Nuclear Instruments and Methods in Physics Research A 378 (1996) 363–368

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

An air-cooled gradient resistor column for the KFUPM 350 kV ion accelerator

M. Raashid, R.E. Abdel-Aal, A.A. Naqvi, M.A. Al-Ohali, M.M. Nagadi

Energy Research Laboratory, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

Received 1 August 1995; revised form received 23 February 1996

Abstract

An air-cooled gradient resistor column has been designed and implemented for the KFUPM 350 kV ion accelerator. The air-cooled column overcomes operational limitations on the acceleration voltages obtained with the old water-cooled column and improves on reliability and maintainability. The new column consists of five sections, each having sixteen 8 MΩ 15 W resistors connected in a series-parallel combination. Corona shields defining equipotential circular planes have been incorporated to maintain a uniform potential difference across the column sections. In order to protect the gradient column and accelerator tube against arcing, spark gaps are provided on each corona shield. The new column has been tested over the full range of 0–320 kV across the accelerator tube for extended durations without arcing. Both electrical and mechanical aspects of the new design are discussed, measurement techniques used during installation and testing are described, and performance data are given.

1. Introduction

For the past seven years, the Energy Research Laboratory (ERL) of King Fahd University of Petroleum and Minerals (KFUPM) has been operating a 350 kV high current light ion accelerator facility [1]. The accelerator tube has five sections, with the beamline end of the tube grounded. A gradient resistor column (GRC) with five sections is connected across the accelerator tube and maintains equal acceleration voltages across the tube sections. The old gradient resistor column consisted of a water-cooled resistor chain containing 1650 carbon composition (20 kΩ, 2 W) resistors connected in series. This corresponds to a total column resistance of 33 MΩ and a maximum bleeding current of about 10 mA. High beam currents require a large bleeding current through the column to ensure transportation of the beam without upsetting the voltage gradient due to beam deflection or defocusing. On the other hand, smaller beam currents allow a proportionally smaller bleeding current which reduces power losses in the HV power supply and in the column resistors and simplifies the column design. Reduced power dissipation allows the use of natural air cooling instead of forced cooling. The relatively high bleeding current in the original design was required to match the high beam currents of up to 12 mA from the General Ionex model 740 high current ion source. At present, experiments using the accelerator require a maximum beam current of only about 1.5 mA, and therefore a lower bleeding current can be used.

During the past years of accelerator use, it was observed that the gradient column resistors blew up frequently, which practically limited operation to accelerator voltages upto 250 kV only. Problems were attributed to the use of ordinary carbon composition resistors in a water-cooled environment which caused corrosion. Repairing the old column has been a tedious and time consuming task which required complete dismantling of the resistor column, leading to possible accelerator shutdown for intervals as long as two weeks. In order to avoid difficulties faced with the old GRC, a new air-cooled gradient resistor column which is easy to maintain and repair was designed and implemented. In the following sections, the salient features of the new column are described and its performance tests and results are reported.

2. The air-cooled gradient resistor column

2.1. Design criteria

i) The lower beam current requirement allows a significant reduction in the column bleeding current, thereby reducing power dissipation in the column resistors. This allows column operation with natural air cooling, thereby eliminating the problem of resistor damage by corrosion

PII S0168-9002(96)00444-5

associated with water cooling. Air cooling also allows free access for testing and repairing the column resistors.

ii) Use of precision high voltage resistors with larger resistance values and higher power ratings allows a considerable reduction in the total number of resistors in the column. This also reduces maintenance effort and repair time.

iii) Incorporation of equipotential circular planes between the column sections helps maintain a uniform distribution of the acceleration voltage over the sections, a feature that was not available in the original column design.

iv) Addition of spark gaps on each corona shield protects the gradient column resistors and accelerator tube against arcing.

