ENHANCING SURFACE IONIZATION AND BEAM FORMATION IN VOLUME-TYPE H^- ION SOURCES

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Abstract

The ion source for the Spallation Neutron Source (SNS) is a radio frequency, multi-cusp, volume-type source equipped with a conventional Cs collar re-entrant into the plasma chamber and surrounding the outlet aperture. The source is capable of delivering 35-50 mA of H^- with a normalized rms emittance of less than 0.2 π mm mrad to the SNS accelerator. Design studies utilizing Cs flow, H^- ion formation and plasma transport calculations have been performed to improve the H^- yield with respect to the position and shape of the re-entrant Cs collar. Likewise, design studies to determine the optimal shape of the source outlet aperture have also been performed using the code PBGUNS. The shape of the outlet aperture has been altered with respect to the current design to (i) minimize rms emittance values, (ii) significantly reduce beam halo (iii) increase the stability of the plasma meniscus and (iv) improve suppression of the co-extracted electron beam. By integrating the source outlet aperture and Cs collar assembly into a single mechanical unit both improvements can be implemented by retrofitting a single component to the source and a slight modification of another. This report provides details of the design studies and the physical design of the integrated collar/outlet aperture assembly.

1 INTRODUCTION

Today, many ‘volume-type’, high-intensity H^- ion sources used in conjunction with accelerators employ, in one form or another, a ‘collar’ structure located in the extraction region of the plasma chamber [1,2]. Fig. 1 shows the outlet aperture assembly of the ion source used by the Spallation Neutron Source (SNS) [3]. Collars were first added to this type of ion source to assist in suppression of parasitic electrons which are co-extracted with the negative ion beam [4]. Later, it was found that the use of such a structure combined with the addition of Cs vapor, could significantly increase the H^- yield from the source [5]. Typically, a 3-fold increase in H^- yield is observed with the addition of Cs to the SNS ion source and enhancements as high as 5-fold have been reported for similar sources [6]. Adding a slight negative bias (~10V) to the collar with respect to the plasma chamber can also achieve significant increases in H^- yield [2]. This report first discusses the physical basis of this phenomena: negative ion formation on the surface and negative ion transport through the plasma, and derives an improved design for the SNS ion source collar based on these considerations.

By physically extending the collar through the outlet aperture of the source the shape of the first electrode of the extraction system can also be modified in the new design. Ion beam extraction simulations are performed to determine the optimum shape of this electrode to minimize emittance of the extracted beam by creating a more favorable plasma-beam boundary.

In total, the design should result in an ion source with (i) improved H^- yield for a given RF power level (ii) lower source emittance (iii) reduced beam halo (iv) more stable plasma-beam meniscus (v) improved suppression of the parasitic electron beam. Operation of the SNS source at lower power levels could greatly improve the reliability and availability of the source.

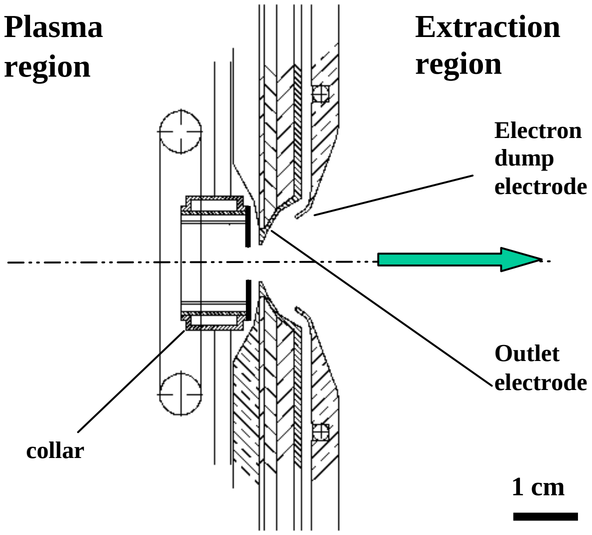

Figure 1: The original Cs collar and outlet electrode employed in the SNS ion source.

