UMER Enters a New Regime of High Tune-Shift Rings

Rami A. Kishek
Institute for Research in Electronics & Applied Physics
University of Maryland, College Park, MD, USA

Research sponsored by US DOE HEP, DOE FES/HEDP, and DOD ONR
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Outline:
1. The need for high-quality beams
2. High Intensity: Terra Incognita
3. UMER: A tool for probing space charge physics
4. Results and issues

Research sponsored by US DOE HEP, DOE FES/HEDP, and DOD ONR
I like to thank my colleagues ...

Present Members of UMER Group

Patrick O'Shea  Rami Kishek  Santiago Bernal  Mark Walter
Kai Tian  Christos Papadopoulos  Diktys Stratakis  Gang Bai  J. Charles Thangaraj  Chao Wu
Martin Reiser  Terry Godlove  Irving Haber  Donald Feldman  Dave Sutter  Ralph Fiorito  Renee Feldman
Bryan Quinn  Webmaster
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Present Members of UMER Group

Senior Faculty
- Patrick O'Shea
- Rami Kishek
- Santiago Bernal
- Mark Walter

Graduate Students
- Kai Tian
- Christos Papadopoulos
- Diktys Stratakis
- Gang Bai
- J. Charles Thangaraj
- Chao Wu

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

Bryan Quinn
Webmaster

http://www.umer.umd.edu/
Benefits of High-Quality Beams

Spallation Neutron Source

Large Hadron Collider (LHC), CERN, Geneva

Free Electron Lasers

Heavy Ion Inertial Fusion
Benefits of High-Quality Beams

Spallation Neutron Source

Large Hadron Collider (LHC), CERN, Geneva

Typical requirements:
1 nC, 1 ps, 1 μm emit

Free Electron Lasers

Heavy Ion Inertial Fusion
High Quality = High Space Charge Intensity

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

Intensity Parameter
High Quality = High Space Charge Intensity

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

Intensity Parameter
High Quality = High Space Charge Intensity

\[ \chi = \frac{1}{1 + \frac{\beta y l_o}{2l} \left( \frac{\varepsilon_n}{a} \right)^2} \]

Intensity Parameter
High Quality = High Space Charge Intensity

\[ \frac{k}{k_0} = \frac{v}{v_0} = \sqrt{1 - \chi} \]

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

Emittance-Dominated

Space-Charge-Dominated

Intensity Parameter

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

High Quality = High Space Charge Intensity

\[ \frac{k}{k_0} = \frac{\nu}{\nu_0} = \sqrt{1 - \chi} \]

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

Normalized oscillation frequency

Emittance-Dominated

Space-Charge-Dominated

Rings

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

Intensity Parameter

High Quality = High Space Charge Intensity

Betatron (single-particle):
\[ \frac{k}{k_0} = \frac{\nu}{\nu_0} = \sqrt{1 - \chi} \]

Plasma (Collective):
\[ \frac{k_p}{k_0} = \sqrt{2\chi} \]

Normalized oscillation frequency

Emittance-Dominated

Space-Charge-Dominated

Rings

Sources

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


IREAP
Different Machines in Parameter Space

- ▲ = electrons
- ● = protons
- ■ = heavy ions

beta*gamma vs. Intensity Parameter
Different Machines in Parameter Space

- ▲ = electrons
- ● = protons
- ■ = heavy ions

Graph:
- **ILC**
- **LHC**
- **SNS - Neutron**
- **HI Fusion**

Axes:
- Vertical: \( \beta \gamma \)
- Horizontal: Intensity Parameter
Different Machines in Parameter Space

