Review of Scaled Penning H^- Surface Plasma Source with Slit Emitters for High Duty Factor Linacs

Abstract

The Penning H^- surface plasma source (SPS) has been used at Rutherford Appleton Laboratory (RAL) for 20 years to provide the 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 that 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 H^- current 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. A source with these parameters would be suitable for the European Spallation Source (ESS) and other high-power proton driver projects.

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- This presentation originates in a review of H^- sources prepared for CEA/Saclay in preparation for the European Spallation Source (ESS) proposal.
- The laboratory work and scaling laws developed for the Penning H^- surface plasma source (SPS) described here were done in Los Alamos in the 1980 – 1993 by Vernon Smith, Paul Allison, Bill Ingalls, and Joe Sherman. Penning H^- SPS was invented in Novosibirsk, Russia.
- Principal hypothesis of the work is that by reducing the cathode surface pulsed temperature rise, the Penning SPS duty factor can be extended.
- Previous similar presentations were made at the 7th ESS General Meeting in Seggau, Austria (Sept. 2001) and the H^- Workshop Meeting held in Saclay, France (Nov., 2001) in support of the ESS Technical Advisory Committee.

Topics on the scaling of slit Penning H^- SPS sources to longer duty factors

- Review fundamental assumptions for scaling the 1X cathode to larger cathode surfaces. For the 4X Penning SPS, the cathode area is four times larger than the 1X cathode area.

- Historical comparison of the Penning 1X operated at Los Alamos National Lab (LANL) and Rutherford-Appleton Lab (RAL) with the LANL 4X in terms of cathode power loading and H^- beam production efficiency.

- 4X source measurements (current, emittance, scaling law results) at LANL with slit extraction system.

- Conclusion for reaching 5% duty factor (df), 100-mA H^- source using a slit extractor.

Empirical study of pulsed 4X source operation with aperture and slit emitters at 29 keV*

Parameter	Aperture (r=0.27cm)	Slit ($0.28 \times 1.14 cm^2$)
Discharge voltage (V)	130	93
Discharge current (A)	180	197
Magnetic Field (G)	400	500
Gas flow (sccm)	**230**	**50**
Pulse length (ms)	1	1
Repetition rate (Hz)	5	5
H^- current (mA)	**100**	**250**
Beam noise, p-p (%)	+/- 20 (1987)	+/-1
ε_x (πmm-mrad) (rms, norm.)	0.22	0.15
ε_y (πmm-mrad) (rms, norm.)	0.23	0.29

* **H. Vernon Smith, Jr., et. al. Proc. Of the 1987 Particle Acc. Conf. (Washington, D.C.), (March, 1987), 301.**

- Renewed interest in slit beams for RFQ injection in past decade
  - Matching injector beams to RFQs with solenoids and asymmetric beams studied at RAL.
  - Injectors with 0.3 (πmm-mrad) (rms, norm) emittance may be acceptable in linac design.
- As early as 1985 slit H^- beams were injected into a RFQ using quadrupoles with some success. (O. R. Sander, et. al., IEEE Trans. On Nuclear Sci., (Oct., 1985), 2588.)

