H^- BEAM OPERATION OF THE IUCF STRIPPER LOOP*

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Abstract

The design and development using a 0.62 MeV molecular hydrogen beam for injection of a low energy proton storage ring to enhance the brightness and vary the rf microstructure of the beams from the IUCF cyclotrons were previously reported.[1,2] The performance of the device, called a "stripper loop", is limited by the stripping properties of the H_2^+ ion and by the resulting low energy (0.31 MeV) of the circulating proton beam. However, peak beam intensity gains of nearly 6 were obtained. Larger beam intensity gains are predicted when the stripper loop is injected with 0.62 MeV H^- ions. In recent development studies using an H^- beam for injection, brightness gains of nearly 11 were obtained for proton beam energies of 180 and 200 MeV with pulse periods of about 2 μS. The modifications required to inject H^- ions into the stripper loop and the results of the beam development studies are presented and compared with theoretical predictions.

Introduction

Traditional pulse-suppression techniques employed to reduce the duty factor of cyclotron beams cause a corresponding reduction in the average beam intensity as well. Many experiments which require a duty factor reduction, such as the intermediate energy neutron time-of-flight measurements now being conducted at IUCF,[3] usually require a high average beam intensity. Pulse repetition rates for these experiments of between 0.5 and 5.0 MHz are needed to reduce the background caused by neighboring beam bursts, which corresponds to a duty factor reduction of between 5 and 70 for the beams available from the Indiana cyclotrons. (The rf frequency range of the Indiana Cyclotrons is 25 to 30 MHz.) Average beam intensity reductions of this magnitude would make many such experiments impractical. What is needed is a method to maintain the average beam intensity by increasing the number of particles per pulse as the pulse period is increased.

At IUCF, a small isochronous storage ring which accumulates the DC beam from the 0.62 MV ion source terminal prior to injection into the cyclotrons was developed to test the feasibility of accomplishing this. The basic idea is to avoid throwing away the unused beam when operating at reduced duty factors by storing the output from the ion source during the long intervals between pulses and to deliver it all at once to the cyclotrons. This method of varying the rf microstructure of cyclotron beams over a broad range while maintaining a high average beam intensity was originally proposed for a coupled cyclotron system at the University of Colorado.[4] A plan view of the IUCF stripper loop which was located in the 0.62 MeV injection beam line to the small cyclotron to minimize the cost of the development effort, is shown in Fig. 1. Another motivation for this development was to increase the brightness and adjust the pulse period of the beams from the Indiana cyclotrons to match the injection requirements of the electron-cooled storage ring now under construction here.[5] Higher brightness beams were also desired to explore the high intensity limits of the cyclotrons. The results of the recent development studies using a 0.62 MeV H^- beam for injection into the stripper loop are discussed and compared to the previously reported results using an H_2^+ beam for injection.

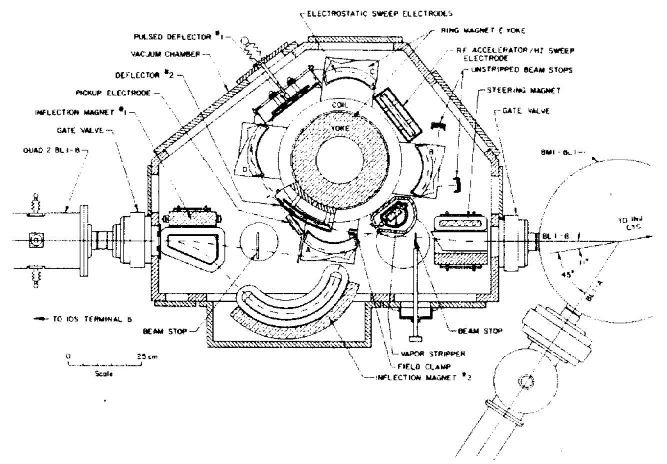

Fig. 1. Plan View of Stripper Loop

Stripper Loop Operation

The stripper loop is filled by the injection of partially stripped molecular ions (H_2^+) or H^- ions from the 0.62 MV ion source terminal. For the case of H_2^+ ion injection, the incident and circulating beam trajectories are made coincident using inflection magnet #1 and by stripping the H_2^+ ions to protons of half the kinetic energy in the vapor canel located between the ring magnet sectors A and B. Stripping injection is also used to increase both beam current and the phase space density. A fraction of the stored beam is extracted from the ring by a pulsed electrostatic deflector (#1) which can operate at an adjustable sub-harmonic (from .01 to .9 MHz) of the cyclotron rf frequency. A second DC electrostatic deflector and a combined function magnet are used to focus and steer the beam back into the injection beam line to the cyclotron.

