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Folded tandem ion accelerator facility at Trombay

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Abstract. The folded tandem ion accelerator (FOTIA) project at BARC has been commissioned. The analysed carbon beams of 40 nA(3^+) and 25 nA(4^+), at terminal voltage of 2.5 MV with $N_2 + CO_2$ as insulating gas, were obtained. The beams were characterized by performing the Rutherford back scattering (RBS) on gold, tin and iron targets. The beam energy of 12.5 MeV for $^{12}C^{4+}$ was consistent with the terminal voltage of 2.5 MV. The $N_2 + CO_2$ mixture is being replaced by SF_6 gas in order to achieve 6 MV on the terminal. In this paper, some of the salient features of the FOTIA and its present status are discussed.

Keywords. Folded tandem ion accelerator; carbon beam; magnets; electrostatic deflector; quadrupole lenses; foil/gas strippers; Rutherford back scattering.

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1. Introduction

In recent years the low energy heavy ion accelerators have played an important role both in basic and applied sciences particularly in the fields of nuclear physics, astrophysics, material science, accelerator mass spectrometry, atomic spectroscopy, etc. The accelerator mass spectrometry is one of the important areas where the tandem accelerators are being increasingly used because of their ultra sensitivity to the measurements. Although there are a large number of Van-de-graaff accelerators in different laboratories only in two cases they have been converted into folded tandems [1,2]. A project [3,4] was taken up to convert the 5.5 MV CN model Van-de-Graaff accelerator which existed at BARC into a folded tandem for accelerating both light and heavy ion beams. It involved designing, fabrication, installation and commissioning of a folded tandem ion accelerator (FOTIA) with a terminal voltage of 6 MV (figure 1). The layout of the FOTIA (figure 2) was worked out on the basis of beam optics studied in detail [4,5].

In the present system, negative ion beams extracted from the SNICS-II source are pre-accelerated up to 150 keV. They are then injected into the low energy accelerating tube through a 70°-magnet and a 20°-electrostatic deflector. An electrostatic quadrupole triplet and an einzel lens focus and match the beam parameters to the acceptance of the low energy tube. The electrons of these accelerated negative ions get stripped off at the stripper and desired charge state of the positive ions thus produced is selected with a 180° magnet inside the high voltage terminal before being bent into the high energy accelerating tube.

