The University of Maryland Electron Ring Program – Recent Developments

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W. Stem, D. Sutter, and H.D. Zhang

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Research sponsored by US DOE & DOD
1. Introduction to the U. Maryland Accelerator Research Group
2. Facilities description
3. A glimpse of current research
   - Beam halo
   - Resonant excitation of envelope modes
   - Nonlinear optics
   - New emittance measurement technique
   - Soliton Formation
   - Design of an extraction section
4. Summary
• **Laboratory for Photocathode Research:**
  Advanced facility for preparation and testing of self-healing photocathodes.
  TUPMA17, TUPMA18, TUPMA21

• **Beam Diagnostics Development Laboratory:**
  Development of advanced intercepting and non-intercepting diagnostics in support of UMER and collaborative experiments at other national and international accelerator labs (JLAB, SLAC, ANL, LANL, FERMI@Trieste).
  WEPBA20

• **The University of Maryland Electron Ring (UMER):**
  Beam dynamics experimental studies relevant to hadron and ion machines, over long path lengths, using low-energy electrons in a compact ring geometry.
Hallmarks of the Maryland program

• Education in accelerator and beam physics, with emphasis on hands-on experience.
  – 18 Ph.D. degrees awarded since 2000.
    4 more expected by end of this year.
  – Dozens of masters and undergraduate students.
  – Internships for high school students.

• Close-coupling with theory and simulation.
  – ELEGANT\textsuperscript{1}: tracking code commonly used in the community.
  – WARP\textsuperscript{2}: self-consistent 3-D PIC code for space charge modeling.

\textsuperscript{1} Elegant developed by M. Borland, ANL
\textsuperscript{2} WARP developed by A Friedman, D. Grote, and J.-L. Vay, LLNL and LBNL
UMER – A Scale Model of a High-Intensity Ring

Original Mission: Study Space Charge Dynamics

- low energy 10 keV
- high current 0.5-100 mA
- low-emittance 0.3-3 μm

- Safe
- Reproducible results
- Available: accelerator and beam physicists are the users
- Flexible: lattice, magnets, apertures

~10^{10} particles or up to 14 nC

Lap time = 197 ns, (5.08 MHz)
Pulse Length = 15 to 145 ns,
Full-Lattice Period = 0.32 m (std. lattice)
Vacuum Pipe radius = 25.4 mm

Shown: UMD graduate Charles Thangaraj (2009), now at FNAL
UMER Beam Parameters

UMER spans a broad range of intensities through the use of an aperture plate.

Calculated for operating tune $\nu_\text{ox} = \nu_\text{oy} = 6.6 = k_0 R$

<table>
<thead>
<tr>
<th>$I$</th>
<th>$\varepsilon_{\text{n,rms}}$</th>
<th>$a_{\text{ave}}$</th>
<th>$\nu_i/\nu_o$</th>
<th>$\Delta\nu_{\text{coh}}$</th>
<th>$\Delta\nu$</th>
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<tbody>
<tr>
<td>[mA]</td>
<td>[\mu m]</td>
<td>[mm]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>0.4</td>
<td>1.6</td>
<td>0.85</td>
<td>$-0.005$</td>
<td>$-0.94$</td>
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<td>6.0</td>
<td>1.3</td>
<td>3.4</td>
<td>0.62</td>
<td>$-0.05$</td>
<td>$-2.4$</td>
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<td>21</td>
<td>1.5</td>
<td>5.2</td>
<td>0.31</td>
<td>$-0.17$</td>
<td>$-4.5$</td>
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<td>78</td>
<td>3.0</td>
<td>9.6</td>
<td>0.18</td>
<td>$-0.67$</td>
<td>$-5.4$</td>
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<tr>
<td>104</td>
<td>3.2</td>
<td>11.1</td>
<td>0.14</td>
<td>$-0.91$</td>
<td>$-5.6$</td>
</tr>
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</table>

$\frac{\nu_i}{\nu_0} = \sqrt{1 - \chi}$

$\chi = \frac{K}{k_0^2 a^2}$

Enables beam lifetime studies and stability as a function of space charge

See Santiago Bernal TUPAC31
Goal: to induce controlled mismatches and observe effect on halo, comparing to theoretical models

Experiment – induced mismatch

Phase Space from Tomography

See Hao Zhang’s talk: FR0AA6, Friday 9:45 am
**Envelope Resonance Excitations**

**Goal:** to resonantly excite quadrupole and breathing envelope modes using a fast esq. Use excitation as an emittance diagnostic, as well as a way to seed instabilities.

