LA-UR-02-6285

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Title: NEW DEVELOPMENTS WITH H- SOURCES

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Submitted to: SEVENTEENTH INTERNATIONAL CONFERENCE ON THE
APPLICATION OF ACCELERATORS IN RESEARCH AND
INDUSTRY (CAARI2002)
DENTON, TEXAS
NOVEMBER 12-16, 2002

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Form 836 (8/00)

New Developments with H^- Sources
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Abstract

Existing spallation neutron source upgrades, planned spallation neutron sources, and high-energy accelerators for particle physics place demanding requirements on the H^- sources. These requirements ask for increased beam currents and duty factor (df) while generally maintaining state-of-the-art H^- source emittance. A variety of H^- sources are being developed to address these challenges. These include volume sources with and without the addition of cesium for enhanced H^- production, increased df cesiated H^- Penning and magnetron sources, and cesiated surface converter H^- sources. Research on surface films of tantalum metal for enhanced volume H^- production is also being studied. Innovative plasma production techniques to address the longer df requirement without sacrificing H^- source reliability and lifetime will be reviewed. The physical bases, the goals, and perceived challenges will be discussed.

Introduction

This paper addresses the development of H^- sources for charge-exchange injection into synchrotron accelerators and proton compressor/storage rings. A recent article[1] provides a review of the H^- charge-exchange injection process on these machine types. At least five synchrotrons located at Brookhaven Alternating Gradient Synchrotron (AGS)[2], Deutsches Elektronensynchrotron (DESY)[3], Fermilab[4], High Energy Accelerator Research Organization(KEK)[5], and the Rutherford-Appleton Laboratory(RAL) ISIS project[6], and are operating with H^- charge-exchange injection. With the exception of ISIS, these machines operate at less than 1% H^- source duty factor (df is given by the product of beam pulse width and repetition rate), and all have found satisfactory H^- source solutions for operations with lifetimes generally exceeding a few months. However, pulsed spallation neutron sources[7] are now pushing the development of H^- sources to new limits, especially in the area of long duty factors and high currents. Figure 1 shows the H^- current vs df performance for a selection of operating H^- sources or extensively developed H^- sources. The H^- source type is indicated by the symbol defined in the legend box. Among projects requiring advanced H^- sources are the European Spallation Source (ESS) [8], the KEK/Japan Atomic Energy Research Institute (JAERI) Joint Project[9], the Los Alamos Neutron Science Center (LANSCE) upgrade project [10], the Oak Ridge National Lab (ORNL) Spallation Neutron Source (SNS) [11], and the Superconducting Proton Linac (SPL) [12]. Without development work, longer duty factors and higher H^- current demands have the effect of reducing both H^- source lifetime and reliability.

H^- production mechanisms, performance, and latest advances are reviewed in the next section with some hardware examples. The goal is not to give an exhaustive review of H^- sources, but to be illustrative of the challenges and possible solutions. A review[13] summarizes H^- sources and physical principles up to early 1970s. Recent H^- source review articles are found in references [14,15,16].

Fig. 1. Summary of operating or demonstrated H^- source current vs duty factor (df).

H^- Production Mechanisms and Review of Source Performance

Pure H_2 and Tantalum H^- Volume Sources. Development of early H^- ion sources[17] were discussed in terms of single-step H^- formation by electron bombardment of H_2 [18,19]. In the continuing development of pure H_2 plasmas with a higher concentration of H^- [20,21] for source applications, results were obtained which could not be explained in terms of cross sections discussed in [18,19]. This work led to the suggestion that vibrationally excited $H_2(v)$ molecules were fundamental to the enhanced H^- production, which led to further experimental[22,23] and theoretical[24] work confirming a two-step process in which cold electrons disassociate vibrationally excited $H_2(v)$ molecules to H^- and atomic hydrogen. This early work provided the basis for the two-chamber H^- volume source where a driver region with high electron temperature is separated from the H^- production region with a low electron temperature by a magnetic filter[25,26]. A recent article[27] has summarized cross section data for electron-impact inelastic processes on vibrationally excited H_2 molecules. Multicusp magnetic fields are usually used for plasma confinement, and optimization of the multicusp field with a magnetic filter is described in [28].

The first four entries of Table 1 summarize representative H^- volume sources operating in H_2 mode. Regardless of whether the discharge power P_d is inductively coupled rf at 2-MHz or pulsed discharge using tungsten filaments, 25-40 kW power is required to achieve the noted H^- current. The rf-driven H^- volume source[30] is the operations source at the DESY injector, and has operated for >25,000 hours without failure[31].

Table 1. Summary of pure H₂ and tantalum-film H⁻ volume sources.