Cathode Cs surface coverage for optimal H^- surface production

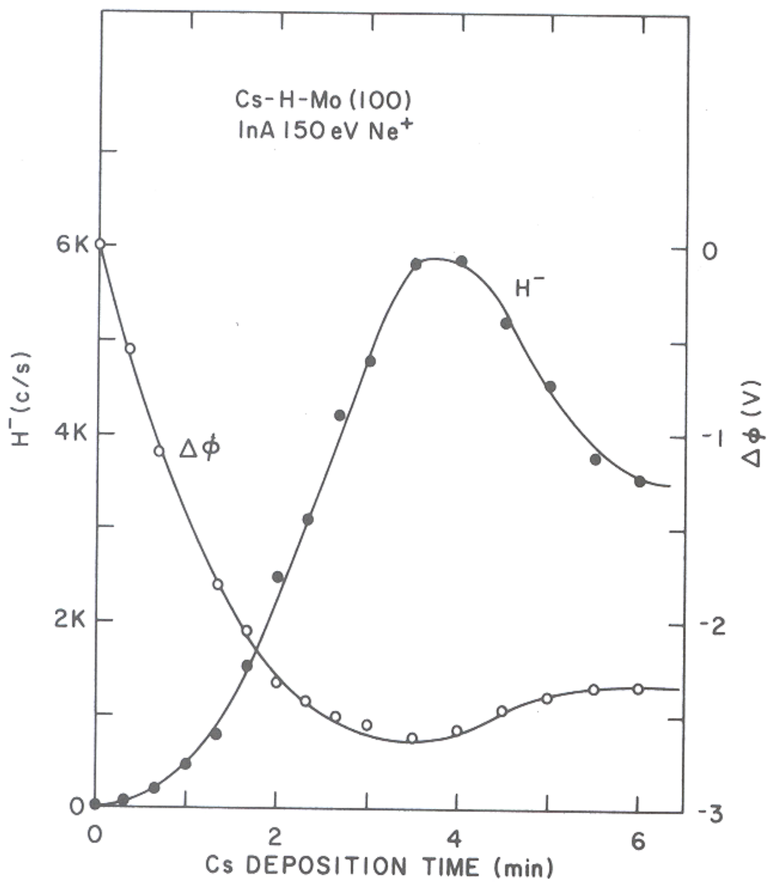
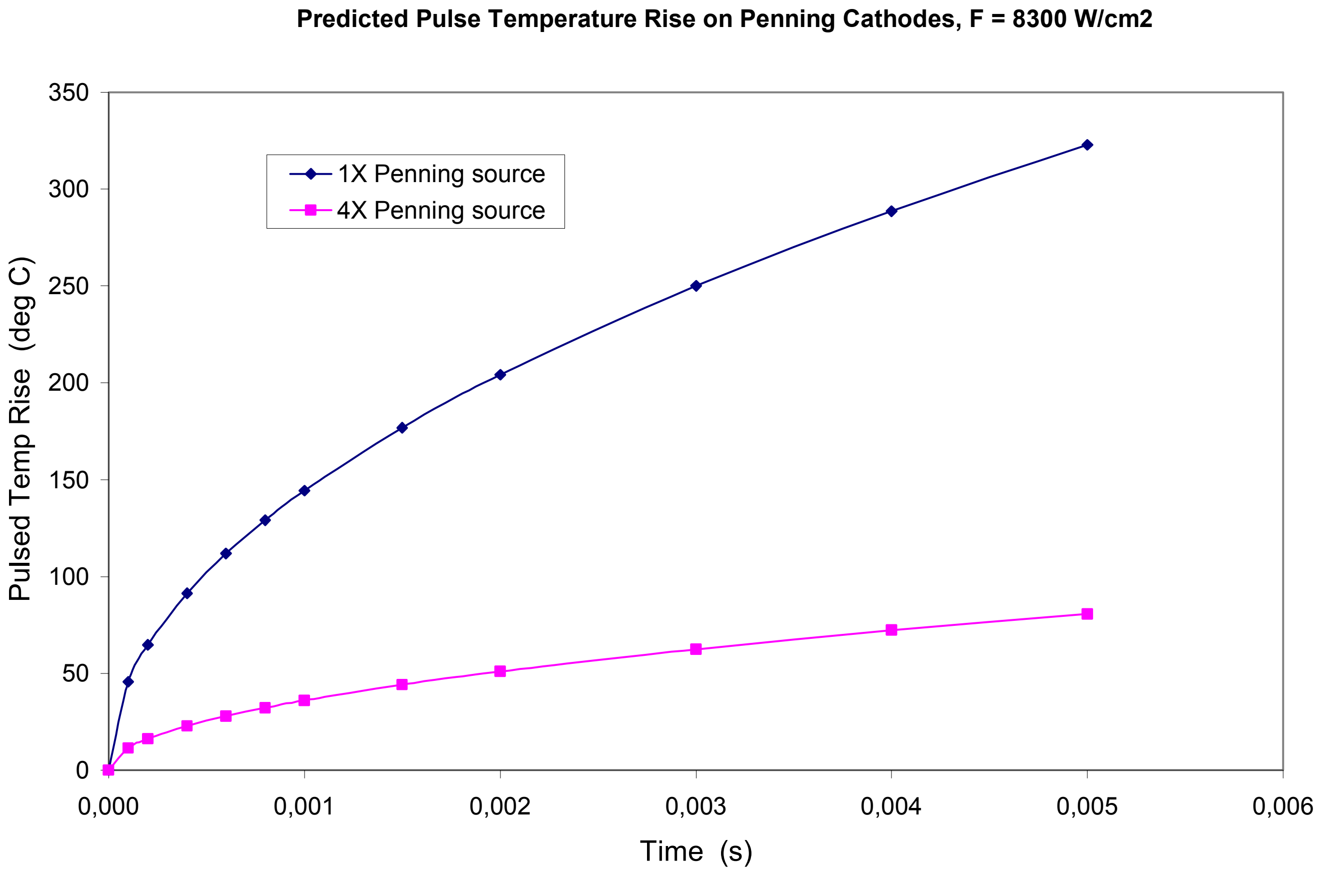


Fig. 3. Variation of ϕ and H^- yield with Cs deposition time. The Mo(100) surface was exposed to 4.5 L of H_2.

- M. L. Yu, BNL 50727, Proc. Of the Symp. On the Production and Neutralization of Negative Hydrogen Ions and Beams (1977).
- Cesium coverage on molybdenum surface determined by deposition time.
- Maximum of H^- yield corresponds to minimum of the surface work function.
- H^- desorbed from surface by Ne^+ ion.

Pulsed temperature rise on Penning cathode surface, $\Delta T = 2F\text{sqrt}(\Delta t/(\pi K \rho C))$*



- Cesium becomes unbalanced for efficient H^- production under conditions of rising surface temperature.
- By principles of surface heating, a Penning source scaled up in size should be capable of higher df.
- Ref. Carslaw and Jaeger, "Conduction of Heat in Solids", Oxford, 1959, p. 75.