- ▲ = electrons
- ● = protons
- ■ = heavy ions

X-ray sources

ILC
LHC
SNS - Neutron
LCLS
HI Fusion
Different Machines in Parameter Space

- ▲ = electrons
- ● = protons
- ■ = heavy ions

X-ray sources

ILC

LHC

SNS - Neutron

UMER

ERL

LCLS

HI Fusion

beta*gamma

Intensity Parameter

1.0
Henricus Hondius
*Polus Antarcticus*
(1639)

Credits:  http://www.pbs.org/wgbh/nova/shackleton/surviving/mapping3.html
What do we expect to happen? E.g., Resonances
What do we expect to happen? E.g., Resonances

Tune Diagram
No Space
Charge

Credits: Santiago Bernal, output of WinAgile code
What do we expect to happen? E.g., Resonances

Tune Diagram
No Space Charge

Jackson Laslett: Tune shift limit $\Delta \nu < 0.25$

$$\Delta \nu = \nu_0 - \nu = \nu_0 \left(1 - \frac{\nu}{\nu_0}\right) = \nu_0 \left(1 - \sqrt{1 - \chi}\right) \approx \nu_0 \frac{\chi}{2}$$

Credits: Santiago Bernal, output of WinAgile code
What do we expect to happen? E.g., Resonances

Tune Diagram
No Space
Charge

\[ \Delta \nu = \nu_0 - \nu = \nu_0 \left(1 - \frac{\nu}{\nu_0}\right) = \nu_0 \left(1 - \sqrt{1 - \chi}\right) \approx \nu_0 \frac{\chi}{2} \]

Jackson Laslett: Tune shift limit \( \Delta \nu < 0.25 \)

Credits: Santiago Bernal, output of WinAgile code
Cheating Laslett – is it possible?
Cheating Laslett – is it possible?

- Experiment: Rapid bunching at AGS
  \[ \Delta \nu = 1.9 \]

- Simulation: Resonance crossing by rapid acceleration
  Month and Weng, 12th International Accel. Conf., p. 324 (1983)
  Hofmann and Beckert, IEEE-NS 32 (PAC 85), 2264 (1985)

- Theory: Cannot simply replace \( v_0 \) by \( v \)
  Fedotov,
  Franchetti,
  Hofmann,
  Holmes,
  Machida,
  …
Cannot Simply Extrapolate
Cannot Simply Extrapolate

Venturini & Gluckstern: Resonances spaced further apart

More Intense
Cannot Simply Extrapolate

Venturini & Gluckstern: Resonances spaced further apart

Hofmann: Resonances broaden at higher intensities

Cannot Simply Extrapolate

Venturini & Gluckstern: Resonances spaced further apart

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Cannot Simply Extrapolate

Venturini & Gluckstern: Resonances spaced further apart

Hofmann: Resonances broaden at higher intensities

Importance of the Particle Distribution
Emittance-dominated:
Resonances property of lattice
Intense beams have more complex distributions
Intense beams have more complex distributions

$\chi = 0.21$

Emittance-Dominated
Intense beams have more complex distributions

\[ \chi = 0.21 \]

Emittance-Dominated

\[ \chi = 0.9 \]

Space-Charge-Dominated
Intense beams have more complex distributions

\( \chi = 0.21 \)
Emittance-Dominated

\( \chi = 0.9 \)
Space-Charge-Dominated

Nebula
What do we Need to Understand?
What do we Need to Understand?

Effects

- Emittance Growth / Energy Spread
- Halo formation and evolution
- Stability

Possible Causes

- Density or energy modulations
- Anisotropy
- Machine Errors and Control
- Resonances
The UMER Concept

Experiment → Simulation

Theory
The UMER Concept

Martin Reiser: "Let there be a ring" (with extreme tune shifts)

Experiment  Simulation

Theory
UMER Mission:
Use 10 keV electrons to inexpensively model space charge effects, i.e., to probe unknown territory.