The limiting factor in the brightness gain of the stored beam, in our low energy application, is the continuous energy resolution degradation caused by the repetitive passage through the stripping vapor. The maximum brightness gain is reached when the circulating beam phase space dilution caused by these interactions reaches equilibrium with the rate of density increase from the continuous addition of freshly stripped particles. The beam extracted from the ring is bunched to form the narrow pulse widths required for acceleration with good energy resolution. The f/2 klystron buncher system has a limited velocity acceptance of about 0.1% compared to the 4.1% acceptance of the stripper loop magnets, hence the useful beam for acceleration is only a fraction of the total beam accumulated. For time-of-flight experiments, a fraction of the circumference of the stripper loop is extracted so that only a single rf pulse is populated after bunching, which further reduces the amount of beam available for acceleration. The cyclotrons also have a limited transverse acceptance in each inflection and extraction channel, so that the transmission of beam through the cyclotrons is proportional to the incident 6-dimensional brightness. Hence, only about 1% of the average beam current extracted from the stripper loop is transmitted through the cyclotrons.

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The H_2^+ ion is not ideal for filling the stripper loop because the maximum circulating proton beam energy (0.31 MeV) is half the incident beam energy. This aggravates the energy resolution degradation of the circulating beam which must pass through the vapor canal. The low extracted beam energy also limits the energy of the beams accelerated by the cyclotrons to about 80 MeV. In addition, the breakup of the H_2^+ ions in the vapor canal can proceed by several processes, only one of which yields protons suitable for accumulation in the ring.[6,7] The net result is a threefold reduction in the number of incident protons available for filling the ring. For these reasons, the performance of the stripper loop using an H^- beam for injection was studied.

Stripping Properties of H^- Ions

H^- beams are injected into the stripper loop using both inflection magnets #1 and #2, and stripped to protons having the same energy. Hence, the maximum circulating beam energy is 0.62 MeV, which allows the acceleration of the extracted proton beam to the field limit of the cyclotrons (200 MeV). The Duoplasmotron source in terminal B was modified to deliver about 25 μA of H^- with an emittance of 3π mm-mr. Both the emittance and intensity of this beam are about 5 times smaller than for the positively charged proton beams from this source. The polarity of the 0.62 MV high voltage power supply was reversed to accelerate the beam for injection into the stripper loop. Because of the excellent beam emittance, the transmission of the H^- beam from the ion source terminal into the ring magnet was over 90%.

Stripping the H^- ions to protons is a two step process requiring the conversion of the H^- ion to a neutral hydrogen atom.[8] Measurements of the stripping fraction (H^- out/H^- in) as a function of the areal density of the vapor gas were made and compared with similar measurements using the H_2^+ beam and with the expected stripping fraction from the known cross sections.[8] From these data, which were taken for incident H^- beam energies of 0.37, 0.57, and 0.61 MeV, the cross section for the stripping of H^- ions to any other charge state was determined to be about 1.3 times that for the conversion of H_2^+ ions to any other charge state. This ratio is in reasonable agreement with the published data.[7,8] A measurement of the production of protons in the canal as a function of the vapor density was also made at these energies and found to be somewhat larger than expected. In addition, the measured H^- stripping and H^+ production fractions were relatively independent of the incident beam energy. This disagrees with the H^- stripping measurements of Tawara et al.[8] using N_2 as the stripping medium, which shows a decrease in cross section with energy. The cause of the discrepancy may be the stripping vapor used in our measurements. A commercially available long molecular fluorocarbon chain (C_7F_{14}) is used in the stripper loop. It may be that during the interaction of the H^- ions with the large molecules in the vapor canal, the probability of a two step conversion to a proton in a single interaction is quite large. A plot of the H^- stripping and H_0 and H^+ production fractions for a 0.61 MeV H^- beam is shown in Fig. 2, and is nearly identical to similar plots for the two lower energies. The effective H^- to H^+ stripping cross section measured is about equal to the H_2^+ stripping cross section, 1.6×10^{16} cm^2. The predicted brightness gains using the stripper loop injected with a 0.62 MeV H^- beam made from these measurements are shown in Fig. 3 as a function of the vapor density. Similar predictions for the 0.62 MeV H_2^+ beam are also shown for comparison.

