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Section II. Tubes and related problems

TESTS OF COMPRESSED GEOMETRY ACCELERATION TUBES IN THE OAK RIDGE 25URC TANDEM ACCELERATOR *

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In an effort to improve further the voltage performance of the Oak Ridge 25URC accelerator, the original acceleration tubes will be replaced with NEC compressed geometry acceleration tubes. In this paper, we report on tests in the 25URC accelerator of two prototype compressed geometry acceleration tube designs. One of the designs utilizes a novel aperture which provides enhanced electron and ion trapping.

1. Introduction

In an effort to improve further the voltage performance of the ORNL 25URC accelerator +, we are engaged in a program of replacing the original acceleration tubes with tubes of a compressed geometry design. In this design, which utilizes a modified National Electrostatics Corporation (NEC) high-gradient 17-cm-long tube section, the 3-cm-thick heatable aperture assembly provided as part of the original installation is replaced with an aperture assembly of essentially zero length. This change has two beneficial effects. The first is that seven tube sections can be installed in the space previously occupied by six, thus increasing the effective insulator length per unit column length by a factor of $7/6 = 1.17$. The second is that removal of the high-current feed-throughs which are an integral part of the heatable aperture assembly removes a source of vacuum leaks in the 25URC accelerator.

Tests on a compressed geometry configuration, similar to that described in this report, were first reported by Assman et al. [1]. A subsequent test, using a column structure more closely resembling the 25URC column, was reported by Raatz et al. [2]. While both of these tests produced gradients which substantially exceed those used in working NEC accelerators, they suffered from several limitations: first, they were performed in relatively small, low-capacitance columns unlike the 25URC accelerator; second, they were performed over relatively short periods; and third, they did not involve operation with beam. The tests described in this report are the first in which compressed geometry tubes have been installed in a large accelerator and operated with beam over a period of months.

The installation and tests described in this report represent the first two of three phases of the tube replacement program for the 25URC accelerator. In the first phase, two tube units ++, 26 and 27, were replaced with compressed geometry tubes in June 1986 and tested in the interval July 1986 to October 1986 [3]. In the second phase, units 19–25 were replaced with compressed geometry tubes in November 1986 and tested in the interval November 1986 to March 1987. In the third phase, scheduled for August 1987, the final 18 units will be replaced. This sequential approach was chosen to provide an opportunity to evaluate prototype designs before retrofitting the entire accelerator.

As a result of the compressed geometry tube installation, the number of 17-cm-long tube sections used in the 25URC accelerator must be increased by 24. To provide an unambiguous comparison between new and

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+ Note: The accelerator has been operated, with beam, at terminal potentials of 22.0 MV for scheduled experiments and 23.5 MV for tests.

++ Note: The configuration of the 25URC accelerator is based on 27 61-cm-long live modules or "units" separated by two major and three minor dead sections. Proceeding from bottom to top, the units are grouped in the following way: 1–4, 5–9, 10–13, 14–18, 19–22, 23–27.

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reconditioned tube sections, 28 new tube sections were installed in the second phase of the replacement program in units 19 + 20 and 24 + 25. All other 17-cm-long tube sections used in the first and second phases of the replacement program were reconditioned tube sections.

2. Aperture and electrode design

As noted by Assmann et al. [1], replacement of the heatable aperture assembly with a simple "zero length" flat aperture reduces the strength of the lens effect associated with the aperture. This reduction in lens strengths results in a reduction in trapping efficiency for ions and electrons originating from the aperture and from ionization of residual gas. While it appears that reduced trapping efficiency might lead to impaired tube performance, the importance of this effect in practice is not clear. To investigate this question in a systematic way, we have installed and tested compressed geometry tubes of two designs: a "conventional" design, similar to that described by Assmann et al., and a new design, developed for the present program, which has improved ion and electron trapping. This new design was used for units 23–27. The conventional design was used for units 19–22.

As shown in fig. 1, the technique used to improve ion and electron trapping for the new design is replacement of the conventional flat aperture with a vee-shaped aperture. Specifically, use of a vee-shaped aperture "tilts" the electric field in the region of the aperture so that it has a larger radial component. This radial component of the electric field imparts higher radial velocities to ions and electrons originating at or near the aperture and thus leads to improved trapping [4].

