CONSTANT-CURRENT VARIABLE-VOLTAGE (CCVV) ACCELERATORS

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Variable beam energy at constant current is useful for various applications, such as (1) neutral injection in fusion reactors, where the beam energy should be reduced during the startup phase, and (2) ion implantation in semiconductors. We discuss a dc accelerator which, in a multiaperture configuration, could accelerate 10 A or more of D⁻ ions to 1—2 MeV for neutral injection. In the case of ion implantation, a single channel would be used for ions such as B⁺ or As⁺. Constant current is maintained by strong focusing while the energy may be varied over a very large range. The beam is accelerated by a series of identical modules that contain electrostatic quadrupole (ESQ) focusing elements; these are designed for conservative voltage-holding in air. We present numerical simulations that support various details of the design concept. We discuss our 200-keV prototype system which uses a single ESQ accelerating module; its single channel was designed for 200 mA of H⁻. It will soon be operational and will provide the first demonstration of ESQ-focused CCVV operation.

Introduction

A new constant-current variable-voltage (CCVV) accelerator will be described. The system, shown in Fig. 1, consists of an ion source [1], a preaccelerator operating at fixed voltage and current [2], [3], a matching/pumping module, and an ESQ-focused main accelerator. The latter consists of a series of identical accelerating modules; it could operate at constant current with variable voltage with a range as large as 20—1000 kV.

The CCVV accelerator is in some respects a pencil-beam version of the sheet-beam transverse-field focusing (TFF) dc accelerator, which was previously tested by the Magnetic Fusion Energy (MFE) group at LBL [4], and many of the characteristics are similar. Also, the Heavy Ion Fusion Accelerator Research (HIFAR) group at LBL has had extensive experience with electrostatically focused transport and acceleration of pulsed beams [5], and we have drawn on this experience as well. The system described here differs from these and others that have been proposed [6] or built [7] in its CCVV feature and in simultaneously offering both (1) identical, stackable modules, and (2) dc operation.

Our particular ESQ rod support structure allows independent control of focusing and acceleration voltages; this is the key to CCVV operation, to modularity, and to flexibility in choice of overall length. We can lengthen the acceleration channel to match the length of the graded insulating column, as in Fig. 1; this in turn reduces internal gradients and the solid angle accessible for voltage breakdown mechanisms. The ESQ focusing forces also help to avoid breakdown by sweeping out most undesired particles transversely.

We describe design details of a prototype, shown in Fig. 2, which accelerates a single beam; future CCVV systems will use multiple apertures if larger currents are needed. This fusion prototype system uses a volume-production H⁻ or D⁻ source [1]. The preaccelerator, which operates at a constant 100 kV, includes an electron trap [2], [3]. The preaccelerator is incorporated into a matching/pumping unit; we will call this combination the <u>PMP module</u> for short. In order to minimize H⁻ stripping and its side effects, the PMP module is designed for high pumping conductance. The system is designed to handle up to 200 mA of H⁻, about twice the value presently available from the source. The PMP module is followed by a well-pumped acceleration module which operates at very low pressure. This CCVV module can add as much as 100 keV to the beam energy. For energies above 200 keV, more accelerating modules can be added to the stack, as in Fig. 1.

We also discuss applicability of the CCVV concept to ion implantation in semiconductors; for this case it is especially useful to be able to operate over a wide energy range at constant current.

CCVV Acceleration

At an early planning stage, we decided that the system would operate in air, rather than SF₆. We chose a conservative average field of 5 kV/cm for the graded insulator, which led to a length of about 2 meters for a 1-MeV system. Envelope simulations showed that a CCVV accelerator could have been designed with only one-fourth of this length while maintaining conservative fields (nominally 40 kV/cm) between electrodes.

Such a discrepancy in length is undesirable. It occurs in highperveance Pierce columns, which necessarily have short acceleration channels. A discrepancy between internal and external lengths requires re-entrant electrode supports, each with its own individual shape; such a structure cannot be extended in a modular fashion. Moreover, a short-accelerator, long-insulator design does not take advantage of the increased voltage-holding reliability that could result if the acceleration length were stretched out to agree with the length of the external insulator. Our new approach overcomes these problems: the modules are stackable so that if the maximum beam energy needs to be changed, modules can simply be added or removed; voltage breakdown is alleviated as discussed above; cost is reduced because all of the modules are identical.

The 100-keV CCVV modules shown in Figs. 1 and 2 are each 20 cm long. There are nine in the 1-MeV example shown in Fig. 1; in fact, we are planning to build a facility at LBL to test a 1-MeV system.



