HPSim – Advanced Online Modeling for Proton Linacs

by Lawrence Rybarcyk

Accelerators and Electrodynamics Group,
Accelerator Operations and Technology Division

HB2016 Workshop
Malmö, Sweden
July 3-8, 2016

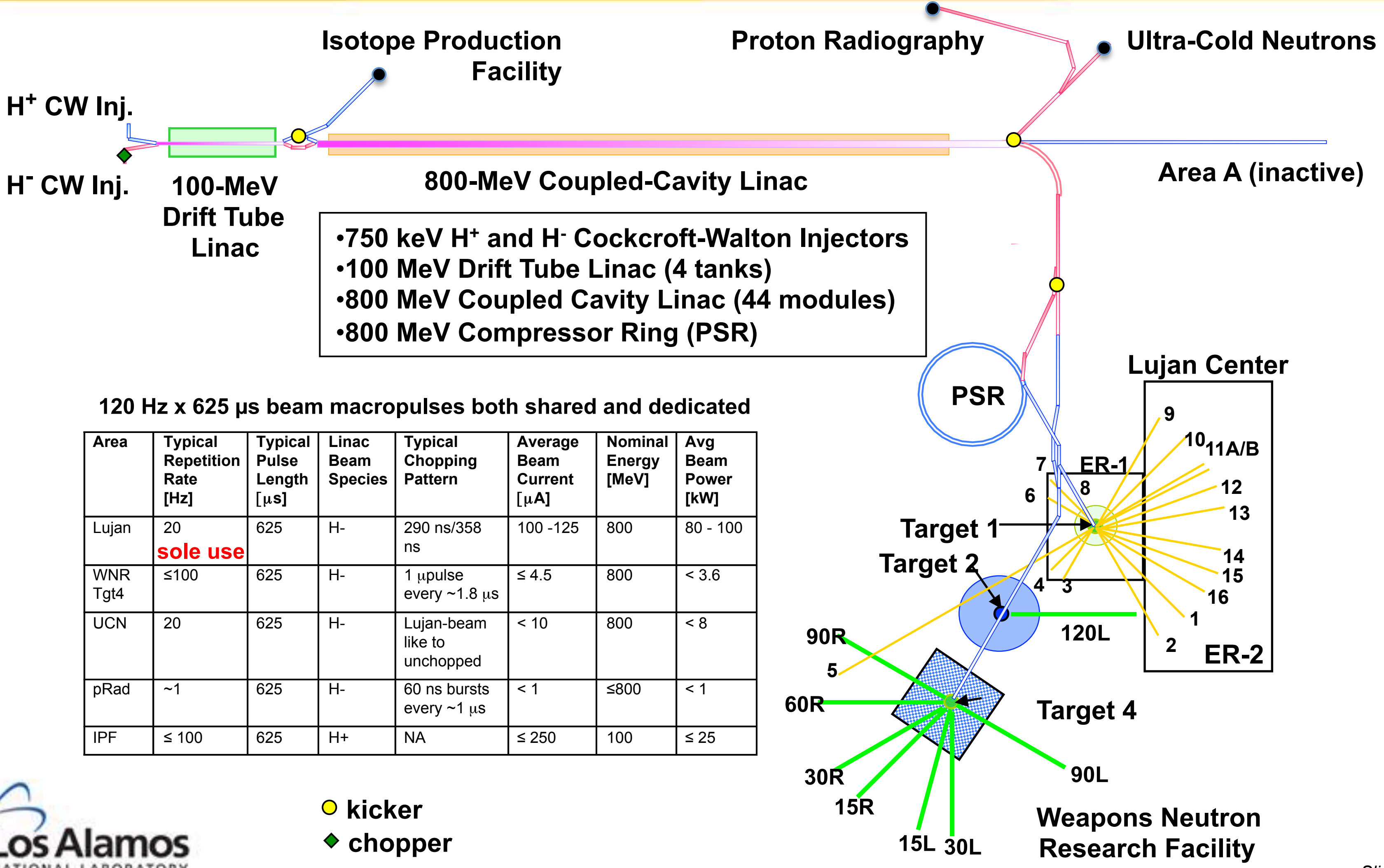
Outline

- 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

LANCSE Facility Overview – Complex, Multi-beam Operations



- •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)

