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NEUTRAL BEAM INJECTOR FOR 475 keV MARS SLOSHING IONS

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ABSTRACT

A neutral beam injector system which produces 5 MW of 475 keV D⁰ neutrals continuously on target has been designed. The beamline is intended to produce the sloshing ion distribution required in the end plug region of the conceptual MARS tandem mirror commercial reactor. The injector design utilizes the LBL self-extraction negative ion source and Transverse Field Focusing (TFF) accelerator to generate a long, ribbon ion beam. A laser photodetachment neutralizer strips over 90% of the negative ions. Magnetic and neutron shield designs are included to exclude the fringe fields of the end plug and provide low activation by the neutron flux from the target plasma. The use of a TFF accelerator and photodetachment neutralizer produces a total system electrical efficiency of about 63% for this design.

INTRODUCTION

The sloshing ion beamline must continuously deliver a total of 8.86 MW of D⁰ at 475 keV into the 5.56 T point of both plug end cells of MARS at an angle of 70-80°. Of this incident power, 5.68 MW is trapped by the plasma for the calculated trapping fraction of 0.64. The remaining 3.18 MW of neutral beam power passes through the plasma and strikes two water cooled beam dumps some distance from machine axis. The sloshing ion neutrals are produced by the standard arrangement of ion source, accelerator, and neutralizer. The high beam energy dictates that negative ions be used to achieve reasonable neutralization efficiency. The un-neutralized ions in the beamline are deflected out of the neutral beam path and collected by internal beam dumps. The materials used in the dumps and other beamline components have been chosen for low activation wherever possible.

The fringing magnetic field from the plug yin-yang must be shielded from the ion source and ion beam regions prior to and during neutralization. The residual magnetic field in the beamline should not exceed 2-5 G for proper operation of the ion source and negligible deflection of the ion beam in the accelerator and neutralizer regions. The shield must exclude transverse magnetic fields of 0.5-0.6 T and axial fields of less than 0.1 T. For simplified maintenance of the beamline, it is desirable to attenuate the neutron flux from the plug plasma to levels where hands-on maintenance is possible within a reasonable time of a reactor shutdown. Depending on the materials selected for the beamline, the neutron shielding will

therefore be required to limit the neutron flux to about 10^6 n/cm²-sec at the ion source region. This will require an attenuation of about a factor of 10^5 - 10^7 by the shielding in and around the beamline. Increasing the distance of the sources from the target plasma will decrease the amount of magnetic and neutron shielding required, but eventually lead to additional losses of the beam due to the finite angular divergence of the accelerator. The beamline length and position should be picked to minimize shielding and remote maintenance requirements without producing excessive neutral beam losses from scrape off on the duct walls and collimators due to optical divergence.

BEAMLINE ION SOURCE

The MARS sloshing ion beamline is illustrated in Figures 1 and 2. The LBL self-extraction negative ion source shown in Figure 3 has been selected in the beamline design. The ion sources are two meters long (out of the figure) and utilize a cesiated molybdenum surface or volume production processes³ to convert positive ions formed by an rf plasma generator in a magnetic multipole bucket containment geometry into negative ions. The bias voltage for accelerating the ions to the converter also accelerates the subsequently formed negative ions away from the surface. Geometric shaping of the converter focuses these D⁻ ions into the extraction slit. Electrons in the plasma and from the converter surface are reflected from the accelerator entrance by a small transverse magnetic field produced by SmCo₅ magnets. The ions are pre-accelerated to 80 kV prior to injection into the TFF accelerator by a standard electrostatic single slot accelerator. The ion beam prior to acceleration is 1.5 cm wide x 200 cm long and has an average current density of 47 mA/cm². The ion source is therefore required to produce 7 A/m per meter of source length. Compared to the published value of 5 A/m previously obtained, this seems like a very reasonable projection for MARS.

