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ACCELERATOR RESEARCH STUDIES

Task A: Study of the Physics of Space-Charge Dominated Beams for Advanced Accelerator Applications

Task B: Studies of High-Power Gyroklystrons and Application to Linear Colliders

Task C: Theory and Simulation of the Physics Space-Charge Dominated Beams

Annual Report for the Period June 1, 2003 to May 31, 2004

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Table of Contents

PROGRESS REPORT

Task A:
Study of Physics of Space-Charge Dominated Beams for Advanced Accelerator Applications

This progress report covers the research conducted during the first year of the grant period (from June 1, 2003 to May 31, 2004) for giant number DEFG0294ER40855. Our Task A is concerned with the space-charge physics in beams for advanced accelerator applications. This task has as its major focus the development and construction of the University of Maryland Electron Ring (UMER) project. This period has been characterized by enormous progress in the installation and operation of UMER. Currently, thirteen ring sections and a test Y-section have been installed, circum-navigating 280° of the first turn. We have now obtained a wealth of experimental data from UMER over nearly that entire distance, providing rich material for further experimental and theoretical studies. The following sections break down our progress in various areas: mechanical engineering and magnets, operations and experiments, diagnostics and electronics, and theory and simulation. During the past year, the UMER group (comprising Tasks A and C) gave eight invited talks and seminars, published or submitted eleven papers in refereed journals, and an additional fourteen papers in conference proceedings.

1. Mechanical Engineering and Magnets

Since the beginning of the grant period, we have added four 20° ring sections and a prototype Y-section to the UMER setup, bringing the total up to 14 sections out of 18 [see Fig 1]. Experiments on this setup are nearing completion as we prepare the next installation. The major new component we procured is a prototype Y-section for attaching the injector to the ring [Fig. 2]. The section consists of a short section of glass underneath the pulsed dipole, attached to a metal crotch on one side and straight pipe on the other. The glass was coated with a 60 nm-thick layer of aluminum oxide to minimize impedance and to prevent charging of the glass. Rather than disrupt ongoing experiments on UMER, we installed this test Y-section towards the end of the UMER beamline, at about 250°. Initial tests indicate this Y-section performs as expected, but suggest we probably need some minor modifications to the design. We are currently awaiting a detailed beam test including the fast pulsing of the dipole before ordering the final Y-sections for injection and extraction.

The pulsed dipole as well as the large DC quadrupoles needed for the Y-section have been fully designed (T.F. Godlove), the quadrupoles have been fabricated, and the pulsed dipoles are under construction, to be completed shortly (M. Walter). The general design features of the pulsed dipole have been reported before. Reviewing, the injected beam bunch must be deflected 10° left to enter the ring, then 10° right for the returning beam. This allows a 20° angle between the two arms of the injector Y-section. The circulation time is ~200 ns. The main problem is the inductance of the dipole. The proposed pulser method involves a long pulse for the multi-turn beam, which avoids the inductance problem, and a short injection pulse of the opposite polarity, which must have a fall time of 20-30 ns.

Because of the expected inductance, initial designs were based on a single sided circuit instead of the normal double side. The latter method reduces the effect of the external leads by bringing the connections to nearly the same point on the printed circuit. However, when WARP simulations were performed on the single sided design, a vertical oscillation was found, due to a small horizontal field (~2%), in turn due to the lack of cancellation of the external leads. With this in mind, a unique double-sided design was developed, shown in Fig. 3. The design uses six loops to reduce inductance, with three loops on the topside and three loops on the underside, shifted in location to improve the field quality.

Currently, the pulsed dipole power supply remains under construction (T.F. Godlove and B. Quinn). It is to consist of a superposition of two pulsers: a long-pulse one for beam circulation in the ring, and a short-pulse with opposite polarity and twice the amplitude for injection/extraction. The long-pulse power supply has been completed and is in the testing stage. The short-pulse supply is to be completed in the coming months.

In addition, the mechanical team (led by M. Walter) is in the process of replacing the ring quadrupoles with a slightly larger design that has the benefit of providing more room for alignment adjustments and also for accommodating multiple magnets inside the same mount, as is needed for skew quadrupole correction. The original ring quadrupoles were based on a difficult compromise. The diameter needs to be as small as possible to reduce heating, given the constraint of the beam pipe diameter and available axial space. During this past year, when the need for additional quads became clear, it was decided to order new printed circuits with slightly larger diameter because of conflicts encountered with the tolerances of the bent ring tubing and the quadrupole mounts. New quadrupoles were designed and then fabricated by Multi-Plate Circuits, Inc, with the same axial length, 4.65 cm, but with the radius increased from 2.79 to 2.95 cm. New aluminum mounts were designed to provide cooling fins to dissipate the added heat. The field quality is essentially identical to the original units. Thanks to the low cost of the UMER magnets and mounts, the benefits of this magnet upgrade are well worth the almost negligible cost. We have already upgraded half of the magnets and will complete the other half upon closing the ring.

The remaining three induction gap sections have been ordered and are expected to arrive shortly. Finally, the mechanical team has completed fabrication of nearly all the capacitive Beam Position Monitors (BPMs) and the Phosphor-screen/BPM actuators, installing them in each completed section. The team has additionally designed a new three-stage actuator for interchanging an energy analyzer with a Phosphor-screen or a BPM, under vacuum. This allows us to retroactively gather information on the beam energy spread anywhere along the first turn, even after closing the ring.

2. Operations and Experiments

At the start of the current grant period, we have successfully transported the UMER beam over nine sections, or nearly half the first turn, and into the large diagnostic chamber. Moreover, we have done so for a number of different operating points spanning a wide range of intensities from the emittance-dominated to the extremely space-charge-dominated regimes. The operating point was easily interchanged by rotating the aperture wheel in the source, therefore altering the current and emittance of the injected beam. Emittance measurements with a pepperpot mask (S. Bernal and H. Li) and the first time-resolved measurements with a slit-wire scanner were performed (M. Walter and D. Lamb). No major instabilities were observed, but halos, beam cross-section rotations and mismatch oscillations were evident in most cases [Fig. 4].

While at that stage it was possible to set the magnets and read some of the diagnostics using our computer LabView interface, beam alignment (steering) was a tedious process that typically took several days, and furthermore was not quite reproducible. Beam matching was even more difficult. So over the summer a graduate student (H. Li) developed a unified interface for acquiring data from all the diagnostics, including the Phosphor screens, and also for controlling all the power supplies. The student also developed an automated beam steering algorithm based on real-time image processing, beam steering and quadrupole current scans, which maximizes the amount of knowledge we have of the beam given the relative paucity of centroid measurement locations. The technique is independent of the absolute position of the phosphor screens in the ring chambers. It yields an electron beam that moves as parallel and as close as possible to the magnetic axes of the ring quadrupoles; the limiting factor is the mechanical tolerance of the quadrupole placement itself (±0.25 mm for the magnetic axis of individual quads.) The "video" alignment can also be used for absolute calibration of the capacitive beam-position monitors, the only position diagnostics with multi-turn operation of UMER. The procedure was successfully tested on a 7.2 mA beam, resulting in better alignment and less beam distortion from image forces. A typical automated alignment takes about 5-10 min/section, plus the time to move diagnostics, and is reproducible from day to day.

Currently, H. Li is working on a similar algorithm for optimizing the matching of the beam, and also on a "brute-force" algorithm for finding a global optimum for matching. These techniques are anticipated to improve the beam quality and reduce the observed halo. Sensitivity and correction to rotational errors also appear to be a cause of the halo, and are being separately addressed by R. Kishek in conjunction with H. Li. All the steering and matching algorithms employed have been thoroughly tested by simulation before experimental testing on UMER.

In addition, electron beams of different currents were characterized in the injection section, through emittance measurements, profiling and phase-space mapping (tomography). We have used standard quadrupole scans to determine the emittance of an emittance-dominated beam, and to obtain a detailed phase map through tomography techniques. Similar quadrupole scans were employed for two cases of space-charge-dominated beams. An interesting observation is the persistence of the cathode grid in the beam distribution downstream, as seen in some of the Phosphor screen output (see Fig. 5).

We have a graduate student (Y. Huo) experimenting with the generation of perturbations on the beam using photoemission from a laser beam incident on the cathode by means of a mirror in the first chamber of the injector (see setup in Fig. 6). The results are encouraging, and the perturbations can be tracked over the entire first turn. The student is concurrently modeling the evolution of these perturbations using the 3-D WARP particle-in-cell code.

