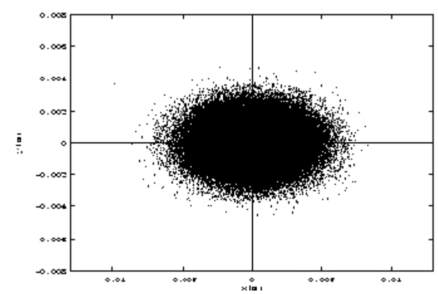
Beam Dynamics Overview

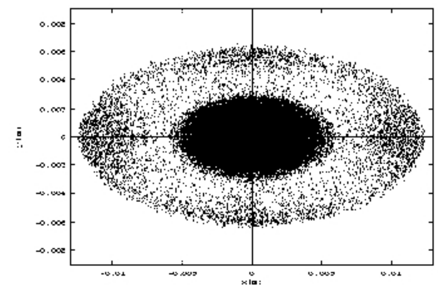
Outline

- **Introduction**
  - Scientific Goals
  - Beam Dynamics Team
  - Overview of our beam dynamics approach
- **Accelerator Physics**
  - Beam-Beam
  - Space Charge in Linacs
  - Space Charge in Rings
- **Applied Math Issues**
- **Comp. Sci. Issues**
- **Leveraging**
- **Conclusion**

Importance of the Beam Dynamics Effort to the HENP Mission

- Large scale beam dynamics simulations, used in concert with theory and experiment, are essential to understanding important issues that affect present and proposed accelerator facilities:
  - Luminosity at Tevatron
  - Beam losses at FNAL and BNL boosters
  - Beam-beam effects at LHC and RHIC
  - Beam halos
  - Electron cloud effects*
  - E-cooling in Tevatron and RHIC





- High fidelity 3D simulations of certain phenomena (beam-beam collisions, space charge effects) demands the use of parallel supercomputers
  - Large-scale simulations
  - Multiple simulations in a large parameter space

*will be discussed in W. Mori's talk

Goals and Approach

- Develop a set of interoperable software modules to describe necessary beam dynamics effects
- Integrate these components in an extensible framework to compose accelerator physics applications
- Develop parallel, scalable algorithms to maximize the performance and flexibility of the physics modules
- Reuse existing beam dynamics packages wherever possible, develop new capabilities as needed
- Provide build system and code distribution tools, test suites and documentation; human interface and standard lattice description

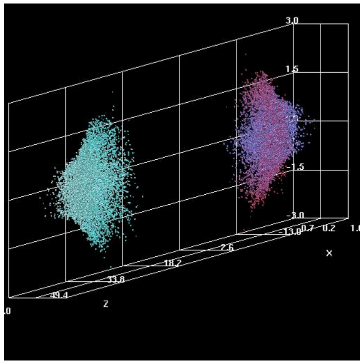
Our objective is to create a comprehensive simulation environment capable of modeling a broad range of accelerator physics effects

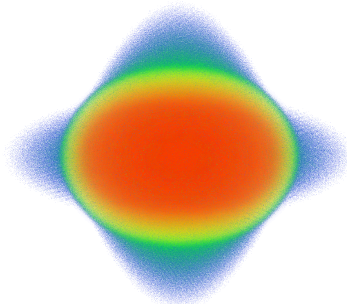
Beam Dynamics Team Members

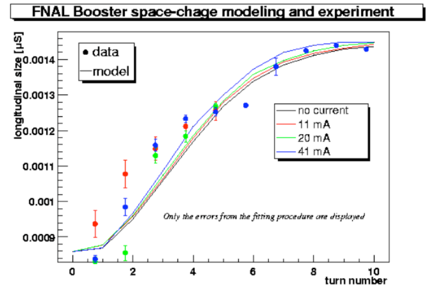
- **LBNL: A. Adelmann, P. Colella*, G. Fubiani***, M. Furman, R. Gerber, P. McCorquodale*, E. Ng, J. Qiang, R. Ryne, D. Serafini*, C. Siegerist**, J.-L. Vay**
- **LANL: S. Habib, T. Mottershead, F. Neri, P. Walstrom, K. Campbell, D. Higdon, C. Rasmussen**
- **FNAL: J. Amundson, P. Spentzouris, N. Angeloff*****
- **BNL: R. Samulyak**
- **UCLA: V. Decyk**
- **U. Maryland: A. Dragt**
- **UC Davis: K-L. Ma, B. Wilson*****

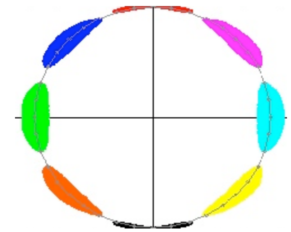
*APDEC
**NERSC/Viz
***Students

Beam Dynamics Collaboration Team







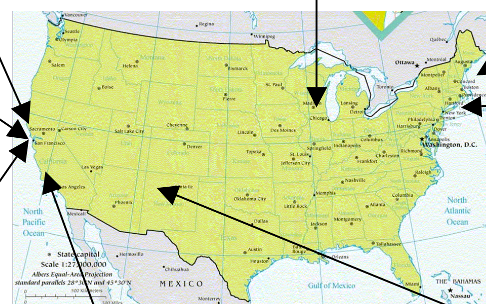


LBNL
Beam-beam modeling, space charge in linacs & rings, parallel Poisson solvers, collisions

UC Davis
Visualization, multi-resolution techniques

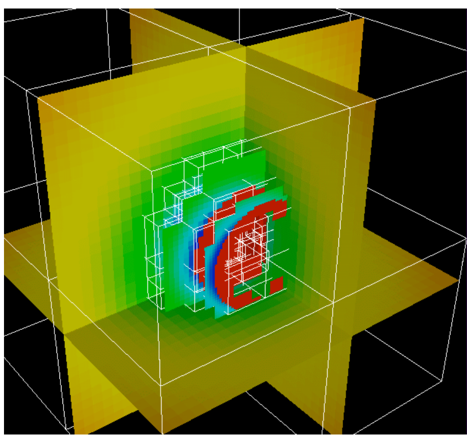
FNAL
Software Integration, Lie methods, space charge in rings, FNAL Booster sim/expt

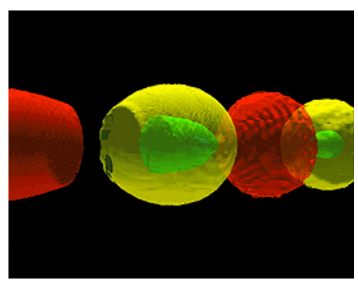
BNL
Wakefield effects, Space charge in rings, BNL Booster simulation

