Proceedings of International Collaboration on Advanced Neutron Sources (ICANS-VII), 1983 September 13-16
Atomic Energy of Canada Limited, Report AECL-8488

DEVELOPMENT OF A HIGH CURRENT INJECTOR FOR A SPALLATION NEUTRON SOURCE

B.G. Chidley, G.E. McMichael and M.R. Shubaly

Atomic Energy of Canada Limited
Chalk River Nuclear Laboratories
Chalk River, Ontario, Canada K0J 1J0

Summary

A spallation neutron source for breeding fissile material must have high efficiency and reliability to be competitive with other sources of fissile fuel. A study by Tunnicliffe et al in 1976[1] suggested a breeder based on a proton linac with an output of 300 mA average current at 1 GeV. Although such an accelerator is feasible with present technology, development work is needed before a practical device can be built. Bartholomew[2] at ICANS-V described an accelerator breeder development program that included the ZEBRA[3] accelerator (300 mA average at 10 MeV) and its precursor RFQ1[4] (75 mA average at 600 keV). This paper describes the injector development program at Chalk River, including the ion source, transport line, and structure to accelerate a proton beam to an energy suitable for further acceleration in a drift tube linac.

Injector Requirements

The injector for a spallation neutron source must deliver a high current proton beam at 100% duty factor at an energy suitable for further acceleration in a drift tube linac. For this discussion we shall assume the values of ZEBRA[3] (300 mA at 2 MeV). The injector is a relatively small component of a large and expensive installation, so system parameters must be chosen to optimize the cost and efficiency of the entire installation rather than for economy or convenience of the injector. High reliability and long component lifetime are essential requirements of the injector. Low beam spill and high efficiency of conversion of rf power to beam power are important only if they influence reliability or erosion of components.

In addition to providing an output beam matched to the admittance of the drift tube linac, the injector must have the capability of variable current operation from zero to full design value while maintaining the emittance match.

The most suitable configuration for the injector is to use a dc column operating below 100 kV followed by a radio-frequency quadrupole (RFQ) accelerator. At CRNL high current operation of a 750 kV dc column proved to be very troublesome and the largest 100% duty factor 750 keV proton beam ever obtained spark-free for 30 minutes was below 50 mA.

To obtain pertinent design information and operating experience prior to ZEBRA construction, RFQ[4] is being built to accelerate 75 mA of protons to 600 keV. RFQ1 operating at 2.5 times the ZEBRA frequency and at a lower surface electric field will have relatively similar space charge and beam loading. RFQ1 has been designed for conservative electric fields and modest currents, so that operation near the space charge limit can be conveniently studied and operation will be possible over a range of voltages. Basic specifications for the two RFQ's are given in Table 1.

Table 1

	RFQ1	ZEBRA
dc injector output	50 keV	75 keV
RFQ output	600 keV	2 MeV
output current	75 mA	305 mA
frequency	269 MHz	108 MHz

The aims of the RFQ1 experiment are to gain practical experience with design, construction, operation and diagnostics. Of particular interest will be the operation near the current limit and a comparison of observed transmission with the results from computer particle dynamics codes.

Figure 1 shows the dc injector to the start of the radio-frequency quadrupole of RFQ1. Requirements are summarized in Table 2.

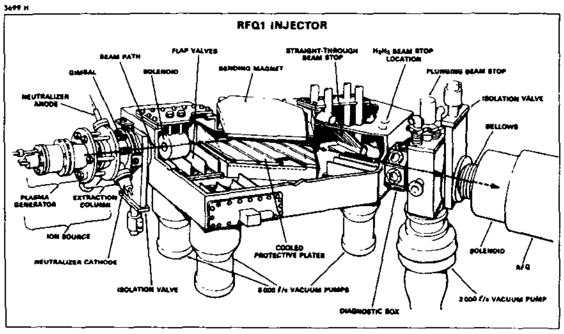

Fig. 1 RFQ1 dc injector.

Table 2

DC Injector Requirements

1. High dc current

RFQ1	115 mA H_1^+	(> 230 mA total)
ZEBRA	375 mA H_1^+	(> 750 mA total)

2. Fixed energy

RFQ1	50 keV
ZEBRA	75 keV

3. Low emittance - High brightness

RFQ1	$\varepsilon_n = 3\ \pi$ mm-mrad
ZEBRA	$\varepsilon_n = 6\ \pi$ mm-mrad

4. Variable current

Zero to full current with ramp times of tens of seconds to tens of minutes.