Finally, we have conducted a series of experiments (J. Harris and A. Valfells) using the beam position monitors to measure the longitudinal evolution of the initially rectangular profile of the 24 mA and the 85 mA beams over 6 m (180 degrees). In addition, we have experimented with a Gaussian/parabolic profile (generated by photoemission). We found good agreement with the one-dimensional cold fluid theory for rectangular beams, and with the longitudinal envelope equation for the gaussian/parabolic beams. We measured alpha in the case of the rectangular beams, but were unable to measure it for the gaussian beam. We are currently planning an improved series of longitudinal experiments which also look at transverse-longitudinal coupling and dispersion-related effects, to be completed by the summer. In addition, we have obtained a set of filters for altering the pulse shape at the source, allowing us for instance to generate a long-pulse parabolic beam.

3. Diagnostics and Electronics

The electronics team (led by B. Quinn) has completed the fabrication of nearly all the electronics. In addition, the team has implemented a large number of enhancements to the wiring schemes, such as quick-connects and switchboxes for easier modification of the wirings, and also a computer controlled relay box for switching polarities of the steering dipoles power supplies. These changes were necessitated by the new alignment and matching algorithms required by the experiment.

Based on the results of the energy analyzer tests on the Long solenoid Experiment (LSE, funded by a separate grant), the design of the third-generation energy analyzer was slightly modified and three such devices are expected to arrive soon (two for the LSE and one for UMER). The physics of the energy analyzer turned out to be extremely complicated, particularly because of the space charge inside the device and because of the high resolution demanded by the LSE. In addition, UMER imposes the requirement to withstand a high voltage of 10 kV (nearly twice as high as the LSE) requiring some modification and high voltage testing. The energy analyzer research (Y. Zou and Y. Cui) has been the subject of several recent publications by our group. The present third-generation energy analyzer provided impressive results, measuring an energy spread in the sub-eV to eV range, in very good agreement with the lower limit of the beam energy spread set by the intra beam scattering and non-adiabatic acceleration.

A prototype pulser for the induction gaps (J. Harris) is now operating in single-shot mode at low voltage. We are working on improving the switching, pulse shape, matching, and preparing for HV testing.

4. Theory and Simulation

As mentioned in the preceding section, UMER's unique energy analyzer resulted in a number of publications, which also included theoretical studies using a 1-D self-consistent model (Y. Zou) as well as an envelope solution (Y. Cui).

The observation of a halo as well as rotated beams in the 9-section experiments presented at PAC'03 inspired additional studies of quadrupole rotation effects and halo formation (R. Kishek). The initial results indicate significant sensitivity to quadrupole rotation errors in the injector – for instance, injecting a beam rotated by a mere 5° is sufficient to induce a halo within a few meters – the scale in which the halo was observed in UMER. Of course, the sensitivity to rotational errors in the injector itself depends on the particular matched solution chosen. Since the injector uses seven magnets when only four constraints are needed to match, there is an infinite number of possible matched solutions. Some are better than others. Using the results H. Li's brute-force calculations for global matching, we are now seeking optimized solutions that not only match the beam in the rms sense, but also do so in a way that is least sensitive to rotational errors.

For this purpose, an envelope code has been developed (Kishek) that includes rotational effects, based on John Barnard's moment equations [PAC'95]. In addition, Kishek has been examining particle trajectories in rotated beams via large-scale self-consistent simulations with the particle-in-cell code WARP, with the goal of better understanding halos in linearly-coupled systems.

The WARP code is also being applied in 3-D to model the propagation of perturbations in the beam, such as perturbations generated by the laser (Y. Huo and R. Kishek). The modeling is done in such a way as to be able to independently track the particles initially in the perturbation. Doing this in 3-D required significant code development that we have almost completed.

In preparation for anisotropy studies, M. Reiser and H. Li have a developed an analytical solution of the matched K-V envelope equations for a "smooth" asymmetric focusing channel. This approach has the advantage of highlighting the scaling with the physics parameters, provides better physical insight, and therefore assists in designing such an experiment. This work has been submitted for publication in *Journal of Applied Physics*.

FIGURE

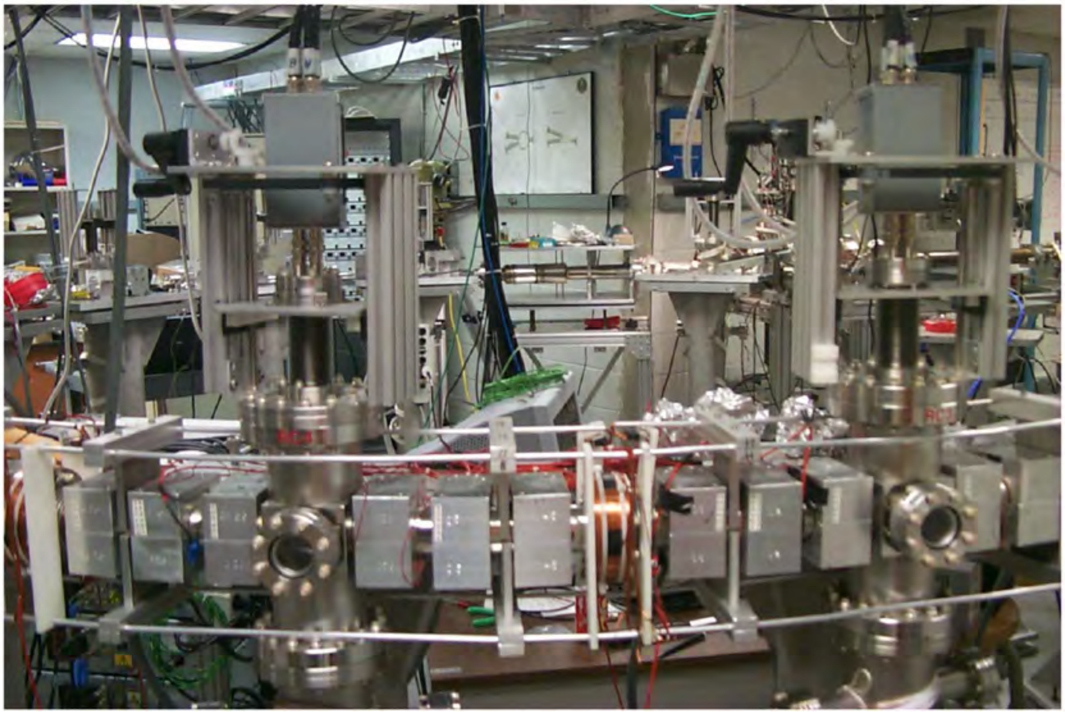

Fig. 1 Photograph of UMER as of September 2003.

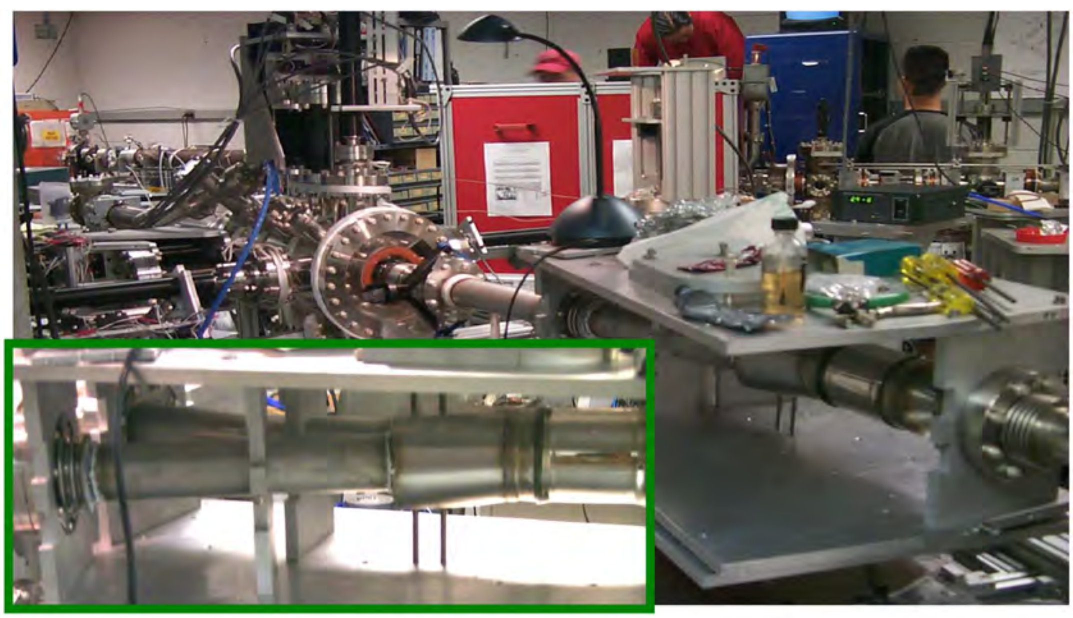

Fig. 2 Photograph of Y-section as installed on UMER, September 2003.

