# Injector Design for High-Current CW Proton Linacs*

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*Abstract*

We present an injector design for high-power cw proton linacs with particular emphasis on intense neutron-spallation sources. Long-term operational reliability and availability dominate over specific beam parameters for these accelerators. We discuss technical requirements for the ion source and low-energy beam transport line and compare different options. A prototype design for a 75-kV, 110-mA cw proton injector is presented.

## I. INTRODUCTION

The development of radio-frequency quadrupole (RFQ) accelerators has provided an effective match between dc ion source injectors and radio-frequency, drift-tube accelerators which greatly enhances the practicality of building high-current cw proton linacs for intense neutron spallation sources [1]. These RFQ accelerators reduce the required injection energy to a limit set by beam perveance rather than by linac beam dynamics and can support long-term, cw operation. Accelerator-based conversion (ABC) of weapons-grade fissile materials, accelerator transmutation of nuclear waste (ATW), and accelerator production of tritium (APT) are possible applications of this technology. After discussing the design considerations for these injectors, we present a preliminary design for these applications.

## II. INJECTOR SPECIFICATIONS

The cw injectors for neutron-spallation sources must provide stable proton beams with high availability. The total number of protons on target will be an important measure of operation. These injectors will have to provide >100-mA cw proton beams at energies up to 100 keV with a 95% beam fraction normalized emittance of 1.2 πmm-mrad at the RFQ match point.

A design for an accelerator to produce tritium is being developed at the Los Alamos National Laboratory (LANL). This accelerator is expected to be on line for 7800 hours/year with an overall availability of 85%. Injector availability must exceed 98% during the scheduled on-time. Periodic ion-source maintenance may be done no more often than once a week during a single scheduled 8-hour maintenance period. The injector fault rate (primarily high-voltage faults) must be limited to less than one per hour. Means must be provided in the injector to reestablish the beam in the linac quickly with minimal perturbation and beam spill. The low-energy beam transport (LEBT) line must provide proper matching and centroid control at the RFQ entrance. Non-interceptive beam diagnostics are needed to ensure proper tuning and on-line monitoring of the injector beams.

## III. ION SOURCE

The choice of ion source for these cw applications will be made on the basis of proven performance for long-term availability and operational stability as well as current and emittance requirements. Ion source gas and power efficiencies are useful criteria for cw source selection. We define the ion-source gas efficiency, η, as

$$\eta = 6.95\, i_{H^+}(A)/Q_{H_2}(sccm) \quad (1)$$

where the proton current is expressed in Amperes (A) and the hydrogen flow is given in standard cubic centimeters per minute (sccm). The power efficiency, ζ, is given by

$$\zeta = j_{H^+}(mA/cm^2)/P_d(kW) \quad (2)$$

where $j_{H^+}$ is the proton current density at extraction and $P_d$ is the discharge power. Other important operating parameters of interest for a cw ion source are the proton current, proton fraction, beam emittance, and source lifetime.

Table I summarizes the demonstrated characteristics of a few candidate sources. These are the multicusp source with filament drive [2], the multicusp source with 2.0 MHz rf drive [3], the monocusp ion source [4], and the 2.45 GHz electron-cyclotron resonance (ECR) ion source [5]. Emitter radii are given immediately below the source description in the first column, and the extraction voltage is given in the second column. The total beam current (proton current in parentheses) is given in the third column. A high proton fraction (the ratio of the proton current to the total current) is desirable to limit beam perveance and to eliminate mass analysis prior to RFQ injection. Note that the monocusp source results are for deuterium. The discharge power is presented in the fourth column, while the power efficiency, ζ, is shown in the fifth column. The duty factor (df) employed for the data is shown in the sixth column while the gas efficiency, η, is in the seventh column. Finally, the measured normalized emittance at the 95% beam-fraction level is shown in the last column. A Gaussian beam-emittance model has been used to obtain the 95% beam-fraction emittance values.