The gas efficiency of the ion source is assumed to be 30%, a slight improvement over the 20% published value. The neutral gas flowing from the source produces an average pressure in the pre-accelerator of about 2×10^{-4} torr. This pressure causes 15% of the ion beam to be lost due to stripping by the neutral gas. A TFF transport region at 80 keV with differential gas pumping will be used immediately after the preacceleration region to decrease the gas pressure to 10^{-6} torr before the high voltage accelerator. This introduces an additional 9% loss of the ion beam by charge exchange, but at the low preacceleration energy so that the average power loss is low. Charge exchange losses in the accelerator are below 1% at the 10^{-6} torr background pressure. The Low Energy Beam Transport (LEBT) system will be described in the next section.

One of the two sources seen in Figure 2 is for redundancy. At any time a single source will be used to produce the sloshing ions. A built-in 50% redundancy is required because failure of one source effectively shuts down the reactor, and the time required to turn on a built-in conditioned source is considerably shorter than to open the facility to air for repairs of a single source. Isolation valves are provided for repair of one source without affecting the other. Remote maintenance can possibly permit repairs of one even while the other is operating.

ACCELERATOR

There are several accelerator options which can be utilized for the sloshing ion beam. Systems which use rf acceleration and quadrupole focusing, such as the LASNL-RFQ and the BNL-MEQALAC⁽⁴⁾, provide high energy acceleration without very high voltages. These systems are conceptually safer and easier to protect and maintain than DC systems. However, the time averaged current density is low in the rf system, and the electrical efficiency is lower than in a DC system due to joule heating and power supply modulator inefficiencies. The standard DC multiple grid accelerators utilized today in positive ion systems could possibly be reconfigured to produce the 475 kV negative ion beam. These very high voltages, however, can contribute to stray electron and radiation induced breakdowns in the accelerator column which cause unreliable operation. The stored energy in each grid must also be minimized to eliminate melt down problems associated with the arc breakdowns. A DC ESQ (Electro-Static Quadrupole) system⁽⁵⁾, in which the beam is focused by electrostatic quadrupoles between accelerator stages, reduces the probability of breakdown occurring over the entire accelerator column. The accelerator length is also adjustable by the quadrupole parameters so that reasonable voltage gradients can be achieved.

The quadrupole based accelerators are limited to sources which produce an array of multiple circular beamlets in order to provide space for the quadrupole electrodes. A high voltage accelerator which is compatible with the long slit beams of the self-extraction negative ion source is under development at LBL. This accelerator, called the TFF⁽⁶⁾ (Transverse Field Focusing), utilizes alternating curved electrodes producing a transverse electric field to focus and transport the ion beam. A D.C. voltage applied between successive electrode pairs will also accelerate the ions. The advantages and disadvantages of the TFF system compared to the DC ESQ and MEQALAC are listed in Table 1. The TFF accelerator is a relatively new application of the well known electrostatic transverse electric field energy analyzers in use for many years. While development is required for use in the MARS beamline, the principles of TFF system is well known and justifies consideration for MARS.

The Transverse Field Focusing (TFF) system selected for MARS is a type of one-dimensional electrostatic strong-focusing system used for transport and acceleration of the charged beam from the ion source to the neutralizer. It is suitable for one-dimensional focusing of a ribbon-shaped ion beam by an electric field applied transversely. This causes the beam particles to follow circular arcs, as shown by Figure 4. In the absence of space charge the required electric field is

$$E_t = mv_t^2 / rq = 2W/r \quad (1)$$

where W is the kinetic energy in eV. For spatial uniformity the electric field must be applied between two concentric cylindrical electrodes spaced a distance S apart, biased with voltage $\pm V_t$ relative to the potential of the equilibrium trajectory

$$E_t = 2V_t/S. \quad (2)$$

A beam particle not on the equilibrium surface will be strongly focussed toward the equilibrium surface by the combination of electrostatic and centrifugal forces. This focusing theory has been published by Anderson⁶. The theory is supported by trajectory computations, but has not yet been confirmed experimentally.

If the beam space charge is not negligible the space charge forces will tend to expand the beam in the transverse direction while the focusing forces resist the blow-up. The strength of the transverse electric field should be adjusted accordingly, with appropriate choices of the voltage V_t and dimensions r and S . This condition limits the beam-carrying ability of the TFF to about 20 to 60 mA/cm². This capacity is larger than the beam-carrying capacity of alternative focusing systems such as the various versions of dc or rf multipoles.

