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*Title:*DESIGN AND TESTING OF A DC ION INJECTOR SUITABLE
FOR ACCELERATOR-DRIVEN TRANSMUTATION*Author(s):*J. D. Schneider
E. Meyer
R. R. Stevens
L. Hansborough
J. Sherman*Submitted to:*International Conference on Accelerator-Driven
Transmutation Technologies and Applications
Las Vegas, NV
July 25-29, 1994**DISCLAIMER**

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Design and Testing of a DC Ion Injector Suitable for Accelerator-Driven Transmutation

J. David Schneider, Earl Meyer, Ralph R. Stevens, Jr., Lash Hansborough, and Joseph Sherman
*Accelerator Operations and Technology Division, Los Alamos National Laboratory, Los Alamos, New Mexico
87545 USA*

Abstract. For a number of years, Los Alamos personnel have collaborated with a team of experimentalists at Chalk River Labs (CRL) near Deep River, Ontario, Canada who were pursuing the development of the front end of a high power cw proton accelerator. At the termination of this program last year, Los Alamos acquired this equipment. With the help of internal Laboratory funding and modest defense conversion funds, we have set up and operated the accelerator at Los Alamos. Operational equipment includes a slightly modified Chalk River Injector Test Stand (CRITS) including a 50 keV proton injector and a 1.25 MeV radio-frequency quadrupole (RFQ) with a klystron rf power system. Substantial upgrading and modification of the ac power system was necessary to provide the required ac voltage (2400 vac) and power (2 MVA) needed for the operation of this equipment. A companion paper describes in detail the first ion source and beam-transport measurements at Los Alamos.

Many of the challenges involved in operating an rf linear accelerator to provide neutrons for an accelerator-driven reactor are encountered at the front (low energy) end of this system. The formation of the ion beam, the control of the beam parameters, and the focusing and matching of a highly space-charge-dominated beam are major problems. To address the operating problems in this critical front end, the Accelerator Operations and Technology Division at the Los Alamos National Laboratory has designed the APDF (Accelerator Prototype Demonstration Facility). The front end of this facility is a 75 keV, high-current, ion injector which has been assembled and is now being tested.

This paper discusses the design modifications required in going from the 50 keV CRITS injector to the higher current, 75 keV injector. Major innovative changes were made in the design of this injector. This design eliminates all the control electronics and most of the ion source equipment at high potential. Also, a new, high-quality, ion-extractor system has been built. A dual-solenoid lens will be used in the low energy beam transport (LEBT) line to provide the capability of matching the extracted beam to a high-current ADTT linac. This new injector is the first piece of hardware in the APDF program and will be used to develop the long-term, reliable cw beam operation required for ADTT applications.

INTRODUCTION

High power cw proton injectors have been built in the past two decades at several national laboratories both for neutral beam experiments and for neutron production applications. One of the first such injectors was the 600 kV, 100 mA proton injector built by Morgan et al at the Oak Ridge National Laboratory using a duoplasmatron ion source in the DCX-2 injector [1]. At Sandia Laboratory, a 200 kV, 150 mA injector was built by Brainard using a single ring, cusp ion source for tests of a medical neutron source [2]. At the Lawrence Livermore Laboratory, the rotating target neutron source (RTNS-II) employing a 300 kV, 200 mA duopigatron ion source was built to provide neutrons in a production facility for material testing [3]. At the Los Alamos National Laboratory, a 75 keV injector was built and tested for the Fusion Materials Irradiation Test (FMIT) facility with a cusp-field bucket ion source [4]. This injector produced 240 mA of total hydrogen ion current; the associated RFQ accelerator accelerated 60 mA of H_2^+ ions to 2 MeV. More recently, the accelerator group at Chalk River Labs built a proton test stand with a microwave proton source [5]. This 50 keV injector and RFQ demonstrated beams of greater than 100 mA from the injector and over 55 mA accelerated by the RFQ to 1.25 MeV. Thus, there have been several successful demonstrations of the feasibility of high-current, dc injectors. However, implementing reliable, long-term operation in a production mode remains to be demonstrated.

