Overview of Computational Challenges for Coherent Electron Cooling

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DOE/NP SBIR-STTR Exchange Meeting
Gaithersburg, September 13, 2010

Office of Nuclear Physics – Exploring Nuclear Matter - Quarks to Stars
NERSC
TECH-X CORPORATION

Presentation Outline

- Tech-X Corporation
  - Overview & Capabilities
  - Commercialization
- Project Motivation
  - Future DOE/NP facility: the Electron-Ion Collider
  - Electron cooling could provide the necessary luminosity
- Phase II tasks & Project status
- Simulating a Coherent e- Cooling (CeC) system
  - Simulating the modulator
  - Simulating the free-electron-laser amplifier
  - Simulating the kicker
- Summary, future plans, acknowledgments

Tech-X Corporate Overview

5621 Arapahoe Ave.
Boulder, CO 80303
http://www.txcorp.com

Tech-X Corp. is a software and R&D organization with more than 60 employees, roughly 2/3 PhDs

We have multiple offices in the U.S.

Headquarters in Boulder, Colorado

Foreign subsidiaries: England & Switzerland

Resellers: China, India, Korea and Taiwan

TECH-X CORPORATION

Tech-X activities & expertise span full range of Computational Science & Engineering, High Performance Software & Computer Science –

<u>Scientific Discovery, Design & Engineering</u>: Collaboration with top groups at labs & universities; publishing refereed articles; invited talks; Fortune 500 & international customers

<u>Computation</u>: Developing commercial quality software for scientific applications; high-performance computing; speeding up applications

<u>Data Analysis</u>: Extracting content from large data sets rapidly using innovative and proven technologies, large scale data mining, high fidelity visualization

<u>Distributed Computing</u>: Generating, accessing, transferring, and analyzing remote data efficiently

<u>Systems Integration</u>: Combining disparate capabilities and technologies to facilitate collaboration and interoperability by leveraging open source and proprietary components

New science, education & applications achieved via commercial & open software

VORPAL® Computational application for electromagnetics (particle accelerators, oscillators, cell phones) and plasmas (semiconductor manufacturing)

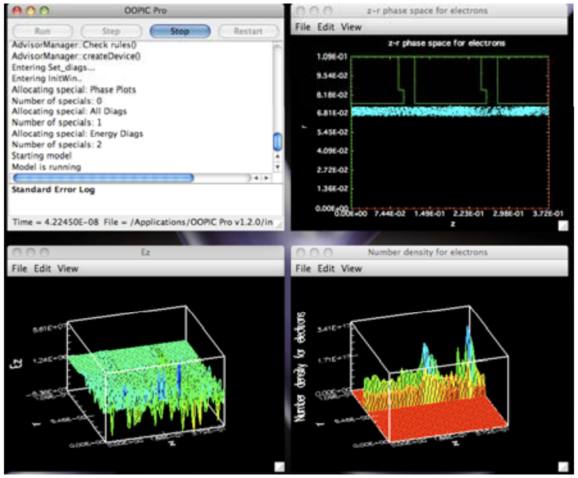
OOPIC Pro™ Fast, GUI-based analysis tool for plasmas and electromagnetics

FACETS™ Multiphysics framework for distributed simulations with initial application for fusion device modeling

nature

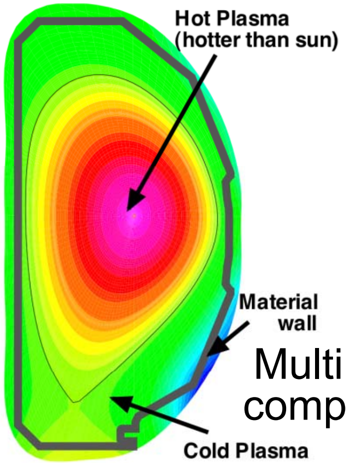
Dream beam

Cover story computations



```
AdvisorManager::Check rules()
AdvisorManager::createDevice()
Entering Set_diags...
Entering InitWin..
Allocating special: Phase Plots
Number of specials: 0
Allocating special: All Diags
Number of specials: 1
Allocating special: Energy Diags
Number of specials: 2
Starting model
Model is running
Standard Error Log
Time = 4.22450E-08  File = /Applications/OOPIC Pro v1.2.0/in
```

Interactive modeling; Education



Multiphysics computations

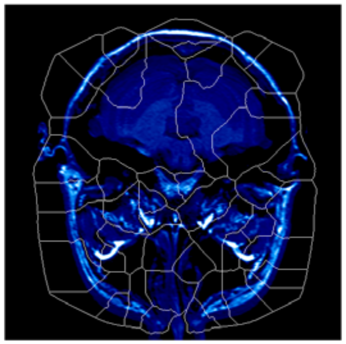
Data Analysis, application speedup & 3D viz via commercial libraries and open standards

