THE TANDEM DYNAMITRON

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SUMMARY

A two-stage tandem accelerator system, powered by a Dynamitron high voltage generator, is currently undergoing factory tests. The parallel-coupled, cascaded-rectifier generator has been designed for a 5 mA current capability at maximum guaranteed voltage for future high current operation. A large diameter gas stripping canal is used in two-stage operation to optimize beam transmission. Titanium getter-ion pumps are mounted in the terminal at the ends of the stripper assembly to insure acceptable vacuum conditions in the fully shielded acceleration tubes. Guaranteed specifications of this model series are 150 μA of targeted proton current at 10 MeV. The injector has delivered up to 250 μA of H^- and the generator has operated at 5.7 MV during initial testing. The complete system is now being assembled for beam test. Some novel features of this new tandem are described and operational performance characteristics measured during factory testing are reported.

INTRODUCTION

Tandem accelerator systems have traditionally been low current devices.[1] Recent developments in the technology of negative ion production have demonstrated that currents in the range of 200 μA to 2 mA of H^- are now readily available.[2, 3] In order to exploit such sources, a new Dynamitron high voltage generator has been developed as the power source for a two-stage tandem accelerator system.[4, 7]

In order to deliver 1 mA target current, the power supply must have a 5 mA current rating. Two mA are required for beam load, the ionization leakage currents are comparable to the beam load[4] and, one mA is used in the resistor divider on the acceleration tubes. The parallel-coupled, cascaded rectifier Dynamitron is designed for a current rating of 5 mA over the voltage range from 1.5 to 5.0 MV.

A detailed description of the main physical features of the voltage generator and the performance results obtained to date are presented. Injector performance data is included to indicate that future beam current performance should well exceed the present guaranteed specifications.

TANDEM SYSTEM DESCRIPTION

A plan view of the prototype Dynamitron tandem system is shown in Fig. 1. This system is being constructed for the Reactor Physics Division of Argonne National Laboratory. In Table I, we have listed the physical and performance specifications of the Dynamitron tandem. Three major functional groupings of equipment can be recognized in Fig. 1: the negative ion injector, the Dynamitron accelerator, and the beam transport system.

Negative Ion Injector[3]

Hydrogen negative ions are directly extracted from the offset-grid duoplasmatron ion source to an energy of 25 keV. The extracted ion beam is focused with an einzel lens through a pair of sweep plates to a rejection aperture. These plates are driven at 2 MHz for pulsed operation, and chop the dc beam to pulses of 25 to 100 ns in time width, depending on sweep amplitude. A gap lens at 125 kV accelerates and focuses the beam through the 30° inflection magnet to a waist near the first gap in the energy modulator (buncher). The buncher is driven at 6 MHz and introduces an energy modulation of the order of 10 keV in the ion beam, for pulsed operation. After drifting through a bunching length of about 2 m, the modulated beam pulse has been compressed to a FWHM < 1 ns.

The ion source is vacuum pumped through an insulating manifold with a 15 cm oil diffusion pump operating at ground potential. Only the ion source and its requisite power supplies are operated at the injection potential of 150 kV. Additional vacuum pumping is provided by a 10 cm station on the buncher housing. A variable electrostatic lens is located immediately before the entrance to the acceleration tube, to provide an optical matching element which will maintain the crossover at the stripper canal for all values of terminal potential. Hence, the injector can be operated at a fixed beam energy, which is required during the pulsed mode of operation.

Dynamitron Accelerator

Voltage Generator. The vacuum tube rectifiers can be seen in operation in Fig. 2. A photograph of the interior of the voltage generator is shown in Fig. 3, viewed from the driven or high energy end. Ninety-two rectifier tubes are used, 46 on each side of the structure. The two large stainless steel liners, which are insulated from the pressure vessel, are the driving RF electrodes. Semicircular corona rings capacitively couple RF voltage from the electrodes to the rectifier cascade. SF_6 gas serves as the insulating medium between the electrodes and the corona rings. The only electrical connection from the power supply to the acceleration tubes is accomplished at the terminal. Electrical gradient along an acceleration tube is established by a resistor divider, with a total resistance of the order of $10^{10}\ \Omega$ ($\simeq$ 500 μA at 5 MV per tube).