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

Six additional modules would produce the maximum beam energy of 1.6 MeV required for the current U.S. baseline design for ITER (the International Thermonuclear Experimental Reactor).

Our design avoids breakdown along the beam path by stretching out the channel and by using transverse fields; it avoids breakdown along the external insulator by choosing a conservative gradient. However, in high-voltage CCVV applications with many modules, there may be danger of long-path breakdown along the internal pumping space. Breakdown voltage can become relatively independent of electrode spacing above a certain voltage level [8]. This effect could be avoided in our system by inserting suitable devices between modules to limit the available path lengths.

A beam envelope simulation for a seven-module, 800-keV case is shown in Fig. 3; Table 1 gives the electrode voltages used in this simulation. (Note that the focusing voltage V_f is defined as the voltage between pairs of electrodes in a quadrupole.) The table shows that the voltage along the external insulator is graded fairly uniformly for full-voltage full-current operation. If the voltage were reduced at constant current, the focusing voltages would also be reduced; however, the relationship is not quite linear.

The effects of perturbations in electrode voltages and beam current have been simulated. The results do not impose unusual stringency on the power supply specifications. Our estimates of the effect of misalignments and the experience of the HIFAR group at LBL do not indicate exceptionally tight mechanical tolerances for most CCVV applications.

Preacceleration/Matching/Pumping Module

The PMP module occupies the central portion of Fig. 2. The ESQs in this module convert the round, nearly parallel beam formed by the preaccelerator into a size and shape that is suitable for subsequent ESQ



Fig. 2. CCVV prototype, showing PMP module and a single CCVV acceleration module. The large graded insulator rings are cast from epoxy; the small insulating rods near the ESQ electrodes are Torlon.

We use ESQ-focused transport instead of the usual combination of magnetic quadrupoles and gas neutralization used in other low-energy beam transport (LEBT) systems for intense H⁻ beams. Our approach avoids plasma buildup and the plasma fluctuation problems that have occurred in some of these other systems.

200-keV CCVV Prototype

The 100-keV PMP module and the single ESQ accelerating module shown in Fig. 2 form the 200-keV prototype system. The large cylindrical insulators shown in the figure are cast from Abatron epoxy and are bonded to the aluminum gradient rings; this assembly is wellshielded from the accelerated beam by the deeply corrugated electrode supports. Numerical simulations showed that the ends of the insulators need to be deeply recessed in the gradient rings in order to obtain acceptably low field strengths at these critical points. This limits the mean overall gradient to the 5 kV/cm figure mentioned above. A model was built and tested; breakdown in air always occurred between rings, not along the insulator, and occurred at about twice the anticipated operating voltage.

The corrugated ESQ electrode supports were economically fabricated by a commercial spinning/rolling technique. The main cost was





TABLE 1 Electrode voltages used in the 200 mA H⁻ beam envelope simulation (Fig. 3). V_s is referred to ion source, V_g is referred to ground, and V_f is the focusing voltage (see text). Module 1 is the PMP module.

Mod	Elect	Vs	Vg	Vf	[Mod	Elect	Vs	Vg	Vf
1	1a	100	-700	-20	Ī	5	5a	421	-379	29
	1b	80	-720				5b	450	-350	
	1c	80	-720	20			5c	469	-331	31
	1d	100	-700				5d	500	-300	
	1e	79	-721	21		6	60	510	281	31
	1 f	100	-700			0	0a 6h	550	250	51
2	2.	100	670	22			60	571	200	20
2	2a 25	120	-072	22			64	600	-200	2)
	20	177	-050	22			ou	000	-200	
	20	200	-023	25		7	7a	618	-182	32
	20	200	-000				7b	650	-150	
3	3a	227	-573	23			7c	666	-134	- 34
	3b	250	-550				7d	700	-100	
	3c	275	-525	25	[0	80	710	Q 1	31
	3d	300	-500			0	oa Rh	719	-01 50	51
	4	225	175	25			80	784	-16	16
4	4a	323	-4/5	25			00 84	200	0	10
	4D	274	-400	26			ou	000	0	
	40	3/4	-420	20						
	40	400	-400							

the template, so that duplicate parts for additional modules will be inexpensive. We adopted the spinning process for other parts, such as corona rings.

Computer simulations were used to calculate heat loads on the ESQ accelerator electrodes and determined the water cooling requirements. The heat loads mainly originate from stripping of H^- in the region of high gas density near the source. In addition to heat, currents are also produced in the various electrodes. Our simulations provide estimates of these currents and suitable power supplies have been provided.

