A LOW ENERGY STORAGE RING FOR PULSE STACKING AT IUCF*

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Introduction

Some experiments require a variable microscopic duty factor. Long path neutron time-of-flight measurements, for example, have this requirement to distinguish between the detection of fast and slow particles from neighboring beam bursts and to effect a significant reduction in the cosmic ray background.[1] For medium energy (100-200 MeV) high resolution neutron time-of-flight measurements, pulse repetition rates from 0.2 to 1.0 μs are required, which corresponds to a duty factor reduction between 10 and 100 for most cyclotrons. In addition, the recent interest in coupling cyclotrons to other types of particle accelerators, such as storage rings[2] or synchrotrons,[3] requires a similar modification of the time structure as well as an increase in beam brightness (phase space density). While cyclotrons normally deliver short (<0.5 ns) bursts of intense beams of variable energies, a reduction in the pulse repetition rate is also accompanied by a comensurate decrease in the average beam intensity. At Indiana, injection of beam from the existing cyclotrons into the electron cooled storage ring now under construction[4,5] calls for a duty factor reduction of over 200 together with a peak beam burst intensity increase of about a factor of 30. This is not possible with the traditional methods of pulse selection presently used with cyclotrons.

A method for providing a highly variable duty factor without sacrificing beam brightness was recently suggested for coupled cyclotron systems by the University of Colorado cyclotron group[6] and is now being developed at Indiana. A low energy isochronous storage ring is used to store beam from the 0.62 MeV ion source pre-injector. The stored beam current is allowed to accumulate to the transverse phase space limit before being extracted for injection into the cyclotron at a pulse rate selected by the user. The device, which we call a "stripper loop", was constructed to test the feasibility of the Colorado suggestion and to explore the space charge limits of the injector cyclotron with more intense beams. The design and operating details of the stripper loop and the preliminary results of the initial development efforts are described below.

Stripper Loop Design and Operation

A plan view of the stripper loop, which is filled by the injection of partially stripped unpolarized molecular ions (H_2^+, D_2^+) or H^- ions from the 0.62 MeV ion source pre-injector terminal B, is shown in Figure 1. The incident beam trajectories are made coincident with the circulating beam path by stripping the ions to their most probably charge state in a vapor canal located in the field free straight section between ring magnet sectors A and B. Stripping of the incoming beam is also necessary so that newly stripped ions can occupy the interstices in the largely-empty phase space volume of the circulating beam. Then on a microscopic scale, Louivilles' theorem is not violated and the beam brightness can be increased. The stored beam is kicked out of the ring and back into the transfer beam line to the injector cyclotron by a pulsed deflector (#1) followed by an electrostatic deflector (#2) and a small steering magnet. The basic concept then is to avoid throwing away the unwanted beam when operating at reduced pulse repetition rates by storing the ion source output in the ring and pulsing beam of higher brightness out at the desired rate.

The design parameters of the stripper loop are listed in Table 1. The ring magnet, whose yoke is common to all four sector magnets, occupies 40% of the orbit circumference. This factor is the same as for the IUCF separated sector cyclotrons, for which the betatron focussing frequencies are known.[7] Magnetic field measurements of the assembled magnet were made to verify these parameters and to precisely determine the shape of the stored beam path and the inflection and extraction trajectories. Additional pole tip windings were added to each sector magnet and connected in opposed pairs (figure eight coils) to provide first harmonic field corrections to facilitate beam centering in the ring. The ring magnet is designed to accept partially stripped molecular ions using inflection magnet #1, and H^- ions using both inflection magnets #1

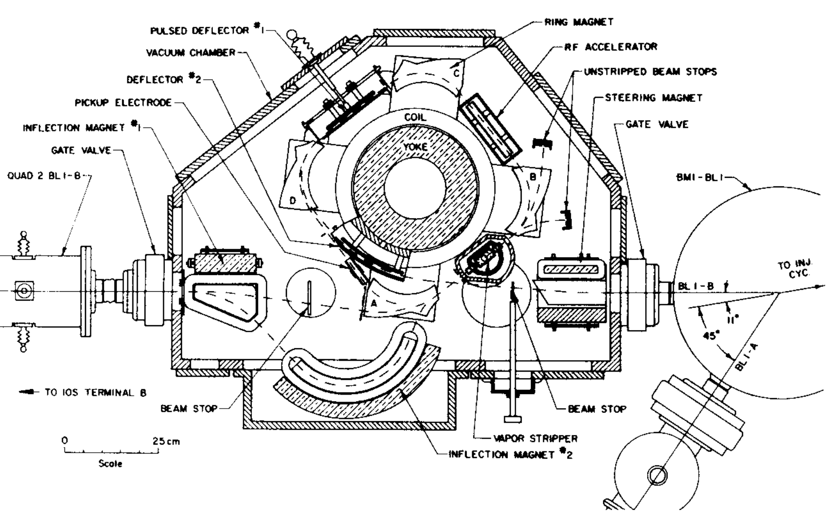

Figure 1. Plan view of stripper loop vacuum chamber and elements. Partially stripped molecular ions or H^- beams are incident from the left. Beam extracted from the ring are directed into the injector cyclotron (to the right) for acceleration.

