# A 30-kV PROTON INJECTOR FOR PIGMI*

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## Summary

A 30-kV proton injector designed for matching a 31-mA proton beam into the radio-frequency quadrupole (RFQ) section of the PIGMI accelerator has been constructed and tested. This injector uses a small efficient duoplasmatron ion source and a single-gap extraction system for creating a convergent ion beam, and a three-element unipotential einzel lens for focusing the ion beam into the RFQ. A description of this prototype injector is presented, along with the experimental data obtained during the testing of this system.

## Introduction

Under the PIGMI (Pion Generator for Medical Irradiations) program at the Los Alamos National Laboratory, the major technologies for constructing a compact linear accelerator for pion therapy have been identified and developed, and the configuration of this accelerator has been described.[1] The PIGMI accelerator begins with a small proton injector, followed by an RFQ linac.

The RFQ linac dramatically simplifies the low-energy end of the accelerator. It can accept a 30-keV proton beam from the injector and accelerate it to 2.5 MeV in 1.8 m, at which point the beam is easily injected into the conventional drift-tube linac. In addition, the RFQ also provides >90% capture of the 31-mA proton beam, as well as radial focusing. Thus, the RFQ has eliminated the need for a large high-voltage Cockcroft-Walton power supply, a complex multicavity buncher system, an extensive low-energy beam-transport system, and associated control instrumentation.

The 30-keV injection energy was chosen to minimize the length of the RFQ with the optimum capture efficiency, while allowing reliable operation of the single-gap high-brightness extraction system. Injector operation at 30 kV dramatically simplifies the design and makes the system small while increasing the reliability. In addition, this low injection energy for the RFQ allows electrostatic focusing of the ions because it is more effective than magnetic focusing at this energy. Thus, an einzel lens can be used to match the 30-keV proton beam from the injector into the RFQ.

In the PIGMI experimental program, a prototype of this compact 30-kV injector has been constructed and tested. This injector contains a small, efficient duoplasmatron ion source, a single-gap extraction system, an einzel lens, and diagnostics equipment enclosed in a small re-entrant vacuum chamber that attaches directly to the vacuum housing of the RFQ. A self-contained equipment cabinet contains the electronics, power supplies, and other systems to operate the ion source, extraction system, vacuum system, and einzel lens.

## Injector Description

### Duoplasmatron Ion Source

A new duoplasmatron ion source was constructed for this prototype injector. This small ion source uses the same filament, intermediate electrode, plasma aperture, and plasma expansion-cup geometry as the previous PIGMI injector,[2] but has a smaller anode housing, a more compact arc magnet coil, and a simpler water-cooling system. The water cooling is maintained by channels cut into the copper housing for the arc magnet coil. The housing is brazed onto the intermediate electrode so that the coil is not exposed directly to the water. Magnetic field calculations were used to scale down the anode housing and arc magnet coil to give the same magnetic field between the intermediate electrode and anode as measured in the previous source, with only a small increase of the magnet coil ampturns. The final design for this duoplasmatron is seen in the cutaway view of the injector shown in Fig. 1.

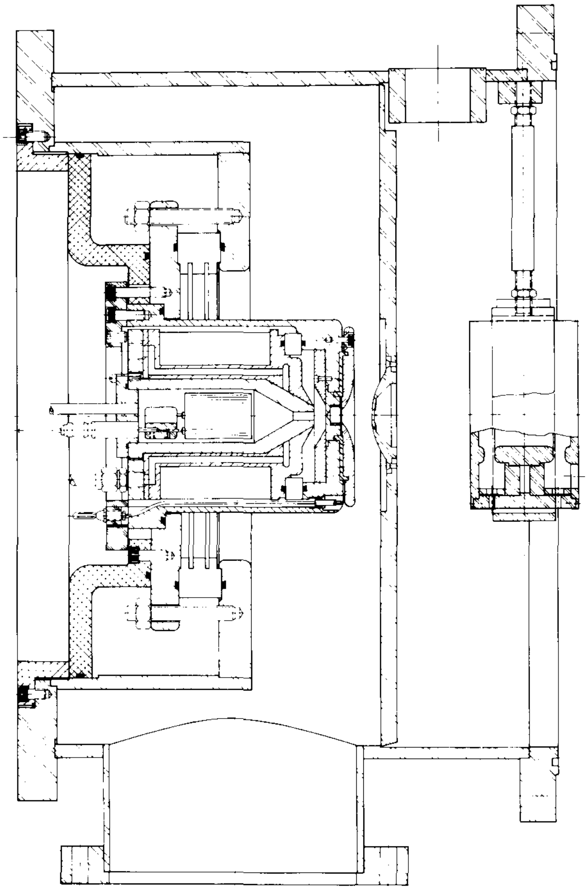

Fig. 1. Cutaway view of the 30-kV injector.

