Approaches to Higher Brightness Beams in RF Photocathode Guns:

The Longitudinal Dynamics Problem and the Short Bunch Blow-Out Approach

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Outline

- Credits
- Some Definitions
- The Longitudinal Crisis
- Paths to Improving the Beam Brightness
- The Short Bunch Blow-Out Regime
- Remaining Theoretical Issues
- Towards Experimental Verification
- Conclusions

Credits

Original Theoretical Work

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Calculations and Simulation Work

Paolo Pierini

Support and Experimental Program

Carlo Pagani
Paolo Michelato
Daniele Sertore
Massimo Fusetti
Massimo Bonezzi

Some Definitions (1)

- Transverse and Longitudinal Beam Brightness:
  (C. Pellegrini)

$$B_T \qquad \frac{I}{\varepsilon_n^2} \qquad B_L \qquad \frac{N_b}{\gamma\sigma_z}\frac{1}{\sigma_E}$$

- FEL power and gain:

$$P = P_0 e^{z/L_g} \qquad L_g \qquad \frac{\lambda_u}{\rho_{\mathrm{FEL}}}$$

- The universal scaling parameter
  (neglecting undulator parameters):

$$\rho \qquad \left[\frac{1}{\gamma^2\beta_f}\frac{I}{\varepsilon_n}\right]^{1/3}$$

More Definitions (2)

- **Applying the requirements**:

❶ Energy spread small compared to energy transfer:

$$\sigma_E \leq \rho \rightarrow \sigma_E \quad \rho$$

❷ Phase space of beam overlaps well with radiation:

$$\varepsilon_n \leq \gamma\lambda_r \rightarrow \varepsilon_n \quad \gamma\lambda_r$$

❸ Focusing period longer than gain length:

$$\beta_f \geq L_g \rightarrow \beta_f \quad L_g$$

Constraints ❷ and ❸ demand
a good transverse beam density.

- We obtain:

$$\boxed{\rho \quad B_L}$$

Better FEL performance requires
better longitudinal and transverse brightness.

Even More Definitions (3)

- Maximum charge that can be extracted from a photocathode gun:

$$Q_{\max} = \frac{I_A}{c}\gamma'\sigma_r^2$$

where

$$\gamma' \approx \frac{eE_0}{2mc^2} \text{ in a RF gun}$$

$$\gamma' \approx \frac{eE_0}{mc^2} \text{ in a DC gun}$$

- Example:

$$\sigma_r = 1.2\,\mathrm{mm}$$

$$\mathrm{E}_0 = 150\,\mathrm{MV/m}$$

$$Q_{\max} \approx 12\,\mathrm{nC}$$

We wish to stay far away from $Q_{\max}$.
As one approaches this limit,
the bunch energy spread becomes large.

Still More Definitions (4)

- Induced energy spread:

$$\frac{\Delta\gamma}{\gamma} = \frac{2Qc}{\sqrt{3}I_A\gamma'\sigma_r^2} - \sigma_\varphi \cos\bar{\phi}$$

As $Q \to Q_{\max}$ the RF term $\sigma_\varphi \cos\bar{\phi}$ cannot compensate for the space charge induced energy spread.

Large energy spread in the gun leads to bunch lengthening and non-linear effects which creates emittance dilution.

And More Definitions (5)

- Bunch lengthening
(due to perturbative longitudinal forces):

$$\left.\frac{\sigma_{\text{beam}}}{\sigma_{\text{laser}}}\right|_z = \frac{\hat{I}}{I} = 1 + \Delta_{SC} - \Delta_{RF}$$

where

$$\Delta_{SC} = \frac{\hat{I}}{I_A} \frac{f(A_l, \gamma)}{\left(\gamma' \sigma \sin \bar{\phi}\right)^2}$$

[In a DC gun (non relativistic) the above is valid given $\bar{\phi} = \pi/2$]

and

$$\Delta_{RF} = O(1)$$

- The aspect ratio, is given by

$$A_l \equiv \left.\frac{\sigma_r}{\sigma_z}\right|_{\text{laser}}$$

Present guns use "cigar" beams with LOW aspect ratios ($A << \gamma$).

The Longitudinal Crisis

❶ The benchmark code does **NOT** describe longitudinal dynamics properly.

(Parmela with an r-z mesh for space charge calculations).

❷ Final emittance (brightness) **measured** is higher (lower) than expected values at relevant charges.