5. Reliable operation
    - freedom from sparking
    - long component lifetimes
    - stable output (low noise and minimum oscillation of beam envelope)
6. Match to RFQ acceptance
    - over full current range

Ion Source, DC Column, and Low Energy Beam Transport

To provide the high brightness beam required by the RFQ it is planned to start a high quality beam and minimize the length and number of transport elements between the source and the RFQ. Multiple apertures are required for high currents so the plasma generator must give a uniform current density over the extraction area to reduce mismatch between apertures. The plasma must be quiescent to reduce both "time-averaged" mismatch and deleterious effects on space charge neutralization in the beam transport line. In addition all components must be designed with adequate cooling to have long lifetime and provide stable, repeatable operation.

A duoPIGatron meets most of these requirements. It has high arc and gas efficiency, and although the proton fraction is low, it is not much different from other plasma generators of the same size. An experimental program to improve its proton fraction is in progress.

The electrode geometry is designed to minimize aberrations and so produce a bright beam with a minimum of halo. Beamlet stacking can be used to reduce the effective emittance from the multi-aperture array. The extraction column must operate at high gradient to handle the high current density. To provide reliable operation of the accelerator, sparking in the extraction column must be reduced. To achieve this, electron backstreaming and sensitivity to x-ray fields must be minimized. Backstreaming is reduced by minimizing beam spill, by effective suppression of electrons from the beam generated plasma, and by minimization of electron production in the extraction gap. Sensitivity to x-ray fields is reduced by effective shielding of the ceramics and by the proper choice of electrode materials. Figure 2 shows a cross section of the triode accel-decel extraction column used at Chalk River for up to 500 mA total output.

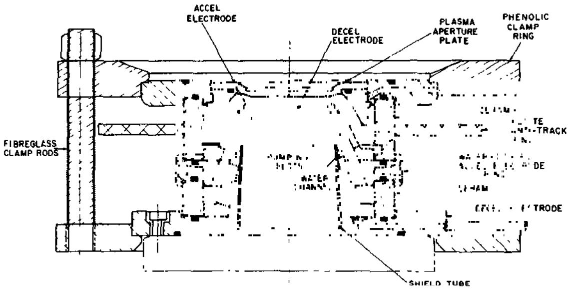

Fig. 2 Triode accel-decel extraction column.

The transport line is kept as compact as is consistent with species selection, vacuum pumping, and diagnostics to reduce convective instabilities. Matching from the extraction column is achieved with a double focusing bending magnet (which also provides for species selection) and two solenoids. For low energy high current beams, good space charge neutralization is necessary to reduce growth in beam size and emittance. This can be achieved by keeping the gas pressure in the transport system relatively high (4-9 x 10^{-3} Pa) although this leads to high charge exchange losses so a preferable alternative may be a plasma bridge neutralizer and this approach is being investigated. Scraping of the neutralized beam is to be avoided as this often leads to emittance growth.

Variable beam current at a fixed energy is obtained by operating the plasma generator on a mixture of argon and hydrogen and varying the argon fraction to vary the proton current from zero to design value while keeping the perveance constant. This requires careful control of the two gas flows and the arc current but does provide variability from zero to full current with the emittance decreasing slowly as the proton current decreases. The required variation of gas flows and arc current are shown in Fig. 3.

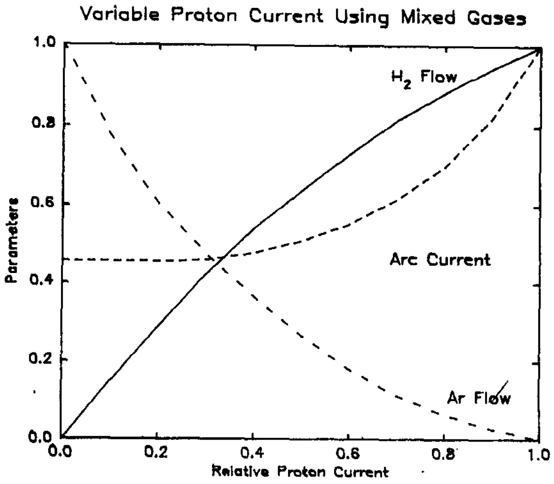

Fig. 3 Variation in gas flow and arc current to give variable beam current.