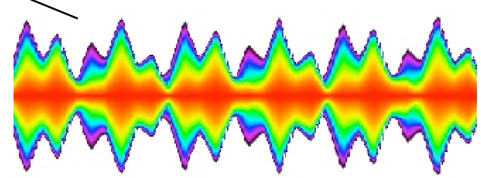


$$M=e^{:f_2:}\, e^{:f_3:}\, e^{:f_4:}\ldots$$
$$N=A^{-1} M A$$

U. Maryland
Lie Methods in Accelerator Physics, MaryLie







APDEC
Parallel Poisson Solvers, AMR

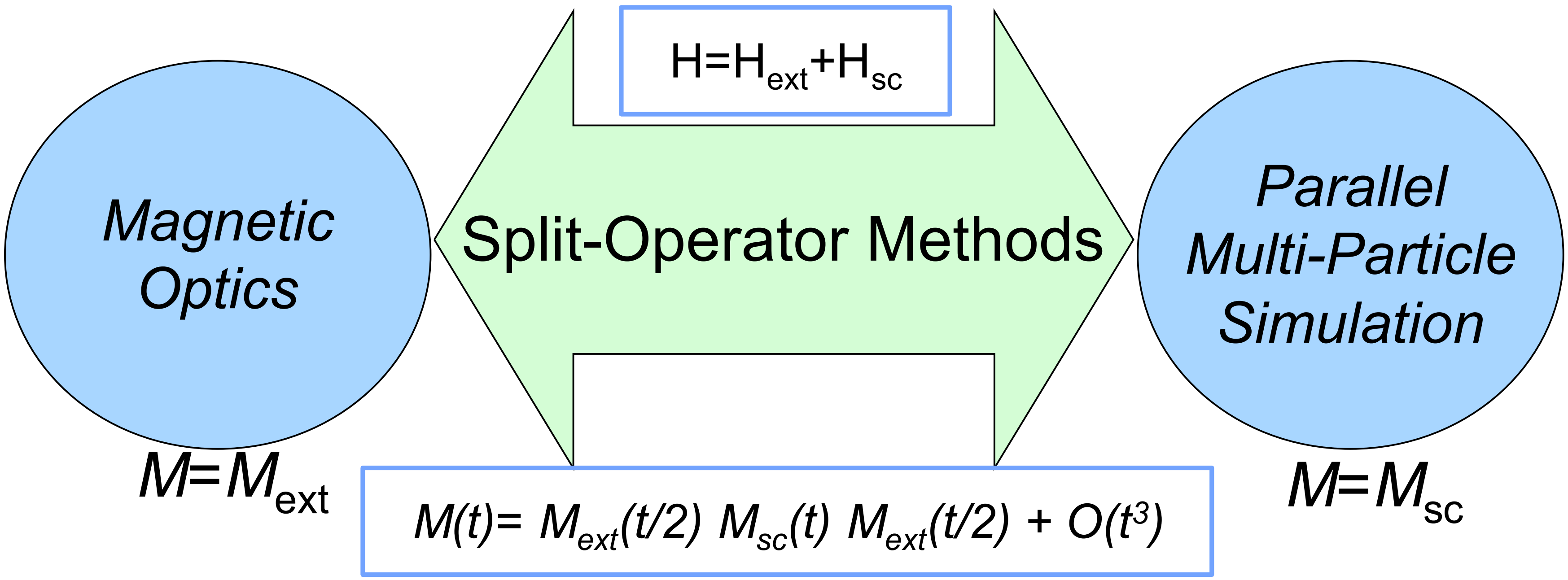
UCLA
Parallel PIC Frameworks

LANL
High order optics, beam expts, collisions, multi-language support, statistical methods

Beam Dynamics Overview

- The beam dynamics effort covers topics such as beam-beam effects, space-charge physics, wake field effects, high order optics, and intrabeam collisions
- Connections to HENP projects:
  - Modeling beam-beam effects in the Tevatron, LHC, and RHIC
  - Modeling high intensity beams in rings, including
    - ✔ FNAL booster, BNL booster, NLC damping rings, SNS ring
  - Modeling beams with space charge in linacs
    - ✔ SNS, SPL, KEK/JAERI
  - Modeling electron-cloud effects
    - ✔ LHC
- Applications share core modules wherever possible, e.g. space charge solvers

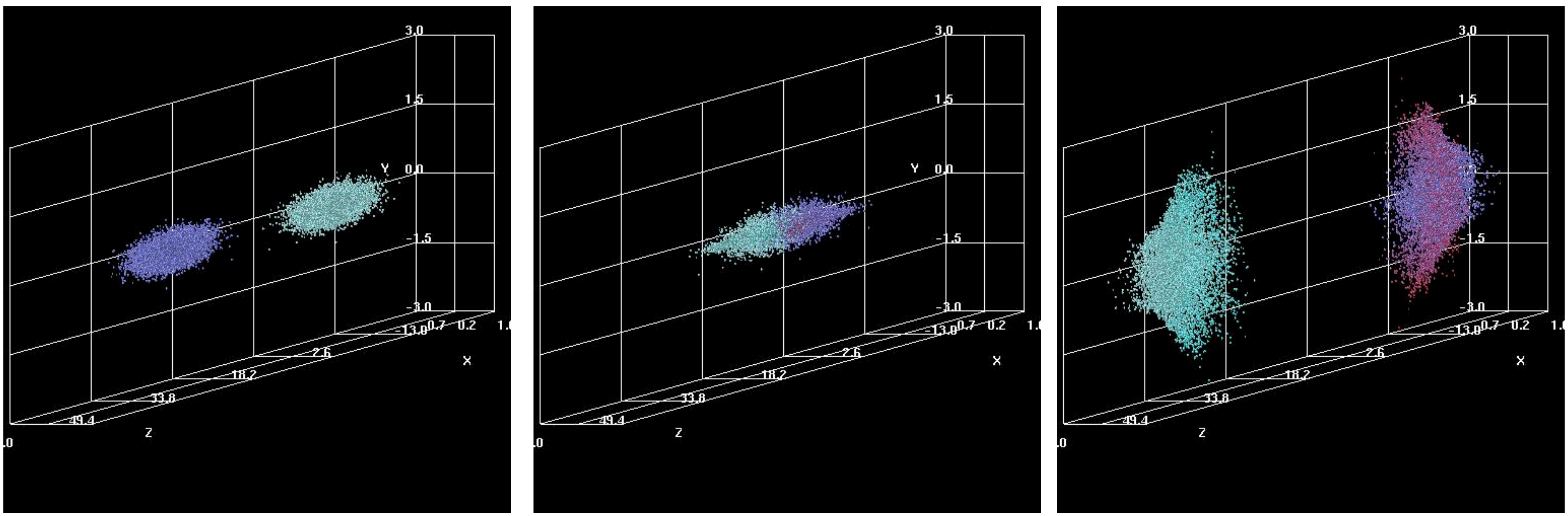
Split Operator Approach



- **Note that the rapidly varying s-dependence of external fields is decoupled from slowly varying space charge fields**
- **Leads to extremely efficient particle advance:**
  - **Do not take tiny steps to push ~100M particles**
  - **Do take tiny steps to compute maps; then push particles w/ maps**

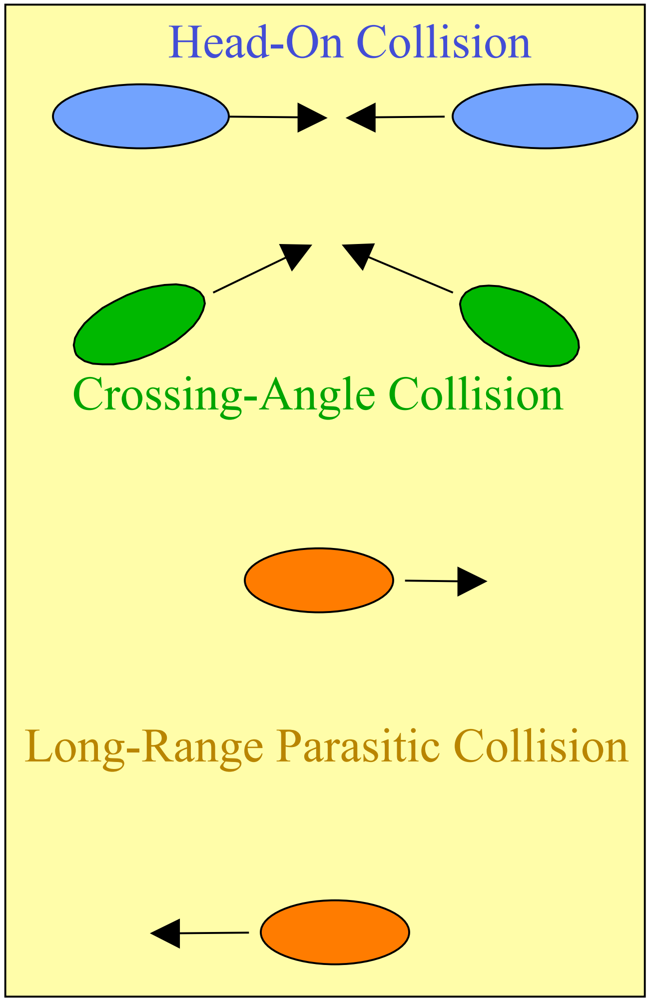
Simulation of Beam-Beam Effects

- **Beam-beam interaction sets a strong limit on the luminosity of high energy colliders**
- **We have developed new code modules which can be used to model beam-beam effects with high accuracy and over long distances using parallel computers**



