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FINAL Technical Report

Final Report

"Stability Limits and Properties of Dense Nonneutral Plasmas"
(15 Sept. 1997-14 Sept. 2001
grant number DOE DE-FG02-97ER54433)

submitted by R. E. Pollock, 14 Dec. 2001
Indiana University, Swain Hall West, Bloomington IN 47405-7105

DISCLAIMER

Motivation

Nonneutral plasmas, their confinement and behavior, represent a rapidly evolving subfield of plasma physics. Beginning in 1994, the application of a torque has been shown to counteract a natural tendency to radial growth in dense nonneutral plasmas, leading to indefinite confinement. In the case of ion plasmas, density increases reaching the Brillouin limit in small systems, and approaching that limit with more populous systems, have now been demonstrated. For electron plasmas, however, the densities which have been achieved, while comparable, are far below the (higher) Brillouin limit. The prospect of very high density remains unrealized.

The original "rotating wall" torque application method couples an external applied oscillatory field to a helical wave mode. The torque input is accompanied by power input through wave dissipation. This limits the strength of the applied torque to values low enough to allow plasma cooling to counteract the input power. For ion plasmas, spoiling the vacuum can give a little collisional cooling. For electron plasmas, high magnetic field gives radiation cooling.

This project proposed to explore the density limits for electron nonneutral plasmas by constructing a trap with enough B field to take advantage of radiation cooling, and to examine alternate methods of torque injection. Taking advantage of local resources, the interaction between charged particle beams and trapped plasmas would be examined, in particular with respect to torque and power transfer from beam to plasma.

Grant Activities

A 1.7 T superconducting solenoid was procured in year one, mapped in October 1998. Novel features include a steel enclosure, restricting stray field so operation in close proximity to other magnetic elements is possible, and room temperature transverse field coils, permitting rapid and convenient magnetic alignment. In year two a complete electron trap was assembled with 2 nTorr vacuum, in an enlarged enclosure giving cryogenic service access. A first electron plasma was obtained in December 1999.

In parallel, an existing lower field trap was exposed to fast proton beams in the IUCF Cooler ring in 1999 and 2000. (During 1998, a beam microprobe project sharing the same ring location was completed.) The ring optics were modified by the addition of localized steerer chicanes for the 2000 run to give greater control over beam direction at the plasma location, and it was confirmed that the plasma was surprisingly sensitive to direction of the proton beam, as well as more weakly sensitive to beam translation. Lacking theoretical understanding of this phenomenon, a program of numerical simulation of beam-plasma drag force has been initiated, and some results are beginning to emerge.

When funding was terminated after year three, work was scaled back to concentrate on the (helical slow beam) - (electron plasma) study which was described in the 1997 proposal. In the past eighteen months a proton source has been assembled from borrowed parts. Beam studies began December 2000, showing that a well-focussed beam of 1 - 10 microamp intensity could be delivered in the energy range 2 to 10 keV. A beam transport line has been fabricated and is undergoing commissioning. Designs of the unique components needed to create the offset helical trajectory have been developed through extensive computer modelling. We expect to observe the first beam-plasma interaction in this system in spring 2002. The work will form a PhD dissertation project for D. Todd.

Fiscal Review

Table 1 shows a summary. The 4 year expenditures follow the proposal 3 year budget quite closely.

Outreach

Talks were presented at three nonneutral plasma workshops (Berkeley, Boulder, Princeton) and a poster at the most recent in the series (San Diego). Group posters were presented at five APS-DPP meetings (Louisville, Denver, New Orleans, Seattle, Quebec City) and student posters at two APS-DNP meetings (Asilomar, Williamsburg). Numerous colloquia and seminars have been presented.

A substantial student involvement has been an important element of this program. Many of the undergraduates have gone on to graduate study in physics or related fields.

A Website is maintained which contains, for example, apparatus details, selected results, descriptions of representative simulations:
<http://media.physics.indiana.edu/~pollock/plasma.html>

Attachments

A - List of Publications
B - List of Seminars and Colloquia
C - Copies of papers, and of poster abstracts.

Table 1 - Fiscal Overview

The complete official accounting for expenditures on this grant is maintained by Indiana University. However, as an account manager ought, the principal investigator maintains a parallel record. From it, the table below compares major items in the 1997 three year budget with the actual Nov. 30, 2001 four year experience.

Item (numbers are kilo$)	Budget	Actual	B - A
a faculty summer salary	34.0	33.8	0.2
b graduate student support	45.7	32.4	13.3
c undergraduate support	17.3	9.8	7.5
d professional & technical staff	21.1	35.2	(14.1)
e personnel subtotal a+b+c+d	118.2	111.2	7.0
f fringe benefits	13.3	15.2	(1.9)
g fee remission	12.1	4.5	7.6
h travel	4.8	12.0	(7.2)
i publication	2.0	0.0	2.0
j miscellaneous subtotal f+g+h+i	32.2	31.7	0.5
k capital equipment (> 5.0k/item)	204.0	154.2	49.8
l equipment,materials & supplies	30.9	63.4	(32.5)
m major & minor equipment subt.	234.9	217.6	17.3
n indirect costs (50%, ex. k & g)	84.6	100.3	(15.7)
o total e+j+m+n	470.0	460.8	9.1

Notes:

A number of instruments and components, budgeted under table entry k, fell below the present > 5k$ capitalization limit, and thus appear under l, subject to n.

A few equipment items (eg low energy proton source) were assembled from laboratory surplus or constructed in lab shops, reducing k but increasing d and l.

Other differences are minor, so the complete project follows the budget quite closely in level of effort and in fund distribution.

A - Group publications on work germane to DOE grant

Published, in Refereed Journal

Beam electron microprobe, D. Stoller, T. Dueck, M. Muterspaugh, R. E. Pollock, Nucl. Instrum. Methods A **423** 489-492 (1999).

Published, in Conference Proceedings

Proton beam - electron plasma interactions, R. E. Pollock, Jennifer Ellsworth, M. W. Muterspaugh, D. S. Todd, Proc. 1999 Nonneutral Plasma Workshop (nnp III), Princeton NJ, Aug 5, 1999. A. I. P. Conf. Proc. **498** 336-344 (1999).

Submitted to be published, A.I.P Conf. Proc (2002). (Proceedings of the UCSD nnp workshop, Aug 2001, F. Anderegg, editor):

An experiment to transfer angular momentum from a helical low energy proton beam to a trapped electron plasma. D. S. Todd, R. E. Pollock.

[prior to grant period, included for completeness]

Spin-up of an electron plasma - first results. R. E. Pollock, F. Anderegg, A. I. P. Conf. Proc. **331** 139 (1994) nnp II, Berkeley, J. Fajans, ed.

Contributed poster papers, published abstract

APS-DPP, Quebec City, 26 Oct. 2000:

Electron plasma expanded by a tilted fast proton beam. R. E. Pollock, D. J. Bahr, Robert A. Kopenec, D. S. Todd, Bull. Am. Phys. Soc **45#7** 304 (2000).

APS-DNP, Williamsburg, 5 Oct. 2000:

Compression of a non-neutral plasma using a rotating electric field.
D. Bahr, R. Pollock, Bull. Am. Phys. Soc. **45#5** 16 (2000).

APS-DPP, Seattle, 16 Nov. 1999:

Growth in electron plasma radius caused by a fast proton beam, R. E. Pollock, M. W. Muterspaugh, D. Todd, Jennifer Ellsworth, Bull. Am. Phys. Soc **44#7** 108 (1999)

APS-DNP, Asilomar, Oct.1999:

J. Ellsworth (student poster, title and abstract not available)

APS-DPP, New Orleans, 18 Nov. 1998:

Power input calibration for a weakly ionizing non-neutral electron plasma, R. E. Pollock, T. Dueck, M. Muterspaugh, D. Stoller, Bull. Am. Phys. Soc. **43#8** 1807 (1998).

[prior to grant period, included for completeness]

APS-DPP, Denver, 15 Nov. 1996:

Proton beam tests of an electron plasma target. R. Pollock, D. Stoller, A. Sarrazine, H. Gerberich, T. Sloan, Bull. Am. Phys. Soc. **41#7** 1603 (1996).

APS-DPP, Louisville, 7 Nov. 1995:

Development of a nonneutral electron plasma target at the Indiana Cooler. R. E. Pollock, M. Pelath, A. Sarrazine, M. Schatten, T. Sloan, Bull. Am. Phys. Soc. **40#11** 1737 (1995).

In Process

D. Stoller PhD dissertation - first draft complete, target early 2002

D. Todd PhD dissertation - (slow beam)-plasma experiment beginning, target late 2002

full report on (fast beam)-plasma experiments

beam-plasma drag force simulations in 1D and 2D

B Project-Related Talks, Seminars, Colloquia
(July 1997 - Sept. 2001)

July 31, 1997, Boulder CO, Workshop on Non-Neutral Plasmas, contribution selected for oral presentation,
"Plasma collider - fast protons and slow electrons"

Dec. 11, 1997, Bloomington IN, IUCF Visiting Committee,
"The Non-Neutral Plasma Research Program at IUCF"

Feb. 4, 1998, East Lansing, MI, seminar,
" Traps in Rings; Beams as Plasmas"

June 2, 1998, San Diego, CA, non-neutral plasma group lunch,
"Plasma Calorimetry"

June 10, 1998, Bloomington IN, NSF Site Visit
"The Non-Neutral Plasma Research Program at IUCF"

Nov. 6, 1998, Bloomington IN, condensed matter seminar
"Non-Neutral Plasmas - simply marvellous if uncondensed"

Nov. 14, 1998, Bloomington IN, IUCF Program Advisory Committee
successful defense of plasma targetry continuation proposal - CE76

Nov. 23, 1998, College Station, TX, TAMU cyclotron seminar
"Storage Ring-Traps; Beams-Plasmas"

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12 Jan. 99 "Single-Species Plasmas", P408 lecture

14 Jan. 99 "Probe Beams and Trapped Plasmas", NSF site visit, 20 m talk & poster

5 Feb. '99, "The Physics of Trapped Plasma Targets", nuclear physics group seminar

10 Feb. '99, "The Physics of Trapped Plasmas", physics department colloquium

3 June '99, "Plasma Physics at IUCF", for IU visiting committee

14 July '99, "Non-neutral Plasmas", REU lunch tutorial

5 Aug. '99, "Proton Beam - Electron Plasma Interactions", Princeton NJ Non-neutral plasma workshop (published)

12 Sept. '99, "Storage Conundra", STORI99 invited talk, to be published

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25 Apr. '00 "Trapped Plasmas", P408 lecture

15 June '00 "Particle Accelerators", Quarknet summer institute lecture

26 July '00 "Why is a Beam not a Plasma ? ", REU summer lecture series

19 Sept. '00 "Nonneutral Plasmas", inaugural lecture, distinguished lecturer series, Crane Naval Warfare Laboratory

26 Oct. '00 Quebec City poster, "Electron plasma expanded by a tilted fast proton beam".

An Experiment to Transfer Angular Momentum from a Helical Low Energy Proton Beam to a Trapped Electron Plasma

D. S. Todd, R. E. Pollock

Indiana University Department of Physics and Cyclotron Facility (IUCF)
Milo B. Sampson Lane, Bloomington IN 47408-1398

Abstract. As part of a continuing program of beam-plasma interaction studies, a low energy (2 -10 keV) proton beam will be injected on a helical trajectory into a trapped electron plasma in a 1.6 T cryogenic solenoid. The proton source is a conventional duoplasmatron, but operated well below its design extraction energy. Beam tests over the desired energy range have established a mode with submillimeter beam focus and currents of a few μA. The beam will be transported into the high field, displaced, and then inflected by a sudden impulse onto an offset helical trajectory of low pitch. The electron plasma trapping potential will provide a fine pitch control and will serve as an analyzer of the residual longitudinal momentum (helix pitch). Previous experiments in this laboratory employing proton beams of high energy (50-300 MeV) in a storage ring have shown that an electron plasma absorbs angular momentum and energy from the proton beam - for example exhibiting expansion through beam misalignment which breaks the trap azimuthal symmetry. The expectation is that a lower energy beam, traversing the plasma at velocity well below that of a typical wave mode, may be more effective in torque transfer. A possibility may exist for significant plasma compression with judiciously chosen settings of the helix position offset relative to the plasma surface. Progress in design and implementation of the low energy injection scheme will be presented.

