Optimum beam creation in photoinjectors using space-charge expansion I: theory and simulation

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Space-charge and emittance growth

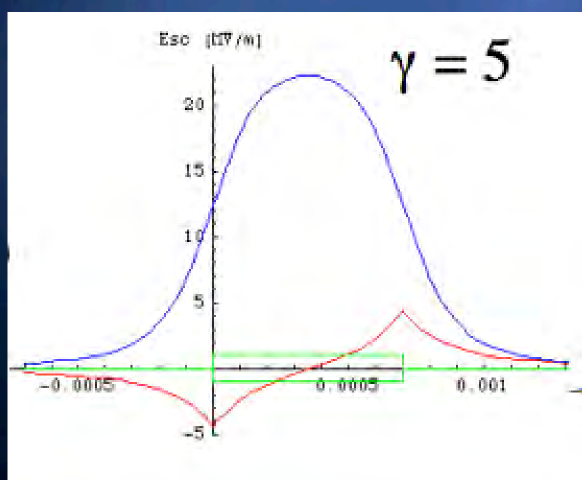
- The self-fields in electron sources are strong, scaling as
  - Beam density
  - γ^{-2}
- Emittance growth arises from
  - Non-uniformity of defocusing in *t (z)*
  - Nonlinearity in *r*

Self-electric fields in beams

Uniformly filled cylinder of charge (*beer can*):

$$E_z(\tilde{z}, r=0) = \frac{\tilde{\rho}}{2\varepsilon_0}\left[\sqrt{R^2 + (\tilde{L}-\tilde{z})^2} - \sqrt{R^2 + \tilde{z}^2} + \left(2\tilde{z} - \tilde{L}\right)\right]$$

$$E_r(r,\tilde{z}) \cong \frac{\tilde{\rho}}{2\varepsilon_0}\left[\frac{(\tilde{L}-\tilde{z})}{\sqrt{R^2 + (\tilde{L}-\tilde{z})^2}} + \frac{\tilde{z}}{\sqrt{R^2 + \tilde{z}^2}}\right]\frac{r}{2}$$



The first beer can

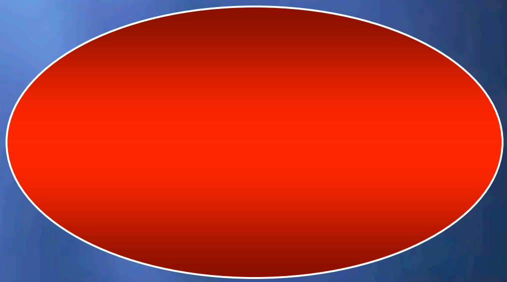
Time dependence of forces fixed by “emittance compensation”

Beam shaping beyond the beer-can

- Uniform beam = optimum emittance compensation?
  - Not even theoretically…
- "Beer-can" beam suffers from
  - Edge erosion, non-uniform distribution
  - Nonlinear fields at edges
  - *Severe practical difficulties with laser*
- Luiten-Serafini proposal:
  - Use *any temporally shaped* ultra-short pulse
  - Longitudinal expansion of well-chosen shaped radial profile

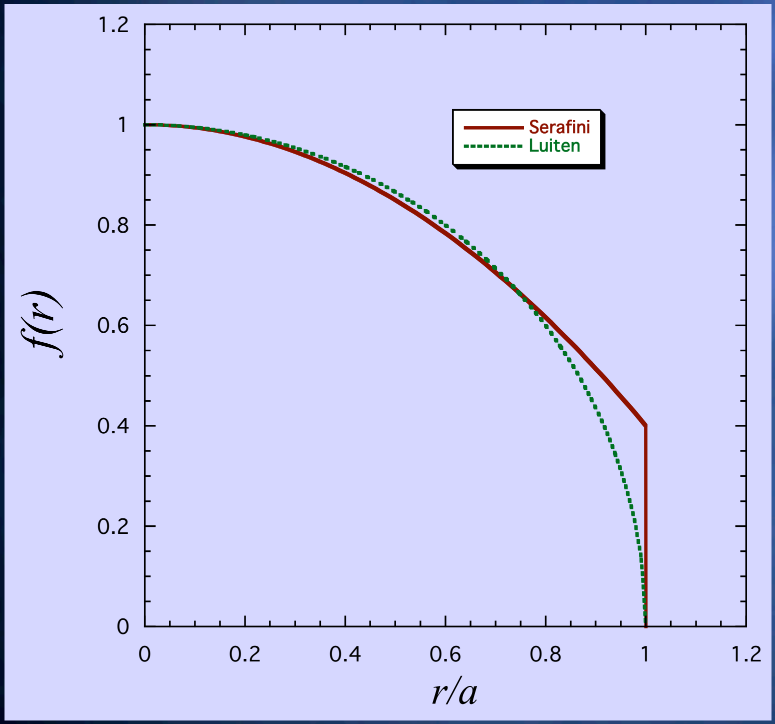
$$I(r) = I_0\left(1-(r/a)^2\right)^{1/2}$$