120 Hz x 625 µs beam macropulses both shared and dedicated

Area	Typical Repetition Rate [Hz]	Typical Pulse Length [µs]	Linac Beam Species	Typical Chopping Pattern	Average Beam Current [µA]	Nominal Energy [MeV]	Avg Beam Power [kW]
Lujan	20 sole use	625	H-	290 ns/358 ns	100 -125	800	80 - 100
WNR Tgt4	≤100	625	H-	1 µpulse every ~1.8 µs	≤ 4.5	800	< 3.6
UCN	20	625	H-	Lujan-beam like to unchopped	< 10	800	< 8
pRad	~1	625	H-	60 ns bursts every ~1 µs	< 1	≤800	< 1
IPF	≤ 100	625	H+	NA	≤ 250	100	≤ 25

HPSim Created to Fill a Need

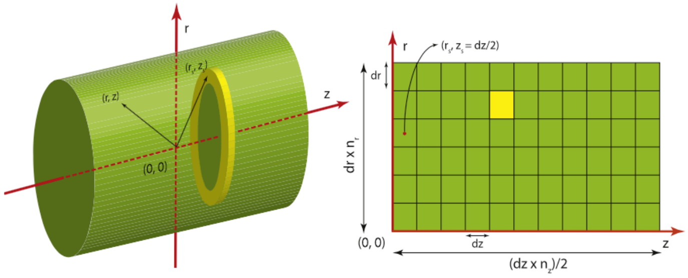
- LANSCE injectors produce only partially bunched beams that result in longitudinal tails and beam spill along linac
- Physics-based tune-up employs envelope and single-particle tools, necessary but insufficient
- Empirical tuning required to achieve low beam-loss, stable, high-power operation
  - Other, 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