**Status:** We have designed, simulated, and built an electrostatic quadrupole to observe and manipulate these resonances at UMER.

**Will Stem, TUPAC32**

**Nonlinear Optics at UMD**

**Goal:** reconfigure UMER to test concepts of nonlinear optics

- Further work on pure octupole lattice: S.D. Webb et. al (submitted to PRL)
- Nonlinear Optics at UMD
  - Synergy with Integrable Optics Test Accelerator (IOTA) at Fermilab
  - **Simulation:** Predict IOTA and nonlinear UMER performance for intense beams (WARP code)
  - **Experiment:** Modify UMER lattice to include octupole channel
    - map nonlinear phase space
    - observe halo suppression
    - stability near beam resonance

**Possible configuration of UMER lattice for NO experiment.**

**Drift space with matched β’s to be replaced by axially-varying oct. channel**

**Schematic of WARP simulation.**

**Nonlinear Field**

axially-symmetric thin lens kick
**New Emittance Diagnostic for Beams with Space Charge**

**Goal:** Take advantage of the insensitivity of divergence to space charge to make a quad-scan type emittance diagnostic

– Emittance is calculated from 2 radius & divergence measurements obtained from OTR near and far field images. (No need do complete quad or solenoid scan)

– For negligible space charge, a formula is given for the emittance.

– A procedure is developed for beams with linear space charge.

**Simulation Test:** emittance measured using different methods

Kamal Poor Rezaei, WEPBA20

Experimental Observation of Soliton Wave Train in UMER

**Goal:** understand the behavior of large-amplitude perturbations

**Observation:** formation of KdV-type solitary waves when nonlinear steepening balances wave dispersion.

22 mA beam, 25% density perturbation

UMER Extraction Section

Goals:
- Minimize perturbation to recirculation
- Exceed rings admittance
- Transport full range of UMER beams

Status:
- WARP space charge model finished
- Mechanical design complete
- Ready to cut metal…
Conclusions

• The UMD accelerator research program is geared towards study of key challenges in beam dynamics at the Intensity Frontier.

• In the past year, the group has branched into exciting new directions.

• We are interested in collaborations with the accelerator community.

• UMER is available for experiments and for code benchmarking.
Backup Slides
IDEAL TUNE DEPRESSION VS. FOCUSING: 3 BEAMS AND TWO LATTICES

![Graph showing tune depression vs. focusing for 3 beams and two lattices.](image)

- **Nominal** $\sigma_{0X} = \sigma_{0Y}$ (deg./period)
- **Tune Depression**, $\sigma / \sigma_0$
- **Curves** for different currents and lattice separations:
  - 0.6 mA, S=32cm
  - 6 mA, S=32cm
  - 21 mA, S=32cm
  - 0.6 mA, S=64cm
  - 6 mA, S=64cm
  - 21 mA, S=64cm

**Key Observations**:
- **Emittance Dominated**: Lower currents, higher lattice separations.
- **Sp. Charge Dominated**: Higher currents, lower lattice separations.

