REVIEW OF SCALED PENNING H$^-$ SURFACE PLASMA SOURCE WITH SLIT EMITTERS FOR HIGH DUTY FACTOR LINACS *

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Abstract

The Penning H$^-$ surface plasma source (SPS) is used at Rutherford Appleton Laboratory (RAL) to provide required H$^-$ beams for charge-exchange injection into the 800-MeV proton synchrotron on the ISIS spallation neutron source. The RAL source is based on the first H$^-$ Penning SPS operated at Los Alamos. Since the original technology exchange, Los Alamos has developed scaled-up versions of the Penning H$^-$ SPS with the goal of extending the H$^-$ beam duty factor (df) while maintaining high beam brightness. A 250-mA H$^-$ beam with rms normalized emittance of <0.3 (πmm-mrad) in both transverse planes has been extracted from a 4X scaled Penning source at a discharge df of 0.5%. Using discharge scaling laws and the 250-mA results, it is predicted that a 4X Penning H$^-$ SPS with a slit emitter would be capable of producing >100-mA, low emittance H$^-$ beams in the 5% df range.

1 INTRODUCTION

Proposed accelerator drivers for short and long pulse spallation targets for neutron beam production place demanding requirements on the injector section[1]. For the short-pulsed mode the European Spallation Source (ESS) proposes 100-mA H$^-$ beams in a linac operating at 5% df (50 Hz, 1.0 ms)[2]. The purpose of this paper is to review the dimensionally and discharge-power scaled H$^-$ Penning surface-plasma sources (SPS) using slit emitters in terms of high H$^-$ current and comparatively long df requirements (5%). Previously published work on the 4X scaled Penning source at Los Alamos showed that 250-mA H$^-$ current could be extracted at 29 keV from a slit emitter[3] at 0.5% df (5 Hz, 1 ms). This attractive beam current was somewhat overshadowed by asymmetric emittances of 0.15 X 0.29 (πmm-mrad) rms, normalized, which was thought to be difficult to match to a radio-frequency quadrupole (RFQ). However, over the past ten years RFQ design activities have shown that RFQs with a beam acceptance of 0.3 (πmm-mrad) are possible while still maintaining a high-quality linac design[2]. Further, design studies of matching beams with asymmetric emittances in the transverse planes to an RFQ using solenoid-lens[4] and quadrupole magnet focusing[5] low-energy beam transport (LEBT) systems indicate successful matches are possible. Thus there is a renewed interest and acceptance of the use of slit beams as injectors for RFQs.

2 PENNING H$^-$ SPS SCALING LAWS AND HISTORICAL PERSPECTIVE

Application of discharge scaling laws to the SPS H$^-$ Penning discharge for scaling source dimensional parameters up by the factor 4 in two of the three spatial dimensions has led to the source equations summarized in Table 1. Here the subscript 4X refers to the Penning SPS H$^-$ source with a cathode area four times the 1X source. These equations are based on the general theory of surface H$^-$ production[6] and discharge scaling laws contained in standard texts[7] on discharge physics. The prospect for increased 4X source df (df_{4X}) is related to the decreased cathode power load, F_{4X}. A fundamental limit to the stability of the Penning discharge and hence stable H$^-$ beam formation is the cesium equilibrium concentration in the discharge volume and cathode surfaces[8]. The pulsed temperature rise of a surface[9] is given by $\Delta T_{nX} = 2F_{nX}\mathrm{sqrt}(\Delta t/(\pi K\rho C))$ where ΔT_{nX}=pulsed temperature rise, F_{nX} = cathode power load(W/cm^2) = $V_{nX}I_{nX}/(3CA_{nX})$, Δt=pulse length(s), K = thermal conductivity constant(W/cm^{o}C), ρ=density(gm/cm^3), and C=specific heat (J/gm^{o}C). The index n equals one (1X) or four (4X) for the discussion in this paper. The factor (1/3) in F_{nX} comes from equipartitioning the total discharge power to each of the two cathodes and to the anode. The fundamental hypothesis of the 4X technology is that by decreasing the pulsed surface temperature rise the proper cesium balance can be maintained at longer duty factors. The beam current density defined as entry 11 in Table 1 is defined as $j_{nX} = i_{nX}/EA_{nX}$. The emission area EA_{nX} is equal to the emission slit length (y_{nX}) multiplied by its

Table 1. 4X and 1X H$^-$ source parameters.

