PRODUCTION OF 20 TO 50 MeV NEUTRAL HYDROGEN BEAMS

J.J. Guy Durocher (Member), C. Sean Bohun[*] and Gary R. Smith

University of Manitoba Accelerator Centre
Department of Physics, University of Manitoba
Winnipeg, Manitoba, Canada
R3T 2N2

Abstract

Neutral hydrogen beams with energies between 20 and 50 MeV and fluxes on target of up to 4 x 10^{12} H^o/sec/cm^2 are being routinely extracted from the University of Manitoba Spiral Ridge Cyclotron [1]. Variable energy H^o beams are produced by stripping a single electron from the H^- beam inside the cyclotron using carbon foil strippers. Fluxes of up to 10^{14} H^o/sec/cm^2 are expected using a metal vapor stripping system presently in the final stages of testing. We describe the methods by which the H^o beams are produced and some of the problems associated with beam extraction and transport to the experimental site.

Introduction

The hydrogen atom is undoubtedly the most widely investigated of all atomic species. The atom and its ions have been studied extensively from both theoretical and experimental view points. Beams of hydrogen are also widely used as probes in the investigation of other atomic and nuclear systems. In the past such beams have been made up of either positive (ie. protons) or negative hydrogen ions accelerated to the desired energy.

Recently, interest has arisen in the investigation of neutral hydrogen atoms moving at relativistic velocities. Such particles could be used in studies including investigation of: fundamental electromagnetic interactions with materials [2], the basic study of the relativistic atoms' behavior [3], in-flight beam polarization [4] and high energy ion implantation. A program was initiated at the University of Manitoba Accelerator Centre in late 1984 to develop a 10 to 50 MeV variable energy neutral hydrogen beam facility for use in experiments studying these phenomena.

The University of Manitoba Spiral Ridge Cyclotron is an H^- accelerator capable of extracting 20 to 50 MeV protons through use of a stripping foil which removes two electrons from the ion. Production of a beam of neutral Hydrogen atoms requires that only one electron be removed from the H^- ion. This extra electron is bound with an energy of 0.75 eV [5], in comparison to the more tightly bound (13.65 eV [5]) electron. Thus the problem to be faced in H^o production is devising a method whereby it is possible to transfer between 1 and 13 eV to this extra electron. Transferring precisely this amount of energy is, however, a difficult problem for the case of an ion travelling at one third of the speed of light.

Since the stripping of the extra electron proceeds via a Coulomb process, one must expose the electron to an electric field of an appropriate strength. Direct use of an electromagnetic field proves to be technically unfeasible due to the high field strengths required [6]. Similarly, transferring energy directly in the form of a photon by using an appropriate wavelength laser is ruled out due to the low cross sections involved [7]. One is therefore left with using the electric field near an atom as would be seen by the H^- as it passes through matter. The matter can be in a gas, liquid or solid state.

H^- Orbit Calculations

A problem of major importance in the production of H^o beams is the determination of the optimal stripping positions at which an electron may be removed from the accelerated H^- ion. Since an H^o beam cannot be focused or steered, beam extraction will only be possible if the momentum vector of the H^- ion at the stripping point is pointing directly at the final H^o target position. Thus the beam extraction efficiency will be a strong function of the stripping position.

Extensive calculations of the H^- beam dynamics within the cyclotron were carried out to determine the optimum H^- focussing parameters and stripping foil positions. These calculations were done using a FORTRAN program, NEUTRA_STRIP, which calculates the position and momentum vector of the H^- ion at a locus of points on its orbit [8]. This information is then used to determine the optimum stripping point for maximum H^o extraction.

These calculations considered a number of H^- beam energies and H^o exit geometries. The predictions of the 35 MeV calculations were checked experimentaly and the stripping position predicted by NEUTRA_STRIP was found to be within +/- 2 mm and +/- 0.2 degrees of the position which resulted in maximized H^o production.

H^o Production

Residual Gas Stripping

Production of relativistic H^o beams at the University of Manitoba Accelerator Centre has proceeded via three stages of development representing three different methods of striping the circulating H^- beam in the cyclotron. In the initial phase, the beam was stripped using the residual gas present within the cyclotron. Beam loss due to gas stripping in particle accelerators is a well known phenomenon which has long plagued accelerator physicists. It was also known that an appreciable amount of the H^- beam was stripped of only one electron, thus producing neutral rather than positively charged particles. This phenomenon was exploited in the development of techniques and apparatus needed for producing and monitoring H^o beams.

