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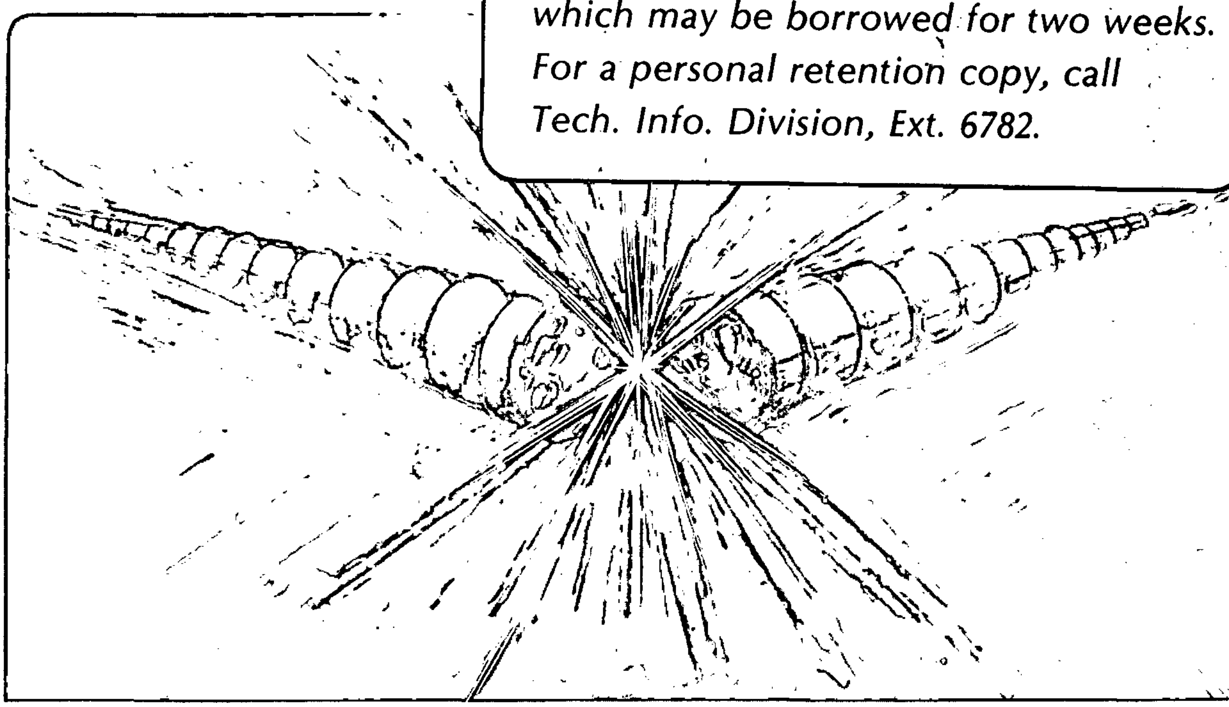

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DISCLAIMER

EFFICIENT, RADIATION-HARDENED, 400 AND 800-keV NEUTRAL BEAM INJECTION SYSTEMS

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ABSTRACT

We present designs for two negative-ion based neutral beam lines with reactor-level power output. Both beam lines make use of such technologically advanced features as high-current-density surface-conversion ion sources, transverse-field-focussing (TFF) acceleration and transport, and laser photodetachment. For the second of these designs, we also presented detailed beam and vacuum calculations, as well as a brief description of a proof-of-principle test system currently under development.

INTRODUCTION

Recent advances and new concepts in negative-ion-based neutral beam systems have enhanced the attractiveness of these systems for magnetic fusion applications. These new developments include 1) demonstration of dc H^- ion source operation at over 5 A per meter of source length,[1] 2) the concept of using strong-focussing electrostatic structures for low-gradient DC acceleration of high-current sheet beams and transport of these beams around corners,[2-4] and 3) the impending development of oxygen-iodine chemical lasers, which when combined with a configuration of the laser system in which the D^- beam passes through the laser cavity,[5] provides the realistic possibility of efficient conversion of negative ions to neutral atoms by photo-detachment of one electron from the negative ion.

The present paper describes two specific beam line designs based on these advances in negative-ion neutral beam technology. Part I is a feasibility study of an 800 keV, 25 MW (per beam line) DC system for a tokamak reactor application.[6] This system was thought through to the conceptual design stage, meaning that space and vacuum requirements, electrode shapes and sizes, component feasibility, and overall system performance (e.g., currents, voltages, beam admittance) were considered. As a result of recent programmatic changes, we decided that, with the exception of further studies of beam line neutronics (an area of concern in connection with the feasibility of neutral beams in reactor applications), we would terminate the design study at this point; hence no further design calculations for this system were performed.

