PROGRESS IN THE DEVELOPMENT OF A 4 MV POSITIVE ION ACCELERATOR FOR HIGH BEAM CURRENTS

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Summary

The symmetrical 4 MV cascade generator is a dc accelerator power supply which provides both high voltage and high current capability at low ripple voltage.[1] The problems usually encountered in the accelerating tube like total voltage effect, electron loading, and X-ray generation were solved by utilizing built-in permanent magnets for the deflection of the backstreaming electrons. This design reduces electron loading and brings the X-ray intensity down to a harmless level. With a R. F. ion source of conventional design, proton currents up to 1 mA at 4 MeV were actually obtained on the target. A further increase in the beam current is expected by the use of a duoplasmatron ion source.

Operational data of the 4 MV dc accelerator

A brief description of the general layout of the dc accelerator is helpful for further discussion of its most significant features.

The 4 MV dc power supply is a pressurized symmetrical cascade generator which consists of 20 stages. It includes two high voltage transformers, two series of ac capacitors and 80 selenium rectifiers. The simplified circuit diagram is shown in figure 1. The column of dc or smoothing capacitors was omitted in order to reduce the total capacitance of the power supply. It was found that the natural stray capacitance of the high voltage terminal with respect to the walls of the pressure tank, which amounts to about 150 pF, has a sufficient smoothing effect. Measurement of the resulting ripple voltage with and without the dc smoothing capacitors shows only a slight increase when omitting these capacitors. Figure 2 illustrates these findings.

The dc generator is energized from a rotating 60 kW frequency converter-set generating an ac voltage at a frequency meter located in the wall of the pressure tank opposite the high voltage terminal. At constant ac input voltage the dc output voltage is a function of the load current, as plotted in figure 3. To compensate the ac input voltage for voltage drop, a feed-back loop, from the generating voltmeter to the field excitation of the medium frequency generator is provided. This regulating system guarantees an overall stability of the accelerating voltage of $\pm$ 0.1 percent between no-load and the rated current of 5 mA.

To provide good electrostatic shielding with respect to the pressure vessel, the cascade generator and the accelerating tube are surrounded by highly polished corona rings of elliptical cross-section (Figure 4). The height of the accelerator is 4 m which accounts for the relatively low voltage gradient of 1 MV/m.

The R. F. ion source and its auxiliary equipment at high voltage, such as the 30 Mc/s push-pull oscillator, and the 6 kV and 60 kV dc power supplies for ejection and focusing of the beam are located inside the high voltage terminal. Electric power is supplied by a 400 c/s alternator of 3.5 kW driven through an insulating shaft by a motor at ground potential. Four other insulating shafts are used for the remote control of the following functions: ejection voltage, focusing voltage, oscillator power control and needle valve control for the gas supply of the ion source.

Adequate space has been provided in the high voltage terminal for future incorporation of a duoplasmatron ion source.

The accelerator is enclosed in a steel vessel under an atmosphere of pressurized insulating gas at 165 lbf/in^2. The gas is a mixture of 90 percent nitrogen, 8 percent carbon dioxide and

10 percent the breakdown voltage of the insulating gas.

To dissipate the power losses of the cascade generator, a continuous stream of insulating gas is maintained with the aid of a fan situated in a closed loop between the accelerator tank and a heat exchanger. The heat exchanger is cooled by a refrigerating machine.

A 3-stage mercury diffusion pump and a rotating forevacuum pump are the main parts of the vakuum producing equipment. To provide continuous pumping, even during weekends and holidays, a Chevron baffle and a liquid nitrogen trap have been installed in series, between the diffusion pump and the pumping manifold.

Beam tube design considerations

During the various stages of development, different types of acceleration tubes were designed and tested in the 4 MV generator. The first successful beam tube design was developed at the University of Basel.[2] This acceleration tube is under continuous operation since several years and presents trouble-free performance up to 3 MV. It is subdivided into 20 stages made of porcelain insulators sealed together by metal flanges and O rings. Good wall shielding is provided by the particular shape of the electrodes. The most significant feature of this acceleration tube is the suppression of the backstreaming electrons by means of built-in permanent magnets.