2 COLLAR DESIGN CONSIDERATIONS

This section discusses the issues related to the design of an optimal collar-outlet aperture geometry: surface H^- formation; transport of H^- ions through plasma; and the formation of a suitable plasma-beam meniscus to insure high beam quality.

2.1 The Role of Cs in ‘Volume’ Sources

Overall, the introduction of Cs into ‘volume’-type H^- ion sources primarily modifies the surfaces of the plasma chamber, near the extraction region, lowering the work function and creating substantial negative surface ionization. To a far lesser extent, Cs vapor participates in ionization processes occurring in the volume. This conclusion follows from consideration of the actual quantity of Cs consumed during operation of the source.

In the SNS source, we typically dispense Cs for a period of ~30 min. from SAES Cs_2CrO_4 dispensers [7] at a temperature 550 C and can usually maintain enhanced H^- output for at least ~8 hours and in one case achieved ~80 hours of continuous operation. Estimation of the quantity of elemental Cs released during a cesiation 'dose' was determined to be ~$3x10^{18}$ Cs atoms from the dispensers [8]. At the operational pressures of the source, collisional flow dominates and Cs should evacuate the source at a rate of ~8x slower than the H_2 gas based on the ratio of the square root of their masses. If the Cs were present in the volume of the plasma chamber, as would be required for volume ionization processes to be significant, it would be swept out of the source in 2.2s along with the H_2 feed gas (~30 SCCM flow). If we assume Cs is only volatilized during the plasma pulse this quantity of Cs would be exhausted from the source in 73s. Clearly, the Cs resides on the surface during the vast majority of its lifetime in the ion source.

This phenomenon can be seen in other H^- 'volume'-type ion sources, for example, the JAERI multi-aperture source used for neutral beam injection into fusion machines [9]. In this case, a dose of 150 mg or $8x10^{20}$ atoms of Cs is delivered into the source and enhanced the H^- yield is observed for ~1 week or 3000 shots at 200 ms of 7.8A of H^-. The measured H_2 evacuation rate of the source is $3x10^{21}$ molecules/s through 253, 1 cm-diameter openings. At this rate, even if we assume Cs is only released from the surface during the pulse, the entire Cs supply would be depleted from the source in ~10 plasma shots. Clearly, once again Cs must reside on the surface for the vast majority of its lifetime in the source and therefore surface ionization must account for the observed enhancement of the H^- yield.

In these cases, the term 'volume ion source' is misleading since, most of the H^- beam results from surface rather than volume ionization processes. Therefore, in the ion source design, careful consideration should be granted the interior surfaces of the source. The next sections show how the location within the source and chemical composition of the surface is extremely important to H^- beam production.

2.2 H^- Ion Formation

Several studies have been conducted with well-defined beams of H, H_2, H^+, H_2^+ and H_3^+ incident on cesiated metal surfaces with varying degrees of adsorbed H_2. Cross sections describing H^- formation through these processes tend to be scattered because of uncertain conditions of the surface and difficulties in transporting low energy ion and atom beams [10,11]. It seems reasonable, for design purposes, to use the formulation of Rasser [12] since it well represents typical measurements and is employed in successful models of H^- production in 'volume' sources [13]. The equation has the form

$$\beta^- = (2/\pi)\exp(-\pi(\phi - A)/2av) \qquad (1)$$

Here β^- is probability that an incoming H atom or ion will be converted to an H^- ion, ϕ is the effective work function of the surface (with Cs), A is the electron affinity of H^-, a is a decay constant ($3.1x10^{-5}$ s eV/m) and v is the atom or ions incoming velocity.

