Summary of Working Group A: Injector Design

Ivan Bazarov, Xiangyun Chang, Massimo Ferrario, Bob Garnett, Dmitry Kayran, Sergey Kurennoy, John Lewellen, Ji Qiang, Dave Sutter, Xijie Wang
Outline of Discussion Topics

• Injector design theory, new concept and methodology
• Computational requirements and challenges in the injector design
• Current available computation tools
• Simulation codes verification and validation
Injector Design: Theory and Methodology

- Model independent multivariate optimization
- Electron current amplification through secondary electron emission
- Optimized lower energy and high energy electron merging systems
- A simple design of a high brightness Superconducting RF photoinjector with external Solenoid for emittance compensation has been discussed
Computational Requirements and Challenges

- An accurate model during electron emission including Schottky effect, thermal emittance, space-charge effects
- An accurate space-charge model for beam with large aspect ratio and large energy spread and varying scale length
- An accurate model to model transverse and longitudinal beam halo
- High statistic resolution to include the modeling the diagnostic
- Wakefield seems not be important in the RF gun but important in the linac
Current Available Computational Tools

- ASTRA:
- GPT:
- IMPACT-T:
- PARMELA:
- HOMDYN:
<table>
<thead>
<tr>
<th>Code Name</th>
<th>Dim.</th>
<th>Wake field</th>
<th>Sp. charge Model</th>
<th>Parallel</th>
<th>Doc.</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astra</td>
<td>2 1/2d</td>
<td>no</td>
<td>2d ring ?</td>
<td>No</td>
<td>Yes</td>
<td>No?</td>
</tr>
<tr>
<td>GPT</td>
<td>2 1/2d - 3d</td>
<td>no?</td>
<td>pt-2-pt + 3d mesh</td>
<td>Yes</td>
<td>Yes</td>
<td>Half?</td>
</tr>
<tr>
<td>Impact-T</td>
<td>3d</td>
<td>no</td>
<td>pt-2-pt + 3d mesh</td>
<td>Yes</td>
<td>Und. Const.</td>
<td>Yes</td>
</tr>
<tr>
<td>Parmela</td>
<td>2d – 3d</td>
<td>yes</td>
<td>2d ring + 3d mesh + pt-2-pt</td>
<td>No</td>
<td>Yes</td>
<td>Wld. be</td>
</tr>
<tr>
<td>Homdyn</td>
<td>3d envelope</td>
<td>yes</td>
<td>Analytical</td>
<td>No</td>
<td>Yes</td>
<td>Not yet</td>
</tr>
</tbody>
</table>
Simulation Codes Verification and Validation

- Code benchmark should be done for a number of cases with parameters which account for different operation regime, e.g. low emittance, high charge, large aspect ratio beam, large energy spread beam, beam with initial halo.
- Dedicated experiments are needed for testing the simulation codes, e.g. SPARC, GTF, PITZ, ……
PARMELA

Bob Garnett
Los Alamos National Laboratory

Workshop on High Average Power & High Brightness Beams
UCLA
November 8-10, 2004
Outline

• Present Status of PARMELA
• PARMELA Code Description
  - Main Features
  - Additional Features
    Space Charge
    Wakefields and BBU
    CSR
• Validation, Benchmarking, & Limitations
• Areas of Improvement / Collaborations?
PARMELA has been compared to measurements.

- NBS 5-MeV Race-Track Microtron:
  
<table>
<thead>
<tr>
<th>Measured PARMELA</th>
</tr>
</thead>
</table>
  | $\varepsilon_{tn}$ (mm-mrad) | 0.63±0.14  
  | $\Delta E$ (keV) | 5.0 10-15  

- Photo-Injector measurements at the SLAC Gun Test Facility (GTF).


Figure 2. Projected emittance vs bunch charge as measured at GTF for Gaussian pulses, and PARMELA simulation results for the same parameters.
PARMELA has been compared to other codes.