* ΔT = temp increase (^{o}C), F = cathode heat flux (W/cm^2), Δt = pulse time (s)

K = thermal conductivity constant (W/(cm^{o}C), ρ = density (gm/cm^3), C = specific heat (J/(gm^{o}C)

Penning H^- SPS discharge scaling laws

Entry	*Discharge Parameter*	*4X – 1X Relationship*
1	Discharge pressure (Torr)	$P_{4X} = P_{1X}/4$
2	H_2 gas mass flow (sccm)	$Q_{4X} = Q_{1X}$
3	Discharge magnetic field (G)	$B_{4X} = B_{1X}/4$
4	Discharge Voltage (V)	$V_{4X} = V_{1X}$
5	Discharge Current (A)	$I_{4X} = I_{1X}$
6	Cathode area (cm^2)	$CA_{4X} = 4CA_{1X}$
7	**Cathode power load (kW/cm^2)**	$\mathbf{F_{4X} = F_{1X}/4}$
8	Discharge current densities (A/cm^2)	$J_{4X} = J_{1X}/4$
9	Emission area (cm^2)	$EA_{4X} = 4EA_{1X}$
10	Extracted H^- beam current (mA)	$i_{4X} = i_{1X}$
11	Extracted H^- beam current density (mA/cm^2)	$j_{4X} = j_{1X}/4$
12	**H^- beam production efficiency (mA/kW)**	$\boldsymbol{\xi_{4X} = \xi_{1X}}$

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

Component	*RAL 1X*	*LANL 1X*	*LANL 4X*
Ion Source			
L (mm) Cathode-cathode gap	5	4.3	17
W (mm) Discharge depth	2	3	12 (17)
T (mm) Discharge length	10	12	16
Emission slit			
y (mm) Perpendicular B field	10	10	11.4
x (mm) Parallel to B field	0.6	0.5	2.0 (2.8)

Penning SPS H$^-$ Geometry

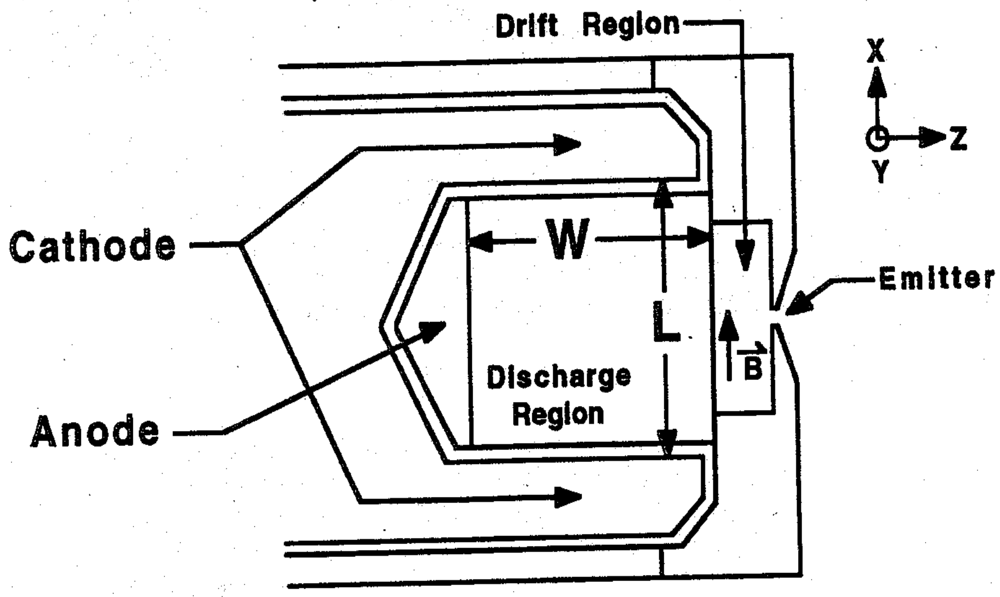
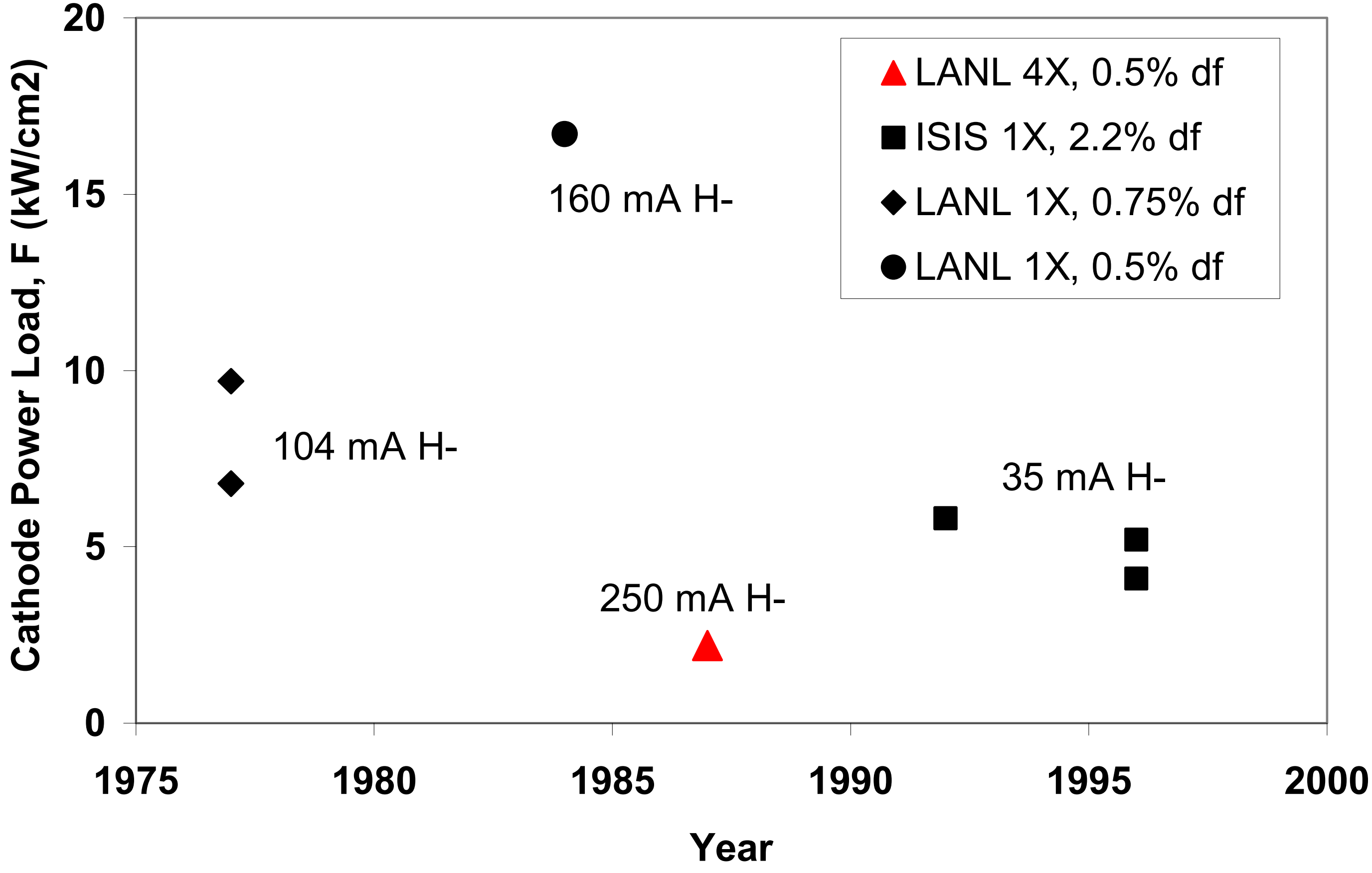


