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ACCELERATOR DEPARTMENT
(AGS)

BNL 6434

DSR-1

Internal Report

BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, L.I., N.Y.

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INTERNAL BUNCHING IN THE ALTERNATING GRADIENT SYNCHROTRON

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January 16, 1961

In 1958, V.I. Veksler¹ proposed a radiofrequency particle separator for use with the Dubna synchrotron. His proposal involved rebunching the protons into much shorter bunches within the synchrotron. The object of this report is to study several methods of rebunching in the Brookhaven Alternating Gradient Synchrotron (AGS) and to assess their relative merits.

Since Veksler proposed his separator, other methods of radiofrequency particle separation have been suggested. In particular, the separator now under construction at CERN² does not rely on short bunches for its operation, but uses two or three external deflecting cavities with appropriate lens systems between them. Also, linear accelerators, such as Project "M" at Stanford University, Stanford, California, which operate at 3000 Mc will emit bunches which are already short enough and no rebunching will be necessary.

Perhaps the most difficult aspect of the rebunching process is the requirement that there shall be no protons between bunches because such protons would give rise to contamination of the beam of wanted particles. A practical difficulty is the relatively low cutoff frequency of the vacuum chamber, 980 Mc in our case. In order to avoid the possibility of propagating large amounts of microwave power around the ring, one would prefer to operate the buncher at a frequency below cutoff.

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A diagram of a separator is shown in Fig. 1. The primary beam consists of short bunches of length $Kc\tau$ where τ is the reciprocal of the rebunching frequency, and K is a constant less than or equal to 0.5.

At the target, the secondary particles are produced in short bunches. They are momentum analyzed, and the distance "d" from target to deflecting cavity D, must be large enough for the mixed bunches of secondaries, formed at the target to separate into their components. The phase of the deflecting voltage relative to the bunching voltage is chosen so that the wanted particles are deflected in one direction and the unwanted particles are deflected in the opposite direction.

It is not necessary to operate the deflecting cavity at the same frequency as the buncher. For example, one could bunch at 675 Mc, choose a bunch length of 90° at this frequency ($K=\frac{1}{4}$), and run the deflector at 1350 Mc. This is a frequency at which high power L band klystrons are available. Or one could bunch at 953.3 Mc, choose a bunch length of 60° ($K=\frac{1}{6}$), and deflect at 2860 Mc, which is the standard S band linac frequency.

In either case, for optimum separation, the drift length d (Fig. 1), should be chosen so that the bunches of wanted and unwanted particles have separated by half a wavelength of the deflecting frequency by the time they reach the deflector.

The optimum values of d for the separation of 10 Gev π and K mesons are 50 meters for S band deflection and 110 meters for L band deflection, the velocity difference of π and K mesons at this energy being only about 0.001c.

Several methods of rebunching will be considered. They are:

- I. Switch off the old rf and switch on the new rf simultaneously. Then raise the new rf voltage adiabatically so as to shrink the new bunches.
- II. Attempt an adiabatic transfer by gradually introducing the new rf voltage and then removing the old rf voltage.
- III. Same as II, but in reversed order.
- IV. Phase jump methods as proposed by L.C. Teng³.

Method I:

To estimate the capture efficiency, it is only necessary to superimpose the new phase plane diagram on the old one. This has been done in Fig. 2. Those particles in the new buckets are captured and those outside them are lost to the inner walls of the vacuum chamber or to some appropriately placed stopper. The diagram has been plotted for an old rf of 4.5 Mc and a new one of 675 Mc. Two cases are shown. The full line curve is for a new rf voltage equal to the old one, and the broken line curve is for a new rf voltage equal to four times the old one. In both cases, the value of B is assumed to remain unchanged from its normal rate of rise. The circle shows the old bunch of width 20° at 4.5 Mc.

In the first case, over 70% of the particles are lost, and the new bunches are 180° long. To compress them adiabatically to 90° would require a final rf voltage of $(\frac{180}{90})^4$ x (old rf voltage), or about 3 Megavolts for the Brookhaven AGS.

In the second case, capture efficiency is about 60%, but the new bunches are almost 360° long and to compress them to a length of 90° would require a final voltage of about 200 Megavolts.

Such "brute force" methods of rebunching are clearly inefficient if one's aim is to rebunch all the particles with as little rf power as possible.

Method II:

The old rf voltage remains on, while the new one is gradually introduced.

Let $B = 0$. The equation of motion of the particles is then

$$\frac{d^2\varphi}{dt^2} = \Omega^2 (\sin\varphi + Kt \sin n\varphi) \quad (1)$$

$$\text{where } \Omega^2 = - \frac{NqV_m h\omega^2 \Gamma}{2\pi E_s}$$

The symbols are those used by Livingood⁴ (p.88). At $t = 0$, $\varphi = \varphi_1$ and

$$\frac{d\varphi}{dt} = \pm \Omega \sqrt{2(\cos\hat{\varphi} - \cos\varphi_1)}$$

where $\hat{\varphi}$ is the peak value of φ .

In the Brookhaven AGS, the total bunch width is about 20° at 4.5 Mc. All particles should be oscillating within the limits $(\pi+0.18) > \phi > (\pi-0.18)$. To be quite safe, limits of $\pi \pm 0.4$ were taken. This gives $\hat{\phi} = \pi \pm 0.4$. Using this value of $\hat{\phi}$, and four different values of ϕ_i , Eq.(1) was numerically integrated. The equation was integrated by the Runge-Kutta method on the N.Y.U. 7090 Computer, the integration interval being one microsecond. The value of K was set at 200, which gives an amplitude rise of $N \cdot V_m/5$ volts per millisecond for the new rf.

