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On the performance of the HVE high-current light-ion 3 MV Tandetron™ accelerator system

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ABSTRACT

High Voltage Engineering has successfully completed the factory tests of a 3 MV Tandetron™ based accelerator system, fulfilling the rigorous requirements of the Facility for Research in Experimental Nuclear Astrophysics, part of the Saha Institute of Nuclear Physics, Kolkata, India. To satisfy requirements, High Voltage Engineering has developed a unique high-current light-ion injector. The injector includes two multicusp ion sources, one for H^- and one for He^+, and a Na charge exchange canal. Extensive measurements yield routine production of about 70 μA analyzed He^- and 1 mA H^-. The Tandetron™ designed and tested at 3 kW of beam power features low ripple (27 V_{RMS} at 3 MV), a particle transmission of at least 60% over the entire terminal voltage range, 200 kV up to 3 MV. In addition, the dual slit stabilization system ensures long term terminal voltage stability, ±30 V per hour at 3 MV.

1. Introduction

The 3 MV Tandetron™ accelerator system will be used to study low energy nuclear reactions of astrophysical interest, like the s-process nucleosynthesis, the p-process reactions and astrophysical scenarios related to fusion of heavy ions (^{12}C, ^{16}O and ^{20}Ne). Since the cross-section of the charged-particle-induced nuclear reaction drops almost exponentially with decreasing energy the absolute incident beam energy must be accurately known while maintaining a low beam energy spread. The low reaction rate of various nuclear reactions of astrophysical interest also demands for high current ion beams, both pulsed (neutron induced reactions) and continuous. In addition, long measurement times (several hours) are anticipated, which asks for stable long-term system performance.

High-current MeV ion beams of H and He are used in many other research/application fields. For example, deep level H ion implantation is used in semiconductor industry for lifetime control of minority carriers in power devices [1]. Clearly, the high wafer throughput requirement of the semiconductor industry can be achieved with particle accelerators capable of transporting beams with several hundreds of μA to mA current intensities.

High Voltage Engineering (HVE) has developed, built and tested a dual source multicusp ion injector (MCI) for tandem accelerators capable of producing high current negative ion beams of H^- (∼3 mA) and He^- (∼70 μA). The MCI is already in use at several laboratories/facilities and it is also part of the Tandetron™ accelerator system that will be used by the Facility for Research in Experimental Nuclear Physics (FRENA) at the Saha Institute of Nuclear Physics, Kolkata, India. The design characteristics of the accelerator system and the MCI have been largely addressed in previous work [2,3]. This paper will summarize the performance of the FRENA accelerator system, with an emphasis on the light ion beam performance.

2. Accelerator system overview

An extensive overview of the accelerator system has been already given [3]. In brief, the system consist of: coaxial Tandetron™ accelerator, three ion sources (the two aforementioned multicusp ion sources and a Cs-sputter ion source for heavy elements, the so-called SO-110 ion source), a chopper–buncher system, analyzing magnets, two dedicated high-energy beam lines, one for nuclear astrophysics (NAP) and one for pulsed beam application (PBA). The NAP beamline features a 90° analyzing magnet (NMR probe-controlled, $\Delta B/B = 10^{-5}$ per hour) with a dual slit stabilization system, ensuring a long term terminal voltage stability, lower than ±30 V (i.e. 10^{-5}) per hour at maximum terminal voltage [3].

The two multicusp ion sources are housed in a single cabinet with a footprint of $1.8 \times 1.4\ m^2$, a front view being given in Fig. 1. The HVE SO-120 ion source features direct negative H^- extraction, producing 1 mA H^-, largely sufficient for FRENA

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Fig. 1. Front view of the dual-source multicusp injector enclosed in cabinet.

requirements. As mentioned before, the source output can be upgraded to several mA. The low ion velocity in the plasma ensures low ion beam energy spread (5–10 eV). The quiescence of the plasma is the result of the absence of strong magnetic fields and moderate plasma density (~10^{11} cm^{-3}) in a relatively large volume (~400 cm^3). At this plasma density, its meniscus is comfortable tunable to match the extraction geometry, thus allowing optimal beam formation. The silent plasma ensures a stable meniscus for beam formation with little hash (<1%). The SO-120 beam emittance is 7.5 mm mrad, measured for 63% of the extracted 1 mA H^- at 30 keV beam energy [4]. Tests performed at HVE using a 2 MV Tandetron™ with this ion source yielded a beam brightness at 2 MeV of ~20 A m^{-2} rad^{-2} eV^{-1} for an area of ~1 mm^2 and a half angle divergence of 3 mrad thereby outperforming many dedicated microprobe single ended accelerators [5].

It is widely accepted that negative He^- production can be achieved only in a two step process. First, He^+ is extracted from an ion source, for the present system the HVE SO-130 multicusp ion source. Second, the positive He^+ is directed through an electron donor (charge exchange) canal in which a low pressure alkali metal vapor is maintained. The positive He^+ beam (8–13 mA) is focused by a second order corrected double focusing permanent magnet into the center of the charge exchange canal (CEC). After charge exchange, the resulting ion beam is analyzed by a 30° degrees magnet. Design considerations of the entire MCI have been previously described [2]. The charge exchange efficiency from He^+ to He^- in several alkali metal vapors has been summarized by Schlachter [6]. The results indicate that the maximum charge exchange efficiency for Li is about 0.5% at 13 keV, about 1.9% for Rb at 8 keV, and about 1.7% for Na at 12 keV. When He^+ ion beams of 20–25 keV are used to produce He^-, the maximum charge exchange efficiency (~1%) is obtained with Na as a charge exchange medium. For 20 keV He^+, the charge exchange efficiency for Rb and Li drops to ~0.6% respectively ~0.4%. Thus, at 20–25 keV incoming He^+ beam energy the charge exchange efficiency of Na is almost twice the charge exchange efficiency of Li or Rb. This aspect motivated HVE to develop a charge exchange canal that uses Na. The main requirements of the new Na CEC were: reliability, minimum Na loss during operation, low maintenance and operator-friendliness.

