PARMELA

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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?

Present PARMELA Status

- **PARMELA is both proprietary and Government owned:**

  - Copyright asserted and licensed January 1999 through agreement between DOE and UC/LANL.

  - Licenses issued by LANL Technology Transfer Division.

  - Licensing fees collected:

    U.S. Gov't, Nonprofits, Academic Institutions – No fee.

    15% - TT Division, 35% - Individual Innovator(s), 50% - LAACG Support

- **Executable code is distributed through the LAACG:**

  - Web-based distribution through an FTP server.

  - Source code written in Fortran 95 / Lahey LF95 Compiler.

  - MS Windows operating environment only for now. Linux next.

    Windows NT (version 4 and higher) , 2000, XP

  - Code documentation and user manual exist.

  - User help available by contacting the LAACG members.

  - Configuration control also performed by the LAACG.

Who uses PARMELA?

- **As of FY 2003, 371 Users World-Wide, 206 U.S. Users**
- **Government-Funded Labs: 48%**

  SLAC, TJAF, ORNL, LANL, LBNL, LLNL, ANL, BNL, Fermilab, NRL, NASA, SANDIA
- **Academic Institutions: 28%**

  Stanford, MIT, Cornell, U. of Maryland, Duke, MSU, U. of Michigan, U. of Illinois, Illinois Inst. Of Tech., Rensselaer, Vanderbilt, U. of Nevada…
- **Commercial Companies: 20%**

  Boeing North American, SAIC, Advanced Energy Systems, Titan, Tech-X Corp., Siemens, Varian, Eaton, Axcelis Technologies, Teledyne Electronic Technologies, KLA-Tencor…
- **Private Individuals: 4%**

All major players in the high-power FEL business use it!

SLAC, JLAB, Boeing, etc.

What are the main applications of PARMELA?

- Design and Simulation of FELs
- Commercial Linear Accelerator Applications:

    Medical Linacs
    Food Sterilization
    Ion Implanters

- Photoinjectors
- Beamlines / Transport Systems
- High-Intensity Electron and Ion Linacs

Main Features of PARMELA

• Integrates macroparticle trajectories through the fields in 3-D using phase (time) as the independent variable.

• Can be used to simulate beam dynamics of beam transport and accelerator systems (Normal Conducting and Superconducting).

• Includes accelerating, focusing, space-charge, CSR and wake fields.

• Can read in 2-D and 3-D field distributions:

RF fields generated by Superfish or MAFIA

Static magnetic fields from Poisson

• Can be run in real-time or batch mode.

Execution time varies as a function of macroparticle number, time step, type of space-charge calculation, CSR, etc.

Main Features of PARMELA (cont.)

- **Large number of beam line, accelerator cavity, and other elements are modeled:**

    DRIFT, SOLENOID, QUAD, CATHODE, ESQUAD, BEND,
    BUNCHER, CHOPPER, STRIPPER, RF CAVITY, TANK,
    DTLCELL, TRWAVE, WIGGLER, SEXTUPOLE, COIL

- **Includes random and systematic alignment errors facilitating studies of performance for off-normal (error) conditions.**

- **Cathode modeling included. This allows simulation up through the wiggler.**

- **Several initial beam distributions can be generated:**

    - K-V Distribution

    - Uniform Spatial Distribution

    - Gaussian or Uniform With No Energy Spread including the "Quiet Start" method to eliminate shot noise (correlations).

    - Can read in a EGUN or ISIS distribution.

How does PARMELA calculate space-charge (SC)?

SCHEFF (2-D)

- **2-dimensional r-z PIC Method:**
  - **Transform to beam rest frame.**
  - **Divide beam volume into a grid of discrete r and z values.**
  - **For each charge ring at (r_i, z_j) use a Green's function method to approximate $E_{r,i}$ and $E_{z,j}$ due to every other ring at (r_k, z_l).**
  - **Each macroparticle receives an x, y, and z impulse in the rest frame.**
- **Effects of neighboring bunches can be included.**
- **γ-dependent auto-meshing and field interpolation.**
- **Effects of conducting-wall image charges can be included.**
- **Fast algorithm compared to some other methods.**
- **Accurate even with small number of macroparticles – Good smoothing due to 2-D.**
- **Agrees well with other SC algorithms such as 3-D point-to-point. Also used in our other codes where it has been benchmarked.**

How does PARMELA calculate space-charge (SC)?

