# Advances in Proton Linac Online Modeling

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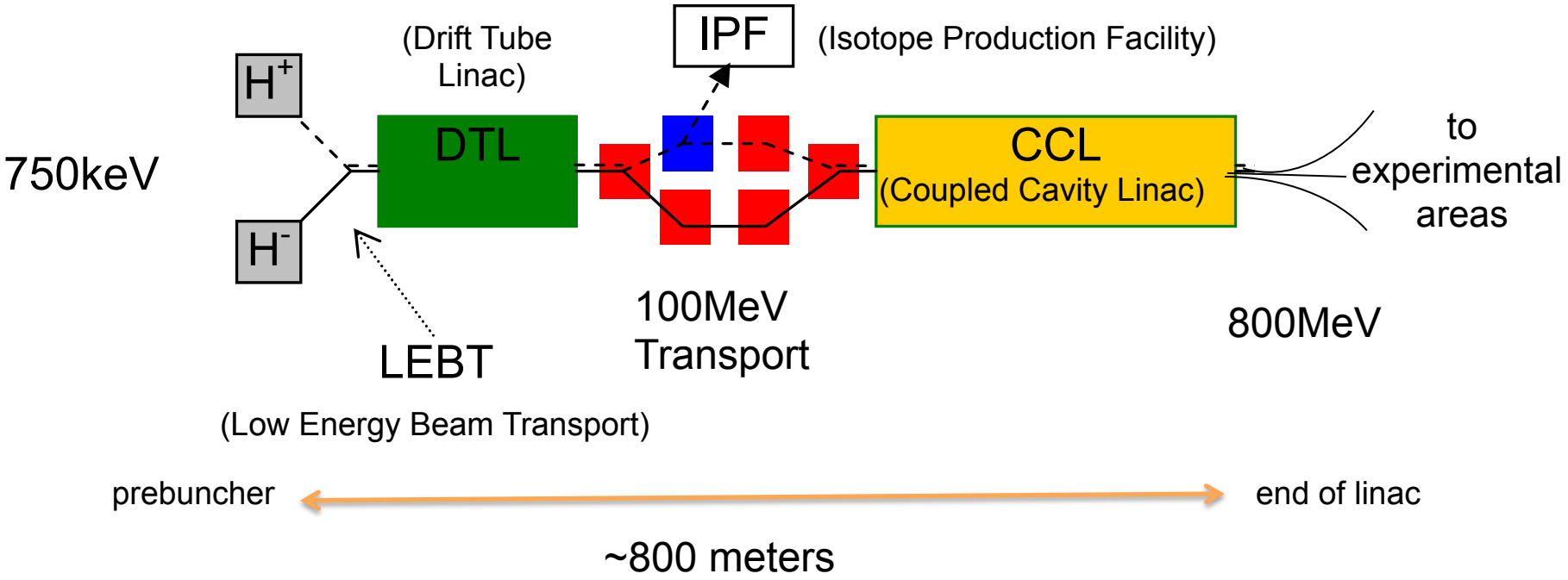
# Outline

- Existing online modeling tools
- Motivation
- High Performance Simulator (HPSim)
  - Performance & benchmarks
  - Applications

# A typical RF linac consists of injectors, transports and RF accelerating structures

Los Alamos Neutron Science Center (LANSCE) Linac
collection of ~5100 RF gaps, 400 quads, drifts, dipoles …

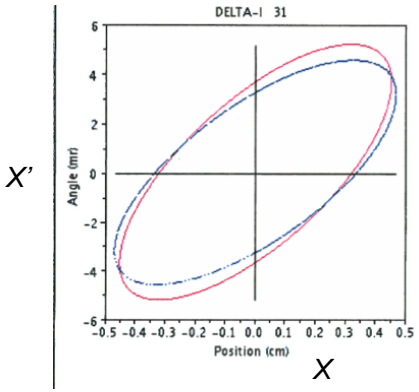


# Existing Online Modeling Tools

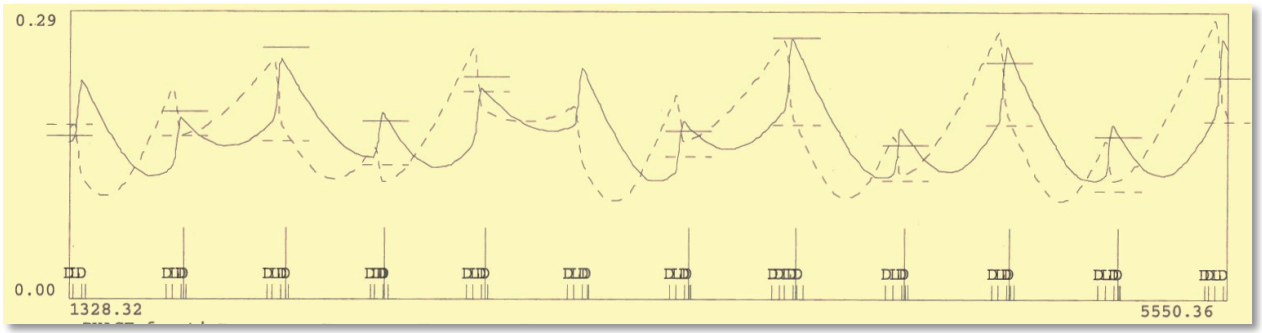
- TRACE2D/3D (LANL)
  - well established online modeling tools for proton linac
  - envelope model, linear space charge
- XAL online model (SNS)
  - more recent development, widely adopted
  - envelope + single particle model, linear space charge
  - linac + ring
  - tools: PASTA, SLACS, orbit correction, etc.
- ESS linac simulator (ESS)
  - latest development
  - envelope model, nonlinear space charge force assuming Gaussian distribution
  - multi-particle, offline