With this first model, problems were encountered due to the relatively high electric energy stored in the ac and dc capacitors. At voltages above 3.2 MV the surfaces of the electrodes were damaged by spark-overs in the beam tube. Significant progress was made with the introduction of high-ohmic damping resistors between the cascade generator and the acceleration tube, the omission of the dc capacitors and the reduction of the ac capacitances. Performance of the dc generator was not deteriorated by these modifications.

Based upon these experimental results plus theoretical considerations, it was decided to subdivide the acceleration tube into 80 stages of 50 kV each. It was anticipated, that due to the lower operating voltage of the individual stage a better protection of the accelerating gaps by external spark-gaps could be achieved. The ratio of the break-down voltages of the external spark-gaps to the internal accelerating gaps was increased in favour of the latter ones. With the present beam tube design, the potential of the individual electrodes is controlled by a bleeder-chain which draws a current of 0.5 mA at 4 MV. The enclosure of the accelerating tube consists of porcelain insulators which are sealed to aluminum flanges so that 4 stages will form a solid unit of 200 kV. A special cement of extremely low vapor pressure is utilized for sealing. The flanges of the 200 kV units are screwed together and sealed with Viton O rings. For experimental purposes, the internal mechanical assembly of the beam tube is designed in such a way that the electrodes and their supports can easily be replaced without dismantling the 200 kV units. All internal metallic parts are made of stainless steel. Figure 5 shows a section of the dismantled experimental acceleration tube.

In the design of a high-current accelerating tube, the following factors must be taken into consideration:

1. A safety factor of 2 or 3 has to be allowed with respect to the ratio of the break-down voltage to maximum operating voltage of the single stage. This applies, in particular, to the design of the internal and external surfaces of the insulators.

2. The same rule applies to the break-down voltage of the vacuum gaps. For this reason, the shape of the electrodes has to be such, that a low and uniform field strength will be achieved over the entire surface.

The high safety factor suggested in paragraphs 1 and 2 is necessary when taking into account the total voltage effect. This effect can be summed up by the empiric statement that: the break-down voltage of the entire acceleration tube will always be considerably lower than the break-down voltage of a single stage multiplied by the total number of stages.

3. For various reasons, it is required that the electrodes or their supports have a suitable shape in order to provide good wall shielding. If this rule is violated, metallic deposits may be found on the internal surfaces of the insulators. These deposits are caused by electrode material that is evaporated under the influence of spark-overs.

Furthermore, it cannot be denied that the insulator material may alter its properties under the influence of electron bombardment. Finally, the accumulation of charged particles on the insulator surfaces will cause an electrostatic deformation of the cross-section of the ion beam or frequent displacement of the beam focus from the center of the target.

4. The performance of the dc accelerator is strongly influenced by the backstreaming electrons which are accelerated and directed towards the high voltage terminal of the beam tube. When striking the accelerating electrodes, every electron will liberate a multiple number of secondary electrons, and this effect will finally result in an avalanche. To a lesser extent, a similar multiplication effect takes place by the collisions between the ions of the beam and the molecules of the residual gas.[3] Experiments have shown that the secondary electrons can be neglected up to dc voltages of 2.5 MV or 3 MV, depending on the design of the beam tube. In the case of wide-aperture accelerating tubes for high beam currents, this effect will be more significant. At higher voltages, however, the current of backstreaming electrons increases exponentially with voltage. Obviously, the electron current constitutes an additional undesirable load on the dc power supply. If a considerable fraction of the backstreaming electrons strikes the electrodes, the uniform voltage distribution, provided by the bleeder-chain, is no longer guaranteed. Thus, local spark-overs resulting in total voltage break-downs will occur. Furthermore, the high X-ray intensity ionizes the insulating gas which has as a result a flow of large corona and leakage currents. Voltage break-downs will occur with an X-ray intensity of about 10 r/h at the high voltage terminal. In view of the many undesirable effects caused by the multiplication and acceleration of the backstreaming electrons during their flow from the target to the ion source, it is necessary to deflect these particles from the axis of the acceleration tube by suitable electrostatic or magnetic fields, like inclined field electrodes or permanent magnets.[4] The latter method was successfully introduced into the design of the 4 MV beam tube. The permanent magnets are included in the electrodes. On the entire length of the acceleration tube, the horizontal magnetic fields of these permanent magnets are radial to the axis of the tube, so that the ion beam, which is only slightly deflected by the weak magnetic fields, follows a long spiral curve.

