Coherent Electron Cooling (CeC) needed for high luminosity future Electron-Ion Colliders

- 2007 Nuclear Science Advisory Committee (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. (http://www.er.doe.gov/np/nsac/index.shtml)
  - Resolving the proton spin puzzle
- 2009 Electron-Ion-Collider Advisory Committee (EICAC):
  - Selected CeC as one of the highest accelerator R&D priorities (http://web.mit.edu/eicc)
- Why CeC over alternative cooling approaches?
  - Stochastic cooling has shown great success with 100 GeV/n Au+79 in RHIC
    - Blaskiewicz, Brennan and Mernick, "3D stochastic cooling in RHIC," PRL **105**, 094801 (2010).
    - **However, it will not work with 250 GeV protons in RHIC! (greater number of particles)**
  - High-energy unmagnetized electron cooling could be used for 100 GeV/n Au+79
    - S. Nagaitsev et al., PRL 96, 044801 (2006). Fermilab, relativistic antiprotons, with g~9
    - A.V. Fedotov, I. Ben-Zvi, D.L. Bruhwiler, V.N. Litvinenko, A.O. Sidorin, New J. Physics **8**, 283 (2006).
    - Cooling rate decreases as γ^{-2}, which **is too slow for 250 GeV protons!**
  - CeC could yield six-fold luminosity increase for polarized proton collisions in RHIC
    - Breaks the γ^{-2} scaling of conventional e-cooling because it does not depend on dynamical friction

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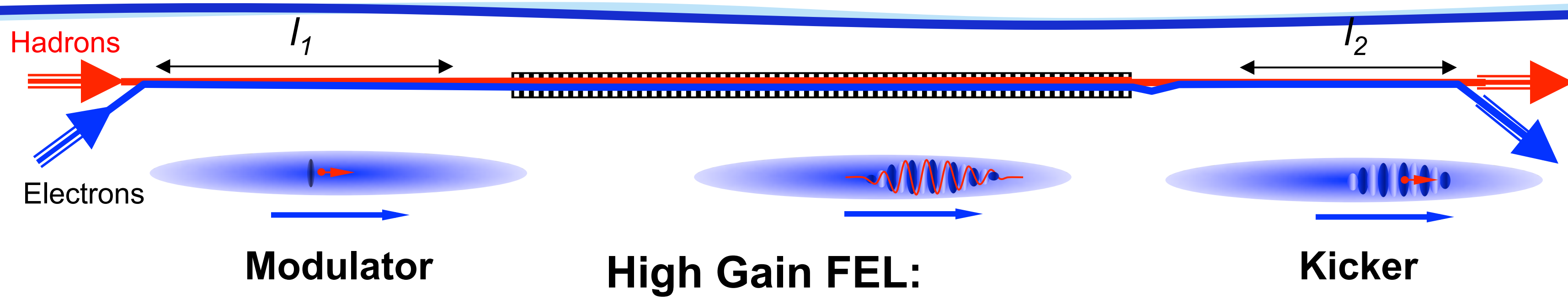
Significant uncertainty in how to build a Coherent Electron Cooler (CeC)



Amplifier of the e-beam modulation

Longitudinal dispersion for hadrons gives correct kick phase

- Combined cooler has never been built or tested
  - Only individual components are understood (e.g., high-gain FELs)
- Theory of the cooler can be solved only with simplified assumptions
  - Infinite, constant electron density (finite, inhomogeneous density needed)
  - Quasi-3D FEL theory (full 3D needed)
  - Linearized Vlasov (non-linearities need to be included)
  - Simplified transport and focusing (realistic 3D transport needed)
- Researchers uncertain about
  - How much dephasing occurs between cooler components?
  - What is the effect of space-charge in the cooler?
- Tolerances are unknown and there are few tunable parameters in experiment
  - Can change electron beam current, undulator strength, quad strengths in modulator and kicker