Figure 2. A schematic that shows the important geometrical dimensions of the Penning SPS source. L is the cathode-cathode gap, W is the discharge depth (along the beam direction z), and T (out of the paper) is the discharge length. The magnetic field direction is also shown.

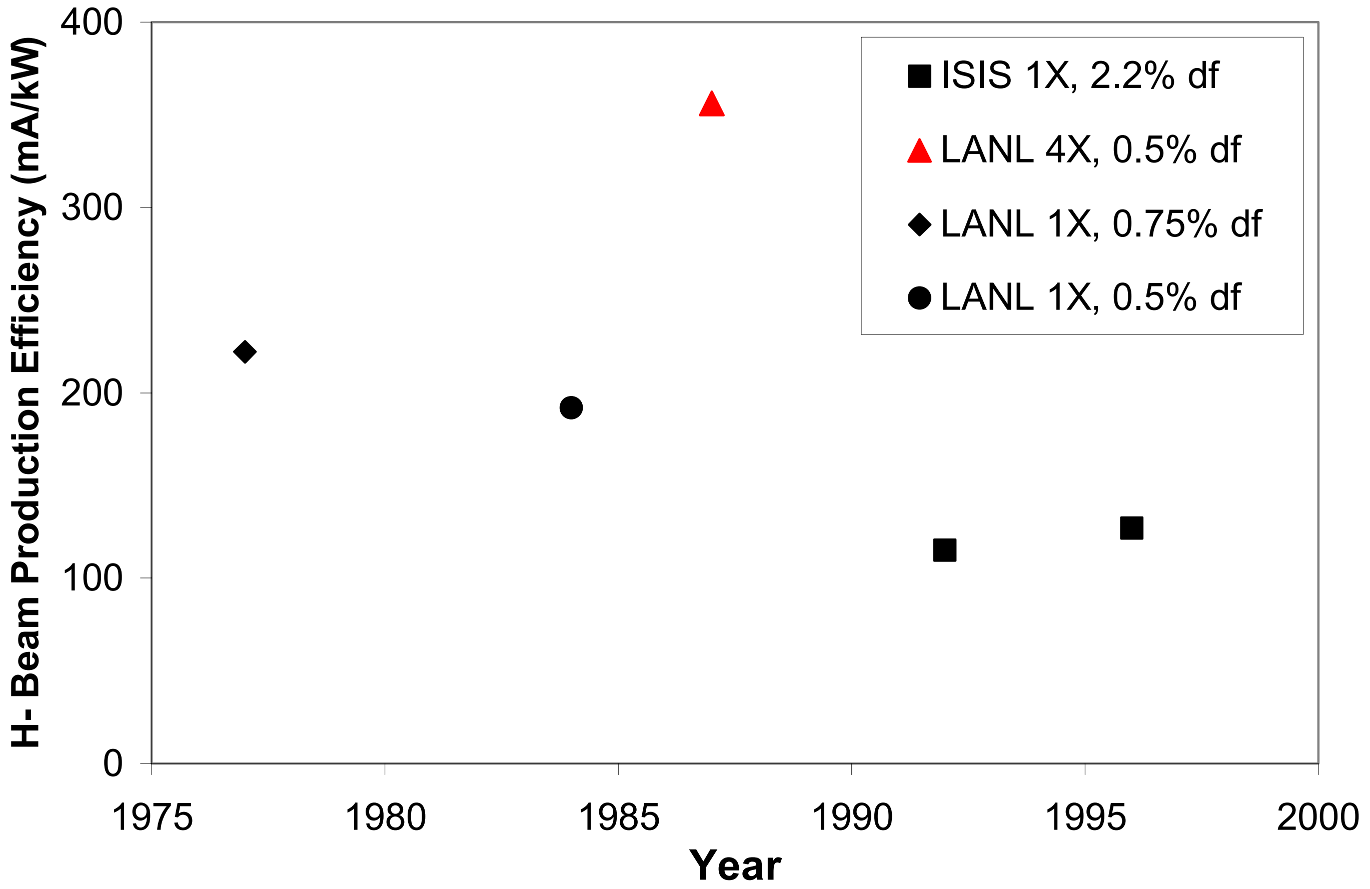
- Penning geometry
  - L=cathode-cathode gap
  - W=discharge depth
  - T=discharge length
- B field in direction of x and L
- Emission slit: Y(long), X(narrow)
- Coordinate system indicated