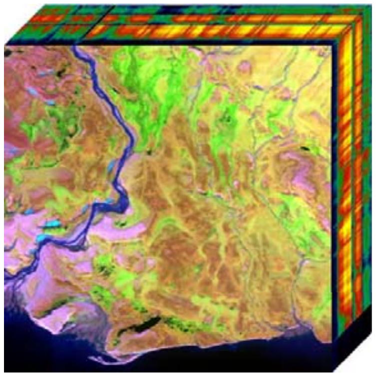
FastDL® Facilitating task-based parallel computing in the 4GL, Interactive Data Language, as well as to scripting and object-oriented languages

GPULib™ An easy-to-use software library for computation acceleration using Graphics Processing Units (GPUs)

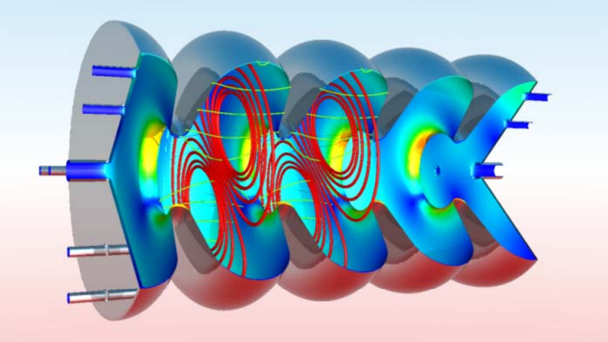
VizSchema™ Marking up data and data importers for visualizing large data sets

Parallel processing for image analysis





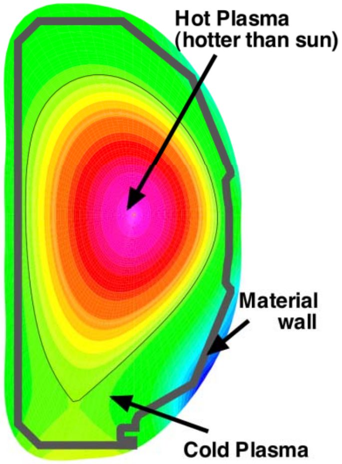
Acceleration of hyperspectral imaging using GPUs



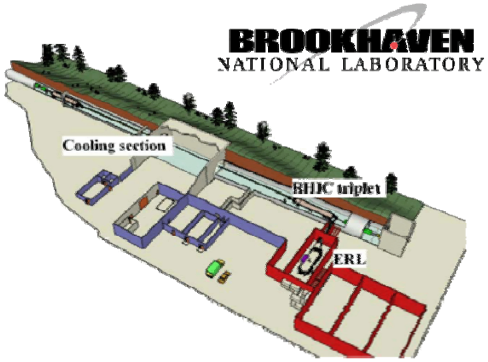
Award winning visualizations

Direct benefits to Office of Science: new science, modeling complex systems; designing RF cavities

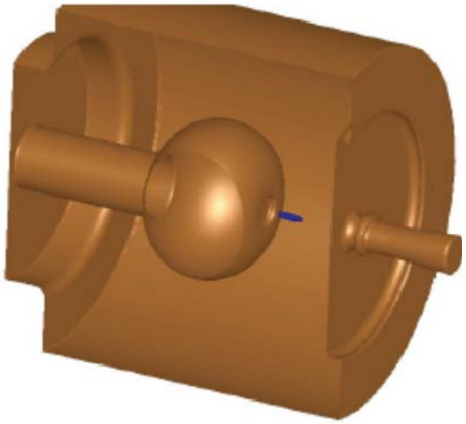
- Leading FES SciDAC project
  - Key member of HEP/NP/BES SciDAC project “ComPASS”
  - Participate in several others
- Simulate key physics of large-scale systems
  - “conventional” electron cooling for RHIC, magnetized & not
  - help reduce cost and risk
- Simulating a wide range of SRF structures
  - DC and rf electron guns
  - crab cavities for LHC upgrade
  - e- multipactor in rf couplers



Tech-X leads the Scientific Discovery through Advanced Computation Project: FACETS



Model key physics in large-scale scientific systems: e.g. e- cooling designs for RHIC