The results are shown in Fig.2. The particles oscillate at their old frequency. After some time, they may be captured into new high frequency buckets at the limits of their oscillation. If they are not captured, they continue to oscillate with slightly reduced amplitude. There is a chance of capture once every half cycle of phase oscillation.

A mechanical analogy for this situation is a ball rolling back and forth in a concave dish. The dish has corrugations whose depth increases with time. It can only be captured when it comes to rest at the extremes of its oscillation, and, if caught, it will oscillate rapidly in the new "bucket". If it is not caught, it may be unable to climb into this bucket next time and then its amplitude of oscillation will drop by one new bucket width. There will be some particles that repeatedly fail to be captured, but, if the corrugations grow without limit, every ball will eventually be captured. The last ones to be captured will occupy buckets towards the bottom of the dish.

Phase plane diagrams are shown in Figs.4 to 8. They were plotted by the 7090 Computer using a plot routine kindly supplied by J. Suich of Brookhaven. They were derived from the following equation:

$$\frac{d^2\phi}{dt^2} = \Omega^2 (\sin\phi - \sin\phi_s + Kt \sin n(\phi - \phi_s))$$

where $\Omega^2 = - \frac{Nq V_m h \omega_s^2 \Gamma}{2\pi E_s}$, the symbols being those used by J.J. Livingood (p.88).

Therefore,

$$\frac{1}{\Omega^2} \left(\frac{d\varphi}{dt} \right)^2 = 2 \left(-\cos\varphi - \varphi \sin\varphi_s - \frac{Kt}{n} (\varphi - \varphi_s) + C \right)$$

to evaluate C, let $\frac{d\varphi}{dt} = \frac{d\varphi_i}{dt}$ when $\varphi = \varphi_i = \varphi_s + \frac{\pi}{2n}$.

$$\text{Then } \frac{1}{\Omega} \frac{d\varphi}{dt} = \sqrt{-2 \left[\cos\varphi + \varphi \sin\varphi_s + \frac{Kt}{n} \cos n(\varphi - \varphi_s) - C \right]} \quad (2)$$

$$\text{where } C = \frac{1}{2} \left(\frac{1}{\Omega} \frac{d\varphi_i}{dt} \right)^2 + \cos \left(\varphi_s + \frac{\pi}{2n} \right) + \left(\varphi_s + \frac{\pi}{2n} \right) \sin\varphi_s.$$

In the Brookhaven AGS, all particles should be oscillating within the limits $+0.18 > \varphi/\Omega > -0.18$.

From Eq. (2), φ/Ω can be plotted as a function of φ , to give phase diagrams.

Five phase diagrams are shown in Figs. 4 to 8. They are for $\Omega_s = \pi$ and $n = 50$. Each diagram is a family of nine curves, labeled one to nine. Each curve is for a different φ_i/Ω . The value of φ/Ω varies in steps of 0.02 from $\varphi/\Omega = 0.08$ (curve 1), to $\varphi_i/\Omega = 0.24$ (curve 9). The nine curves are the trajectories of nine sets of particles with different peak values of momentum. Curve 6 corresponds approximately to the extreme particles in the AGS after transition.

Figs. 4 to 8 are for $Kt = 0, 0.5, 1.0, 2.0$ and 4.0 . The low value of n ($=50$), ($f=225$ Mc) was chosen because it is easy to see the formation of the new buckets as time increases when the new frequency is not too high. High frequencies give rise to fine structure which is difficult to resolve because of the coarse mesh of the plot routine, (see Figs. 11 and 12, where $n = 150$).

The amplitude of the new rf increases from 0 (Fig. 4) to 4.0 NV_m , (Fig. 8). Only the upper half plane is shown, the lower half plane being its mirror image. As the amplitude increases, cusps appear on the trajectories which approach the φ axis from both sides. At some stage in the growth of the new rf, a pair of cusps belonging to a given trajectory will meet on the φ axis. The trajectory is now divided into separate loops. The small loops on the outside are new buckets, and particles which were on these parts of the trajectory when the loops formed are

captured into them. The rest of the particles travel around the remainder of the loop and some more of them will be caught when the next buckets form. The process can be seen in Figs. 4 to 8.

In Fig. 7, capture is complete. All the trajectories are divided up into small loops. A further increase in amplitude (Fig. 8), only serves to make the new bunches narrower.

One can easily calculate the value of Kt for complete capture.

Suppose n is large. Then Eq. (2) can be written

$$\frac{1}{\Omega} \frac{d\phi}{dt} \approx \sqrt{-2 \left[\cos\phi - \cos\phi_s - \frac{1}{2\Omega^2} \left(\frac{d\phi_i}{dt} \right)^2 + \frac{Kt}{n} \cos n(\phi - \phi_s) + \sin\phi_s (\phi - \phi_s) \right]}$$

The last cusp to close is the one at $\phi = \phi_s$. The problem is, therefore, to find the value of $\frac{Kt}{n}$ for which $\frac{1}{\Omega} \frac{d\phi}{dt} = 0$ when $\phi = \phi_s$.

