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Developing High Brightness and High Current Beams for HIF Injectors

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Developing High Brightness and High Current Beams for HIF Injectors*

Abstract

The US Heavy Ion Fusion Virtual National Laboratory is continuing research into ion sources and injectors that simultaneously provide high current (0.5-1.0 Amps) and high brightness (normalized emittance better than 1.0 π-mm-mr). The central issue of focus is whether to continue pursuing the traditional approach of large surface ionization sources or to adopt a multi-aperture approach that transports many smaller "beamlets" separately at low energies before allowing them to merge. For the large surface source concept, the recent commissioning of the 2-MeV injector for the High Current eXperiment has increased our understanding of the beam quality limitations for these sources. We have also improved our techniques for fabricating large diameter aluminosilicate sources to improve lifetime and emission uniformity. For the multi-aperture approach, we are continuing to study the feasibility of small surface sources and a RF induced plasma source in preparation for beamlet merging experiments, while continuing to run computer simulations for better understanding of this alternate concept. Experiments into both architectures will be performed on a newly commissioned ion source test stand at LLNL called STS-500. This stand test provides a platform for testing a variety of ion sources and accelerating structures with 500 kV, 17-microsecond pulses. Recent progress in these areas will be discussed as well as plans for future experiments.

Keywords: Heavy Ion Fusion, Ion Sources, Injectors, Accelerators

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Introduction

The D-T target of a heavy ion inertial fusion (HIF) power plant requires around 5 MJ of beam energy delivered in a time window of tens of nanoseconds for ignition [1]. This, together with the desire to have the ion stop in the target to maximize efficiency, demands the source injector of the a HIF driver deliver approximately 1 mC of total charge. Beam transport and bunch length compression in the accelerator dictate this amount of charge must be delivered in multiple beams. And given cost considerations of induction linacs, it is desirable to have the beams as closely backed together as possible [2]. In many point designs the input to the linac optimizes with approximately 100, 0.5 Amp beams that are 20-μs long with ion energy of 2 MeV. The radius of each beam is 1 cm, and the beams are spaced apart by 7-10 cm [3]. It is this configuration of beams that the source injector must deliver.

In addition to the total power requirement of the target, the possible energy gain of a target increases with decreasing delivered beam spot. Since the spot size on target is directly related to the beam emittance, the phase space occupied by the beam, emittance or brightness is an important figure of merit for the accelerator and the injector. Brightness is proportional to I/ε_{-}^{2}, where I is the current and ε is the emittance. In the source injector it can also be thought of as proportional to J/T, where J is the current density and T is the ion temperature. So high brightness can be achieved by either low temperature or high current density sources. While a lower emittance is always better, a four times RMS normalized emittance of 1.0 π-mm-mr per beam exiting the injector is thought to be adequate. The maximizing of beam brightness while meeting the total current criteria and configuration of the accelerator, has been the effort of focus for the Source Injector task area of the United States Heavy Ion Fusion Virtual National Laboratory (HIF-VNL) [4].

Single Aperture Per Beam

Achieving high brightness with low ion temperature is the method of using a single source aperture for each of the 100 beams of a driver. Making the assumption of a single aperture and applying the Child-Langmuir equation for space charge limited emission reveals the necessity for large voltage ($I \sim V^{3/2}$) to achieve high current, typically around 500 kV for 0.5 Amps. But voltage breakdown scaling ($V \sim d^{1/2}$) for large gaps results in falling current density ($J \sim V^{3/2}/d^2$) as the voltage rises. Thus, the ion temperature must be low (~0.5 eV) to achieve the necessary brightness, and the emitter surface must also be large, ~ 10 cm diameter, to achieve the total current. In addition, a pierce electrode must surround the emitter in order minimize beam aberrations due to bad source gun optics. Thus, the beam-to-beam spacing must be at least 25-30 cm. This is about 3 times larger than the input of the accelerator and necessitates a long, complicated matching section that focuses the beams to a smaller size and funnels them together [5].

