BORON ION BEAM PRODUCTION WITH THE SUPERNANOGAN ECR ION SOURCE FOR THE CERN BIO-LEIR FACILITY

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Abstract

To deliver B^{3+} ions for medical research the compounds decaborane and m-carborane were tested using the metal ions from volatile compounds (MIVOC) method with the Supernanogan 14.5 GHz ECR ion source. Using decaborane the source delivered less than 10 μA intensity of B^{3+} and after operation large deposits of material were found inside the source. Using m-carborane 50 μA of B^{3+} were delivered without support gas. For m-carborane, helium and oxygen support gasses were also tested, and the effects of different source tuning parameters are discussed. The average consumption of m-carborane was 0.1 mg/μAh over all operation.

INTRODUCTION

Over the last fifty years the field of ion beam therapy has developed from its first tests at the Lawrence Berkeley National Laboratory to, amongst other things, a powerful tool for the treatment of cancer tumours [1]. While the majority of treatments are conducted with protons, heavier ions provide different radiobiological properties and could be more useful in some cases [2]. Different ion species may hold specific advantages for treatment however, a comprehensive study of different viable species has not been completed. Ion beam therapy has been pioneered using carbon ions while helium, boron, lithium, oxygen and other light ion species require further studies to determine their radiobiological properties. No facility currently existing has been designed to deliver this range of ions from protons to neon exclusively for medical research. After discussion at CERN with many representatives of the radiobiological community a strong desire for such a facility has been expressed. Such a facility would allow for fundamental research in this field with new ion species, delivery techniques, and diagnostic tools [3].

The ion injection chain for the LHC starts with a 4.2 MeV/u ion Linac, followed by the Low Energy Ion Ring (LEIR) where the beam is multi-turn injected, and its emittance reduced with an electron cooling scheme. The ions then continue to the LHC through the PS and SPS synchrotrons. The energy range of LEIR (as the LHC lead injector it accelerates Pb^{54+} to 72 MeV/u) does not match the 430 MeV/u carbon beams that are delivered at for medical treatment, however with upgrades to the machine this should be achievable [4]. In the period between LHC fills, it could be envisaged to use LEIR for the delivery of different ion types. Regardless of how the beam is acceler-

ated for injection into LEIR, an ion source is needed. The chosen source must be capable of delivering most of the ions from protons to neon. The Supernanogan is a commercial, permanent magnet, 14.5 GHz ECR ion source currently being used at Heidelberg Ion Therapy Center, the Centro Nazionale di Adroterapia Oncologica (CNAO) and MedAustron to deliver carbon and protons [1]. The Supernanogan is capable of being operated with a micro-oven and gas mixing [5]. Of the ions up to neon, four ions present difficulties for producing ion beams. Beryllium, boron, lithium, and fluorine have not been routinely delivered from ECR ions sources and so production techniques for these ions require verification. Boron was selected to be investigated first using the Helmholtz-Zentrum Supernanogan, Berlin [6].

EXPERIMENT SETUP

Previously boron has been produced using the MIVOC technique at the University of Jyväskylä [7] and at the Flerov Laboratory for Nuclear Reactions (FLNR) in Dubna [8]. Both experiments used the same compound, m-carborane $C_2H_{12}B_{10}$, to deliver between $100 - 200$ μA of $^{11}B^{3+}$. For this work a second compound, decaborane, was also chosen as an alternative source of boron material in case problems arose with m-carborane. The relevant properties of decaborane and m-carborane are given in Tables 1 and 2.

Table 1: M-carborane Properties.

Property	Value
Atomic Formula	$C_2H_{12}B_{10}$
Mass Ratio	24 : 12 : 110
Melting Point	546 K
Vapor Pressure	0.05 mbar (at 300 K)
Phase at 300 K	Crystalline Solid

Table 2: Decaborane Properties.

Property	Value
Atomic Formula	$H_{14}B_{10}$
Mass Ratio	14 : 110
Melting Point	373 K
Boiling Point	486 K
Vapor Pressure	0.269 mbar (at 300 K)
Phase at 300 K	Crystalline Solid

