Lawrence Berkeley National Laboratory
Recent Work

**Title**
THE NATIONAL NEGATIVE-ION-BASED NEUTRAL BEAM DEVELOPMENT PLAN

**Permalink**
https://escholarship.org/uc/item/5p68v8n8

**Authors**
Cooper, W.S.
Pyle, R.V.

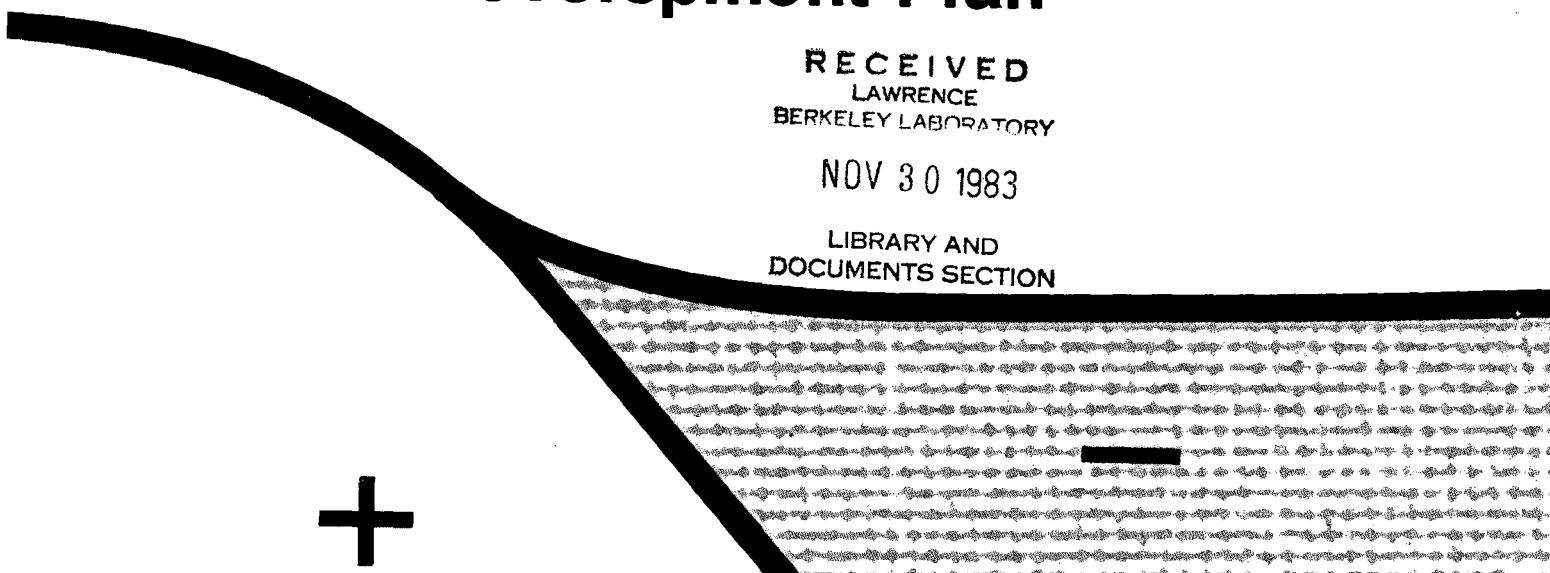
**Publication Date**
1983-08-01

eScholarship.org Powered by the California Digital Library
University of California

PUB-464
c. 1

# The National Negative-Ion-Based Neutral Beam Development Plan

RECEIVED
LAWRENCE
BERKELEY LABORATORY
NOV 30 1983
LIBRARY AND
DOCUMENTS SECTION



For Reference
Not to be taken from this room

Prepared by
The Lawrence Berkeley Laboratory
and The Office of Fusion Energy of The
U.S. Department of Energy

PUB-464
c. 1

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

## DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal 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 its 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, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

PUB-464

# The National Negative-Ion-Based Neu ral Beam Development Plan

Prepared by
The Lawrence Berkeley Laboratory
and The Office of Fusion Energy of The
U.S. Department of Energy

August 1983

Scientific Editors:
W. S. Cooper
R. V. Pyle

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Prepared for the U.S. Department of Energy under Contract
DE-AC03-76SF00098

NEGATIVE ION NEUTRAL BEAM DEVELOPMENT PLAN

FOREWORD

This Negative-Ion-Based Neutral Beam Development Plan delineates the long range neutral beam program of the Development and Technology Division of the Office of Fusion Energy (OFE). The plan addresses both tokamak and mirror needs, and lays the groundwork for the application of negative-ion-based neutral beams on reactors of either type in the 1990's.

High-power beams of neutral atoms can be used to heat, drive current in, and refuel reacting plasmas. The beam energies required for these applications on fusion reactors and in some cases on upgrades of machines now operating or under construction, require that these beams be produced by systems based on negative ions. Neutral beam systems in use to date are based on acceleration and neutralization of positive ions of hydrogen and deuterium. While these systems work well, the scalability to the higher beam energies required in the future is severely limited because of the marked reduction in neutralization efficiency as energy is increased. Beams of negative ions, on the other hand, can be converted to neutrals efficiently at arbitrarily high energies.

In order to plan for future applications, OFE requested that the Lawrence Berkeley Laboratory (LBL), prepare an integrated national negative ion development program plan. The plan, presented in this document, covers facilities required, program milestones, and decision points. It includes identification of applications, experiments, theoretical research areas, development of specific technologies and reactor development and demonstration facilities required to bring about the successful application of negative-ion-based neutral beams. Particular emphasis is placed on those activities leading to use on existing plasma confinement experiments or their upgrades. The plan will be updated and modified as development progress and changing user needs dictate.

The plan represents the efforts of many individuals throughout the Magnetic Fusion Energy program, and includes the results of a User/Developer Workshop held at the Princeton Plasma Physics Laboratory to receive and incorporate final comments from the Magnetic Fusion Energy Community. The plan therefore represents a consensus of the technical experts of the community.

Robert J. Dowling
Director
Division of Development and Technology
Office of Fusion Energy
Office of Energy Research

# Contents


Executive Summary ..... 4
Objective ..... 5
Confinement Goals and Requirements ..... 6
- Present Experiments ..... 6
- Next-Generation Machines ..... 6
- Reactors ..... 7
- Generic Goals and Requirements ..... 8

R&D Status and Needs Assessment ..... 9
- Confinement Physics ..... 9
  - Plasma Heating in Tokamaks and Mirrors ..... 10
  - Creation of Potential Barriers in Mirrors ..... 10
  - Current Drive in Tokamaks ..... 11
  - Other Applications ..... 11
- Technology ..... 12
  - Ion Sources ..... 13
  - Accelerators ..... 17
  - Transport Systems ..... 18
  - Neutralizers ..... 19
  - Systems ..... 21
  - Test Facilities ..... 21
- Applied Plasma Physics ..... 22
  - Negative-Ion Production and Interactions ..... 22
  - Beam Diagnostics ..... 23
  - Polarized Beams ..... 24

R&D Program Description ..... 25
- Strategy ..... 25
  - Proof-of-Principle Demonstration ..... 27
- Activities ..... 28
- Facilities ..... 29
- Prototypes ..... 31
- Milestones ..... 32

Resource Assessment ..... 33
- Personnel ..... 33
- Facilities ..... 33
- Budgets ..... 33

References ..... 34


# Contributors


We wish to acknowledge the efforts of the many people who have contributed in some way to this plan, especially the following:

| | |
|---|---|
| D. Arnush | TRW |
| R.R. Borchers | LLNL |
| H.P. Eubank | PPPL |
| J.H. Fink | Negion/LLNL |
| T.S. Green | Culham |
| H.H. Haselton | ORNL |
| C.D. Henning | LLNL |
| J.R. Hiskes | LLNL |
| P.J. Kortman | SAI |
| D.H. Metzler | GE/FEDC |
| D.R. Mikkelsen | PPPL |
| P. Poulsen | LLNL |
| K. Prelec | BNL |
| R.E. Price | DOE/OFE |
| C.E. Singer | PPPL |
| T.J. Sluyters | BNL |
| H.S. Staten | DOE/OFE |
| L.D. Stewart | EXXON/PPPL |

# Executive Summary

Neutral-beam systems based on the production, acceleration, and neutralization of negative ions of the hydrogen isotopes can be used to refuel, heat, drive current in, create and maintain electrostatic potentials in, and provide diagnostics for reactor plasmas. The earliest definite application perceived in current planning for negative-ion-based neutral-beam systems is for potential barrier generation on a mirror FPD in 1994. A possibly earlier application has surfaced recently — a 200-keV system for an upgrade of MFTF-B now under consideration for inclusion in the National Mirror Fusion Program Plan. We will incorporate this application, if it is approved, in the next draft of our plan.

Concepts and technologies that can lead to applications of negative-ion-based neutral beam systems in the mid-1990's exist. Specifically, a 1-ampere steady-state $H^-$ source has been operated, accelerator and beam-transport concepts that permit placement of the major part of the neutral-beam system outside of the reactor's radiation shielding are under development, and three techniques exist for converting negative-ion beams to neutral beams. One of those offers the possibility of conversion efficiencies in excess of 90%.

This document presents a plan to develop reliable neutral-beam systems for application in the 1990's. The R&D effort focuses on the design, construction, and testing of an efficient, steady-state 475 kV, 5–10 A ($D^-$) beam line for application on a mirror ETR in 1994.

**Specific objectives are:**

- □ Demonstrate 1-A, 80-keV beam — 1983
- □ Demonstrate 1-A, 160-keV beam — 1985
- □ Complete conversion of NBETF to negative ions (10 A, 500 kV, DC) — 1986
- □ Demonstrate laser photoneutralizer module and plasma neutralizer — 1986
- □ Demonstrate current drive with neutral beam on a tokamak — 1987
- □ Begin ETR prototype beamline construction — 1987
- □ Operate on mirror ETR — 1994

It will require an aggressive program to achieve these objectives. Funding constraints at present limit the choice of options. The primary and backup choice for key components, together with the FY 84 funding status, are shown in Table ES-I, below:

**Table ES-I: Options for Development of Key Components**

| Component | Primary Concept | Funded in FY 84 Presidential Budget? | Backup Concept | Funded in FY 84 Presidential Budget? |
|---|---|---|---|---|
| Source | LBL Surface Conversion | Yes | BNL Surface Conversion | No |
| Accelerator, Transporter | Transverse Field Focusing | Yes | Electrostatic Quadrupole | No |
| Neutralizer | Laser Photodetachment | Yes | Gas Cell | Yes |
| 500 keV Facility | Upgrade NBETF | Yes (Conceptual Design) | — | — |

# Objective

Negative-ion-based neutral beams can provide fluxes of particles, momentum, and energy at particle energies high enough for these fluxes to penetrate into the central regions of reactor-size plasmas. These beams can therefore be used to refuel, drive current in, create and maintain electrostatic potentials in, and heat confined plasmas. They also may be used to diagnose the plasmas. Reactor-compatible systems must successfully deal with the problems of tritium contamination and remote maintainability.

The objective of this plan is to describe and help ensure the development of practical systems capable of performing these functions in time for application on next-generation fusion experiments and reactors. The Plan will outline the present understanding of the confinement and neutral-beam physics involved, summarize the current neutral-beam R&D status, assess needs in these areas, and present a program to accomplish the timely development of practical negative-ion-based neutral-beam systems. It will be updated periodically.

The draft Comprehensive Program Management Plan for Magnetic Fusion Energy[1] calls for a selection to be made of a reactor confinement concept for an Engineering Test Reactor (ETR) when sufficient information is available, possibly as soon as 1988. Regardless of the confinement concept selected, the ETR will require services (such as heating, current drive, or creation of potential barriers) that can be provided by neutral beams. It is possible that some of these services can also be provided by rf systems. An important function of this Plan will be the delineation of studies and experimental developments necessary to proceed through a proof-of-principle stage for negative-ion-based neutral beams, to permit a meaningful comparison of negative-ion-based neutral-beam systems with competing systems, so that the best choice can be made for ETR and reactor applications.

