This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

UCRL - 75605

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 or 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.

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

A METHOD FOR ACHIEVING COMPLETE NEUTRALIZATION
OF A HIGH-ENERGY CHARGED PARTICLE BEAM

J. W. Beal

V. K. Neil

April 3, 1974

This paper was prepared for submission to
Nuclear Fusion

A METHOD FOR ACHIEVING COMPLETE NEUTRALIZATION
OF A HIGH ENERGY CHARGED PARTICLE BEAM*

J. W. Beal and V. K. Neil

Lawrence Radiation Laboratory, University of California
Livermore, California

ABSTRACT

Several concepts of a controlled fusion reactor utilize a beam of neutral atoms with kinetic energy in the range of 200 keV. Presently existing beams in the range of 10-20 keV are converted to neutral beams with an efficiency of like 85% via the electron capture mechanism. At 200 keV this conversion efficiency drops to like 20% because of the rapidly decreasing electron capture cross-section with increasing beam energy. This note suggests recycling the charged beam back through the neutralizer cell while continually removing the neutralized particles thus improving the overall efficiency. In principle, this recycling can be accomplished by a properly designed magnetic guide field.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

I. Introduction

Several concepts of a controlled fusion reactor utilize a beam of neutral deuterium atoms with kinetic energy in the range of 200 keV. These neutral atoms are injected into a magnetic field configuration where they are ionized and trapped to form a thermonuclear plasma.

Presently beams consisting of a few amperes of D^+ with kinetic energy in the range of 10 keV are passed through a neutralizer cell and converted to D^0 with an efficiency of about 95%. At 200 keV the conversion efficiency drops to about 20%. This fraction is the equilibrium ratio of neutralized to unneutralized particles at 200 keV. Increasing the length or density of the neutralizer does not increase the ratio, therefore it is desirable to pass the charged beam through the neutralizer cell several times while continually removing the neutralized particles. This recycling of the beam can in principle be accomplished by a properly designed magnetic guide field - in fact, a storage ring.¹ The stored beam passes through a neutralizer cell, and on the average a particle will remain in the ring for 5 turns before being neutralized and leave the ring.

If a D^0 beam of 5A equivalent is desired, then a 5A beam of D^+ is injected, and the circulating current in the ring is 25A. The injected current need not come from a single source, since injection at several points in the ring may be possible. For application to mirror-type devices, only one neutralizer cell is used so that the extracted D^0 beam is fed to one target. For injection into toroidal devices several neutralizer cells may be employed to feed D^0 beams into the torus at different points.

II. The Ring

In its simplest form, the ring might consist of two straight sections with no bending magnetic field, and two 180° bending magnets. One straight section would contain the injector and the other the neutralizer cell. Strong magnetic fields are not required, as the magnetic rigidity (magnetic field strength B times bending radius ρ) for 200 keV D^+ is 0.91 kG - m. From considerations of particle dynamics in the ring, a configuration consisting of four straight sections and four 90° bends may be preferable, such a configuration is shown schematically in Fig. 1. Any magnetic field configuration (lattice, in accelerator terms) used must be such as to maintain the proper beam optics in the neutralizer region so that the emerging D^0 beam will have the desired focal properties. It seems feasible that a lattice can be designed to meet these requirements, although the lattice may consist of bending magnets, independent focusing magnets, and drift spaces.

The region over which neutralization takes place must be localized to prevent neutralization in other portions of the ring. If a conventional

gas neutralizer cell is used, the gas that leaks out must be rapidly pumped. In fact, the condition to be satisfied is

$$p_n \ell_n \gg p_o C \quad (1)$$

where p_n is the pressure in the neutralizer cell, ℓ_n is the length of the cell, p_o is the pressure in the ring and C is the circumference of the ring. Typically $p_n \sim 10^{-3}$ torr and $\ell_n \sim 0.3$ m will be sufficient to approach closely the equilibrium ratio of D^0/D^+ , while C may be ~ 10 m. Therefore p_o should be $\sim 10^{-6}$ torr or less. This requirement may prove formidable in the design of the vacuum system, therefore other neutralizers should be investigated. A gas jet directed across the beam would reduce diffusion of gas out of the neutralizing region. A foil neutralizer would be excellent from the standpoint of beam optics as well as vacuum requirements, but at present no suitable foils exist.