As part of the work on residual gas stripping, a study was carried out to determine the effects of residual gas pressure and the cyclotron's magnetic field on the H^o extraction efficiency. The extracted H^o yield was found to be strongly dependent on the cyclotron's magnetic field strength; variations of a factor of five or more could be induced by small adjustments (<0.01%) to the magnetic field. This observation is consistent with the effect of the magnetic field strength on local vertical focussing of the H^- beam. By moving the vertical focussing points on a given orbit, one would expect to affect the Z component of the H^- particle's momentum at the stripping point. Since the Z component of the H^o beam momentum affects its divergence, the value of this component must be approaching zero for maximum extraction efficiency.

The effect of the residual gas pressure on the H^o extraction efficiency was more difficult to quantize since it was not possible to locally vary, or even monito, the gas pressure within the cyclotron. Since only the mean pressure in the cyclotron tank could be monitored, it was not possible to correlate the pressure at any particular radius with the stripping efficiency at the corresponding H^- energy. It was observed that if the tank pressure rose a factor of ten, the stripping efficiency at the energies measured rose by about a factor of three.

The efficiency of residual gas stripping was found

CH2387-9/87/0000-1869 $1.00 © IEEE
PAC 1987

to be of the order of 0.01% for a pressure of 10^{-6} torr in the cyclotron. This proved sufficient to carry out the first experiments using neutral hydrogen beams of approximate fluxes of 10^9 H^o/sec/cm^2. These studies, carried out in conjunction with members of Oak Ridge National Laboratory, observed optical radiation emitted from metallic and non-metallic surfaces bombarded with such H^o beams [2,9].

Carbon Foil Stripping

The second stage of development involved stripping the H^- beam with a thin Carbon foil. Work at Fermi National Accelerator Laboratory with 200 MeV H^- beams found it is possible to strip H^- to H^o with about 80% efficiency using a 20 g/cm^2 C foil [10]. Since the electron exchange process and thus stripping efficiency is a function of particle velocity [11], one can scale the final results to the University of Manitoba energy range and obtain an estimate of the stripper thickness needed. For 20 to 50 MeV energies, the required foil thicknesses range from 7.0 to 11.0 g/cm^2.

The beamline and associated experimental structures used in Stage 2 are illustrated in Figure 1. Also shown are the stripping foil probe assembly and the calculated stripping points within the cyclotron for production of 20, 35 and 50 MeV neutral beams, along with equilibrium orbits for H^- ions of those energies. The H^o extraction beamline is placed alongside the proton exit beamline and sits within the cyclotron vault.

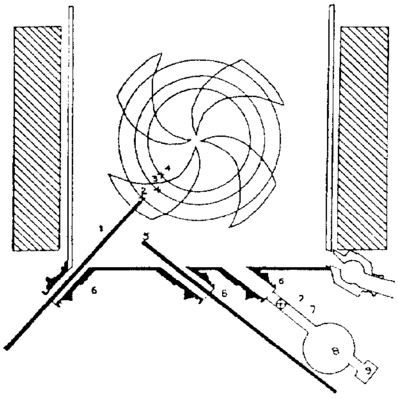

Figure 1. Layout of the University of Manitoba Cyclotron showing H^o facility: 1, probe assembly for stripping H^- beam; 2, 3, 4, equilibrium orbits for 50, 35 and 20 MeV H^- beams. Stripping points are indicated by +. 5, proton pick-off probe; 6, bellows; 7, 12 mm diameter collimators; 8, experimental chamber; 9, beam current monitors.

The energy of the extracted H^o beam is varied by moving the carbon stripping foil to the calculated position on the desired energy H^- orbit. The stripping point chosen is that which results in the neutral beam proceeding in a straight line to the exit port on the cyclotron. Since the H^o beam will arrive at different angles with respect to the exit port for different energies, the experimental beam line is pivoted about the exit port and provides the straight line path needed by the emerging particles.

The extracted H^o particles pass through 12 mm diameter collimators located at the entrance and exit of the transport pipe and which define the horizontal extent of the beam. The collimators allow passage of some 25% of the generated H^o flux. The height of the beam is determined by the vertical momentum component of the circulating H^- beam within the cyclotron at the stripping point and may be minimized by adjusting the magnetic field to optimize the vertical focussing of the H^- beam. This resulted in a 4 mm by 12 mm elliptically shaped beamspot at the target site.

The target site is located in an experimental chamber some 1.85 m from the stripping point in the cyclotron. While passing through the target the H^o atoms are stripped of their remaining electron and the resultant proton beam is monitored to determine the initial H^o flux. This is accomplished through the use of two current monitors: a secondary electron emission monitor and a Faraday cup.

