H^- SOURCE DEVELOPMENT FOR JYVÄSKYLÄ CYCLOTRON

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Abstract

A new H- ion source terminal has been constructed since 2000 for the Jyväskylä cyclotron "H^- acceleration Project". The source-extraction system design is based on the development work performed at TRIUMF. The source generates more than 5 mA of H^- at 5.8 keV with an un-normalized emittance within 100 π-mm-mr. Special devices for H^- injection, extraction and beam merging have been completed by the Jyväskylä cyclotron group. 60 μA of proton beam at 30 MeV has been successfully extracted for physics experiments and will be used for IGISOL program and isotope production. Efforts in improving the source emittance and the injection line to bring the target current up to 100 μA are in progress.

1 INTRODUCTION

High intensity proton beams are needed from the Jyväskylä cyclotron for IGISOL (Ion Guide Isotope Separator On-Line) experiments and for isotope production. For proton acceleration and extraction, the intensity was limited to about 20 μA due to limitations at the electrostatics deflector. This leads to the H^- Acceleration Project [1]. While the Jyväskylä cyclotron group has improved the cyclotron vacuum, installed a foil extraction system and a 20 degree recombination magnet to join the existing external beam line, the H^- source and its associated extraction system were developed at TRIUMF with a joint effort from Jyväskylä. The most demanding requirement on the source is that the program will need 3-5 mA at 5.8 keV injection for the acceleration and extraction of a 30 MeV beam. It also requires a very good emittance in the region of 50-100 π-mm-mr un-normalized. The desired routinely available external proton beam should be 100 μA or higher.

For H^- acceleration and taking protons out at 30 MeV, one has the options of extracting the protons at 30 MeV full energy or at that energy before the H^- ions reach their higher final energy. In the case of the former, the H^- injection has to be at 5.8 keV. For the latter, it can be higher than 5.8 keV. The first option has to be chosen thus we concentrated our effort on the 5.8 keV beam development. Before a source-extraction system was designed or a modification on the existing proton source was attempted, some measurements were made using a 20 mA (at 30 keV) source. To our surprise, we obtained only about 1 mA transportable at 5.8 keV at 3kW, but 1.5 mA at 0.7 kW. For a 3.9 keV beam, only 0.5 mA was obtained. It seems that space-charge effect is very strong at these intensities and low energies. It was deemed necessary to develop a new source-extraction system, which has the capability of partially overcoming the space-charge phenomenon.

2 SOURCE-EXT. DEVELOPMENT

Our development took several stages during late 1999 and early 2000. Prior to that time the H^- source used has been under study at 30 keV beam energy for some time and several options were available. Various extraction schemes were explored and the most productive one was selected. The need of neutralization to compensate the space-charge effect was recognized before meaningful emittance measurements could be made. Emittance measurements were carried out using various combinations of source and extractor versions.

2.1 Source Options

In the begining of our study the source is basically the same as the one reported in 1995 at Cape Town [2], except that the confinement magnets had been upgraded from SmCo bars to NdFeB. The confinement field strength increases 50%. The beam intensity extracted at 30 keV improved moderately whereas the emittance reduced from 0.9 π-mm-mr (4rms) to 0.6 π-mm-mr at 20 mA dc without Cs injection. This source plus Cs injection was used for a 3.6 mA, 1 MeV cyclotron beam test reported in 1998 at Caen. In 1999, a further improvement in emittance to 0.4 π-mm-mr was obtained when the confinement length was elongated to 25 cm. Overall brightness improvement over the 1995 source was up to a factor of 5. This source structure indeed gave an extremely tight beam size at high arc power at 30 keV. The emittance scanner had to be modified to cope with the high beam density. In anticipating the tight emittance requirement for the 5.8 keV beam, we prepared two 15 cm magnet structures. They can be used separately or combined to become a 30 cm source. Methods of further reducing the emittance exist but are not fully employed yet. These are, for example, the use of multiple filaments, LaB_6 cathodes, stronger filter, smaller extraction aperture with longer gap, on-line emittance beam tune in addition to intensity tune and finally Cs injection.

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2.2 Extraction structure

Several extraction configurations were used in the course of our development. Due to the limitation of paper space, the hardware drawings of these options are not shown. Instead, the corresponding potential changes along the beam path are illustrated in Fig.1. One of the most striking differences in high current H^- beam extraction from high current proton beam extraction is the electron beam loading. Thus the Jyväskylä (Berkeley) extractor originally for proton and H_2^+ extraction cannot be adopted.