The only know ion sources that can achieve such a low ion temperature are the surface ionization sources. These sources work by applying a layer of alkali metal atoms on a low work function substrate, usually tungsten. The tungsten and is heated up to above 1000°C and absorption chemistry of the alkali metal on the tungsten substrate, results in a layer of ions just off the surface of the tungsten. These ions are extracted when high voltage is applied. In addition to the advantage of the low ion temperature, surface sources also have the advantage of a fixed emitter surface. Unfortunately, these sources run at high temperatures, which create heat load issues, and work only with alkali metals, which can create contamination problems after extended use.

Our understanding of issues related to the single aperture concept has improved with the retrofit of the ELISE/ILSE 2 MeV injector [6] for the High Current eXperiment (HCX) [7,8]. The beam from the 2-MeV injector had persistently shown an outer rim as shown by the beam profile in figure 1. Intensive simulation and experimental effort indicated that poor beam optics in the source gun triode was the cause. After shrinking the size of the emitter, thus lowering the current, and redesigning the electrodes in the source gun, the simulations showed the disappearance of the outer rim, which was demonstrated in the experimental beam profile, as shown in figure 2. The program has also significantly improved its process for making aluminosilicate surface ionization sources. The technique coats a tungsten plug with aluminosilicate doped with an alkali metal, which is then sintered on to the tungsten. Previously the uniformity of the sintered surface, which effects uniformity of ion emission, was poor and inconsistent. Now a uniform aluminosilicate surface can consistently be produced. HCX is currently using one of these new sources.

With HCX taking over operations of the 2-MeV injector, the program would be left without a high voltage platform to test new sources and injector concepts except for the commissioning of a new 500 kV ion source test stand, STS-500, at LLNL [9]. Figure 3 is a picture of the test stand. A high voltage platform sits above an insulator column, which grades the 17-μs, 500 kV pulse down to ground through a water resistor. A pulse-forming network whose output is connected to a step-up pulse transformer generates the pulse. A diagnostic tank sits below the column. Sources are mounted from the top and extend downward into the column with beams emitted downward into the diagnostic tank. The high voltage platform and column are exposed air to facilitate changing the source or accelerating structures inside the column. The first source test on STS-500 will be a detailed characterization of emission uniformity for the aluminosilicate sources coated with the new technique mentioned above. There will also be experiments developing a pepper pot diagnostic for these high current heavy ion beams.

After these experiments are completed, the source will be used to study beam aperturing of high current ion beams. Aperturing can be a way to improve beam brightness since the edge of the beam is usually the part that is affected by aberrations that increase emittance. By removing this outside edge, the beam current will be reduced, but the emittance may be reduced more, so that the total brightness increases. Unfortunately, aperturing high current beams can be problematic because the beam potential (~5kV) can trap the many electrons produced by ions impacting surfaces. The electrons can degrade the beam quality and even source performance if allowed to back stream all the way to the source. There has been some success with aperturing if an electron trap is used to stop electrons. The proposed experiments would look in detail at understanding under what conditions is an electron trap necessary and what type of electron traps can be used to maintain beam quality.

Multiple Apertures Per Beam Concept

Recently, the source injector program has recently begun to study a different concept, based on the neutral beam work of the magnetic fusion energy community [10]. The idea is to have many small apertures, around 100, to create ~ 5 mA "beamlets" which are accelerated up to ~ 1 MeV before the beamlets are allowed to merge and create one of the hundred 500 mA beams. Figure 4 shows a schematic of this design for a single beam. The beamlets are extracted and accelerated through a series of plates with matching hole patterns, or grid plates, and then merged together during the last section of acceleration. Since the merging of the beamlets causes emittance growth, a bright beam can only be achieved if the current density of the beamlets is high. Given a high enough current density and a reasonable transparency for the aperture grid, the beam spacing that can be achieved at the source is comparable to the spacing of the beams at the accelerator. Further, the beamlet merging section of the injector could also serve as the matching section, if an elliptical pattern of beamlets is used and the beamlets are aimed together with the appropriate convergence angles. Thus, a source injector using this concept has the potential to be much smaller and less complex than the large source concept.