The Stage Two neutral beam facility has also been used to conduct a number of experiments. In collaboration Oak Ridge National Laboratory, we have used H^o beams as probes for studying optical radiation emitted from metallic and non-metallic surfaces of some twenty different materials [2,9]. Preliminary studies of the behavior of relativistic neutral hydrogen beams have also been conducted [3].

Although tests showed it was possible to achieve approximately 6% stripping efficiency for 35 MeV H^- using a 9 micrograms/cm^2 C foil [12] backed by a 90% transmission Ni grid [13], the use of C foil is not appropriate for the situation where a variable energy H^o beam is sought. Since for each H^- energy, a different thickness of C would be required for maximum stripping efficiency, a series of thin C foils would be needed with the appropriate manipulating hardware. The geometrical constraints presented by stripping the H^- beam within the cyclotron make this option unattractive.

Metal Vapor Stripping

In the third stage of development of the Neutral Hydrogen Beam Facility the carbon stripping foil will be replaced by a variable density metal vapor stripper. With the use of such a system stripping efficiencies greater than 80% are anticipated for all H^- energies. Since the cyclotron is potentially capable of accelerating up to 20 microamperes of H^-, we expect to achieve H^o flux intensities greater than 10^{14} H^o/sec/cm^2. Work is nearing completion on this stage of the facility development.

A variable density gas or vapor target is the most feasible alternative to stripping with a series of carbon foils. The gas option is ruled out due to the unacceptable gas load on the cyclotron's vacuum pumping system. Therefore a metal vapor stripping target was chosen. Lead was selected because of its high electron density, relatively low boiling point and its ability to plate out within a small area rather than covering the entire interior of the cyclotron.

On the basis of the work with C foil and calculations of stripping points within the cyclotron [8], it was determined that a Pb stream 1 mm diameter and between 3 and 5 μg/cm^2 thick was required. A Pb stream with these characteristics requires a steady source of Pb vapor at a constant pressure along with a nozzle to form the stream. In the present design, the Pb vapor will be supplied by heating molten Lead to approximately 1000 K in a tantalum oven. Power is supplied by passing current through heating wire wrapped around the body of the oven. High temperature epoxy is used to maintain wire positioning and provide electrical insulation. While operating, the temperature of the oven will be monitored and controlled by a PC/XT microcomputer. The system is designed to contain enough Pb for approximately two weeks of continuous operation.

The shape and uniformity of the Pb stream produced is a function of the nozzle through which the Pb exits the oven. A thorough literature search failed to provide any reference to a metal jet of the required size (1 mm diam.) or flow rate (up to 5.6×10^{-5} kg/sec of Pb). None of the standard texts on fluid dynamics provided guidelines for the design of the nozzle and the only description of a supersonic jet for vaporized heavy metals [14] produced a vapor stream some 25 times larger in diameter.

Despite the large scaling factor involved, that design was selected for the nozzle. The main criterior used in scaling the design was the requirement that the size of any surface imperfections in the nozzle be less than 1% of the diameter of the throat to keep turbulence in the jet stream to a minimum. With a nominal throat diameter of 80 micrometers, this meant that any imperfections had to be smaller than 1 micrometer. Electron micrographs of the surface of the nozzle's throat showed that the 1% criterion was satisfied.

The oven is fitted into a 2 mm thick jacket of machineable ceramic to prevent excessive heat loss which would reduce the system efficiency and which might affect the cyclotron operation. Similarly, the nozzle section is encapsulated in a fused quartz sleeve with a hole on one side to allow for the Pb jet. Quartz was used over the nozzle region since the dimensions involved made machining a ceramic sleeve impractical.

The oven and its ceramic and quartz sleeves then mount in a water cooled aluminum housing which provides mechanical support. The housing also provides a radiation shield protecting the ceramic from the RF field and from stray H^- ions. A cutaway view of the stripper assembly is shown in Figure 2.

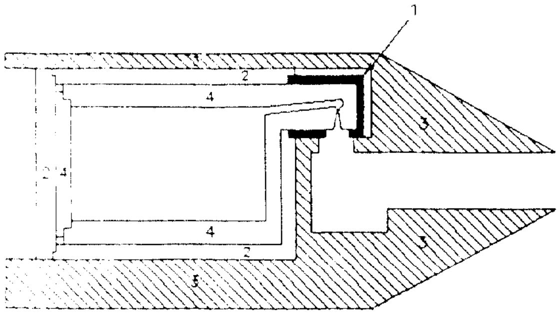

Figure 2. View of metal vapor stripper assembly: 1, fused quartz insulating sleeve; 2, ceramic insulating sleeve; 3, Aluminum housing; 4, Tantalum oven.

