



Multi-Scale Modeling for Beam-Beam Depolarization

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Tech-X: high-performance computational science and applications

- Founded in 1994
- ~35 people, 2/3 PHDs, Boulder, Colorado
- Leader of national projects, national lab partner
- Expertise in
 - High-performance computational software for research and engineering simulation and design
 - Enhancing code performance through porting to modern hardware (AVX, GPUs, Phi)
 - High-performance visualization and graphical user interfaces



Only supplier of commercial, high-performance EM and particle simulation tools for wide variety of applications

SIMULATIONS EMPOWERING YOUR INNOVATIONS



Tech-X philosophy and success

- The Tech-X plan is to develop computations for DOE needs, continuously converting IP to commercial grade software with a significant addressable market.
- Over \$1M commercial revenue for FY 2018
- Tech-X has spun out products to the oil exploration, plasma processing, and defense industries
- Perform service to community: USPAS, APS DPB, IEEE, AAC
- Tech-X software has been purchased by many DOE labs including FNAL, LANL, SLAC.
- Tech-X is a subcontractor for DOE labs, including Sandia.
- Tech-X software is in use by multiple EU labs (members of ELI, TU-Darmstadt) as well as labs in China and Japan



Origin of nuclear spin

- Where does nucleon spin come from?
 - ~20% from constituent quarks
 - What about the rest? Gluons?
- Question being studied at RHIC by colliding spin-polarized protons
 - 60–65% polarization at 100 GeV/beam
 - 55% polarization at 250 GeV/beam
- Electron-ion colliders will provide much more precise probes
 - eRHIC at BNL, MEIC at Jlab
- **Maintaining polarization of both beams is critical**



Accurate spin tracking simulations are essential

- Interaction of colliding beams affects spin
 - Direct effect: EM fields from proton beam alters electron spin
 - Indirect effect: EM fields from one beam alter the other's orbit, changing spin precession
 - Already observed in e-p collisions at much lower intensities than eRHIC
 - Understanding and mitigating these effects is critical
- Additional effects:
 - Magnet fringe fields
 - Variations in machine optics



Project Overview

- Two main thrusts:
 1. Provide fast, accurate spin-polarized particle tracking code (gpuSinTrack)
 2. Add integration between tracking codes and VSim PIC software for detailed studies of beam-beam interaction and nonlinear effects
- Project term ended April 2020, most work completed Fall 2019
- Feature-complete gpuSpinTrack delivered to BNL collaborators



Spin-tracking capabilities

- State-of-the-art spin tracking code: gpuSpinTrack
 - Grown out of several previous codes, with additional capabilities
 - Orbit tracking from TEAPOT
 - Spin tracking from SPINK
- Full nonlinear orbital motion; full 3D spin motion
- Sensitive to spin-orbit resonances
- Accelerated for GPU
 - Particle tracking is “embarrassingly parallel”
 - Particles are independent (absent space charge and other collective effects)
 - Experience the same computational process



Spin tracking work in Phase II

- New polarized particle species: electrons and positrons
- (Incoherent) synchrotron radiation, including quantum fluctuation effects
- New element type: combined function sector bend (CFSB)
- Using GPU-accelerated random number generation library for modeling of stochastic effects/processes
- Extensive benchmarking and quality assurance work
- Updates to user interface and documentation
- Build system cleanup
- Preliminary eRHIC simulation



Combined Function Sector Bend (CFSB)

- Needed for modeling feed-down multipole field content in bends (due, e.g., to magnet offsets)
- Used in a new RHIC lattice design that aims to minimize polarization loss on the acceleration ramp
- Implemented a split-operator symplectic integrator by separating the Hamiltonian into two parts, $H = H_B + H_K$, H_B corresponding to the “pure” bend and H_K to the “kick” due to the quadrupole and higher-order content of the field
- Can also be used in AGS simulations
- Developed a new CUDA kernel and C wrappers, updated the user interface



New capability for tracking e^- and e^+

- Enabled trajectory and spin integration in gpuSpinTrack for electrons and positrons
- Required code infrastructure work: Codes from which gpuSpinTrack evolved were designed to model polarized proton beams at RHIC, assumption of protons (charge polarity, rest mass, anomalous magnetic moment) was hard-coded in many places
- Previously implemented element kernels, spin tracking “machinery”, and user interface updated for the new species
- Presently can track e^- and e^+ through drifts, sector and rectangular bends, multipoles, CFSBs
- New capability was extensively and rigorously tested
- Necessary for modeling the synchrotron radiation in bend magnets



Modeling synchrotron radiation

- Implemented a new element type SRSB, a sector bend with (incoherent) synchrotron radiation, including the quantum fluctuation effect
- Assume instantaneous photon emission in the direction of the electron (or positron) motion
- We model the photon emission as a compound Poisson process with the mean number of photons emitted per unit time

$$\langle N \rangle = \int_0^\infty n(u) du = \frac{5\alpha c \gamma}{2\sqrt{3}\rho} \approx .010533c \frac{\gamma}{\rho}$$

