Recent Improvements to CHEF

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What is CHEF ?

- a body of software for accelerator computations
  a set of libraries and a standalone application. The application uses a subset of the capabilities provided by the libraries which are meant to be used independently.
- native C++ implementation
- Ancestry dates back to the early 1990s
- Since 2005: Formalized development. Extensive revision and modernization.

A Bit of History

Late 1980s and 1990's:

- A. Dragt, J. Irwin, E. Forest and others show how Hamiltonian dynamics in the context of accelerators can be formulated in a way that puts (local) maps, rather than (global) Hamiltonians in the central role.
- Analytical maps can be approximated by Taylor series. M. Berz shows that automatic differentiation techniques are a natural fit to perform operations on Taylor maps and releases the first production quality AD engine (the basis for the code COSY).

Design Objectives

- Unified framework for:
  - tracking and map generation
  - linear and nonlinear analysis
- Approximations under user control
- Separated propagation physics
- Local geometry

Library Hierarchy

components — High level Components
- Site viewer
- Beamline browser
- Phase space display etc …

physics_toolkit — Tools for calculating lattice functions, moment propagation, normal form analysis etc …

bmlfactory — YACC based parsers. MAD8,XSIF,MADX

Beamline — Beamline creation, manipulation and edition. Tracking.

Mxyzptlk — Automatic differentiation/differential algebra engine for perturbation theory and tracking.

basic_toolkit — Utility functions, Linear Algebra, Memory management, Physical Constants

Automatic Differentiation

Consider f and its derivatives evaluated at x_0.
For any composition $g = h \circ f$ one can compute g and its derivatives at x0 exactly.
Algebra of derivatives ← → Algebra of polynomials

Performance and minimal memory footprint are the main challenges

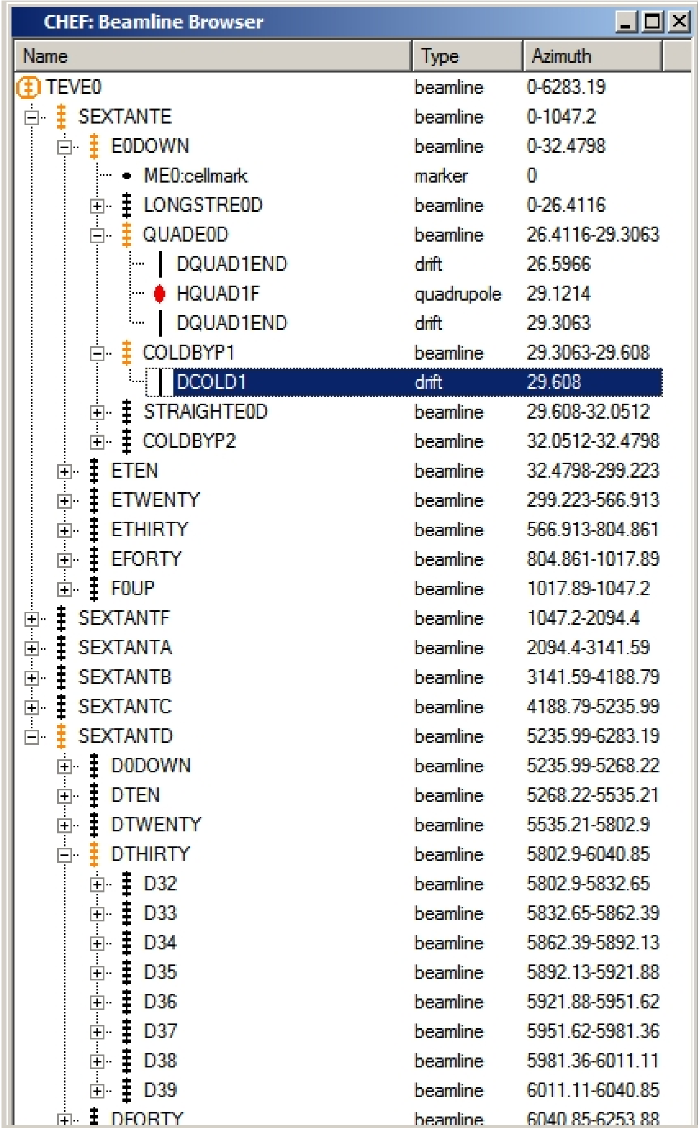
The no of coefficients is large: $(n + m)! / n!\, m!$
Implementation requires careful attention to low level details:
memory management, individual coefficient access mechanism, etc