Source	I (mA)	P _d (kW)	P _{eff} (mA/kW)	e/H ⁻	df (%)
BNL ²⁹ (H ₂)	35	25 (W filament)	1.40	20	0.5
DESY ^{30,31} (H ₂)	40	27 (rf, 2 MHz)	1.48	26	0.08
JAERI ³² (H ₂)	14	30 (W filament)	0.47	10	5
SSC ³³ (H ₂)	30	40 (rf, 2 MHz)	0.75	20	0.35
ANL ³⁴ (H ₂ +Ta)	4-5	0.7 (microwave, 2.45 GHz)	5.7-7.1	20	100
TRIUMF ³⁵ (H ₂ +Ta)	20	4.8 (Ta filament)	4.2	4	100

The DESY performance has been accomplished by coupling rf power to the plasma through an Al₂O₃ cylinder, as seen in Fig. 2. The e/H⁻ ratios for pure H₂ mode (column 5, Table 1) are typically 20-30:1 with exception of the JAERI results where the ratio is 10:1. For the JAERI source[32], H⁻ production saturates at 14 mA at P_d < 30 kW. Power efficiencies for producing H⁻ is defined as P_{eff} = I/P_d where I is the H⁻ current. P_{eff} are listed in column 4. These range from 0.5 to 1.4 mA/kW for the pure H₂ mode entries of Table 1. The final column contains the ion source df operation in per cent.

Fig. 2. Line drawing of the DESY rf volume source. Improved lifetime and reliability have been achieved by coupling the 2-MHz rf power through the Al₂O₃ dielectric.

Measurements[36] have shown that wall recombination of atomic hydrogen using Ta filaments leads to enhanced H₂(v) populations as compared to W filaments. Comparison of tantalum and tungsten filaments in H⁻ volume sources has shown increased H⁻ beam production when Ta is used[29,37,38]. In the case of [29], a lowered e/H⁻ ratio was also found in beam extraction experiments with Ta filaments. Vacuum Ultraviolet (VUV) light is observed to be enhanced in a multicusp source when Ta filament is compared with W filament operation[39]. Here, VUV light is identified with precursor of H₂(v)

molecule formation. The final two entries in Table 1 summarize results from (1) a 2.45 GHz microwave-driven source experiment[34] with Ta film on the plasma chamber wall, and (2) a multicusp source operating with Ta filaments[35]. Both of these sources are operating at 100% df (cf arrow in Fig. 1). As much as 80 mA H^- was extracted from the DESY low df internal rf antennae multicusp source with a tantalum collar where small amounts of alkali metal are present from antenna sputtering[40]. The fourth column gives the calculated P_{eff} for all six sources. It is suggestive that Ta films are beneficial in some H^- sources as H^- production efficiencies 2-4 times greater than the pure H_2 volume sources are observed.

Cesiated Volume Sources. Addition of Cs to multicusp H^- volume sources operating with W filaments[41] and 2-MHz rf[42] both increased the H^- production efficiency and decreased the e/H^- ratios. The origin of injecting Cs for enhancement of H^- production in hydrogen plasmas came from a study of magnetron (planotron) and Penning H^- sources[43,44] (see below). That H^- ions can be copiously produced from cesiated source anode components has been studied theoretically[45,46] and experimentally[47,48,49].

A representative summary of cesiated volume source performance is shown in Table 2. There has been intense development of the SNS rf multicusp source at Lawrence Berkeley National Lab(LBNL), where cesium is introduced in a collar adjacent to the emission aperture[41,50]. Summaries for the SNS H^- ion source and injector development have recently been given[51,52], and results are 33mA H^- radio frequency quadrupole (RFQ) beam transmission from 36mA injected H^- current. Simulations for the SNS electrostatic low-energy beam transport (LEBT) agree well with measurements[53]. The SNS cesiated multicusp H^- source uses a 2-MHz antennae imbedded in the plasma for the primary plasma generation. Antennae development is in progress at ORNL[54], yielding a 0.25mm thick multi-layered porcelain coating that has

Table 2. Summary of representative cesiated multicusp H^- ion sources.

Source	I (mA)	P_d (kW)	P_{eff} (mA/kW)	e/H^-	df (%)
SNS ⁵² (H_2 +Cs)	50	55 (rf, 2 MHz)	0.91	2	6
IAP ⁵⁵ (H_2 +Cs)	120	48 (W filament)	2.5	7	6
JAERI ³² (H_2 +Cs)	72	56 (W filament)	1.3	0.7	5
SSC ⁵⁶ (H_2 +Cs)	100	40 (rf, 2 MHz)	2.5	1	0.1

been tested successfully for 107 continuous hours at 25-mA beam current and full 6% df. A second 10-layer antennae with 0.8mm porcelain thickness has been fabricated, and is awaiting further lifetime/reliability tests. Figure 3 shows one of the newly fabricated SNS porcelain antennae.