2.2. Gradient resistor column assembly

Caddock precision high voltage resistors of the MG series were chosen for the new column because of their inductance-free design [2]. The resistors have been successfully used in similar accelerator high voltage installations [3]. Fig. 1 shows the electrical design of the new column with a bleeding current of 2 mA at the maximum acceleration voltage of 320 kV. The design is based on a parallel-series combination of sixteen 8 MΩ resistors for each of the five sections. For comparison, parameters of the old and the new column designs are listed in Table 1, with the latter using resistors rated at 15 W and 30 kV. The table indicates improvements in the new design for both voltage and power ratings at room temperature. The reduced tolerance on the resistor values, from 10% to 1% (or 0.1% optionally), makes it easier to achieve almost equal values for the section resistances. This leads to equal voltage distribution over all sections without having a pre-select resistors individually for matching values. With 10% tolerance for resistors in the old design, the worst-case increase in the section voltage can be as high as 17%, while the 1% tolerance for the Caddock resistors the increase becomes as low as 1.6%.

Fig. 2 shows the mechanical arrangement of the new gradient resistor column. The column structure is supported on four cylindrical Teflon rods, each 30 mm in diameter. Teflon was chosen for its high insulation resistance, ease of machining, and light weight. Another arrangement sometimes employed in similar installations uses a box structure, often made up of sheets joined together, for supporting the column resistors. This has the disadvantage that seams and sharp edges could act as guides for sparks along the surface, thus increasing the possibility of arcing [4]. The cylindrical rods providing support in the new design overcome this limitation and allow more space around the resistors for improved air circulation and more efficient heat dissipation. Larger space also makes it easier to clean the resistors, visually inspect them for signs of damage, and simplifies their replacement in case of a fault. Easy inspection and repair of the column in situ is an important feature of the new design. The Teflon rods are machined with 2.5 mm-deep grooves on their surface with equal mark and space distances of 4 mm. The grooving introduces a discontinuity in the surface path and increases the effective insulating length on the rod surface by a factor of 62.5%, which helps prevent the formation of spark tracks along the surface [5]. The Caddock resistors are mounted in pairs, with each pair electrically connected (and physically mounted) in parallel in a double-helical arrangement between the Teflon rods as shown in Figs. 1 and 2. The Teflon rod passes between the resistor pairs, which ensures a minimum spacing of about 22 mm between adjacent resistors connected in parallel.

The circular aluminum corona shields, which define the equipotential planes between the voltage sections, are 3 mm thick and 425 mm in diameter. Each circular shield has four holes for the Teflon rods to pass through and the

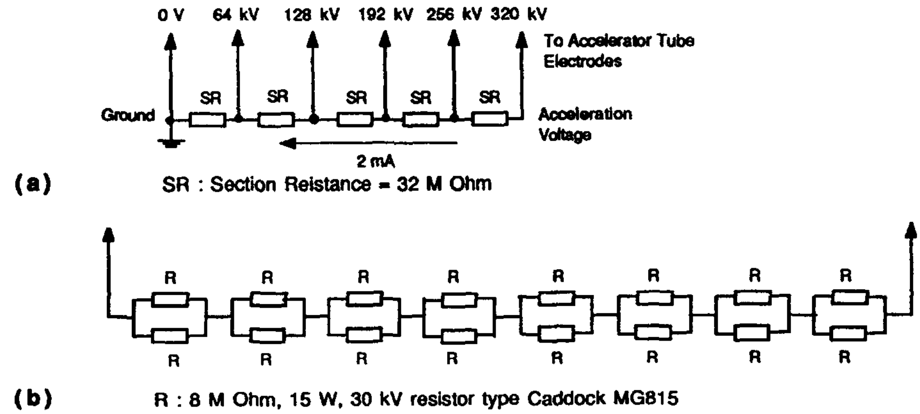

Fig. 1. Electrical design of the new gradient resistor column. (a) Equivalent circuit of the column showing voltages and current at 320 kV acceleration voltage. (b) Section implementation using 8 MΩ Caddock resistors.