Experimental results

The acceleration tube showed excellent voltage conditioning properties. Up to 1 MV, no increase in the internal gas pressure due to outgassing was noted. From 1 MV to 3 MV the conditioning procedure required 4 hours. From 3 MV to 4 MV the rate of voltage rise had to be reduced. The last 25 percent of the rated voltage required 26 hours for conditioning. Total conditioning time was 30 hours.

In order to minimize the number of voltage break-downs and maintain the rate of voltage increase proportional to the progress in the conditioning procedure, the empiric rule that most of the spark-overs are preceded by sudden and fast fluctuations of the accelerating voltage was used. The fluctuations in the dc voltage were measured by means of a pick-up electrode located opposite the high voltage terminal. Normally, this electrode is used for the continuous measurement of the ripple voltage. The signals from the pick-up electrode were used to trigger an electronic protective circuit, which immediately reduced the ac input voltage by about 10 percent. This figure was assumed to be a sufficient safety margin. From previous break-down statistics, it was concluded that this protective circuit reduced the number of break-downs to about 20 percent.

For measuring the beam density profile, and the location of the beam focus on the target, with respect to the optical axis of the tube, a special monitoring device was used together with an oscilloscope. The beam monitor consisted mainly of a thin pick-up electrode which was rotated through the beam. The entire device could be shifted around the axis of the beam by remote control, thereby allowing measurement of the beam density profile in any desired direction. The speed of rotation, and the oscilloscope sweep, were adjusted in such a way that the beam profile became directly visible on the screen as function of the beam diameter. By means of a zero pulse, the actual position of the beam with respect to the optical axis of the tube could be identified. The beam monitor was positioned at a distance of about 2 m from the lower end of the beam tube, above the target.

Two typical oscillograms of the beam density profile are shown in figures 6 and 7.

At 4 MV and 1 mA proton current on the target the beam diameter was found to be 7 mm, which compares favorably with the theoretical figure of 6 mm obtained from the 2 mm diameter aperture of the ion source and the magnification factor 3 of the acceleration tube. The beam diameter is defined as the diameter of the beam density profile, at 50 percent of peak value.

The deflection of the beam by the permanent magnets was found to be 1.5 mm over the voltage range from 1 MV to 4 MV.

Figure 8 illustrates the considerable difference in performance of two identical accelerator tubes, of the wide-aperture type, with and without permanent magnets. These measurements were taken at a constant proton current of 300 μA on the target and vacuum of 2×10^{-6} torr at the lower end of the beam tube. The total load current of the 4 MV cascade generator and the X-ray intensity are plotted as a function of the accelerating voltage. The X-ray intensity was measured outside the pressure tank at a horizontal distance of 6 m from the lower end of the accelerating tube.

In the accelerating tube, with permanent magnets, the X-ray intensity, due to Bremsstrahlung, does not exceed the extremely low level of 4 mr/h at 4 MV. The total load current, which includes the current through the bleeder-chain, increases linearly with voltage, without any indication of electron loading.

Without any suppression of the back-streaming electrons, X-ray intensity and electron loading rapidly increase in such a way that above 3 MV frequent break-downs occur due to excessive ionization of the insulating gas. The cascade generator cannot withstand the resulting drain.