AD engine: mxyzptlk

Jet : a data type that aggregates all coefficients. Operations are generalized to this type (similar to what is done for matrices). Other types (Maps, LieOperator use Jet as a building block.

- takes max advantage of C++ operator overloading
- templates and implicit conversion provide simultaneous support for complex and double Jet types. The latter can be mixed.
- Reference point and space dimensionality are a run-time choice.
- highly optimized implementation:
  - 6^{th} order (6d) map for a ring with a few 100 elements can be computed in >10 min
  - At first order, overhead compared with traditional matrices is minimal.
  - Small and dynamic memory footprint

Beamlines



CHEF: Beamline Browser

Name	Type	Azimuth
TEVE0	beamline	0-6283.19
SEXTANTE	beamline	0-1047.2
E0DOWN	beamline	0-32.4798
ME0:cellmark	marker	0
LONGSTRE0D	beamline	0-26.4116
QUADE0D	beamline	26.4116-29.3063
DQUAD1END	drift	26.5966
HQUAD1F	quadrupole	29.1214
DQUAD1END	drift	29.3063
COLDBYP1	beamline	29.3063-29.608
DCOLD1	drift	29.608
STRAIGHTE0D	beamline	29.608-32.0512
COLDBYP2	beamline	32.0512-32.4798
ETEN	beamline	32.4798-299.223
ETWENTY	beamline	299.223-566.913
ETHIRTY	beamline	566.913-804.861
EFORTY	beamline	804.861-1017.89
F0UP	beamline	1017.89-1047.2
SEXTANTF	beamline	1047.2-2094.4
SEXTANTA	beamline	2094.4-3141.59
SEXTANTB	beamline	3141.59-4188.79
SEXTANTC	beamline	4188.79-5235.99
SEXTANTD	beamline	5235.99-6283.19
D0DOWN	beamline	5235.99-5268.22
DTEN	beamline	5268.22-5535.21
DTWENTY	beamline	5535.21-5802.9
DTHIRTY	beamline	5802.9-6040.85
D32	beamline	5802.9-5832.65
D33	beamline	5832.65-5862.39
D34	beamline	5862.39-5892.13
D35	beamline	5892.13-5921.88
D36	beamline	5921.88-5951.62
D37	beamline	5951.62-5981.36
D38	beamline	5981.36-6011.11
D39	beamline	6011.11-6040.85
DFORTY	beamline	6040.85-6253.88

Hierarchical (single rooted tree)

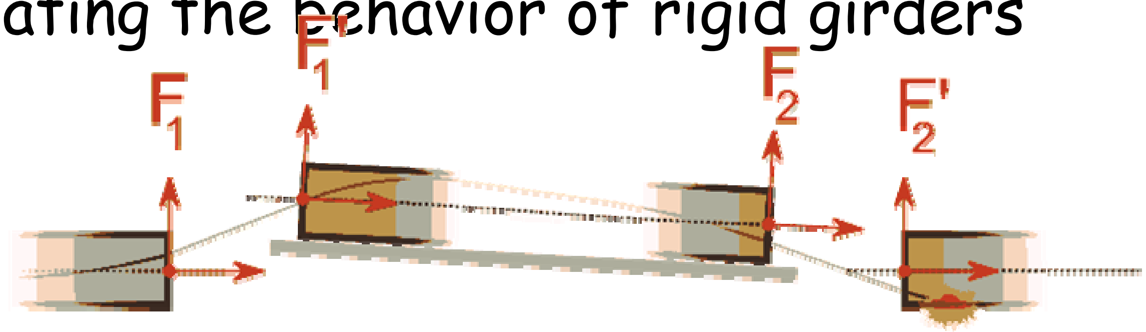
- container endowed with standard STL iterators (depth or breath first)
- can be edited, transformed

