CYCLOTRON INJECTION TESTS OF HIGH-INTENSITY H2+ BEAM

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Abstract

A test stand designed for high-intensity q/a = 0.5 beams has been assembled at the development labs of Best Cyclotron Systems, Inc. (BSCI) in Vancouver, Canada. The Versatile Ion Source (VIS) ECR source from LNS-INFN Catania delivers high-current, high-quality beams of H_2^+ ions to a small 1 MeV cyclotron under development at BCSI. A primary goal is to design systems capable to deliver 10 mA of protons (5 mA H_2^+) on neutrino-producing targets for the DAEδALUS and IsoDAR experiments. Progress and status of the R&D program are presented.

INTRODUCTION

Members of the neutrino community have proposed the IsoDAR and DAEdALUS experiments to, respectively, search for sterile neutrinos and CP violation in the neutrino sectors [1,2,3]. Both experiments require accelerators able to supply 10 mA proton beams. In particular, DAEdALUS needs 800 MeV protons, while IsoDAR will use a beam of 60 MeV protons. To achieve this high current, molecular H_2^+ ions will be injected and accelerated in the cyclotrons, easing space-charge effects at injection and allowing stripping extraction at the top 800 MeV/amu energy.

Capture efficiency in the central region of a compact cyclotron is typically 10%; if the beam can be effectively pre-bunched at the cyclotron RF frequency, a factor of two improvement could be obtained. Hence currents from the (CW) ion source must be around 25 to 50 mA. Space charge is important at these current levels and can prevent reaching this goal.

A first-phase R&D program to test injection of high-intensity H_2^+ beams is underway at BCSI. This project, a collaborative effort between MIT, LNS-INFN (Catania), and BCSI, utilizes the VIS source shipped from Catania and mounted on a test stand assembled at the Vancouver development labs of BCSI. The source delivers beam to an axially injected 1 MeV cyclotron that is being built by BCSI. Characterization of the source for H_2^+ beam production has taken place this summer. Inflection and acceleration tests will be completed in early 2014.

THE TEST STAND

Figure 1 shows the layout of the test stand. The VIS source, has produced 40 mA of proton current [4]. In a test stand at LNS-INFN (Catania), 15 mA of H_2^+ was observed, by adjusting only the inlet gas pressure and microwave power but no other changes.

A solenoid with a 44 cm effective length, and10 cm bore is located 50 cm from the extraction point of the source. It provides primary focusing, and also the means of separating protons from H_2^+ ions. The test stand was, originally configured for H^- and did not allow for a bend to analyze the beam. We decided to test solenoid focusing to separate the beams instead of developing a Wien filter. Indeed, a Wien filter has a significant disadvantage in that the electrical field destroys space-charge compensation, with a resulting deleterious effect on the beam emittance.

An emittance meter can be installed in a 6-way iso-160 vacuum T located about 1.5 m after the solenoid.

The drift tube buncher will be placed at about 1.7 m after the solenoid. Molybdenum grids 0.1 mm thick, are mounted on the accelerating gaps between the electrode and ground. The grids have a square mesh size of 5 mm.

A Bergoz 100 mm bore DCCT is a primary current monitor. After this device another 6-way iso-160 vacuum T houses a collimator and movable beam stop.

Finally come two magnetic quadrupoles, which can be rotated around the beam axis, and the last solenoid magnet. These allow flexible adjustment of beam focus and shape at the entrance of the spiral inflector inside the cyclotron magnet.

CENTRAL REGION

The 1 MeV cyclotron central region is critical to establish the injection feasibility of H_2^+ molecules at the levels required by the DAEδALUS and IsoDAR experiments. The final injection system consists of a Spiral Inflector (SI) to bend the beam onto the median plane and a set of electrodes connected to the two RF cavities that drive the beam along the first acceleration turns. The design of this system is a compromise between the characteristics of the DEAδALUS/IsoDAR cyclotrons and the properties of the small cyclotron developed by BCSI. These elements were designed by iterating between the 3D particle paths in the median plane and different models of SI in order to determine the optimal beam-matching conditions. The 3D electrostatic structures of the SI and the central region were studied by means of dedicated MATLAB codes and OPERA Vector Field, applying the back/forward particle integration technique. The SI was designed to transport the 60 keV beam of