ENTRY	SOURCE PARAMETER	4X – 1X RELATIONSHIP
1	Discharge pressure	$P_{4X} = P_{1X}/4$
2	H_2 gas mass flow	$Q_{4X} = Q_{1X}$
3	Disch. magnetic field	$B_{4X} = B_{1X}/4$
4	Discharge Voltage	$V_{4X} = V_{1X}$
5	Discharge Current	$I_{4X} = I_{1X}$
6	Cathode area	$CA_{4X} = 4CA_{1X}$
7	Cathode power load	$F_{4X} = F_{1X}/4$
8	Disch. current densities	$J_{4X} = J_{1X}/4$
9	Emission area	$EA_{4X} = 4EA_{1X}$
10	H$^-$ beam current	$i_{4X} = i_{1X}$
11	H$^-$ beam current density	$j_{4X} = j_{1X}/4$
12	H$^-$ beam production eff.	$\xi_{4X} = \xi_{1X}$

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width (x_{nX}) – see Table 2. The x_{4X} = 2.8mm is somewhat larger than the value of 2.0mm desired from the factor 4X scaling, and was the result of a fabrication error.

Table 2 shows dimensional comparisons of the the RAL source, LANL 1X source, and the 4X source as developed at LANL. It is noted the LANL and RAL Penning sources have nearly identical dimensions, reflecting the earlier technology exchange between the two labs[10]. Thus, both the LANL 1X and RAL sources may be referred to as 1X sources. Further definition of the ion source and emission slit components are described in Fig. 2 of ref.[3].

Table 2. Comparison of the LANL and RAL 1X SPS dimensions with the 4X source.

Component	RAL 1X	LANL 1X	LANL 4X
Ion Source			
L (mm) Cath-cath gap	5	4.3	17
W (mm) Discharge depth	2	3	17
T (mm) Disch. length	10	12	16
Emission slit			
y (mm) Perp. to B field	10	10	11.4
x (mm) Parall. to B field	0.6	0.5	2.8

Figure 1 shows the measured F_{nX} for the 1X and 4X sources plotted versus performance publication date. The RAL 1X source data are from [11,12], and the LANL 1X source data are from[13,14]. The i_{nX} for the various sources are indicated. An observation for the 1X sources is that H^- current is inversely rated to the duty factor with the product of $(i_{1X})(df_{1X})$ = 80 (mA%) being nearly constant. The exploratory experiment completed for the 4X slit emitter which produced 250 mA H^- did not probe the df_{4X} limit. However, 4X source has been operated at 2.3% df_{4X} with circular emission apertures with F_{4X} = 2.5kW/cm^2[3], slightly more than the 2.2kW/cm^2 shown in Fig. 1. It is readily apparent from previous 4X circular aperture measurements and the data contained in Fig. 1 that the 4X slit source df_{4X} could be increased.

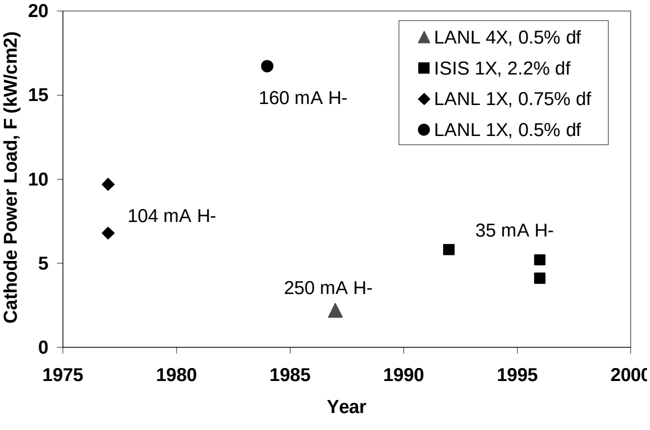

Fig. 1. Measured cathode power loads for the 1X and 4X scaled H^- Penning SPS.

Another useful factor to consider in scaled H^- Penning SPS technology is the H^- beam production efficiency ξ_{nX} shown as entry 12 in Table 1[3]. The definition of $\xi_{nX} = j_{nX}/F_{nX}$, thus $\xi_{4X} = \xi_{1X}$ is expected from the scaling laws.

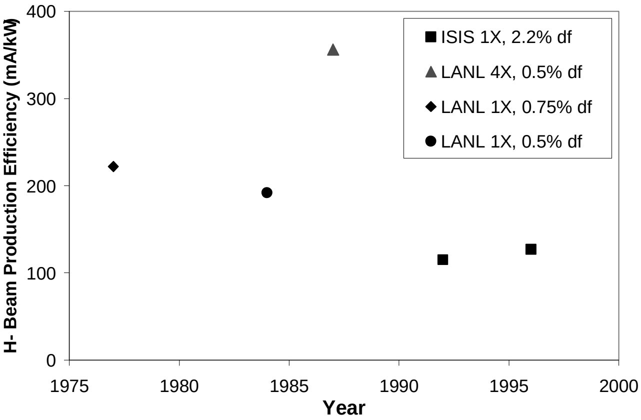

Fig. 2. H- beam production efficiency for the 1X and 4X sources plotted vs data publication year.

The publication data used in Fig. 1 is used to construct Fig. 2, where ξ_{nX} is plotted vs year for the 1X and 4X sources. It is noted that the 4X source has a beneficial increase of about factor 2 in ξ_{4X} compared with ξ_{1X}[3].