❸ Bunch lengthening appears to be the main effect. Longer beams lead (quadratically) to larger RF contributions, and so emittance dilution, at the gun exit.

Comments

- A uniform time profile, which gives the best transverse emittance compensation, produces high longitudinal non linearities.

The previous issues are relevant to “cigar” beams which have non linear longitudinal fields in the tails.

An Example

The BNL/SLAC/UCLA 1.6 cell gun
Data by D. Palmer, SLAC

Energy	40 MeV
Energy Spread (rms)	0.25%
Laser Spot Size	1 mm radius
Charge	1 nC
Expected Peak Current	100 A

Emittances:

Measured Emittance	1/3 nC	1.2 mm-mrad
PARMELA Emittance	1/3 nC	1.5 mm-mrad
Measured Emittance	1 nC	4.75 mm-mrad
PARMELA Emittance	1 nC	2+ mm-mrad

Emittance contributions from thermal, RF, multipole and magnetic field sources have all been examined.

Paths to Improving Beam Brightness

- Combined gun/accelerator
  (LANL, UCLA)

- “Better” emittance compensation:
  higher acceleration in the laminar flow regime
  (SLAC)

- Higher symmetry in gun:
  axial RF coupling, or only off axis asymmetries.
  (SLAC/BNL/UCLA, DESY, UCLA PWT)

- Magnetic compression?

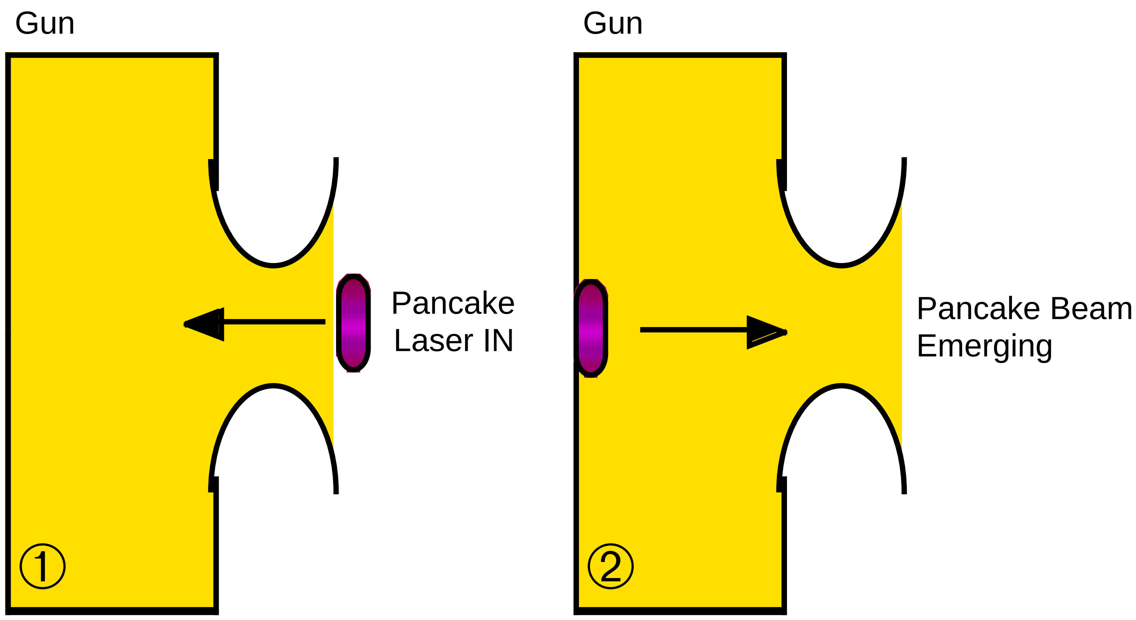
- Cathode thermal emittance studies
  (LASA, DESY)

Novel path: use of ultrashort bunches to generate “linear” bunch lengthening forces without inducing large energy spreads