The basic parameters of the vee aperture are the inside diameter, outside diameter of the conical element, and cone angle (defined as the angle between the aperture surface and a perpendicular to the axis of symmetry). These parameters were determined on the basis of ray trace calculations performed with the SLAC electron trajectory code of Hermannsfeldt [5]. The results of typical calculations made with this code are shown in fig. 2 where we show electron trajectories for compressed geometry designs with conventional flat apertures and vee apertures with a 30° cone angle. The parameters chosen were inside diameter 2.54 cm, outside diameter of the conical element 3.8 cm, and cone angle 30°. This cone angle was chosen as a compromise between trapping efficiency and the possibility of a one-to-one correspondence between ion trajectories between adjacent electrodes – a condition which we feared might lead to excessive microdischarge conditioning [6]. With a cone angle of 30°, all ion trajectories with an initial energy less than 500 eV appear to be stopped in two tube sections.

As a consequence of the change in spacing which results from removal of the heatable aperture, it is

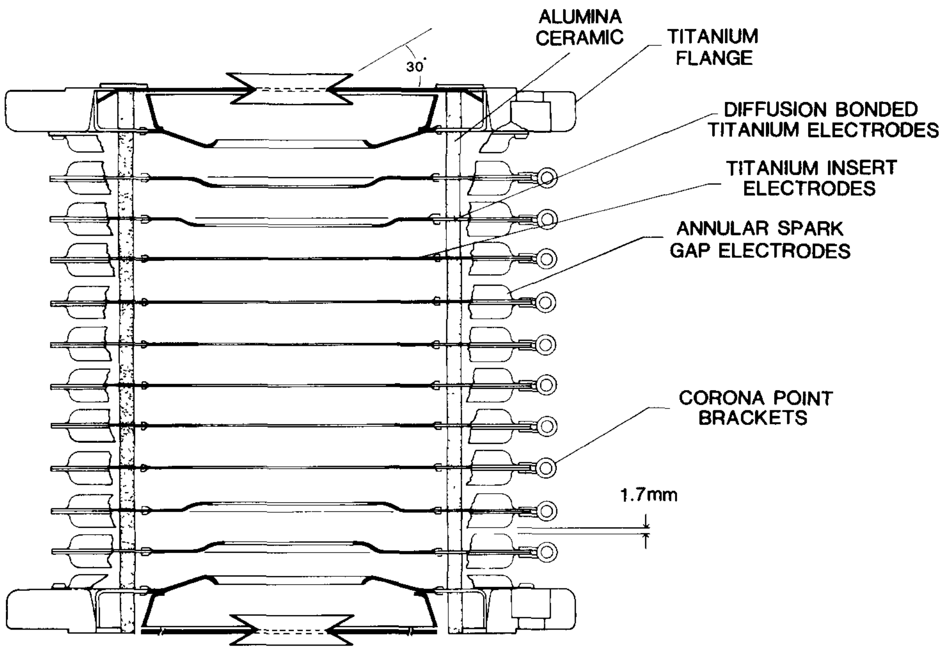

Fig. 1. Section view of compressed geometry tube section with vee apertures.