Cathode power loads (F_{nX}), H^- beam, and df performance for Penning 1X SPS



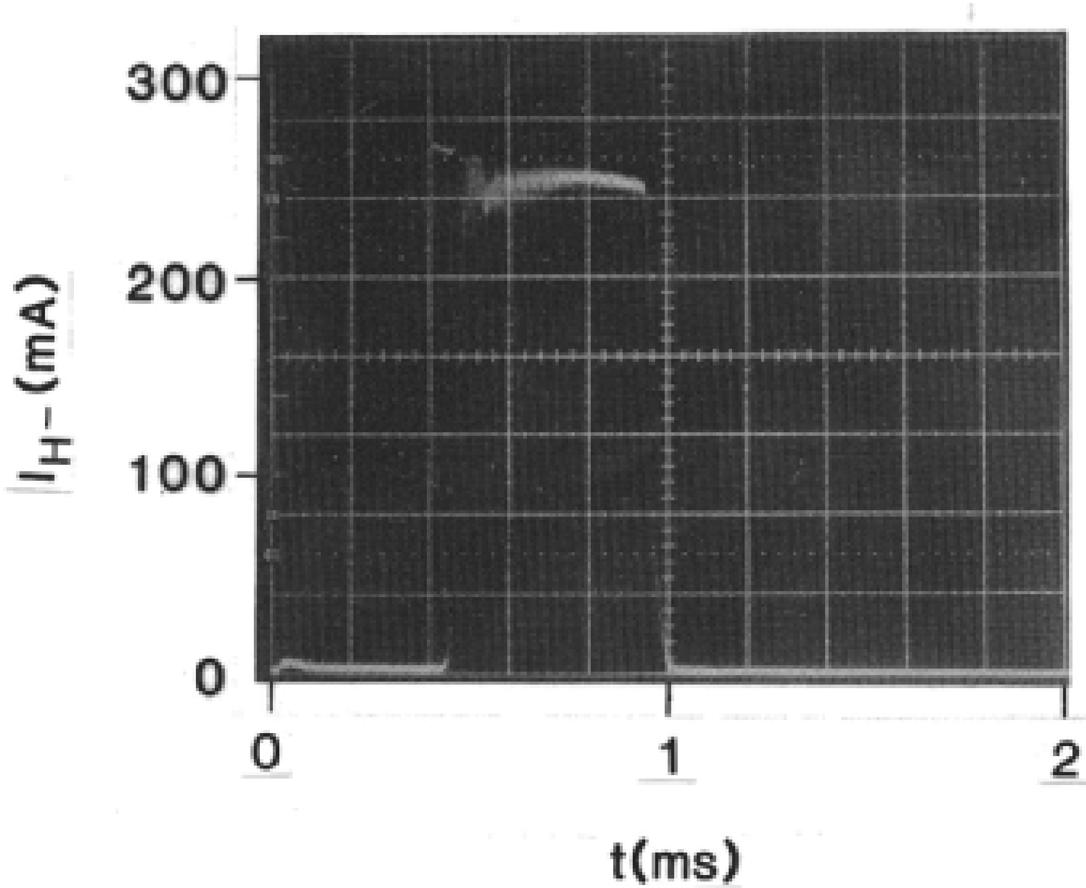
- The 1X source H^- current and df are inversely related with their product constant and equal to $(i_{1X})(df_{1X})$ = 80(mA%).

H⁻ Beam Production Efficiency (ξ_{nX}) is enhanced for the 4X compared to 1X



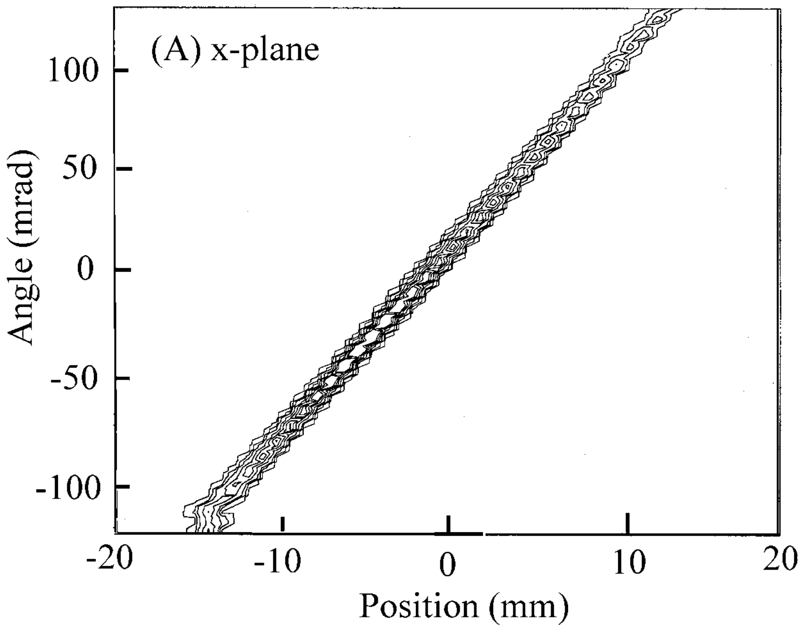
- Smaller differences in the LANL and RAL 1X sources may arise from differences in the anode geometry.