ADTT DESIGN REQUIREMENTS

Injector requirements for ADTT applications entail producing sufficient total beam current from the ion source (140 mA) to give a 100 mA proton beam at the RFQ match point from an injector

which is capable of long-term, stable operation in a production environment [6]. The transverse beam emittance requirement at the RFQ input is $0.20 \pi \text{ mm-mrad rms}$ normalized, and the longitudinal emittance must have energy error less than $\pm 1 \text{ keV}$. Matching to the RFQ requires precise control of the Twiss and centroid parameters. An injector employing a dual solenoid lens system with beam steering coils can effect this matching.

In addition to matching the transverse and longitudinal phase space to the RFQ, the injector must also provide a means of turning on the ion beam in a controlled manner. This will probably require ramping the beam current to the accelerator with a $\sim 100 \mu\text{s}$ ramp time thus permitting the rf control loops to remain locked. Injected beam current modulation with a small (few percent) amplitude modulation may be needed to permit an on-line measurement of the K_{eff} of the accelerator-driven assembly.

Long-term reliability is the key issue in the design of this injector. The concept of simplicity, ease of access, and modularity in system design are used throughout. The ion source was chosen on the basis of low power, stability, efficiency, simplicity, and proven performance. Ion source component lifetimes must be increased and means must be provided to implement automated fault recovery after high voltage trips. Routine maintenance will be necessary to carry out replacement of critical components prior to on-line failure. A computer control system will set and monitor injector parameters and has the potential for automatic sequencing procedures and turn-on algorithms. This control system can keep critical parameters within specified limits and can provide closed-loop feedback. Development of these control functions will be done after the injector hardware is commissioned.

DESIGN FEATURES OF THE 75 keV APDF INJECTOR

Fig. 1. Schematic diagram of the APDF Injector.

Key features are the simple ion source structure, the proven single-gap 75 kV extractor, and a simple, compact beam transport system with non-interceptive diagnostics. The ion source is at high potential (75 kV) and a solid, integral, insulator unit allows all of the ancillary ion source components and electronics to remain at ground potential. A schematic diagram of this injector is shown in Fig. 1 and a photograph of the assembled system is shown in Fig. 2.

This injector uses the same microwave proton source that was developed for CRITS [7]. This source has high gas and discharge-power efficiencies and provides a 75% proton fraction in the extracted beam. Operational details are discussed in a companion paper [8]. A mechanical hydrogen gas flow system is used. An insulated ion source coil design is employed so that the coils are operated at ground potential. Thus, no gas controller or power supplies are required at high potential.

Vacuum pumping is provided by a 2500 l/s turbomolecular pump that is capable of uninterrupted operation with only minor periodic maintenance. This pump is mounted on top of the beam diagnostic box located just after the extractor in the LEBT line. All these design features have been chosen to ensure long-term reliability and stability of operation.

All beam line components are water cooled and collimators are placed both at the exit of the accelerating column and the beam diagnostic box to intercept beam halo. Non-interceptive beam

Fig. 2. Photograph of the APDF Injector.

those done for the CRITS injector were carried out using both the beam envelope code TRACE [9] and the macroparticle code SCHAR [10]. The expected beam envelopes for the design beam are shown in Fig. 3. The input beam was determined by scaling the observed beams from the CRITS injector with the same extracted current density (250 mA/cm^2). We are therefore assuming that the input beam parameters are determined only by the beam perveance. Simulations were also done with SCHAR assuming a 4-D waterbag phase space distribution. These simulations predict that the emittance growth in the LEBT due to solenoid aberrations is only 1.0%. Experiments on the

Fig. 3. Beam envelopes for the design beam of the APDF Injector.

diagnostic systems permit on-line monitoring of beam parameters. A current transducer measures the low-frequency components of the beam current while a conventional ac toroid monitors frequencies up to 4 MHz. CCD cameras measure horizontal and vertical beam profiles at both the exit of the accelerating column and at the RFQ entrance. These profile monitors permit continuous on-line beam measurements and provide input to the closed-loop feedback systems.