INTRODUCTION

In the past few years, a proton beam in the Cooler storage ring at the Indiana University Cyclotron Facility (IUCF) has been used for first tests of the response of an electron plasma to a passing fast beam. Initial experiments indicated an energy transfer from beam to plasma which was substantially larger than predicted from single particle collision rates, and which exhibited variation from one beam exposure to the next — indicative of some significant uncontrolled parameter. A non-destructive monitor of plasma radius was then developed [1] so that transfer of energy and angular momentum could both be observed. With this new capability it was found that the beam torque on the plasma was unexpectedly sensitive to beam translations and rotations with respect to the trap symmetry axis. In particular, the beam angle was identified as the uncontrolled parameter in the early studies. A description of this work is being prepared for publication elsewhere.

The beam in the storage ring is fast and rigid, so that particle velocity ($v/c > 50\%$) is much larger than plasma wave or thermal velocities ($v/c < 2\%$). The beam is thus unlikely to participate in the dynamics through two-stream instabilities. We suspect that

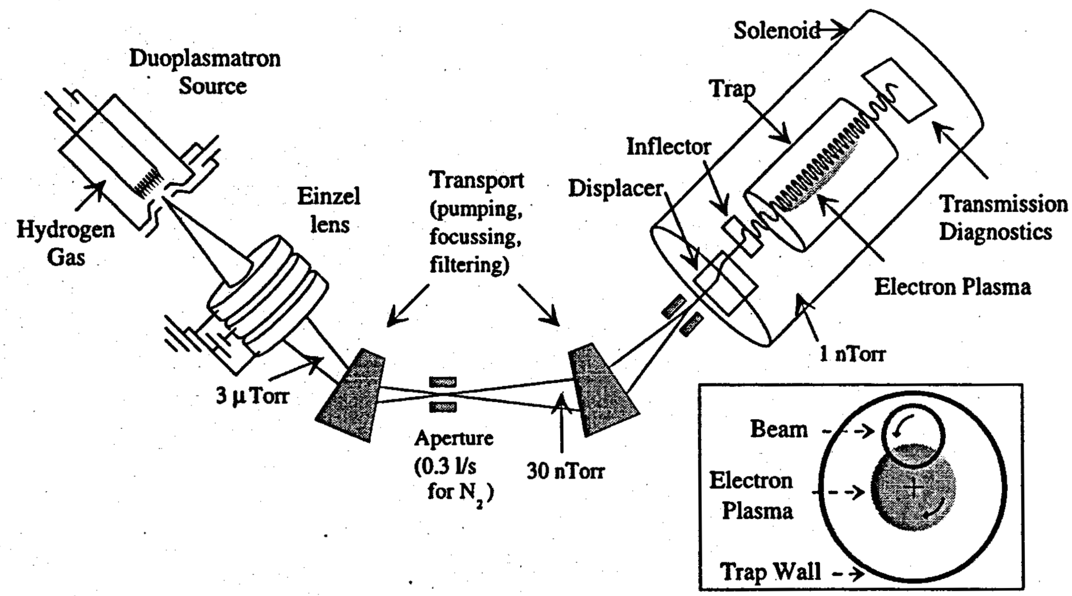

FIGURE 1. Beam-plasma layout in the laboratory. Inset gives an end view of the "corkscrew" beam interacting with the electron plasma.

the plasma density perturbation (the plasma attempting to screen out the beam collective field) is being dragged through the rotating plasma by the immovable beam and the resulting viscous drag is responsible for the observed torque.

The experiment whose preparation is described in the present report is an attempt to probe the beam-plasma interaction in the opposite beam velocity limit. Using ion source technology we can prepare a beam of protons in a much lower velocity range ($0.2\% < v/c < 0.5\%$). We have designed transport elements to carry this beam into the high field trap solenoid, to produce controlled displacements, and to convert longitudinal into transverse momentum so the beam path is a helix of variable pitch. By analogy to electron cooling, the angular momentum of the beam helical motion may be transferrable to the plasma. The proton helix rotates at the cyclotron frequency while the electron plasma counterrotates at the rotation frequency of drift motion in its self electric field(see inset Figure 1).

SOURCE AND TRANSPORT

A hydrogen-fed duoplasmatron ion source will produce a beam whose principle charged components are protons, H_2^+, and H_3^+ [2]. By operating the source far below its intended extraction voltage, we have produced beams with kinetic energies as low as 1keV. Downstream sector magnets allow for the isolation of any of the three ion species, and by employing an einzel lens, proton beams have been focused to sub-millimeter diameter.

The duoplasmatron source has a turbine pumping the chamber adjacent to the extraction aperture. This region maintains a pressure of about 3 μTorr, with the source H_2 gas flow somewhat below the value giving maximum ion current. As the electron plasma tolerates a background pressure of about 3 nTorr, a drop in pressure along the transfer beam line of order 10^3 is needed.

We take advantage of the small beam waist after the first bend to insert a conductance-limiting aperture of 8 mm diameter and 100 mm length where the transition from elastomer seals to bakeable all-metal construction is taking place. The 75 l/s ion pump at the second bend is expected to bring the pressure in this region to the 10^{-8} Torr range.

The final beam waist is located within the displacer in the trap chamber so the last conductance limiter must have a bigger aperture and will reduce the pressure by only about one order of magnitude. If necessary, a second turbopump, normally used for roughing, can be attached to the first magnet chamber after the lens aperture to obtain a further reduction. A schematic layout is given in Figure 1.

DISPLACER AND INFLECTOR

When the beam enters the solenoid it is converging and traveling along the axis of trap. An electrostatic mirror placed on the axis of the trap would convert some of the beam's momentum from parallel to perpendicular to the trap axis, but the range of possible helix radii and guiding center locations would be severely limited, therefore inducing helical motion will be done in two steps. First, an electrostatic displacer radially shifts the beam off-axis, then an electrostatic inflector gives the offset beam a transverse kick to induce cyclotron motion about a magnetic field line.

For displacement, employment of drift motion within the high B field adjacent to the trap is ruled out by space constraints. Because a low-energy beam of finite diameter is spread by the momentum-position correlation (dispersion) imposed as the beam enters the E field element, an E field magnitude $E_0 < 0.1$ MV/m must be used giving a device length >0.2 m.

The displacer is instead located in the throat of the solenoid. The first bend pair occurs in a weak B field and the second bend pair in a moderate B field so the beam exits along a field line (Figure 2). By employing (x, y) pairs, the cyclotron motion can be compensated over a range of beam energies and trap B field strengths. Compensation fails if bends in either plane are separated by an integer multiple of half-gyrowavelengths. In practice this means that the last deflector element lies at $B/B_o < 10\%$. The steel jacket of the solenoid produces a rapid falloff of B (half-length about 0.05 m) in the displacer region which is essential to the selected design.

The four E field values of the displacer plates are to be adjusted so coherent cyclotron motion is minimized. In this way the tuning of the displacer and of the following inflector is largely decoupled.

The inflector is designed to accept a beam of charged particles moving along a B field line in a strong uniform field and to convert most of the momentum from parallel to perpendicular to the trap axis. Note that the adiabatic invariant responsible for mirroring must be broken to do so. A localized electric field impulse will serve provided the time duration is short compared to the cyclotron angular period ($\frac{qB}{m} * dt < 1$).

A planar electrostatic mirror with small gap, tilted at 45°, will give a 90° deflection in the low B limit. The mirror potential qV must exceed half the beam ki-

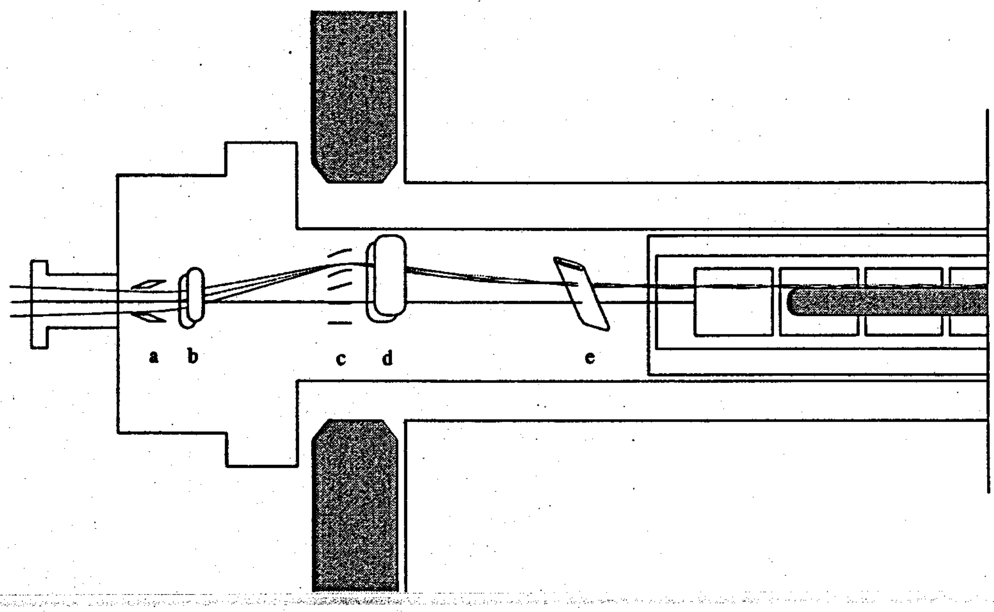

FIGURE 2. Side view of a numerical simulation of the beam being displaced by the four electrostatic elements (a-d) that make up the displacer. The inflector's position is shown (e) for reference.

netic energy T, which limits the concept to beam energies of a few keV. The uniform longitudinal deceleration $a_z = \frac{qE_z}{m}$ reduces the incident speed $v_{z_0} \simeq v = (\frac{2T}{m})^{\frac{1}{2}}$ to zero in time $dt = v/a_z < \frac{m}{qB}$ or rearranging $a_z * \frac{m}{q} = E_z > v * B$ so the force inside the gap is mainly electric. For protons with $\frac{v}{c} = 0.5\%$ (T = 11.7 keV) and B = 1.6 T, this means $E = \sqrt{2}E_z > 2.4$ MV/m. Note the resulting constraint on gap g since $V = g * E > \frac{T}{2q}$, with $E_z = \sqrt{2}E > (\frac{1}{8})^{\frac{1}{2}}(\frac{T}{gq})$. If we choose the minimum E_z then $g > (\frac{1}{8})^{\frac{1}{2}}(\frac{T}{qvB}) = (\frac{1}{8})^{\frac{1}{2}}(\frac{mv}{2qB}) = (\frac{1}{32})^{\frac{1}{2}}R$ where $R = \frac{mv}{qB}$ is the radius of the cyclotron orbit after inflection (R = 9.8 mm, g > 1.75 mm for the speed chosen above). Tracking simulations show that $dt < (\frac{\pi}{2}) * (\frac{m}{qB})$ is tolerable so that we choose g = 2.5 mm and E < 2 MV/m for the inflector mirror.

