Particle Accelerators, 1992, Vols. 37–38, pp. 55–59
Reprints available directly from the publisher
Photocopying permitted by license only

CHARACTERIZATION OF THE PLASMA–SWITCH INTERACTION IN THE LBL HIF ION SOURCE

D. W. HEWETT

University of California, Lawrence Livermore National Laboratory, Livermore, California 94550

and

H. L. RUTKOWSKI

University of California, Lawrence Berkeley Laboratory, Berkeley, California 94720

(*Received 3 December 1990*)

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.

1 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 $\varepsilon_n \leq 5 \times 10^{-7}\ \pi$ m rad.

Though these requirements can be met using metals with a $+1$ valence as a coating on 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

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

where β and γ are the usual relativistic factors and r and $\partial r/\partial z$ are the maximum values of the beam radius and the derivative of that radius with respect to the axial coordinate z, respectively. This expression can be rewritten as

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

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 $v_\perp$ and are discovering ways to reduce it.

We have found the predominant 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; without electrons, the ions, no longer shielded from external potentials, remain localized about the switch mesh that has been charged to a small negative voltage. Thus, the switch mesh confines electrons and localizes/absorbs 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. In practice, these functions place the switch mesh in a harsh environment. To insure technical feasibility, we 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 the object is held at an even lower voltage, electrons are forced farther back and more 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 Figure 1.

For typical parameters $\phi_{sw} = -50$ V and $T_e = 7$ eV, electrons are repelled $\sim 8\lambda_D$, where $\lambda_D = 743\sqrt{T_e/n}$, and n is the plasma feed density. For minimal confinement, we must make 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 the parameters given above and $S_{iw} = 0.0035$ inches (0.005 center to center), the limit on density n is $n \lesssim 3.13 \times 10^{12}$ cm^{-3}. This is the first of several constraints on the arc-generated plasma that must be satisfied for successful ion source performance.

We now assemble some additional constraints that must be satisfied for proper operation of the plasma switch mesh. Looking at the parameter space defined by the arc plasma feed density n and the thermal velocity v_{th} in Figure 2, we define an obvious constraint: the diagonal line represents the product nv_{th}, and if this product is below the line, then the arc is not providing sufficient plasma flux to satisfy the ion beam current requirement during the extraction phase. The electron confinement constraint discussed above is depicted by the horizontal line. A given S_{iw} along with a given T_e impose a maximum arc feed density n that can be confined by the switch mesh. Closer mesh spacing or lower ϕ_{sw} allows confinement of denser plasma.

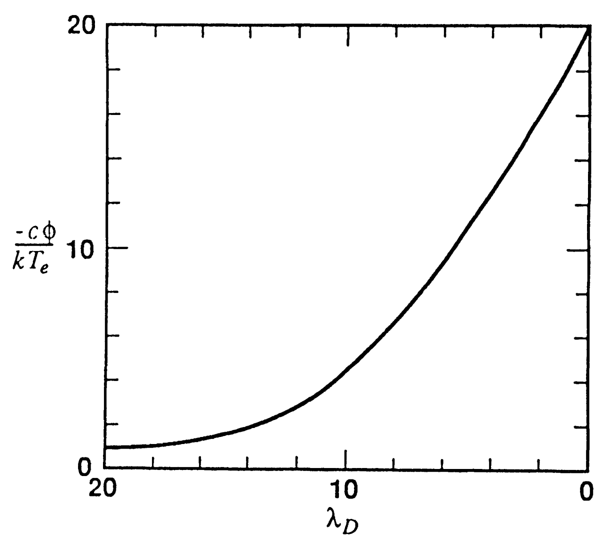

FIGURE 1 The number of Debye lengths λ_D required for a plasma to shield an external negative potential. A surface with a potential of $e\Phi = -20\ kT_e$ requires about 16 λ_D before $e\Phi = -kT_e$, or quasineutrality, can be established. Reading to the left, a surface with $e\Phi = -10\ kT_e$ is about 6 λ_D closer to being a quasineutral plasma than the $-20\ kT_e$ surface. Thus, a $-10\ kT_e$ surface forms a sheath that extends only about 10 λ_D.

