Title

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HEAVY ION FUSION SOURCES*

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Abstract

In Heavy-Fusion and in other applications, there is a need for high brightness sources with both high current and low emittance. The traditional design with a single monolithic source, while very successful, has significant constraints on it when going to higher currents. With the Child-Langmuir current-density limit, geometric aberration limits, and voltage breakdown limits, the area of the source becomes a high power of the current, A~I^8/3. We are examining a multi-beamlet source, avoiding the constraints by having many beamlets each with low current and small area. The beamlets are created and initially accelerated separately and then merged to form a single beam. This design offers a number of potential advantages over a monolithic source, such as a smaller transverse footprint, more control over the shaping and aiming of the beam, and more flexibility in the choice of ion sources. A potential drawback, however, is the emittance that results from the merging of the beamlets. We have designed injectors using simulation that have acceptably low emittance and are beginning to examine them experimentally.

MULTIBEAMLET INJECTOR

A requirement of heavy ion fusion (HIF) is a source the produces a beam with high brightness --- having both high current and low emittance. Traditionally in the HIF program, the sources that have been used are monolithic, solid, hot plate sources. While these have performed quite successfully over the years, they do have limitations. They have poor scaling when going to higher currents and have limited lifetimes before the ions are depleted. Going to multiple beamlets circumvents the scaling problem at high current and allows use of a plasma source which does not have the problem of ion depletion. The multibeamlet injector concept has been extensively studied, with a focus on understanding and minimizing the emittance growth[1]. As part of that work, a procedure for designing a multibeamlet injector was laid out and several examples given. In this paper, that work is extended, using an improved layout of the beamlets and further examining some details.

HIGH CURRENT SCALING

When going to higher currents, the single beam injectors do not scale well. Taking into consideration the space-charge limited current density given by the Child-Langmuir relation, voltage breakdown limits, and limits on the geometry to minimize aberrations, the source radius varies as a high power of the current and the current density varies inversely with the current[1]. The poor scaling can be circumvented by using multiple beamlets --- each beamlet has a low current and avoids the poor scaling. Fixing the total area of the source (the sum of the area of the beamlets), the current density becomes proportional to the total current. The inherent emittance of an injected beam from the temperature of the emitter varies as the square root of the product of the temperature and the beam area. Since the total area of the beamlet source can be much smaller than the area of a single source, the temperature of the emitter can be higher for a multibeamlet injector. This allows use of plasma type sources, which have higher operating temperatures than solid sources.

INJECTOR DESIGN

The design of the injector consists of a pre-accelerator column where the beamlets are accelerated independently, followed by a merging region where the beamlets are merged and further accelerated. The pre-accelerator column consists of a diode followed by a series of apertures plates. The plates act both to accelerate the beamlets with a net voltage drop along the column, and to focus it transversely via a series Einzel lenses. The plates also isolate the beamlets from each other, shielding them from the space-charge fields of their neighbors.

When the beamlets leave the last plate, they begin to interact and merge. A conservation of energy argument can be made, which leads to the conversion to emittance of the "extra" space-charge energy of the beamlet configuration, as compared to a uniform beam. This gives the result that the higher the energy at which the beamlets are merged, the lower the emittance. This must be balanced however with other limits, such as the decreasing focusing strength of the Einzel lenses at higher energies. In the merging region, further acceleration of the beam can be done to bring it up to the required energy for the transport lattice.

One important feature of the multibeamlet injector is that the beamlets can be aimed so that the merged beamlet is exactly matched to the transport lattice as it enters it. This removes the need of a separate matching section. Flexibility is gained by allowing the first quadrupole of the lattice to be of partial length. The merged beam can then be matched to any part of the beam envelope in the lattice.

The system must be designed as a whole. The two fundamental parameters are the number of beamlets and the energy at which they merge. Given constraints on the design, such as material strength of the aperture plates

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(How close can the holes be to each other?) and construction errors, and the desire to minimize the emittance of the merged beam, the rest of the design falls into place.

APERTURE PLATE DESIGN

The shape of the aperture plates is critical to having the beamlets propagate through the pre-accelerator column to the merging region. It is desirable, for robustness, to the the beamlets propagate in a straight line through the column. For this to happen, since the plates supply an accelerating field, the path of the beamlets must be normal to the surface of the plates. The convergence angles of the individual beamlets is set to increase linearly relative to the transverse position. This is to match the linear variation of the transverse velocity relative to transverse position for particles propagating in an alternating gradient focusing lattice.