Simulation efforts in to this concept have focused on developing a qualitative understanding of design rules and establishing a self-consistent point design. The starting point is to understand how to minimize the emittance growth of the merging process. The emittance growth is directly related to the empty phase space between the beamlets being entrained into the merged beam. This empty phase space can be reduced by having the beamlets converge together in the merging region and by maximizing the transparency of the grid plates. Maximizing transparency implies many small holes of beamlets closely packed. Given engineering constraints for making closely spaced holes in thin plates and alignment tolerances, 4 mm diameter holes with 6 mm spacing is a practical design. A hexagonal close pack array with six rings of beamlets for a total of 91 was chosen as a starting point. 91 beamlets was chosen to lower the current per beamlet to allow transport up to 1.2 MeV, the initially chosen merging energy. An Einzel lens lattice, as shown in figure 5, achieves this transport. After initial extraction, the lattice decelerates the beamlet by 100 kV and then accelerates the beamlet by 200 kV, which results in a transverse focusing force, as can been seen from the simulation result in figure 5. The extracted current density from the source is 100 mA/cm^2 and the total beam current is 5 mA.

The specifics of the merging section are constrained by the beam parameters required by the accelerator, 1.6 MeV in energy and an average radius of 1.6 cm, and the beam energy at the beginning of the merging section. In addition, the desire to have the merging section serve as a matching section requires the beamlet packing structure be made elliptical by increasing the spacing in one transverse direction. Then by choosing the converging angles in the merging section appropriately, the parameters of the merged beam at the end of the injector will correspond to the beam parameters in the accelerator at the midpoint of the quadrupoles. Figure 6, which is a simulation of the beam envelope in the merging section and the first few quadrupoles, demonstrates how this matching is achieved with only the addition of a half quadrupole. To achieve those convergence angles, several methods of steering or focusing the beamlets was explored but presently the only practical way of achieving the desired angles is by aiming the beamlets from the source. Thus, the spacing between beamlets is at its smallest at the end of the Einzel lens lattices and largest at the source.

Figure 7 is a plot of the emittance of the merging beam and the first few quadrupoles of transport. Notice that both the x and y emittance stabilize at around 1 π-mm-mr, which is comparable to what can be achieved by the single large source architecture. Further simulations revealed a dependence on the envelope angle of the beamlets as they enter the merging region. These studies indicated a minimum in final beam emittance is achieved when the beamlet transport section provides beamlets with an envelope angle of –3 mr. The Einzel lens simulation shown in figure 5 does not provide this envelope angle, but by optimizing the voltages and positions of the plates, it is possible to achieve the appropriate angle. Simulations were also done exploring the effect of varying the number, the size, and the current of the beamlets. The only significant reduction in emittance is seen when the clearance between the beamlet envelope and the edge of the holes in the plates is reduced. Reducing this clearance will require a more stringent alignment tolerance, which will require a considerable engineering effort to achieve.

Figure 8 shows a plot of the merged beam emittance as a function of ion source temperature. This plot clearly shows little dependence with temperature and implies this source injector architecture is no longer limited to using surface sources, which cannot provide the high current densities. The leading source option is a RF induced gas plasma source. These sources can provide over 200 mA/cm^2 for a variety of gases [11], though HIF would be most interested in noble gases. These sources create plasma in a chamber at a few millitorr of pressure by the application of an RF field from an antenna. Typically a few kilowatts of RF power are needed. In this architecture there would be a single source for each beam, but the aperture plate of the source would be a grid of holes to form the beamlets.

