Fluctuations: a tool to probe intense electron beams

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Real beams don’t have a “flat top” or “a perfect distribution” named after famous people.

Real laboratory beams have unwanted velocity or density modulations.
Current modulation using drive laser

Thermionic + Photoemission (5ns pulse)
Longitudinal Beam dynamics

Longitudinal effects in the RING

Longitudinal effects in the GUN

Electron Gun
Experimental Results of Laser-induced Space Charge waves

At z = 5.75 m

Beam Current (mA)

Time (ns)

Laser induced perturbation

Z = 5.75 m

Fast wave

6.1 ns

Slow wave

Beam Current (mA)

Time (ns)

At z = 5.75 m
Beam Current over multiple turns

- Turn 6
- Turn 5
- Turn 4
- Turn 3
- Turn 2
- Turn 1
- Turn 0

Fast wave  Slow wave

Pure density modulation

Beam Current over multiple turns Experiment (RC10)

Turn 9
Turn 8
Turn 7
Turn 6
Turn 5
Turn 4
Turn 3
Turn 2
Turn 1

Beam current (arbitrary unit)

Time (ns)
Pure energy modulation

Beam Current over multiple turns Experiment (RC10)

Turn 9
Turn 8
Turn 7
Turn 6
Turn 5
Turn 4
Turn 3
Turn 2
Turn 1

Fast wave
Slow wave

Time (ns)

Beam current (arbitrary unit)
Combined density and energy perturbation ("Inverse Humpty Dumpty" experiment)
Beam develops structure: sub-pulse formation

$T_{osc} = 2.5$ ns

**Child-Langmuir Limit at short pulse length**

![Diagram showing Child-Langmuir limit at short pulse length]

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<th>Conventional Child-Langmuir</th>
<th>Real Photo-injector Scenario</th>
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- $\tau_p$ represents the pulse length.

### Explanation

- **Conventional Child-Langmuir**
  - Uniform 1-D current distribution
  - Steady state
  - Pulse length $\tau_p >>$ transit time

- **Real Photo-injector Scenario**
  - Non-uniform 3-D time dependant current distribution
  - Transient state
  - Pulse length $\tau_p <<$ transit time
Comparing transit time in different guns

\[ T = \sqrt{\frac{2D^2 m}{eV_0}} = 1 \text{ ns} \]
\[ D = 2.5 \text{ cm (UMER)} \]
\[ V_0 = 10 \text{ kV} \]

\[ T = \frac{mc\gamma_f}{eE_A} \sqrt{1 - \frac{1}{\gamma_f^2}} \approx 0.37 \text{ ns} \]
\[ \gamma_f = \text{relativistic factor at gun exit} \]
\[ = 13 \text{ for 6 MeV (LCLS)} \]
\[ E_A = \text{average field} = 60 \text{ MV/m} \]

In case of LCLS: \( \tau_p = 10 \text{ ps} \ll T \)

Hence, short pulse effect becomes important when the pulse length is comparable to the transit time.
Onset of virtual cathode oscillations: critical current, critical charge

When the pulse length ($\tau_p$) is comparable to the transit time ($T$), the virtual cathode forms when the following conditions are met:

\[
J_{\text{CRIT}} \approx \frac{3J_{CL}}{4X_{CL}}
\]
\[
Q_{\text{CRIT}} \approx \frac{3}{4}Q_{CL}
\]

Lesson: To have clean beam pulse, operate below the critical current density.
Summary and Conclusions

Longitudinal effects in the RING

- A single density perturbation travels as a fast and slow wave. Wave speed depends on space charge.
- Multiple space charge waves interfere with each other leading to a mixture of density and energy modulations in the beam.

Longitudinal effects in the GUN

- There seems to be practical current limit for RF photoinjectors, below the space charge limit, above which undesirable temporal structure develops on the pulse.
Thanks to

- Don and Renee Feldman
- Brian Beaudoin
- Prof. Patrick O’ Shea
- Prof. Rami Kishek
- Santiago Bernal
- Max Cornacchia
- Dave Sutter
- Ralph Fiorito
- Irv Haber
- Current and previous UMER graduate students
- Collaborators and mentors in other labs