Box 3: Cascade Generators

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In the Introduction to this book, an overview of different accelerator types was given. For accelerators designed along the principle of the "direct voltage technique", two subgroups are available: electrostatic accelerators, in which the high voltage is generated by electrostatic charging, and cascade accelerators, in which the high voltage is generated by rectifying an AC voltage. The technique for obtaining the high voltage in an electrostatic accelerator is described in detail in Chap. 6. In this box, the principal design of the power supplies for different types of cascade accelerators will be briefly described.

Asymmetrical Circuit

The original design of a cascade accelerator, first used by Cockcroft and Walton [1], can be seen schematically in Fig. B3.1. A photo of Cockcroft and Walton's accelerator is shown in Chap. 5. The circuit is asymmetrical;

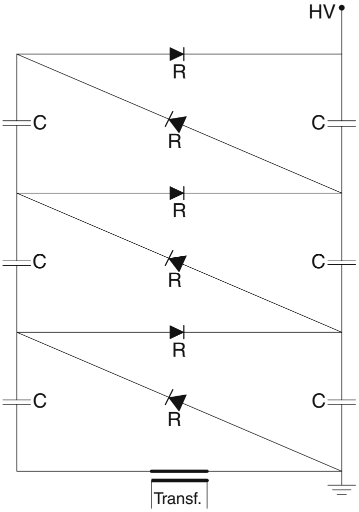

Fig. B3.1. Asymmetrical-circuit cascade generator consisting of capacitors C and rectifiers R sometimes this word is used for this type of accelerator, and sometimes it is called the Cockcroft–Walton type. The circuit was designed to transfer AC into high-voltage DC more than ten years before Cockcroft and Walton used it in their accelerator. It was known in the electrical engineering community as the *Greinacher doubling voltage circuit* after Heinrich Greinacher – a professor of physics at the University of Bern, Switzerland – who developed this circuit around 1920 [2]. The circuit includes n identical stages (in Fig. B3.1, three stages are shown), called cascades. The circuit uses two stacks of series-connected capacitors C. The right capacitor stack in Fig. B3.1 is connected at one end to ground and at the other to the high-voltage (HV) end. The voltage across each capacitor in this stack is constant except for a ripple. One end of the left capacitor stack in Fig. B3.1 is connected to a transformer giving peak voltages of $\pm U$. The voltages at all points along this stack oscillate over a range of $2U$. Series-connected rectifiers R link the two stacks. As the voltage on the transformer oscillates, charge is transferred stepwise through the rectifiers from ground to the HV terminal. The terminal voltage will be $2nU$. The chain can be extended to higher potentials, limited only by the ability of the high-voltage terminal to hold its potential without sparking to the surroundings.

Symmetrical Circuit

In practice, the asymmetrical circuit was soon replaced by a symmetrical circuit, as seen in Fig. B3.2. This employs two transformers and two capacitor stacks (the outer two stacks in Fig. B3.2) that oscillate in voltage. Both oscillating stacks feed one fixed-voltage capacitor stack (the central stack in

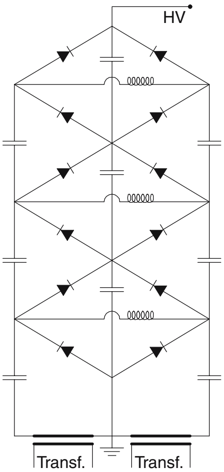

Fig. B3.2. Symmetrical-circuit cascade generator

Fig. B3.2). The advantage of the symmetrical circuit can be seen from the voltage drop ΔU and the voltage ripple δU when it is loaded with a current I. For the asymmetrical circuit, these are given by [3]

$$\Delta U_{as} = \frac{I}{fC}\frac{n}{3}\left(2n^2 + \frac{3}{2}n - \frac{1}{2}\right) \tag{B3.1}$$

$$\delta U_{as} = \frac{I}{fC}\frac{n}{2}(n+1) \tag{B3.2}$$

For the symmetrical circuit, the equations are [3]

$$\Delta U_{s} = \frac{I}{fC}\frac{n}{3}\left(n^2 + \frac{3}{2}\right) \tag{B3.3}$$

$$\delta U_{s} = \frac{I}{fC}\frac{n}{2} \tag{B3.4}$$

Here f is the frequency of the AC supply, C is the capacitance of a given stage and n is the number of stages. For an increasing number of stages n, both the voltage drop and the ripple become considerably lower for the symmetrical circuit compared with the asymmetrical. As both the voltage drop and the ripple vary inversely with the frequency f, a high frequency of the primary sinusoidal voltage is of importance. Accelerators of up to several MV have been constructed. With currents of several hundred mA, they give a total beam power of several hundred kW. These generators have often been employed in injectors to high-energy machines, and they are commonly employed as power supplies in electron microscopy. Asymmetric and symmetric accelerators are often open and not enclosed in an accelerator tank.