Parsers

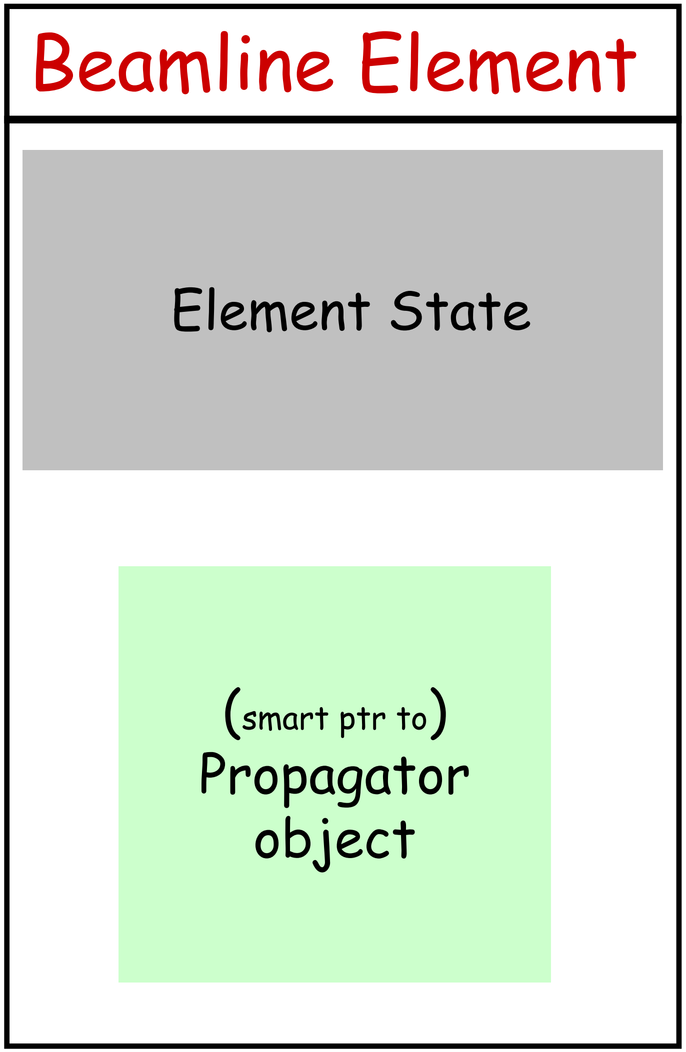
- based on formal (bison/yacc) GLR grammar
- MAD8, XSIF, MADX(soon)
  - expressions
  - macros
- hierarchical structure is preserved in constructed model

Geometry

- Propagation physics expressed in "natural" local coordinates
- "empty space" handles frame transformations between elements, allowing arbitrary placement
- general misalignments may be handled exactly using this mechanism
- alternatively, small misalignments may be handled approximately and locally
- (sub) beamlines may be misaligned as a whole, emulating the behavior of rigid girders