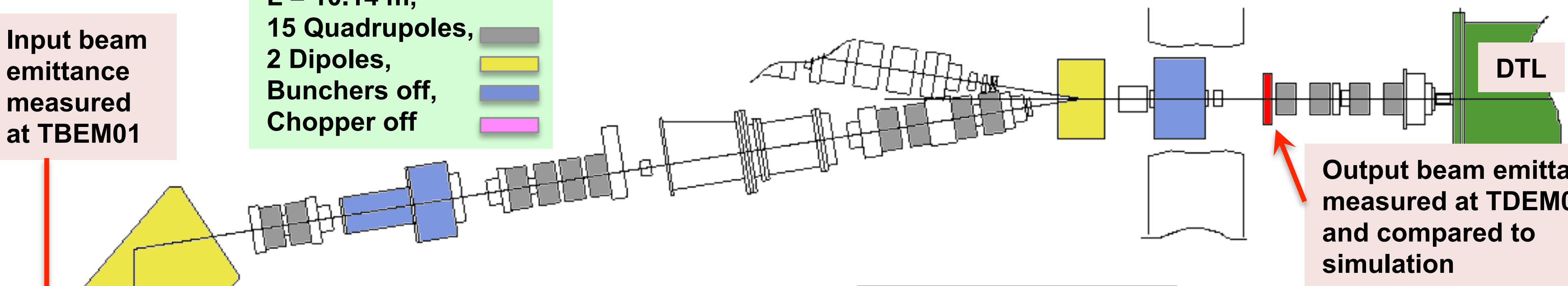
Departures from PARMILA

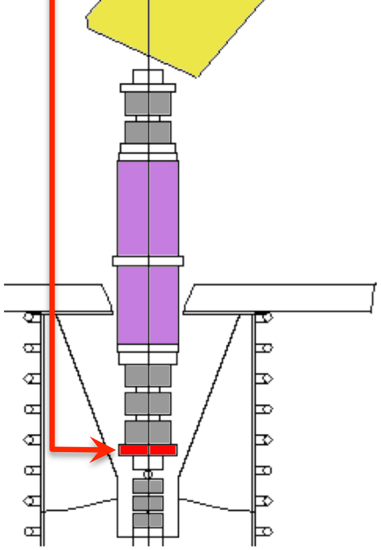
- Simulation only – requires layout generated by other codes e.g. PARMILA & Superfish
- Tracks particles absolute phase, not relative to ref. part.
  - Enables easier tracking when modules are enabled/disabled
- TTF function of β for tracking off-energy particles
- Space-charge focuses on particles in 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



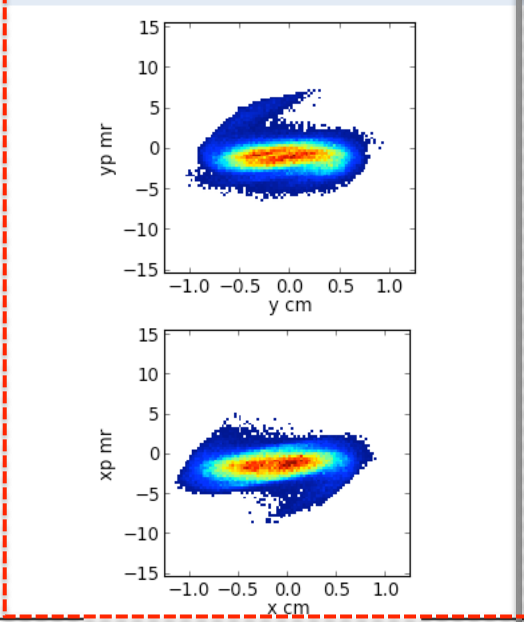


Input beam emittance measured at TBEM01

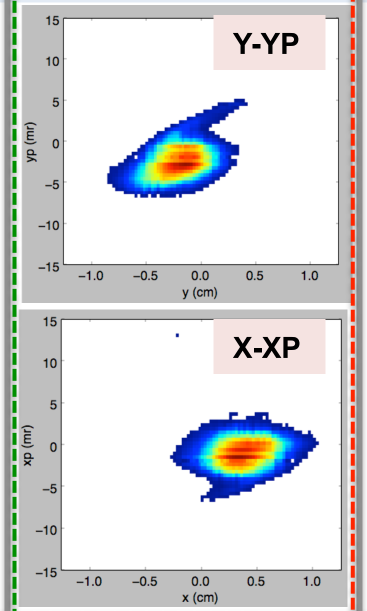
L = 10.14 m,
15 Quadrupoles, ▨
2 Dipoles, 🟨
Bunchers off, 🟦
Chopper off 🟪

Output beam emittance measured at TDEM01 and compared to simulation

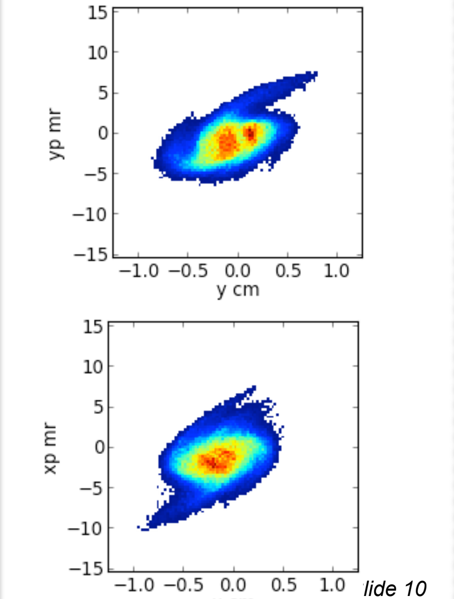
HPSim without SC Compensation
Mismatch Factor = 0.73