3 4X SCALING LAW RESULTS

The 250-mA H^- beam pulse is shown in Fig. 3. The beam noise of +/- 1% is compatible with linear accelerator applications. Measured x-y emittance scans at the 250-mA H^- current are $\varepsilon_x X \varepsilon_y$ = 0.15X0.29 (πmm-mrad) rms, normalized. These measurements are discussed in [15].

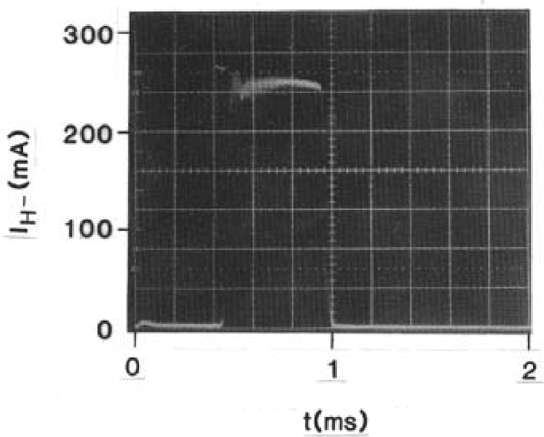

Fig. 3. 250-mA H- beam pulse from the 4X source.

Table 3 summarizes the 1X to 4X scaling results for the slit beam. Column 1 gives the ion source parameter, column 2 gives the 1X actual design and column 3 gives the 4X design based on the scaling laws of Table 1. Column 4 shows the actual result for an optimized 4X source, and column 5 shows results for an aggressively cooled 4X cathode operating in the discharge-only mode[16]. There is generally good agreement between column 3 (4X design) and column 4 (4X actual). The discharge depth W_{4X} was increased from 12 to 17 mm to obtain a quiescent discharge that produces a low-noise beam. To reach the 250-mA 4X current, F_{4X}= 2.2 kW/cm^2 was required, about a factor of two lower than the 4.2kW/cm^2 scaling law prediction. This reduction results in a factor 2 increase in the ξ_{4X} (cf. Fig. 2) compared to that of the 1X sources. One may expect a factor of 5 increase in the 4X source x-plane emittance based on the increase of slit width from 0.5mm to 2.8mm, but only a factor of 2.5 emittance increase is observed (0.15 πmm-mrad vs. 0.06 πmm-mrad).

This paper is concluded by a discussion of the application of the 4X technology to 100-mA, 5% df_{4X} H^- beams. First, from the fifth column of Table 3 the 4X source has already operated at 6% df_{4X} at 125A of arc discharge current. Thus, to reach nominal 6% df at 100-mA H^- from the measured 4X power efficiency in column 4, only 80A of arc discharge current would be required, as $I_{4X}(i_{4X}$=100mA) = (100mA/250mA)197A = 80A. This scaling implies that the H^- beam production is a linear function of the Penning discharge current. This scaling has been demonstrated from 10^{-2} to 10^{2} A arc current in the 1X source[13]. Another observation is that a circular emitter beam on the 4X source operated at 180A discharge with 2.3% df_{4X}[3]. Assuming the product of i_{4X} and discharge df_{4X}(%) is constant (as observed in the LANL and RAL 1X sources – see discussion above), one can write $(i_{4X})(df_{4X})$ = 250mA(180A/197A)(2.3%) = 525(mA%), or at 5% df_{4X} a 105 mA H^- beam could be obtained. Using the linear H^- beam/arc discharge current scaling for the slit beam the 105 mA H^- would require 83A of discharge current. These two rather independent scalings indicate order 100 mA H^- beam may be available from the 4X slit source at 80A discharge current for df_{4X} = 5%. If such performance could be demonstrated, the Penning 4X technology could be considered for application to high-power linac drivers[2].

Table 3. Experimental results for the application of the scaling laws to the 4X H- Penning SPS using slit emitters.

ION SOURCE PARAMETER	**1X ACTUAL**	**4X DESIGN**	**4X ACTUAL**	**4X DISCH ONLY**
L (mm)	4.3 – 5	17	17	17
W (mm)	2 – 3	12	17	17
T (mm)	12	16	16	16
B-field (G)	2200	550	460	500
Duty factor (%)	0.5	2-3	0.5	6%
Disch. Volt (V)	100	100	93	115
Disch. Cur. (A)	180	240	197	125
H^- Cur. (mA)	160	160	250	-
j_{H^-} (mA/cm^2)	3200	800	783	-
F_{nX} (kW/cm^2)	16.7	4.2	2.24	1.76
ξ_{nX} (mA/kW)	192	192	349	-
Emis.(y,x)(mm)	10, 0.5	10, 2.0	**11.4, 2.8**	
rms Emit., (πmm-mrad)	0.17(y), 0.06(x)		0.29(y), 0.15(x)	-

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