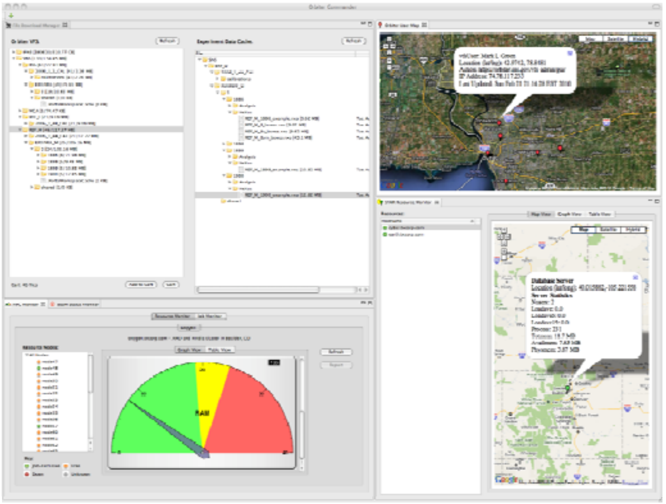


Modeling the JLab e- gun and a wide variety of other SRF structures

Distributed Computation and Access

- Service Oriented Architecture:
  - Services for collaborative, data-intensive, distributed applications using RESTful web services for delivering data rapidly and securely using industry standards
- Component Framework Technologies:
  - OSGi, Eclipse RCP/Equinox, building scalable and reusable native application frameworks
- Graphical User Interfaces and Portals:
  - Human interfaces to complex systems, both Thin- and Thick-clients using a multitier approach for consistent behaviors and Quality of Service

Thin-Client Pilot web portal



Thick-Client Commander desktop application

We combine software sales & services with scientific collaboration & service to the DOE community

- Sales of commercial software licenses:
  - Customers do their own modeling in-house
  - Consulting & training reduce the time to results
  - DOE collaborators get free access to commercial quality software
- Consulting:
  - Build software applications and computational kernels
  - Develop models and perform simulations
  - Apply expertise in high-performance computing
  - Develop, deploy and manage Graphical User Interfaces, as well as native multi-architecture desktop applications
  - Assist with complex technologies (i.e. Web Services, GPUs, MPI)
- Some software libraries are made available to all:
  - Specialized software for physics applications: TxPhysics™
  - HPC tools that lead to more consulting: GPULib™

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A future Electron-Ion Collider facility & Coherent e- Cooling are high priorities

- 2007 NSAC Long Range Plan stated:
  - the existing high-energy nuclear physics program will benefit from "…the accelerator modifications needed to implement beam cooling, which will significantly increase the RHIC luminosity…"

    http://www.er.doe.gov/np/nsac/index.shtml
  - stochastic cooling has shown great success with Au^{+79}, but will not work with protons

    Blaskiewicz, Brennan and Mernick, "3D stochastic cooling in RHIC," Phys. Rev. Lett. **105**, 094801 (2010).
  - CeC could yield six-fold luminosity increase for polarized proton collisions in RHIC

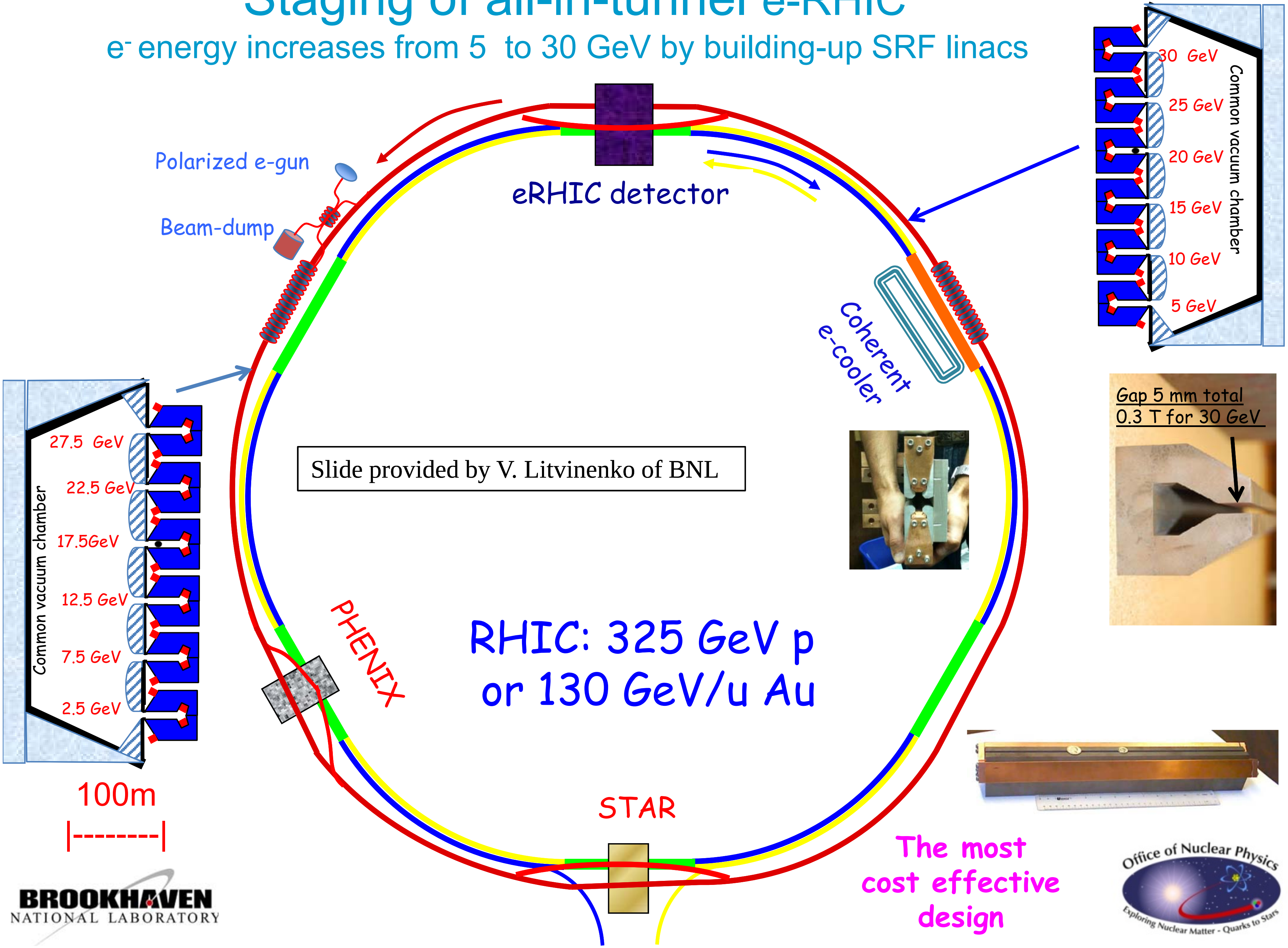
    This would help in resolving the proton spin puzzle.
- Furthermore, the 2007 NSAC Long Range Plan recommends:
  - "…the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider".