When $\phi = \phi_s$

$$\frac{1}{\Omega} \frac{d\phi}{dt} \approx \sqrt{-2 \left[-\frac{1}{2\Omega^2} \left(\frac{d\phi_i}{dt} \right)^2 + \frac{Kt}{n} \right]}$$

$$\text{and } \frac{d\phi}{dt} = 0 \quad \text{when } Kt = \frac{n}{2} \left(\frac{1}{\Omega} \frac{d\phi_i}{dt} \right)^2$$

$$\text{when } n = 50 \text{ and } \frac{1}{\Omega} \frac{d\phi_i}{dt} = 0.24, Kt = 1.44.$$

Therefore, trajectory number 9 (Figs. 4 to 8) should just close at $\phi = \phi_s$ when $Kt = 1.44$. In Fig. 6, $Kt=1$, and trajectory 9 has not quite closed. In Fig. 7 $Kt = 2$, and it has certainly closed by this time.

So far, it has been assumed that trajectories of the same index correspond from one diagram to the next. For example, it has been assumed that curve 9 describes the same set of particles in Figs. 4 to 8.

If the process of capture into new buckets is adiabatic, the proper criterion to use is area in the phase plane. To determine which curve in Fig.4 applies to a given curve in Fig.8, one should calculate, or measure, the area under the curve in Fig.8, including all loops, and find the curve in Fig.4 whose area is the same.

Curves of the same index have the same values of ϕ_i , where $\phi_i = (\phi_s \pm \frac{\pi}{2n})$. It should soon be clear from Fig.13 why this value of ϕ_i was chosen.

When the amplitude of the new rf is zero, the trajectories are circles of radius slightly greater than ϕ_i/Ω . For small amplitudes of the new rf, the circles become modulated by a sine wave, but their area remains approximately constant. This is shown by the full line curve in Fig.13. This constancy of area with varying rf level is a result of the choice of ϕ_i . There may be some variation in area with rf level, depending on the relative phases of the two frequencies at point X, where the curve crosses the ϕ axis, but it is a small variation, especially with high values of n .

The dotted curve of Fig.13 shows what happens when the amplitude of the new rf becomes large enough for the diagram to divide into separate loops. Any further increase in level causes the outside loops to grow, as before, but inside the circle of radius ϕ_i/Ω , the loops have merged. The area outside the circle increases but there is no corresponding decrease of area inside it. The result is a steady increase in area with increasing rf level.

It is, therefore, safe to regard trajectories of the same index as being equivalent, until separate bunches form. After the formation of separate bunches, it is necessary to equate areas. This effect shows clearly in Fig.8, curve 1, where the total area of the four loops is clearly much greater than the area of curve 1, Fig.4.

The curves shown in Figs. 9 and 10 are for $\varphi_s = \frac{5\pi}{6}$. They are similar to the others, except for a slight asymmetry. Figs. 11 and 12 are for $\varphi_s = \pi$ $n = 150$. This is the practical case of bunching at 675Mc. Unfortunately, the plot routine is a little coarse for this case, but nevertheless the bunch formations can be seen. In this case, bunching should be complete when $Kt=4.32$. It is certainly complete in Fig. 12, where $Kt=6.0$.

When $Kt=4.32$, the buncher voltage is $(NV_m \cdot 4.32) = 0.86$ Megavolts. This is the peak rf level necessary for bunching the protons into new 360° bunches at a frequency of 675 Mc.

For an L band (1350 Mc) deflection system, it is necessary to compress the bunches from 360° to 90° . This gives bunches that are 180° long at the deflection frequency. To compress the new bunches by a factor of four, the peak rf voltage must be increased adiabatically by a factor of $(4)^4$, to 230 Megavolts. This offers no improvement over Method I, as far as rf level is concerned, but the capture efficiency is now 100% instead of 60%.

If one could bunch at 1350 Mc and deflect at the same frequency, a two-fold compression from 360° to 180° would be sufficient. One would then need 1.8 Megavolts for bunching. To compress the bunches by a factor of two, this voltage would have to be raised to 29 Megavolts. To do the same thing at 2860 Mc would require about 60 Megavolts.

One could trade capture efficiency for rf level by limiting the voltage during the capture phase. It would then be necessary to get rid of the uncaptured particles by removing the old rf and accelerating for a time. There would then be no danger of capturing additional particles during the compression phase.

Method III:

If it were possible to adiabatically remove the old voltage with $B = 0$, the bunch would be stretched out into a narrow strip parallel to the φ axis. The situation is shown in Fig. 14.

Suppose the original bunch was 0.5 radians wide (± 0.25 radians).

Equating areas over the interval $\varphi = 0$ to $\varphi = 2\pi$,

$$\pi (0.5)^2 = 2\pi \cdot d$$

$$d = 0.3125$$

$$\hat{\varphi} = \Omega \cdot \frac{d}{2}, \quad \text{and } \Omega = 880 \text{ in the Brookhaven AGS}$$

$$\text{therefore, } \hat{\varphi} \approx 14.$$

The initial value of $\hat{\varphi}$ was 220. This reduction in $\hat{\varphi}$ by a factor of 16 would reduce the capture voltage by a factor $(16)^2$.

Unfortunately, it is not possible to achieve truly adiabatic debunching. This is because the frequency of phase oscillation decreases as the rf voltage is reduced. The initial frequency of the phase oscillation is 120 cycles per sec., and towards the end of an adiabatic debunching process it will fall to about 8 cycles per sec.

For a process to be adiabatic, it should extend over several cycles of phase oscillation. To debunch adiabatically would therefore take a second or more. The magnetic field must be "flattopped" during the debunching process and the maximum duration of the flattop is likely to be about 100 milliseconds. Truly adiabatic debunching is therefore out of the question.