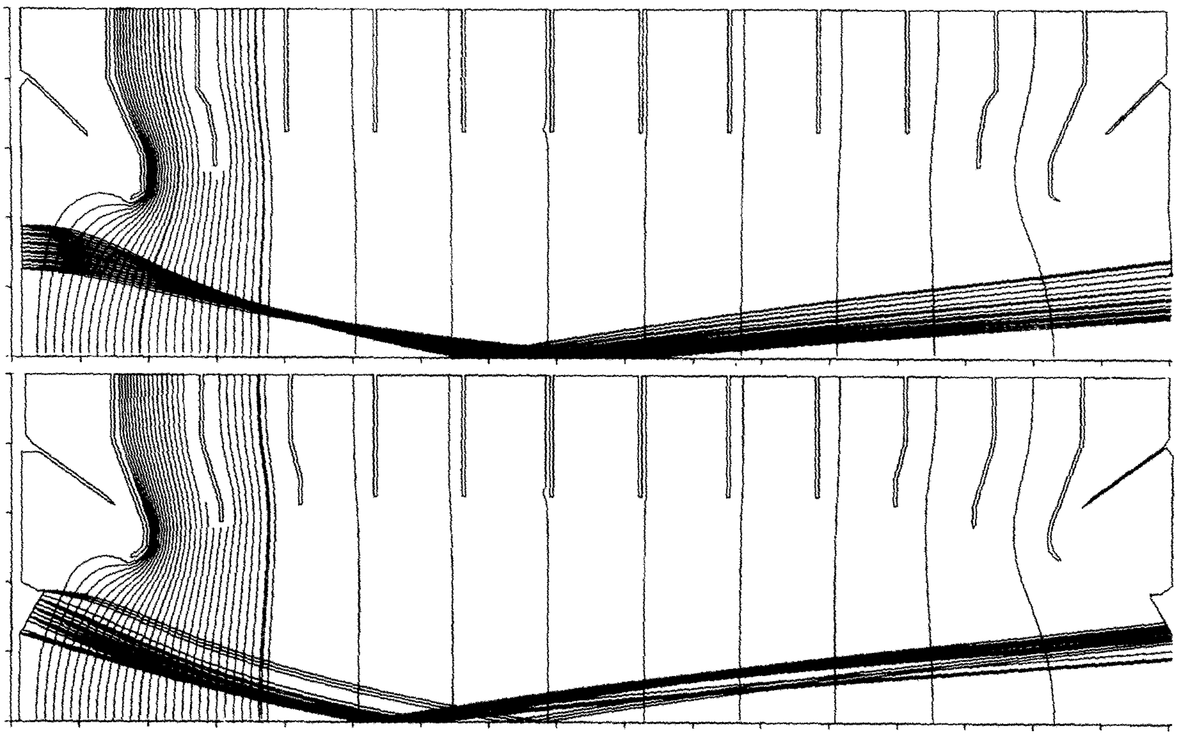

Fig. 2. Electrostatic equipotentials and electron trajectories are shown for two compressed geometry tube configurations. Top: a geometry with flat apertures similar to that proposed by Assmann et al. [1], and bottom: the vee-aperture geometry which is the subject of this report. The electron trajectories shown are for initial energies of 10, 100, and 500 eV and an initial angle with respect to the aperture surface of 90°.

necessary to use insert electrodes of a modified design in the first three gaps of the compressed geometry tube. These are also shown in fig. 1.

The conventional design, used for units 19–22, is similar to that shown in fig. 1 except that the vee-shaped aperture is replaced with a straight 1-mm-thick aperture with a rounded inner diameter. Insert electrodes of the same design were used for both the vee-shaped and straight apertures. Both vee-shaped and straight apertures were fabricated of titanium.

3. Installation in the 25URC accelerator

As shown schematically in fig. 3, installation of compressed geometry tubes in 24 of the 27 units of the 25URC accelerator is based on a modular length of 122 cm extending over three column castings or two units. In order to have the same number of column insulators (5) for each of the seven tube sections, it is necessary to short one column insulator, thereby reducing the total number of column insulators in the module from 36 to 35.

A spacer/lifting ring is provided for each module. This ring, which is approximately 1.4 cm long, has three

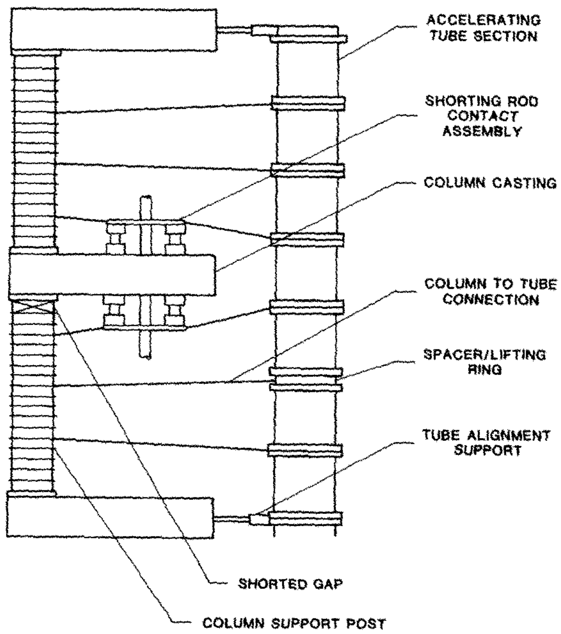

Fig. 3. A schematic view of the installation of compresed geometry tubes in the 25URC accelerator column.

functions: first, to match the length of seven tube sections to the length of the two-unit module; second, to provide a "hard point" for tube lifting operations where lifting forces can be transferred to a ceramic insulator; and third, to provide a component which can be removed transversely so as to allow unstacking of the assembly.

