DESIGN AND OPERATING CHARACTERISTICS OF THE DEVELOPMENTAL H^- ION SOURCE FOR 30-HZ INJECTION INTO THE ARGONNE NATIONAL LABORATORY (ANL) BOOSTER*

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Summary

A tandem-acceleration extended stationary arc duoplasmatron used for 1-Hz injection into the ANL booster is undergoing further development for 30-Hz operation. A 200-μs, 50-MeV H^- beam of at least 4 mA at 30 Hz will be required by the booster in its final development phase. To meet this requirement and to offset losses occurring in the linac and in the 750-keV and 50-MeV beam lines, the source must provide about 10 mA of H^- ions. The present source produces negative ion currents of this order but the H^- component is typically only 50% of the total beam; the remainder of the beam consists of ions with mass numbers in the neighborhood of 17. Source design will be discussed and data will be presented for typical operating conditions on the test bench and in the 75-keV terminal of the preaccelerator. Physical and chemical properties of materials which affect their suitability for use in pulsed ion sources as load-bearing structural materials, as functional components, and as vacuum walls will also be discussed.

Introduction

The rapid-cycling booster-injector for the ANL Zero Gradient Synchrotron (ZGS)[1] will require a 30-Hz, 50-MeV H^- beam of at least 4 mA for pulses of 200 μs duration in its final development phase. During the current H^- injection test, and in the three previous booster runs, the pulse repetition rate has been 1 Hz or less. Several modifications of a tandem-acceleration extended stationary arc duoplasmatron have been used in these tests.[2,3] The design and operational characteristics of these test sources will be reviewed in the next section. An ion source for 30-Hz operation has been designed and built but not yet tested; it will be discussed in a later section.

Design and Operational Characteristics of the H^- Test Sources

The first tests of H^- injection into the booster were conducted in April, 1971. Just prior to the installation of the H^- source and related systems in the 750-kV terminal of the preaccelerator, a bench test in a mock-up of the terminal installation gave a 7.3-mA, 30-kV negative ion beam in a biased Faraday cup 75 in from the source. The 30-keV beam was separated from the neutrals and the other charged components emerging from the source by a 35° electrostatic deflector and then focussed on the Faraday cup by an electrostatic quadrupole doublet. In the terminal, the distance that the deflected and focussed beam travels from the source to reach the 6-in accelerating gap of the high gradient column is 54 in.

During the injection test, a 7-mA, 750-keV negative ion beam was measured at BT-201 (Beam Toroid 201) after the first of two electrostatic quadrupole triplets. A 6-mA beam was measured at BT-301 after the second triplet and before a magnetic quadrupole triplet. About 3 mA, measured at BT-401, was injected into the linac. With no bunching (the buncher had been removed for modification), one-fourth of the injected beam (~ 0.75 mA) was accelerated to 50 MeV; one-third of the 50-MeV beam was transported to the booster, where it gave a circulating current of 30 mA.

The 50% loss in beam between BT-301 and BT-401 was due primarily (perhaps entirely) to the loss of heavy ions which were filtered out by the magnetic quadrupoles. (During the course of emittance measurements on the 750-keV beam from the preaccelerator, it was found that a heavy ion component centered in the mass range of 17-18 u accounted for 50-60% of the negative ion beam.)

The design and operating characteristics of the source assembly used in the first booster run are given in Ref. 2. This assembly differed in several respects from the one shown in Fig. 2. It had eight metal-to-ceramic epoxy joints, one metal-to-metal epoxy joint, and 17 Viton A O-ring seals; four Viton A rings were used in the pulsed gas shutter and several "rad-lab" fittings were used in the gas line from a palladium leak to the ion source. The cathode, discussed in more detail in Ref. 2, was a homemade bifilar, spiral-strip oxide cathode. The oxide coating mix contained $BaCO_3$, $SrCO_3$, nickel powder, amyl acetate and a small amount of pyroxylin (~ 1%). Acetone was used as a thinner for the mix. After the injection test, a portion of the oxide coating was analyzed and found to have a carbon content of 3.8%.

