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Characterization of the Plasma-Switch Interaction in the LBL HIF Ion Source

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Abstract

A new way to characterize the performance of the LBL HIF ion source has been found. In the LBL source, ions are drawn from an arc-generated plasma reservoir in which the electrons are confined by a negative-biased "switch" mesh. Stagnation of the plasma is prevented by absorption of the excess ion flow on this mesh. The ion beam is generated by an external negative voltage that provides Child-Langmuir extraction of the ions through the switch mesh. We elucidate the physics requirements of the source and deduce switch mesh parameters needed for successful operation.

I. Introduction

Proposed accelerators for Heavy Ion inertial confinement Fusion (HIF) have stringent requirements on ion beam quality so that the necessary energy can be focused on the target with the needed precision. A crucial beam parameter, the normalized emittance ϵ_n, can only increase in the HIF scheme using induction accelerators and thus can be no smaller than the level delivered by the ion source. The ion source emerges as a critical part of the entire system; it must meet several demands. It must provide a source of low temperature ions of the desired mass with the proper charge state. The source must prevent these ions from entering the accelerator until the desired beginning of the beam pulse and, thereafter, supply enough ions to fill a constant flux beam pulse until the end of that pulse. Finally, ϵ_n should be as small as possible; the goal is $\epsilon_n \leq 5 \times 10^{-7}\pi$ m rad.

Though these requirements can be met using metals with a +1 valence coating a hot plate, sources based on this technology do not offer much flexibility in mass or charge state and they tend to "plate out" on surfaces in the low energy end of the accelerator. An arc source alternative has been pursued at LBL[1] in an effort to provide more flexibility in ion mass by eliminating the +1 valence constraint. The arc-generated plasma easily satisfies the ion flux requirements but encounters difficulties in achieving the required low level of emittance. Normalized emittance ϵ_n can be expressed as

$$\epsilon_n = \pi\beta\gamma r \frac{\partial r}{\partial z}$$

where β and γ are the usual relativistic factors and $r(z)$ is the radial(axial) coordinate of the beam. This expression can be rewritten as

$$\epsilon_n = \pi\gamma r \frac{v_\perp}{c}$$

where $v_\perp/c$ is the perpendicular velocity divided by the speed of light. γ is taken to be unity in that the beam energy leaving the source will be of order 1-2 MeV. Basically there are two ways to control or reduce ϵ_n: 1) reduce r and still provide the necessary current or 2) reduce $v_\perp$. Option 1) will cause the space charge density to increase and that would cause increased focusing difficulties. Thus we have reconsidered the origin of the $v_\perp$ and are discovering ways to reduce it.

We have found the predominate source of ion $v_\perp$ is not the intrinsic temperature of the arc but rather the ion interaction with the "switch" mesh. To understand this interaction we must first consider what function the switch mesh is expected to perform. The electrons must be confined by the switch mesh, as means of confining the plasma. A small negative voltage will confine electrons and absorb or localize ions near this mesh until the extraction voltage is turned on. If the electrons remain confined near the switch mesh even after the extraction voltage is turned on, then an ion space-charge-limited flow from the switch mesh to the extractor electrode will provide constant ion current and further isolate the beam from the fluctuations inherent in the arc source. These functions place the switch mesh in a very harsh environment. We are asking a closely-spaced, thin-wire, switch mesh to robustly survive in a plasma arc. To determine technical feasibility, we carefully look at how closely-spaced and thin the mesh must actually be for realistic ion source parameters.

We rely on sheaths around the switch mesh to provide electron confinement. Debye sheaths form around objects in plasmas due to the greater electron mobility. Excess electrons charge these objects to

$$\phi \sim \frac{kT_e}{q_e}.$$

If object is held at an even lower voltage, electrons are forced further back and ions are absorbed. To solve for the ϕ profile, a nonlinear Poisson's equation must be solved. The electron density in this equation is represented well by a Boltzmann factor

$$n_e = n_0 \exp\left(\frac{-q_e(\phi - \phi_0)}{kT_e}\right)$$

but thermal ion distribution requires a more elaborate treatment to get n_i. Analysis by Forrester[2] leads to a quantitative understanding of the electron standoff distance. Using a numerical solution of the nonlinear Poisson equation with thermal ions, we find the number of Debye lengths λ_D that electrons are repelled by a specified voltage can be determined from the following graph.

For typical parameters, $\phi_{sw} = -90$ V and $T_e = 7$ eV, electrons are repelled $\sim 8\lambda_D$, where $\lambda_D = 743\sqrt{T_{eV}/n}$, where T_{eV} is the electron temperature and n is the plasma feed density. For minimal confinement, we must have the interwire spacing S_{iw} less than twice the distance the electrons are repelled. To insure electron confinement even during the extraction phase we prefer $S_{iw} \lesssim 8\lambda_D$. For fixed λ_D, the more closely spaced the mesh, the higher the density that can be confined. For the parameters given above and $S_{iw} = .0035$ inches (.005 center to center),

$$n \lesssim 3.13 \times 10^{12} \text{cm}^{-3}.$$

We can now begin to assemble some constraints on the operation of the ion source configuration. Looking at the parameter space defined by the arc plasma feed density n and the feed flow velocity u in Figure 2, we first define an obvious constraint: below the diagonal line defined by the product nu, the arc is not providing sufficient plasma flux to satisfy the ion beam requirement during the extraction phase. The electron confinement constraint is depicted by the horizontal line. A given S_{iw} along with an given T_{eV} impose a maximum arc feed density n that can be confined by of the switch mesh. The more closely spaced the mesh the more density that can be confined.