All components of the metal vapor stripper are machined and the system is presently being assembled. The system will next be bench tested. X-ray fluorescence will be used to measure the density of the Pb stream. The stripper will then be tested in the cyclotron using manual temperature control to obtain estimates of the parameters to be used by the computer control system for maximizing H^o production. The full computer controlled system should be in place a few months later. A conservative estimate of the H^o flux on target using this metal vapor stripper system is 10^{14} $H^o/sec/cm^2$. This is expected to be the highest intensity neutral hydrogen beam available in the 10 to 50 MeV energy range.

Summary

Variable energy relativistic neutral hydrogen beams are being produced at the University of Manitoba Accelerator Centre by stripping a single electron from the accelerated H^- beam inside the cyclotron. H^o beam fluxes of over 4×10^{12} $H^o/sec/cm^2$ have been extracted using C foil stripping and fluxes of up to 10^{14} $H^o/sec/cm^2$ are expected using a metal vapor stripping system which is presently in the final stages of testing. The neutral beam facility is currently being used in an active experimental program investigating the behavior of relativistic H^o beams and their interactions with matter.

Acknowledgements

This work is supported by the Natural Sciences and Engineering Research Council of Canada

*N.S.E.R.C. Summer Undergraduate Student, Department of Physics, University of Victoria, Victoria, B.C., Canada

References

[1] J.J.G. Durocher, G.R. Smith, V.P. Derenchuk and J.R. Anderson, "Extraction of variable energy neutral hydrogen beams from the University of Manitoba Cyclotron", Nuclear Instruments and Methods in Physics Research, A253, pp. 302-304, 1987.

[2] O.H. Crawford, "Luminescence from metals and insulators", presented at the Werner Brandt Workshop on Penetration Phenomena: Photon Emission from Irradiated Surfaces, ORNL, Oak Ridge, Tenn., April 15-16, 1985.

[3] G.R. Smith, J.J.G. Durocher, C.S. Bohun, K. Francey and J.S.C. McKee, "Relativistic neutral hydrogen beam studies", presented at the Annual Fall Meeting of the Division of Atomic and Molecular Physics of the Canadian Association of Physicists, Winnipeg, Manitoba, Canada, October 24-25, 1986.

[4] A.N. Zelenskiy, S.A. Kokhanovskiy, V.M. Lobashev, N.M. Sobolevskiy and E.A. Volferts, "A method of polarizing relativistic proton beams by laser radiation", Nuclear Instruments and Methods in Physics Research, 227, pp. 429-433, 1984.

[5] C.L. Perkaris,"Ground state of two electron atoms", Physical Review, 112, pp. 1649-1658, 1958.

[6] G.M. Stinson, W.C. Olsen, W.J. McDonald, P. Ford, D. Axen and E.W. Blackmore, "Electronic dissociation of H^- ions by magnetic fields", Nuclear Instruments and Methods, 74, pp. 333-341, 1969.

[7] S.J. Smith and D.S. Burch, "Relative measurement of photodetachment cross section for H^-", Physical Review, 116, pp. 1125-1132, 1959.

[8] J.J. Guy Durocher, "Neutral hydrogen beam stripping point calculations", University of Manitoba Accelerator Centre Annual Research Report 1985-1986, J.S.C. McKee, ed., ISSN 0832-8234, pp. 64-67, 1986.

[9] J.J. Guy Durocher, G.R. Smith and D.R. James, "MANOR - Experiments in collaboration with Oak Ridge National Laboratory", Ibid., pp. 145-151.

[10] R.C. Webber and C. Hojvat, "Measurement of the electron loss cross sections for negative hydrogen ions on Carbon at 200 MeV", IEEE Transactions on Nuclear Science, NS-28, pp 4012-4014, 1979

[11] H.D. Betz, "Charge states and charge-changing cross sections of fast heavy ions penetrating through gaseous and solid media", Reviews of Modern Physics, 44, pp 465-539, 1972

[12] Arizona Carbon Foil Co. Inc., 4152 East Sixth St., Tucson, Az., USA, 85711

[13] Buckbee Mears Co., 245 E. 6th Street, St. Paul, Minn., USA, 55101

[14] R. Beringer and W. Rall, "Mercury vapor jet and stripper", Reviews of Scientific Instruments, 28, pp. 77-79, 1957