# Confinement Goals and Requirements

Confinement-program goals and requirements, as perceived at the end of 1981, are summarized in Volume VI of the report "The Fusion Engineering Device."[2] Some of the parameters and goals have changed in details since that report was written, but it is the best and most current summary and assessment of the fusion technology program.

## PRESENT EXPERIMENTS

Neutral-beam requirements for present-generation confinement experiments (TMX-U, D-III, PLT, PDX) that require neutral beams, as well as those under construction (TFTR, MFTF-B) can all be handled by extensions of positive-ion-based neutral beams to longer pulse lengths. Negative-ion-based beams, while desirable for some applications on these experiments because of the more nearly monoenergetic beams produced by the negative ion systems, are not essential. However, it would be desirable to install useful negative-ion systems on some of these experiments as steps toward development of reliable systems for next-generation devices. Upgrades of TFTR and MFTF-B, presently under discussion, also might incorporate negative-ion-based systems. For example, 200-keV beams have been proposed for an MFTF-B upgrade.[3]

## NEXT-GENERATION MACHINES

Beam energies required for critical applications on next-generation confinement experiments are generally too high to be satisfied efficiently-by positive-ion-based beams; one exception may be the use of positive-ion-based beams to heat a tokamak to ignition. In the case of tokamaks, the energies are dictated by the requirement that the beams of neutral atoms penetrate into the interior of plasmas that are substantially larger than those in existing machines. This is true whether the beam is to be used for heating or current drive. For mirror machines, the beam energy is set by the need to establish a sufficiently large potential hill for ion confinement in a tandem mirror device. In either case, the beam energies are in the range of a few hundred keV; the atomic physics of the conversion of positive ions into neutrals results in unacceptably poor conversion efficiencies at these energies. The maximum efficiency of conversion of $H^+$, $H^-$, $D^+$, and $D^-$ beams to neutral atoms as a function of energy is shown in Figure 1; from this figure it is clear that if these beam requirements are to be met by efficient systems, they will have to be met by negative-ion-based systems. There is one possible exception that we have noted: if "ripple trapping"[4] could be used, it might be possible to heat tokamaks efficiently with positive-ion-based systems.

It is too early in the ETR planning cycle to specify ETR neutral-beam requirements clearly. Some studies have been done, however, that are directly relevant, and a great deal of work has been done for FED-class experiments. We summarize these studies in Table I, which shows neutral-beam requirements for FED-A, which we take at this stage of planning as being representative of a tokamak ETR, and for a tandem mirror ETR.

The National Mirror Plan[5] shows in its main-line sequence, reproduced in Figure 2, a tandem mirror FPD/ETR beginning operation in 1994. In the present preliminary conceptual design, the plug cell potential barrier for this reactor requires 9.5 MW of 475-keV neutral beams (the entry shown in Table I); no alternate technique has been identified to fulfill this need. Negative-ion beam development is therefore critical for this aspect of the mirror program. This mirror application dictates the national negative-ion planning.

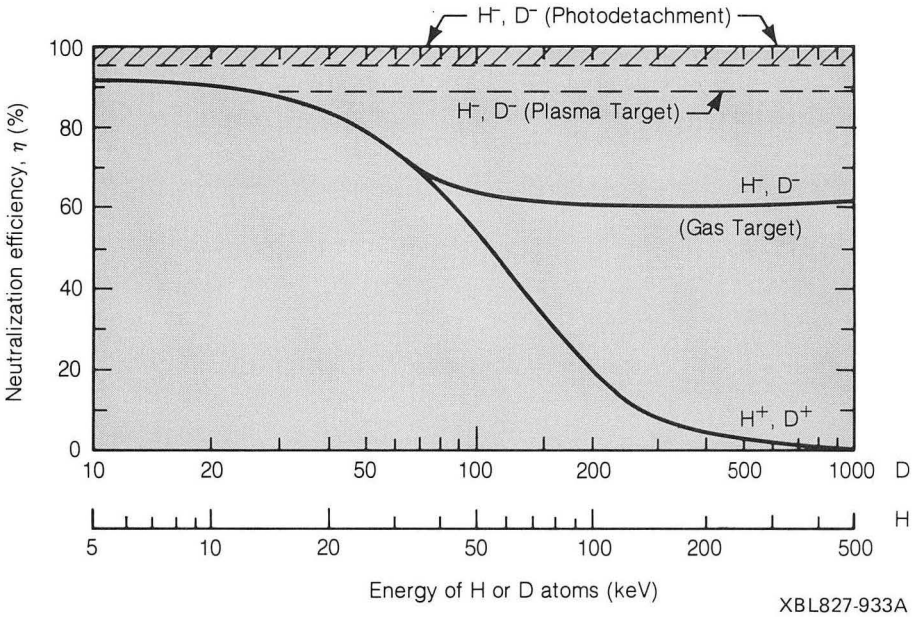



**Figure 1: Energy dependence of the maximum efficiency of converting $H^-$ and $D^-$ ions to neutral atoms.**

| Class of Machine | Representative Machine | Beam Application | Beam Characteristics: Energy (keV) | Beam Characteristics: Power into the Plasma (MW) |
|---|---|---|---|---|
| Next-generation | Tokamak ETR (FED-A) | Heating | 400–800 | 40–50 |
| | | Current Drive | Steady-State: 400–800 | 40–50 |
| | | | Internal Transformer: 175–400 | 20–40 |
| | Mirror ETR | Plug Cell Potential Barrier | 475 | 9.5 |
| Reactor | INTOR-Class Tokamak | Heating | 400 | 40 |
| | | Current Drive | Steady-State: 1000–2000 | 110 |
| | | | Internal Transformer: 400 | 60 |
| | MARS Tandem Mirror | Anchor Cell Potential Barrier | 475 | 18 |

**Table I: Representative Neutral Beam Requirements For Fusion Reactors**

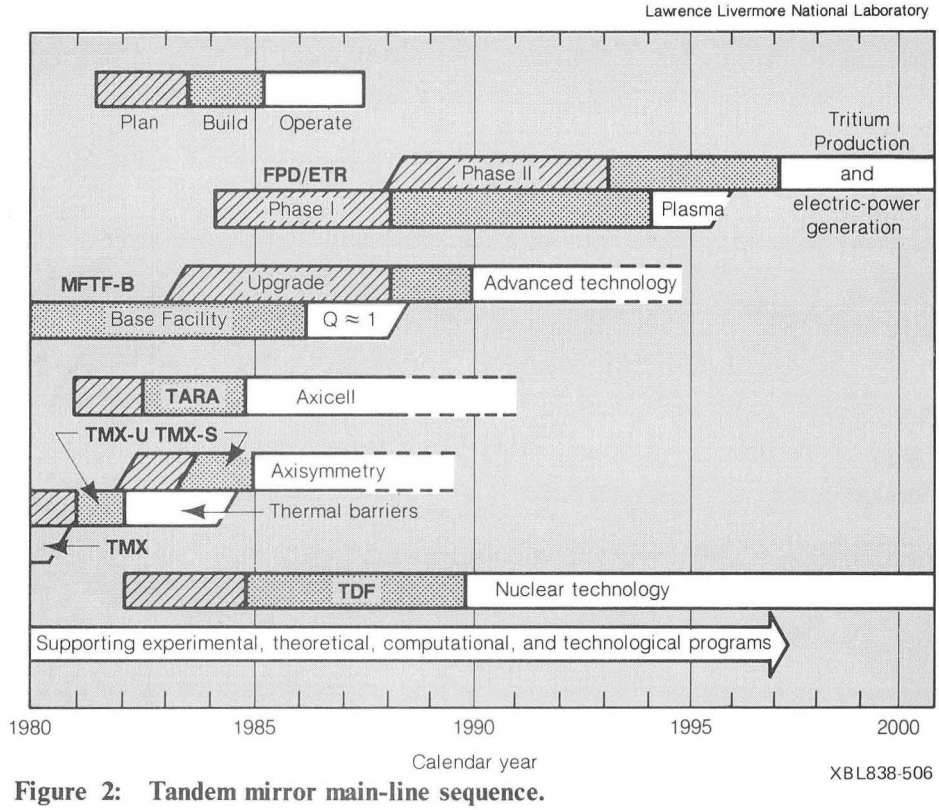



**Figure 2: Tandem mirror main-line sequence.**

## REACTORS

Table I also shows typical beam requirements for advanced mirror and tokamak reactors. These facilities would begin operation around the year 2000 or later.

## GENERIC GOALS AND REQUIREMENTS

Table I shows three significant points immediately: 1) all requirements can be met with negative-ion-based injectors initially operating in the energy range of 400–500 keV, with a later upgrade to a few MeV, and with power capabilities of 5 (initially) to 10–20 (finally) MW per beamline, 2) some requirements can only be met, as far as is now understood, with negative-ion-based neutral beams, and 3) only one of the requirements might be met with reasonable efficiency by positive-ion-based systems. It is possible that these requirements can also be met by rf systems, but the relevant experimental and theoretical studies are not yet complete.

Requirements on the beam divergence are likely to be similar to or more stringent than requirements on existing positive-ion-based neutral-beam systems, which are typically 0.5°–1°. Even smaller divergences are highly desirable, since they permit smaller penetrations through the neutron shielding of the reactor, with an attendant reduction in neutron flux through the primary shielding and an increase in the blanket efficiency.

# R&D Status and Needs Assessment

Summaries of the physics, status, and goals of the mirror and tokamak programs are given in the documents "The National Mirror Fusion Program Plan"[5] and "The National Toroidal Program Plan"[6] (in preparation).

## CONFINEMENT PHYSICS

The interaction of beams of neutral atoms with plasmas is essentially classical. In the areas where there have been careful comparisons of theory and experiment, good agreement has been found. This good agreement, plus the classical nature of the physics, makes it likely that theoretical treatments can be carried out and agreement with experiments can be confidently expected in areas in which there are not as yet experiments to confirm the theory. Examination of the most important areas of applications of neutral beams in confinement physics leads to the results summarized in Table II, which show that by and large the physics of the interaction of beams with confined plasmas is reasonably well understood, and that because of the potential impact on tokamak design and on the course of neutral-beam development, the greatest need for additional experimental confirmation is in the area of current drive with neutral beams in tokamaks. Other outstanding questions have to do with high-$\beta$ heating results in tokamaks, and with the effect of impurities on tandem mirror machines.

**Table II: Status of Beam-Related Confinement Physics and Needs Assessment**

| Priority | Topic | Status of Understanding | Need |
|---|---|---|---|
| 1 | Current drive in tokamaks | Probably classical, but has only limited experimental check | Demonstrate convincingly; test at high plasma momentum and with the ion velocity $\geq$ Alfven speed |
| 2 | Effect of beam-introduced impurities on potential barriers in tandem mirror machines | Apparently understood | Quantify impurity level required; measure impurity level in beam and reduce as required |
| 3 | Bulk heating in tokamaks | Classical at low power levels; appears to be less efficient at high power levels, which may or may not be beam-related | Determine cause of reduction in heating efficiency — $\beta$ limit? Reduction in $\tau_E$? |
| 4 | Creation of potential barriers in tandem mirror machines | Apparently understood | Extend to higher levels and longer pulse lengths |

### Plasma Heating in Tokamaks and Mirrors

The heating of plasmas by injection of powerful beams of neutral atoms has been well documented, both in tokamaks and in mirror machines. Indeed, the highest ion energies reported in confinement experiments to date, a mean ion energy of 13 keV in the 2XII-B experiment at LLNL and an ion temperature of 7 keV in the PLT experiment at PPPL, have been achieved by neutral-beam injection.[7,8] The method of depositing energy into plasmas appears to be completely classical, and is well understood. Plasma heating has been observed to be proportional to the beam power injected except in tokamaks at the highest power levels reached to date; this decrease in heating efficiency at high power levels has variously been postulated to be due to an MHD instability as the $\beta$ limit of the tokamak was approached or to some other mode of deterioration of the energy confinement time. More work is needed to explain these observations.