  - Uniform *ellipsoidal* beam dynamically created!
  - Linear space-charge fields (3D)
  - Radial shaping need only be approximate



3D ellipsoid
("planetary
distribution")

“Forgiveness” in distributions



- Luiten: little effect of longitudinal pulse shape
  - What are limits in initial length?
- Radial shape can be approximate
  - Original Serafini example

Can we marry Luiten-Serafini scheme to <u>classic emittance compensation</u>? Issues:

- Positive
  - Laser *very* forgiving
  - Excellent transverse *and* longitudinal phase space
  - Shorter pulses possible?
- Negative
  - Cathode image charges drive incorrect final state (~one-sided ellipsoid)
  - Larger energy spread during compensation
  - Charge fluctuations somewhat more important
- Experiments at LLNL, ORION, SPARC? Next talk

How does the Luiten-Serafini scheme work?

- Inject current of arbitrary time-profile

$$I(t_0) = Qg(t_0)$$

- Note maximum in function $g \sim \tau^{-1}$
- Assume disk-like beam $c\tau << a$
- Longitudinal force only dependent on initial position in *r* and *t*:

$$\begin{aligned} F_z(r,t_0) &= -eE_0 + 4\pi e\sigma_b(r)\int_0^{t_0} g(\tilde{t}_0)d\tilde{t}_0 \\ &= -eE_0 + 4\pi e\sigma_b(r)G(t_0) \\ &= -eE_0(1-\alpha(r)G(t_0)) \end{aligned}$$

$$\alpha(r) = 4\pi\sigma_b(r)/E_0$$

$\sigma_b(r)$ is beam surface charge density

Longitudinal dynamics

- Assume no radial motion over time of interest
- Energy and energy gain

$$\gamma(z,t_0) = 1 + \gamma'(t_0)z$$

$$\gamma'(t_0) = \frac{F_z(t_0)}{m_e c^2} = \gamma_0'\left(1 - \alpha G(t_0)\right)$$

$$\gamma_0' = \frac{|eE_0|}{m_e c^2}$$

- Velocity integral

$$c\left[t(t_0) - t_0\right] = \int_0^z \frac{dz'}{\beta(z',t_0)} = \frac{1}{\gamma'(t_0)} \int_1^{\gamma(z,t_0)} \frac{\gamma d\gamma}{\sqrt{\gamma^2 - 1}}$$

$$= \frac{1}{\gamma'(t_0)} \sqrt{\left[\gamma'(t_0)z\right]^2 - 2\gamma'(t_0)z}$$

Asymptotic limit

- Large γ, with *z* held constant

$$c\left[t_f(t_0)\right] \cong z + ct_0 + \frac{1}{\gamma'(t_0)} - \frac{1}{\gamma'_0}$$

- Drop constant *z* ("screen" positon)
- Mapping can be used to calculate current density

$$J(r,z,t_f) = \frac{g(t_0)\sigma_b(r)}{\partial t_f / \partial t_0}$$

$$\frac{\partial t_f}{\partial t_0} = 1 + \frac{\gamma'_0 \alpha(r)}{c\gamma'^2(t_0)} g(t_0) \approx 1 + \frac{\alpha(r)}{c\gamma'_0} g(t_0)$$