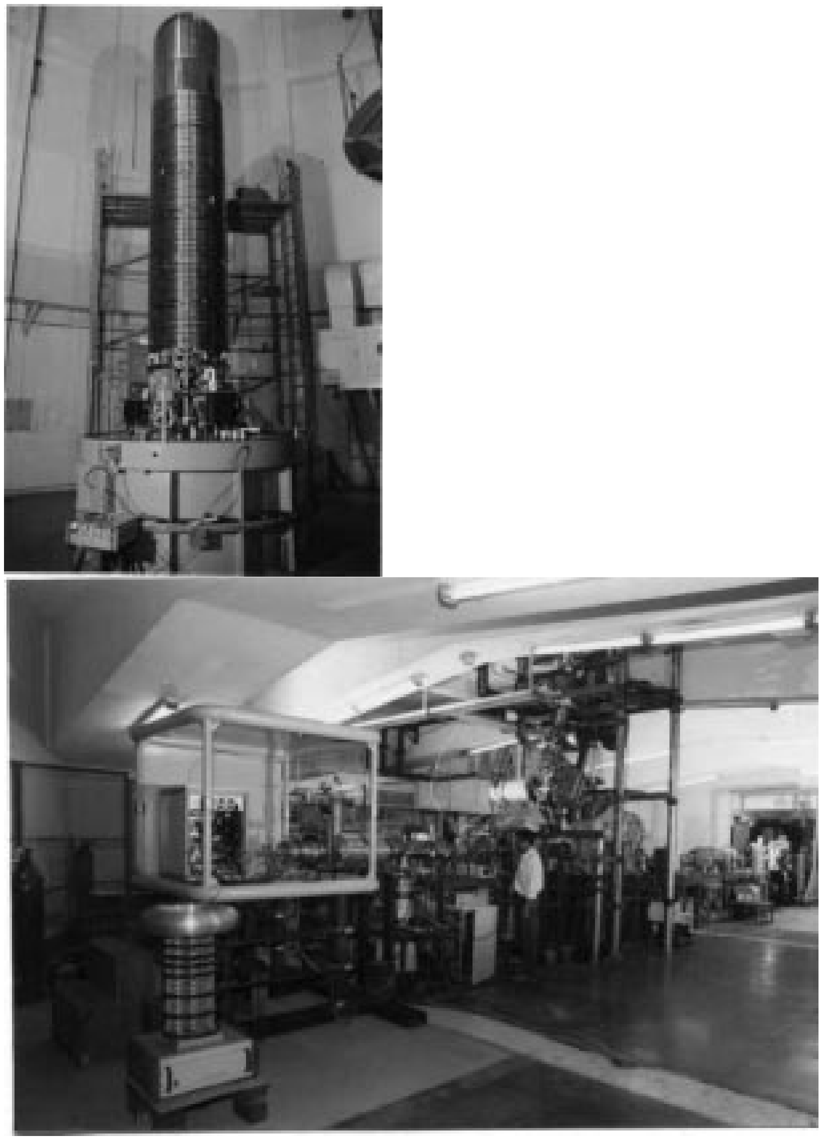

Figure 1. Perspective view of the Folded Tandem Ion Accelerator (FOTIA) facility at BARC. Upper portion: the high voltage column section, lower portion: (L to R) ion source, low and high energy beam lines and the scattering chamber.

As at the exit of the 180° magnet the beam diverges, an electrostatic quadrupole doublet is used to focus the beam before it enters the high-energy accelerating tube. The beams accelerated in the high energy accelerating tube are focussed using a magnetic quadrupole triplet before being analysed by a 90°-magnet. In table 1, final beam energies (E_F) and relative intensities corresponding to different charge states produced at the stripper in the terminal are listed.

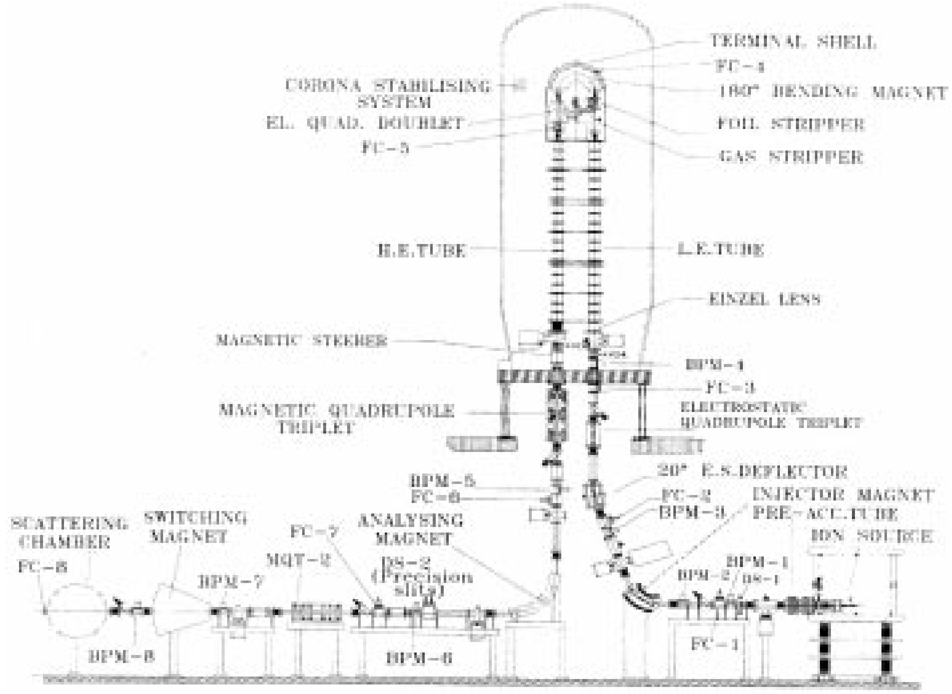

Figure 2. Schematic diagram of the folded tandem ion accelerator.

Beam profile monitors (BPM), precision double slits and pneumatically operated Faraday cups (FC), developed indigenously, have been provided at strategic points for monitoring and measurement of the beam intensities. The FOTIA project has been completed recently [6] and all the components (low and high energy beam lines, high voltage column section, charging assembly, SF_6 gas handling and computer control systems, magnets, electrostatic and magnetic lenses, steerers, scattering chamber, etc.) have been working satisfactorily. In the following sections, details of some of these sub-systems are given.