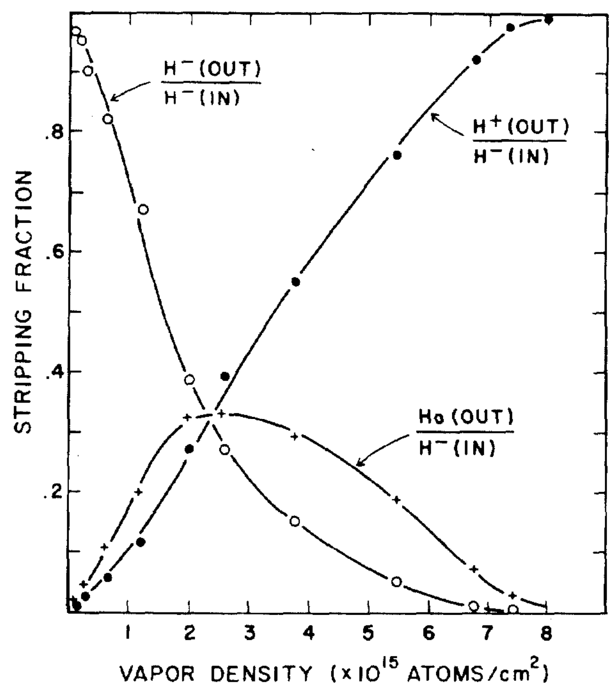

Fig. 2. H^-,Ho and H^+ Stripping fractions vs Vapor Density.

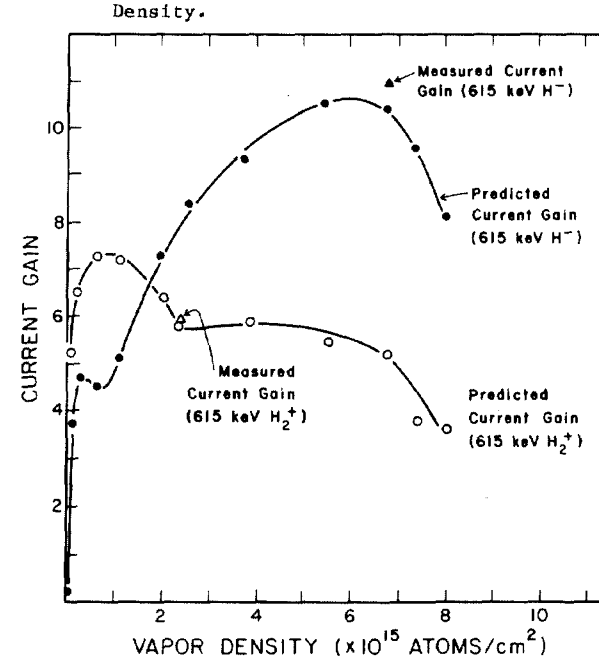

Fig. 3. Predicted and Measured intensity Grins vs Vapor Density.

Performance of the Stripper Loop with H^- Beam Injection

After some adjustment of the inflection trajectory and the ring magnet harmonic coils, circulating 0.37, 0.57, and 0.61 MeV proton beams were achieved using the H^- beam for injection. Because of the relatively low intensity of the H^- source, the maximum circulating beam current observed at 0.61 MeV was about 0.4 mA. Attempts to raise the circulating beam current by lowering the vapor pressure and increasing the accumulation time beyond 10 μS were not successful because the transverse beam instability encountered at lower energies was again observed during these measurements. The circulating beam current at which the instability occurred (0.4 mA) was less than the 0.6 mA observed for the 0.31 MeV circulating beam during the H_2^+ development runs. From previous measurements,[2] the instability is not caused by space charge effects. Vertical electrostatic sweep electrodes in the ring magnet gaps and the vapor canal also have no effect on the instability, which eliminates an interaction of the circulating beam with secondary charged particles in the ring as a possible cause as well. A plausible explanation for the cause of the instability, which limits the maximum current that can be stored in the ring for long accumulation times, has not been determined.