<table>
<thead>
<tr>
<th>Code</th>
<th>Platform</th>
<th>CPU</th>
<th>Num. particles</th>
<th>Mesh points</th>
<th>Mesh size</th>
<th>Integration</th>
<th>CPU time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOMDYN</td>
<td>PC  Win</td>
<td>1 Gz</td>
<td>75 slices</td>
<td></td>
<td>0.13 μs</td>
<td>Automatic</td>
<td>45</td>
</tr>
<tr>
<td>BEAMPATH</td>
<td>PC  Win</td>
<td>1 Gz</td>
<td>10^11</td>
<td>256 x 2048</td>
<td>50 x 50 μm</td>
<td>Automatic</td>
<td>8000</td>
</tr>
<tr>
<td>PARMELA</td>
<td></td>
<td>1 Gz</td>
<td>2.5 x 10^5</td>
<td>25 x 75</td>
<td>“</td>
<td>“</td>
<td>9846</td>
</tr>
<tr>
<td>spech3d</td>
<td></td>
<td>1 Gz</td>
<td>10^10</td>
<td>32 x 32 x 1024</td>
<td>Automatic</td>
<td>“</td>
<td>1.4 10^5</td>
</tr>
<tr>
<td>ASTRA</td>
<td></td>
<td>1.8 Gz</td>
<td>1.5 x 10^5</td>
<td>20 x 60</td>
<td>Automatic</td>
<td>Adaptive</td>
<td>420</td>
</tr>
<tr>
<td>Trezi Stat.</td>
<td>16 nodes</td>
<td>1.8 GHz</td>
<td>5.0 10^7</td>
<td>20 x 30</td>
<td>Automatic</td>
<td>Adaptive</td>
<td>7.5 10^7</td>
</tr>
<tr>
<td>Trezi Lin.</td>
<td>PC  Win</td>
<td>1.8 GHz</td>
<td>0.1 10^7</td>
<td>20 x 30</td>
<td>Automatic</td>
<td>Adaptive</td>
<td>7.4 10^7</td>
</tr>
</tbody>
</table>

Electron bunches, 1 nC, 10 ps

- PARMELA is routinely used to benchmark other codes.
- Validation and benchmarking continues through the various user-community applications of the code.

**INITIAL ACCELERATION**
A comparison of the dynamics between PARMELA and PIC codes [7], has shown that:
1- the image charge model is good enough to represent the boundary conditions at the origin
2- the computation of space charge forces, performed in the frame of the center of mass of the bunch in PARMELA type codes, when the Lorentz factor is small give good enough results compared with PIC or Lienard-Wiechert codes
3- neglecting the radial force generated from the beam self-induced azimuthal magnetic field does not affect the results
PARMELA has been compared to other codes (cont.)

Claudio Parazzoli, et al. “Boeing Design Codes”
Navy MWFEL Design Code Review, March 24-25, 2004
Naval Postgraduate School, Monterey, CA

• PARMELA accuracy in question for low-energies near the cathode for high-brightness regime.
• Did numerical comparison of PARMELA results with ARGUS PIC simulations.
• Found good agreement for bunch charge < 7 nC and pulse lengths < 50 psec.
• May need codes like ARGUS or MAFIA (pushing particles) if in higher space charge regimes.
Normal-Conducting Photoinjector for High Power CW FEL

- Sergey Kurennoy, LANL, Los Alamos, NM, USA

An RF photoinjector capable of producing high continuous average current with low emittance and energy spread is a key enabling technology for high power CW FEL. We designed a 2.5-cell, \( \pi \)-mode, 700-MHz normal-conducting RF photoinjector cavity with magnetic emittance compensation. With the electric field gradients of 7, 7, and 5 MV/m in the three subsequent cells, the photoinjector will produce a 2.5-MeV electron beam with 3-nC charge per bunch and the transverse rms emittance below 7 mm-mrad.

Electromagnetic modeling was used to optimize the RF cavity, ridge-loaded tapered waveguides, and RF couplers, which led to a new, improved coupler iris design. The results, combined with a thermal and stress analysis, show that the challenging problem of cavity cooling can be successfully solved. The manufacturing of a demo 100-mA (at 35 MHz bunch repetition rate) photoinjector is underway. The design is scalable to higher power levels by increasing the electron bunch repetition rate, and provides a path to a MW-class amplifier FEL.
2.5-cell Photoinjector: Beam Dynamics

Comparison of MAFIA TS2 and Parmela results for 3-nC bunch charge
LANL Comparison of PARMELA and MAFIA 2D PIC

Navy MWFEL Photoinjector
2.5 MeV, 10 nC/bunch

IMPACT-T - A 3D Parallel Beam Dynamics Code for Modeling High Brightness Beams in Photo-Injectors

Ji Qiang
Lawrence Berkeley National Laboratory

Work performed under the auspices of the
DOE Grand Challenge in Computational Accelerator Physics,
Advanced Computing for 21st Century Accelerator Science and Technology
Project using resources at the
Advanced Computing Laboratory and the
National Energy Research Scientific Computing Center
What is new in the IMPACT-T code?