Propagator Architecture

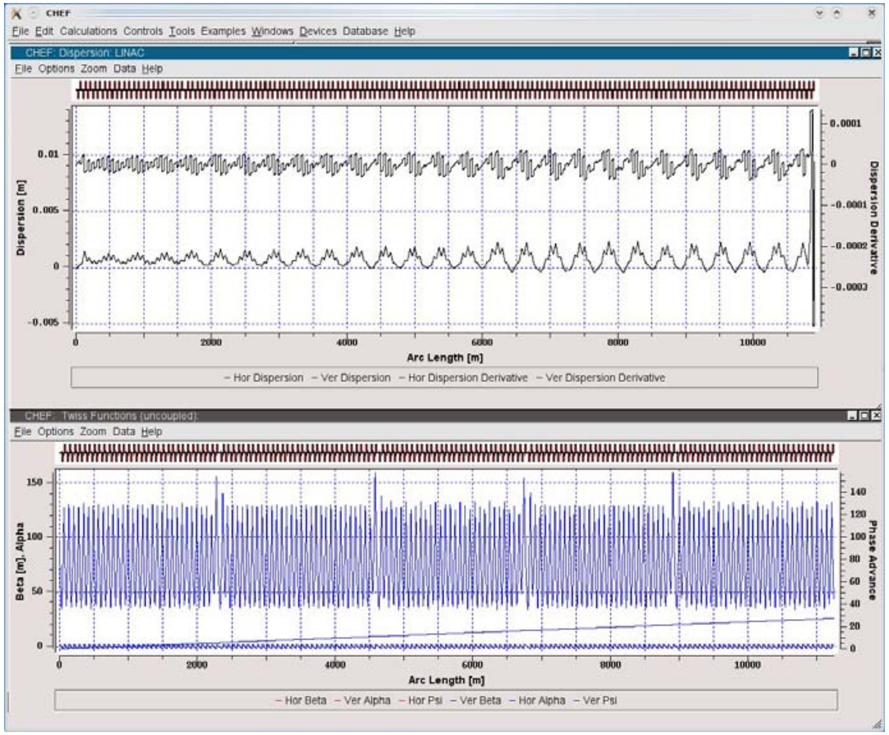


- Propagation physics is encapsulated in a Propagator object
- Propagators can be specified at runtime
- Useful to introduce domain-specific approximations
- Propagator handles finite aperture extent when specified (implemented as decorator)
- Details of propagation (e.g. thin kicks, integrator) are *hidden* from the rest of the code
- Propagators propagates either Particles or JetParticles (templated)

Analysis

- At first order, Maps obviously allow standard lattice computations, coupled and uncoupled.
- Generalization to higher orders is also available: normal forms, higher order dispersion, momentum compaction factor and so forth.