### Creation of Potential Barriers in Mirrors

Axial confinement of the plasma in a tandem mirror machine depends on the use of neutral beams or ICRH to create and sustain a local potential maximum. Successful use of neutral beams for this purpose was demonstrated in the TMX experiment.[9] It was recently shown in the upgraded version of TMX, TMX-U, and in Gamma 6, that a modification of this concept, the injection of neutrals nonperpendicularly to the magnetic field to create a component of the ion population that "sloshed" between mirror confinement points, could enhance this potential maximum[10,11] in a way that could be used to reduce the energy loss out the mirrors by electrons (the first step in demonstrating the "thermal barrier" concept). The neutral-beam-related physics appears to be well understood.

Neutral beams used for maintaining potential barriers in tandem mirror machines will require a lower degree of impurity atoms than will beams for use on tokamaks. If high-Z impurity ions are trapped in the potential well, they greatly enhance the rate of trapping of deuterium ions from the center cell because of the strong Z-dependence of the Coulomb scattering rate. The potential well therefore tends to fill up with deuterium ions, which depends not only on the rate of introduction of impurity ions by the beams, but also on the rate at which they are lost from the potential well. According to computations, an oscillating magnetic field can greatly enhance the rate of radial loss of high-Z ions. If this phenomenon can be successfully applied, the maximum fractional level of impurities in the beam (using oxygen as a typical example) is thought to be approximately $10^{-3}$; if no means can be found to enhance the loss of these impurities, the requirement drops to about $10^{-6}$, a difficult requirement to meet without momentum selection. APP-funded programs are underway to develop diagnostic schemes to measure the level of these impurities (see section on Beam Diagnostics, page 23).

### Current Drive in Tokamaks

Mechanical fatigue due to cyclic stresses may unacceptably limit the lifetime or increase the cost of a pulsed tokamak. It may, therefore, be necessary to operate a tokamak reactor in a steady state, or quasi-steady-state mode. One promising possibility is to use neutral beams to sustain the circulating current. Two schemes have been proposed. In one scheme, beams drive the current continuously.[12] In the other scheme, the "internal transformer" mode,[13] beams are used to quickly create a circulating current which may then be allowed to "coast" for a fraction of the L/R decay time of the current before the cycle is repeated. Alternatively, the internal transformer current may sustain the plasma while an external transformer is reset to its starting flux. Negative-ion-based neutral beams offer two potential advantages for this application: first, the same system can be used to drive the current and to heat the plasma, and second, the overall system power efficiency can be very high. The efficiency of current drive is of the order of 0.1 A/W for current drive in the steady state mode, and of the order of 1 A/W for the internal transformer mode. A completely convincing demonstration of beam current drive, for instance one in which neutral beams drive the current for many L/R times, has not been attempted or achieved. Experiments to date have only perturbed, not sustained, the circulating current.[14] A test of beam current drive seems to be the most critical missing element in the physics of the application of neutral beams to plasmas. It may be possible to do a definitive current-drive experiment on TFTR; this possibility should be explored.

### Other Applications

Negative-ion-based neutral beams offer advantages in many applications over positive-ion-based neutral beams: they will have a higher overall system power efficiency, except at low energies; they will be nearly monoenergetic; and, they will ultimately be freer from impurities because laser photoneutralizers can selectively discriminate against the conversion of common negative impurity ions into neutrals. Therefore, negative-ion-based beams can be expected to replace positive-ion-based beams for many applications. These include, in the case of mirror machines, center-cell heating and the pumping out of the machine of low-energy trapped ions, as well as the use of low-Z atomic beams for potential control in tandem mirror end plugs.[15]

Applications proposed for tokamaks include use of the energy dependence of the trapping efficiency and the beam aiming direction to control the plasma profile, and the injection of high-energy (1 to 2 MeV/nucleon), low-current beams of low-Z atoms (C, O) for current drive and bulk heating.[16]

It may be possible to at least partially fuel tokamak or mirror reactors with neutral beams. It appears that unreasonably high velocities are required for a solid pellet to penetrate to the center of a fusion plasma. If mixing is inadequate to permit fueling with partial penetration of fuel pellets, and if the power requirement is not unreasonable, fueling could be accomplished with neutral beams. It is important in this context to

appreciate the fact that some of the fueling beams might have to operate with tritium.

A recent proposal to inject nuclearly polarized atoms into a confined plasma could result in a welcome 50% increase in the fusion reaction rate, and/or a reduction in neutron activation problems.[17] This is also a possible long-range application of negative-ion-based neutral beams.

Finally, there have been numerous proposed and actual applications of neutral beams to diagnose confined plasmas. These all hinge on the ability of the beams to provide neutral atoms of known species and density at a preselected point within the plasma. These applications include the use of multi-MeV $Li^0$ beams for measuring the velocity distribution of alpha particles in a fusion plasma,[18] and numerous applications involving hydrogen or deuterium beams, including techniques for measuring the local ion energy distribution, the local density and possibly velocity distribution of fully stripped impurity ions, and even the pitch-angle scattering rate and effective Z in tokamaks.[19] As these diagnostic techniques are applied to larger plasmas, it becomes more and more necessary to create the neutral beams from negative ions.

## TECHNOLOGY

Within the U.S. MFE Program, the development of neutral beam hardware is funded by the Development and Technology Division of OFE. In the following sections, we summarize the current status of concepts and the status of the development of components for negative-ion-based systems.

In Figure 3 we show a schematic of a negative-ion-based neutral injector, as it is presently conceived. Negative ions are produced in a source and are accelerated to moderate energy, 80–150 keV. The negative-ion beam is then transported through a pumping section to remove gas from the system and minimize beam losses due to stripping. This transport section also serves to modify the beam width and divergence to match the beam characteristics to those required by the final accelerator that

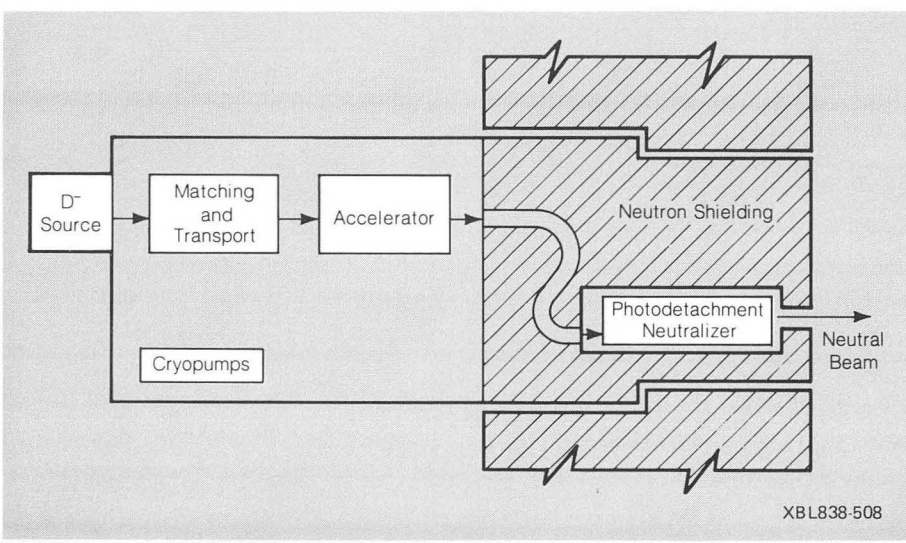



**Figure 3: Schematic of a negative-ion neutral beam injector.**

increases the beam energy to the final value, which may be 400 keV – 2 MeV. After final acceleration, the beam is transported through a maze in the neutron shielding, then passes into a neutralizer (a photoneutralizer is shown), where the negative ions are converted into neutral atoms.

Recent advances in ion-source technology, new concepts in beam transport and acceleration systems, and the impending application of efficient laser photoneutralizers have enhanced the prospects of using negative-ion-based neutral beam systems on reactors. The application of these advances should lead to neutral injection systems that are both highly efficient (60–80%) and radiation-hardened. No technological concepts are lacking for the application of negative-ion-based neutral beams even to reactors; what is lacking is the experimental verification that the concepts will work as anticipated.

The following sections summarize the R&D status and needs of the various facets of negative-ion-based neutral beam technology; the same information is summarized in Table III.

**Table III: Status of Technology and Needs Assessment**

| Priority | Topic | Status | Need |
|---|---|---|---|
| 1 | TFF beam transport and acceleration | Computer studies only | Demonstrate beam transport at 80 keV and acceleration to 500 keV experimentally |
| 2 | Oxygen-Iodine laser for photoneutralizer | 2 kW for 4 Min | Operate ~2 kW module at full power density with neutral beam; verify reactor compatibility |
| 3 | Improve source | Steady-state operation at $\geq$ 4 A/m (Deuterium) | Upgrade to 6 A/m; desirable to eliminate Cs and improve gas efficiency |
| 4 | Plasma neutralizer | Benchtop experiments | Operate with neutral beam; verify reactor compatibility |

## Ion Sources

Systems studies based on the electrostatic strong-focusing concepts for transport and acceleration of the beam and on a laser photoneutralizer, desirable for overall efficiency, lead to both sources and accelerator/transport systems that can handle thin (1–2 cm) sheet beams of $D^-$ ions. An appropriate measure of the beam is the current per unit length along the sheet. Negative ion sources have operated at LBL continuously with an output of 1.3–1.4 A of $H^-$, from a 25-cm-long slot. This is equivalent to 3.7–4 A/m of $D^-$ (the current varies inversely as the square root of the mass of the ion), which is thought to be already

within a factor of approximately 2 of the current-carrying capability of electrostatic accelerators and transport systems operating in the 400–800-keV range.

A "surface-conversion" source[20] that produces negative ions on a cesiated molybdenum surface imbedded in a plasma, and operates steady-state, is shown in Figure 4. A source using a similar principle, but operating at a higher current density, is under development at BNL[21] and is shown in Figure 5. Present and near-term activities with these ion sources are devoted to cesium control, studies of hydrogen-plasma generation, $H^-$ current-density uniformity, and heat-transfer studies. Similar work outside the U.S. is underway at the Institute of Nuclear Physics, Novosibirsk, at the Kernforschungszentrum, Karlsruhe, and at the Institute for Plasma Physics, Nagoya.

