COUPLING CYCLOTRONS TO OTHER MACHINES

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Abstract.-Coupling of cyclotrons to other accelerators and to research equipment will be reviewed in the context of some working examples which indicate both the limitations imposed by cyclotron characteristics and the advantages which have benefited particular applications. Some aspects of the problem of using a cyclotron to fill a storage ring or synchrotron will be explored and test results of a scheme for preparation of a suitable beam macrostructure by phase modulated transfer between cyclotrons with internal stacking will be presented. Limitations in the use of storage structures in the preparation of beams of enhanced brightness will be assessed. It appears evident that there remains considerable scope for further advancement in the exploitation of cyclotron characteristics in coupled systems.

1. Introduction.-Internal targets in the earliest circular accelerators were largely supplanted by extracted beams to gain clear target access and better control over background and beam properties. After strong focusing elements came into general use, beam transport to multiple target stations became commonplace while modern computational aids now allow quite sophisticated design solutions which optimize beam characteristics for a given experiment. We note, for example, the interchange of longitudinal and transverse phase space and/or time focus "rebunching" to obtain pulses with a narrow time spread and the numerous spectrograph matching solutions1) to render an experiment with high resolution at least somewhat immune to the accelerator beam quality. The most commonplace example of coupling an accelerator such as a cyclotron to another "machine" is thus the coupling to experimental apparatus in the general sense.

Coupling of cyclotrons to other accelerators has a shorter history. At the low energy end, external injection to eliminate the spatial and access constraints on ion sources such as polarized sources was appearing in mid-1960's (see for example the 1965 Karlsruhe polarization conference or the 1966 Gatlinburg cyclotron conference proceedings). In the past 15 years we have seen numerous examples of higher energy coupling such as the connection of linac to cyclotron (Alice, Orsay), of cyclotrons to cyclotrons (Dubna, SIN, Indiana ...), of cyclotrons to electrostatic machines (Livermore, Duke) and the converse (Vicksi, ORNL). Many more cases are under construction and have been described during this conference. Despite the intricacies of the accelerator interconnection problem there are a number of elegant solutions in the literature. A review talk was given earlier in this conference which gave examples of the six-dimensional matching process2). At the risk of oversimplification I choose to refer to the coupling of cyclotrons to experiments, to other cyclotrons, or to linear and DC accelerators as traditional coupling systems from the point of view that they have received and are receiving a great deal of careful attention elsewhere and their implementation has reach a condition of relative maturity. In this paper I will concentrate on a few less well-explored problems, in an admittedly somewhat sketchy fashion, with the intention of exposing situations in which the characteristics of a cyclotron beam limit the coupling efficiency and operating modes by which some of the limits can be extended.

2. Filling a Ring.-One of the possible couplings of a cyclotron to another machine which is not commonly encountered is the injection of cyclotron beam into a synchrotron or storage ring. Even in an energy range in which the cyclotron would seem to be the most economical source of beam, the customary choice of injector is a linear accelerator. The simple explanation is the mismatch in macroscopic time structure, with the cyclotron generating a more-or-less continuous beam of intensity 10^{-6} to 10^{-4} Amperes while the ring fill sequence accepts beam for 10^{-5} to 10^{-3} seconds with a repetition cycle 10^{-1} seconds or longer but with the capacity to accept stored currents of 10^{-2} to 1 amps. We see that the time-averaged cyclotron current is of appropriate magnitude provided that the beam which is generated by the cyclotron, at times when the ring is not ready to accept beam, is not thrown away but accumulated while waiting for the next fill interval. A linear accelerator which normally operates intermittently because of the high power consumption can deliver currents of the order of 10^{-2} Amps, which fill the ring to the stability limit in a few tens of revolutions, and can then be turned off until the next fill interval.

To pursue the question of a cyclotron filling a ring we have to ask why the cyclotron gives less peak current than the linac, what forms of temporary storage are feasible (inside the cyclotron or in a separate ring) and finally whether a cyclotron with time cycle adjusted to match the requirements of a synchrotron or storage ring is competitive in cost and complexity with the traditional injector.