This structure, in addition to providing a high current capability, maintains three fundamental properties of the existing Van de Graaff tandems which contribute to their success: relatively small quantities of stored energy on the insulated column structure, a uniform cylindrical section over the length of the column structure for optimum electrostatics, and a self-healing dielectric in the event the terminal or column structure discharges to ground.

With the Dynamitron configuration, the mounting structure must insulate from ring to ring in the cascade, as the driving RF voltages are induced across opposite corona rings. Mechanically, the column structure is a box girder with large sheets of poly-methyl methacrylate oriented as the vertical structural members[5]. Because of the favorable elastic deformation properties in tension of the vertical structural members, it is not necessary to prestress the structure by applying a compressive end load, as is required for a glass structure. These girders can then be cantilevered from each end of the pressure vessel. The two structures are connected in the terminal region with a linkage which distributes the loads in the terminal such that the entire structure appears to be a fully constrained beam. As a measure of the strength of the structure, a cantilevered single column has supported 1500 pounds (682 kg). In the tandem configuration, the column structure can be easily separated into two self-supporting cantilevered beams by removing the connecting linkage.

Acceleration Tubes. A similar self-supporting configuration is utilized for the acceleration tubes. The tubes are located concentric to the centerline of the column. Since the primary structural material is glass, a self-supporting acceleration tube must be prestressed to insure that it remains in compression. The tubes are cemented sections of pyrex glass and stainless steel fully-shielded electrodes, assembled in 2' (0.61 m) modules on a precision jig. Stepped couplings with an elastomer o-ring, seal three modules together to form a 6' (1.83 m) structure with precision stepped end flanges. Delrin (polymerized formaldehyde) cinch rods connect the end flanges across the length of the tube and are tensioned by individual springs to provide the compressional forces. Two flanged sections are then bolted together at the ends to assemble the 12' (3.66 m) acceleration tube required for each end. Each tube is capable of individual support as a cantilevered beam. The entire acceleration tube and stripper assembly, which has a free, unsupported span of 36 feet (11.0 m) has been subjected to extensive load tests. A photograph of the structure, under test on the main factory floor is shown in Fig. 4. A large diameter section is used on the entrance of the negative ion tube, to optimize the optical, vacuum and mechanical properties in this critical region. Mechanical connection is made across the terminal region to evenly distribute the load of the stripper canal assembly. Net deflection under design load is 1.5 mm as measured by a Keuffel and Esser micro-alignment telescope. The structure is elastic, within the resolution of the instrument (± .05 mm). Each tube assembly is supported by an adjustable mount, external to the pressure vessel. Positional adjustments can be made either at these mounts, or at the terminal connecting rods. The only mechanical connection to the pressure vessel or column structure is the bellows pressure seal which surrounds the mounting manifold for each tube. This system has an advantage, that the acceleration tubes are directly supported from the same stable reference as the injector and beam transport system, i.e., the building floor.

Stripper Assembly. Optimum beam transmission through the tandem requires that complete stripping of the negative ion beam occurs at the terminal potential, and that stripping be negligible in the negative ion acceleration tube. In this system, a gas target (O_2, for example) is used as the stripper. Gas is supplied to the center of a long tube, 0.25" (0.63 cm) or 0.5" (1.27 cm) in diameter, and 50" (127 cm) in length. Since target thicknesses of the order of 1000 micron-cm are required[1], the pressure at the center of the canal is about 20 μ. With the smaller diameter canal, it is possible to select apertures at the end of the acceleration tubes such that the majority of the gas load can be pumped down the positive ion acceleration tube. Thus, the requirement for terminal pumping can be avoided. When more intense negative ion beams are employed ($\gtrsim$ 300 μA), the emittance of the beam inevitably increases. Optical considerations then require that the diameter of the canal be increased. Since the conductance of a long tube is proportional to the cube of its diameter, the increased gas load will require terminal pumping for the 0.5" (1.26 cm) canal.