One of the most critical issues for these sources is charge exchange in the extraction gap from neutrals leaking from the plasma chamber. If charge exchange occurs, ions of different energies will be produced and degrade the beam quality. The effect is hard to simulate and will depend on the operating pressure of the source. Therefore experiments on a 100 kV test stand are presently being conducted to understand the magnitude of this effect. The experiments have started by exploring the tradeoff between pressure, RF power, and extracted current density since the same current density can often be achieved at a lower pressure by increasing the RF power. The plan would then be to measure charge exchange by running the beamlet through a dipole field used as a spectrometer. In the years to come, experiments on STS-500 will be performed to understand the beamlet transport and merging process of this concept. There would be a scaled beamlet experiment in which the current density would be reduced so that the full system could be modeled at 500 kV instead of 1.6 MeV. There would also be a full-scale test of the first 500 kV of the beamlet transport system. If these tests are successful, then the HIF-VNL would be in a position to build a full scale system.

Summary

The US HIF-VNL is pursuing two different source injector concepts to try and meet the challenge of a source injector for heavy ion fusion. The approach that has been explored in the past would use a single aperture for each of the 100 beams of the injector. The criterion of high brightness forces the use of surface ionization sources for this approach and leads to a large and complex source injectors and matching section. A new concept that has only recently been pursued would use multiple apertures to create many beamlets for each beam. These beamlets would be transported and accelerated separately up to 1 MeV before being allowed to merge. This approach promises a great reduction in size and complexity of the source injector. The leading source option for this approach is a gas plasma source, which provides the necessary current density. Experiments for both approaches will be conducted on a newly commissioned 500 kV ion source test stand. Based on the results of these experiments, the architecture of the source injector for future machines in the HIF-VNL research plan will be determined.

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Captions

Figure 1: Vertical profile measurement of ILSE beam at end of ESQ injector. The profile is for one time slice during the middle of the beam. The y-axis units are arbitrary.

Figure 2: Vertical profile measurement of HCX beam at end of ESQ injector after modifications to source geometry. The y-axis units are arbitrary.

Figure 3: Picture of STS-500, a newly commissioned 500 kV ion source test stand.

Figure 4: Schematic diagram of multiple aperture source injector to produce one 500-mA beam.

Figure 5: EGUN simulation of a single beamlet though an Einzel lens transport lattice.

Figure 6: Simulation of the beam envelope in the merging section of the multiple aperture injector and the first few quadrupoles of the accelerator.

Figure 7: Plot of x and y normalized emittance as a function path length through the merging section and the beginning of the accelerator.

Figure 8: Plot of normalized emittance as a function of ion temperature of the source.

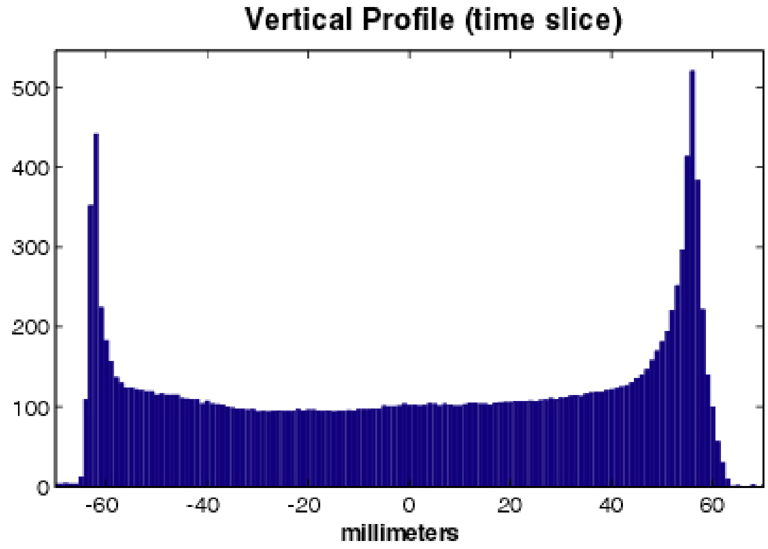

Vertical Profile (time slice)
500
400
300
200
100
0
-60
-40
-20
0
20
40
60
millimeters

