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PROGRESS ON THE LOS ALAMOS HEAVY-ION INJECTOR *

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ABSTRACT

Heavy-ion fusion using an induction linac requires injection of multiple high-current beams from a pulsed electrostatic accelerator at as high a voltage as practical. Los Alamos National Laboratory is developing a 16-beam, 2-MeV, pulsed electrostatic accelerator for Al^+ ions. The ion source will use a pulsed metal vapor arc plasma. A biased grid will control plasma flux into the ion extraction region. This source has achieved a normalized emittance of $\epsilon_n < 3 \cdot 10^{-7} \text{ m-rad}$ with Al^+ ions. An 800 kV Marx prototype with a laser fired diverter is being assembled. The ceramic accelerating column sections have been brazed and leak tested. Voltage hold off on a brazed sample was more than doubled by selective removal of the Ticusil braze fillet extending along the ceramic. A scaled test module held 250 kV for 50 μs , giving confidence that the full module can hold 175 kV per section. The pressure vessel should be received in June 1986. High-voltage testing of a 1 MV column will begin by early 1987.

INTRODUCTION

As part of the U.S. Department of Energy's Heavy-Ion Accelerator Research (HIFAR) program Los Alamos National Laboratory is developing and building a multiple beam injector to produce high-voltage, high-current input beams needed for induction linear accelerators being pursued by Lawrence Berkeley Laboratory. In this paper we discuss progress in the development, design, and construction of this injector including source development, pulse power design, column fabrication, and high-voltage testing.

The current design criteria for this accelerator are:

- Number of Beams - 16
- Particle Energy - 2 MeV
- Current per Beam - 150 mA
- Ion Mass - 27 (Al^+)
- Pulse Length - 6 μs
- Beam Normalized Emittance - $4 \times 10^{-7} \text{ m-rad}$
- Energy and Current Flatness - 0.1 percent

*Work performed under the auspices of the USDOE.

Originally this electrostatic accelerator was designed as a prototype injector to feed a 125 MeV induction linac for a High-Temperature Experiment (HTE). However, the injector will now be used as a test bed for source and injector development and to supply beams for lower energy experimental induction accelerators. As a consequence a number of the specifications have been refined. The original HTE injector could use ion masses of 20 to 40 AMU while we have focused on 27 for this machine. The flatness criteria on the beam energy and current are now treated as developmental goals. Higher currents per beam will be pursued later, as required.

The injector may be needed as early as 1989 for an Induction Linac System Experiment (ILSE). In this case an ion with a charge to mass ratio of about 10 is needed, for example C^+ or Al^{++} , rather than 20 to 40. The current desired would be the maximum transportable in an electrostatic quadrupole focusing system, or about $0.2 \mu C/m$. For a 2 MV accelerator this would be about 1000 ma/beam of either C^+ or Al^{++} . These may require either larger diameter beams, or an alternative to aperture focusing in the higher energy portions of the injector. ILSE would require a shorter pulse, only 1 μs . At this stage we are proceeding to test the injector at the design specifications and study the modifications to the source, electrodes, and pulsed power needed to achieve these objectives.

The injector design is shown in Fig. 1. Sixteen separate beams are accelerated electrostatically through apertures in flat electrodes inside a 1-m-long accelerating column of 85 percent alumina ceramic rings brazed to niobium grading rings.

Fig. 1 Injector Assembly

The column voltage is created and maintained by a 2 MV Marx generator with a special circuit designed to control voltage pulse flatness across a water resistor voltage divider until diversion

by a laser triggered spark gap. The individual sources are powered by a motor driven alternator contained in the Marx high-voltage dome. The accelerating column is made of aluminum oxide rings brazed to niobium high-voltage feedthrough rings. The Marx generator and the accelerating column are cantilevered from opposite ends of a pressurized containment vessel. The column, Marx, and high-voltage dome are insulated by SF₆ gas at 3 atm pressure contained in a stainless steel pressure vessel.

The injector is being completed in two phases. First a single beam will be accelerated to 1 MeV to test voltage standoff, pulsed power operation, and the vacuum arc source. The second phase, a multiple beam 2-MeV injector, will add more pulsed power, an additional column module, additional ion optics, and improved sources. We expect to begin testing at 1 MV in 1987 and complete Phase I by the end of 1987. We plan to complete Phase II in 1988.

ION SOURCE

The ion source for this injector is being developed by the University of New Mexico.¹ We have concentrated efforts on metal vapor vacuum arcs that have the following advantages: 1) rapid turn-on, 2) simplicity of fabrication and operation, 3) generation of clean plasma with little species contamination, 4) production of a wide variety of ions from metals and semiconductors, 5) potentially high ion flux, and importantly 6) drastically reduces the column heat loading compared to hot sources.

Our experiments have shown that this source meets our objectives. Both aluminum and indium plasmas have been generated. A biased grid electrostatically separates ions from electrons and prevents plasma prefill in the extraction gap. This allows rapid and quiet beam initiation. A 20 cm² anode produced peak current densities of 15 mA/cm² for Al⁺ and In⁺. Time of flight measurements indicated that beam ions were predominantly in the +1 ionization state with no observable species contamination. A divergence measurement with a channel-electron-multiplier array implies a normalized emittance of $\epsilon_n < 3 \times 10^{-7}$ π-m-rad. This exceeds our design requirements and those for both the HTE accelerator and ILSE.

PULSED POWER SUPPLY

Several changes have recently been made in the pulsed power design¹ that improve the predicted performance.