2. Magnets

As can be seen in figure 2 three dipole magnets [7] are used in the FOTIA and have been developed indigenously. While two of these magnets (70°-injector, 90°-analysing magnet) are at ground potential, the third, 180°-folding magnet, is located inside the high voltage terminal. The pre-accelerated beam is analysed by the 70°-dipole magnet [8]. Out of all the charged particles extracted from the ion source, the negative ions of the particular mass are selected for injection into the low energy accelerating tube. The magnet has a bending radius of 40 cm and was designed for a magnetic field of 14 kG in the pole gap of 4 cm. It can bend the ions having mass-energy product $(ME/q^2) \leq 15$. A magnetic field of 14.5 kG was realised at a current of 180 Amp. The field uniformity (± 0.1%) was also found

Table 1. Final beam energies at a terminal voltage of 6 MV.

Ion	Z	q^+	Relative%	E_F (MeV)
^{1}H	1	1	100	12
^{4}He	2	2	100	18
^{12}C	6	3	12	24
		4	52	30
		5	33	36
^{16}O	8	4	24	30
		5	47	36
		6	23	42
^{24}Mg	12	5	24	36
		6	39	42
		7	25	48
^{28}Si	14	5	16	36
		6	34	42
		7	31	48
^{32}S	16	6	28	42
		7	34	48
		8	19	54
^{37}Cl	17	6	29	42
		7	33	48
		8	18	54
^{40}Ca	20	7	31	48
		8	26	54
		9	12	60

Table 2. Analysed beam currents from the ion source with different cathode samples.

Required beam	Sample used	Current @ FC1 (μA)	Current @ FC2 (μA)
^{1}H^{-}	TiH	25	4.5
^{7}Li^{-}	LiF	22	0.3
^{12}C^{-}	Graphite	30	5.0
^{16}O^{-}	Fe2O3	38	24
^{28}Si^{-}	Si(Natural)	25	13
^{35}Cl^{-}	NaCl	35	11

to be as per specifications [8]. Several beams were extracted from the ion source and then analysed using the 70°-magnet. Analysed beam currents of several microamperes were measured (table 2) on the Faraday cup (FC2) located after the 70°-magnet and transported to the beam profile monitor (BPM) located at the entry of the low energy accelerating tube. In these measurements, the cathode voltage was 2 kV. Since the ion beams are extracted using positive voltage, the current at Faraday cup (FC1), mounted before the 70°-magnet, contains electrons and other negative ions produced from the corresponding samples used at the ion source. A typical mass spectrum obtained with graphite cathode sample is shown in figure 3. For 100 keV pre-accelerated beam, the transmission through the 70° magnet was found to be more than 90%. The controlling and monitoring of the various parameters

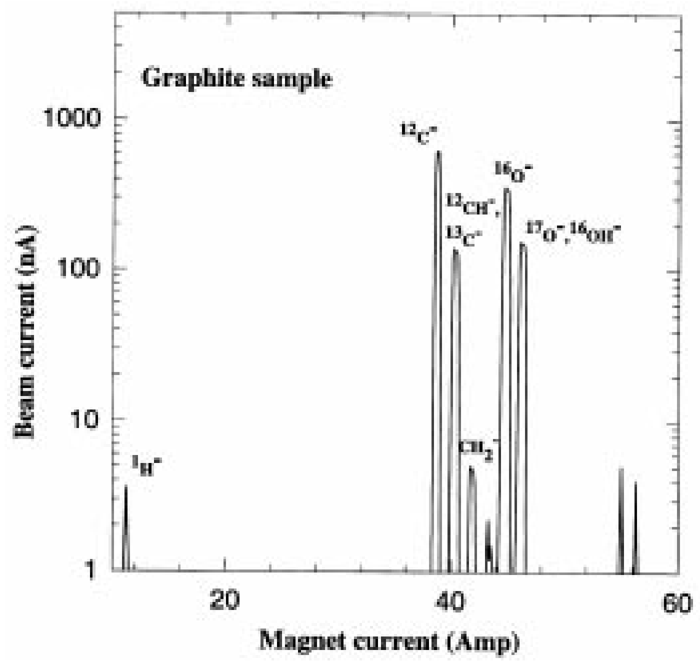

Figure 3. Mass spectrum for graphite cathode sample.

of the ion source located at the high voltage, was done using the fiber optic data telemetry system [9] developed for FOTIA.