Figure 1

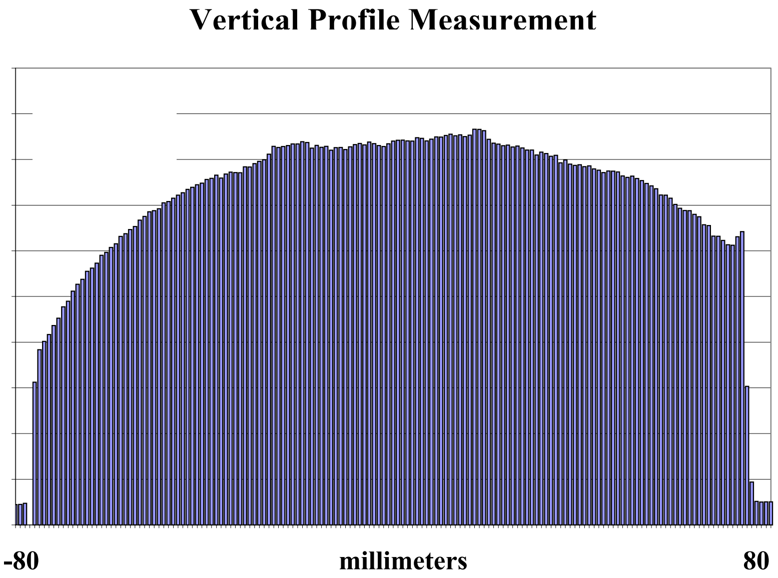


Figure 2

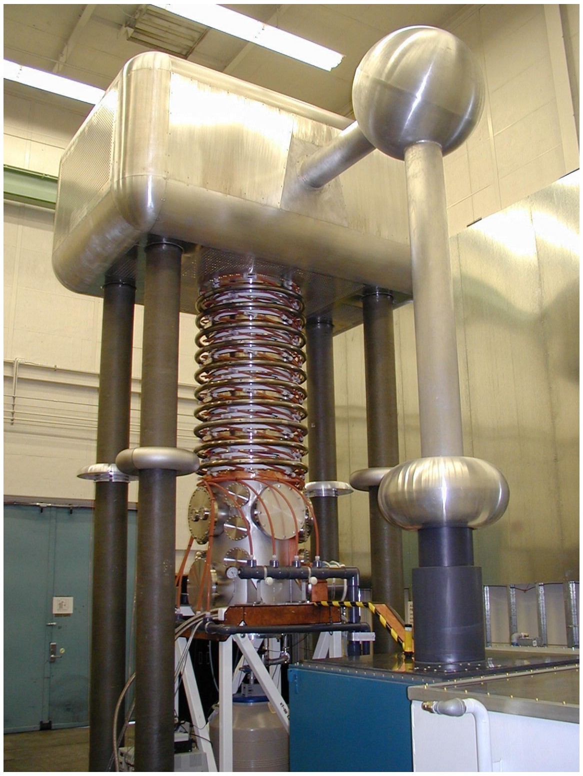


Figure 3

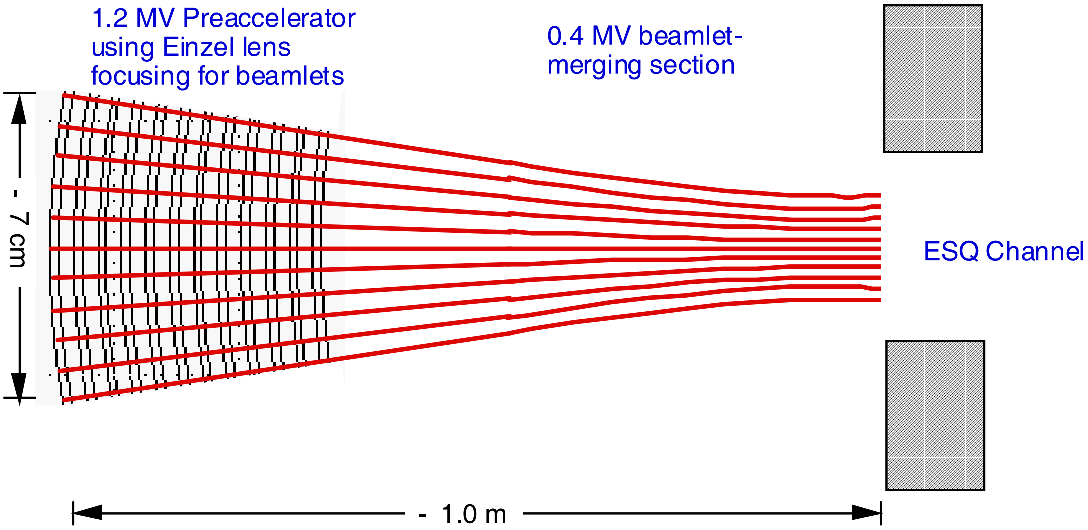

1.2 MV Preaccelerator
using Einzel lens
focusing for beamlets
0.4 MV beamlet-
merging section
ESQ Channel
- 7 cm
- 1.0 m

Figure 4

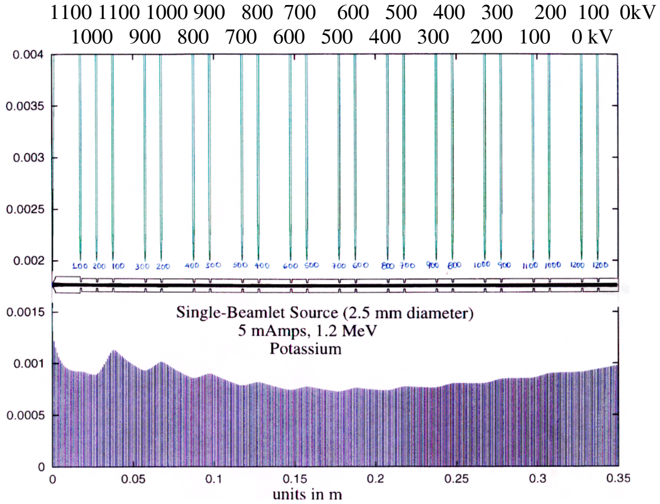

1100 1100 1000 900 800 700 600 500 400 300 200 100 0kV
1000 900 800 700 600 500 400 300 200 100 0 kV