For most applications there is a maximum practical limit to the deflection angle caused by the transverse electric field. Therefore, our designs consist of a series of TFF stages as in Figure 2, which bend the beam alternately in one direction and then the other direction. The transverse focusing must be strong enough to compensate for the space charge blow-up in the gaps between focusing stages. If it is desired merely to transport the beam without acceleration the electrode potentials of adjacent stages are identical except for the reversal of polarities $\pm V_t$. To accelerate the beam, a longitudinal electric field E_z is applied between stages, superimposed upon the transverse electric field E_t . The acceleration increases the kinetic energy W and therefore requires increased values of r and V_t with each accel stage, in accordance with equations (1) and (2). The electric field intensities required to satisfy MARS requirements are not extreme, and we do not expect difficulties in holding high voltage. However, the ribbon-shaped beam will also have smaller space-charge forces tending to blow up the beam in the long direction.

We believe these can be compensated for by slightly curving the electrodes in this direction.

Losses of power and of beam particles by collisions with background gas are potentially severe in a TFF system. For D^- ions the most important type of gas collision is collisional electron detachment. Most of the resulting D atoms will go tangentially to the outer (negative) electrode, where they will deposit energy and produce secondary electrons with a multiplication coefficient in the range 1 to 5. These secondary electrons will be attracted to an adjacent positive electrode, where they will arrive with energy $2 V_0$. The beam transport and the gas pumping system must be designed such that the gas pressure is low enough that these losses are tolerable.

For the reasons above, a multi-stage differential pumping system is required to reduce the background gas pressure to about 10^{-6} torr before high voltage acceleration. The D^- ion source operates at a pressure of 10^{-5} torr, and the gas pressure must be reduced as quickly as possible to avoid loss of a large fraction of the D^- beam. Solutions to these problems have been achieved by the neutral beam group at LBL, Berkeley, for the FED-A Tokamak. These solutions are adequate for MARS requirements. D^- ions are extracted from the source by a 80 kV pre-acceleration stage and then transported through a differential pumping system shown in Figure 2 by a Low Energy TFF Beam Transport system (LEBT). The differential pumping system consists of four stages, each with continuously-operated cryopanel. Monte Carlo computations of the gas flow indicate that the required pressure reduction will be attained, but that about 15% of the 80 keV D^- beam will be lost by collisional electron detachment, most likely in the pre-acceleration stage where the gas pressure is over 10^{-4} torr. This beam loss reduces the effective beam density, but does not constitute a serious power loss at this relatively low energy.

As shown by Figure 1 the D^- beam enters the low-pressure TFF accelerator to be accelerated from 80 keV to 475 keV. The accelerator consists of four stages, each of which is designed with the dimensions and the electrode potentials appropriate for the beam energy and density. The focus voltages V_0 are progressively increased from about ± 25 kV at low energy to about ± 50 kV at 475 keV. The length of the four-stage accelerator is about 1 meter.

After the beam is accelerated to 475 keV, it is desirable to transport it through a neutron shield about 1 meter thick before the beam is neutralized by photodetachment. The neutron shield has the purpose of protecting the ion source and accelerator from neutron activation and neutron damage. Monte Carlo neutron flux computations and the neutron activation computations show the feasibility of hands-on maintenance, as opposed to remote maintenance. The High Energy Beam Transport (HEBT) consists of two large-radius TFF stages, each with a 90-degree bend, to attenuate the neutron flux. The overall

attenuation must be at least about of factor of 10^6 to reduce the neutron activation sufficiently for hands-on maintenance. We define hands-on maintenance as a residual activity not greater than 2.5 mR/hr two days after reactor shut-down.

The negative ion beam energy, from the ion source through the different accelerator stages just described, is shown in Figure 5. The last 50 kV of acceleration between the HEBT and the neutralizer is provided to inhibit electron flow from any plasma in the neutralizer to the TFF focusing electrodes in the HEBT. The final accelerator performance parameters are shown in Table 2. While 25% of the initial ion beam current is lost in the accelerator due to charge exchange with the background gas, the total power lost is less than 10% of the final beam power. Other losses due to the ion source electrical efficiency, stripping fraction, and duct losses dominate the power expenditure required to make the sloshing ion neutral beam.