To utilise the MIVOC technique, the Supernanogan oven was removed and the bias tube, which is used to mount the oven bayonet inside the chamber and act as a port for the coaxial RF transport line into the plasma chamber, was attached to a valve separating it from the MIVOC vacuum section. A vacuum chamber was attached to this, with two valves going to the MIVOC chamber and an ion pump respectively. The MIVOC chamber itself was separated from the rest of the vacuum system by a needle valve with a maximum flow of $1600\ cm^3s^{-1}$. This configuration is shown in Fig. 1. For both compounds the ampoule containing the compound was filled under an argon atmosphere, sealed with the needle valve closed and then attached to the vacuum system. Prior to operation some vacuum pumping was done in the MIVOC vacuum section to remove most of the argon before opening the valve to the plasma chamber. Throughout the experiment source pressure measure-
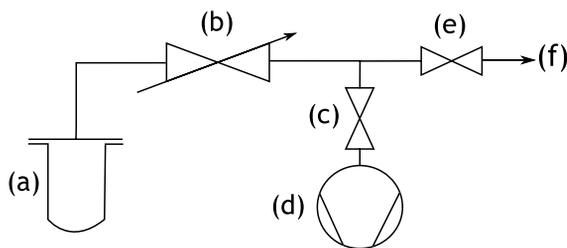
Figure 1: Diagram of the MIVOC setup attached to the injection end of the Supernanogan source. (a) Glass ampoule containing compound. (b) Needle valve with max $1600\ cm^{-3}s^{-1}$ flow. (c) Valve. (d) Vacuum Pump. (e) Valve to source bias tube, open for operation. (f) Source bias tube to plasma chamber.

ments were taken near the gas inlet, inside the RF matching cavity which attaches the RF waveguide to the source plasma chamber. Charge state intensities were measured using a Faraday cup after ion species separation through a spectrometer magnet.

DECABORANE

Decaborane was the first compound investigated. The needle valve was opened gradually until boron ions began to be extracted from the plasma. The minimum valve opening which allowed for $^{11}B^{3+}$ to be extracted corresponded to a source pressure of 3.36×10^{-6} mbar. Up to 480 μA of H^+ could be extracted while operating with decaborane. Over 24 hours the source conditions were varied however even after 24 hour conditioning of the source only 10 μA of $^{11}B^{3+}$ could be extracted. When the source was dismantled after operation, a macroscopic amount of material was found deposited inside the bias tube, and throughout the source. It is suspected that the decaborane underwent pyrolysis as described in [9]. Decaborane pyrolysis results in hydrogen and non-reactive hydrides, which would account for both the material deposited inside the source and the high H^+ intensity measured. No further analysis was performed on the deposited material.
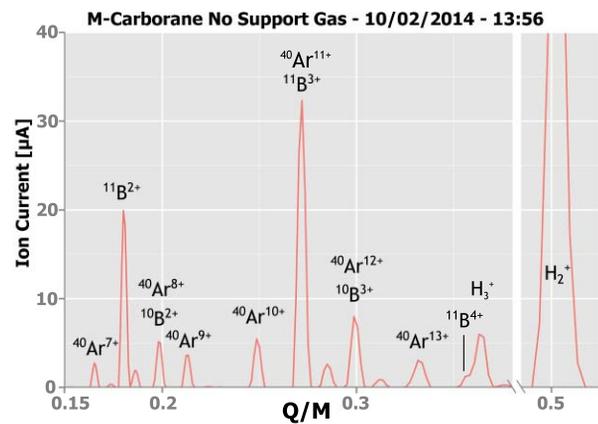
Figure 2: M-carborane charge state distribution without upport gas. 11 W injected RF power, 3.4×10^{-4} mbar at gas inlet valve, -50 V bias voltage, 15 kV extraction voltage. The observed Argon peaks come from filling the MIVOC container under an Argon atmosphere. The H_2^+ peak reaches 190 μA.

M-CARBORANE

The experiment setup for m-carborane was identical to hat of decaborane. The source was started without support gas, with injected RF power of 50 W, needle valve allowing pressure of 2×10^{-6} mbar, and bias voltage of -50 V. These conditions were arbitrary, and resulted in an immediate extracted current of $^{11}B^{3+}$ of 35 μA. Lowering the injected RF power to 30 W increased this to 45 μA. Fig. 2 shows a harge state distribution for 35 ± 1 μA of $^{11}B^{3+}$, however ome argon contamination is included. The argon distribuion implies that this contamination is on the order of 5 μA.

The extracted intensity of $^{11}B^{3+}$ showed a strong sensifivity to the injected RF power. The most stable intensity was achieved with the minimum possible 11 W of injected power which produced 38 ± 1 μA. The maximum intensity achieved was 56 ± 1.5 μA and was achieved with higher gas pressure in the source, with 30 W of injected RF power. Fig. 3 shows the initial source tuning. The sensitivity to the RF power was a limit on the extracted intensity during iniial tuing as once the power was increased above 50 W the plasma became very unstable, with very large variations in the extracted intensity of $^{11}B^{3+}$.