Other cesiated volume source development has been done at Institut fuer Angewandte Physik (IAP)[55], JAERI[32], and the Superconducting Super Collider (SSC)[56], with continuing work at IAP for ESS and JAERI for the KEK/JAERI Joint Project. The IAP source is comprised of four tungsten filaments contained within a copper cylinder. Improved Cs delivery has allowed extraction of 120-mA H^- beam at 50 Hz in 1.2 ms pulses with 48 kW of discharge power. Based on filament wear, a lifetime of 15-20 days is projected at $P_d=40$ kW. The JAERI source uses two tungsten filaments, and it has

achieved 72 mA H^- current at 56 kW discharge power while operating at 5% df (50 Hz, 1 ms). The filament lifetime is estimated to be 100 hours.

Comparing Tables 1 and 2, P_{eff} for the cesiated volume sources appear to be enhanced by about a factor of two compared to the pure H_2 volume sources. The largest improvement for cesium addition is in the e/H^- ratio where factors 20 – 30 improvement are achieved.

Fig. 3. Newly fabricated SNS porcelain antennae.

H^- Cesiased Surface Converter Sources. The physical bases for H^- production in this type of source are contained in [43,44]. The surface converter source was first developed for fusion applications[57,58]. The surface converter source concept[58] has led to several fundamental H^- surface conversion measurements including cesiated tungsten and molybdenum surfaces[59], measurement of conversion efficiencies in barium[60], transport of negative ions using converters in multicusp sources[61], studying the surface conversion process with different discharge configurations[62], and use of rf antennae in surface converter sources[63]. A sputtering code TRIM[64] was developed, and used in some of these H^- source developments.

Table 3 contains a summary of three cesiated surface conversion H^- sources in operation or under development: (1) the Los Alamos National Lab (LANL) LANSCE production source[65,66], (2) the KEK surface converter source[67], and (3) the LANSCE H^- upgrade project[68,69,70] done in collaboration with LBNL. In the

Table 3. Summary of cesiated surface converter H^- sources.

Source	I (mA)	P_d (kW)	P_{eff} (mA/kW)	e/H^-	df (%)
LANSCE Production ^{65,66}	18	2.4 (W filament)	7.5	2.4	12
KEK Production ⁶⁷	21	5.0 (LaB ₆ filament)	4.18	4.3	0.4
LANL Upgrade ⁶⁸	40	8.0 (W filament)	5.0	2	6

listed surface-converter production sources, extracted H^- ions are born on the converter surface. In the case of the LANSCE source the converter is biased to -250 to -300V

range while the KEK converter is biased to -500V . These converter sources use multicusp magnet plasma confinement. P_{eff} for the surface converter sources are three to seven times greater than the cesiated multicusp volume sources (see Table 2) with similar e/H^- ratios. The LANSCE production source operates on a 28-day recycle schedule, and has had high reliability for the past several years. The LANSCE source operates at 12% df (120 Hz, 1 ms). The KEK source was originally designed for > 42 days continuous operation[67], but has now achieved 250 days lifetime[71] with a new LaB_6 filament shown in Fig. 4. The KEK source operates at 0.4% df (0.2 ms, 20 Hz).

Fig. 4. Photograph of the KEK LaB_6 filament, which allows 250 days operation at 0.4% df.

The LANSCE upgrade project resulted in production of the desired 40-mA H^- design current[68,70] and a versatile accelerating column which successfully transported the 80-keV 40-mA beam[69]. However, an unexpected emittance growth occurred. The production source emittance is $1.1 \pi\text{cm-mrad}$, 1rms lab at 18 mA while at the higher H^- currents (> 25 mA) the upgrade source emittance grew to approximately $2.7 \pi\text{cm-mrad}$ 1rms, lab. Beam tests on the LANSCE 750-keV beam line showed the higher emittance beam could not be transported[72]. The emittance growth is thought to arise from mixing 300-eV surface converted H^- ions with few eV volume-produced H^- ions. Mixing of surface and volume production H^- has been previously observed[73] in the magnetron source – a source similar in geometry to the surface converter source. Beam mismatch at the plasma meniscus between the two H^- species has been modeled with the PBGUNS code[74], and the results are shown in Fig. 5. The predictions are similar to observations: with 100% surface converter H^- (left side of Fig. 5) emittances are $1 - 1.3 \pi\text{cm-mrad}$, while the mixing of 30% 12 eV volume ions gives a predicted X2.5 emittance growth. The low temperature H^- volume component may arise from fast H^- ions originating on the converter, but undergo resonant charge exchange with plasma atomic hydrogen[75], resulting in few eV H^- ions. The LANSCE upgrade development was limited to 6% df

because of test stand discharge power limitations, but LANSCE operations df requirement remains at 12%.