Focusing in the narrow dimension of the beam is rather critical because the plasma target in the end plug is only 28 cm thick in this direction. The beam must travel about 10 meters without further focusing after it leaves the HEBT. This imposes a maximum allowance beam divergence angle in this direction of ± 0.8 degrees.

The D^- beam produced by the ion source will have a maximum transverse kinetic energy of 6 eV because of the geometry of the self-extraction electrode. As the beam is accelerated it will probably be compressed in the thin direction, perhaps by a factor of two. Conservation of phase space requires that the transverse kinetic energy increase as a consequence of the beam compression. We estimate that the 6 eV transverse energy will thereby be increased to 24 eV. The maximum divergence angle in this direction will be

$$\theta = \tan^{-1} [(24/475.000)^{1/2}] = 0.41 \text{ degrees}, \quad (3)$$

which is adequate for the purpose.

The beam is transported and focused in the short direction by TFF, and is also made to converge in the long direction by shaping of the electrodes of the ion source and the TFF as seen in Figure 1. The width of the beam is about 2 meters at the ion source but only a few tens of centimeters at the plasma target. This beam convergence has the effect of intensifying the injection of sloshing ions and causing them to be trapped where their turning points are correct for generating the sloshing ion distribution.

NEUTRALIZER

A system is required to neutralize the ions from the ion source and accelerator prior to injection into the MARS plasma. The fast neutral atoms from this neutralizer can be produced by stripping and

change exchange in the gas or plasma cell, or stripping in a laser photodetachment neutralizer. These options are summarized in Table 3. The gas cell utilizes neutral gas from the ion source with additional injected gas if necessary to provide a target thickness adequate for neutralization. While 50-60% of the negative ions can be stripped without any power input, the gas cell produces a significant gas load for pumping and multiple ion species in the beam. The plasma cell neutralizes up to about 80% of the ions, but is undeveloped at this time due to problems in generating large, highly ionized plasmas of significant extent to achieve high stripping. Partially ionized plasmas are not useful due to excessive ionization of the fast neutral beam by the gas molecules in the beam path decreasing the stripping fraction to the gas cell level. The gas load and power requirements are unknown at this time for the plasma neutralizer.

A laser neutralizer^(7,8) strips the negative ion by photodetachment in a laser resonator. Over 95% stripping of the negative ions is possible at the expense of about 1 MW of power required by the laser. Presently, this system produces no gas load for pumping in the beamline that is not isolated to the laser. A very transparent window provides gas and impurity isolation between the COIL (Chemical Oxygen-Iodine Laser) system and the beamline in present designs. The laser photodetachment neutralizer is under development for use with the LBL self-extraction sources.

The laser photodetachment neutralizer selected for MARS can achieve over 95% stripping of the ion beam emerging from the accelerator. A beam of D^- ions traveling a length l at a speed v through a region illuminated by a total laser flux P will be stripped with a fraction f given by

$$f = 1 - \exp(-\sigma LP/hv)$$

where σ is the photodetachment cross section and $h\nu$ is the photon energy. For a COIL laser, $\sigma/h\nu$ is $1.2 \times 10^{-5} \text{ cm}^2/\text{erg}$. The ion beam can be passed directly through the laser resonator to maximize the laser flux. The interaction length can also be increased by folding the resonator with multiple mirrors as shown schematically in Figure 6. The stripping fraction for the MARS beam line as a function of the number of folds is shown in Figure 7. The 95% stripping fraction is achieved for a resonator of 40 folds and a power flux on the mirrors of 75 kW/cm^2 . Cooled mirrors of SiC will be used with a reflectivity of greater than 0.999 to handle this high power flux.

The parameters of the folded laser resonator have been calculated by a model based on the Rigrod analysis.¹⁰ These are summarized in Table 4. The laser gain is for the TRW supersonic COIL laser and the gain length is selected to produce the 75 kW/cm^2 for 40 folds of the resonator. A 70 kW COIL laser will be required for the beamline on each end cell. Electrical efficiencies of up to 16% have been

previously estimated for this laser.¹¹ The effect of this laser electrical efficiency on the total electrical efficiency utilized in the system design is shown in Figure 8, and produces beamline efficiencies of greater than 70% excluding power supply losses.