Table 1
A comparison between the electrical characteristics of the original and the new designs for the gradient resistor column

Parameter	Old design	New design
General		
Number of gradient sections	5	5
Number of resistors per section	330	16
Total number of resistors	1650	80
Resistor value	20 kΩ	8 MΩ
Resistor arrangement	Series	Parallel-series (see Fig. 1)
Total column resistance [MΩ]	33	160
Bleeding current at 320 kV acceleration voltage [mA]	9.7	2
Cooling requirements	Forced cooling with deionized water	Natural Air convection
Resistor specifications		
Type	Carbon composition	Caddock MG815
Dimensions (length × diameter)	17.8 × 8 mm	150 × 9 mm
Tolerance [%]	±10	±1
Maximum voltage rating	700 V	30 kV
Maximum power rating [W]	2	15
Temperature coefficient PPM/°C	1200	80
Maximum operating temperature before derating [°C]	105	125
Resistor operating conditions at 320 kV acceleration voltage		
Voltage stress	194 V	7.5 kV
Power dissipation [W]	1.88	8

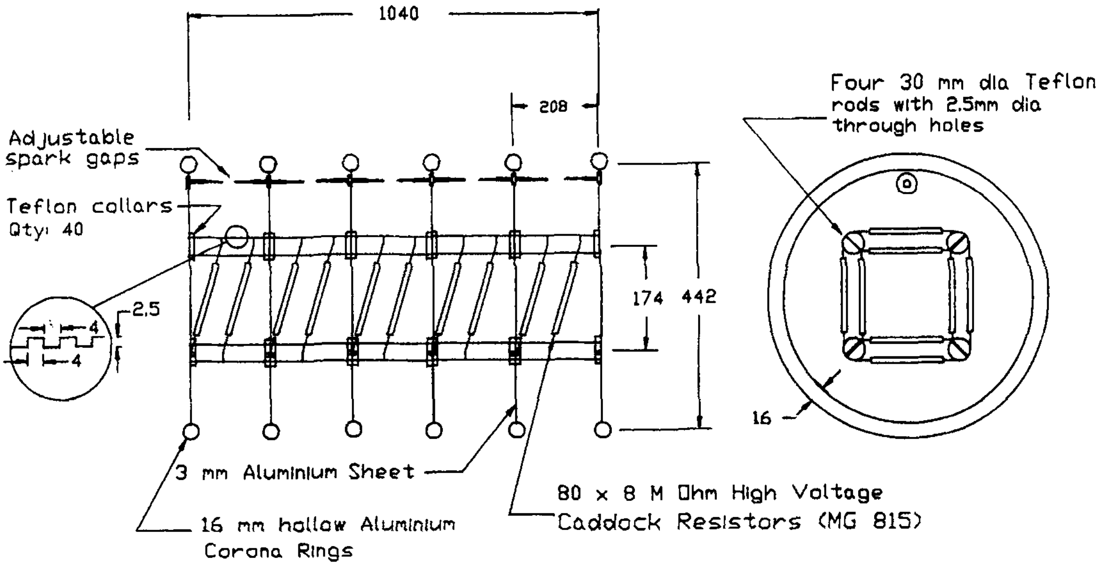

Fig. 2. Mechanical design of the new gradient resistor column. All dimensions are in mm (not to scale).

shields are fixed to the four rods using special Teflon collars. A hollow aluminium corona ring with an external diameter of 16 mm is welded to the rim of each shielding plane. The rings help prevent sparking between the sharp edges of adjacent shields. The corona rings also provide a means of connecting the gradient section voltage to the corresponding electrodes on the accelerator tube through clamp-on contacts.

Each of the spark gap assemblies consists of two conductors separated by an adjustable short distance and provides protection against build up of excessive voltage across a section. Spark gaps are mounted on the corona shields as shown in Fig. 2. The spark gaps were adjusted such that arcing takes place at a section voltage which is slightly above the normal maximum operating value. Gap distances were determined from data given in Ref. [6]. There are mainly two scenarios where the section voltage may exceed the maximum limit. In the first, the total applied voltage may exceed the upper operating limit of the acceleration voltage, causing all section voltage to exceed their limit simultaneously. This will result in arcing across all the spark gaps, thereby grounding the HV terminal and causing the tripping of the HV power supply. In the second scenario, an imbalance in the voltage distribution among the various sections of the column may be caused by the beam striking the internal electrodes of the accelerator tube or due to some faulty section resistors. In this case, the voltage across some sections would exceed the safe operating voltage, causing arcing across the spark gap of that section. Short-circuiting of that section by arcing increases the voltage across other sections, leading to successive arcing across their gaps and the eventual short-circuiting of the whole column and the tripping of the HV power supply as in the previous scenario.