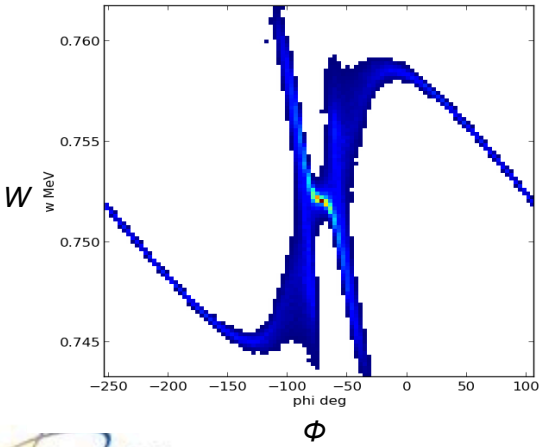
# Is the envelope model adequate for online modeling?

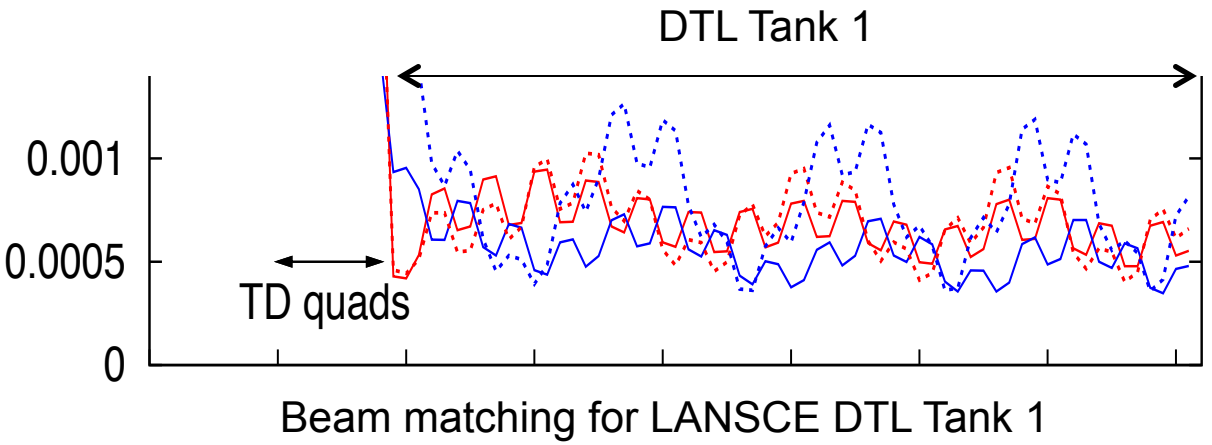
- Match & steer a nicely formed beam → adequate