At the completion of the first booster run, the equipment removed from the 750-kV terminal to make way for reinstallation of the H^- ion source and its power supplies and control equipment was put into storage until space became available several weeks later for a new ion source facility; the space occupied by the former test facility was undergoing modification in preparation for the installation of a second preaccelerator. During construction of the new test facility, epoxy seals were eliminated from the source and the procedure for making cathodes was revised by eliminating pyroxylin from the coating mix and discontinuing the use of acetone as a thinner. The Viton A O-ring used to seal the cathode assembly mounting flange to the intermediate electrode was replaced by a gold wire ring.

The new test facility was put into operation on September 1, 1971. It was found that elimination of all epoxy seals and modifications in the procedures for making and processing cathodes to eliminate carbon made no significant difference in the performance of the source. Initial attempts to replace Viton A

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O-rings with gold-plated C-rings or with solid gold rings failed because source components designed for Viton rings were stressed beyond their yield points by the forces required to compress the metal rings and Al_2O_3 surface finishes adequate for Viton seals resulted in small but detectable leaks with the metal rings. A source assembly was successfully sealed with gold rings after the overstressed components were replaced with stronger ones and the alumina sealing surfaces were finished to 10 u in or better.

Elimination of all organic seals gave no improvement in the performance of the unbaked source. A leak developed in the H^+ section of the source when heating tapes were used to raise the temperature of this section to 230°C and that of the H^- section to 170°C. The leak was sealed by retightening the bolts holding the H^+ section together. A second attempt to bake the source out under vacuum ended in failure when the pulsed gas shutter was damaged by the fracturing of an alumina guide sleeve. When the H^+ section of the source was dismantled, it was found that the gold rings sealing against the copper (OFHC) anode had diffusion bonded to the anode. The copper anode was replaced by one made of 304 stainless steel.

While the source was disassembled, the homemade cathode was replaced by a dispenser cathode made by Semicon Associates of Lexington, Kentucky. The new cathode had an emitter area of 5.1 cm^2, about 1/3 of the area of the cathode it replaced. The source components were then placed in a vacuum furnace and baked out at a temperature of 255°C. After the components had cooled, the furnace was back-filled with dry N_2 and the source parts were removed and assembled.

The source was operated briefly with the dispenser cathode on January 4, 1972, shortly before the ion source test stand was shut down and dismantled in preparation for installation of the source and related systems in the 750-kV terminal for the second booster run. A current of 7 mA was obtained during initial test-stand operation of the source with a dispenser cathode.

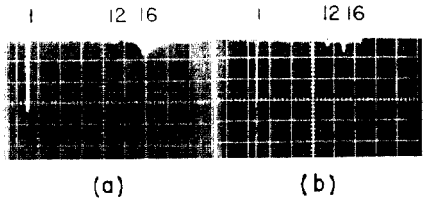

Fig. 1 Mass Spectra Recorded on a Storage Oscilloscope. (a) For an Unbaked Source with Viton O-Rings and a Homemade Cathode. (b) For a Furnace-baked, Gold-Seal Source with a Dispenser Cathode

The spectra shown in Fig. 1 were obtained after the collector plate of the Faraday cup was modified to permit a small, collimated portion of the beam to enter the vacuum chamber of a bending magnet. Several minutes were required to obtain each spectrum, with the source pulsing at a 1-Hz rate. The magnetic field increased at a constant rate. Z modulation of the oscilloscope beam was used to sample a portion of the ion current pulse. Line width and/or height were affected to some extent by noise-induced jitter, by pulse-to-pulse jitter in the beam current, and by the amplitude and duration of the Z-modulation pulse; the results should be regarded as qualitative rather than quantitative evidence of a reduction in heavy ion contamination following replacement of the homemade cathode and furnace bakeout of the source parts.

