THE CCVV HIGH-CURRENT MEGAVOLT-RANGE DC ACCELERATOR

O.A. Anderson, W.S. Cooper, W.B. Kunkel, J.W. Kwan, R.P. Wells, C.A. Matuk, P. Purgalis,

We describe a constant-current variable-voltage (CCVV) accelerator, intended to operate in the MeV energy range but tunable down to a few percent of an MeV without loss of beam current. We present experimental results from our 200-keV single-beam prototype system designed to accelerate up to 0.2 A of H^+ or H^- or the equivalent current of heavier ions. The beam is accelerated by a series of stackable 100-keV modules, the number depending on the maximum beam energy required. We discuss a proposed 1 MeV accelerator and a conceptual design for a multiaperture system accelerating 10 A of D^- ions to 1–2 MeV for current drive in a fusion reactor. The use of electrostatic quadrupole focusing allows a conservative design with reduced risk of voltage breakdown and allows us to maintain high currents while varying the beam energy. These features are useful for fusion reactor startup and for industrial applications, such as semiconductor processing and surface hardening.

Introduction

We describe various applications of a constant-current variable-voltage (CCVV) accelerator, and describe recent testing of a prototype. Design details were recently discussed elsewhere [1]. The concept is indicated in Fig. 1. There is an ion source and a preaccelerator [2, 3], which are not relevant here. There is an ESQ matching module and an ESQ-focused main accelerator, which could operate at constant current with variable voltage over a range as large as 20–1000 kV.

The CCVV accelerator is a flexible, pencil-beam version of the sheet-beam transverse-field focusing (TFF) dc accelerator, which we previously developed and tested [4], [5]. The system described here differs from others that have been proposed [6] or built [7] in its CCVV features and in simultaneously offering easily stackable modules and dc operation. Each pair of ESQ rods has a separate electrical connection, allowing independent control of focusing and acceleration voltages; this facilitates CCVV operation, modularity, and flexibility in choice of overall length. The average gradient can be made uniform and the acceleration channel can be lengthened to match the length of the graded insulating column (Fig.1). These features simplify construction and also improve voltage-holding reliability.

Our prototype, shown in Fig. 2, can accelerate a single beam of up to 200 mA of H^+ or H^- or the equivalent current of heavier ions; a multiple-beam system would be used for larger currents. The preaccelerator, which operates at a constant 100 kV, is incorporated into a beam-matching module with high pumping conductance. Preliminary operation of this module was reported previously [8]. We have recently added and tested a 100 keV ESQ-focused acceleration module. This 20-cm long CCVV module can be adjusted to either accelerate or decelerate the beam [1, 8]. For energies above 200 keV, more accelerating modules can be added to the stack, as in Fig. 1, where there are nine CCVV modules. We have proposed to build a facility at LBL to test a 1-MeV system [8]. Three additional modules would produce the maximum beam energy of 1.3 MeV required for the current U.S. baseline design for ITER (the International Thermonuclear Experimental Reactor) [9], as discussed further on.

CCVV Acceleration

Each pair of ESQ rods in the CCVV accelerator (Fig. 1) has separate electrical connections, allowing continuous adjustment of beam energy while maintaining a uniform average voltage gradient if desired. Since the current-carrying capability is independent of the average longitudinal gradient, we can make the accelerator internal length fit the external insulator length. In our designs for experimental facilities [8], we choose a length which allows operation in air rather than SF_6. For lower voltage applications, as in our prototype 200 kV accelerator (Fig. 2), an average gradient of 5 kV/cm is reasonable, so that our 100 kV module length is 20 cm. In the design for a 1-MeV facility, the lengths of most of the stackable modules were increased to 30 cm, giving 3.3 kV/cm [8].

Our freedom to lengthen the accelerator should also increase reliability for voltage holding. It reduces internal gradients and the solid angle accessible for voltage breakdown mechanisms along the beam path. The ESQ focusing forces also remove most secondary ions and electrons generated within the ESQ sections. Long-path breakdown along the pumping space is avoided as discussed in Ref. [1].