The 180° magnet (figure 4) ($ME/q^2 = 10$, $R = 30.5$ cm) has been tested for its field uniformity and it was found to be ± 0.15%. A magnetic field of 10.2 kG was measured at 100 Amp. The close loop cooling system for the magnet, consisting of cooling jackets, a reservoir (jacketed dome), a circulating pump, valves etc, was used for cooling the magnet coils. However, it was observed that the temperature of the coils rises to above 100°C with the above water cooling system. This problem was studied, in detail, in collaboration with Reactor Safety Division (RSD) and Accelerator and Pulsed Power Division (APPD) of BARC. In order to bring down the temperature of the magnet coils to an acceptable value of about 50°C it was found necessary to blow about 1000 litres/min of SF_6 inside the magnet coils and to its surrounding areas [10]. An additional line was erected through the centre of the column section for this purpose. Appropriate modifications for this purpose were made in the gas handling system. Extensive testing was done for various coil currents with additional temperature sensors at various locations inside the high voltage terminal. It was observed that with the additional cooling, the temperatures remain within the acceptable limit of 50°C (figure 5). To monitor the temperature of the 180°-magnet coils and the surrounding areas, inside the terminal where control electronics is mounted, temperature sensors using IC LM335 were designed, fabricated and installed. The sensor circuit, used continuously, is a ground referred thermometer and gives voltage output of 10 mV/°C. With these sensors, the temperatures can be monitored remotely from the main control console.

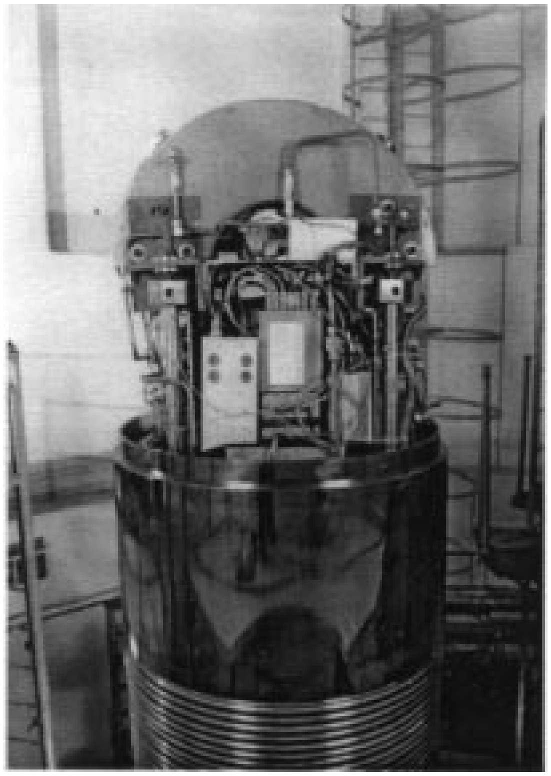

Figure 4. 180°-folding magnet inside the high voltage terminal.

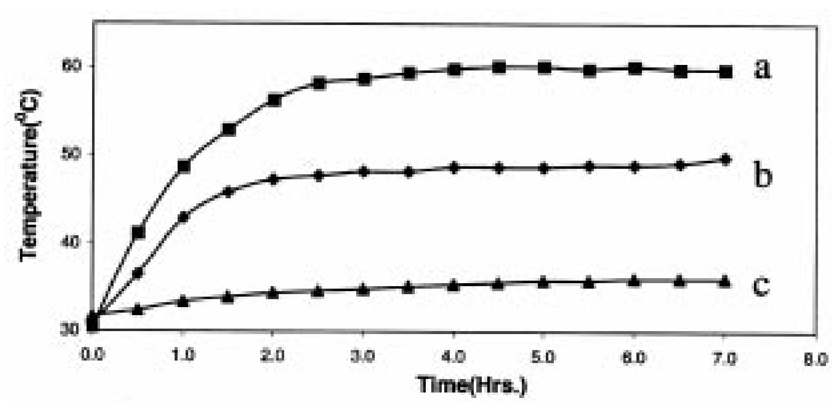

Figure 5. Variation of coil temperature with time: (**a**) without additional cooling, (**b**) with additional cooling, (**c**) temperature of electronics area with additional cooling.