The constraint that bounds the operation region on the right has its origin in the Bohm sheath criterion[2]. In essence, ions begin to leave electrons behind when their flow velocity exceeds the sound velocity

$$c_s = \sqrt{\frac{kT_e}{m_i}}.$$

If the ion arc feed velocity u is too large, the electrons are left behind too far from the switch mesh. The distance d in the governing Child-Langmuir equation $J = \chi \frac{\phi^{3/2}}{d^2}$ becomes too large. When d becomes too large, the ions slow due to their own space charge. As the ions slow below the sound speed, electrons can keep pace with the ions again–resulting in an oscillation in the distance the electrons are held behind the switch mesh. These oscillations only occur if the plasma feed velocity exceeds the ion sound speed. However, should that criterion be exceeded, the oscillations that ensue cause an unacceptable level of fluctuation in the ion beam current.

We have displayed these constraints in Figure 2. It is easy to see if the switch mesh S_{iw} is too coarse or the electrons are too cold, there is no window for ion source operation. We need not an operating *point* but a finite size window to allow for some level of arc fluctuation. We must balance window size against the need for robust, repetitive operation that argues for the coarser mesh.

LBL now manages this tradeoff successfully in the desired parameter range but has now encountered another physics constraint. It is impossible for the ions to pass through this switch mesh without some enhanced $v_\perp$ depending on the proximity of their trajectory to a switch mesh wire. This velocity enhancement is unavoidable and acts to increase ϵ_n. The increase is not large but is just large enough to keep the experimental ϵ_n up around $2\pi \times 10^{-6}$ m rad–a factor of 4 above the experimental goal. Techniques to minimize this emittance growth are not obvious though some trends are now emerging from PIC simulation. One possibility is now being tested experimentally. The idea is to couple the extraction voltage to the switch bias voltage so that when the extraction voltage is turned on, the switch voltage is reduced in magnitude to the plasma potential. The electrons now move within a λ_D of the switch mesh and shield more of the ions from the transverse kick they get from the switch mesh. The switch mesh however is held at the plasma potential so that the extraction potential cannot push the electrons farther back towards the arc, thereby changing the extraction-switch mesh distance d so crucial for constant space-charge limited ion flow.

A recent suggestion has been made that rf "ovens" could provide ions that are only a fraction of an eV compared to the present arc source ion temperature $\sim 5eV$. Low ion temperture appears to provide no advantage because the electrons must still be confined by the switch mesh and present designs require electron temperatures $\sim 5eV$. The transverse ion temperature resulting from the transverse kick of the switch mesh is on the order of $50eV$.

References

1. H.L. Rutkowski, R.M. Johnson, W.G. Greenway, M. Gross, D.W. Hewett, and S. Humphries Jr, "Multiple Arc Ion Sources for Heavy Ion Fusion," *Reviews of Scientific Instruments*, 61, No. 1, (pg. 553) 1990.

2. A. T. Forrester, *Large Ion Beams*, J. Wiley, 1988.

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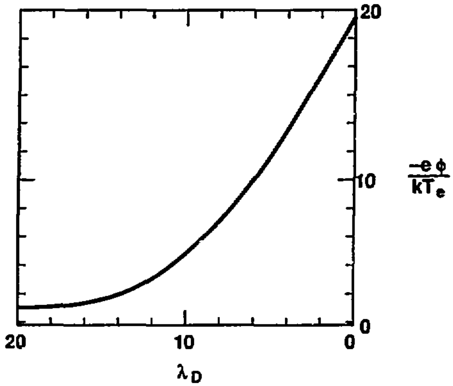

Figure 1

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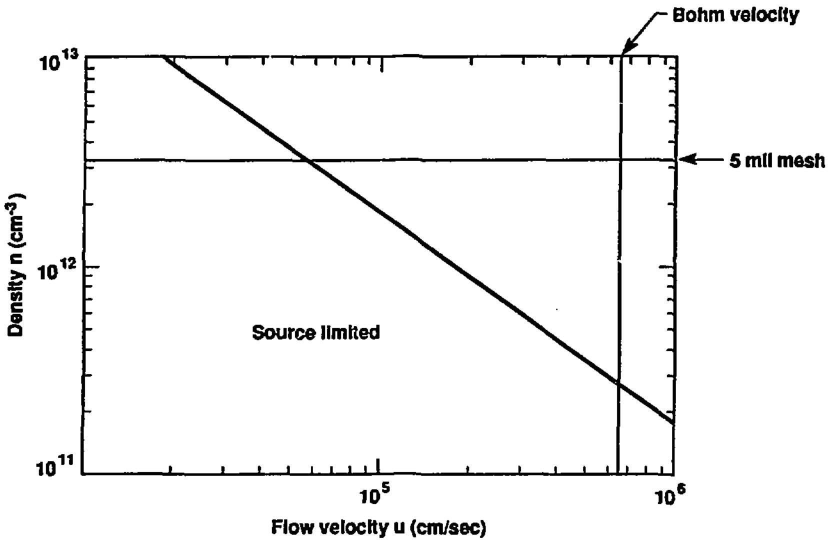

Figure 2

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