Transverse Profiles in LANSCE CCL



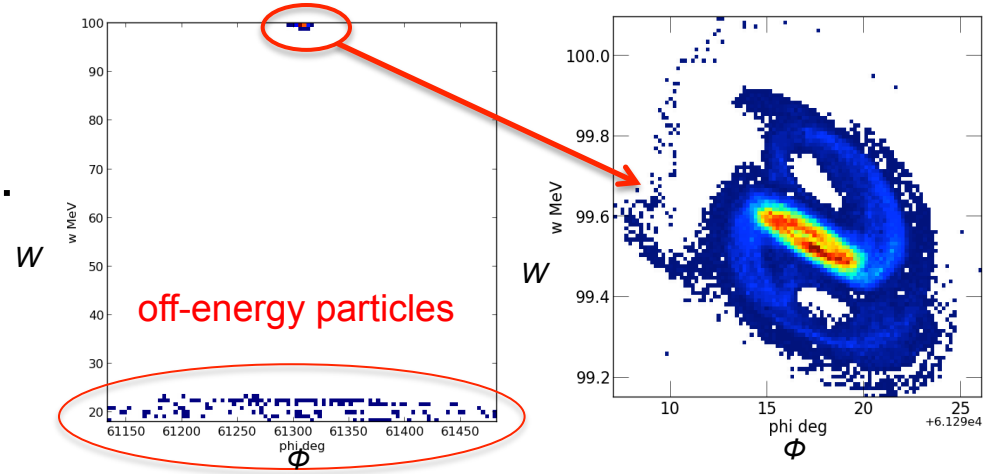



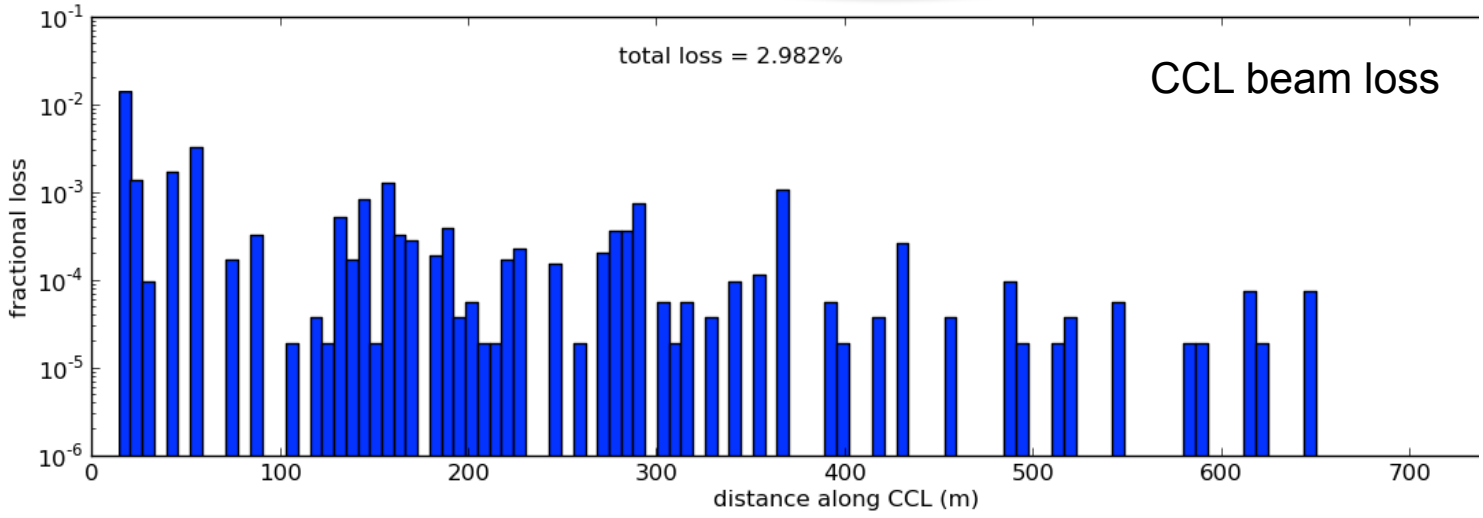

Beam matching for LANSCE DTL Tank 1

# Is the envelope model adequate for online modeling?

- Beam loss?
- Beam tails & halos?
- Off-energy particles? …

Longitudinal phase space at the end of LANSCE DTL




CCL beam loss

# We need a better online modeling tool for high power operation

## Low-power tune-up

- envelope model
- direct beam measurements

## Empirical tweaking

- subjective
- inefficient
- not optimal

## High-power operation

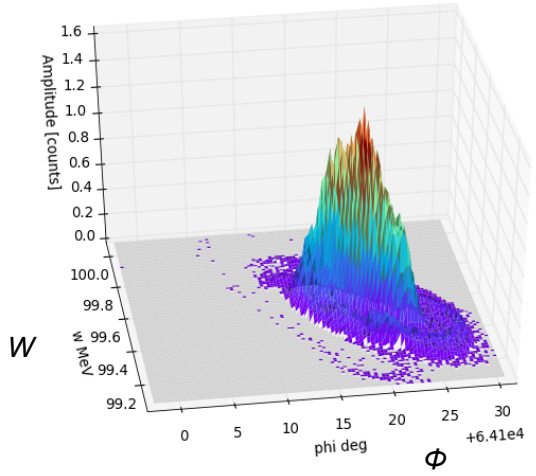
- lack of non-interceptive diagnostics
- lack of online beam modeling tool for high power beam
  - beam loss ?
  - nonlinear space charge ?

→ Multi-particle : slow

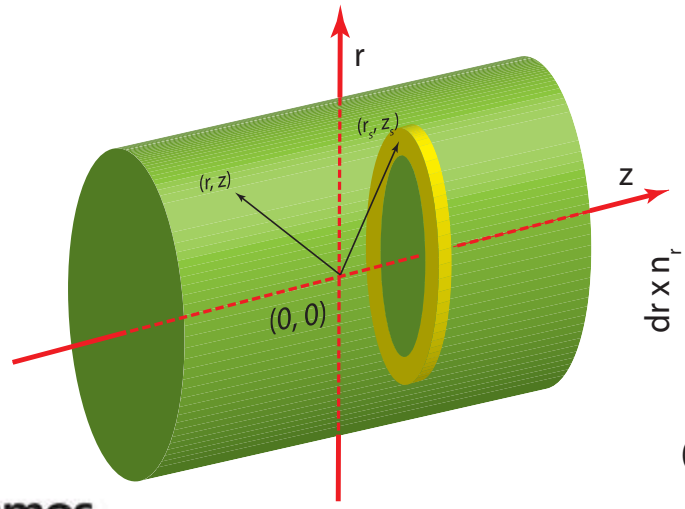
# High Performance Simulator (HPSim)

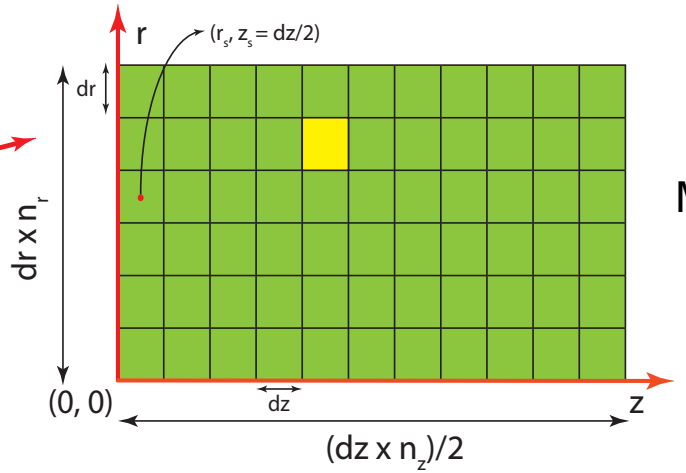
# HPSim: strike a balance between speed and accuracy

- Accurate enough
  - multi-particle →simulate real beam distribution
  - nonlinear space charge: SCHEFF 2D (PIC)
- Fast enough
  - sub-seconds up to several seconds depending on the size & scale of the simulation