After leaving the mirror, the cyclotron motion about a fixed guiding center would lead to a second mirror encounter and to the beam returning along the incident direction. The mirror angle must therefore be reduced, and the mirror must have an edge so the helical path wraps around the edge with sufficient pitch to clear the backside. By tilting the mirror about a second axis normal to the field and to the first axis, the encounter may be delayed until a full cyclotron period giving a minimum pitch = 2g. The proper choice of the two direction cosines which specify the double tilt gives a similar minimum pitch over the design range 5 < R < 10 mm. Figure 3 shows tracking through a planar mirror with semicircular ends to illustrate this point. The view is down the gap. The E field is generated from a 2D relaxation. Note the spread in pitch caused by field non-uniformity in the end region at the lower rigidity. Periodic focussing by the regularly spaced grid wires contributes to the spread in helix pitch, but is omitted here for clarity.

The longitudinal velocity at 1.6 T and 5 mm pitch is v/c = 0.04% with a stopping potential of 75 eV. This potential is in the range of the electron trap end potential so it

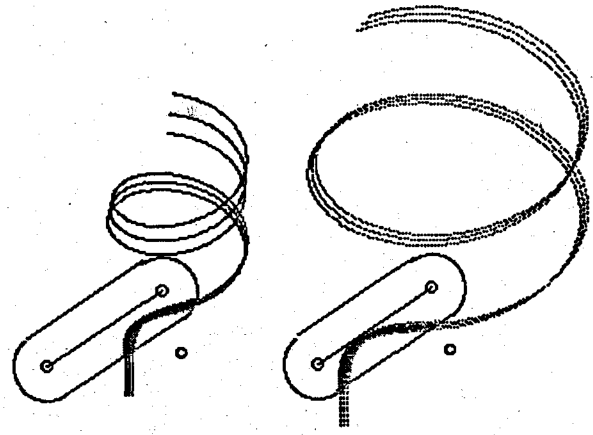

FIGURE 3. Doubly-tilted inflector imparts helical motion to beam entering from below along B=1.3T field. Proton beams of 2keV with E=0.6kV/mm (left), and 8keV with E=1.6kV/mm (right), give helix radii of 5 and 10 mm respectively. Note that entering the non-uniform field of the semi-cylindrical end (in order to obtain clearance at the lower energy) results in an increased spread in helix pitch. The starting rays are separated in x by ±0.3mm. The auxiliary steering wire on the lower right is unbiassed in these examples.

is possible to further reduce the longitudinal velocity as the proton helix enters the trap. This reduction is discussed in the following section.

BEAM-PLASMA INTERACTION

The electron plasma is confined axially by an inverted potential well which is formed by keeping the end rings of the trap at ground potential and floating the center of the trap near 200 V. A positive charge entering the trap will be slowed parallel to the axis by the plasma trapping well. For a beam on a helical trajectory this slowing occurs and causes a decrease in pitch or complete reflection of the beam. The decreased pitch is advantageous since the beam rotates more and interacts longer with the plasma before leaving the trap. The fact that the plasma potential reduces the well potential near the axis means that beam particles nearer the axis of the trap will not be slowed as much as ones near the wall of the trap as is seen in the numerical simulations of Figure 4. In the figure, the beam can be seen to rotate about the trap axis as it travels the length of the plasma. The presence of the plasma's radial electric field introduces an $\mathbf{E} \times \mathbf{B}$ drift about the trap center that would not be present were the plasma not there. Note that, though the electric field is weaker for the beam outside the plasma than for a beam on the edge of the plasma, the reduction of the former's helix pitch gives it more interaction time for the drift to take place and gives both beams a similar precession angle while passing the plasma. Though the precession of the beam helix will complicate post-interaction beam diagnostics, it will have little effect on the torquing mechanism.

Adjusting the beam helix position and radius will allow for the application of different torques. A compressional torque is expected when the helix straddles the plasma surface, whereas an expansion torque should be seen when the beam and plasma are coaxial.

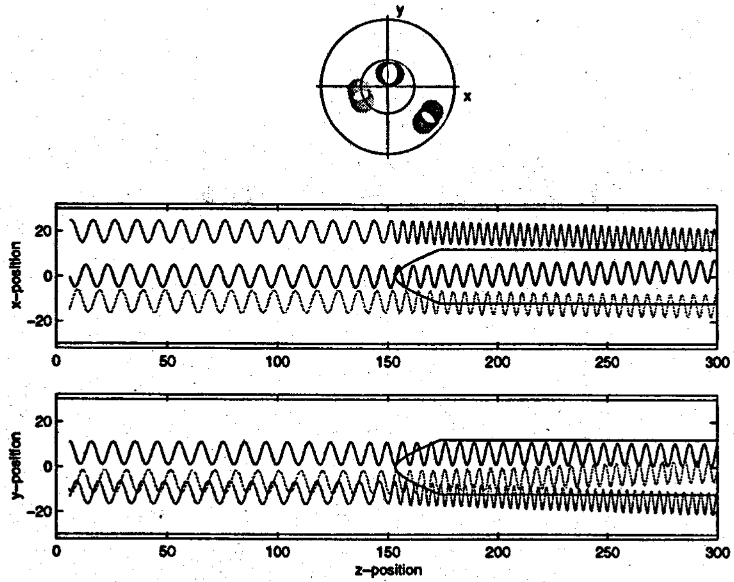

FIGURE 4. Numerical simulation of protons on helical trajectories fired at an electron plasma trapped in a negative potential energy well. The well is created by a cylinder of radius 30 being grounded except for $z \geq 150$ where the cylinder potential is positive.

STATUS

The electron plasma portion of the setup was placed in service last year. The proton source was commissioned at the start of 2001, and designs of transport, displacer and inflector elements have been developed based on measured beam properties. We are presently waiting for UHV welded vacuum components to emerge from our shop. The tests of proton beam properties in the empty solenoid should then be followed by the first slow beam-plasma studies later this year.

ACKNOWLEDGMENTS

This work has been supported in part by the U.S. Department of Energy under grant DE FG0297 ER 54433 A002, and by the U.S. National Science Foundation under grant NSF PHY 96 02872.

REFERENCES

1. Pollock, R. E., Ellsworth, J., Muterspaugh, M. W., and Todd, D. S., "Proton Beam-Electron Plasma Interactions", in *Non-Neutral Plasma Physics III*, edited by J. J. Bollinger, R. L. Spencer, and R. C. Davidson, AIP Conference Proceedings 498, New York, 1999, pp. 336–337.
2. Moak, C. D., Banta, H. E., Thurston, J. N., Johnson, J. W., and King, R. F., *The Review of Scientific Instruments*, 30, 694–699 (1959).

Proton Beam-Electron Plasma Interactions

R. E. Pollock, Jennifer Ellsworth, M. W. Muterspaugh, D. S. Todd

Indiana University Department of Physics and Cyclotron Facility (IUCF)
Milo B. Sampson Lane, Bloomington IN 47408-1398

Stored, cooled proton beams of 200 MeV with intensities up to 3 mA pass along the axis of a Penning-Malmberg trap containing a nonneutral plasma of 10^{10} electrons. The plasma is maintained in a warmed steady state by injecting energy and angular momentum; the elevated temperature giving weak ionization to replenish lost electrons. Comparing charge density wave velocity with diocotron mode frequency gives continual non-destructive monitoring of plasma radius and density. The beam is observed to cause an increase in plasma radius indicating a torquing mechanism not yet understood. The effect is weakly sensitive to shifts in beam position or angle. Monitoring power input shows either "cooling" (increased electron loss rate) or heating depending on regulation method. Extension of these studies to higher containment fields will be described.

INTRODUCTION

Study of properties of long-lived nonneutral plasmas began at Indiana University five years ago. A warm electron plasma can be stabilized by controlled power input, permitting quite detailed examination of near-equilibrium properties. A full description of techniques developed for creating, controlling and monitoring this plasma target is beyond the scope of this brief paper, and will be published elsewhere (1). The next section provides an abbreviated summary of relevant system properties.

For the past three years, experimental study of the effect of particle beams of high velocity on a trapped electron plasma has been carried out by placing the plasma in the path of a stored proton beam in the IUCF Cooler. Initial observations were limited to energy transfer from beam to plasma at beam intesities below 0.2 mA, and showed evidence for two mechanisms: one present with coasting beam (no time structure); and the second with bunched beam (multiple harmonics of the 2 MHz orbit frequency). The magnitude of the heating by coasting beam was in excess of estimates based on single particle scattering by two or three orders of magnitude. Bunching the beam increased the heating with a term quadratic in beam current, apparently a collective mechanism

CP498, *Non-Neutral Plasma Physics III,* edited by John J. Bollinger, et al.

involving charge density wave excitation. By overlapping a beam orbit harmonic with a plasma standing charge density wave resonance (Gould-Trivelpiece mode (2)), the bunched heating could be enhanced more than one-hundred-fold. The bunched beam heating was strong enough off-resonance to limit beam currents to below 0.5 mA.

In the past few months, a new capability of non-destructive plasma radius monitoring with beam present, has shown that angular momentum transfer from beam to plasma is significant. In the same interval, a new injector for the storage ring has made intensities up to 2 -3 mA available. A sampling of observations of beam-induced plasma expansion, and the revisions to our understanding of the power transfer comprise the two beam interaction sections below.

This data must be understood as an interim report on work in progress. Some variability among beam exposures indicates the presence of uncontrolled parameters in the interaction process. At higher beam currents, the plasma appears sensitive to beam properties which are not visible to the present storage ring diagnostics. Further investigation may reveal ways to use the plasma response as an aid to optimization of storage ring behavior.

SYSTEM PROPERTIES

The electron plasma is contained by a modified form of Malmberg-Penning trap with $B < 0.23$ T, length $0.37 < L < 0.52$ m, wall radius $R_w = 0.051$ m, and a vacuum in the range $0.3 < p < 2$ nTorr. The plasma is formed at low density by off-axis injection from a tungsten filament, then heated by a broadband noise signal applied to a ring electrode so ionization of residual gas can be used to raise the density to any desired value below the confinement potential limit of 200 eV. The input power is then reduced to sub-nanoWatt level to allow the plasma temperature to fall to about 4 eV where a weak, continuing ionization can balance slow loss of particles to maintain a constant particle number. The containment lifetime for a plasma electron lies in the range from 1 to 10 minutes, improving with increasing magnetic field or with the application of an (uncalibrated) torque by means of the "motor", a rotating dipole or quadrupole electric field applied to eight sector electrodes near one end of the trap. The plasma itself can be maintained in the time-independent near-equilibrium state for days or weeks, allowing quite detailed examination of its properties.

