HPSim – Advanced Online Modeling for Proton Linacs

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Outline

• Introduction & Motivation
• HPSim - Features, Structure and Performance
• Benefits and Applications
Introduction

• High-power linacs, e.g. LANSCE, are designed for low beam-loss operation using multiparticle codes

• However, during tune-up, linac operations typically rely on simple envelope and single-particle models, which can only provide limited information

• Multi-particle tools offer advantages for machine operations but are typically tedious to use and limited by available computer resources

• HPSim was developed to bring multi-particle simulation capability to the control room and aid in the setup, monitoring, optimization, etc. of an operating linac
LANSCE Facility Overview – Complex, Multi-beam Operations

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<td>Lujan</td>
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<td>WNR Tgt4</td>
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<td>1 µpulse every ~1.8 µs</td>
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<td>UCN</td>
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<td>pRad</td>
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<td>60 ns bursts every ~1 µs</td>
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<td>≤ 100</td>
<td>625</td>
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<td>≤ 250</td>
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120 Hz x 625 µs beam macropulses both shared and dedicated

• 750 keV H⁺ and H⁻ Cockcroft-Walton Injectors
• 100 MeV Drift Tube Linac (4 tanks)
• 800 MeV Coupled Cavity Linac (44 modules)
• 800 MeV Compressor Ring (PSR)

Isotope Production Facility
Proton Radiography
Ultra-Cold Neutrons
Area A (inactive)

Lujan Center
Target 1
Target 2
Target 4
Weapons Neutron Research Facility

Los Alamos National Laboratory
Operated by Los Alamos National Security, LLC for NNSA
HPSim Created to Fill a Need

• LANSCE injectors produce only partially bunched beams that result in longitudinal tails and beam spill along linac

• Physics-based tune-up employs envelope and single-particle tools, necessary but insufficient

• Empirical tuning required to achieve low beam-loss, stable, high-power operation
  – Other, similar facilities also follow the same approach (HB2010 WG-D summary)

• A fast, more accurate multi-particle beam dynamics simulation tool in the control room could improve this situation!
What is HPSim?

- **High-Performance Simulator** for proton linacs
  - PARMILA physics model (well benchmarked)
  - Multi-particle, nonlinear space charge, etc. (more realism)
  - GPU-based (accelerated, low-cost workstation platform)
  - Online/Offline modes (direct connection to linac control system)
HPSim – Physics Model

- PARMILA provides the basis for the physics in HPSim
  - Phase And Radial Motion in Ion Linear Accelerators: a design and simulation code from Los Alamos Accelerator Code Group
    - Has been used for designing/simulating LANSCE, SNS and other linacs
    - Well tested and benchmarked
  - Multi-particle, z-code (transfer map)
    - Faster than t-code, e.g. PARMELA, more accurate than envelope
    - RF gap transformation (drift - kick at the midplane - drift) with transit-time factors, TTF(k, r)
  - Non-linear 2D (r-z) particle-in-cell (PIC) space-charge algorithm SCHEFF

SCHEFF 2D ring-of-charge r-z mesh
Departures from PARMILA

• Simulation only – requires layout generated by other codes e.g. PARMILA & Superfish
• Tracks particles absolute phase, not relative to ref. part.
  – Enables easier tracking when modules are enabled/disabled
• TTF function of $\beta$ for tracking off-energy particles
• Space-charge focuses on particles in rf bucket
  – Exclude off-energy particles
• Space-charge algorithm includes scaling feature wrt. beam size and energy
  – Reuse previously calculated field table to increase code performance while maintaining accuracy
Features Presently Supported in HPSim

- **Transport Devices**
  - Buncher: single-gap
  - Circular aperture
  - Dipole magnet
  - Drift
  - Quadrupole magnet
  - Steerer (impulse)
  - Rectangular aperture
  - Rotation
  - Space-charge compensation

- **Linac Structures**
  - Drift Tube (DTL)
  - Coupled Cavity (CCL)

- **Input Distributions**
  - DC waterbag
  - 6D waterbag
  - Text file of 6D coordinates

- **Space Charge**
  - SCHEFF 2D (R-Z)

- **EPICS channel**
Space-Charge Compensation Reflects Beam Neutralization in LANSCE H- 750 keV LEBT

- Input beam emittance measured at TBEM01
- Output beam emittance measured at TDEM01 and compared to simulation

HPSim without SC Compensation
Mismatch Factor = 0.73

Measurement
Y-YP
X-XP

HPSim with SC Compensation
Mismatch Factor = 0.16

L = 10.14 m, 15 Quadrupoles, 2 Dipoles, Bunchers off, Chopper off

L = 10.14 m, 15 Quadrupoles, 2 Dipoles, Bunchers off, Chopper off
Powered by GPU Technology

- Graphics Processing Unit (GPU) enables high-performance and 24/7 availability at low-cost
- Once, just for gamers, now powers some of the world’s fastest supercomputers, e.g. ORNL Titan (18,688 GPUs)
- NVIDIA K20c GPU
  - 2496 CUDA Cores
  - 5 GB RAM
  - Peak double/single precision performance: 1.17/3.52 Tflops
  - Street price: ~$3K US
  - (faster GPU’s now available)
  - Requires WS w/PCIe bus and HD PS
Designed for Speed and Ease of Use