Lattice Functions



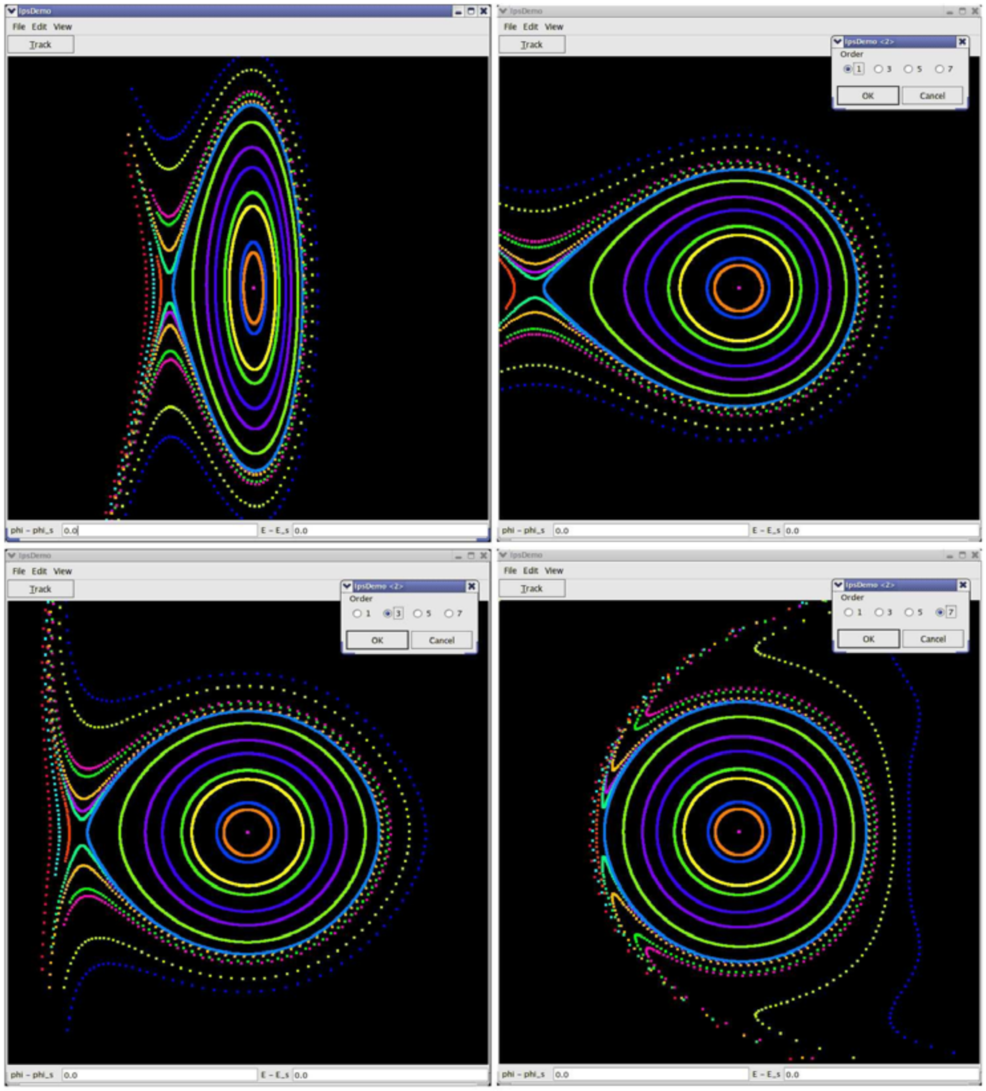
generalized horizontal beta functions

Beamlines (Linac) | Ring

Standard and coupled functions for both lines and rings.

Choice of parametrizations for coupled lattice functions.

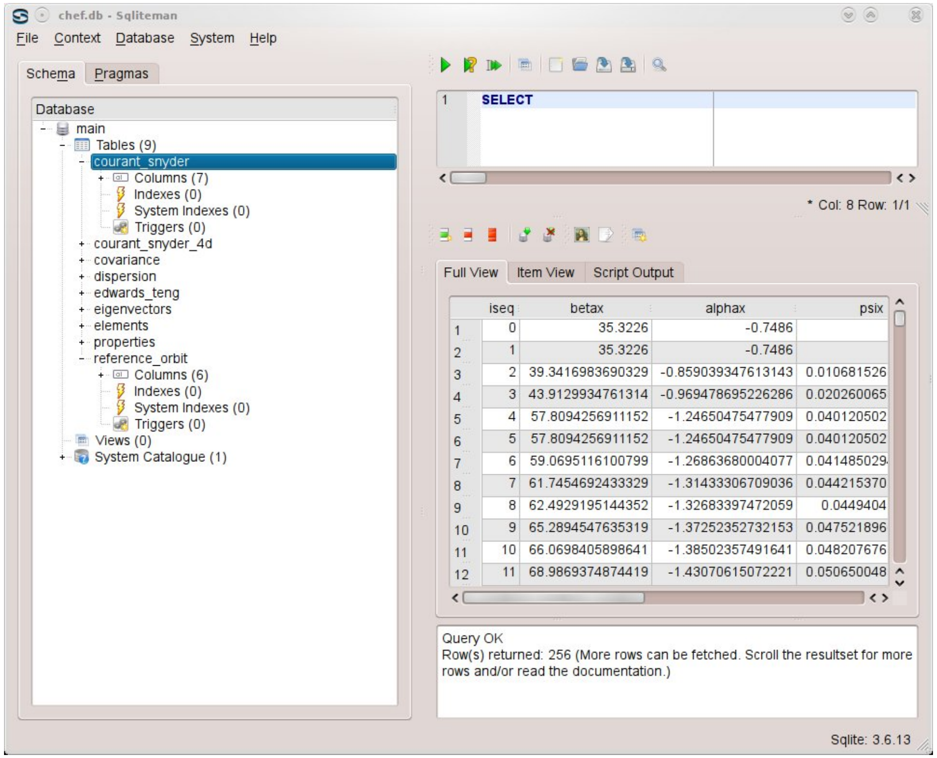
Normal Forms



- Phase space contours for a sinusoidal rf bucket in std (E-phi) coordinates (top left)
- After successive Normal Form transformations at orders 1, 3 and 7

