OVERVIEW AND STATUS OF THE TRANSVERSE-FIELD FOCUSING (TFF) ACCELERATOR

O.A. Anderson, C.F. Chan, W.S. Cooper, J.W. Kwan,
C.A. Matuk, H.M. Owren, J.A. Paterson, P. Purgalis and L. Soroka
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

The Transverse Field Focusing (TFF) system described here is a prototype for a negative-ion based neutral beam line with possible applications in the U. S. magnetic fusion energy program. The prototype system consists of four main modules: (1) H^- source, (2) 80 keV pre-accelerator, (3) TFF matching/pumping (M/P) section, and (4) 180 keV TFF accelerator. The first three modules have been installed on the beam line, with the fourth to follow soon. The crucial module, invoking the most difficult (and interesting) physics and engineering issues, is the M/P section. It performs: (a) gas removal from the beam by differential pumping, (b) electron removal, (c) beam thickness reduction to match the TFF accelerator parameters, and (d) beam-edge confinement. The four beamline modules are discussed in this survey, with emphasis on design features of the M/P section.

Introduction

In the future, the U.S. magnetic fusion energy program may require high current, steady-state neutral beams at energies around 500 keV, based on negative ions. Possible designs for such beamlines, utilizing ribbon beams with high-perveance transverse-field focusing (TFF), have been reported previously [1,2,3]; these designs could deliver up to 25 megawatts per module. The prototype TFF system illustrated in Fig. 1 and described in this report will provide 1.3 A of H^- beam at 180 keV in d.c. operation.

The TFF concept arose in 1979 [4] from a combination of circumstances. The steady-state H^- sources then available [5,6] inherently produced beams with a ribbon configuration. Furthermore, the current densities were in a range that made it feasible to extract the beam with a single large-aperture slot-type accelerator [7,8]. A ribbon beam is also the optimum shape for any type of neutralizer. All of this led to a logical neutral beamline concept for MFE applications [7] but there were two problems: handling the large gas load from typical H^- sources and shielding the source and accelerator from the fusion reaction neutrons. The TFF concept offers a solution to both problems: the TFF beam is inherently curved, which allows the design of efficient neutron traps [9,10] as well as efficient differential gas pumping [11] at the input end.

H^- Source

The surface-conversion source [5,12] has been chosen as convenient for testing the TFF system. The bucket-type plasma chamber (Fig. 1) is surrounded by magnets. A curved molybdenum converter plate is placed in a null-field region near the center of the chamber. Cesium vapor is injected which coats the converter surface. With a negative bias (about 150 V) on the converter, H^- ions are produced by desorption or by reflection of the incoming H^+ ions. The cylindrical shape of the converter focuses the H^- ions onto a crossover region at the collimator. This collimator defines the range of transverse beam energy. When suitably biased [13] it also serves, in conjunction with the adjacent magnets, as a trap for low energy electrons.

Pre-accelerator

After the 150 eV H^- beam passes the crossover point, it expands geometrically as it approaches the pre-accelerator. Positive ions from the plasma chamber follow the beam and keep it neutralized. These positive ions are repelled and a sheath is formed at the pre-accelerator entrance. The pre-accelerator, visible in Fig. 1, is a large-aperture (5 x 25 cm) high-perveance type designed especially for this application [8].

During initial operation, cesium efflux from the source caused voltage breakdown problems in the pre-accelerator. Only after the grids were conditioned by repeated high voltage pulses was it possible to operate at full power. When the pre-accelerator was shut down for a period, it was found advisable to apply occasional pulsing to keep the grids conditioned.

The pre-accelerator beam was studied with an emittance analyzer at various perveances. The results agreed well with simulations using the WOLF code [12]. Thirty-second 1 amp pulses of H^- ions were obtained at 80 keV energy, with duration limited only by power supply capability.

TFF Matching/Pumping Section

The next module in the TFF system is the matching/pumping (M/P) section (Fig. 1) where the beam undergoes differential gas pumping, electron removal, thickness compression and beam-edge confinement.

