Science & Technology Facilities Council

Accelerator Simulations - Issues and Challenges

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ASTeC-RAL

What do we want to use codes for?

Codes to generate basic lattices

Codes to optimise lattices

Codes to examine specific processes

Codes to model specifc items of hardware

Codes to track a beam through an entire accelerator

Codes to track a beam through a section of an accelerator

Paraxial tracking, high-order tracking, with/without space-charge

Ray tracing codes, PIC codes, Vlasov solvers, analytical codes

Codes to handle different kinds of particles, neutralised beams etc.

Codes with increasingly sophisticated models of physical effects

Why are Codes Important?

- Generate the basic underlying machine design
  - sets of self-consistent parameters
  - optimised for performance
  - avoid resonances, instabilities, minimise non-linear effects
- Establish likely machine performance
  - predict effect and correction of failure mechanisms
  - bracket allowable errors
  - control/reduce beam loss
  - identify beam properties on exit (e.g. to a target)
  - quantify output energy, emittance & halo at full current
- Indicate whether novel ideas are feasible
- Develop commissioning strategies
- The codes themselves must be “certified” at some level

Availability, Sophistication, Limitations

- **Availability: Many useful beam dynamics codes exist for simulation of linacs and rings**
  - the variety is good but comes with redundancy
  - much effort on benchmarking different codes
- **Sophistication: a lot of them are pretty sophisticated**
  - 3D External and Space-Charge fields
  - Parallel codes: simulation of actual number of particles in beam bunch, 10^9, 10^{12}?
  - Detailed machine error simulations and correction
- **Limitations: still far from reproducing experimental data to make them reliable for supporting real-time machine operation**
  - Efforts at SNS, J-PARC, GSI; long-term goal for ESS

The Codes

- Beam Optics codes
  - Transform envelope with analytical space charge
  - Used as basis for most tuning algorithms
- PIC Dynamics codes
  - **Linacs:** Parmila, Parmela, Tracewin, Dynamion ….
  - **Rings:** Orbit, Simpsons, Simbad, OPAL....
  - 10^6 to 10^9 particles, with 3-D space charge
  - Matrix/map based, thin lens+drift, direct integration
  - Do a good job on core simulations; not so well on halo
  - Agree at few % level with experiments
- Integrating dynamics codes
  - Impact, Track, Tstep (Parmela)
- Ray-tracing codes
  - Zgoubi, G4beamline...
- Can now integrate ~10^9 particles through field maps

Beam Optics Codes *v.* Beam Tracking

Beam optics codes
(example: Trace-3D)

- Matrix based, usually first order
- Hard-edge field approximation
- Space charge forces approximated
- Beam envelopes and emittances
- Fast, Good for preliminary studies
- Simplex optimisation: Limited number of fit parameters

Beam dynamics codes
(example: TRACK, IMPACT)

- Particle tracking, all orders included
- 3D fields including realistic fringe fields
- Solving Poisson equation at every step
- Actual particle distribution: core, halo …
- Slower, good for detailed studies including errors and beam loss
- Larger scale optimisation possible

➢ **Optimisation via optics codes + added terms for specific effects**

➢ **But it is more appropriate to use beam dynamics codes:**

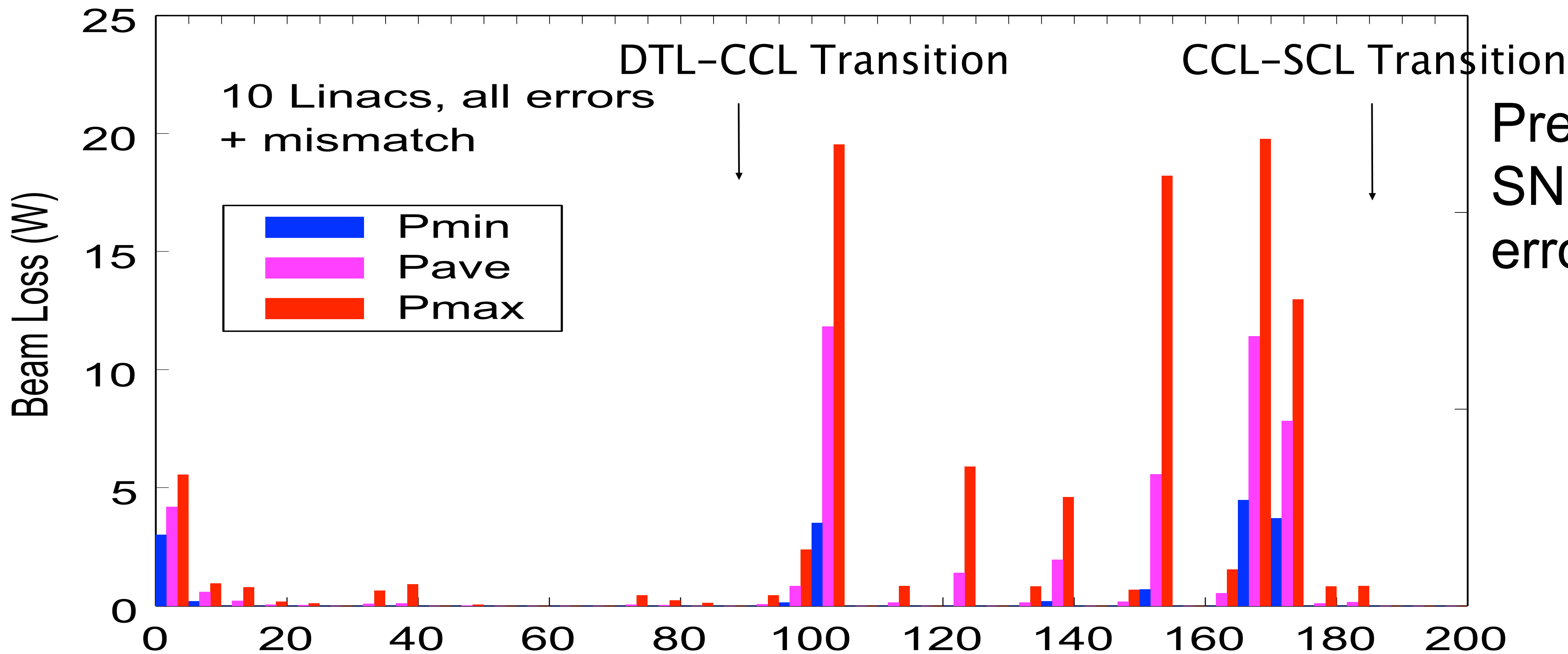
- More realistic representation of the beam especially for high-intensity and multiple charge state beams (3D external fields and accurate SC calculation).
- Include quantities not available from beam optics codes: minimise beam halo formation and beam loss.
- Now possible with faster PC's and parallel computer clusters.

Code Limitations

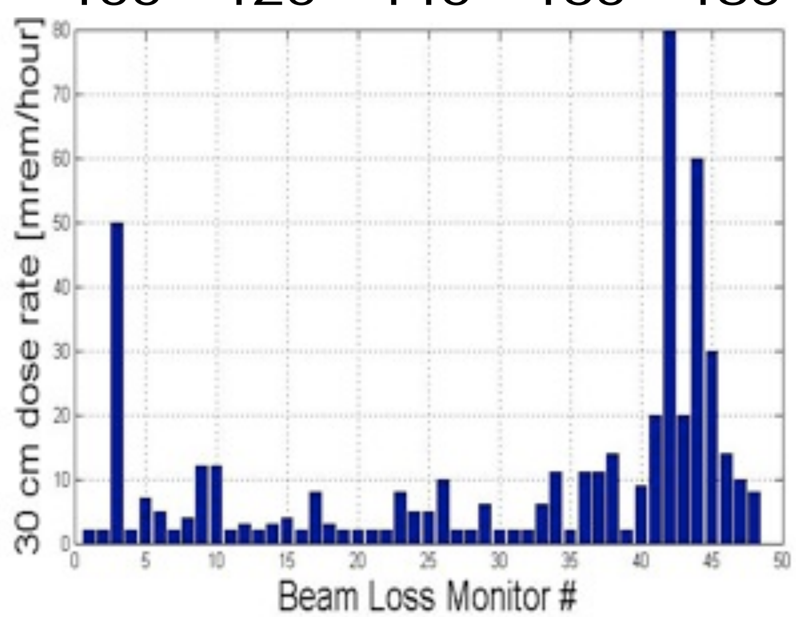
Main issues when modelling real machines:

- An accurate 6-D description of the initial beam particle distribution
  - beam characterisation, need plenty of diagnostics
- Magnets and their alignment can be accurately mapped
- An accurate description of the fields is needed:
  - The axial RF field distribution in RFQ's is not measurable
  - The RF field distribution in SC cavities at operating temperature may not be known
  - RF phase & amplitude errors are transient
- Some diagnostic measurements are not accurate enough for the codes

Codes can agree well qualitatively



Predicted beam loss in SNS warm linac with errors



Measured activation in the SNS CCL

Measured Residual activation at 1 ft after ~ 48 hrs

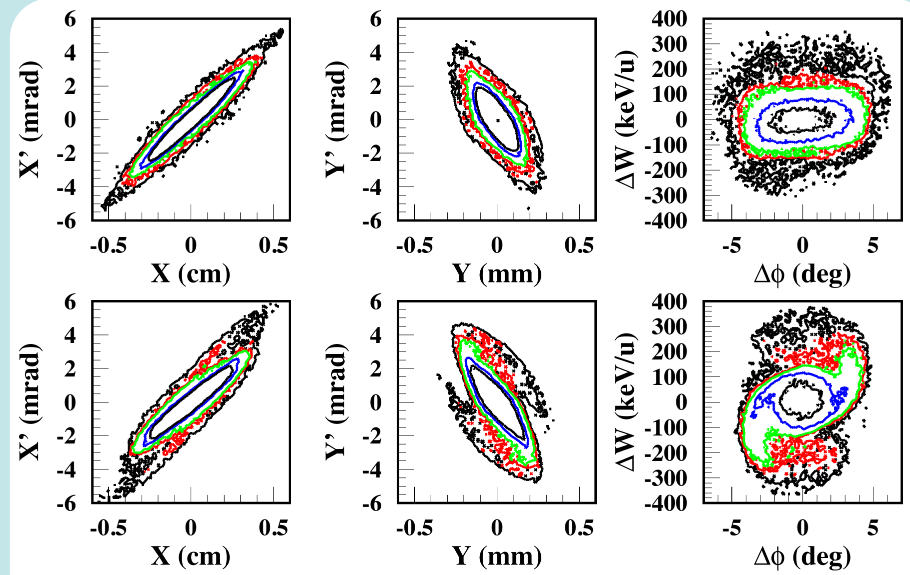
1 W gives ~ 100 mRem/hr at 1 ft after ~ 12 hrs

