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THE PRESENT STATUS OF CHAIN CHARGING SYSTEMS OPERATING IN LARGE ELECTROSTATIC ACCELERATORS

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Résumé. — En tant que système de transport de charges, la chaîne composée alternativement d'anneaux conducteurs et isolants constitue une structure plus uniforme qu'une courroie conventionnelle fabriquée en tissu. Par conséquent, au point de vue stabilité, la chaîne devrait être supérieure aux courroies. De plus, la chaîne ne peut pas se déchirer et produit très peu de poussière; elle est relativement insensible à l'humidité et les anneaux isolants peuvent être protégés de façon intrinsèque contre les dommages causés par les décharges grâce à leur forme convenablement choisies. Bien que l'idée d'utiliser la chaîne en tant que transporteur de charges ne soit pas nouvelle, ce n'est que récemment que des chaînes offrant une capacité suffisante de transport de charges, résistance et fiabilité à long terme, ont fait leur apparition sur le marché. A présent, il y a plusieurs accélérateurs électro-statiques en fonctionnement dans le monde qui utilisent les chaînes. On présente ici les données d'exploitation recueillies par plusieurs laboratoires. Il est également question des caractéristiques des deux systèmes de transport de charges par chaînes accessibles sur le marché.

Abstract. — A charging chain consisting of alternate insulating and conducting segments is inherently a more uniform structure than a conventional woven fabric charging belt. Consequently, in terms of voltage stability caused by variations in the charging system, a chain should be superior to a belt. In addition, a chain produces no lint and little dust; it is relatively insensitive to moisture and the insulating segments can be intrinsically protected from spark damage by careful design of the conducting segments. Although the basic concept of using a chain to carry charge is far from new, it was not until comparatively recently that chains with sufficient charge carrying capacity, strength and long-term reliability have become available commercially. There are now several large electrostatic accelerators in operation around the world that are routinely using such charging chains and actual operating data from several of these laboratories is presented. The characteristics of two commercially available charging chain systems are reviewed.

1. Introduction. — The development of the Van de Graaff generator has been described by Herb [1] and more recently the development of large electrostatic accelerators has been summarized by Bromley [2]. Van de Graaff charged his first working model using a silk belt 6 cm wide and many of the large accelerators now in operation use a cotton neoprene belt 50 cm wide. Lord Kelvin first suggested using a chain consisting of alternate conducting and insulating segments to carry charge to the high voltage terminal of an elec-

trostatic accelerator; it is Righi [3] who is first credited with actually making such a device in the late 1800's. So, although the idea is not new, it was not until comparatively recently that chains with sufficient charge carrying capacity, strength and long-term reliability have become available commercially. National Electrostatics Corporation [4] (NEC) has produced and marketed the eminently successful Pelletron [5, 6] and High Voltage Engineering Corporation [7] (HVEC) will market the Laddertron [8]. A comparison of these two systems is shown in table I.

TABLE I
Charging chain characteristics

	Laddertron	Pelletron (*)
Metal segment length (cm)	3.7	3.2
Metal segment diameter (cm)	2.0	3.2
Mass per unit length (g/cm)	64	8
Linear speed (m/s)	10	14
Kinetic energy per unit length (J/cm)	3.2	0.8
Nominal maximum charging current (μA)	500	100

(*) One chain only.

2. **Charging chain systems.** — 2.1. **PELLETRON.** — In 1946, work was started on the forerunner of the Pelletron by Herb and his associates at the University of Wisconsin. The Pelletron charging chains resulting from this development consist of metal cylinders with well rounded ends joined by links of solid plastic. The links swing on pins which are provided with self-lubricating sleeves that require no oil. In 1965, NEC had incorporated the Pelletron charging chain into its line of accelerators, which at present range in voltage from 300 kV up to 14 MV. Although the Pelletron was originally developed for use in a vertical configuration, it has also been adapted for use in a horizontal configuration. Several HVEC machines, originally designed for belts, have been successfully converted to Pelletron charging systems, the MP Tandem at Yale [9] being the first such conversion. The MP Tandems at Chalk River, Heidelberg and Munich have now all undergone similar conversions. Operating data from these laboratories are presented below.