<table>
<thead>
<tr>
<th>Energy</th>
<th>10 keV ± 0.2 %</th>
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<tbody>
<tr>
<td>Current Range</td>
<td>0.6-100 mA</td>
</tr>
<tr>
<td>rms Emittance ($\pi$)</td>
<td>0.2-3 μm</td>
</tr>
<tr>
<td>Circulation time</td>
<td>200 ns</td>
</tr>
<tr>
<td>Pulse length</td>
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<tr>
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Beam injected with large tune-shift

3.7 m

100 ns
~ 5.75 m

5 ns
~ 30 cm
Design Goal

- Lowest-Current (1 mA): 100 Turns
- High-Current (100 mA): 10 Turns
\[ \chi = 0.37 \]
$\chi = 0.37$

**Tune Shift**

- Injected: 1.5
- After 25 turns: 0.7 - 1.0

*up to 125 turns*  
$\uparrow 1 \text{ mV}$

5 $\mu$s

*IREAP*  
S. Bernal, Advanced Accelerators Concepts, 2006
Design Simulations Show UMER Works

Mixture of random errors

No errors, or,
Shifted operating point

\[ \varepsilon_{n,\text{rms}} \text{ (\text{\textmu}m)} \]

\[ S \text{ (m)} \]

Design Simulations Show UMER Works

- Mixture of random errors
- No errors, or, Shifted operating point

\[ \varepsilon_{n,\text{rms}} \text{ (\mu m)} \]

- 10 Turns

Experiment Complex: Many Lessons Learned

Issue: Sensitivity to Ambient Field (e.g., Earth B-Field)
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Earth Field Measurements, D. Sutter & S. Bernal

- Moved Scope Cart
- Moving Optical Table
- Moved Rack with Imaging Computer
Experiment Complex: Many Lessons Learned

Issue: Sensitivity to Ambient Field (e.g., Earth B-Field)

Earth Field Measurements, D. Sutter & S. Bernal

Vertical Component (Gauss)

Moved Scope Cart
Moved Optical Table
Moved Rack with Imaging Computer
Space Charge Requires Dense Lattice
Space Charge Requires Dense Lattice

Issue: Little room for diagnostics

Solution: Systematized quad-scan technique

Hui Li
Mark Walter, TUPAS047
Chao Wu, MOPAS033
Space Charge Requires Dense Lattice

Issue: Little room for diagnostics

Solution: Systematized quad-scan technique

Hui Li
Mark Walter, TUPAS047
Chao Wu, MOPAS033

Alternative: Operate at longer betatron wavelengths

Santiago Bernal, THPAS030
Halo can be created at source
Halo can be created at source

Issue: Halo very sensitive to cathode placement

Irv Haber, THPAS031

2001 2006
Halo can be created at source

Issue: Halo very sensitive to cathode placement

Irv Haber, THPAS031

Incorporate more realistic initial distribution into codes

Christos Papadopoulos, THPAS032

WARP Simulation
High-Current Operation
Tune Scan Results

Inject Same Beam: 5 mA, 10 keV, 60 ns
Nominal Tune: \( \nu_0 = 76.0° \)
**Tune Scan Results**

Inject Same Beam: \( 5 \text{ mA, 10 keV, 60 ns} \)

Nominal Tune: \( \nu_0 = 76.0^\circ \)

\( \nu_0 \sim 71.5^\circ \)

\( \nu_0 \sim 70.8^\circ \)
Importance of Beam Distribution (Reprise)
Importance of Beam Distribution (Reprise)

Detailed Phase Space Measurement
- Time-resolved Energy Analyzer
- Tomography (transverse)
- Fast Imaging

Ability to manipulate distribution
- electronics
- laser photoemission
- induction modules
Examples of Phase Space Measurement
Compact Energy Analyzer

High resolution:

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

Y. Cui, et al, Rev Sci Inst, 2004
Examples of Phase Space Measurement

Compact Energy Analyzer

High resolution:
- $10^{-4}$ energy
- 1 mm spatial
- few ns time

High-Fidelity Tomography

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

Diktys Stratakis, Invited Talk, WEZC01
2 PM Tomorrow (Room C)
Predictive Power of Simulation