    EIC Collaboration website: http://web.mit.edu/eicc/

    Science goals of a future EIC facility:
    - Precision imaging of sea-quarks and gluons to determine spin, flavor and spatial structure of the nucleon
    - Definitive study of the universal nature of strong gluon fields in nuclei
- In November 2009, the Electron-Ion-Collider Advisory Committee (EICAC) selected CeC as one of the highest accelerator R&D priorities.

Staging of all-in-tunnel e-RHIC

e^- energy increases from 5 to 30 GeV by building-up SRF linacs



Slide provided by V. Litvinenko of BNL

RHIC: 325 GeV p
or 130 GeV/u Au

The most cost effective design

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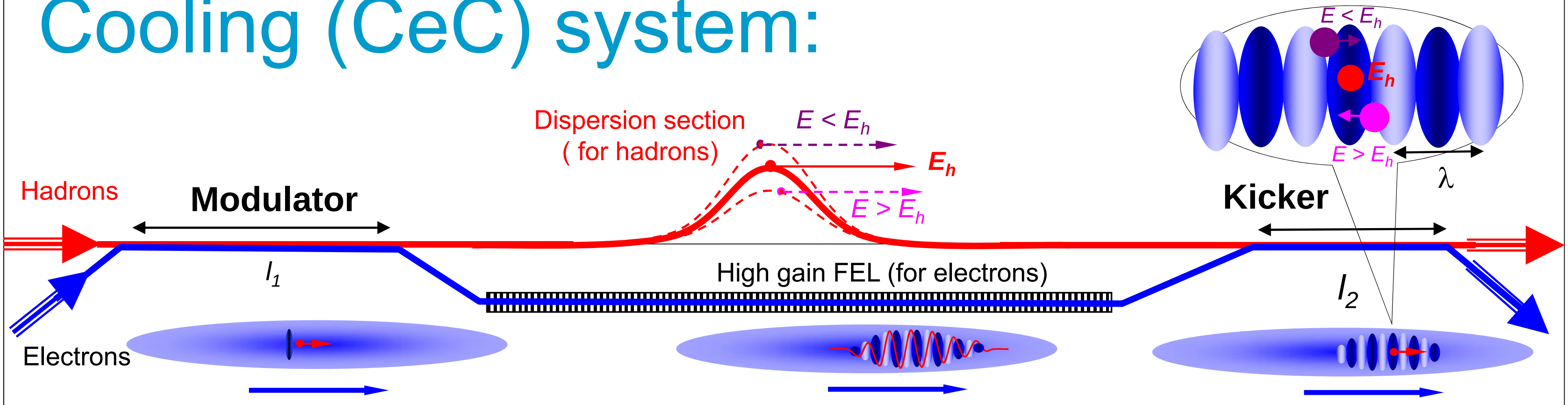
Schematic of a Coherent electron Cooling (CeC) system:



Litvinenko & Derbenev, "Coherent Electron Cooling," Phys. Rev. Lett. 102, 114801 (2009).