To facilitate diagnostic work with these pairs of units, new shorting rod contacts were provided as shown in fig. 3. With these shorting rod contacts, it is possible to operate any combination of the bottom three tube sections, the middle tube section, and the top three tube sections.

To accommodate the three "odd" units in the accelerator (numbers 5, 14, and 23), a tube section similar to that shown in fig. 1 was developed. This tube section, which has seven insulating gaps, provides a fractional increase in insulator length of $40/33 = 1.21$ per unit over the original design and matches the compressed geometry tube length to the 61-cm unit modulus. When installed, this special tube section is partially reentrant into the adjacent minor dead section.

4. Measurements

Evaluation of the compressed geometry tubes is based on a sequence of measurements – beginning before the removal of the original equipment tubes. These are briefly summarized below:

(a) GVM calibrations: Since shorting all units except 26 and/or 27 results in a significant distortion of the electric field near the terminal, a generating voltmeter (GVM) correction factor must be applied to gradients measured with only these units live. To facilitate these corrections, the GVM calibration was measured, with beam, for units 26, 27, and 26 + 27 live. These calibrations then provided corrections (less than 5%) which were used for all subsequent tests of units 26, 27, and 26 + 27.

(b) Determination of the "maximum stable voltage" of units 26 + 27 prior to removal of the old acceleration tubes: To provide reference data for evaluation of the new tubes, units 26 and 27 were conditioned separately and then together to their highest stable voltages. These voltages, as limited by sparks, were 1.15 MV, 1.10 MV, and 2.08 MV for units 26, 27, and 26 + 27, respectively.

As an aside, we note that these limiting voltages did not appear to be a function of tank gas pressure, indicating that the spark mechanism was internal rather than external to the tube.

(c) Measurement of the "maximum stable voltage" of units 26 + 27 without tubes: To provide a better understanding of the sources of voltage limitation, we measured a set of breakdown voltages for units 26, 27, and 26 + 27, without tubes. Using a procedure which approximated the conditions which are present during tube conditioning, we recorded an average of seven sparks for each combination of units at pressures of 69.0 and 82.5 psig. With one exception, no conditioning effects were observed. The results of these measurements may be summarized as follows: For a given pressure, the breakdown voltages are additive, i.e., the average breakdown voltage for units 26 + 27 is equal to the sum of the breakdown voltages for units 26 and 27 measured separately. The observed breakdown voltages are in good agreement with single column spark gap measurements (when corrected for the large number of gaps). In the top of fig. 5, we show the "maximum stable voltage" for units 26 + 27 at 69.0 and 82.5 psig. In this context, maximum stable voltage was arbitrarily defined as the next-to-lowest spark voltage.

(d) Measurement of the operating characteristics of units equipped with compressed geometry tubes: To provide a convenient comparison, attention was primarily focused on the relative performance of modular pairs of units, i.e., units 19 + 20, 21 + 22, 24 + 25, and 26 + 27. Units 26 + 27 were conditioned and tested at intervals of approximately two, four, and ten weeks after installation in June 1986. Units 19–25, along with units 26 + 27 (which had previously been conditioned) were conditioned and tested at intervals of approximately two and fourteen weeks after installation in November 1986.

5. Results and discussion

As a background for discussion of the performance of the compressed geometry tubes, it is useful to mention two general observations concerning the conventional design tubes which have been used in the 25URC accelerator. The first is that it has been our observation that tube voltage performance improves with operating time – over a scale of at least several years. The second is that in contrast to the original equipment tubes, the reconditioned tubes installed in 1983 * exhibited intense, gradient dependent, continuous X-ray levels which we believe are due to field emission and which have been observed to decrease with time and sparks. The source of these intense, continuous X-ray levels is not understood.

