RFQ ACCELERATORS FOR HEATING THERMONUCLEAR PLASMAS*

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Abstract

The radio-frequency quadrupole (RFQ) accelerator has been developed to generate high-current ion beams for a wide variety of applications. It has also been suggested that this type of accelerator could be used to produce megawatt ion beams to heat thermonuclear reactor plasmas. For a tokamak reactor, an RFQ accelerator can be designed to provide negative deuterium ions that are neutralized before injection through the tokamak magnetic field. Also, it may be possible to use singly charged, positive, heavier ions that traverse the magnetic field with minimal deflection and then become multiply ionized upon striking the tokamak plasma. We present preliminary RFQ beam-dynamics designs for both deuterium and oxygen ions.

Introduction

In the quest for a method to extract thermonuclear power from a magnetically confined plasma, the tokamak scheme has received intensive study. Results from the Princeton Plasma Physics Laboratory[1] have shown that plasma confinement has been adequate for the highest temperatures attained so far. However, to achieve appreciable levels of commercial power, new methods must be developed to heat the plasma to ignition temperatures. One of the most attractive methods of furnishing additional heating is through the use of a multi-megawatt beam from an ion accelerator. To assist in transporting the beam through the tokamak magnetic field, an accelerator can be used to generate a beam of negative ions, which are then neutralized either in a gas or by photodetachment. After traversing the outer magnetic field, the neutral beam enters the tokamak torus and transfers its energy to the plasma. Initially, deuterium ions of 1-2 MeV/amu were suggested for this purpose, but more recent proposals[2] show that heavier negative ions such as oxygen may be even more suitable. In addition, it may be possible to accelerate singly charged positive ions in the range Z = 5-10 to about 1 MeV/amu and transport them through the tokamak field without the necessity for neutralization.[2]

The radio-frequency quadrupole (RFQ) accelerator has been developed to generate ion beams for a wide variety of applications.[3] Its continuing success makes it a natural candidate for use in tokamak heating. At present, a state-of-the-art RFQ accelerator operating with 425 MHz will accelerate a low-emittance, 100-mA beam of protons from 0.1 to 2.0 MeV. To generate high-power beams for tokamak heating will require RFQ designs that are based on an entirely different region of parameter space. We are aware of no previous work in this area. To illustrate the possibilities, we present two RFQ beam-dynamics designs. One is for a deuterium ion beam accelerated to 1 MeV, and the other is for a singly charged oxygen ion beam accelerated to 16 MeV. Either positive or negative ions can be accelerated, and, if desired, the final energy can be raised by increasing the RFQ length. To meet the objectives, our design procedures required unusual values of several RFQ parameters such as operating frequency, aperture diameter, injection energy, and pole voltage. The emphasis was upon generating the required beams in a single channel. If necessary, multiple-channel RFQ accelerators could be used to further increase the total beam power.

RFQ Accelerators for Deuterium and Oxygen Ions

Accelerators for tokamak heating must have very high beam power. To achieve this, we have examined the beam-current limits[4] for single-channel RFQ accelerators and have selected two high-current designs to illustrate their general properties. These examples have much higher beam currents than any previously discussed RFQ designs. To raise the current capacity, it was necessary to use a low operating frequency for the RFQ, larger negative values of the synchronous phase angle, and higher beam-injection energy. In addition, the usual final accelerator section was eliminated to permit the gentle bunching section to operate through the highest possible range of beam energy. These procedures resulted in output beams with higher transverse and longitudinal emittances than conventional RFQ accelerators, but these trade-offs are acceptable for tokamak heating applications.

The characteristics of the deuterium RFQ accelerator are given in Table I.