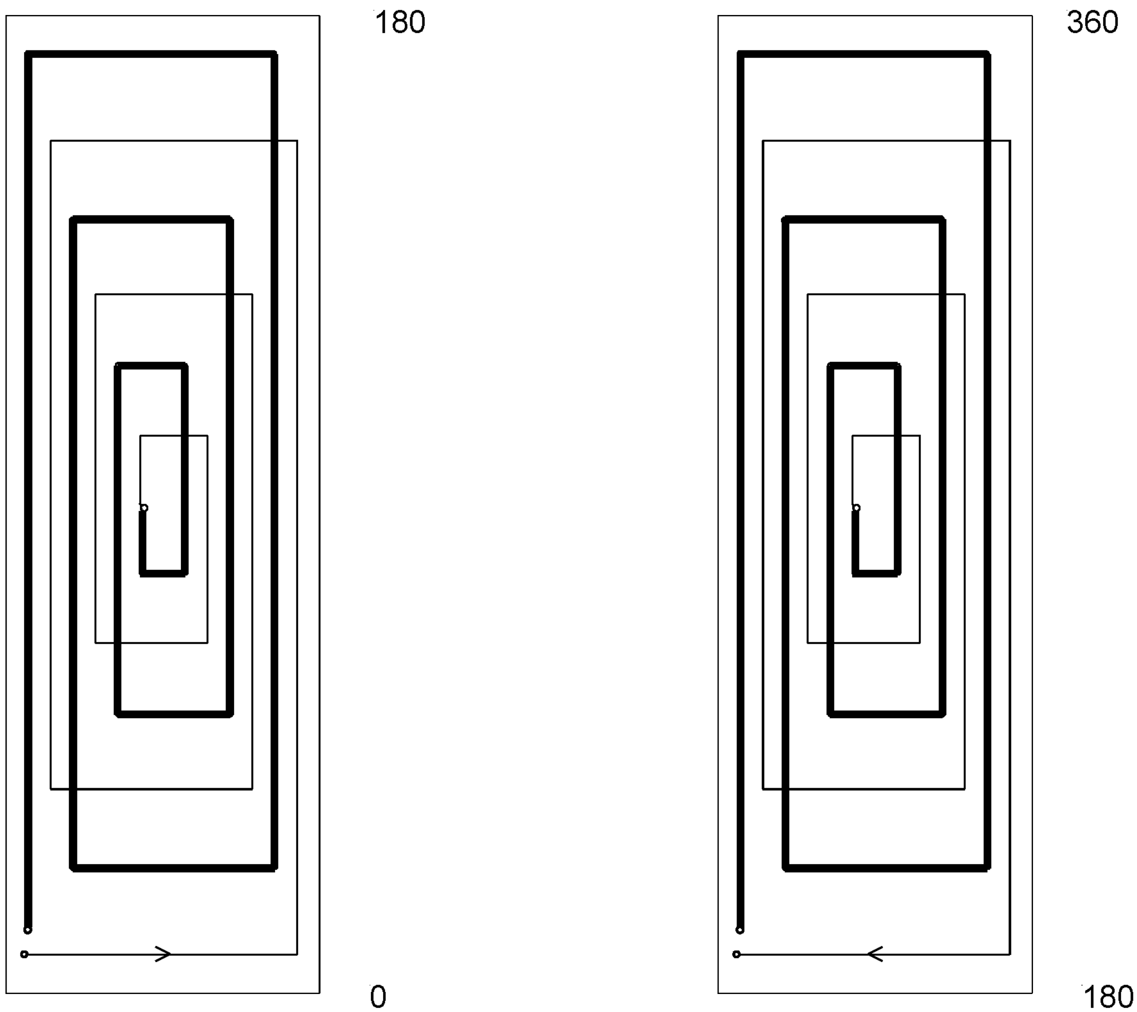

Fig. 3. Pulsed-dipole layout. Heavy lines are on top, light lines on the underside.
Arrows show the current direction.

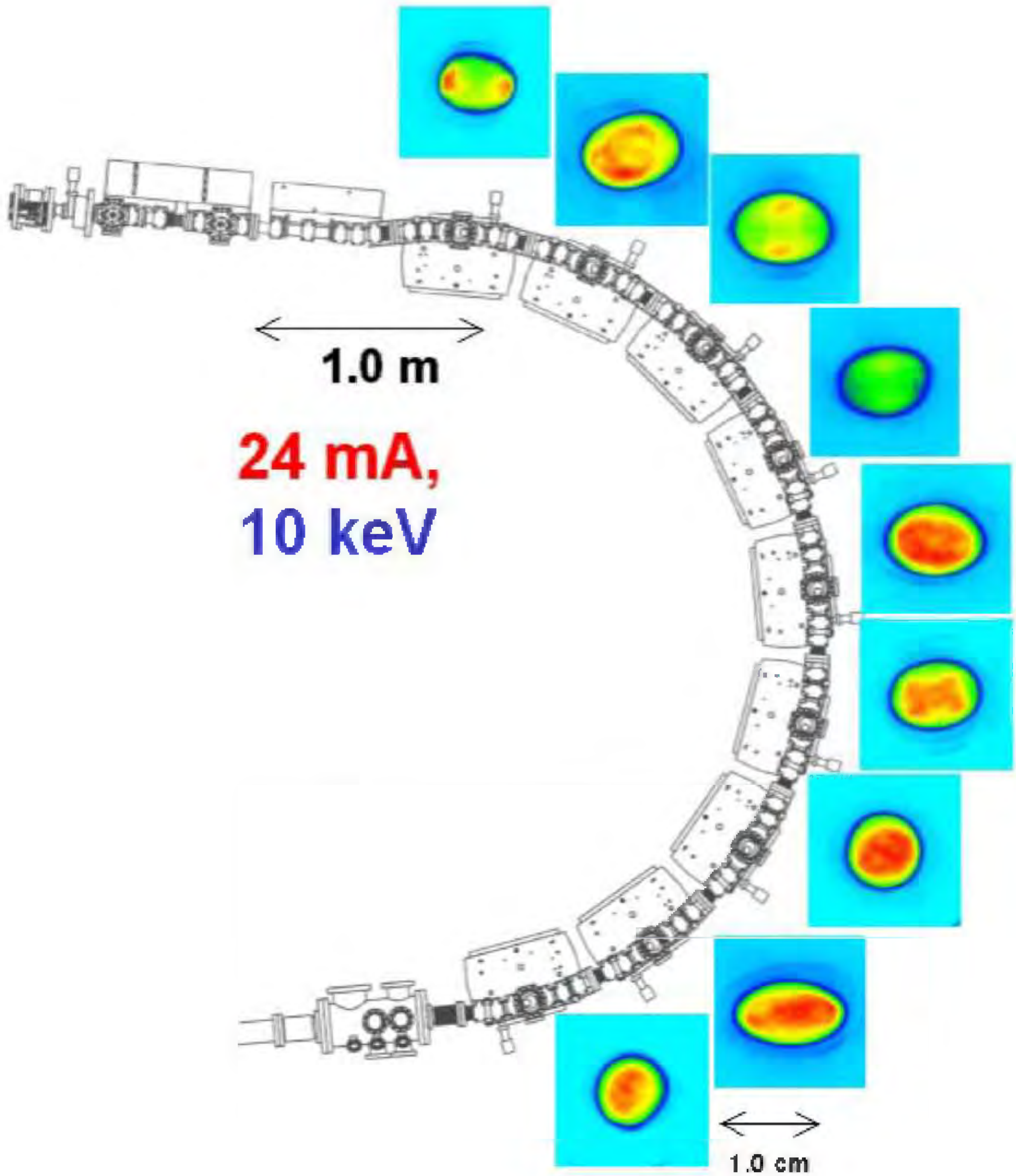

Fig. 4. Experimental results from UMER using a 24 mA beam, presented at the 2003 Particle Accelerator Conference. The false-color pictures enhance the halo. Note that no attempt was made in this experiment to carefully match the beam, align it, or compensate for rotational errors.