Measurement



HPSim with SC Compensation
Mismatch Factor = 0.16

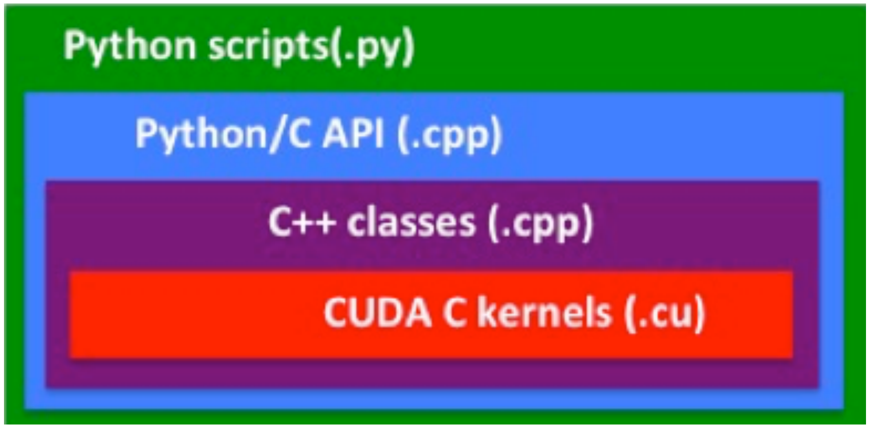


Powered by GPU Technology

- 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

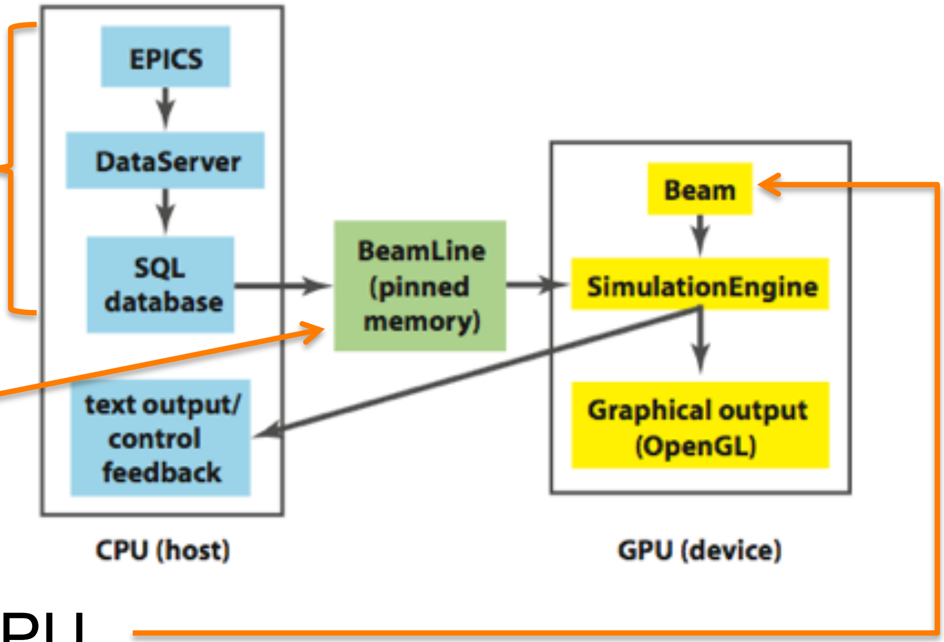


- Ease-of-use comes through high-level Python interface to HPSim
- Python also provides rich numerical and visualization libraries

X. Pang et al., Comp. Phys. Comm. 185, 744, 2014.

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



EPICS

DataServer

SQL database

text output/ control feedback

BeamLine (pinned memory)

Beam

SimulationEngine

Graphical output (OpenGL)

CPU (host)

GPU (device)