In Fig. 5, a section drawing of the stripper canal is presented. This assembly contains two, high-speed titanium getter ion pumps, mounted on each end of the assembly. Apertures can be used to divide the gas flow between these pumps and allow the vacuum conditions in the negative ion acceleration tube to be minimized. Since the getter ion pumps have a finite life which is directly proportional to gas load, a recirculating pump is used to recover most of the escaping gas and and recirculate it to the stripping canal. In the drawing, a diffusion pump is shown attached to the high conductance housing surrounding the canal. Experiments have shown that at least 95% of the gas can be recirculated with either a diffusion pump or turbomolecular pump[6]. The resultant gas load on the getter pumps is of order less than 1 $\mu\ell$/s. Under these conditions, the getter pumps have a lifetime in excess of 1000 hours.

Two 25 cm oil diffusion pumps with appropriate baffles are used to pump the acceleration tubes, one from each grounded end of the accelerator. In full operation the average pressure in the acceleration tubes calculates to be $< 5 \times 10^{-6}$ torr.

Additional Features. Several additional features are novel and worthy of note. First, the tandem accelerator is directly convertible for the high current positive ion applications that are the forte of the Dynamitron. A high current duoplasmatron positive ion source with pulsing capability will be mounted in the terminal, in place of the stripper canal. This is of special interest to multiple use facilities that may require high currents for specific research problems. At the Argonne National Laboratory this feature will find immediate application in neutron physics studies. Second, an off-axis negative ion source can also be included in the terminal, with negative hydrogen ion currents of the order of 100 μA. The negative ions would be inflected onto the accelerator axis. Tandem operation (stripper canal alignment) would not be affected. In this manner, the Dynamitron tandem system could be used as a powerful injector stage for a three-stage facility. Third, an off-axis electron gun can be supplied. Again, this feature may be of considerable importance in a multiple use facility. Finally, three service ports are provided for the pressure vessel. Two large vertical doors are located at each end, and a circular port is located behind the liner in the terminal area. In addition, the pressure vessel is flanged at the end of the terminal region. Since the tubes and columns are self-supporting in cantilever, it is possible and practical to; remove the terminal bridging linkage and stripper canal, connect the negative ion acceleration tube to the pressure vessel for support, disconnect the low energy acceleration tube from its external mount, and then displace the low energy end of the pressure vessel laterally for complete access to the interior. Lateral rails and casters are provided for this operation. The alignment of the negative ion injector and beam transport systems is not affected. Since the high energy section of the tank remains in place, it provides a reference for realignment of the pressure vessel at reassembly. All the acceleration tubes and the stripper canal will require realignment. Although the entire lateral displacement can be accomplished in a single day, this procedure will probably not be required after initial assembly. However, the feature offers an attractive advantage to axial displacement of the column structure, as is required with existing tandems.

Beam Transport System

The main components of the beam transport system can be recognized on Fig. 1. The ion beam crossover at the stripper canal is shifted towards the injector by the weakly convergent optical properties of the positive ion acceleration tube. This becomes the virtual object for the first magnetic quadrupole doublet lens. By adjusting the quadrupole, the ion beam can be recrossed at the entrance slit to the analyzing magnet. Appropriate magnetic steerers provide dog-leg steering through the entrance slits. Since the magnet is a symmetric stigmatic sector (double focusing), the crossover at ehe entrance slit is refocused to the exit slit with unity magnification. This analyzing magnet is used as the momentum dispersive element in the energy control system. A slit feedback system employing logarithmic amplifier controls the terminal voltage by applying a corrective signal to the main RF voltage control system. The feedback system is conditional[9], and switches to a secondary standard (a precision resistor divider) if the beam is removed from the slits. Appropriate magnetic switchers and lenses can be employed to transport the beam to various target locations.