The laser arrangement shown in Figure 1 consists of an isolated laser coupled to the rear of the beamline in a low magnetic field region. The laser light is sent to a series of mirrors at the ends of long tubes which act to protect the mirrors from any sputtered materials in the beamline. These tubes are fabricated from cooled aluminum for low activation. A separate set of mirrors are provided for use with the redundant ion source, but the laser beam from a single gain section can be moved to these mirrors during operation so that only one laser is required per end cell.

MAGNETIC SHIELD

The fringing field of the MARS magnets must be shielded away from the injection system to avoid perturbation of the ion beam trajectories and to avoid interference with the operation of the ion source discharge and self-extraction system. The fringing field within the ion source must be less than a few Gauss, and the fringing field in the neutralizer must be less than 5 Gauss. Within the TFF, the tolerance is somewhat larger because the electrostatic strong-focusing corrects for weak magnetic perturbations.

We propose to enclose the entire injection system in a cylindrical super-conducting magnetic shield as shown in Figure 9. Such a shield performed well in the Baseball II experiment¹² in a magnetic field of 0.15 Tesla. The cylindrical shield will be about 6 meters in diameter and 8 meters long. The shield will enclose both ends of the cylinder, except for apertures required for the beam, the structure, power, cooling, lasers, pumping, etc. The main shield will be a single sheet of Niobium-Titanium several millimeters thick, operating at 4 degrees Kelvin and engineered to exclude a maximum field of 0.6 Tesla with a superconducting current density of 100 kA/cm². The magnetic shield will be fabricated of sheet metal, joined by heliarc welding.

The superconducting shield will operate in a separate vacuum system, as shown in Figure 9. A steel structure is required inside the shield to resist the magnetic forces. Thermal shields are required at liquid nitrogen temperature to reduce the radiative heat load on the liquid-helium temperature superconductor. The superconducting shield is protected by neutron shielding.

To be conservative, a variable-pitch bucking coil will be installed outside the superconducting shield to buck out the fringing field component parallel to the beam axis. Because of the required penetrations through the main magnetic shield, supplementary shielding

is required around the sensitive parts of the injection system. The supplementary shielding will consist of a box of mu-metal or magnetic material surrounding the ion source and a similar box surrounding the neutralizer. In each case the supplementary shields operate at the voltage of the components they are adjacent to.

TRAPPING FRACTION

In principle, the sloshing ions could be injected either at the point of maximum potential (Point A) or at the opposite turning point (Point A'). Injection at Point A has the liability of locally depositing a cold electron with each ionized neutral. The cold electron will be electrostatically trapped by the high potential and will require heating to several hundred keV. For this reason it is preferable to inject sloshing ions at Point A', although this requires a higher injection energy because of the potential difference. At this point the plasma cross-section is wide and thin, with semi-diameters 1.57 and 0.14 meters, respectively. To get a reasonable trapping fractions, the 475 keV beam will be injected in the long direction, which is parallel to the x-axis at the +z end of MARS.

In a three-dimensional magnetic field, Point A' is actually a three-dimensional surface defined by the condition $B(\text{vacuum}) = 5.56$ T. The injection path is chosen to coincide as closely as possible with this surface. This is the reason Figure 1 shows the injection path at an angle of 75 degrees relative to the z axis. The path length for trapping of the sloshing ions is about 1.6 meters.