100 200 100 300 200 400 300 500 400 600 500 700 600 800 700 900 800 1000 900 1100 1000 1200 1200
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Single-Beamlet Source (2.5 mm diameter)
5 mAmps, 1.2 MeV
Potassium
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
units in m

Figure 5

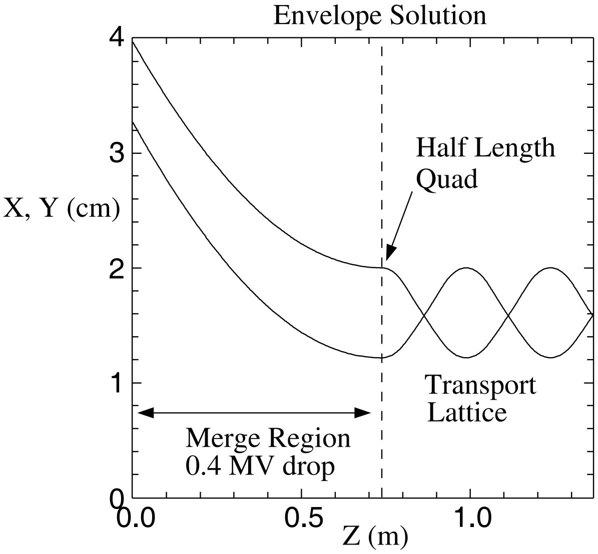

Envelope Solution
4
3
2
1
0
X, Y (cm)
Half Length
Quad
Transport
Lattice
Merge Region
0.4 MV drop
0.0
0.5
1.0
Z (m)