In FOTIA, the beams accelerated in the high energy tube are focussed using a magnetic quadrupole triplet (MQT). For this purpose, a quadrupole triplet was designed, fabricated and installed. For shifting the beam axis, if required, magnetic steerers have been fabricated and installed in the beam line. The high energy beam is analysed by the 90°-dipole magnet designed [7] for a magnetic field of 14 kG and $ME/q^2 = 50$ with a radius of curvature of 75 cm. Each of the two coils of the magnet, made of 56 turns of 12 mm × 12 mm hollow (hole dia. 8 mm) copper conductor has a resistance of 40 mΩ and can carry a maximum current of 500 Amp. A magnetic field of 14 kG was obtained at 425 Amp. A 500 Amp power supply, supplied by Technical Physics and Prototype Engineering Division (TPPED) of BARC [11], was used in these measurements.

3. High voltage column section

The high voltage column section [12] consists of six modules; each designed for one million volt. Each module has 4 ceramic insulating posts which can withstand high compressive stresses. The insulating posts are ceramic to metal bonded with 18 corona gaps connected by equipotential hoops. To ensure that each insulating column post was under compressive stress a screw jack assembly was designed, tested and installed. The screw jack assembly consists of a conical seat, spherical washer, round nut and a bolt.

The electrical power, required in the terminal, for 180°-magnet, ion pump, foil and gas strippers, quadrupole doublet, Faraday cup and other electronic components, is generated by the 5 KVA, 3 phase, 440 volts alternator. The alternator, connected by a perspex shaft (consisting of 3 pieces; each 99 cm long machined to an accuracy of 100μ) is driven by a 10 HP motor rotating at 1450 rpm. The natural frequency of the shaft assembly was found to be far off from the rotational frequency of the shaft (25 Hz). The vibration measurements were made with six modules constructed using actual ceramic column posts with two separator plates combined together to form a small dead section. This dead section accommodates a specially designed flexible coupler. The maximum vibration amplitude with both perspex shaft and pellet chain running was found to be less than $50\,\mu$ [13]. Based on the experience at 14 UD BARC-TIFR pelletron at Mumbai, it was decided to accept these vibration levels. The corresponding velocity and the acceleration values were also found to be within the safe limit.

The high voltage system of FOTIA consists of different components like charging chain mechanism, high voltage measuring device and control system. A pellet chain charging system, made of metallic pellets and nylon links, is used for generating the voltage on the terminal. The charging takes place by induction method. The pellet chain is driven by a 7.5 HP, 600 rpm motor which is mounted on a see-saw mechanism. The high voltage measurement system of FOTIA uses a generating voltmeter (GVM) mounted on the inside surface of the tank, in front of the high voltage terminal. The high voltage control system uses a corona probe mounted inside the tank opposite to the GVM. The high voltage tests were carried out using N_2+CO_2 mixture as an insulating gas. At a tank pressure of 98 psig, a sustained voltage of 3.4 MV was achieved on the terminal [14].

4. SF_6 gas handling system

In the old 5.5 MV Van-de-Graaff accelerator, a mixture of 80% nitrogen and 20% carbon dioxide was used as insulating gas, at a pressure of 225 psig. However, in FOTIA, SF_6 will be used as insulating gas, which has a dielectric strength of approximately 2.2 times that of the N_2+CO_2 mixture at 98 psig. Since hydrocarbon free environment is required inside the accelerator tank, it is necessary to use oil free equipments. The new gas handling system [15], which consists of an oil free compressor, a centrifugal blower, a heat exchanger, dust filters, dryers and a vacuum pump etc, was designed, installed and commissioned in collaboration with Reactor Services and Maintenace Division of BARC. The gas handling system, is used mainly: a) to transfer SF_6 gas from storage tank to accelerator tank and vice versa, b) to evacuate the accelerator tank to a pressure about 0.5 Torr (this maintains purity of gas by minimizing the contamination of SF_6 by residual air), c) to remove moisture and breakdown products by recirculating gas in a close loop system containing activated alumina dryer, heat exchanger, blower and filters, d) to maintain the temperature, inside the accelerator tank, to its designed value. A filter assembly, capable of stopping dust particles beyond 0.1 μ size, has also been installed in the gas line at the entry of the accelerator tank.