Non-destructive diagnostics include an $N' = N/L$ monitoring process, in which a transverse kick is applied every 3 s to induce tranverse displacement for measurement of the (diocotron + magnetron) revolution frequency of the displaced plasma column about the trap symmetry axis. Negative feedback returns the plasma to the trap axis between measurements. The "kicked frequency" FFT peak is stable in the range $12 < f_k < 60$ kHz at $B_z = 0.144$T, corresponding to $1\ 10^{10}$/m $< N' < 5\ 10^{10}$/m.

The plasma potential V_{pl} is measured by exciting one or more standing charge density wave resonances (axisymmetric Gould-Trivelpiece modes). To lowest approximation, the wave velocity v_w is given simply by the plasma potential $(v_w/c)^2 = qV_{pl}/mc^2$. The calibration is verified by the destructive dump pulse technique (lowering potential of one endcap until loss of particles is seen). An effective length for the plasma is extracted which agrees with the electrostatic expectation to about 10%. The exponential leading edge of the dump pulse also gives a check on plasma temperature. However because the ionization rate is exponentially sensitive to temperature, the stabilized plasma is essentially a constant temperature system with kT about 4 eV.

The ratio of V_{pl} to line charge density $qN'/(4\pi\varepsilon_0)$ gives the logarithmic factor $[1 + \ln (R_w/R_{pl})^2]$ from which the plasma radius R_{pl} is extracted. The absolute value of R_{pl} is subject to systematic uncertainties from end effects and other corrections which are believed to be established at about the 20% level. The relative precision is much better, so that small changes in radius are readily observed as system properties are varied.

The G-T resonance gives a useful method for stabilizing the value of V_{pl}. An rf synthesizer supplies a sinusoidal signal to a ring electrode. The frequency is tuned just below the resonance peak. If the plasma density drifts downward, the peak overlaps the synthesizer signal more strongly and the resulting enhanced wave amplitude supplies power for ionization to restore the equilibrium. By measuring the transmitted wave amplitude excited by the line source, and the damping width of the resonance signal (weakly excited by a swept source or the broadband noise source), the absolute power input can be determined.

An independent check of the power input calibration is obtained by using additional power to slowly raise the number of electrons at a measurable rate and making use of the 20 eV chemical potential ((ionization energy + 3/2 kT): creating a pair of electrons from one energetic tail electron in a collision with H_2 residual gas; then adding thermal energy to the new one). The two methods are in reasonable agreement (3).

In the absence of beam, as the particle number N is varied, power input required to maintain a plasma is found to increase nearly linearly with N^2. This behavior is illustrated in Figure 1. To display the similarity of shape, the (+) vertical scale has been adjusted to obtain agreement at large density. One would expect terms linear in N', for example to maintain constant temperature in the presence of radiation cooling. This is a likely explanation for the curvature and offset at the lower left. It is tempting to ascribe the dominant $(N')^2$ term to an electron loss mechanism of this form. However this is not consistent with loss rate observations when the heat source is removed.

An example of the use of the non-destructive plasma radius determination in the absence of beam is shown in Figure 2, a comparison of the volume density in equilibrium with the density observed when heat is removed and the plasma allowed to "free fall". The density is somewhat higher at higher magnetic confinement fields. The freefall and equilibrium shapes are similar, but with lower density in freefall.

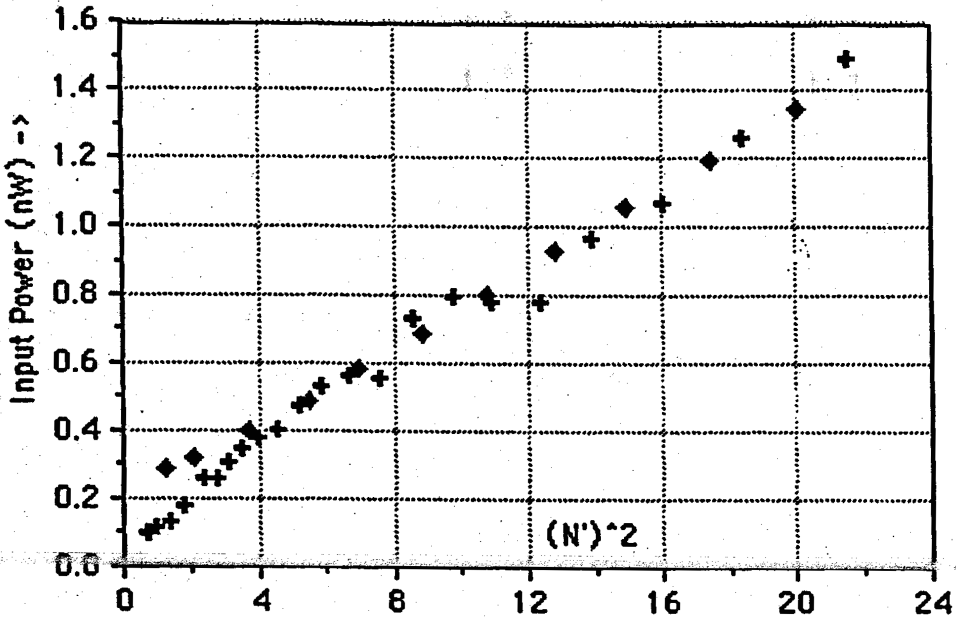

FIGURE 1. Heat input (arbitrary units) versus equilibrium number of electrons per unit length N' squared (N' in units of 10^{10}/m). The diamonds and crosses refer to broadband and monochromatic heat input regulation methods respectively. The positive intercept of the ordinate is evidence for a small contribution from terms linear in N'.

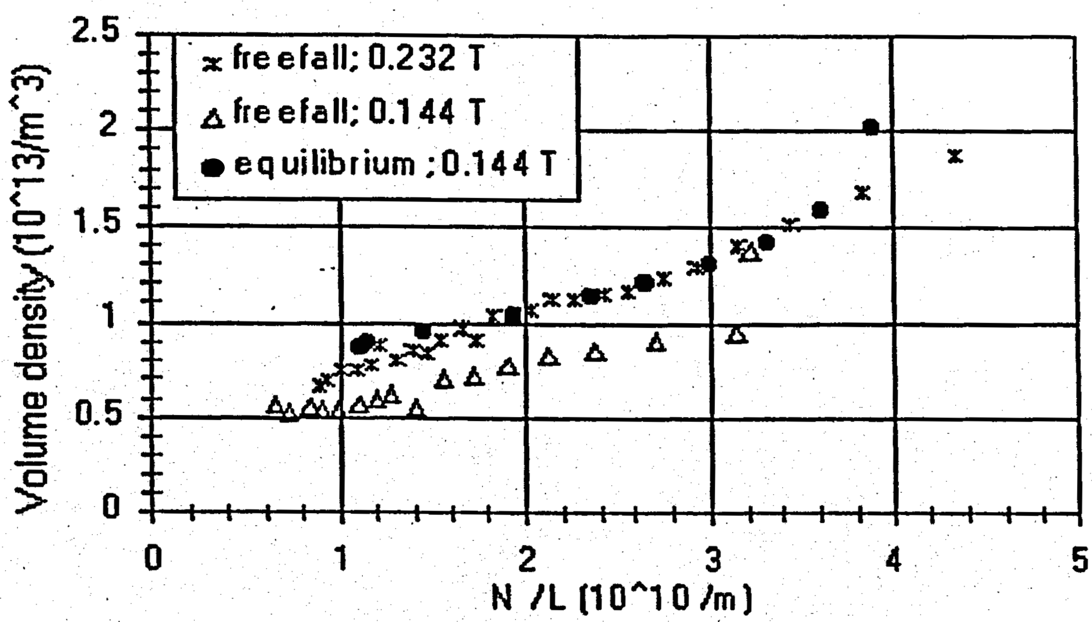

FIGURE 2. Plasma volume density n (electrons/m^3) versus N/L (electrons/m). Three data sets show "heated" equilibrium, and "freefall" unheated decline, the latter at two field levels. The plasma radius adjusts itself as electrons are lost so the volume density falls about half as fast as N/L. While the freefall density is lower than the equilibrium density for the same B field, the similarity of shape suggests that the decline proceeds through a set of near-equilibrium states.

BEAM- PLASMA TORQUE

Using the non-destructive plasma radius measurement scheme described in the preceding section allows radius changes to be monitored in the course of exposure to a fast proton beam. The quantity $(R_{pl}/R_w)^2$ gives the fraction of the trap cross-sectional area occupied by plasma. Well below the Brillouin limit, this is proportional to the canonical angular momentum per particle. Observations indicate that the beam-plasma interaction involves a significant and unanticipated angular momentum transfer leading to radial growth of the plasma.

As shown in Figure 3, the plasma area can be doubled with a beam current of about 0.3 mA, overwhelming the limited compression torque of a rotating electric dipole field "motor". The motor amplitude is adjusted for each beam current to supply half the power required to maintain plasma equilibrium. Note that at zero beam current, the motor torque is sufficient to raise or lower the plasma area by 30%.

Arguing from angular momentum conservation, one would expect no torque in a system with axial symmetry. However attempts to reduce the observed radial expansion by changes in beam position and angle have been largely unsuccessful. Using storage ring localized parameter combinations, it is possible to carry out the four-dimensional search over a restricted range of beam offsets. Results in the horizontal plane are

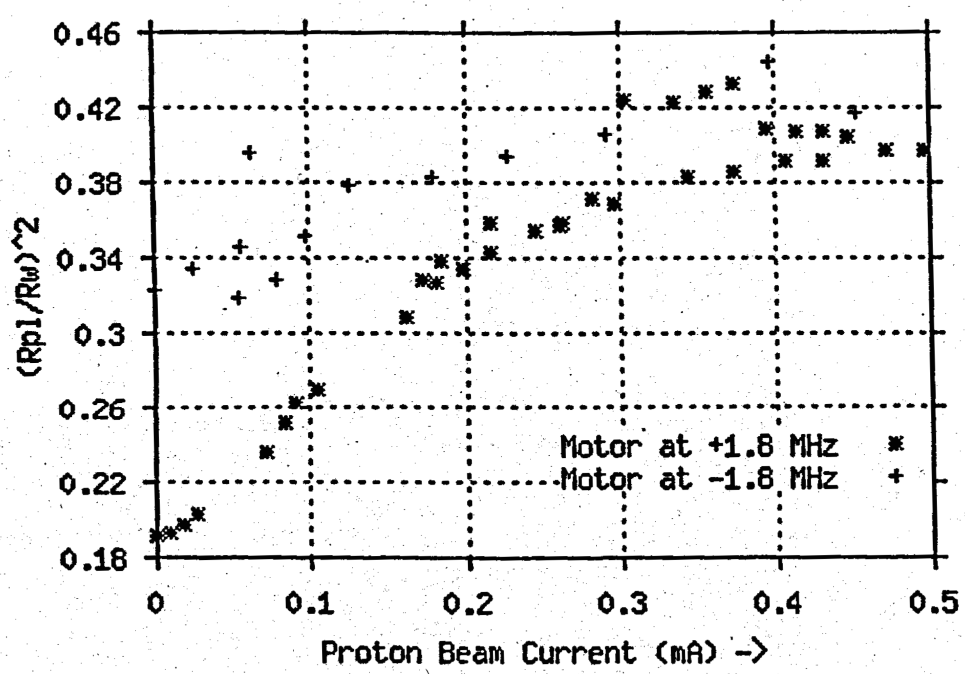

FIGURE 3. Comparison of beam torque with rotating field torque over a range of beam currents. The motor's dipole field rotates at + 1.8 MHz or -1.8 MHz in the laboratory frame, giving compression for the former. A beam of 0.1 mA causes a change in equilibrium radius comparable to that produced by turning off the rotating field. Note reduced slope and reduced reproducibility at currents above 0.3 mA.

shown in Figure 4. Plasma expansion increases only slightly for large transverse beam displacements. The dependence on beam angle is stronger, but the scan could not be extended further to show either a decrease on the right side (if optimal alignment gives maximum torque) or a rise on the left (if optimal alignment gives minimum torque). To resolve this issue, stronger steering magnets sets could be added to the storage ring to span a wider range of beam angles.