The beam of fast atoms will be trapped by ionizing collisions with four species of trapped particles: (charge exchange is negligible at these high relative speeds)

- 475 keV sloshing D^+ ions trapped in the thermal barrier
- 28 keV thermal D^+ and T^+ ions either trapped in the barrier or passing through
- 28 keV thermal He^{++}
- 24 keV thermal electrons

Table 5 shows the computation of the reaction rate $\langle n \rangle \langle \sigma v \rangle$ for ionization of the 475 keV neutrals by collisions with each of these species. Here $\langle n \rangle$ is the average density of each of these species along the injection path and $\langle \sigma v \rangle$ is the rate coefficient for ionization, averaged over the distribution of relative speeds. If the density profile is quartic, the relationship between the average density $\langle n \rangle$ and the z-axis density n is the following:

$$\langle n \rangle = 0.8 n$$

(1)

Since the beam speed is much greater than the thermal speeds of the 28 keV ions, the relative speed is simply equal to the beam speed. In the case of the 475 keV D^+ , the average relative speed is estimated to be larger by a factor of 1.4. The electron thermal speed is much greater than the beam speed and is available in the literature. From Table 5, the total reaction rate for trapping sloshing ions is 4.33×10^6 ions/s. The penetration depth for exponential beam attenuation is

$$\begin{aligned} &= v/(\text{reaction rate}) = \frac{6.77 \times 10^8}{4.33 \times 10^6} \\ &= 156 \text{ cm} \end{aligned} \quad (6)$$

The portion of the beam path useful for trapping sloshing ions is about $L = 160$ cm. Therefore the trapping fraction is

$$f = 1 - \exp(-L/\chi) = 64.1\%. \quad (7)$$

BEAM DUMPS

The beamline has an internal ion dump and an external neutral dump. The unneutralized ions in the neutral beam are removed by a parallel plate electrostatic deflector system toward the ion dump. Aluminum dumps are desired for low activation, and can be used if the power flux is not too great. Table 6 lists the parameters calculated for copper dumps at normal incidence to the beam. The power flux is low on both dumps, and the copper erosion acceptable. Data for aluminum sputtering at 475 kV is not available, but trends at lower energies indicate that aluminum sputters even less than copper.¹³ The results for copper then represent a reasonable expected erosion for the MARS dumps. The low power fluxes permit low technology dumps such as back cooled plates to be used. Angling the dumps can further reduce this flux if necessary to produce reliable, long life dumps. The beam dumps are not a problem in this system due to the high stripping of the laser neutralizer and the long distance (approximately 20 m) from the accelerator to the neutral dump. If a gas neutralizer had been chosen, the internal ion dump would have had to continuously dissipate over 2 kW/cm^2 for at least one full power year.

RADIATION DAMAGE AND ACTIVATION

As discussed in Reference 9, one of the objectives of the Transverse Field Focusing System is to achieve radiation-hardening by means of the High Energy Beam Transport (HEBT), which transports the high-energy D^+ beam through a radiation shield using a convoluted path to attenuate the neutrons streaming from the reactor plasma to the

injector. If the neutron attenuation is adequate there will be no serious problems with neutron damage or neutron activation of the ion source and accelerator. The neutron shielding for MARS beamlines is shown in Figure 2. It is desired to provide the capability of hands-on maintenance of the ion source and accelerator. In other reactor studies hands-on maintenance has been defined as the capability of maintaining an apparatus such as an ion source with no special radiation shield after a cooling-off period of 48 hours. However, it seems unlikely that economics would permit shutting down the reactor for 48 hours if a maintenance problem occurs. Therefore, if we use this definition of on-hands maintenance we must postulate a remote system for removal and replacement of an ion source. After the cooling-off period the ion source could be serviced with no further remote handling.

Preliminary computations indicate that if low-activation materials are chosen the allowable neutron flux at the injector is about 10^6 n/cm²-s. The neutron flux where the injector duct enters the first wall will be about 10^{13} n/cm²-s. Therefore the neutron attenuation in the neutron shield and in the HEBT must be approximately 10^7 . In principle this attenuation is possible if the beam channel is sufficiently narrow and convoluted.

To verify the feasibility of this neutron attenuation, three-dimensional Monte Carlo computations are required using a code such as MCNP¹⁵. After computation of the residual neutron flux, the resulting activation of the injector materials must be computed. These computations have been carried out in a preliminary version by C. de Seynes¹⁶. His results indicate that on-hands maintenance will be marginal under MARS conditions.