Courtesy: John Galambos, SNS

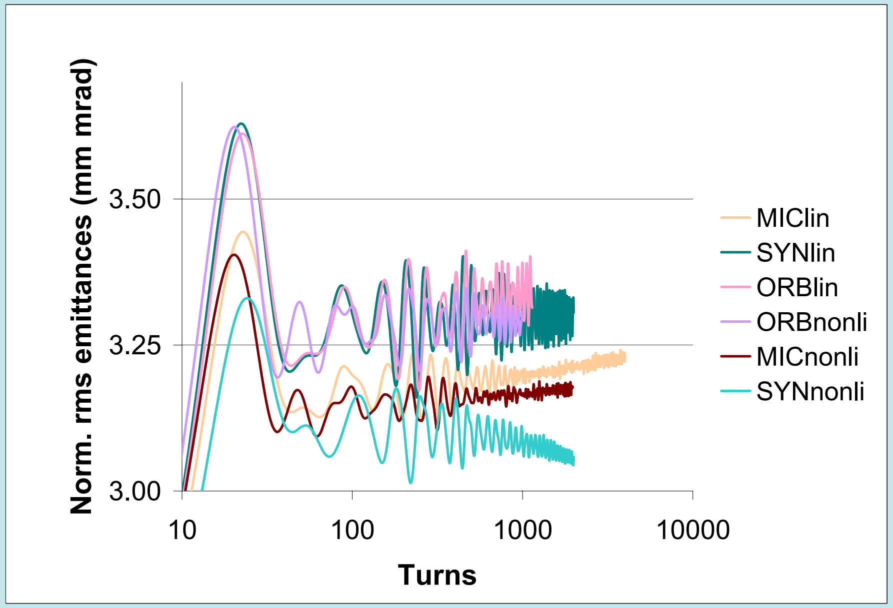
Code Benchmarking

- All codes should have a set of basic tests, preferably with known analytical solutions
- Benchmarking should cover
  - code *v.* code
  - code *v.* experiment
  - code *v.* experiment *v.* theory
- Recent examples
  - Montague resonance tests with CERN PS, $2Q_h$-$2Q_v$=0 (ACCSIM, SYNERGIA, MICROMAP, SIMPSONS, IMPACT, ORBIT, SIMBAD)
  - HIPPI linac injector comparison
  - Electron cloud studies (PEHT, PEHTS, QUICKPIC, HEADTAIL)
  - Study of Hofmann resonance diagrams at J-PARC (TRACEWIN)

See ICFA Beam Dynamics Newsletter 41, December 2006

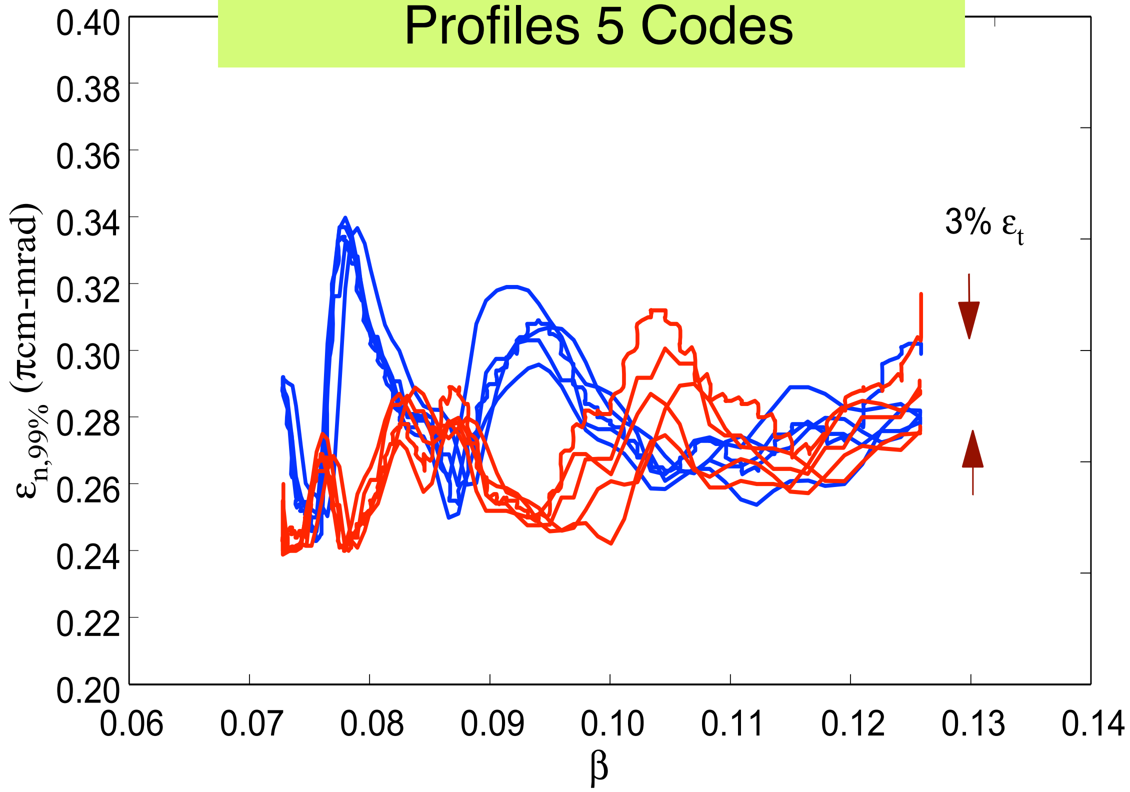


Longitudinal phase space: comparison between simulations using PARMILA and TRACK of SNS-DTL, 38 mA H^- beam, 10^5 particles. Discrepancies caused by different fringe field models and space-charge routines.

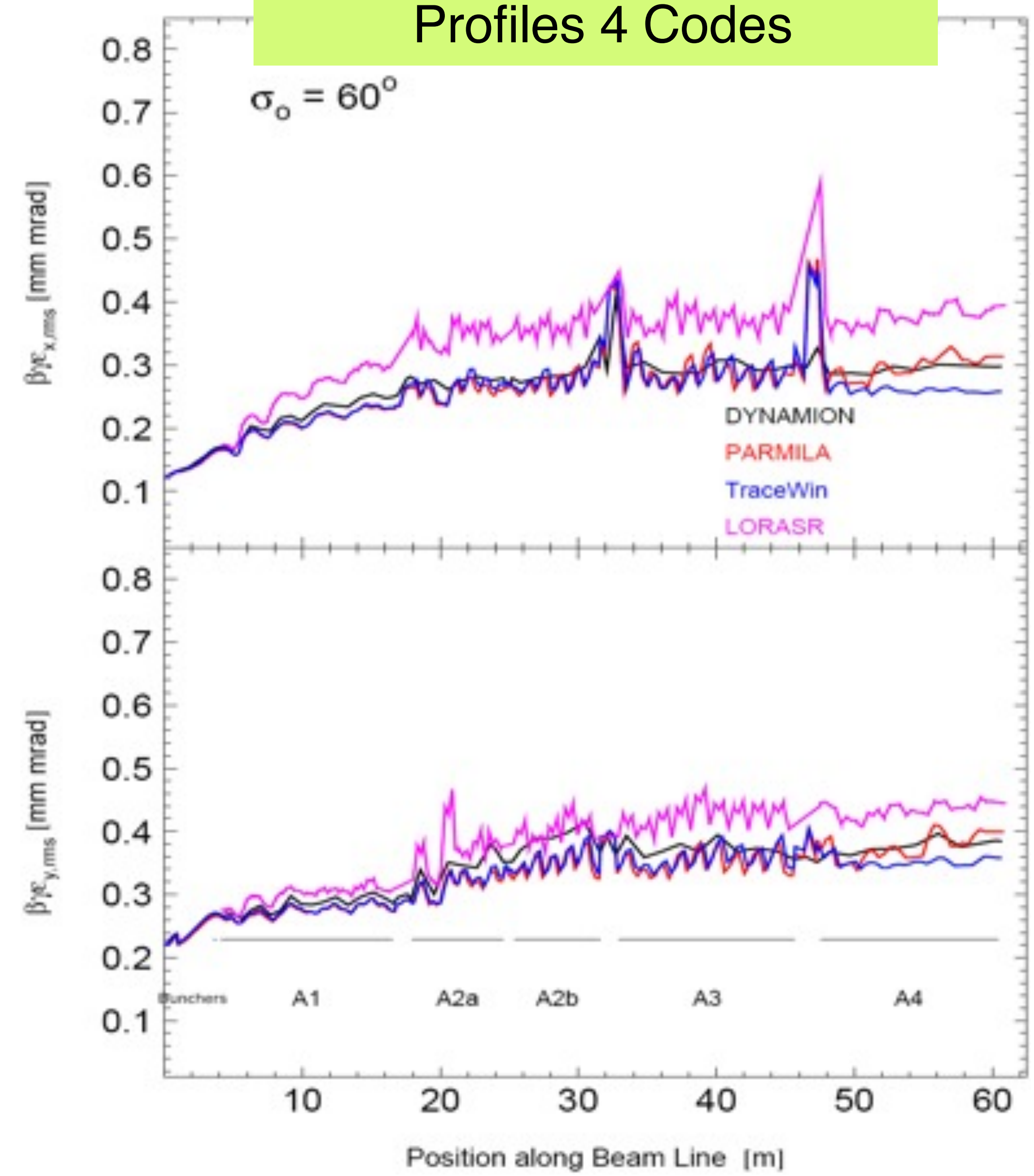


Benchmarking: Agreement at few % level

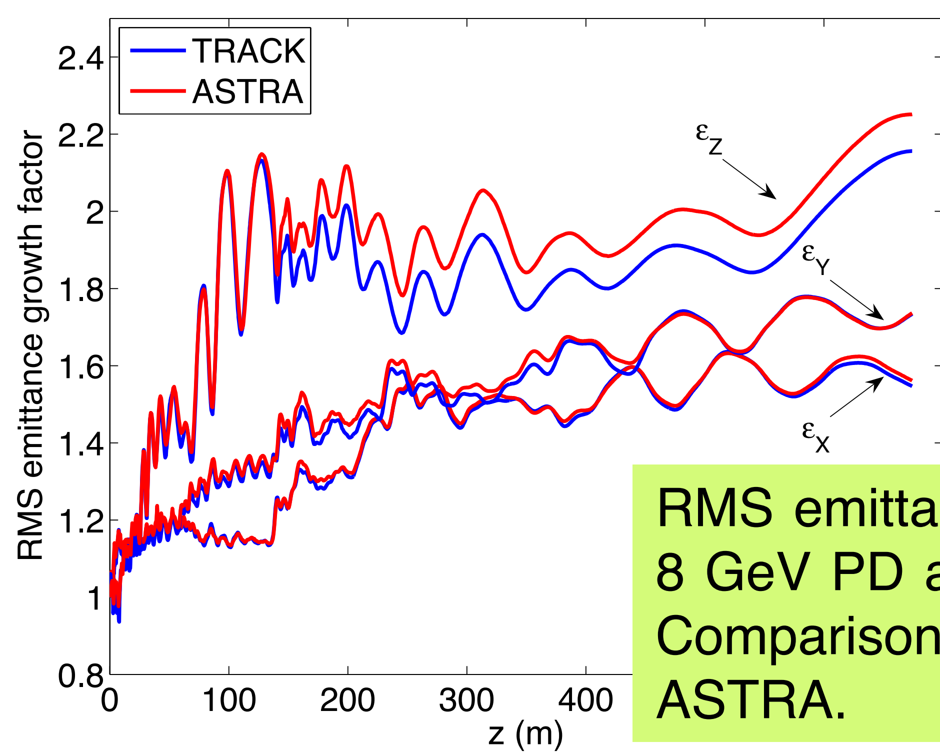
SNS DTL-1 99% Emittance.
Profiles 5 Codes