Two methods of injection into the ring have been considered. By extracting D^0 atoms from the ring instead of D^+ , the limitations of Liouville's theorem are circumvented. John Hiskes² has suggested that these limitations can also be circumvented at injection by injecting D_2^+ molecular ions. The injection of D_2^+ at 400 keV provides a simple means of placing 200 keV D^+ on the proper orbit in the ring. As the D_2^+ passes through the neutralizer cell the first time, the reactions $D_2^+ \rightarrow D^+ + D^0$ and $D_2^+ \rightarrow 2D^+ + e$ take place with roughly equal probability. At this energy the cross-sections for these reactions are approximately two orders of magnitude larger than the cross section for charge exchange. In addition, whenever molecular ions are dissociated, there is no feasible return path for reforming them; therefore, the yield of atoms is determined solely by the target. The D^0 beam passes out of the ring and the D^+ beam

circulates in the ring. It should be noted that the reactions $D_2^+ + D_2^+ \rightarrow 2D^+$ are negligible at this energy. The D_2^+ must pass through the neutralizer cell headed in the right direction. The radius of curvature of a D_2^+ ion is twice that of a D^+ ion in the same magnetic field, so that proper injection of D_2^+ may be accomplished as shown schematically in fig. 2. The disadvantage of this injection scheme lies in the fact that D_2^+ ions are rather scarce. Present day ion sources produce more D^+ than D_2^+ .

The second method for injection is a standard one for multi-turn injection into an accelerator, namely exploiting a resonance in the radial oscillation of a particle about the equilibrium orbit (radial betatron oscillation)³. For example we consider a ring as shown in fig. 1. The ring may be designed so that $\nu_r = 1$, where ν_r is the number of radial betatron oscillations per turn. This condition is satisfied by a spatially uniform magnetic field, but can also be achieved in the four-sided lattice in Fig. 1 by proper choice of dimensions and radial gradient of the magnetic field in the bends. As an example, the condition is satisfied if the bending radius $\rho = 1\text{m}$, the length of the straight sections is $\sqrt{2}\text{m}$, and the condition

$$-\frac{\rho}{B} \frac{dB}{dr} \bigg|_{r=\rho} = \frac{1}{2} \quad (2)$$

is satisfied in the bends, where B is the bending magnetic field.

In such a lattice, a radially deflecting electric or magnetic field in the north and south straight sections (radially inward in the north, radially outward in the south) will cause the orbit of a particle to move east, away from the inflector located in the west straight

section. The motion is analogous to the $\vec{E} \times \vec{B}$ drift of particles in crossed electric and magnetic fields. In this manner particles may be injected continually into the ring with enough radial aperture to accomodate the eastward motion for about 10 turns. This injection scheme would result in a flat beam passing through the neutralizer, but a flat beam of 2" may be more useful than a round one. Furthermore, this is merely one example of so called "resonance" injection. Others will be investigated.

III. Possible Difficulties

One difficulty that can be laid to rest is the effect of multiple scattering as a particle makes several transits through the neutralizer. If the neutralizer cell has a pressure of 10^{-3} torr and is 30 cm long, the root mean square scattering angle for one transit is about 0.1° . This angle increases as the square root of the number of transits, therefore it will remain comfortably small for the number of transits required.

On the other hand, the electrostatic self-force of the beam presents a serious problem unless the self-electric field is very nearly canceled by the presence of background electrons. To illustrate the problem of self-forces, we consider a simple model of a beam with uniform charge density out to radius $r = a$ and zero beyond. The beam is surrounded by a perfectly conducting pipe of radius b . The radial electric field is given by (mks units)

$$E_r = \frac{\lambda}{2\pi\epsilon_0} \begin{cases} r/a^2, & r < a \\ 1/r, & a < r < b \end{cases} \quad (3)$$

in which λ is the charge per unit length in the beam. The electrostatic potential ϕ on the axis of the beam is

$$\phi = \frac{\lambda}{4\pi\epsilon_0} \left[1 + 2 \ln (b/a) \right] \quad (4)$$

It is convenient to express the effect of the self-field in terms of the resultant change in v_z (or v_x , but for our model the two are equal). If x is the radial displacement of a particle from the beam axis, we have

$$\frac{d^2 x}{dt^2} + \nu_e^2 \nu_c^2 x = \frac{eE_r}{m} \quad (5)$$

in which ν_c is the particles' circulation frequency in the ring, m is particle mass, and ν_e is the value of ν_z provided by the magnetic guide field. The effective ν_z is found from $\nu_z^2 = \nu_e^2 - \Delta\nu^2$ with $\Delta\nu^2$ the contribution from the self-forces of the beam. From Eqs. (3) and (5) we have

$$\Delta\nu^2 = e\lambda/2\pi\epsilon_0 d^2 m \nu_c^2 \quad (6)$$

This quantity is just $2(\omega_p/\omega_c)^2$, where ω_p is the plasma frequency of the beam. It is desirable, in fact necessary, for this quantity to be small. In conventional particle storage rings, ν_z must be generally within a quarter of an integer of ν_e . The device under discussion is not a conventional storage ring in the sense that particles are contained for a few turns only. But if we consider ν_e of the order of unity, $\Delta\nu^2$ certainly must be less than unity.