The effective work function for a Cs coated metal surface can be calculated from the fractional Cs coverage on the surface [14]. The work function of an uncoated metal is typically ~ 4-5 eV which is lowered to 2.1 eV for the case of full Cs coverage. The minimum work function of 1.8 eV occurs at coverage of ½ monolayer. Eq. 1 shows that H^- yield is essentially nonexistent for uncoated metal surfaces (ϕ = 4-5 eV), maximum at ½ monolayer and increases strongly with the velocity of the incoming ion or neutral.

2.3 Mean Free Path of H^- in a Plasma

Riz and Pamela have studied the destruction of negative H ions upon passage through plasma using the 3D NIETZSCHE Monte-Carlo code [15]. The three most important destruction processes taken into account are: e + $H^- \rightarrow 2e + H$; $H^+ + H^- \rightarrow 2H$ and; $H^- + H \rightarrow e + H_2(v')$. The probability of H^- destruction as a function of distance traveled through the plasma is shown in Fig. 2. The plasma parameters typical of a small multicusp H^- ion source in the extraction region (n_e~n_{H+}~10^{12} cm^{-3}; Te~1eV; T_{H+}~T_H~0.5 eV; n_H~10^{14} cm^{-3}) have been used.

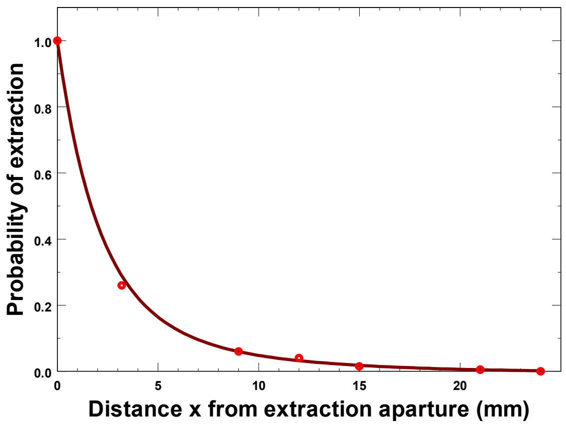

Figure 2: Probability of an H^- ion surviving after passing a distance x through the plasma.

Thus, Fig. 2 shows only those surfaces near the extraction aperture are important for H^- ionization since, the mean free path of H^- through the ion source plasma is ~ 2 mm.

2.4 Plasma Meniscus Formation

The location and shape of the plasma-beam meniscus is extremely important to the optical properties of the extracted beam, the temporal stability of the beam and electron suppression. The computer simulation, PBGUNS has been proven useful [16] in modeling H^- extraction from plasma and in employed here to optimize the shape of the new outlet aperture.

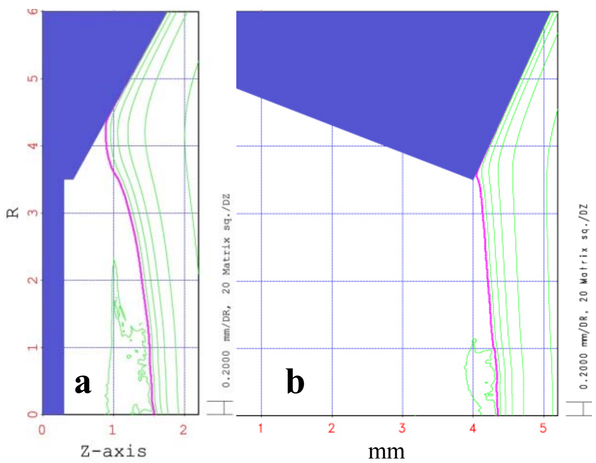

Figure 3: PBGUNS calculation of the plasma-beam meniscus for –65kV extraction and 20 mA H^- beam for both the (a) original and (b) new outlet aperture design

Fig. 3a shows the original outlet aperture shown in Fig. 1, the calculated voltage contours and plasma-beam meniscus. A high degree of curvature, in this design, gives rise to higher than optimal emittance and significant halo in the extracted ion beam. The downstream location of the meniscus prevents full function of the transverse magnetic field to suppress electron extraction. Lack of a clearly defined anchor point of the meniscus creates temporal instabilities in the sheath. Fig. 3b is the optimized geometry described in the next section.