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The iron plasma-expansion cup in this duoplasmatron uses a boron nitride insulator along the straight side of the cup. This self-biasing electrode, suggested by Bacon[3] for this geometry, increases the proton fraction in the extracted ion beam to 90% or more, compared to the 70% this geometry yields without the insulator.[4]

### Extraction System and Vacuum Housing

The cutaway view of the injector in Fig. 1 also shows the arrangement of the 30-kV extraction gap and high-voltage isolation of the ion source within the re-entrant vacuum housing. The high-voltage isolation is maintained by a single glass insulator held between two O-ring surfaces by permali bolts. The radial alignment of the ion source is maintained by precision-machined lips on each surface. The outside of the insulator and the permali bolts are enclosed in a pressurized Lucite dust cover (1 atm psig of nitrogen gas) to insure against breakdown across the insulator caused by dust or moisture.

As seen in Fig. 1, the ions are extracted from the duoplasmatron by a single gap 30-kV extraction system. The focus electrode and extractor electrode in this system were designed with the ion extraction code SNOW[5] to give a small convergent beam of 31 mA at 30 kV, with a 1.5-cm extraction gap. To prevent electrons (generated in the residual gas by the ion beam) from backstreaming through the extraction gap to the ion source, a magnetic dipole field is maintained just beyond the extraction electrode by small permanent magnets.

A turbomolecular pump located near the ion source efficiently pumps the gas load in the extraction gap. The gas in the transport system is pumped directly by the RFQ vacuum system, because the injector housing is bolted directly to the accelerator. This arrangement, coupled with the small apertures between the various regions, will allow differential pumping and a large pressure difference between the ion source and accelerator.

### Beam Transport and Diagnostics

As previously mentioned, the low energy of the proton beam and the close coupling of the injector and RFQ allow the ions to be focused into the RFQ with an electrostatic lens. A three-element unipotential lens was designed, along with the extraction system, to accomplish this task. The calculated beam optics for the final design of this system, with a 31-mA proton beam, is shown in Fig. 2.

As seen in Fig. 2., a drift space of ~4.5 cm exists between the back of the extractor electrode and the first electrode of the einzel lens. This space has been used for insertion of beam-diagnostics equipment. A biased beam stop and a multiwire beam harp can be individually inserted to measure the extracted ion current or beam profile. In addition, a small window-frame steering magnet can be inserted to magnetically steer the extracted ion beam through the einzel lens and into the RFQ. This steering can be used to compensate for small misalignments in the system.

### Equipment Cabinet

The equipment cabinet, shown in Fig. 3 with the injector mounted, is a self-contained system for operating the injector. The entire high-voltage region of the injector has been enclosed in an interlocked, grounded cabinet (76 in. high by 24 in. wide by 41 in. deep). As seen in Fig. 3, the front half of the cabinet contains, from the bottom up, the turbomolecular pump power supplies; the high-voltage power supply; the ion source power supplies located at high voltage; an oscilloscope for monitoring the arc pulse; the einzel-lens control and meter; the pulsing and timing controls and the interlock system; and the ionization gauge controller. The rear portion of the cabinet contains the high-voltage isolation transformer (rated for 3 kVA at 50 kV), the hydrogen gas bottle, regulator and gas distribution system, the ac distribution panel, the high-voltage crowbar system, the einzel-lens power supply, and the closed-loop cooling system for the ion source. An interlocked Lucite rear door gives easy access to the high-voltage region in the cabinet, and thus to the back of the ion source and the associated power supplies. This makes routine maintenance and trouble-shooting of the system very easy and rapid. Also, the transparent door allows inspection of the system during operation. In addition, the panels on both sides of the cabinet can be removed and the high-voltage region is visible during operation through interlocked Lucite panels within the cabinet.