We introduce the equivalent radius $R = C/2\pi$, with C the circumference of the ring. In terms of R we have

$$\gamma_c = v/R = \pi c/R \quad (7)$$

in which v is the particles' speed and c is the speed of light. We may now write Eq. (6) in the form

$$\gamma_c^2 = (v/2\pi mc)^2 (R/aB)^2. \quad (8)$$

Alternatively, we may express γ_c^2 in the terms of the potential ϕ given by Eq. (4). We have

$$\gamma_c^2 = 2(e\phi/mc^2) (R/a)^2 \left[1 + 2 \ln (b/a) \right]^{-1} \quad (9)$$

The parameters in Table I will suffice for a numerical example. From Eq. (4) we find $\phi = 123$ kV. Inserting this value in Eq. (9) we arrive at the frightening value, $\Delta v^2 = 243$.

If the beam ionizes the background gas, a regime might be reached in which the potential would have some small positive value, perhaps $100V^{\frac{1}{2}}$. This situation would appear tolerable from the above calculation. However, such a regime will not be reached in the time required for one turn. Two solutions to this problem suggest themselves, first we might consider providing an excess of electrons in the ring before the beam enters. These electrons could possibly be provided by a hot emitting surface. This scheme has the disadvantage that a large negative potential must be tolerated before the beam enters. In practice it may be easier to

increase the beam current slowly enough so that ionization of the background gas can keep pace and suppress the potential. The question of neutralizing the beam is clearly critical to the entire concept, and requires more study.

Since the device is a storage ring, one must be concerned with all the known coherent instabilities that can occur in such devices. The fact that a high degree of neutralization prevails in the ring eliminates some instabilities, but it may enhance others. The theory of instabilities is rather well established if the beam has uniform density around the ring, and should apply to the beam in this device. Predictions based on this theory must be incorporated into the detailed design of the ring. However, the fact that a typical particle is in the ring for only 5 turns or less may in itself suppress the growth of unstable coherent motion.

TABLE I

Example parameters for the Storage Ring.

R mean radius of the ring	1.54m
ρ bending radius	1 m.
s length of straight sections	$\sqrt{2}$ m
a minor radius of the beam	.05 m
b minor radius of the vacuum tank	.10 m
$1 + \ln (b/a)$	2.38
β particle speed/speed of light	1.46×10^{-2}
λ charge per unit length	5.7×10^{-6} coul/m
e electron charge	1.6×10^{-19} coul.
mc^2 rest energy of deuteron	1.876×10^6 keV
electron capture cross-section $D^+ + e \rightarrow D^0$ (200 keV)	2×10^{-13} cm ² /molecule
dissociation cross-section $D_2^+ \rightarrow D^+ + D^0$ (200 keV) $\rightarrow 2D^+ + e$	1.5×10^{-16} cm ² /molecule

REFERENCES

1. This scheme has some of the features of that proposed by I. N. Golovin, in "Proceedings of the Intersociety Energy Conversion Engineering Conference," Las Vegas, Nevada (1970). Energ; 79, Box 9123, Albuquerque, New Mexico.
2. The authors are indebted to John R. Hiskes for this suggestion as well as much helpful discussion of the ideas presented here.
3. The idea of exploiting the $v_x = 1$ resonance, as well as the lattice described to achieve $v_x = 1$, was suggested by Lloyd Smith of Lawrence Berkeley Laboratory.
4. See, for instance, A. H. Futch, et. al., The Physics of Fluids 5 1277, (1962). These authors treat the potential inside a mirror-confined plasma. The work has been extended to steady-state beams by Gordon W. Hamilton in an unpublished note.

Figure Captions

- 1: Schematic of the storage ring.
- 2: Paths of injected $\bar{U}_2^+$ beam and circulating O^+ beam

FIG. 1

FIG. 2.