7 Voltage Distribution Systems – Resistors and Corona Points

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7.1 Introduction

This chapter presents the development of the two main technologies for grading the voltage of accelerators – resistors and corona systems. The voltage-holding ability of accelerators depends upon management of the distribution of electric-field stress, which relies on the voltage distribution system (Sect. 7.2). Although modern resistor systems are now the norm, corona grading provided an adequate bridging solution for large machines while resistor protection was perfected (Sect. 7.3). The large amount of energy stored in the electric field of such machines is broadcast during a spark and causes resistors to fail (Sect. 7.4). These failures motivated the improvement of resistors and techniques to protect them (Sect. 7.5). The development of resistor systems that survived sparks in large machines is largely the story of the protection strategies to reduce the coupling of spark energy to the resistors (Sect. 7.6). The crucial ingredients for such protection include spark gaps intrinsic to the accelerator, aerial effects, local shielding and the structure of the resistors themselves.

The confirmation of the success of resistor systems depends on the measurement of their resistance to a few percent, for which in-machine testing is of limited value (Sect. 7.7). It is fortunate, therefore, that modern systems are so effective in maintaining resistance value that now the main resistor failure mode is mechanical damage. Modern systems have overcome all of the historic problems, at least for machines with terminal voltages up to 25 MV.

7.2 Why Is Voltage Grading Needed?

The high-voltage limit of early electrostatic accelerators was set by discharges adjacent to the terminal along the long, uninterrupted insulating columns supporting the terminal. If the region of concentrated gradient could be shared, then the combination of several insulators and subsidiary electrodes might support a much higher voltage than would a single long insulator. The electrostatic accelerator built at Melbourne University between 1946 and 1948 had two corona rings added to the column, as seen in Fig. 7.1. These act as subsidiary electrodes to relieve the voltage stress adjacent to the terminal.

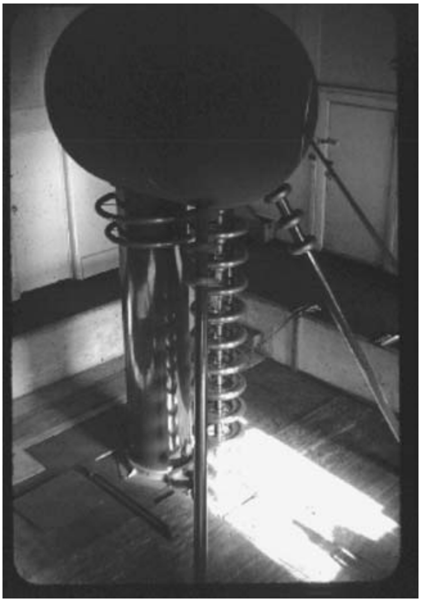

Fig. 7.1. The insulating column on the Melbourne University Van de Graaff has two corona rings near the terminal. These reduce the electric stress on the column adjacent to the terminal by spreading portions of it to the regions at the corona rings

The extension of such subdivision to the entire long column insulator stimulated the development of voltage-grading devices to control the electric field at each subsidiary electrode.

In contrast to the supporting column, the accelerator tubes had individual metal electrodes to establish the electric fields that accelerated the beam. These were only referenced to the gradient by external corona rings, which can also be seen in Fig. 7.1. Presumably, the voltage on the rings was established by fortuitous corona from the well-rounded rings. The evolution from fortuitous corona to deliberate voltage-grading devices marks the progress of electrostatic accelerators in their battle to increase the voltage at which they spark.

Machine sparks are triggered when the region of highest electric stress breaks down. This can occur either on the inside of the accelerating tube, where the breakdown is in vacuum, or in the external region of the accelerator structure, where air or high-pressure gas is the insulation environment. If the highest stress can be spread in a controlled manner among several locations then the peak stress is decreased and the machine can be pushed to higher voltages until, once again, some gap is overstressed. The voltage-grading system is the main tool to control the sharing of the high stress burden.

