ION SOURCE DEVELOPMENT AND INJECTOR DESIGN FOR ZEBRA

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Summary

The requirement for high and variable current in ZEBRA, and the acceptance limits (on both energy and phase space distribution) of the RFQ place stringent demands on the injector design. For variable current, the ion source extraction voltage must be varied over a wide range ($I \propto V^{3/2}$) to maintain a matched beam, however the RFQ has a limited range of injection energy. The 75 keV injection energy made necessary by current limits in the RFQ will require that care be taken to ensure reliability. Beam spill limits in downstream structures and RFQ beam dynamics require minimal beam halo and precise control of the phase space distribution. Following a discussion of these problems, and the approaches being taken at Chalk River to solve them, a conceptual design for the ZEBRA injector is presented.

Introduction

The injector for ZEBRA[1] must provide a proton current variable from less than 40 mA to more than 375 mA with less than a 15% variation in output energy. The beam is to have very low halo (< 2%) and should "uniformly" fill a defined ellipse in phase space throughout the full current range. Space charge limits in the RFQ[1] have forced the injector voltage to 75 kV from the original 50 kV value. This higher voltage increases the potential for damage by high voltage transients caused by sparking. To produce an injector with the required performance, an extensive development program is underway at Chalk River. This program covers development of plasma sources and extraction columns, studies of the transport of high-current space charge neutralized beams, design of injector packages and control systems, and development of beam simulation codes.

Ion Source and Injector Development

Two facilities are currently in operation. The Ion Source Test Stand (ISTS) is being upgraded to provide 900 mA at 80 kV. In addition a 50 kV, 100 mA supply will soon be available for development of tetrode extraction columns. The main feature of ISTS is an Emittance Measuring Unit (EMU) with a dynamic range of $\sim 10^5$. Power dissipation in the EMU dump limits beams to $\sim$ 8 kW for typical beam sizes ($\sim$ 80 mm dia). However a straight through dump can handle 35 kW and work is underway to design a 75 kW dump. The Injector Test Experiment (ITE) can provide 750 mA at 50 kV. The ITE beam line has a 60° bending magnet with adjustable entrance and exit angles and a simple pepperpot-plate emittance device in the proton beam line. This facility will be used to commission injector packages (as for the RFQ1 experiment[1]) and for beam transport studies and development of beam diagnostics.

A desirable plasma source would provide a uniform (± 2.5% over a 30 mm diameter extraction area) high current density ($\sim$ 400 mA/cm^2) cool ($T_i <$ 0.2 eV) plasma with high proton percentage ($\sim$ 90%) and would have high arc and gas efficiency. Component lifetime should give over 500 hours of full power operation with no significant degradation in performance. At Chalk River, a program is underway to develop such a source. Initial development has been done on a duoPIGatron source with a plain PIG region. The duoplasmatron feed provides a good environment for either a standard oxide cathode or a refractory compound hollow cathode and provides a good electron source. The magnetic field in the PIG region can be controlled to optimize operation over a wide current range. A current density of 445 mA/cm^2 with acceptable uniformity over a 20 mm diameter extraction array (derived from extracted beam measurements) can be achieved with a 14 A, 100 V arc. For a properly tuned source, noise levels are less than 3%. With this source, proton fraction is approximately 45% at full current. This fraction is unacceptably low. To facilitate parametric studies and optimization, a new source has been designed and fabricated.

Studies of duoPIGatron sources with both axial- and orthogonal-cusp PIG regions have begun. Initial results indicate that, for the beam current range of interest, these sources have lower arc and gas efficiency than the simple duoPIGatron. To provide more basic measurements on the source plasma and to provide better input values for codes such as BEAM[2], a system is being constructed to traverse double floating Langmuir probes across and into the source plasma and to sweep these probes to give values for electron density and temperature. A spectrum analyzer is being used to study the noise spectrum of the source plasma and to help determine the mechanisms producing the noise.

The extraction column must not only provide a high-brightness, low halo beam, but it must also operate reliably. Catastrophic breakdowns leading to complete loss of beam are not the only problem - small "tics" in the column will yield, momentarily, a poor quality beam that increases beam spill in the downstream part of the accelerator. For good quality beams, the geometry in the beam region is extremely critical. Small aberrations that would not be noticed in most accelerators are intolerable in a high current beam. The best approach to electrode design is a) calculation of the optics of a proposed design using a simulation code like BEAM, b) modification of the design to reduce aberrations, and c) experimental verification of the design by emittance measurements. This technique has yielded designs that provide beams with 2% or less halo and very high brightness.

Most of the work to date has been done on triode columns that are more appropriate for beams of up to 50 keV. However, with the increased energy required for ZEBRA, tetrode columns are being considered. So far only computer simulations of tetrode columns have been performed, however a power supply that will permit testing of tetrode columns is on order.

