Electrode shaping in DC gun for low emittance beam

0) It must work!

1) Cathode field

2) Gun voltage

3) Transverse focusing
   a) Electric
   b) Magnetic

4) Parametrized geometry

5) Other ideas…
Cathode field

1) Cathode field $E_{||} = V / \text{gap}$, sets min spot size for a given bunch charge (and emittance)

$$r \sim 2 \sqrt{\frac{q/\pi}{\varepsilon_0 E_{||}}}$$

E.g. $V = 500 \text{ kV}$, gap = 5cm

$\Rightarrow E_{||} = 10 \text{ MV/m}$, $r = 1\text{mm}$
Gun voltage

2) Space charge in the gun vicinity $F_\perp \propto 1/\gamma^2$

- e.g. $250\text{kV}$ is 56% worse than $500\text{kV}$
- $750\text{kV}$ is 56% better than $500\text{kV}$

Though not directly related to emittance, high gun voltage is essential from operational point of view

- Minimize time of flight dependence on the gun voltage fluctuations
- To avoid $\beta < 1$ dedicated cavity design
- More difficult matching to RF focusing, energy gain depends on transverse position
Breakdown voltage vs. gap

Adopted from P. Slade “Vacuum interrupter” book

In what follows, the most pessimistic dependence is being used

\[
\begin{align*}
V(kV) &= 58 \times d(\text{mm})^{0.58} \\
V(kV) &= 64 \times \text{gap (mm)}^{0.55} \\
V(kV) &= 123 \times d(\text{mm})^{0.34}
\end{align*}
\]

\[
\begin{align*}
E(\text{MV/m}) &= 58/d(\text{mm})^{0.42} \\
E(\text{MV/m}) &= 64/\text{gap (mm)}^{0.45} \\
E(\text{MV/m}) &= 123/d(\text{mm})^{0.66}
\end{align*}
\]
Transverse focusing

3) **Ideally, gun is to counteract the space charge defocusing**

\[
\frac{1}{f_{s.c.}} = - \frac{\Delta p_{\perp}(r)}{r p_{||}} = - \frac{I \text{ gap } mc^2}{I_0 r^2 \text{ eV}} \frac{1}{\beta_f \gamma_f} \ln \frac{(1+\gamma_i)\text{ gap}}{(1+\gamma_f)z_i}
\]

*E.g. \( V = 500 \text{ kV}, \text{ gap} = 5\text{ cm} \)
*I = 2A, \( r = 1\text{ mm}, z_i = 1\text{ mm} \)

\( f_{s.c.} \sim -8 \text{ cm, very strong (charge dep.)} \)
Electrostatic focusing

Cathode shaping by Pierce-like shaped cathode

relatively weak, i.e. Cornell gun has 25° and \( f \sim 55 \, \text{cm} \) at 500 kV

One of the reasons for its weakness is the anode defocusing

\[ f = 4V \frac{1 + \frac{1}{2} \frac{eV}{mc^2}}{1 + \frac{eV}{mc^2}} \frac{1}{E_2 - E_1} \]

E.g. \( V = 500 \, \text{kV}, \) gap = 5 cm

\( \Rightarrow f_{\text{anode}} \sim -15 \, \text{cm} \)
Magnetic focusing

Pros:

• no need to sacrifice $E_{\text{cath}}$ by Pierce-like shapes, should give higher brightness

• can be made as strong as needed and adjusted for different charge per bunch running

Cons:

• DC gun structures tend to be bulky, hard to localize the fields

• Need bucking coil to cancel $B$ at the cathode

Can be done!
Parametrized geometry

4) Cornell study
Results (80 pC, 1.3 m after the gun)
Results recapped

- Relatively weak dependence on voltage: 20% in emittance over 250 – 400 kV range if the gap is made correspondingly small to maximize the cathode field (as limited by the breakdown condition)
- Cathode angles ~25° are near optimum
- Variable recess has a weak effect (~5%) on emittance
Ultimate gun?

5)

a) Maximize the electric field at the cathode
b) Have sufficient voltage
c) Provide strong focusing

⇒ Two gap gun with solenoids
Cathode field $\sim 15$ MV/m
Total voltage $\sim 700$ kV
(e.g. 250+450kV with
15 and 50 mm gaps)