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TABLE 1

Predicted Stripper Loop Storage Ring Design Parameters

Ring Dimensions:	
Circumference	1.79 m
Betatron Frequencies Q_r, Q_z	1.05, 1.06
Vapor Canal Length	7.0 cm
Vapor Stripper Fluid	C_7F_{14}; Mole. Wgt. = 350
Ring Magnet Dipoles:	
Number of Sectors	4
Magnet Half Angle	18°
Ring Magnet Fraction	0.4
Max. Field Strength	1.3 T
Magnet Radius	12 cm
Magnet Gap	1.0 cm
Electrostatic Deflector #1: (Pulsed)	
Length	16 cm
Gap	0.8 cm
Deflection Angle	19.9 mRad
Capacitance	35 PF
Max. Voltage (varies with duty cycle)	1.0 - 2.0 KV
Min. Rise/Fall Time	50 nSec
Pulse Repetition Rate	10 < F < 900 KHz
Circulating Beam Properties:	
Injection Ions	H_2^+, D_2^+, H^-
Acceptance	$\Delta p/p$ = 4.1%
Max. Rigidity ($B\rho$)	0.20 T.M
Orbit Period	165 < T < 325 nSec
Extracted and Accelerated Beam Properties:	
Max. Energy: H_2^+ and D_2^+ Injection	80 MeV
H^- Injection	200 MeV
Cyclotron Beam Pulse Selection Ratio	1:39 to 1:3000
Beam Brightness Gain: H_2^+ Injection	8
H^- Injection	160
Beam Pulse Width	0.37 pSec FWHM

and #2. For H_2^+ injection, the circulating proton beam energy is half the kinetic energy of the incident beam, and is limited by the source terminal voltage to about 310 keV. The accelerated proton beam energy from the cyclotrons is then limited to 80 MeV. This energy limit will not apply to future operation with H^- ions, for which the stored beam energy is equal to the incident beam energy, and the maximum accelerated proton beam energy is 200 MeV.

The pulse deflector (#1) is powered by a high voltage pulse generator of commerical manufacture.[8] The supply is driven by a variable width pulser whose output is triggered by an adjustable harmonic of the cyclotron RF frequency {F/3(N+1)}. Pulse periods of 1.1 to 100 μs are achieved at the 1 kv amplitude needed for extraction. The lowest repetition rate is arbitrarily limited by the RF harmonic generator divide circuit, while the highest repetition rate (1.1 μs) is determined by the duty cycle capabilities of the kicker pulse generator.

Stripping Mechanisms and Effects

One of the limiting features of the stripper loop performance, particularly in this relatively low energy regime, is the continual beam quality deterioration that occurs on each successive pass through the stripper gas because of multiple scattering, energy straggling and energy loss. The effects are more pronounced for the H_2^+ ions, which were used in all of the development studies presented here, because of the lower circulating beam energy. The properties of the circulating beam become even more confused because the breakup of the H_2^+ ions by collisional dissociation in the vapor canal can proceed by at least two processes yielding protons.[9] The two breakup modes, $H_2^+ \rightarrow H^+ + H$, and $H_2^+ \rightarrow H^+ + H^+ + e^-$, have about equal cross sections of 0.16×10^{-16} cm^2 at 0.62 MeV, but the stripped particles from the second process have an angular divergence of 10 mrad due to the coulomb explosion.[10] Hence the density profile of the protons exiting the stripper has a bright core surrounded by a larger area of a lower density. The protons in the core, produced by the first dissociation reaction, are more closely matched to the acceptance of the ring and should yield most of the circulating beam. Over the operating energy range of the ring, the H_2^+ dissociation cross section varies inversely with the incident energy. The benefits of raising the circulating beam energy to reduce the effects of energy straggling and multiple scattering are therefore diminished by the necessity to raise the vapor pressure to maintain a reasonable stripping fraction. The phase space area increase caused by the stripper can be minimized by placing a double waist and a time focus at its center. This condition is nearly realized in our system. Nevertheless, the competition between the increasing circulating beam density from the addition of freshly stripped particles and the decreasing beam density due to losses caused by the phase space blowup leads to an upper limit on the gain in beam brightness in the ring.