The beamlets are aimed to match into the elliptical beam of an alternating gradient focusing lattice. Therefore, the focal points in the two transverse planes are not the same --- the focus is astigmatic. The convergence angles of the beamlets, x' and y', can be written

$$x' = xa'/a$$

$$y' = yb'/b$$

where x and y are the transverse location of the beamlets at some z longitudinal location where the size and convergence of the out edge of the beamlets is given by a, b, a', and b'. No surface has been found which exactly meets these requirement. However, an approximate surface can be constructed.

Given the linear variation of the beamlet convergence angle, in order for the beamlet path to be normal to the surface, the intersection of the surface with any z-x or z-y plane must be circular. Furthermore, the circles in all of the z-x planes must be concentric with each other, and likewise for the z-y plane. The centers of the circles in the z-x and z-y planes will be different. This leads to a method of construction of the surface whereby the intersection with the z-x plane at y=0 is fixed, and then for each point in that circle, a circle is generated in the z-y plane that the point lies in. Similarly the intersection can be fixed in a z-y plane. This method produces surfaces described by the following equations, depending on which plane the intersection is fixed.

$$(z - z_b)^2 = \left[z_a - z_b - \sqrt{(z_0 - z_a)^2 - x^2} \right]^2 - y^2$$

$$(z - z_a)^2 = \left[z_b - z_a - \sqrt{(z_0 - z_b)^2 - y^2} \right]^2 - x^2$$

The z_a and z_b are the center of the circles in the x and y planes respectively, and z_0 is the location of the surface where it intersects the axis, x=y=0. Neither of these surfaces are exactly normal to the beamlet path. However, given the design parameters, where z_a and z_b are much greater than the transverse positions, the error is small. Given a transverse size of the order of 5 cm and radii of order 1 m, the error (as measured by the differences in the two surfaces) is of the order of several microns, less than typical machining tolerances. To make the errors symmetric, the actual surface used is the average of the two surfaces.

OPTIMAL BEAMLET ARRANGEMENT

In order to minimize the emittance of the merged beam, the beamlets must be packed as close to each other as possible. Hexagonal dense pack should be ideal. In the previous study[1], an arrangement similar to close pack was used, where the beamlets were laid out on ellipses instead of hexagons, that had the advantage of having a smooth edge. It was thought that having the smooth edge was more important than a slightly denser pack. It has since been determined that a dense pack is optimal, producing the lowest emittance, even with a more ragged beam edge. The beamlets are packed with uniform spacing and only those within a proscribed ellipse are used. In some cases, removing beamlets on the outermost corners can further reduce the emittance. See Figure 1 for an example layout.

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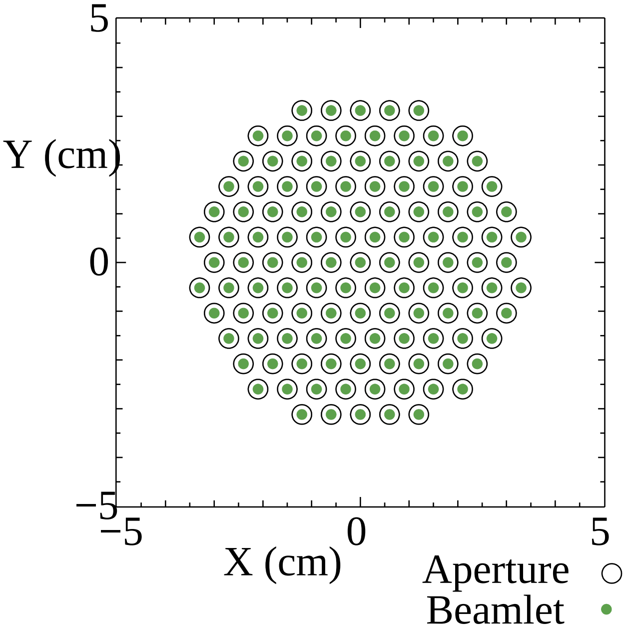

Figure 1: Example arrangement of beamlets with hexagonal packing and outermost corners removed.

Another issue effecting the merged emittance is the ellipticity of the arrangement. With an elliptical arrangement of beamlets, the emittances of the merged beam in the two transverse planes are significantly different. The emittance in the plane of the major radius of the ellipse is greater. After propagating some distance ,however, the emittances equilibrate. There is a concern, though, that the initially different emittances could potentially lead to halo or other other problems. Therefore, a circular arrangement of beamlets was adopted. The resulting emittances where significantly less different, though still not the same since the convergence angles of the beamlets in the two planes still differ. In this case, the length of the first quadrupole of the lattice was varied in order to get an exact match. Typically the length is just over half the normal length. See Figure 2 which shows the envelopes for an example case.