3. Performance of the accelerator system

Pulsed light ion beams are created by using a patented chopper–buncher configuration [7]. It operates at a pulse repetition frequency of 125, 250, 500, 1000, 2000 and 4000 kHz. Pulsed beams of H and He with a pulse length of ~1 ns have been routinely measured with a "fast" Faraday cup at the end of the PBA beam line [3].

The 3 MV "coaxial" high-current Tandetron™ accelerator [8] has been designed to transport high current ion beams, about 500 μA. The Cockroft-Walton solid state power supply of this particle accelerator is capable of delivering upcharge currents in excess of 1.5 mA. The TV ripple is in the 10^{-5} range, e.g. 27 V_{RMS} measured at 3 MV. Based on the experience of systems with similar setup, the long term accelerator voltage stability is anticipated to be ± 7 V/h.

3.1. Hydrogen performance

During the factory test phase the SO-120 has proven to be reliable, stable and robust. The filament lifetime for H^- output currents of ~1 mA is in excess of 300 h, other users report filament lifetime of more than 600 h for similar operating conditions. The ion source design allows for easy and fast filament exchange (~30 min), thus minimizing system down time. In the case of filament replacement the large pumping capacity of the MCI vacuum system consisting of two turbo molecular pumps of 600 l/s keeps machine downtime to a minimum. In addition, the large pumping capacity minimizes the He^- losses.

Measurements characterizing the accelerator system performance are summarized in Table 1. The SO-120 ion source routinely delivers H^- ion beam currents in excess of 500 μA. The ion optics design of the LE beam line ensures that 90% of the current obtained from the SO-120 is available for injection in the tandem accelerator. The patented "Q-snout" lens [9] of the tandem accelerator matches the injector ion optics with the accelerator ion optics yielding ~70% hydrogen particle transmission through the accelerator over a wide range of the terminal voltage, from 200 kV (only 7% of the rated TV) up to 3 MV. Special precautions are implemented to safely transport beams with power in excess of 2 kW [3]. For H, pulse widths of ~1.6 ns (FWHM) with intensity of ~7 pC have been routinely measured. The chopper–buncher utilization was about 18%.

Summarized in Table 1, carbon particle transmission through the accelerator, summed over charge states 1–6 at 3 MV TV, was ~85%. The stripper gas pressure was optimized for charge state 3+.

3.2. Helium performance

As observable in Table 1, the SO-130 ion source coupled with the Na charge exchange canal produces ~70 μA He^-. To our knowledge, this injector offers the largest He^- DC beam available for injection in tandem accelerators. The analyzed negative He^- beam current was measured, with a Faraday cup at roughly 2 m after the CEC. Using 70 μA/10 mA suggests a charge exchange efficiency of 0.7%. Given the beam energy (20 keV) and given that the lifetime of the $J = 3/2$ and $J = 1/2$ states of He^- of about 10 μs while these metastable states carry about 50% of the total He^- current [10], we estimate that roughly 30% of the He^- found in the $J = 3/2$ and $J = 1/2$ states is neutralized before reaching the Faraday cup. This implies that the charge exchange efficiency of the present system is about 0.85%, closely matching the reported charge exchange efficiency (~1%). The remaining He^- losses are attributed to the interaction between the ion beam and the rest gas. Finally, the

Table 1
Summary of analyzed ion source beam currents and of H, He and C particle transmission through the 3 MV Tandetron™ accelerator.

Atomic species	E_{beam} (LE) (keV)	I_{beam} (analyzed) (eμA)	I_{beam} (Injected in Tandetron™) (eμA)	TV (kV)	Charge state (HE) (eC)	I_{beam} (HE) (eμA)	Particle transmission (%)
H	30	648	230	200	+1	165	71.7
		469	409	2000		252	61.6
		451	421	2000		323	76.7
		620	583	3000		361	61.9
		563	524			360	68.7
		618	576			375	65.1
He	20	63	53	2250	+2	69.5	65.6
		70	59	3000	+2	65.3	55.3
C	35	–	41.8	3000	+1	0.8	1.9
				3000	+2	15	17.9
				3000	+3	55	43.9
				3000	+4	34.6	20.7
				3000	+5	1.1	0.5
				3000	+6	0.1	0

excellent particle transmission through the Tandetron™ accelerator ensures useful He^{2+} beam current at target in excess of 60 eμA.

At a chopper–buncher utilization of 25%, pulse width for He^{2+} of ~1.9 ns (FWHM) at a pulse intensity of about 1.2 epC have been measured.

4. Conclusions

HVE has successfully designed, built and tested a unique high current light ion injector. For months, the compact MCI proved to be versatile, user-friendly, reliable and requiring low-maintenance. The Na CEC and the MCI ion optics design have ensured He^{-} currents of about 70 μA, to our knowledge the largest He^{-} beam currents commercially available. The ion source SO-120 incorporated in this accelerator system delivers 1 mA analyzed H^{-}. For more powerful tandem accelerators, the high-current SO-120 can deliver beam currents in excess of 3 mA analyzed H^{-}. Overall, the accelerator system has delivered beam powers in excess of 2 kW at NAP beam line target position and nanosecond high intensity pulses of H and He beam at the PBA target position. The particle transmission through the accelerator (70% at only 7% of the rated TV), the low ripple (10^{-5} range) and the anticipated long term beam energy stability will make it suitable for the research fields pursued at FRENA.

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