UNILAC RMS Beam Size.
Profiles 4 Codes



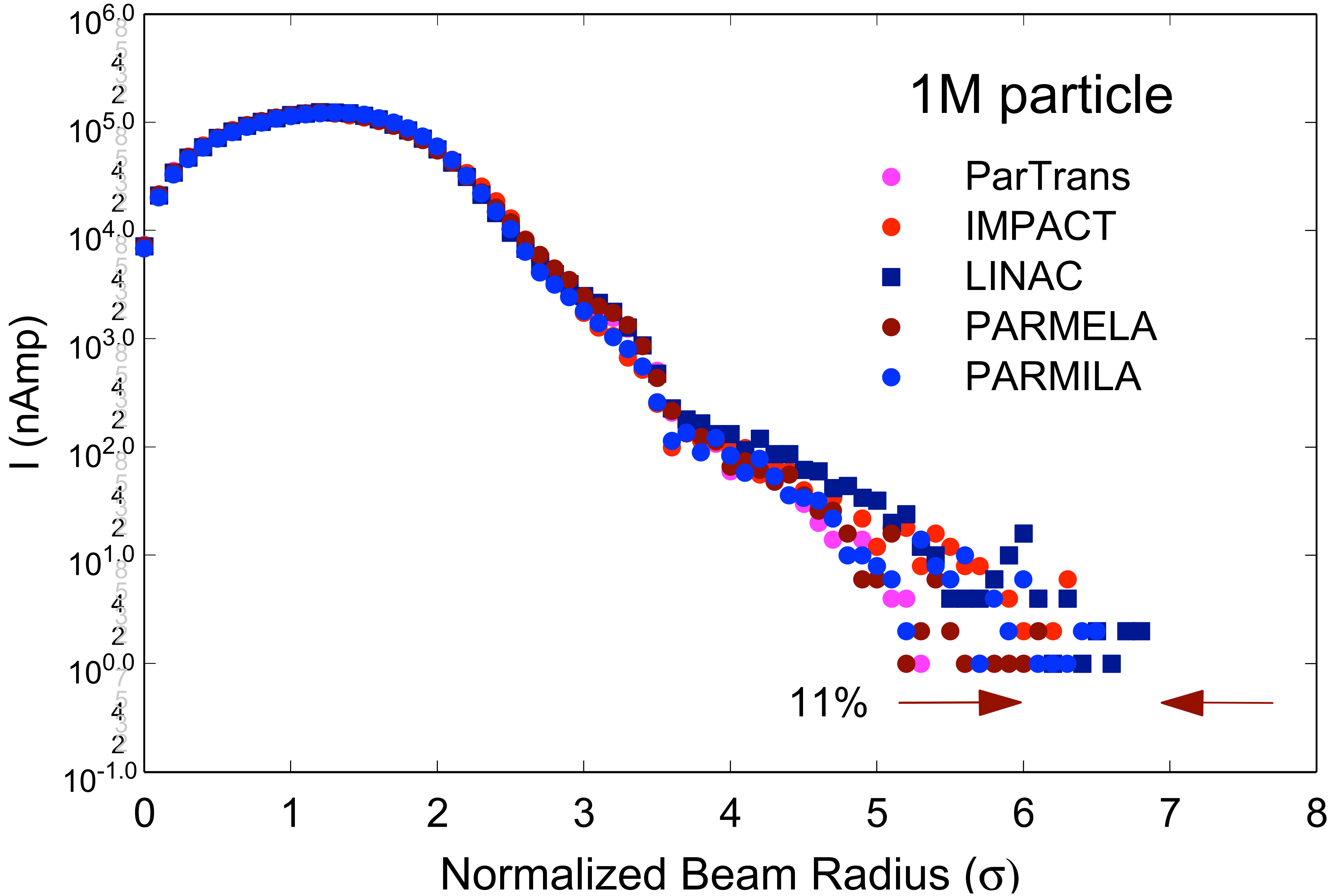
Courtesy: Lars Groening, GSI



RMS emittance growth in Fermilab 8 GeV PD at 43 mA, 10^8 particles. Comparison between TRACK and ASTRA.

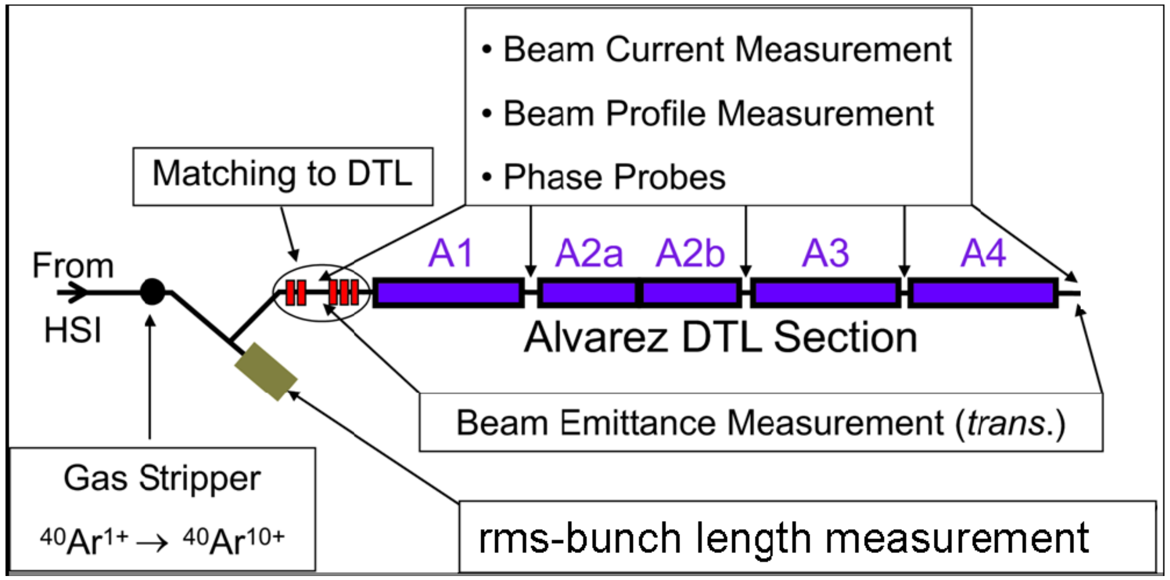
Codes Differ in the Details

SNS Radial Distribution at 7.5 MeV

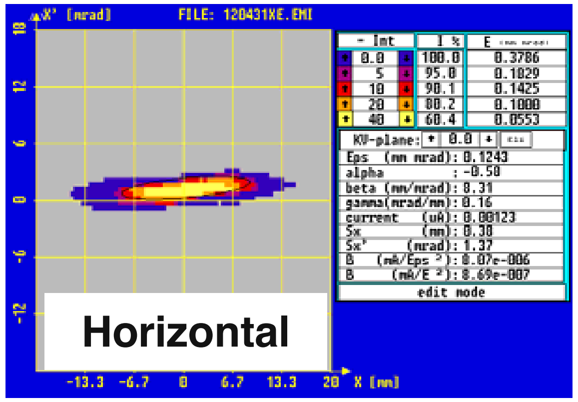


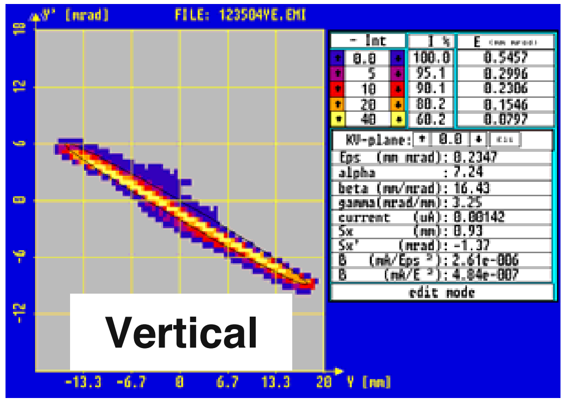
Simulations may provide more information than diagnostics can measure

Schematic set-up of the experiments



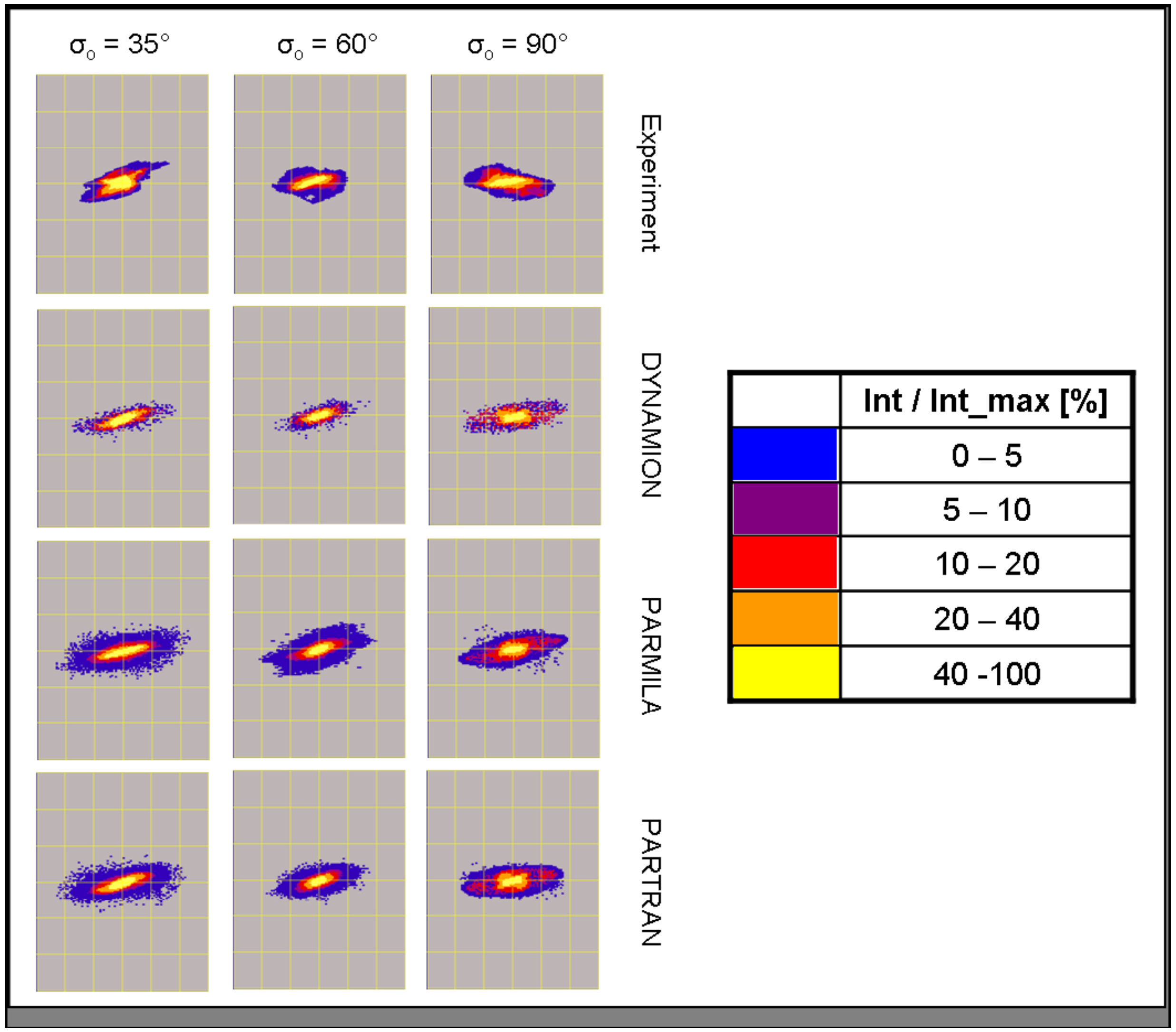
Initial Distribution: Measured in front of DTL Reconstructed and Input to Simulations