Since the frequency of phase oscillation decreases as the rf voltage is reduced, it would be of advantage to make the rate of decay of rf voltage decrease with time. For this reason, an exponential decay has been chosen in the numerical examples which follow.

It now remains to be seen how effectively one can debunch in the 100 millisecond interval that is available for this purpose.

For an exponential decay of rf voltage, the appropriate equation of motion of the proton is

$$\frac{d^2 \varphi}{dt^2} = \Omega^2 e^{-t/t_0} \sin \varphi \quad (3)$$

$$\text{at } t = t_0, \varphi = \varphi_1$$

$$\varphi_i = \Omega \sqrt{2 (\cos \hat{\varphi}_i - \cos \varphi_i)}$$

This equation was integrated numerically at intervals of 10 Microseconds for the extreme particles in the old bunch. For this purpose, the bunch width was taken to be ± 0.25 radians. This gives $\hat{\phi}_1 = (\pi + 0.25)$.

After a few preliminary trials, the value of t_0 was chosen to be 0.01, a somewhat arbitrary choice. With $t_0 = 0.01$, the rf voltage falls to 1% of its value in 46 milliseconds. A wiser choice of t_0 might have been $t_0 = 0.015$ or 0.02.

Eleven values of ϕ_1 were taken, and the results are shown in Fig.15. Only one trajectory has been plotted in detail. The others are all similar, and it is the final momentum that is of interest rather than trajectories during the debunching process.

This rather rapid debunching is far from adiabatic. Nevertheless, the momentum spread has been reduced from ± 220 to ± 45 . This factor of 1/5 in momentum spread implies a factor of 1/25 in bunching voltage, a rather substantial gain.

Capture by the New RF

The peak value of ϕ has been reduced from 220 to 45, relative to the old frequency of 4.5 Mc, by removing the old rf voltage exponentially over a period of 100 milliseconds. Actually, after about 70 milliseconds debunching is complete with $t_0 = 0.0022$.

The minimum rf level required to recapture all the debunched particles will now be calculated.

Two phase plane diagrams are given in Fig.16. One is for zero rf amplitude, and the other is for a small rf amplitude. As the new rf voltage is introduced, the trajectories, which were parallel to the ϕ axis, become sinusoidal, and eventually meet on the ϕ axis. As in the preceding cases, capture will be complete when all the trajectories meet on the ϕ axis. The last trajectories to make an intersection will be those which are farthest from the ϕ axis. In other words, the particles with the largest value of $|\dot{\phi}|$ will be captured last.

This is analogous to a group of ball bearings running along a horizontal surface on which there are corrugations of growing amplitude. The balls of highest momentum will be the last ones to be captured in a trough.

After capture by the new rf, the phase equation, for $\varphi_s = \pi$, is:

$$\begin{aligned} \dot{(\varphi)}^2 - (\dot{\varphi}_1)^2 &= -2\omega^2 (\cos\varphi - \cos\varphi_1) \\ \omega^2 &= - \frac{N_2 q V_{m2} h_2 \omega_s^2 \Gamma}{2\pi E_s} \cos(\varphi_s)_2 \end{aligned}$$

where subscript 2 denotes new rf values.

Before removal of the old rf

$$\Omega^2 = - \frac{N_1 q V_{m1} h_1 \omega_s^2 \Gamma}{2\pi E_s} \cos(\varphi_s)_1$$

where subscript 1 refers to old rf values. Therefore,

$$\omega^2 = \frac{V_{m2}}{V_{m1}} \frac{h_2}{h_1} \frac{N_2}{N_1} \frac{\cos(\varphi_s)_2}{\cos(\varphi_s)_1} \Omega^2$$

$$\text{Therefore, } \dot{(\varphi)}^2 - (\dot{\varphi}_1)^2 = -2 \frac{V_{m2}}{V_{m1}} \frac{N_2}{N_1} \frac{h_2}{h_1} \frac{\cos(\varphi_s)_2}{\cos(\varphi_s)_1} \Omega^2 (\cos\varphi - \cos\varphi_1). \quad (4)$$

Suppose V_{m2} is just large enough for adiabatic capture to be complete. After debunching, before the application of the new rf, $V_{m2} = 0$, and $\hat{\varphi} = 45$ relative to the old frequency. Relative to the new frequency, $\hat{\varphi} = 45$. $n = 45.150$. As V_{m2} is increased, $\hat{\varphi}$ will increase, and it is necessary to compute its value when capture is complete.

After capture is complete, the area of a loop of height H can be shown to be equal to $8H$. If the capture process is adiabatic, the area of rectangle ABCD, Fig.16a will be equal to the area of one of these loops.

$$\text{Then } 8H = 2 \cdot 2\pi \cdot 45 \cdot 150$$

$$\text{or } H = 3375\pi$$

$$\text{when } \varphi = \pi, 3\pi \dots \dot{\varphi} = 3375\pi$$

$$\text{when } \dot{\varphi} = 0, \varphi = 0, 2\pi \dots$$

Let $\varphi = \pi$ and $\varphi_i = 0$. Then $\dot{\varphi}_i = 0$ and $\dot{\varphi} = 3375\pi$.

Substituting the following values in Eq. (4):

$$N_1 V_{m1} = 0.2 \text{ Megavolts}$$

$$\cos (\varphi_s)_1 = -0.866$$

$$\cos (\varphi_s)_2 = -1.0$$

$$\Omega = 880$$

$$\frac{h_2}{h_1} = 150$$

we find

$$N_2 V_{m2} \approx 44 \text{ Kilovolts.}$$

We therefore need about 50 Kilovolts to capture all the debunched particles. To adiabatically compress the bunch from 360° to 90° by raising the voltage would require $50 \times (4)^4 \text{ KV}$ or 12.5 Megavolts peak rf.