100 MeV beam at the end of the LANSCE DTL




SCHEFF 2D Meshing and field calculation

# HPSim: fast multi-particle online modeling

- Physics model → PARMILA
  - Pros
    - well-established, proven to work for decades
    - multi-particle, location-based (z-code), transfer maps
    - PIC space charge: SCHEFF 2D, PICNIC 3D
    - DTL, CCL, CCDTL, SC
  - Cons
    - algorithms are made for designing machines from scratch →
      - off-design scenarios: absolute phase instead of relative phase, scaled TF, space charge for beam in bucket, etc.
    - difficult to input real world machine parameter →
      - database (SQLite) : static geometry of the machine, engineering to physics conversion, calibrations
    - slow (minutes or longer) → GPU

# Graphics processing unit (GPU): fast and cost effective

- Video game → scientific computing (2007 NVIDIA CUDA)
- "Democratized" supercomputing platform : most accessible and popular
- Cost effective!
  - $500 vs. a few thousand dollars
  - cheap to make a standalone system that is available 24/7

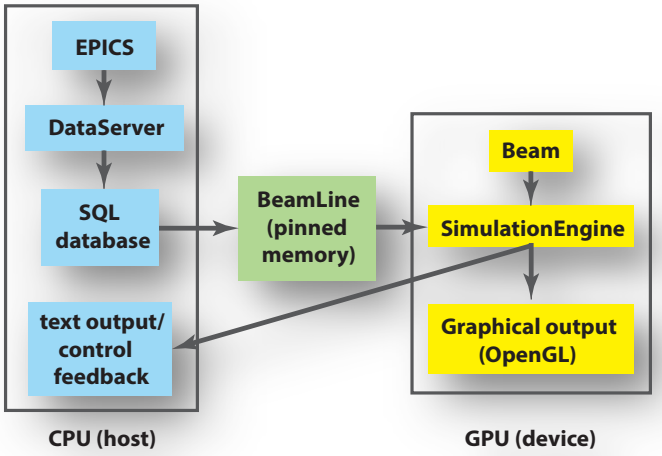
- Outstanding parallel computing performance
  - Compare to CPU: Instruction throughput (x3-20) & memory bandwidth (x5)
  - Powers some of the world's most powerful supercomputers
    - Titan (Oak Ridge National Lab, 2012)
    - Summit (Oak Ridge National Lab, future)
    - Sierra (Lawrence Livermore National Lab, future)

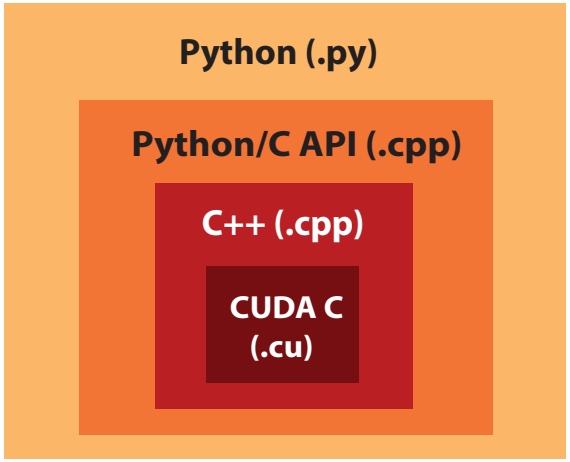
# GPU gives dramatic performance boost!

- Speedups (NVIDIA GTX 580 vs. Intel Xeon E5520 2.27GHz)
  - without space charge: up to 160
  - space charge: up to 45

  *X. Pang, L. Rybarcyk, Computer Physics Communications, 185, 744, 2014*
- Front-to-end run time (NVIDIA Tesla K20c)
  - 64K particles
  - 800-meter-long LANSCE linac (750KeV to 800 MeV)
    ≈ 5100 RF gaps + 400 quads + 6000 space charge
  - 5.5 seconds!
- To further improve
  - newer features, lastest GPUs, multiple GPUs