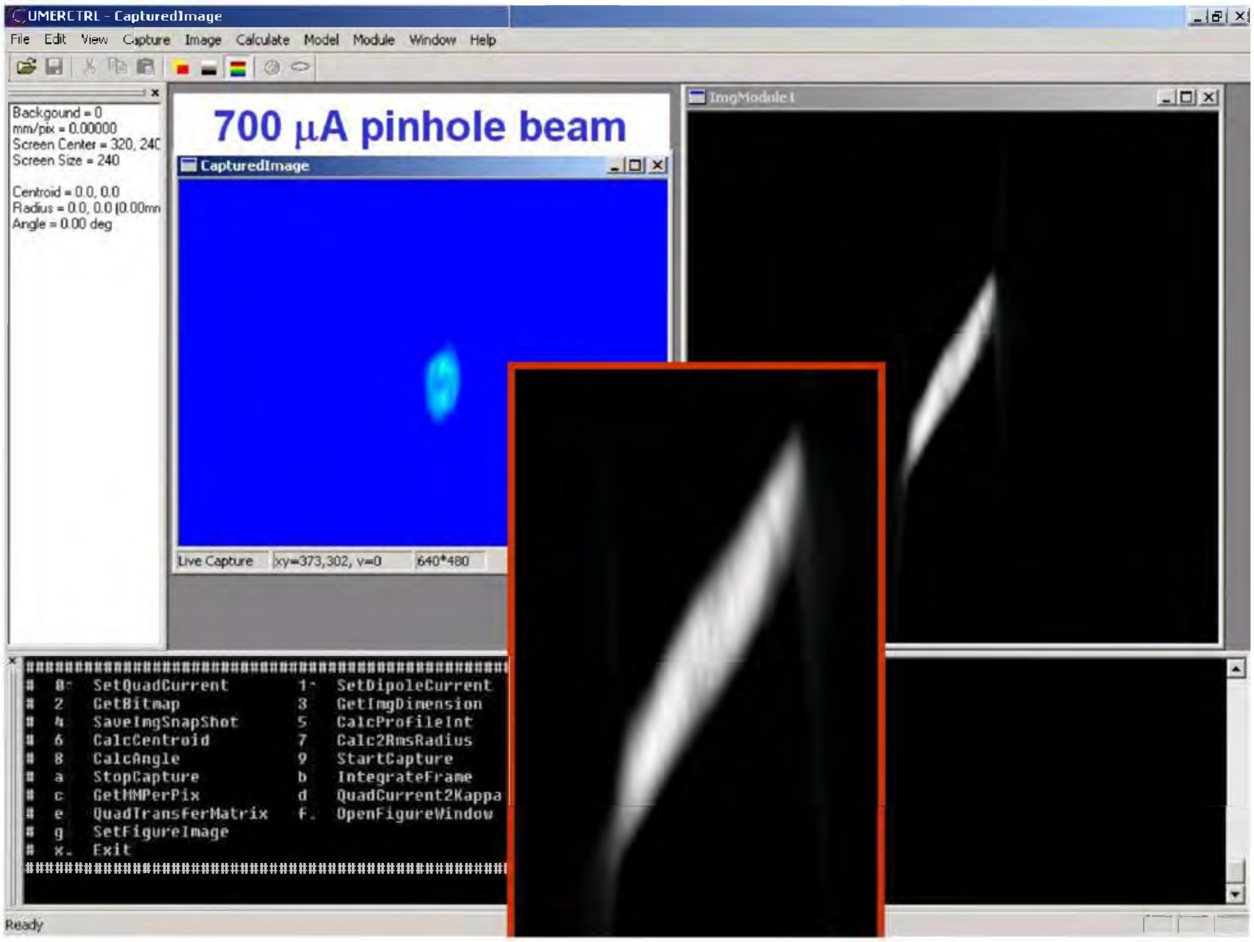

Fig. 5 Tomographic mapping of the transverse phase space of the 0.7 mA (emittance-dominated) beam.

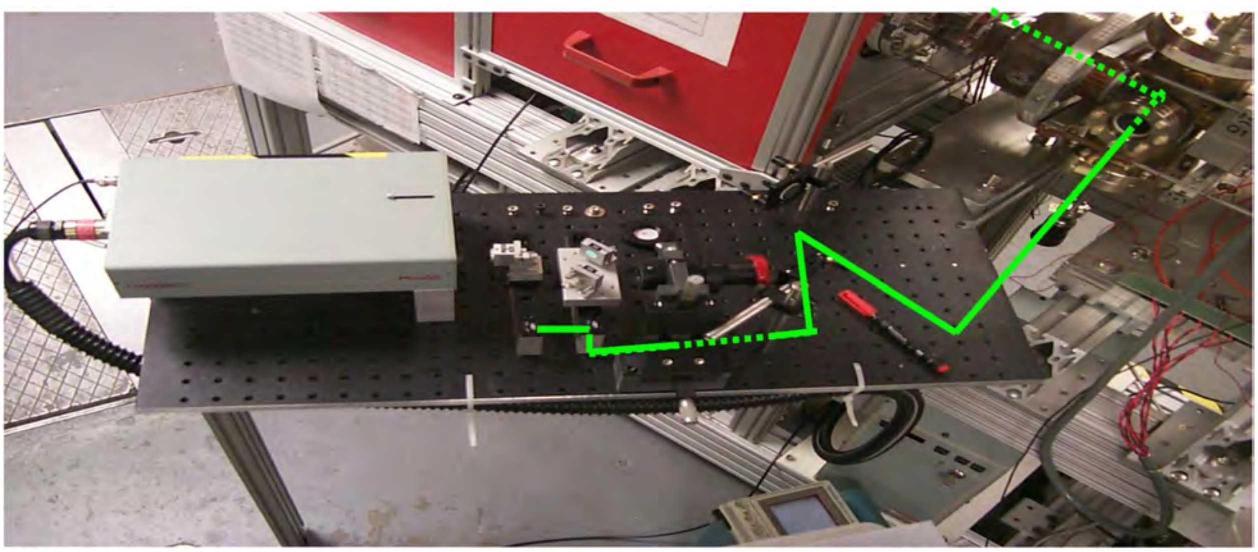

Fig. 6 Photograph of laser setup for generating perturbations on the UMER beam.

5. Publications and Presentations

The research conducted for Task A is closely tied to Task C, thus some of the papers listed here also pertain to the work done in Task C.

Invited Talks

1. R.A. Kishek, *"HIF Research on the University of Maryland Electron Ring (UMER),"* 15th International Symposium on Heavy Ion Inertial Fusion, Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, June 2004.

2. R.A. Kishek, *"Modeling of Halos and Intense Beams,"* 2004 Advanced Accelerator Concepts Workshop (AAC'04), Stony Brook University, NY, June 2004.

3. R.A. Kishek, *"The University of Maryland Electron Ring (UMER): A Model for Future Accelerators,"* Colloquium, Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, January 2004.

4. R.A. Kishek and S. Bernal, *"The University of Maryland Electron Ring (UMER): A Model for Future Accelerators,"* Princeton Plasma Physics Laboratory, December 2003.

5. S. Bernal, *"Beam experiments in the extreme space-charge limit on the University of Maryland Electron Ring (UMER),"* American Physical Society, Division of Physics of Plasmas, 45th Annual Meeting, Albuquerque, NM, October 2003.

6. R.A. Kishek, *"Our Experience at the University of Maryland Electron Ring (UMER),"* Lawrence Berkeley National Laboratory, October 2003.

7. M. Reiser, *"Past and Future Directions in Beam Physics - Personal Perspectives,"* Special Colloquium honoring Prof. Ingo Hofmann's 60th Birthday, GSI Darmstadt, Germany, September 2003.

8. R.A. Kishek, *"Simulations of Single-Turn Experiments at the University of Maryland Electron Ring,"* Halo '03 Workshop, Montauk, New York, May 2003.

Publications in Refereed Journals

1. **Invited:** S. Bernal, H. Li, T. Godlove, I. Haber, R.A. Kishek, B. Quinn, M. Reiser, M. Walter, Y. Zou, and P.G. O'Shea, *"Beam Experiments in the Extreme Space-Charge Limit on the University of Maryland Electron Ring (UMER),"* Physics of Plasmas, to appear (2004).

2. **Invited:** J.-L. Vay, P. Colella, J.W. Kwan P. McCorquodale, D.B. Serifini, A. Friedman, D.P. Grote, G. Westenskow, J.-C. Adam, A. Heron, and I. Haber, *"Application of Adaptive Mesh Refinement to Particle-in-Cell Simulations of Plasmas and Beams,"* Physics of Plasmas, accepted for publication (2004).

3. Y. Cui, Y. Zou, A. Valfells, M. Walter, I. Haber, R.A. Kishek, S. Bernal, M. Reiser, and P.G. O'Shea, *"Design and Operation of a Retarding Field Energy Analyzer with Variable Focusing for Space-Charge Dominated Electron Beams,"* Review of Scientific Instruments, submitted (2004).

4. Martin Reiser and Hui Li, *"Solutions of the matched K-V envelope equations for a `smooth' asymmetric focusing channel,"* Journal of Applied Physics, submitted (2004).

5. Y. Zou, H. Li, M. Reiser, and P.G. O'Shea, *"Theoretical Study of Transverse Emittance Growth in a Gridded Electron Gun,"* Nuclear Instruments and Methods A, accepted for publication (2004).

6. H. Li, S. Bernal, R.A. Kishek, I. Haber, Y. Zou, P.G. O'Shea, and M. Reiser, *"Simulation studies on matching of space-charge-dominated beams for the University of Maryland Electron Ring (UMER),"* Nuclear Instruments and Methods A, accepted for publication (2004).

7. I. Haber, S. Bernal, C. M. Celata, A. Friedman, D. P. Grote, R.A. Kishek, B. Quinn, P.G. O'Shea, M. Reiser, and J.-L. Vay, *"Collective Space-Charge Phenomena in the Source Region,"* Nuclear Instruments and Methods A, accepted for publication (2004).