7.3 Corona Grading Systems

Given the early experience with corona rings, it was quite natural for machines to have evolved purposely-designed corona devices to grade the voltage from the terminal to ground. Figure 7.2 shows the corona point system mounted on the accelerator tube electrodes in Herb's high-pressure accelerator in 1937, the forerunner of modern electrostatic accelerators [1]. Connections from these corona points to the column also provided the grading for the column rings.

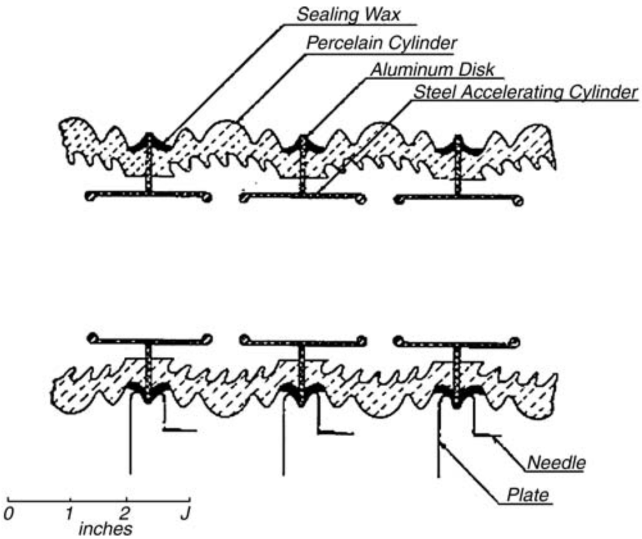

Fig. 7.2. Corona current from the needles to the opposite plates provided the voltage grading in the 1937 air-pressurized accelerator (Reprinted from [1], copyright 1937, with permission from the American Physical Society)

In spite of the head start corona systems enjoyed, high-ohmage resistors soon became the solution of choice for the machines of the day with modest terminal voltages. Resistors were convenient and commercially available, and generally were not damaged by machine sparks. However, as the terminal voltage of machines grew, so too did the failure frequency of the resistors.

The operational and financial costs of failed resistors reignited the use of corona grading systems by NEC in the 1970s as an inexpensive and spark-tolerant alternative. In Fig. 7.3, one can see the evolution from the 1937 version to the open corona point system for the NEC 14UD Pelletron. An advantage of a corona system over one based on resistors is that the voltage across a corona discharge is much less sensitive to changes in the current due to beam loading, for example. Figure 7.4 shows that a reduction by a factor of 2 in the column corona current, from 10 to 5 μA, results in only a

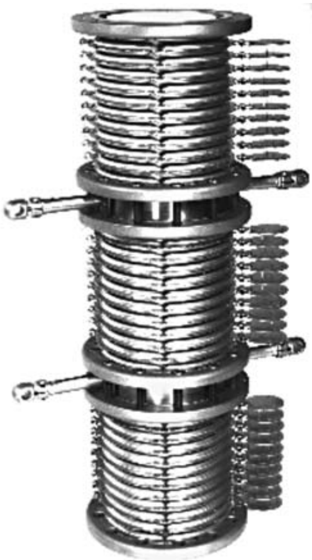

Fig. 7.3. Open corona point system on an NEC accelerator tube

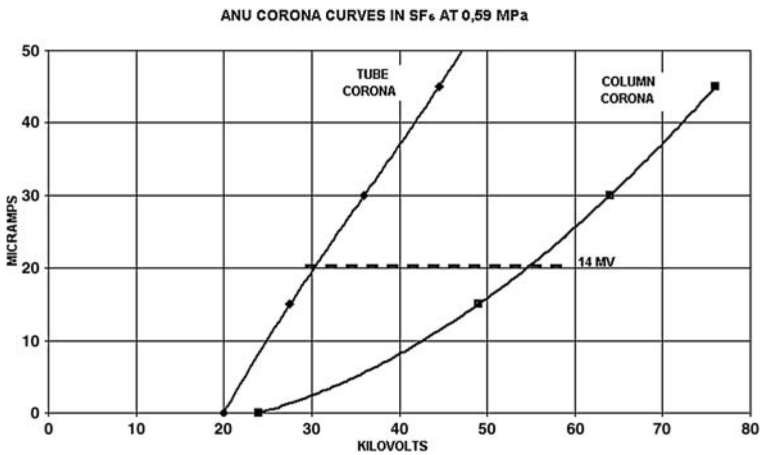

Fig. 7.4. The current carried by the corona grading system in the NEC 14UD vs. the voltage across the gap