SPCH3D (3-D)

- **Fast 3-D PIC routine written by Rob Ryne for IMPACT.**

  See Ji Qiang, et al., NIM A 457 (2001) 1-11

  - Uses a cloud-in-cell algorithm for charge deposition on the grid and for field interpolation.

  - Field solution is based on a convolution of the charge density and the Green's function of the potential.

  - The 3-D convolution is performed using a FFT-based algorithm to implement the open boundary conditions.

  See R.W. Hockney and J.W. Eastwood, "Computer Simulation Using Particles,"

- **Also has γ-dependent auto-meshing.**
- **Includes effects of image charges for a flat cathode.**
- **Larger number of macroparticles required to minimize numerical noise effects.**
- **Fast, but not as fast as SCHEFF.**

PARMELA calculates wakefields.

- PARMELA can do a single-bunch beam loading calculation to correct particle energies due to the effects of wakefields:
  - Based on a TBCI (MAFIA) calculation for a Gaussian longitudinal beam distribution.
  - The change in energy of a single particle is parameterized using fitted coefficients for a wakefield from a side-coupled cavity scaled to correct for frequency.

- PARMELA does *not* calculate beam breakup (BBU) effects.
  - This is done as a separate analysis after the accelerator structure is known.
  - Use MAFIA and CUMBBU* codes, or others.
  - Iterate design to minimize these effects.

**R.L. Gluckstern, R.K. Cooper, and P.J. Channell, Part. Accel. 16, 125 (1985)*

PARMELA has a 1-D CSR routine.

- Present implementation uses an algorithm developed at Boeing. Implemented by Lloyd Young.

  See B. Koltenbah, et al., NIM A 487 (2002) 249 – 267.

- This approach assumes the beam bunch is a line charge ignoring transverse effects.

- More work needs to be done for high-power, high-brightness applications. We need well-developed and experimentally-verified CSR models for this regime to more accurately predict beam emittances – This is not just an issue with PARMELA, but with other codes also.

CSR Code Comparison

	3D	δE	σE	ε-Growth
3D	TRAFIC4	-0.058	-0.002	1.4
	TREDI	-0.018	-0.001	1.84
2D	Program by R.LI	-0.056	-0.006	1.32
1D	Elegant	-0.045	-0.0043	1.55
	CSR_CALC (P. Emma)	-0.043	-0.004	1.52
	Program by M. Dohlus	-0.045	-0.011	1.62

From Talk by Luca Giannessi, ENEA, C.R. Frascati
ICFA Beam Dynamics Mini Workshop
Coherent Synchrotron Radiation and Its Impact on the Dynamics of High Brightness Electron Beams
January 14-18, 2002 at DESY-Zeuthen (Berlin, GERMANY)
http://www.desy.de/csr

PARMELA has been validated through operating facilities.

- NBS 5-MeV Race-Track Microtron was first machine designed (1982) and built (1986) using PARMELA.
- More recent examples:

  Fermilab A0 Photoinjector

  UCLA Neptune Facility

  LANL – AFEL, APEX, etc.

  LCLS design effort (up to 140 MeV)

  Industrial & Medical Linacs

  Many others….
- Almost every modern electron linac built has been designed with PARMELA.

PARMELA has been compared to measurements.