A more exact computation of the neutron flux and activation is now in progress. Preliminary results indicate that the neutron attenuation is greatly improved if realistic three-dimensional boundary conditions are used and if materials are selected for their neutronics properties. Materials for the injector components have been selected for low activation, short decay times, and effective neutron shielding. The major components are as follows:

Neutron shielding	Tungsten
Structural	HT-9 stainless steel
High voltage insulation	Alumina
Electrical and thermal conductors	Aluminum

BEAMLINE PERFORMANCE

Once the beam has been formed, accelerated, and neutralized, the last loss mechanism is due to reionization or scrape off in the long duct leading toward the target. The reionization loss has been calculated by a simple gas evolution and build up code for the MARS geometry assuming a Gaussian beam profile. Figure 10 illustrates this duct loss for the angular divergence of the beam in the short dimension at two gas pressures. The divergence previously calculated of less than 0.5 degrees means that pressures in the duct should be limited to below 5×10^{-6} torr for less than 5% loss. This is the baseline design allowance for this beam loss mechanism.

The final sloshing ion beam line design parameters are listed in Table 7. The 475 keV neutral beam line has a total electrical efficiency of about 63% including estimated power supply losses. Of the 8.86 MW injected into the end cells, 64% or 5.68 MW is absorbed by the plasma. The power transfer efficiency from the wall plug to the plasma is, therefore, $5.68/14.1 = 40\%$, in spite of a 71.5% efficiency in forming, neutralizing, and transporting the neutral beam.

CONCLUSION

The MARS sloshing ion neutral beamline has been based on components under development or planned to be developed in the next few years. The following components must be developed to produce this efficient 475 keV beamline:

1. Continuously operating deuterium negative ion sources capable of producing 5-7 A/m of a sheet beam. This includes an rf plasma generator for long lifetime.
2. A focusing ion beam transport and acceleration system adaptable to the above ion source. The TFF system appears to be the best candidate at this time.
3. Laser photodetachment neutralizer for over 90% stripping of the ion beam.
4. Superconducting magnetic shield capable of excluding transverse fields of up to 0.6 T.
5. Continuously operating cryopumps.
6. Reliable beamline power supplies with a high availability.

The beam dump technology is presently available. If a gas neutralizer is ultimately used, then some type of energy recovery will have to be developed to protect the interior ion dump. In addition, research on the cleaning and conditioning of neutral beam components

leading to faster turn-on times is necessary. The availability of future reactors with neutral beams will increase if conditioning of the surfaces is understood.

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Table 1. Advantages and Disadvantages of Transverse Field Focusing (TFF)

Advantages over alternatives such as MESQ and MEQALAC

- Higher beam-carrying capacity ($40\text{--}60 \text{ mA/cm}^2$, $\sim 8 \text{ A/m}$)
- Compatibility with LBL sources of ribbon-shaped D^- beams
- Compatibility with the laser photodetachment neutralizer
- Now under active study and development at LBL
- Moderate electric field requirements ($20\text{--}50 \text{ kV/cm}$)
- Beam transport for several meters and around corners
- Compatibility with neutron shielding.

Disadvantages

- Loss of 15-20% of the beam by gas collisions (mostly at low energy)
 - Power losses by secondary electrons
 - Versions of the Culham effect require adequate gas conductance
 - Substantial requirements for space and for magnetic shielding
 - New development is required.
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Table 2. Accelerator Parameters

	<u>Voltage</u> (kV)	<u>Pressure</u> (torr)	<u>Current Lost</u> (%)	<u>Power Lost</u> (MW)
Source	475	10^{-3}	--	0.54
Pre-accelerator	395	2×10^{-4}	15	0.33
LEBT	395	$10^{-4} - 10^{-6}$	9	0.17
Accelerator	395 - 50	10^{-6}	1	0.06
HEBT	50	10^{-6}	1	0.09
Neutralizer	0	10^{-6}	5	0.49
Duct/Collimator	0	10^{-6}	5	0.47
TOTAL	475	-	36%	2.15 MW