Parallel-Driven Circuit

A third principle, shown in Fig. B3.3, for obtaining a high voltage for a cascade accelerator was introduced by Radiation Dynamics Inc. Their product is called the Dynamitron. Inside the accelerator tank, two large semicylindrical RF electrodes are mounted near the wall of the tank, surrounding the column. These electrodes are supplied with power from an RF oscillator at 100 kHz, and they form the tuning capacitance of an LC resonant circuit. The high-voltage column is enclosed by half rings with smooth exterior surfaces to inhibit corona and spark discharges. In these segments along the accelerator column, secondary voltages are induced by capacitive coupling. These segments are coupled to rectifiers, and the rectified voltages from each segment are added up in two rows on opposite sides to supply the terminal with a high voltage. The tank is filled in the normal way with spark-protecting gas. The DC voltage produced by each segment is 50 kV. At the end of the 1970s, Kenn Purser [4] designed a similar type of parallel-driven circuit to

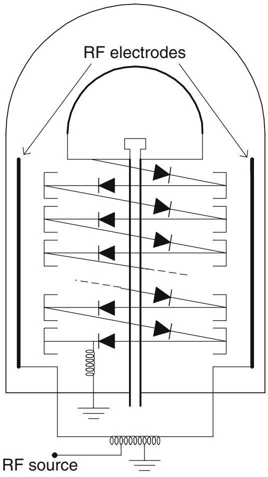

Fig. B3.3. Parallel-driven circuit

be used for the at that time new Tandetrons produced by General Ionex Corporation. The Tandetron (today produced by HVEE) is a compact tandem for material analysis, accelerator mass spectrometry, ion implantation etc. The Tandetron has a 50 kHz driver delivering several mA with very high stability. For accessibility, the high-voltage stack in Tandetrons up to 3 MV is at a right angle to the accelerator column. In the 5 MV Tandetron delivered in 2001–02 to the Centro de Micro-Analisis de Materiales in Madrid [5], the high-voltage stack is parallel to the high-energy column. A photo of the Madrid machine is shown in Fig. B3.4. A very high beam current can be accelerated in a parallel-driven accelerator, with a total power of up to 200 kW. Driving the stages in parallel instead of in series reduces the stored energy to levels comparable with electrostatic accelerators. Minimizing stored energy is important, especially in MV accelerators, because the high stored energy released in a discharge can damage capacitors, rectifiers, column components etc. Parallel-driven accelerators are ordinarily designed for higher voltages than are series accelerators and are enclosed in a tank.

Insulating-Core Transformer

The design of an insulating-core transformer is shown in Fig. B3.5, and a photo can be found in Chap. 28. The core is divided into sections separated by spacers of insulating material. The core is excited through the primary windings (using a three-phase, 400 V system at 50 or 60 Hz). Input power is magnetically coupled to secondary coils (three per deck) by a three-phase iron core electrically insulated between each deck. Each of all the secondary sections is coupled to a rectifier operating as a voltage divider and is an

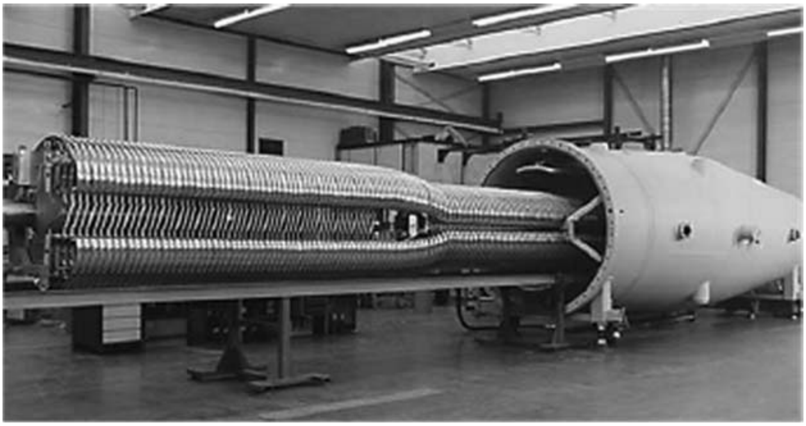

Fig. B3.4. The 5 MV Tandetron in Madrid (by courtesy of G. Garcia López)

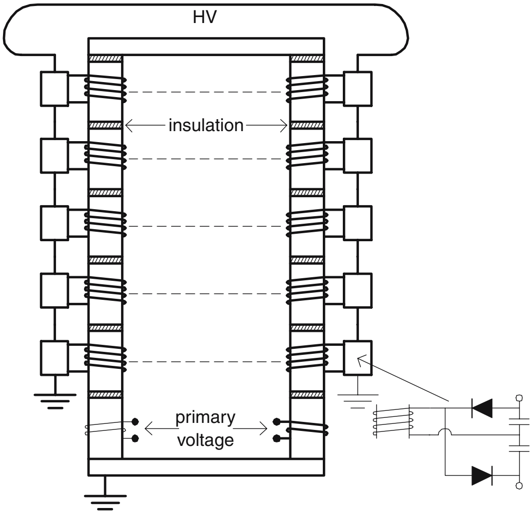

Fig. B3.5. Insulating-core transformer, two phases of the three-phase system are shown in the drawing

independent 50 kV unit. The rectifier outputs are connected in series to produce the high voltage. This type of voltage supply is housed in a tank filled with gas and can be built to be very compact. Units up to several MV and tens of mA giving a beam power up to several hundred kW are available. The accelerating column may be directly connected to the high-voltage terminal or may be physically separated from the transformer and connected to it by a high-voltage shield cable. Insulating-core transformers have long been produced by HVEE and VIVIRAD, and they are often used in industrial applications; see Chap. 28.

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