Power Supply

We plan to use a different approach from the one used in power supplies for positive-ion-based neutral beam systems. These positive-



Fig. 4. Monte Carlo simulation results for gas pressure, H⁻ beam stripping loss and power loss along beam axis in the preaccelerator/matching/pumping module.



Fig. 5. Beam envelopes and quad locations for the one-CCVVmodule prototype system accelerating 80 mA of H⁻ to the full energy of 200 keV (see text).

Fig. 6. Beam envelopes and quad locations for the one-CCVVmodule prototype system decelerating the same beam to 30 keV. ion accelerators handle large currents (~100 amperes) at relatively low voltage (~100 kV) and are protected from damage by fast series and shunt switches which remove voltage and divert current in a few microseconds. CCVV accelerators will reach such large voltages that this type of switching may become impracticable. However, we believe that fast switching will be unnecessary because of the greatly increased accelerator impedance. It should be possible to protect against breakdown damage by a combination of current-limiting resistors and primary control of the power supplies. The beam current will be switched on and off via the plasma source. We will test this simpler electrical system with the 200-keV prototype accelerator.

The voltages required for the various electrodes were determined by envelope simulations such as the one shown in Fig. 5. The parameters I = 80 mA, $\in_N = 1.6 \times 10^{-6} \pi$ m-rad, represent typical operation of our present H⁻ source. The beam in this example is accelerated to the full energy of 200 keV.

CCVV Deceleration for Ion Implantation

Not only can a CCVV module accelerate the beam, it can decelerate as well, if the voltages are rearranged. This feature could be useful for ion implantation in semiconductors, where one needs to produce layers at a wide range of depths. Simulations (such as in Fig. 6) show that the output beam energy can be reduced from 200 keV to 30 or even 20 keV without any change in current; the beam in the PMP module stays at the nominal 100-keV energy. The simulations shown in Figs. 5 and 6 were done for an H⁻ beam but would apply approximately to an ion implantation beam (e.g., B⁺ or As⁺) for a current reduced by the square root of the mass ratio; the power supply polarities would, of course, be reversed.

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References

[1] K.N. Leung, K.W. Ehlers, and R.V. Pyle, "Optimization of H⁻ Production in a Magnetically Filtered Multicusp Source," Rev. Sci. Instrum. <u>56</u>, 364 (1985).

[2] O.A. Anderson et al., "Design of a 200 mA DC H⁻ Injector for an RFQ," Proc. of the 1987 Particle Accelerator Conference, Washington, DC, March 16-19, 1987; IEEE Cat. No. 87CH2387-9, p. 289.

[3] O.A. Anderson, W. S. Cooper, W. B. Kunkel, C. F. Chan, L. Soroka, C. H. Kim, A. F. Lietzke, C. A. Matuk, P. Purgalis, and R. P. Wells, "Accelerator and Transport Systems for High-Current Negative-Ion Beams," Proceedings of the IAEA Technical Committee Meeting on Negative Ion Beam Heating, Culham Laboratory, July 15-17, 1987; also published as Lawrence Berkeley Laboratory report LBL-23748.

[4] O.A. Anderson, D.A. Goldberg, W.S. Cooper and L. Soroka, "A Transverse-Field Focusing (TFF) Accelerator for Intense Ribbon Beams," 1983 Particle Accelerator Conference, Santa Fe, NM; IEEE Trans. Nucl. Sci. <u>30</u>, 3215 (1983).

O.A. Anderson et al., "Overview and Status of the Transverse-Field Focusing (TFF) Accelerator," 1985 Particle Accelerator Conference, Vancouver, B.C.; IEEE Trans. Nucl. Sci. <u>32</u>, 3509 (1985).

[5] D. Keefe, "Developments in Accelerators for Heavy Ion Fusion," IEEE Trans. Nuc. Sci., <u>32</u>, 3277 (1985); and other papers in this volume.

[6] D.A. Goldberg et al, "A Multi-Apeture Electrostatic Quadrupole (MESQ) Accelerator for Neutral Beam Injection," Bull. Am. Phys. Soc. <u>27</u>, 1142 (1982).

[7] E.A. Abramyan et al, "Transformer Type Accelerators for Intense Electron Beams," IEEE Trans. Nucl. Sci. <u>18</u>, 447 (1971)

[8] A. Maki et al, "On the Breakdown Phenomena in Vacuum," SINKU [Japanese Journal of Vacuum Technology], <u>18</u>, 119, (1975).