# User-friendly by design



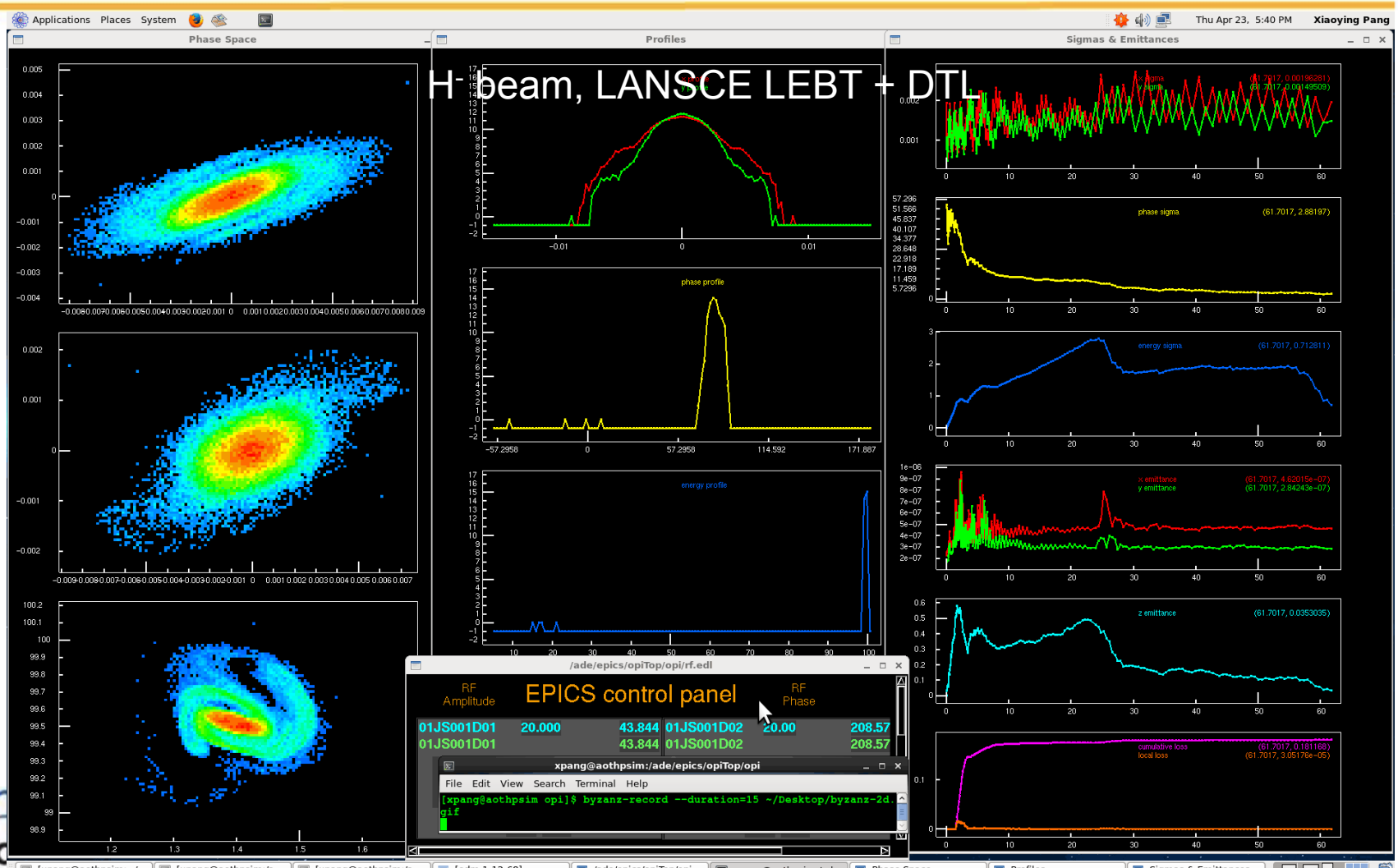




HPSim ⟷ Users

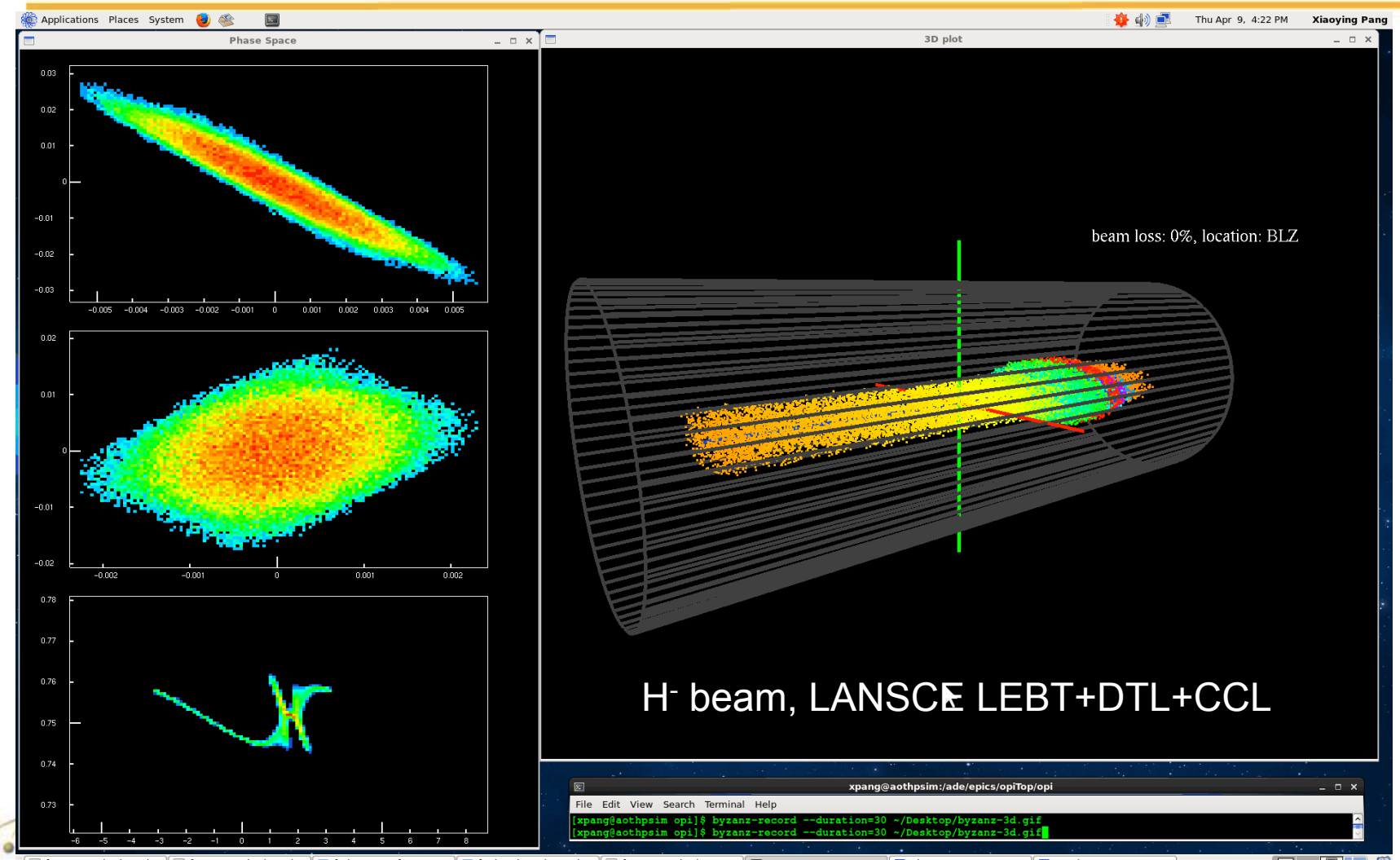
Python

- Shallow learning curve
- No compilation
- Pseudocode like syntax
- Rich numerical & visualization libraries