- This gives

$$J(r,z,t_f) = \frac{g(t_0)\sigma(r)}{1 + \frac{\alpha(r)}{c\gamma'_0} g(t_0)}$$

Case of large expansion

- To have a final state dominated by space-charge, we have $\alpha(r) >> c\tau\gamma_0'$ and $J(r,z,t_f) \approx \frac{eE_0^2}{4\pi m_e c}$
- This distribution is
  - Uniform current density
  - Uniform charge density
  - *Independent of initial conditions*, as long is initial beam is short (in practice <200 fs)
- This is a general characteristic of plasma rearrangement; uniform density inside of a *Debye length* from surface

Beam shape

- Look at expansion of beam edge (front)

$$c\left[t_f\left(t_{0,edge}\right)\right] \cong ct_0 + \frac{1}{\gamma'\left(t_{0,edge}\right)} - \frac{1}{\gamma'_0}$$
$$\approx ct_0 + \frac{\alpha(r)}{2\gamma'_0} \approx \frac{2\pi m_e c^2}{E_0^2}\sigma_b(r)$$

- Now assume the magic distribution

$$\sigma_b(r) = \frac{3Q}{2\pi a^2}\left[1-\left(\frac{r}{a}\right)^2\right]^{1/2}$$

- An ellipsoidal profile results!

$$ct_{f,edge} \cong \frac{3Qm_e c^2}{E_0^2 a^2}\left[1-\left(\frac{r}{a}\right)^2\right]^{1/2}$$

The optimum beam distribution and emittance compensation

- Uniformly-filled ellipsoid is optimum beam shape
  - Linear space charge forces in all 3D
- There is emittance growth during rearrangement process
- Process is in any case imperfect
  - Image charges, laser imperfections…
- We *need* emittance compensation
  - Can the two schemes be married?
  - Can existing hardware be adopted?

Initial PARMELA simulation study

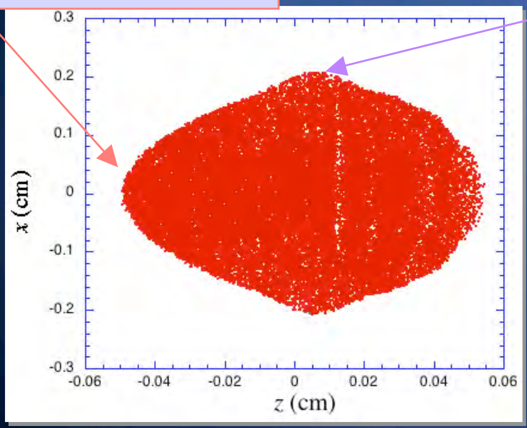
- PARMELA (UCLA) study
  - Computationally intensive problem
- Standard SPARC injector (LCLS Ferrario-Scenario)) conditions
  - 120 MV/m peak on-axis field
  - 2700 G solenoid
  - Post-acceleration in SLAC TW section, 13.5 MV/m, B_z=560 G
- Beam initial conditions chosen to:
  - Avoid image charge effects (σ_b (α) limit)
  - Produce emittance compensation
  - These are slightly at odds…
- Parameters:
  - Q=0.33 nC
  - Initial longitudinal Gaussian σ_t =33 fs (cutoff at 3 σ)
  - Transverse Gaussian with σ_x =0.77 mm (cutoff at 1.8 σ).
  - Launch at 33 degrees to mitigate energy spread — bad for compensation
- Note: no challenge to laser parameters, need *not* have perfect radial profile

Ellipsoidal beam in simulation

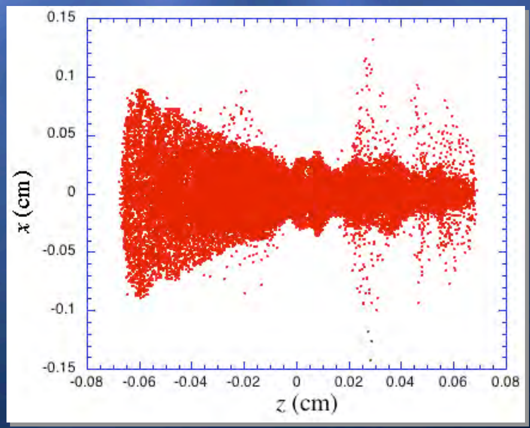
- Final bunch length 1.3 mm (full), 105 A peak current.
- Some longitudinal asymmetry due to image charge
- Small artifact from non-ideal radial/long. profile; transverse space-charge
- At low energy (only) the ellipsoidal beam shape is visible
  - Transition to emittance dominated regime destroys shape (it is no longer needed!)

