Uniformly filled ellipsoidal beam distributions at the UCLA Pegasus Laboratory

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Outline

• Ellipsoidal beam distributions
• Pegasus photoinjector
• Ultrashort photocathode driver laser pulses
• Longitudinal diagnostics: RF deflecting cavity
• Beam measurements
• Beam brightness
• Conclusions
A little bit of history

• Ideal beam distributions.
  – Kapchinsky-Vladimirsky, uniformly filled ellipsoids, waterbags, pancakes and cigars have always helped theorists in accelerator beam physics.
  – The problem is how to generate such beams in real systems

  – Blow-out regime of photoinjectors.

  – No particular longitudinal shape needed

  – Existing hardware compatibility
What's so special about ellipses?

- Analytical field expressions
- Linear space charge fields in each direction [Kellogg, Foundation of potential theory, 1929].

\[
\vec{E} = (E_x, E_y, E_z) = \frac{\rho_0}{\varepsilon_0} (M_x x, M_y y, M_z z)
\]

- For a spheroid

\[
M_z = \frac{1 + \Gamma}{\Gamma^3} (\Gamma - \arctan(\Gamma)), \quad M_x = M_y = \frac{1}{2} (1 - M_z) \quad \Gamma = \sqrt{A^2 / C^2 - 1}
\]
Pegasus laboratory

- Small accelerator laboratory in the sub-basement of the physics department (joint program with Rosenzweig, Pellegrini)
- Laser room, control room, radiation shielded bunker
- Home of the first UCLA SASE FEL experiments
- Now advanced photoinjector laboratory just recently commissioned
  - New state-of-the-art ultrafast drive laser Ti:Sa
  - Currently 2 grad, 2 undergraduate students
- Initial laboratory mission:
  - Study photoinjector extreme longitudinal dynamics.
  - Tests of blow-out regime.
  - Develop advanced longitudinal diagnostics.
  - Applications of ultrafast beams. (electron diffraction, FELs)
Ultrashort laser pulses

- New state-of-the-art Ti:Sa laser system.
  - Micra.
    - Feedback on Verdi pump alignment
    - 100 nm bandwidth (adjustable)
    - Integrated pump
  - Legend-Elite
    - Integrated Evolution 30
    - 1 KHz rep rate
    - 3.3 mJ after compression
    - 35 fs FWHM
- Ultrashort laser pulses cathode illumination
  - Control dispersion in transport
  - Thin non linear crystals
- Iris imaged onto cathode.
  - Dynamics dominated by surface charge density on the cathode.
Pegasus beamline

- Gun
- Solenoid
- Diffraction target
- Diagnostic screens
- 50/100 µm movable slit
- Mirror box
- Quadrupoles
- RF deflector
- Dipole
- Faraday cup
Photoinjector commissioning. Spring 07

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser pulse length</td>
<td>30 fs (rms)</td>
</tr>
<tr>
<td>Laser energy</td>
<td>0.5 - 300 µJ</td>
</tr>
<tr>
<td>Laser spot size</td>
<td>0.1 – 1 mm</td>
</tr>
<tr>
<td>E-beam energy</td>
<td>3-5 MeV</td>
</tr>
<tr>
<td>E-beam charge</td>
<td>1 – 300 pC</td>
</tr>
</tbody>
</table>

- Sharp rise when ultrashort laser hits cathode
- Schottky enhancement
- Faraday cup charge collection drop-off
Pegasus relativistic electron diffraction

• Diffraction pattern using $10^8$ electrons with an electron beam 5 times shorter than current state-of-the-art.
• Not the subject of this talk (but ellipses even here....)
RF deflector

- X-band cavity (9.6 GHz)
- Originally designed for a 12-15 MeV beam. (up 500 kV deflecting voltage)
- Plug-n-play (portable rf source).
- Very good temporal resolution (< 50 fs) for the 4-5 MeV Pegasus beam even on the closest beamline screen.
- Two independent calibration methods
  - Measure power in cavity
  - Measure centroid position vs. phase

- Fundamental diagnostics in low-energy beam line. (allow to see inside the beam…)

Courtesy of J. England

Figure 3: Cutaway drawing of the assembled 9-cell cavity design.
**Ellipsoidal beam I: projected ellipse**

Using the quadrupole to focus vertically the beam to an horizontal line

- Charge 17 pC
- rms length ~300 fs
- Very sharp ellipsoidal beam boundary due to the ultrashort beam on the cathode

![Temporal profile](image.png)

\[ \sigma_z = 310 \text{ fs} \]
Using the quadrupole to focus the beam on the screen, we effectively obtain a two dimensional projection of the uniformly charged ellipsoidal distribution

\[
\rho(x, y, z) := \begin{cases} 
1 & \text{if } \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} < 1 \\
0 & \text{otherwise}
\end{cases}
\]

\[
\rho_{\text{proj}}(x, z) := \int_{-\infty}^{\infty} \rho(x, y, z) \, dy
\]
**Ellipsoidal beam II: sliced ellipse**

Using the slit aperture to select an horizontal slice of the beam distribution
Asymmetry in ellipsoidal boundary

- Increasing the charge we observe the development of an asymmetry in the ellipse boundary.

- Reversing the deflecting voltage by going 180 degrees off in phase, we obtain the same picture upside down.

- Simulations predict this effect, which is mainly due to the image charge at the cathode that pulls on the beam tail.
Bunch length vs. $Q$

- Luiten’s paper gives a simple formula for asymptotic bunch length:

$$\frac{\sigma}{\tau} = \frac{\Delta}{\sqrt{t}} e^{-\frac{2mE}{E_0}}$$

- In reality we observe a more dynamical behavior.

- As the beam gets more energetic the aspect ratio in its own rest frame is not pancake-like anymore.

- Energy spread contribution to bunch length.

- Asymmetry depending on surface charge density.
Wonders of a deflecting cavity

- Inhomogeneous emission from cathode
Transverse emittance

- Transverse beam quality (measured with pepper-pot technique allowing phase space reconstruction) is at the thermal emittance level.

- …which unfortunately is quite high (Mg cathode + surface roughness). Measured with solenoid scan.
Longitudinal phase space

- Diagnostic screen around the bend.
  - Dispersion. Horizontal axis is energy.
  - Turn deflector on. Vertical axis is time.

- Need to decrease betatron beam size at the diagnostics screen.

- Design shorter dipole to allow quadrupole lenses closer to detection screen. (in progress)

- Aim to resolve <20 KeV uncorrelated energy spread (experiment in the next six months).
Peak brightness

- Peak brightness at low energy is very high, but not much different than other optimized designs (working point of current state-of-the-art injectors).

- 18 pC, 300 fs rms, 0.7 mm-mrad. \( \sim 1 \cdot 10^{14} \text{ A/m}^2 \)

- What is really new here is:
  - Shorter beams.
  - More linear phase spaces (transverse and longitudinal).
  - Control beam tails.
  - Ease requirements on laser system.
Conclusions

• First direct observation of uniformly filled ellipsoidal beam distribution
• Dynamic regime. Need to take into account beam evolution. (need particle tracking simulations)
• Simple configuration of photoinjector yielding relatively good results.
• Clear path for improving brightness at Pegasus (higher field on cathode, better thermal emittance).
• Low charge, ultrashort beams are the future of photoinjectors (ultrafast beam sourcing).

Acknowledgements.

J. Moody, R. J. Englang, T. Tan.
Aspect ratio

- Analytical field expressions
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