- 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

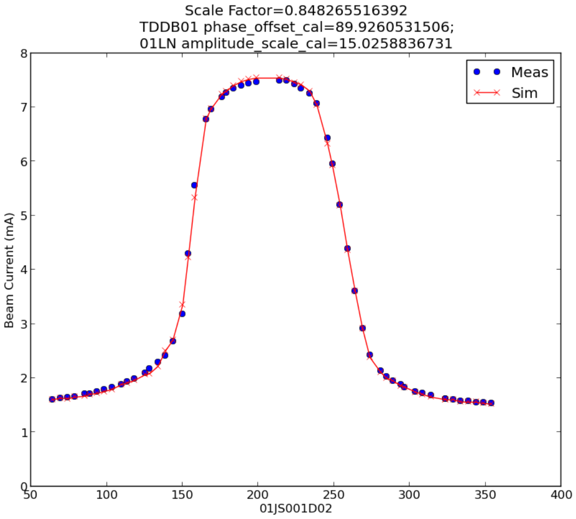
- Serverless, flat-file like for minimal overhead and data consistency
- Description of linac layout and physics design
  - Rf cavity dimensions, design field strengths, etc.
- Conversion rules required to transform control parameter values to calibrated physics model quantities
  - E.g. DTL module amplitude 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!

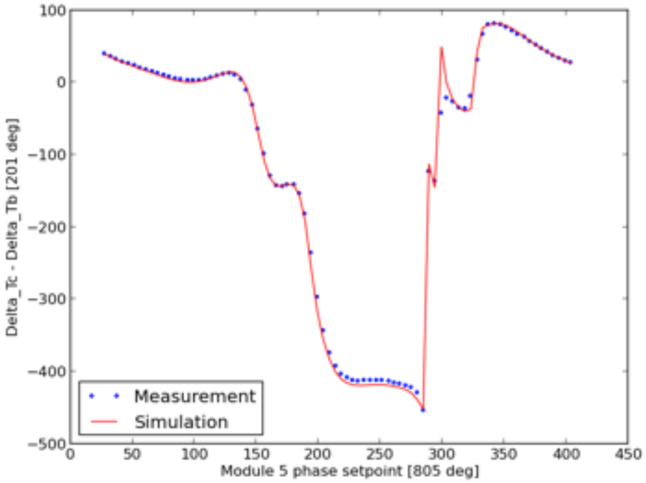
- Speedups (NVIDIA GTX 580 vs. Intel Xeon E5520)
  - GTX580: CUDA cores: 580, 1.5 GB
  - Beam transport without space charge: **up to 160**
  - Space charge routine only: **up to 45**
- LANSCE simulation on NVIDIA K20c
  - H- beam from 0.75 to 800 MeV
  - 64K macroparticles
  - Size of problem: ~800 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



LANSCE DTL absorber-collector style phase scan



LANSCE CCL beam-phase style phase scan

Numerous Benefits and Applications

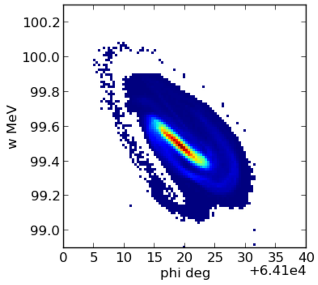
- Faster and more realistic linac beam simulations in the control room opens up new possibilities
  - Improved Tune-up and Monitoring
  - Virtual Beam Diagnostic
  - Optimization
  - Virtual Accelerator
  - …

HPSim for Machine Tuning and Monitoring

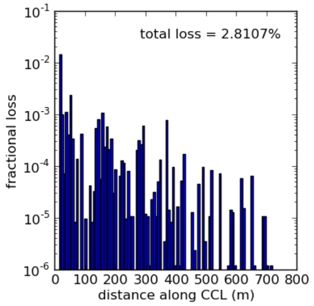
- HPSim can function as a virtual beam diagnostic
  - Providing beam information where diagnostics do not exist or are incompatible with operation
- New information for tuning
  - Direct beam information, not just indirect spill measurements
- Track the impact of parameter changes on beam performance