- **NBS 5-MeV Race-Track Microtron:**

	Measured	PARMELA
ε_{tn} (mm-mrad)	0.63±0.14	0.75
ΔE (keV)	5.0	10-15

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

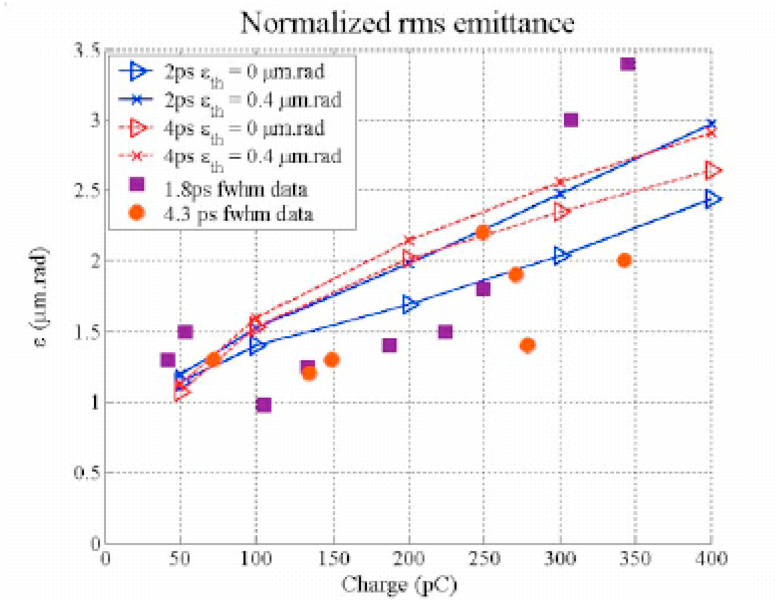


Figure 2. Projected emittance vs bunch charge as measured at GTF for Gaussian pulses, and PARMELA simulation results for the same parameters.

M. A. Wilson, et al., "Performance of the 5 MeV Injector for the NBS-Los Alamos Racetrack Microtron," Proceedings of the 1987 Particle Accelerator Conference.

C. Limborg, et al., "PARMELA vs Measurements for GTF and DUVFEL," Proceedings of EPAC 2002, Paris, France.

PARMELA has been compared to other codes.

C. Limborg, et al., "Code comparison For Simulations of Photo-Injectors," Proceeding of the 2003 Particle Accelerator Conference.

Table 1 – Comparison CPU time

Code	Platform	CPU	Num. particles	Mesh points N_r x N_z	Mesh size h_r x h_z	Integration step	CPU time (s)
HOMDYN	PC Win		75 slices			0.13°	45
BEAMPATH	PC Win	1 GHz	10^4	256 x 2048	50x50μm^2	0.1°, 1°	8000
PARMELA	"	1 GHz	2.5 10^4	25 x 75	"	"	9846
" spch3d	"	1 GHz	10.10^4	32 x 32 x 1024	Automatic	"	1.4.10^4
ASTRA	"	1.8 Ghz	1.5 10^4	20 x 60	Automatic	Adaptative	420
Tredi Stat.	16 nodes	1.8 GHz	5.0 10^4	20 x 30	Automatic	Adaptative	7.5 10^5
Tredi Lien.	PC Win	1.8 GHz	5.0 10^4	20 x 30	Automatic	Adaptative	7.4 10^4

Electron bunches, 1 nC, 10 ps

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

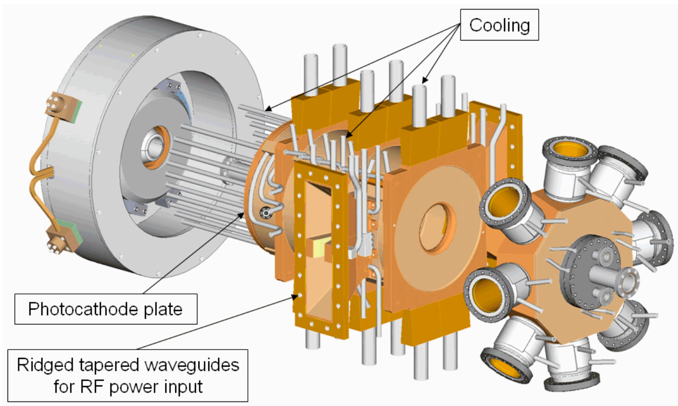
- **PARMELA is routinely used to benchmark other codes.**
- **Validation and benchmarking continues through the various user-community applications of the code.**