25% decrease in voltage. This voltage stiffness allows the machine to operate stably with a smaller demand on the pellet chain charging system. Indeed, many Pelletrons operate with grading corona currents of only 1 to 5 μA.

One substantial disadvantage of the corona point system is that the corona extinguishes when the gap voltage reduces below the threshold. In the case of the column corona device illustrated in Fig. 7.4, a voltage < 23 kV across a column corona point gap would strand the accelerator without any reliable grading at all. Shorting out some sections of the accelerator to preserve enough gradient to keep the remaining corona points lit ameliorates this problem. The process of shorting out sections of the column breaches the pressure barrier of the accelerator and so entails some risks to the expensive SF_6 inventory and to personnel. On the positive side, this solution preserves the focusing strength of the tube entrance – necessary to maintain consistent optics and therefore good beam transmission (Chaps. 8 and 13). An alternative is to reduce the pressure of the insulating gas in order to reignite the corona at the lower gradient. This option is even less palatable, since it requires operation of the complex gas-handling system and is expensive in time and in technical effort.

To obviate the need to change the gas pressure in the entire machine, NEC developed a system in which the corona point assemblies are mounted in a series array of separately pressurized insulating tubes, one of which is shown in Fig. 7.5. This tube, like an NEC accelerator tube, comprises titanium electrodes bonded to ceramic insulators protected by annular spark gaps. Each electrode, supporting a triplet of corona points in the grading tube, is attached to a corresponding electrode on either the acceleration tube or the column. The pressure in this system of tubes is easily altered to tailor the gradient for lower-voltage operation.

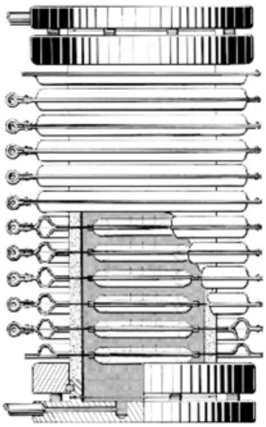

Fig. 7.5. Enclosed corona point system that allows the insulating-gas pressure to be conveniently lowered to increase the corona current for low-gradient operation

Pelletrons employ straight-field accelerator tubes rather than ones with inclined fields, so transmission degradation due to uneven voltage grading is not an issue, but gradient reliability and cost are. The choice of corona assemblies solved the cost problem but not that of gradient variations. The consequence of gradient nonuniformity is that some of the gaps operate at

20% higher voltage than the average. These overstressed gaps will be the first to break down, triggering a discharge of the entire machine. A machine operating at 12 MV, limited by a 20% gradient nonuniformity, would perform at 14.7 MV if the gradient nonuniformity were reduced to 2%. The extreme sensitivity of the voltage across a corona-graded gap to the distance from the points to the next plane, to dulling of the points with wear and to breakdown products coating the needle tip results in very nonuniform gradients [2]. Figure 7.6 shows the SF_6 breakdown products accumulated on the tip of a corona point.

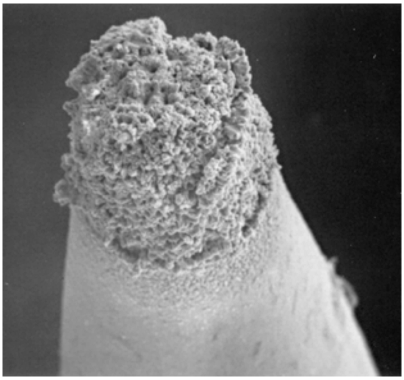

Fig. 7.6. SF_6 breakdown product deposits on a corona point tip. Magnification 100×

At best, the corona current, and so the voltage, is not constant but varies as the discharge dances around the interface between the deposit and the bare metal and occasionally from protuberances on the deposit itself. The statistical coincidences of the hundreds of corona fluctuations can instantaneously overvoltage a gap, triggering a spark.