8. S. Bernal, B. Beaudoin, Y. Cui, M. Glanzer, T. F. Godlove, J. Harris, M. Holloway, I. Haber, R.A. Kishek, W-T. Lee, H. Li, D. Lamb, B. Quinn, M. Qurius, M. Reiser, A. Valfells, M. Virgo, M. Walter, M. Wilson, R. Yun, Y. Zou, and P. G. O'Shea, *"Intense Beam Transport Experiments in a Multi-Bend System at the University of Maryland Electron Ring (UMER),"* Nuclear Instruments and Methods A, accepted for publication (2004).

9. Y. Zou, Y. Cui, I. Haber, M. Reiser, and P.G. O'Shea, *"Longitudinal space-charge effects in a retarding field energy analyzer,"* Physical Review Special Topics - Accelerators & Beams **6**, 112801 (2003).

10. **Invited:** C.M. Celata, F.M. Bieniosek, E. Henestroza, ..., S. Bernal, Y. Cui, D. Feldman, T.F. Godlove, I. Haber, J. Harris, R.A. Kishek, H. Li, P.G. O'Shea, B. Quinn, M. Reiser, A. Valfells, M. Walter, Y. Zou, *et al., "Progress in heavy ion fusion research,"* Physics of Plasmas **10 (5)**, 2064 (2003).

11. **Invited:** R.A. Kishek, S. Bernal, C.L. Bohn, D. Grote, I. Haber, H. Li, P.G. O'Shea, M. Reiser, and M. Walter, *"Simulations and experiments with space-charge-dominated beams,"* Physics of Plasmas **10 (5)**, 2016 (2003).

Publications in Conference Proceedings

1. A. Valfells, J. Harris, B. Quinn, S. Bernal, I. Haber, M. Walter, A. Diep, M. Reiser, and P. G. O'Shea, *"Initial Studies of Longitudinal Beam Dynamics on UMER,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

2. B. Quinn, B. Beaudoin, S. Bernal, D. Cohen, A. Diep, W. Lee, M. Glanzer, M. Qurius, M. Reiser, M. Walter, and P.G. O'Shea, *"Design and Calibration of a Fast Beam Position Monitor,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

3. H. Li, R.A. Kishek, S. Bernal, T. Godlove, M. Walter, P.G. O'Shea, and M. Reiser, *"Beam optics design on a new injection scheme for the University of Maryland Electron Ring (UMER),"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

4. I. Haber, S. Bernal, R. A. Kishek, P.G. O'Shea, M. Reiser, A. Friedman, D.P. Grote, and J.-L. Vay, *"Space-Charge-Dominated Phenomena in the Source Region,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

5. M. Walter, S. Bernal, A. Diep, M. Glanzer, I. Haber, J. Harris, R.A. Kishek, D. Lamb, W. Lee, H. Li, B. Quinn, M. Qurius, A. Valfells, M. Reiser, and P.G. O'Shea, *"Alignment of*

Components at the University of Maryland Electron Ring," Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

6. M. Walter, D. Lamb, S. Bernal, I. Haber, R.A. Kishek, H. Li, B. Quinn, M. Snowel, A. Valfells, M. Reiser, and P.G. O'Shea, *"Time Resolved Emittance Measurement in the University of Maryland Electron Ring,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

7. M. Walter, S. Bernal, T. Godlove, I. Haber, R.A. Kishek, H. Li, B. Quinn, A. Valfells, Y. Zou, M. Reiser, and P.G. O'Shea, *"Electro-mechanical Design for Injection in the University of Maryland Electron Ring,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

8. S. Bernal, B. Beaudoin, Y. Cui, A. Diep, T. Godlove, I. Haber, J. Harris, R.A. Kishek, D. Lamb, H. Li, M. Glanzer, B. Quinn, M. Reiser, A. Valfells, M. Walter, M. Wilson, R. Yun, Y. Zou, and P.G. O'Shea, *"Beam Transport Experiments over a Single Turn at the University of Maryland Electron Ring (UMER),"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

9. Y. Cui, Y. Zou, I. Haber, R. Kishek, A. Valfells, M. Reiser, and P.G. O'Shea, *"Experimental Study of Beam Energy Spread in the Space-Charge Dominated Beams,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

10. Y. Zou, Y. Cui, M. Reiser, and P.G. O'Shea, *"Space-Charge Effect in Retarding Field Energy Analyzer,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

11. J.W. Kwan, J.-L. Vay, F.M. Bieniosek, E. Halaxa, G. Westenskow, and I. Haber, *"Beam Optics of a 10-cm Diameter High Current Heavy Ion Diode,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

12. P.A. Seidl, D. Boca, F.M. Bieniosek, C.M. Celata, A. Faltens, L.R. Prost, G. Sabbi, W.L. Waldron, R. Cohen, A. Friedman, S.M. Lund, A.W. Molvik, and I. Haber, *"The High Current Transport Experiment for Heavy Ion Inertial Fusion,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

13. R.A. Kishek, S. Bernal, I. Haber, H. Li, P.G. O'Shea, B. Quinn, M. Reiser, and M. Walter, *"Beam Halo from Quadrupole Rotation Errors,"* 29th ICFA Advanced Beam Dynamics Workshop on Beam Halo Dynamics, Diagnostics, and Collimation, Montauk, NY, May 2003, ed., J. Wei, W. Fischer, and P. Manning, (New York: AIP Press **693**, 2003), p. 89.

14. C.L. Bohn, I.V. Sideris, H.E. Kandrup, and R.A. Kishek, *"Mixing of Regular and Chaotic Orbits in Beams,"* Proceedings of the LINAC 2002, Gyeongju, August 2002, CD-ROM ISBN: 89-954175-0-1 **98420**, 2003), p. 391.

PROGRESS REPORT

Task B:
Studies of High Power Gyroklystrons and Application to Linear Colliders

In the past year the gyroklystron project experienced a set-back when oil from the roughing pump inadvertently contaminated the entire high-vacuum system. This set-back cost us several months of clean-up and other work as described in the experimental section below. In addition, we were still battling the problem of non-uniform azimuthal current density that we had measured coming from our temperature-limited (TL) magnetron injection gun (MIG) and which we had attributed to our low peak power results with our second harmonic tube.

In spite of these problems, we continued to make progress on all aspects of the project and we are close to our near-term goal of interfacing our gyroklystron with the Haimson accelerator structure and our long-term goal of demonstrating that gyroklystrons are viable sources for linear collider applications.

We used the "opportunity" given to us by the oil contamination incident to improve the design of some of our vacuum components and to improve the conductance of our principle source of pumping in the output waveguide. We made further improvements to our modulator system and the feed-forward phase-control concept to enhance their reliability.

In addition to the time spent on system repair and on the fabrication of the parts necessary for our four-cavity second harmonic tube rebuild, we spent a considerable amount of time on two fronts to try to minimize or eliminate altogether the non-uniform azimuthal current density problems associated with our temperature-limited emitter. First, our ongoing interaction with Semicon culminated this year in the long-awaited delivery of two emitters that have been processed by a procedure significantly different than the "time-honored" procedure of the past and that should have considerably better temperature uniformity than previous versions of this emitter. The improvement will be measured shortly in our processing station that is now on-line.

Second, we have designed a number of space-charge-limited (SCL) MIGs that could eliminate the problem of non-uniform emission. The simulated results indicate that these devices can produce beams with beam qualities as good as those from their TL counterparts. We are now currently looking for a way to build one of these devices to see if the actual performance can live up to the promise of the computations.

We have also made progress on a number of theoretical and experimental fronts, including a look at the effects of overlapping resonances in gyroklystrons, improved mode conversion devices for the gyroklystron-accelerator interface, and even alternative output modes for the gyroklystron system that could improve system stability both at zero-drive conditions and saturated output levels. Furthermore, we have continued to interact with private industry in an effort to secure a completely new MIG that could allow us to achieve the peak power performance predicted by our computer simulations.

The net result of our effort this year is that we have overcome the contamination set-back and we are assembling the four-cavity rebuild to evaluate the performance of the current MIG. We have positioned ourselves to be ready to try a new MIG if the present gun cannot supply a beam of the required quality. We have also worked to be at the point that we will be ready to test the Haimson accelerator structure before the end of the year irrespective of which electron source we will need to use. Details of these efforts are described below.

1. Theoretical Work

1.1 Design of Space-Charge-Limited Magnetron Injection Guns (SCL-MIGs)

A number of SCL-MIGs were designed this year. The first design is summarized in our paper, "Space-charge limited magnetron injection guns for high-power gyroklystrons," which was accepted for publication in the 2004 Special Issue for High Power Microwaves in *the IEEE Transactions on Plasma Science*. Three more designs have been completed and we are in the process of writing a paper to be submitted to *Physical Review Letters* in the next few weeks.