Embedded Database

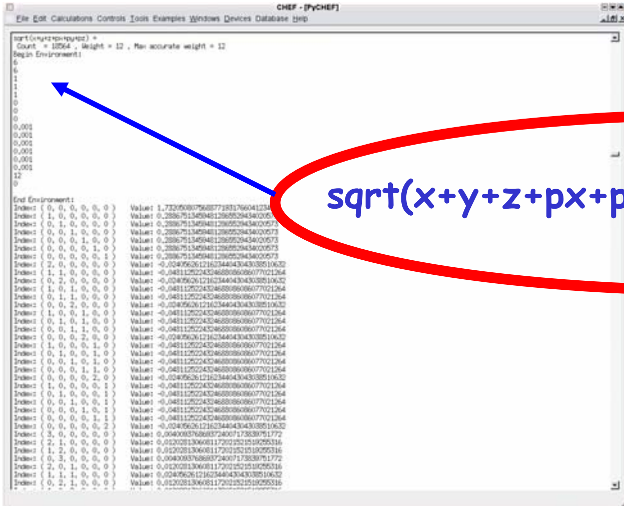
- Embedded SQL database is used internally to store and manage computed quantities (lattice functions, ref orbit, maps, labels etc)
- Standard queries enable element selection, tabulation, sorting etc
- Established tools are available to browse and display exported data.



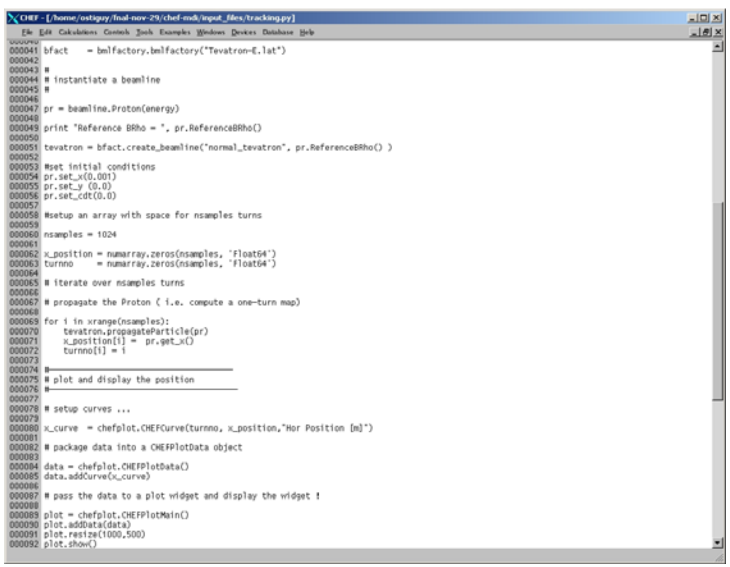
Python Bindings

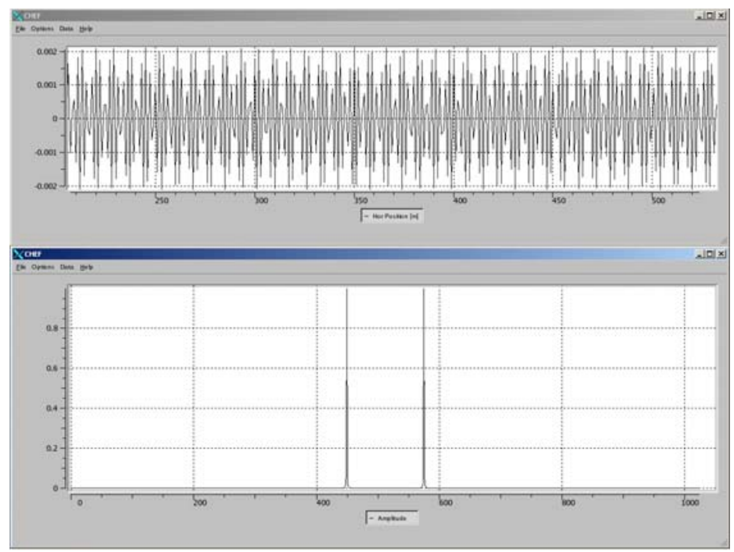
- Many codes are now structured as a high level control shell, implemented in an interpreted language. Computation intensive functionality is implemented in a compiled language and accessed through a dedicated layer.
- CHEF provides a comprehensive set of bindings for python, which is widely used and is a good match for c++ concepts.
- The code SYNERGIA (3d space charge) uses this mechanism to import needed functionality.