A beam envelope simulation for the ten-module, 1000-keV CCVV accelerator of Fig. 1 is shown in Fig. 3. The ESQ voltages for

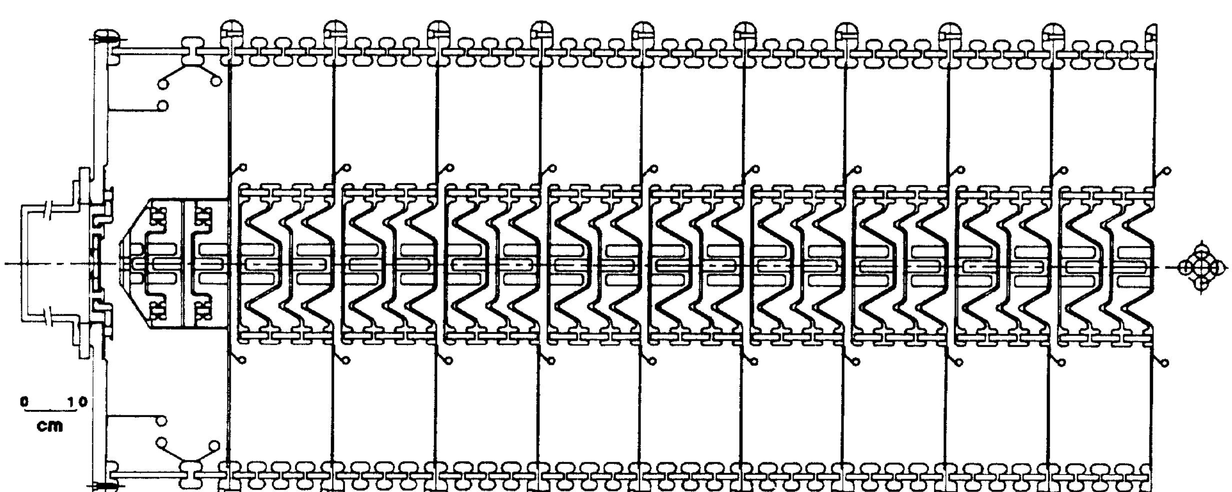

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Fig. 1. Conceptual design of 1-MeV CCVV accelerator, showing 100-keV matching/pumping module and nine CCVV accelerator modules of 100 keV each. The overall length is about 2 meters, not counting the ion source.

this structure are determined by the beam current density, the emittance, and an assumption about the acceleration voltage gradient (assumed uniform in this case). The quadrupole transverse voltages were chosen to be proportional to the fourth root of the beam energy. Electrical and mechanical tolerances are discussed in Ref. [1].

200-keV CCVV Prototype

The 200 keV prototype is shown in Fig. 2. The first module contains the ESQ-focused matching/pumping section. The round, nearly parallel beam extracted from the ion source is transported at about 100 keV and converted into a phase-space format that is matched for subsequent ESQ acceleration. Gas pressure from the ion source is rapidly reduced because of the high pumping conductance in the beam extraction region and the open construction of the ESQ cage. A Monte Carlo code was used for the system design [1].

A single 100-keV ESQ accelerating module is shown in Fig. 2; details of the mechanical design are given in Ref. [1]. In the case of H^- or D^- operation, beam stripping produces heat loads and electrical currents to the electrodes; water flow and power supply requirements were estimated with the help of computer simulations [1]. As discussed further on, the measured loads turned out to be smaller than our conservative estimates.

Testing the CCVV Prototype

The matching/pumping module was tested with a 1.4 cm diameter H^- beam (measured at the source aperture) at 100 kV beam energy. Pulse length was up to 3 seconds without any breakdown problems. There was no measurable beam loss. The amount of full energy electrons in the beam was too small to be measured (less than one or two percent). The beam emittances before and after the ESQ module were equal within our 10 percent measurement uncertainty. The envelope parameters of the output beam were in reasonable agreement with those predicted by an envelope code. Using a larger diameter beam (2.9 cm), we transported up to 64 mA of H^- beam through the first module. The current was limited by the performance of the present H^- source.

Because of test stand scheduling conflicts, only preliminary tests of the the CCVV accelerator module have been performed. We used the 1.4 cm diameter beam at about 30 mA, running 70 ms pulses at 200 keV. We will run long pulses and obtain 200 kV emittance data when the test stand is again available (probably in April).

In our design it was difficult to estimate the effect of stray particles from beam-gas collisions. Even though our H^- source was operated at high gas pressure (14 mTorr) in order to maximize its output, our ESQ electrode currents (around 4 mA) were much smaller than our worst-case estimates. Our open-system high pumping conductance design was evidently quite effective.

