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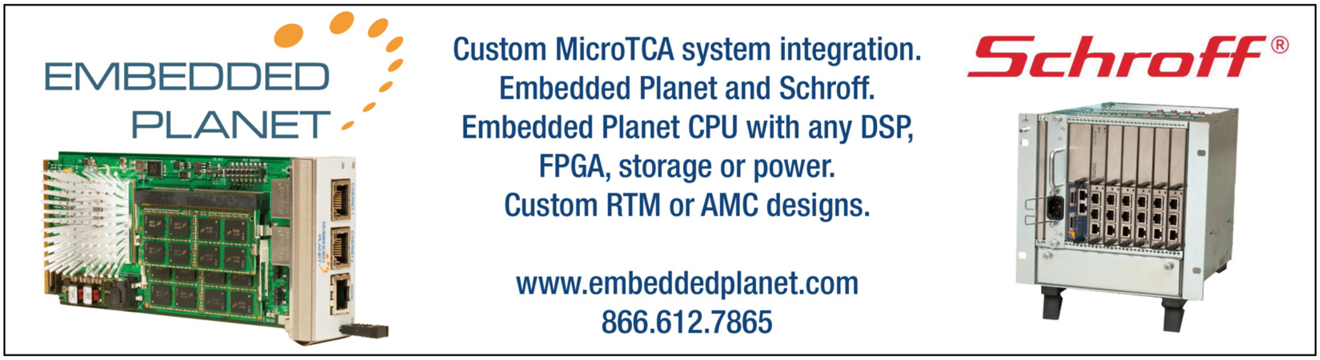

REVIEW OF SCIENTIFIC INSTRUMENTS **83**, 02A728 (2012)

Investigation of ISIS and Brookhaven National Laboratory ion source electrodes after extended operation[a)]

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Linac4 accelerator of Centre Européen de Recherches Nucléaires is under construction and a RF-driven H^- ion source is being developed. The beam current requirement for Linac4 is very challenging: 80 mA must be provided. Cesiated plasma discharge ion sources such as Penning or magnetron sources are also potential candidates. Accelerator ion sources must achieve typical reliability figures of 95% and above. Investigating and understanding the underlying mechanisms involved with source failure or ageing is critical when selecting the ion source technology. Plasma discharge driven surface ion sources rely on molybdenum cathodes. Deformation of the cathode surfaces is visible after extended operation periods. A metallurgical investigation of an ISIS ion source is presented. The origin of the deformation is twofold: Molybdenum sputtering by cesium ions digs few tenths of mm cavities while a growth of molybdenum is observed in the immediate vicinity. The molybdenum growth under hydrogen atmosphere is hard and loosely bound to the bulk. It is, therefore, likely to peel off and be transported within the plasma volume. The observation of the cathode, anode, and extraction electrodes of the magnetron source operated at BNL for two years are presented. A beam simulation of H^-, electrons, and Cs^- ions was performed with the IBSimu code package to qualitatively explain the observations. This paper describes the operation conditions of the ion sources and discusses the metallurgical analysis and beam simulation results. © *2012 American Institute of Physics*.
[http://dx.doi.org/10.1063/1.3680078]

I. ISIS ION SOURCE AND OPERATION

The ISIS operational ion source[1] has successfully provided beam for the ISIS spallation neutron source for over 25 years. The H^- Penning surface plasma source was first developed by Dudnikov[2] in 1974. The version used at ISIS comprises a molybdenum anode and cathode between which a low-pressure hydrogen discharge is produced (Figure 1). A transverse magnetic Penning field is applied across the discharge. The anode is hollow and has three equal-sized holes through which cesium vapor is fed from an oven via a heated transport line (held at 300 °C) into one side of the discharge via two of the holes. Hydrogen gas is pulsed via a piezoelectric valve into the discharge via the third hole. The anode and cathode are housed in a stainless steel source body, the body is air cooled and the mounting flange is water cooled. The beam is extracted through a 0.6 mm by 10 mm slit in the aperture plate (plasma electrode). There is a 2.3 mm gap between the extraction electrode and the aperture plate. The source is pulsed at 50 Hz. After extraction, the beam is bent through a 90° sector magnet mounted on a refrigerated cesium trap and further accelerated by a post-extraction acceleration gap.