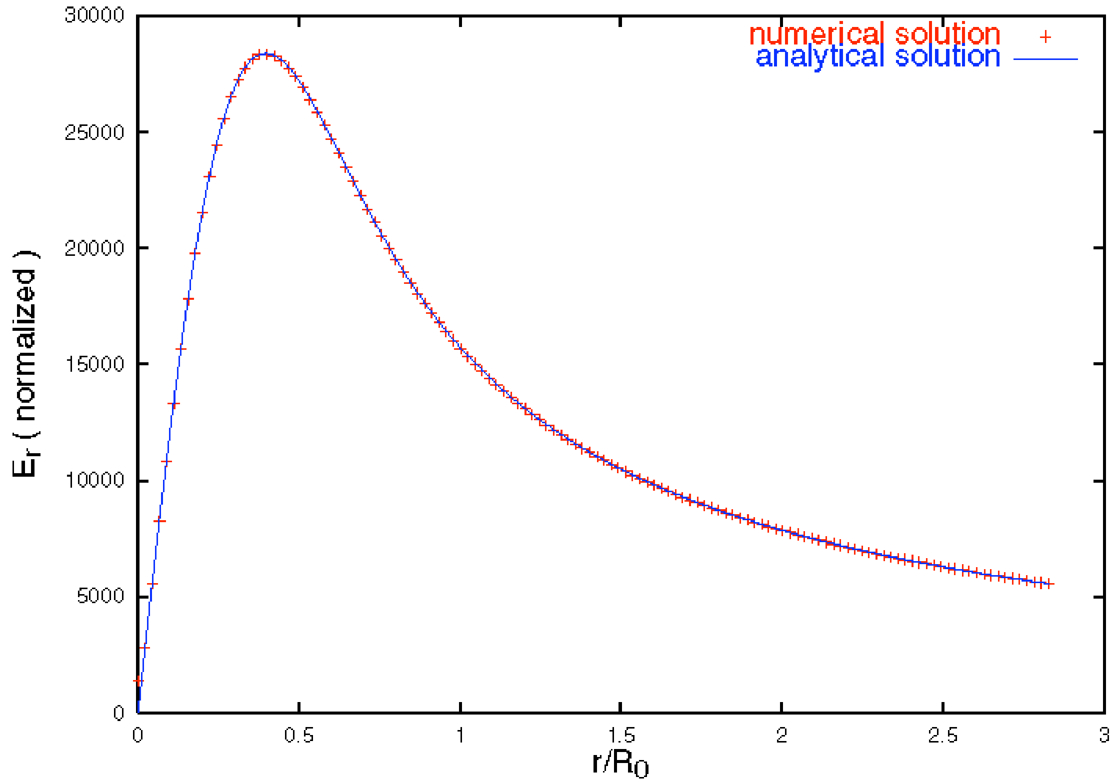
Main Features

- Multiple physics models:
  - strong-strong (S-S); weak-strong (W-S)
- Multiple-slice model for finite bunch length effects
- New algorithm -- shifted Green function -- efficiently models long-range parasitic collisions
- Parallel particle-based decomposition to achieve perfect load balance
- Lorentz boost to handle crossing angle collisions
- W-S options: multi-IP collisions, varying phase adv,…
- Arbitrary closed-orbit separation (static or time-dep)
- Independent beam parameters for the 2 beams
- Now being used in parametric studies to predict pbar lifetime for the Tevatron as a function of:
  - Aperture size, proton emittance, proton intensity, antiproton emittance, beam-beam separation, chromaticity, and machine bare tune

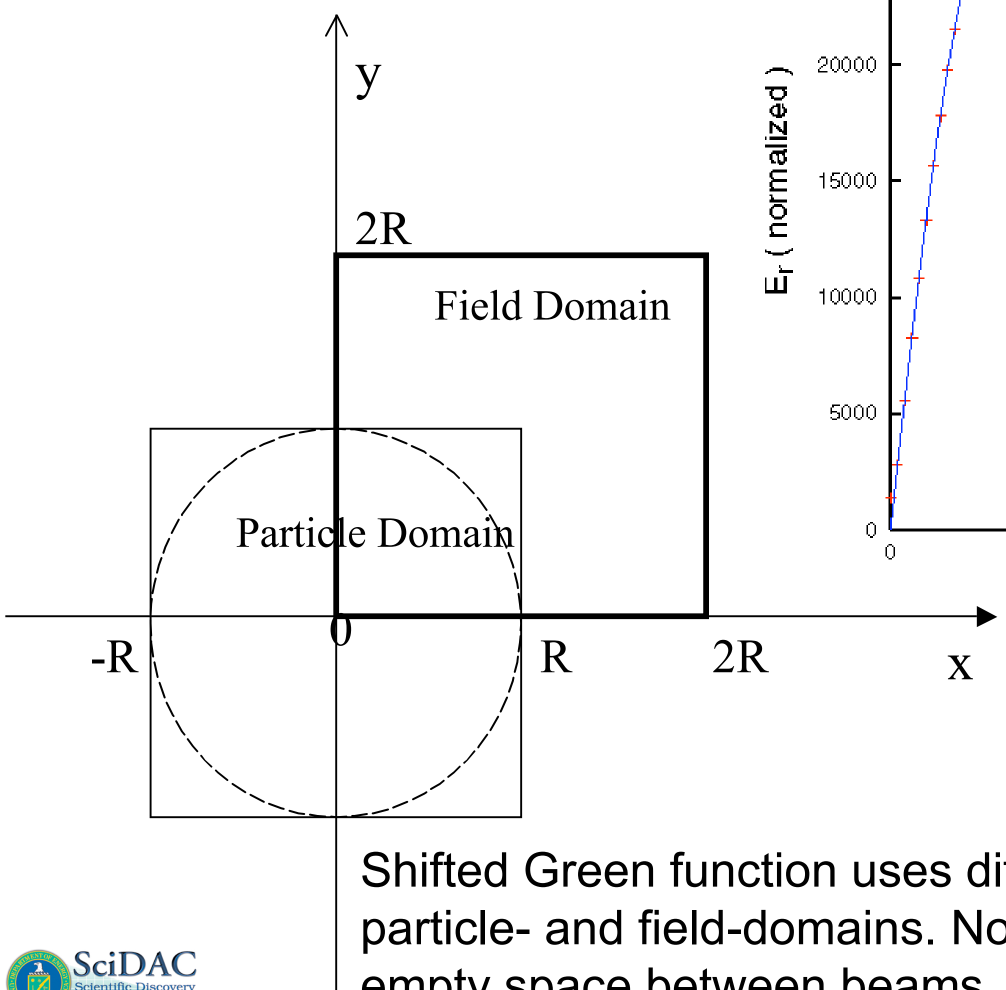


Comparison between Numerical Solution and Analytical Solution

Radial Electric Field vs. Distance inside the Field Domain with
Gaussian Density Distribution



Good agreement between analytical and numerical calculation of electric field vs. radius in a Gaussian beam.