An aspect of this problem which prevents a simple analysis but which provides much of the interest is that the act of intermediate temporary storage can give access to some slow processes which modify beam properties that are effectively invariant on the short time scale of conventional transport. Macroscopic duty factor is of course itself one of the beam characteristics which in this example we would like to modify. Beam brightness (phase space density) may also be changed if there is a change in charge state during one of the stacking procedures.

We look first at the question of intensity limitations and at some schemes for stacking inside the cyclotron ring, then return to the general question in the context of intermediate storage.

3. The Question of Intensity.-For a linear accelerator, the focusing elements which are needed to gain transverse stability despite electric defocusing are generally strong enough to give a relatively high space charge limit so that apart from an rf capture efficiency factor of order 1/2, the intensity can be estimated from the product of ion source brightness and the two transverse acceptances. Peak intensities are often tens of milliAmperes.

In a cyclotron with an internal source, the relatively weak axial focusing in the first few turns imposes a transverse stability limit on intensity, while the coherent longitudinal space charge effect further limits the extracted intensity in single turn mode. Intensities commonly encountered are usually no more than a few hundred microAmperes internal or a few tens of microAmperes external. By using a cyclotron geometry with low average field and large turn separation combined with external injection into a strong field which has high flutter, as in the new SIN injector, it is now possible to design for external beams of at least several milliAmperes.

It is informative to contrast the instantaneous brightness (maximum number of particles per unit six-dimensional phase space volume) of linacs with cyclotrons. For consistent units we can express the longitudinal phase space area in units of "millimeter-milliradians" (more correctly micrometers) by recognizing the relation between time and pulse length and expressing the energy spread in terms of an angle $\theta = \Delta P/_{p}$. For example, IUCF at 6 μA (with transverse emittances of 1π mm mrad, $\Delta E/_{E}$ 10^{-3}, Δt 3 10^{-10} sec, and rf frequency 30 MHz) has 1.3 10^{3} protons mm^{-3} $mrad^{-3}$, while LAMPF at 350 μA with 9% duty factor, emittance 3π mm mrad $\Delta E/_{E}$ 310^{-3} and 120 Hz rep rate gives about 2 10^{3} mm^{-3} $mrad^{-3}$. The brightness is comparable and it is averaging over the narrow time burst microstructure of the cyclotron that gives the apparently lower current density on a microsecond time scale. These machines are not the technological limit. Radiofrequency quadrupole linear accelerator structures can increase the low energy capture efficiency of linear structures while phase compression and better bunching techniques can further increase the brightness of the beam from a cyclotron by comparable amounts.

We note that the beam brightness is primarily constrained by the characteristics of ion sources and low energy bunchers rather than by the accelerator structure. However, to exploit this brightness in stacking a cyclotron beam into a ring (synchrotron or storage devices) it is necessary to find a mechanism for interleaving pulses within the cyclotron rf structure.

4. Stacking Inside A Cyclotron.-A method of preparing the TRIUMF beam for synchrotron injection has been discussed by Richardson.[3] By modifying the isochronous field profile near the extraction radius, the beam may be made to slip in phase and gain energy very slowly. It is claimed that the equivalent of 100 turns will accumulate in a radial interval of 2 or 3 cm allowing an extracted pulse in excess of 10^{10} particles every 20 μs. This process may be viewed as a use of the cyclotron field and rf to perform an operation on the internal beam which increases the azimuthal length while reducing the radial width, keeping the density constant. The microscopic duty factor is increased while the macroscopic duty factor is decreased in intermittent extraction to suit the synchrotron injection requirements.

If the field of an isochronous cyclotron is given a bipolar, radially localized perturbation, the longitudinal phase space develops a synchrotron-like stable region and an unstable stagnation point as shown in Fig. 1. By choosing the initial phase so that the beam approaches an unstable point along the separatrix, the turn separation may be reduced and the microscopic duty factor increased. Note however that this stack is not oriented for simple extraction without further manipulation. By introducing a time dependence in the perturbation (e.g., rapid change in dee voltage or phase or a pulsed valley magnet) it may be conjectured that analogs of synchrotron procedures such as rf capture exist. At the moment, however, the large stable phase bucket or trap which can be created remains a curiosity awaiting exploitation.