250-mA H^- beam pulse extracted from the slit emitter ($0.28 \times 1.14\ cm^2$) on the 4X source

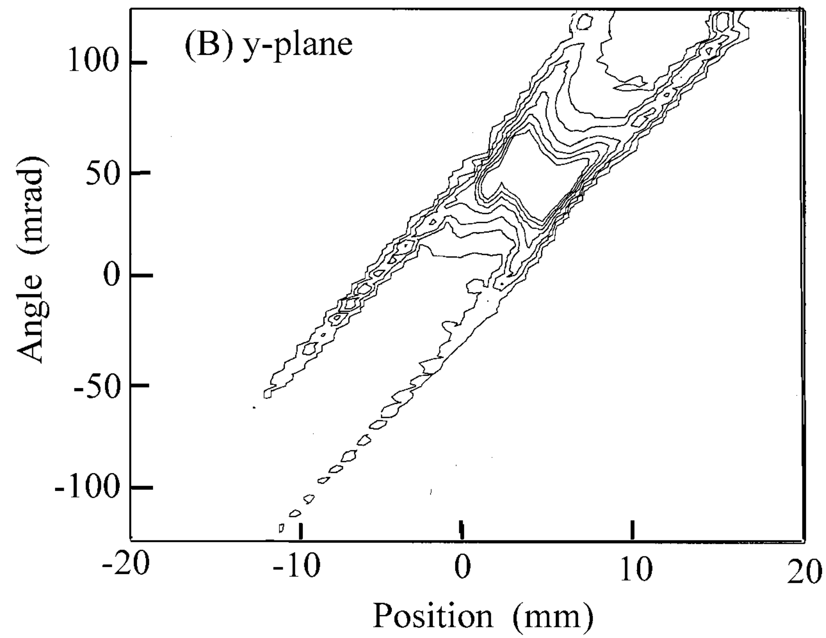


- Beam noise of order +/- 1% is consistent with linear accelerator applications.

Emittances measured for the 250-mA H^- beam current in the two transverse planes at 29 keV



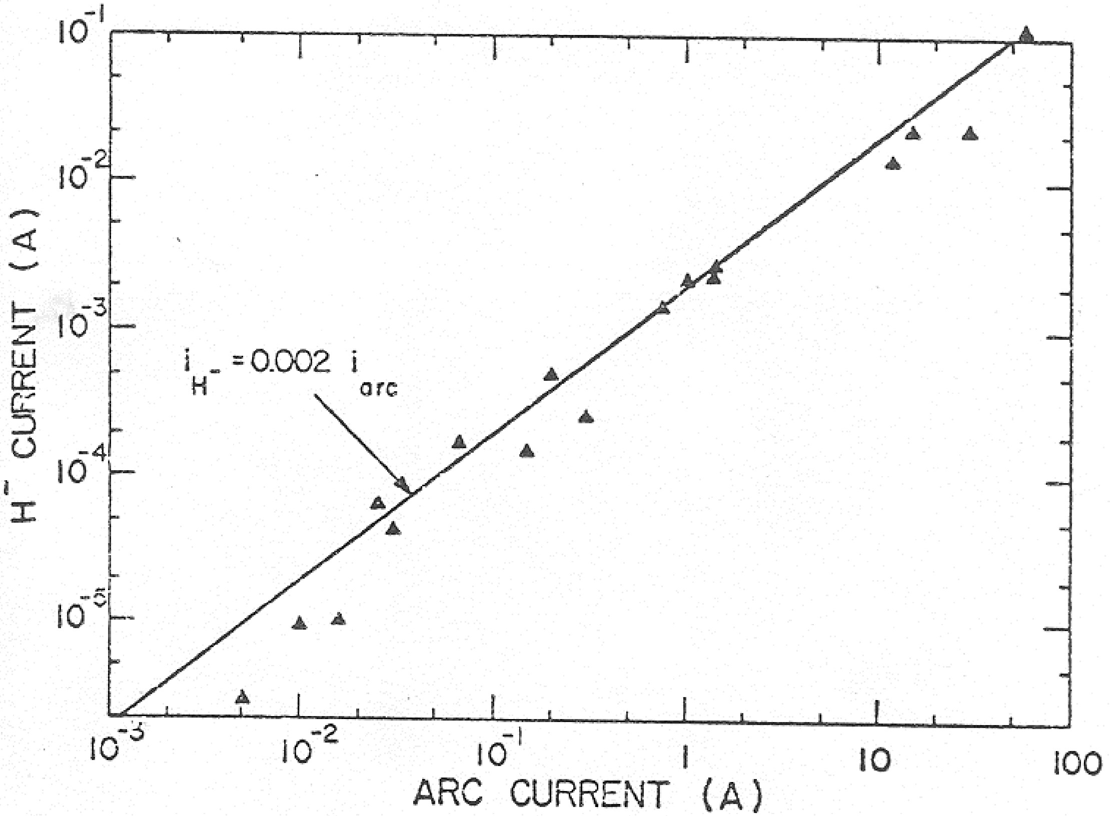
X-plane rms normalized emittance = 0.15 (πmm-mrad). Beam appears to follow a Gaussian distribution to a beam fraction of F = 0.95.