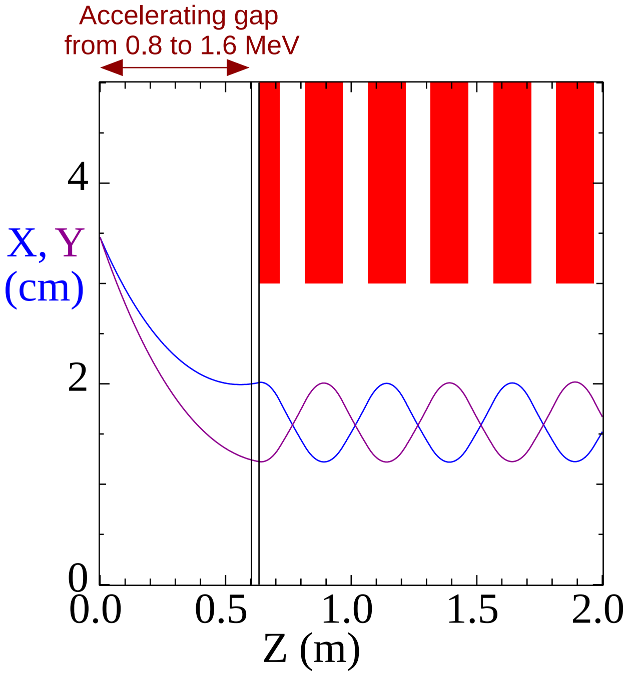

Figure 2: Envelopes for an example case, starting with a round arrangement of beamlets for the merge.

OPTIMIZED DESIGNS

Table 1: Parameters of optimized pre-accelerator columns

Beamlet Spacing (mm)	# Beamlets	Merge Energy (MeV)	Normalized Emittance (π-mm-mrad)
6	121	1.2	0.80
		0.8	0.86
	199	1.2	0.70
		0.8	0.76
5	121	1.2	0.60
		0.8	0.62
	199	1.2	0.51
		0.8	0.55

Using the hexagonal packing and an overall circular extent, optimized designs were created for differing number of beamlets, and values of merging energy and beamlet separation. Table 1 gives the resulting emittances obtained. An approximately 20% reduction in emittance was found by switching to hexagonal packing, a small but not insignificant difference. Going to a more tightly packed arrangement with less material between the apertures could potentially lead to further improves. The caveats though are that the plates may not be stable enough, the smaller aperture separation leads to sharper corners which may reduce the voltage holding, and the plates supply less shielding so the beamlets will interact more before exiting the column.

A further refinement of the design is spreading out evenly the pre-accelerator column plates. This should simplify construction and alignment. This leads to somewhat less flexibility in optimizing the beamlet focusing resulting in a small increase in emittance. The increase is of the order of a few percent. Figure 3 shows the beamlet envelope in the pre-accelerator column for the case with 121 beamlets, merging at 0.8 MeV and with 5 mm between beamlets.

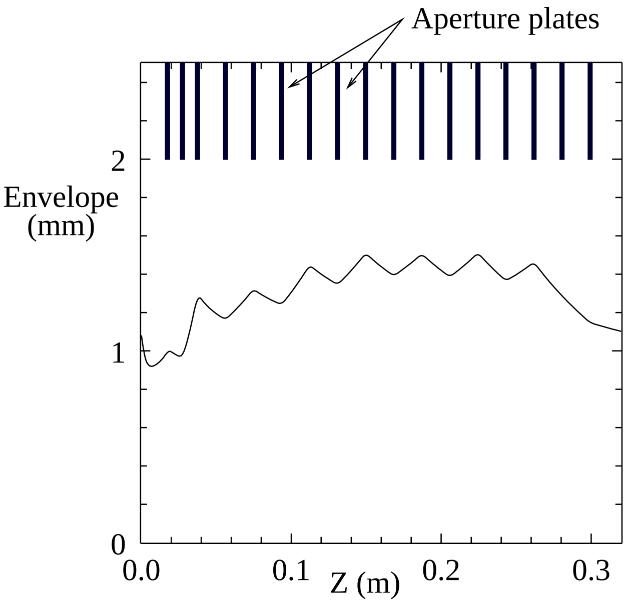

Figure 3: The beamlet envelope in the pre-accelerator column for the optimized case with 121 beamlets, merging at 0.8 MeV and with 5 mm between beamlets.

CONCLUSIONS

The single beam sources that have traditionally been used for heavy-ion fusion experiments and driver design have proven successful but have limitations, such as poor scaling in the source size at higher currents. To circumvent the poor scaling, many small beamlets are used and are merged. Designs of merging multi-beamlet injectors have been done that meet the requirements for example transport lattice, including a low emittance. The next step is experimental validation, which is in progress.

REFERENCES

[1] D. P. Grote, Enrique Henestroza, and Joe W. Kwan, Phys Rev ST AB, January 8, 2003.