Beam transport considerations require that beam energy flatness, out of the injector, be extremely good--the goal is ±0.05 percent. The largest perturbation on beam voltage is voltage droop of the Marx, due to the charge flow (current x time). The beam current is not large, but when current in the Marx charge resistors and trigger resistors is taken into

account, the total charge flow is too large to be compensated by making the Marx capacitance larger because of weight limitations. In our initial design for the Marx, droop was compensated by putting negatively charged stages at the bottom of the Marx. Shunt resistors around the negative stages caused the voltage on these stages to droop at a relatively high rate, so that the total droop on the negative stages was equal in magnitude (but opposite in sign) to the droop on the rest of the Marx, thus compensating for the Marx droop. The disadvantage of this technique was that several negative stages were required to keep the negative exponential fall in a sufficiently linear region, thus requiring more stages to get the 2.0 MV desired. In the new design² the first stages are an LC inversion generator³ with output voltage waveform of the form $(1 - \cos(\omega t))$. The linear portion of this waveform can be used to compensate for Marx droop. This circuit gives better compensation than the RC decay circuit, and has the added advantage of adding to the output voltage, rather than subtracting from it.

The Marx triggering has also been changed. The size of the Marx inter-stage trigger coupling resistors is determined by a trade-off between better triggering and Marx voltage droop rate. The minimum value of a trigger coupling resistor that is required to keep the droop small is in the neighborhood of 20 kOhm. Testing of the Marx with this magnitude of trigger coupling gives extremely large delays and jitter. Past experience with this type of Marx generator indicates that trigger coupling resistors must be no larger than 1 kOhm. A new trigger coupling scheme, using a small resistance in series with a small (~ 1 nF) coupling capacitor in place of the large resistor, has been tried with very satisfactory results in a small model Marx generator. We will be trying this soon in the full injector Marx.

ACCELERATING COLUMN

The accelerating column⁴ is made up of a stack of alumina rings brazed to niobium electrodes that feed the voltage from grading rings on the outside of the column to the accelerating electrodes inside. The voltage on the grading rings is determined by a liquid resistor voltage divider.

Recent analysis has shown that, because of the capacitance of the column to the tank walls, the voltage division along the column at the beginning of the pulse does not follow the resistive division with sufficient accuracy. The circuit model of the column used in a computer circuit analysis is shown in Fig. 2. The capacitances were calculated using an electric field analysis program. The resistive divider is designed so that, with 2.0 MV on the column, each of the 11 accelerating gaps has 175 kV except the gap nearest the anode, which has 75 kV for reasons having to do with the ion optics. The transient circuit solution gives 280 kV on the first (75 kV) gap, 230 kV on the next gap, and 100 kV on the gap nearest ground. These voltages approach the equilibrium values determined by the resistive voltage division

with time constants on the order of 10-15 μ s. These transient voltage errors cause three problems: the ion optics in the column will not be correct, with potential effects on beam emittance and divergence; the beam edge may hit an electrode; and the overvoltage on the first few gaps will increase the probability of electrical flashover.

Fig. 2 Accelerating Column Circuit Model

Fig. 3 High-Voltage Test Assembly

Several approaches have been considered to alleviate this problem. They include

1. Reducing the value of grading resistors and injecting ions from the source when the voltages reach equilibrium.
2. Increasing the series resistance in the Marx.
3. Adding capacitance between grading rings to compensate for the capacitance to ground.
4. Connecting Marx sections directly to the column.

We are still investigating the best solution.

HIGH VOLTAGE TEST SECTION

The high-voltage test section shown in Fig. 3 is a reduced size model of the accelerating tube. High-voltage tests on this model should be very useful in determining whether we will be able to hold off 175 kV across each of the 2.900-in-long ceramics in the accelerating tube.

This test section consists of the same 85 percent alumina rings vacuum brazed with Ticusil to the same thickness niobium feed through rings as the accelerating tube. The 2.900-in ceramic ID is also the same. However, the test section ceramics are 8-in ID by 10-in OD as compared to the 26-in ID by 28-in OD ceramics on the accelerating tube. The test section is insulated with oil rather than SF_6 . Voltage breakdown problems are much more likely to occur inside the evacuated test section where electrons move freely.

The most likely spot for high-voltage breakdown to initiate is the negative triple junction at the vacuum-ceramic-niobium interface at the negative end of the ceramic. The geometry here is critical. The Ticusil fillet extended 2-mm all along the ceramic. We removed this by electrostripping in two solutions. The silver and copper from the Ticusil alloy was removed in NaCN solution, leaving the titanium. This was removed by electrostripping in NaCl solution and repeating the entire process several times. Finally the anodized coating on the niobium was removed with a 50 volume percent HNO_3 , 10 volume percent HF solution.

If we demonstrate that the column can hold off high voltage for periods up to 50 μs before the source is fired, then voltage equilibration along the column should be greatly enhanced. We have just begun tests on the high-voltage test section with the fillet removed. A peak voltage of 267 kV drooping to 251 kV has held for 50 μs with essentially no voltage conditioning.

These test sections results are quite promising for the full accelerating column with much larger area. In some cases, voltage breakdown scales inversely with the one tenth power of electrode area. If this applies to ceramic columns and 50 μs pulses, then a voltage of only 250 kV is required on this small scale test to confirm voltage standoff on the 2 MV accelerating column, with 11 gaps at 175 kV. We exceeded this value.

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