# 2D GUI for tuning and continuous monitoring



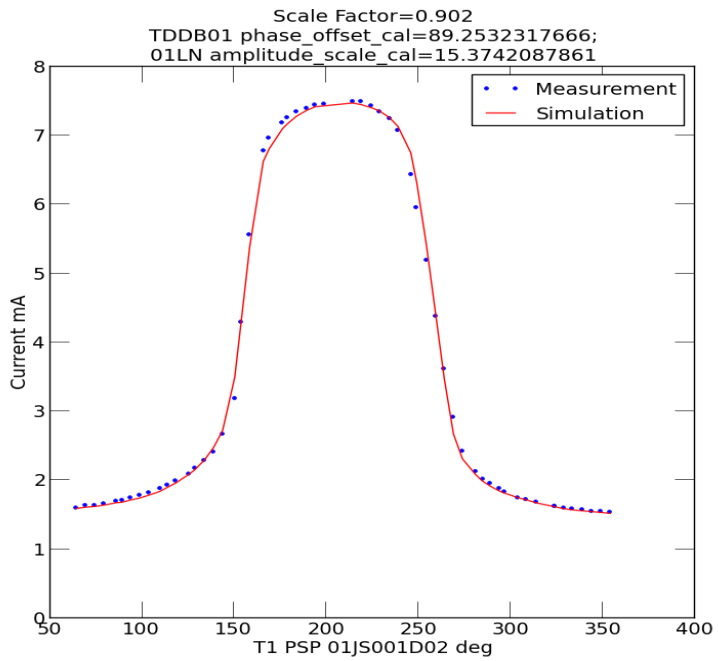
# 2D/3D GUI follows a bunch through the linac



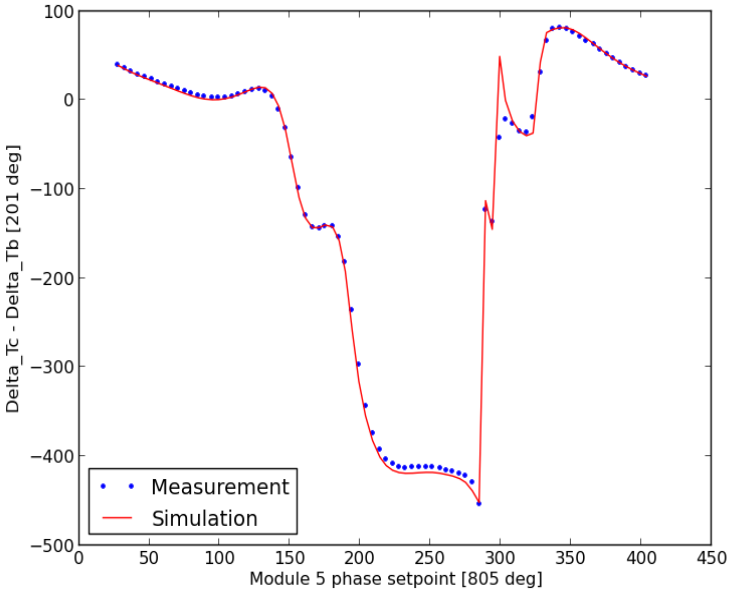
# Longitudinal beam dynamics benchmark - phase scans