Fig. 5. Predicted emittance growth for plasma-energy mismatched beams vs % of volume species. The volume component is assumed to have 12 eV directed energy in the sheath region while the surface converter H^- have 300 eV directed energy. Note the major effect is mostly independent of an assumed H^- temperature variation.

Surface-Plasma Sources (SPS) - Cesium H^- Magnetron and Penning Sources. Unlike the cesiated volume sources but similar to the cesiated surface converter H^- sources, the cesiated magnetron and Penning sources have cold cathodes typically biased to -100V potential relative to the anode potential. The physical bases for these sources are again in [43, 44]. A limiting factor in extending the df of these sources is the maintenance of the proper Cs balance in the discharge and cathode surfaces[76]. Experiments have shown that a Cs coverage giving minimal work function is required to maintain optimal H^- production[77,78]. A fundamental difference between the magnetron and Penning sources is that the H^- ions from the magnetron cathode production surface have line-of-sight trajectory to the emission surface as in the surface converter H^- sources, while H^- produced on the Penning cathode must undergo the charge-exchange process on atomic hydrogen[79] to reach emission. In this regard, emittance measurement comparisons between the Penning and magnetron sources have shown an advantage of lower beam emittance for the Penning[80]. The SPS H^- sources are in use at the majority of operating charge-exchange based synchrotron accelerators. Table 4 shows a summary of representative results on the magnetron and Penning H^- SPS sources. All entries use a slit emission-extraction system except the BNL magnetron which uses a 2.8mm diam. emission aperture. The LANL 1X Penning and ISIS Penning have essentially the same discharge chamber dimensions. Fig. 6 shows a photo of the RAL Penning source which is in use at the ISIS facility. This ion source is under development at RAL for possible

ESS application[93]. The development goals are 70 mA H^- current at short-pulse df of 1.2 ms, 50 Hz, and 70 mA H^- current at long pulse df of 2.5 ms, 50/3 Hz. Design rms normalized emittance is < 0.3 (π mm-mrad) with lifetime of > 20 days.

Fig. 6. Photograph of the Penning H^- source used in production at the ISIS spallation neutron source.

The P_{eff} listed in Table 4 show the magnetron and Penning H^- SPS are the most efficient producers of extracted H^- ion beams. P_{eff} is typically 15 times greater than pure H_2 volume production (Table 1), a factor of 7-8 more efficient than cesiated volume (Table 2), and approximately three times more efficient than the H^- surface converter sources (Table 3). The BNL magnetron is noted to be exceptionally efficient, where 45 mA H^- is delivered for 1 kW of discharge power. The magnetron and Penning e/H^- ratios are similar to the cesiated volume sources, whereas the demonstrated df for these sources is less than the H^- multicusp or surface converter sources. Lifetimes for the BNL and Fermilab magnetrons are 6-9 months while the comparatively longer df ISIS Penning has a lifetime of up to 50 days[93].

Table 4. Summary of magnetron and Penning H^- SPS.

Source	I (mA)	P_d (kW)	P_{eff} (mA/kW)	e/H^-	df (%)
BNL-magnetron ^{81,82}	100	2.2	45	1	0.7
Fermilab-magnetron ^{83,84}	80	5.1	15.8	2	0.13
DESY-magnetron ⁸⁵	60	6.6	9.1	2	0.12
ISIS-Penning ⁸⁶⁻⁸⁸	35	2.8	12.5	2.8	2.5
LANL-1X Penning ⁸⁹	108	4.8	22.5	1.6	0.5
LANL-1X Penning ⁹⁰	160	18	8.9	2.2	0.5
LANL-4X Penning ^{91,92}	250	18.3	13.7	2.2	0.5

Data presently available on Penning [92] and magnetron[82] H^- sources suggest they may be extended to the 100 mA, 5% df (50 Hz, 1 ms) range. An oscillogram showing a

4X Penning 250 mA H^- current pulse at an arc discharge df of 0.5% is shown in Fig. 7. The LANL 4X source is scaled a factor of four in two of the three spatial

Fig. 6. Oscilloscope showing a 250-mA H^- beam current pulse from a Penning SPS.

dimensions[91,92]. Measured 1rms normalized emittances are 0.15 (π mm-mrad) (narrow slit dimension) by 0.29 (π mm-mrad) (long slit dimension) for an unoptimized slit extraction system at 29 keV extraction energy. A magnetron scaling calculation[82] shows that the BNL magnetron may be extended to 4.6% df at 100-mA H^- current.