Future prospects

The experiments did not indicate that the limit of the current capability of the acceleration tube was approached. The proton beam had to be limited to 1 mA only because of the considerably shorter life-time of the R. F. ion source at higher currents. For these reasons, it is expected that with minor modifications such as enlargement of electrode apertures, the acceleration tube will sustain higher beam currents.

The large space inside the high voltage terminal, the high output power of the alternator in the terminal, and the forced artificial cooling of the insulating gas will allow the installation of a duoplasmatron ion source without any design changes except for the number of remote controls.

References

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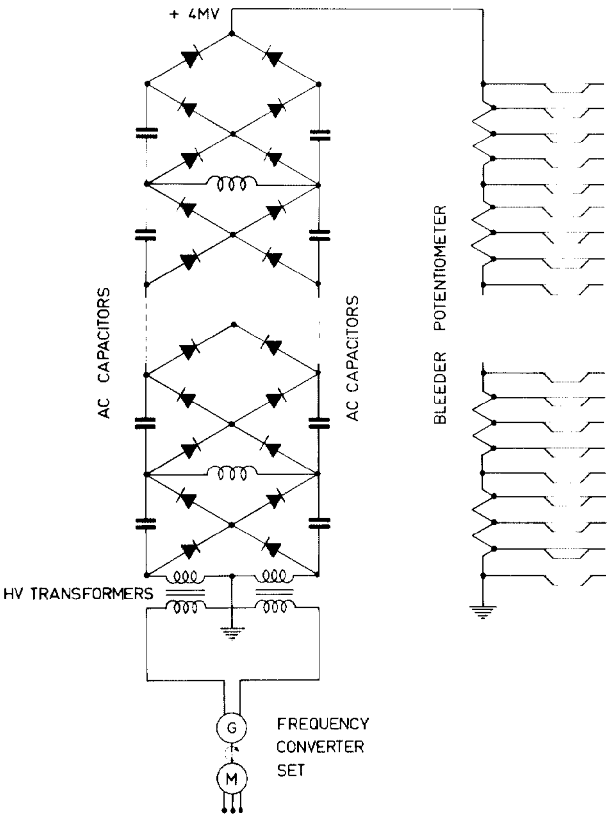

Fig. 1. Circuit diagram of the symmetrical 4 MV cascade generator.

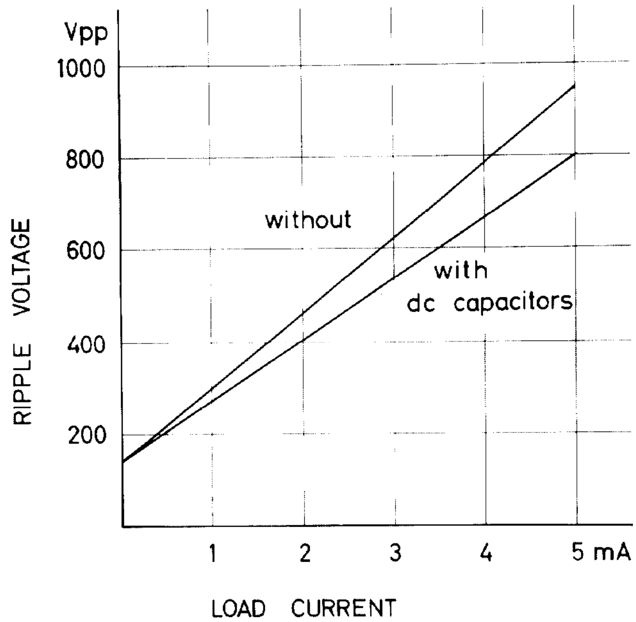

Fig. 2. Ripple voltage of the symmetrical 4 MV cascade generator with and without dc capacitors versus load current.