More drastically, the corona produces corrosive SF_6 breakdown products, which attack the Pelletron charging chains, shortening their life to as little as a few hundred hours in extreme cases [3]. The corona also creates and mobilizes particulates, which, when they jump in the electric field, detonate discharges of the full machine. The enclosed corona system removes the breakdown products from the main accelerator environment, thus avoiding only some of these problems but concentrating the others in the enclosed system. However, the substantial cost of enclosed systems, their gradient nonuniformity, and their imperviousness to both inspection and easy repair, prevented their wide adoption.

The success of relatively inexpensive and robust NEC resistor systems using Welwyn [4] resistors has now supplanted both open and enclosed corona grading as the technology of choice in Pelletron accelerators.

7.4 The Need for Better Resistors

In the 1960s, HVEC developed the EN tandem accelerators, which achieved terminal voltages >5 MV. The success of the EN, which used resistors to grade the column, encouraged HVEC to produce the larger FN machines. The FNs exceeded their 7.5 MV expectation, running at and above 10 MV. These accelerators were soon joined by the HVEC MP machines, which were intended for operation at 10 MV but were pushed higher by the success of the FNs. The higher terminal voltages uncovered extra problems for the grading resistors. The resistors were exposed to a factor of 4 to 6 increase in spark energy in the higher-voltage machines, owing to the stored energy increasing with the square of the terminal voltage.

Unfortunately, the resistors then in use changed in value by >25% after a short exposure to high-voltage and sparks, causing beam transmission problems. This was because these accelerators used inclined-field accelerating tubes, in which the beam was deflected from one side of the axis to the other (Chaps. 8 and 13). Because these deflections we carefully designed to compensate each other, the tube relied on the voltage gradient being uniform. A nonuniform gradient led to the beam emerging away from the machine axis. Much research time was lost and much technical effort expended on locating open-circuit resistors and reshuffling the rest to smooth out the gradient in order to put the beam back near the axis.

An increase in resistance of a resistor by 25% will overstress its insulating gap, lowering the maximum useful voltage of the accelerator. A decrease of resistance by 25% for enough resistors exposes unchanged resistors to a higher than nominal voltage, thus also triggering sparks. Even more catastrophically, resistors frequently failed open-circuit and sparked continuously – the machine had to be opened for their replacement.

Resistor assemblies, although commercially available, failed so frequently that their cost soon became an uncomfortable burden. This drove the need to improve the reliability and to lower the cost of resistor voltage-grading systems.

7.5 Evolution of Resistors

Resistors made of metal-oxide-coated ceramic cylinders displaced carbon resistors, which required mechanical support and generally had unacceptable failure rates. Originally, metal oxide resistors used hollow ceramic-rod substrates, but these were susceptible to discharges through the center since one could not ensure that the accelerator's insulating gas would penetrate into this volume [5]. Spark damage to their protective coating was another failure mode of the standard high-voltage resistors [6]. Uncoated, solid-ceramic-core resistors are now the preferred option for use in accelerators and are available from several manufacturers.

The thick metal-oxide resistive layer is usually employed in a spiral pattern. Since a spiral is inductive and so susceptible to turn-to-turn high transient voltages and subsequent failure, low-inductance patterned resistors are an option [7]. Metal-oxide-on-ceramic resistors are sufficiently robust, however, that even ones with a spiral patterned resistive coating are entirely successful.

7.6 Spark Protection

Resistors must maintain their initial value to a few percent in spite of being subjected to severe overvoltages during sparks. Successful resistor systems minimize the voltage stress they suffer by exploiting the protection strategies discussed below.