Summary

A review of current H^- sources and their physical bases has been given. Emphasis has been placed on the H^- production mechanisms, and operational characteristics. No attempt has been made here at systematic discussion of beam emittance available from these sources. Systematic H^- beam emittance comparisons have recently been made[94]. Adequate H^- source technology is available for H^- -based synchrotron operations. The institution of a comparatively high-current (40 mA), long-lived, Cs-free H^- source at DESY has reached a significant goal for H^- injector development for short df ($< 1\%$) machine operations. The situation for such long-lived H^- sources is less clear for the longer df spallation neutron sources based on compressor and storage rings. Technology for 5% df, 40-50 mA H^- appears to be in hand now. Prospects are good for extending the 2-MHz external antennae development to longer df as similar technology involving 160 kW power for 15 second shots has been developed in the fusion community[95]. Paths to 100 mA H^- current, 5% df applications seem to be possible using cesiated volume sources, and the Penning and magnetron SPS technology. These latter sources would require considerable development to demonstrate that the current is available simultaneously with required beam emittance, reliability, and lifetime. Careful attention will have to be paid to the H^- production and extraction processes in the surface converter source to reach the 12% df, 40 mA, and 0.13 (π mm-mrad) 1 rms normalized emittance

goal. Tantalum films in all cases seem to act as a catalyzer for H^- production, but the degree of the effect is variable. There is increasing activity in the exploration and use of 2.45 GHz microwave technology in the production of plasmas for H^- extraction. Plasma production by 2.45 GHz microwave drive using the $H_2 - Ta$ system was reported in [34], and discussed in this review. Identification of H^- has also been made in H_2 mode using 2.45 GHz microwave plasma production and magnetic filters[96, 97, 98]. Several mA H^- has been extracted from a Cs surface converter source using 2.45 GHz plasma production[99]. Although no systematics for these latter H^- sources were presented here, H^- production from microwave plasmas is at an early stage, and sufficient development may lead to enhanced H^- source lifetime and reliability.

Acknowledgements

The authors acknowledge Jens Peters (DESY), John Thomason (ISIS-RAL), Akira Takagi (KEK), and Roderich Keller (LBNL) for providing figures and helpful discussions in preparing this work. We also acknowledge helpful discussions with Jim Alessi (BNL), Chuck Schmidt and Doug Moehs (Fermilab), Hidetomo Oguri (JAERI), Robin Ferdinand and Raphael Gobin (CEA-Saclay), Detlef Kuechler (SPL), and Thomas Kuo(TRIUMF). The authors also acknowledge the LANSCE Division at LANL for providing support to prepare and present this review.

References

- [1] G. I. Dimov, Rev. Sci. Instrum. 67(10), 3393 (1996).
- [2] D. S. Barton, et. al., IEEE Trans. on Nuclear Science 30(4), 2787(1983).
- [3] C.-M. Kleffner, N. Holtkamp, M. Nagl, H. Poggensee, and J. Peters, Proc. of the XIX Int. Linac Conf., Argonne National Lab Report ANL-98/28, 875(1998).
- [4] C. Hojvat, et. al., IEEE Trans. On Nuclear Science 26(3), 3149(1979).
- [5] S. Fukumoto, Part. Accel. 20(1), 71(1986).
- [6] I. S. K. Gardner, Proc. of the 6th European Particle Accelerator Conference, (Stockholm, Sweden), 98(1998).
- [7] John M. Carpenter, Thomas H. Blewitt, David L. Price, and Samuel A. Werner, Physics Today 32(12), 42(1979).
- [8] Seventh ESS General Meeting, Seggau, Austria, Sept. 2001.
- [9] M. Ikegami, T. Kato, K. Hasegawa, and Y. Yamazaki, "High-Intensity Proton Linac for the KEK/JAERI Joint Project", Proc. of the 20th ICFA Advanced Beam Dynamics Workshop(ICFA-HB2002), Fermilab(2002), to be published.
- [10] D. H. Fitzgerald, H. Ahn, B. Blind, M. J. Borden, R. J. Macek, F. Neri, M. A. Plum, C. R. Rose, H. A. Thiessen, C. A. Wilkinson, and M. V. Zumbro, Proc. of the 1997 Particle Accelerator Conference, IEEE Catalog No. 97CB36167, 1012(1997).
- [11] Jie Wei, "The Spallation Neutron Source Project – Physical Challenges and Technical Issues", Proc. of the 20th ICFA Advanced Beam Dynamics Workshop(ICFA-HB2002), Fermilab(2002), to be published.
- [12] R. Garoby, "Status and Plans of the SPL Study at CERN", Proc. of the 20th ICFA Advanced Beam Dynamics Workshop(ICFA-HB2002), Fermilab(2002), to be published.
- [13] K. Prelec and Th. Sluyters, Rev. Sci. Instrum. 44(10), 1451(1973).

