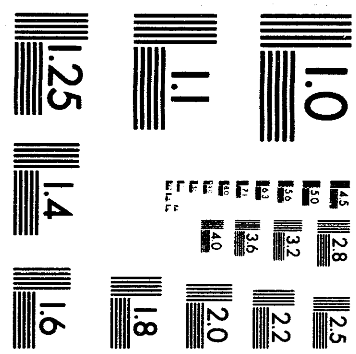

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Concluding Report:
Simulation Models for Computational Plasma Physics

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Simulation Models for Computational Plasma Physics

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ABSTRACT

In this project, we enhanced our ability to numerically simulate bounded plasmas that are dominated by low-frequency electric and magnetic fields. We moved towards this goal in several ways; we are now in a position to play significant roles in the modeling of low-frequency electromagnetic plasmas in several new industrial applications. We have significantly increased our facility with the computational methods invented to solve the low frequency limit of Maxwell's equations (DiPeso, Hewett, accepted, J.Comp. Phys., 1993). This low frequency model is called the Streamlined Darwin Field model (SDF, Hewett, Larson, and Doss, J. Comp. Phys., 1992) has now been implemented in a fully non-neutral SDF code BEAGLE (Larson, Ph.D. dissertation, 1993) and has further extended to the quasi-neutral limit (DiPeso, Hewett, Comp. Phys. Comm., 1993). In addition, we have resurrected the quasi-neutral, zero-electron-inertia model (ZMR) and began the task of incorporating internal boundary conditions into this model that have the flexibility of those in GYMNOS, a magnetostatic code now used in ion source work (Hewett, Chen, ICF Quarterly Report, July-September, 1993). Finally, near the end of this project, we invented a new type of banded matrix solver that can be implemented on a massively parallel computer--thus opening the door for the use of all our ADI schemes on these new computer architecture's (Mattor, Williams, Hewett, submitted to Parallel Computing, 1993).

I. INTRODUCTION

There is an obvious need for a laboratory determined to be relevant to long range industrial research to have the capability to numerically simulate a wide range of phenomena. An emerging field is the industrial application of plasmas. Until recently, no capability existed in the low-frequency parameter regime that predominate plasmas used for material processing. One of the goals of the Center for Computational Plasma Physics in the PPRI is extend some recent advances so that we can effectively simulate bounded plasmas that are dominated by low-frequency electric and magnetic fields.

We continue to pursue our recent successes in low frequency electromagnetic plasma modeling. Our models have been employed in Heavy Ion Fusion ion source studies, magnetotail magnetic reconnection, high altitude burst physics, active magnetic media design, plasma waste processing, and plasma etching. In spite of the wide range of physics that some of our recently-developed methods could impact, we find our research is naturally focusing on the enhancement of two existing models that have immediate application. Both of these models are reduced-model algorithms that analytically eliminate higher frequencies. We find the advanced computational research exciting, the motivation compelling, and future needs well-defined for these two models. Other models continue to be investigated but not with the same vigor. The two models that we concentrated on were GYMNOS[1], our magnetostatic, initial value code and ZMR[2], our quasi-neutral, zero-electron-inertia model. Here is a brief summary of what we accomplished during this project.

II. GYMNOS

GYMNOS is an axisymmetric r,z PIC code that has a very general internal boundary capability. We have used it as the basic but general platform on which to build a variety of more general models. One model is our new non-radiative Streamlined Darwin Field (SDF) electromagnetic field model [3](J. Comp. Phys., 1992). This model, implemented by UCD student David J. Larson in a code called BEAGLE[4], has now been updated via a transfusion of the internal boundary/structure capability of GYMNOS--in a code called BGL43. This combination has will be used to understand the differences between capacitive and inductive coupling in a non-neutral plasma.