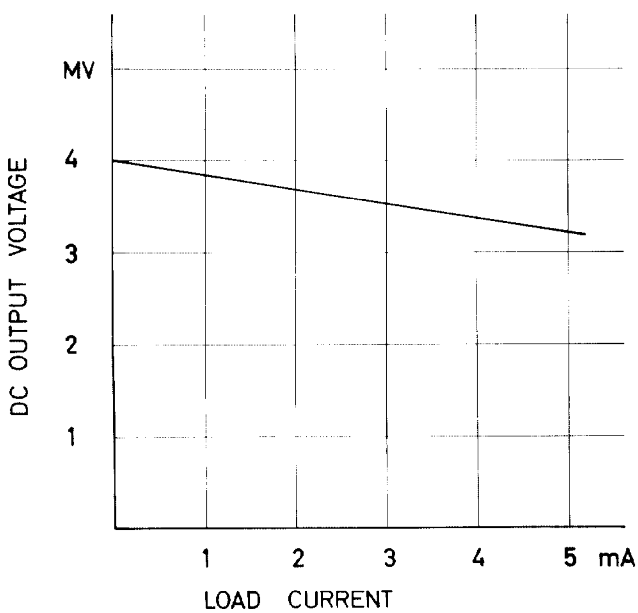

Fig. 3. DC output voltage of the symmetrical cascade generator at constant ac input voltage versus load current.

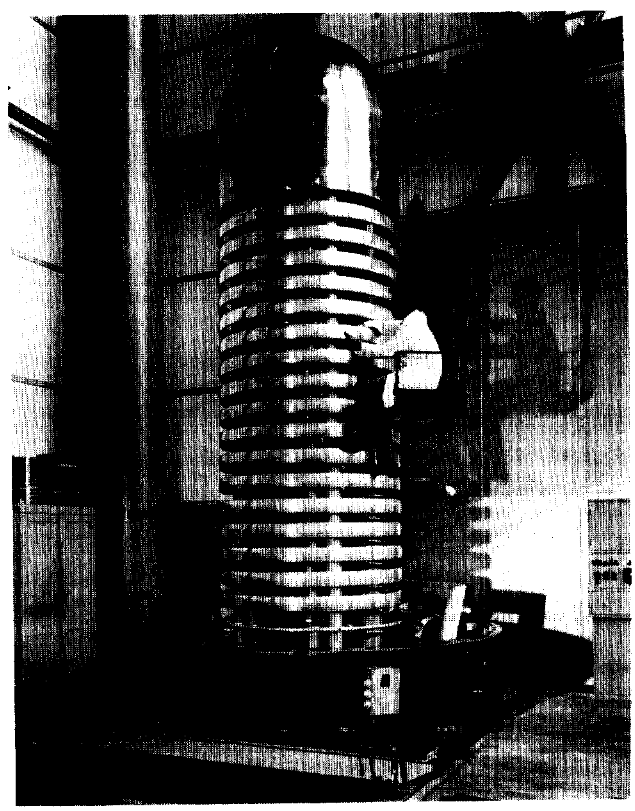

Fig. 4. 4 MeV positive ion accelerator.

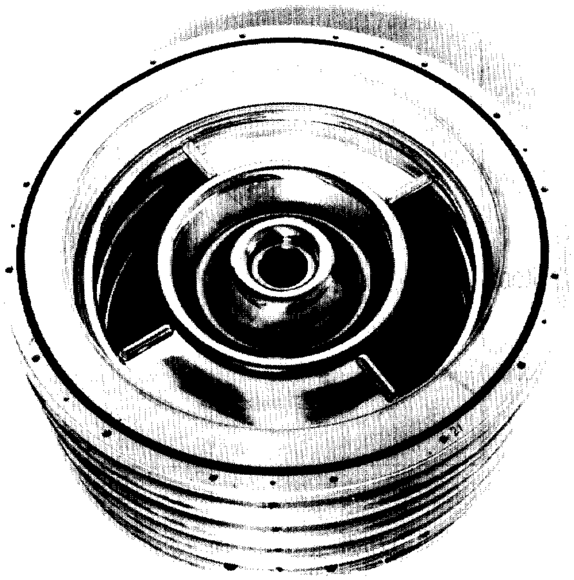

Fig. 5. Section of the 4 MV accelerating tube.

