common: p=5·10^{-12} Torr

New JLab FEL DC Gun: Gap = 5 cm, V=500 kV

$$\left(\frac{dN}{dQ}\right)_{DC} = 2.9\cdot 10^{6} \text{ ions/C}$$

BNL ½-cell Gun: E=2 MeV,
Ions come from z<3.36 (E~750 keV)

$$\left(\frac{dN}{dQ}\right)_{RF,BNL} = 1.5\cdot 10^{6} \text{ ions/C}$$

Conclusions

- Ion bombardment is possible in RF guns
- Ions move in the effective potential field

$$U_{eff} = \frac{Z^2}{A} \frac{ƛ^2 m_u c^2}{4} \left(\frac{q\,|\vec{E}_0\,|}{m_u c^2} \right)^2$$

- RF phase of the beam defines the effective initial velocity and kinetic energy

$$\vec{v}_0 = -ƛc\,\frac{q\vec{E}_0 \sin(\omega t + \phi)}{mc^2}$$

$$T_{eff} = 2U_{eff} \sin^2(\omega t + \phi)$$

- Ions move towards the cathode if acc. voltage is growing and from the gun if V_{acc} is going down. => It is possible to repel almost all ions from a ½ -cell gun by a proper phasing.
- However, ions from the very close vicinity (~50 μm) still will be able to bombard the cathode. Gain to DC guns ~ 100.
- It seems that misphasing will not work in multi-cell guns. Cathode can be biased to a 100’s V – 1 kV.
- Ions cannot penetrate from outside. No biased electrodes needed.

Naive thoughts about Forever-Gun

- 1/2 –cell. Possibly shorter.
- Misphasing to repel ions. Though, this might worsen emittance and energy spread.
- Lower voltage to avoid electron emission (Might be more important than ions).

- This might work if high bunch charge or extremally good emittance is not required.
- More computer beam dynamics studies with misphasing needed
- Understanding effect of electron emission needed