Measurements of the stripping efficiency and energy loss in the vapor canal as a function of the stripper gas thickness were made and found to be in fair agreement with calculations based on the known H_2^+ dissociation cross sections. These measurements and the projected performance of the ring for an incident 0.62 MeV H_2^+ beam are summarized in Table II. The actual pressure in the vapor canal was not measured directly, but was measured in the supply line 45 cm away from the beam. The calibration of this measured pressure with the actual pressure in the stripper was relative and non-linear, but reproducible. The atomic density of the stripper gas (and resultant pressure) for a given measured pressure was determined from the observed stripping fraction (H_2^+ out/H_2^+ in) using the known dissociation cross section. The energy loss per revolution in the ring was measured as described below, and is also in good agreement with the predictions. The predicted intensity gain of the beam extracted from the ring and accelerated by the cyclotrons, which is limited by the acceptance of the bunchers in the injection beam line, is relatively independent of the stripper gas trickness. This was verified in the development runs. However, the momentum acceptance of the ring is nearly 40 times larger than for the buncher, so for the stripping efficiencies shown in Table II, the circulating beam intensity gain should be limited only by space charge effects. The number of revolutions required to reach the predicted space charge limit (1.5 ma) for an incident 60 μA H_2^+ beam (normally available from the source) is also given in Table II.

Circulating Beam Properties

Several diagnostic tools not previously used at IUCF, but common to most synchrotron facilities, were installed in the ring to measure the circulating beam properties. Some of the parameters measured besides the beam intensity gain were the fill rate and lifetime of circulating beam, the tune, isochronism, the momentum acceptance of the ring, and their variation with energy and intensity. The new diagnostics are an RF accelerator cavity to add back the energy lost in the vapor canal, and a cylindrical wall current pickup to monitor the coherent intensity modulation, the incoherent Schottky noise, and the relative intensity of a chopped circulating beam. These devices, the inflection and extraction elements, and the various slits and moveable stops that monitor beam losses, which are shown in Figure 1, effectively fill the four field free regions of the circulating beam path.

The broadband RF accelerating electrode, which subtends 10% of the ring orbit circumference, was used to measure the energy loss of the beam caused by passage through the vapor canal. The application of a

TABLE II

Calculated Stripper Loop Performance vs. Vapor Pressure

Measured Vapor Pres. (μm Hg)	Pressure in 7 cm Canal (μm Hg)	Stripper Gas Thickness (Atoms/cm^2)	Measured H_2^+Out / H_2^+In	H^+ Out / H_2^+ In	Measured E-Loss / Turn (ev)	No. Turns to reach E-Spread Limit*	No. Turns to reach Space Change Limit**	Current Gain
400	5	0.6×10^{16}	.82	.27	24	27	101.	7
500	10	1.1×10^{16}	.68	.50	44	15	54	8
650	21	2.35×10^{16}	.46	.83	99	7	32	6
800	52	5.96×10^{16}	.14	1.30	>160	4	21	5

*This limit set by the buncher acceptance.
**Assuming an Incident 60 μA H_2^+ Beam.

symmetrical triangular waveform to the accelerator electrode at precisely the beam orbit frequency causes an energy gain equal to 20% of the peak voltage for the beam in one half of the ring, and an equal energy loss for the beam in the other half. The resulting modulation of the circulating beam intensity was observed on the wall current monitor. The amplitude of the applied votage causing the maximum intensity modulation is a measure of the beam energy loss per turn in the vapor stripper. The measured energy loss compares favorably with that expected from the known stripper gas pressure. However, the maximum observed beam intensity modulation was only 60 to 70% of the circulating beam intensity, indicating that this loss mechanism is not the limiting factor in the buildup of intensity in the ring.