The beam extracted from the stripper loop was bunched with an f/2 sub-harmonic buncher and injected into the cyclotrons for further acceleration. A plot of the intensity loss profile for a 180 MeV proton beam with a pulse period of 2.5 μS using the stripper loop with H^- injection is shown in Fig. 4. A plot of an 80 MeV proton beam having nearly the same pulse period using the stripper loop with an incident 0.62 MeV H_2^+ beam and of a 135 MeV proton beam pulse selected 1:4 (period = 0.13 μS) using traditional chopper techniques to throw away the unwanted pulses are also shown in this figure for comparison. From these data, the measured intensity gain of the 180 MeV beam is nearly 11 when differences in the source intensities available are taken into account. This is in good agreement with the calculated gain shown in Fig. 3. The predictions

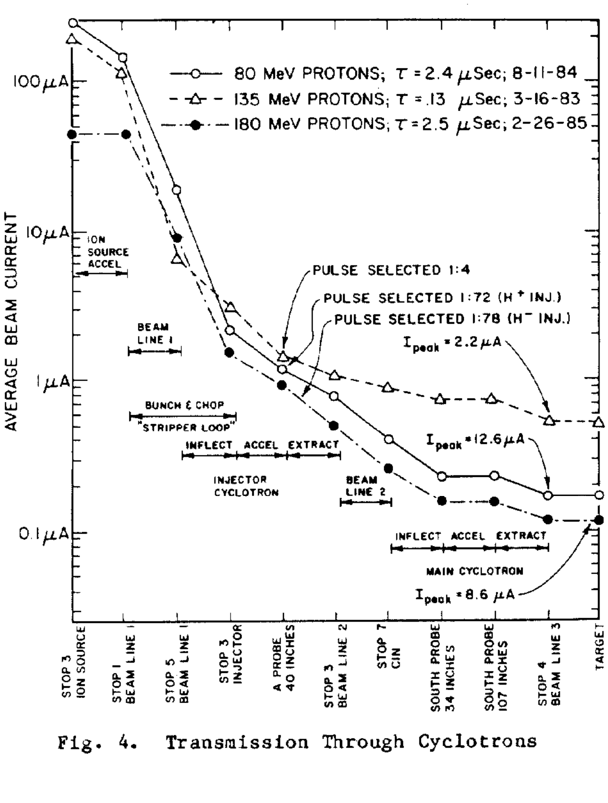

Fig. 4. Transmission Through Cyclotrons

show a broad peak in the intensity gain near a vapor density of 7×10^{15} atoms/cm^2, which is also observed experimentally. The peak brightness gain observed for both H_2^+ and H^- operation of the stripper loop are also shown in Fig. 3. The transmission of the 180 MeV beam through the cyclotrons is nearly identical to the 80 MeV beam from the stripper loop, and is limited to about 1% for the reasons stated earlier. The peak beam intensity observed during this development run is equivalent to 8 μA if all rf pulses are populated, which is adequate to meet the needs of many experiments. Similar results were obtained at a proton energy of 200 MeV.

Summary

Considerable effort has been put into the development of the stripper loop to determine the limits of its operation. For long accumulation times (>10 μS), the presence of the circulating beam instability presently poses a limit to the brightness gain that can be achieved with the system. However, a more practical limit to the brightness gain, which occurs at pulse repetition rates of interest to most cyclotron users (between 1 and 5 μS), is the cumulative effect of the circulating beam energy spread which takes place in the vapor canal. These effects are amplified by the small velocity acceptance of the buncher systems and the phase acceptance limits of the cyclotron. Operating a stripper loop at higher energies would help matters somewhat, but would require thicker targets to overcome the decreasing stripping cross sections. In addition, at higher energies, the size of the storage ring and power requirements of the pulsed deflector raise the cost of the system considerably. Perhaps a better solution to high brightness pulsed beams is to use intense, low emittance, pulsed sources. It is doubtful that the stripper loop will be capable of providing the intense beam pulses desired for injection into the new electron-cooled storage ring, and the beam brightness achieved so far is not sufficient to test the intensity limits of the cyclotrons. Nevertheless, the IUCF stripper loop has produced higher brightness beams than previously achieved without it, and its performance is sufficient to meet the requirements of several experiments. Development of the device will continue to determine the cause of the circulating beam instability.

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