Differential Gas Pumping

The weakly bound H^- outer electron is easily stripped by background gas, which is emitted copiously by the source. Although about 7% of the beam is unavoidably lost due to stripping in the pre-accelerator, further loss can be minimized if the gas pressure is lowered efficiently with a differential pump. The geometry of the TFF system is ideally suited to this purpose. Using rods for the outer electrodes and solid structures for the inner electrodes,

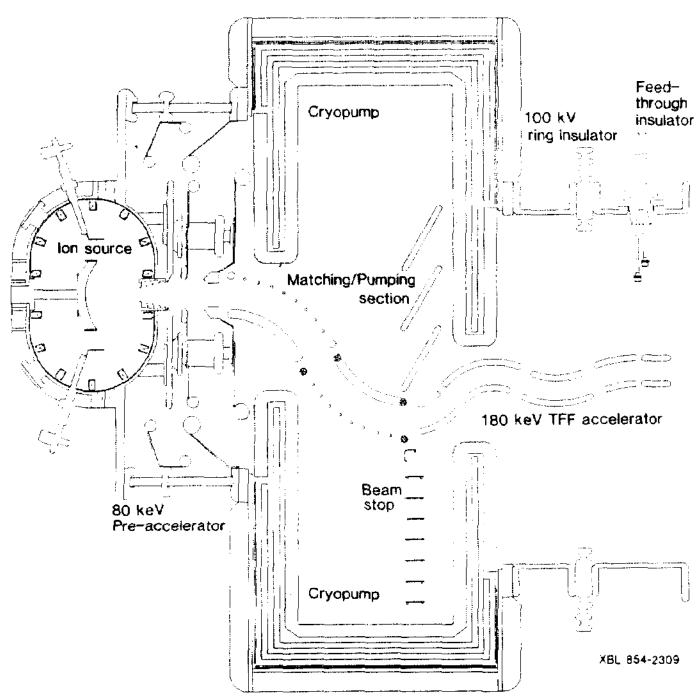

Fig. 1. Schematic plan view of 180 keV prototype TFF system, to scale. The cryopump is 34 cm wide.

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the M/P section is partitioned into two compartments lined with cryopanels as shown in Fig. 1. There is further pumping in the next compartment, also shown. According to Monte Carlo calculations, the pressure is lowered by nearly three orders of magnitude in a remarkably short distance (the cryopump is only 34 cm long) [14]. Thus, the anticipated beam loss is only 3% in the matching section and 0.08% in the TFF accelerator.

Electron Removal

Approximately 10 percent of the beam current coming out of the source is carried by electrons, which gain energy in the pre-accelerator together with the ions. As indicated in Fig. 2, these electrons are removed in the M/P section with the help of a magnetic field, which deflects them about 45 degrees in the vertical direction. This loss of forward momentum makes them fall into the inner electrode, as shown. The ions are deflected only slightly, and their trajectories are straightened out again by the second set of magnets.

Although the electron trajectories can be calculated analytically for vacuum fields, one can only get approximate results when the electrons are mixed with an intense ion beam. A computational procedure [15] was developed for the final design of the electron trap.

Experimentally, we have found no electrons beyond the M/P section, indicating that the trap for high-energy electrons performs its function.

Beam Thickness Compression

The beam exiting the pre-accelerator is about 3 cm thick. A TFF accelerator designed to handle such a thick beam with sufficient electrode clearance would be rather bulky and would require large focusing potentials between its electrodes. The matching section solves this problem by compressing the beam to the optimum thickness. As discussed in [2] and [3], the focusing potentials at the final TFF accelerator stage (the stage with the largest potentials) are minimized if the beam is compressed to the thickness where the transverse beam pressure is half the space charge pressure. Since the present experiment is a prototype for a 400 keV beamline, the matching section was designed using this number. Using the formulae developed in [3], the two matching section bends were built with central radii of 21 cm. Computer modeling had verified that this was correct [3].

Beam-Edge Confinement

The TFF dynamics are mainly two-dimensional, involving only the direction of beam propagation and the short dimension of the ribbon cross section. But near the beam edges there is a space-charge electric-field component in the third direction, which is vertical in the present experiment. For this reason, the electrodes are given a special shape, indicated in Fig. 3, which produces a vertical field component in the vicinity of the beam edges. This field counteracts the space charge force and maintains the beam edges in equilibrium. The electrode shape was calculated analytically [3,16] and was checked by computer modeling.