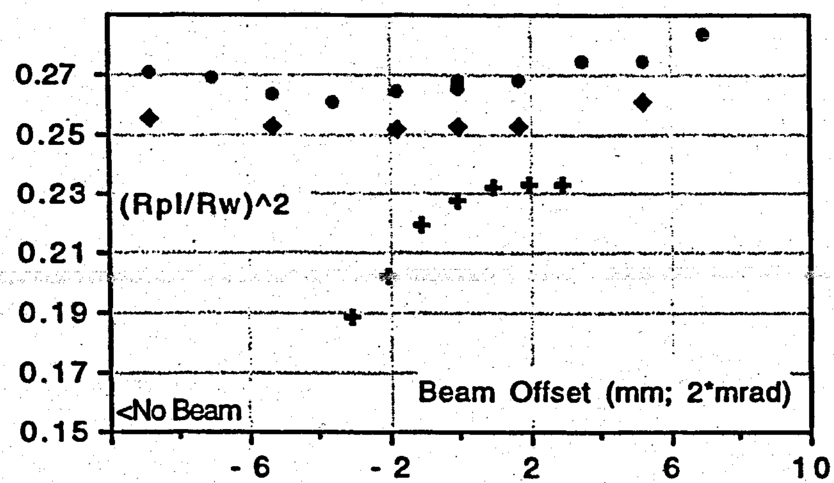

FIGURE 4. Sensitivity of beam-caused expansion to misalignment of beam relative to plasma. Plot bottom represents plasma in equilibrium with no beam. Beam position scan, spanning 16 mm at beam currents of 0.27(♦) and 0.58 mA (•), shows a weak enhancement for large displacements. The angle scan, covering 3 mrad at 0.27 mA (+). appears to show that expansion is reduced when misaligned, but if so, the inferred reduction on the right side was inaccessible.

Tests for sensitivity of the beam-caused expansion to other parameters show that beam bunching, changes in vacuum by turning off or firing pumps, operating with different motor settings, while causing changes in the equilibrium plasma area in the absence of beam, do not alter the tendency in all cases for the beam to cause a radius increase, with decreasing rate of increase at higher beam currents.

As an example, the question of how the magnetic field strength might affect the observed plasma expansion was addressed in one short run, where three fields extending up to the strength limit of the present trap were used. For this run the rotating dipole field was set at 0.48 MHz, where heating of the plasma by the motor field is weakened, with a fixed large amplitude. Data at the 0.144 T level is sparse because that field value was studied more extensively in other beam exposures. The general trend of a rise at low beam current with saturation at higher current was observed for all three fields, but the initial slope was steeper for higher fields, as was the equilibrium radius in the absence of beam. The data are presented in Figure 5.

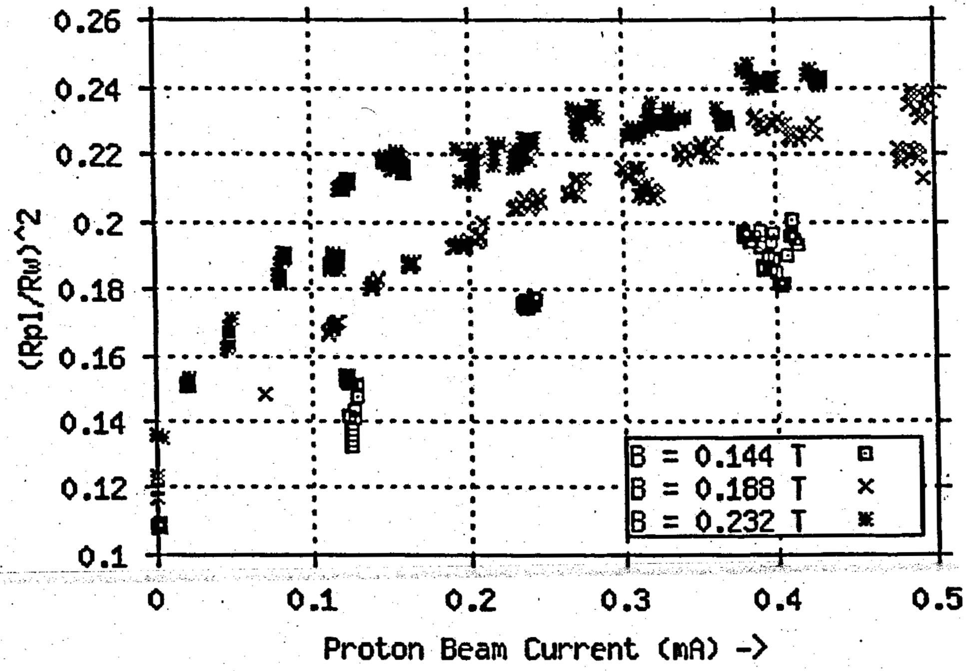

FIGURE 5. Radial expansion vs beam current for three trap magnetic fields. The rotating dipole amplitude was near maximum so the plasma radius was smaller than in Figure 3. Note that higher field gives a larger plasma area, and that the slope with beam current is steeper for higher fields.

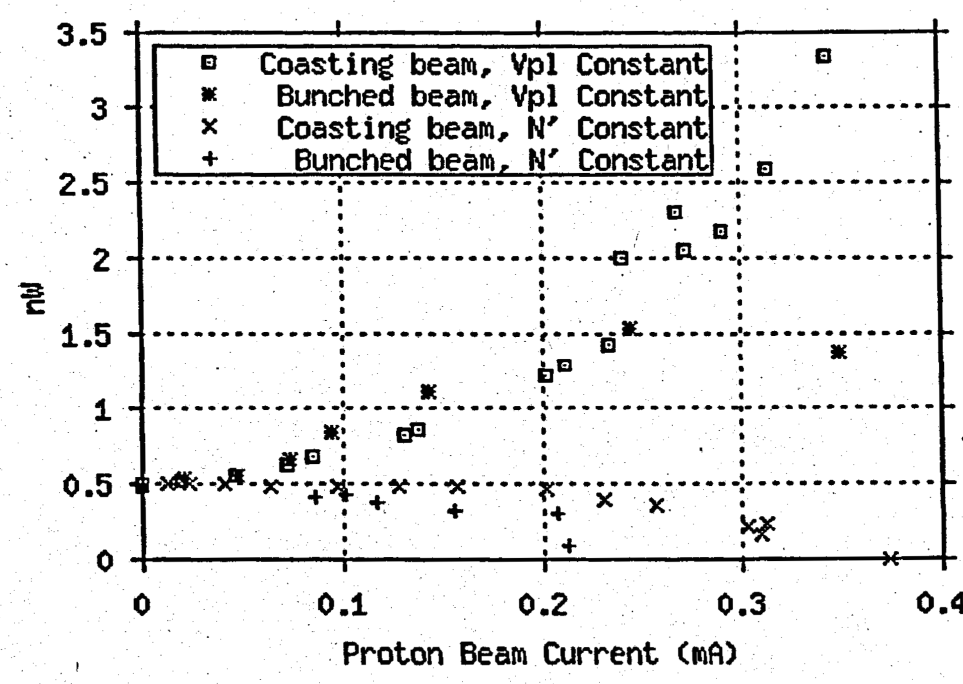

FIGURE 6. Heat input (nanoWatts) vs beam current with plasma potential fixed shows that more power must be supplied as N' grows. For plasma N' = N/L held constant as beam current is varied, the coasting beam heats the plasma very little up to 0.2 mA, while the bunched beam adds a quadratic term.

BEAM - PLASMA POWER

The transfer of energy from beam to plasma is seen as a drop in the power applied to maintain a time-independent state. However the power input to maintain the plasma depends markedly on the stabilization mechanism. An example is shown in Figure 6. If N' is held fixed, beam heating is indicated by the negative slope. However if plasma potential is regulated, a strong "cooling" is indicated by the positive slope.

If the plasma potential is held constant, increasing radius requires a higher line density N' = N/L with increasing beam. As shown in Figure 1, the power input grows with N' so this regulation method should exhibit a power demand increasing with beam current as though the beam were cooling the plasma. However the observed cooling is too strong for quantitative agreement with this explanation.

In contrast, if N' is held fixed, the strong "cooling" is eliminated, the power input from the coasting beam is near zero at currents below 0.2 mA, while the bunched beam adds a collective heating term, quadratic in beam current. For higher beam currents Figure 6 shows that even the coasting beam may be developing a collective enhancement above 0.2 mA. The plasma shows new features at beam currents above 0.5 mA which are not included in the above data sample, including a step drop in radius at a current between 0.5 and 1 mA, accompanied by fluctuations in plasma power demand (turbulence?) and sensitivity to details of storage ring setup. Plasma has been maintained with coasting beams up to 2.5 mA, with luminosity (beam particles/s x plasma electrons/cm^2) above 10^{25} cm^{-2} s^{-1}. However the stability and controllability are less satisfactory than in the region beolw 0.5 mA.

FUTURE DIRECTIONS

The observed transfer of both energy and angular momentum from a fast beam to a trapped nonneutral electron plasma may be counteracted to some extent. An electron plasma may tolerate power input by operating at higher trap magnetic fields, where radiation cooling is faster. A superconducting solenoid trap of 1.75 T is being commissioned which will raise the cooling rate by a factor of fifty. Magnetic and UHV components are completed, and the electrode structure is being machined.

The torque input may be better tolerated by exploiting resonant enhancement of the torque associated with the launching of helical charge density waves (4). For study of waves of the form $\cos(m_\theta\theta - m_z\pi z/L)$ with m_θ, m_z = 1, 2, a newly-constructed swept rotating signal source and frequency-agile phase sensitive detector are allowing a systematic exploration of the plasma response in transmission mode. Figure 6 shows a representative sweep in dipole mode. Control and calibration of torque input to the plasma from study of such modes is just beginning.