- Beam based calibration
- Phase scans for DTL and CCL

DTL tank1 – absorber / collector



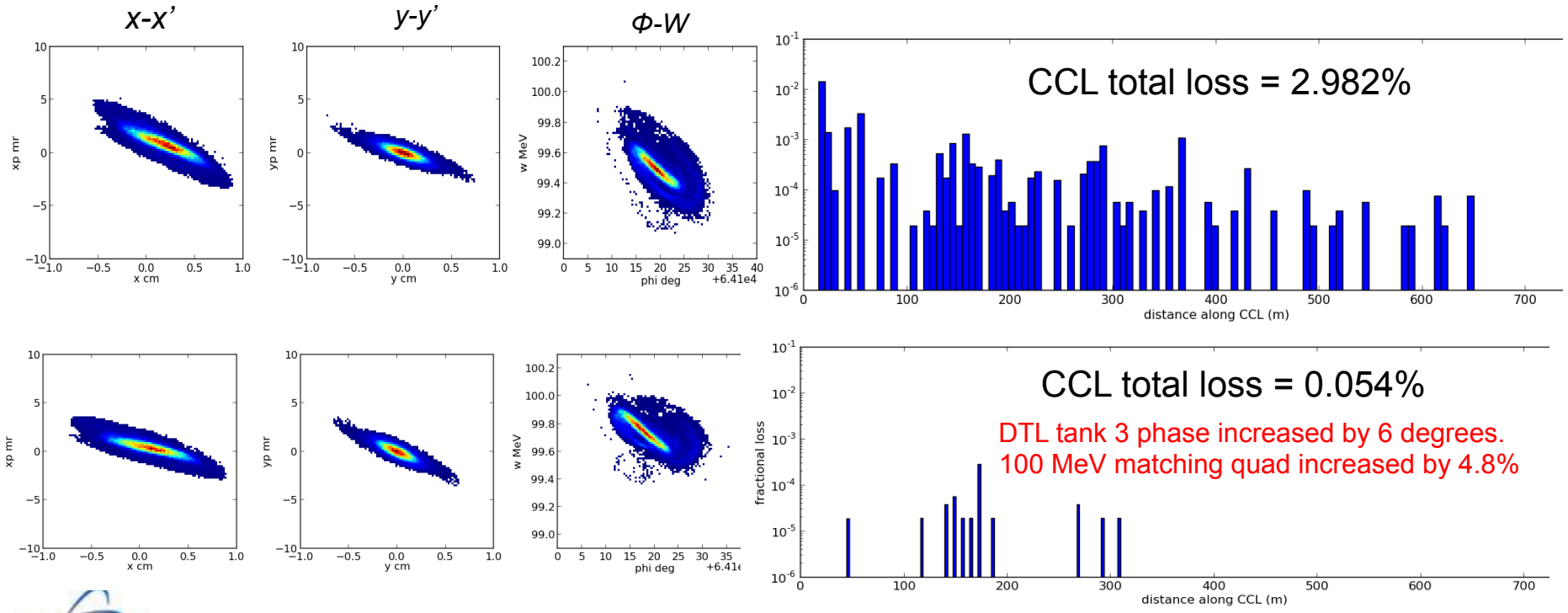

CCL module 5 – deltaT loops (phase measurement diagnostics)



# Applications

# Guided tuning, what-ifs, & operator training all possible with HPSim

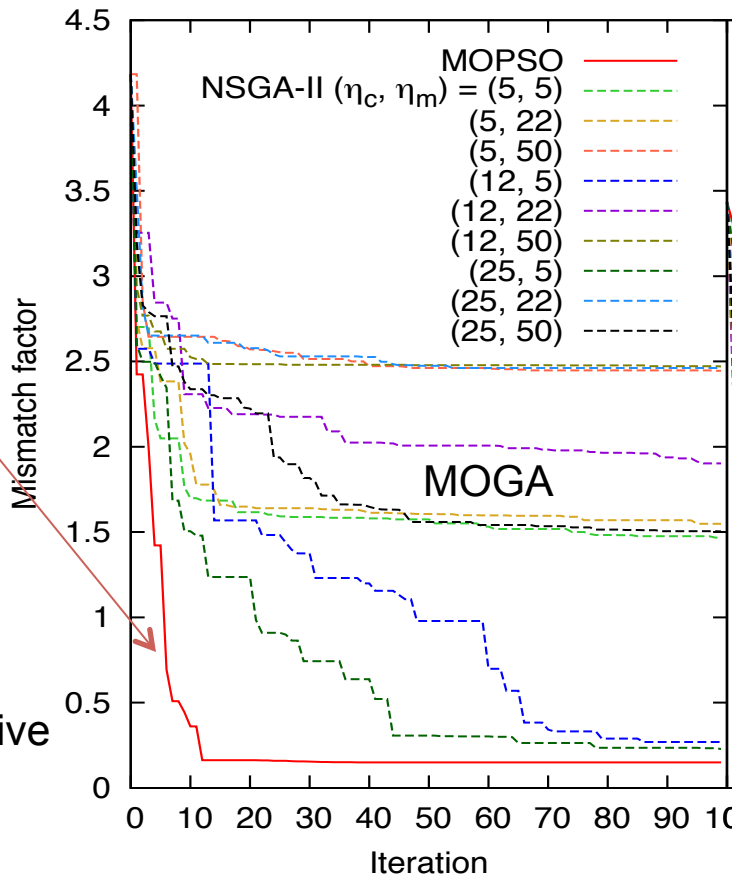
- Characterize beam while tuning to reduce beam spill
- What-ifs : new diagnostics, operation mode, beam line,  and operator training
- Troubleshooting operational problems