Although all of the power supplies for operating the ion source are located at high voltage, the manual control for the power supplies, as well as the stepping motors for computer control, are located at ground potential with insulated shafts to the control Variacs. All meters for the power supplies are located at high voltage, but are visible through glass windows on the front panel of the cabinet. The oscilloscope and current transformer used to monitor the arc pulse are at ground potential, with the current lead from the arc pulser to the ion source isolated through the current transformer. The timing pulse for the transistor arc pulser and power supply is supplied

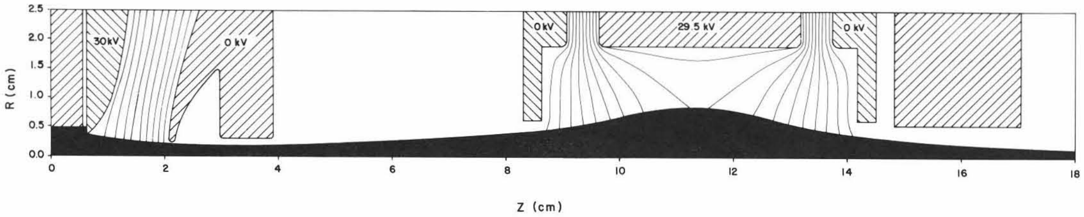

Fig. 2. Calculated ion-beam optics for the 30-kV injector, including the einzel lens.

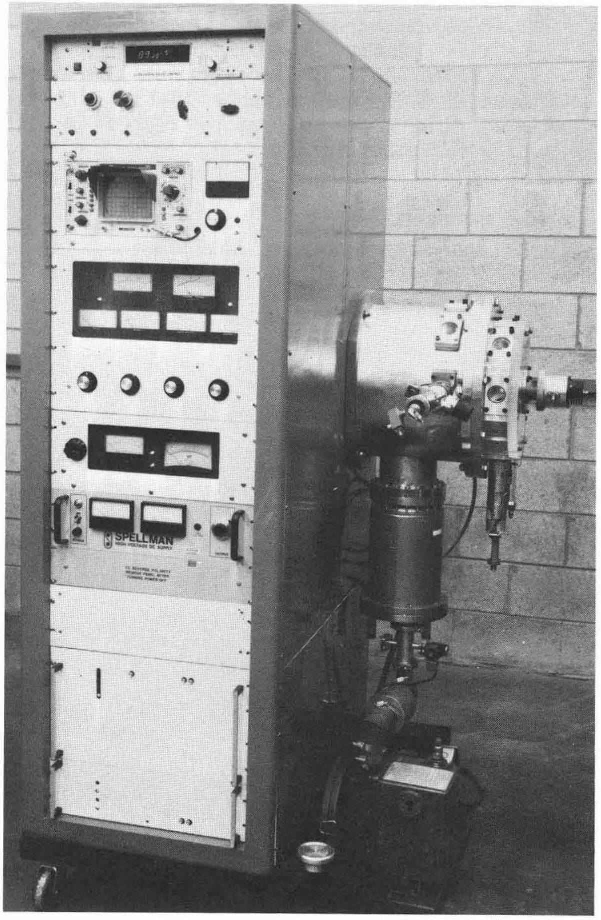

Fig. 3. The 30-kV injector and equipment cabinet.

from the master timer at ground potential through a fiber-optics link. Space has been left in the injector high-voltage region for a microprocessor to monitor the ion-source power supplies and provide the information to the control system for the accelerator through another fiber-optics link.

The high voltage in the cabinet is supplied by a rack-mounted power supply located just below the high-voltage region. The high voltage for the einzel lens is supplied by a small potted high-voltage power supply controlled by a Variac. The high-voltage isolation transformer is mounted on the rear floor of the cabinet. The hydrogen gas bottle also is mounted on the rear floor of the cabinet at ground potential, with the high-pressure gas (~20 psi) fed from the regulator to the hydrogen flow system in the high-voltage region through PVC tubing. The closed-cycle water system for the ion source is located on the rear floor of the high-voltage region in the cabinet; the water system contains a submersible vane pump mounted in a 10-ℓ water reservoir, and a small automotive heater radiator mounted on a Lucite frame below the exhaust fan located in the top of the equipment cabinet.