- [14] Charles W. Schmidt, "Review of Negative Hydrogen Ion Sources", Proc. of the 1990 Linear Accelerator Conference, Los Alamos Report (LA-12004-C), 259(1990).
- [15] R. Keller, "Ion Source and Low-Energy Beam Transport Issues for H⁻ Accelerators", Proc. of the 1999 Particle Accel. Conf., IEEE Catalog No. 99CH36366, 87(1999).
- [16] J. Peters, "Review of High Intensity H⁻ Sources and Matching to High-Power RFQs", Proc. of the 2000 European Particle Accelerator Conf., 113(2000).
- [17] K. W. Ehlers, Nucl. Instrum. Meth. 32, 309 (1965).
- [18] G. J. Schulz, Phys. Rev. 113(3), 816(1959).
- [19] G. J. Schulz and R. K. Asundi, Phys. Rev. Letters 15(25), 946(1965).
- [20] E. Nicolopoulou, M. Bacal, and H. J. Doucet, J. Phys. (Paris)38, 1399 (1977).
- [21] M. Bacal, A. M. Bruneteau, W. G. Graham, G. W. Hamilton, and M. Nachman, J. Appl. Phys. 52(3), 1247(1981).
- [22] M. Allan and S. F. Wong, Phys. Rev. Letters 41(26), 1791(1978).
- [23] G. C. Stutzin, A. T. Young, A. S. Schlachter, K. N. Leung, and W. B. Kunkel, Chem. Phys. Letters 155(4,5), 475(1989).
- [24] J. N. Bardsley and J. M. Wadehra, Phys. Rev. A20, 1398(1979).
- [25] J. R. Hiskes, Comments At. Mol. Phys. 19(2), 59(1987).
- [26] K. W. Ehlers and K. N. Leung, Rev. Sci. Instrum. 53, 1423 (1982).
- [27] R. Celiberto, et. al., Atomic Data and Nuclear Data Tables 77, 161(2001).
- [28] K. N. Leung, K. W. Ehlers, and R. V. Pyle, Rev. Sci. Instrum 56(3), 364(1985).
- [29] J. G. Alessi, K. Prelec, and D. McCafferty, 6th International Symposium on the Production and Neutralization of Negative Ions and Beams, AIP Conf Proc. No. 287, 387(1992).
- [30] J. Peters, Rev. of Sci. Instrum. 69(2), 992 (1998).
- [31] J. Peters, 9th International Symposium on the Production and Neutralization of Negative Ions and Beams, AIP Conf. Proc, Saclay, France (2002), to be published.
- [32] H. Oguri, Y. Okumura, K. Hasegawa, Y. Namekawa, and T. Shimooka, Rev. of Sci. Instrum. 73(2), 1021(2002).
- [33] K. Saadatmand and N. C. Okay, Proc. of H⁻ Ion Source Workshop for High-Energy Accelerators, Dallas, Texas, May, 1992.
- [34] David Spence and Keith R. Lykke, Proc. of the XIX International Linac Conference, Argonne National Lab Report ANL-98/28, 508(1998).
- [35] T. Kuo, D. Yuan, K. Jayamanna, M. McDonald, R. Bartman, W. Z. Gelbart, N. Stevenson, P. Schmor, and G. Dutto, Rev. Sci. Instrum 69(2), 959(1998).
- [36] R. I. Hall, I. Cadez, M. Landau, F. Pichou, and C. Schermann, Phys. Rev. Letters 60(4), 337(1988).
- [37] T. Inoue, Y. Matsuda, Y. Ohara, Y. Okumura, M. Bacal, and P. Berlemont, Plasma Sources Sci. Technol. 1, 75(1992).
- [38] J. Peters, PhD Thesis, Universitaet Frankfurt, 107(2001).
- [39] M. Nishiura, M. Sasao, Y. Matsumoto, M. Hamabe, M. Wada, H. Yamaoka, and M. Bacal, Rev. of Sci. Instrum 73(2), 949(2002).
- [40] J. Peters, Rev. Sci. Instrum. 73(2), 900(2002).
- [41] K. N. Leung, C. A. Hauck, W. B. Kunkel, and S. R. Walther, Rev. Sci. Instrum. 60(4), 531(1989).