Image charge effect

Artifact of initial conditions

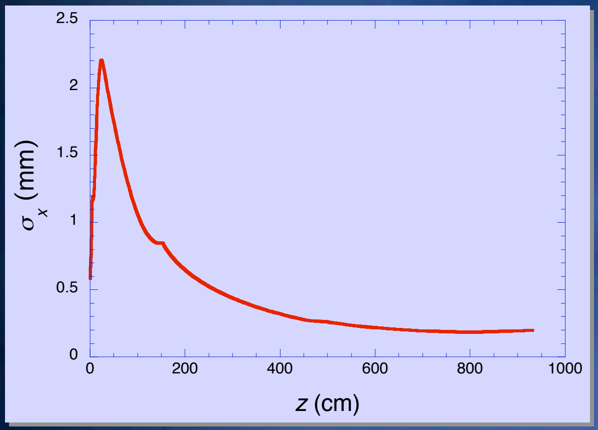


Beam distribution showing ellipsoidal boundary (12.5 MeV)

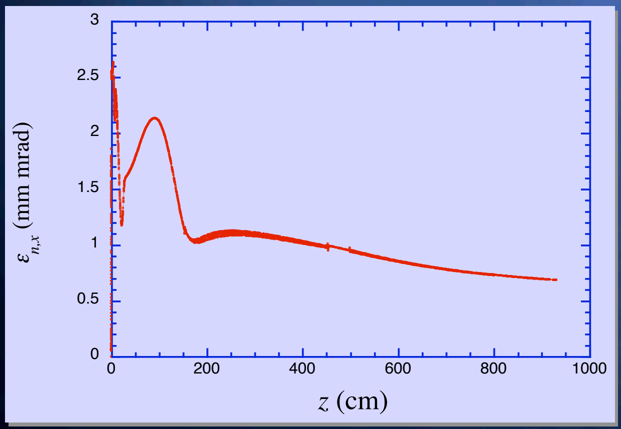


Beam distribution at high energy shows Boundary collapse (84.5 MeV)