TFF Accelerator

The TFF accelerator, which is under construction, will accelerate the 80 keV beam to 180 keV. It will provide about 230 kW of negative ions at an energy which would be inefficiently neutralized (only 20%) for positive ions, even in the case of deuterium. However, the purpose of this experiment is not only to demonstrate an efficient 180 keV beam, but also to demonstrate the feasibility of producing powerful neutral beams at energies of 400 keV or more [1]. Therefore the hardware for the present TFF accelerator was designed as the first half of a 400 keV system. The analytic and computer designs reported previously [1,2,3] considered a six-stage accelerator with 31% energy gain per stage. The design which will actually be tested is based on a four-stage system which accelerates the beam from 80 to 400 keV with 50% energy

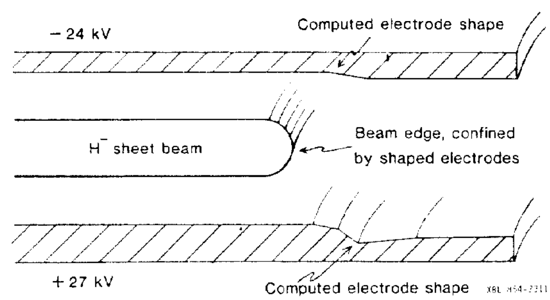

Fig. 3. Beam edge confinement. The TFF beam passes into the paper. The picture is rotated 90 degrees so that the top beam edge appears at the right. The electric field is purely transverse except near the beam edge where it has a downward component (to the left in this picture).

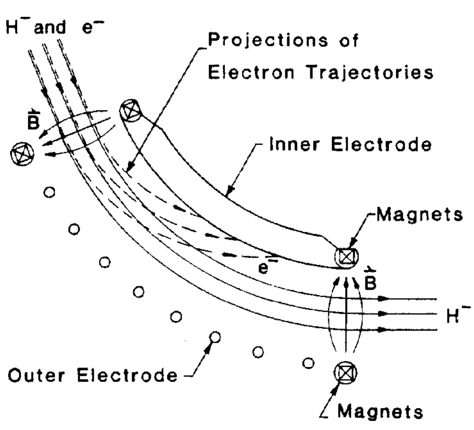

Fig. 2. Schematic of electron trap. The electrons are deflected up out of the paper at about 45 degrees (see text). The magnetic return path is not shown.

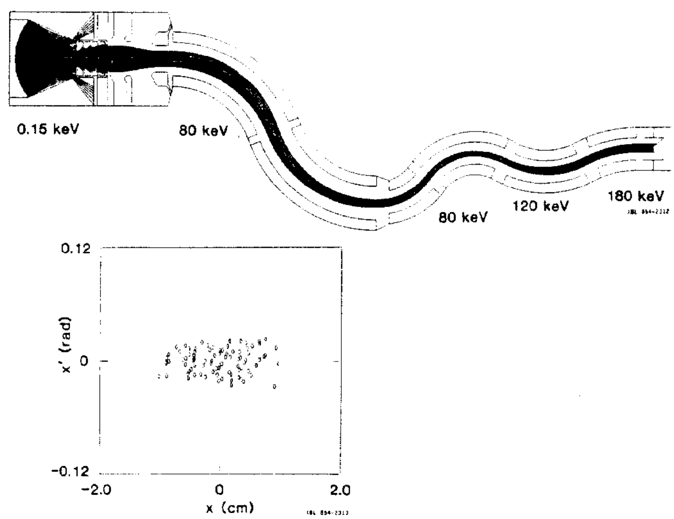

Fig. 4. (a) Computed beam trajectories for the two-stage TFF accelerator (see text). (b) Phase plot at the exit, showing the individual beamlets.

gain per stage. This step toward simplification of the mechanical and electrical design was undertaken only after thorough checking with the computer model, which revealed that the gap dimensions need somewhat tighter tolerances with such strong acceleration, and that the gaps need to be a few mm longer on one side of the beam than the other. (Design principles for high-gain TFF acceleration will be discussed in detail elsewhere.) The results from the computer model for two-stage acceleration to 180 keV (the first half of the simplified 400 keV design) are shown in Fig. 4a; the gap asymmetry on this scale is almost imperceptible. The emittance diagram (Fig. 4b) shows no degradation from the strong acceleration and is nearly identical with the older results [3].

Use of fewer electrodes reduced the number of water/electrical feed-throughs and allowed a simple design for the main insulator, indicated in the schematic of Fig 1. Many other design details are described in [17].

Conclusions

The TFF system design is complete, and the final module is under construction. Test results for the source and pre-accelerator were quite favorable [12]. Testing of the M/P section has barely begun, with good indications so far. The beam seems to undergo the desired compression, and is electron-free. The complete system will be ready for testing at the end of the year.

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