High fidelity, comprehensive simulations reduce risk, guide

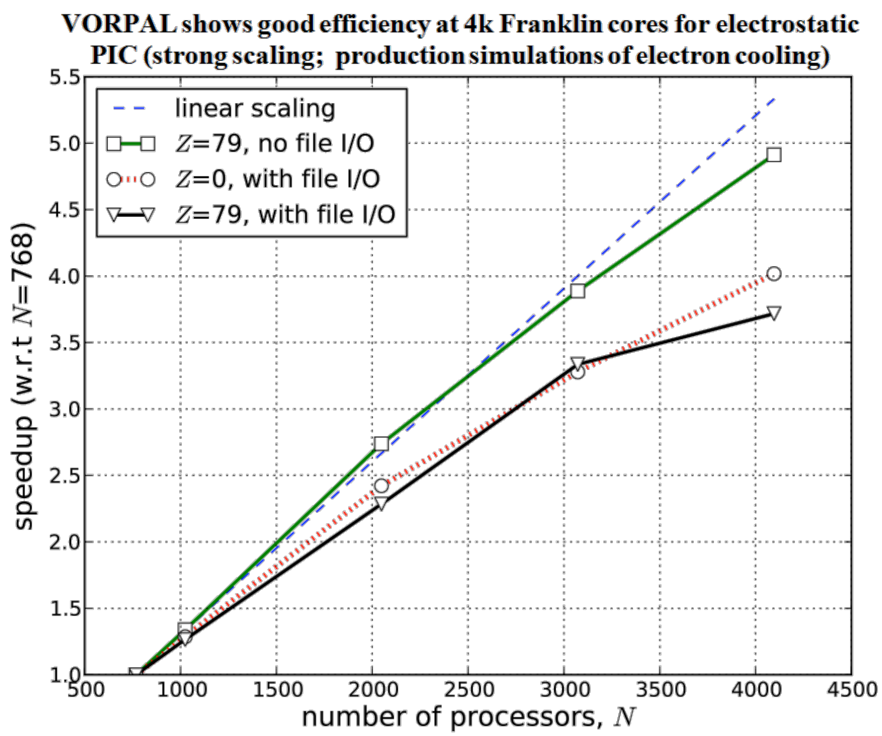
- High-fidelity, comprehensive simulations can include important effects that are difficult to understand in pure theory:
  - Finite, inhomogeneous electron beam density
  - Space charge effects
  - Realistic external focusing fields
  - Realistic electron beams from a linac
- Start-to-finish simulations address coupling issues
- Risk reduction & confidence building through
  - Verification of simulations through comparison with theory
  - Verification of simulations by comparing different typesr
    - e.g., Vlasov-Poisson simulations verify 1D & 2D PIC simulation results
  - Validation of simulations through comparison with experiments
- Also - simulations can guide both experimental design and interpretation of experimental results

Realistic simulations difficult

- Modeling the entire cooler (in 3D) requires coupling different simulation tools and types
  - Vorpal can model the modulator with 3D δf-PIC
  - Genesis 1.3 can model the high-gain FEL
  - Vorpal can model the kicker with explicit 3D PIC
- Modulator signal-to-background is so small (10^{-3}) that explicit PIC requires more than 10^4 particles *per cell* to accurately see signal
- Noise and subtle correlations in 6D phase space make FEL simulations challenging
  - "Particle-clone pair" approach reduces noise, implemented in modified version of GENESIS
- Simulations must be parallelized and scalable to large numbers of processors (10^4)

Tech-X has needed domain knowledge and computational expertise

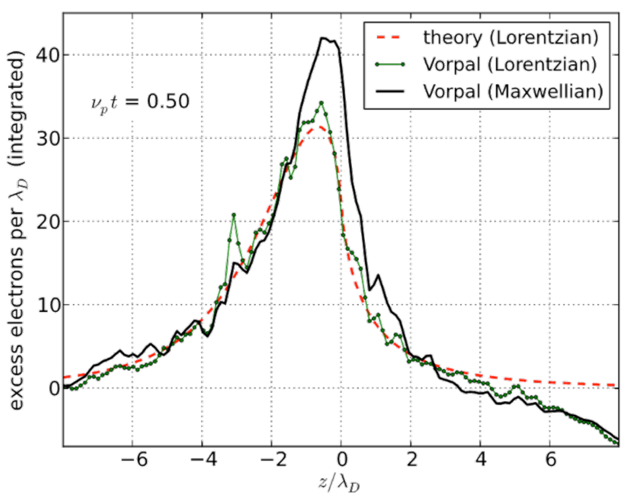
- Tech-X has domain expertise in computer science and computational accelerator and plasma physics
- Tech-X has the Vorpal simulation suite
  - Electrostatics and Electromagnetics
  - Explicit Particle-In-Cell (PIC) and δf PIC
  - Parallel and scalable to 10^4 processors
- Vorpal's unique features make it the best tool for CEC simulations