- Speed comes from number-crunching simulation kernels written in NVIDIA CUDA C and C++ that run on GPU
- Python/C API’s hides complex code from user
- Ease-of-use comes through high-level Python interface to HPSim
- Python also provides rich numerical and visualization libraries

Code Structure Splits Workload Between CPU and GPU

- EPICS data acquired and stored in serverless SQLite database (online)
- Model is updated with corresponding physics values and written to ‘pinned’ memory for GPU
- Beam created/stored on GPU
- Simulation from point A to point B performed on GPU
- Graphic outputs (online mode, GPU) or text data (offline mode, CPU) for post-processing
Machine Model Resides in Database

- Serverless, flat-file like for minimal overhead and data consistency
- Description of linac layout and physics design
  - Rf cavity dimensions, design field strengths, etc.
- Conversion rules required to transform control parameter values to calibrated physics model quantities
  - E.g. DTL module amplitude set point to cavity field, $E_0$ (MV/m)
- Triggers that force recalculation of model quantities when control parameters are updated
  - E.g. RF Off command updates cavity fields to zero
Outstanding Code Performance!

- Speedups (NVIDIA GTX 580 vs. Intel Xeon E5520)
  - GTX580: CUDA cores: 580, 1.5 GB
  - Beam transport without space charge: up to 160
  - Space charge routine only: up to 45

- LANSCE simulation on NVIDIA K20c
  - H- beam from 0.75 to 800 MeV
  - 64K macroparticles
  - Size of problem: ~800 m, over 5100 RF gaps, 400 quads & 6000 space-charge kicks
  - Total time: 5.5 sec!
Accurate Predictions Require Model Calibration

- Transformation of control set points to physics quantities
- Calibration functions/transformations stored in database
  - Magnets: mapping measurements, e.g. G vs. I
  - Bunchers & Linac: beam-based measurements, e.g. cavity phase offset and amplitude scale factor for each RF module
Numerous Benefits and Applications

• Faster and more realistic linac beam simulations in the control room opens up new possibilities
  – Improved Tune-up and Monitoring
  – Virtual Beam Diagnostic
  – Optimization
  – Virtual Accelerator
  – …
HPSim for Machine Tuning and Monitoring

- HPSim can function as a virtual beam diagnostic
  - Providing beam information where diagnostics do not exist or are incompatible with operation
- New information for tuning
  - Direct beam information, not just indirect spill measurements
- Track the impact of parameter changes on beam performance

Initial condition and predicted spill

CCL input beam  CCL losses

Post-tweak beam and predicted spill

CCL input beam  CCL losses

Adjustment to DTL Module 3 Cavity Field Phase

Continuous Online Monitoring – A New Way to View Linac Operations
HPSim for Optimizing Machine Set Points

- HPSim + optimization routines can improve operating set points based upon user defined objectives
- Benefits:
  - Avoids completely empirical approach in high-dimensional parameter space
  - Optimize on beam quantities, e.g. emittance, phase spread, etc., not just losses
HPSim + Multi-Objective Particle Swarm Optimizer (MOPSO) - Fast and Effective

- Globally optimized compromise of objectives in multi-dimensional space
- Transverse beam match: LEBT to DTL
  - 2 Objectives: Max. trans., min. mismatch
  - Parameter: 4 quad gradients
  - Time: few secs
- DTL Longitudinal Tune
  - 3 Objectives: Min. long. emit., min. lost beam power, min. output beam phase width
  - Parameters: 11 RF (phs. & amp.)
  - Time: 16 min.
HPSim as a Virtual Accelerator

- Virtual Accelerator provides user with EPICS-based control of realistic physics model of the linac

- Benefits:
  - Test bed for new ideas/algorithms
  - Less risky and costly than experiments on real accelerator
  - Available 24/7

- Example:
  - Model-Independent Dynamic Feedback Technique for Accelerator Tuning

Adaptive tuning of LANSCE LEBT devices maintains DTL output current under time-varying input beam and buncher phases while performance deteriorates under static set points

A. Scheinker et al. PRSTAB 16, 102803, 2013
Status and Future Plans

• Testing and development to continue
• Further integration into LANSCE control room during startup this year
• Finally, release to open source community planned in the future
Summary

• HPSim is a fast, accurate multi-particle beam dynamics tools for use on operating ion linacs
• It’s architecture along with GPU technology make it an effective and inexpensive way to bring this type of beam dynamics simulation tool to a control room setting
• The Python interface gives the user an easy and flexible way to run the code and enables creativity and exploration of new ideas
• For an operating linac, it can serve as a virtual beam diagnostic, aid in optimization of control settings or as a virtual accelerator and test bed
Thank you!

I would like to acknowledge my colleague, Dr. Xiaoying Pang, whose work was instrumental in the development of this code!