UP1 18 Electron plasma expanded by a tilted fast proton beam*. R. E. POLLOCK, D.J. BAHR, ROBERT A. KOPENEC, D. S. TODD, *Indiana University and IUCF, Bloomington IN 47408-1398* A cooled coasting 0.20 GeV proton beam targets a magnetically-confined cylindrical electron plasma. Beam position and angle relative to trap symmetry axis are varied to map out density variations in the plasma equilibrium and to compare with a calibration by broadband axisymmetric heating. Preliminary analysis of June 2000 data shows a plasma radius increasing monotonically with increasing tilt angle. The sensitivity of the plasma to this broken symmetry provides an on-line coasting beam direction indicator with sensitivity of 0.1 mrad at 0.1 mA. The plasma also expands in response to beam position offset and to beam angular momentum (skew correlation between position and angle). Energy transfer from beam to plasma, also measured, is sensitive to beam alignment and intensity in a more complicatec fashion. *This work supported in part by the Department of Energy under grant DE FG0297 ER 54433 A002, and by the Nationa Science Foundation under grants NSF PHY 96 02872 and REU 9S 87875.

AS 2 Compression of a Non-Neutral Plasma using a Rotating Electric Field D. BAHR, *Luther College* R. POLLOCK, *Indiana University Cyclotron Facility* This project studies the compression of an electron plasma confined radially in a solenoid and axially by end caps that impose an electric potential. Heat, in the form of a electric field from an electric noise generator, is used to equilibrate the plasma at higher temperatures, where changes are easier to observe. The heat ionizes the minimal background gas to feed the plasma electrons so it can exist in the trap for long periods of time. A set of plates, the motor, was used to apply a rotating electric field to the plasma, giving it both angular momentum and energy. The electric field configuration of this motor was varied between a dipole and a quadrupole shape. The diocotron frequency, the frequency of revolution when off- axis, and the Gould-Trivelpiece frequency, the excitation of the lowest monopole mode, were used to determine the plasma radius. Also of interest are resonant frequencies that occur in the plasma and are excited by the motor, since these may give better compression of the plasma. Greatest compression was found near these resonant frequencies in the plasma or when the motor amplitude was large.

FP1 46 Growth in Electron Plasma Radius Caused By Fast Proton Beam* R.E. POLLOCK, JENNIFER ELLSWORTH, M.W. MUTERSPAUGH, D.S. TODD, *Indiana University Cyclotron Facility (IUCF)* A slightly warmed nonneutral electron plasma is stabilized in a long-lived state with slow particle loss to the trap wall balanced by weak ionization of background gas. Sub-nanowatt power is input by noise, or a line source tuned below a resonance, while a rotating electric field provides compressional torque. From line charge density, extracted from the diocotron frequency, and plasma potential, extracted from a G-T mode frequency, a non-destructive measure of the plasma radius is obtained. When the plasma is bombarded by 0.2 GeV protons in the IUCF storage ring, this radius is observed to increase with proton current. The effect is insensitive to changes in beam position or angle relative to the plasma symmetry axis. Torque estimated from proton-electron Coulomb scatter is orders of magnitude too small to explain the observations. The mechanism for beam-induced radial growth remains unexplained. Progress toward torque calibration, and containment with higher magnetic field, will be described. *Work supported by US DOE (DE FG0297 ER 54433) & US NSF (PHY 96-02872, 94-23896).

J5S 37 Power Input Calibration for a Weakly Ionizing Nonneutral Electron Plasma* R. E. POLLOCK, T. DUECK, M. MUTERSPAUGH, D. STOLLER, *Department of Physics, Indiana University* An electron plasma can be sustained indefinitely by elevating its temperature so that ionization of residual gas provides new electrons to replace those lost to the trap walls. Methods have been developed for regulating the power input so the plasma properties are constant with time, and for determining the absolute value of the input power. This allows the plasma to serve as a calibrated calorimeter, for example in studies of energy exchange with particle beams, or in use as a pressure gauge. Two independent calibration methods are compared, one based on plasma growth rate using the chemical potential for H2 gas ionization, and the other based on damping of energy stored in a standing charge density wave which is excited off-resonance. Observations supporting the calibration procedures will be presented, uncertainties limiting the level of agreement discussed, and implications of the plasma power budget reviewed.

*This work supported in part by the U. S. Department of Energy under grant DE FG0297 ER54433 and by the U. S. National Science Foundation under grants NSF PHY 96-02872 and 94-23896.

9R 1 Proton Beam Tests of an Electron Plasma Target R. POLLOCK, D. STOLLER, A. SARRAZINE, H. GERBERICH, T. SLOAN, *Indiana University and IUCF* Stored protons of 45 MeV striking a non-neutral electron plasma have shown the stability of a beam-target system. The plasma had a length of 0.5 m, with 10 ^{1}0 electrons maintained in a steady state by torque from a rotating electric quadrupole field and thermal energy from a noise source. A plasma temperature of a few eV allowed ionization of background gas to regulate electron number. Proton beam currents up to 0.2 mA were used, either coasting (no time structure) or bunched (rf cavity and electron cooling) to form narrow pulses. Coasting beam was observed to heat the electron plasma consistent with energy transfer via particle collisions, limiting the luminosity to about $10^{24} cm^{-2} s^{-1}$, useful for atomic physics research. A higher trap B field with radiation cooling would raise this limit. Bunched beam gave extra heating, which varied with plasma length, indicating a resonance of a standing density wave with a harmonic of the 1.03 MHz orbit frequency. Increased radial transport was observed after exposure to the proton beam, probably caused by patchy-charge deposits on trap surfaces, and alleviated by raising the wall temperature.

4R 1 Development of a Non-Neutral Electron Plasma Target at the Indiana Cooler*. R. E. POLLOCK, M. PELATH, A. SARRAZINE, M. SCHATTEN, T. SLOAN, Indiana University Cyclotron Facility (IUCF) -- Work in progress on development of a dense plasma target for use in a proton storage ring will be reported. The plasma is confined in an elongated trap of the Malmberg-Penning type. The end confinement is provided by uniform gradient columns. The transverse confinement is provided by a uniform magnetic field, at present limited to 0.2 T. A rotating quadrupole field is applied to counteract radial growth. Off-axis injection is employed to maintain a clear path along the trap axis for passage of the stored particle beam in the IUCF Cooler. Using a regulated ionization of the nanoTorr background gas, a stable population of more than 10^{10} electrons has been obtained. The plasma has been maintained for periods up to one week. Non-destructive diagnostic methods under development and plans for beam-plasma interaction studies will be described.

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Spin-up of an Electron Plasma - First Results

R. E. Pollock* and Francois Anderegg+

**Physics Department, Indiana University, Bloomington IN 47405 and*
+Institute for Pure and Applied Physics, University of California at San Diego
La Jolla CA 92093

Abstract. The application of a rotating electric quadrupole field to a pure electron plasma confined in an elongated Penning trap of the Malmberg type operating at 1 Tesla is shown to produce an unusually long-lived state. The observations are consistent with an assumption that the rotating field suppresses the radial expansion from transport due to alignment imperfections that normally limits the lifetime of such a plasma to a few thousand seconds. With the rotating field in operation, a lifetime of 20 hours was obtained.

INTRODUCTION

A one-component plasma (OCP), confined transversely by a uniform magnetic field and axially by electrostatic fields, forms a very stable system with interesting properties (1). The plasma can persist for a very long time. For small numbers of particles in a confinement volume of small dimension, lifetimes of months to years have been reported (2). Collisions with neutral particles of background gas give rise to radial transport and a finite lifetime (3). However a dense OCP in a trap elongated along the B field direction has an anomalously-shortened confinement time (4). The elongated geometry increases difficulty in maintaining the strict cylindrical symmetry required for the angular momentum conservation which inhibits radial growth. Even with careful construction and alignment of the B field direction along the axis of symmetry of the conducting trap walls, a long plasma column is observed to expand radially and then dissipate through collisions with the side walls. The time scale is on the order of tens of minutes, reducing approximately as the square of the length of the trapped plasma

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column. The lifetime is sufficient for studies of plasma properties, but there are applications of the trapped OCP which would benefit from further improvement.

The plasma column rotates about its own axis to generate the inward **v x B** force which counteracts radial electric repulsion. In a frame of reference rotating with the column, the conducting wall is seen to rotate in the opposite sense. Imperfections in the cylindrical symmetry of the wall can create a drag torque on the column. It is plausible to conjecture that a wall rotating in the opposite sense in this frame could produce a torque of opposite sign to counteract the imperfection torque. In the lab frame this would be a rotating field with the same sense of rotation as the column and greater angular velocity. Experiments have been carried out (5, 6) which showed a small increase in column central density when a rotating field was applied of angular velocity which exceeded the angular velocity of the column center. The long-term effect of a continued application of a rotating field was not addressed in this work. There may be a distinction between column radial compression, and the prevention of a radial expansion.

The best form of rotating field is open to debate. A rotating dipole field can interact with the dipole moment of the charge distribution, and induce undesirable growth of an m = 1 diocotron mode. For the present experiments, a rotating quadrupole field was used, in the hope of coupling more strongly to the second moment of the charge distribution. The configuration was based on a suggestion (7) that the field might induce an electric quadrupole deformation of the charge distribution, a deformation which would be static in a frame rotating at the "motor" frequency. The rotating field could then couple to the deformation to exert a torque. More recently, a mechanism based on rotational pumping via the end region deformation of the plasma column has been proposed (8).

The rotating field introduced to exert a torque may also add energy to the trapped plasma column, raising the temperature of the electron column sufficiently that some of the electrons in the tail of the kinetic energy distribution exceed the ionization threshold of residual gas in the trap volume, and liberate new electrons which can add to the total number confined. By operating at a sufficiently high B field magnitude, radiation cooling will oppose energy input from the rotating field and may then maintain the column temperature below the ionization threshold.

The paper is organized in the following way. A description of the apparatus is followed by a section on observations, first in the absence of the rotating field, second in the regime where heating is dominant and third where a long-lived state is observed which does not appear to rely on replenishment through ionization. The final section summarizes our conclusions.

APPARATUS

Experiments were conducted on the "IV" apparatus at UCSD (9). The axial magnetic field was provided by a superconducting solenoid with a uniformity better than 2% over the confinement length. An additional coil pair was adjusted to add a 0.2% transverse field to improve the alignment of the magnetic field with the axis of the trap electrodes. A baked vacuum chamber in the form of a Type 310 stainless steel cylinder with ion pump and auxiliary Ti sublimation pumping provided a base pressure of $7 \cdot 10^{-11}$ Torr in the confinement region (0.3 nTorr with filament on).

The trap electrodes take the form of an axial array of eleven hollow cylinders of gold-plated OFHC copper, with inside diameter 57.2 mm and length, including spacer, of 58.4 mm. Two of the cylinders are sectored for signal monitoring and control. One has four insulated sectors of 58° width and 90° spacing. The second has eight insulated sectors of 27° width and 45° spacing. The electron source is a filament in the form of a spiral of thoriated tungsten wire. It is operated outside the main part of the magnetic field where the B field strength is 1.1% of the interior value. A grid close to the plane of the spiral is biased positive by about 10 V to extract electrons continuously from the heated filament. With 100 W of power, the filament operates at about 1850K and emits about 0.2 mA of electron current. A set of six additional cylinders lying between the filament and the trap are biased to maximize transmission of electrons through the trap. With the filament biased to 70 V, about 40 μA can be observed in a continuous beam of diameter about 3 mm.