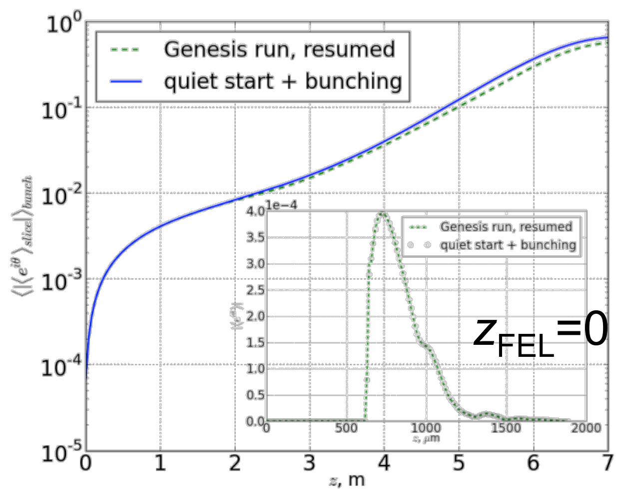
Tech-X has made significant progress in simulating the CeC system

tools: Vorpal → GENESIS 1.3 → Vorpal

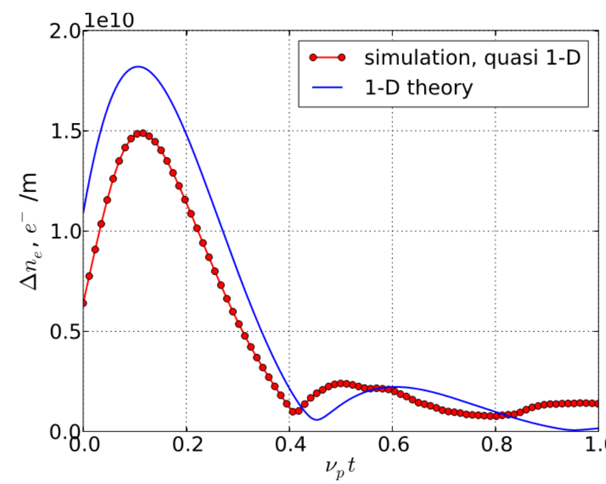
3D δf-PIC (beam frame) | 3D FEL simulations (lab frame) | 3D electrostatic PIC (beam frame)



Debye shielding in the modulator matches theory.



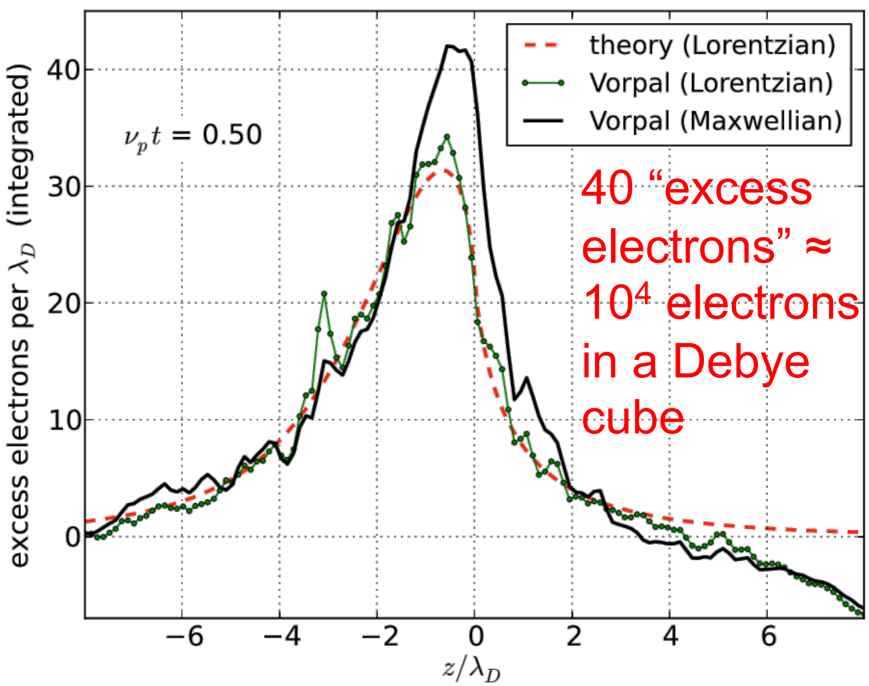
Algorithm for electron position & energy modulation matches Genesis internal method.