Table I
Comparison of Candidate Ion Sources for CW Linacs

| | $V_{ext}$ (kV) | i (mA) | $P_d$ (kW) | ζ (mA/cm²kW) | df (%) | η | ε (95%) (πmm-mrad) |
|---|---|---|---|---|---|---|---|
| Multi-cusp [2] (filament) $r_e$ = 0.4 cm | 60 | 56 (45) | 7.1 | 13 | 100 | 0.07 | 0.59 |
| Multi-cusp [3] (2.0 MHz rf) $r_e$ = 0.32 cm | 35 | 82 (70) | 18 | 12 | .3 | 0.02 | 0.60 |
| Monocusp [4] (filament) $r_e$ = 0.65 cm | 200 | 200 (120) D+ | 1.5 | 60 | 100 | 0.14 | - |
| ECR proton [5] (2.45 GHz) $r_e$ = 0.35 cm | 42 | 96 (67) | 0.6 | 290 | 100 | 0.31 | 0.60 |

The ECR ion source developed at the Chalk River Laboratory is a promising candidate for this application based on proven cw performance and high gas and power efficiencies [6]. A schematic diagram of this ECR source is shown in Fig. 1. The basic ECR geometry has been modified to optimize the production of protons by eliminating the axial confinement geometry. The 2.45-GHz microwave frequency is sufficiently low that the required axial magnetic field of 875

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Gauss does not dominate the beam emittance after extraction. Current densities up to 500 mA/cm$^2$ at 90% proton fraction have been obtained. This source has been used for several years with the RFQ1 project at Chalk River and has demonstrated sufficient lifetime and stability at a 90 mA total current level to support extended operation of their cw RFQ [7].

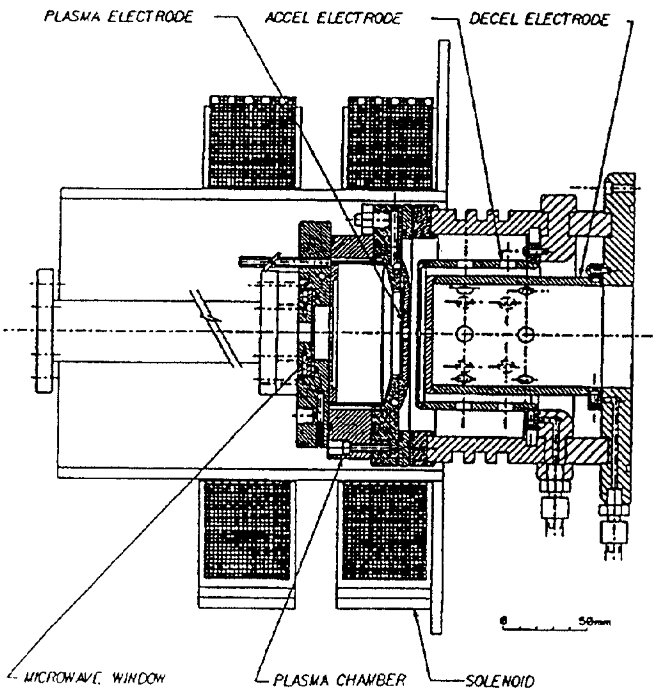


Fig. 1. Schematic Diagram of the Chalk River ECR Ion Source.

Another promising ion source for this application is the rf-driven, multicusp, volume source [3,8]. A 2.0-MHz version of this source has been tested and has demonstrated 85% proton fraction for low-duty-factor beams [3]. The gas efficiency of this source is expected to increase for cw (100% df) operation. Tests are needed to extend the operation of this source to full cw operation.

Our initial preference for the ECR ion source over the rf-driven volume source is based largely on the improved power efficiency. The ECR source operates with <1 kW of 2.45 GHz microwave power, while the volume source may require >20 kW of 2 MHz rf power to produce similar beam currents densities. Additional testing of several candidate ion sources under expected cw operating conditions is required before a final choice can be made.