- Integrated Green method to accurately compute the space-charge forces for a beam with large aspect ratio
- Shifted Green method to efficiently compute the space-charge forces from the image charge
- Multiple slices/bins to handle the beam with large energy spread
- Parallel implementation on high performance computer to allow multiple million, high resolution simulation
Green Function Solution of Poisson’s Equation (cont’d)

**Hockney’s Algorithm:** - scales as $(2N)^3 \log(2N)$


\[
\phi_c(r_i) = h \sum_{i'=1}^{2N} G_c(r_i - r_{i'}) \rho_c(r_{i'})
\]

\[
\phi(r_i) = \phi_c(r_i) \text{ for } i = 1, N
\]

**Shifted Green function Algorithm:**

\[
\phi_F(r) = \int G_s(r, r') \rho(r') dr'
\]

\[
G_s(r, r') = G(r + r_s, r')
\]
Test of Image Space-Charge Calculation Using a Shifted Green Function Method

- **e^+**
- **e^-**
- **cathode**

![Graph showing electric potential vs. distance](image)

**Legend:**
- Shifted-Green function
- Analytical solution
Green Function Solution of Poisson’s Equation

Integrated Green function Algorithm for large aspect ratio:

\[
\phi_c(r_i) = \sum_{i'=1}^{2N} G_i(r_i - r_{i'}) \rho_c(r_{i'})
\]

\[
G_i(r, r') = \oint G_s(r, r') \, dr'
\]

![Graph showing the comparison of different methods for \(E_y\) and \(x\) (sigma)]
Xrms vs. Position

- Parallel simulation w/ IMPACT-T using 1M particles is 2x faster than simulation w/ PARMELA using 100K particles
- Reasonable agreement for test case with azimuthal symmetry
Zrms and Relative Energy Spread vs. Position
HOMDYN
(Higher Order Modes DYNamics)
Massimo.Ferrario@LNF.INFN.IT

Acknowledgements:

J. B. Rosensweig, L. Serafini,
The HOMDYN model

Normal Modes Expansion of Cavity fields
We describe the field evolution under the slowly varying envelope approximation for each resonant mode

Analytical propagation of field from bunch to bunch, including an external generator

Longitudinal and Transverse Beam Laminarity
We describe the bunch dynamics of a uniform charged cylinder under the Multi-Slice approximation

Analytically computation of slice Space Charge Fields
BEAM DYNAMICS MODELING IN HOMDYN

On Axis

\_t

Space Charge

RF Field

Off Axis

\_t

Longitudinal and Transverse Wake Field

SPARC general workshop 25-27 Ottobre 2004
Multi-Slice approximation and Envelope Equations:

\[
\dot{z}_s = c \beta_s
\]

\[
\dot{\beta}_s = \frac{e}{m_{oc} \gamma_s^3} \left( E_{z}^{acc}(z_s, t) + E_{z}^{wake}(s_s, t) + E_{z}^{sc}(\xi_s, t) - E_{z}^{sc}(\xi_s, t) \right)
\]

\[
\ddot{R}_s + \beta_s \gamma_s^2 \dot{\beta}_s \dot{R}_s + \left( K_{s}^{sol} + K_{s}^{rf} \right) R_s = \frac{2c^2 k_p}{R_s \beta_s} \left( \frac{G(\xi_s, A_r)}{\gamma_s^3} - \left( 1 + \beta_s^2 \right) \frac{G(\xi_s, A_r)}{\gamma_s} \right)
\]

\[
+ \left( \frac{4 \varepsilon_n c}{\gamma_s} \right)^2 \frac{1}{R_s^3} + \left( \frac{4 \varepsilon_n c}{\gamma_s} \right)^2 \frac{1}{R_s^3}
\]

\[
\Delta \xi(t)
\]

\[
L(t)
\]

\[
R_s(t)
\]
Comparison with PARMELA/UCLA

==> good agreement
Comparison HOMDYN with ASTRA (Ph. Piot)

Figure 43: Transverse beam parameter evolution along the beam line from the photocathode up to the exit of the third harmonic section calculated with ASTRA (solid lines) and HOMDYN (dashed lines).