Initial condition and predicted spill

CCL input beam



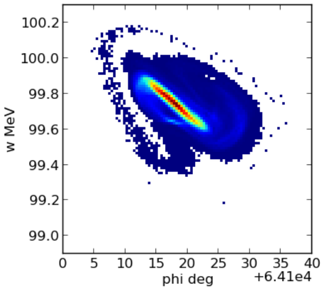
CCL losses



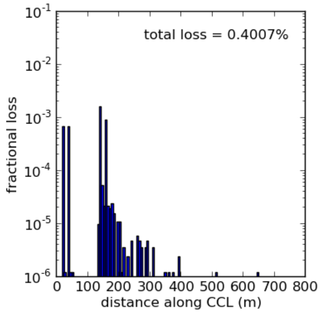
Adjustment to DTL Module 3 Cavity Field Phase

Post-tweak beam and predicted spill

CCL input beam

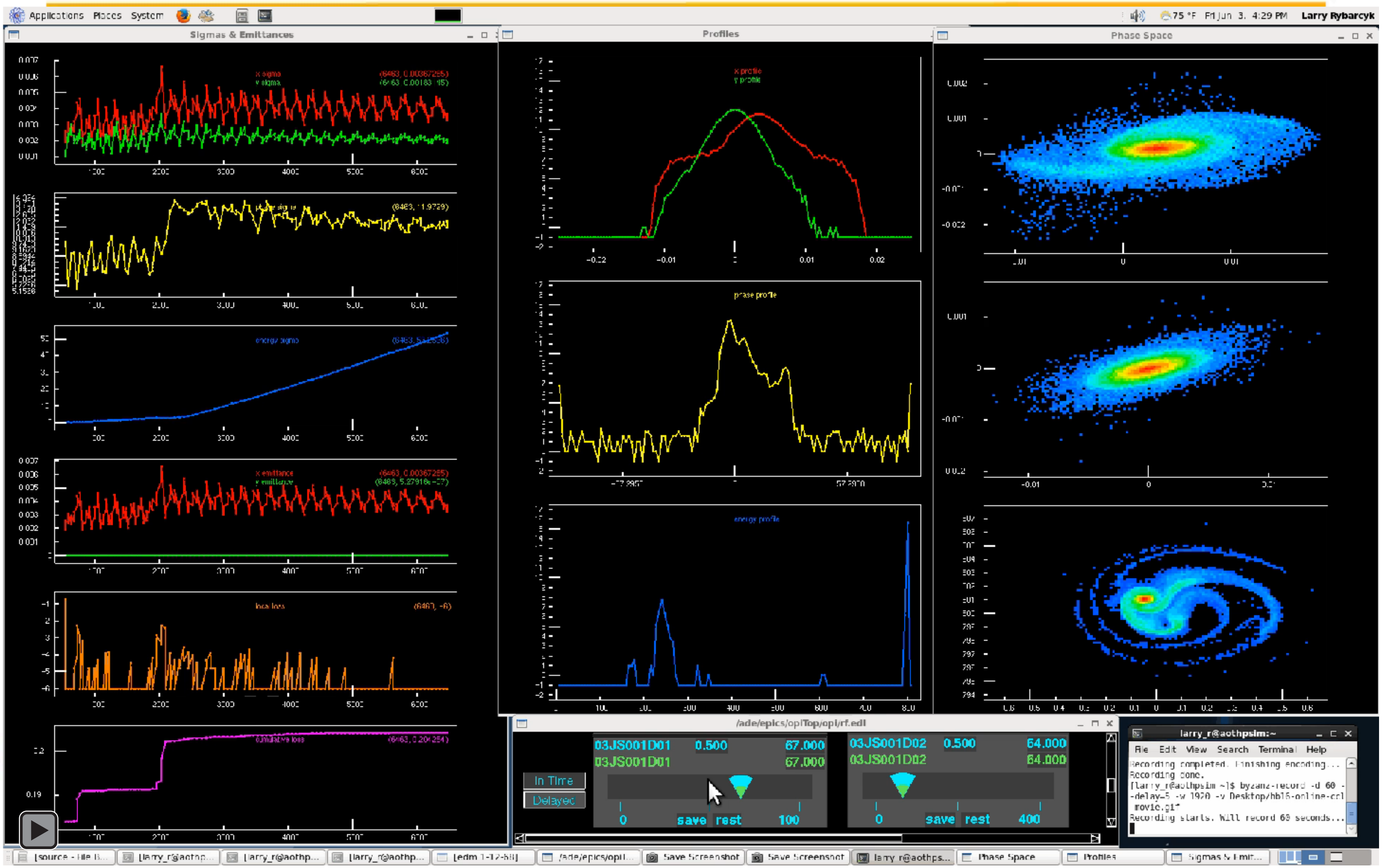


CCL losses



L. Rybarcyk, et al, IPAC2015, p.1234, 2015

Continuous Online Monitoring –
A New Way to View Linac Operations



03JS001D01 0.500 67.000
03JS001D01 67.000
0 save rest 100

03JS001D02 0.500 64.000
03JS001D02 64.000
0 save rest 400

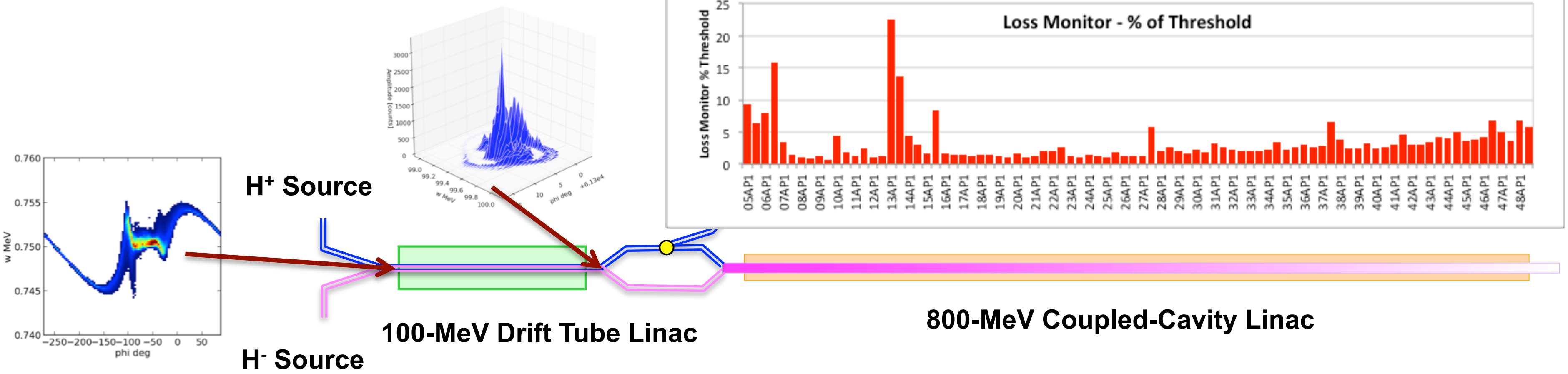
larry_r@aothpsim:~