- Coherent Electron Cooling concept
  - uses FEL to combine electron & stochastic cooling concepts
  - a CEC system has three major subsystems
    - **modulator**: the ions imprint a "density bump" on e- distribution
    - **amplifier**: FEL interaction amplifes density bump by orders of magnitude
    - **kicker**: the amplified & phase-shifted e- charge distribution is used to correct the velocity offset of the ions

Motivation for the Phase II project:

- Provide computational support and design tools for the electron cooling design team at BNL
- Reduce technical risk and, if possible, costs
  - Near term: (perhaps) for a proof-of-principle experiment of Coherent Electron Cooling at RHIC
  - Long term: for design, construction & commissioning of a full-scale CeC system for eRHIC

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SBIR Phase II Project

Contract # DE-FG02-08ER85182

"Designing a Coherent Electron Cooling System for High-Energy Hadron Colliders"

Principal Investigator: David Bruhwiler

Grant monitor: Manouchehr Farkondeh

Funded by DOE Office of Science, Office of Nuclear Physics

Project tasks & status

Original schedule was symmetric in Years 1 & 2

40 GeV/n Au^{+79} in Year 1 & 250 GeV protons in Year 2

- After 12 months, funds are 45% expended
  - Symmetry in schedule was artificial; difficulties are being addressed in Y1
- 1) δf-PIC simulations of the modulator, for range of parameters
  - Validated against theory for single ion; boundary issues have been identified and are being addressed; multiple ions are now being simulated
- 2) GENESIS 1.3 simulations of the high-gain FEL amplifier
  - Use of GENESIS is well understood, including correct coupling of δf-PIC output from VORPAL into the FEL amplifier, with correct shot noise
- 3) PIC simulations of kicker, using amplified e- distribution from FEL
  - GENESIS particle output is now correctly coupled into VORPAL; strong density ripples are clearly seen; working to resolve boundary issues
- 4) Characterize effective velocity drag
  - Task 4 cannot begin until Task 3 is further along.
- All tasks are expected to be completed on schedule.

Papers & Presentations

A.V. Sobol, D.L. Bruhwiler, G.I. Bell, A. Fedotov and V.N. Litvinenko, “Numerical calculation of dynamical friction in electron cooling systems, including magnetic field perturbations and finite time effects,” New Journal of Physics (2010), in press.

Partially supported by previous SBIR and by ComPASS SciDAC project.

B.T. Schwartz, D.L. Bruhwiler, V.N. Litvinenko, S. Reiche, G.I. Bell, A. Sobol, G. Wang and Y. Hao, “Massively parallel simulation of anisotropic Debye shielding in the modulator of a coherent electron cooling system and subsequent amplication in a free electron laser,” Journal of Physics: Conference Series (2010), in press.

Partially supported by ComPASS SciDAC project.

Invited talk at HB2010:

D.L. Bruhwiler, “Overview of Computational Challenges for Coherent Electron Cooling,” 46th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (Morschach, Switzerland, September, 2010).

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VORPAL simulations of the modulator: validation against theory for a simple case

- Recent analytical results for e- density wake

  G. Wang and M. Blaskiewicz, Phys Rev E ***78****, 026413 (2008).*

$$\tilde{n}(\vec{\mathrm{r}},\mathrm{t}) = \frac{Zn_o\omega_p^3}{\pi^2\sigma_{\mathrm{vx}}\sigma_{\mathrm{vy}}\sigma_{\mathrm{vz}}}\int_0^{\omega_p t}\tau\sin\tau\left(\tau^2+\left(\frac{\mathrm{x - v_{hx}}\tau/\omega_p}{r_{Dx}}\right)^2+\left(\frac{\mathrm{y - v_{hy}}\tau/\omega_p}{r_{Dy}}\right)^2+\left(\frac{\mathrm{z - v_{hz}}\tau/\omega_p}{r_{Dz}}\right)^2\right)^{-2}d\tau$$

  - theory makes certain assumptions:
    - single ion; arbitrary velocities
    - uniform e- density; *anisotropic* temperature
      - Lorentzian velocity distribution
      - now implemented in VORPAL
    - linear plasma response; *fully 3D*
- Dynamic response extends over many λ_D and $1/\omega_{pe}$
  - thermal ptcl boundary conditions are important

Modulator simulations are successfully validated.

Simulated e- density agrees with theory [7]

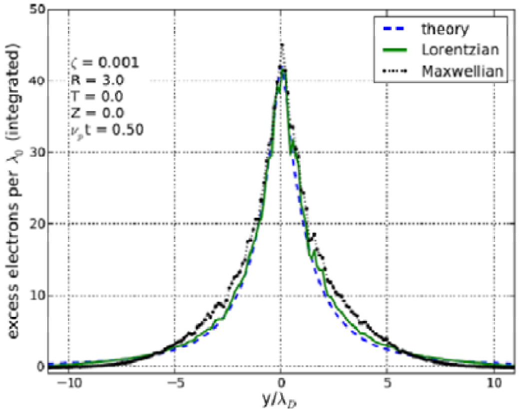


Figure 1: Longitudinal charge density perturbation in the vicinity of the Au^{+79} ion, for the case of a stationary ion in an anisotropic plasma with both Lorentzian and Maxwellian e^- velocity distributions.