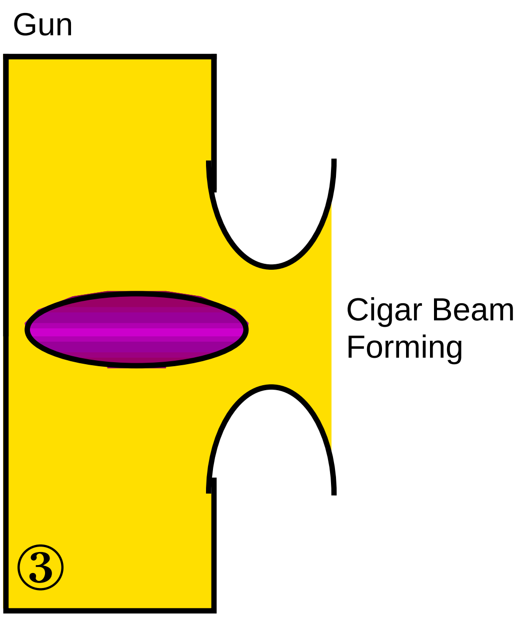
The Short Bunch Blow-Out Regime

We wish to avoid non linear space charge forces.

- Consider generating a “pancake” beam:



which is “blow-out” to a “cigar” beam by strong, but linear space charge forces:



Final Current after Blow-Out

- Due to the short laser pulse $\hat{I} >> 1$.

  $\Delta_{SC} >> 1$, and we can neglect Δ_{RF}.

- Thus, the final current is determined by the space charge forces:

$$I = \frac{\hat{I}}{1 + \Delta_{SC} + \Delta_{RF}} \approx \frac{\hat{I}}{\Delta_{SC}}$$

- Hence,

$$I = \frac{I_A \left(\gamma' \sigma \sin \bar{\phi}\right)^2}{f\left(A_l, \gamma\right)}$$

The final current is independent of the initial peak current!

Blow Out Regime Comments

- The initial “pancake” blows-out to a “cigar”, but unlike the usual cylindrical distribution, this beam has a more ideal elliptical distribution (phase space).

- In addition, the final energy spread can be small.

- Creating a equivalent laser pulse would be challenging, and it is unclear if the distribution would be preserved through the transrelativistic half cell.

- Example: 3-1/2 cell S-band RF gun

$$\sigma_r = 1.2\,\text{mm}$$

$$A_l = 46(300\text{ps})$$

$$E_0 = 150\ \ \text{MV/m}$$

$$I = 2.3\,\text{kA}$$

$$\frac{\Delta\gamma}{\gamma} = 0.5\%$$

(Preliminary PIC simulation shows $\varepsilon_n < 1\text{mm}-\text{mrad}$)

Remaining Theoretical Issues

- Does the theory agree with simulations over a large parameter space?

- Does the model agree with experimental results?

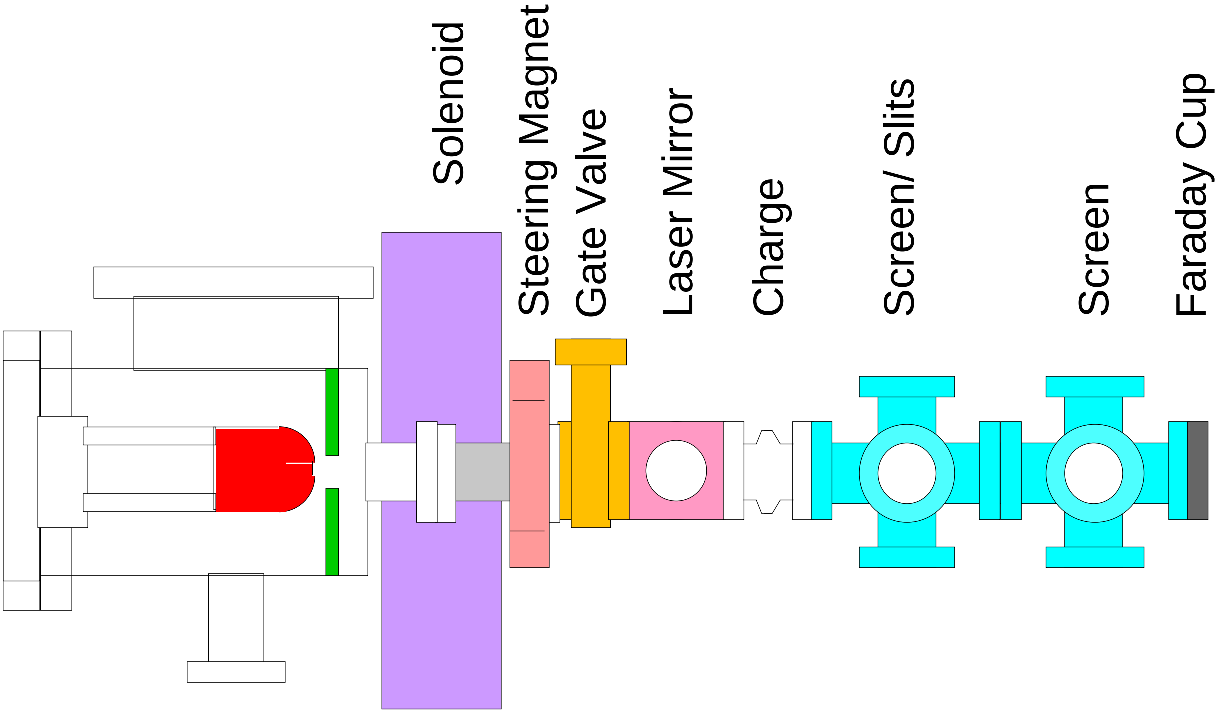
- To what degree is the resulting distribution like an ideal KV (elliptical beam)?