2.2. **LADDERTRON.** — Allen [8] and his associates at the University of Reading carried out development work leading to the Laddertron now in use at the Nuclear Structure Facility (NSF) Daresbury. The charging current limitation on a single Pelletron chain is nominally about 100 μ A. To increase the total available charging capacity, Herb has simply used multiple chains; in the Laddertron, two chains are linked by a metal rung. In the Pelletron, it is only possible to induce charge on one half of each pellet since the other half is in contact with the grounded drive pulley. In the Laddertron, it is possible to induce charge on both sides of the connecting rung as well as both pellets. Consequently, the Laddertron can carry four or five times as much current as a single Pelletron chain. A Laddertron is in use in the NSF pilot machine and will be used in the NSF Tandem at Daresbury. Although it was developed for use in a vertical configuration, it has been adapted to run in a horizontal configuration by HVEC. At the time of writing, factory tests have demonstrated that the

Laddertron will run horizontally, but so far it has not been operated in an MP Tandem accelerator to generate voltage.

3. **Operating data.** — Operating data from several laboratories is summarized in table II. The charging system performance at each laboratory is reviewed in some detail below.

3.1. **CAMBERRA (PELLETRON).** — The installation and initial testing of the 14 UD Pelletron in 1973 has been described by Titterton [10] and by Ophel *et al* [11]. To date, since its acceptance the accelerator has operated approximately 10 000 hours. The accelerator was conditioned to 18.1 MV without tubes and now runs routinely up to 13 MV.

In October 1975 one of the three original chains broke after 3 500 hours of operation and three new chains were fitted. At the same time as the chain replacement, new drive sheaves with side contacts were installed. After a further 2 100 hours of running, one of the new chains broke; this chain was rebuilt using undamaged links and sufficient new links to replace the damaged and suspect ones. These chains are still in operation a year later with no further breakages. No damage to the column structure resulted from either of these breakages. While the chains can carry a maximum charging current of 150 μ A, in normal operation the charging current varies from 20 to 100 μ A.

Although the terminal ripple of the 14 UD has not been measured at 10 MV, measurements [12] made near 7 MV imply a ripple of less than 1.3 kV.

3.2. **DARESBUURY (LADDERTRON).** — The Nuclear Structure Facility (NSF) at Daresbury will use the Laddertron charging chain which has been successfully tested on the pilot machine for a total of more than 1 500 hours. The pilot machine has sustained a maximum gradient of 3.5 MV/m with 0.76 MPa of pure SF₆ insulating gas. There is a terminal ripple of 1.6 kV at the chain frequency of 0.9 Hz but there is no detectable ripple at the rung frequency of 240 Hz as

TABLE II
Operating data to April 1977

Laboratory	Charging System	Max. Voltage (MV)	Total Operating Time (h)
Canberra	14 UD Pelletron	14	10,000
Chalk River	MP Pelletron	13	16,600
Daresbury	Laddertron	10 (1)	1,500
Heidelberg	MP Pelletron	13	11,500
Munich	MP Pelletron	16 (2)	3,100
Rehovot	14 UD Pelletron	14	— (3)
Yale	MP Pelletron	13	16,000

(1) NSF Pilot machine.
(2) Without accelerator tubes.
(3) Machine accepted april 2, 1977.

measured with a capacitive pick-off having a flat response from 300 Hz downwards (rolling off by 3 dB at 0.1 Hz).

It is not at present possible to quote typical lifetimes for the Laddertron components but based on observed wear rates, it is expected that the pulley wheel tires and the Laddertron bearings should last at least 20 000 hours.

Since the Laddertron was first installed, the insulating links have been changed from glass filled to monocast nylon, the pitch has been reduced from 53 to 42 mm to improve voltage holdoff, the insulator design and the electrostatics near the insulator bearing have been improved and the rigidity of the rungs has been improved for smoother running. There have been no unusual component failures.

3.3. HEIDELBERG (MP PELLETRON). — A Pelletron charging system was installed in the Heidelberg MP Tandem Accelerator during the summer of 1975 and to date has operated for a total of more than 11 500 hours. Because of bearing problems which had been observed both at Chalk River and Yale in the small 7 cm diameter idlers, NEC used small idlers of 10 cm diameter in the Heidelberg installation. This change necessitated reversing the central idler mounts. Both sets of chains drive generators in the high voltage terminal. The chains are capable of delivering more than 600 μ A of charging current to the high voltage terminal and have sustained a maximum gradient of 2.2 MV/m. A terminal ripple of 300 to 400 V has been observed when all frequencies above 30 Hz are eliminated.