Initial distribution
Predictive Power of Simulation

Initial distribution

Simulation Prediction

Downstream

X-Y

R. Kishek, AAC 2002
Uniform Focusing

X-X'

IREAP
Predictive Power of Simulation

Homogenization of beam is different in configuration and phase space

Initial distribution

Simulation Prediction

Downstream

X-Y

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Predictive Power of Simulation

Homogenization of beam is different in configuration and phase space

Initial distribution

Simulation Prediction

Experiment

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R. Kishek, AAC 2002
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tomography

X-X’

D. Stratakis, 2007
Deliberate Manipulation of Beam Distribution
Deliberate Manipulation of Beam Distribution

Beam Current

J. Charles T. Thangaraj, THPAS033
Deliberate Manipulation of Beam Distribution

Beam Current

J. Charles T. Thangaraj, THPAS033

At $z = 0.54m$

Laser induced perturbation

At $z = 5.11m$ (RCB)

Perturbation splits into fast and slow space charge waves

100 ns

Time

Normalized Current

Normalized Current
Deliberate Manipulation of Beam Distribution

Beam Current

J. Charles T. Thangaraj, THPAS033

Average Energy

K. Tian, PRSTAB, 2006

- Laser induced perturbation
- Perturbation splits into fast and slow space charge waves

Time:

100 ns

Energy (eV):

- WARP-RZ
- Experiment
- 1-D Theory
Deliberate Manipulation of Beam Distribution

Beam Current

J. Charles T. Thangaraj, THPAS033

Average Energy

K. Tian, PRSTAB, 2006

Brian Beaudoin, WEPMS001
Deliberate Manipulation of Beam Distribution

Beam Current
J. Charles T. Thangaraj, THPAS033

Average Energy
K. Tian, PRSTAB, 2006

Brian Beaudoin, WEPMS001

Time

Laser induced perturbation

Perturbation splits into fast and slow space charge waves

Normalized Current
Normalized

Normalized

Energy (eV)

WARP-RZ
Experiment
1-D Theory

Time (ns)

Gap Voltage

Time (nsec)

100 ns

10 ns
Deliberate Manipulation of Beam Distribution

Beam Current
J. Charles T. Thangaraj, THPAS033

![Graph showing laser induced perturbation and normalized current over time with a 100 ns interval.]

Average Energy
K. Tian, PRSTAB, 2006

![Graph showing energy vs. time with WARP-RZ, Experiment, and 1-D Theory lines.]

Brian Beaudoin, WEPMS001

![Graph showing normalized plate voltage over time with 200 ns interval and 10 ns gap voltage over time with 10 ns interval.]

IREA
Fast Imaging

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

Without perturbation  With perturbation

Ralph Fiorito, FRPMS033
Kai Tian, THPAS034
Conclusion
Conclusion

• Beams with intense space charge are largely unexplored territory, especially in rings

• Particle distribution is of fundamental importance
List of UMER-Related Presentations

Invited Talks:

5:30 PM Tue (Rm. A+B): Rami Kishek (UMER overview), TUZBAB03
2:00 PM Wed (Room C): Diktys Stratakis (Tomography), WEZC01

Posters:

MON PM:
  Chao Wu, MOPAS033 (Controls)
TUE PM:
  Mark Walter, TUPAS047 (Controls)
  Mark Walter, TUPAS048 (Extraction)
WED AM:
  Brian Beaudoin, WEPMS001
    (Energy perturbations)
THU PM:
  Santiago Bernal, THPAS030
    (Low-current beams)
  Irv Haber, THPAS031 (Halos)
  Christos Papadopoulos, THPAS032
    (Skew quadrupoles, Halos)
  J. Charles Thangaraj, THPAS033
    (Density perturbations)
  Kai Tian, THPAS034 (Fast imaging)
FRI AM:
  Ralph Fiorito, FRPMS033 (OTR)

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