For pulsed operations a post acceleration sweeper is used to truncate the tails of the pulse to $\simeq$ 2 ns, and thereby reduce the signal to noise ratio. Care must be exercised in pulsed operation that the time dispersion introduced by the path length difference between the extreme rays in passing through the analyzing magnet is compensated in the switcher. This can be accomplished to some degree by bending the beam in the switcher in the same direction as in the analyzer[8]. Except for the necessity to design the beam handling components to withstand beam powers of 1.5 kW in $\lesssim$ 3 mm diameter spots, the beam transport system is quite conventional.

PRELIMINARY PERFORMANCE RESULTS

Voltage Generator. Testing of the voltage generator under a resistive load was initiated about 1 November 1968. The rectifier components were fully assembled on the column and the voltage generator was essentially complete. The terminal components and acceleration tubes were not included. Resistive loads were constructed from 2 W. Carbon composition resistors arrayed on two separate mounting boards. The main load had a resistance of about $1 \times 10^{10}\ \Omega$, and the metering resistor divider was about $2 \times 10^{10}\ \Omega$ at 5 MV. Experimental measurements have shown that the factory calibration of this type of divider board agrees with threshold nuclear reactions to 2%, in the absence of ionization induced corona leakages[10]. Since the calibrations have not yet been checked at 5 MV, we anticipate the ± 2% factory calibration to the probable error of the voltage measurements.

An operational summary of these tests for the period up to 23 January 1969 is presented in Fig. 6. Total time accumulated on the generator is now 518 hours. To date, the voltage generator has operated for a short period at 5.7 MV and for 5.5 hours at 5.5 MV without a voltage excursion. The reliability of the system at 5.0 MV has been conclusively demonstrated by a 50 hour run over a period of six days without a voltage excursion or spark out. At 5.0 MV, the current load on the generator was $\simeq$ 750 μA.

Measurements of the sparking limit as a function of insulating gas pressure were performed with the dew point of the insulating gas between -40 and -50°C which was maintained by circulating the gas through an absorber of activated alumina. At a given gas pressure, the limit could be reproducibly determined. The voltage was increased from below 5 MV in 0.1 MV steps and held at each point for 15 min. When a level was reached where the machine would spark, the value was recorded, and the procedure was then repeated. These points could be established within ± 0.1 MV. Initially, several points were obtained illustrating a linear dependence ranging from 4.7 MV at 65 psig to 5.5 MV at 85 psig. However, after increasing some internal spark gap settings, the limit at 65 psig increased to 5.2 MV. This illustrates that these measurements are very difficult of interpretation as the main tank sparks may only be secondary events that are triggered by a primary discharge at a protective gap in the rectifier cascade. In any case, during the later part of the testing the sparking limit could not be found at 80 psig with the highest voltage attained. The maximum working pressure in the vessel is 100 psig.

Using a capacitive probe technique, the terminal ripple of the voltage generator has been measured. A summary of the ripple frequencies and amplitudes is given in Table II for 4 MV. The fact that the observed ripple components are slow or periodic assures that they can either be compensated or eliminated. Notable is the absence of fast voltage spikes commonly observed on the Van de Graaff generators.

INJECTOR MEASUREMENTS

During acceptance tests at ORTEC, the injector operated at full peak pulsed current for a 50 hour period with < 10% down time for adjustments. Under test at Westbury, the injector has routinely delivered 250 μA dc for extended periods. In the pulsed mode of operation, peak H^- pulse currents > 5 mA were observed at ORTEC with $\lesssim$ 0.8 ns FWHM. Pulses were measured by a biased, fast faraday cup. The rise time of the oscilloscope was 0.4 ns. Emittance was measured by a slotted plate and copy paper technique. In pulsed mode the result was 1.9 mrad-cm-MeV$^{1/2}$, and in dc mode, 1.5 mrad-cm-MeV$^{1/2}$.

CONCLUSIONS

The existence of intense H^- negative ion sources with an emittance contour acceptable by the Dynamitron tandem, indicates that tandem systems with a delivered current on target of 1 mA are probably realizable. Present system guarantees for this model series are 150 μA dc targeted proton current, and 2 mA peak pulsed current with < 1 nsec FWHM, at 10 MeV for two-stage tandem operation; and, 1 mA dc proton current at 5 MeV in single-stage operation, with a terminal ion source and crossed-field analyzer. On the basis of the demonstrated performance results, it can be anticipated that operation in excess of guaranteed specifications will be obtained with this system. When this performance is achieved, the Dynamitron Tandem will surely take its place as a significant new contribution to Tandem technology.