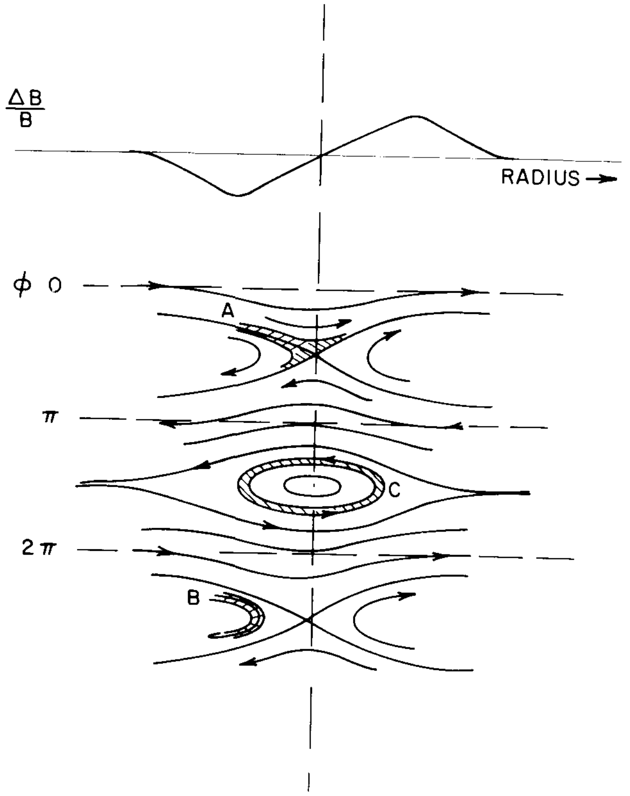

Figure 1. Phase trap in a cyclotron generated by a bipolar field perturbation introduced by trim coils. Beam at the optimum phase will pass through this region with only a modest phase excursion. A change of initial phase onto the separatrix at A can lead to a stack oriented on an R,ϕ diagonal. A larger phase offset can lead to deceleration and a radial density increase as at B. A synchrotron phase bucket exists at C which, if filled, could hold beam indefinitely.

5. The 360° Dee as a Phase Compressor.-We have become accustomed to operating the rf resonators in a cyclotron in the manner that gives the maximum energy gain per turn. For a dee of physical azimuthal width θ_D the optimum gain is obtained for $h\theta_D = 180°$, where the rf harmonic number h is the integer ratio (orbit period/rf period). For a particle of half the velocity

the electrical length increases to the value $h\,\theta_D$ = 360° and a particle loses as much energy leaving the dee as it gains on entering, giving no net acceleration.

In a separated sector cyclotron the dees can be electrically independent. Moreover it is relatively easy to obtain more net acceleration than the minimum required for normal operation. At IUCF we have operated each of the two cyclotrons with one resonator shut off completely at energies up to 80% of their design maximum. It is interesting to speculate on ways to put the second resonator to good use when it is not needed for acceleration.

Measurements on the IUCF injector cyclotron of the bunched beam after the first half turn show very clearly the bunching effect of the first dee crossing if the phase departs from that of optimum energy gain for $h\theta_D$ -180°. The orbit trajectory within the dee is nearly a straight line so that if energy is gained on entering and lost on leaving the dee the phase will advance and conversely. The klystron buncher amplitude that gives the narrowest beam pulse thus depends on starting phase.

If one dee is used for acceleration and the other is operated at a different frequency so that its electrical length is 360° it might be used as a device to manipulate the longitudinal phase space independent of acceleration.

Although the IUCF dee (θ_D = 38°) was not designed for this purpose and gives null acceleration first for the prime number h = 19, it is possible to consider a practical example of acceleration on h_1 = 8 at 28 MHz (about 25 MeV/amu) with the second dee operated at 35 MHz (h_2 = 10) and beam pulse selected at 7 MHZ. Each beam pulse sees the dees at a constant relative phase. The higher frequency dee gives little energy gain. For deuterons accelerated from 0.25 MeV to 5 MeV in the injector cyclotron with 30 kV amplitude on each dee we obtain

$$d\phi/dn = {}^{-}1/2(eV_D/E)(\theta_D/2\pi)(h_1\tau_{RF})(2\pi/\tau_{rf})\sin\phi$$

where the effective turn number
$n = (E/2eV_D)\csc(180-h_1\theta_D/2)$.