4 REFERENCES

[1] J.R. Alonso, Review of Scientific Instruments 67, 1308 (1996).
[2] J. Peters, Review of Scientific Instruments 71, 1069 (2000).
[3] R. Keller, these proceedings.
[4] K.N. Leung, C.A. Hauck, W.B. Kunkel and S.R. Walther, Rev. Sci. Instrum. 61 (1990) 1110.
[5] K.N. Leung, D.A. Bachman and D.S. McDonald, Rev. Sci. Instrum. 64 (1993) 970.
[6] K.N. Leung, C.A. Hauck, W.B. Kunkel and S.R. Walther, Rev. Sci. Instrum. 60 (1989) 531.
[7] SAES Getters S.p.A. Via Gallarate, 215 20151 Milano, Italy.
[8] M. Succi, R. Canino and B. Ferrario, Vacuum 35 (1985) 579.
[9] Y. Okumura, et al AIP Conf Proc. 210 (1990) 169.
[10] A.W. Kleyn, AIP Conf Proc. 210 (1990) 3.
[11] M.E. Kishinevskii, Sov. Tech. Phys. 20 (1976) 799.

3 DESIGN OF THE INTEGRATED COLLAR/OUTLET APERTURE

The above analysis has shown that Cs-coated surfaces within a few mm of the plasma-beam meniscus are extremely important for H^- production and that these surfaces must be bombarded with high temperature H and H^+ from the plasma core. Analysis using Eq. 1 and the assumed plasma parameters suggests that hot neutrals (T~0.5 eV [13]) play the dominant role in H^- production. The original design (Fig. 1) prevents direct irradiation of suitable ionization surfaces with particles from the plasma core. The new design, shown in Fig. 4, employs a conical ionization surface that is directly exposed to particle flux from the plasma core and is in the closest possible proximity to the plasma sheath.

PBGUNS simulations (Fig. 3b) have been used to optimize the angle of the outlet aperture to (i) anchor the meniscus in close proximity to the ionization surface which also provides better electron confinement and (ii) to achieve the lowest degree of meniscus curvature and consequently the minimum beam emittance and halo.

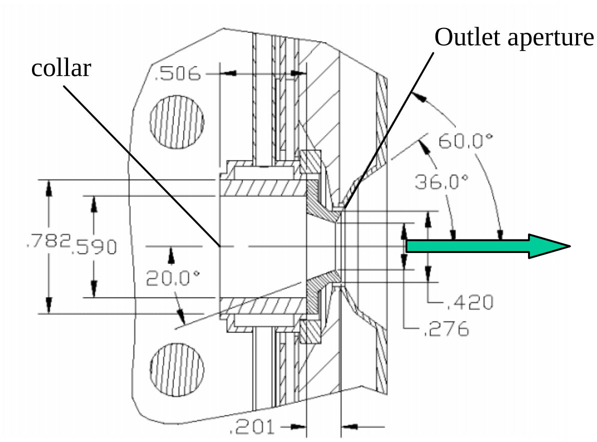

Figure 4: Final design of the integrated Cs collar/ exit aperture.

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[12] B. Rasser, et al Sur. Sci. 118 (1982) 697.
[13] O. Fukumasa and K. Yoshino, AIP Conf Proc. 439 (1997) 54.
[14] G. Alton, Surface Sci. 175 (1986) 226
[15] D. Riz and J. Pamela, RSI 69 (1998) 916; D. Riz and J. Pamela, AIP Conf Proc. 439 (1997) 62; D. Riz and J. Pamela, AIP Conf Proc. 380 (1995) 3.
[16] R.F. Welton, M.P. Stockli, J.E. Boers, R. Rauniyar, R. Keller, J. Staples and R. Thomae Rev. Sci. Instrum. 73 (2002) 1013.