Longitudinal Beam Physics on UMER

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Outline

• Importance of longitudinal structure
• Some gun physics
• Launching waves
• Speed of sound
• Beam transport
Real electron beam distributions are not named after famous people!

Real beam = Asymmetric Bactrian Camel with Attendant Obelisk Distribution
Problem Statement

Problem:
Real beams have **unwanted** velocity (energy) or density modulations

Reasons:
- Drive laser fluctuations in photoinjectors
- Over-focusing or under-focusing in longitudinal focusing systems

Technique:
- Introduce perturbation “**deliberately**” in an intense beam and study its evolution.
- **UMER** provides the platform for such experiments
### Sources of problems

<table>
<thead>
<tr>
<th>What</th>
<th>Where</th>
<th>How</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space charge (self) fields</td>
<td>electron source, low energy injector/linac,</td>
<td>Space charge converts density modulation to energy modulations, and causes time dependant defocusing</td>
</tr>
<tr>
<td>Wakefields/Higher OM</td>
<td>Cavities and structures</td>
<td>Bunch structure can excite high frequency modes</td>
</tr>
<tr>
<td>Coherent Synchrotron Radiation (CSR)</td>
<td>bends</td>
<td>Bunch structure can excite coherent synchrotron radiation</td>
</tr>
</tbody>
</table>
Two Types of Longitudinal Problems on UMER

- Longitudinal effects in the gun and space charge driven instabilities
- Longitudinal effects in multi-turn transport: evolution of perturbations

These are relevant to other accelerators
1. Longitudinal structure and space charge instabilities in the gun
Space-charge driven longitudinal beam breakup

Pulse Shapes at 17.5 MeV

0.5 nC

3 nC

1.0 nC

4 nC

2.0 nC

5 nC
Child- Langmuir Limit Revisited

Conventional Child-Langmuir Analysis:
Uniform 1-D current distribution
Steady state
Pulse length $\tau_p \gg$ Electron transit time $T$

Real Photoinjector Analysis:
non-uniform 3-D time-dependant current distribution
transient state
Pulse length $\tau_p <$ Electron transit time $T$
Cathode – Anode Transit Time (T) in guns

Non-relativistic

$$T = \sqrt{\frac{2D^2m}{eV_0}}$$

- $D = A/C$ gap = 2.5 cm in UMER
- $V_0 =$ Gun voltage = 10 kV

For UMER gun $T \approx 1$ ns

Relativistic

$$T = \frac{mc\gamma_f}{eE_A} \sqrt{1 - \frac{1}{\gamma_f^2}}$$

- $\gamma_f =$ relativistic factor at gun exit $\approx 3$ for 1 MeV
- $E_A =$ average applied electric field $\approx 30$ MV

For Relativistic gun $T \approx .15$ ns

For a typical RF photoinjector $\tau_p \approx 0.01$ ns
Charge per Pulse vs Drive Laser Intensity

Experimental data

Critical Current ($J_{\text{crit}}$) in short pulse mode
for onset of space charge instabilities

Critical current density:

$$J_{\text{CRIT}} = 2 \frac{1 - \sqrt{1 - \frac{3}{4} X_t^2}}{X_t^3} J_{CL}$$

$$X_t = \tau_p / T$$

Critical charge density:

$$Q_{\text{CRIT}} = 2 \frac{1 - \sqrt{1 - \frac{3}{4} X_t^2}}{X_t^2} Q_{CL}$$

Short pulse mode $X_t << 1$

$$J_{\text{CRIT}} \approx \frac{3}{4 X_t} J_{CL}$$

$$Q_{\text{CRIT}} \approx \frac{3}{4} Q_{CL}$$

UMER is a unique test bed for studying the evolution of current perturbations.

Thermionic only, 100ns pulse
Thermionic + Photoemission (5ns pulse)

Electron Beam

Heater
Photocathode

Drive Laser
UMER Drive Laser Setup

E-beam

UV (355nm) Laser
FWHM = 5ns

Electron Gun

Nd:YAG Laser

KTP/BBO Crystals
Perturbation **below** the critical current density

At large laser power, **perturbation splitting into sub pulses**

Perturbation **above** the critical current density
Charge per pulse vs laser intensity
Onset of longitudinal instability
Experimental data

Critical Current Density vs. pulse length

*Simulation*

\[ J_{\text{CRIT}} = 2\frac{1 - \sqrt{1 - \frac{3}{4}X_t^2}}{X_t^3} J_{\text{CL}} \]

\[ X_t = \frac{\tau_p}{T} \]

2. Evolution of longitudinal structure in beam transport
Experimental Results of Laser-induced Space Charge waves

Near gun

At \( s = 5.75 \) m
Evolution of Multiple Pulses

Modulation observed to disappear, return, then start to disappear again as beam travels through UMER

John Harris,
PhD dissertation 2005
https://drum.umd.edu/dspace/handle/1903/2906
Theory of Space Charge Waves
(1-D Cold fluid model)

Space charge line density \( \Lambda(z,t) = \Lambda_0 + \Lambda_1 e^{i(\omega t - kz)} \)