- [42] K. N. Leung, D. A. Bachman, and D. S. McDonald, *Rev. Sci. Instrum.* 64(4), 970(1993).
- [43] Yu. I. Belchenko, G. I. Dimov, and V. G. Dudnikov, *ZhTF* 43, 1720(1973).
- [44] Yu. I. Belchenko, G. I. Dimov, and V. G. Dudnikov, *Proc. of the Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams*, Brookhaven National Laboratory report BNL 50727, 79(1977).
- [45] T. Okuyama and Y. Mori, *Rev. Sci. Instrum.* 63(4), 2711(1992).
- [46] Yu Belchenko, *Rev. Sci Instrum.* 64(6), 1385(1993).
- [47] P. W. van Amersfoort, J. J. C. Geerlings, R. Rodnik, E. H. A. Granneman, and J. Los, *J. Appl. Phys.* 59(1), 241(1986).
- [48] S. T. Melnychuk, M. Seidl, W. Carr, J. Isenberg, and J. Lopes, *J. Vac. Sci Technol* A7(3), 2127(1989).
- [49] M. Seidl, H. L. Cui, J. D. Isenberg, H. J. Kwon, and B. S. Lee, *Proc. of the 6th International Symposium on the Production and Neutralization of Negative Ions and Beams*, AIP Conf. Proc No. 287, 25(1992).
- [50] M. A. Leitner, D. W. Cheng, R. A. Gough, R. Keller, K. N. Leung, S. K. Mukherjee, P. K. Scott, M. D. Williams, *Proc. of the 1999 Part. Accelerator Conf., IEEE Catalog Number 99CB36366*, 1911(1999).
- [51] R. Thomae, P. Bach, R. Gough, J. Greer, R. Keller, and K. N. Leung, *Proceedings of the Linac2000*, Stanford Linear Accelerator Report SLAC-R-561, 233(2000).
- [52] R. Keller, R. Thomae, M. Stockli, and R. Welton, "Design, Operational Experiences, and Beam Results Obtained with the SNS H⁻ Ion Source and LEBT at Berkeley Lab", 9th International Symposium on the Production and Neutralization of Negative Ions and Beams, AIP Conf. Proc, Saclay, France (2002), to be published.
- [53] R. F. Welton, M. P. Stockli, J.E. Boers, R. Rauniyar, R. Keller, J. Staples, and R. W. Thomae, *Rev. Sci. Instrum.* 73(2), 1013(2002).
- [54] R. F. Welton, M. P. Stockli, Y. Kang, M. Janney, R. Keller, R. W. Thomae, T. Schenkel, and S. Shukla, *Rev. Sci. Instrum* 73(2), 1008(2002).
- [55] K. Volk, A. Maaser, and H. Klein, *Proc. of the XIX International Linac Conference*, Chicago, IL, Argonne National Lab report ANL-98/28, 896(1998).
- [56] K. Saadatmand, G. Arbique, J. Hebert, R. Valicenti, and K. N. Leung, *Rev. Sci. Instrum.* 67(3), 1318(1996).
- [57] Kenneth W. Ehlers, *Proc. International Ion Engineering Conf., ISLAT83 and IPAT83* (Kyoto), 54(1983).
- [58] K. W. Ehlers and K. N Leung, *Rev. Sci. Instrum.* 51(6), 721(1980).
- [59] P. J. M. van Bommel, K. N. Leung, and K. W. Ehlers, *Proc. of the 3rd International Conf. on the Production and Neutralization of Negative Ions and Beams*, AIP Conf. Proc. No. 111, 258(1983).
- [60] C. F. A. van Os, P. W. van Amersfoort, and J. Los, *J. Appl. Phys.* 64(8), 3863(1988).
- [61] C. F. A. van Os, A. W. Kleyn, L. M. Lea, A. J. T. Holmes, and P. W. Amersfoort, *Rev. Sci. Instrum.* 60(4), 539(1989).
- [62] C. F. A. van Os, K. N. Leung, and W. B. Kunkel, *Appl. Phys. Lett.* 57(9), 861(1990).
- [63] C. F. A. van Os, K. N. Leung, and W. B. Kunkel, *J. Appl. Phys.* 69(6), 3485(1991).
- [64] J. P. Biersack and W. Eckstein, *Appl. Phys A34*, 73(1984).