In Part II of this report we present the results of detailed calculations for the accelerator and associated components of a 400-500 keV, 5-10 A module, and describe a proof-of-principle experiment for such a system. This module could serve as a prototype beam line for a mirror or tokamak Engineering Test Reactor or as an initial study leading toward an 800 keV system for steady-state tokamak current drive (see Part I); both these options are discussed in Ref. 7.

I. FEASIBILITY STUDY OF AN 800 keV SYSTEM FOR STEADY-STATE TOKAMAK CURRENT DRIVE AND HEATING

For tokamak reactors to operate essentially steady-state, some means of creating and sustaining the circulating current that provides plasma confinement is required. In principle, this current can be driven by rf waves or by neutral beams injected tangentially into the plasma. We have recently studied the feasibility of developing a suitable 800 keV negative-ion-based neutral injection system; the proposed application was for steady-state current drive and heating of the FED-A Tokamak.[6]

The proposed beam line is shown in plan view in Fig. 1. The beam line design uses

a Lawrence Livermore National Laboratory, University of California, Livermore, CA 94550, and on assignment from Negion, Inc.

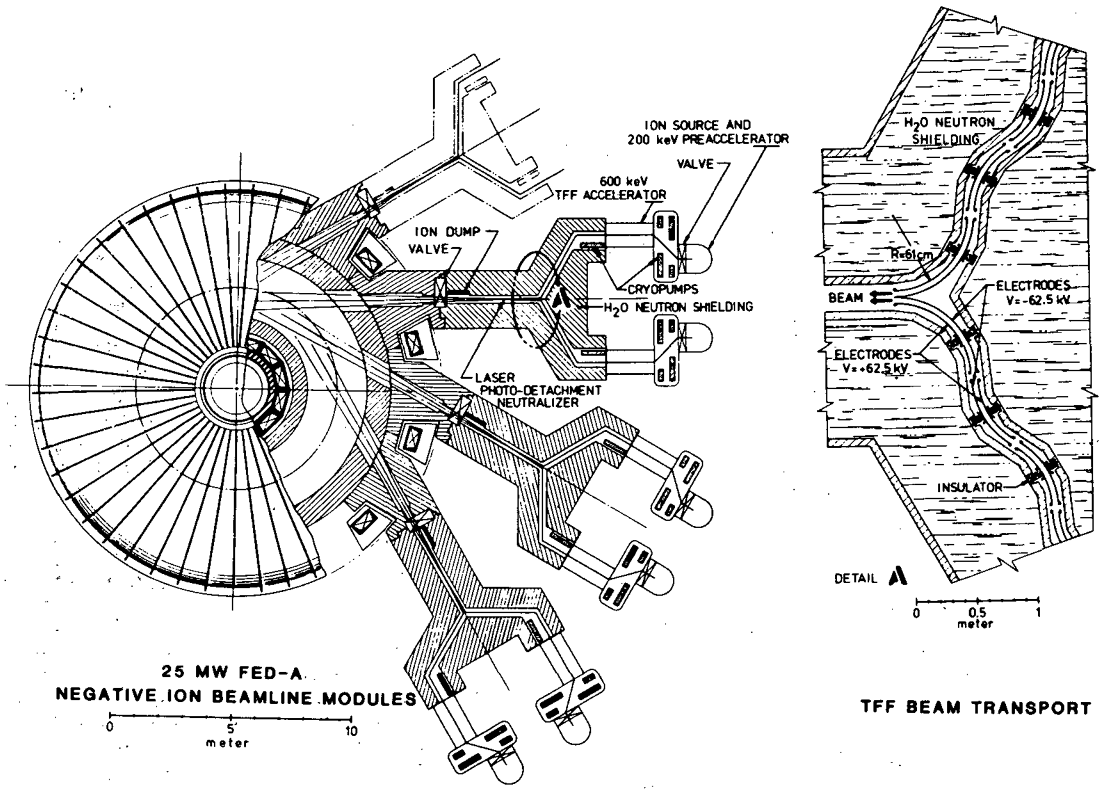

Fig. 1. Plan view of tokamak showing four 800 keV 25 MW radiation-hardened beam lines. Inset at right shows schematic of TFF electrode structure used to transport the accelerated beam through the shielding walls.

electrostatic strong focussing provided by alternating transverse electric fields[3,8] (the TFF or Transverse Field Focussing concept) in the pumping/transport section, in the main accelerator, and in the neutron shield. A standard electrostatic pre-accelerator produces a 200 keV beam. Then the main accelerator raises the D^- beam energy from 200 keV to 800 keV with low gradients (nowhere exceeding 40 kV/cm); the transverse fields can be expected to inhibit total column breakdown by preventing the acceleration of locally-produced electrons and positive ions through more than one stage.