The 6D Distribution is parameterized to reproduce the measured 2D projections on phase space planes

Comparison: 3 Codes vs experiments



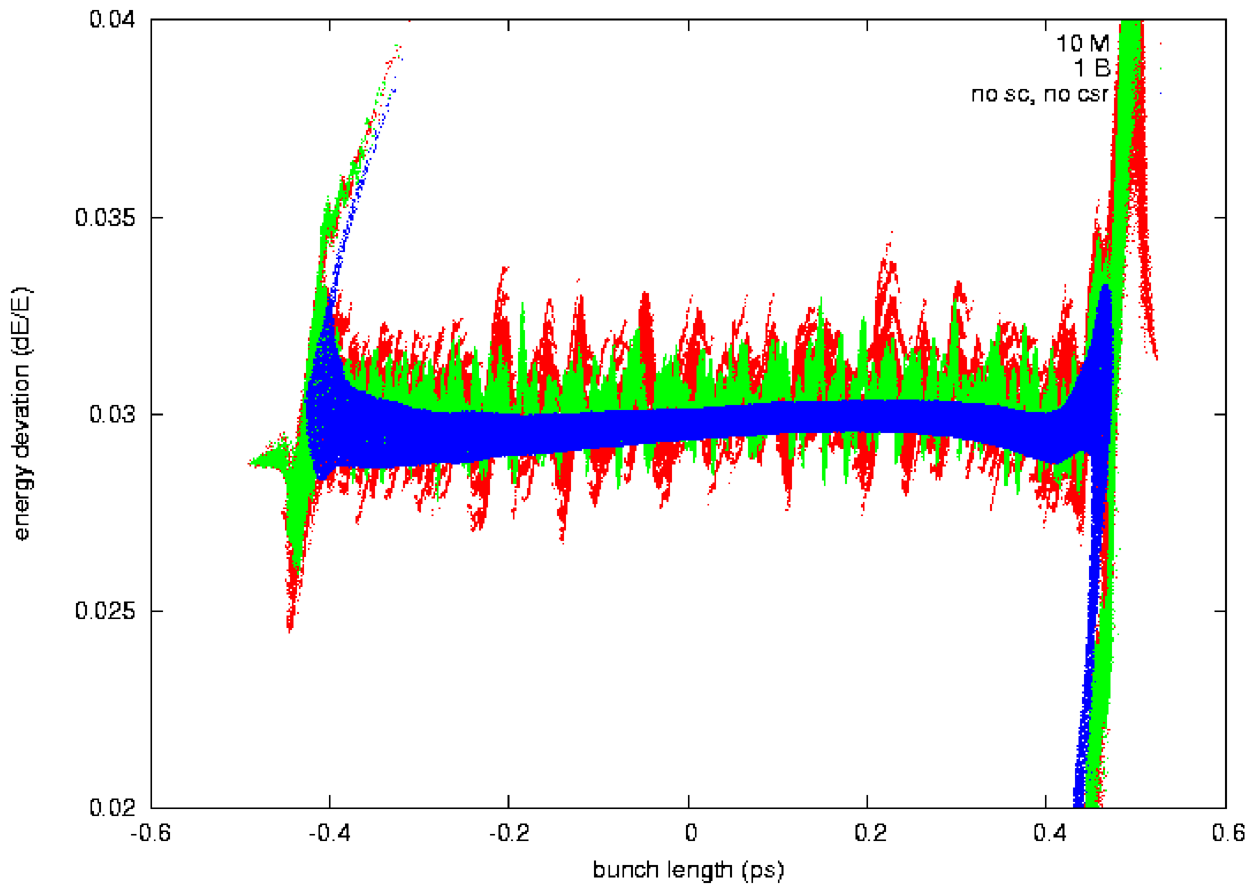
Horizontal phase space plots at the DTL exit.
Left: σo =35◦; centre: σo =60◦; right: σo =90◦.
The scale is ± 24 mm (horizontal axis)
± 24 mrad (vertical axis)

EU-FP7 HIPPI Comparison

Simulation with ~10^9 Particles

- With super-fast computers and parallel processors can now simulate a large number of particles: actual number if possible
  - Suppress noise from the PIC method: enough particles/cell
  - More detailed simulation: better statistics, better characterisation of beam halo

Final Longitudinal Phase Space Distribution w/o SC and CSR
(Using **10M** and **1B** particles)



Simulation with ~10^9 Particles

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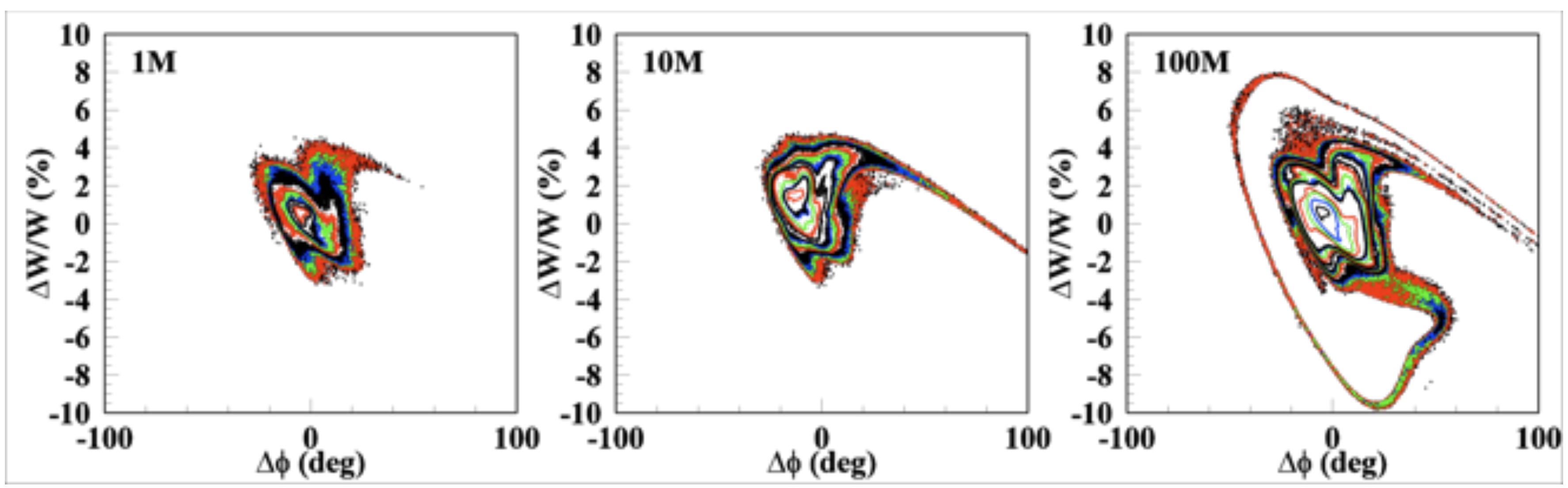
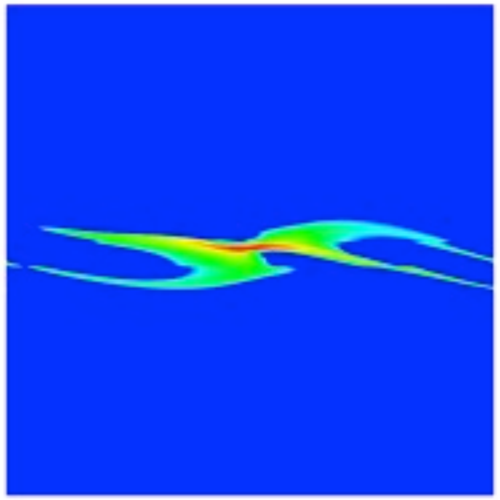
Longitudinal Tracking of the SNS RFQ





Phase space plots for 8.65×10^8 protons after 30 cells in the SNS RFQ.

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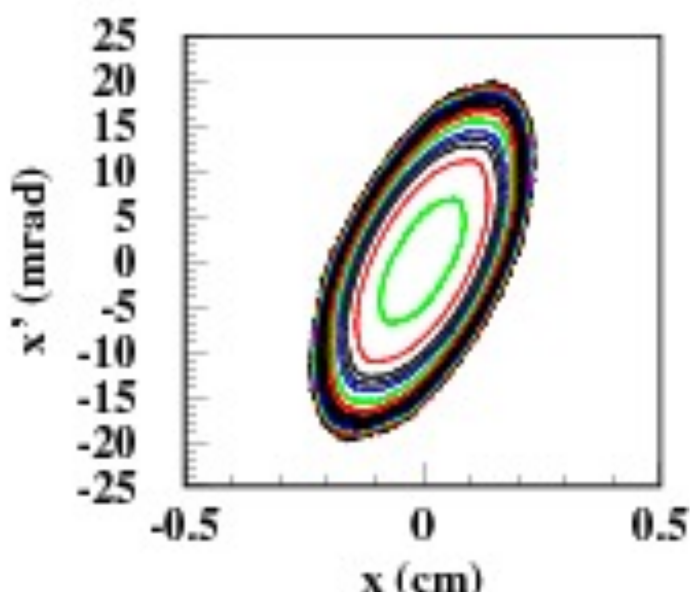
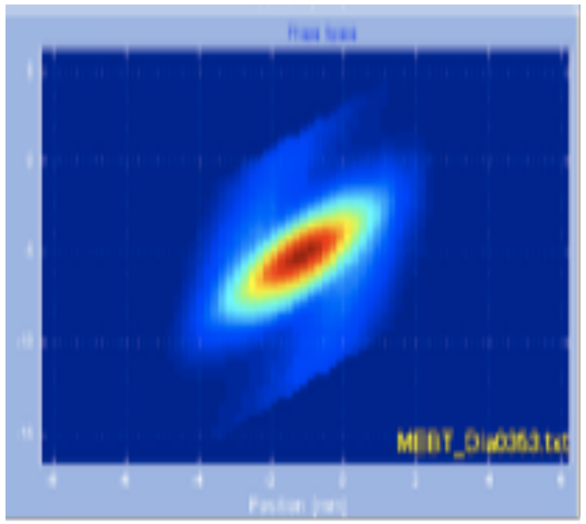
Even 1 billion particles may not provide enough detail