Operation of a source containing Cs is a nuisance, and carries with it the possibility of Cs contamination of the beamline and reactor vessel. A series of experiments is underway both within the US (LBL) and abroad (Culham, Ecole Polytechnique, JAERI) to investigate the possi-

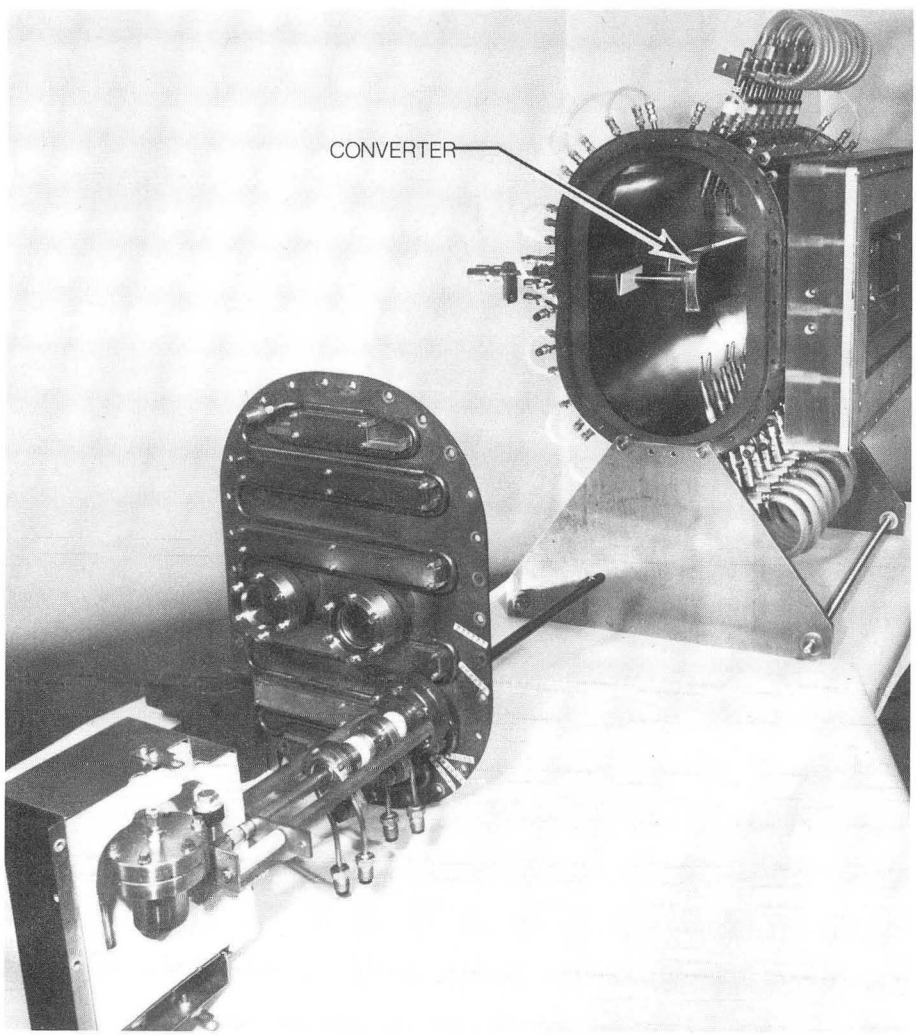



**Figure 4: The LBL 1-Ampere $H^-$ source.**

bility of producing sufficient fluxes of negative ions in the volume of the source plasma without the addition of Cs. These sources have not been developed to the point where meaningful comparisons with surface-conversion sources are possible, but some of the results are encouraging, and progress is rapid. Another approach that could yield a Cs-free source is also under investigation at BNL. In this approach low-work-function cathodes that do not require Cs are used.

Theoretical work to help provide atomic and surface physics data required for understanding and improving surface- and volume-production sources is centered at LLNL.

It is possible to produce a negative ion beam from a beam of positive ions by double electron capture when the positive-ion beam traverses an alkali metal or alkaline-earth-metal vapor target. $D^-$ beams of 2.2 A have been produced this way.[22] Fusion-oriented development of negative-ion sources using this charge-conversion technique is being carried out at the Centre d'Etudes Nucleaires, Grenoble, and at the Kurchatov Institute, Moscow. This type of negative-ion source is not being

Brookhaven National Laboratory

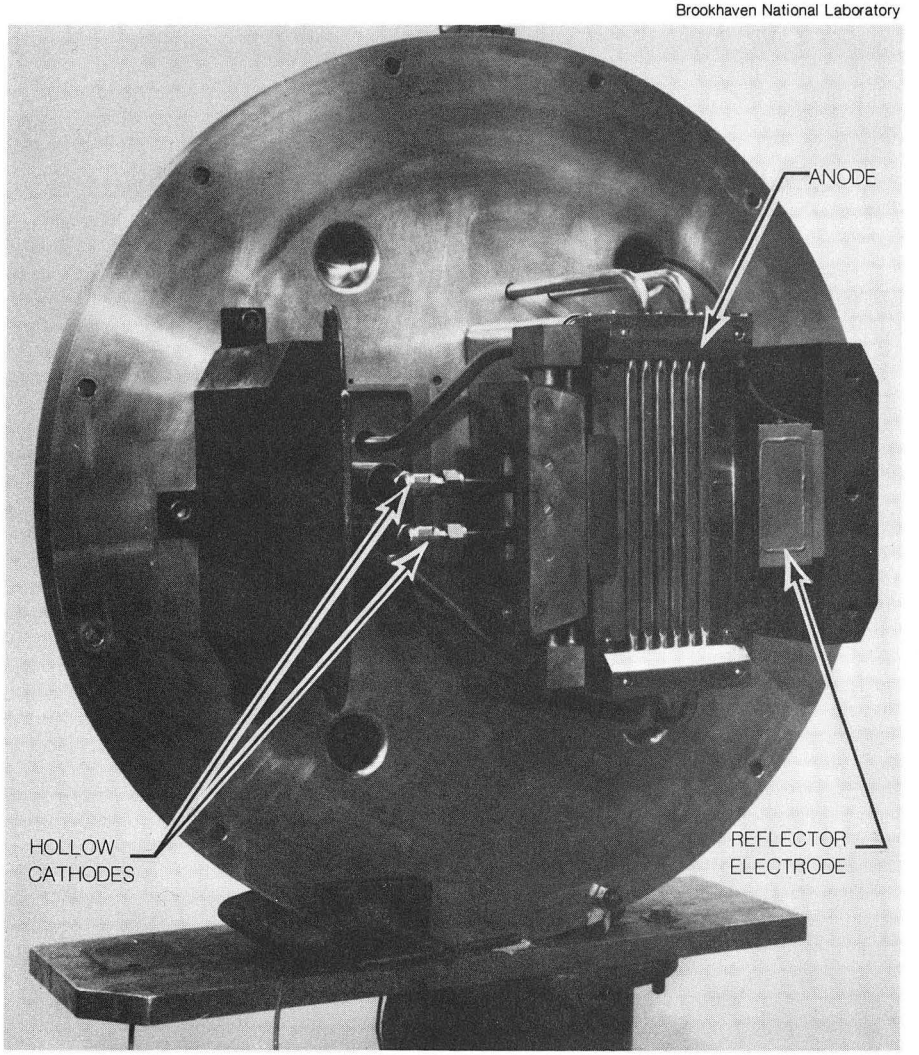



**Figure 5: The BNL $H^-$ source.**

developed for fusion applications within the U.S.

It is essential to form a beam of low-energy negative ions for acceleration with a minimum of attendant electrons, since the electrons are accelerated in electrostatic accelerators along with the negative ions. Adequate electron control ($< 5\%$) has been demonstrated for the surface-conversion sources, and is under investigation for the volume-production sources.

It is likely that all these sources operate at sufficiently high gas efficiency to limit the losses due to premature stripping of the beam to 10–15% of the negative-ion current; this loss can be made to occur at less than full energy, however, so the loss represents a power loss of under 10%.

Beam divergence, which is proportional to the square root of the transverse energy of the negative ions produced by the source, is still under investigation, but appears to be adequate for applications shown in Table I. The characteristic transverse energy of ions produced by surface-conversion sources is a few eV, and is probably considerably smaller for volume-production sources.

It is likely that the current-carrying capacity of a negative-ion-based neutral beam system will ultimately be limited by the properties of the accelerator and transport system, rather than by limitations in the negative-ion source. It is still important, however, to press for the development of sources capable of producing higher current densities than presently exist; the excess current can be trimmed by apertures with little power loss but with a substantial improvement in gas efficiency or beam emittance (reduction in transverse ion energy) or both.

### Accelerators

A 1-A $H^-$ beam has been accelerated at LBL to 34 keV for 7 s, using a conventional electrostatic accelerator. Such accelerators have been operated at ORNL with positive-ion beams of 0.35 A to 600 keV.[23] Nevertheless, other types of accelerators, namely rf or dc with electric (i.e., nonmagnetic) strong focusing, offer significant advantages over the simple "Pierce" type that is the workhorse in the positive-ion neutral-beam program. Because of their higher efficiency, dc accelerators are preferable to rf; the goal is therefore to push dc acceleration to the highest practical limit. Accelerators employing strong focusing offer the advantages of high current-carrying capability, tolerance of stray or poorly optimized beam, and (probably) a reduction in the probability of breakdown, because of the predominantly transverse electric fields.

The most promising candidate for a strong-focusing dc accelerator that produces a sheet beam uses the Transverse Field Focusing (TFF) principle[24] — the beam encounters transverse electric fields (applied by curved metal electrodes) that alternate in direction along the beam and focus the beam in the transverse direction. The beam can be accelerated by applying a potential difference between opposing pairs of plates along the accelerator; a schematic of a TFF accelerator is shown in Figure 6. This type of geometry offers a good match to sources which can produce

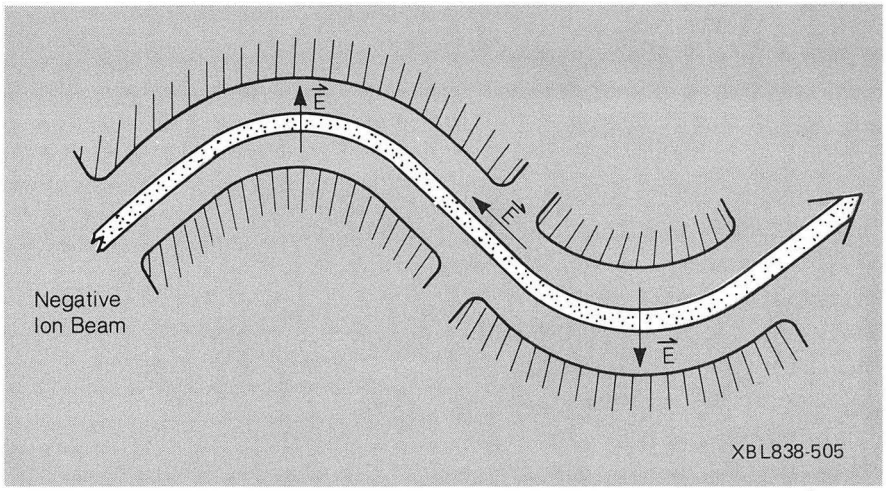



**Figure 6: A schematic drawing of the TFF accelerator concept.**

a sheet beam, and to a laser photoneutralizer (see section on Neutralizers, page 19), which requires a sheet beam for optimum efficiency. Choice of a sheet beam over an array of cylindrical beamlets, such as can be produced by the ESQ (Electrostatic Quadrupole) accelerator,[25] while desirable, is not essential; we shall adopt the sheet-beam configuration, however, for planning purposes.

The application of the TFF principle to negative-ion acceleration has only been studied computationally; the results to date are very encouraging. One important question has to do with the ends of the sheet beam — it appears that the ends of the electrodes can be suitably curved so that restoring forces prevent the beam space charge from causing beam loss in these regions, but this idea has not yet been tested experimentally. Another unresolved question has to do with breakdown — it will be important to verify that the alternating transverse fields inhibit breakdown along the whole length of the accelerator, and to determine the maximum practical beam energy that can be produced by this type of accelerator. A third critical question has to do with the current-carrying capability of TFF accelerators, which is closely related to the problem of voltage breakdown. Designs that we have examined computationally can handle 6 A of $D^-$ ions per meter of source length for maximum electric fields of 40 kV/cm, which we consider conservative. This value (6 A/m) is less than a factor of 2 larger than current-generation sources have produced, and can be increased at the expense of a higher probability of breakdown in the accelerator.

It appears that the accelerator and transport systems represent the highest risk items in the area of technology; they are therefore called out as the highest priority topic in Table III.

Backup approaches are the ESQ (Electro-Static Quadrupole) and the RFQ (Radio-Frequency Quadrupole) accelerators.[26,27] Compared with the TFF accelerator, the ESQ has somewhat lower current-carrying capability and a longer bending radius for transport through a maze; the RFQ has lower over-all system efficiency.