From measurements on a test stand, single beamlet normalized emittance is 0.34 π mm·mrad for 93% of 85 mA (total current). For a triangular array, as will be used on RFQ1, the effective emittance is 2.4 π mm·mrad and for a full array of 7 apertures, as will be used for ZEBRA, the emittance is 4.9 π mm·mrad. Spark free runs of 3.5 hours at 475 mA (total current), 42 keV have been achieved.

RFQ Accelerator

The current limit for no emittance growth in an RFQ is 3 * 10^4 β^3 amps, where β is the particle velocity expressed as a fraction of the speed of light. Above this limit, emittance growth will occur although operation without beam loss is possible if the structure admittance is large enough to tolerate the increasing emittance until β is larger. The upper current limit for 50 keV injection with manageable emittance growth is about 100 mA. RFQ1 can be operated at 50 keV input but ZEBRA must have a higher injection energy (75 keV in the present design). Design parameters for the RFQ of RFQ1 are given in Table 3.

Table 3

RFQ1

Input Energy	50 keV
Output Energy	600 keV
Input Current	90 mA
Output Current	75 mA
Maximum Electric Field	24.86 MV/m (1.5 * Kp)
Vane Length	2.32 m
Vane Voltage V	
Design	73 kV
Maximum	88 kV
Average Bore Radius r_0	0.464 cm
Minimum Radius a_{min}	0.399 cm
CURLI Current Limit at 300 keV	125 mA
Nominal Input Conditions	
ε (normalized)	3 π mm-mrad
α	1.1175
β	5.454 cm/rad
Structure Power	up to 310 kW
Beam Power	45 kW

The large power dissipation makes cooling of the structure a major design consideration, with the region of rf contact between sheel and vanes being particularly troublesome. To eliminate the need for dynamically adjustable end tuners with their rf contact problems, strapped vanes and adjustable vane supports will be used.

The large beam spill (15 mA) represents a high gas load in the RFQ. Adequate pumping will be required for the RFQ structure as well as for the injector and beam stop. The complete RFQ1 vacuum system has 3 diffusion pumps (25000 L/s), 8 cryopumps (16000 L/s), one ion pump (2000 L/s), and one titanium sublimator (4000 L/S) for a total pumping capacity of 47000 L/s.

The present design value of the maximum electric field on the vane surface is 1.25 times the Kilpatrick limit (1.25 * Kp) but it will be operated at 1.5 * Kp or higher for improved performance. Typical values used in pulsed RFQ's are 2.0 to 2.5 * Kp but there have been doubts expressed that these can be maintained in a cw device. Recent results on the Japanese LITL accelerator[5] show satisfactory cw operation at 1.8 * Kp and an experiment is in progress at CRNL to measure sparking limits in an unmodulated cw RFQ. For RFQ1 a very conservative limit has been used to ensure that an adequate measurement regime is possible to determine space charge current limits over a wide range of operating parameters.

A schematic cross section of RFQ1 is shown in Fig. 4 with the region of interest from a beam dynamics viewpoint indicated by the central hatched square. Within this region the quasistatic approximation can be used in which the vane tips are considered to be equipotential surfaces and the effects of rf currents can be neglected.

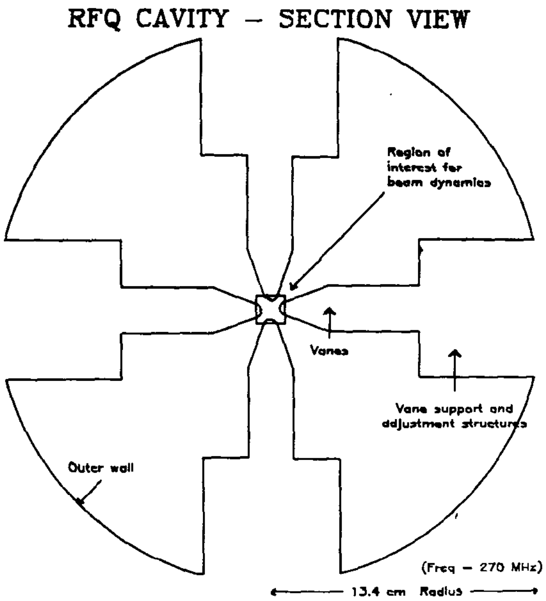

Fig. 4 RFQ1 cross section.