Two codes were used to design the SCL-MIGs. It was found that EGUN was somewhat unreliable in that small changes in the numerical parameters would often cause large changes in the simulated results. For this reason, the use of EGUN was abandoned after the completion of the first SCL-MIG paper. The code TRAK, along with the necessary supporting codes, was used for the remaining SCL-MIG designs and to re-evaluate the performance of the design presented in the IEEE TPS paper.

All four designs have the same nominal design parameters and all give very similar results. The SCL-MIGs are designed to produce 500 * 500 kV of beam power with an average perpendicular-to-parallel velocity ratio of 1.5. All designs, according to TRAK, achieved these parameters with a ballistic parallel velocity spread less than 2.0%. The peak electric fields were below ~100 kV/cm and the peak cathode loadings were less than 9 A/cm^2 for all designs.

The first design was a simple two-electrode diode (not counting the inner conductor of the coaxial tube). It was designed by using the anode of the current temperature-limited MIG (TL-MIG) without modification, and by changing the shape of only the cathode assembly to produce the required results. Basically, the emitter is “recessed” into the cathode in order to decrease the local electric field and subsequently the space-charge limit. The shape of the recessed area is adjusted to provide proper focusing and minimize the axial velocity spread. Simulations show that the TL-MIG and the SCL-MIG have comparable beam quality and that the cathode loading and the peak electric field of the SCL design are within 10% of the TL-MIG values. Edge effects of the SCL-MIG were investigated by putting small (12 mil) gaps between the emitter and the focus electrodes and no significant spurious current was calculated.

The remaining three designs included two control electrodes to adjust the cathode current independently of the voltage (via a potential difference between the emitter and the control electrode). One design utilized small electrodes to achieve a current control of +/-50%. Another design had control electrodes that almost completely covered the cathode in order to allow a sufficiently high potential to cut-off the beam current even when full anode-cathode voltage was applied. The control anode positions were optimized to minimize spread, and as stated earlier, the beam quality was virtually identical to that of the diode SCL-MIG. A reverse potential of about 7% on the control electrode is needed to cut off the beam completely. The peak field at cutoff is about 135 kV/cm on the control anode surface, but the fields in the ceramics that support the control electrodes are less than 20 kV/cm.

The net result of these theoretical efforts is that all indications are that an SCL-MIG could be developed successfully and may be a viable approach to eliminate the non-uniform azimuthal current density problem that has plagued our TL-MIG to date.

1.2 Stochastic Phenomena in Relativistic Gyrodevices

Relativistic gyro-amplifiers for driving future linear accelerators might approach a 100 MW peak power level. Presently, the work is focused on achieving this power in gyroklystrons operating at the second cyclotron harmonic, and the operating voltage is in the range of 400 to 500 kV, i.e. the kinetic energy of electrons is close to the rest energy.

In these devices, the RF field amplitude is rather large, and interaction of relativistic electrons with electromagnetic (EM) waves of large amplitudes can strongly perturb the electron energies. Correspondingly, the electrons can move from the initial cyclotron resonance at, let's say, the second cyclotron harmonic, $\omega \approx 2\Omega_0(\gamma_0)$, (here ω and Ω_0 are the wave frequency and the initial electron cyclotron frequency, respectively, and γ_0 is the initial electron energy normalized to the rest energy) to the resonances at neighboring first and third cyclotron harmonics. In the theory of dynamic systems it is known that, in principle, overlapping of resonances can cause stochastic behavior of such systems (Chirikov criterion of overlapping). Therefore, one can expect that such an overlapping of cyclotron resonances in relativistic gyrodevices can cause a stochastic motion of electrons.

Previous attempts to find stochasticity of electron motion in gyrodevices (corresponding studies were carried out in Europe, viz. U.K. and Finland) were restricted by consideration of an isolated resonance and, hence, were quite unsuccessful: electrons always exhibited a stable motion in the cases under study. We have considered a simple case of overlapping resonances relevant to our gyroamplifiers. It was assumed that relativistic electrons interact with an EM wave of large constant amplitude and the interaction can take place at the first three cyclotron harmonics, among which the second one is a dominant. It was found that in such a model, under certain conditions, electrons indeed exhibit stochastic motion, and that the third harmonic interaction contributes more to the appearance of stochasticity than the fundamental one. A manuscript describing these results ("Overlapping of resonances and stochasticity of electron trajectories in cyclotron masers" by G. S. Nusinovich, R. Ngogang, T. M. Antonsen, Jr., and V. L. Granatstein) was submitted in the end of 2003 to *Physical Review Letters*.

It is planned to consider some studies of correlation between stochastic electron motion and stochasticity of outgoing microwave radiation. Also, more realistic models of relativistic gyroamplifiers will be analyzed.

2. Experimental Work

2.1 Four-Cavity Tube Rebuild

The rebuild of our four-cavity tube is complete. Last year we focused on redesigning the input cavity to have a lower quality factor and to be more stable. This work was completed and the vacuum-compatible circuit is ready to be assembled.

Last year we had a system failure and the microwave tube came up to air in such a way that oil from the roughing pump contaminated the vacuum hardware. This contamination resulted in a rather long delay while we cleaned the entire system. The vacuum cross had a stainless-steel jacket with pumping holes that had become jammed in place and had to be remade. We used this set-back to redesign the pump-out port to improve the conductance by about 50%. The rough pump was replaced with an oil-free pump and the valve system was modified to further protect the vacuum integrity.

At this point everything is finally ready and tube assembly is just about to begin.

2.2 Experimental System Repair and Upgrade

The implementation of the capacitor-charging system is still awaiting the testing of the new four-cavity tube. During the past year there was a failure in the cathode heating control circuit and we have had to replace the pressure and current interlocks as well as the indicators in order to repair the unit. The pressure trip now comes directly from one of the ion pump control units, and this change has been implemented. We are still waiting for parts for the new current interlock, but cathode activation is currently underway nonetheless and the current circuitry should be in place before we are ready to test the circuit.

We have prepared to do an X-ray scan of the gun in order to assess the present MIG status with respect to azimuthal current uniformity. We will compare these results with results from a similar study performed three years ago to assess the degradation of the MIG over this period. We will also measure current non-uniformity at various emitter temperatures to quantify the effect of near-space-charge-limit operation on current uniformity. This will also provide a basis for comparison with the new MIG from Calabazas Creek Research.

This X-ray test will be our first step after the emitter has been activated. Afterward, we will begin the evaluation of the amplifier capabilities of this tube.

2.3 Phase Control

Slight modifications were made in the phase control system in the past year, in particular, we improved the control of the arbitrary waveform generator in order to enhance our ability to define the waveforms necessary to accurately control the phase of the input signal. However, we are still awaiting improved gain performance before we can attempt to integrate the phase control system with the gyroklystron tube.

2.4 Emitter Research and Replacement

We continued this year with our support of Semicon Associates with respect to the design, fabrication, and analysis of large annular emitters. The support consisted primarily in the time and effort of our project engineer, Bart Hogan, who managed to work with the engineers of Semicon to finally deliver the emitters that we had ordered several years ago. These emitters are now in house and will be tested in the emitter processing workstation soon to evaluate their temperature uniformity.

A second interaction with Semicon involved an inspection by Bart Hogan of the emitter which is currently being fabricated for the MIG under construction by Calabazas Creek Research, Inc (CCR) via a DOE SBIR Phase II contract. The technology developed while building the emitters for our project was transferred to this emitter fabrication procedure. We expect to continue to work with Semicon and perhaps with Spectramat on the CCR emitters to try to maximize the CCR MIG performance.

2.5 Construction of the Emitter Processing Workstation

Final touches were made to the processing workstation and the ability to provide over 2 kW of heating power was integrated with the system. We will begin heating old and new emitters this month to characterize the temperature uniformity.

2.6 Design, Analysis, and Testing of Ripple-Walled Converters

A complete study of ripple-wall converters was performed in the past year in order to evaluate the bandwidth and related performance of the ripple-wall converter to be used to connect the gyroklystron to the accelerator structure and to develop testing techniques to be used to test the remainder of the interface hardware. The study indicated that mode purities near 100% were indeed feasible with the design and fabrication techniques that we have developed. Furthermore, the measured bandwidth of these devices agrees well with the theoretical calculations. Details of this study are given in paper, "Ripple-wall mode converters for high power microwave applications," which was submitted *to IEEE Transactions on Microwave Theory and Technology*.

2.7 Accelerator Integration

The fabrication of all the parts necessary to connect the output of the gyroklystron to the input of the Haimson accelerator structure is progressing but is not yet complete. All parts are expected to be on hand this summer and we will complete the cold test evaluation of the complete system using techniques developed in the ripple-wall converter investigation described in the previous subsection.

