ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA05

AN H^{-} INJECTOR FOR THE ESS STORAGE RING

V. Dudnikov†, M. Popovic, M. A. C. Cummings
Muons, Inc., Batavia, IL, USA

Abstract

H^{-} charge exchange (stripping) injection into the European Spallation neutron Source (ESS) Storage Ring requires a 90 mA H^{-} ion source that delivers 2.9-ms pulses at 14-Hz repetition rate (duty factor ~4%) that can be extended to 28~Hz (df 8%). This can be achieved with a magnetron surface plasma H^{-} source (SPS) with active cathode and anode cooling. The Brookhaven National Laboratory (BNL) magnetron SPS can produce an H^{-} beam current of 100 mA with about 2-kW discharge power and can operate up to 0.7 % duty factor (average power 14 W) without active cooling. We describe how active cathode and anode cooling can be applied to the BNL source to increase the average discharge power up to 140 W (df 8%) to satisfy the needs of the ESS. We also describe the use of a short electrostatic LEBT as is used at the Oak Ridge National Laboratory Spallation Neutron Source to improve the beam delivery to the RFQ.

INTRODUCTION

H^{-} charge exchange (stripping) injection [1] into the European Spallation neutron Source (ESS) Storage Ring requires 80 mA H^{-} ion source that delivers 2.9-ms pulses at 14-Hz repetition rate (duty factor ~4%) [2, 3] that can be extended to 28 Hz (df 8%). This can be achieved with a magnetron surface plasma H^{-} source (SPS) with active cathode and anode cooling. The Brookhaven National Laboratory (BNL) magnetron SPS can produce an H^{-} beam current of 100 mA with about 2-kW discharge power and can operate up to 0.7 % duty factor (average power 14 W, energy efficiency up to 67 mA/kW) without active cooling [4]. An RF SPS in SNS have energy efficiency ~1 mA/kW [5]. We describe how active cathode and anode cooling can be applied to the BNL source to increase the average discharge power up to 140 W (df 8%) to satisfy the needs of the ESS. We also describe the use of a short electrostatic LEBT as is used at the Oak Ridge National Laboratory Spallation Neutron Source to improve the beam delivery to the RFQ.

ADVANCED DESIGN
OF MAGNETRON SPS

An advanced design of magnetron SPS with the spherical focusing of emitted negative ions and forced cathode and anode cooling is shown in Fig. 1. This new magnetron SPS is capable for DC operation with high average negative ion current generation.

Cross sections of new magnetron are shown in Fig. 1 [6]. A disc shape cathode (1) has 18-mm diameter D and 12-mm thickness H. A surrounded anode (2) is separated from the cathode by insulators (3). A vacuum gap between cathode and anode is d~1 mm. Cathode is cooled by liquid or gas flux flowing through the cooling tube (5) with OD~4 mm. The magnetron is compressed by ferromagnetic poles (4).

A working gas is injected to the discharge chamber through a channel (10). Cesium is added to discharge through second channel (11). Magnetic field, created by magnet (13) and formed by magnetic poles (4) has direction along axis of cooling tube (5).