### Transport Systems

An important new feature of conceptual negative-ion-based neutral-beam systems is that the TFF, or other, strong-focusing principle can be used to transport an already accelerated beam of negative ions around corners to eliminate direct streaming of particles through the transport system. This feature can be applied with great advantage in two areas of beamline design; first, a TFF transporter can be used to transport an intermediate energy (80–150 keV, typically) beam through a maze in a differential pumping section, and second, the same concept can be used to transport the full-energy beam through a maze in the neutron shielding. The first application reduces the pressure in the high-voltage accelerator to minimize beam loss by premature stripping and also provides a means of matching the beam emittance to the high-voltage accelerator; the second provides a neutron trap to reduce the neutron flux through the beam duct to acceptable levels. A conceptual design for a 400-keV beamline utilizing TFF transporters for these purposes[28] is shown in Figure 7.

This TFF transport concept has been evaluated computationally for application to negative-ion systems. Electron transport systems using related principles were constructed and demonstrated to work in the 1950's;[29] this work was done in connection with backward wave oscillator development. One of the major tasks of the R&D program will be to demonstrate that TFF transporters and accelerators can be made to

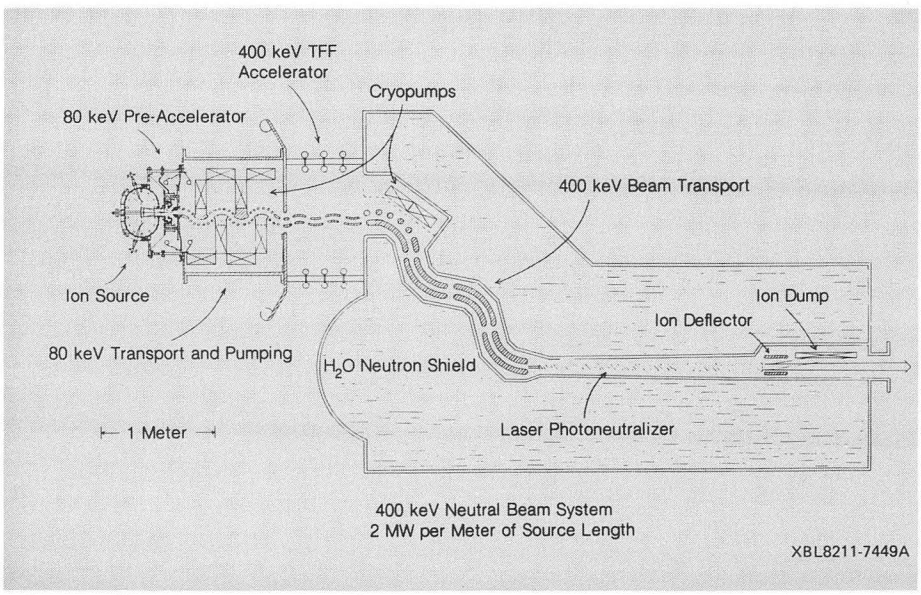



**Figure 7: A conceptual design for a 400 keV negative-ion-based beamline utilizing TFF beam transporters.**

work; the dc high-voltage accelerator is probably the highest risk item in the area of required technological development. As in the case of the accelerator, the possible backup approaches for the transport system are the ESQ and the RFQ structures.

### Neutralizers

There are three possible choices of a neutralizer to convert the negative ions into neutral atoms: gas targets, plasma targets, and photon targets (as can be provided by a laser cavity resonator). The first two use collisions with neutral or charged particles to remove the lightly attached electron; the third uses photodetachment of the electron. All three have been demonstrated to work,[30,31,32] and all three are usable over the entire range of beam energies we are considering.

Gas targets are straightforward to make and represent a low-risk choice, but have the lowest conversion efficiency ($\leq 60\%$), and introduce a considerable complication in beamline design, since a) large amounts of gas from the neutralizer must be pumped away (this gas load is much bigger than that from the source), b) the 40% of the beam that is not neutralized after passage through the neutralizer consists of nearly equal parts of positive ions and negative ions, requiring two ion dumps each capable of handling high power beams, and c) 40% beam loss represents a severe penalty in overall system efficiency, although direct-energy-recovery techniques could reduce this penalty.

A plasma target is more complex than the gas target, since to gain its full advantage, the plasma target must be substantially ionized. The ion density required is about $10^{13}$ $cm^{-3}$, and the length from 1 to 2 meters. The conversion efficiency is about 80%, and, while the gas problem cannot be entirely dispensed with, at least with the application of differential pumping and plasma transport in a weak magnetic field, it may be possible to remove the problem to a more convenient part of the beamline; the dual-dump problem remains, although the power densities are reduced by at least a factor of 2.

The most attractive alternative is to use photodetachment to convert the negative ions to neutrals. The physics is completely understood; negative-ion beams have been converted to neutral beams by a pulsed Nd laser with nearly 100% efficiency.[32] Substantial development is required, however, to produce suitable, efficient, dc laser systems. In a practical laser neutralizer, the ion beam traverses the laser resonant cavity; there is no external laser beam. The laser losses are almost entirely in the mirrors and windows; therefore, to maximize system efficiency, it is important to minimize the cross-sectional area of the laser beam. These considerations lead naturally to the thin-sheet beams that were discussed in connection with sources and with TFF transporters and accelerators. The leading candidate laser for this application is the oxygen-iodine chemical laser,[33] which operates at 1.315 $\mu$. A prototype of such a laser has operated at 2 kW for 4 min.[34] For application as a photoneutralizer, a single laser rated at about 200 kW, or a group of lasers operating in parallel and totaling the same power, all operating steady-state, would be required.[35] A schematic of such a photoneutral-

izer is shown in Figure 8. Conversion efficiencies of 95% or higher appear achievable; this greatly simplifies the dump design, since only $D^-$ ions must be dealt with, and power densities on the dump are low.

The greatest technological uncertainties for a laser photoneutralizer are in developing low-loss mirrors and windows, which are required to be at or slightly beyond the current state of the art, in optimizing the design of the cavity and laser gain medium and the design of the chemical plant for maximum efficiency, and in demonstrating that the laser can operate successfully in the neutral-beam and reactor environment. We can expect beneficial "spin-off" from a substantial (approaching

Lawrence Livermore National Laboratory

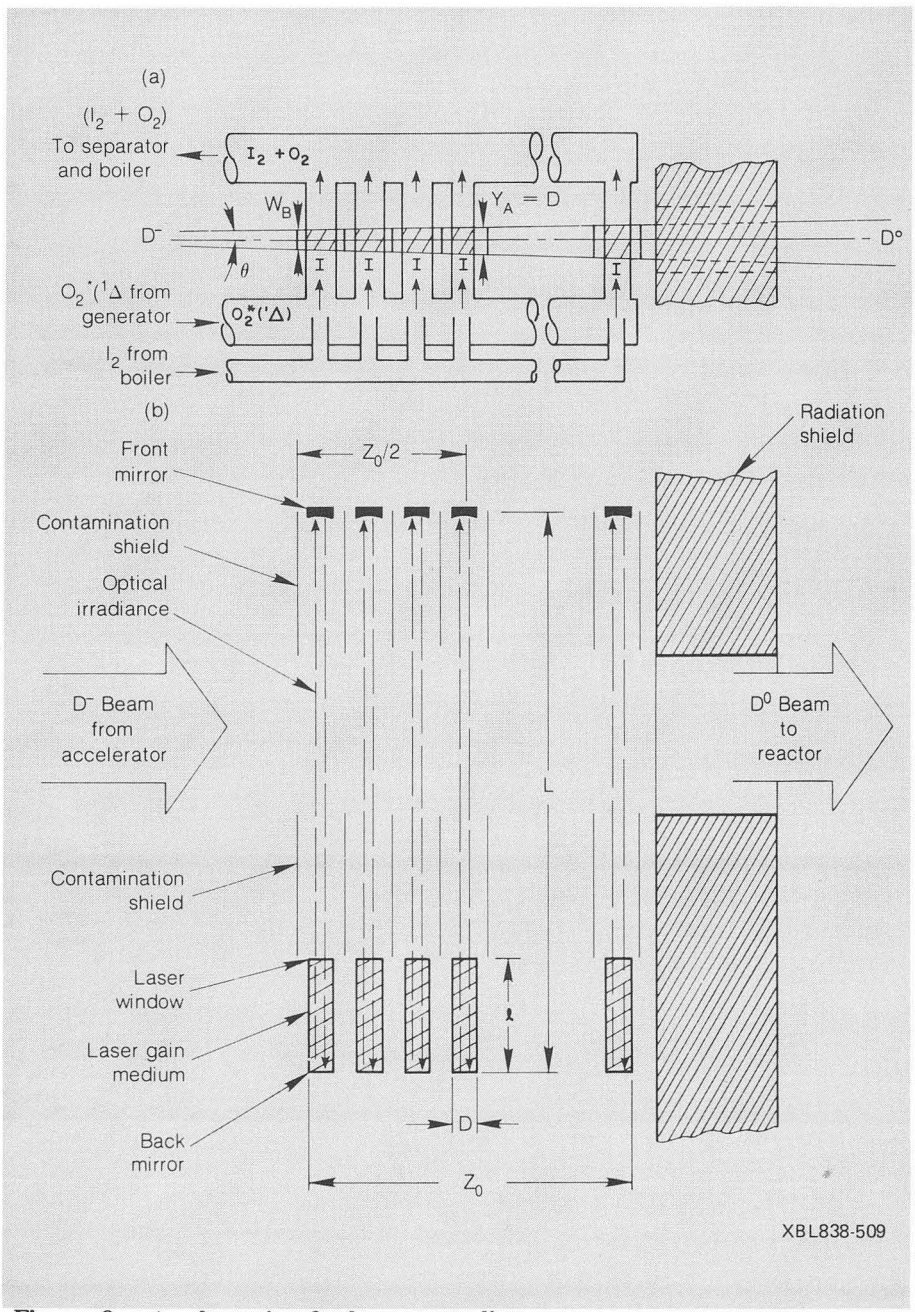



**Figure 8: A schematic of a laser neutralizer.**

$10M/year) program within the Department of Defense for development of this same laser, but it is not clear how that program will influence the timing of negative-ion-based beam development. If necessary, gas or plasma neutralizers could be used in the first applications.

At this wavelength, 1.315 $\mu$, the photons have enough energy to detach the electron from $D^-$ ions, but not from impurity ions $C^-$, $OH^-$, and $O^-$; this choice of wavelength therefore provides substantial discrimination against impurities in the beam.

### Systems

The study of negative-ion-based neutral beam systems is still in the conceptual stage. Preliminary studies have been made of 200-, 400-, and 800-keV systems[28,36–38] from the point of view of compatibility of beamline components, pumping requirements, and stripping losses. Neutronics studies have been performed by "rule-of-thumb" estimates and by preliminary Monte-Carlo calculations;[39] more accurate Monte-Carlo calculations are needed. None of the systems has been optimized. In addition, one study of the suitability of an oxygen-iodine chemical laser for a photoneutralizer has been done; this study indicated that overall system efficiencies of 70% should be achievable.[35] Systems studies should be expanded in all these areas, plus others.

It is important to assess the suitability of negative-ion-based neutral-beam systems in a reactor environment as soon as possible, so that problems can be recognized and tackled at an early stage. It is especially important to study at an early stage the questions of tritium compatibility and remote maintenance. Tritium contamination will occur due to tritium leaking from the reactor into the neutral-beam system; it is even possible that some fueling beams will operate with tritium. Some parts of the beamline will become activated by neutron bombardment and will have to be remotely maintained; in general, the entire neutral-beam system within the reactor vault must be capable of being remotely maintained in case of an accidental tritium spill.

Trade-off studies will be necessary to consider and optimize the multiple uses of neutral-beam systems for heating, current drive, potential generation, fueling, etc, to permit a meaningful comparison with competing rf systems.

### Test Facilities

Within the DOE-funded negative-ion program, there exists only limited capability to develop and test negative-ion components and systems in the U.S. Some capability exists at BNL and LBL; the capabilities of these test facilities are summarized in Table IV. As one can see from this table, development can only be carried out at present to the level of about 1 A and at energies of few 10's of keV. This capability is adequate for source development, but is inadequate for accelerator development, which is aimed at beam energies of 400 keV or higher.