Figure 44: Longitudinal beam parameter evolution along the beam line from the photocathode up to the exit of the third harmonic section calculated with ASTRA (solid lines) and HOMDYN (dashed lines).
Experimental validation at the A0 photoinjector (J. P. Carneiro et al.)

- 1.6 cells gun, 1.3 GHz, 40 MV/m peak field, 1.3 KG solenoid
- 9 cells Tesla structure, 1.3 GHz, 15 MV/m accelerating field

**Diagram:**
- Gun
- 9-cells TESLA structure
- Quads
- PepperPot

**Emittance (mm-mrad)** computed by HOMDYN and PARMELA/Orsay

**Figure 6.10:** (a) mesure de l’émittance verticale normalisée $\sigma_y$ pour un faisceau de charge $Q=8 \text{ nC}$ à $z=3.8 \text{ m}$ en fonction du courant dans les solénoides pour trois dimensions transverses $\sigma_x$ de la tache laser sur la cathode et (b) comparaison du cas $\sigma_x=1.6 \text{ mm}$ avec les codes de simulations Homdyn et Parmela.
A Few Comments on the Photoinjector Performance

X.J. Wang
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11973, USA

Presented at the UCLA High-Power Brightness Beams Workshop

Nov. 9, 2004
Challenges in High-Brightness Electron Source R&D

- Stability and Reliability
- Timing jitter and its control
- Better Theoretical Understanding
- Thermal Emittance – fundamental limit and importance of beam instrumentation
- Improve performance – 6-D optimization
- Next Generation Electron source:
  1. CW injector – DC, RF, SRF, what should be? 3H - Heat, Heat and Heat;
  2. Brighter sources - Higher field gun, pulse DC gun, laser plasma source and others.
Laser-Induced Explosive Emission

Graph showing the probability of IE formation versus laser power density. The graph indicates a sigmoidal relationship between the two variables with the probability increasing significantly as the laser power density increases.

(b) Graph showing a threshold at 67 MV/m, above which the probability of IE formation sharply increases.

(a) Graph showing the time evolution of laser pulse and intense electrons.
RF Photoinjector Theory

- Are all emittance uncorrelated?

\[ \mathcal{E} = \sqrt{\mathcal{E}_{ther}^2 + \mathcal{E}_{rf}^2 + \mathcal{E}_{sc}^2} \]

K-J.’s theory:

\[ \epsilon_{nx}^{sc} = \frac{\pi}{4} \frac{1}{\alpha k \sin \phi_0} \frac{I}{I_A} \mu_x(A) \]

Emittance growth (Rieser):

\[ \frac{\mathcal{E}_{ni}}{\mathcal{E}_{nf}} \approx \left[ 1 + \frac{N r_0 \bar{x} U}{15 \sqrt{5} \gamma_0 \epsilon_{ni}^2 w_0} \right]^{1/2} \]
Experimental observation of high-brightness microbunching in a photocathode rf electron gun

X. J. Wang, X. Qiu, and I. Ben-Zvi

National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973
(Received 13 February 1996)

We report the measurement of very short, high-brightness bunches of electrons produced in a photocathode rf gun with no magnetic compression. The electron beam bunch length and the charge distribution along the bunch were measured by passing the energy chirped the electron beam through a momentum selection slit while varying the phase of the rf linac. The bunch compression as a function of rf gun phase and electric field at the cathode were investigated. The shortest measured bunch is $370 \pm 100$ fs (at 95% of the charge) with $2.5 \times 10^8$ electrons (170 A peak current); the normalized rms emittance of this beam was measured to be $0.5\pi$ mm mrad and the energy spread is 0.15%. [S1063-651X(96)51110-4]