ION SOURCES AND INJECTORS FOR HIF INDUCTION LINACS

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Abstract

For heavy ion fusion (HIF) induction linac drivers, a typical injector requires total beam current of 50-100 A and is comprised of many individual beams of 0.5-1.0 A each. As a step towards developing a full ion driver for inertial fusion energy (IFE) power plants, an Integrated Research Experiment (IRE) will be proposed within a few years [1]. The IRE will have a linac of more than 150 MeV and beam current about 18 A (ion mass 39). At present, a compact multiple-beam injector is being developed to meet the IRE specifications. In our design, about 100 miniature beamlets (of a few mA each) will be merged to form each 0.5 A beam at the matching section. The beamlets have current density up to 100 mA/cm2 at the ion source (as opposed to 3.5 mA/cm2 used in previous low current density large beam designs). With optimized positioning and aiming, the miniature beamlets can quickly merge and match into an ESQ channel thus minimizing the matching section size requirement. Simulation results have shown that when the beamlet current is small and the number of beamlets are large, the emittance of a 1.6 MeV, 0.5 A beam (after merging) at the end of the injector is 1.0 π mm-mrad.

1 INTRODUCTION

In the USA, the primary approach for heavy ion driven inertial fusion (HIF) is to use ion beam drivers based on high current induction linacs. The driver can have an array of N • 100 parallel ion beams with final beam energy in the multi-GeV range. The total required beam charge is • 1 mC. For beam pulse length of • 20 µs at the ion source, the beam current is • 50 A. Typical ions of interest for drivers (based on target penetration range) have mass > 100 amu. However, in the near future, lighter ions such as K are useful because they provide an opportunity to do experiments at high ion velocities on medium length accelerators. In an electrostatic system, the beam current can be scaled according to the square root of (Z/M) in order to keep the same perveance for other ion species.

2 HIGH PERVEANCE ION SOURCES

High current heavy ion beams have significant space-charge effects, so the current in each beam is limited by the focusing capability of the ion source. The traditional approach is to use a low current density ion source to deal with the space charge problem at low energy. An alternate approach uses a multiple-aperture ion source to extract a large number of high current density miniature beamlets to circumvent the space charge problem; they are further accelerated to a high energy before they are merged into a single beam.

2.1 Single-Aperture Ion Source

In order to accelerate and transport a single beam containing 0.5 A of K ion current through the 1.6 MV ion gun with a proper convergence, the beam current density at the ion source emitting surface must be less than 3.25 mA/cm2. A typical ion gun design as obtained by the EGUN code is shown in Figure 1. This design is based on a 25 kV/cm average focusing gradient and a small aperture channel at high voltages to minimize breakdown problems. The emitter is a 14 cm diameter alumino-silicate source. The beam emittance as calculated by EGUN is less than 1 π-mm-mrad.

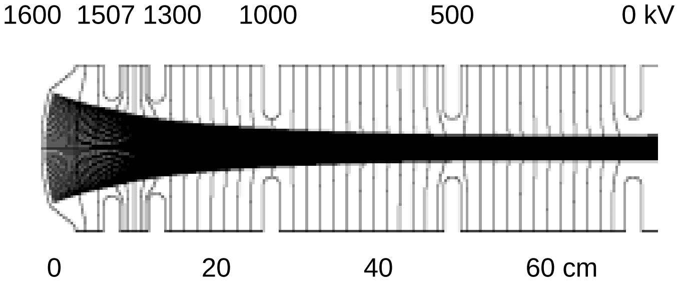

Figure 1: Ion gun design for a low current density, 1.6 MeV, 0.5 A Potassium beam.

2.1 Multiple-Aperture Ion Source

High current density can only be achieved by small low current beamlets. At low energy where the space charge effect is strong, the beamlets are extracted, accelerated and focused by a system of multiple-aperture electrodes. We can further improve the focusing capability of the electrode system by arranging them in an Einzel lens configuration, i.e., an accel-decel scheme with a net acceleration. After accelerating the beamlets to • 1 MeV energy, they are merged together to form the required beam of • 0.5 A. Figure 2 shows the optics design of a 1.2 MV ion gun for a miniature beamlet with 100 mA/cm2 at the source aperture.