TRACK, 10^9 particle simulation

Courtesy: Mustapha, ANL



SNS measurement in MEBT

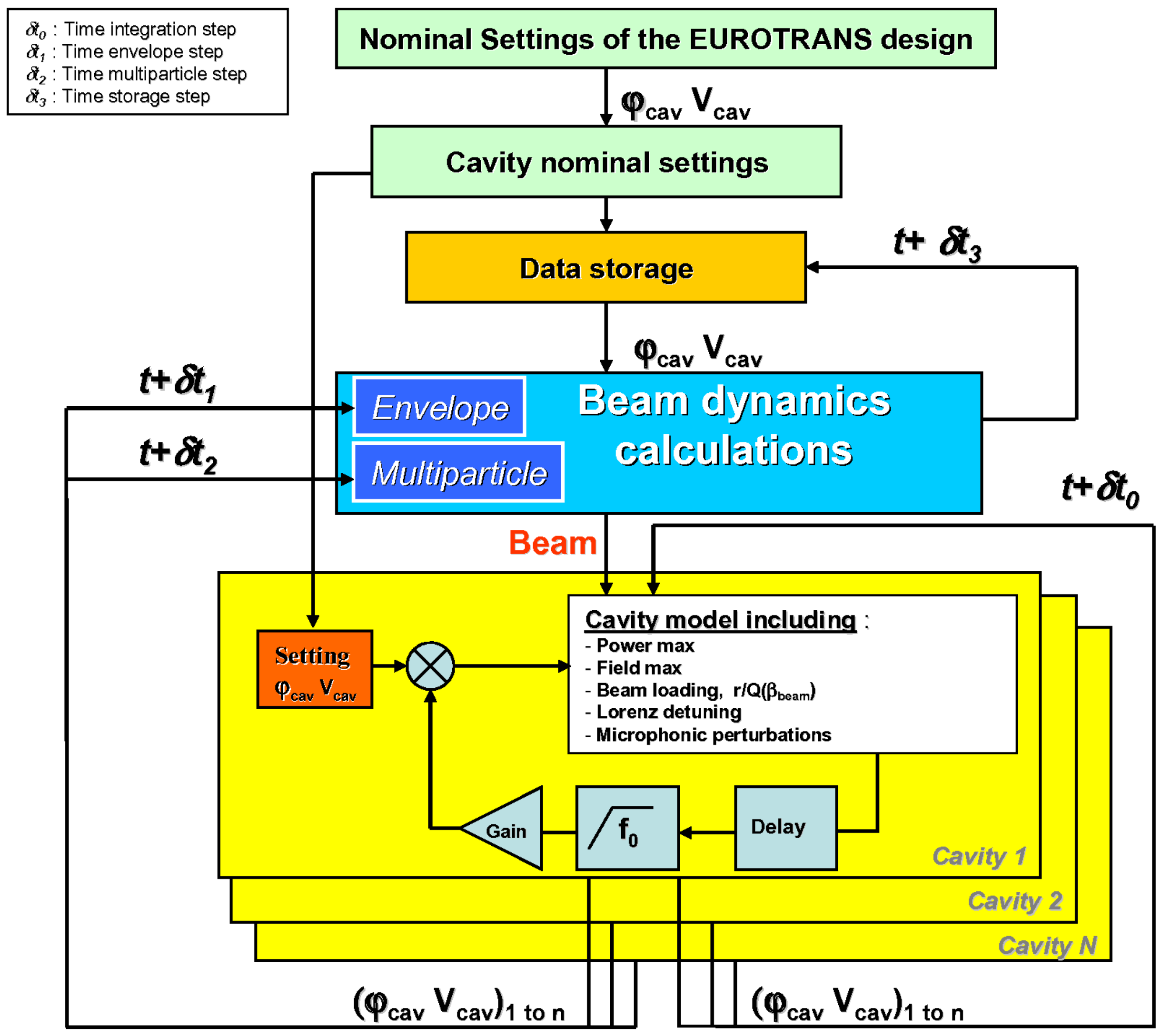
Courtesy: Jeon, SNS

The Rôle of Codes in Machine Tuning

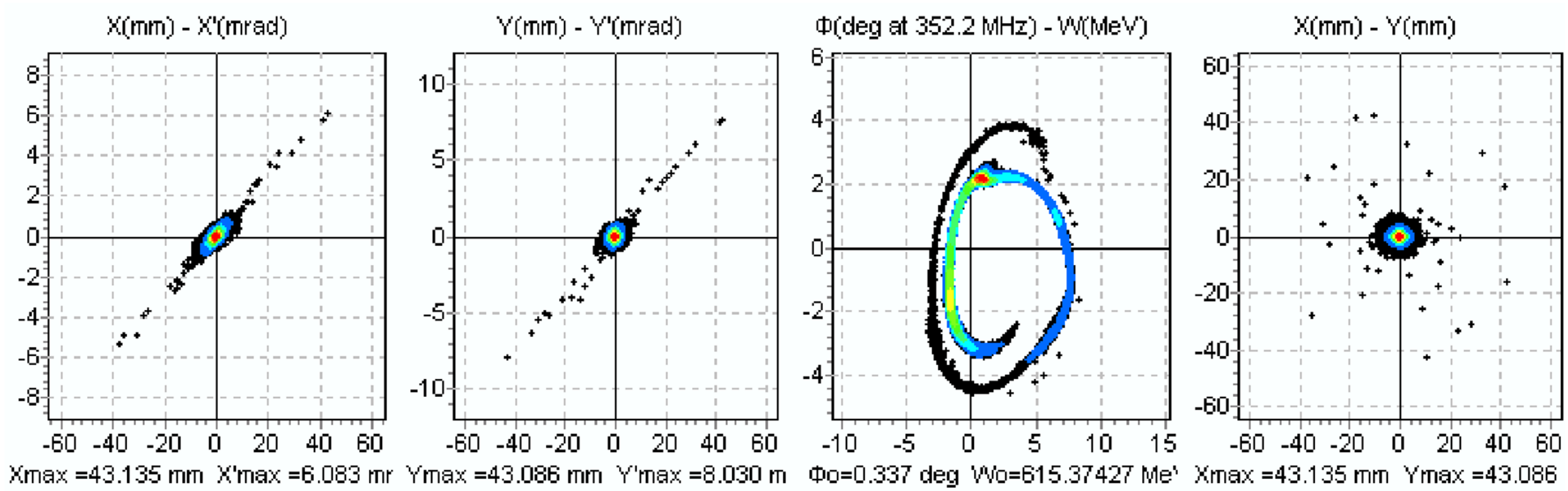
- Steering strategies, model-based *v.* empirical
- Matching strategies, model-based *v.* empirical
- Combined with beam measurements
  - profiles & halo
  - emittance
  - beam loss
  - longitudinal measurements
- Good developments in the use of tracking codes during machine operation (e.g. how to compensate for failed RF cavities)

Dynamic Compensation for Failed RF Cavities

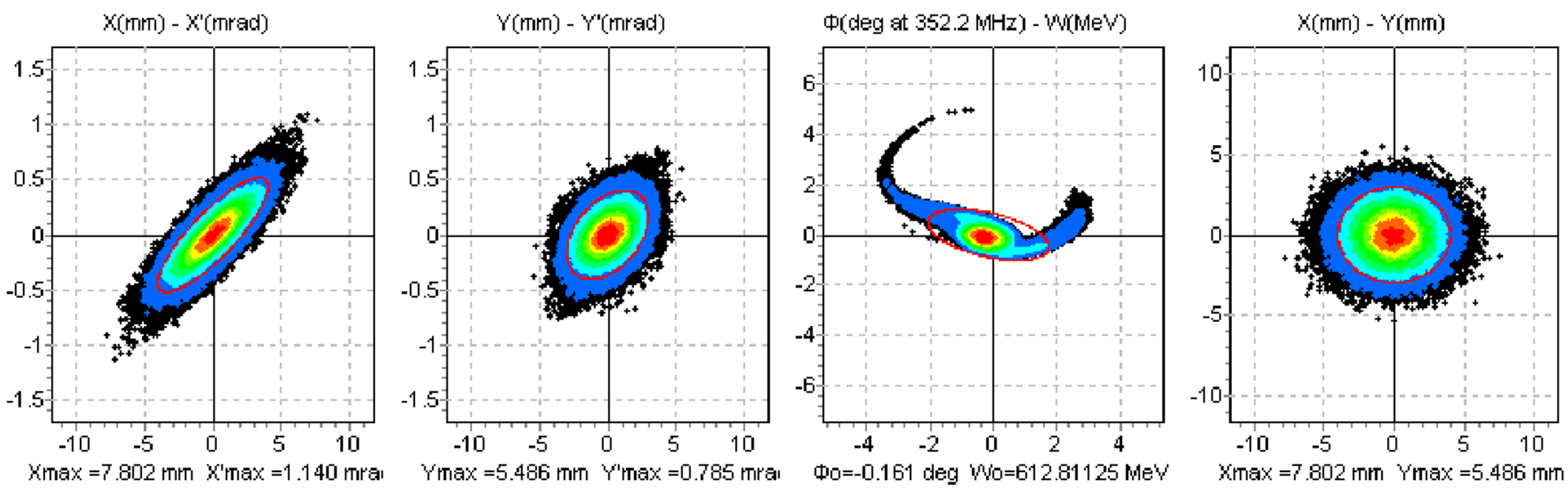
- XT-ADS superconducting linac (J-L Biarotte, D. Uriot)
- New simulation tool, mixes transient behaviour with full 6D description of beam dynamics via TRACEWIN. (PRST-AB, Vol 11, 072803, 2008)
- Simulation of 10 ms of linac operation takes ~22 hrs with 10,000 particles and 1 Gb memory
- Includes feedback loops
- Modelling suggests that fast returning system can be devised without interrupting the beam. <10% emittance growth, no beam loss after 3 ms.