- [65] Ralph R. Stevens, Jr., Rob L. York, John R. McConnell, and Robert Kandarian, Proc. of the 1984 Linear Accelerator Conf, Gesellschaft fur Schwerionenforschung Report GSI-84-11, 226(1984).
- [66] R. L. York, Ralph R. Stevens, Jr., R. A. DeHaven, J. R. McConnell, E. P. Chamberlain, and R. Kandarian, Nucl. Instrum. And Methods in Phys. Res B10/11, 891(1985).
- [67] A. Takagi, Y. Mori, K. Ikegami, and S. Fukumoto, IEEE Trans. on Nucl Sci., NS-32 (5), 1782(1985).
- [68] S. Hoekstra, K. N. Leung, R. Thomae, and B. Prichard, Proc. of the 7th European Particle Accelerator Conf., Vienna, Austria, 1604(2000).
- [69] R. Keller, J. M. Verbeke, P. Scott, M. Wilcox, L. Wu, and N. Zahir, Proc. of the 1999 Part. Accelerator Conf., IEEE Catalog Number 99CB36366, 1926(1999).
- [70] Benjamin A. Prichard, Jr., and Ralph R. Stevens, Jr., "Status of the SPSS H⁻ Ion Source Development Program", LANL Report No. LA-UR-02-547(2002).
- [71] A. Takagi, KEK, priv. communication.
- [72] Rodney C. McCrady, Mark S. Gulley, and Andrew Browman, LANSCE-6 Technical Report, LA-UR-01-6005(2001).
- [73] Yu. I. Belchenko, G. I. Dimov, and V. G. Dudnikov, Izvestiya Akademii Nauk SSSR. Seriya Fizicheskaya 37(12) 2573(1973).
- [74] J. E. Boers, Proc. of the 1995 Particle Accelerator Conf., IEEE Catalog No. 95CH35843, 2312(1995).
- [75] C. F. Barnett, et. al., Atomic Data for Fusion 1, Oak Ridge National Lab Report, ORNL-6086 (July, 1990).
- [76] G. E. Derevyankin and Vadim Dudnikov, Proc. of the 3rd International Symp. on the Prod. and Neut. of Negative Hydrogen Ions and Beams", AIP Conf Proc. No. 111, 376(1983).
- [77] M. L. Yu, Phys. Rev. Letters 40(9), 574(1978).
- [78] W. G. Graham, Proc. of the 2nd Int. Symp. on the Prod. and Neut. of Negative Hydrogen Ions and Beams", Brookhaven National Lab report BNL 51304, 126(1980).
- [79] V. G. Dudnikov, Proc. of the 2nd Int. Symp. on the Prod. and Neut. of Negative Hydrogen Ions and Beams", Brookhaven National Lab report BNL 51304, 137(1980).
- [80] H. Vernon Smith, Jr., and Paul Allison, Rev. Sci. Instrum. 53(4), 405(1982).
- [81] James G. Alessi, Proc. 4th Symp. on the Prod. and Neut. of Negative Hydrogen Ions and Beams", AIP Conf Proc. No. 158, 419(1987).
- [82] J. Alessi, Proc. of the 20th ICFA Advanced Beam Dynamics Workshop(ICFA-HB2002), Fermilab(2002), to be published.
- [83] C. W. Schmidt and C. D. Curtis, Proc. 4th Symp. on the Prod. and Neut. of Negative Hydrogen Ions and Beams", AIP Conf Proc. No. 158, 425(1987).
- [84] D. P. Moehs, 9th International Symposium on the Production and Neutralization of Negative Ions and Beams, AIP Conf. Proc, Saclay, France (2002), to be published.
- [85] J. Peters, Proc. of the 18th International Linear Accelerator Conf, Geneva, Switzerland, 199(1996).
- [86] R. Sidlow and N. D. West, Proc. 3rd European Particle Accelerator Conf., 1002(1992).
- [87] R. Sidlow, P. J. S. Barratt, A. P. Letchford, M. Perkins, and C. W. Planner, Proc. 5th European Particle Accelerator Conf., 1525(1996).

- [88] J. W. G. Thomason and R. Sidlow, Proc. 7th European Particle Accelerator Conf., 1625(2000).
- [89] Paul W. Allison, IEEE Trans. on Nucl., Sci 24(3), 1594 (1977).
- [90] H. Vernon Smith, Jr., Joseph D. Sherman, and Paul Allison, Proc. of the 1988 Linear Accelerator Conf, CEBAF Report-89-01, 164(1988).
- [91] H. Vernon Smith, Jr., Paul Allison, and Joseph D. Sherman, Rev. Sci Instrum. 65(1), 123(1994).
- [92] Joseph D. Sherman, William B. Ingalls, Gary Rouleau, and H. Vernon Smith, Jr., Proc. of the 20th ICFA Advanced Beam Dynamics Workshop(ICFA-HB2002), Fermilab(2002), to be published.
- [93] J. W. G. Thomason, R. Sidlow, and M. O. Whitehead, Rev. Sci. Instrum. 73(2), 896(2002).
- [94] R. F. Welton, et. al., 9th International Symposium on the Production and Neutralization of Negative Ions and Beams, AIP Conf. Proc, Saclay, France (2002), to be published.
- [95] W. Kraus, P. McNeely, E. Speth, B. Heinemann, O. Vollmer, and R. Wilhelm, Rev. Sci. Instrum 73(2), 1096(2002).
- [96] K. Jayamanna, D. Yuan, T. Kuo, M. McDonald, P. W. Schmor, and G. Dutto, Rev. Sci. Instrum. 67(3), 1061(1996).
- [97] M. Tanaka and K. Amemiya, Rev. of Sci. Instrum. 71(2), 1125(2000).
- [98] R. Gobin, K. Benmeziane, O. Delferriere, R. Ferdinand, F. Harrault, and J. D. Sherman, 9th International Symposium on the Production and Neutralization of Negative Ions and Beams, AIP Conf. Proc, Saclay, France (2002), to be published.
- [99] A. Takagi and Y. Mori, Rev. of Sci. Instrum. 71(2), 1042(2000).