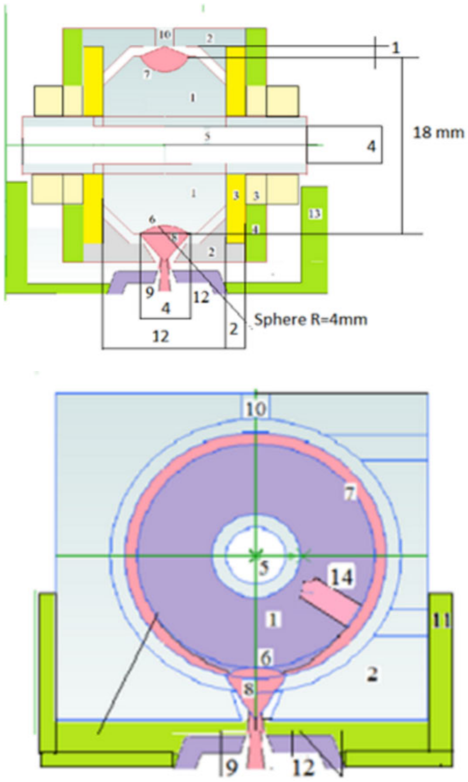


Figure 1: (Collar online) Cross sections of magnetron SPS with cathode cooling. (top- along the magnetic field; bottom- median transverse to the magnetic field section): 1-cathode disc; 2-anode; 3-insulators; 4-magnetic poles; 5-cooling tube; 6-spherical dimple (negative ion emitter, $R = 4$ mm); 7-cylindrical grove (discharge channel, $r = 3$ mm); 8-flux of focused negative ions; 9-negative ion beam extracted through emission aperture (2 mm diameter); 10-gas inlet; 11-cesium inlet; 12-extractor; 13-magnet; 14-hollow cathode.

The discharge in the crossed E×B fields is localized in the cylindrical grove (7) as in the semiplanotrons SPS. The cylindrical grove focus emitted negative ions to the anode surface and fast particles keep anode surface clean by sput-

---

† dvg43@yahoo.com

tering the flakes and deposit. A plasma drift in the discharge can be closed around the cathode perimeter or can be bracket by shallow cylindrical grove. For beam formation are used negative ions emitted from the spherical dimple (6), geometrically focused to the emission aperture made in anode (2). These ions are extracted by electric field applied between anode (2) and extractor (12). The spherical dimple with a curvature radius $R \sim 4$ mm has a working surface of ~ 12 mm^2.

For the emission current H^- of 0.1 A, it is necessary to have the emission current density on the cathode surface $J_e \sim 1$A/cm^2, which is acceptable for pulsed operation. The emission current density of H^- ~ 0.1 A/cm^2 necessary for 10 mA extraction is acceptable for DC operation. The anode (2) is cooled by gas or liquid flow flowing through the cooling tube attached to the anode front. The material of cathode and anode for H^- beam production is Molybdenum. The surface of spherical dimple should by mirror smooth for efficient negative ion emission and sharp focusing into the emission aperture.

The three-dimensional image of a magnetron SPS with cooled cathode is shown in Fig. 2. Photographs of cathode and anode of magnetron SPS with active cooling is shown in Fig. 3.

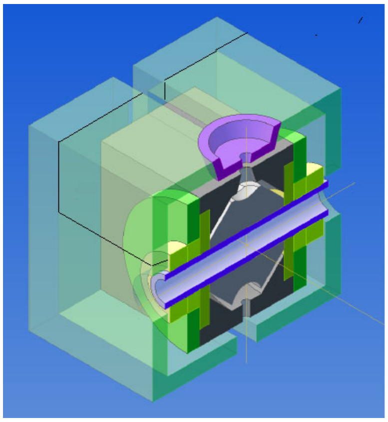


Figure 2: Three-dimensional image of a magnetron SPS with cooled cathode.

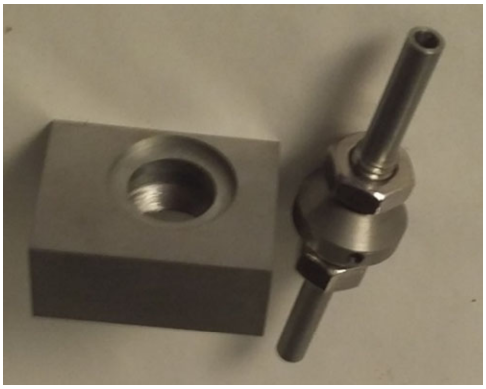


Figure 3: Photographs of cathode and anode of magnetron SPS with active cooling.

For heavy negative-ion production it is possible to use some compound with necessary elements and necessary emission and discharge properties such as LaB_6 [7]. Two stage extraction/acceleration is preferable for operation with high average beam current for collection of co-extracted electrons to the electrode with low potential. A gas valve [8] can be used for pulsed operation.