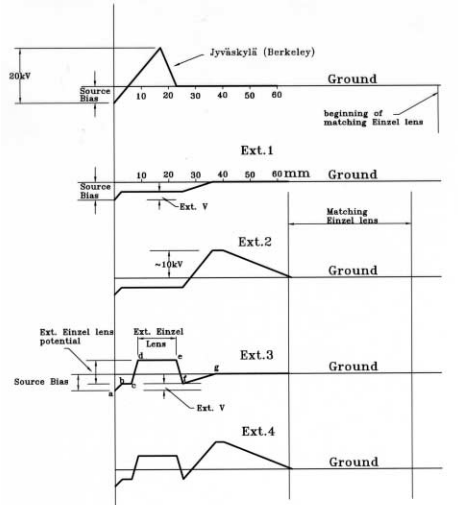

Fig.1. Potential arrangement of extraction electrodes.

The first two systems used were the old 3-electrode structure [2] with a matching decel-accel einzel lens added, and with the energy electrode grounded (Ext.1) or biased (Ext.2). The beams were measured with a Faraday cup after a 20 mm ϕ collimator 40 cm downstream from extractor. The cup current at 5.8 keV as a function of arc power for Ext.1 is shown in Fig.2. It can be seen that not only the beam intensity is small but is decreasing with increase of arc power. This phenomenon can be best explained by space-charge effect at low beam energy. The ext.2 structure makes only small improvement. In order to boost the initial beam energy at the first few millimeters out of the plasma exit, an accel-decel einzel lens was added inside the magnetic filter structure of the extractor electrode. The potential changes are shown for the cases of Ext.3 and Ext.4. The initial beam energy increases from 2 keV to about 10 keV. As a result, Ext.4 leads to a substantial improvement in cup current particularly the negative slope with increasing arc power now becomes slightly positive. Again, the space-charge effect still dominates.

2.3 Neutralization

Although the use of Ext.4 configuration was able to increase the cup current at 5.8 keV by a factor of 2 at 2 kW arc power compared to that from Ext.1, there will be very little gain by increasing the source power beyond 2 kW. Current intensity above 3 mA seemed to be difficult to achieve. Furthermore, the tuning of the source was very sluggish and consistent emittance measurement could not be made. It was decided then to try the principle of neutralization [3]. Argon gas was fed into the first Einzel lens region with a flow of 2-3 sccm. Beam path gas pressure increased by a factor of 3 (gauge reading from $5x10^{-6}$ to $1.5x10^{-5}$ torr). In the balance of space-charge effect reduced and gas stripping loss increased, up to 4 mA at 3.2 kW was obtained as seen in Fig.2. About 1 mA is lost on the collimator at this power giving a total beam of 5 mA. With a given mix of hydrogen flow, argon feed and pumping speed a linear relationship between cup current and arc power was revealed. A different relationship resulted if the gas feed is continuously adjusted at different power levels. Later, only hydrogen feed to the source and pumping baffles were used to change the beam path pressure.

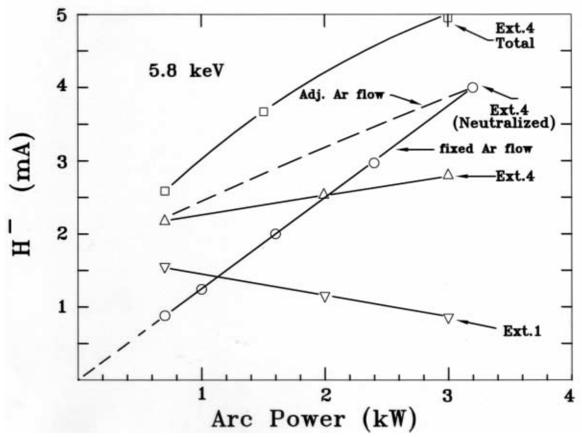

Fig.2. Faraday cup current as a function of arc power.