Response of Beam to Failed RF Cavity (CEA-ADS)

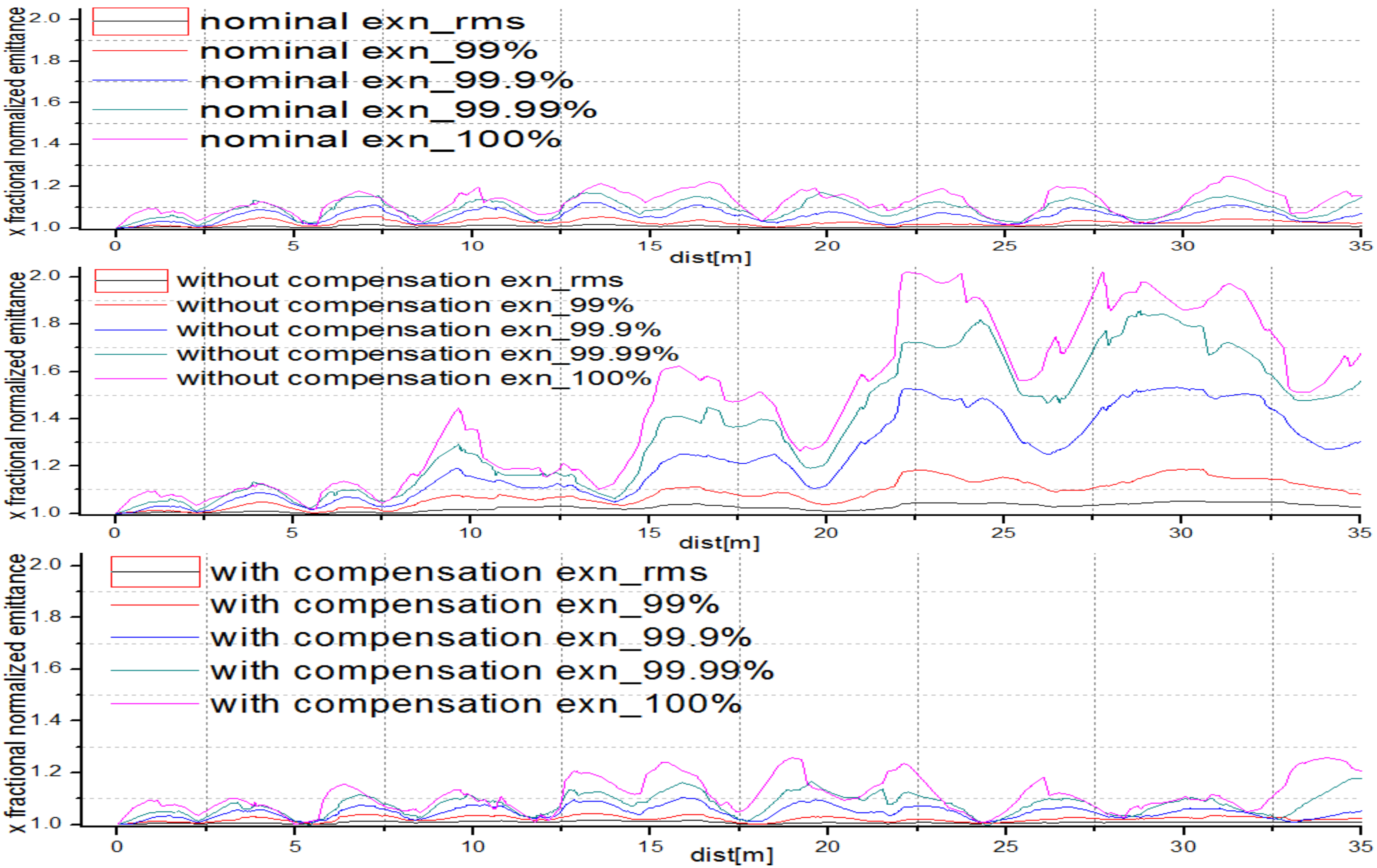


no compensation



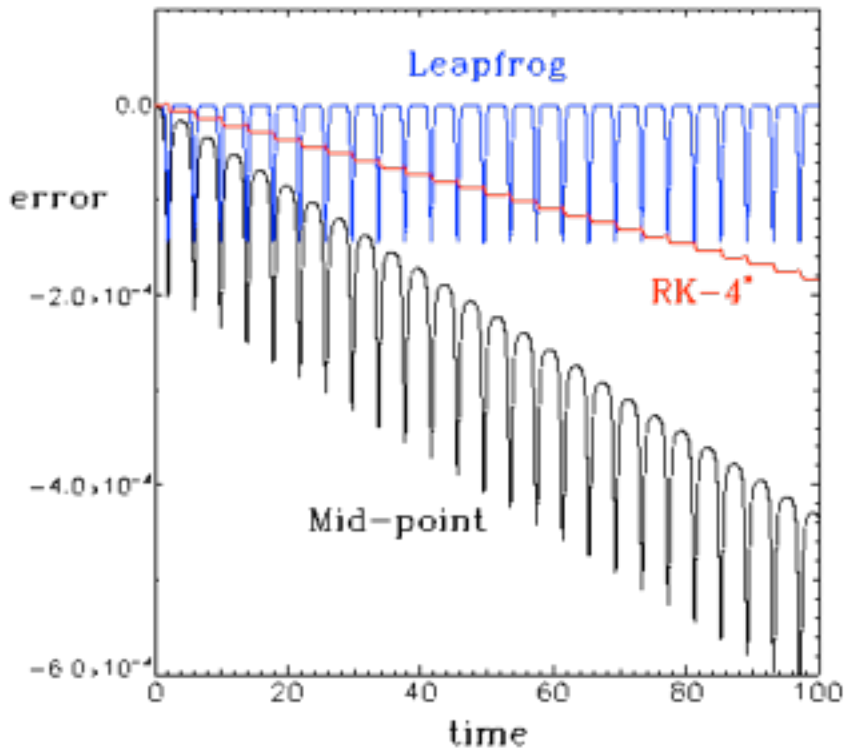
with compension

Chinese ADS Linac Compensation

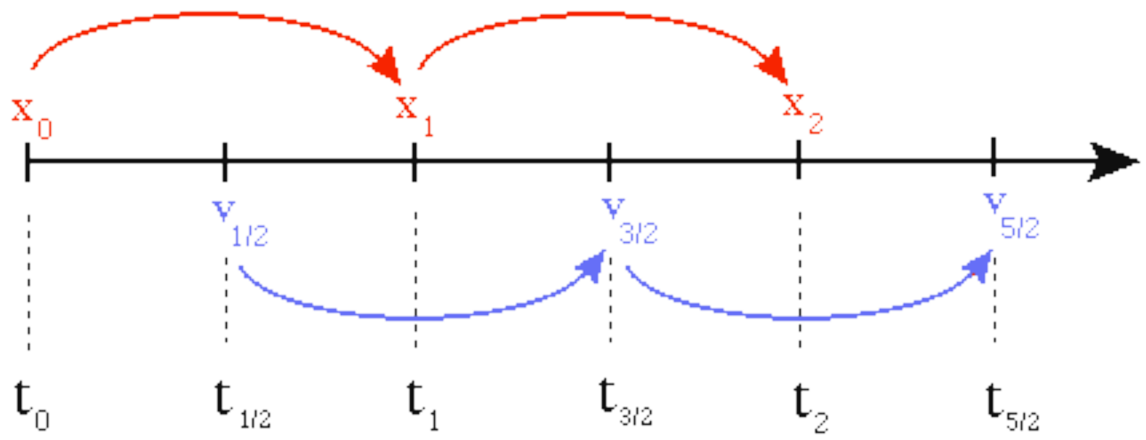


Limitations with Rings Codes

- Need to track particles for many turns
  - convergence issues, build up of errors
  - With fast parallel processors, can manage ~10^4 turns (FAIR requires ~10^6, probably impossible at the present time)
  - Sometimes resort to analytical field models
  - Halo modelling more difficult (less reliable) than in linacs.
  - Instabilities hard to model (treatment via impedances, approximations) - **important issue**



Need for symplectic algorithms



Step length must be chosen to allow plasma oscillations to be represented $(\omega_p h/\beta c \ll 2)$

Example Code: IMPACT

- IMPACT=Integrated Map and Particle Accelerator Tracking
- Models beam dynamics with space charge in linacs; MARYLIE-IMPACT is a development to include rings.
- Key features:
  - map generation capabilities
  - 3D parallel Poisson solvers
  - detailed treatment of RF cavities (*c.f.* quads + fringe fields)
  - computes trajectory and maps around that trajectory
  - particle manager to reduce communication and obtain high performance

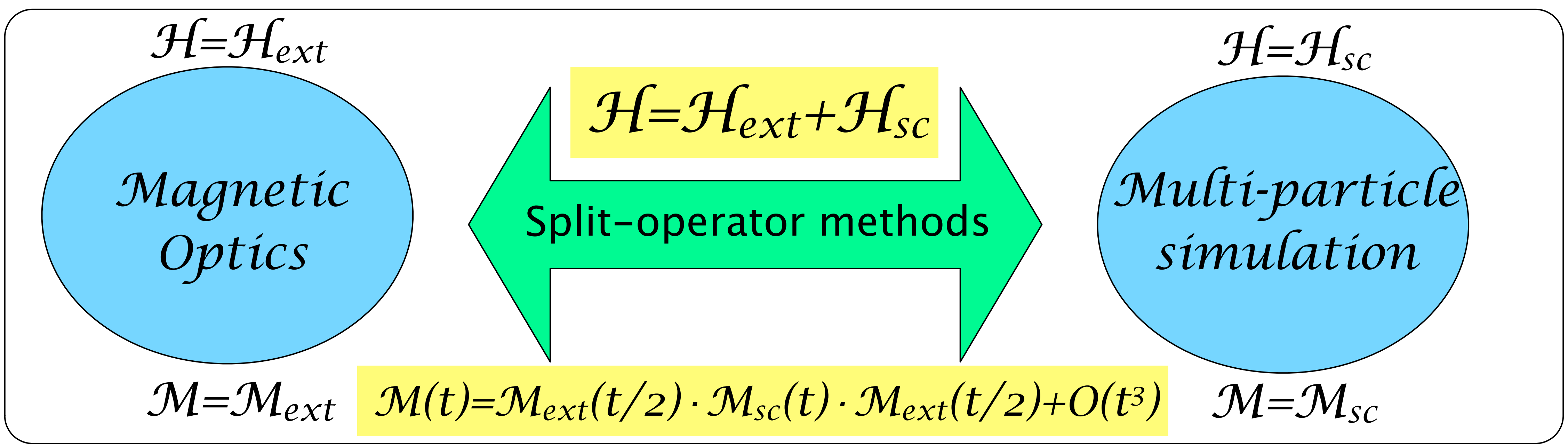
Example Code: IMPACT

- IMPACT=Integrated Map and Particle Accelerator Tracking
- Models beam dynamics with space charge in linacs; MARYLIE-IMPACT is a development to include rings.