Evidence for an intensity limiting mechanism is found in Figure 2, which is a photograph of the amplified output of the wall current pickup for 20 μs after pulsing half the circulating beam out of the ring. Because the ring is isochronous, there is no debunching of the remaining beam as it continues to circulate. The observed notches are the coherent signal from the hole put in the beam and are seperated by the orbit period (231 ns). The amplitude of the notches slowly decreases with accumulation time as the hole is filled with freshly stripped beam until after 6 μs, the beam intensity in both halves of the ring is equal. But the notches then invert, indicating that the intensity in the former hole continues to increase to a maximum at 14 μs, and then drops in intensity again until all evidence of the initial hole vanishes after 20 μs (or 87 resolutions). This phenomenon indicates that the intensity in the hole rises above that of the remaining longer lived circulating beam until an instability develops which reduces the stored beam to a lower equilibrium level. The peak intensity extracted from the ring was measured on an external beam stop as a function of the pulse period under the same consitions as those in Figure 2, except that the pulse width of deflector #1 was made slightly longer than the orbit period to insure that the entire stored contents of the ring were extracted. The data are illustrated in Figure 3 and compared with a photograph of the coherent signals observed on the pickup electrode. Both the photograph and the graph have the same time scale. The onset of the beam instability is evident in the photograph by the increase in the noise level at 14 μs, which is coincident with the peak in the extracted beam intensity. The conclusion from this measurement is that the peak circulating beam intensity is achieved as the instability is reached.

The circulation time at which the instability occurs decreases with increasing stripper density and with incident beam intensity. At very low vapor pressures or very low incident beam intensities, the overfill phenomenon and instability are not observed. At extremely high vapor pressures, (>6 x 10^{16} atoms/cm^2), the instability is also not observed, which could be an indication that the instability varies with emittance. Measurements made at one lower circulating beam energy (208 keV) showed that the onset of the instability occurred at a lower stored beam current (by about a factor of four).

Possible sources of this intensity and energy dependent instability were explored. The most obvious candidate, a transverse space charge induced instability which causes a betatron tune shift, was studied by observing the Schottky betatron sidebands of the circulating beam. These average spectrum analyzed signals are shown in Figure 4 for a 208 keV stored proton beam. The central peak in the spectrum is the orbit frequency of the circulating beam (3.561 MHz) and the two satellite peaks are the betatron sidebands. The absolute value of $|Q_r-1|$ determined from this spectrum was 0.09, which is in mild agreement with the value Q_r = 1.05 calculated from the magnetic field data. However, the radial tune was scarcely affected by varying the circulating beam intensity, which argues against a large space charge tune shift as the cause of the instability. This is consistent with our estimate of the maximum stored beam current achieved in the ring of 0.8 ma. This is about half the predicted current (1.5 ma) required to observe the space charge tune shifts. The Schottky signals were also used to determine the momentum acceptance and isochronism of the ring by measuring the orbit frequency as a function of the ring magnetic field. The ring is isochronous to 0.10%, which agrees with the magnetic field data. However, the momentum acceptance is only about 40% of the design value, which suggests that the orbit centering or the placement of the stripper or inflection elements in the ring is not correct. While this may be limiting the amount of circulating beam that can be achieved, it is probably not contributing

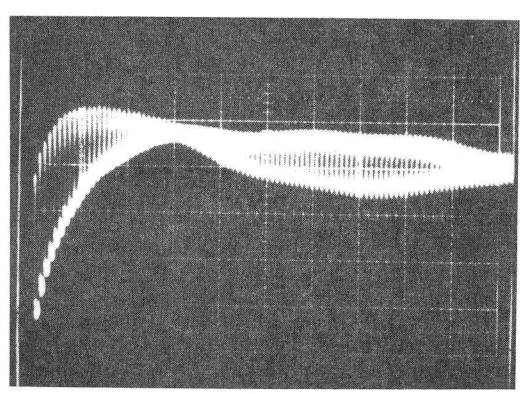

Figure 2. 5 μSec/Div; 50 mU/Div.

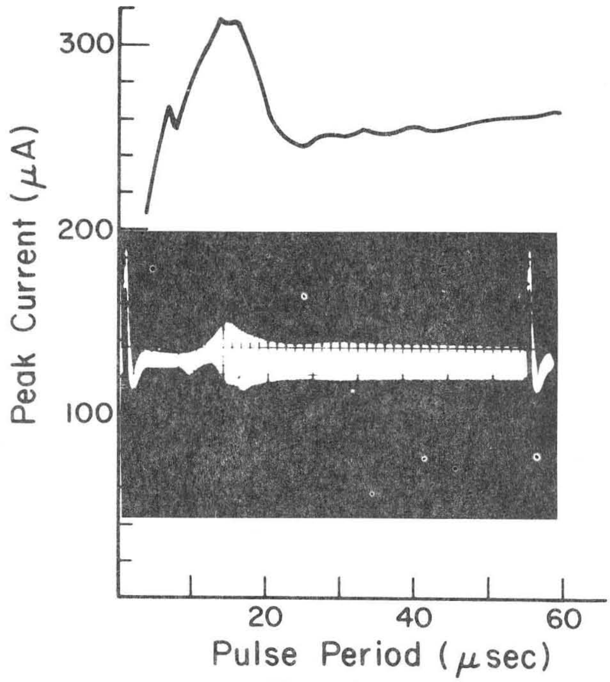

Figure 3.

to the development of the instability.

