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April 20, 1951

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It is generally believed that charged particles cannot be accelerated from ground potential to ground potential unless they pass through a system which has associated with it a time varying magnetic field. D.c. electric fields must satisfy the equation $\oint E ds = 0$, while the time varying fields used in radiofrequency accelerators and betatrons are freed from this restriction of scalar potential theory. In 1932, A. J. Dempster[1] produced protons with an energy of 45 Kev, by passing them from an electrode at +22.5 kv d.c. to ground. The protons were first accelerated to ground potential, with an energy gain of 22.5 Kev. A small fraction of the protons then picked up an electron from a residual gas molecule, and "coasted" to a second electrode at +22.5 kv. Then a small fraction of these neutral hydrogen atoms lost their electrons, and were accelerated to ground with a second gain in energy equal to 22.5 Kev. An accelerator of this type is obviously impractical for several reasons. The probability of neturalizing a proton varies inversely with a high power of the particle velocity, so the scheme would not work at energies of interest to nuclear physicists. Even at the low energies where neutralization is not negligible, the energy spread of the beam would be wide because charge exchange could take place at all points along the beam trajectory.

It does appear, however, that charge variation can be utilized in a practical manner to circumvent the apparent restrictions of potential theory. If one

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[1] A. J. Dempster, Phys. Rev. 42, 901 (1932).

accelerates negative hydrogen ions (H^- or D^-) to an electrode at +V volts, strips off the two electrons by a thin foil at that point, and accelerates the protons or deuterons to ground potential, he will have doubled the effective voltage of the accelerator. The stripping foil can be of thin collodion, for example, so the energy loss and scattering would be negligible. The stripping cross sections are of order 10^{-16} cm^2, so a foil with 10^{16} atoms per cm^2 will strip more than one half of the beam. Such a foil weighs less than 1 microgram per cm^2. Therefore any physically realizable foil will give good stripping; its thickness can be as small as to give no appreciable straggling or scattering. (The energy loss can be a few hundred electron volts.)

An accelerator of this type is now being designed to give 4 Mev protons. It is to be constructed by L. C. Marshall and J. Woodyard of the Electrical Engineering Department of the University of California. The acceleration column is a conventional one, as presently used in Van de Graaff generators. The overall length is 6 feet, so the gradient is about 0.7 MV per foot. The whole system is immersed in oil, so no high pressure tank is required. The voltage is supplied by a Cockcroft-Walton circuit, which operates at 500 KC. Such a circuit has been brought to a high state development by J. Woodyard, of this Laboratory, and is used as the primary ion source power supply for the Bevatron. The individual sections of the circuit are constructed as "plug-in units," each of which contains two rectifiers, two transformers, and two capacitors. In the event of the failure of some component, one would replace the whole unit which was giving trouble.

One of the most attractive features of the machine is that the ion source is near ground potential, so no electronic or electromechanical devices are required at high potential. One can compensate automatically for variations in the high potential, by changing the injection voltage; the output energy can thus be kept exceedingly constant in time.

Many existing Van de Graaff generators are equipped with duplicate accelerating columns. One column is used as a "differential pumping tube," to handle the gas from the ion source at high potential. It should be possible to accelerate negative ions up the pumping column, which would no longer be needed for its original purpose. In the high voltage electrode, the ions could be bent through 180° in a magnet, then stripped, and finally accelerated back to ground through the usual acceleration column. The magnet would be of the annular type, to save weight, and would require adjustment in its field whenever the energy was charged.

In a magnetic field of 18,000 gauss, the diameter of a proton orbit is approximately:

$$D = 6.3\sqrt{E} \text{ inches}$$

where E is the proton energy in Mev. Since the spacing between centers of the two columns is normally greater than 12 inches, it is seen that the doubling method is practical, in a mechanical sense, for all presently operating Van de Graaff generators.

The literature on ion sources for negative hydrogen ions is rather limited, but Bennett[2] describes a source which gave 0.02 μ amp of H^- ions. Dr. James Tuck has recently informed the author of some experimental results on negative hydrogen ion production at Los Alamos. The work was done by W. Arnold, J. Phillips, G. Sawyer, E. Stovall and J. Tuck. It was found that if low energy protons or deuterons were sent through a thin foil of Al or SiO, that up to 20 percent of the incident ions emerged with negative charge. For deuterons of 30 Kev incident on a foil 10 μ gm per cm^2 thick, the ratio $[D^-/D^+ \text{ incident}]$ is 0.20. The ratio $[D^-/D^+]$ emergent, has been measured at several incident energies, and has the

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[2] W. Bennett, Phys. Rev. 49, 91 (1936).

following values: 50 Kev, 4.5 percent; 30 Kev, 7 percent; 20 Kev, 10 percent; 10 Kev, 26 percent. The currents of negative hydrogen ions are limited only by the heating of the foil. One could obtain high currents by using a rotating foil, if heating turned out to be serious. A rotating foil would not be troublesome mechanically, since no pressure difference exists across the foil. Ion sources giving proton currents in excess of one milliampere are now available, so the accelerator proposed in this note should be capable of giving a few hundred microamperes of high energy protons.

The problem of injecting protons into a synchrotron might be simplified by using the charge exchange mechanism described above. There is a well known theorem which states that it is impossible to inject charged particles into a stable orbit in a steady magnetic field. H^- ions could be directed from outside a synchrotron field, onto a thin foil placed at the midpoint of the aperture of the "doughnut." If the ions were tangent to the equilibrium orbit as they passed through the foil, they would reverse their curvature and follow stable circular paths. This method of injection might be very useful in the initial testing of a proton synchrotron, where small currents would be satisfactory. One could explore the orbits in a low, steady field, and assure himself that the magnetic design was correct.

The author is indebted to Dr. Tuck for permission to quote his data before their publication. This work was done under the auspices of the Atomic Energy Commission.