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# Response to FESAC survey, non-fusion connections to Fusion Energy Sciences: Applications of the FES-supported beam and plasma simulation code, Warp

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# Response to FESAC survey, non-fusion connections to Fusion Energy Sciences: Applications of the FES-supported beam and plasma simulation code, Warp*

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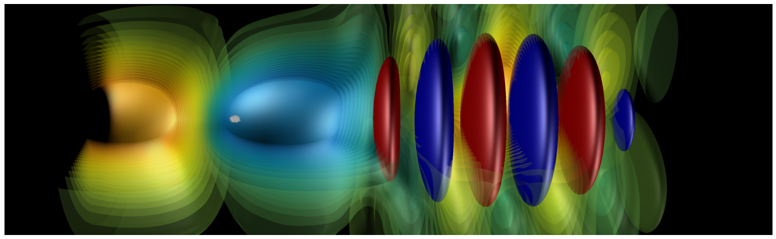

Warp simulation of Laser-Plasma Acceleration

The Fusion Energy Sciences Advisory Committee's subcommittee on non-fusion applications (FESAC NFA) is conducting a survey to obtain information from the fusion community about non-fusion work that has resulted from their DOE funded fusion research. The subcommittee has requested that members of the community describe recent developments connected to the activities of the DOE Office of Fusion Energy Sciences. Two questions in particular were posed by the subcommittee. This document contains the authors' responses to those questions.

*Category*: High Energy Density Laboratory Plasmas and IFE Science and Technology

*(1) Briefly describe a non-fusion science or technology development in an area supported by or otherwise connected to activities of the DOE Office of Fusion Energy Sciences.*

A particle beam and plasma simulation capability developed under DOE/FES auspices, the Warp code, has been broadly adopted by other groups in the scientific and engineering community. This has enabled developments in basic physics, advanced new approaches to medical therapy and border security, and furthered a range of applications of particle accelerators and plasmas. Warp's original purpose was to support FES' heavy-ion beam-driven inertial fusion energy ("Heavy-Ion Fusion," or HIF) research program. The intense beams of the HIF program's experiments required the capabilities of both particle-accelerator and kinetic plasma codes. Research using ion beams to heat matter continues on the Neutralized Drift Compression Experiment (NDCX-II) at LBNL, an element of FES' high energy density laboratory plasmas (HEDLP) program. While the original intent of Warp's developers was to create an optimized tool for the HIF mission, it has been adopted for use on problems ranging from laser-plasma acceleration to anti-hydrogen trapping, and from rare-isotope beam generation to inverse-Compton gamma ray sources. Warp offers unique capabilities in structure (it is user-programmable and "steerable") and algorithms (a good number of significant new algorithms first appeared in it). Through FES' efforts, the code was released with an open-source license, and this has greatly amplified its world-wide impact. For details concerning Warp's applications and methods see: http://blast.lbl.gov/warp_applications.html .

*(2) What societal benefits, including contributions to other areas of science and technology, have or are likely to result from the development described above?*

The applications listed below represent significant benefits to society from FES's Warp code effort. These contributions range from basic physics (anti-H trap, positron trap) to national security (gamma source), and from medical technology (capture of proton beams) to broader accelerator applications (HEP and rare-isotope facilities). Through its support of Warp development, FES has also contributed materially to the advancement of computational physics, with important techniques (listed below) appearing first in Warp.

List of Warp's application areas:

-- Ion accelerators for high-energy density physics and heavy ion fusion.
-- Laser plasma accelerators, where Warp has become a principal code.
-- H- beam chopping for Fermilab's Project-X.
-- The University of Maryland Electron Ring (UMER), supported by HEP, FES, and other sponsors.
-- Anti-hydrogen traps (Warp studies led to the adoption of octupole fields in the CERN trap).
-- Paul traps (at Princeton, and in Japan).
-- A non-conventional Penning-Malmberg trap for positron confinement.
-- Electron-Cyclotron Resonance (ECR) ion sources (for rare isotope machines and other applications).
-- Ion and electron "guns" (injectors).
-- Capture and control of laser-accelerated proton beams, ultimately for therapy and other uses.
-- Beam space-charge neutralization.
-- Collective space-charge effects in a wide variety of particle beam applications.
-- Electron-cloud buildup and multipacting phenomena (unwanted stray electron multiplication).
-- Inverse Compton scattering, and a compact gamma-ray source for materials interrogation.
-- Coherent synchrotron radiation and free-electron lasing, for HEP and other applications.
-- Proton injection, beam merging and nonlinear space charge dynamics in the Integrable Optics Test Accelerator (IOTA) ring under construction at Fermilab

Computational techniques developed in, and incorporated into, Warp include:

-- The use of "warped" Frenet-Serret coordinates in particle-in-cell plasma simulations, allowing the efficient treatment of "bent" beam systems such as in ECR ion sources and circular accelerators.
-- The use of "cut cells" in a 3-D particle-in-cell code, allowing boundaries that are not restricted to "Lego bricks."
-- The use of adaptive mesh refinement for both electrostatic and electromagnetic particle-in-cell simulation.
-- The use of a Lorentz-boosted frame of reference, allowing unprecedented efficiency in simulating laser-plasma accelerators and electron-cloud problems.
-- The introduction of novel methods for avoiding spurious "numerical Cherenkov" effects, advancing the Lorentz force law in a relativistically invariant manner, injecting a laser through a moving planar antenna, and wideband filtering that runs efficiently in parallel.
-- The development of novel algorithms for simulating coherent synchrotron radiation and free-electron lasing.
-- Exploration of a highly-scalable domain decomposition technique for pseudo-spectral Maxwell solvers (with minimal spurious dispersion)
-- Extension of the analysis and application of Perfectly-Matched-Layers (outgoing-wave boundary conditions for electromagnetic waves) to very-high-order and to pseudo-spectral solvers.

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