Y-plane rms normalized emittance = 0.29 (πmm-mrad). Deviations of the emittance distribution from a Gaussian model occurs at the beam fraction F = 0.63.

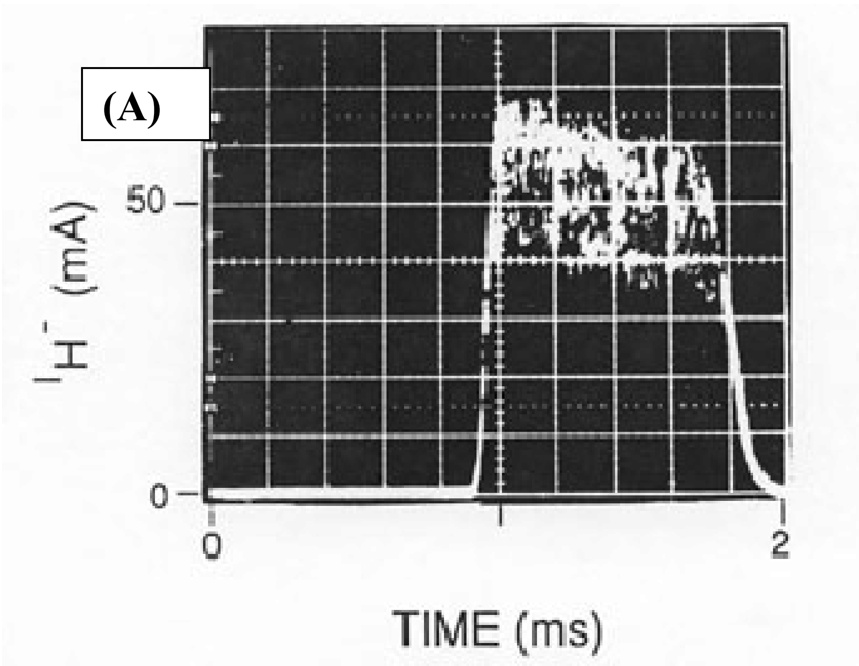
- Measurements made with electric sweep-type emittance scanners, located about 10cm from the extraction electrode.

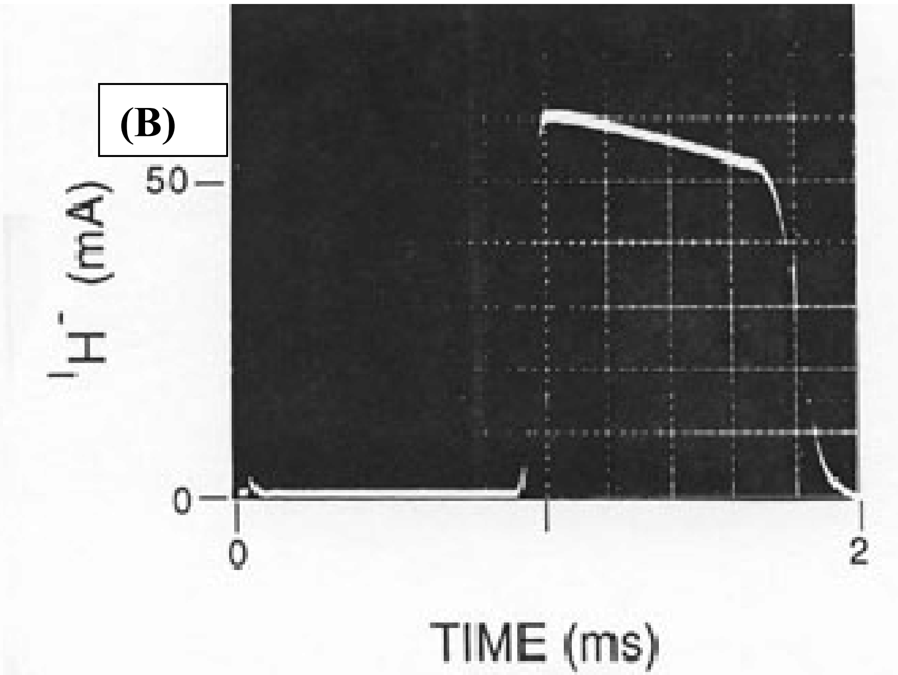
SPS H^- current dependence on discharge current for a slit LANL 1X Penning SPS



- Linear generation of H^- beam vs discharge current observed over several orders of magnitude.
- Paul Allison, IEEE Trans. on Nuclear Science, Vol NS-24(3), 1594(1977).

Beneficial effect of adding N_2 to 4X Penning discharge for beam noise reduction (1988).





(A) H^- current with no N_2 gas added to the H_2 discharge. (A) and (B) used circular emitters.

(B) H^- current with 0.5% N_2 added to H_2 discharge. All other ion source parameters the same as in (a). (effect discovered in 1988)

Performance of the Penning 4X SPS slit beam.