Experience at Chalk River, and elsewhere, has identified a number of factors affecting reliability[3]. The major factor is the generation of x-rays by backstreaming electrons, especially as voltages increase above 40-50 kV. Two approaches can be taken to ameliorate this problem. Generation of backstreaming electrons can be reduced by a) reducing beam spill on electrodes, b) reducing the gas presure in the column and c) provision of effective suppression of electrons from the beam plasma. The deleterious effect of the x-rays can be reduced by proper shielding of ceramic insulators and by proper choice of electrode materials. For example, on the present extraction column, use of a molybdenum-faced accel electrode increased the usable voltage by up to 50%, and the extractable current by 75%. Proper cooling of electrodes is also important - present designs use a conduction cooled accel electrode designed to ensure good cooling, and an internally cooled ground (decel) electrode. Thick copper walls in the electrodes provide not only improved cooling, but also good x-ray shielding.

Transport of high-current, high-current-density, space-charge neutralized beams is a major concern for ion sourcerers. The deleterious effects on beam emittance of magnetic transport elements are being studied at Karlsruhe and Darmstadt. At Chalk River large amplitude (> 20%) modulation at ∿ 100 kHz on a drifting beam was observed when the extraction voltage was varied 10% from the proper value[4]. One of the required diagnostics in a high current injector will be a spectrum analyzer - for both beam generated and plasma-source-generated noise. Development of non-destructive beam diagnostic devices, for example J.S. Fraser's tomographic scanner[5], is well underway. However the processes in the beam, especially a beam comprised of many beamlets, are not well understood. Further development of non-destructive beam diagnostics is required before significant headway can be made in the study of beam transport.

The ZEBRA Injector

In addition to the considerations above, three additional requirements for the ZEBRA injector are receiving special attention. The first is the requirement for a 10-fold variation in output current within a limited energy range. Since the matched curve for an extraction column varies as $V^{3/2}/m^{1/2}$, and current variation by scraping off part of the beam leads to a large halo growth, other techniques must be used. One possible solution would be to use a biased RFQ, however this would add to problems in the RFQ design and to difficulties with matching to the drift-tube-linac acceptance. Another possible solution would be use of a two-stage injector. This requires two high-power, high-voltage power supplies, one of them floating. Furthermore the injector becomes much more complex and the transport elements required between the two columns may lead to unacceptable emittance growth. The proposed design uses a single stage injector with two tricks of ion sourcery to provide the required current variation within given voltage constraints. If excess gas is fed to the plasma source, much of the H_1^+ is converted to H_3^+. This not only reduces the proton current, but also increases the effective mass of the extracted beam, reducing the matched current at a given voltage. This secondary effect could be further enhanced by feeding a small amount of a heavier gas, such as argon, to the source. Preliminary studies using excess hydrogen indicate a reduction in proton current by a factor of four should be achievable using this technique. A further reduction by a factor of 2-3 can be achieved by using a neutralizer tube between the source and magnet. The neutralizer converts ions to neutrals that will pass through the mass separation magnet unaffected. Emittance measurements on the ion fraction of such a neutral beam show that the emittance is not significantly degraded by scattering - in fact the effects of scattering seem to be more than compensated for by reduced space charge blow-up. However, alignment is critical as any scraping by the neutralizer tube leads to an increase in halo.

Beam dumps are a second area of injector design receiving special attention. The ion source produces a 50-60 kW beam. With reasonable care in controlling beam size, this leads to power densities in the range of 1-2 kW/cm^2. This power density can be handled by properly designed copper swirl-tubes as used on ITE. They are easy to fabricate, have a reasonable safety margin, and have proven to be trouble-free. It may be necessary to plasma spray the swirl tubes with a thin layer of molybdenum or tungsten to reduce erosion of the copper by sputtering and other processes.

The third area is associated with damage from spark induced transients. No matter how well an extraction column is designed, it will spark eventually. When it does, all nearby electronic equipment suffers. Extensive shielding, filtering and transient suppression will only reduce the damage, not prevent it. On present systems, the power supplies in the high voltage dome are the most affected. Computer data acquisition and control systems, as will be required on the ZEBRA injector, are especially sensitive to damage and perturbation by high voltage transients. The solution to this sensitivity is to put as much of the electronics as possible at ground potential. Because the power supplies for the source are SCR regulated, most of the supply can be at ground by replacing the output transformer in the supply with a high voltage isolation transformer (see Fig. 1). This has the added advantages of reducing the amount of telemetry across the high voltage interface and of keeping the links between the computer and the power supplies at ground. Cost of the isolation transformer is increased but the total system cost will likely be reduced - if only in the costs of required spare parts. The high voltage dome will be more compact, especially as all the