The ISIS operational ion source routinely produces 55 mA of H^- ions during a 200–250 μs pulse at 50 Hz for uninterrupted periods of up to 50 days. The average lifetime of a source is about 21 days. Table I gives a summary of typical conditions for the operational source.

After only five days of operation, the signs of electrode surface wear become visible. The cathode surfaces start to show a redistribution of electrode material away from the two anode holes where cesium vapor is fed in. The material is redistributed on the cathode surfaces near the third hole in the anode where the hydrogen is delivered. This process is caused by Cs^+ ions sputtering the molybdenum surface after being accelerated by the cathode plasma sheath potential. A groove along the length of the anode also starts to appear. This is

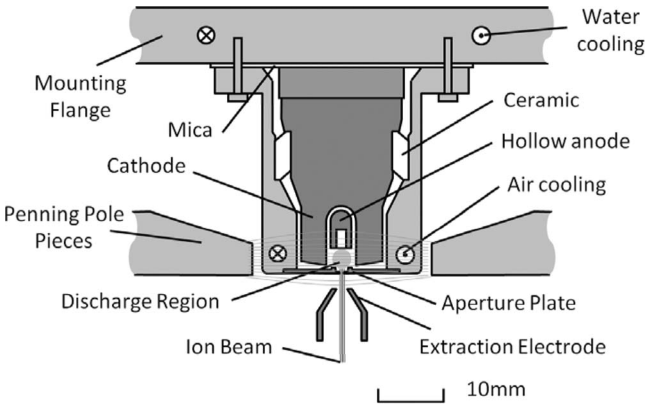

FIG. 1. A cross section though the ISIS Penning source.

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TABLE I. ISIS operational source running parameters.

Discharge current	55 A
Discharge voltage	60–70 V
Discharge pulse length	600–800 μs
Repetition rate	50 Hz
Extraction voltage	17 kV
Extraction current	100–500 mA
Extraction pulse length	200–250 μs
Cesium oven temperature	160–190 °C
Cesium consumption	≈3 g/month
Hydrogen consumption	10–20 ml/min
Electrode temperatures	400–550 °C
H^- beam current at ground plane of post extraction acceleration gap	50–55 mA
H^- beam current at entrance to linac	30–35 mA

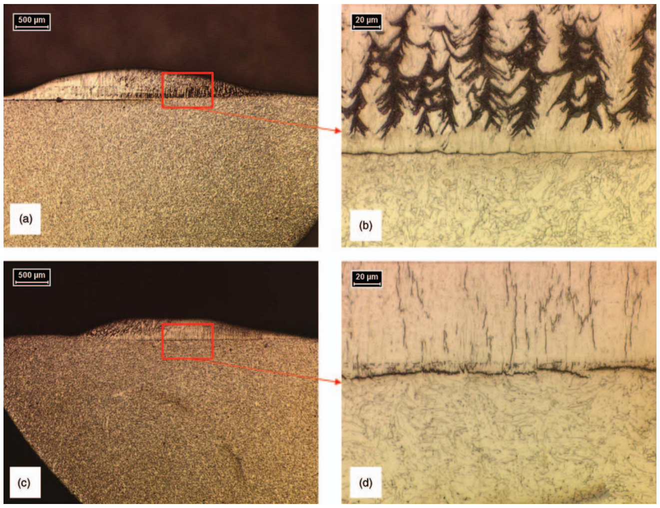

FIG. 2. (Color online) Micrograph of the Mo-cathode of the ISIS Penning source, the region facing the hydrogen injection (a) shows a dendritic growth structure (b) and the one facing Cs-injection (c) a column-like growth pattern (d). Cracks are visible between bulk and the deposited layers.