5. Vacuum system

In FOTIA, ions are injected and then accelerated through the accelerating tubes and finally transported to the target chamber line covering a long path of about 35 meters. Since the charge exchange cross sections for heavy ions are very large it is necessary to minimize the residual gas pressure and maintain ultra high vacuum in the accelerator tubes and rest of the beam transport system. This is also required to reduce the loss of intensity and spread in energy of the ion beams. Also, the accelerating tubes are subjected to very high voltage gradient of about 2 MV/m, and this requires a hydrocarbon free and clean vacuum for smooth operation of the accelerator. The FOTIA vacuum system [16,17] comprises of about 35 m long, 100 mm diameter beam lines including various diagnostic devices, two accelerating tubes, and three vacuum chambers for dipole magnets. All the beam line components are UHV compatible, fabricated from stainless steel 304L grade material and are fitted with metal gaskets. This enables degassing of the beam lines at elevated temperature. A distributed pumping system having seven pumping stations has been used to maintain UHV for the total volume of about 3×10^5 cm^3 and surface area of 1.5×10^5 cm^2 for the whole accelerator including an experimental beam line and a 80 cm diameter scattering chamber [17]. The type of the pumps installed in a particular section is based on the gas load in that section. The ion source section has a large gas load, which increases substantially whenever samples are changed in the ion source. A turbo-molecular pump, with the speed of 1600 litres/sec, maintains ultra high vacuum in this region. The other sections, which are thoroughly degassed and have very small degassing loads from metal surfaces, are pumped by a combination of titanium sublimation and sputter ion pumps or only by sputter ion pumps.

6. Control system and electronics

For controlling and monitoring the parameters of the FOTIA a PC based control system has been designed, fabricated and installed. This system has been designed as a network of PCs with a front-end interface using CAMAC instrumentation and uses QNX real time operating system. There are large number of ion source components (like extractor, einzel lens, cathode, filament etc.) located inside the high voltage deck which is raised to -150 kV. The control and monitoring of these devices is done from ground level. A time multiplexed optical fiber, for transmitting and receiving signals is used. The special feature of the system is that it has only one fiber for sending the signals and another one for receiving all the channels as compared to multiple fiber systems which use one fiber for each channel [9]. For controlling the devices (foil stripper, ion pump, Faraday cup, folding magnet and temperature sensors etc.) located inside the high voltage terminal, a fiber optic system was obtained from NEC. This has 21 channels for controlling and monitoring the above devices which were interfaced with the fiber optic system. The controllers, for interfacing electrostatic and magnetic steerers, quadrupole lenses, 50 kV charging power supplies, Faraday cups and the 75 kV einzel lens power supply, have been designed, fabricated and installed. In order to have stable ion beam through FOTIA, the terminal voltage requires good stabilization. Generating voltmeter and control slit signals are used for controlling the terminal voltage. The corona stabilization system provides regulated discharge from the terminal through corona drain system to ground. A proper circuit using 4D21 vacuum tube was designed for stabilizing the terminal voltage using GVM output as a feedback signal for the corona control system. In order to monitor the parameters such as chain current, column current, GVM pickup etc a local control unit was fabricated with a signal-conditioning card integrated inside the unit. Provision has also been made for remote monitoring of these parameters through CAMAC system. The entire control system was used extensively during high voltage tests and beam trials and it has worked satisfactorily [18].

7. Performance tests and characterization of the beam

The column structure of the FOTIA was tested for high voltage with N_2+CO_2 mixture filled in the accelerator tank at 98 psig. A voltage of 3.4 MV was achieved on the terminal [14]. The terminal voltage is expected to exceed 6 MV with SF_6, as the electric breakdown strength of SF_6 insulating gas, at 98 psig, is about 2.2 times that of the N_2+CO_2 mixture. The beam trials were started towards end of the year 1999 and the analysed carbon and oxygen beams of about 12 nA (C^{3+}) were obtained [19].

In order to characterize the beam an experimental beam line consisting of control slits, magnetic quadrupole triplet and steerer, gate valves, beam profile monitors, Faraday cups, switching magnet and scattering chamber was set up and made operational. A vacuum in the range of 10^{-8} Torr was obtained in the entire beam line.