Velocity \( v(z,t) = v_0 + v_1 e^{i(\omega t - kz)} \)

Current \( I(z,t) = I_0 + I_1 e^{i(\omega t - kz)} \)
Derivation of Sound Speed
(one-dimension cold-fluid model)

Definition of perturbation

\[ \begin{align*}
\Lambda(z,t) &= \Lambda_0 + \Lambda_1 e^{i(\omega t - kz)} \\
v(z,t) &= v_0 + v_1 e^{i(\omega t - kz)} \\
I(z,t) &= I_0 + I_1 e^{i(\omega t - kz)}
\end{align*} \]

Continuity equation

\[ \frac{\partial (\Lambda v)}{\partial z} + \frac{\partial \Lambda}{\partial t} = 0 \]

Momentum equation

\[ \frac{\partial v}{\partial z} v_0 + \frac{\partial v}{\partial t} = \frac{q}{\gamma_0^3 m} E_s \]

Maxwell’s equation and boundary conditions

\[ E_s = -\frac{g}{4\pi\varepsilon_0} \left( \frac{\partial \Lambda}{\partial z} + \frac{1}{c^2} \frac{\partial I}{\partial t} \right) \]

\[ g = 2 \ln \frac{b}{a} \]

Dispersion equation

\[ (\omega - kv_0)^2 - C_s^2 k^2 = 0 \]

\[ C_s = \text{Sound speed} \]

Phase velocity of fast/slow waves

\[ \begin{align*}
v_f &= \frac{\omega}{k_+} = v_0 + C_s \\
v_s &= \frac{\omega}{k_+} = v_0 - C_s
\end{align*} \]

\[ C_s = \sqrt{\frac{q g \Lambda_0}{4\pi\varepsilon_0 \gamma_0^5 m}} \quad \text{or} \quad C_s = \sqrt{\frac{egI}{4\pi\varepsilon_0 m v_0 \gamma^5}} \]

For UMER \( C_s \approx 10^6 \text{ m/s} \)
Evolution of Space-Charge Waves
Fast (Forward) and Slow (Backward) Waves

Definition of perturbation

\[
\begin{align*}
    v_1(0,t) &= \delta v_0 p(t) \\
    I_1(0,t) &= \eta I_0 p(t) \\
    \Lambda_1(0,t) &= (\eta - \delta) \Lambda_0 p(t)
\end{align*}
\]

Assume pure density perturbation \( \delta = 0 \)

Algebraic equations of

\[
\begin{align*}
    \Lambda_1(z,t) &= \frac{\Lambda_0}{2} \eta \left[ h \left( t - \frac{z}{v_0 - C_s} \right) + h \left( t - \frac{z}{v_0 + C_s} \right) \right] \\
    v_1(z,t) &= \frac{C_s}{2} \eta \left[ -h \left( t - \frac{z}{v_0 - C_s} \right) + h \left( t - \frac{z}{v_0 + C_s} \right) \right]
\end{align*}
\]

Red = slow (backward) wave
Blue = fast (forward) wave

\( h \) function is a wave that depends on the initial conditions etc.
Evolution of Space-Charge Waves

\[ \Lambda_1(z,t) = \frac{\Lambda_0}{2} \eta \left[ h\left( t - \frac{z}{v_0 - C_s} \right) + h\left( t - \frac{z}{v_0 + C_s} \right) \right] \]

\[ v_1(z,t) = \frac{C_s}{2} \eta \left[ -h\left( t - \frac{z}{v_0 - C_s} \right) + h\left( t - \frac{z}{v_0 + C_s} \right) \right] \]
Space Charge Wave Transport
Experimental Results from UMER
**Experimental Results of Laser-induced Space Charge waves**

- **Near gun**
  - Laser induced perturbation

- **At s = 5.75 m**
  - $C_s \text{ (theory)} = 1.30 \times 10^6 \text{ m/s}$
Multiturn observation of waves in UMER
Multiturn observation of waves in UMER

Space charge wave propagation

Normalized Current

Time (ns)

Turn Number
Space Charge Waves & Instabilities

Heater Photocathode

UV (355nm)
FWHM= 5ns
Nd:YAG
Laser

Electron Beam

At large laser power:
explosive splitting in gun

At low laser power:
gentle splitting in transport

Perturbation splitting into sub pulses

5.8 ns

At s= 5.75 m

Normalized Current

Time (ns)

Normalized Current

Time (ns)
Space Charge Converts Density Modulation into Energy Modulations

Experiment at Brookhaven DUV FEL after perturbed beam is accelerated to 75 MeV

Q = 0.16 nC

Jonathan Neumann, Dissertation 2005

https://drum.umd.edu/dspace/handle/1903/2437
Is the inverse Humpty-Dumpty Effect possible?

Humpty Dumpty sat on a wall.
Humpty Dumpty had a great fall.
All the king’s horses and all the king’s men
Couldn’t put Humpty together again.

Illustration by John Tenniel From *Through the Looking-Glass*. 