On January 20, 1972, the first day of operation during the second booster run, currents of 7-8 mA were obtained at BT-201, 6-6.5 mA at BT-301, about 3 mA at BT-401, and 2 mA at BT-501, which measures the 50-MeV beam from the linac. During the remainder of the run, which ended on February 4, 1972, these results were duplicated on a number of occasions but never significantly improved upon. A transport efficiency as high as 80% in the 50-MeV beam line resulted in beams of up to 1.6 mA injected into the booster. A peak circulating current of 150 mA was obtained.

In contrast with the previous booster run in which the source operated throughout the entire run with no component failures, a number of failures occurred during the second run. The shutter valve, which had been modified to eliminate Viton shock absorber and sealing rings,[2] hung up on three occasions because of insufficient clearance (measured in tenths of a mil) and/or misalignment (tenths of a mil). On a fourth occasion, the valve failed when a shock absorber spring broke. There were two extractor grid failures during the run. The first occurred when a leak developed in the H^+ section of the source and was probably due to physical and chemical sputtering. The second grid failure occurred when a short developed in a transistor in the blocking circuit which normally terminates the output pulse of the extraction voltage supply in less than 1.0 us when the current exceeds a preset value.

Difficulty was encountered in striking an arc each time the source was turned on after having been let up to a dry nitrogen atmosphere for repairs. The arc current would start at several amperes and gradually build up to a normal value of 40-60 A. Dispenser cathodes are poisoned by carbon and by any material (platinum, titanium, zirconium, nickel, silver, chromium, copper, etc.) that alloys with barium. Since the poisoning was only observed immediately after a pumpdown, it could not have been caused by a metal. During pumpdown, the partial pressures of water vapor, hydrocarbons and oxides of carbon are orders of magnitude higher than normal pressures during source operation. Poisoning of the cathode probably occurs when the cathode is heated too soon after the start of pumpdown. Several days before the end of the run, efforts to obtain emission from the poisoned cathode failed and it was replaced by a homemade oxide cathode.

On March 1, 1972, after the ion source test stand had been put back together, the source was operated without the shutter valve to study the feasibility of operating with a continuous gas flow. The source components had been baked out in the vacuum furnace and then assembled and put under vacuum several days

earlier. A 6.6-mA beam was obtained at a 1-Hz rate. With an estimated gas flow of ~ 10 cm^3/min, the sublimator power supply was being pushed to its limit and occasionally tripped off. On March 2, a 7.5-mA beam was obtained during a brief run. On March 7, the pulse repetition rate was gradually increased to 8 Hz; the beam current was about 6 mA. On March 8, the source was taken apart so that the charge exchange cell geometry could be modified. The cell, with a bore tapering from 1.19-1.69 cm over a length of 15.75 cm, was modified by enlargement of the last 10.57 cm of its length to a constant diam of 1.90 cm. The resulting source geometry is shown in Fig. 2. On March 14, 1972, a current of 9.9 mA was obtained at a 1-Hz rate in the first test of the new geometry. On the 15th, an 11-mA beam was obtained at a 10-Hz rate. On the 16th, the rate was increased to 16 Hz; the beam current was limited to about 8 mA by the extraction voltage supply, which was not designed for this kind of service.

A 1-Hz bench test of the shutter valve was begun on March 14 and continued until the valve failed on March 24 after more than 8 x 10^5 pulses. When the valve was dismantled, several small chips of stainless steel of unknown origin were found but there were no score marks to indicate that these chips had caused the valve, which operated quite freely after dismantling, to drag. Valve failure may have resulted from a machining burr that broke loose and caused the valve to lock immediately.

After several more days of gas pumping tests, a period of about a week followed in which the system remained under vacuum but was not used. Every morning it was found that the ion pump had tripped off during the night and the pressure had climbed to the low micron range. After rough pumping, the ion pump worked normally; no leaks were found in the system. It is believed that the ion pump tripped off because of gas desorbed from saturated titanium flakes which broke loose from a cool surface and landed on a warmer one.