**Values**:
- 1.83 A
- 2.73 A
- 3.09 A
- 0.85 A
- 1.28 A
- 1.44 A

**Legend**:
- Solid blue line: 0.6 mA, S=32cm
- Dashed red line: 6 mA, S=32cm
- Solid green line: 21 mA, S=32cm
- Solid black line: 0.6 mA, S=64cm
- Dashed red line: 6 mA, S=64cm
- Solid green line: 21 mA, S=64cm
Containment of Long Bunches

No Containment

Minimization of waves
1.013 MHz, 60 v

Overcorrecting Inducing Multiple waves
1.013 MHz, 130 v

## Education/Training: Recent PhD Graduates

<table>
<thead>
<tr>
<th>Student</th>
<th>PhD year</th>
<th>Placement</th>
<th>Currently @</th>
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<tbody>
<tr>
<td>Yun Zou</td>
<td>2000</td>
<td>Industry</td>
<td>GE Global Research</td>
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<tr>
<td>Yupeng Cui</td>
<td>2004</td>
<td>KLA-Tencor</td>
<td>Velodyne Acoustics</td>
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<tr>
<td>Hui Li</td>
<td>2004</td>
<td>Microsoft</td>
<td>Embarcadero Technologies</td>
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<tr>
<td>John Harris</td>
<td>2005</td>
<td>NRL</td>
<td>Colorado State University</td>
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<tr>
<td>Jon Neumann*</td>
<td>2005</td>
<td>NRL</td>
<td>Naval Research Laboratory</td>
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<tr>
<td>Nathan Moody*</td>
<td>2006</td>
<td>LANL</td>
<td>Los Alamos National Laboratory</td>
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<tr>
<td>David Gillingham</td>
<td>2007</td>
<td>NRL</td>
<td>Institute for Defense Analysis</td>
</tr>
<tr>
<td>Kai Tian</td>
<td>2008</td>
<td>J-Lab</td>
<td>Stanford Linear Accelerator</td>
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<tr>
<td>Diktys Stratakis*</td>
<td>2008</td>
<td>BNL</td>
<td>Brookhaven National Laboratory</td>
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<tr>
<td>J. Charles Tobin*</td>
<td>2009</td>
<td>FNAL</td>
<td>Fermi National Accelerator Laboratory</td>
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<tr>
<td>Chao Wu</td>
<td>2009</td>
<td>FDA</td>
<td>Hillcrest Labs</td>
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<tr>
<td>Chris Papadopoulos</td>
<td>2009</td>
<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory</td>
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<tr>
<td>Eric Montgomery*</td>
<td>2009</td>
<td>UMD</td>
<td>U. Maryland</td>
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<tr>
<td>Mike Holloway</td>
<td>2010</td>
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<tr>
<td>Matt Virgo</td>
<td>2010</td>
<td>ANL</td>
<td>Argonne National Laboratory</td>
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<tr>
<td>Brian Beaudoin</td>
<td>2011</td>
<td>UMD</td>
<td>U. Maryland</td>
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<tr>
<td>Daniela Moody</td>
<td>2012</td>
<td>LANL</td>
<td>Los Alamos National Laboratory</td>
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<tr>
<td>Zhigang Pan *</td>
<td>2013</td>
<td>(NRL)</td>
<td>Naval Research Laboratory</td>
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</table>