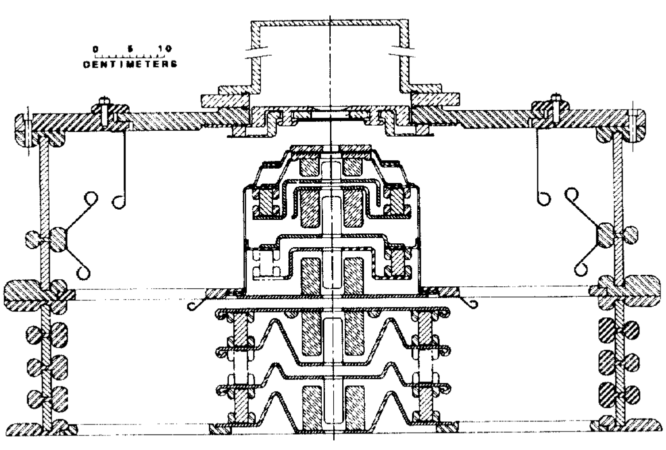

Fig. 2. The 200-kV CCVV prototype, showing matching/pumping module and a single CCVV acceleration module. Small insulating support rods are shown near the ESQ electrodes.

ITER Beamline Design

At present the baseline design for the ITER (International Thermonuclear Experimental Reactor) neutral beam system [9] calls for 70 MW of D^0 delivered to the plasma. To meet this requirement it is proposed to use three ports with a total of 9 beamlines arranged in a vertical stack of three beamlines per port. Each beamline (Fig. 4) contains two vertical arrays of 45 accelerating channels per array and each channel accelerates 0.14 A of D^- to 1.3 MeV. Therefore, each beamline delivers up to 8.75 MW of D^0, so that eight beamlines can deliver the required power while one beamline is on standby.

The proposed system will use improved D^- sources, multiaperture CCVV accelerators, and gas neutralizers. The residual ions remaining after neutralization are swept out by electrostatic deflectors into beam dumps. Cryopanels, located at the accelerator exit and neutralizer exit pump the excess gas.

The 1.3 MeV ESQ-focused accelerator design includes a 100 keV matching/pumping module and twelve 100 keV accelerator modules, with overall length 260 cm. If the energy requirements should change, modules can be added or deleted. The CCVV feature permits varying the beam energy at constant current, avoiding shine through during the low plasma density phase of startup.

The size of the CCVV modules and the number of modules required was determined by the chosen current per channel (0.14 A). If high-current sources become available, the size of the modules can be scaled up and the number reduced. For example, 0.56 A/channel could be handled by ESQ modules operating at the same electric field strengths but scaled up a factor of two in all dimensions. The mechanical construction would be considerably simplified.

Power System

We plan to use a different approach from neutral beam systems based on positive ions, where the low-impedance accelerators handle large currents (~100 A) at relatively low voltage (~100 kV) and fast series and shunt switches, acting in a few microseconds, provide fault damage protection. This type of protection is less practicable for megavolt CCVV applications; fortunately, the increased accelerator impedance favors other types of control, as discussed below.

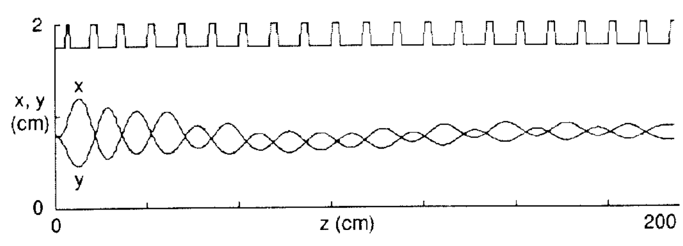

Fig. 3. Beam envelopes and quad locations for a system (see Fig. 1) with standard matching/pumping section and nine CCVV modules, accelerating 200 mA of H^- from 100 keV to 1 MeV.

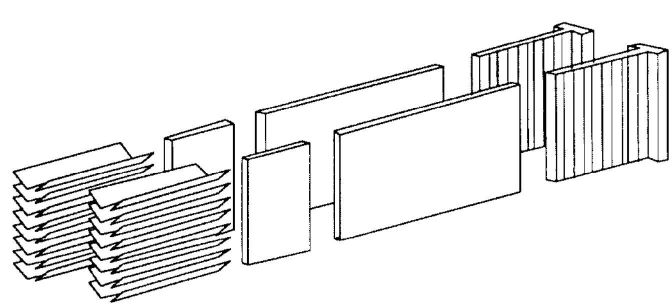

Fig. 4. Schematic of ITER beamline. From right to left are the CCVV accelerator assemblies, the gas neutralizers, the electrostatic ion separators, and the beam dumps.