Similar facilities for fusion-related negative-ion development exist outside the U.S., in particular at the Culham Laboratory in England, at the

**Table IV: Existing and Near-Term Negative-Ion Test Facility Capability**

| Site | Facility | Parameters | Operational |
|---|---|---|---|
| LBL | TS-I | 2 A, 40 kV, 10 sec | Now |
| | TS-IIIA | 2 A, 160 kV dc | September, 1983 |
| BNL | STS | 2.5 A, 25 kV dc | Now |
| | | 20A, 25 kV, 0.1 sec | Now |

Kurchatov Institute in Moscow, and at the Centre D'Etudes Nucleaires, Grenoble, France.

Table IV also shows the capabilities of a negative-ion test facility at LBL that is being converted from positive-ion research to negative-ion work, beginning in January, 1983. This facility will be able to test the TFF concept of beam transport and acceleration to about 160 keV, the limit of the power supplies. The facility will also have the capability to test negative-ion sources developed at BNL.

It is clear that a substantial increase in test facility capability will be required to test components and develop systems suitable for application on the next-generation confinement experiments; these systems will have to operate in the 5–10-A, 500-keV range.

## APPLIED PLASMA PHYSICS RESEARCH

The Applied Plasma Physics Division of OFE sponsors research that is directly relevant to negative-ion-based neutral-beam development. These efforts are summarized in the following sections.

### Negative-Ion Production and Interactions

Whether negative ions are produced on surfaces or in the volume of a plasma, the production processes are not well understood. APP-sponsored experimental research has indicated that in the case of surface production of negative ions by back-scattering and in the presence of a plasma, the optimum rate of production of negative ions on the surface occurs when the cesium coverage is such that the surface work function is a minimum.[40,41] Theoretical work supports this observation.[42] The yield is also observed to depend on the substrate material[43] and the crystal structure of the substrate.[44] Cesium-coated molybdenum has been found to produce the highest yield of negative ions; this has not been explained. More work should be done in the area of Cs-free low-work-function surfaces. It is likely that source performance can be improved by continuing these efforts to maximize the yield of negative ions from surfaces.

Copious quantities of negative ions have been observed in the volume of otherwise ordinary positive-ion discharge plasmas.[45] The densities of these negative ions may amount to 10% or more of the electron density. While these sources have the advantage of operating without cesium, the

useful $D^-$ current densities obtained are still under investigation, and in addition, electron control may be difficult. It is suspected that the volume-produced negative ions are produced by dissociative attachment of electrons during collisions of low-energy electrons with vibrationally excited hydrogenic molecules. Theoretical studies of these processes have been very encouraging,[46] but as yet there is not quantitative agreement between theory and experiment.

It is important that these fundamental research activities be continued. Achievement of current densities at the accelerator that are much higher than exist today is not the most important goal. Available current densities are already within about a factor of 2 of the maximum that conservatively designed accelerator and transport structures can accommodate, although this maximum can be expected to increase with improved accelerator technology. Higher current densities at the source bring advantages in other areas, however: "excess" current can be discarded in favor of an increase in source-gas efficiency, with an attendant reduction in stripping losses, and a reduction in the mean transverse energy of the ions, with an attendant reduction in beam divergence and an increase in current-carrying capability of the accelerator and transport systems. These current losses can be absorbed at low energy, so that the power losses are small.

**Beam Diagnostics**

Diagnostic requirements for negative-ion-based neutral beams are not likely to differ substantially from those of positive-ion-based neutral beams. In either case, one must measure beam divergence, beam power, and the impurity content in the beam. Analysis of Doppler-shifted visible radiation from neutral beams has been used for some years now to measure the energy distribution and the divergence of positive-ion-based neutral beams. The same techniques can be applied to negative-ion-based neutral beams. If a photoneutralizer is used, there will be much less light to observe, since the background pressure will be lower by a factor of 100 to 1000 than in gas neutralizers (as are used with positive-ion systems), but the observation times will be longer by similar factors. Therefore Doppler-shift spectroscopy can probably still be used, but at a considerable reduction in time resolution.

APP-funded research is underway to apply laser-induced fluorescence spectroscopy to the problems of neutral-beam diagnostics. Impurity content as well as beam divergences can be measured by these techniques. In both cases, a laser is tuned to the frequency of a resonance transition of a ground-state neutral atom in the beam, and the atom is excited. When the excited atom decays back to the ground state, the photon emitted is detected. In this way, a signal is produced that is proportional to the density of ground-state atoms in the beam. If the laser is tuned to an impurity atom transition, the density of impurity atoms can be measured; if the laser is tuned to an atomic hydrogen or deuterium transition, the density of that neutral species can be measured. The Doppler shift can be used to advantage to determine the beam divergence from the profile of the spectral line.

No nonperturbing techniques are currently available for directly measuring the power of a neutral beam.

### Polarized Beams

Fusion-reaction cross sections depend on the relative polarizations of the reacting nuclei. If the reacting deuterium and tritium nuclei are polarized in the same direction, the reaction rate is 50% larger than in the case in which the nuclei are randomly polarized. It is possible to control the direction of the reaction products by controlling the nuclear polarizations;[17] this can be used to advantage in reactor designs. It may be possible to produce high-current beams of polarized neutral atoms; tens of amperes are required. The state-of-the art polarized atomic beam is now about 50 microamperes. Related development is underway within the accelerator community; a group at BNL, supported by the AGS, has as its objective the production of a 1-mA beam of polarized negative ions. Since the payoff is substantial, this is a promising research avenue to pursue. The potential role of a beam or pellets of polarized nuclei in the MFE Program is presently under evaluation.

# R&D Program Description

## STRATEGY

Negative-ion-based neutral beam program planning strategy is dictated by two fundamental considerations:

1. To meet the most pressing identified need for negative-ion-based neutral beam systems, which is for control of electric potentials in the plug cell of a mirror ETR. Mirror planning calls for this machine to begin operation with plasma in 1994, with tritium operation to commence in 1997. Since the beams will be required for startup, 1994 is the target date for beam use.
2. To acquire a data base as soon as possible to permit quantitative assessment of the suitability and desirability of negative-ion-based neutral beam systems for reactor application.

As we can see from Table I, which summarizes confinement needs, negative-ion-based neutral beam development can be conveniently broken into two distinct phases:

Phase I: The development of components and systems to operate with deuterium at the 500-keV level, with a source module size of 5–10 A, steady-state (hours initially, and ultimately months to years)

and

Phase II: Extension of this technology to the 800-keV to 2-MeV level, possibly to source module sizes of greater than 10 A. This phase of development would be undertaken if it were decided that steady-state current drive with beams were needed for tokamaks.

A Program Plan to meet these objectives concentrates on the Phase I objectives, and contains the following major elements:

Phase I

1. Development of dc negative-ion sources with emphasis on beam quality, on increasing the available current/meter to at least twice the value available now, on increasing the gas efficiency, and on the elimination of cesium. This source development will be carried out at LBL and BNL.
2. Demonstration of accelerator and beam-transport technology capable of handling 5- to 10-A beams at 500 keV. The TFF design is the primary approach, with the electrostatic quadrupole (ESQ) as the main backup concept. This plan does not show construction and testing of an ESQ transporter or accelerator.
3. Development of a suitable neutralizer. The primary approach is a photoneutralizer employing the oxygen-iodine chemical laser; this is the most desirable approach, and the prognosis for successful development is sufficiently good that a major effort in this area is warranted early in the program. It will be important to demonstrate a laser module on an operating beam line. Other laser systems would be adopted if they appeared more

suitable. The laser development effort will be carried out in industry. A backup approach is the plasma neutralizer; this development will be carried out at BNL. A gas neutralizer, although less desirable, can also be used.

4. System studies, carried out at LBL, at the confinement laboratories or for them at the FEDC, and in industry, to optimize beamline design and assess the suitability of these systems for reactor applications. Special attention will be paid to survivability, tritium compatibility and maintenance requirements. A very important output of these studies will be the anticipated system availability, efficiency and cost.
5. Prototype development. This development, which is essential to guarantee reliability and reactor compatibility, may be carried out by industry, by a combination of industry and the user (with close collaboration on the part of the development laboratories), or at a national laboratory.
6. Determination of the suitability of neutral beams for current drive in tokamaks. At present, neutral-beam systems have a backup role in the tokamak planning. However, there is the possibility that negative-ion-based neutral beams will be able to perform the dual functions of heating and current drive at high power efficiency, so a timely determination of relevant parameters and experimental verification on a tokamak, not yet identified, is important if tokamak applications are to be properly included in the development program.

The interrelation of these elements is shown schematically as a strategy diagram in Figure 9. A continuation of this Program Plan would lead naturally into Phase II if steady-state current drive were needed for tokamaks:

Phase II

1. Determination of the type of accelerator and transport structures necessary to go to the 800-keV – 2-MeV level. The type of structure adopted in Phase I will be tested to these levels; the backup approach will be an rf structure, such as the radiofrequency quadrupole (RFQ) or Meqalac.
2. Extension of technology to very long pulse (months) capability.

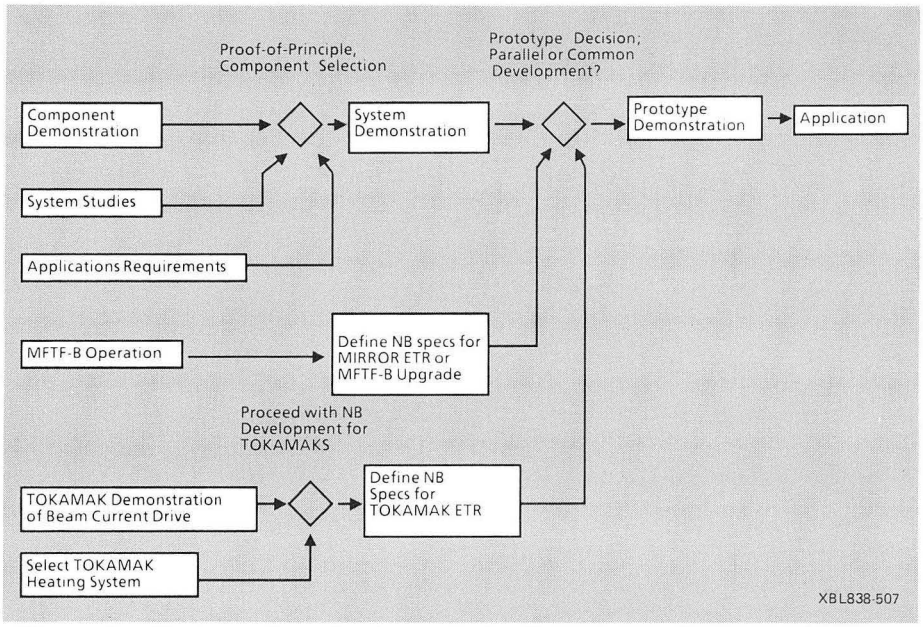



**Figure 9: Strategy for development leading to application of negative-ion-based neutral beam systems.**

## Proof-of-Principle Demonstration

A proof-of-principle demonstration is required before the fusion community can proceed with confidence to the prototype development phase. A proof-of-principle experiment must demonstrate that all the principles involved will work, and that all components will work together. As has been discussed in the section on Technology, the component with the highest risk appears to be the high-voltage accelerator and transport system. If these can be made to accelerate and transport satisfactorily a beam from the source, there is little doubt that a system using an inefficient but low-risk gas cell for a neutralizer can be constructed and operated successfully. On the other hand, to capitalize on the potential high efficiency of a negative-ion-based neutral beam system, it will be necessary to operate the system with an efficient neutralizer, such as a photoneutralizer or a plasma neutralizer. We therefore define two proof-of-principle goals, the second one being for the proof-of-principle of an efficient neutral-beam system:

POP-I: Demonstrate production, transport, and acceleration (with strong-focusing TFF systems) of a 1–2 A $H^-$ beam to 160 keV under steady-state conditions and at full current density. Capability of extrapolation to a practical beamline is a requirement.

