ENERGY LOSS RATES OF ENERGETIC IONS
INJECTED INTO THE FM-1 SPHERATOR

BY

S. L. DAVIS, V. ARUNASALAM, R. J. HAWRYLUK,
M. OKABAYASHI, G. L. SCHMIDT
J. A. SCHMIDT, AND S. SUCKEWER

PLASMA PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

This work was supported by U. S. Energy Research and Development Administration Contract E(11-1)-3073. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States Government is permitted.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America.

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ * ; Microfiche \$1.45

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-50	\$ 4.00
51-150	5.45
151-325	7.60
326-500	10.60
501-1000	13.60

ENERGY LOSS RATES OF ENERGETIC IONS INJECTED INTO THE
FM-1 SPHERATOR

S. L. Davis, V. Arunasalam, R. J. Hawryluk, M. Okabayashi,
G. L. Schmidt, J. A. Schmidt, and S. Suckewer

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

PPPL-1289

October 1976

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ENERGY LOSS RATES OF ENERGETIC IONS INJECTED INTO THE
FM-1 SPHERATOR*

S. L. Davis, V. Arunasalam, R. J. Hawryluk, M. Okabayashi,
G. L. Schmidt, J. A. Schmidt, and S. Suckewer

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

Energy loss rates of energetic ions were studied during neutral beam injection experiments on the FM-1 spherator. Under typical experimental conditions, the injected beam ions slowed-down on the plasma electrons resulting in electron heating. The measured slowing-down rate was found to be in agreement with classical predictions.

Most conceptual designs for producing energy from magnetically confined thermonuclear plasmas include as one of their key elements the injection of multi-megawatt neutral beams to heat the plasma. Inherent in these designs is the use of a simple classical theory¹ to describe the beam plasma interaction. Early experiments indicated varying discrepancies with this classical theory. The discrepancies ranged from energy loss rates a factor of 3 lower² to 3 to 4 times higher³ than theory. However, more recent experiments have shown better agreement⁴⁻⁷. Because of the importance of the beam-plasma interaction to reactor designs as well as future experiments, there is continuing interest in energy loss studies.

In this experiment, the energy loss rates of energetic ions were studied during neutral beam injection experiments on the FM-1 spherator. The slowing-down rates were measured

by observing the neutral charge exchange spectra of the injected ions. Under typical experimental conditions ($0.3 < v_p/v_e < 1.5$ where v_p is the injected ion velocity and v_e is the electron thermal velocity), the beam ions slowed-down on plasma electrons resulting primarily in electron heating. Thus, it was possible to experimentally determine the slowing-down rate due to electron collisions alone.

The FM-1 spherator is an axisymmetric toroidal machine with a levitated superconducting ring. The neutral beam was injected through the plasma and under the floating ring as shown in Fig. 1. The neutral beam source was a Berkeley injector⁸ which was used to study plasma heating effects. Although the main injection energy was 15 keV, the neutralized beam consisted of full, half, and third energy components of predominately atomic hydrogen.

Charge exchange neutrals were detected using an electrostatic analyzer⁹. The analyzer consisted of a helium gas stripping cell, a set of electrostatic deflection plates, and an electron multiplier. The energy resolution of the analyzer was approximately 7%.

Electron densities were measured using a 4 mm microwave interferometer; electron temperatures were measured spectroscopically from the ratio of C III lines. The neutral hydrogen density was measured spectroscopically from the intensity of several hydrogen lines¹⁰.

In general, injected ions lose energy to both plasma electrons and ions. However, the beam energy at which the energy loss

rates to the electrons and ions are equal can be estimated to be approximately 500 eV¹¹. Thus, energy loss to the plasma ions is not important, and the energy of the injected ions as a function of time can be calculated from the classical energy loss rate¹ to the electrons

$$\frac{dE}{dt} = \frac{4\pi e^4 \lambda}{M_e v_p} G_e(v_p)$$

where e and M_e are the electron charge and mass, respectively, and λ is the Coulomb logarithm. The quantity $G_e(v_p)$ is the number of electrons per cubic centimeter which have a velocity less than the velocity of the injected ion.

Typical charge exchange data is shown in Fig. 2. The ordinate represents time and the abscissa represents charge exchange signal with the signal increasing in the negative direction. The delay between the appearance of the signals at 15.0 keV and 12.5 keV is a direct measure of the energy loss rate of the injected ions. To form a complete set of data, similar data were taken at numerous energies and under various conditions. The results are indicated in Fig. 3 and 4.