Maxwellian wakes can differ from Lorentzian

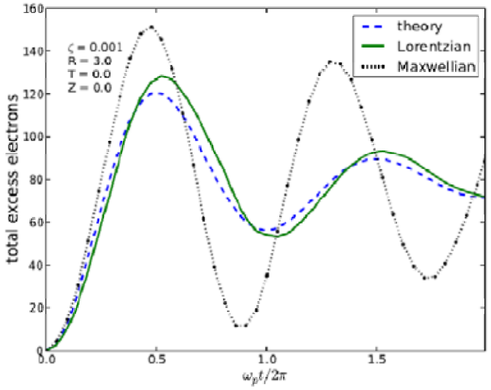


Figure 2: Time evolution of the integrated e^- charge enhancement in the vicinity of the Au^{+79} ion, for the case of a stationary ion in an anisotropic e^- distribution. The time scale is in units of plasma period.

Drifting ion simulations agree w/ theory [7]

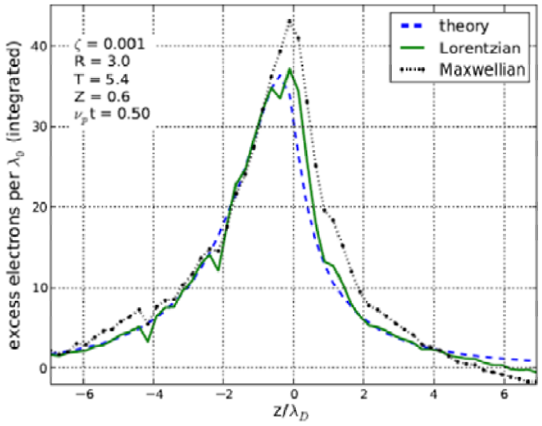


Figure 3: Longitudinal charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

Large transverse drift velocity yields strongly perturbed wakes over many Debye lengths

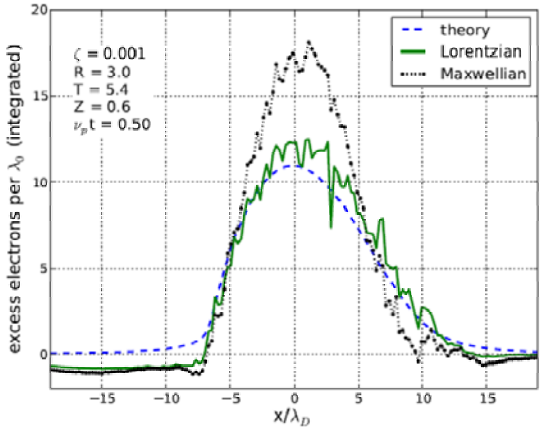


Figure 4: Transverse charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

Modulator output coupled into FEL simulations.

http://pbpl.physics.ucla.edu/~reiche/

Spectrogram of longitudinal e-density perturbation in modulator yields 'bunching' parameters and phases for GENESIS input file.

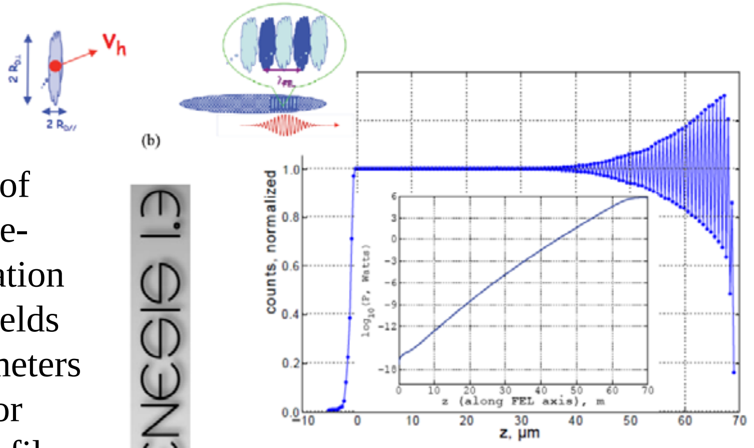
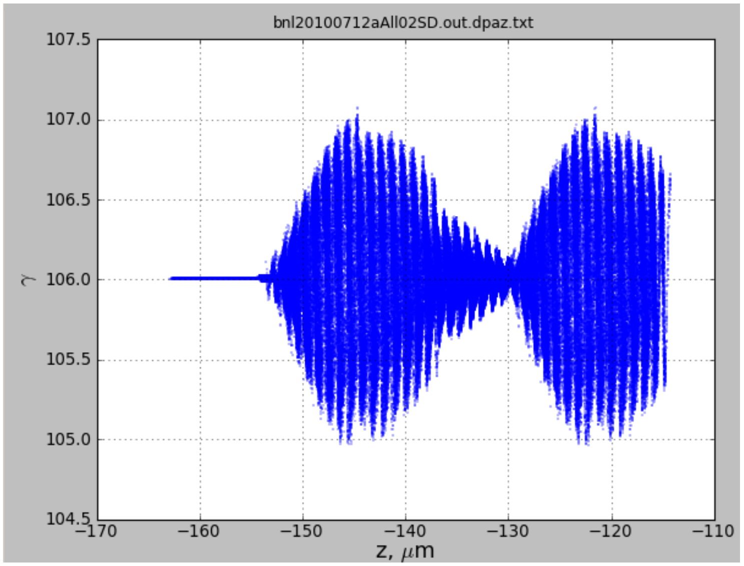