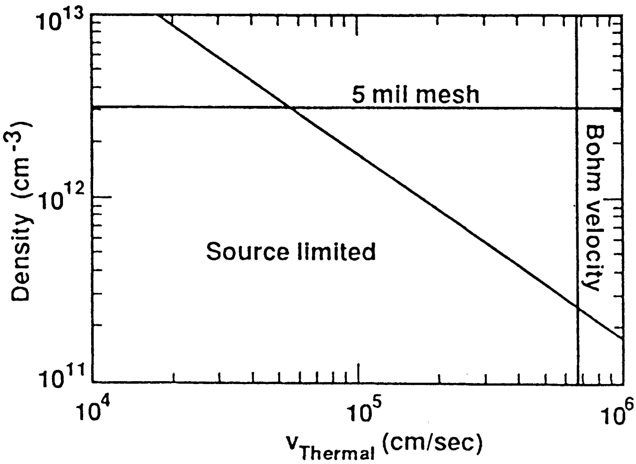

FIGURE 2 Physics constraints of the switch-mesh sheath restrict the density n, thermal velocity v_{th}, and electron temperature T_e of the arc-generated plasma to the triangular region depicted above. For an assumed $T_e = 7$ eV, a 5-mil switch mesh with interwire spacing of 3.5 mil can only confine electrons in the shutoff phase if the plasma density is less than 3.13×10^{12} cm^{-3}. This forms the constraint on the top. On the right, if the ion flow needed to feed the sheath current requirements exceeds the Bohm velocity, the concept of switch-mesh confinement breaks down. The diagonal line, forming the constraint in the lower and left part of the region, reflects the requirement that the product of ion density and v_{th} from the plasma arc source must be sufficient to supply the needs of the needed ion pulse where we use $n_i v_{th} > 1.8 \times 10^{11}$) when the switch is opened.

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

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

We require the arc-generated plasma feed to the switch mesh to be large enough to isolate the switch mesh operation from fluctuations in the arc source. Thus we must have the plasma density from the arc source large enough so that the needed current can be delivered with the ion v_{th} less than the ion sound speed c_s up to edge of the sheath. If the ion flow velocity in the plasma emerging from the arc source is faster than c_s, the concept of switch mesh confinement breaks down.

We have displayed these constraints in Figure 2. It is easy to see that if the switch mesh S_{iw} is too coarse or if the electrons are too cold, there is no window for ion source operation. To allow for some arc fluctuation, we need an operating window rather than a single operating point. We must balance window size against the need for reliable, repetitive operation that argues for the coarser, more robust mesh.

We now manage this tradeoff successfully in the desired parameter range, but we have 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 produce experimental ε_n around $2\pi \times 10^{-6}$ m-rad, a factor of four above the goal. Techniques to minimize this emittance growth are not obvious, though some trends are now emerging from particle-in-cell (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 where they would otherwise 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 cusp-field sources could provide ion temperatures that are only a fraction of an eV, as compared to the present arc-source ion temperature, suspected to be ~ 3 eV. Low ion temperature appears to provide no advantage because the electrons must still be confined by the switch mesh, and present designs require electron temperatures ~ 7 eV. With constant switch voltage the transverse ion temperature resulting from the transverse kick of the switch mesh seems to make further reduction of the ion temperature of the source plasma irrelevant. Present configurations show enhancements of the effective transverse ion temperature from the switch mesh to be on the order of 25 eV, an effect that would dominate the relatively small reduction in initial ion temperature that could be achieved by using the rf cusp-field source.

In conclusion, we are beginning to understand the sheath physics of the plasma-mesh interaction of the LBL HIF curse. We can now infer arc-source plasma properties based on the behavior of the plasma switch mesh. Further we have now procedures for estimating the properties of the switch (mesh spacing, wire size, voltage, etc.) that are needed for it to function in the HIF application. Though progress to date has given emittance that is within a factor of 3–4 of the HIF requirement, a new procedure that involves reducing the voltage magnitude on the switch mesh during the ion pulse extraction phase is now being investigated. If the new procedure works as anticipated from simulation, the present plasma arc source will meet HIF design goals, with the promise that the rf cusp source will work even better.

ACKNOWLEDGEMENTS

Work performed under the auspices of the United States Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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," *Rev. Sci. Instrum.* **61**, 1, (1990) 553.
2. A. T. Forrester, *Large Ion Beams* (J. Wiley 1988).