caused by sputtering from Cs^+ and H^+ ions being back accelerated across the extraction gap, through the aperture slit and hitting the anode. After about ten days, flaking and debris start to appear in the source. The loose flakes have the potential to partially block the aperture slit. This phenomenon results in a measurable step change in source output current. Very large flakes can occasionally short out the anode and cathode resulting in a complete loss of output. The inside of the aperture plate is also an anode for the plasma; after about 15 days, this surface also starts to show signs of wear. There are two ribs on either side of the extraction slit and these are slowly eroded away. Deposits of molybdenum starting to grow on the aperture plate are major source of flake debris. As the source ages further, the wear on the electrodes increase with more material sputtered away and redeposit in the source. After 30 days, there has been significant transference of electrode material.

To get a deeper understanding of how the electrode material is transferred, a very long lifetime source (#48) was analyzed with a scanning electron microscope (SEM) at Centre Européen de Recherches Nucléaires. The source studied had run continuously with very constant operating conditions for 48 days. The current was stable between 31.5 mA and 33.5 mA and the electrodes temperatures slowly increased by 10 °C to 30 °C as the source aged. The temperature of the cesium oven was kept constant at 164 °C and the hydrogen flow rate was kept constant at 17 ml/min. The air cooling and water cooling were also kept constant as was the discharge duty cycle.

The cathode and extraction plate were investigated with the energy dispersive x ray and secondary electron imaging. Traces of cesium were only found inside the aperture plate. The cathode was cross-cut along a plane located half way between the anode tip and the extraction plate at 2 mm from the cathode end. Initially, the arc discharge plasma is populated with electrons, hydrogen, and cesium. Cs^+ ions will be accelerated to the cathode and via sputtering remove molybdenum atoms from the surface. The growth of the Mo-layer is shown in Figure 2. Two microstructures, different from the bulk, are observed. A crack is clearly visible between the bulk material and the deformed region. A micro hardness of 245 $HV_{0.1}$ in bulk material and 490 $HV_{0.1}$ in deformed area was measured and hints to the origin of the release of Mo-flakes.

II. BNL'S MAGNETRON ION SOURCE

BNL's magnetron[3] routinely operates at 6 Hz and delivers H^- pulses up to 100 mA at 35 kV. On the electrodes of an ion source successfully operated during at least two years, wear traces are visible on the cathode, the front anode plate, and the tungsten tip of the puller electrode. No electron dump is required in view of the very favorable e/H^- ratio which is below 1, and the low duty factor (0.5%). An upgrade to 45 kV as would be required to operate a magnetron as Linac4 ion source requires understanding of the origin of the observed wear. Simulations of the BNL magnetron beam extraction were done using the ion optical computer simulation package IBSimu.[4] The geometry includes the cathode, the anode, and the puller electrode. The objective is to observe the extracted beam behavior and simulate the conditions that lead to the damage observed on these elements after extended operation. The extracted H^- beam current density is set to 1.6 A/cm^2, resulting in a current of 100 mA. The electron to H^- ratio is 1/2 to match the working conditions.[3] A

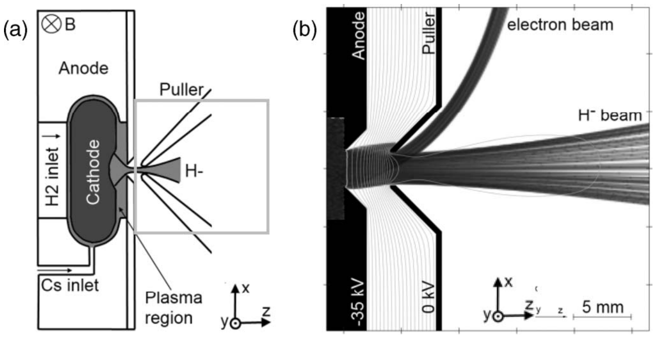

FIG. 3. (a) BNL magnetron scheme with highlighted simulated area; (b) simulated H^- beam and electron extraction.