In the above example, adiabatic capture was assumed. This should not be difficult to achieve, as the values of $\dot{\varphi}$ with regard to the new frequency are high.

$$\hat{\varphi} = 45.150 = 6750$$

It would, therefore, take about one millisecond for the particles with extreme φ to drift one wavelength at the new frequency. A capture phase lasting about 10 milliseconds should be sufficient for adiabatic capture. The compression phase can be quite rapid, as the phase oscillation frequency will be in the kilocycle region. Twenty or thirty milliseconds should be adequate for capture and compression.

The assertion that adiabatic capture is possible in a time interval of ten milliseconds calls for verification. To do this, the following equation was numerically integrated:

$$\frac{d^2\varphi}{dt^2} = \Omega^2 K_1 e^{t/t_0} \sin n \varphi$$

with $K_1 = 0.01$

$t_0 = 0.0022$

$n = 150$

Integration interval = 5 Microseconds

These values of K_1 and t_0 give a value of $K_1 e^{t/t_0}$ which rises from 0.01 at $t = 0$ to 1.0 at $t = 10$ milliseconds. The choice was arbitrary, and a larger value of t_0 might have been better. In any case, some of the results are plotted in Fig. 17. A range of initial values of ϕ was chosen so as to cover one wavelength at the new frequency. The initial value of ϕ was taken as 45, which is the maximum value expected after debunching. The results show that complete capture can be achieved in 7.2 milliseconds when the peak voltage is 50 KV. It is easier to determine the time of capture from the computer output tables of ϕ and $\dot{\phi}$ versus time than it is from Fig. 17, but they are too long to include here.

To produce 60 degree bunches at 953.3 Mc, for use with a 2860 Mc deflector, it would be necessary to raise the rf voltage from a capture level of 70 kilovolts to 90 Megavolts.

It is the adiabatic compression phase after capture that gives rise to these excessively high peak voltages. Suppose for a moment that methods could be devised for operating a buncher above the cutoff frequency of the vacuum chamber. It is inconvenient to do so, but there are no fundamental reasons for imposing an upper limit on the bunching frequency.

Let the bunching frequency be 2860 Mc. We then need 220 kilovolts for capture. Some compression is still necessary, as there must be clear spaces between the bunches if they are to be useful. Compression of the bunches from 360° to 180° will require a sixteen-fold increase in voltage, or a peak voltage of 3.5 Megavolts. For a bunching frequency of 1350 Mc, the necessary peak voltage is only 1.6 Megavolts.

IV. Phase Jump Methods:

Methods similar to those proposed by L.C.Teng could possibly be used to compress the bunch in the ϕ direction. By means of these methods one might be able to avoid the long debunching phase, and so reduce the length of the magnetic field flattop. The method is shown diagrammatically in Fig. 18.

Fig.18a shows the old rf bucket and bunch. In Fig. 18b, the phase of the rf has been jumped so that the bunch is centered on the unstable point. It is left here until it distorts into the shape shown by the dotted ellipse. The rf phase is now returned (Fig.18c). The bunch is elliptical in shape, and will rotate. The rf is switched off when the major axis of the ellipse lies along the ϕ axis. Before switching off the rf voltage, one would have to flattop the magnetic field, otherwise the particles would spiral in.

After capture by the new rf, similar methods might be useful as an aid in compressing the new bunches.

Further analysis is necessary to determine just how useful such techniques would be. They are more likely to be of use in reducing momentum spread than in shaping the new bunches. This is because it is necessary to have a bucket that is large compared with the bunch. A large bucket implies a high rf voltage so that the new rf would have to be raised to a fairly high level before jumping phase. This conflicts with the object of resorting to such techniques, namely, to save rf power.

In the absence of quantitative information about phase jump methods, the various methods of bunching can be summarized as follows:

1. Brute force capture -

Poor capture efficiency
High rf powers

2. Adiabatic capture by new rf, with old rf left on -

High capture efficiency
High rf powers

3. Debunching followed by adiabatic capture by new rf

High capture efficiency   See Table 1
Moderate rf power   See Table 1

Table 1

<u>Bunching Frequency</u>	<u>Deflecting Frequency</u>	<u>Peak RF Voltage</u>
675 Mc	1350 Mc	12.5 Megavolts
953.3 Mc	2860 Mc	90.0 "
1350 Mc	1350 Mc	1.6
2860 Mc	2860 Mc	3.5

Practical Aspects of Microwave Bunching

To bunch and deflect at the same frequency is the best approach from the point of view of power economy. However, to do so involves one in bunching at frequencies above the cutoff frequency of the vacuum chamber. The bunching cavity would have to have the following properties.

1. It would have to have attenuating end sections in order to prevent it from radiating energy around the ring.

2. The central hole along its axis would certainly be of much smaller diameter than the vacuum chamber. It cannot be in position during the early stages of acceleration as the resulting loss of aperture would be intolerable. It would have to be put into position during the latter stages of acceleration.

One method of positioning the cavity, proposed by A. Mashcke of Brookhaven, is to use a disc-loaded cavity, split across its diameter. The two halves could then be brought into position from opposite sides of the vacuum chamber during the latter stages of the accelerating cycle.

Another possibility, proposed by J. Walters of Brookhaven, is to design a cavity with a radial slot, and then to lower it into position when required.