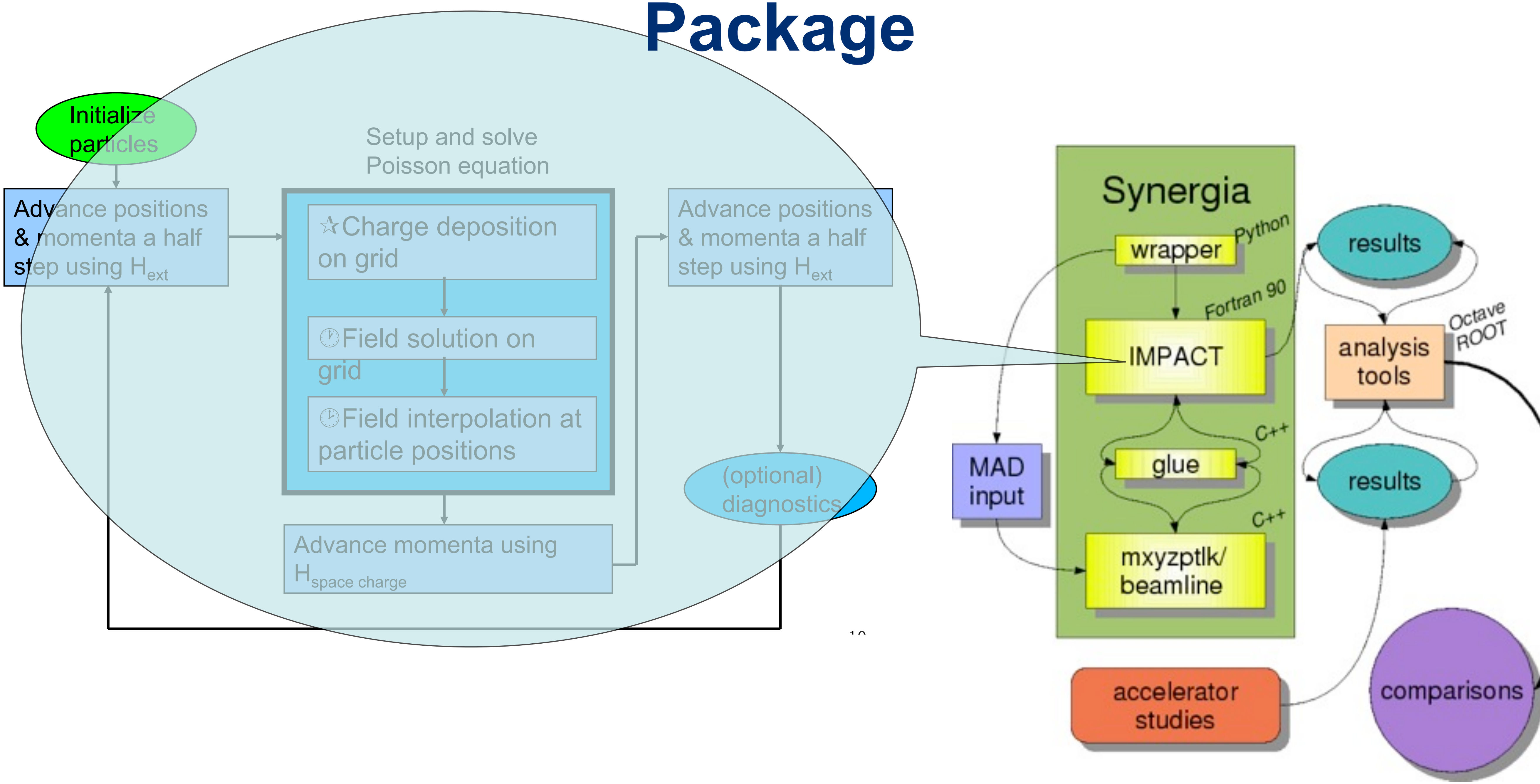
Philosophy:

Do not take tiny steps to push 100m particles

Do take tiny steps to compute maps; then push particles with maps



Components of a typical Beam Modelling Package



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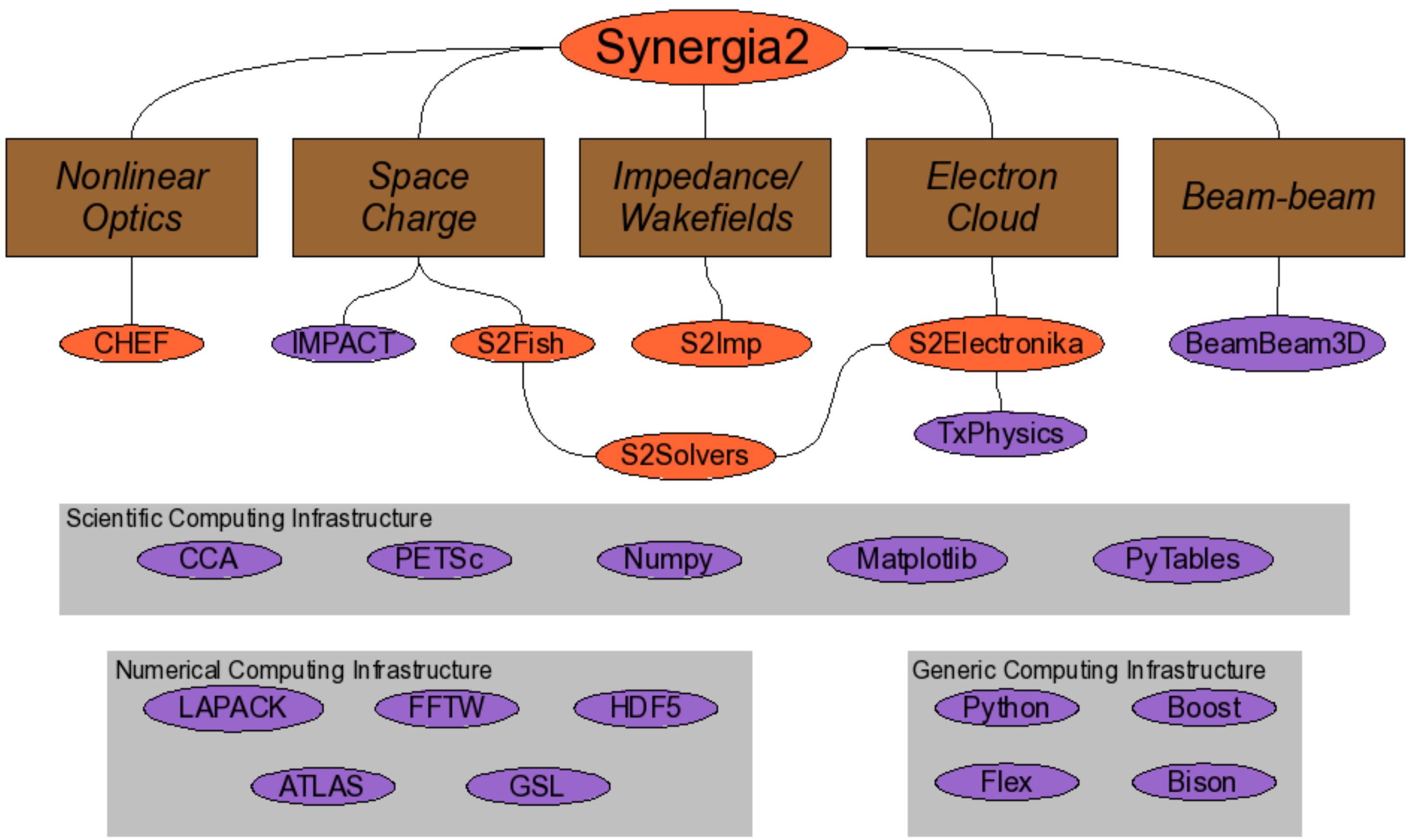

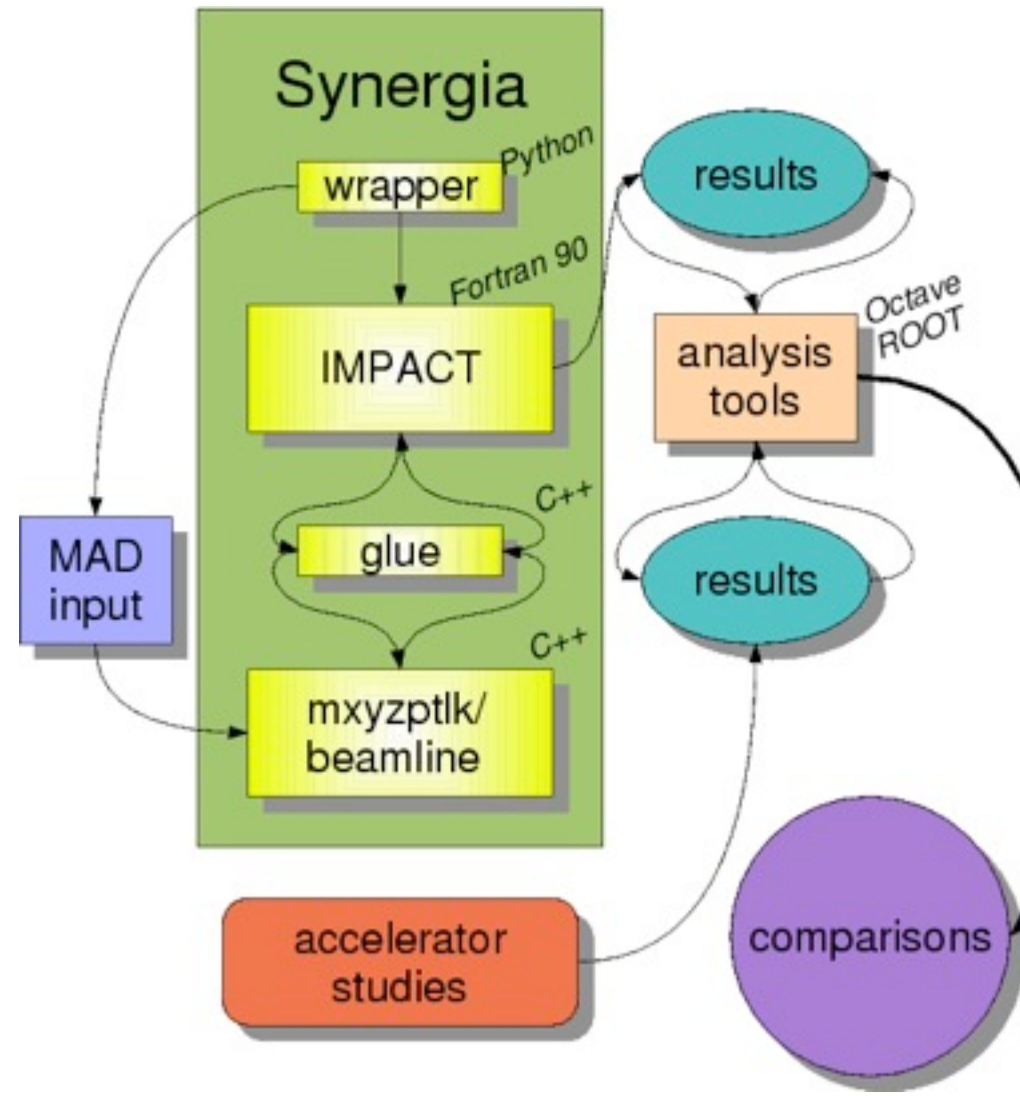

Synergia: Fermilab code, P. Spentzouris

Rings Codes: Typical Inventory

- Single particle transport through various types of lattice elements
- Magnet Errors, Closed Orbit Calculation, Orbit Correction
- Charge exchange injection foil and phase space painting
- RF and acceleration
- Longitudinal impedance and 1D longitudinal space charge
- Transverse impedance
- 2.5D space charge with or without conducting wall beam pipe
- 3D space charge
- Field maps
- Feedback for Stabilisation
- Apertures and collimation
- Study of mechanism for instabilities including Electron Cloud Model
- Suite of routines for beam diagnostics.