The vacuum chamber was dismantled and sandblasted to remove loose film and the ion pump, which showed evidence of saturation, was replaced. After brief runs on April 21 and 24, 1972, in which beam currents of 8.5-9.0 mA were obtained at a 1-Hz rate, the test stand was shut down in preparation for the third booster run.

The ion source and related systems were installed in the 750-kV terminal during the first week in May. The source which had given 11 mA of beam on the test bench was installed without a gas valve. For reasons which are not clear but may be related to a high partial pressure of CO_2 in the accelerating column due to an intermittent and minute leak from the high pressure side to vacuum, only 6 mA of 750-keV beam at BT-201 and 1.5 mA of 50-MeV beam at BT-501 were obtained during initial operation. During the next two months of operation, these initial currents were equaled but never exceeded. Transport efficiency from the linac to the booster was nearly 100%. On July 13, a current of 7-8 mA was obtained at BT-201 and a current of 2 mA was injected into the booster. The sudden and unexplained increase in beam current lasted for less than two days. When the source was put back into operation after replacement of a burned out extractor grid and a cracked high voltage insulator, the currents were back at their earlier levels of 6 and 1.5 mA.

During the course of this booster run, which ended on August 7, it was found that the source could not be operated around the clock with continuous gas flows in excess of 10 cm^3/min. On several occasions, the sublimator handled these gas loads without difficulty in runs lasting 8-10 h. On other occasions, a rapid decrease in pumping speed occurred and the sublimator and ion pump stalled after 10 or 20 min of operation. Round-the-clock operation was achieved by reinstalling the shutter valve.

Singleton[4] has found that "the rate of adsorption of carbon monoxide on titanium increases rapidly with temperature and exceeds 1 liter/cm^2 s at 1000°C." He points out that if the rate of adsorption exceeds the rate of diffusion into the bulk of the sublimator, the adsorption products build up at the surface, thus reducing the sublimation rate. The reduction in sublimation rate allows the titanium film on the walls to saturate, leaving the hot sublimator as the only remaining pumping mechanism. The pumping speed falls off rapidly when this occurs.

When it became clear that the source could not operate with a continuous gas flow, a 30-Hz rotating chopper valve was designed and built. This valve, which has been bench-tested with nitrogen but has not yet been installed in a source, is described elsewhere in these proceedings.[5] Figure 3 shows how the valve will be mounted in the source.

At the present time, the fourth booster run is in progress, with the ion source mounted in the second preaccelerator.[6] 50-MeV H^+ and H^- beams from the two preaccelerators are being injected into the ZGS and the booster on alternate pulses. Maximum beam to the booster thus far has been about 600 μA. There is a beam limitation due to a mismatch between the source and the accelerating column, which is about nine in further away from the source than was the column in the first preaccelerator. The limitation of the 750-keV beam to about 8 mA in the first preaccelerator indicates that there is a lesser mismatch between source and column there also.

Heavy Ion Contamination of the Arc Plasma

Heavy ion contamination of the arc plasma continues to be the main impediment to the production of H^- currents of the required intensity. The major contaminants are hydrocarbons and carbon monoxide, as may be seen from the results of residual gas analysis shown in Fig. 4. The shutter valve was absent and the source was running with a continuous gas flow in excess of 10 cm^3/min. Each spectrum took about 100 s to record and there is no correlation between the times at which the peaks were recorded and the times at which the source was pulsed. The vacuum chamber has a volume of approximately 500 liters. The argon peaks at mass-to-charge ratios of 20 and 40 are due