2.8 Advanced Output Cavity Testing

The testing methodology of an “advanced” output cavity which extracts the output power through eight slots in the inner conductor wall into a circular waveguide has been improved significantly in this past year. New radial and axial probes that can be inserted into the drift region and rotated to sense azimuthal field variations have been constructed and tested. We found that the Marié converter used in the testing process was inadequate and we are in the process of building a filter which should allow us to excite the cavity in the proper mode. Material which should imitate the loading in the drift region has been obtained and we expect to complete the circuit characterization before the end of May.

3. Support Activities

3.1 Organizing the RF 2003 Workshop

The 6th Workshop on High Energy Density and High Power Radio Frequency (RF 2003) was held from June 22 to June 26 at the Coolfont Resort and Conference Center in Berkeley Springs, West Virginia. The Workshop was hosted by the Institute for Research in Electronics and Applied Physics (IREAP) of the University of Maryland, College Park and received support from the U.S. Department of Energy, Division of High Energy Physics. As its name implies, this was the sixth in a series of biannual workshops devoted to exchanging information and ideas on high power microwave sources and components. In the first few workshops, the focus was relatively narrow and was centered on microwave systems for particle accelerators; however, the scope has now been broadened to include radar and HPM systems, space exploration, neutron sources and even plasma heating in controlled thermonuclear fusion research.

Participation was by invitation and some 75 participants presented a total of 52 papers. In addition to the scheduled presentations, there was an animated and sustained interaction among participants in the beautiful and peaceful Appalachian mountain locale. Participants came from the U.S., Germany, Russia, Israel and Japan; unfortunately, participants from China had to cancel their attendance due to the SARS epidemic. Participation by national research laboratories, private industry and universities was well balanced. There was also strong participation by graduate students bearing testimony to the strong future prospects of research and development activity on high power microwave systems.

Invited talks describing the RF systems for future linear colliders at DESY in Germany and at SLAC in the U.S. kicked off the Workshop and were especially stimulating because of the widely differing technical approaches taken by those two institutions. In addition, excellent invited talks were presented which were pertinent to diverse areas of application including HPM, Deep Space Telemetry Tracking and Command, ECRH, the Spallation Neutron Source and advanced millimeter-wave radar. Another set of stimulating invited talks presented the state-of-the art in RF technology including multiple beam klystrons, 3-D design codes, RF pulse compressors, quasi-optical systems and plasma filled microwave generators. A special treat was an evening spent hearing reminiscences about the early days of microwave tube invention and development; Ned Birdsall told of his experiences in the U.S. and Yuriy Pchelninikov told of his experiences in the Soviet Union.

The General Chairman of RF 2003 was V.L. Granatstein. The Workshop Chairmen and Proceedings editors were G.S. Nusinovich and S.H. Gold.. The Proceedings have been published by the AIP (AIP Conference Proceedings, volume 691).

4. Summary and Plans for the Upcoming Year

As stated in the introduction, we are approaching an exciting time in the life of this project. We will be testing the rebuild of the four cavity, frequency-doubling tube that theoretically gives us the required power, gain and stability which would enable us to energize the Haimson accelerator structure. If the tube is successful, we are poised to begin testing of the accelerator structure this summer. If the MIG still limits performance, we are poised this summer to replace the MIG with the CCR gun and hopefully to begin testing of the Haimson structure before the end of the year.

Incorporation of the Haimson device in our experimental set-up will be the principal goal of the upcoming year, and all efforts will be focused on achieving that goal. In addition to characterizing the tube performance, we will need to test the new charging system as well as the new heater interlock system. As the tube performance allows, we will also need to install and test the TWT input driver assembly and the phase-control system. The final task related to the principal goal is to complete the construction and testing of the GKL-accelerator interface. We will test all individual parts and the assembly with the operating mode. We will try to test the assembly with other potential spurious modes as well and we will do simulations of spurious mode propagation in the interface assembly for all relevant modes in order to assess the performance of interface and to look for potential problems so that we can devise ways of avoiding these problems.

After completing the "advanced" output cavity study, and aside from the theoretical efforts led by Dr. Nusinovich, the only tasks we will perform will be directly related to the MIG issue. We will test both old and new emitters in our processing station, and we will continue to explore the capabilities of space-charge limited MIGs. We will continue our interaction with Semicon and CCR, and in addition to the current efforts, we would like to try to look at how to maintain high-quality pores in Tungsten-matrix cathodes, in terms of cutting and post-processing techniques, so that we can improve the current uniformity of TL cathodes and the lifetime of SCL cathodes.

5. Publications and Presentations

1. W. Lawson, H. Raghunathan, and M. Esteban, "Space-Charge Limited Magnetron Injection Guns for High-Power Gyrotrons," to be published June 2004 in *IEEE Trans. Plasma Sci.*

2. W. Lawson, M. Esteban, H. Raghunathan, B. Hogan, and K. Bharathan, "Ripple-Wall Mode Converters for High Power Microwave Applications," Submitted to *IEEE Trans. Microwave Theory Tech.*

3. G. S. Nusinovich, R. Ngogang, T. M. Antonsen, Jr. and V. L. Granatstein, "Overlapping of resonances and stochasticity of electron trajectories in cyclotron masers," submitted to *Phys. Rev. Lett.*, 2003.

4. E. S. Gouveia, W. Lawson, B. Hogan, K. Bharathan, V.L. Granatstein, "Current Status of Gyroklystron Research at the University of Maryland," Presented at RF 2003, 6th Workshop on High Energy Density and High Power RF, Berkeley Springs, WV, June 22-26, 2003. Published in High Energy Density and High Power RF, AIP Conference Proceedings 691, New York: AIP Press, 2003, pp.79-88.

5. M. E. Read, Lawrence Ives, George Miram, Philipp Borchard, Lou Falce, Wesley Lawson, Gregory Nusinovich, V. L. Granatstein, and Kim Gunther, "Advanced Magnetron Injection Guns for Coaxial Gyrotrons and Gyroklystrons," presented at IVEC 2003 in Seoul, Korea, May 2003. Conference Record p. 34.

6. Wesley Lawson, S. Gouveia, Bart Hogan, and V. L. Granatstein, "Experimental Results of a Four-Cavity 17 GHz Gyroklystron," Invited talk presented at IVEC 2003 in Seoul, Korea, May 2003. Conference Record p. 42.

7. Jeff Neilson, Lawrence Ives, M. E. Read, Max Mizuhara, David Marsden, Tom Robinson, Jorge Guevara, Wesley Lawson, Bart Hogan, "W-Band Gyroklystron for High Power RF Applications," presented at IVEC 2003 in Seoul, Korea, May 2003. Conference Record p. 42.

8. W. Lawson, B. Hogan, K. Bharathan, S. Gouveia, and V. L. Granatstein, "Preparation of a 17 GHz Gyroklystron for Accelerator Driver Experiments," presented at the *30th Int. Conference on Plasma Sci.*, Jeju, Korea, June 2003. Conference record, p. 168.

9. W. Lawson, "Space-Charge Limited MIGs for Gyro-Devices," presented at the *30th Int. Conference on Plasma Sci.*, Jeju, Korea, June 2003. Conference record, p. 168.
10. W. Lawson, "Accelerator and RF Sources," presented at the IVEC 2003 Mini-course, 31 May 2003.
11. Wes Lawson, Steve Gouveia, Bart Hogan, and Victor Granatstein, "Operation of a Four-Cavity Gyroklystron for Advanced Accelerators," presented at the 2003 Particle Accelerator Conference, Portland Oregon, May 2003. Conference Record, p.42.

PROGRESS REPORT

Task C:
Theory and Simulation of the Physics of Space Charge Dominated Beams

1. Introduction

The Task C Theory and Simulation effort employs both theory and simulation to examine the complex nonlinear physics of space-charge-dominated beams. The emphasis of this work is on explaining experimentally observed behavior, and is primarily directed toward physics important to the main UMER program as well as other experiments at the University of Maryland. Collaboration with research on other experiments has also been a significant program goal, especially with research personnel in the Heavy Ion Fusion Research effort who have been a major source of relevant experimental measurements and much of the numerical expertise employed in the UMER simulation effort, particular in development of the WARP simulation code. In the current period this has led to the realization that many of the details of beam propagation in UMER, as well in other beam systems, can be dominated by the characteristics of the distribution function as the beam emerges from the source. This is true even for systems where the bulk of the beam evolution is not dominated by space charge, because the source region is often space charge dominated nevertheless. Therefore recent emphasis has been on understanding the source region. Also part of this emphasis is the development of new numerical techniques to improve modeling of the source region to assist in refined understanding of measured source behavior and for assisting in the design of future sources.