Conditioning of the compressed geometry tubes was characterized by the same phenomena as has been observed for conventional geometry tubes, namely, sparks (increasing in voltage roughly monotonically), pulsed X-ray and vacuum activity, and intense, continuous

* Note: More than 75% of the acceleration tubes of the 25URC accelerator were replaced in the interval August–October 1983 with reconditioned tubes of conventional NEC design [7].

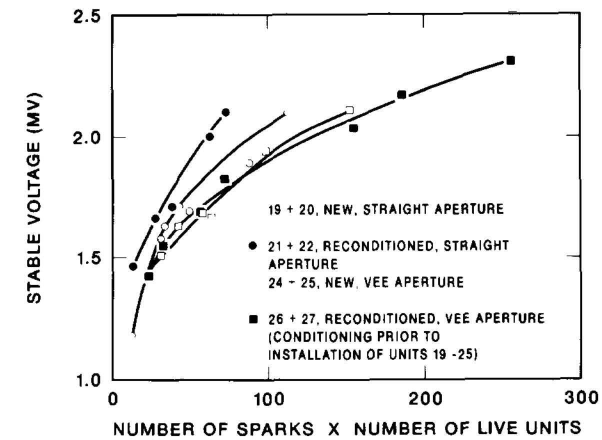

Fig. 4. Stable voltage for two units in MV is shown as a function of the number of sparks multiplied by the number of live units for each spark for four groups of two units equipped with compressed geometry acceleration tubes. Aperture design and tube section history are indicated on the figure.

X-ray levels. A notable characteristic of both types of compressed geometry tubes is that they appear to decondition with respect to pulsed X-ray and vacuum activity only slightly with time.

Two important parameters can be used to describe the voltage performance of acceleration tubes: conditioning difficulty and maximum stable gradient. As a measure of the first of these, fig. 4 shows the stable voltage measured for pairs of units (seven sections) at the end of conditioning intervals as a function of the number of sparks multiplied by the number of units, of the pair, which were live during each spark **. (This method of presentation assumes that a spark tends to increase the attainable stable voltage.) As can be seen, there are large differences between different pairs of units. However, differences of this magnitude were also observed for the conventional geometry tubes installed in 1983 and we are not convinced that the observed differences are significant. We also note that the number of sparks multiplied by the number of live units required to reach 1.9 MV for pairs of units is 19% lower for the compressed geometry tubes than for the conventional geometry tubes installed in 1983. We also note that the time required to reach 1.9 MV for pairs of units was about the same for the compressed geometry tubes and the conventional geometry tubes installed in 1983.

As indicated above, we have noted that voltage performance appears to improve with operating time. Thus, we believe the most meaningful comparison of maximum stable gradient is for tubes at the same time after installation. In table 1, we show such a comparison for a time after installation of approximately three months. Specifically, we show in this table the maximum stable gradient measured for various combinations of units in the group 19–27 for the compressed geometry tubes and for the conventional geometry tubes installed in 1983.

In the lower part of fig. 5, a slightly different perspective on voltage performance is shown, namely, a comparison of the maximum stable voltage achieved with units 26 + 27 for the compressed geometry tubes

** Note: As shown in fig. 3, each of the modular pairs of units (19 + 20, 21 + 22, 24 + 25, 26 + 27) consists of seven tube sections. Using the shorting rod contacts shown in fig. 3, these pairs of units may be operated with all seven sections live or with either three or four sections live. "Two units live" corresponds to operation of seven sections while "one unit live" corresponds to operation of three or four sections.