File Edit View Search Terminal Help

```
Recording completed. Finishing encoding...
Recording done.
[larry_r@aothpsim ~]$ byzanz-record -d 60 -
-delay=5 -w 1920 -v Desktop/hb15-online-ccl
 movie.gif
Recording starts. Will record 60 seconds...
```

HPSim for Optimizing Machine Set Points

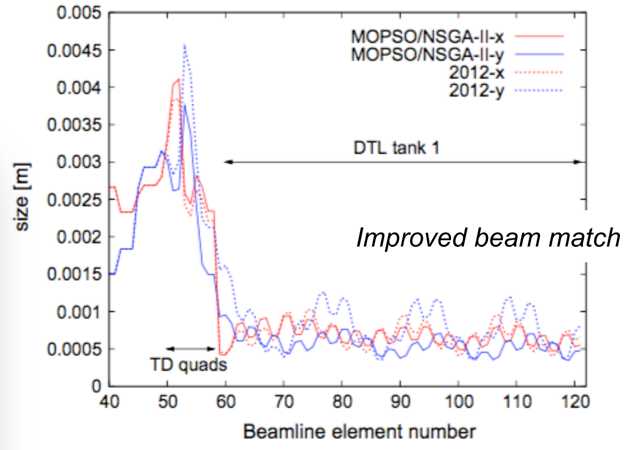
- HPSim + optimization routines can improve operating set points based upon user defined objectives
- Benefits:
  - Avoids completely empirical approach in high-dimensional parameter space
  - Optimize on beam quantities, e.g. emittance, phase spread, etc., not just losses