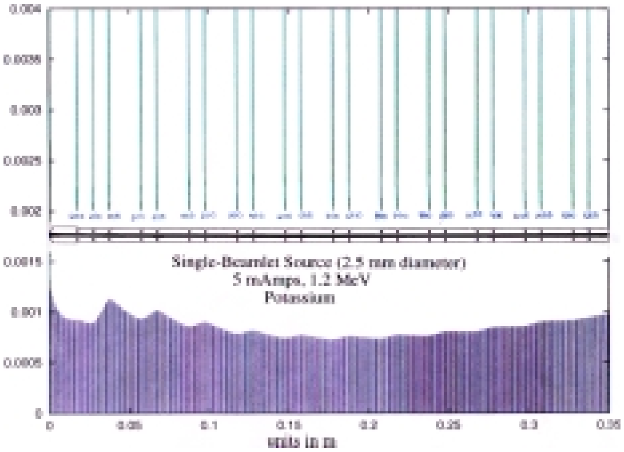

Figure 2: Ion gun design for a 1.2 MeV, 5 mA potassium beamlet.

The aperture diameter was limited to • 2.5 mm by the focusing capability of the Einzel lens system at the high-energy end. Thus each miniature beamlet carries 5 mA of K and a cluster of 100 beamlets is needed to produce a 0.5 A beam. Figure 3 is a schematic diagram of the multiple-aperture ion source. The most critical issue in this high current density approach is the emittance growth due to beam merging. Our design incorporates 3 features to minimize the emittance growth: (1) use a large number of beamlets (• 100); (2) let the beamlet merging takes place at energy • 1.2 MeV; (3) geometrically aim the beamlets inward to produce a strong focussing effect and to minimize the length of the merging region.

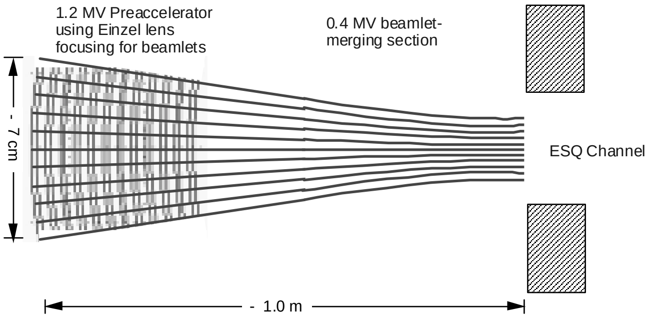

Figure 3: Schematic diagram of the multiple-beamlet system with a merging/matching section.

Figure 4 shows the emittance growth and how it reaches equilibrium in about 10 m after entering the ESQ channel in the linac. In the simulation, the 100 beamlets have a total current of 0.5 A and occupy 7% of the grid area. The final beam emittance is 0.85 •-mm-mrad if each beamlet has an initial emittance of 0.005 •-mm-mrad. When the initial beamlet emittance is raised to 0.01 •-mm-mrad and 0.02 •-mm-mrad, the final emittance only increases to 1.0 •-mm-mrad and 1.2 •-mm-mrad respectively. This effect simply means that emittance growth is dominated by the space charge effect in the merging process and is not very sensitive to the initial ion temperature.

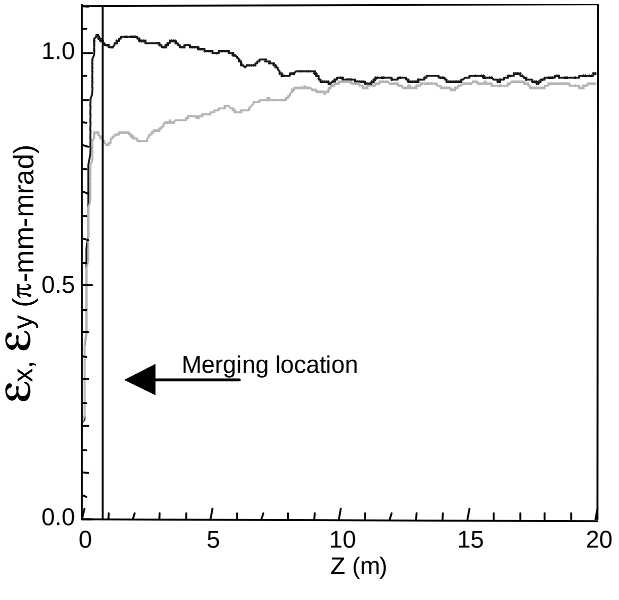

Figure 4: Emittance growth due to beamlet merging and matching.