Each sheet beam is 1.1 m high and 1.5 cm wide in the transport section, and carries 5.5 A. The beams are generated by surface-conversion negative ion sources of the type being developed at LBL and BNL; there are six of these sources per beam line, each 1.1 m high, three per channel. Each source has its own isolation valve. The beams from each set of three sources are aimed to intersect at the target. Similar sources are shown in more detail in Part II.

Pumping is by cryopumps capable of on-line regeneration, under development at

LLNL.[9] A 200 keV transport section is provided for both beam matching and pumping; additional pumping is provided after acceleration to the final beam energy of 800 keV.

TFF transport sections are used to transport the 800 keV sheet beam, about 1.5 cm thick, through multiple bends in a channel through the neutron shielding. These bends prevent line-of-sight streaming of neutrons and greatly attenuate the neutron flux. The beamline vacuum vessel is a double-walled chamber constructed of low-activation 5254 aluminum alloy; the volume between the walls is filled with borated water for neutron moderation and absorption.

The flux of neutrons through the beam duct is being studied with the MCNP (Monte Carlo for Neutrons and Photons) code. The code input uses the standard ORNL energy distribution[10] with a cosine distribution in angles, which is a conservative model. Preliminary estimates give an attenuation factor of 10^5. More work is required in this area to obtain better estimates of these numbers and to verify that hands-on maintenance can be performed on the sources. Final results will be reported separately.[11]

After transport around the final bend, the negative ion beam passes through an array of vertically-oriented laser cavities with a total power dissipation of around 200 kW where approximately 97% of the negative ions are converted to neutral atoms by electron photodetachment. The length of this array in the beam direction is 3 m. Suitable lasers in the 10-kW range are now under development in programs funded by the Air Force. These oxygen-iodine chemical lasers operate at a wavelength of 1.3 microns, which corresponds to a photon energy adequate to remove the electron from a D^- ion, but inadequate to strip the electron from common impurity ions such as O^- and OH^-, or to create D^+ ions. The beam in the neutralizer is about 3 m high, but is very thin (a few cm) in the narrow direction, which permits efficient use of the lasers. This narrow cross section also permits electrostatic deflection of the remaining 3% of the negative ions and any impurities into an ion dump at one side of the beam.

A single beamline would inject 25 MW of 800 keV deuterium atoms into FED-A; two ports would therefore be required for injection of the required 50 MW. The additional beamlines shown in Fig. 1 could be used as back-up. For current drive, tangential injection would be used as shown. Analysis of a similar neutral injection system[12] operating at 250 keV indicated an overall system power efficiency of the order of 70%.

The major uncertainties center around the TFF acceleration and transport sections, and the laser photodetachment neutralizer. TFF transport at much lower power levels has been demonstrated in an electron device using a similar principle,[13] but the first experimental demonstration of acceleration and transport of negative ion beams at relevant current densities by a TFF device will not take place for about 2 years. This beamline design requires an extrapolation by a factor of about 1.4 in deuterium negative ion current density at the ion source above what has been achieved experimentally at LBL. We expect at least this much progress in negative ion source development at either LBL or BNL, or both.

The conclusion of this brief study is that the injection of up to 100 MW of 800 keV deuterium atoms into an FED-A size tokamak is probably feasible, and can be considered as an option for current drive.

II. 400-500 keV R&D STUDY

The National Negative-Ion-Based Neutral Beam Plan,[7] in addition to requiring a demonstration of the components which a realistic negative-ion-beam line comprises, suggests that such a beam line be capable of accelerating a 5-10 A D^- beam to 400 keV. A system meeting these requirements is shown in Fig. 2. The components shown include the LBL surface conversion ion source[1], an 80 keV preaccelerator, an 80 keV beam transport and pumping section, a 400 keV TFF accelerator, a neutron shield with 400 keV TFF transport, a laser photoneutralizer, and an ion deflector and dump for the small residual ion component in the neutral beam.

A preliminary proof-of-principle version of the above beamline will produce a 1-2 A, 25-cm wide ribbon beam of H^- ions and will utilize a 160 kV test facility at LBL. Because of power supply limitations only the first three stages (160 keV) of the six-stage 400 keV TFF design will be tested.