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

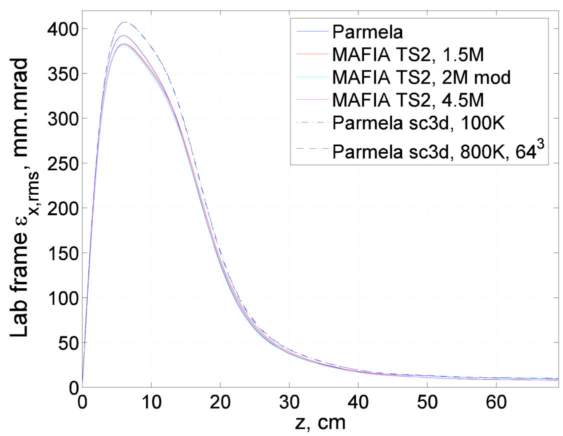
- **PARMELA accuracy in question for low-energies near the cathode for high-brightness regime.**
- **Did numerical comparison of PARMELA results with ARGUS PIC simulations.**
- **Found good agreement for bunch charge < 7 nC and pulse lengths < 50 psec.**
- **May need codes like ARGUS or MAFIA (pushing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

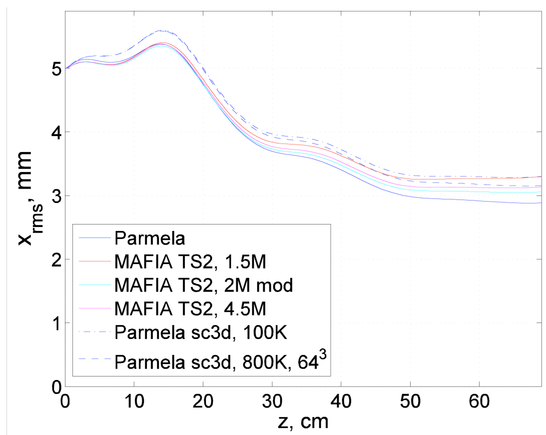
LANL Comparison of PARMELA and MAFIA 2D PIC