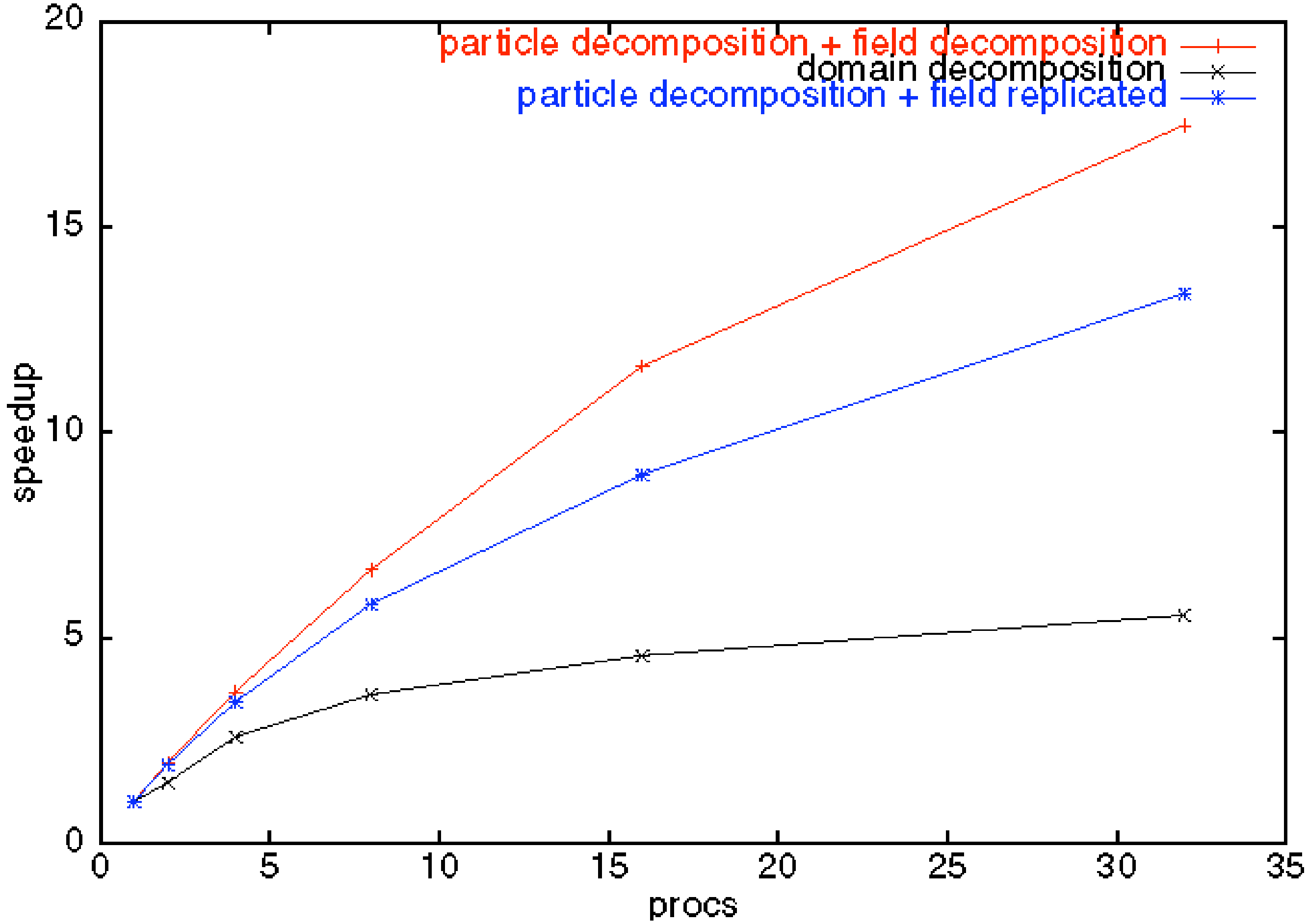


Shifted Green function uses different particle- and field-domains. No grid in empty space between beams.

Weak-strong beam-beam test case: 1M particles, 1000 turns, 74 maps/turn

PEs	time (sec)
128	1612
256	858
512	477
1024	303
2048	212

A Comparison of Scalability in Strong-Strong Model Using
a) Domain-decomposition b) Particle-Decomposition c) Particle+Field-Decomposition

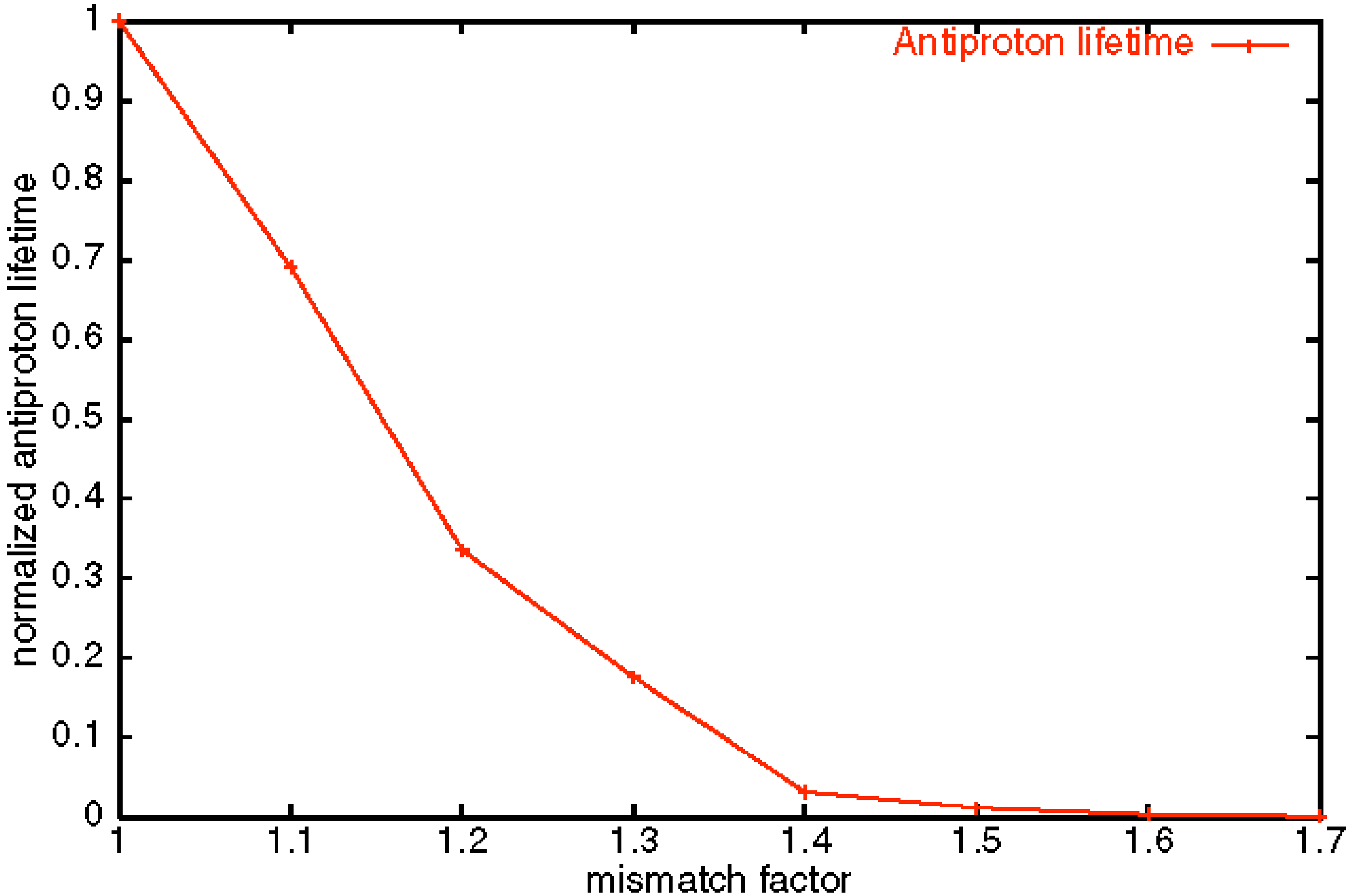


Due to nature of beam-beam interaction (extreme particle movement between kicks), standard approach to domain decomposition is not efficient. Hybrid particle+field decomposition is best for this type of problem.