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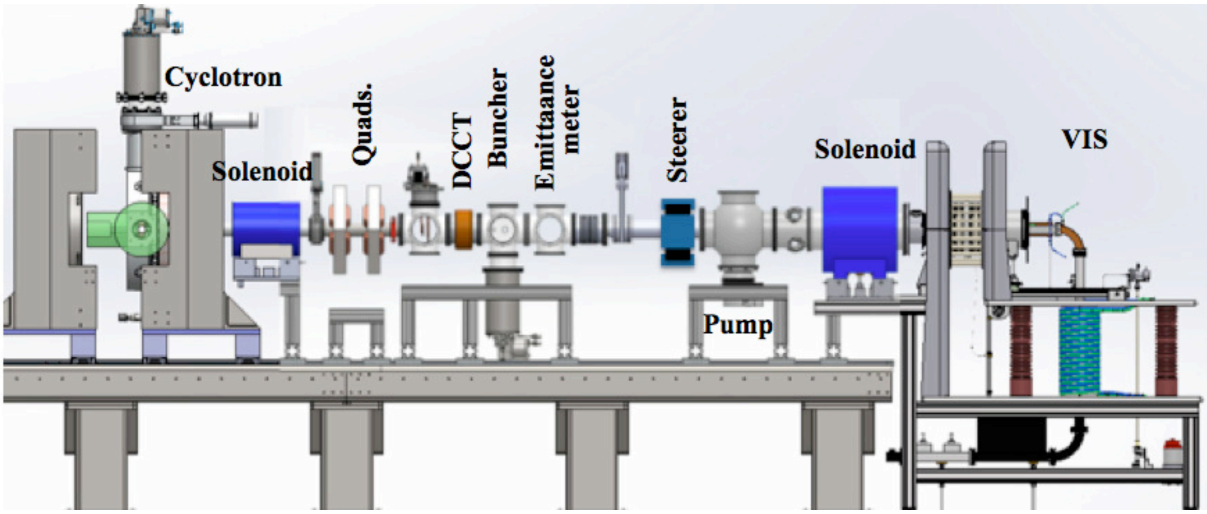

Figure 1: Layout of the test stand at the BCSI development lab in Vancouver, Canada. The ion source is in a high-voltage cage (not shown) at far right; the test cyclotron is on the left. Total length of the test stand is about 5 meters.

H_2^+ molecules from the axial line into the median plane of the cyclotron. The gap between the electrodes is 15 mm to ensure sufficient space for the high-intensity beam. Accommodating such a large gap drives the total size of the device to about 8 cm and places the electrodes in a volume where the vertical component of the magnetic field is not constant. As the analytical model for an SI assumes a constant field, taking this into account added to the complexity of our design. The inner surfaces of the electrodes have a "V" shape because it allows improved beam focusing. The maximum voltage at the SI is 22 kV (±11 KV), and compensating for the fringe field at the electrode edges was achieved by cutting 5 mm from the total length of the electrode and introducing a small scaling factor to the voltage. Also, a tilt angle of 21° was introduced to place the beam along a suitable injection trajectory for matching with the acceleration orbit. The simulation results (without space-charge effects) show a good beam transport through the device.

The small cyclotron central region was designed with two RF-cavities instead of the four planned for the DAEδALUS/IsoDAR cyclotrons. The operating frequency is the 6^{th} harmonics to stay near the operating frequency range of the RF cavities of BCSI cyclotron and because this frequency was the design frequency of the DAEδALUS project. The shaping of the dee tips up to a distance of 10 cm from the machine center has to guarantee the vertical focusing of the beam, which in the first acceleration gaps depends mainly on the electric field effect and on the crossing phase. Due to the high harmonic (6^{th}) and frequency of 49.2 MHz, the focusing action of only two cavities is not enough, so less than 50% of the beam injected, in the acceptance phase, reaches the final energy of 1 MeV. The phase acceptance range of the present central region is just a little larger than 20° RF. As a result of the simulations done, we strongly suggest reducing the operating frequency of the IsoDAR cyclotron to the 4^{th} harmonic. Preliminary simulation of the central region with four RF cavities operated in 4^{th} harmonic shows a larger phase acceptance and a beam transmission near 90%.

ION SOURCE CHARACTERIZATION

Components from LNS-Catania arrived in Vancouver in April 2013. A team from LNS installed and commissioned the source, and throughout the summer personnel from LNS, MIT, and UCLA conducted tests with the H_2^+ beam. These tests included optimization of the H_2^+ beam current, H_2^+/proton ratio, removal of protons from the H_2^+ beam (via solenoid focusing), and performing emittance measurements. As the RF cavities of cyclotron and the buncher had not been completed by the end of our first experimental window, we plan to complete the inflection, capture, and buncher-efficiency tests in January-February 2014.

Preliminary Tests

The VIS is optimized for protons at a microwave power of about 1400 watts, but the optimum ratio of protons to H_2^+ occurs at a substantially lower power (≈600 W). Maximum H_2+ current seen was around 4 to

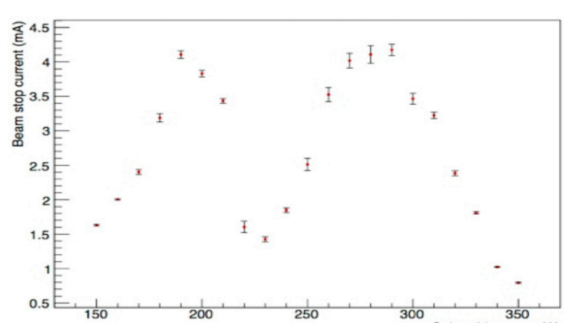

Figure 2: Beam stop current vs. solenoid current. He beam current is detected on beam stop behind a ϕ=20 mm collimator. Protons peak at 190 A, H_2^+ at 280 A. Extraction voltage was lowered to 40 kV to better match the range of solenoid current.