3. Installation and testing

All the 80 Caddock resistors were individually tested using a Hiptronics mega ohmmeter model HV15 which applies 8 kV to the resistor. Measurements have shown all resistor values to fall within the ±1% specified tolerance. The resistors were then mounted on the Teflon supports in the double helical arrangement shown in Fig. 2 and soldered together to form the parallel-series circuit arrangement shown in Fig. 1. Layout and soldering were carried out according to standard recommended practices for high voltage circuits [7]. Total resistance for each of the five sections was found to be within the ±1% of the theoretical calculated values. The total column resistance was also measured by the HP 3457A microprocessor-based multimeter and found to deviate from the nominal value of 160 MΩ by only −0.3%. The ratio of the total column resistance to the resistance of section 2 was measured as 4.99774, as compared to the expected nominal value of 5. In addition to the total accelerator voltage, it was desired to measure the individual section voltages because the ratio of the total voltage to the section voltage is an indication of the column performance. Conventional high voltage measuring devices usually require one of their terminals to be grounded. Therefore, only the voltage on section 1 (sections are numbered from the grounded end of the accelerator tube) as well as the total accelerator voltage could be measured using the Fluke digital multimeter model 73 in conjunction with the 40 kV high voltage probe model 80K-40. At an accelerator voltage of 30.2 kV, section 1 voltage was 6.00 kV, giving a ratio of 5.09. Using the Fluke meter and probe, it was not possible to determine this ratio for any of the other sections which have both their ends floating.

To avoid this limitation, a high voltage probe was locally fabricated to measure the high voltage between floating ends of individual sections. The probe uses two 500 MΩ resistors connected in series with the terminals of a Beckman 4 1/2 digit multimeter model 4410B used as a current meter on the range 0–200 μA. In this way, the probe covers the maximum section voltage range of 0–64 kV on a single current range. The probe was tested by measuring section 1 voltage, where the reading from the locally fabricated probe agreed with that of the Fluke's probe to within 0.2%. Measured voltages across sections 2, 3, 4 and 5 were found to be in good agreement with that of section 1 over the full range of accelerator voltage, as indicated in Table 2. The value for the total accelerator voltage was read from the HV digital readout on the remote machine console in the control room. Clamped on the section corona rings, the home-made meter was left self-supported across the column section being measured. This arrangement proved adequate except for measurements on sections 4 and 5 at high accelerator voltages. These sections are closer to the accelerator terminal deck where coupling between the meter resistors and the large HV terminal structure may affect the meter reading. Such suspected readings are not included in Table 2. Fig. 3 is a plot of section 2 voltage measured with the home-mode HV probe versus the total accelerator voltage. The solid line is a linear fit to the data and has a slope of 0.19665. It is noted that measured section voltages in Table 2 and Fig. 3 should be corrected for the loading effect of the 1000 MΩ input resistance of the home-made probe by multiplying the measured section voltage by 1.0256. The corrected slope of the fitted line in Fig. 3 is therefore 0.20168. The inverse of this slope (4.95835) represents the average ratio between the total accelerator voltage and section 2 voltage. This value closely matches the figure of 4.99774 obtained earlier for the ratio between the total column resistance and section 2 resistance as measured using the HP 3457A multimeter. The results indicate that the new gradient resistor column maintains equal section voltages over the full range of 0–320 kV for the total accelerator voltage.

The new column has been in routine use in the ac-

Table 2
Voltages measured using the home-made HV probe across the five sections of the column at various values of the acceleration voltage applied as indicated on the console digital readout. Section voltages shown do not include correction for voltmeter loading effect