SciDAC Scientific Discovery through Advanced Computing

Office of Science U.S. DEPARTMENT OF ENERGY

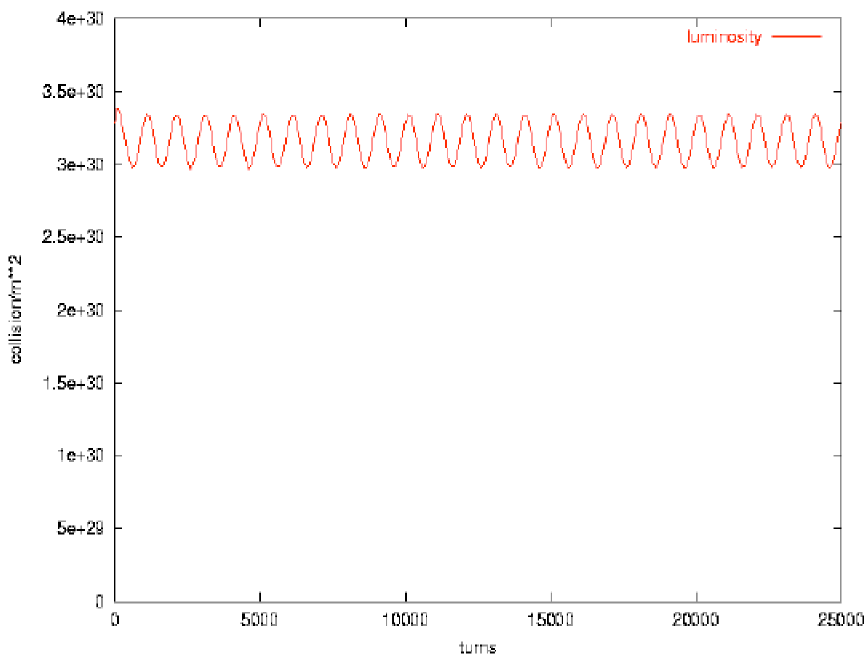
Antiproton Lifetime vs. Proton Mismatch Factor at 150 GeV in the Tevatron



Pbar lifetime depends strongly on mismatch factor of proton beam

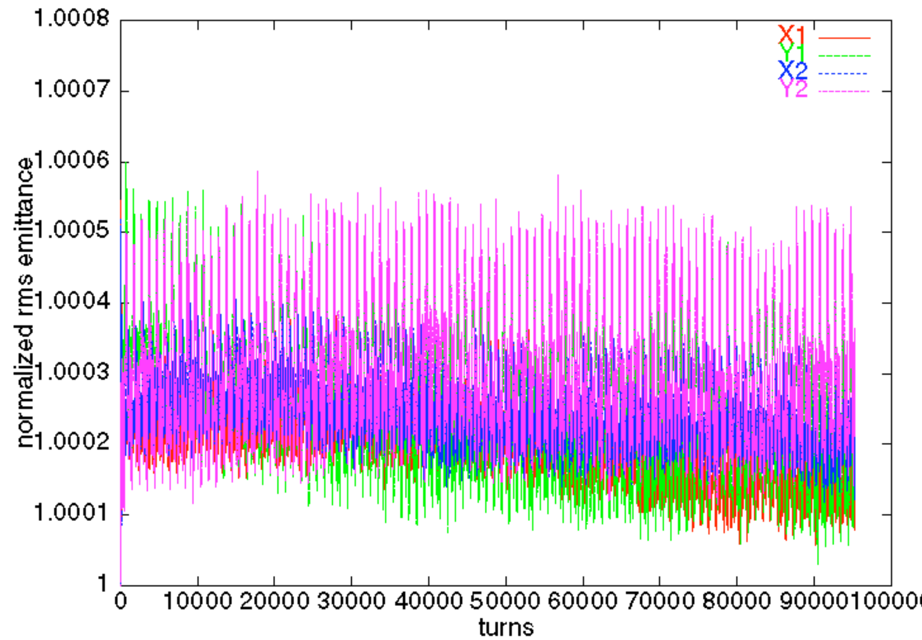
LHC Strong-Strong Beam-Beam Interaction Luminosity vs. Turns during Sweeping Process

Luminosity vs. turn #



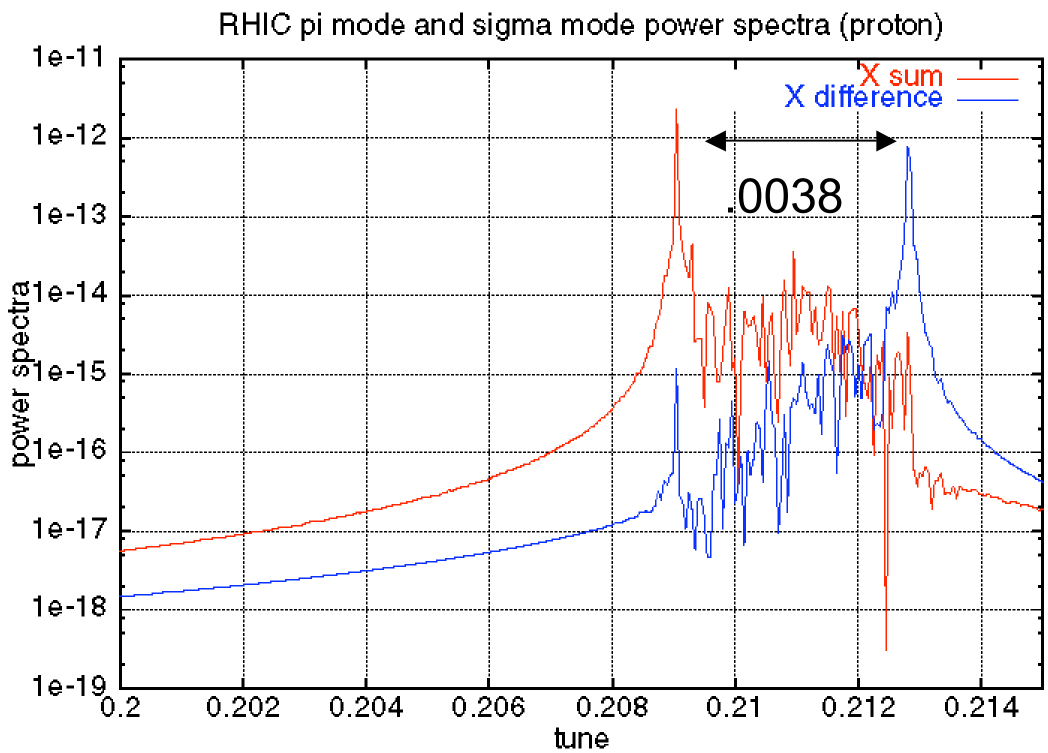
Clear signature of beam sweeping is present in luminosity observation…

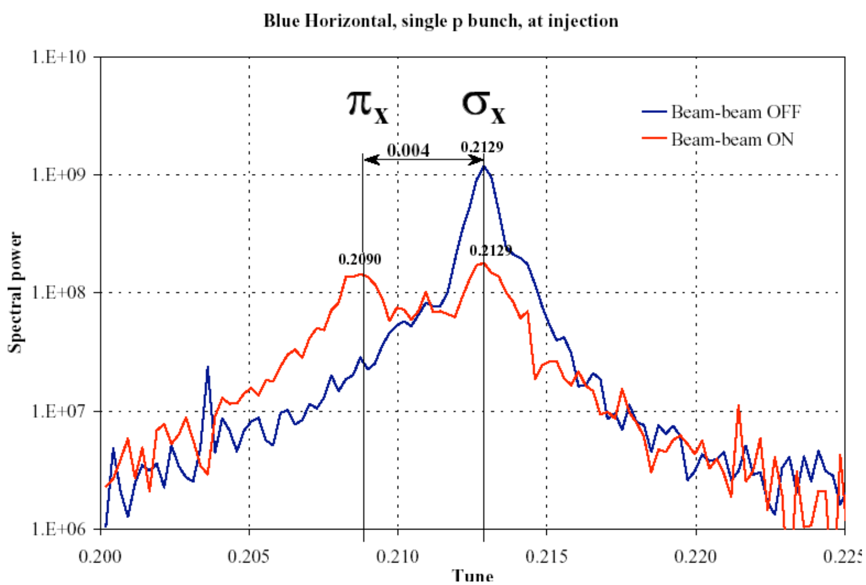
emittance vs. turn #



…but the sweeping does not hurt the beam emittance until intensity reaches ~10x nominal

RHIC strong-strong simulations: beam-beam spectrum





Simulation results are in good agreement with measurements of Fischer et al.