Accelerator Power Supply for ITER

The high-frequency technology under investigation for generating high voltage (1 MV) for ITER is similar to that adopted widely by the low voltage power supply industry. To reduce the size of the transformer components we propose to use a frequency between 50 and 100 kHz. Although the overall size of a high voltage power supply is mainly dictated by the high-voltage gradients, the use of high frequency reduces the energy storage due to stray capacitance and allows rapid primary control. This should eliminate the need for costly shunt switching fault protection. Switching power supplies using solid state devices have achieved efficiencies approaching 90% in low voltage converter applications [10]. We are also investigating the use of vacuum devices.

To achieve high overall efficiency, we are investigating a modularized step-up technique to generate the high voltage which we call the Cascaded Resonant Transformer Rectifier (CRTR) system (Fig. 5). We maintain high efficiency by minimizing the leakage inductance, maximizing the shunt inductance, and by tuning to cancel the reactive losses. The ferromagnetic materials being tested are the nickel-zinc and manganese-zinc ferrites. We are in the process of constructing a ten stage, 100 kV prototype driven by an advanced MOSFET frequency converter. Details will be given upon completion of the prototype.

Although high frequency technology reduces the energy storage, in the megavolt range the electrodes must nevertheless be protected from the energy in stray capacitance. In the standard way, a lossy inductance will be inserted in series with the stray capacitance. This lossy inductance, which uses toroidal magnetic material, limits the spark-down current and absorbs most of the energy.

CCVV Deceleration for Ion Implantation

A CCVV module can also be used for deceleration. This reduces the design current, but, in fact, applications such as semiconductor processing require relatively small current. Using the same envelope code that we used to design our CCVV accelerators (cf. Fig. 3), we have shown [1] that the output voltage of our CCVV prototype (slightly modified) can be varied between 200 kV and 20 kV at a constant current of 80 mA. The beam energy in the matching/pumping module remains unchanged. We hope to test this type of operation in the near future. A design optimized for low energy flexibility, with quadrupoles shortened to reduce the phase advance, could be tunable from 200 kV to 10 kV or less, depending on the current.

Advanced Semiconductor Applications

Most modern commercial ion implanters for semiconductor manufacturing are multi-purpose machines, operating from 200 kV to less than 20 kV. The lower energies are used to produce fast switching shallow junction devices. Devices have also grown vertically, to three and four metal layers, so that 200 kV performance remains important. Reasonably constant throughput and good divergence are also essential in a production system. In present commercial systems, these requirements are met by two-stage accelerator systems, e.g., a 20 kV injector with a 180 kV boost. Current drop off becomes serious only below 20 kV, and beam divergence of 1° to 2° has been adequate up to now. However, as feature sizes push below 1 micron, future systems may require reduction of beam divergence to 0.5°, or less, for high aspect ratio structures. The CCVV decel structure is capable of meeting these anticipated future requirements.

Our CCVV envelope results described above take the beam emittance into account but not the effect of nonlinearities in the system. Fully self-consistent particle dynamics in the CCVV system will soon be studied using the ARGUS 3D code [11]. Meanwhile, we have estimated the output divergence angle at low energies. Depending on the ion source, beam divergence of less than 0.5° appears to be feasible. Beam expansion can be used to cool the beam to a lower transverse temperature than that in the plasma source.

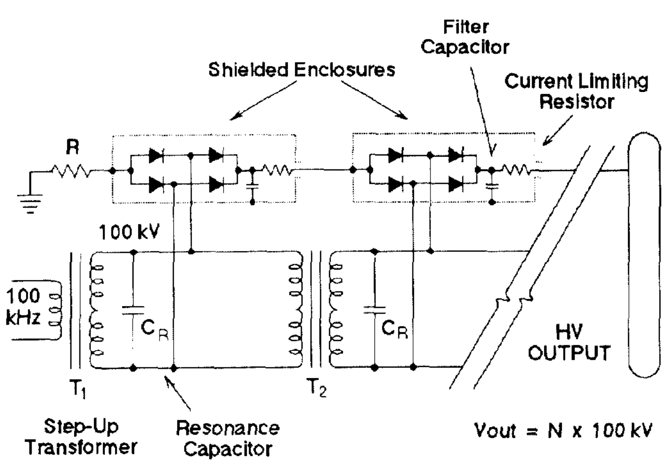

Fig. 5. Proposed power supply concept. Two modules are shown; ten would be required for a 1 MV system.

Acknowledgments

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