REFERENCES

1. P.H. Rose and A. Galejs, "Prog. in Nucl. Tech. and Inst.," Vol. II, ed. F.J.M. Farley, (North Holland, 1967).
2. K.W. Ehlers, Trans. IEEE NS-12: 3, 811 (June 1965).
3. R. Nuspliger, ORTEC, priv. communication.
4. M.R. Cleland, P.R. Hanley and C.C. Thompson, 1969 Nat. Particle Accel. Conf. Proc., paper B-24.
5. C.F. Mason, Trans. IEEE NS-14: 3, 157 (June 1967).
6. RDI Technical Report, to be published.
7. M.R. Cleland and P. Farrell, Trans. IEEE NS-12: 3, 227 (June 1965).
8. H. Naylor, K.H. Purser and P.H. Rose Trans. IEEE NS-12: 3, 305 (June 1965).
9. Varian Model 9024, adapted to Dynamitron energy control.
10. F.R. Stevenson and D.J. Gauntner, preprint 68-43, NASA Lewis Research Center, Cleveland Ohio, 1968.

TABLE I

Item	Tandem Dynamitron
Vessel Dia., ft. (m)	8.5 (2.60)
Vessel lgth., ft. (m)	34.0 (10.4)
Terminal Dia., ft. (m)	3.5 (1.07)
Accel. Tube lgth., ft. (m)	12.0 (3.66)
Insulating Gas, psig	75 (SF_6)
Terminal Potential, MV	0.8-5.0
H^+ Energy, MeV	1.6-10.0
dc H^+ Current, μA	150
Pulsed H^+ Current, μA	2000
Peak Pulse Width, ns	< 1

TABLE II

Component Frequency	Ampl. (Volts p - p)
120 Hz	800
360 Hz	180
116 kHz	400
0 (1 MHz)	80

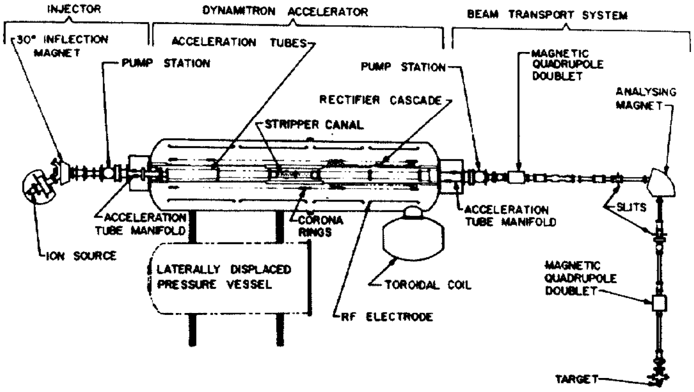

Fig. 1. ANL Dynamitron Tandem, plan view.

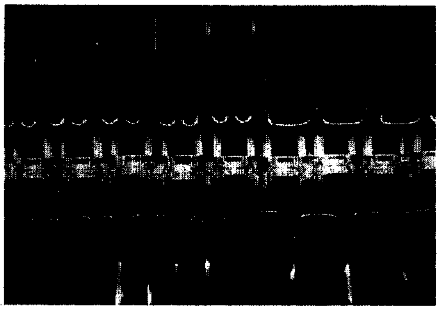

Fig. 2. Rectifier cascade in operation.

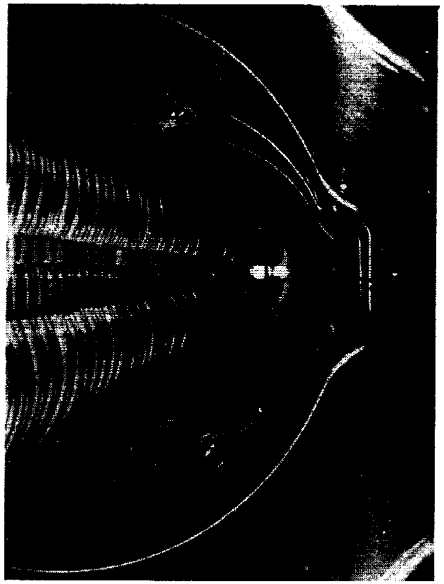

Fig. 3. Voltage generator, interior view.