* Received prestigious awards

Includes both ONR-funded and DOE-funded students
<table>
<thead>
<tr>
<th>Institution</th>
<th>Point of Contact</th>
<th>Area of Common Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lawrence Berkeley / Livermore National Laboratories</td>
<td>Alex Friedman, Dave Grote, Jean-Luc Vay</td>
<td>Development, benchmarking, and use of the WARP code.</td>
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<tr>
<td>Princeton Plasma Physics Laboratory</td>
<td>Ron Davidson, Ed Startsev</td>
<td>Study of solitons in electron beams</td>
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<tr>
<td>Los Alamos National Laboratory</td>
<td>Bruce Carlsten, Nathan Moody</td>
<td>Development of a 100 kW-class FEL</td>
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<tr>
<td>Thomas Jefferson National Accelerator Facility (FEL)</td>
<td>Dave Douglas, Shukui Zhang</td>
<td>Non-interceptive diagnostics</td>
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<tr>
<td>Fermi National Accelerator Laboratory</td>
<td>Gustavo Cancelo</td>
<td>Use of ESECON boards for fast beam control</td>
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<tr>
<td>Argonne National Laboratory, Advanced Wakefield Accelerator</td>
<td>John Power, Manoel Conde</td>
<td>Development of advanced accelerator diagnostics for space-charge-dom. beams</td>
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<tr>
<td>SLAC National Accelerator Laboratory (SPEAR3 and LARP/CERN)</td>
<td>Jeff Corbett, Alan Fisher Kai Tian</td>
<td>Development of high dynamic range beam imaging diagnostics, THz measurements</td>
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<tr>
<td>Naval Research Laboratory</td>
<td>Kevin Jensen, Phillip Sprangle</td>
<td>Cathode theory and simulation; rf thermionic injector development</td>
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<tr>
<td>FERMI@Elettra</td>
<td>Simone DiMitri, Marco Veronese</td>
<td>Development of advanced emittance and phase-space diagnostics</td>
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<tr>
<td>Calabazas Creek Research, Inc.</td>
<td>Lawrence Ives, Lou Falce</td>
<td>Precision machining of controlled-porosity reservoir cathodes</td>
</tr>
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</table>
Observation of a Multi-stream instability

No longitudinal focusing – Beam expands and wraps around ring

Onset of instability: $t_{\text{onset}} = 16.5 \mu s$

Experimental

- 6 mA beam
- $\eta = 0.5$

Beam becomes “DC”

$\frac{c_s}{v_0} = 0.013$

Phase Space (Simulation)

$V_z$ vs $Z$

$<c_s$

Comparison between Theory, Simulation and Experiment

\[ t_{onset} = \frac{C}{4c_s} \left( \frac{2}{\eta} - \eta \right) \]

\( \eta \) = fill factor

\( \eta = \frac{\text{injected pulse length}}{\text{ring lap-time}} \)

Onset of Instability

\[ c_s = \left( \frac{qg\Lambda_0}{4\pi\varepsilon_0\gamma_0^5 m} \right)^{1/2} \]

- 0.6 mA Beam
- 6 mA Beam
- 21 mA Beam
- 78 mA Beam
- 104 mA Beam

- Experiment
- Simulation (WARP)

Pulse Length (ns)

Onset of Instability (\( \mu s \))
Beam Lifetime and Losses (No Longitudinal Focusing)

Automated Scans ~ 24 hours

Quad Scan
1. Set even quads (D)
2. Set odd quads (F)
3. Measure beam intensity every turn (norm to 1st turn)
4. Repeat at new D,F Quad values
Current Dependence of Tune Diagrams


Coherent Tune Shift Measurement


survival after 20th turn (before the alignment, and with some defective magnets)

0.6 mA  
6 mA  
21 mA
Mapping of Resonances over Wide Range of Tunes

Work in Progress

Shown: fraction of transmitted current after 10 turns
For each of 2000 operating tunes

6 mA beam: $\chi \sim 0.8$, $\sigma/\sigma_o \sim 0.45$
Injected incoherent tune shift from space charge $> 3.0$

Stop bands narrowed and growth rates reduced after detailed mechanical survey and alignment in 1/2012

Sutter, Beaudoin, Bernal, Koeth 2012
Longitudinal Confinement with Induction Cells

**Line-charge density**

\[ \vec{E}_z \neq 0 \quad E_z \approx 0 \quad \vec{E}_z \neq 0 \]

Energy Profile

\[ \Delta E \]

Head

**Tail**

Time

\[ (mA) \]

Application of Induction cell Ear fields keeps beam confined for > 1000 turns

Long Wavelength Limit

\[ E_z \propto -\frac{d\lambda}{dz} \]

0.6 mA beam

Demonstrated long-distance recirculation of a beam with high space charge, using induction focusing.

Stored charge after 1/2012

Before 1/2012

Laslett tune shift (from space charge) at injection = 1.0

UMER design goal: 100 Turns

0.6 mA beam, $\sigma/\sigma_o = 0.85$

11.5 km