## Experimental Results

The prototype 30-kV injector system has been assembled and successfully tested. The assembled system was tested as shown in Fig. 3, but with several additional diagnostics beam boxes, one which had a 120-ℓ/s turbomolecular pump attached to it. For these tests the typical operating parameters were

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| Arc voltage | 120 V |
| Arc current | 15 to 20 A |
| Arc magnet current | 0.9 A |
| Filament current | 30 A |
| Hydrogen gas flow | 1.0 atm cc/min |
| Arc chamber pressure | 180 microns |
| Column pressure | $6 \times 10^{-6}$ torr |
| Einzel lens voltage | 0 to 32 kV |

The injector was operated at 60 Hz, with a 75-μs pulse width; it produced a 25-mA ion beam with a 31-kV extraction voltage. The extracted current increased to 30 mA at 33 kV, indicating that the extraction gap must be shortened to obtain the required 31 mA of protons at 30 keV.

During testing of the injector, an emittance measuring station was positioned with the slits at the same position as the RFQ entrance would be during accelerator operation. Emittance scans made at 31 keV, with an extracted beam current of 25 mA, gave a normalized emittance of 0.039π cm•mrad for 96% of the beam. This is in excellent agreement with the normalized emittance of 0.037π cm•mrad measured for this source, with a 25-mA beam at 112 keV, on the LAMPF ion-source test stand. Measurements on the test stand also showed that the proton fraction in the beam was ~90%, and that the ion source could operate stably at a 6% duty factor.

The emittance measurements at 31 keV were made using the einzel lens; therefore, these measurements include the aberrations of the lens, a possible explanation for the small difference in the two measurements described above. However, these emittance measurements also showed that the einzel lens could be adjusted to produce a converging beam with the proper match for the RFQ, as shown in Fig. 4., where the acceptance of the RFQ, the experimental phase space of a 25-mA beam, and the calculated phase space for a 31-mA beam are overlaid on the same plot.

During magnetic field measurements it was found that the flux leakage into the plasma expansion cup of the new duoplasmatron was almost double the value measured on the larger version of this source. This is probably from saturation caused by using a thinner and smaller iron anode housing; this is also suspected as the cause of the larger emittance from this ion source (~0.04π cm•mrad) relative to the emittance of the larger version of the ion source (~0.03π cm•mrad). However, small changes in the anode aperture mounting arrangement could reduce the flux leakage and increase the brightness of this injector, if necessary for accelerator operation.

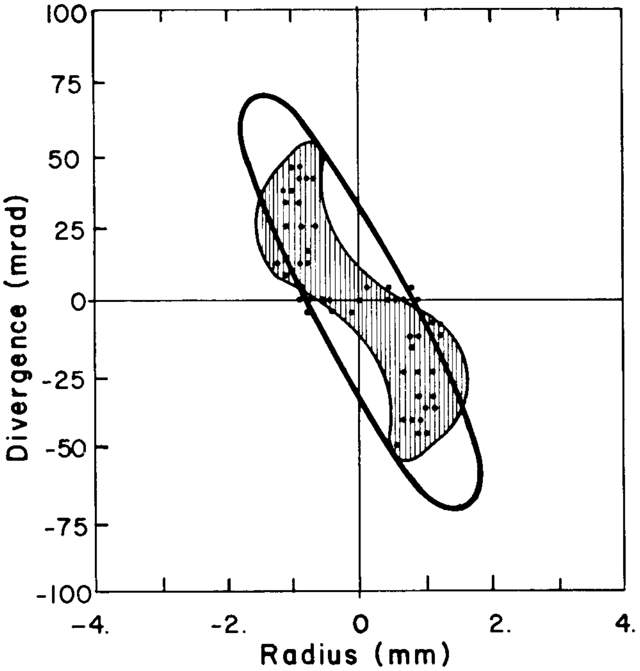

Fig. 4. Overlay of calculated (dots) and measured (vertical lined area) ion-beam phase space with the calculated acceptance (ellipse) for the RFQ.

## Acknowledgments

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