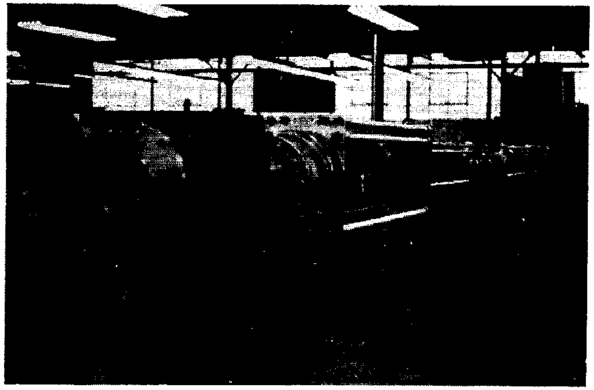

Fig. 4. Acceleration tubes during static load test.

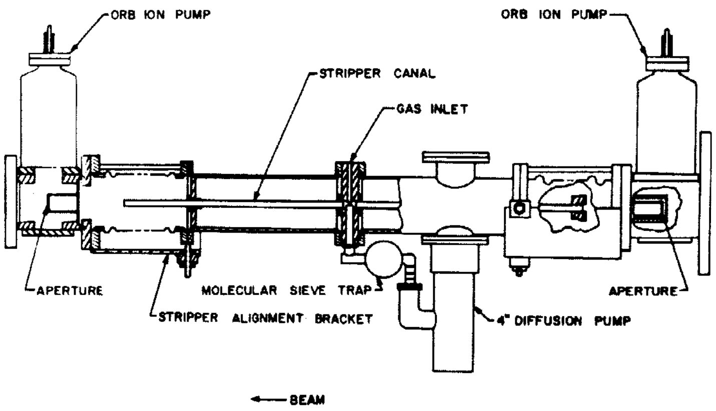

Fig. 5. Stripper canal assembly, section view

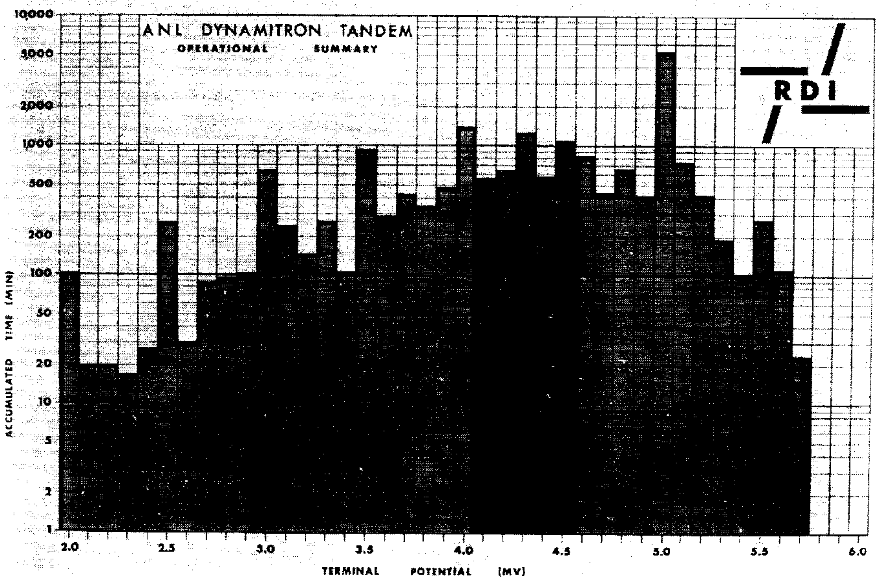

Fig. 6. Operational summary, voltage-time Histogram, 23 January 1969.