7.6.1 Spark Gaps

In order for the minimum spark energy to be transferred to the resistors, the majority of the energy should be dissipated elsewhere in the accelerator structure. The safest medium for spark energy dissipation is in the insulating gas, since it is not permanently damaged by the discharge. The safest locations for the relieving discharges are in the robust spark gaps between the equipotential rings and in the spark gaps on the structural column.

The ring gaps are best, since they are furthest from the more delicate insulating components such as the accelerator tube and column insulators, let alone the resistors. In the NEC 14UD, the rings provide $2.6\,\mathrm{cm}^2/\mathrm{kV}$ of spark gap, and a similar figure would be true for the HVEC FN. In an MP, however, with fewer, larger-cross-section rings, the ring spark path is somewhat less capable.

Unfortunately, not all the spark energy travels via the ring gaps, as inspection of any other spark gap in an accelerator attests. Indeed, in the 14UD, the density of inter-ring spark marks is a maximum between the column posts and diminishes close to the posts as the post spark gaps assume more of the discharge burden.

Almost as important as the ring spark path in minimizing the exposure of the resistors to damage is the spark-energy-carrying ability of the column structure. In the 14UD, the column spark gaps provide $0.5\,\mathrm{cm}^2/\mathrm{kV}$ of protection. HVEC machines, with spark gap buttons, offer about $0.02\,\mathrm{cm}^2/\mathrm{kV}$. A similar situation obtains for grading elements mounted directly on the accelerator tube, with the NEC tube having $0.4\,\mathrm{cm}^2/\mathrm{kV}$ and the HVEC tube about $0.024\,\mathrm{cm}^2/\mathrm{kV}$. Because of these large differences, it could be argued that grading elements on an HVEC column would be subject to ~ 20 times the spark energy as those in a Pelletron. However, since the whole area of the annular spark gap does not participate in a given discharge, this is probably an overestimate. Qualitatively, the inference that "the larger the spark gap area the better the protection" is supported by the experience of resistor lifetimes. The attrition rate for unshielded resistors in MP and FN accelerators demanded the development of local shielding for resistors [9]. This is in contrast to the success of essentially unshielded resistor elements in the largest NEC accelerator, the 25URC at the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory shown in Fig. 7.7 [8].

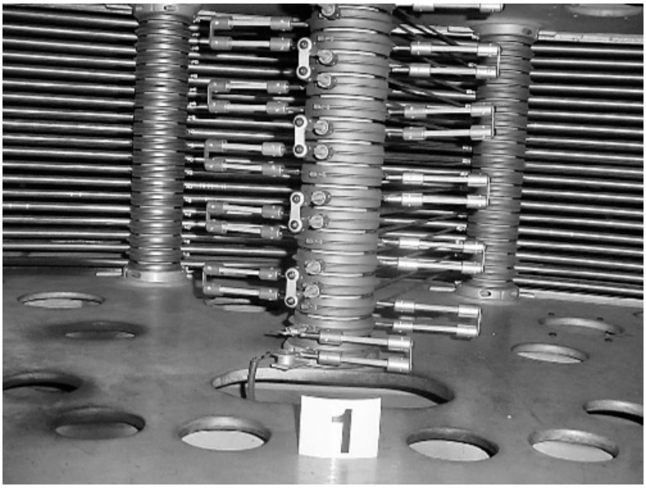

Fig. 7.7. The column resistors in the 25URC are mounted on an auxiliary post well away from the rings. The generous provision of spark gaps on the posts of NEC Pelletrons allows the resistors to survive without local spark shielding [8]

7.6.2 Coupling of Spark Energy to Resistors

The geometry of the resistors themselves and how they are attached to the column also affect their exposure to spark energy. Early resistor assemblies were series connections of individual resistors arrayed in long sticks. Figure 7.8 shows a more modern version using two metal-oxide-on-ceramic resistors based on a University of Rochester [11] innovation and developed at Brookhaven National Laboratory for their MP accelerators [9]. These assemblies, like their multiple carbon forebears, inevitably span parts of the column ~ 50 cm apart.