One question remains - How much contamination is to be expected between bunches? This is difficult to answer. Contamination can arise from particles outside the initial bunches. However, the initial bunches appear to be clean and measurements indicate that there are no particles between them.

Another source of contamination could be particles of unexpectedly high momentum deviation after the debunching phase. However, it is not easy to see where they would come from, except from particles that were not initially bunched.

Provided that the initial bunches have no particles between them, it is probable that the final bunches will also have no particles between them. If there should be contamination between the new bunches, it could always be removed by accelerating for a few milliseconds with the new rf before targeting.

If one could bunch at S band, and it seems quite possible to do so, one could construct a relatively short rf separator. For the separation of 10 GeV π and K mesons, one would need 50 meters between target and deflector. Following CERN², one would need an additional 37 meters between deflector and Bubble Chamber. This gives a total separator length of 87 meters. This assumes that it is possible to momentum analyze in the 50 meter drift space between target and deflector. For the same energy, the CERN-type separator is 155 meters long.

Another advantage to be gained from internal bunching is the avoidance of loss of wanted particles at the stopper. With the CERN scheme, complete separation without loss is not possible. The loss of wanted particles at the stopper is typically 36%. With internal bunching, no such loss is necessary, especially if the bunches are made a little shorter than 180° at the deflecting frequency.

The peak rf voltages necessary for rebunching at L or S band are remarkably low. However, whether the advantages to be gained by rebunching are worth the added complexity is open to question.

Acknowledgements:

The author would like to thank Dr. J.P. Blewett for suggesting this investigation. He would also like to thank H. Hahn, A. Maschke and J. Walters for many helpful discussions, and J. Suich for supplying the plotting routine.

DSR:ms
1/22/62

Distribution: AD-B1, B2, B3

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DEPT. OR PROJECT AGS

FIG. 1

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FIG. 2

BY _____ DATE _____
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FIG. 3

```

0.24205E-00 I
0.23721E-CC I
0.23237E-CO I
0.22752E-CC I
0.22268E-CC I
0.21784E-00 I
0.21300E-CC I
0.20816E-CC I
0.20332E-CC I
0.19848E-CC I
0.19364E-00 I
0.18880E-00 I
0.18396E-CO I
0.17911E-CC I
0.17427E-CO I
0.16943E-CC I
0.16459E-CC I
0.15975E-CC I
0.15491E-CC I
0.15007E-CC I
0.14523E-CC I
0.14039E-CC I
0.13555E-CC I
0.13071E-CC I
0.12586E-CC I
0.12102E-CC I
0.11618E-CO I
0.11134E-00 I
0.10650E-CC I
0.10166E-CC I
0.96819E-01 I
0.91978E-01 I
0.87137E-01 I
0.82296E-01 I
0.77455E-01 I
0.72614E-01 I
0.67773E-01 I
0.62932E-01 I
0.58091E-01 I
0.53250E-01 I
0.48409E-01 I
0.43568E-01 I
0.38728E-01 I
0.33887E-01 I
0.29046E-01 I
0.24205E-01 I
0.19364E-01 I
0.14523E-01 I
0.96819E-02 I
0.48409E-02 I
-0.16298E-07 I

```

Fig. 4

0.27347E-CC I
0.26800E-00 I
0.26253E-00 I
0.25707E-CC I
0.25160E-CC I
0.24613E-CC I
0.24066E-CC I
0.23519E-CC I
0.22972E-00 I
0.22425E-CC I
0.21878E-00 I
0.21331E-CC I
0.20784E-CC I
0.20237E-00 I
0.19690E-CC I
0.19143E-00 I
0.18596E-CC I
0.18049E-CC I
0.17502E-CC I
0.16955E-CC I
0.16408E-CC I
0.15861E-CC I
0.15315E-CC I
0.14768E-CC I
0.14221E-CC I
0.13674E-00 I
0.13127E-CC I
0.12580E-00 I
0.12033E-CC I
0.11486E-CC I
0.10939E-00 I
0.10392E-CC I
0.98450E-01 I
0.92981E-01 I
0.87512E-01 I
0.82042E-01 I
0.76573E-01 I
0.71103E-01 I
0.65634E-01 I
0.60164E-01 I
0.54695E-01 I
0.49225E-01 I
0.43756E-01 I
0.38286E-01 I
0.32817E-01 I
0.27347E-01 I
0.21878E-01 I
0.16408E-01 I
0.10939E-01 I
0.54694E-02 I
-0.37835E-07 I

```

#####
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
(2.89159E 00,3.38659E 00)5.00003E-03

```

Fig. 5

[illegible][illegible]