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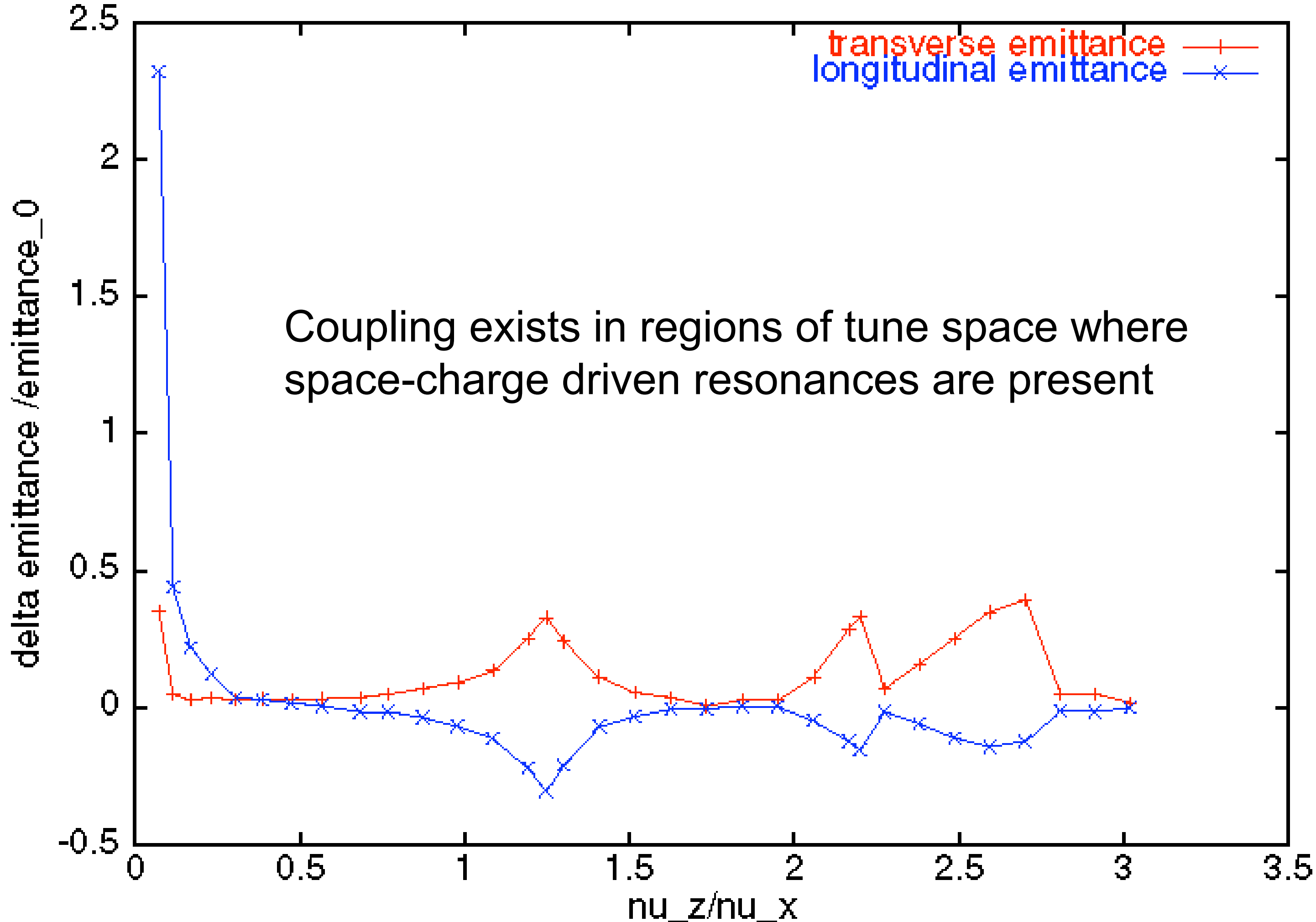
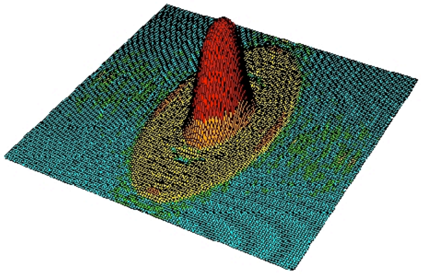
3D Parallel Simulation Studies of Anisotropic Beams (w/ I. Hofmann)

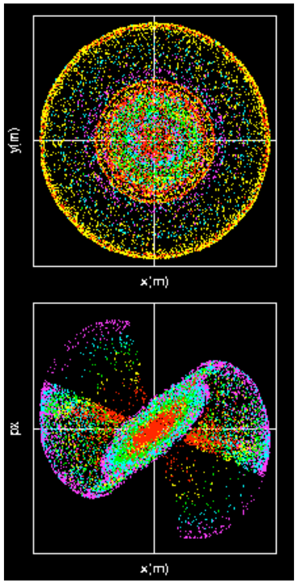
Emittance growth as a function of tune ratio (Kx=0.5, emittance ratio=2.0)

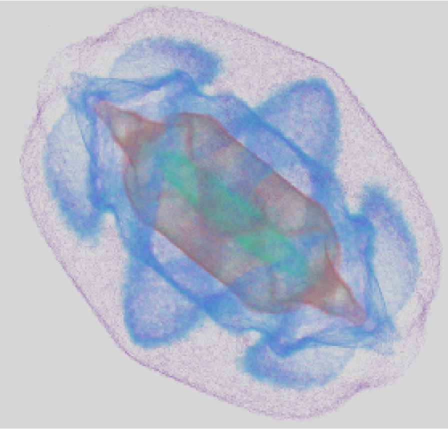


Parallel Beam Dynamics Timeline

- Roots in 1980s: Lie methods
- and early 1990s: LANL-funded PIC code development
  - 2D parallel PIC on TMC-CM5
- Mid 1990s: DOE Grand Challenge
  - LANL/SLAC/Stanford/UCLA effort
  - IMPACT developed
    - ✔ 3D space charge; 2 types of b.c.'s
    - ✔ Original parallelization via Ferrel-Bertschinger algorithm
    - ✔ Later modified to use particle manager
- 1999: DOE/HENP bridge funding to SciDAC project
  - Added LBNL, FNAL, BNL, JLab
- 2001: SciDAC Project
  - Extension from linac modeling to modeling high intensity beams in circular machines
  - Additional physics (beam-beam, wakes, collisions,…)
  - Extensible framework, integrated components







Space Charge in Linacs

- Re-use and further develop the modules of the IMPACT (Integrated Map and Particle Accelerator Tracking) code
- Split-operator approach combines parallel 3D space charge w/ beam optics
- Parallel implementation follows Decyk's particle manager approach; dynamic load balance; restart capability
- Recent physics enhancements include
  - 2 integrators (map-based, Lorentz force)
  - Multiple types of structures (DTL, CCDTL, CCL, SCL)
  - Integration through field maps
  - Additional solver boundary conditions (6 total)
  - Error study capability (field gradient, misaligment, rotation)
  - Family of codes: IMPACT, FIX2D/3D (envelope), THETA (design)
- Worldwide use: I. Hofmann (GSI), F. Gerigk (RAL), M. Ikegami (KEK/JAERI), D. Jeon (ORNL), FNAL
- Applied to analysis of LEDA halo expt; stability and equipartitioning of anisotropic beams; SNS linac

Extending the IMPACT paradigm

Moving beyond linac simulation requires…

- **Full nonlinear beam optics (MaryLie, MXYZPLT, MAD…)**
  - ✔ **On the fly computation of reference trajectory and maps**
  - **Nonlinear symplectic tracking**
  - **Integration and extension of existing capabilities**
  - **One example: MaryLie+IMPACT**