Integrating for small ϕ we see $\phi_2/\phi_1 = (n_1/n_2)^{2.8}$ where the exponent = $\pi h_1(V2/V1)(19/360)\csc 28°$.

The predicted phase compression ($\phi \sim 0°$) or expansion ($\phi \sim 180°$) is a factor of seven for each doubling of the beam energy so that an auxiliary dee operated at lower voltage would still have a useful effect on the beam phase spread. A phase compression results in an energy spread expansion, limiting the maximum useful compression. If the incident beam has a well defined energy, it is presumably best to carry out the compression at low energy.

An electrode could be constructed in such a way that its physical length varied with radius eg from 18° at injection to 36° at large radius so that for h = 10 the acceleration approaches zero and the beam spreads over a very wide phase interval in a stack suited to pulsed extraction with large microscopic duty factor.

The relation to the method of phase compression/expansion through a dee voltage that depends on radius should be noted.$^{4)}$ In a complete treatment one must carefully take into account the phase dependent effects on orbit centering in the radial phase space.$^{5)}$

Figure 2 shows the phase space flow for a dee system near the null acceleration velocity. For constant θ_D within an isochronous structure, the accelerated equilibrium orbit returns to a fixed fraction of the longitudinal momentum from the null line. The flow lines show how area is conserved and how an electrode that departs from 360° width can give some acceleration or deceleration in addition to the bunching.

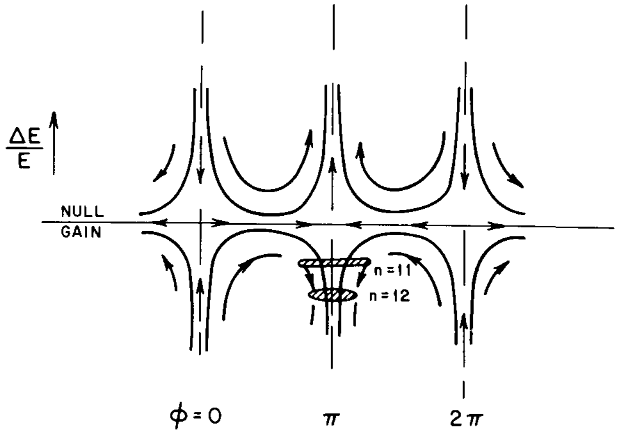

Figure 2. Phase flow for a dee of length close to 360°. The phase compression of the first injected turn (energy equivalent to 11 turns starting from rest) is shown. See text.

6. Phase Skew Injection.-A snapshot of the beam in a conventionally-operated isochronous cyclotron at a particular instant of time would show many individual beam bunches distributed like the spokes of a wheel with the number of spokes being given by the harmonic number h and the number of bunches per spoke being equal to n the number of revolutions between injection and extraction. Most of the cyclotron interior would be seen to be empty. The total beam contained is clearly hn times the number of beam particles/bunch and is widely distributed in energy.

To use the cyclotron field volume more efficiently in preparing a beam for ring injection,one would rather see the beam distributed uniformly over the circumference at a single energy like the rim of a wheel rather than a spoke. One way to obtain a somewhat better approximation to this ideal is to introduce a bunch-to-bunch variation in the injection phase. Suppose, for example, we have a machine set up for normal isochronous 100 turn operation at the optimum phase ϕ = 0. If the phase is shifted instead to 33.56°, for a sinusoidal rf waveform the turn number increases to 120 turns. If we inject a single bunch at this phase and after one revolution, a second bunch at a phase ϕ = 32.82° which requires only 119 turns to reach full radius, the two bunches will arrive at this radius at the same time. A sequence of slightly changed starting phases requiring 118, 117, 116---turns for successive bunches will result in an azimuthal stack, in the example 41 turns extending over 67° in azimuth. Note that a finite phase spread in each bunch results in a radial width at extraction that ultimately limits the practical number of bunches per stack. In this example a 3° phase width would give the stack a maximum radial width corresponding to 4 times the normal turn spacing. For stacks containing <50 turns, a linear variation in phase with turn number gives a radial distribution of bunch centroids with a slight bow as indicated in Figure 3. Lowering the dee voltage to increase the turn number while simultaneously reducing the phase skew per turn increases the stack density while maintaining the same radial width up to a limit set by inflector clearance during injection.