Script Examples



sqrt(x+y+z+px+py+pz) Order = 12





Linac Modeling

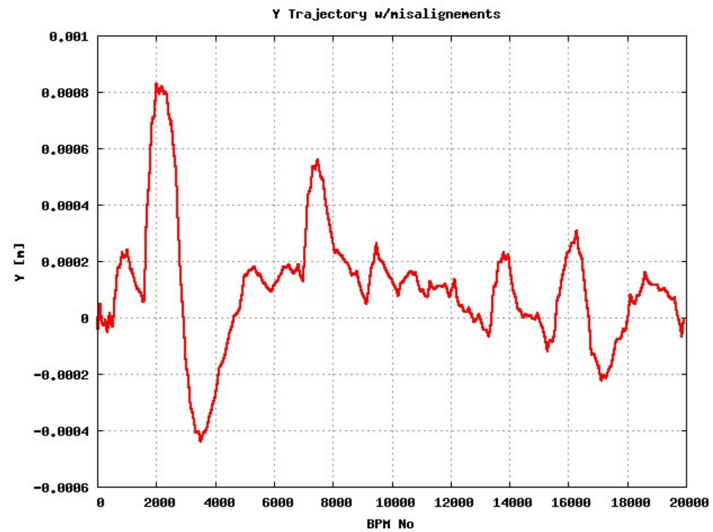
Although maps techniques remain useful for single pass machines (e.g. final focus design), the emphasis in that context is more on conventional tracking.

CHEF has been adapted for high energy linacs. Specifically, we added:

- reference trajectory in the presence of acceleration
- Linac-specific accelerating structure element
- wakefields

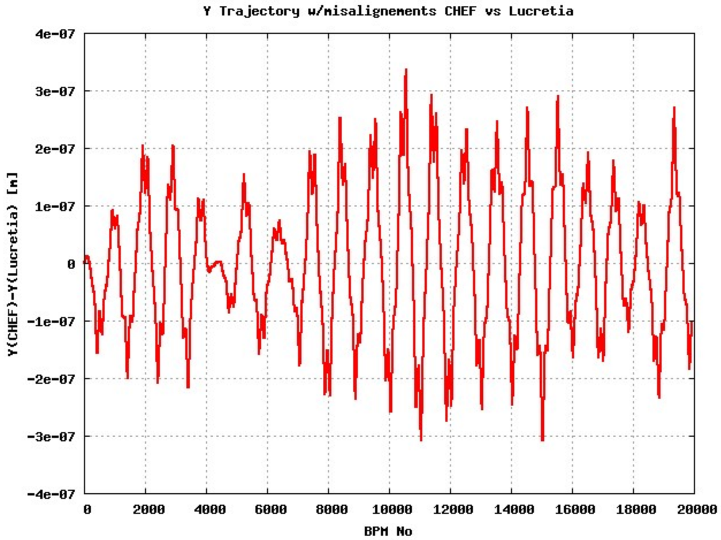
Comparisons with other linac codes show excellent agreement.

Benchmark: Trajectory w/misalignments



Sample trajectory in ILC linac with misaligned elements (cavities and quads).

