Ion Back-Bombardment in RF Guns

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with contributions from
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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

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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.

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) \[ m \dddot{r} = f, \quad \dddot{f} = q \vec{E} + \frac{q}{c} \vec{v} \times \vec{B} \]

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

2) \( (\xi \cdot \nabla) \vec{E} \ll \vec{E} \iff \frac{|\xi|}{L} \ll 1 \quad L \sim \text{a few cm’s, } \xi \sim 10-100 \mu \text{m} \)

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

3) \( \nabla \times \vec{E} = -\frac{1}{c} \frac{\partial \vec{B}}{\partial t} \implies \vec{B} = -\lambda (\nabla \times \vec{E}_0) \sin(\omega t + \phi) \)

4) \[ \left| \frac{\vec{v} \times \vec{B}}{c} \right| \sim \left| \frac{\xi}{\lambda} (\nabla \times \vec{E}_0) \right| \sim \frac{\xi}{L} |\vec{E}| \ll |\vec{E}| \]

To the first order in \( \xi/L \) and using slow and fast components, \( r_0 \) and \( \xi \):

5) \[ m(\dddot{r}_0 + \dddot{\xi}) = q \vec{E}(r_0, t) + q (\xi \cdot \nabla) r_0 \vec{E} + \frac{q}{c} \vec{v} \times \vec{B}(r_0, t) \]
Analytical model: Effective potential energy

0\textsuperscript{th}-order approximation: \[ m\dddot{\xi} = q\bar{E}_0 \cos(\omega t + \phi) \quad \Rightarrow \]

\[ \dddot{\bar{\xi}} = -\chi^2 \frac{q\bar{E}_0 \cos(\omega t + \phi)}{mc^2}, \quad \dddot{\bar{\xi}} = \chi c \frac{q\bar{E}_0 \sin(\omega t + \phi)}{mc^2} \]

1\textsuperscript{st}-order approximations with averaging:

\[ \dddot{\bar{r}}_0 = -\chi^2 c^2 \left( \frac{q}{mc^2} \right)^2 \left( \bar{E}_0 \cdot \nabla \right) \bar{E}_0 \cos^2(...) + \bar{E}_0 \times (\nabla \times \bar{E}_0) \sin^2(...) \]

\[ -\frac{\chi^2 c^2}{2} \left( \frac{q}{mc^2} \right)^2 \left( \bar{E}_0 \cdot \nabla \right) \bar{E}_0 + \bar{E}_0 \times (\nabla \times \bar{E}_0) \right) = -\frac{\chi^2 c^2}{4} \left( \frac{q}{mc^2} \right)^2 \nabla \mid \bar{E}_0 \mid^2 \]

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

\[ U_{eff} = m \frac{\mid \ddot{\bar{\xi}} \mid^2}{2} = \frac{\chi^2 mc^2}{4} \left( \frac{q \mid \bar{E}_0 \mid}{mc^2} \right)^2 = \frac{Z^2}{A} \frac{\chi^2 m_u c^2}{4} \left( \frac{q \mid \bar{E}_0 \mid}{m_u c^2} \right)^2 \]
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 0th-order equation is

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

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

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

Important: \( v_0 \) depends on the RF phase when ionization happens.
BNL 1/2-cell SRF Gun

- $f_{RF} = 703.75$ MHz
- $E_{\text{max}} = 30$ 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 $\phi=0$. The effective kinetic energy is 0.

(Initial velocity of ions is 0.)
Ions originating off-axis: 2D aspects

Because the $\nu_0$ points almost directly towards the cathode and $\nabla U_{\text{eff}}$ is almost parallel to the gun axis, the problem can be treated as 1D.
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 $\rho = \frac{I}{\text{Ave}}$. 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:

$$
\cos \mu = \frac{\text{Tr}(M)}{2} \iff \left| \frac{\text{Tr}(M)}{2} \right| \leq 1
$$

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

If electron current is well below $I_s$, the beam can considered as DC with $\rho = \frac{I}{\text{Ave}}$.

Let’s use: $f_b=10$ MHz, $q_b=1.0$ nC, $I=10$ mA.
Frequency of ions oscillations $f_i \approx 500$ kHz $\Rightarrow \mu \approx 15^\circ - 20^\circ$. Time it takes for an ion with $E=250$ eV reach the cathode is $\sim 100$ nsec.
Effect of the electron beam: Cont’d

Superfish File Gun 5cm Iris

Contour lines of $V_b$

Beam Rad.

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

$$\frac{1}{f} = \frac{r'}{r} = \frac{qEl}{2T_kr} \approx 0.03$$
Comparison to a DC gun

Common: $p = 5 \cdot 10^{-12}$ 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

\[ U_{eff} = \frac{Z^2}{A} \frac{\lambda^2 m_u c^2}{4} \left( \frac{q |\vec{E}_0|}{m_u c^2} \right)^2 \]

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

\[ \vec{v}_0 = -\lambda c \frac{q \vec{E}_0 \sin(\omega t + \phi)}{mc^2} \]

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

- 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 \( \frac{1}{2} \)-cell gun by a proper phasing.
- However, ions from the very close vicinity (~50 \( \mu \)m) 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