The energy (velocity) dependence of the instability has not been precisely measured. The factor of four difference in the observed circulating beam intensity for the two energies studied above (208 and 308 keV) suggests a strong velocity dependence which needs to be studied.

Conclusions and Future Developments

These initial development efforts with the stripper loop have demonstrated the ability of the system to provide intense pulsed beams of variable duty factor. The very preliminary results are encouraging, with extracted peak beam currents 10 times more intense than previously available for injection into the injector cyclotron achieved. This beam was chopped and bunched in the low energy beam line, accelerated to 80 MeV in the cyclotrons, and directed to the neutron time-of-flight facility for evaluation. Pulsed beam intensities equivalent to a DC beam of 14 μA with pulse periods between 3 and 10 μs were achieved. This is three times higher than the best previous performance of the cyclotrons and is within a factor of two of the predicted intensity gain. Measurement of the time and energy widths of the beam were made using the neutron facility. A spectrum for the $^7Li(p,n)^7Be$ reaction is shown in Figure 5. The beam energy resolution (149 keV) and burst width (0.37 ns) were equal to the performance of the normal duty factor beams available

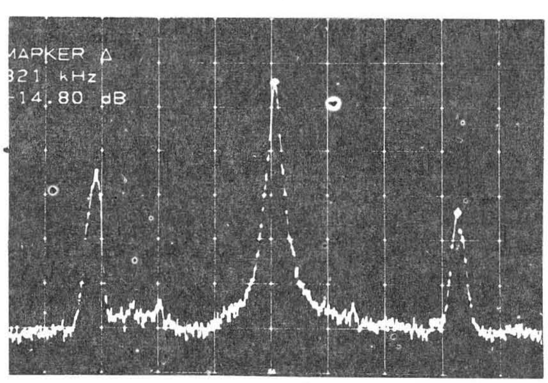

Figure 4.

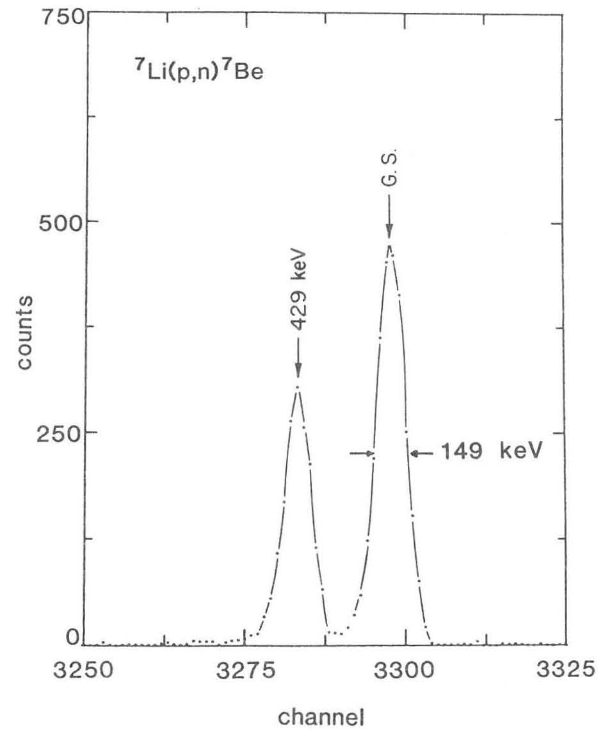

Figure 5.

from the cyclotrons.

Detailed studies of the performance limits of the stripper loop are continuing. While several fundamental properties of the ring and extraction system need to be measured and perhaps modified. Its initial use with the H_2^+ beam is good enough to be made available to our users. The velocity dependence of the instability, which occurs at an unexpectedly low circulating beam current, needs to be investigated. For this reason, an H^- beam capability is being developed. Because of the higher circulating beam energy and a less complicated stripping mechanism of the H^- beam, higher circulating beam currents are anticipated. The H^- stripping cross section is approximately a factor of ten larger than for the H_2 beam,[11] and the energy loss varies inversely with the beam energy, hence an improvement of a factor of 20 over the H_2^+ beam performance is expected. It remains to be seen if the observed instability will indeed limit the performance of this type of storage ring at these low energies.

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