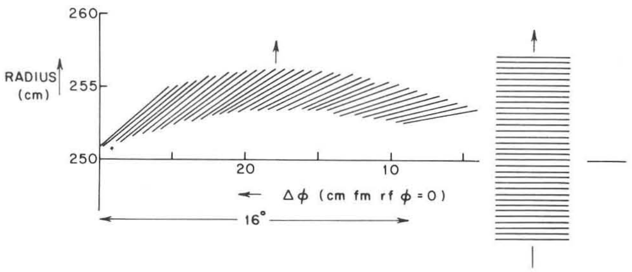

Figure 3. Phase skew stacking. The 33 turns at the right are accelerating after normal injection at the optimum phase. The total turn number is 500 and the phase width of each bunch is 4°. On the left is shown the stack produced by a uniform phase slip of 0.5°/turn. Note the increase in the number of particles in an energy band acceptable for synchrotron injection.

If this stack can be extracted in a single turn, for example with a vertical kick, followed after one-quarter betatron cycle by a septum magnet, it has properties well-matched to the injection requirements of a synchrotron or storage ring.

This scheme was tested at IUCF in November 1980 by operating the two cyclotrons from frequency sources differing by 5 kHz so that injected turns in the main stage slipped by 360 degrees in 200 microseconds or about 0.3° per revolution. A gamma ray monitor with a plastic scintillator was used to look at the beam stopping in an internal probe or after extraction on an external stop in the beam line. The monitor pulse could be timed both with respect to the cyclotron rf and with respect to a trigger pulse derived from the relative phase of the two cyclotrons. As expected, a plot of starting phase versus rf phase at arrival at a given radius showed a well-defined stack with a slight curvature. The beam, conventionally extracted, showed a similar correlation plot indicating that the stack had been peeled off over the space of several turns as predicted by the ratio of radial stack width to deflector aperture. Some of the results are shown in Figures 4 and 5.

The repetition rate for stack formation could be increased by an order of magnitude by introducing a cyclic 50 kHz path length variation in a bend in the injection beam line. Rapid modulation of the rf resonator phase is difficult because of the high Q of these structures.

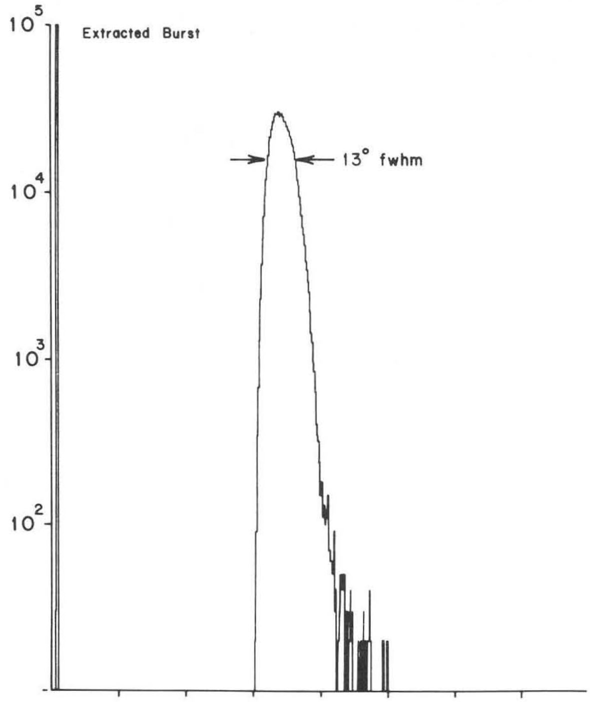

Figure 4. Extracted 80 MeV proton beam from IUCF during phase skew injection test. The peak current is 1μA with about 5% macroscopic duty factor. The beam-off intensity is reduced enough for immediate application on slow pulsed beam experiments.