- Distribution in energy u given by

$$n(u) = \frac{\sqrt{3}}{2} \frac{\alpha c \gamma}{\rho} \frac{1}{u_c} \int_{u/u_c}^\infty K_{5/3}(y) dy$$

- where the critical photon energy u_c is

$$u_c = \hbar\omega_c = 3\hbar c \gamma / 2\rho$$



Preliminary eRHIC Simulation

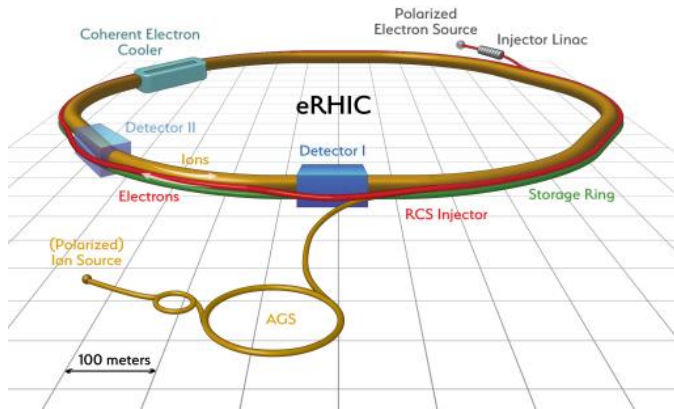
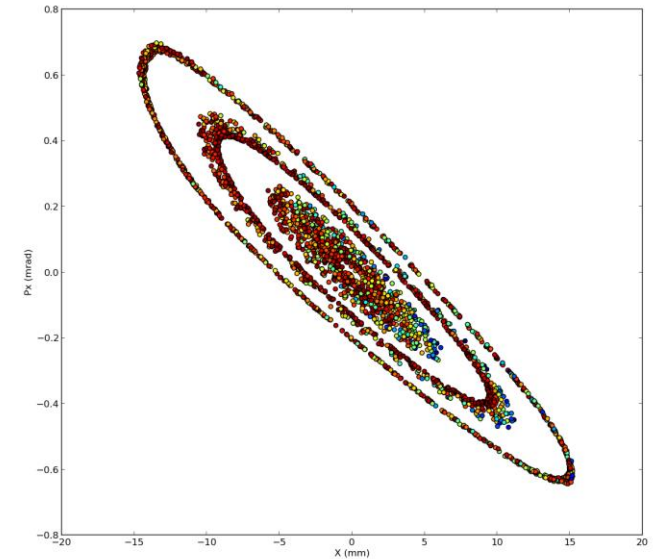


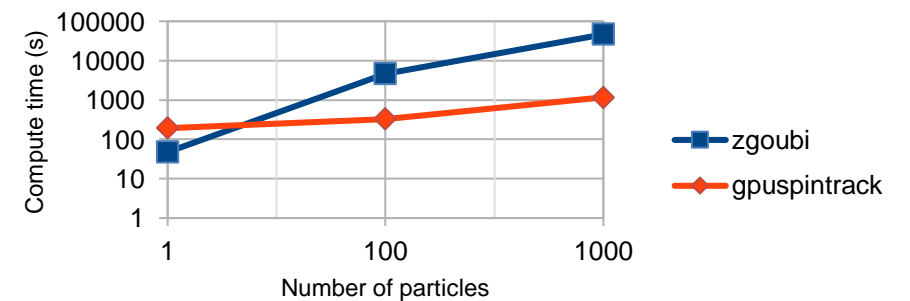
Image courtesy <https://www.bnl.gov/cad/eRhic/>

- 4096 element SXF lattice developed for Rapid Cycling Synchrotron
- Necessary elements ported to GPU
- Developed battery of eRHIC-specific unit tests
- Need magnet scaling parameters to be able to run with RF Cavities at design power

Phase-space of select electrons at first lattice element, colored by spin defect



Single-core tracking simulation time for 100 turns through RCS Lattice





GPUSpinTrack Usability Enhancements

- Ensured accuracy by implementing unit tests for all new features
- Updated documentation
- Eliminated unused features and libraries
 - ~50% reduction in code base
- Ensured code works out of the box
 - Stable, standalone version of Tech-X “bilder” system for GPUSpinTrack handles necessary packages, dependencies, and installation
 - Experimental build using SPACK package manager



GPUSpinTrack build system

- A reliable build process is critical for scientific software

 Bilder



 **CMake**



Makefiles

- Builds and installs software and all dependencies
- Can handle multiple architectures, platforms, and compilers
- > 150 packages available

- Cross-platform build system generator
- Build the code on a supercomputer or your Mac laptop
- Windows possible as well