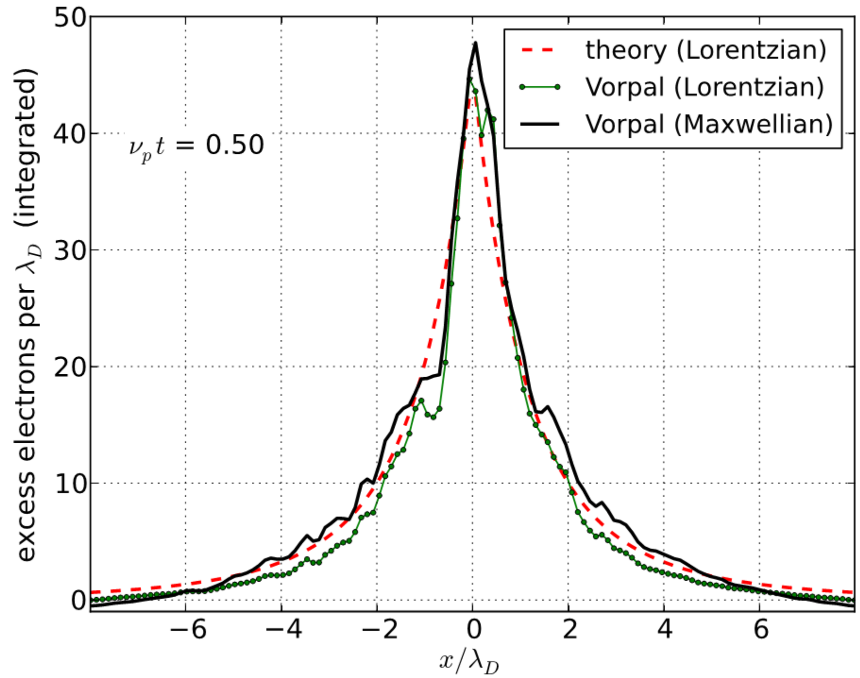
Charge density modulation in Vorpal simulations of the kicker matches theory.

Tech-X successfully verified modulator simulations with idealized model

- Dashed curves: Idealized theory assuming a uniform density electron beam, and a Lorentzian velocity distribution
  - Wang and Blaskiewicz, Phys Rev E **78**, 026413 (2008)
- Solid Curve (green): Vorpal simulation with the same assumptions
- Solid curve (black): Vorpal simulation using a Maxwellian velocity distribution.