Vane tip shapes have been investigated that allow an increased vane voltage for a specified peak surface field. In this way focusing fields can be reached which are closer to the optimum before being limited by sparking problems. Vane profiles considered were a) the idealized 2-term potential (which cannot be built in practice), b) POP[6] style (the radius of curvature at the tip is the same as for the idealized, but uses a circular arc rather than hyperbolic), c) a constant radius of curvature tip (rather than varying with aperture), and d) a tip with constant center of curvature. The transmission calculated for the various vane shapes using the computer program PARMTEQ are shown in Fig. 5. These curves show how the vane tip profile influences the output current.

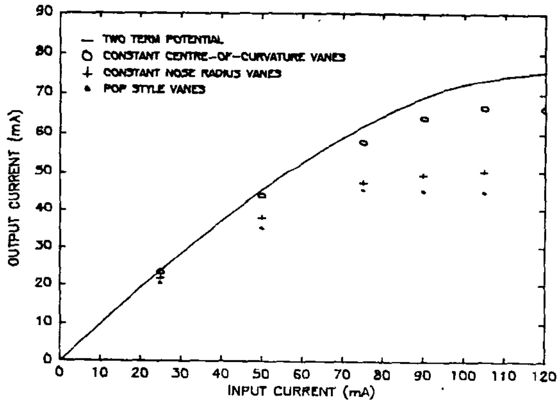
Transmission of RFQ1 for different vane tip profiles.
Calculated with PARMTEQ using 8–term potential function.
Vane voltage adjusted to make peak field – 1.25*Kilpatrick.

Fig. 5 Calculated transmission for various vane tip profiles.

Participants from the United States, Germany and Japan took part in a design review of RFQ1 held at Chalk River in June. All aspects from conceptual design to mechanical details were involved in the review. Suggestions in numerous areas are being implemented - in particular on the mechanical design (the present phase of our work).

The present status of RFQ1 is as follows. The ion source has been tested. Some parts of it will be used as they are presently designed and fabricated. Drawings are finished for the injector with construction expected to be finished mid-1984. The drawings for the RFQ are expected to be completed at the end of 1984 with the RFQ operational at the end of 1986.

Acknowledgements

The authors would like to acknowledge the work of members of the ZEBRA group, including S.O. Schriber for system requirements, L.D. Hansborough, R.B. Turner, A. Walton, T. Tran Ngoc, D. Beaulieu, and J.E. Anderchek for mechanical design, J. Ungrin, R.M. Hutcheon and J.C. Brown for rf discussions, and L.W. Funk and M.S. deJong for diagnostics and tranport lines.

References

1. P.R. Tunnicliffe, B.G. Chidley, J.S. Fraser, "High Current Linear Accelerators and Nuclear Power", Proc. 1976 Proton Linear Accelerator Conf., Atomic Energy of Canada Limited, Report AECL-5677, 36 (1976).
2. G.A. Bartholomew, "Research Opportunities with Prototype Accelerators for an Accelerator Breeder", ICANS-V Proceedings ISSN 0344-5789, 89 (1981).
3. B.G. Chidley, J.C. Brown, G.E. McMichael, S.O. Schriber, M.R. Shubaly and J. Ungrin, "Design and Constraints for the ZEBRA Injector, RFQ and DTL", Proc. 1981 Linear Accelerator Conf., Los Alamos National Laboratory, Report LA-9234-C, 49 (1981).
4. M.R. Shubaly et al., "RFQ1: A 600 keV, 75 mA CW Proton Accelerator", IEEE Trans. Nucl. Sci., NS-30, No. 2, 1428 (1983).
5. N. Ueda, T. Nakamishi, S. Arai, T. Hattori, T. Fukushima, Y. Sakurada, T. Honma, N. Tokuda, S. Yamada, M. Takanaka, A. Otano, A. Mizobuchi, Y. Hirao, "Design, Construction and Performance of the INS RFQ Linac LITL", IEEE Trans. Nucl. Sci., NS-30, No. 4, 2975 (1983).
6. J.E. Stovall, K.R. Crandall, R.W. Hamm, "Performance Characteristics of a 425 MHz RFQ Linac", IEEE Trans. Nucl. Sci., NS-28, No. 2, 1508 (1981).