2. Source Studies

Measurement and simulation of beam characteristics during propagation in the UMER ring have revealed complex evolution of the internal transverse structure. Detailed measurement and simulation of the beam in the source region have therefore been conducted to aid in understanding the source physics and the degree to which details of the initial beam distribution function influence the observed downstream behavior. A significant contribution to the observed beam characteristic from the cathode grid has been identified. For sufficient potential difference between the cathode and the cathode-grid, a virtual cathode is formed downstream of the cathode-grid. In addition to strongly affecting the gross transverse dynamics, such as total beam current and emittance, this process perturbs the transverse distribution sufficiently that a marked hollowing of the velocity distribution is observed both in experiment and in simulation. The transverse velocity distribution, as measured by the pepper-pot mask has been observed to take on the appearance of a donut. Further consequences of this behavior have been inferred from the necessity of including this velocity-space hollowing in simulations in order to best reproduce downstream observations.

While a picture has emerged that explains many of the observed beam characteristics, there are still a number of unexplained phenomena that are currently under investigation. For example, under many conditions, beam halos are observed soon after the beam exits the source region. Simulations are underway to examine possible causes for the observed halos. Simulations are also underway that to use recent detailed measurements of the beam distribution function emerging from the source to refine predictions of the detailed downstream behavior.

3. Longitudinal Beam Physics

Understanding the longitudinal physics in source region is also important because the downstream longitudinal beam evolution can be strongly influenced by details of the initial longitudinal distribution. And the initial longitudinal distribution also affects the transverse downstream evolution, since dispersion as the beam is bent can couple a longitudinal velocity spread into a transverse component. Measurements of the longitudinal velocity distribution are therefore an important component of the UMER diagnostics. Measurements of the longitudinal characteristics of the beam emerging from the source are currently underway on a separate test stand that features a gridded cathode gun with characteristics similar to the one in the UMER source. These measurements will aid in gaining a detailed understanding of the longitudinal characteristics of the UMER beam. The retarding energy analyzer currently employed for precise measurement of the longitudinal distribution is, from a beam physics standpoint, much like the source region (operating in reverse as the beam is decelerated) and can be strongly affected by space charge.

An added source of complexity in the energy analyzer is the time evolution of the collected current, which appears to depend on the details of the formation of a sheath in the region of the collector electrode. The techniques for doing the full time-dependent PIC simulations necessary to understand the both the UMER source region as well as the energy analyzer, are not yet straightforward. Numerical methods that include mesh refinement in the region of the emitter surface are being developed for the purpose of correctly simulating the temporal behavior in the source region. These techniques are also being benchmarked against ion experiments on the STS500 test stand at LLNL. Ion experiments on space-charge-dominated beams, such as STS500 at LLNL as well as the HCX at LBNL are suitable as a testbed for examining transient behavior because of the slower characteristic timescales for ion beam evolution. The scaled physics in these space-charge-dominated experiments can often be identical to the space-charge-dominated electron experiments such as UMER. Since the diagnostic suites in each of the experiments under investigation is slightly different, using simulation to separately examine the relevant beam behavior is a particularly useful way of examining the limitations of each set of diagnostics as well as the limitations of the simulation model. This combination provides a valuable process for refining both interpretation of the experimental results as well as the simulation tools.

4. Publications and Presentations

The research performed for Task C is closely tied to the work done for Task A, thus some of the papers listed here are also listed for Task A.

1. S. Bernal, H. Li, T. Godlove, I. Haber, R.A. Kishek, B. Quinn, M. Reiser, M. Walter, Y. Zou, and P.G. O'Shea, *"Beam Experiments in the Extreme Space-Charge Limit on the University of Maryland Electron Ring (UMER),"* Physics of Plasmas, to appear (2004).

2. S. Bernal, B. Beaudoin, Y. Cui, M. Glanzer, T. F. Godlove, J. Harris, M. Holloway, I. Haber, R.A. Kishek, W-T. Lee, H. Li, D. Lamb, B. Quinn, M. Qurius, M. Reiser, A. Valfells, M. Virgo, M. Walter, M. Wilson, R. Yun, Y. Zou, and P. G. O'Shea, *"Intense Beam Transport Experiments in a Multi-Bend System at the University of Maryland Electron Ring (UMER),"* Nuclear Instruments and Methods A, accepted for publication (2004).

3. R.A. Kishek, S. Bernal, C.L. Bohn, D. Grote, I. Haber, H. Li, P.G. O'Shea, M. Reiser, and M. Walter, *"Simulations and experiments with space-charge-dominated beams,"* Physics of Plasmas **10 (5)**, 2016 (2003).

4. S. Bernal, B. Beaudoin, Y. Cui, A. Diep, T. Godlove, I. Haber, J. Harris, R.A. Kishek, D. Lamb, H. Li, M. Glanzer, B. Quinn, M. Reiser, A. Valfells, M. Walter, M. Wilson, R. Yun, Y. Zou, and P.G. O'Shea, *"Beam Transport Experiments over a Single Turn at the University of Maryland Electron Ring (UMER),"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR.

5. H. Li, S. Bernal, R.A. Kishek, I. Haber, Y. Zou, P.G. O'Shea, and M. Reiser, *"Simulation studies on matching of space-charge-dominated beams for the University of Maryland Electron Ring (UMER),"* Nuclear Instruments and Methods A, accepted for publication (2004).

6. I. Haber, S. Bernal, C. M. Celata, A. Friedman, D. P. Grote, R.A. Kishek, B. Quinn, P.G. O'Shea, M. Reiser, and J.-L. Vay, *"Collective Space-Charge Phenomena in the Source Region,"* Nuclear Instruments and Methods A, accepted for publication (2004).

7. I. Haber, S. Bernal, R. A. Kishek, P.G. O'Shea, M. Reiser, A. Friedman, D.P. Grote, and J.-L. Vay, *"Space-Charge-Dominated Phenomena in the Source Region,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR.

8. J. Harris, A.Valfells, B. Quinn, S. Bernal, I. Haber, M. Walter, A. Diep, M. Reiser, and P. G. O'Shea, *"Initial Studies of Longitudinal Beam Dynamics on UMER,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR.

9. Y. Cui, Y. Zou, A. Valfells, M. Walter, I. Haber, R.A. Kishek, S. Bernal, M. Reiser, and P.G. O'Shea, *"Design and Operation of a Retarding Field Energy Analyzer with Variable Focusing for Space-Charge Dominated Electron Beams,"* Review of Scientific Instruments, submitted (2004).

10. Y. Cui, Y. Zou, I. Haber, R. Kishek, A. Valfells, M. Reiser, and P.G. O'Shea, *"Experimental Study of Beam Energy Spread in the Space-Charge Dominated Beams,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR.

11. Y. Zou, Y. Cui, I. Haber, M. Reiser, and P.G. O'Shea, *"Longitudinal space-charge effects in a retarding field energy analyzer,"* Physical Review Special Topics - Accelerators & Beams **6**, 112801, (2003).

12. Y. Zou, Y. Cui, M. Reiser, and P.G. O'Shea, *"Space-Charge Effect in Retarding Field Energy Analyzer,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR.

13. J.-L. Vay, P. Colella, J.W. Kwan P. McCorquodale, D.B. Serifini, A. Friedman, D.P. Grote, G. Westenskow, J.-C. Adam, A. Heron, and I. Haber, *"Application of Adaptive Mesh Refinement to Particle-in-Cell Simulations of Plasmas and Beams,"* Physics of Plasmas, accepted for publication (2004).

14. J.W. Kwan, J.-L. Vay, F.M. Bieniosek, E. Halaxa, G. Westenskow, and I. Haber, *"Beam Optics of a 10-cm Diameter High Current Heavy Ion Diode,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR, to appear (2004).

15. C. M. Celata, F. M. Bieniosek, E. Henestroza, J. W. Kwan, E. P. Lee, G. Logan, L. Prost, P. A. Seidl, J.-L. Vay, W. L. Waldron, S. S. Yu, JJ. Barnard, D. A. Callahan, R. H. Cohen, A. Friedman, D. P. Grote, S. M. Lund, A. Molvik, W. M. Sharp, G. Westenskow, Ronald C. Davidson, Philip Efthimion, Erik Gilson, L. R. Grisham, Richard Majeski, Hong Qin, Edward A. Startsev, S. Bernal, Y. Cui, D. Feldman, T. F. Godlove, I. Haber, J. Harris, R. A. Kishek, H. Li, P. G. O'Shea, B. Quinn, M. Reiser, A. Valfells, M. Walter, Y. Zou, D. V. Rose, D. R. Welch, *"Progress in heavy ion fusion research,"* Physics of Plasmas **10 (5)**, 2064 (2003).

16. P.A. Seidl, D. Boca, F.M. Bieniosek, C.M. Celata, A. Faltens, L.R. Prost, G. Sabbi, W.L. Waldron, R. Cohen, A. Friedman, S.M. Lund, A.W. Molvik, and I. Haber, *"The High Current Transport Experiment for Heavy Ion Inertial Fusion,"* Proceedings of the 2003 IEEE Particle Accelerator Conference, Portland, OR.