Table 3. Summary of Neutralizer Options

	<u>Gas/Vapor Cell</u>	<u>Plasma Cell</u>	<u>Laser</u>
Optimum Stripping Fraction	50-60%	~ 80%	> 95%
Exiting Species	D ⁰ , D ⁺ , D ⁻	D ⁰ , D ⁺ , D ⁻	D ⁰ , D ⁻
Gas load	> 10 ¹⁷ mol/cm ² of neutralizer	< 10 ¹⁶ ions/cm ²	None
Power Requirements	None	Unknown	0.5-1 MW
Level of Development	Developed	Not Developed	Under Development

Table 4. Laser Photodetachment Neutralizer Parameters

• Folded Chemical Oxygen Iodine Laser (COIL) Resonator

Mirror size	3 cm x 4 cm
Reflectivity	0.999
Window transmission	0.999
Gain	0.01 cm^{-1}
Gain length	400 cm
Scattering losses	0.2%
Power on mirrors	75 kW/cm^2
Neutralizer length	2m
Number of folds	40
Laser efficiency	10%
Laser power	70 kW
Wall power	0.7 MW (each)
Stripping fraction	95%

Table 5. Computation of Reaction Rate

<u>Specie</u>	<u>D⁺</u>	<u>D⁺ & T⁺</u>	<u>He⁺⁺</u>	<u>Electrons</u>	<u>Total</u>
Temperaure, keV	475.	28.	28.	24.	
<n>, 10 ¹³ cm ⁻³	2.97	4.35	0.261	7.84	
v (relative), 10 ⁻⁸ cm/s	9.57	6.77	6.77	>> 6.77	
Sigma, ionization cross-section 10 ⁻¹⁶ cm ²	0.4	0.73	2.9		
<σ v>, 10 ⁻⁸ cm ³ /s	3.83	4.98	19.6	0.65	
<n> <σ v>, reaction rate, 10 ⁶ ionization/s	1.14	2.17	0.51	0.51	4.33

Table 6. MARS High Heat Flux Components - Neutral Beamlines

<u>Beam Dump</u>	<u>Average Power Density (W/cm²)</u>	<u>Total Power (MW)</u>	<u>Erosion Rate For Copper (cm/month)</u>	<u>Dump Life (Years)</u>
Interior (ions)	190	0.3	1×10^{-4}	78
Exterior (neutrals)	480	2.26	2.4×10^{-4}	30

- Assumed 15% acceptable loss from 6 mm thick dump
 - Blistering is not a problem
 - Power peaking due to Gaussian Beam Profile is not expected to exceed 1.5 times the average
 - Power levels and lifetime estimates are acceptable for MARS
-

Table 7. MARS Sloshing Ion Beamline Parameters

Energy (keV)	475
Injected Power (MW)	8.86
Trapping Fraction	0.64
Trapped Power (MW)	5.68
Source Current Per End (A)	13.6
Source Size Per End	1.5 cm x 200 cm
Current Density at Source (mA/cm ²)	47
Current Density at Neutralizer (mA/cm ²)	34
Current at Target Per End (A)	9.3
Source Efficiency (kW/A)	20
Source Gas Efficiency (%)	30
Total Laser Power (MW) (2 systems required)	1.4
Beamline Power (MW)	12.4
Neutral Beam Efficiency (%)	71.5
Power Supply Efficiency (%)	86
Total Wall Plug Power (MW)	14.1
Total System Efficiency (%)	62.8
Overall System Efficiency (%)	40.3

Figure 1. MARS Sloshing Ion Beam Line and Dump with Magnetic and Neutron Shielding

Figure 2. MARS Sloshing Ion Beam Line

Figure 3. Schematic Diagram of the LBL Self-Extraction Negative Ion Source

Figure 4. Transverse Field Focusing (TFF) Accelerator and Beam Transport System

Figure 5. Beamline Voltage Profile for TFF Accelerator and Transport Stages

Figure 6. Folded Laser Photodetachment Resonator with Multiple Mirrors

Figure 7. Laser Photodetachment Neutralizer Stripping Fraction vs. Number of Folds

Figure 8. Slashing Ion Beam Line Efficiency vs. Laser Efficiency

Figure 9. MARS Magnetic Field Profiles in Beam Line Location

Figure 10. MARS Sloshing Ion Beam Line Total Duct Losses