At Heidelberg, the main disadvantages of the Pelletron are seen as the large number of moving or rotating parts and the increased vibration levels. Out of a total of 144 small idlers, approximately 18 have had to be changed each year because of bearing failures. On two occasions, rivets have dropped out of the chain connecting pins but because of the tension in the chain, the pins have remained in position and no actual breakage has occurred. The contact wires on the pick-up wheels are a problem since they break off after a relatively short time; arcing then occurs to the pick-up wheels and causes instabilities in the charging currents. Self-charge, generated by friction of the pellets on the drive sheaves, can be eliminated by the regular application of oil to the drive sheaves.

Since its installation, the Pelletron has performed well during a two year period.

3.4. MUNICH (MP PELLETRON). — As part of a conversion program on the Munich MP Tandem Accelerator, a Pelletron charging system was installed during the summer of 1975. Because of the complexity and difficulty of the overall program, the chains have only operated for a total of just over 3 000 hours to date. At Munich the first opportunity arose to test the voltage holding capabilities of the Pelletron system in an MP Tandem column structure without accelerator

tubes [13]. Although some predictions of the voltage holding capability had been made and the MP Tandems at Chalk River, Heidelberg and Yale had operated with Pelletrons at the voltage limit of the accelerator tubes (~ 13 MV), Munich successfully demonstrated that the chains could sustain a total potential of 16 MV with pure SF₆ insulating gas at a pressure of 0.76 MPa.

A total charging current of more than 600 μ A can be delivered to the high voltage terminal. Even though the original inductor power supplies have been replaced by stabilized, more precise units, the reasons for the unusually high ripple (6 kV at 1 to 2 Hz and 1 kV at 400 Hz) are not understood at the moment.

No major modifications have been made to this system, which is basically identical to that at Heidelberg, but a number of minor changes have been made including several replacements of the pick-up wheels. Because the total operating time on this system is relatively low, it is difficult to assess its long-term reliability, although based on experience elsewhere it should be good. No unusual component failures have been observed to date.

3.5. REHOVOT (PELETRON). — The 14 UD Pelletron was officially accepted on April 2, 1977 [1]. The charging chains have delivered 600 μ A of charging current to the high voltage terminal and in nine hours the tubes were conditioned to a voltage of 14 MV.

3.6. YALE (MP PELLETRON). — Not only did Yale University have the first operational MP Tandem Accelerator, this laboratory also holds the distinction of having the first MP to be converted from the original belt charging system to a Pelletron charging chain. The Pelletron was installed in May 1973 and to date has operated more than 16 000 hours. Following the initial installation there were a number of modifications [9] during the first year of operation:

- 1) flaring the inductor electrodes to eliminate sparking between these electrodes and the chains,
- 2) changing the material used for the large intermediate idlers, in order to eliminate the leakage paths that were seriously reducing the charge available at the high voltage terminal,
- 3) circumferentially grooving the surface of the large intermediate idlers to eliminate lateral oscillations of the chain,
- 4) installing tapered cylindrical shield electrodes at each idler assembly to eliminate discharges through the idler bearings.

In June, 1974 just prior to making modifications 3) and 4), one of the small idlers was shattered and in consequence the chain fell off the large supporting idler, caught on the steel support bracket and broke. There was no significant damage to any of the rest of the accelerator and the chain was repaired by repla-

(1) Private communication (april 1977).

cing two or three links. There have been no further problems with the Pelletron chains and no substantial modifications have been made to the system since July, 1974.

Although it appears that the total charging current is limited to about 400 μA (for six chains), operating the accelerator at 13 MV only requires a charging current of 260 μA . In comparing the Pelletron with belt performance, the overall impression at Yale is one of much greater reliability and beam stability. This impression is reinforced by the fact that it has been possible to operate for periods of four to six months without opening the accelerator tank even during periods of operation between 12 and 13 MV. Component failures in the system are limited to an occasional replacement of some of the small idlers (two or three per year) because they have become chipped, cracked or have a bearing problem.

3.7. CHALK RIVER (MP PELLETRON). — A Pelletron charging system was installed in the Chalk River MP Tandem Accelerator in the summer of 1974 and to date has operated for more than 16 600 hours. The Chalk River conversion was essentially identical to that at Yale and all four of the modifications made at Yale were also made at Chalk River.

Shortly after the initial installation of the Pelletron, one of the screws holding a small idler in place became loose. Eventually the idler fell from its mount and became lodged between two pellets on the centre chain causing the chain to break. It was necessary to replace several of the pellets but the only damage to the rest of the structure was in the form of small dents on the outside protrusion of about eight accelerator tube electrodes.