The results in Fig. 3 show the charge exchange energy plotted as the ordinate and the appearance time plotted as the abscissa. The slopes of these curves are the energy loss rates of the ions. The three sets of data represent the full, half, and one-third energy components of the beam. The solid lines are computed from the measured electron temperature and

density using the classical energy loss expression given above. No fitting procedure was used. The calculation takes into account the rapid variations in the temperature and density which occur during the initial part of the injection pulse. In the case shown, the temperature peaked near 15 eV approximately one millisecond after the injection began while the density gradually increased from $5 \times 10^{11}/\text{cm}^3$ to $7.5 \times 10^{11}/\text{cm}^3$ during the first two milliseconds. The ratio of captured beam energy to plasma energy becomes greater than 2 within the first millisecond after injection. The calculations are seen to agree quite well for all three energy components of the beam.

Figure 4 shows a combination of two different sets of data and their respective theoretical predictions. In these cases the temperatures and densities of the spherator were changed to produce a variation in the energy loss rates. The possible errors in the temperature measurement could approach 25%, thus the theoretical curves are within experimental errors. The important feature of this plot is that the variation in slope of both sets of data is reproduced by the theoretical curves. This is an indication that the parametric dependence of the energy loss rates is in reasonable agreement with theory.

Figure 5 shows the observed energy distribution of the charge exchange signal. The solid curve indicates a theoretical prediction using the calculated charge exchange time and energy loss rates. The charge exchange rate was calculated from the measured neutral density⁷ and the energy loss rate was

calculated as before. The amplitudes of the theoretical curves were normalized to the experimental data. The width in energy of the charge exchange spectra should be proportional to the energy loss rates and inversely proportional to the charge exchange rate. That the width of the curves is in good agreement with experiment is another check on our results.

In this experiment we have measured the energy loss rates of energetic ions under various conditions in the FM-1 spherator. Under typical conditions the coupling was primarily to plasma electrons. Observations were in good agreement with classical theory.

We would like to thank H. P. Eubank for his assistance and for the use of his charge exchange analyzer. It is also our pleasure to acknowledge useful discussions with R. J. Goldston.

* This work was supported by U. S. ERDA Contract E(11-1)-3073.

1. B. A. Trubnikov, Rev. Plasma Phys. 1, 105 (1965),
(Consultants Bureau, New York).
2. R. J. Burke and R. F. Post, Phys. Fluids 17, 1422 (1974).
3. J. H. Ormrod, AECL Report No. 2669, Chalk River, Ontario,
1967 (unpublished).
4. D. M. Cox, H. H. Brown, I. Klavin, and B. Bederson, Phys.
Rev. A 18, 1409 (1974).
5. R. J. Goldston, Nuclear Fusion 15, 651 (1975).
6. J. G. Cordey, E. P. Gorbunov, J. Hugill, J. W. M. Paul,
J. Sheffield, E. Speth, P. E. Stott, V. I. Tereshin, Nucl.
Fus. 15, 441 (1975).
7. L. A. Berry, C. E. Bush, J. L. Dunlap, P. H. Edmonds,
T. C. Jernigan, J. F. Lyon, M. Murakami, W. R. Wing, Plasma
Physics and Controlled Nuclear Fusion Research 1974 1, 113
(1975).
8. K. H. Berker, W. R. Baker, W. S. Cooper, K. W. Ehlers,
W. B. Kunkel, R. V. Pyle, and J. W. Stearns, Second Symp.
on Ion Sources and Formation of Ion Beams, Berkeley, Calif.
(22 Oct. 1974).
9. H. P. Eubank and T. D. Wilkerson, Rev. Sci. Inst. 34, 12 (1963).
10. S. Suckewer, R. J. Hawryluk, M. Okabayashi, and J. A. Schmidt,
App. Phys. Lett., to be published.
11. T. H. Stix, Plasma Phys. 14, 367 (1972).

763555

Fig. 1. Top view of neutral beam injection in the FM-1 spherator.

763298

Fig. 2. Typical charge exchange signals shown for two different energies.

763299

Fig. 3. Charge exchange energy versus appearance time of signal. Solid lines indicate theoretical predictions.

763857

Fig. 4. Charge exchange energy versus appearance time for varying plasma conditions.

763589
Fig. 5. Charge exchange signal versus energy. Solid curves indicate normalized theoretical predictions.