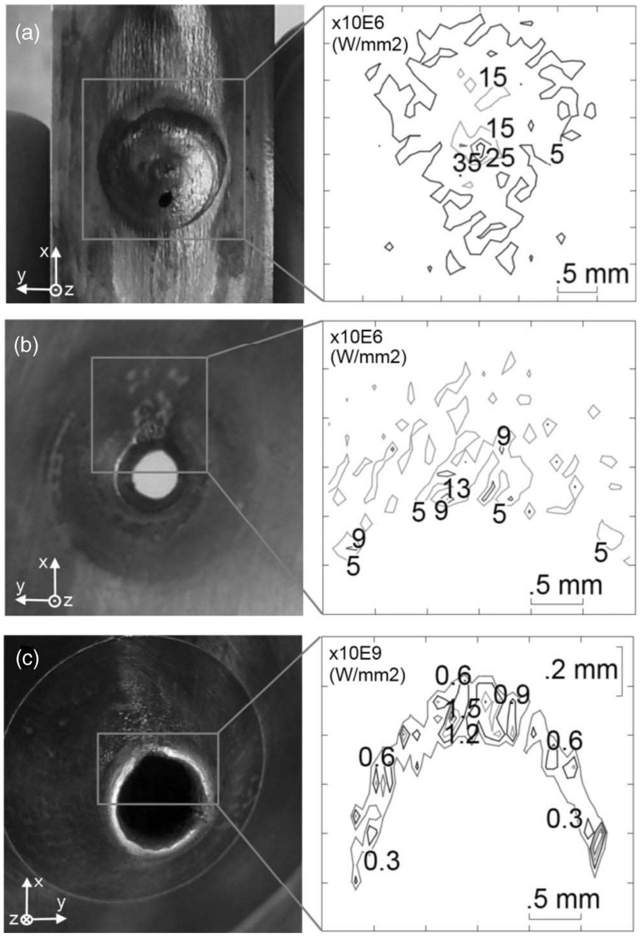

FIG. 4. Pictures and corresponding power density isolines of: (a) positive ions on the cathode dip, (b) positive ions on the anode surface, and (c) electrons and H^- ions on the puller electrode tungsten tip.

three-dimensional magnetic field map was calculated with OPERA (Ref. 5) using the known magnet geometry and adjusting the peak field to 900 G. This field map is imported and used in the simulations.

As a result of the simulation, it is noted that the extracted H^- beam is transmitted at close to 100% through the puller electrode and that the electrons, whose trajectories are bent by the magnetic field, are largely dumped on the tungsten tip of the puller electrode (Figure 3). The current of 30 mA dumped on the W-puller tip corresponding to 60% of the co-extracted electron current. The location of the interaction area in the simulation coincides with the observed electrode damage. The software package includes the creation of positive ions within the extraction region, i.e., originating from ionization of Cs vapors (or rest gas particles largely dominated by hydrogen). Once ionized, the resulting positive ions will travel backwards in direction of the anode. A Cs-current of 6 mA is arbitrarily set in the simulation only aiming at qualitative illustration of the process. The Cs-ions hit the cathode at a very concentrated point, close to its central dip. This may lead via sputtering of Mo-atoms to the formation of a hole comparable to the one observed experimentally (Figure 4(a)). On the vacuum side of the plasma electrode, a current of 3 mA of Cs ions is assumed; its impact is distributed on a larger area and its peak power density accordingly reduced (Figure 4(b)). The deposition profile matches the observed traces likely due to sputtering. The power density of the incoming electrons on the puller electrode surface reaches a maximum power density of 1.5×10^9 W/m^2 (Figure 4(c)).

III. DISCUSSION, CONCLUSION, AND OUTLOOK

Based on the observation of two of the most successful cesiated H^- ion sources worldwide, we conclude that sputtering and pulsed electron energy deposition are the leading electrode wear mechanisms. Despite a very favorable e/H^- ratio, a fraction of the co-extracted electrons is driving the wear mechanism of BNL's 35 kV puller electrode. Qualitative description of the wear mechanism was possible with modern 3D beam simulation packages that demonstrated impressive flexibility. Cesium and hydrogen positive ions are the likeliest candidates at the origin of the observed sputtering.

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