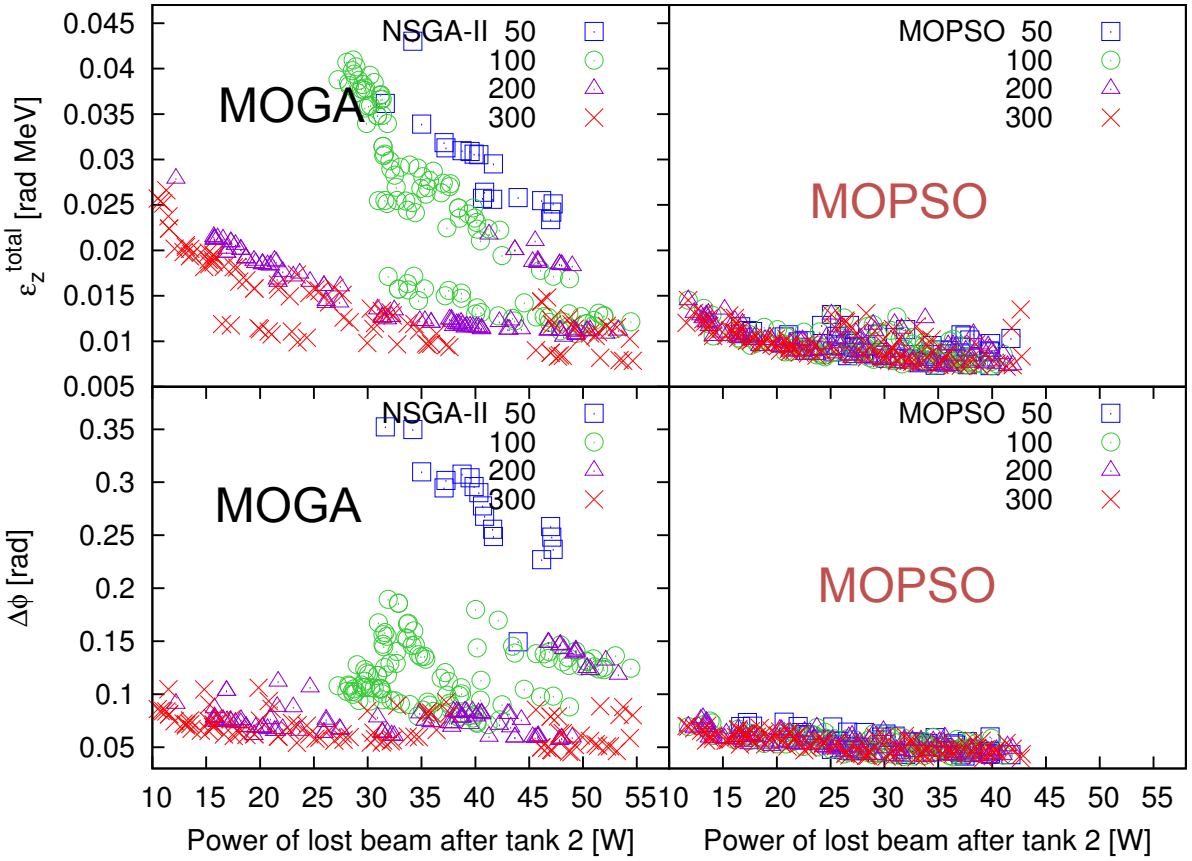
# HPSim + Multi-Objective Particle Swarm Optimization(MOPSO) = powerful online/offline machine setting optimizer

- Automatically tuning several machine parameters to find optimal set points that will produce minimum
  - mismatch factor
  - beam loss
  - power of lost beam
  - emittances
  - phase width …
- MOPSO can be fast enough for online optimization
  - multi-objective, global optimization
  - fast convergence, faster than multi-objective genetic algorithm (MOGA)

MOPSO (runtime to convergence = a few seconds)



# HPSim + MOPSO can produce optimal machine set points




Optimize DTL beam

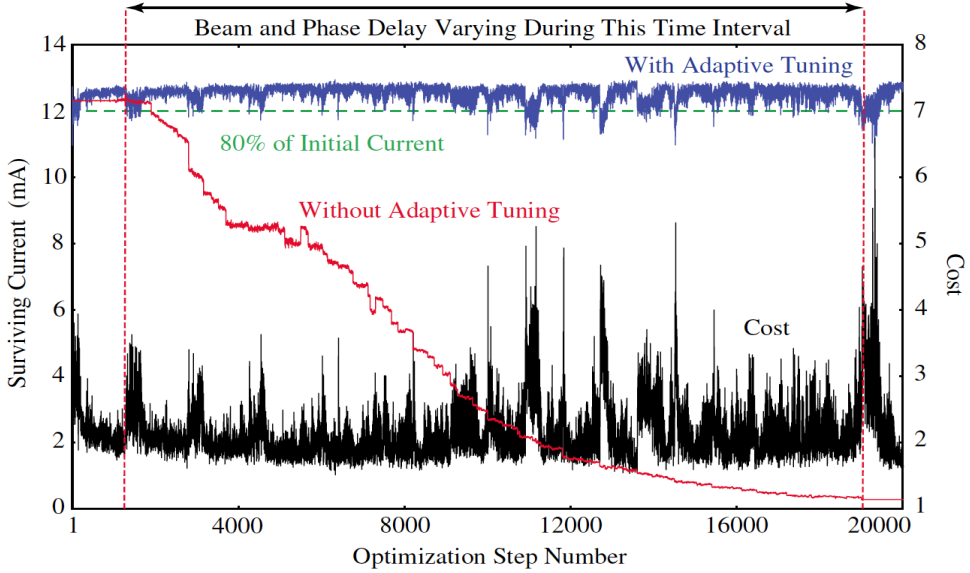
- **11 parameters**
  - RF phase & amplitude
- **3 objectives**
  - emittance z
  - phase width
  - power of lost beam
- runtime to convergence
  - **MOPSO = 16 mins**
  - MOGA >= 1 hour

*X. Pang, L. Rybarcyk, NIM-A, 741, 124, 2014*
*X. Huang, J. Safranek, NIM-A, 757, 48, 2014*
*X.Huang, J. Safranek,* arXiv:1502.07799

# HPSim: a test bed for new control and tuning schemes

- Testing on real machine can be risky and costly
- HPSim → virtual experimental environment
  - resembles the real accelerator
  - safe, inexpensive, efficient and productive
- Model Independent Accelerator Tuning first tested with HPSim before carrying out real experiments

*22 quads, 2 buncher phases*




*A. Scheinker, et al. PRSTAB, 16, 102803, 2013.*
*A. Scheinker, et al. NIM-A, 756, 30, 2014*

# Autonomous particle accelerator?


real accelerator

supervised learning

HPSim

deep learning

unsupervised learning

reinforcement learning

# Summary

- **High Performance Simulator (HPSim)** is an accurate and fast online multi-particle modeling tool for high power proton linac operation
  - multi-particle, enhanced PARMILA
  - easy to simulate real-world off-design scenarios
  - accelerated by GPU : subseconds to seconds
  - flexible & user-friendly: Python
- Applications
  - continuous monitoring
  - guided tuning, what-ifs, operator training
  - online/offline machine setting optimization
  - test-bed for new ideas!

# Thank you!