Beam simulations similar to those done for the CRITS injector show that the beam is 99% space-charge neutralized. Assuming the same neutralization for the APDF injector, SCHAR predicts there is an additional emittance growth of 2.2% due to the relaxation of the input phase space distribution as the beam is transported from the source to the RFQ. Thus, we expect an overall emittance growth in the LEBT of 3.2%. The calculated phase space distribution at the RFQ match point as predicted by SCHAR is shown in Fig. 4.

APDF INJECTOR SYSTEMS

The engineering of the APDF injector is patterned after the successful designs of previous cw injectors, but includes enhancements to obtain better long-term reliability. The microwave ion source is identical to that used on CRITS except that the plasma electrode was modified to have an 8.4 mm-dia. emission aperture, thus giving a more conservative 250 mA/cm^2 extracted current density at the design current (140 mA) [8]. Electrode shapes for the extraction system were confirmed by SNOW simulations after optimizing the design with an extensive parameter search. The accelerating column design is based on the FMIT column and employs a single accelerating gap and subdivides the voltage with an intermediate electrode so that each of the two insulator rings in the column runs at half the total voltage. This intermediate ring is held at proper potential by a

Fig. 4. Expected APDF phase space distribution at the RFQ match point.

Model 4810) are used to measure the beam profiles. A Balzers 2500 l/s turbomolecular pump backed by a Leybold-Hereaus DK-60 provides the vacuum pumping. This pumping system produces an ultimate vacuum in the low 10^{-7} torr region and can maintain a beam line vacuum in the low 10^{-5} torr range for a hydrogen flow of 4 to 5 sccm.

The ground level rack for this injector has been configured with the water manifolds on one side and with the ac power distribution on the other side of the rack. Thus, all utilities needed for the injector are located in a single area and brought in from this rack on a common duct. This arrangement provides a compact package, permitting easy installation of the injector onto any accelerator.

The LEBT focusing system employs a dual-solenoid lens located just after the beam diagnostic box. A dual-solenoid lens was chosen instead of the conventional separated, two-solenoid lens system [11] for simplicity and compactness. This choice should permit easier alignment and can be operated as a non-rotational lens by operating with the solenoid fields opposing. This mode of

Fig. 5. Photograph of the APDF Injector Dual-Solenoid Lens.

operation limits steering effects in the solenoids if there are centroid errors in the input beam. Each solenoid lens is constructed with simple, rugged, bifilar pancake coils that are enclosed in an assembly with steel yoke and pole pieces for a design field of 0.4 Tesla. A photograph of this lens system is shown in Fig. 5. The dual-solenoid provides the required two-knob tuning capability needed for an optimal RFQ match. Magnetic field measurements confirmed the Flux-2D design calculation and showed that there are no saturation effects in the magnet steel for fields well above the design field. Both the calculated and the measured axial magnetic field strengths at the expected operating field are shown in Fig. 6 for one of the lenses in the dual-solenoid system; the other lens is identical. There are sufficient ampere

water resistor that also provides cooling to the ion source baseplate. High voltage shields are incorporated in the column to shield the insulators and an electron trap is placed at the interface of the accelerating column and the beam transport line. Extractor shield tubes prevent the insulators from seeing the beam or the beam-induced plasma. Pressed alumina insulator rings are assembled into a column by G-10 insulating rods and sealed with O-rings. All beam tubes and other surfaces that can be exposed to beam impingement or radiation are water cooled.

The beam diagnostics are located in the beam diagnostic box just after the extractor. A Bergoz dc current transformer measures the beam current and CCD cameras (COHU

Model 4810) are used to measure the beam profiles. A Balzers 2500 l/s turbomolecular pump backed by a Leybold-Hereaus DK-60 provides the vacuum pumping. This pumping system produces an ultimate vacuum in the low 10^{-7} torr region and can maintain a beam line vacuum in the low 10^{-5} torr range for a hydrogen flow of 4 to 5 sccm.