The Pelletron charging system has now run reliably for almost three years. The distribution of operating time at various terminal voltages during this period is shown in figure 1. The chains will carry a total charging current of more than 600 μA although in practice less than 400 μA is required for operation at 13 MV with 70 μA of corona current and 80 μA of drain caused by the ^{137}Cs radiation source. On one occasion a rivet was lost from one of the chain connecting pins, an incident similar to those at Heidelberg, but again, because of the chain tension, the pin remained in position. Pick-up wheel contact wires continue to be a minor problem, in spite of the fact that several modified designs have been tried. The only other components that have caused problems are the idler bearings. Small idler bearings fail at the rate of approximately ten each year but only three large idler bearings have failed since the system went into operation. The normal mode of failure is that the bearings become rough or stiff; very rarely has a bearing actually seized.

Terminal ripple is continuously monitored with a capacitive pick-off having a response that is flat from 1 kHz down to 10 Hz and rolling off by 3 dB at 1 Hz.

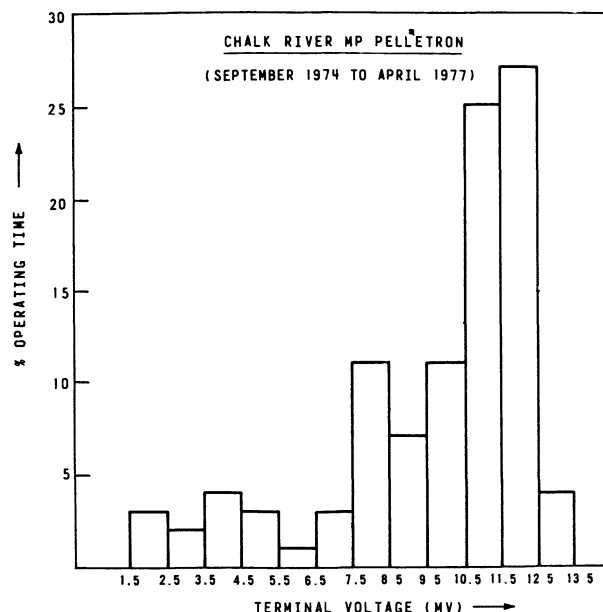


FIG. 1. — The distribution of operating time at various terminal voltages since the installation of the Pelletron charging system.

The measured peak to peak ripple is less than 500 V at 12.5 MV and less than 200 V at 10 MV.

During its first three years of operation, the Pelletron charging system has proven to be reliable and trouble-free. Although the Pelletron is insensitive to moisture, the SF_6 insulating gas is recirculated through activated alumina almost continuously to remove corona and spark produced decomposition products which could cause damage to the chain insulating segments as well as induce voltage breakdowns.

4. Summary. — The two types of chain charging systems described in this paper, the Pelletron and the Laddertron, while differing in detail are similar in many ways. Both produce good terminal voltage stability with ripples as low as 200 V peak to peak being observed at 10 MV. Although the Pelletron was designed for vertical operation, it has been successfully adapted to run in a horizontal configuration; it appears as if the Laddertron can also be adapted to run horizontally.

Both types of chains have the disadvantage of a large number of moving parts which produce high audio noise levels in and around the accelerators. There is the ever present question of what happens when a chain breaks. Although the kinetic energy per unit length of the Pelletron is only one quarter that of the Laddertron, the probability of a complete Pelletron chain break caused by the loss of a connecting pin is expected to be higher than the probability of a complete Laddertron chain break from the same cause. Whereas the loss of one connecting pin will cause a complete break in the Pelletron, it is predicted that the Laddertron chain will still remain intact even if the connecting pin on one side of a segment is lost.

In actual practice, the NEC vertical machines have survived several chain breaks without any major damage. The Pelletron has, to date, a cumulative total of almost 50 000 hours of operation in MP Tandems and while both the Chalk River and Yale accelerators have had chain breaks, neither break was caused by the loss of a connecting pin and one chain breaking has not caused a second chain to break. There was no significant damage to the accelerator structure in either case. As yet, the question of what damage would occur were a Laddertron chain to break, remains unanswered.

The lifetime of a Pelletron chain would appear to be in excess of 20 000 hours; two MP Pelletrons are now approaching this value with little observable wear to the insulating segments or connecting pins. Based on experience to date, the Laddertron should have a

similar lifetime. Because the total cumulative operating time for conventional belts in large electrostatic accelerators must be at least an order of magnitude greater than the total cumulative operating time for chains, it is difficult at present to make a true operating cost comparison between the two systems. However, in making any such comparison, a monetary value would have to be ascribed to the benefits which have resulted from using a chain charging system in terms of the increased operating efficiency and improved terminal voltage stability.

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