Figure 6: Histogram of electron beam particle counts after propagating 60 meters in an λ_0=700 nm FEL, bin width = $\frac{\lambda_0}{2}$. Inset: Optical power along FEL axis.

Lasing provoked by two well-separated ions (in the modulator) drives energy modulations



Effect of two ions in the modulator

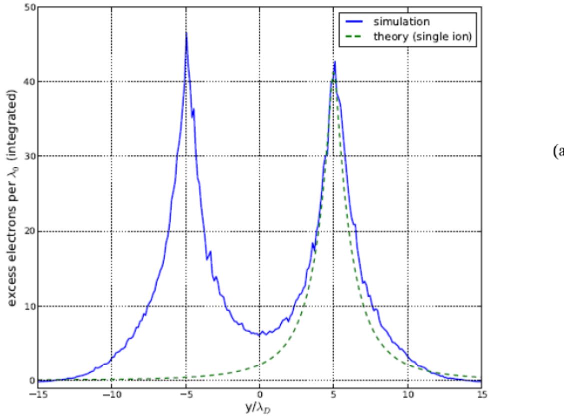
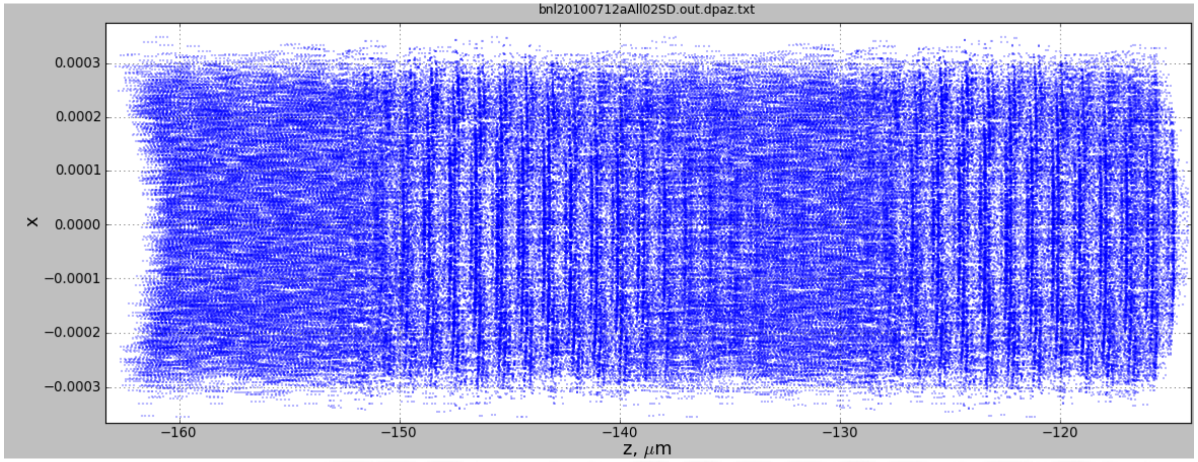


Figure 5: Transverse charge density perturbation of a plasma in the vicinity of two stationary Au^{+79} ions separated by $10\lambda_D$. Dotted line: theoretical prediction for a Lorentzian velocity distribution.

FEL amplified response in electron density distribution, from two well-separated ions (in the modulator)