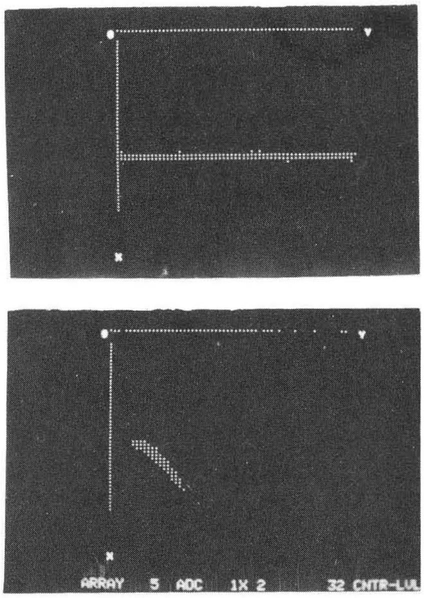

Figure 5. Phase-phase plots for IUCF injector cyclotron a) normal injection. The beam is narrowly bunched in rf phase but shows no macrostructure. b) The chopper-buncher frequency is shifted 5 KHz with respect to the cyclotron rf. Note the correlation between macroscopic (starting) phase and phase at full radius in qualitative agreement with predictions such as indicated in Figure 3

7. Status of Internal Stacking Schemes. We have briefly discussed a few ideas for modifying the phase space distribution of cyclotron beams prior to extraction. These examples have in common the requirement for modifications in the extraction process and the capacity to prepare a "stack" containing perhaps 20 to 100 times the number of particles within a single cyclotron bunch. In combination with a second process, such as increasing the cyclotron bunch density to the space charge limit, or stacking on injection into the ring, these internal manipulations can be of considerable value in achieving an efficient transfer from cyclotron to ring.

Whereas conventional cyclotron operation aims for extraction of well-separated turns after acceleration in as few turns as possible, these stacking schemes have in common an improvement in macroscopic stack density as the number of turns of acceleration is increased to minimize the empty volume between bunches on adjacent turns. Modern separated-sector cyclotrons, without the internal sources which require phase slip for axial stability on the first turns, can be made so isochronous that several thousand turn operation may be obtained if desired.

8. Brightness Enhancement by Stripping.-Beam density in phase space is the parameter ultimately controlling event rate in an experiment of a given precision. An accelerator which can raise a beam to a useful energy without going to the most probable charge state at that energy has an inherent capability for preparation of a beam of increased brightness by repetitive passage through a stripper. Although stripping injection into synchrotons is in widespread use, in this application the internal beam brightness may not be much greater than that of the injector beam, the stripping being used as a simple, efficient stacking tool. Many cyclotrons can produce extracted beams such as H^-, H_2^+, $^3He^+$ etc. which can then be stripped. The opportunity to increase the beam brightness by recirculating the stripped beam through the stripper is not in widespread use although the benefits can be shown to be rather great.

The incident beam and the circulating beam have different magnetic rigidities and can therefore be made to follow identical paths incident on the stripper. After stripping, the newly stripped particles occupy interstices in the largely-empty phase space volume occupied by the circulating beam so that Liouville's Theorem is not violated on a microscopic scale even though the density rises. The stripper must be thick enough to convert a large fraction of the incident beam to the equilibrium state while the probability of changing to some other charge state must be low enough to permit a large number of revolutions. The minimum stripper thickness required depends on the ion species and energy. The beam quality deteriorates on each successive pass through the stripper because of multiple scattering and energy straggling. The effects are minimized by arranging if possible a small transverse double waist and a time focus at the stripper. Competition between the increasing density owing to freshly stripped particles and the decreasing density due to the incoherent blowup leads to an upper bound on the brightness. We can characterize the effects of the stripper by the emergent beam dimensions after one pass of an incident beam of vanishing emittance in comparison with the actual incident beam. Suppose at the stripper waist the incident beam divergence angle is θ_o and the increase in one turn is θ_1. After n turns the circulating beam current i_c will exceed the incident current by a factor n while the circulating beam divergence angle θ_c will be given by $\theta_c^2 = \theta_o^2 + (n+1)/2\theta_1^2$ where the factor 2 comes from averaging over a distribution of a number of passes. For a given waist size θ_c^2 is proportional to the beam emittance while the brightness B is proportional to i_c/θ_c^4 considering only the two transverse dimensions. We maximize the brightness with respect to turn number n and find:

$$n_{max} = 1 + 2\,\theta_o^2/\theta_1^2$$

$$\theta_c^2{}_{max} = 2\theta_o^2 + \theta_1^2$$

$$B_{max}/B_o = 1/4(n_m+2)$$

There is a substantial increase in brightness if $\theta_o^2 >> \theta_1^2$ with the optimum emittance being then about twice the incident emittance.

As an example to illustrate the magnitude of the increase in phase space density which may be achieved, Table I shows a calculation for H^- beams of 10 MeV and 200 MeV with emittance comparable to the IUCF beam emittance of $1.0\pi/\beta\gamma$ mm mrad and stripping by carbon foil thick enough for 95% charge state conversion. The waist size is given by $X_c = \varepsilon_c/\pi\theta_c$ where X_c/θ_c is chosen to be 1 meter. Over this wide range the brightness is seen to increase by a factor of about 1000. Calculations at 800 MeV[6)] indicate that this factor continues be quite large at higher energies.

This very bright circulating beam may be used with an internal target, with thickness and fractional overlap with the circulating beam at the target chosen so the probability of removal is + $1/n_{max}$ per turn. Alternatively, if more space for the experiment is required than can be found in the lattice of the beam recirculating ring, the beam may be continuously extracted from the periphery of the phase volume giving a current similar to the incident current but with the emittance reduced by a factor of 25 to 35 in both planes.

Table I. Brightness Enhancement for H^-

Beam Energy	10	200	MeV
Foil Thickness	6	100	$\mu g/cm^2$
Input Emittance	6.8π	1.4π	mm mrad
θ_o^2	6.8	1.4	10^{-6}sterad
θ_1^2	47	5.5	10^{-10}sterad
n_{max}	2900	5300	turns
β_{max}	725	1325	

An interesting application of these ideas was proposed at the Colorado cyclotron. By using an isochronous recirculator to maintain the narrow phase spread of the extracted cyclotron beam while building up the circulating current to the transverse space charge limit, and then extracting in a single turn, it was proposed to create a very intense single short pulse for long-path neutron time-of-flight experiments. An H_2^+ 0.6 MeV "stripper loop" based on this idea is under construction at IUCF to demonstrate feasibility and to create a more intense pulse for studies of the space charge limits of the IUCF injector and possible future application to our neutron program. At this low energy the brightness increase is limited to a factor of about 20 to 50 but rapid pulsed extraction is less difficult.

Summary.-Over a fifty year period cyclotron enthusiasts have learned to make accelerators with very high performance and to couple these to experiments and to other continuous beam accelerators in sophisticated ways. Using a cyclotron as a pulsed injector for a synchrotron or storage ring may now also be becoming feasible although there is scope for new ideas including some rather unusual ways to operate the cyclotron. Ideas about new uses for beam storage devices are gradually changing our perception of the most important properties of an accelerator. In particular, the acceleration of strippable beams can lead to emittance reduction without intensity loss by means of a recirculator. Duty factor may also become a more freely adjustable parameter with devices to modify micro-and macro-structure inside or outside the cyclotron.

" DISCUSSION "

D.A. LIND : Comment : Short stacked beams permit preparation by reaction of exotic targets in one beam burst with study by successive bursts. Study of second order processes becomes possible.

W. JOHO : Comment : One can enhance the stacking at the outer radius by a decrease in the peak accelerating voltage as a function of radius. This could be achieved by adding another RF system which acts only at the outer radius.

R. POLLOCK : Yes, I agree.

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