Space-Charge Simulations of UMER

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Simulation/Experiment Integration
Central to UMER Program

• Simulation (including space-charge when necessary) extensively used from early design, through commissioning, to current research.

• Close agreement obtained between the code (mostly WARP here) and experiment.

• Examples:
  – Halo Mitigation
  – Bunch-end interpenetration
  – Multi-Stream Instability

• Ability to achieve close agreement gives confidence both in understanding of the experiment as well as in the code fidelity.
WARP used for space-charge Simulation: Hybrid Accelerator/Plasma Code

- **Geometry:** 3D (x,y,z), 2D-1/2 (x,y), (x,z) or axisym. (r,z)
- **Multiple Descriptions of Lattice Elements:**
  Hard edged, gridded, moment
- **Python and Fortran:** “steerable,” input decks are programs
- **Field solvers:**
  - Electrostatic - FFT, multigrid; AMR; implicit
  - Magnetostatic - FFT, multigrid; AMR; implicit
  - Electromagnetic - Yee, Kark, PSATD; PML; AMR
- **Parallel:** MPI (1, 2 and 3D domain decomposition)
- **Boundaries:** “cut-cell” --- no restriction to “Legos”
- **Reference frame:** lab, moving-window, Lorentz boosted
- **Surface/volume physics:** secondary e-/photo-e- emission, gas emission
- **Diagnostics:** extensive snapshots and histories

Courtesy J.-L. Vay
UMER: Simulations Traced Halo to Cathode

Halo Particles

Before

After

d = 0.5 mm

d = 0.1 mm

Simulation Credits: Haber
Data: Bernal/Walter/Haber/Kishek
Simulation/Code Comparison

Bunch-lengthening without Longitudinal Focusing

This comparison takes into account the Wall Current Monitor’s AC circuit Characteristics.

Black: Experiment
Red: Simulation

Koeth, Haber, et al., PAC 2011.
Multi-Stream Instability
Observed and Simulated

• Overtaking and interpenetration eventually create multiple streams.

• Successive streams are closer in velocity.
  – As the stream velocity separations near the wave-propagation velocity the beam become unstable.
  – The unstable wavelength is of order of several pipe diameters.
  – This instability is in addition to the normal plasma two-stream mode which occurs at a shorter wavelength and saturates at a low level.

• The unstable behavior is seen both in simulation and experiment.
Comparison of current from experiment (black) and simulation (blue). Onset of instability in experiment is observed earlier than in simulation. (Ongoing)
Conclusion

- The simulations work.
Extras
z-Vz phase space from the simulation after the instability is well developed. Unstable wavelength is $\sim 1\text{m}$, compared to $\sim 0.05\text{m}$ pipe diameter.
Soliton Train Formation from Large Initial Perturbation

- Laser illumination used to initiate a short-pulse large-amplitude current perturbation.
- After several turns initial pulse evolves into a soliton train.
- Tests used to verify soliton characteristics
  - Shape preserved after collisions
  - Product width$^2$*amplitude is constant
- Simulation/experiment agreement achieved
  - Agreement requires some adjustment of initial pulse width from what is expected.
WARP Success at UMD

• Transverse

• Longitudinal (r-z geometry)
  – Bunch-end interpenetration (Koeth, PAC)
  – Soliton Formation (Charles Thesis)
  – Multi-Stream Instability

• Three-Dimensional
RMS Matched Beam ~1989

Simulation vs. Experiment

<table>
<thead>
<tr>
<th>z</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 cm</td>
<td>-2.25</td>
</tr>
<tr>
<td>17.0 cm</td>
<td>-1.0</td>
</tr>
<tr>
<td>44.2 cm</td>
<td>1.0</td>
</tr>
<tr>
<td>57.8 cm</td>
<td>2.0</td>
</tr>
<tr>
<td>98.6 cm</td>
<td>5.0</td>
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<tr>
<td>524.2 cm</td>
<td>36.3</td>
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</table>
Virtual cathode oscillations predicted by simulation were measured by spectrum analyzer near predicted frequency.