A further investigation into the intensity and injected RF power relationship is shown in Fig. 4. This secondary investigation was at fixed pressure of 3.5×10^{-7} mbar which during previous tuning had given the best stability of extracted $^{11}B^{3+}$ intensity. Higher injected power caused a reduction in extracted intensity of $^{11}B^{3+}$ without any decrease in stability. While Fig. 4 shows this trend the intensity peaks at 30 W. The data point at 30 W may be anomalous and verification would be required in further work. Higher powers than 70 W were not investigated as the extracted $^{11}B^{3+}$ intensity fell to 0 μA past 70 W at this pressure. At higher pressures the intensity did not fall to 0 μA but the stability became very poor with variations in extracted intensity of up to 10 μA on a second-to-second timescale. A long term

stability test was conducted over 21 hours. During this test the intensity fell by 5 μA and the short-term stability remained constant at ± 1 μA.
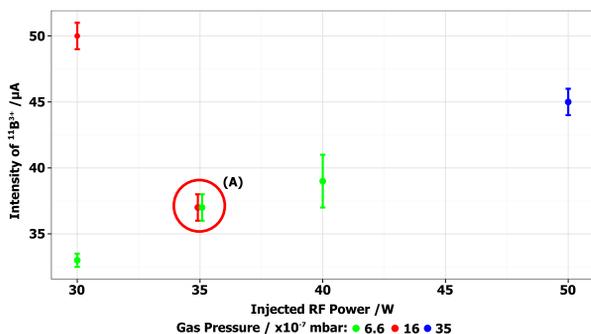
Figure 3: For these tests the extraction voltage was fixed at 15 kV and the bias voltage at -70 V. During initial tuning at 16×10^{-7} mbar an inverse relationship between injected RF power and extracted intensity was observed. (A) Note these two points are different pressure but the same intensity and instability, they have been separated for visibility but are both at 35 W. The error bars indicate the second-to-second variation in the observed intensity.
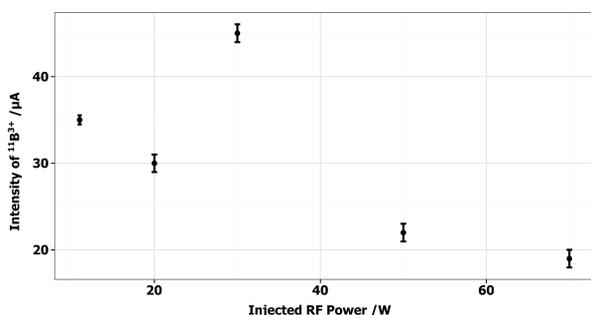
Figure 4: A follow up test to Fig. 3. The extraction voltage was fixed at 15 kV, and the bias disk at -70 V. Constant pressure of 3.5×10^{-7} mbar was maintained to observe the inverse power and extracted intensity relationship. The error bars indicate the second-to-second variation in the observed intensity.

Two support gases were investigated with m-carborane, helium and oxygen. With helium support gas up to 40 μA of $^{11}B^{3+}$ could be extracted at 1.36×10^{-6} mbar of pressure in the source, compared with 6×10^{-7} mbar without support gas. With this increased pressure in the source the plasma could tolerate up to 70 W of injected RF power before becoming unstable. This was 20 W more than it could tolerate without support gas. At lower injected RF power (50 W) the extracted intensity of $^{11}B^{3+}$ was lower compared to operation without support gas. Oxygen was also investigated however, much lower boron intensities (around 15 μA) were extracted than operation with helium or without support gas.

Over the 4 days of operation with m-carborane a consumption rate of 0.1 mg/μAh was observed being converted into $^{11}B^{3+}$. This is higher previously observed at JYFL and FLNR where 0.02 mg/μAh was converted into $^{11}B^{3+}$. Additionaly up to 235 μA of $^{11}B^{3+}$ were observed with the JYFL source compared with 56 μA from the Supernanogan.

CONCLUSIONS

In conclusion, using m-carborane, the Supernanogan is capable of delivering up to 50 μA of $^{11}B^{3+}$ varying by up to 1 μA on a second-to-second timescale. The long term stability tests suggest this intensity can be sustained over 24 hour periods limited only by the size of the ampoule containing the material, with a consumption rate of 0.1 mg/μAh. Both helium and oxygen support gases were tested with m-carborane which allowed for higher injected RF power of 70 W before instabilities arose, however the extracted intensity was not higher than operation without support gas. Increasing the pressure of just m-carborane did not allow for increased extraction intensity either. Further investigation into the intensity–RF dependence could be done to try to understand why increased injected power reduced the extracted intensity.

Decaborane was also investigated but delivered a very low intensity of $^{11}B^{3+}$. This is suspected to be caused by pyrolysis of decaborane during diffusion through the bias tube into the plasma chamber. If decaborane were to be re-investigated, cooling of the diffusion channel should be considered. The decaborane pyrolysis deposited macroscopic amounts of boron compounds throughout the source.

ACKNOWLEDGEMENTS

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