MaryLie/IMPACT

- Combine optics, control, and optimization capabilities of MaryLie with IMPACT solvers and RF cavity model
- Enhanced front end
  - MAD lattice description, also backward compatible w/ MaryLie
  - Methodical treatment of units
- Performance optimization of tracking routines (25% peak)
- Example suite includes benchmarks of test cases with known solutions
- Wake field module

ML/I is now being used to perform parallel 3D simulations including space charge and wake fields simultaneously

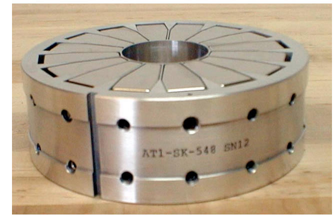
Wake Field Module and Applications

- Implements theoretical models (resistive wake forces, RLC contours, etc) applicable to resistive walls, RF cavities and other accelerator chamber elements
- Has a capability to use wake functions in tabular format
- Parallel software with low communications cost
- Test runs of an 800 MeV proton beam propagating in a simple FODO channel
- **BNL Booster Modeling:**
  - We have started numerical simulations of the beam dynamics of 200 MeV proton beams in the BNL Booster
  - Main elements of the Booster generating wake fields:
    - ✔ 36 dipoles, 48 quadrupoles (resistive wake field model is satisfactory)
    - ✔ Injection, dumper, tune, and ejection kickers. Wake fields cannot be approximated using analytical models; tabulated wake functions precomputed using a Maxwell equation solver

Performance

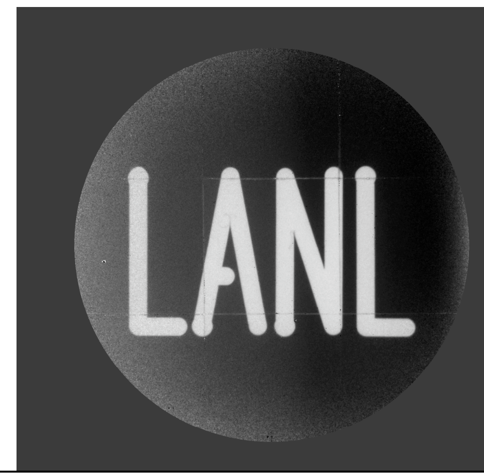
- Taylor series tracking routine performs at 375 MFLOP per processor on the NERSC IBM/SP
- Accomplished by
  - Code reorganization
  - Use of BLAS routine DGEMM
  - Loop unrolling
  - Thanks to NERSC User Services for their assistance
- Optimization of symplectic tracker is underway

Comparison with experiment: Realistic modeling of fringe fields and aberration effects



- Past experiments at ANL and BNL
- Recent proton microscope expt at LANL
  - Designed by T. Mottershead, LANL
  - Used 4 permanent magnet quads

Designed with MaryLie; Performed as Predicted



First microscope results

Magnified image 9 meters from the object. The edge resolution has been measured to be about 3 microns rms.

Toward a multi-language,extensible integration framework: Synergia

- Prototype supports F90, C++, and Python
- Reuse existing beam dynamics packages
  - IMPACT, MXYZPLT, MaryLie, ML/I, …
- Provide build system and code distribution tools
- Human interface and standard lattice description (MAD)
- Can be easily extended to include other physics modules and/or computation algorithms

Synergia Interface Example

```
ip = impact_parameters.Impact_parameters()
ip.processors(16,4)
ip.space_charge_BC("trans finite, long periodic round")
ip.input_distribution("6d gaussian")
ip.pipe_dimensions(0.04,0.04)
ip.kinetic_energy(0.400)
ip.scaling_frequency(201.0e6)
ip.x_params(sigma = .004 , lam = 1.0e-4)
ip.y_params(sigma = .004 , lam = 1.0e-4)
pz = ip.gamma() * ip.beta()*ip.mass_GeV
ip.z_params(sigma = 0.10, lam = 3.0e-4 * pz)
ip.particles(2700000)
ip.space_charge_grid(65,65,65)
booster = impact_elements.External_element(length=474.2,
                                           kicks=100, steps=1, radius=0.04,
                                           mad_file_name="booster.mad")
for turn in range(1,11):
    ip.add(booster)
my_impact = impact.Impact(ip)
currents = ( 1.0e-10, 0.011, 0.020, 0.042 )
for current in currents:
    ip.current(current)
    my_impact.prepare_run("bs1_I%0.3f" % current,
                          clock_limit = "01:30:00")
    my_impact.submit()
```

Identifiable names

Beam parameters specified in m, GeV

Trivial use of Python to configure run

multiple runs in one script

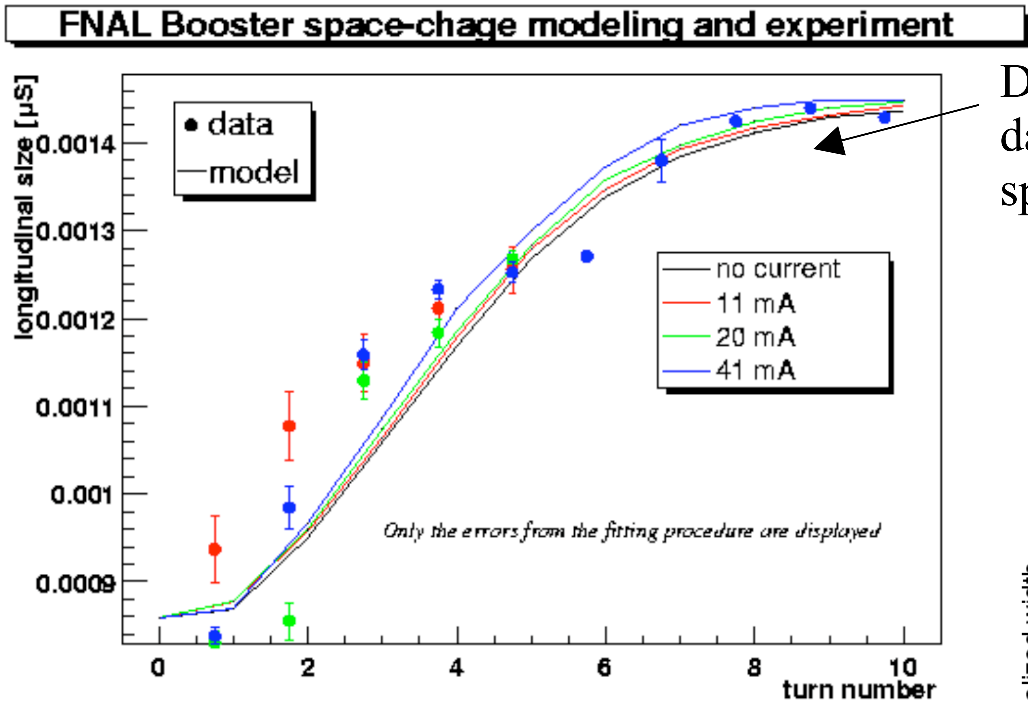
FNAL Booster Study

- **The Booster is a rapidly cycling machine (66 ms cycle) that accelerates protons from 400 MeV to 8 GeV**
- **The success of the FNAL neutrino program, the quest to understand the nature and properties of neutrino masses, depends on the Booster**
- **Multi-particle dynamics effects, such as space-charge effects, are responsible for machine losses which limit intensity**

