The University of Maryland Electron Ring Experiment – a Plasma in Motion

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Outline:
1. High-quality beams and Plasmas
2. UMER – what is it?
3. Recent Results

Research sponsored by US DOE HEP, DOE FES/HEDP, and DOD ONR
Close Cousins

Princeton Paul Trap

A Beam in the beam-frame

U. Maryland Electron Ring

An Accelerated Plasma

3.7 m
Benefits of Intense Beams

- Solving the Energy Crisis / Global Warming
- Material Characterization
  - Pulsed neutron sources
  - Short-pulse intense X-ray lasers
- Nanoscience / biosciences
- High Luminosity Colliders

Typical requirements
1 nC, 1 ps, 1 µm emit

Heavy Ion Inertial Fusion

Spallation Neutron Source

X-Ray Free Electron Lasers
# Measures of Beam Quality

<table>
<thead>
<tr>
<th>Measure</th>
<th>Formula</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emittance</td>
<td>$\tilde{\varepsilon}_{x,n} = \frac{1}{mc} \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle xp_x \rangle^2}$</td>
<td>Phase space volume - compactness</td>
</tr>
<tr>
<td>Generalized Perveance</td>
<td>$K \equiv \frac{2I}{I_o (\beta \gamma)^3}$</td>
<td>Space charge energy / total kinetic energy</td>
</tr>
<tr>
<td>Brightness</td>
<td>$\bar{B}<em>n = \frac{2I}{\pi^2 \varepsilon</em>{x,n} \varepsilon_{y,n}}$</td>
<td>Phase space density</td>
</tr>
<tr>
<td>Intensity</td>
<td>$\chi \equiv \frac{K}{k_0^2 a^2}$</td>
<td>Dimensionless, transport dynamics</td>
</tr>
</tbody>
</table>

\[
\chi = \frac{1}{1 + \frac{1}{K \left( \frac{\varepsilon_n}{\beta \gamma a} \right)^2}}
\]

\[
\bar{B}_n = \frac{I_o}{\pi} \frac{\beta \gamma}{\pi a^2} \left( \frac{\chi}{1 - \chi} \right)
\]
\[ \chi \equiv \frac{K}{k_0^2 a^2} \]

Davidson: \( s_b \)

\[ \frac{k}{k_0} = \sqrt{1 - \chi} \]

\[ \frac{k_p}{k_0} = \sqrt{2\chi} \]

Betatron (single-particle)

Plasma (Collective)

Emittance-Dominated

Space-Charge-Dominated

\( \lambda_D > a \)

\( \lambda_D < a \)

**Intense Beams = Plasmas**

- **χ = 0.21**
- **χ = 0.7 - 0.9**

- **Nebulae**

Experiment

Simulations

- **Cathode**

- **Halo**

**z ~ 0.15 – 1 m**

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Bernal, Kishek, Haber, and Reiser, PRL, **82**, 4002 (1999).
These oscillations can result in nonlinear $x$-$y$ coupling

$\chi = 0.98$

$z \sim 0 - 5 \text{ m}$

oscillation scale length
~ plasma wavelength

WARP3D Simulations: Source of Halo Identified

R-R’ phase space at gun exit. Halo shows sensitivity to cathode alignment

WARP simulations, I. Haber
The University of Maryland Electron Ring (UMER)

Use 10 keV electrons to inexpensively model space charge effects in other accelerators

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>10 keV ± 0.2 %</td>
</tr>
<tr>
<td>Current Range</td>
<td>0.6-100 mA</td>
</tr>
<tr>
<td>rms Emittance ( (\text{n}) )</td>
<td>0.2-3 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Circulation time</td>
<td>200 ns</td>
</tr>
<tr>
<td>Pulse length</td>
<td>5-100 ns</td>
</tr>
<tr>
<td>Zero-Current Tune</td>
<td>7.6</td>
</tr>
<tr>
<td>Depressed Tune</td>
<td>1.5 – 6.5</td>
</tr>
</tbody>
</table>
Parameter Space is Multi-Dimensional

Intensity Parameter

\( \beta \gamma \)

\( \text{COST} \)

\( \text{Livingston Axis} \)

\( \text{Reiser Axis} \)

X-ray sources

\( \text{ERL} \)

\( \text{LCLS} \)

\( \text{UMER} \)

\( \text{SNS - Neutron} \)

\( \text{HI Fusion} \)

\( \text{ILC} \)

\( \text{XFEL} \)

\( \Delta = \text{electrons} \)

\( \bullet = \text{protons} \)

\( \blacksquare = \text{heavy ions} \)

\( \text{COMPLEXITY}^{10} \)

\( L = \text{electrons} \)

\( G = \text{protons} \)

\( I = \text{heavy ions} \)

\( \text{ERL} \)

\( \text{PTSX} \)
UMER Multi-Turn Results (in progress)

\[ \chi = 0.21 \]

up to 125 turns

\[ \chi = 0.7 \]

up to 60 turns

**Tune Shift**
- Injected: 0.80
- After 25 turns: 0.45

**Tune Shift**
- Injected: 3.3
- After 25 turns: 0.9-2.0

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Ability to modulate beams in a controlled fashion

Laser Beam adds 5 ns perturbation on 100 ns pulse

Induction module can add 10-ns energy perturbations
**Longitudinal Space Charge Waves**

Interchange of energy and density modulations

**Beam Current**

*At z = 0.64m*

Laser induced perturbation

**Normalized Current**

- At z = 0.64m (RC6)
  - Laser induced perturbation
- At z = 5.11m (RC6)
  - Perturbation splits into fast and slow space-charge waves

**Average Energy**

*K. Tian, PRSTAB, 2006*

- WARP-RZ
- Experiment
- 1-D Theory

**Normalized Plate Voltage RC7**

- 10 ns
- 200 ns

**Time**

**Beam Current**

**Average Energy**

**C. Tobin**

**B. Beaudoin**

K. Tian, PRSTAB, 2006
Fast Imaging

Time-Resolved Imaging with Optical Transition Radiation (3ns)

Without perturbation

With perturbation


Sliding 3-ns gate along parabolic bunch
Examples of Phase Space Measurement

Compact Energy Analyzer

High-Fidelity Tomography

High resolution:

10^{-4} energy
1 mm spatial
few ns time

Y. Cui, et al, Rev Sci Inst, 2004

D. Stratakis, R. Kishek, et al., to appear


Recent Results

Merger of 5 beamlets

Experiment in IC2

Simulation in uniform channel

Y vs X

Y vs X'

X vs X'

Y' vs Y

X' vs Y'

s = 44 cm

D. Stratakis, 2007

R. Kishekek, AAC 2002
Conclusion

• UMER is an exciting and sophisticated facility

“There is obviously so much that can be learned from UMER; … be prepared for a growing production rate of scientific papers!”  -- UMER Advisory Committee*, 12/06

• Future of accelerators is very bright

* CL. Bohn, D. Douglas, A. Friedman, T. Shea, T. Smith, B. Weng
I like to thank my colleagues …

Present Members of UMER Group

Faculty
- Martin Reiser
- Terry Godlove
- Irving Haber
- Donald Feldman
- Dave Sutter
- Ralph Fiorito
- Renee Feldman

Faculty (more)
- Patrick O’Shea
- Rami Kishek
- Santiago Bernal
- Mark Walter
- Kai Tian
- Christos Papadopoulos
- Diktys Stratakis
- Gang Bai
- J. Charles T. Thangaraj
- Chao Wu

Graduate Students
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- Webmaster

http://www.umer.umd.edu/