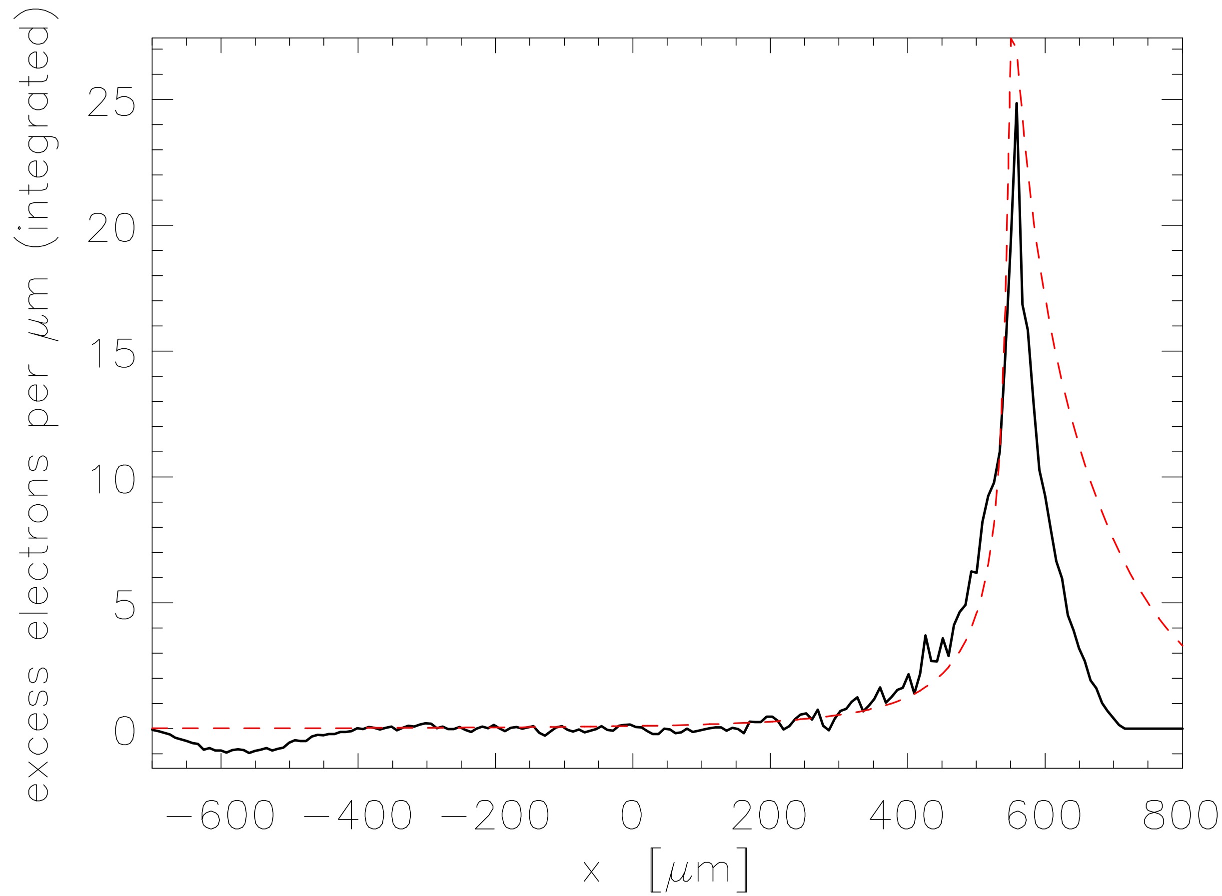
longitudinal charge perturbation



transverse charge perturbation

Vorpal verification: confidence in δf-PIC simulations with realistic electron profiles

- Dashed curve: the theoretical prediction based on uniform density
- Solid curve: shielding response of an ion near the edge of the beam.
- The response is reduced towards the edge of the beam (right)



transverse charge perturbation

Modeling Coherent Electron Cooling

DOE Need

Coherent electron cooling has been proposed to increase the hadron beam luminosity at future electron-ion colliders, including the proposed eRHIC facility and the ELIC facility at Jlab. An EIC has been recommended by the NSAC, and CEC has been identified as one of the highest priorities by the EIC Advisory Committee.

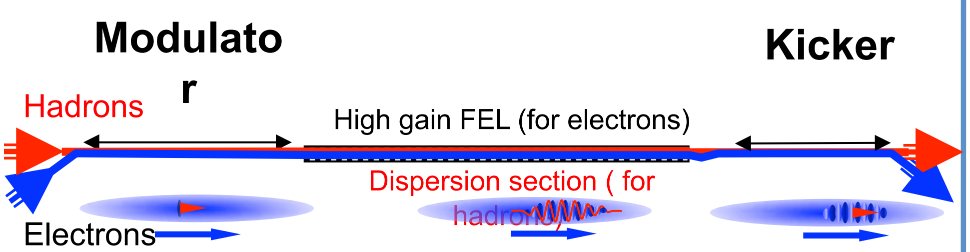
Improvements to these facilities will enable physicists to study and understand proton spin, nucleon properties, and strong gluon fields.

Approach

Tech-X can accurately model Debye screening, its signal amplification in a free-electron laser, and time-evolution of this signal after existing the laser.

We are simulating the three major components of the coherent electron cooling proof of principle experiment with the particle-in-cell code Vorpal and the FEL code Genesis. Improvements are being made to Vorpal and Genesis to make full simulation of the CEC system possible from start to finish.

Concept



High Gain FEL:

Amplifier of the e-beam modulation

Longitudinal dispersion for hadrons gives correct kick phase

Progress & Schedule

Milestone	Date
Improve δf-PIC algorithm for Modulator simulations	Dec 2010
Simulate the shielding response of multiple ions through the modulator	Mar 2010
Couple Vorpal Modulator simulations to GENESIS FEL simulations	April 2011
Simulate the response of an ion at the beam edge	June 2011
Simulate the kicker; Calculate single-pass cooling	Nov 2012
Modify the δf-PIC algorithm for a focused beam	July 2012
Implement Vlasov solvers in 1D/2D/3D	Feb 2013
Simulate electron linac; Generate realistic electron beam	Mar 2013
Simulate single-pass, start-to-finish cooling with realistic electron beam	Jun 2013

Technology for DOE needs faces commercialization challenges

- DOE considers a single machine when funding projects
- DOE needs extreme solutions to extreme problems
- Specifically:
  - There are no commercial entities that produce 250 GeV/nucleon beams
  - There are no commercial colliders
  - There are no commercial applications for coherent electron cooling
- Unlike DOD and NASA, DOE does not generally procure developments made through SBIR (could be changed)