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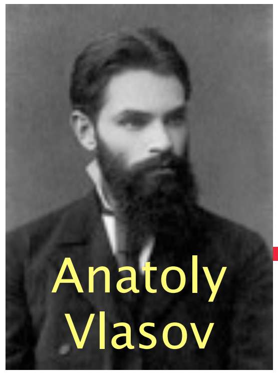


Vlasov Solvers

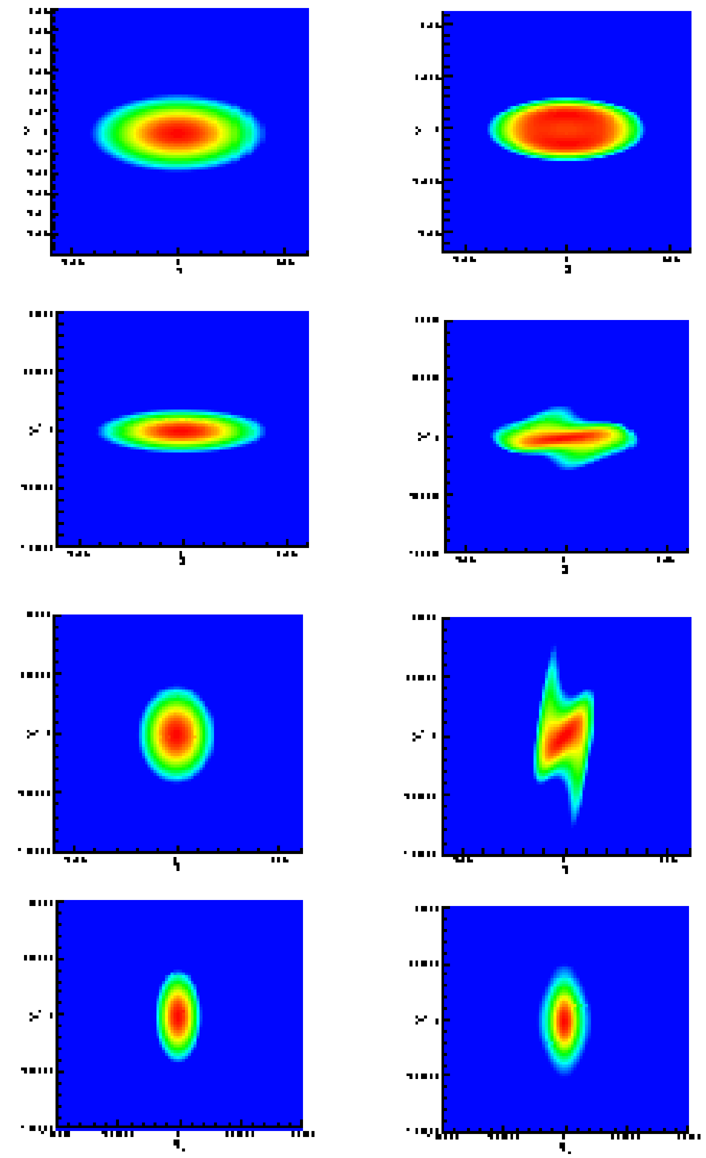
- High intensity beams modelled using Vlasov's equation for the distribution function $f(\mathbf{x}, \mathbf{v}, t)$:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f + \frac{q}{m}(\mathbf{E} + \mathbf{v} \wedge \mathbf{B}) \cdot \nabla_{\mathbf{v}} f = 0,$$

  generally coupled with Poisson's and Maxwell's equations.

- Numerical simulations performed using PIC methods.

- Important noise in PIC methods especially in poorly populated regions of phase-space makes it hard to see phenomena like
  - particle trapping (strong Landau damping) in plasmas
  - halo formation in beams
- Computers now powerful enough to do realistic physics using a grid in 4D and 6D phase space.
- Provides alternative to PIC code for benchmarking



Vlasov solver: 100 mA proton beam in alternating hard-edged electric quadrupole channel.

Ideally codes should include:

- Any type of RF resonator (3D fields)
- Static ion optics devices (3D fields)
- Radio-frequency quadrupoles (RFQ)
- Drift Tube Linacs (DTL)
- Couple Cavity Linacs (CCL)
- Different types of RF cavity (spokes, elliptical, CH-mode etc)
- Solenoids with fringe fields (model and 3D fields)
- Bending magnets with fringe fields (model and 3D fields)
- Electrostatic and magnetic multipoles
- Multi-harmonic bunchers (MHB)
- Axial symmetric electrostatic lenses
- Entrance and exit of HV decks
- Accelerating tubes with DC voltage
- Transverse beam steering elements
- Stripping foils, films for heavy ion beams
- Collimators: horizontal and vertical jaw slits

Codes should be capable of:

- A wide range of E-M elements with 3D fields
- End-to-end simulations from source to target
- Simultaneous tracking of multiple charge states
- Interaction of beams with strippers
- Automatic transverse and longitudinal beam tuning
- Error simulations for all elements: static and dynamic errors
- Realistic correction procedure: transvers and longitudinal
- Simulation with large number of particles for large number of seeds
- Beam loss analysis with exact location of particle loss
- Possibility of fitting experimental data: beam profiles etc
- H- stripping; black body radiation, residual gas, Lorentz stripping
- Inclusion of particle decays
- Accurate non-linear tracking
- Bunch-bunch interaction
- Development to parallelised version in order to simulate actual number of beam particles.

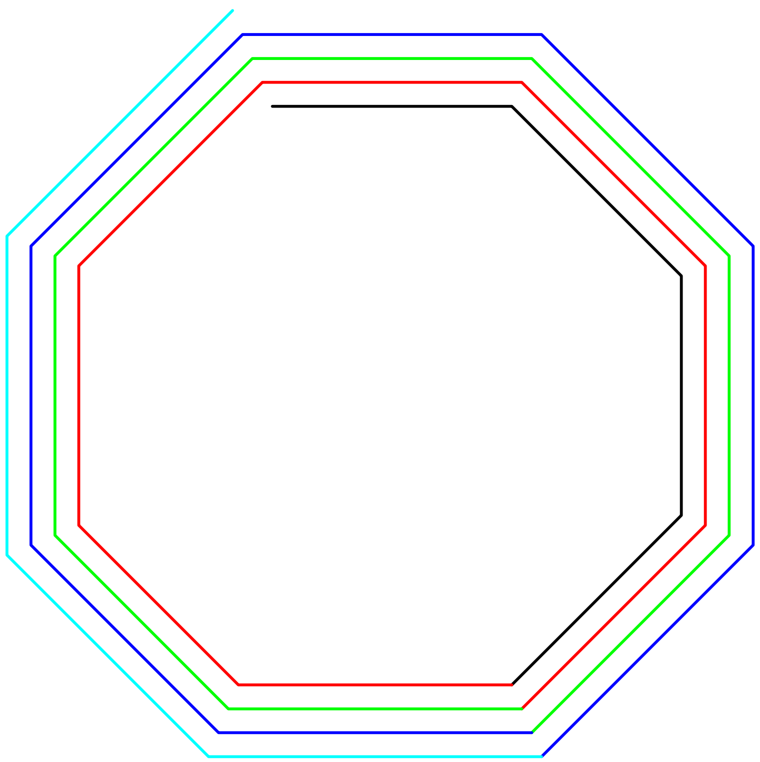
Topical Issues

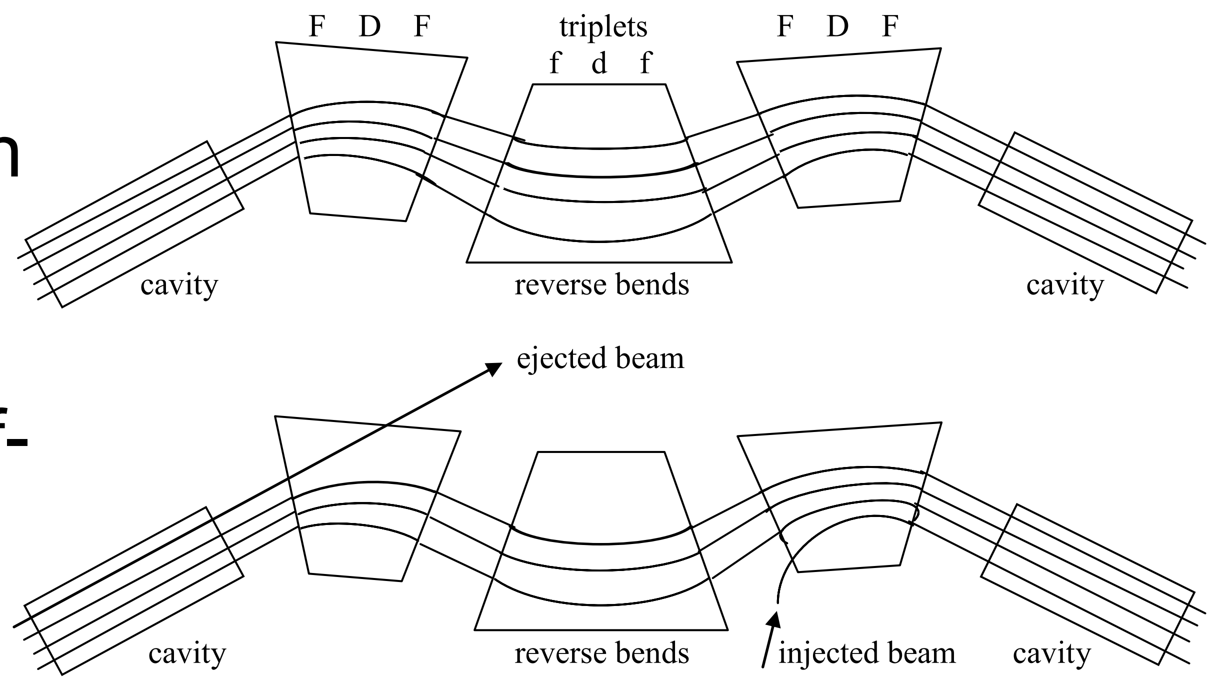
- Modelling FFAGs with space-charge.
- Modelling accelerators with fully 3D field maps.
- Discrepancies between commonly used codes (e.g. TraceWin and Impact for linacs).
- Improved codes/mechanisms for operational simulation (e.g. react to RF breakdown).
- Use of codes to help develop high reliability machines.
- Development of a 3D Vlasov solver.
- Treatment of interacting bunches with different energies (no common rest-frame for Poisson solver)

Treatment of Beams in RF Cavities

"Orbit Separated Cyclotron" (OSC)

- 3-10 MW, 1-1.5 GeV, cw driver for ADSR
- Spiral magnet system with each "ring" requiring different combined function magnet designs
- Separated magnet arcs but common rf cavities
- Beam dynamics similar to linacs (trying to model with TraceWin and IMPACT)
- Modelling with "standard" codes suggested design is valid; modelling with off-axis rf fields written in suggests all beam lost,
- R&D needed over beam behaviour in off-axis rf fields





Do we need a Titan for Accelerator Studies?

- How good are designs done on a laptop
- Do we really need to model 10^9 particles or is 1000 enough?
- Reminder: the MUON1 project at RAL uses many more processors than Hartree.

Other comments:

- Is the advent of fast, high-performance computers at the expense of “proper” programming?
  - do they make clever numerical analysis techniques redundant?
  - does it matter how equations are coded?
- Could we do just as well on a desktop with careful coding?

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Summary

- Many codes, some specific, some general, with different levels of complexity and sophistication.
- Codes often demonstrate how poor is our understanding of how our machines work.
- Perhaps we put too much emphasis on how well codes should predict beam behaviour
  - *Machines are never built exactly like our computer models say they should be.*
  - *There are always unknown errors introduced during fabrication & assembly*
  - *We never know the exact initial conditions*
- We can come close, and the codes will give a good indication of what the beam will look like
- It is important to to show how the beam will change with machine parameters (errors, cavity failure etc)
- Simulations can predict much more than diagnostics can achieve
- Despite huge advances in computer power and availability, there is still a great deal to address