Console digital readout [kV]	Section 1 voltage [kV]	Section 2 voltage [kV]	Section 3 voltage [kV]	Section 4 voltage [kV]	Section 5 voltage [kV]
20.2	3.88	3.88	3.88	3.88	3.88
30.3	5.84	5.84	5.84	5.84	5.84
40.9	7.89	7.88	7.88	7.89	7.89
54.4	10.50	10.50	10.50	10.51	10.51
102.2	19.90	19.90	19.89	19.92	19.90
159.7	30.97	30.97	30.94	31.00	30.94
208.6	40.54	40.56	40.52	40.58	40.42
220.4	42.87	42.89	42.90	42.93	42.67
234.0	45.51	45.53	45.59	45.62	
245.4	47.76	47.72	47.85	47.90	
256.1	49.88	49.94	49.90	49.93	
260.1	50.49	40.56	50.53		
266.2	51.95	52.03	52.00		
277.1	54.22	54.25	54.24		
288.6	56.72	56.60	56.57		
299.7	58.99	58.97	58.93		
311.3	61.35	61.28	61.19		
322.4	63.64	63.65	63.57		

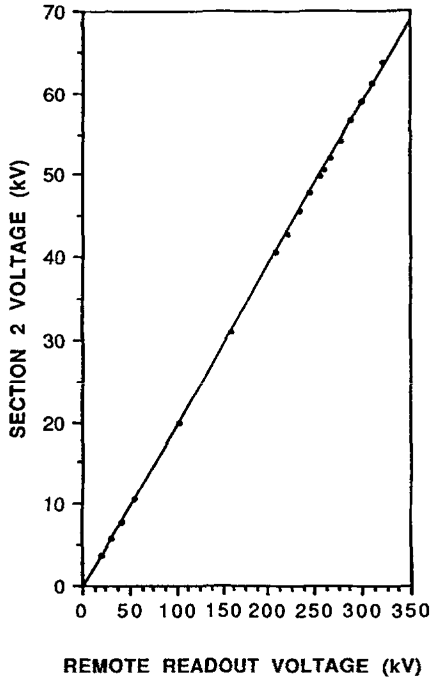

Fig. 3. The voltage measured across section 2 using the home-made HV probe versus the total acceleration voltage displayed on the remote machine console. Section voltage is not corrected for the loading effect of the probe.

celerator program of research experiments since its installation in April 1995, and satisfactory operation was verified for extended durations without arcing. The column was successfully tested with a 0.85 mA proton beam transported through the accelerator tube at a total energy of 350 keV. To observe the effect of beam defocusing on section voltages, the beam profile was altered by adjusting the controls of a solenoid lens located on the acceleration terminal before the accelerator tube while monitoring section voltages. During beam tuning with this typically large value of beam current, no appreciable changes were observed on the voltage distribution over the column sections from earlier measurements without beam.

4. Summary

An air cooled gradient resistor column has been designed and implemented for the KFUPM 350 kV ion accelerator. The new column offers many practical advantages in terms of reliability and maintainability over the previous water-cooled design. Reduced bleeding current allows operation at a proportionally reduced power. This permits the use of a much smaller number of larger-valued air cooled resistors. The column contains equipotential planes in the form of corona shields, providing a more uniform voltage distribution across the sections. In order to protect the accelerator tube from damage due to over-voltage, spark gaps are provided between the shields. The new column has been successfully tested at voltages upto

320 kV, which is the maximum rated value for the accelerator voltage.

Acknowledgements

This work is part of KFUPM/RI Energy Research Laboratory project supported by he Research Institute of King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

The authors would like to thank K. Purser and C. Westerfeld for helpful comments and suggestions and M. Abdel-Salam, K. Alsoufi, and M. Al-Haddad for useful discussions.

References

[1] H. Al-Juwair, G. Blume, R.J. Jaarsma, C.R. Meitzler and K.H. Purser, Nucl. Instr. and Meth. B 24/25 (1987) 810.

[2] Caddock Electronics Inc., 1717 Chicago Avenue, Riverside, CA 92507, USA.

[3] D.C. Weisser, Nucl. Instr. and Meth. A 328 (1993) 138.

[4] K. Purser, Southern cross corporation, Danvers, MA 01923, USA, private communication.

[5] C. Westerfeldt, Triangle Universities Nuclear Laboratory, Durham, NC 27706, USA, private communication.

[6] J.H. Watt (ed.), American Electricians' Handbook, 9th edition (McGraw-Hill, New York, 1970).

[7] H. Khalifa (ed.), High-Voltage Engineering: Theory and Practice (Marcel Dekker, New York, 1990).