An injection energy of 75 keV has been selected based on previous experience with the Fusion Materials Irradiation Test (FMIT) injector [9]. We have designed an ion-extractor system to produce the required 110 mA of protons assuming a proton fraction of 85% and $H_2^+$ and $H_3^+$ fractions of 7.5% each. This design entails a total extracted current of 130 mA. The extracted current density is chosen to be 235 mA/cm$^2$, so the emitter radius, $r_e$, is 0.42 cm. The equivalent electron perveance of this beam is 0.29 μP. The extractor design was done using the SNOW code [10]. The electron trap is a proven design used in the FMIT injector. Calculations have been made varying the injected current from the ion source; this geometry has a minimum emittance at the design current of 130 mA. Additional designs for lower proton fractions have also been developed.

## LOW-ENERGY BEAM TRANSPORT SYSTEM

The LEBT system transports and matches the beams extracted from the ion source to the RFQ accelerator. The design beam predicted by the SNOW simulation has an envelope radius of 0.43 cm and an envelope divergence of 46 mrad, while the input beam required by the RFQ has an envelope radius of 0.21 cm and an envelope convergence of 41 mrad.

There are two basic approaches that can be used for the beam-transport system depending on whether electric or magnetic optics are employed. Electrostatic-transport systems have been used to transport 100-mA, 100-keV $H^-$ beams and could be used in this application for proton beams [11]. This option is less sensitive to beam noise and beam instabilities but is limited by space-charge effects for high-perveance beams.

Magnetic-transport lines, on the other hand, generally entail space-charge neutralized beams. A two-solenoid, magnetic-lens system [12] preserves the cylindrical beam symmetry and is extremely versatile in beam matching to the RFQ. This transport system requires that the beam be space-charge neutralized to ≥95%. Figure 2 shows a layout of the preferred two-solenoid lens, direct-injection LEBT. Beam dynamics simulations with 85% proton fraction show that <0.5 mA of $H_2^+$ and $H_3^+$ contaminant ions enter the RFQ for this design. These currents are much less than the expected proton losses in the RFQ and should not pose an operating problem.

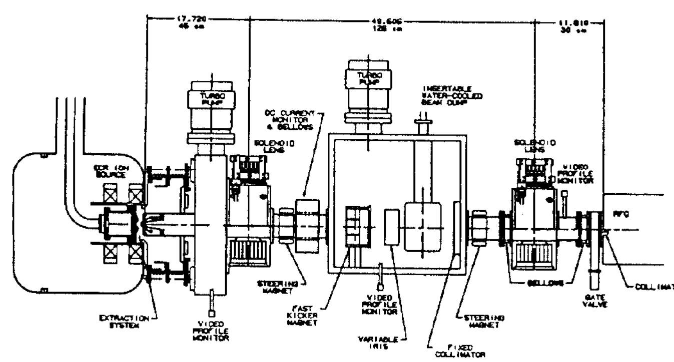

Fig. 2. Layout of the High-Current Proton Injector.

In addition to the focusing lenses, steering elements are needed to correct for minor alignment errors. Steering algorithms have been developed to provide independent control of both centroid position and angle in both transverse planes using two steering pairs. This control is needed to provide optimum tune into the RFQ [13].

A fast kicker magnet provides a means to turn off the proton beam within several microseconds if a fault should occur anywhere in the accelerator or target systems. There is provision to insert a variable iris at the midpoint of the LEBT to limit the beam current to the accelerator and to facilitate beam turn-on. We plan to employ an accelerator design in which the tune is relatively insensitive to beam current so that the accelerator will be brought up to full power by ramping up a low-current, cw beam. This mode of turn-on entails less transient loading of RF systems and permits continuous adjustment of beam tune during ramp-up.

Non-interceptive, beam-diagnostic elements are included in the injector to facilitate beam tuning and to diagnose operating problems. Optical profile monitors provide continuous, on-line beam profile monitoring. Tomographic techniques can be used to deduce the beam emittance [14].