POP-II: Demonstrate operation under steady-state conditions of a negative-ion system ($\geq$ 1A, $\geq$ 160 keV) with an efficient neutralizer. If a laser neutralizer is chosen, tests with a single module of a design capable of being extended to the full neutralizer will be satisfactory.

POP-I will demonstrate that a negative-ion-based neutral beam system

can be built, although it may not be the most efficient design; POP-II will demonstrate that a highly efficient system can be built.

## ACTIVITIES

The activities required to implement the strategy just discussed and illustrated in Figure 9 are shown in Figure 10. In Figure 10, we identify the activity, the organization responsible for carrying out the activity, and show the expected duration. Major decision points and the POP demonstrations are shown.

From this activity analysis we conclude that:

1. with an aggressive program, it is possible to meet the anticipated 1994 start-up date for application of negative-ion-based neutral beams on a mirror ETR, and
2. new and upgraded facilities will be required. These requirements will be addressed in the next section.

Figure 10a

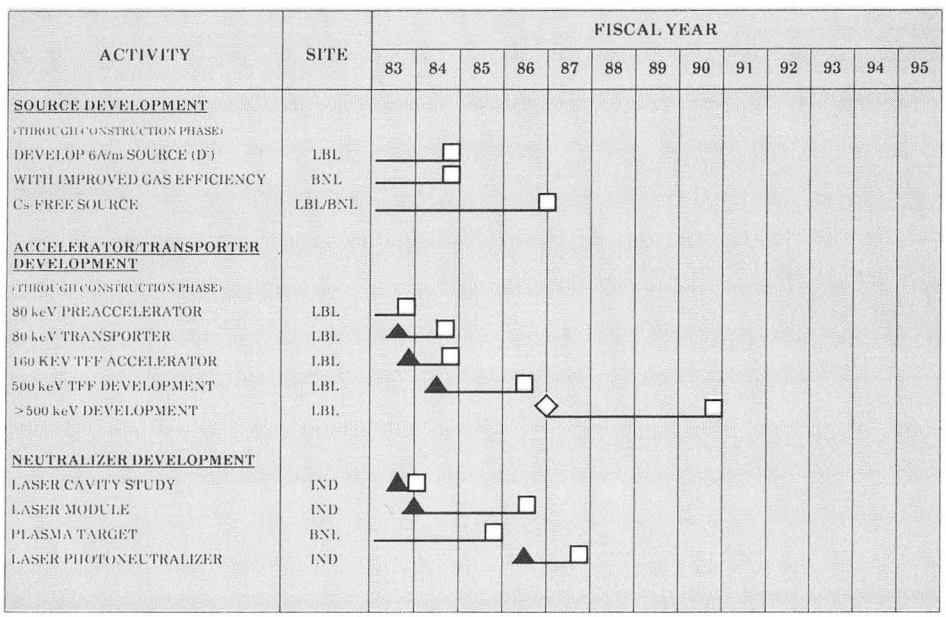


Figure 10b

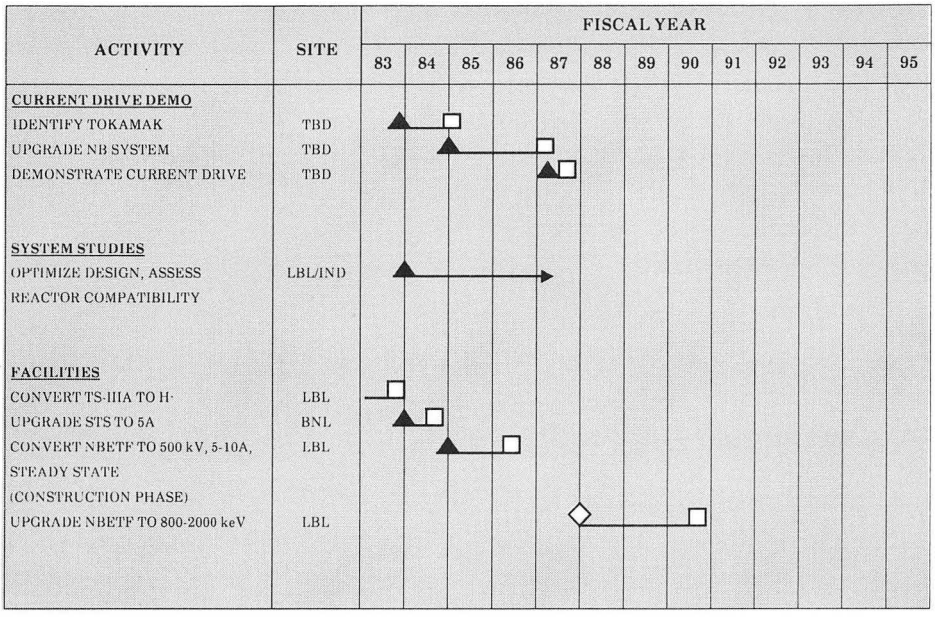
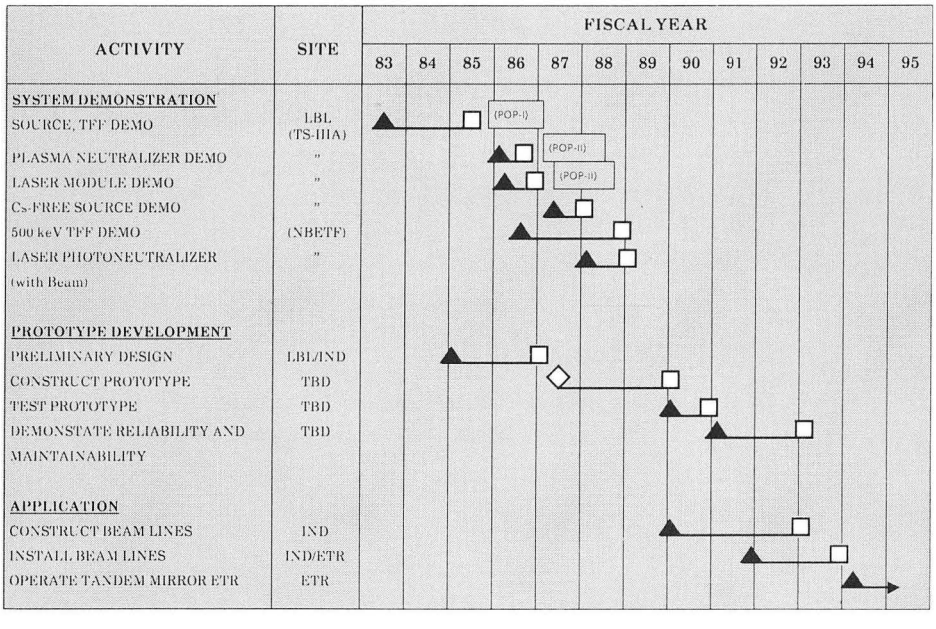



Figure 10c




## FACILITIES

We can analyze the facility requirements, already shown on the activity chart (Figure 10), in terms of the Phase I and Phase II objectives:

Phase I:

1. Source development can be carried out on existing facilities at LBL and BNL. A modest upgrade of the 25-kV BNL facility (STS) from 2.5 A to 5 A is highly desirable.

2. Transport-system development can be carried out on Test Stand IIIA (TS-IIIA), an existing facility at LBL being converted to negative-ion operation in FY83. TFF accelerators require injection of a beam preaccelerated to 80–150 keV. The power supply of TS-IIIA, which is limited to 160 keV, will therefore permit only limited testing of a TFF accelerator — probably only two acceleration stages could be tested. It is known that instabilities can grow in multiple stage accelerators of this type; therefore, it is necessary ultimately to test these designs to the 500-keV level. A new or upgraded facility will be required to do this.
3. It does not appear likely that a major DOE facility will be required for laser development. Demonstration of the compatibility of a laser module with an operating beam can be carried out on an upgraded existing facility.
4. Some upgrade of an existing tokamak facility may be required to assess the suitability of neutral beams for current drive because the L/R time for current decay in tokamaks is longer than the pulse length of their neutral-beam systems. More effort is required to determine these requirements.
5. System studies do not require new facilities.
6. Prototype development will require a new facility, but this would most likely be included in the user's (ETR) construction program. We therefore do not identify this effort with an R&D facility requirement.

Phase II:

Extension of technology to the 800-keV – 2-MeV level with pulse lengths of months will require a new facility or an upgrade of an existing one. All the major facility requirements for Phase I can be incorporated into a single facility having 10-A, 500-kV, dc capability. Phase II requirements could be accommodated by an upgrade of the Phase I test facility or by a new one.

Phase I Test Facility:

The Phase I facility could be either a new facility or an upgrade of an existing one. The best candidate for upgrading is the NBETF at LBL; positive-ion planning calls for completion of positive-ion R&D on the NBETF at the end of FY84, which fits nicely into the negative-ion schedule. The NBETF can be relatively easily reconfigured for negative-ion acceleration, but the present power supplies are limited to 170 kV. A more desirable choice would be to upgrade the facility to 500 keV as soon as it is available; this is the option shown in the planning.

In Table V, we show the present (April 1983) capabilities of the NBETF, configured for positive-ion use, and the capabilities for negative-ion use after the proposed first-stage upgrade. The NBETF high-voltage power supply consists of two transformer-rectifier modules conservatively rated at 17 A, 170 keV, dc, operating in parallel. One option for negative-ion use would consist of isolating one of the modules

and reconnecting the two in series, to give ~ 10 A, ~ 350 kV, dc capability. An additional 10-A, 150-kV power supply would bring the system capability to the 500-keV level. The present basic cooling system is capable of dissipating 11 MW for 30 s, 5 MW for 4–5 min, or 2 MW steady-state. A dedicated cooling tower would be required to go to dc operation at the 5-MW level. The existing cryosystem is probably adequate for negative-ion operation, but this question has not been studied. The test cell would probably need to be relocated and enlarged to accommodate adequate high-voltage stand-off capability and source-to-target distance. More effort is required to determine the optimum configuration of the upgraded facility.

**Table V: Proposed Upgrade of NBETF Facility for Negative Ion Use**

| Sub-System | NBETF Capability (April, 1983) | Upgraded Capability (March, 1986) |
|---|---|---|
| High Voltage Power Supply | 65 A, 120 kV, 30 sec | 10 A, 500 kV dc |
| Beam Dump Cooling System | 11 MW, 30 sec; 5 MW, 200–300 sec; 2 MW dc | 5 MW dc |
| Cryosystem | 400 W at 4.2 K | TBD |

## PROTOTYPES

To ensure system integration and to demonstrate reliability and maintainability, essential for application of neutral beam on an ETR-class experiment, it will be necessary to build and operate a prototype neutral-beam system. We show the decision to do this early in FY86, which allows eight years for the prototype phase and construction and installation of neutral-beam systems on the ETR. This is a very ambitious schedule, but should be possible.

This prototype development could be carried out at a development laboratory or elsewhere. The most desirable location for the prototype development is probably at the ETR site, with the effort coming jointly from the development laboratory, industry, and the ETR staff. ETR facility construction may dictate that design, construction, and component testing be done elsewhere (as was the case for TFTR).

## MILESTONES

Milestones derived from the activity chart shown in Figure 10 are listed in Table VI.