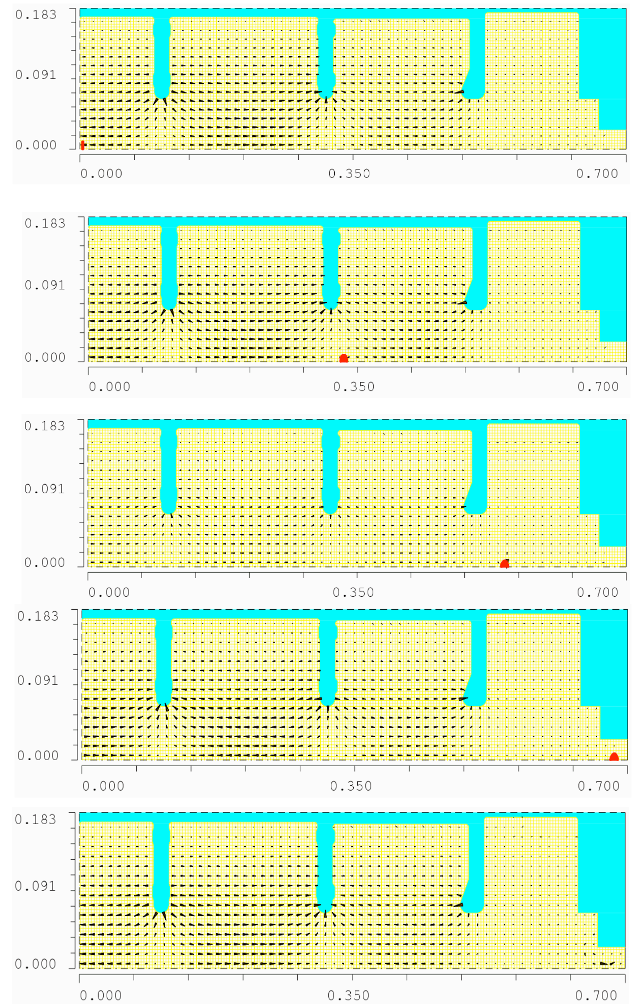


Navy MWFEL Photoinjector

2.5 MeV
3 nC / bunch





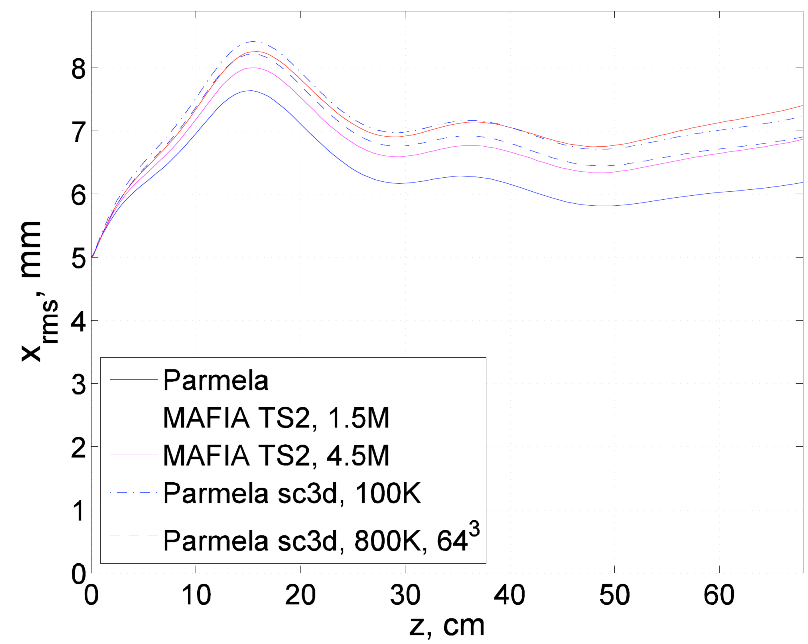


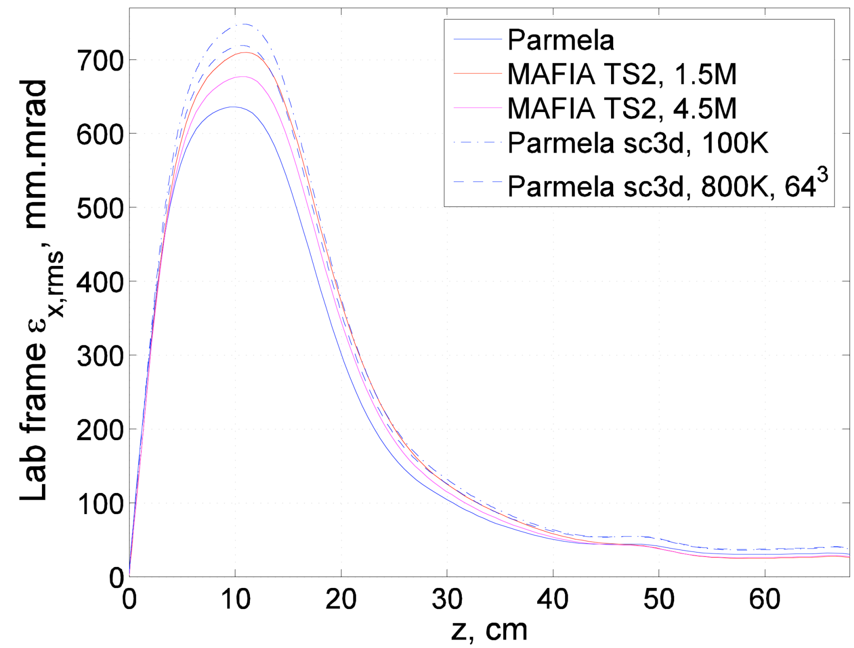
S. Kurrennoy, “Comparison of Parmela and MAFIA Simulations of Beam Dynamics in High Current Photoinjector,” Proceedings of the 2004 Free Electron Laser Conference, Trieste, Italy, August 29-September 3, 2004.

LANL Comparison of PARMELA and MAFIA 2D PIC

Navy MWFEL Photoinjector

2.5 MeV, 10 nC/bunch





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PARMELA and other codes need improved modeling of the cathode physics!

- Need to know the initial beam distribution better – emittance and brightness predictions.
- Gaussian distribution assumed – Not supported by measurements.
- Better photo-emission model incorporated into a PIC code – New parameterizations used in PARMELA and other codes?
- DOE is already funding this:
  - SLAC (K. Ko) PIC3P Code for the LCLS X-Ray FEL
  - Tech-X Corporation, VOORPAL Code
- We should take advantage of their efforts and progress.

Areas of Improvement / Collaborations

- Standardized input/output data formats – Make PARMELA SDDS compliant?
- Parallelization of PARMELA to speed up computations and to allow improved statistics, etc. – We now have some experience because of RIA code development efforts.
- Improved cathode model(s).
- Improved CSR modeling.
- We would be willing to collaborate in any of these areas!

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