During a spark, sections across the diameter of the column will be at substantially different voltages because the spark gaps and/or rings on one side of the column will fire before those on the other side. A resistor string joining the two sides of the column would be subject to a megavolt RF spike rather than the 40–60 kV DC for which it was intended. In addition, the long assemblies act like dipole aerials, picking up energy from the spark's

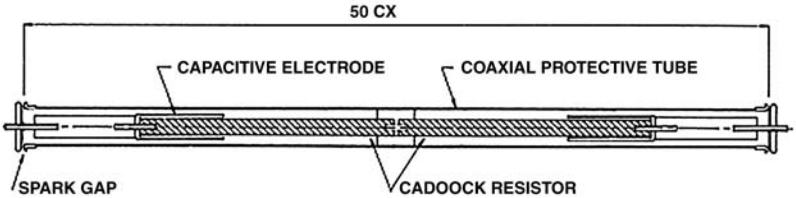

Fig. 7.8. The Brookhaven National Laboratory MP column resistor assembly (Reprinted from [10], copyright 1993, with permission from Elsevier)

electromagnetic RF field. The effective aerial of a 50 cm resistor string will absorb more RF power than will a compact assembly, typically ∼15 cm long. As well, a long resistor string, combined with the column structure to which it is attached, forms a loop aerial that will couple inductively to the spark RF current. The loop area of $\sim 50 \times 50\,\mathrm{cm}^2$ dwarfs the $\sim 15 \times 4\,\mathrm{cm}^2$ of the modern compact designs [10]. The RF pickup suffered by a compact assembly could be argued to be a factor of ∼140 less than for a long assembly.

The stresses on the resistors discussed above impose an extra gradient along the resistor axis. Since a strong pulse of electric field perpendicular to the resistor axis has been recognized as a danger too, placing them between parallel metal plates has been shown to increase their survivability [12]. Modern metal tube shielding has grown from this. If possible, even shielded resistor pairs are best dispersed to minimize the field between shielding tubes [10].

Figure 7.9 shows the compact resistor arrangement in the ANU 14UD, and Fig. 7.10 that in the FSU FN. In the 14UD, resistor pairs across adjacent voltage gaps are mounted well away from one another to reduce the

Fig. 7.9. The compact column and tube resistors in the ANU Pelletron

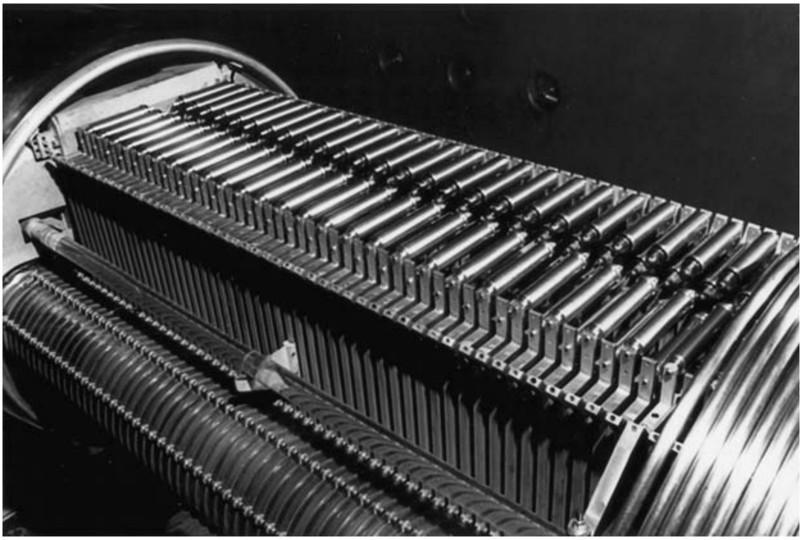

Fig. 7.10. Compact column resistors in the Florida State University FN

tube-to-tube electric field. In the FN, resistor pairs are mounted on alternate column sections for separation.