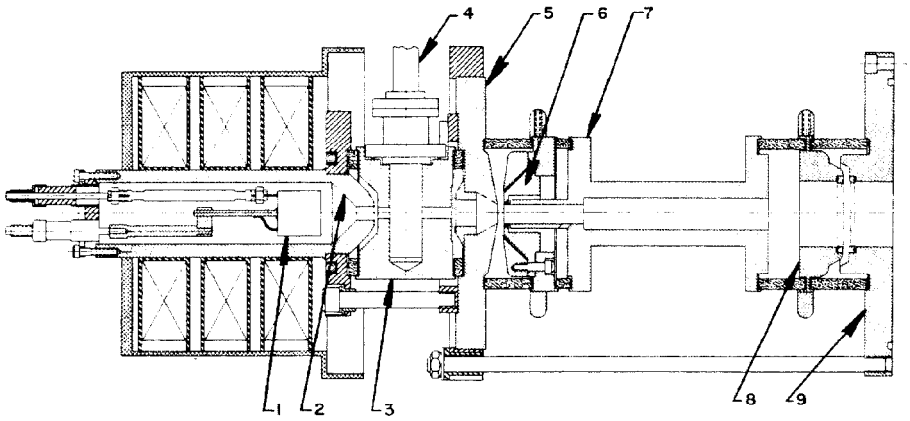

Fig. 2 Geometry of the Gold-Seal Source
(1) Cathode. (2) Intermediate Electrode (mild steel). (3) Anode (OFHC or 304 S.S.). (4) Pulsed Gas Shutter. (5) Source Grid Electrode. (Mild steel, with 304 S.S. insert.) (6) Extractor Grid Support (304 S.S.). (7) Charge Exchange Cell (304 S.S.). (8) Suppressor Grid (304 S.S.). (9) Ground Electrode (304 S.S.).

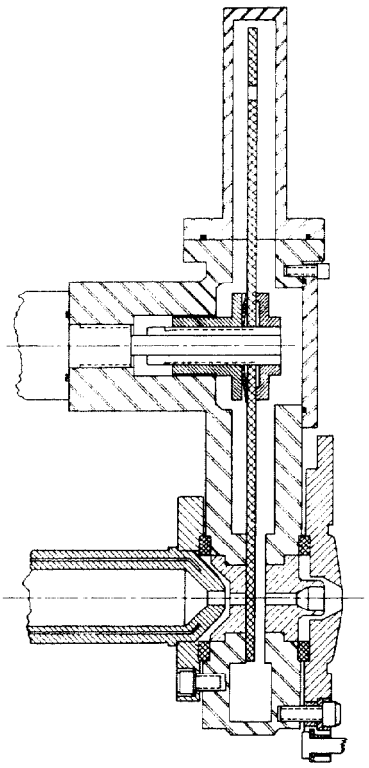

Fig. 3 Geometry of the Rapid-Cycling Source with a 30-Hz Rotating Shutter

Time (t)	(min)	0.0	22	33	131	150
Vessel Pressure	(Torr x 10^{8})	3.0	79	120	160	180
Source Pressure (uncorrected)	(μ)	<1	118	125	133	140
Cathode Heater Current	(A)	0.0	37	37	37	37
Cathode Heater Voltage	(V)	0.0	5.1	5.1	5.1	5.1
Arc Current	(A)	0.0	0.0	44	56	56
Arc Voltage	(V)	0.0	0.0	145	145	145
Extractor Current	(A)	0.0	0.0	0.0	5	5
Extractor Voltage	(kV)	0.0	0.0	0.0	~20	~20
Arc Pulse Length	(μs)	-	-	300	300	300
Beam Pulse Length	(μs)	-	-	-	180	180
PRR	(Hz)	-	-	1.67	1.67	1.2
Beam Current	(mA)	-	-	-	8.6	8.0