Although GYMNOS is primarily used to study ion source behavior[5], we have also used GYMNOS to proof test new algorithms. One example is our new algorithm that allows space-charge-limited emission to be accurately resolved with of order 10 mesh points between the anode and cathode. While routine in 1D with many (several 100) mesh points, multi-dimensional embodiments that accurately describe beam emittance become prohibitive--and thus intractable as design tools. Added to GYMNOS, these new methods provide beam transient modeling in general axisymetric geometry (including time-dependent voltages on internal structures) in a couple of minutes on a CRAY 2. We also built a more general boundary description, based on the actual location of the physical boundary rather than just the enclosed Lego-building blocks, that is essential for slow moving particles within a few cells of the curved boundary.

For another example, UCD student Matt Gibbons has started looking at a new type of Direct Implicit PIC model[6] with only the electrostatic part of the fields done implicitly. Working within the GYMNOS/BEAGLE framework, electromagnetic fields are again done with the SDF method. The resulting field equations appear to be much more straightforward and promise to be much more robust--especially to new geometries. Previous codes (AVANTI[7]) based on the full DIPIC algorithm were not easily modified to new configurations and suffered from serious numerical energy loss for some mesh/time step combinations. We searched for a merger of these proven DIPIC concepts with the Smooth-Particle-Hydrodynamics[8] but the needed flexibility was not found.

III. ZMR

The other model that we concentrated on is our quasi-neutral, zero-electron-inertia hybrid (fluid electron-kinetic ion) code ZMR[2] For high density, low temperature plasmas (such as plasma processing chambers), the Debye shielding distance is typically smaller than any practical computational mesh spacing. This limit, in which the Debye length becomes vanishingly small, is the essential feature quasi-neutrality. In addition to many other areas, we have started to apply ZMR to plasma etching. Though essential physics such as ion flux to the wall, chemistry, and collisions remain to be added, ZMR demonstrated the basic coupling mechanisms between the plasma and the external "hot-plate" coil in the TCP (transformer coupled plasma) plasma processing chamber.

We need to add analytic sheath boundary conditions, collisions, and chemistry added to ZMR. Further, we need to infuse GYMNOS boundary technology into ZMR so that we can easily change the geometry of our simulated device to match experiment. In addition, we need to fully prooftest our recent addition of a dielectric structure capability in ZMR between the antenna and the plasma.

IV. COMPUTATIONAL SUPPORTING RESEARCH

Our low-frequency electromagnetic simulations rely on models that are elliptic and our Dynamic Alternating Direction Implicit (DADI) method[3] very effectively serves as the heart of many of our field algorithms. For the coupled equations of the SDF method, we found a new coupled equation version of DADI called CEDADI that has proven two order of magnitude faster that competing methods[3]. We further enhanced CEDADI using block tridiagonal methods for another factor of 4 increase in speed[9].

It is clear that the future of computing lies with massively parallel MP architecture. Tim Williams, a noted massively parallel expert, started working with us part time in the last part of this project to help investigate a MP implementation of DADI. This effort has been very successful! Our breakthrough[10,11] has emerged through a new approach for solving the banded matrices that are the underpinnings of DADI. Rather than simply give each row or column to a processor in the alternate directions, we can now distribute the matrix solve for each row or column over many processors. This means: 1) that we make use of the truly MASSIVELY parallel machine, and more importantly, 2) we have found a way to organize the distributed calculations on these lines that will drastically cut the number of messages that must be passed--breaking through the theoretical parallel efficiency limit for solving single banded systems independently.

V. SUMMARY

Integrating over the wide range of applications to which we have applied our models, we are quite pleased with our progress. Our success with this project have strengthened our ability to undertake and quickly succeed with new opportunities--the goal of this project. While our ultimate success is yet to be measured, our models have already been used for a wide variety of applications including: ion source studies, magnetotail magnetic reconnection, high altitude burst physics, and plasma etching. We have no shortage of new ideas and algorithms. We're actively planning our future and the support for this project has played a crucial role in our success.

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