Emittance compensation excellent



Beam size evolution

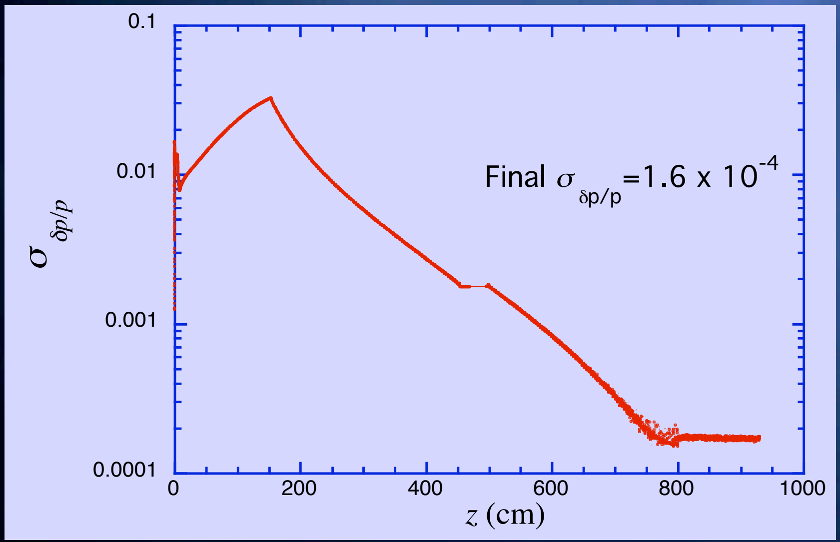


RMS emittance evolution

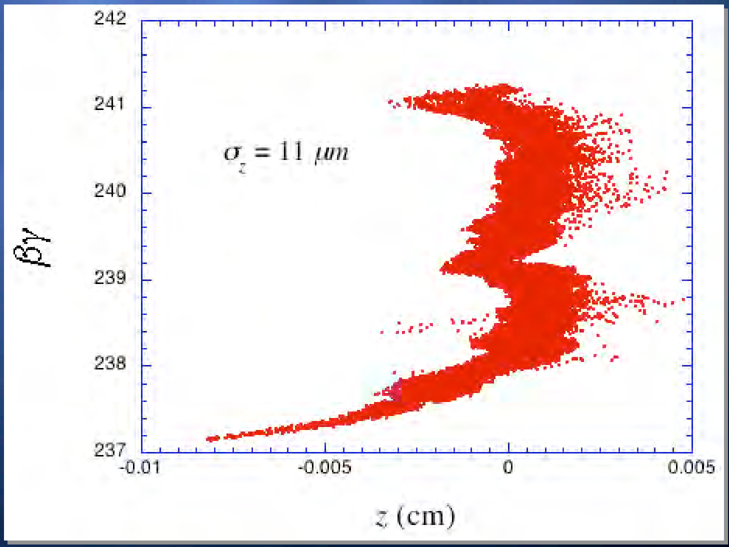
- Emittance evolution slightly different than standard scenario
  - Later turn-on of transverse space-charge
  - Delay of plasma oscillations
  - Enhance solenoid in TW section to speed up oscillations
- Final emittance <0.7 mm mrad!
- Excellent performance at much higher current than standard operation: 105 A vs. 48 A

Longitudinal phase space advantages

- Initial fast — but not large — longitudinal emittance growth due to rearrangement/expansion
- Shortest pulse possible given E-field
- Extremely small final energy spread
  - Shorter beam
  - Approx. linear space charge (linear chirp contribution)
- Excellent compression! Use as diagnostic of SC forces



Energy spread evolution



Longitudinal phase space after compression

Maximum brightness

- This scheme produces higher brightness than standard LCLS-like designs
  - Is it *the* optimum?
- What is maximum brightness in this scheme?

$$B_{\max} = \frac{2I}{\left(\sigma_x \sigma_{x'}\right)^2} \cong 8\pi J_{\max}\left(\frac{m_e c}{\sigma_{p,x}}\right)^2 \approx \frac{2eE_0^2 m_e c}{\sigma_{p,x}^2} \approx \frac{ecE_0^2}{k_b T_c}$$

or, for example $B_{\max} \cong 4 \times 10^{14}\ \mathrm{A/(m\text{-}rad)^2}$

with "standard" numbers $k_b T = 0.9\ \mathbf{eV},\ E_0 = 120\ \mathbf{MV/m}$

Note: independent of charge! Make cathode temp small…

Experimental outlook

- We are looking at several appropriate photoinjectors:
  - ~~LLNL PLEIADES:~~
    - ~~Proposed w/S. Anderson for LDRD~~
    - ~~non-optimized scenario~~
    - ~~difficult funding of machine at present…~~
  - SLAC NCLTA ("ORION", "E163")
    - We want higher involvement, including TW undulator FEL
    - Good for program, including laser acceleration.
    - Winter 2005
  - SPARC (Frascati)
    - Optimized environment
    - Also Fall 2005
    - Discuss from this perspective (…grazie a Pietro M. e Carlo V.)

Talk II

- Experimental signatures
  - Configuration space
  - Phase spaces
- Experimental realities
  - Cathode emission time
  - Laser intensity/handling issues
- Measurement issues (SPARC context)
  - Time-resolved measurements at low energy
    - Aerogel-based Cerenkov measurements
  - RF deflector-based measurements

Future computational investigations

- Longer photoemission effects (talk II)
- Jitter studies
- Non-uniform cathode emission
- Velocity bunching a la Serafini-Ferrario