Figure 6

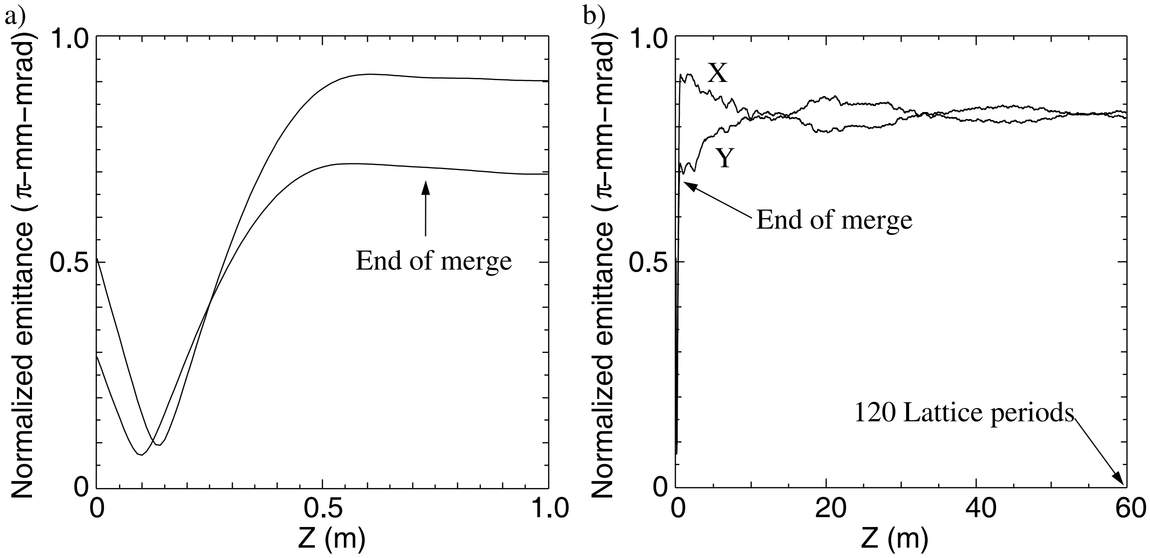
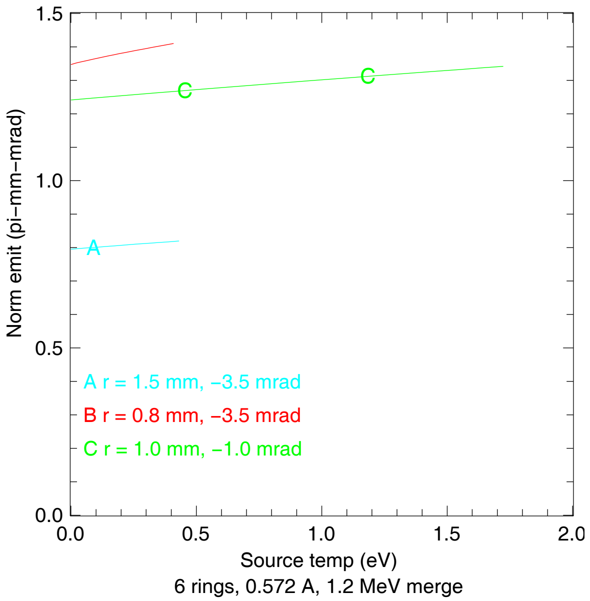

a)
b)
Normalized emittance (π–mm–mrad)
1.0
0.5
0
Z (m)
End of merge
X
Y
120 Lattice periods
20
40
60

Figure 7



1.5
1.0
0.5
0.0
Norm emit (pi-mm-mrad)
0.0
0.5
1.0
1.5
2.0
Source temp (eV)
6 rings, 0.572 A, 1.2 MeV merge
A
C
C
A r = 1.5 mm, −3.5 mrad
B r = 0.8 mm, −3.5 mrad
C r = 1.0 mm, −1.0 mrad

Figure 8