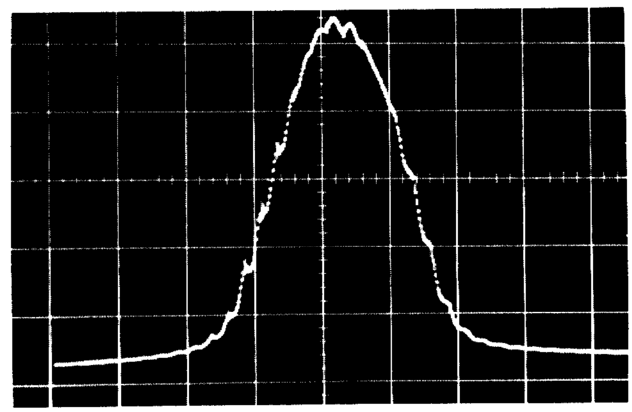

Fig. 6. Beam density profile.
Accelerating voltage: 4 MV
Total proton current: 300 μA
Horizontal display : 2.5 mm/Div

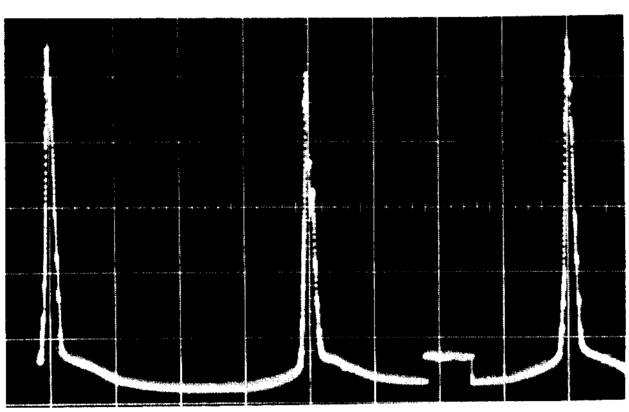

Fig. 7. Beam density profile.
Accelerating voltage: 4 MV
Total proton current: 630 μA
Horizontal display : 12.5 mm/Div

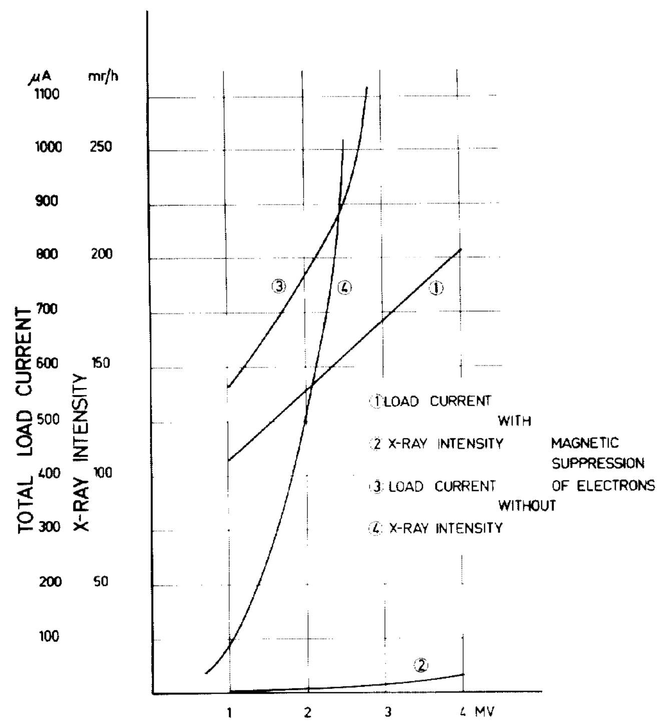

Fig. 8. Total generator load current and X-ray intensity with and without suppression of secondary electrons versus accelerating voltage.