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turns to operate the lenses with the fields opposing, which may be useful if the input beam errors are significant. The dipole and higher multipole field components were also measured and are well

Fig. 6. Axial magnetic field measurement for one of the solenoids in the APDF LEBT.

below the 0.1% level and thus are not important. No steering was incorporated into the original design of this injector, but provision has been made to place Lambertson coils in the solenoid lenses when the injector is mounted onto the RFQ.

The injector employs a computer control system to monitor and control the setpoints of the various injector subsystems. This control system uses a Motorola 68040 microprocessor in the input-output controller and runs with EPICS™ software. A software-based run permit system is employed for proper turnon and hardware protection. A hard-wired safety interlock system is used for personnel protection.

INITIAL OPERATING EXPERIENCE

The injector has been assembled and initial beam tests carried out. Low current (7mA) beams were extracted at 30 kV. Although the accelerating column alone (no ion source) had been operated at 100 kV without corona, high voltage problems were encountered at 50 kV with the ion source support structures. A number of modifications were subsequently made both to the ion source coil support stands and to the electrostatic guard rings to limit corona and prevent sparking. The injector was then conditioned to 75 kV without beam. Beam currents up to 60 mA were then obtained for a short time at 50 kV. Based on the operating experience on CRITS, we anticipate that the design current of 140 mA will be achieved at 75 kV after the ion source operation is optimized.

DISCUSSION

The initial beam tests at 50 kV demonstrated that this injector was operating close to the current levels expected from the previous work on CRITS where 75 mA beams had been observed at this voltage. Based on the experimental results obtained on CRITS and on the SNOW simulations of the extractor system, we can predict the beam parameters that should be produced with the APDF extraction system. We anticipate running the ion source with a 8.4 mm-dia. emission aperture and with an extracted current density of 250 mA/cm². Data taken on the microwave ion source [7] has

Fig. 7. Alpha-beta tuning diagram for the APDF Injector.

shown that as the emission aperture diameter is increased from 5.0 to 7.0 mm, there is only a 20% increase in the beam emittance; thus the ion source emittance for the APDF injector is predicted to be 0.13 π mm-mrad, rms normalized. Simulations with SNOW for an ion source with an 8.4 mm-dia. emission aperture operated with 250 mA/cm² extracted current density at 75 kV extraction voltage, show that the maximum divergence angle of the extracted beam at perveance match remains at the same 26 mrad as predicted for the 50 kV case with a 5.0 mm-dia. emission aperture. Assuming that the beam envelope size at the exit of the extractor is equal to the emission aperture radius of 4.2 mm, the phase space parameters of the extracted beam are determined and we can model the beam transport line in this injector. The results of the TRACE

Fig. 8. Calculated emittance growth in the APDF LEBT.

the expected emittance growth due to solenoid aberration and to non-linear space-charge effects. The overall emittance growth predicted in these simulations as a function of effective beam current is presented in Fig. 8.

calculation are shown in Fig. 3 where the above input beam is transported through the dual-solenoid lens to the RFQ match point. The solenoid lens strengths are adjusted to give a matched beam with $\alpha = 1.36$ and $\beta = 0.004$ cm/inrad, which are typical RFQ match parameters. The alpha-beta tuning diagram for this lens system is then calculated for the two extreme zero excitation cases and is shown in Fig. 7. The cross-hatched area shows the region in alpha-beta space that can be reached for this dual lens system. This region is more than adequate to match the expected input beams to an RFQ accelerator for the ranges of beam currents and emittances expected in these applications. The beam transport line was then simulated with the SCHAR code to determine

CONCLUSIONS

We anticipate carrying out an experimental program of beam measurements similar to those done on CRITS in order to characterize the beams produced by this injector. The results that we have obtained together with the simulations of the expected performance of this injector indicate that we should be able to meet all the requirements needed for ADTT applications.

ACKNOWLEDGMENTS

The authors wish to acknowledge the work of Thomas Zaugg, Patrick Schafstall and David Hodgkins in building and testing this injector and of Richard Martinez for engineering design. This work was supported by the Defense Nuclear Agency under the auspices of the U. S. Department of Energy.

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