TABLE I
RFQ PARAMETERS

Ion	Deuterium	Oxygen
Frequency (MHz)	25	5.9
Energy: initial, final (MeV)	0.2, 1.0	0.4, 16.0
Aperture diam: initial, final (cm)	16, 12	18, 12
Number of cells	34	58
Length (m)	3.4	26
Pole-to-ground voltage (kV)	615	1150
Peak surface field (MV/m)	20	17.5
Input current (A)	2.0 3.0	1.5
Output current (A)	1.8 2.4	1.4
Input rms emittance (cm·mrad)	0.33π 0.33π	0.33π
Output (rms) emittance (cm·mrad)	2.1π 2.1π	1.5π
Output beam power (MW)	1.8 2.4	22

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The beam-dynamics results are from Version B of the PARMTEQ[5] simulation code, which includes space-charge effects. The emittances listed are normalized rms values, without the factor of 4 that is sometimes introduced. For an input beam of 2.0 A, the output beam power is 1.8 MW. For a 3.0-A input, the output beam power is 2.4 MW. The characteristics of the oxygen RFQ accelerator are given in the right column of Table I. The output beam power is 22 MW. By increasing the length of the deuterium accelerator, it may be possible to not only increase the final beam energy, but also to raise the beam current, both contributing to an increase in beam power.

Figure 1 shows the deuterium accelerator pole-tip shape in the x-z plane. The small number of cells (34) and

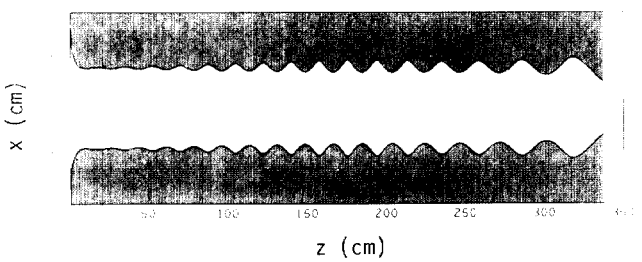

Fig. 1. Deuterium RFQ pole-tip shape in the x-z plane. Ions move from left to right while being bunched, focused, and accelerated.

the high pole-to-ground voltage (615 kV) are consistent with producing the final 1-MeV energy. Figure 2 shows three simulation profiles of the 2.0-A injected beam plotted as a function of cell number. To represent the dc beam, the simulations were performed by injecting a

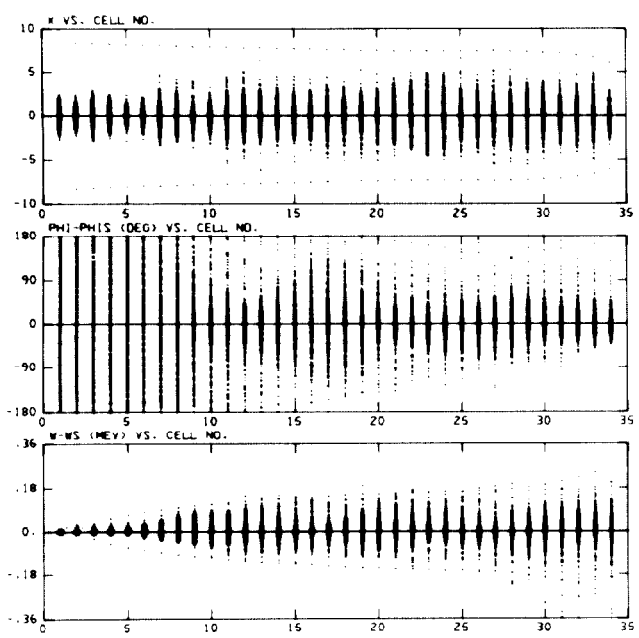

Fig. 2. Simulation results for a 2.0-A beam injected into the deuterium RFQ. The top profile shows the radial position (cm scale) of 360 injected particles as a function of cell number. The center profile shows the longitudinal phase extent of the beam, and the bottom profile is the deviation in energy from the synchronous value.

monoenergetic beam of 360 particles spread uniformly in 2π of longitudinal phase angle. A two-dimensional waterbag distribution was used to represent the transverse phase space. The top part of Fig. 2 shows the radial extent of the beam; the vertical scale is in centimeters. Plotted in the center is the phase spread of the beam, and at the bottom is the deviation in energy from the synchronous value. Figure 3 shows the input and output x and y phase space plotted with centimeter-radian scales, as well as the longitudinal phase space plotted with degree-MeV scales.