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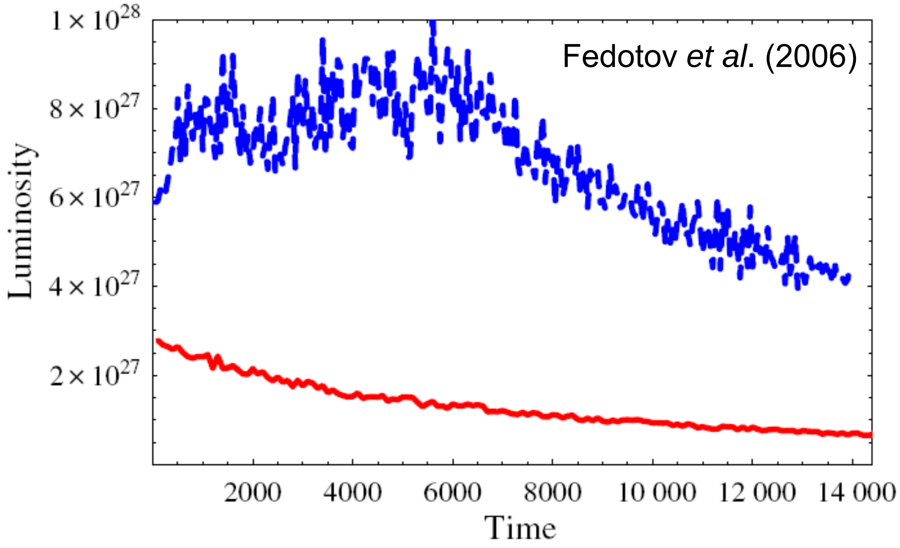
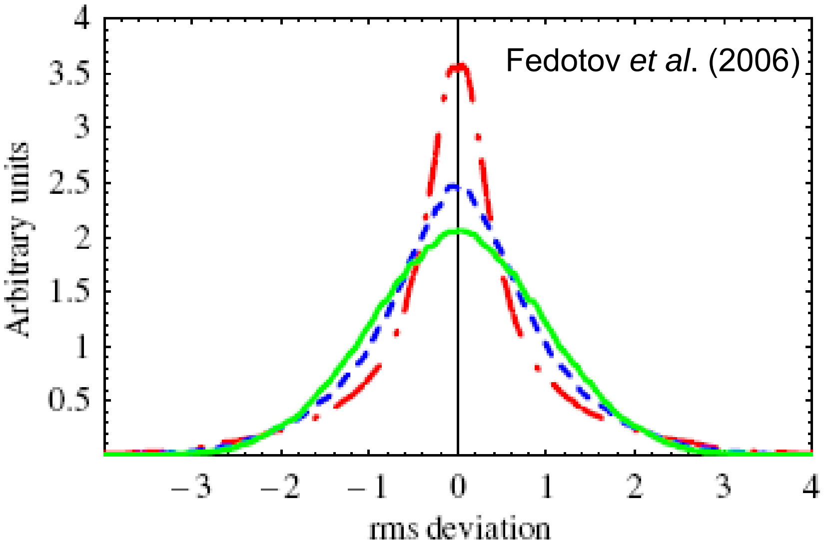
Full e- cooling sim's are distinct from simulating micro-physics of a single pass

- BETACOOL code is used to model many turns
    - A. Sidorin *et al*., *Nucl. Instrum. Methods* A **558**, 325 (2006).
    - A. Fedotov, I. Ben-Zvi, D. Bruhwiler, V.N. Litvinenko, A. Sidorin, New J. Phys. **8**, 283 (2006).
  - variety of "conventional" electron cooling algorithms are available
    - i.e. simple models for dynamical friction and diffusion
  - various models for "heating" are included
    - intra-beam scattering (IBS), beam-beam collisions, etc.
- Never used for CeC





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Plans for future work

- Demonstrate coupled simulations of complete system
  - next, macro-particles from GENESIS coupled into VORPAL, with phase shifted ions, to model the kicker section
    - transfer of particles into VORPAL is working
    - BC issues are being addressed
- Characterize effective velocity drag
  - need to develop a parametric model
    - e.g. from ‘conventional’ magnetized cooling:

$$\rho_{\min} = \left(Ze^2 / 4\pi\varepsilon_0\right) / m_e V_{ion}^2$$

$$\rho_{\max} = V_{ion} / \max\left(\omega_{pe}, 1/\tau\right)$$

$$r_L = V_{rms,e,\perp} / \Omega_L\left(B_{\|}\right)$$

$$V_{eff}^2 = V_{e,rms,\|}^2 + \Delta V_{\perp e}^2$$

$$\mathbf{F} = -\frac{1}{\pi}\omega_{pe}^2 \frac{(Ze)^2}{4\pi\varepsilon_0} \ln\left(\frac{\rho_{\max} + \rho_{\min} + r_L}{\rho_{\min} + r_L}\right) \frac{\mathbf{V}_{ion}}{\left(V_{ion}^2 + V_{eff}^2\right)^{3/2}}$$

V. Parkhomchuk, Nucl. Instr. Meth. in Phys. Res. A **441** (2000), p. 9.

- Non-ideal modulator simulations
  - multiple ions
  - finite e- beam size; external magnetic fields

TECH X

Acknowledgments

We thank I. Ben-Zvi, A. Fedotov, A. Herschkowitz and other members of the BNL Collider Accelerator Department for many useful discussions.

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We thank J.R. Cary, P. Stoltz and other members of the VORPAL development team for assistance and useful discussions.

VORPAL

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