Proper setting of the ion-source parameters can be achieved by tuning for optimum beam profiles. The tune of the focusing and steering elements can also be monitored on line by these profile monitors with a positional accuracy of ±0.2 mm. Optimal monitoring locations are at the LEBT midpoint and at the RFQ entrance. A dc transductor will provide continuous monitoring of the LEBT beam current. An insertable beam dump is provided for limited off-periods when it is undesirable to turn off the ion source. Water-cooled collimators and apertures will be used throughout the transport line to intercept any errant beam. The $H_2^+$ and $H_3^+$ molecular ion beams in large part will be intercepted on the collimators at the entrance of the RFQ and on the fixed collimator at the LEBT midpoint.

This design was done for a nominal current density of 235 mA/cm$^2$. Designs have also been carried out for other current densities ranging from 200 mA/cm$^2$ to 500 mA/cm$^2$. The two-solenoid-lens LEBT has sufficient flexibility to match any of these beams to the RFQ. Figure 3 shows the α-ß tuning diagram for the 235-mA/cm$^2$ design. This diagram shows loci of match-point parameters at the RFQ entrance that can be obtained for a given excitation of the first solenoid as the strength of the second solenoid is varied. The use of two solenoids provides an adequate tuning range in α-ß space to accommodate tuning variations in the proton beams. In these simulations, the input beam is assumed to be fully neutralized. The emittance parameters were obtained by scaling the 235-mA/cm$^2$ results from SNOW to the maximum emittance allowed by the RFQ and then requiring the beam envelope size and divergence to be unchanged. These calculations were done for a total emittance of $6\varepsilon_{rms}$ which corresponds to 95% beam fraction for a Gaussian beam. Similar tuning diagrams were found for beams with 95% neutralization (7 mA effective current) and for ±15% current variations from the nominal 130 mA extracted beam.

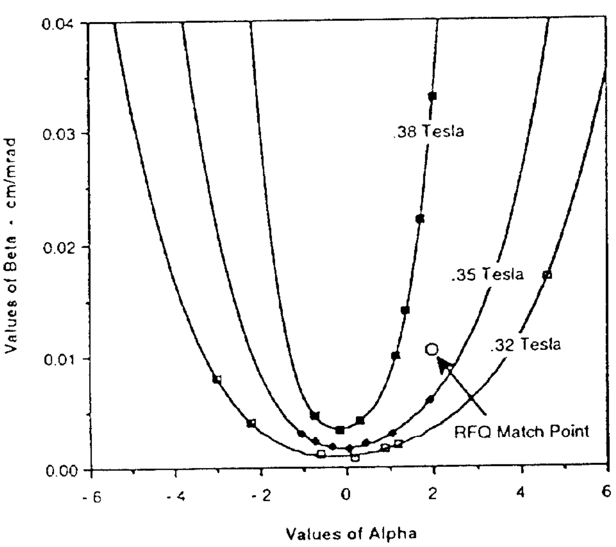


Fig. 3. α-β Tuning Diagram at RFQ Entrance for the High-Current Proton Injector.

Error studies indicate that beam centroid positioning errors should be less than ±0.50 mm and ±10 mrad at the RFQ match point. Optical aberrations are limited by conservative solenoid-lens designs with the beam filling less than half the magnet bore. The use of adequate pressure in the transport line (1 x 10$^{-5}$ torr of a suitable background gas) ensures that beam neutralization limits non-linear, space-charge-induced emittance growth in the LEBT.

## IV. SUMMARY

A basic injector design for high-current, cw, proton linacs is presented. With the advent of RFQ accelerators, the required injectors can be designed for much lower injection energies with most of the ion-source, ancillary systems at ground potential. An ECR ion source operating with a standard high-voltage column feeding a magnetic-transport line using solenoid lenses appears to be a suitable design. Particular attention must be paid to long-term, operational stability and reliability. Further testing of this injector system is needed to prove that the required long-term operation can be achieved.

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