Fig. 6

Kt = 2.0ZTAB=3.141590 N ±50.0

ACCELERATOR DEPT. REPORT
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0.36632E-00 I		99		99		
0.35899E-00 I		9 9		9 9		
0.35166E-00 I		88		88		
0.34434E-00 I		987789		987789		
0.33701E-00 I		7		7		
0.32969E-00 I		8766 89		98 6678		
0.32236E-00 I	99	9 65567		76556 9	99	
0.31503E-00 I	9	7 5 8		8 5 7	9	
0.30771E-00 I	988	86544 6		6 44568	889	
0.30038E-00 I	89	4334579		9754334	98	
0.29305E-00 I	9877	9753223		3223579	7789	
0.28573E-00 I	78	42112468		86421124	87	
0.27840E-00 I	8766 9	86 1 13		31 1 68	9 6678	
0.27107E-00 I	67	53 2579		9752 35	76	
0.26375E-00 I	97655 8	7 2 14		41 2 7	8 55679	
0.25642E-00 I	54456	9 41 6		6 14 9	65445	
0.24910E-00 I	86 4 79	63 3 8		8 3 36	97 4 68	
0.24177E-00 I	433 5	8 2 25		52 2 8	5 334	
0.23444E-00 I	753223	51 1 7		7 1 15	322357	
0.22712E-00 I	9 112468	4 9		9 4	864211 9	
0.21979E-00 I	42 13	74 3		3 47	31 24	
0.21246E-00 I	6 1 579	9 3 6		6 3 9	975 1 6	
0.20514E-00 I	8 3 2	6 2 8		8 2 6	2 3 8	
0.19781E-00 I	52 14	2 15		51 2	41 25	
0.19048E-00 I	7 68	851		158	86 7	
0.18316E-00 I	41 3	479		974	3 14	
0.17583E-00 I	9 25				52 9	
0.16851E-00 I	63	74 3		3 47	36	
0.16118E-00 I	1 79	9 6		6 9	97 1	
0.15385E-00 I	8 2 4	3 2 8		8 2 3	4 2 8	
0.14653E-00 I	5	6 1		1 6	5	
0.13920E-00 I	1 36	2 5		5 2	63 1	
0.13187E-00 I	8	8 79		5 8	8 4	
0.12455E-00 I	4 2	1 4		97 1 5	2 7	
0.11722E-00 I	7	5		4 5	5	
0.10990E-00 I					1 9	
0.10257E-00 I	9 1				97 3	
0.95242E-01 I	3 79	4 3		3 4		
0.87916E-01 I		7 6		6 7		
0.80590E-01 I	6 4	9 8		6 9	4 6	
0.73263E-01 I	2			8 2	2	
0.65937E-01 I		3 2			3	
0.58611E-01 I		3				
0.51284E-01 I						
0.43958E-01 I						
0.36632E-01 I	1 36				63 1	
0.29305E-01 I	8	6 15		51 6	8	
0.21979E-01 I						
0.14653E-01 I						
0.73263E-02 I						
-0.37951E-07	1	2	3	4	5	6

Fig. 7

ACCELERATOR DEPT. REPORT
DSR-1

Kt = 4.0ZSTAB=3.141590 N 50.0

0.46198E-00 I		99		99		
0.45274E-00 I		9889		9889		
0.44350E-00 I		8778		8778		
0.43426E-00 I		7667		7667		
0.42502E-00 I	99	965569		965569	99	
0.41578E-00 I	9889	858858		858858	9889	
0.40654E-00 I	8778	742247		742247	8778	
0.39730E-00 I	7667	963 369		963 369	7667	
0.38806E-00 I	9655 9	851 158		851 158	9 5569	
0.37882E-00 I	854458	8 8		8 8	854458	
0.36958E-00 I	742247	72 27		72 27	742247	
0.36034E-00 I	631136	61 16		61 16	631136	
0.35110E-00 I	952 259	95 59		95 59	952 259	
0.34186E-00 I	84 48	4 88		88 4	84 48	
0.33263E-00 I	73 37	88 2		2 88	73 37	
0.32339E-00 I	2 2	71 17		71 17	2 2	
0.31415E-00 I	6 6	6 6		6 6	6 6	
0.30491E-00 I	95 59	5 5		5 5	95 59	
0.29567E-00 I	4 4	4 49		94 4	4 4	
0.28643E-00 I	83 38	93 3		3 39	83 38	
0.27719E-00 I	2 27	82 28		82 28	72 2	
0.26795E-00 I	71 1	1 1		1 1	17 17	
0.25871E-00 I	6 6	7 7		7 7	6 6	
0.24947E-00 I	5 5	6 6		6 6	5 5	
0.24023E-00 I	5 9	5 5		5 5	9 5	
0.23099E-00 I	94 4	5 4		5 4	4 49	
0.22175E-00 I	3 3	94 9		9 49	3 3	
0.21251E-00 I	28 1	3 3		3 3	82 1	
0.20327E-00 I	82 7	2 28		82 2	7 28	
0.19403E-00 I	7 1	81 1		1 18	7 7	
0.18479E-00 I	6 6	7 7		7 7	6 6	
0.17555E-00 I	6 5	6 6		6 6	5 5	
0.16631E-00 I	5 49	6 6		6 6	94 5	
0.15707E-00 I	4 3	5 5		5 5	4 4	
0.14783E-00 I	9 3	4 4		4 4	82 3	
0.13859E-00 I	3 1	4 4		4 4	1 1	
0.12935E-00 I	2 9	9 3		3 9	2 2	
0.12011E-00 I	81 7	3 3		3 3	7 7	
0.11088E-00 I	3 3	3 3		3 3	3 3	
0.10164E-00 I	9 28	4 9		4 9	9 9	
0.92396E-01 I	3 1	4 3		4 3	82 3	
0.83156E-01 I	2 9	3 3		3 3	1 1	
0.73917E-01 I	81 7	3 3		3 3	7 18	
0.64677E-01 I	3 3	3 3		3 3	3 3	
0.55437E-01 I	9 3	3 3		3 3	9 3	
0.46198E-01 I	81 7	3 3		3 3	7 18	
0.36958E-01 I	3 3	3 3		3 3	3 3	
0.27719E-01 I	9 3	3 3		3 3	9 3	
0.18479E-01 I	81 7	3 3		3 3	7 18	
0.92395E-02 I	3 3	3 3		3 3	3 3	
-0.63563E-07 I	81 7	3 3		3 3	7 18	