- Is the lack of a control on the final pulse an issue?

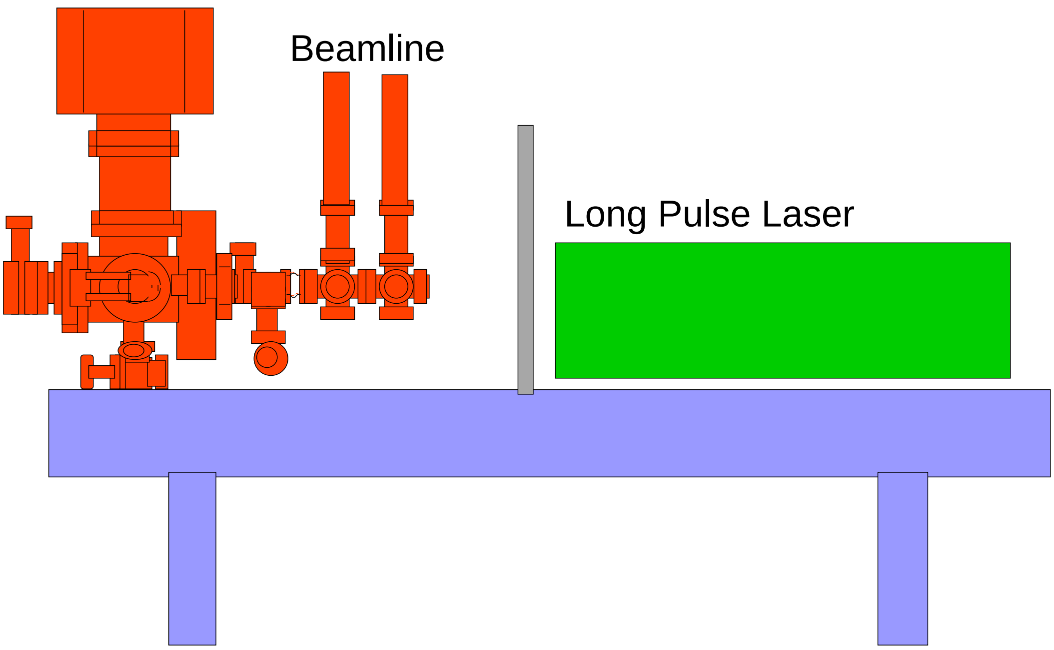
- Is the final "smoothed" time structure of the beam an advantage?

Towards Experimental Verification

- A DC gun based on the CERN design is being constructed at LASA for cathode testing:



- Table top physics is back (big tables):



DC Gun Test of Short Bunch Blow-Out

- The DC Gun will be available soon (1998).
- A ~300 fs UV laser is available now.
- Pulse length diagnostic requires work!

Parameters:

Beam Energy	100 KeV
Gradient	10 MV/m
Gap	1 cm
Laser Spot Size	0-3 mm
Laser Pulse Length	0.3-1 ps

- Advantage/Disadvantage of DC gun based measurement:
  - ▲ Available
  - ▲ No RF effects
  - ▼ Low energy
  - ▼ Not really an RF gun

Conclusions

Longitudinal forces strongly influences the final beam brightness produced.

Solutions which “manage” the longitudinal dynamics, and produce higher brightness are critical for future FEL systems.

Multicell guns, material studies, and RF field symmetrization are all being pursued.

The short bunch blow-out regime may be a path to increasing the brightness.

Tests of the short bunch blow-out regime are planned.