FNAL Booster Experiments

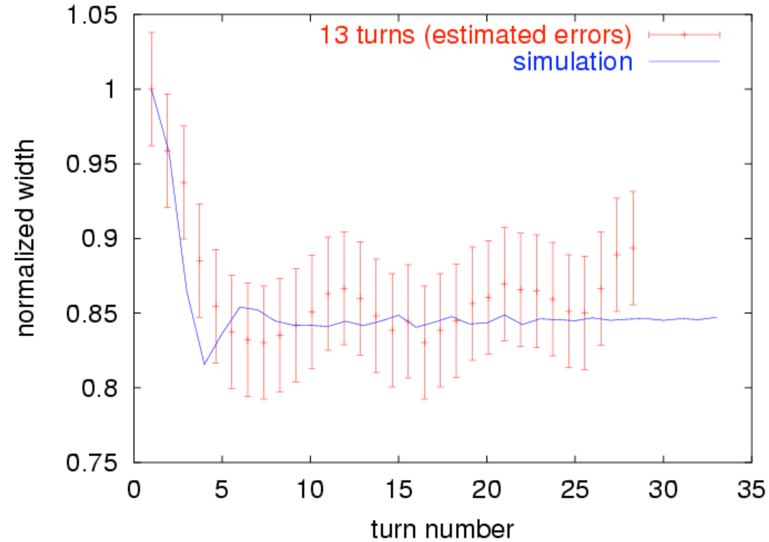
- **FNAL has provided dedicated beam time at the Booster to perform experiments. The experimental data are compared with results of large-scale simulations to help understand machine performance and beam losses.**
- **The simulations used Synergia to combine IMPACT's space charge routines with MXYZPLT beam optics**

Data versus Model Comparisons



DC operation with low current:
data consistent with predicted small space charge effect.

High current with mismatch



First data/MC comparisons:
good qualitative agreement within machine operation uncertainties.

Much more data collected; analysis/modeling under way.

Applied Math

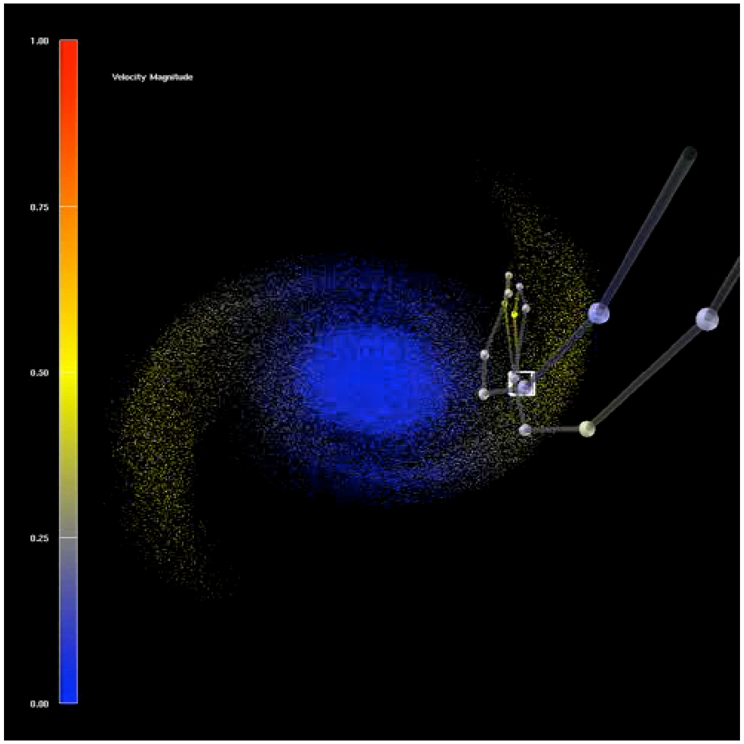
- Parallel Poisson Solvers
  - Developments at APDEC, LBNL, LANL
    - ✔ Multi-level (Chombo)
    - ✔ Spectral-based
    - ✔ Special situations (Hockney algorithm; James algorithm; long-range b-b; long beams in cylindrical, elliptical, or toroidal pipes)
- Statistical methods
  - Computer model evaluation, inference
    - ✔ Determining beam distribution function from wire scanner data

Computer Science Issues

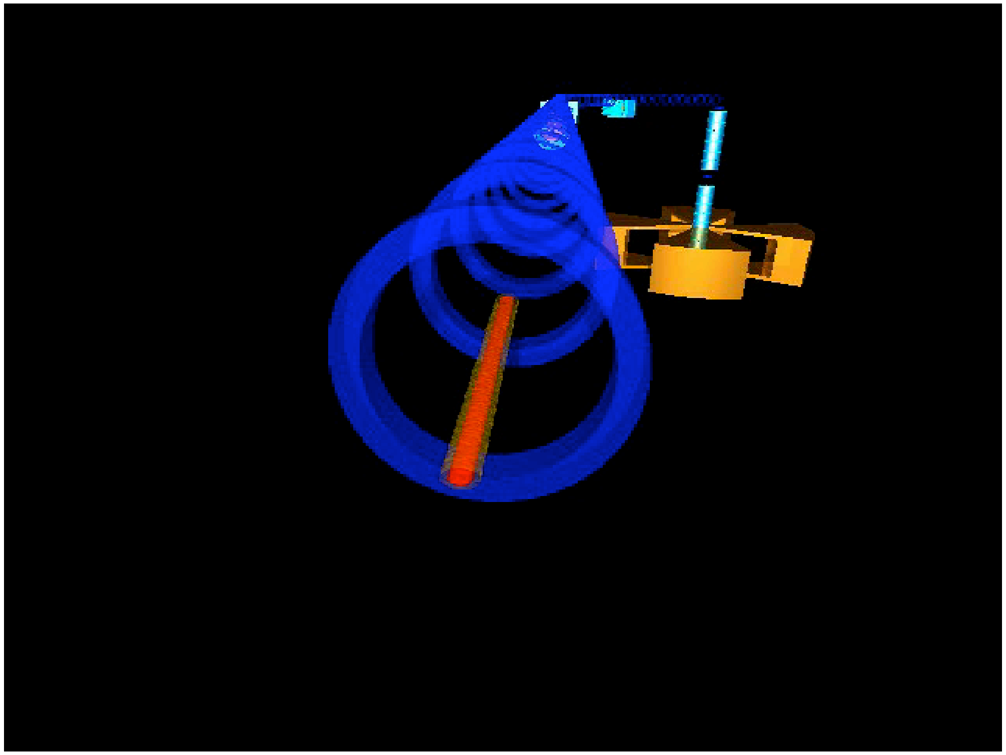
- Software engineering tools
  - Source code mgmt using CVS
  - Build systems (make)
  - Software testing: Example problems & test suites
- Extensible, integrated frameworks
  - Language interoperability
    - F90, C++, python
  - Scripting (python)
- Platform portability
  - Config files

Visualization:
Collaboration involving NERSC and PSI

- Andreas Adelmann and Cristina Siegerist (NERSC viz group)



- Andreas Adelmann and PSI viz group



- Multi-res viz techniques: Kwan-Liu Ma et al., UC Davis (see talk by E. Ng)

Leveraging

- LBNL: Internally supported programs in advanced simulation of accelerators, electron effects modeling, symplectic solvers, viz support, time on Alvarez
- FNAL: Dedicated experiments at the Booster, MXYZPLT support, collaboration on Tevatron simulation
- LANL: Computer time on QSC, Venom, ACL cluster, MaryLie support, data from LEDA and radiography experiments
- UCLA: support for PIC framework
- U. Maryland: support for MaryLie
- NERSC USER SERVICES +++

What have we done (with 50% funding) and what did we say we would do?

- Done or in progress:
  - “Develop interoperable modules” and integrate them in an extensible framework
  - “Continued development of IMPACT”
  - “Parallel Poisson solver development”
  - “Parallel Beam-Beam Capability”
  - “Modeling Intense Beams in Circular Machines”
  - “Parallel Ionization Cooling”
  - “MaryLie Testbed”
  - “Wakefield Effects”
  - “Dark Current Calculation” (see K. Ko’s talk)
- Postponed to FY03:
  - “Parallel Coulomb Collisions”
- Omitted:
  - “Benchmark CSR simulation w/ expts”
  - “Parallel RFQ Code”
- Not planned for in the proposal but done in response to DOE priorities:
  - Tevatron modeling, long-range beam-beam effects