The design of the surface-conversion H^- ion source and 80 kV pre-accelerator shown in Fig. 3 has been completed and is under construction. The pre-accelerator is a high perveance single-aperture design.[14]

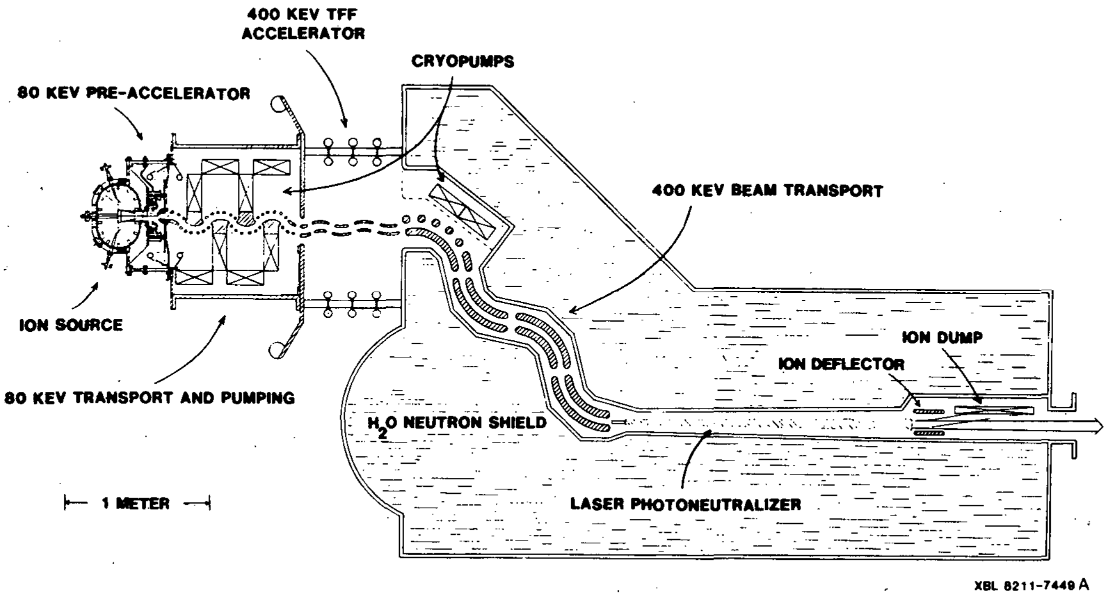

Fig. 2. Plan view of radiation-hardened 400-keV TFF-based beam line.

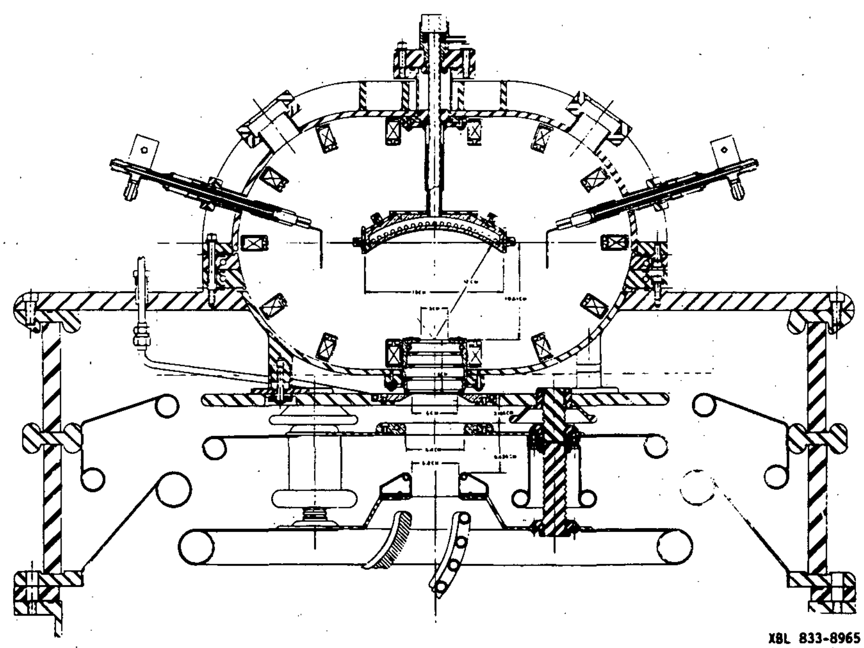

Fig. 3. Surface-conversion ion source and the 80 kV pre-accelerator under construction at LBL. In the magnetic bucket is a cylindrically-shaped converter which is focused at the entrance of a 4-section collimator shown adjacent to a high-perveance 3-electrode 80 keV pre-accelerator. The beginning of a TFF matching section is shown schematically.