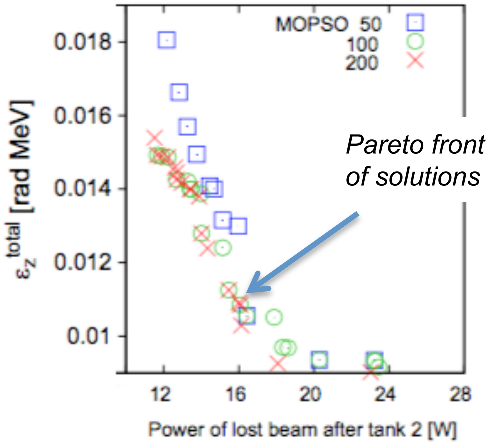
LANSCE LINAC

HPSim + Multi-Objective Particle Swarm Optimizer (MOPSO) - Fast and Effective

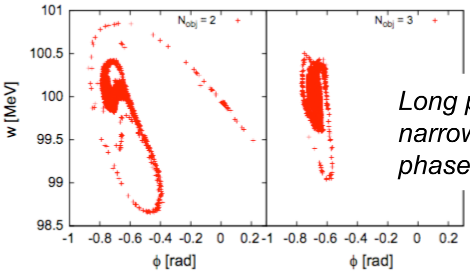
- **Globally optimized compromise of objectives in multi-dimensional space**
- Transverse beam match: LEBT to DTL
  - 2 Objectives: Max. trans., min. mismatch
  - Parameter: 4 quad gradients
  - Time: few secs
- DTL Longitudinal Tune
  - 3 Objectives: Min. long. emit., min. lost beam power, min. output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



Improved beam match



Pareto front of solutions

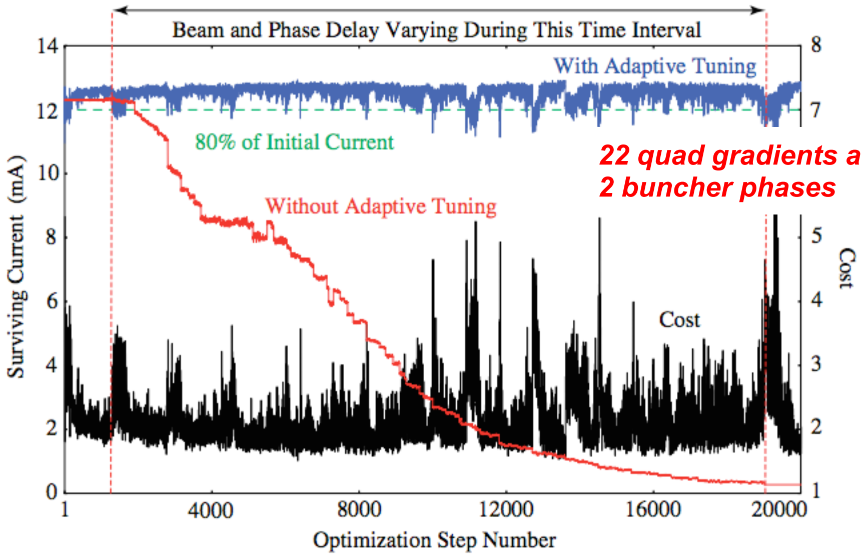


Long phase space narrows after including phase-width objective

X. Pang, L. Rybarcyk, NIM-A, 741, 124, 2014

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



22 quad gradients and 2 buncher phases

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!