A schematic of proposed ESS injector is shown in Fig. 4. It consist from surface plasma negative ion source with magnetron configuration comprising of cathode 1 and anode 2 with emission aperture, extractor electrode 3 and magnetic pole 4. Extracted ion beam is accelerated to grounded electrode 6. Co-extracted electrons collected by electron dump 4. The accelerated beam is focused by electrostatic Einzel lens 1 (7) and lens 2 (9) into RFQ wall aperture 10 and focused by RFQ vanes 12.

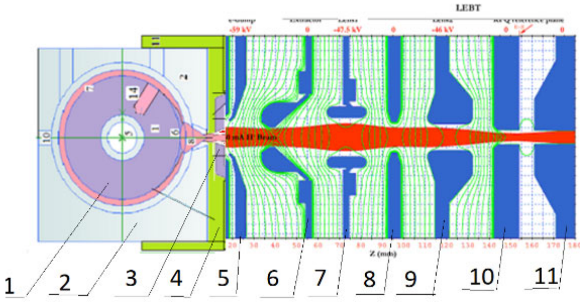


Figure 4: A schematic of proposed ESS injector: 1-cathode, 2-anode, 3-extractoe, 4-magnetic pole, 5-electron damp, 6-grounded electrode, 7-lense 1, 8-grounded electrode, 9-lense2, corrector, 10-RFQ wall, 12-RFQ van.

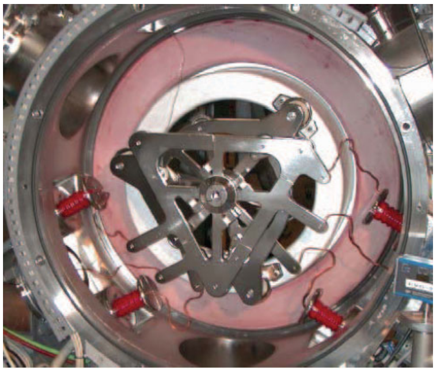


Figure 5: Construction of the LEBT for transporting the H^- beam in RF SPS for SNS to the RFQ.

A design of electrostatic LEBT is shown in Fig. 5. It operates well with H^- beam current equal to 60 mA at 65 kV with df up to 10%.

A joint of beams from two ion sources is presented in [4]. But it more practical to have two separate RFQ for protons and for H^- and joint both beams after RFQ. Figure 6 shows a preferable schematic of joint p and H^- beams.

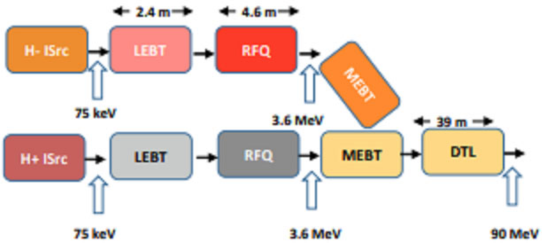
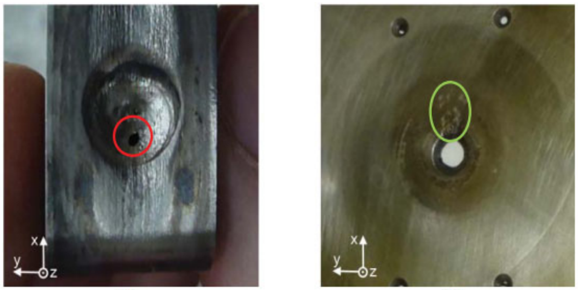


Figure 6: The layout merges the two species in the MEBT from [2].

Figure 7 shows the erosion of material on a BNL magnetron SPS that successfully operated for 2 years: the cathode has a hole of 1.8 mm^2 close to the center of its spherical focusing dimple, and the anode cover plate shows marks in the vicinity of the extraction hole spread in an area of 6.2 mm^2, which does not affect magnetron operation. This damage is produced back-accelerated positive ions of Cs^+ and H_2^+. Estimation of sputtering of cathode and anode magnetron SPS is presented in [9].

Unfortunately, the estimation of Cesium density was incorrect, because during discharge Cesium is strongly ionized and cannot escape the discharge chamber, shown in Fig. 7 [10, 11]. Figure 8 presents a typical oscillogram of the cesium ion current from the collector of the mass spectrometer, illustrating changes in the cesium atoms flux from the source in time at a high (~1000 K) planotron cathode temperature, in conjunction with oscillograms of discharge current I_p and discharge voltage U_d. One can see that cesium atoms leave the source mainly after the end of the discharge pulse. Cesium release during the pulse is small, since cesium is highly ionized and the extraction voltage blocks the escape of cesium ions.