Modern resistor assemblies are compact in order to avoid spanning large distances. The compact designs also offer the operational benefit of greatly improving access to accelerator components such as the charging system and to the resistor assemblies themselves.

7.6.3 Local Shielding

The natural response to the failure of resistors was to protect them locally with spark gaps in parallel with the resistive element. Since this did not solve the problem, more intimate spark gaps, series inductors and parallel capacitors were introduced at Rochester [11] and elaborated at Brookhaven National Laboratory [9], as shown in Fig. 7.8.

This design illustrates almost all of the important features that have evolved into present-day assemblies, with the exception that the resistors span long distances in the accelerator structure.

- Metal-oxide-coated ceramic rod resistors are used instead of wire-wound resistors or several carbon ones.
- The resistors structurally support their integral shields, spark gaps and bypass capacitors.
- A metal tube shields the resistors from direct RF spark energy.
- Metal thimbles are epoxied over the ends of the resistors to:
  - mechanically strengthen the ends of the resistors so that they can better support the structure;

– allow machining to length and squareness to ensure uniformity of the spark gaps;
– provide bypass capacitance.

The use of metal thimbles over the resistor ends is essential and universal. Figure 7.11 shows all the features of current resistor protection techniques, as used in the ANU 14UD Pelletron [13] and in many FN accelerators [14].

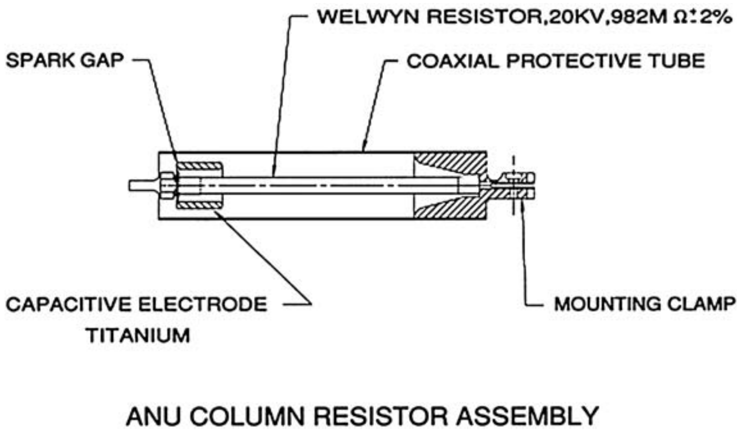

Fig. 7.11. The column resistor for the ANU Pelletron uses a radial spark gap, in contrast to axial ones in all FN variants (Reprinted from [10], copyright 1993, with permission from Elsevier)

7.7 Resistor Performance and Testing

The criterion for satisfactory performance is necessarily imprecise, since resistance measurements done inside the accelerator are confounded by moisture on the resistors themselves and on the insulators that they span. Hygroscopic deposits, usually from SF_6 breakdown products and/or belt dust, exacerbate this problem. In almost all cases, however, in which metal oxide resistors are suspected of changing values, tests that are performed after they have been removed from the accelerator, cleaned and dried show that they are still within their original ±2% tolerance. In-machine testing is therefore limited to discovering gross failures – mechanical failures being the most common, if an infrequent, mode.

A variety of manufacturers have provided resistors that have performed satisfactorily in large HVEC accelerators. In most cases, resistors performed well if protected by adequate local shielding. In NEC Pelletrons, Welwyn [4] resistors have proved entirely satisfactory. Voltage grading is now successfully done using resistors with competent and appropriate protection, thus removing resistor failure from the list of risks to efficient operation of electrostatic accelerators.

The evolution of voltage-grading systems has taught that any solution, however successful in one voltage range, may fail if applied to an accelerator with a much higher terminal voltage. It is fortunate, therefore, that it is unlikely that electrostatic accelerators will be built with voltages higher than the 15 to 25 MV now extant. However, even in more modest machines, designers will need to maintain their vigilance lest they revisit the pitfalls described in this chapter.

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