This design has not been optimized yet because we have not determined whether the 7% beam occupancy or the number of beamlets (100) are the optimum. According to theory [2], the emittance growth is less if these parameters are larger.

3 MULTIPLE-BEAM INJECTORS

The injector system contains the ion source and the matching section. The ion source accelerates a beam to a suitable energy before injecting it into the electrostatic quadrupole (ESQ) matching section.

A HIF driver requires a total beam charge • 1 mC at the target. For beam pulses of • 20 µs at the ion source, and current per beam of • 0.5 A, the muliple-beam injector needs to deliver an array of N • 100 parallel ion beams. A typical example is to consider an array of 84 beams arranged in a 10x10 matrix (with 4 channels removed from each corner).

The multiple-beam matching section has two functions: it transforms each round beam (from the ion source) into an elliptical shaped one (in an ESQ channel) and it steers the beam centroids to match the source array to the ESQ array in the induction linac.

3.1 Injector using Single-Aperture Ion Sources

A preliminary 84-beam injector design based on this low current density option (single-aperture source) has been reported elsewhere [3]. Beam envelopes in the matching section are shown in Figure 5. Figure 6 is a schematic diagram of the outermost beamline in the 84-beam array. Note that the beamline is not straight because at the end of the injector all beamlines are parallel to the axis. Beam steering is done by dipole fields produced by specially shaped (non-circular) ESQ electrodes. The overall dimension of the array is about 6.0 m long, 3.0 m in diameter at the ion source end and 1.0 m diameter at the exit end; it has the shape of a funnel.

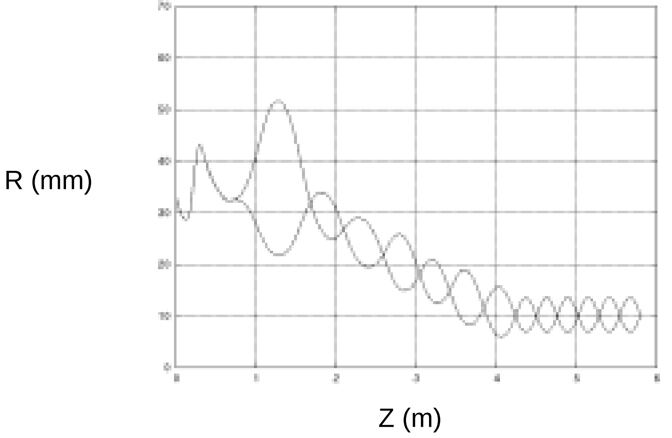

Figure 5: Beam envelopes in the ESQ matching section.

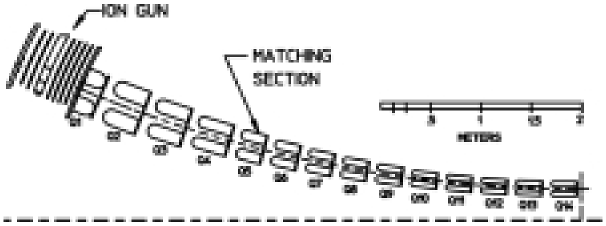

Figure 6: Schematic diagram of the outermost beamline in the matching section.

An alternate matching section design was proposed to steer the beams slowly using a small offset between each ESQ lattice [4]. In this case, the ESQ electrodes are simple parallel round rods. This system has less beam optical aberrations, however the matching section has become 14 m long.

3.2 Injector using Multiple-Aperture Ion Sources

With independent control of individual beamlets, we can produce an elliptical beam spot (as oppose to a circular one) at the entrance of the ESQ channel, thus performing beam merging and envelope matching simultaneously. This special "asymmetric focusing" scheme greatly simplifies the matching condition downstream and it nearly eliminates the conventional matching section. Since the ion source array and the ESQ channel array are matched, the multiple-beam injector will have the same radial size throughout. All the beamlines in the array will be identical and parallel to the axis so no bending is required. For an 84-beam injector, the dimensions of the array (including a matching section but not including the ion source) is approximately 1 m diameter by 1 m long. The result is a dramatic reduction in the size and cost of the injector [5].

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