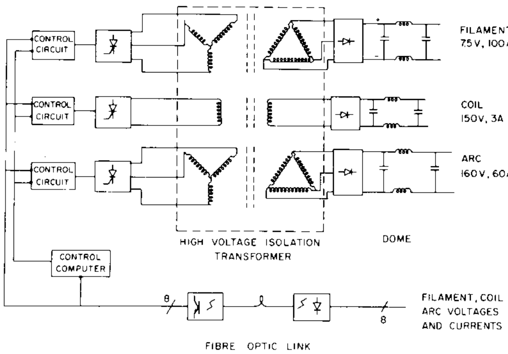

Fig. 1 Schematic of plasma source power supplies.

gas handling system, except the metering valve, will also be at ground. The only components in the dome would be passive filters on the outputs of the power supplies, and a small number of V/f converters to telemeter source parameters to ground. If required, a rugged active crowbar for the arc power could be installed.

Figure 2 shows the conceptual design for the injector. The plasma source is an orthogonal cusp duoPIGatron with a lanthanum hexaboride hollow cathode. The tetrode extraction column has either seven or thirteen apertures - the number will depend on the required uniformity in illumination of the phase space ellipse. Beamlet steering by either aperture displacement or electrode curvature will be used to reduce the effective emittance of the multi-aperture beam. Gross alignment is achieved by a gimbal below the source; fine steering can be achieved by coils wound on the upper end of the 1 m long neutralizer tube. Mass separation is achieved by a 30 cm radius, n=1/2, shaped-pole double-focusing magnet similar to that on the FMIT injector[6]. Separate swirl tube dumps are provided for the straight through beam and the H_2^+ and H_3^+ components. Most of the remaining vacuum chamber is protected by water cooled liners to reduce heating from stray beam. Vacuum valves are installed just below the ion source (to reduce downtime for source changes and maintenance) and at the exit of the injector. Viewports are provided for optical measurement of beam size, position and intensity profile. Vacuum pumping is provided by a combination of turbomolecular and cryopumps. In spite of massive oil contamination on ITE, no deleterious effect on ion source performance has been seen. However, there are concerns about the effect of oil vapor in the RFQ. At the exit of the injector, there are a baffled conical tube to aid in differential pumping of the RFQ, a plunging swirl-tube dump to permit run-up and operation when the RFQ is unavailable, and a weak solenoidal electron trap to decrease perturbation of space charge neutralization by fields in the RFQ. Diagnostics consist of combined tomographic and optical beam size and position scanners at the exit of the ion source and near the injector exit. Simple spectrum analyzers are employed on the beam dumps. A full computer control system for automatic run-up and for data logging is included.

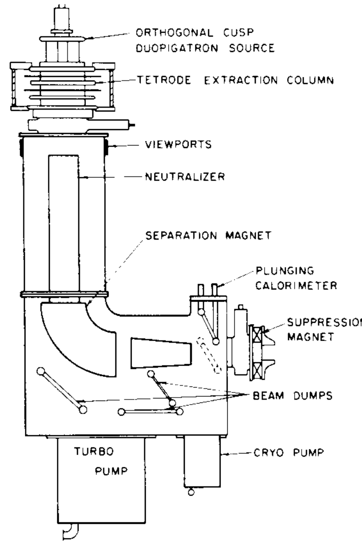

Fig. 2 Conceptual design of the ZEBRA injector.

This design, with modifications prompted by the development programs underway at Chalk River and elsewhere, should satisfy the requirement for the ZEBRA injector. A test of these ideas will be carried out on the 50 keV, 110 mA (H_1^+) RFQ1 injector to be operating in early 1983.

Acknowledgements

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References

1. S.O. Schriber, "ZEBRA (Zero Energy BReeder Accelerator) Program at CRNL - 300 mA-10 MeV Proton Linac", paper presented at this conference.
2. M.R. Shubaly, R.A. Judd and R.W. Hamm, "BEAM, an Improved Beam Extraction and Acceleration Modeling Code", IEEE Trans. Nucl. Sci., NS-28, 2655 (1981).
3. J.D. Hepburn, M.R. Shubaly and J. Ungrin, "Spark Resistant Design for High-Voltage High-Current Accelerating Columns", Low Energy Ion Beams 1980, edited by I.H. Wilson and H.G. Stephens, Institute of Physics, Bristol (1980).
4. M.S. de Jong, private communication (1981).
5. J.S. Fraser, "Developments in Non-Destructive Beam Diagnostics", IEEE Trans. Nucl. Sci., NS-28, 2137 (1981).
6. E.A. Meyer, Los Alamos National Laboratory, private communication (1981).

Discussion

The 100-kHz modulation that we see when we scrape the beam is not present when the scraping iris is not inserted. We look at the entire beam hitting the dump at the end in this observation. We have bent the beam a little so part goes on the dump and part on a protective plate; again, without the iris, we don't see the modulation. We also put an antenna in and didn't see it. There are a lot of things in the short transport that are still not understood.