Algorithms for CeC modeling can be applied to other markets

- Laser-Plasma Acceleration (LPA) community can use Vorpal's new low-noise kinetic capabilities (low-noise particle loading)
- Plasma community will benefit from Vorpal's new Vlasov solvers
  - Plasma processing needs sheath modeling
  - Also useful to NASA and DOD (e.g., Hall thrusters)
- Vorpal's new electrostatic open boundary conditions apply to
  - LPA and beam physics
  - Electron guns
  - Charge buildup on satellites
- Fusion community can benefit from our improvements to δf-PIC
- Improvements to the Vorpal Composer GUI will affect all markets
  - Input file validation streamlines user workflows
  - Remote execution (e.g., at NERSC) from desktop application streamlines user workflows

Dual Use

Tech-X commercialization approach applies to smaller markets

- Previous 5 years: $13M in non-SBIR revenue
- Vorpal has been modularized to target specific markets

VSimEM — Advanced ElectroMagnetics

VSimMD — Microwave Device

VSimPD — Plasma Discharge

VSimPA — Plasma Acceleration

Vorpal Base — Classic ElectroMagnetics and Plasma Physics

- Reuse of infrastructure and marketing resources
- Technology developed for CEC impacts multiple markets
  - LPA → *VSimPA & VSimPD*
  - Plasma Processing → *VSimPD*
  - Space physics / satellite modeling → *VSimPD & VSimMD*
- A 2011 Foresight Report suggests that the plasma processing simulation market (alone) is $13M
  - Vorpal is only now breaking into this market

Vlasov solvers will increase market of *VSimPD*

- Vlasov solvers provide low-noise modeling of the plasma sheath
- This makes it possible for the semiconductor industry to model plasma processing and explore processing optimization
- If 5% of the semiconductor R&D budget is spent on modeling software then have a $1.3B market
- 1% market share is $13M

Company (2010 rank)	2011 ($M)		
	Sales	*R&D*	*R&D/sales*
Intel (1)	49,697	8,350	17%
Samsung (2)	33,483	2,810	8%
STMicro (3)	9,631	2,352	24%
Renesas* (4)	10,653	2,131	20%
Qualcomm** (7)	9,828	2,025	21%
Toshiba (5)	12,745	1,986	16%
Broadcom** (6)	7,160	1,983	28%
TI (8)	12,900	1,716	13%
AMD** (9)	6,568	1,453	22%
TSMC*** (10)	14,600	1,156	8%
Top 10 total	**167,265**	**25,962**	**16%**
Marvell** (11)	3,445	1,030	30%
Nvidia (12)	3,939	1,003	25%

Commercializing Technology for Coherent Electron Cooling

Market Opportunity & Impact

A number of markets need technology developed in this project specifically for modeling the CEC proof-of-principle experiment, including Vlasov for plasma processing, open BCs for vacuum charge and plasma problems, and inhomogeneous background δf-PIC for fusion sciences.

These new features will be packaged into proprietary software modules for the commercial software package Vorpal. Estimates of the sizes of these new simulation markets are believed to be greater than $10M.

Technology & IP Position

Tech-X can accurately model Debye screening, its signal amplification in a free-electron laser, and time-evolution of this signal after existing the laser.

Tech-X protects its intellectual property through closed source (trade sectret) and copyright...

Product Development Milestones

Milestone	Date
Vorpal Composer GUI validation improvements	Feb 2012
Inhomogeneous background δf-PIC	July 2012
Open boundary conditions for electrostatics	Aug 2012
Remote execution from Composer	Nov 2012
Release of Vorpal 6.0	**Nov 2012**
Vlasov implementation	est 2013
Release of Vorpal 7.0	**late 2013**

Company/Team & Business Model

Tech-X was founded in Boulder, CO in 1994. With a staff of more than 70 employees, more than two-thirds of whom have a Ph.D. in a relevant technical discipline, the company has strong expertise in computational physics (plasma physics, accelerator modeling, fusion theory, fluid dynamics, multiphysics simulations), middleware (CORBA, DDS, GRID), scientific visualization and data analysis, climate modeling, as well as high-performance and distributed computing (including GPU computing) applied to engineering and scientific applications.

Improvements to the Vorpal VSimPD module, including improvements to the δf-PIC algorithms and the addition of Vlasov modeling, will allow targeted marketing of Vorpal to markets such as the plasma processing community.