**Table VI Milestones**

| Milestone | | Date |
|---|---|---|
| □ Complete conversion of TS-IIIA (LBL) to $H^-$; begin operation of source with 80-keV preaccelerator | | July 1983 |
| □ Accelerate 1-A dc beam to 80 keV | | December 1983 |
| □ Demonstrate 80 keV TFF transporter | | July 1984 |
| □ Demonstrate 160-keV TFF accelerator | (POP-I) | January 1985 |
| □ Demonstrate plasma neutralizer with beam | (POP-II) | March 1986 |
| □ Complete conversion of NBETF to negative ions | | March 1986 |
| □ Develop improved, CS-free source | | September 1986 |
| □ Demonstrate laser module on beamline | (POP-II) | September 1986 |
| □ Demonstrate current drive with Neutral beams on a tokamak | | January 1987 |
| □ Decision point to proceed with ETR prototype phase | | January 1987 |
| □ Decision point to proceed With $>$ 500-keV facility | | October 1987 |
| □ Begin operation on ETR | | January 1994 |

# Resource Assessment

The resources of the national laboratories and relevant industries are adequate for the tasks. The research and development required represent a logical extension of the research and development already underway in national laboratories and industry in connection with the positive-ion-based neutral-beam program.

## PERSONNEL

The required level of effort at the national laboratories will be about the same as in the combined present positive- and negative-ion-based neutral-beam programs. This makes it possible to have a smooth buildup with skilled personnel.

## FACILITIES

Facilities required up to the prototype stage exist, or can be obtained by upgrading existing facilities. The lead times for upgrades can be substantial (two years or more), so careful scheduling is required.

## BUDGETS

A reliable cost estimate has yet to be carried out. As a frame of reference, the positive-ion development program has cost about $100 M. A similar effort can be expected for Phase I negative-ion system development.

# References


1. The Comprehensive Program Management Plan for Magnetic Fusion Energy, U.S. Dept. of Energy, Office of Fusion Energy (in preparation).

2. The Fusion Engineering Device, Vol. VI, Complementary Development Plan for Engineering Development, DOE/TIC-11600 (October, 1981).

3. K.I. Thomassen and J.N. Doggett, Editors, "Options to Upgrade the Mirror Fusion Test Facility," UCID-19743, Lawrence Livermore National Laboratory (April, 1983).

4. D.L. Jassby and R.J. Goldston, "Enhanced Penetration of Neutral-Beam-Injected Ions by Vertically Asymmetric Toroidal-Field Ripple," Nucl. Fusion, **16**, 613 (1976).

5. The National Mirror Fusion Program Plan, UCAR-10042-82, Lawrence Livermore National Laboratory and the Office of Fusion Energy (August, 1982).

6. The National Toroidal Program Plan, U.S. Dept. of Energy, Office of Fusion Energy (in preparation).

7. F.H. Coensgen, et al, "Stabilization of a Neutral-Beam-Sustained, Mirror-Confined Plasma," Phys. Rev. Lett., **35**, 1501 (1975).

8. H. Eubank, et al, "Neutral-Beam-Heating Results From the Princeton Large Torus," Phys. Rev. Lett, **43**, 270 (1979).

9. F.H. Coensgen, et al, "Electrostatic Plasma-Confinement Experiments in a Tandem Mirror System," Phys. Rev. Lett. **44**, 1132 (1980).

10. T.C. Simonen, et al, "Operation of the Tandem-Mirror Plasma Experiment with Skew Neutral-Beam Injection," Phys. Rev. Lett., **50**, 1668 (1983).

11. K. Yatsu, et al, "Experimental Observation on Enhancement of the Ambipolar Potential by Injection of Neutral Beams in a Tandem Mirror," Phys. Rev. Lett., **43**, 627 (1979).

12. D.R. Mikkelsen and C.E. Singer, "Optimization of Steady-State Beam-Driven Tokamak Reactors," PPPL-1929, Princeton Plasma Physics Laboratory (1982), to be published in Nucl. Technol./Fusion.

13. C.E. Singer and D.R. Mikkelsen, "Continuous Tokamak Operation With An Internal Transformer," PPPL-1936, Princeton Plasma Physics Laboratory (1982), to be published in J. of Fusion Energy.

14. W.H.M. Clark, et al, "Measurements of the Beam-Driven Current in the DITE Tokamak," Phys. Rev. Lett., **45**, 1101 (1980).

15. D.E. Post, L.R. Grisham, J.F. Santarius, G.A. Emmert, "Light Atom Neutral Beams for Tandem Mirror End Plugs," Nucl. Fusion, **23**, 3 (1983).

16. L.R. Grisham, et al, "Plasma Heating With Multi-MeV Neutral Atom Beams," Nucl. Technol./Fusion, **2**, 199 (1982).

17. R.M. Kulsrud, H.P. Furth, E.J. Valeo and M. Goldhaber, "Fusion Reactor Plasmas With Polarized Nuclei," Phys. Rev. Lett., **49**, 1248 (1982).

18. L.R. Grisham, D.E. Post, and D.R. Mikkelsen, "Multi-MeV $Li^0$ Beam as a Diagnostic for Fast Confined Alpha Particles," Nucl. Technol./ Fusion, **3**, 121 (1983).

19. R.J. Goldston, "Diagnostics for Hot Plasmas Using Hydrogen Neutral Beams," PPPL-1952, Princeton Plasma Physics Laboratory (1982); also in "Diagnostics for Fusion Reactor Conditions," **Proc. of the Course Held in Varenna (Como)**, Italy, Sept. 6–17, 1982, Vol. I, p. 263 (1982).

20. K.N. Leung and K.W. Ehlers, "Self-Extraction Negative Ion Source," Rev. Sci. Instrum., **53**, 803 (1982).

21. J.G. Alessi, et al, "BNL Negative-Ion-Based Neutral-Beam Development," **Proc. of the Third Neutral Beam Heating Workshop**, Gatlinburg, TN (October 19–23, 1981); sponsored by the Fusion Energy Division, Oak Ridge National Laboratory.

22. E.B. Hooper, Jr., P. Poulsen, and P.A. Pincosy, "High Current $D^-$ Production by Charge Exchange in Sodium," J. Appl. Phys., **52**, 7207 (1981).

23. O.B. Morgan, G.G. Kelly, and R.C. Davis, "Technology of Intense DC Ion Beams," Rev. Sci. Instrum., **38**, 467 (1967).

24. O.A. Anderson, D.A. Goldberg, W.S. Cooper, and L. Soroka, "A Transverse-Field-Focusing (TFF) Accelerator for Intense Ribbon Beams," Bull. Am. Phys. Soc., **28**, 103 (1983); to be published in **Proc. of the 1983 Particle Accelerator Conference**, Santa Fe, NM (March 21–23, 1983).

25. G.M. Gammel, A.W. Maschke, and R.M. Mobley, "New High-Brightness Multiple Beam Linear Accelerator," Rev. Sci. Instrum., **52**, 971, (1981).

26. K.R. Crandall, R.H. Stokes, and T.P. Wangler, "RF Quadrupole Beam Dynamics Design Study," **Proc. of the 1979 Linear Accelerator Conference**, BNL-51134, Brookhaven National Laboratory (1979).

27. R.H. Stokes, "Radio-Frequency Quadrupole Linear Accelerator for High-Current Applications," **Proc. of the Workshop on the Formation and Acceleration of High Energy Neutral Beams for Magnetic Fusion**, DOE/TIC-11371, U.S. Dept. of Energy (1981).

28. O.A. Anderson, W.S. Cooper, J.A. Fink, D.A. Goldberg, L. Ruby, L. Soroka, and J. Tanabe, "Efficient, Radiation-Hardened, 400 and 800 keV Neutral Beam Injections Systems," LBL-15066, Lawrence Berkeley Laboratory (1983); to be published in **Proc. of the Fifth Topical Meeting on the Technology of Fusion Energy** (special issue of Nucl. Technol./Fusion), Knoxville, TN (April 26–28, 1983).

29. H.A.C. Hogg, "Periodic Electrostatic Beam Focusing," Proc. IEE, Part B, Suppl.12–13, 1016 (1958).

30. For a summary of relevant experimental cross sections and calculated yields in gas targets, see K.H. Berkner, R.V. Pyle, and J.W. Stearns, "Intense Mixed-Energy Hydrogen Beams for CTR Injection," Nucl. Fusion, **15**, 249 (1975).

31. G.I. Dimov, A.A. Ivanov, and G.V. Roslyakov, "Electron Loss of Fast $H^-$ and $H^0$ Atoms in a Plasma Target," Sov. Phys. Tech. Phys., **22**, 1091 (1977).

32. H.C. Bryant, P.A. Lovoi, and G.G. Ohlsen, "Production of Pulsed Particle Beams by Photodetachment of $H^-$," Phys. Rev. Lett., **27**, 1628 (1971).

33. M.W. McGeoch, "Laser Neutralization of Negative Ion Beams for Fusion," in **Proc. of the Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams**, BNL-51304, Brookhaven National Laboratory (October 6–10, 1980), page 304.

34. J.O. Berg, et al, "Chemical Oxygen-Iodine Laser Advanced Technology," U.S. Air Force Report AFWL-TR-82-51 (Oct., 1982); D.J. Miller, et al, "A 2 kW cw Chemical Oxygen-Iodine Laser," talk presented at Lasers '82 Conference, New Orleans (December 13–17, 1982).

35. J.H. Fink, "Effective Photo-Neutralization of Negative Hydrogen Ion Beams," Bull. Am. Phys. Soc., **27**, 1142 (1983); "Laser-Neutralized Negative Ions as a Source of Neutral Beams for Magnetic Fusion Reactors," UCRL-87301, Lawrence Livermore National Laboratory (1982); submitted to Nucl. Technol./Fusion.

36. W.K. Dagenhant, W.L. Gardner, W.L. Stirling, and J.H. Whealton, "Experimental Database and Design Concept for a 1-MW, 200-keV Neutral Beam Line Based on a SITEX Negative Ion Source," to be published in the **Proc. of the Fifth Topical Meeting on the Technology of Fusion Energy** (special issue of Nucl. Technol./Fusion), Knoxville, TN (April 26–28, 1983).

37. K. Prelec, et al, "A Neutral Beam System Based on BNL Negative Hydrogen Ion Sources," **Proc. of the Third Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas**, Grenoble (March 22–26, 1982); to be published.

38. D. Goldberg, O. Anderson, W. Cooper, and J. Tanabe, "Conceptual Design of a 200-keV, 1-MW Negative-Ion-Based Neutral Beam Line," J. Fusion Energy, **3**, 67 (1983).

39. X. de Seynes, "Shielding Considerations for Neutral Beam Injection Systems," M.E. Thesis, Nuclear Engineering Dept., University of California at Berkeley (1983) (unpublished); LBL-15854, Lawrence Berkeley Laboratory (June, 1983).

40. P.J. Schneider, et al, "$H^-$ and $D^-$ Production by Backscattering From Alkali-Metal Targets," Phys. Rev. B., **23**, 941 (1981).

41. M. Wada, "Correlation of $H^-$ Production and the Work Function of a Surface in a Hydrogen Plasma," PhD. Thesis, Nuclear Engineering Dept., University of California at Berkeley (March, 1983) (unpublished); LBL-15800, Lawrence Berkeley Laboratory (March, 1983).

42. J.R. Hiskes and P.J. Schneider, "Formation of $H^-$ and $D^-$ Ions by Hydrogen and Deuterium Particle Backscattering From Alkali-Metal Surfaces," Phys. Rev. B., **23**, 949 (1981).

43. K.N. Leung and K.W. Ehlers, "$H^-$ Ion Formation From A Surface Conversion Type Ion Source," J. Appl. Phys., **52**, 3905 (1981).

44. E.H.A. Granneman, et al, "A Negative Hydrogen Ion Source Based on Specular Reflection of keV Positive Ions on Low Work-Function Surfaces," Bull. Am. Phys. Soc., **27**, 1135 (1982).

45. M. Bacal and G.W. Hamilton, "$H^-$ and $D^-$ Production in Plasmas," Phys. Rev. Lett., **42**, 1538 (1979).

46. J.R. Hiskes, A.M. Karo, M. Bacal, A.M. Bruteteau, and W.G. Graham, "Hydrogen Vibrational Population Distributions and Negative Ion Concentrations in a Medium Density Hydrogen Discharge," J. Appl. Phys., **53**, 3469 (1982).

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720