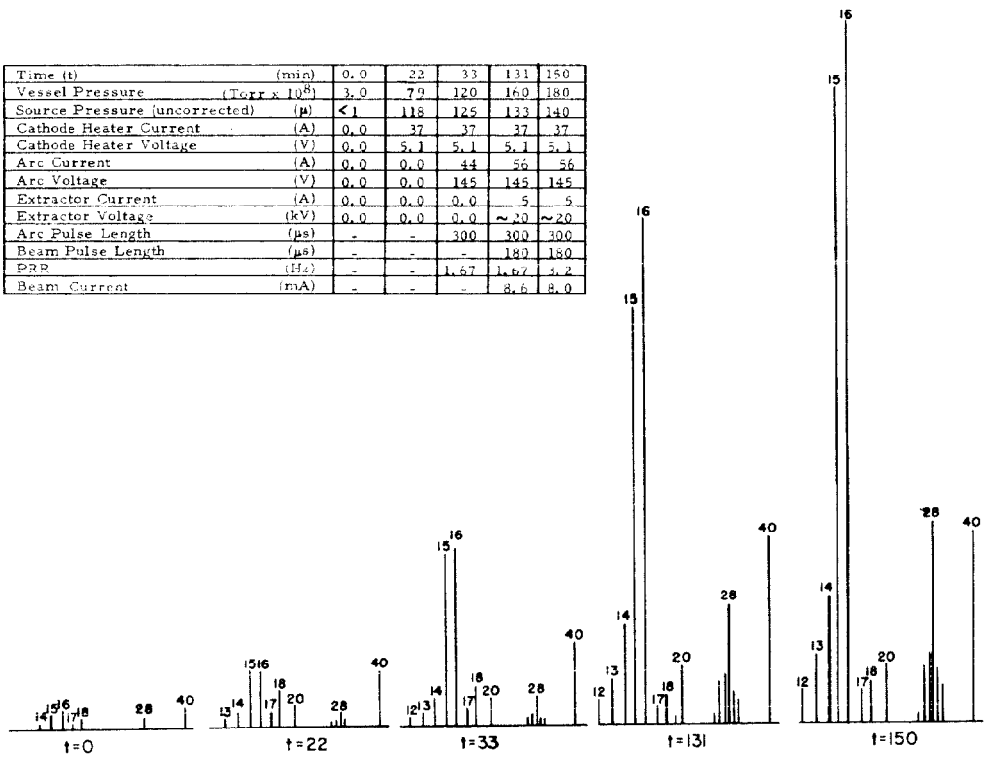

Fig. 4 Results of Residual Gas Analysis During a Beam Run

to the desorption of previously pumped argon from the 400 liters/s ion pump; if the ion pump is isolated from the system, the peaks drop to very small values.

Simonov, Shvilkin, and Kutukov[7] have studied the processes leading to the introduction of impurities into the plasma of a Tokomak plasma confinement device used in controlled fusion experimentation. The discharge chamber is in the form of a solid thin-wall stainless steel liner. The study has shown that even with walls baked at temperatures of 400 to 450°C, initial pumping to ultrahigh vacuum, purification of the admitted gas, continuous through-flow of the gas, and prolonged prior conditioning with discharges of 500 μs duration, high impurity levels result from strong chemisorption of hydrogen ions and excited atoms (on walls activated by the discharge) and catalytic reactions of the sorbed gases with carbon and oxygen present in or on the wall material. Ionization of the volatile reaction products (CO, CH_4, C_2H_6, H_2O, etc.), and fragments from dissociation of these products, results in a high level of plasma contamination. The type of discharge cleaning which occurs with continuous or high-duty-cycle discharges does not occur over the time span of experimentation with very low duty cycle discharges.

The results of this study are applicable to the H^- source, which is constructed almost entirely of carbon-bearing, oxide-covered mild steel and stainless steel. These metals were chosen in preference to pure iron and copper (OFHC) because the latter metals lack the strength and hardness required of load-bearing structural components in bakeable gold seal assemblies.

Plasma contamination due to interactions between room temperature molecular hydrogen and steel walls would be far less than that due to atomic hydrogen and/or hydrogen ions and/or energetic neutrals interacting with the walls. In the design of the rapid-cycling source, an effort has been made to provide sufficient cooling and sufficient shielding of the steel walls by liners and inserts of clean, pure metals such as oxygen-free copper, molybdenum, and tungsten to insure that interactions other than those between steel walls at room temperature (or below) and molecular hydrogen at the temperature of the walls cannot occur to any significant extent.

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