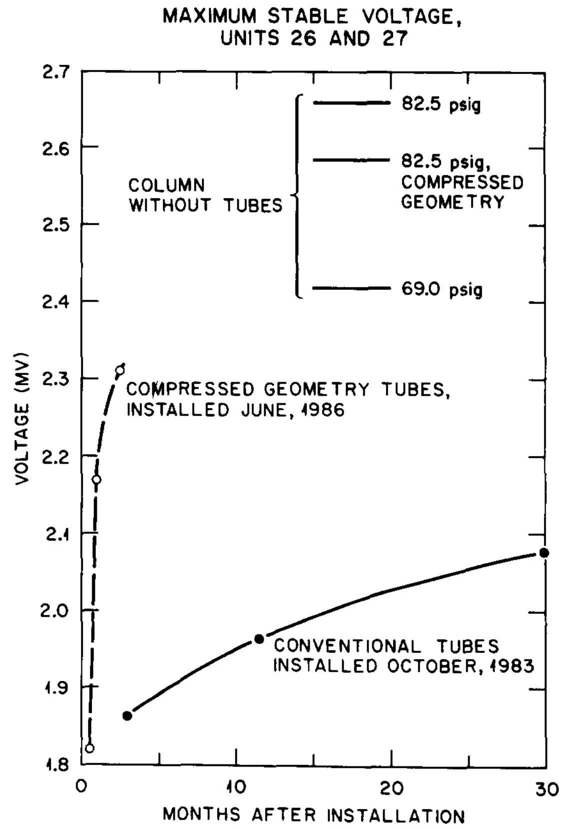

Fig. 5. In the lower part of the figure, the maximum stable voltage measured for units 26 + 27 of the 25URC accelerator is shown as a function of time after installation for compressed geometry and conventional acceleration tubes. In the upper part of the figure, the maximum stable voltage for units 26 + 27 measured without acceleration tubes is shown for two tank gas pressures. The value labeled 82.5 psig COMPRESSED GEOMETRY is a calculated value for 35 column insulators.

Table 1
Maximum stable gradient in MV/unit measured for conventional geometry tubes in March 1984 and for compressed geometry tubes in October 1986 (units 26+27) and March 1987 (units 19–25). In each case, the observed gradients were measured approximately three months after installation.

Unit(s)	Maximum stable gradient (MV/unit)				
	Conventional geometry	Compressed geometry			
	March 1984	October 1986	Improvement	March 1987	Improvement
Average for single units	0.96	1.20	25%	1.12	17%
Average for pairs of units	0.95	1.16	22%	1.07	12%
19–22	0.94			1.04	11%
23–27	0.91			1.04	14%
19–27	0.84			0.96	14%

and conventional geometry tubes installed in 1983 as a function of time after installation. (The data for these conventional tubes are typical of that observed for other conventional tubes in the 25URC accelerator.)

As can be seen from table 1 and fig. 5, installation of compressed geometry tubes has resulted in improved voltage performance. However, it is important to note that the compressed geometry tubes were conditioned more aggressively than the conventional geometry tubes. Thus, some of the differences noted in table 1 and fig. 5 are probably due to differences in conditioning emphasis. We also note that we have no data which determines the ultimate gradient capability of the two compressed geometry aperture designs.

During the course of the last conditioning exercise in February–March 1987, we measured bremsstrahlung spectra for various combinations of units in the group 19–27. For the spectra to be discussed, these measurements were made for gradients of approximately 1.0 MV/unit and at times when no pulsed X-ray activity was present. A comparison of these spectra may be summarized as follows: (1) No significant difference was observed between spectra for pairs of units with vee-shaped apertures and pairs of units with straight apertures. (2) No significant difference was observed in spectra measured for different numbers of units (ranging from two to five) with vee-shaped apertures. (3) A small higher-energy "tail" is clearly observable in spectra measured with four units with straight apertures; this component is not observed when only two units with straight apertures are operated together. We believe the presence of this higher-energy component with straight aperture units and its absence with vee-shaped aperture units is evidence of the improved trapping effectiveness of the vee-shaped apertures. (4) Spectra measured with units 19–27 show a slightly enhanced "medium energy" yield in comparison to spectra measured with units 19–22 and units 23–27. The origin of this effect is not understood.

6. Summary

Compressed geometry NEC acceleration tubes with two different aperture designs have been tested in the Oak Ridge 25URC accelerator. In comparison to conventional geometry NEC tubes, the compressed geometry acceleration tubes appear to provide significantly improved voltage performance. No clear difference in voltage performance, either in ease of conditioning or ultimate capability, was observed for the two aperture designs. Observed bremsstrahlung spectra indicate a small "long-tube effect" with the straight aperture tubes; this effect was not observed with the vee-shaped aperture tubes.

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