(a) (b)

Figure 7: Wear traces on the (a) cathode and (b) the anode cover plate of BNL's magnetron. The location of the traces on the cathode and anode cover plate is indicated by a circle and an ellipse (red and green), respectively.

CONCLUSION

A proposed H$^-$ injector with magnetron surface plasma source and short electrostatic LEBT can be good solution for H$^-$ beam injection into ESS linac.

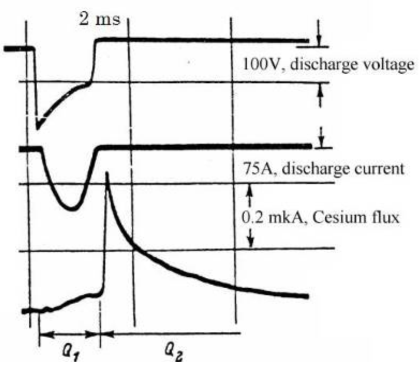


Figure 8: Characteristic oscillogram of cesium ion current from mass spectrometer collector, illustrating the time variation of cesium atoms flux from a planotron SPS at high cathode temperature (~1000 K); also showing oscillograms of discharge current I_d and discharge voltage U_d.

REFERENCES

[1] G. Budker, G. Dimov, and V. Dudnikov, "Experiments on producing intensive proton beams by means of the method of charge-exchange injection", *Sov. Atomic. Energy*, vol. 22, pp. 441-448, 1967. `doi:10.1007/BF01175205`

[2] A. Alekou *et al.*, "The European Spallation Source neutrino Super Beam Conceptual Design Report", Jun. 2022. `doi:10.48550/arXiv.2206.01208`

[3] A. Alekou *et al.*, "The European Spallation Source neutrino Super Beam", CERN, Geneva, Switzerland, Mar. 2022. `doi:10.48550/arXiv.2203.08803`

[4] A. Zelenski, G. Atoian, T. Lehn, D. Raparia, and J. Ritter, "High-intensity polarized and un-polarized sources and injector developments at BNL Linac", *AIP Conf. Proc.*, vol. 2373, p. 070003, 2021. `doi:10.1063/5.0057677`

[5] R. F. Welton *et al.*, "Improvements to the internal and external antenna H$^-$ ion sources at the Spallation Neutron Source", *Rev. Sci. Instrum.*, vol. 85, p. 02B135, 2014. `doi:10.1063/1.4858177`

[6] V. Dudnikov and G. Dudnikova, "Compact surface plasma H$^-$ ion source with geometrical focusing", *Rev. Sci. Instrum.*, vol. 87, p. 02B101, 2016. `doi:10.1063/1.4931700`

[7] V. Dudnikov and J. Paul Farrell, "Compact surface plasma sources for heavy negative ion production", *Rev. Sci. Instrum.*, vol. 75, p. 1732, 2004. `doi:10.1063/1.1695613`

[8] G. E. Derevyankin, V. G. Dudnikov, and P. A. Zhuravlev, "Electromagnetic shutter for a pulsed gas inlet into vacuum units", *Prib. Tekh. Eksp.*, vol. 5, p. 168-169, 1975.

[9] H. Pereira , J. Lettry , J. Alessi, and T. Kalvas, "Estimation of sputtering damages on a magnetron H$^-$ ion source induced by Cs+ and H+ ions", *AIP Conf. Proc.*, vol. 1515, p. 81, 2013. `doi:10.1063/1.4792773`

[10] Yu. Belchenko, V. I. Davydenko, G. E. Derevyankin, A. F. Dorogov, and V. G. Dudnikov, *Sov. Tech. Phys. Lett.*, vol. 3, p. 282, 1977.

[11] V. Dudnikov, *Development and Applications of Negative Ion Sources*, Springer, New York, NY, USA, 2019.