Max vertical scale: 1 mm

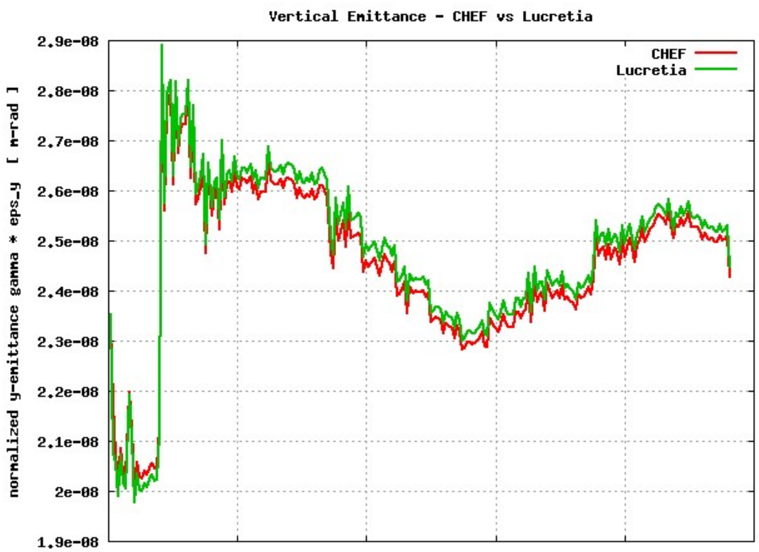


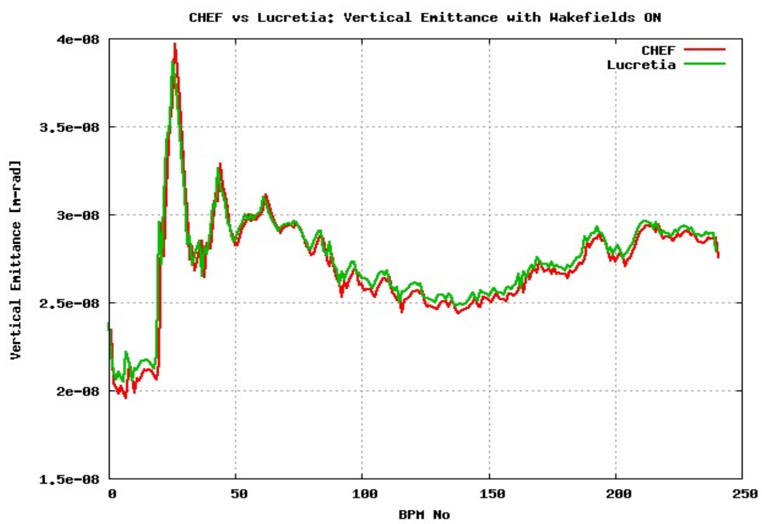
Comparison with Lucretia (SLAC)

Difference trajectory is shown.

Max vertical scale: 0.4 microns

Benchmark: Vertical Emittance Evolution in ILC





Comparison with Lucretia (SLAC)

Vertical emittance

Wakefields OFF

(same misaligments + correctors set to value determined by an emittance minimization algorithm)

Vertical emittance

Wakefields ON

Current Development

- Named “Knobs” and “measurements” objects based on generalized function objects (closures)

  Can be an element attribute, or a map coefficient or an arbitary expression involving others

  (A proof-of-principle implementation exists)

- A basic localized space charge element (based on rigid gaussian / uniform distributions). The sc distribution is determined from the (unperturbed) beam moments.

Of Interest

Synergia

TH5PFP018
Recent Advances in the Synergia Accelerator Simulation Framework
J. F. Amundson, P. Spentzouris, E. G. Stern (Fermilab)

TH5PFP017
Space Charge Simulations for the Mu2e Experiment at Fermilab
J. F. Amundson, P. Spentzouris, E. G. Stern (Fermilab)

COSY

WE3PBC05
Advanced Simulation and Optimization Tools for Dynamic Aperture of Non-Scaling FFAGs and Related Accelerators including Modern User Interfaces
C. Johnstone (Fermilab) M. Berz, K. Makino (MSU) P. Snopok (St. Petersburg State University)

MADX/PTC

TH6PFP081
Resonance Driving Term Experiment at DAFNE
C. Milardi (INFN/LNF) F. Schmidt (CERN)