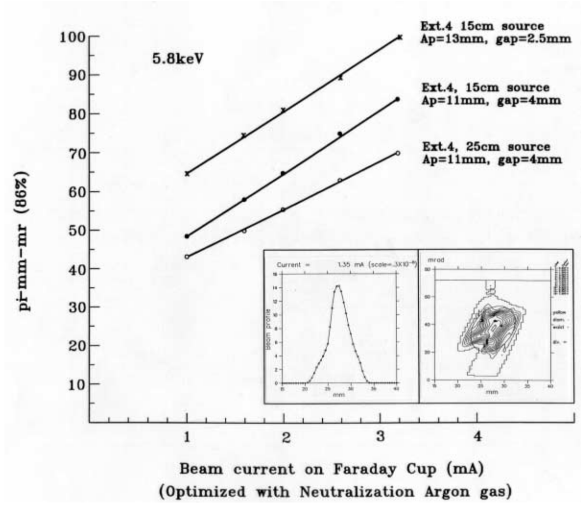

Fig.3. Un-normalized emittance measured with various source and aperture combinations.

2.4 Emittance Measurements

With Ext.4 selected and neutralization technique utilized, non-ambiguous and reproducible tunes to optimize the cup current were possible. Emittance measurements were made at 5.8 keV and 3.9 keV at various arc power levels. Two source options and two plasma exit apertures were configured. The un-normalized emittances at 86% (2σ) obtained at 5.8 keV as a function of cup current are shown in Fig. 3. A typical profile and a phase space plot are included in the inserts. In all cases emittance increases rapidly with beam current. Only at low current the specific emittance can be brought below 50 π-mm-mr using a 25 cm source and an 11mmϕ aperture-4mm gap combination.

3 SOURCE AT JYVÄSKYLÄ

The new H^- ion source and the accompanying extraction system for Jyväskylä K130 cyclotron were designed and constructed based on the tests conducted at TRIUMF. Fig. 4 shows a side view of the source terminal up to the joining flange of the switching magnet of the injection line.

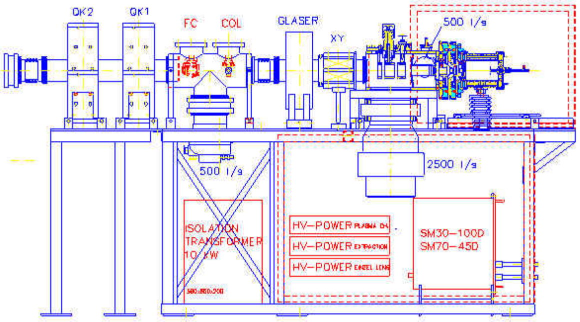

Fig.4. H^- terminal at Jyväskylä K130 Cyclotron.

Two 15 cm magnet structures and two plasma chambers, 17 cm and 32 cm each, were built so that 2 versions of source can be used. The extraction system is the version 4 as described in section 2.2. The terminal optics consists of a third Einzel lens, a glaser and a doublet before joining the main injection line transport. The first series of tests with a 15 cm source were carried out during the summer of 2000. Extracted H^- current was limited initially to about 1 mA at 5.8 keV. After removing sources of contamination and restructuring the vacuum system, the beam intensity increased gradually. In Sept. 2000, a maximum current of 5.8 mA at 5.8 keV was achieved [1]. Emittance scans were not performed at Jyväskylä during these tests, but a scanner will be constructed for this purpose.

4 DISCUSSION

As seen in the section 2, a high current density low energy (5.8 keV) beam extracted out of our source is space-charge dominated. It was partially compensated in the first 40 cm of the beam path by using special extraction arrangement and neutralization, intentionally or un-intentionally. After that the beam has to travel another 14 meters [4] of injection line before reaching the buncher and inflector. For a 1.2 mA extracted from the source, 50% loss occurs at the first 4 meters and only 16% (~200 μA) survives through the inflector. With 10% RF acceptance and a bunching gain of 2.5, beam of 60 μA has been extracted at 30 MeV. In comparison, better than 50% dc transmission has been achieved with a 12-14 keV injection. It was also found that beam current higher than 1.2 mA did not help increase the cyclotron current indicating that the 50 π-mm-mr emittance might be the space-charge limit for the 5.8 keV beam handled by the existing injection line transport. In other words, in order to extract a 100 μA, 30 MeV final beam, a source current of 2.4 mA having an emittance within the space-charge limit will be required.

There are several ways to achieve this goal. Options are: improving the source intrinsic emittance further as discussed in the section 2.1, improving the injection transport for 5.8 keV beam, and utilizing neutralization in the injection path. Finally for a non-relativistic laminar beam, an approximation solution [5] for the Kapchinskij-Vladimirskij equation shows that the envelope grow is strongly related to the square of transport distance. It would be of great benefit if the H^- source station is repositioned to a new location such that the 5.8 keV H^- ions will travel through a shorter injection path.

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