The electrons may be trapped in two modes. In the normal cyclic mode, a negative bias is applied to two rings forming the ends of the containment region. To fill the trap, the voltage on the "inject" ring is raised to ground by a trapezoidal pulse of duration about 5 ms. After a chosen confinement time, a rectangular pulse to ground on the "dump" ring at the other end empties the trap, allowing a measurement of total charge or, by interposing a small diameter collimator hole between the end electrode and the Faraday cup, a measurement of line-integrated density. For the long-lived plasma studies, the dump pulse was not employed, and a single inject pulse was used to refill the trap after an inadvertent loss. Between fillings the filament was not heated, for improved vacuum.

In the work reported here, nine rings lay between the inject ring and the dump ring, giving a length of 0.526 m between the equipotential planes at half the confinement potential. The plasma formed by normal injection contained about $0.5 \cdot 10^{10}$ electrons in a column of diameter about 10 mm surrounding a denser core with the 3 mm diameter of the transmitted beam. See Figure 1a.

On the four-sectored ring, one sector was connected to a high impedance amplifier for observation of coherent signal. The opposite sector received a phase-shifted and amplitude-adjusted copy of the signal for damping of m = 1 diocotron mode. The two remaining sectors were connected to pulse generators of opposite sign, which could be fired to obtain a controlled displacement of the plasma column. Negative feedback was applied most of the time. To measure the line density of the column, the feedback was interrupted, an impulse applied, followed by positive feedback for a few milliseconds, then a 0.2 s interval without feedback in which the FFT diocotron spectrum could be obtained. The ratio of second harmonic to first harmonic amplitudes gives the column displacement from the trap axis. If the period of positive feedback is increased, a sufficient displacement is reached that noticeable loss to the wall occurs. The column displacement at onset of loss thus measures the base width of the column. See Figure 2.

The eight-sector ring served as the "motor" for adding angular momentum to the column. A signal generator fed a four-way splitter through a calibrated attenuator. The splitter fed four channels of phase-shifter/amplifier to generate four drive signals equal in amplitude and phase-shifted in steps of 90°. Each signal fed opposite pairs of wall sectors. This created a rotating electric quadrupole field in the ring interior, rotating with half the frequency of the signal generator. By reversing phases of two channels, the sense of rotation could be reversed. Typical operating parameters were a frequency of 1 MHz and amplitude of 0.2 V.

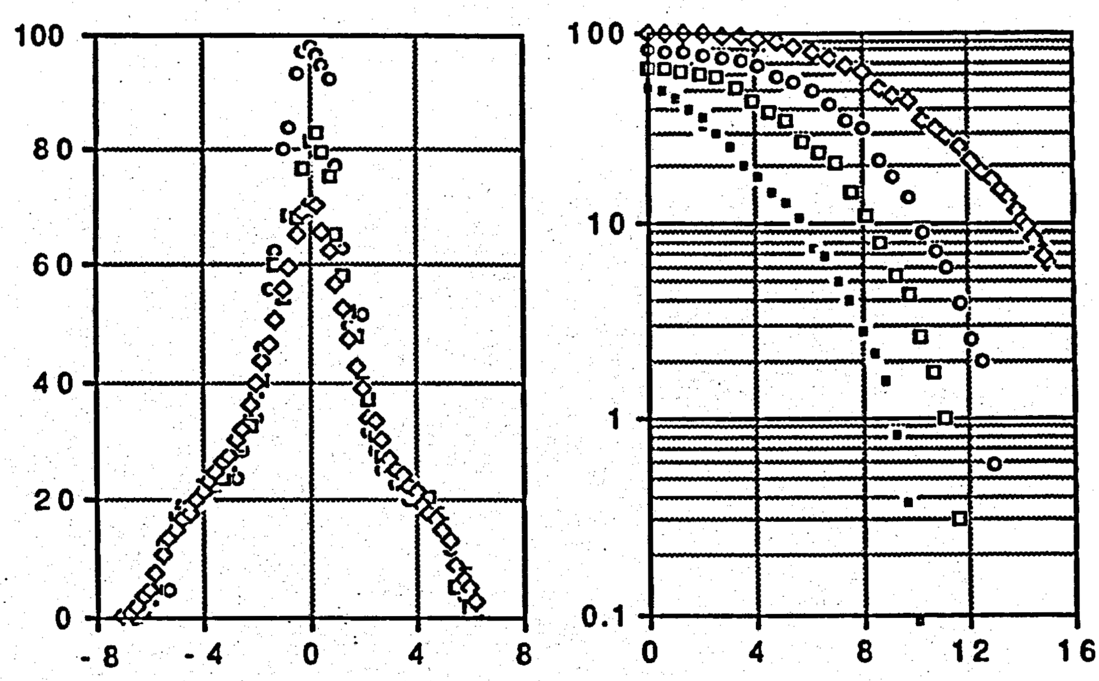

FIGURE 1. Time evolution of radial density distributions in the absence of a rotating quadrupole field. Figure 1a- after 0.3, 1.0 and 2.0 s at 0.39 T. Figure 1b- after 1, 5, 20, and 50 s at 0.15T. Radius in mm, the wall is at 28.6 mm. Vertical scale is arbitrary.

OBSERVATIONS

Plasma Evolution with Motor Off

The evolution of the radial distribution over time was explored to establish the radial expansion rate in the absence of the rotating electric quadrupole field. Figure 1 illustrates the radial expansion over the first minute following injection. On the left, at 0.39 T, relative density scans at 0.3, 1.0 and 2.0 s show the central enhancement in density associated with the details of the injection process decaying within a few seconds. Change in the base width is small on this time scale. On the right, at 0.15 T, the radial density at 1, 5, 20 and 50 s shows a gradual expansion of the not-quite-Gaussian form. The distributions are shifted vertically for clarity. Later, after the edge of the distribution reaches the wall, both the central density and the total electron number will decay with similar mean life.

Persistent State with Ionization and Regulation

The confined electron plasma is so well isolated from its container that very small input power, for example from the noise level of an amplifier whose output is connected to one of the electrodes, is sufficient to raise the temperature and initiate ionization, signalled by a rise in the trap content with time in place of the expected decay. When the electrical environment is made sufficiently quiet that this process is not observed, then the deliberate application of a perturbing signal such as the rotating quadrupole field, can be used to generate electrons at will.

Without a regulation mechanism, the contents of a constant temperature column would grow exponentially with time until the plasma potential approached the end confinement potential. At that point electrons with highest energy will begin to spill out the ends. This is an evaporative cooling mechanism that reduces the temperature and production rate until a balance can be obtained. But note that this is a regulating mechanism only for particle number and temperature. Imperfection torques will still cause radial growth and loss to the wall. However by using the periodic kicking procedure which permits non-destructive monitoring of electron number, one may also maintain a selected column diameter. The diocotron amplitude is adjusted so that the column center reaches a desired distance from the conducting wall of the trap. Particles lying outside the radius corresponding to this separation distance are removed, and the column diameter thereby limited. In a sense this is a kind of controlled "evaporative torque" for counteracting radial growth. With losses both from the ends and the sides, all the principal plasma properties (density, column radius, temperature) can be maintained indefinitely. This is a persistent state for the plasma, but not for its constituents which are continuously replaced by scavenging electrons from the background gas.

Characteristics of this persistent state, which was observed for B fields of 0.15 and 0.4 T, included the following:

i) the state would persist with either sense of motor field rotation, showing that motor torque was not the determining feature;

ii) the number of electrons increased if the end confinement potential were increased, showing that continuous ionization was present;

iii) the number of electrons varied with the duration of positive feedback, showing that scraping of the column on the cylindrical wall was occurring.

The properties of the persistent state could be explored in a non-destructive manner. In the example shown in Figure 2 below, the motor rotation frequency was varied over the range from 0.35 MHz to 0.85 MHz. More ionization was observed at higher frequency, so the amplitude of the rotating quadrupole field was reduced at higher frequency to maintain the diocotron frequency in the range from 15 to 20 kHz. The B field was 0.39T.

The correlation between particle number and displacement after positive feedback seen Figure 2 a) is a property of the circuitry with the important consequence for the regulation mechanism that as the trap contents grow, the column is driven closer to the wall.

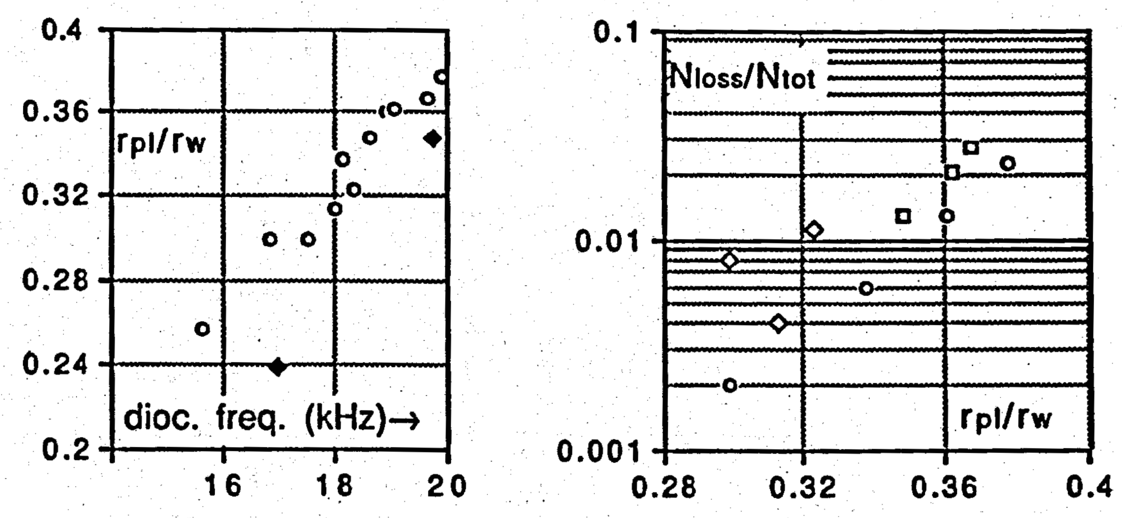

FIGURE 2. a) plasma displacement radius/wall radius vs m = 1 diocotron frequency and sense of motor rotation (circle: normal ccw, solid diamond: reversed cw). Note that the response to reversed motor sense is small but detectable.

b) fractional loss per kick vs rpl/rw. A measure of the radial distribution tail. Symbols (circle, square, diamond) denote motor power attenuator settings increasing in 5 dB steps.

By comparing the FFT spectrum measured soon after positive feedback ended, with a spectrum measured later just before negative feedback began, it was possible to obtain a measure of the fraction of the trap content removed per wall encounter. Figure 2b (right) shows that moving the column closer to the wall leads to increased loss per kick. The scatter in the points below 1% loss/kick shows the threshold sensitivity for this method. With one kick every 5 seconds, loss rates to the wall corresponding to lifetime in excess of ten minutes could be measured. The regulation of particle number and column radius in this persistent state depends on removing particles from the tail of the distribution.

The trap contents were retained overnight on two occasions in this regulating persistent state and showed the change in particle number less than 5 %. The meaning of this result is that the persistent state is readily distinguished from a true decay with mean life less than one week.