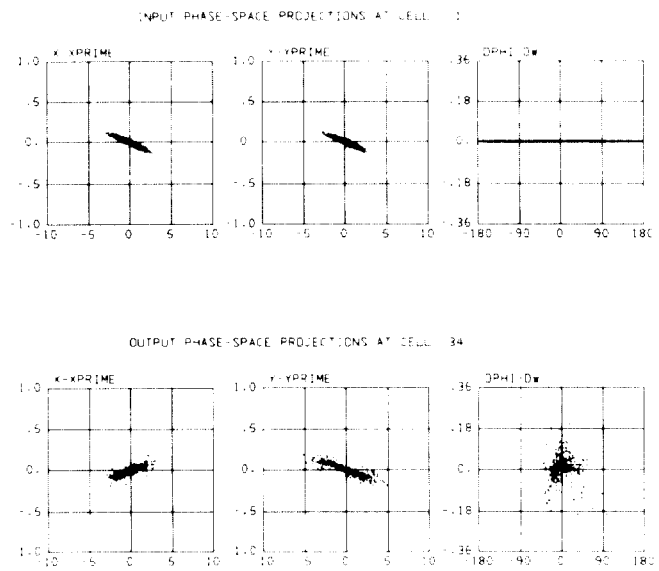

Fig. 3. Input and output phase-space distribution of the deuterium accelerator with a 2.0-A injected beam. The scales are discussed in the text.

An important issue is the accelerator efficiency, and for each RFQ design, we have estimated two efficiency parameters. One is the overall efficiency, wallplug power to beam power, for the injector plus the RFQ accelerator. For this purpose, we assumed the injector was a dc accelerator operating with 100% efficiency. The other efficiency estimate is for the RFQ accelerator alone. These two efficiencies were calculated using the following power ratios:

$$\text{Overall accelerator efficiency} = \frac{P(\text{output beam})}{P(\text{wallplug})}$$

and

$$\text{RFQ accelerator efficiency} = \frac{P(\text{output beam}) - P(\text{input beam})}{P(\text{wallplug}) - P(\text{input beam})}$$

The wallplug power was estimated by assuming the RFQ resonator was of the four-vane type.[6] As discussed later, probably another type of resonator would be used, but power consumption data may be similar. Calculation of the wallplug power was also based upon the product of the following three efficiencies:* dc to rf power, 0.81; ac to dc power, 0.95; and system power, 0.89.

*T. J. Boyd, private communication (1980).

In each column of Table II, the estimated efficiencies are listed for two conditions. They correspond to an RFQ copper resonator operating at room temperature, and to a copper resonator cooled to liquid nitrogen temperature where the conductivity is increased by a factor of 2.5. The power for liquid nitrogen cooling was not included. The room temperature RFQ efficiencies listed in Table II have a range of 32-57%. These values are commensurate to other efficiency estimates[7] made for rf linacs that operate with heavy beam loading.

TABLE II
ACCELERATOR EFFICIENCIES

Ion	Deuterium		Oxygen
RFQ input beam current (A)	2.0	3.0	1.5
RFQ output beam power (MW)	1.8	2.4	22
T = 293 K			
Overall accelerator efficiency (%)	42	45	58
RFQ efficiency (%)	32	36	57
T = 77 K			
Overall accelerator efficiency (%)	56	60	64
RFQ efficiency (%)	47	51	64

Discussion and Conclusions

The operating frequencies of the two accelerator examples are considerably lower than have been used with RFQ four-vane resonators. Probably for the deuterium design (25 MHz), and certainly for the oxygen accelerator (5.9 MHz), another choice of resonator configuration is more appropriate. Several alternatives to the four-vane resonator have been developed for use with low-frequency RFQ accelerators. They are the split-coaxial resonator,[8] the four-rod structure,[9] and the spiral resonator.[10] In addition, a recent paper[11] has discussed a low-frequency resonator having transversely mounted spiral inductors.

Finally, we emphasize that the two accelerator designs presented here were chosen to illustrate the general capability of RFQ accelerators for heating thermonuclear plasmas. These designs are not unique, and other RFQ designs can be generated to achieve optimum performance in a specific application.

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