Ion Source Parameter	SAS (1X)	4X design	4X slit measurements	4X discharge only measurements*
Cathode-Cathode (L) (mm)	4.3	17	17	17
Discharge Depth (W) (mm)	3	12	17	17
Discharge Length (T) (mm)	12	16	16	16
B field (G)	2200	550	400	500
Emission slit (y,x) (mm)	10, 0.5	10, 2.0	11.4, 2.8	
Discharge Voltage (V)	100	100	84	115
Discharge Current (A)	180	240	197	125
Maximum H^- Current (mA)	160	255 (160)	250	Not measured., estimate 160mA
j_{H^-} (mA/cm^2)	3200	800	783	Not measured
Cathode Power Load, Fc (kW/cm^2)	16.7	4.18	2.0	1.76
Cathode Power Efficiency, ξ (mA/kW)	192	192	392	Not measured
Duty Factor, df (%)	0.5 – 0.75	2-3%	0.5, (2.3% df)	6% (15Hz, 4ms)
Emittance, rms norm (πmm-mrad)	0.17(y), 0.06(x)		**0.29(y), 0.15(x)**	Not measured

***H. Vernon Smith, Jr., et. al. Proc. Of the 1987 Particle Acc. Conf. (Washington, D.C.), (March, 1987), 301.**

4X Penning H^- SPS slit beam scaling calculations to reach 5% df, 100 mA H^-

1. i_{4X} vs I_{4X} scaling.

(Extracted H^- current vs discharge current linear scaling.)

From 4X discharge only measurement, the discharge was operated at 6% df with V_{4X}/I_{4X} = 115V/125A. For producing 100-mA H^-:

$I_{4x}(i_{4x}$=100mA) = {100mA/250mA}197A = 80A.

I_{4X}=80A < I_{4X}=125A (demonstrated)

2 Observation that 4X discharge has operated at df_{4X}=2.3% with I_{4X}=180A with circular aperture emitter. The 4X scaling of

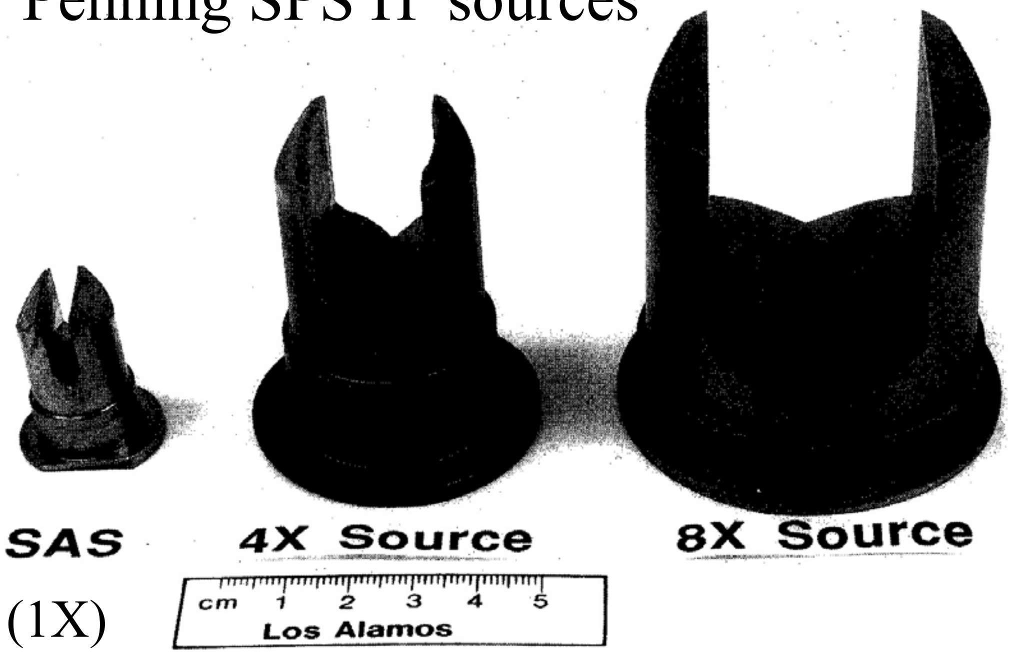
$(i_{4X})(df_{4X})$ = 250mA(180A/197A)(2.3%)
= 525(mA%)

The $(i_{4X})(df_{4X})$ is approximately 6X greater than the product $(i_{1X})(df_{1X})$ = 80(mA%), reflecting a factor of 4 gain in F_{4X} and factor of 2 gain in ξ_{4X}. (factors additive?)

For df_{4X} = 5% gives i_{4X} = 105mA. From i_{4X} vs I_{4X} linear current scaling:
$I_{4X}(i_{4X}$=105mA) = {105mA/250mA}197A
= 83A!

4X Penning H^- Surface-Plasma Source (SPS) with Slit Emitter

Cathodes for 1X, 4X, and 8X Penning SPS H^- sources



(1X)

Scaling based on comparison of 1X-4X performance. Further improvement may be obtained by use of 8X source.

1. The Penning SPS has demonstrated 250-mA H^- current at 197A discharge current at 0.5% duty factor.

2. Beam emittance at 250- mA H^- is y-plane X x-plane = 0.29 X 0.15 (πmm-mrad) rms norm while extracting from a 1.14 X 0.28 cm^2 slit.

3. Application of discharge scaling laws suggests 100-mA H- current may be obtained at 5% df with 80A discharge current.

4. Expertise exists at Rutherford-Appleton Labs to check these predictions.