An 80 keV beam matching section with provision for sweeping out residual electrons is now being designed. Figure 4 shows a computer plot of H^- beam dynamics[15] starting from the source converter plate and ending at the exit of the (prototype) matching section. (The blank regions seen at the collimator entrance are artifacts of the way phase space was divided.) The beam is seen to be compressed by the Pierce gun and the TFF matching section to a thickness of 1.4 cm, from an initial thickness of 5 cm at the Pierce gun entrance.

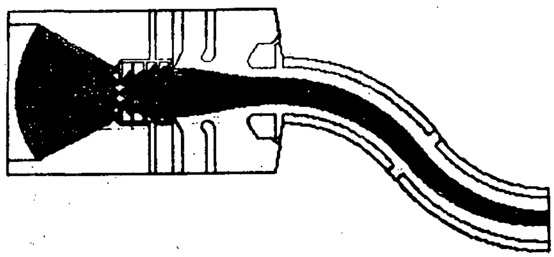

Fig. 4. Dynamics of beam envelope starting at converter plate, continuing through the preaccelerator and TFF matching section (see text).

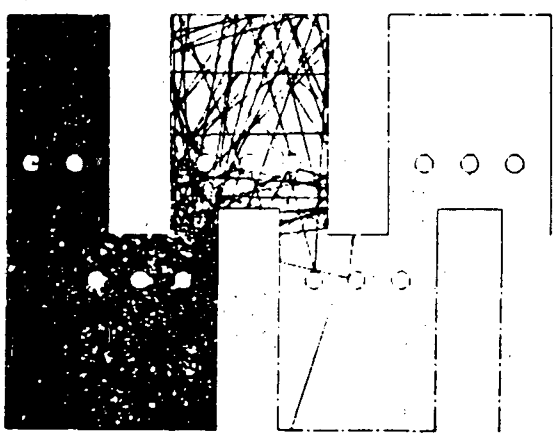

Fig. 5. Idealized geometry used in Monte-Carlo calculation. Efficiency of differential pumping is illustrated by the sharp decrease in density of trajectories in successive stages.

The differential pumping section of Fig. 2 has been modeled for a Monte Carlo computation as shown in Fig. 5. The results of a complete study show a pressure reduction to about 10^{-6} Torr at the entrance to the TFF accelerator, as required for adequately small stripping of the H^- beam. The TFF system used to transport the 80 keV beam through the differential pumping section has been studied with the WOLF code; we find that a beam with reasonably low aberrations goes through with essentially no emittance growth.

The TFF accelerator has been modelled with WOLF[15] for both the 3-stage 160 keV version and the 400 keV version.[3] The latter case is shown in Fig. 6, for a 5.6 A/meter D^- beam with unnormalized emittance of 0.025 π rad-cm at the entrance. Individual beam traces are not visible.[15] A wide range of currents and entrance beam angles has been studied, and the TFF accelerator has been found to be quite insensitive to changes in input.

The 400 keV TFF transport through the neutron shield has also been studied using WOLF[15] (Fig. 7). The D^- beam transport and the exit into the photoneutralizer background plasma is accomplished with no loss of beam quality.

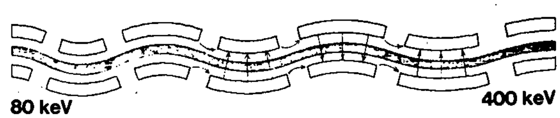

Fig. 6. Calculated beam trajectories for 400 kV TFF accelerator (see text).

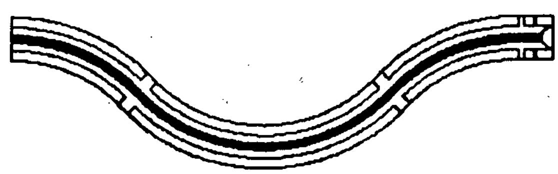

Fig. 7. Calculated trajectories (see text) in TFF system used to transport 400 keV H^- beams. The bending radius is 34.2 cm.

ACKNOWLEDGMENTS

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15. Figures 4, 6 and 7 include such a large number of beam trajectories (typically 100) that individual traces are not distinct. In effect, these figures only show the beam envelopes. We needed a large number of beamlets for accuracy in studying formation of aberrations in the preaccelerator and their possible growth or decay in the TFF sections. These studies were done with a series (of about 25) emittance diagrams which clearly show the dynamics of each of the many beamlets under the influence of space charge and focusing forces. Complete details of these computations will be published separately.

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