First beam on the target was delivered on April 21, 2000. The beam was of carbon ($^{12}C^{4+}$) with an intensity of about 5 nA. The terminal voltage was 2.5 MV. The beam was characterized by performing the Rutherford back scattering (RBS) on gold, tin and iron targets which were in the form of self-supporting foils and thick enough to stop the carbon beam. The targets were mounted inside the 80 cm diameter scattering chamber installed in the beam line. A thin target of ^{197}Au was also used to have an estimate on the beam energy resolution. The elastically scattered particles were detected using the surface barrier detector mounted at $\theta = 160^\circ$ on one of the arms in the scattering chamber. To calibrate the pulse height of the detector, an alpha source was kept on one of the target holders. The pulse height spectra of the back scattered ^{12}C from ^{197}Au (thin) and ^{197}Au (thick) are shown in figure 6. In the spectrum of the thick target (figure 6b),

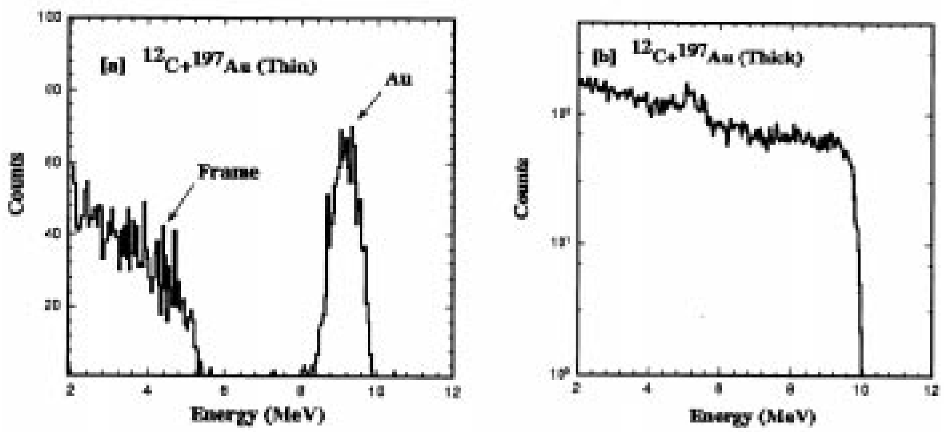

Figure 6. The Rutherford back scattering of ^{12}C from ^{197}Au: (**a**) thin target, (**b**) thick target.

Table 3. Terminal voltages derived from the Rutherford back scattering data.

Target	Scattered energy (MeV)	Incident energy (MeV)	Terminal voltage (MV)
^{56}Fe (thick)	5.24	12.41	2.46
^{120}Sn (thick)	8.31	12.28	2.43
^{197}Au (thick)	9.77	12.38	2.45
^{197}Au (thin)	9.77	12.38	2.45

the center of the falling edge is taken as the scattered particle energy from RBS. Using kinematics, the incident energy (E_i) was calculated from the enengy of the scattered particles for each of the targets mentioned above. The terminal voltage V_T was calculated from this energy E$_i$ using the relation $E_i = E_{is} + (q+1)eV_T$, where E_{is} is the energy of the beam at the exit of the ion source and q is the charge state of the analysed ^{12}C beam selected through both 180° and 90° magnets. In the present experiment charge state of 4^+ was selected. The average terminal voltage calculated using the above RBS data was found to be 2.45 ± 0.05 MV (table 3), which is consistent with the generating voltmeter reading of 2.5 MV [6]. Further details of beam characterization will be published elsewhere [20]. During the commissioning phase the accelerator was run with the N_2+CO_2 gas mixture. To achieve the terminal voltage of 6 MV, the above mixture is being replaced by the SF_6 gas.

8. Summary and conclusions

The FOTIA project at BARC has recently been completed. It would deliver a variety of heavy and light ion beams for basic and applied research. It is an accelerator of its own kind amongst a few in the world. Its construction involved development of state-of-the-art technologies of several important components like dipole magnets, high voltage generator, electrostatic and magnetic focusing and steering devices, vacuum systems, SF_6 gas handling system, computer control system and front line electronics. Several Divisions of BARC have contributed to this effort. An accelerator facility of this type would have costed around 18 crores. However, due to availability of the expertise at BARC and utilization of the infrastructure from the earlier Van-de-Graaff accelerator at the Nuclear Physics Division, it has been possible to set up the facility at a fraction of the above cost. The accelerator is capable of delivering heavy ion beams of up to $A \approx 40$ and energy up to 66 MeV, for ions with charge state of 10^{+}, at a maximum terminal voltage of 6 MV.

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