Long-lived State Without Ionization

If the rotating electric quadrupole field adds energy to the column of plasma, then a cooling mechanism other than evaporation must be present to prevent the temperature from reaching ionization threshold. For electrons and positrons, a field of 1 Tesla gives a temperature cooling time of about 4 s as the conducting cylinder is a waveguide above cutoff at the cyclotron frequency of 28 GHz (10). The input power from all sources must be low enough that ionization is halted by radiation cooling. A test for the absence of evaporative cooling is simply to raise the end confinement potential and observe that the number of particles does not increase. A test for the absence of "evaporative torque" is to reduce the amplitude of the kicked diocotron motion and show that the particle number does not increase. Finally the sense of the motor rotation may be reversed to show that the long-lived state is lost.

Figures 3 and 4 show a few hours of observation of a motor-driven plasma at 1 Tesla and 0.5 MHz. The motor amplitude could be increased to induce ionization for adjusting the number of electrons, then reduced to create a long-lived state. Left overnight on two occasions, a mean life of about 20 hours was observed. The increase of lifetime when the motor was present with the proper sense of rotation, (from 17 m to 20 h) is the magnitude of improvement expected if the presence of the rotating field eliminated the misalignment torque, leaving effects such as the background gas transport as the remaining factor in plasma lifetime determination.

This slowly and regularly decaying state was qualitatively different from the persistent state seen at lower B fields. The persistent state would remain overnight with no change in particle number, but would respond rapidly to small changes in kick amplitude or motor power. The persistent state at low field could be created

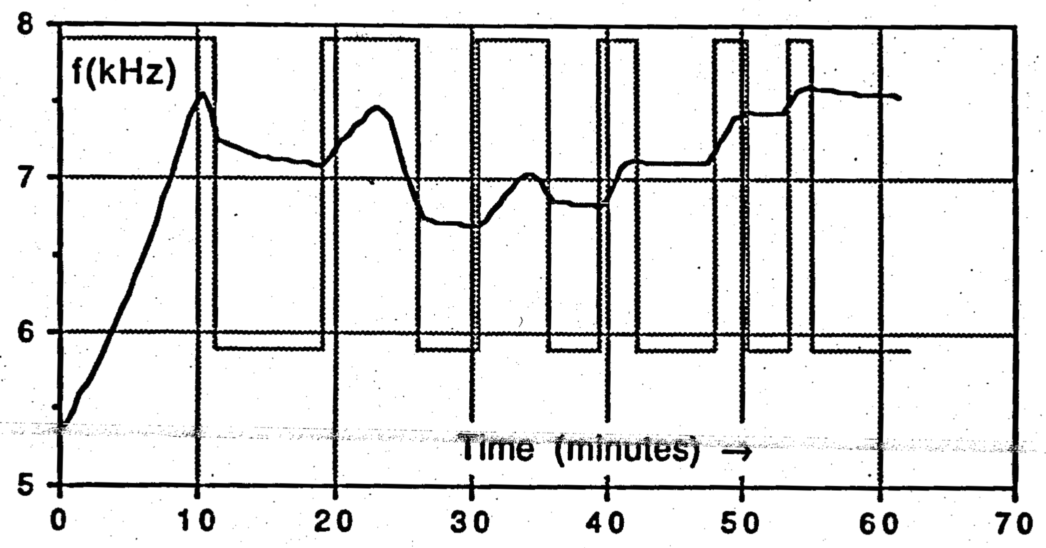

FIGURE 3. A one-hour recording of diocotron frequency, showing the use of variable "motor" power to control build-up of trapped electron number following injection. The dotted line shows manual changes in amplitude of the rotating quadrupole field between values differing by a factor 1.7. An upper frequency limit is set by the potential of the end rings. Note the initial rapid growth ends with an overshoot attributed to evaporative cooling. The rapid change of slope following each power change shows the speed of temperature equilibration at 1 Tesla. The highest sustained number of electrons is obtained by reducing the motor power as a peak is reached.

with either sense of motor rotation, showing that energy input was more important than torque. As seen in figure 4 c), the long-lived state did not survive with the reversed sense of motor rotation.

The temperature of the long-lived plasma was measured by dropping the end potential in very small steps and recording the slope of the exponential loss onset. A longitudinal temperature of 1.8 eV was obtained under the conditions of figure 4. Measuring the charge reaching the Faraday cup at each potential step confirmed the method. This is a nearly non-destructive method as only about 1% of the charge needs to be removed to determine the temperature.

Several measurements of the depth of the plasma potential were made with 140 V and 200 V end confinement. These are logarithmically-sensitive to the column diameter and consistent with a diameter of 5 to 10 mm, perhaps increasing slightly with particle number at fixed field-rotation frequency.

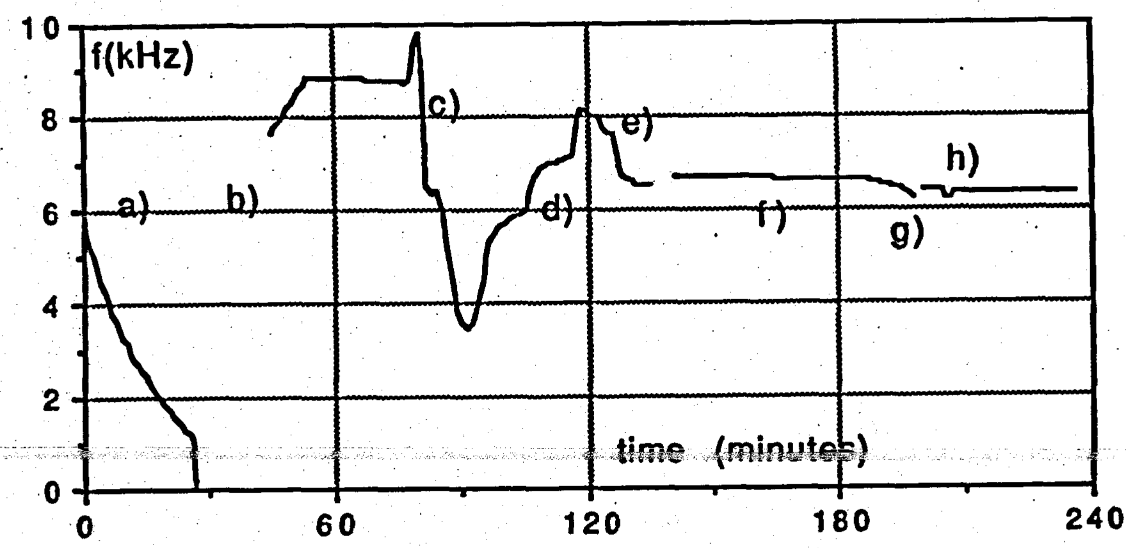

FIGURE 4. Behavior indicative of a long-lived state not accompanied by ionization. A 4 hour chart recording of diocotron frequency. A second trace (not shown here) of the ratio of second to first harmonic amplitudes showed that the column displacement during the f measurement was about 3% of the wall radius, an order of magnitude less than in the conditions where radial loss contributed to the control of radial growth.
a)with the motor off, a mean life of 17 minutes was observed;
b) after refill and controlled build-up by ionization, a very flat trace was observed. The end potential was -200 V, so the overshoot phenomena of Figure 3 were avoided by stopping before the confinement limit was reached;
c) stable state destroyed by a reversal of motor sense. Note rapid heating, a sudden loss of one-third of the electrons, then rapid decay;
d) proper motor sense restored with higher power to replenish the contents;
e) one end potential was lowered from 200 V in steps of 25 V until a noticeable loss was observed. This give a rough measure of the plasma potential of between 125 and 150 V.
f) When the higher potential was restored, the trap contents did not grow as they would if ionization were present. The plasma then was left undisturbed for one hour and a loss rate of 2±1%/hr observed.
g) second potential measurement of 85±5, with irreversible loss at 80 V
h) reversible compression as the end potential is cycled from 200 to100 to 200 V

CONCLUSIONS

The application of a rotating electric quadrupole field to an electron plasma in a confinement field of 1 Tesla gives rise to a stable state with a decay rate reduced by about two orders of magnitude over that observed in the absence of the rotating field. While it is not possible from these first observations to completely eliminate the possibility that a low rate of ionization was affecting the measured lifetime, the consistency of the lifetimes determined by overnight confinement with different starting numbers of particles argues against this explanation.

This report is a first step toward an understanding of the physical processes at work. The shape of the equilibrium density profile has yet to be determined. The best choice of motor rotation frequency, and the minimum cooling required to sustain the thermal equilibrium have yet to be explored. Whether the rotating field can increase the central density or only delay its decay is still an open question.

The techniques for controlled adjustment of the number of electrons in the trap following injection, which were developed as part of this study, have interesting implications. It should be possible to raise the electrostatic confinement potential substantially after filling the trap, and to increase the number of electrons to explore a density regime well beyond the reach of present injection devices.

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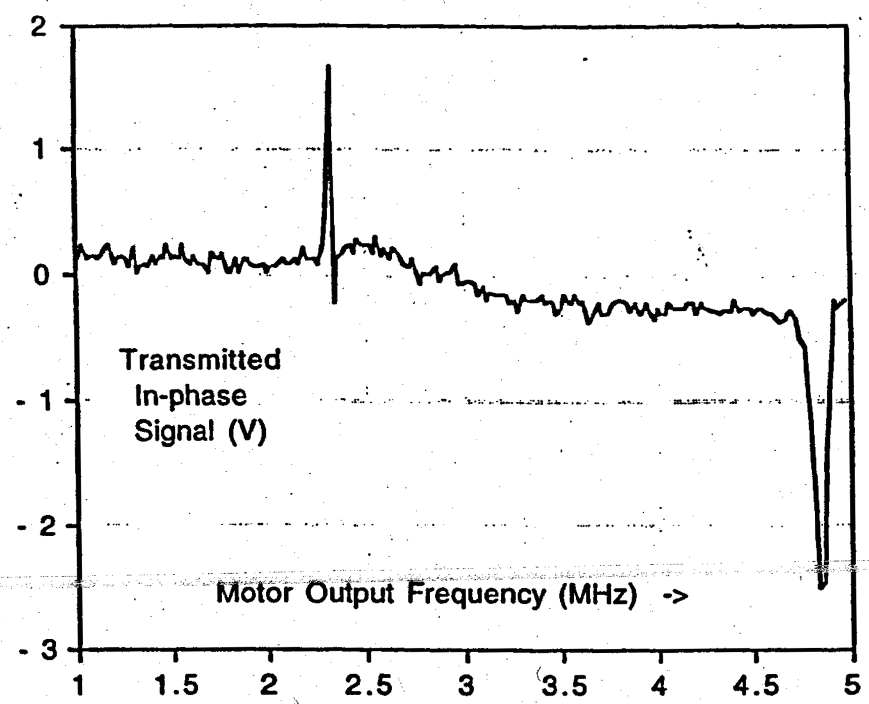

FIGURE 7. A rotating electric field created by eight sector plates at one end of a long electron plasma is swept in frequency from 1 to 5 MHz in 0.1 s. Near the other end of the plasma, two opposite plates sense a dipole mode excitation in phase with the swept "motor" signal. Note the two narrow peaks at 2.3 and 4.8 MHz where the plasma transmits strongly ($m_z = 1, 2?$). A strong $m_\theta = 0$ mode at 4.2 MHz is invisible. Overall signal gain in the "agile multiplier" chain is about +100 dB.

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