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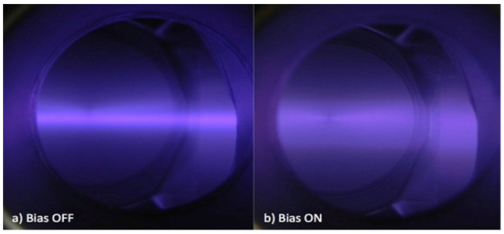

Figure 3: a) Beam profile 50 cm upstream of collimator with bias OFF. b) beam profile with bias ON.

5 mA with a 6 mm extraction aperture. In an attempt to increase this current, the aperture was increased to 8 mm. The H_2^+ current did go up, to 10-12 mA, but beam quality deteriorated. The front disk of the plasma chamber was also changed, from stainless steel to copper and back to boron nitride with very little effect on the H_2^+ beam current. Figure 2 shows a scan of current on the beam stop vs. solenoid current, showing that indeed clean separation of protons from H_2^+ is possible. Width of the peaks reflects the collimator size, not the beam size.

The collecting surfaces (collimator and beam stop) just downstream of the DCCT are not magnetically suppressed, so there is no control over secondary electron current is lacking. To try to make the sum of currents on the collimator and beam stop equal to the DCCT reading, a 50 V bias was placed on both collimator and stop. This did lead to consistent current readings, however did have a significant effect on the beam size, as seen in Fig. 3. These photos indicate that the 50 V is enough to draw the neutralizing electrons away from the beam. The effect is repeatable and instantaneous with application or removal of the bias.

As seen in Fig. 2, the solenoid does provide good separation of protons and H_2^+ Fig. 3a) also indicates that the beam size can be quite small, a few mm across. A series of photographs taken through a window by the collimator shows a clear tight beam at 235 amps, and another one at 330 amps of solenoid current, corresponding to protons and H_2^+, respectively (Extraction voltage 60 kV). With a collimator aperture of 8 mm, 100% of the H_2^+ can be transmitted, but protons are overfocused and less than 5% are calculated to pass through the collimator. However, an unforeseen issue is that the proton beam is focused substantially upstream, and propagates beyond the focus at a divergence such that it is lost on the walls of the vacuum chamber with concomitant heating.

Figure 4 shows a representative emittance scan with an Allison scanner [5] (0.030 mm x 50 mm slits) for two power levels corresponding to a preponderance of protons (a) and H_2^+ (b). The two ellipses are at the same locations, but relative intensities are definitely different. Because of overlap of the ellipses and inability to capture the entire beam in the scanner, extracting good emittance values was difficult however, good estimates indicate our measured emittance is about a factor of two higher than previous VIS values. Further details on these tests have been presented [6].

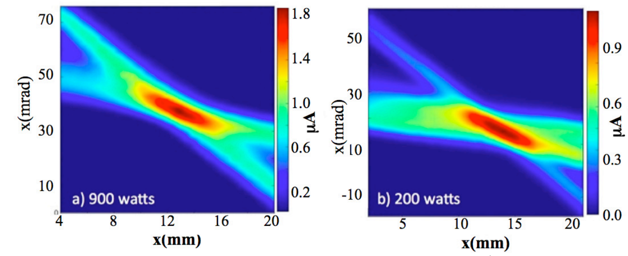

Figure 4: Emittance plots for combined H_2^+ and protons, a) at 900 watts microwave power, b) for 200 watts.

NEXT TESTS

In January 2014 tests will be resumed, including testing of ideas for increasing overall H_2^+ current and further emittance investigations. The principal focus of this campaign, though, will be inflection, capture, and acceleration tests. Our final goal will be to explore space-charge effects on bunching and capture efficiency, and to obtain data that can serve as benchmarks for simulation codes in this complex regime. But we will also investigate the effect of the electric fields of the SI and buncher electrode on space-charge compensation of the beam. We have seen directly that even small electric fields strongly reduce the space-charge compensation generated by residual gas. So even though the SI and buncher electrodes are shielded by the ground electrodes, fields inside these regions will remove neutralizing electrons, and most probably cause emittance growth in the beam. Quantitative data can be obtained by measuring beam sizes while turning on and off the various components. For this, the SI would be changed to a matching dummy cylindrical electrode that could transport the beam to a beam-size diagnostic at the center of the median plane.

Performing these studies as a function of beam current will allow a valuable study of changing space-charge effects in this type of transport and injection system.

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REFERENCES

[1] J.M. Conrad and M.H. Shaevitz, Phys.Rev.Lett. 104, 141802 (2010).
[2] J. Alonso et al. [The DAEdALUS Collaboration], arXiv:1006.0260 [physics.ins-det] (2010)
[3] A. Bungau, et al, Phys. Rev. Lett. 109, 141802 (2012)
[4] R. Miracoli et al. Rev. Sci Instrum. 83, 02!305 (2012)
[5] P.W Allison, J.D. Sherman, D.B. Holtkamp, IEEE Trans. Nucl. Sci. NS-30, 2204 (1983)
[6] J. Alonso et al., ThuP53, ICIS 2013

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