Fig. 8

C.27419E-CC I
C.26870E-CG I
C.26322E-CC I
C.25774E-CG I
C.25225E-CG I
C.24677E-CC I
C.24129E-CC I
C.23580E-CG I
C.23032E-CG I
C.22483E-CG I
C.21935E-CC I
C.21387E-CG I
C.20838E-CG I
C.20290E-CG I
C.19742E-CC I
C.19193E-CG I
C.18645E-CC I
C.18096E-CG I
C.17548E-CG I
C.17000E-CC I
C.16451E-CG I
C.15903E-CG I
C.15355E-CG I
C.14806E-CG I
C.14258E-CG I
C.13709E-CC I
C.13161E-CC I
C.12613E-CG I
C.12064E-CG I
C.11516E-CG I
C.10968E-CG I
C.10419E-CG I
C.98708E-CG I
C.93224E-CG I
C.87740E-CG I
C.82256E-CG I
C.76773E-CG I
C.71289E-CG I
C.65805E-CG I
C.60321E-CG I
C.54838E-CG I
C.49354E-CG I
C.43870E-CG I
C.38386E-CG I
C.32902E-CG I
C.27419E-CG I
C.21935E-CG I
C.16451E-CG I
C.10967E-CG I
C.54837E-CG I

$$K_t = 2.0ZSAB = 2.617990 \cdot N \cdot 50.0$$

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DSR-1	99	99	99	99
0.36685E-00 I	9 9	9 9	9 9	9 9
0.35951E-00 I	88	88	88	88
0.35218E-00 I	987789	987789	987789	987789
0.34484E-00 I	7 7	7 7	7 7	7 7
0.33750E-00 I	8 66 89	8 66 8	8 66 8	8 66 8
0.33017E-00 I	9 65567	9 6556 9	9 6556 9	9 6556 9
0.32283E-00 I	7 5 8	8 5 7	8 5 7	8 5 7
0.31549E-00 I	86544 6	6 44568	6 44568	6 44568
0.30815E-00 I	4334579	9754334	9754334	9754334
0.30082E-00 I	9753223	3223579	3223579	3223579
0.29348E-00 I	642112468	864211246	864211246	864211246
0.28614E-00 I	8 31 13	31 13 6	31 13 6	31 13 6
0.27881E-00 I	5 257	752 5	752 5	752 5
0.27147E-00 I	97 2 14 9	9 41 2 79	9 41 2 79	9 41 2 79
0.26413E-00 I	4 6	6 4	6 4	6 4
0.25680E-00 I	63 3 8	8 3 36	8 3 36	8 3 36
0.24946E-00 I	2235	52 2 8	52 2 8	52 2 8
0.24212E-00 I	975311 468	7 1 15	7 1 15	7 1 15
0.23478E-00 I	42 2	51 1 7	51 1 7	51 1 7
0.22745E-00 I	86 1 135	7 4 9	7 4 9	7 4 9
0.22011E-00 I	3 2 79	9 4 3	9 4 3	9 4 3
0.21277E-00 I	52 14	3 6	3 6	3 6
0.20544E-00 I	7 1 6	6 2 8	6 2 8	6 2 8
0.19810E-00 I	9 4 3 3	8 2 15	8 2 15	8 2 15
0.19076E-00 I	51	51 15	51 15	51 15
0.18343E-00 I	63 25	479	479	479
0.17609E-00 I	8 2 1 79	74	74	74
0.16875E-00 I	5 4	9 3	9 3	9 3
0.16141E-00 I	1	3 6	3 6	3 6
0.15408E-00 I	35	2 8	2 8	2 8
0.14674E-00 I	74 8	62 1	62 1	62 1
0.13940E-00 I	2	5	5	5
0.13207E-00 I	9 3	8 1	8 1	8 1
0.12473E-00 I	1	5 79	5 79	5 79
0.11739E-00 I	6	4	4	4
0.11006E-00 I	2	79	79	79
0.10272E-00 I	4	97	97	97
0.95381E-01 I	8 1	74 3	74 3	74 3
0.88044E-01 I	5	9 6	9 6	9 6
0.80707E-01 I				
0.73370E-01 I	3	8	8	8
0.66033E-01 I	6	3 2	3 2	3 2
0.58696E-01 I				
0.51359E-01 I	8			
0.44022E-01 I	4	6	6	6
0.36685E-01 I				
0.29348E-01 I	2	15	15	15
0.22011E-01 I	7			
0.14674E-01 I		2	2	2
0.73370E-02 I				
-0.45053E-07	1000000000	100000000000	100000000000	100000000000

Fig. 10

```

0.25540E-CC I
0.25029E-CO I
0.24519E-CO I
0.24008E-CC I
0.23497E-CG I
0.22986E-CG I
0.22475E-CO I
0.21965E-CC I
0.21454E-OC I
0.20943E-OO I
0.20432E-OO I
0.19921E-OC I
0.19410E-OC I
0.18900E-CG I
0.18389E-CG I
0.17878E-OC I
0.17367E-CC I
0.16856E-CO I
0.16346E-CC I
0.15835E-CO I
0.15324E-OO I
0.14813E-CC I
0.14302E-CC I
0.13792E-OO I
0.13281E-OC I
0.12770E-OC I
0.12259E-CC I
0.11748E-OC I
0.11238E-OC I
0.10727E-CC I
0.10216E-OC I
0.97052E-OI I
0.91944E-OI I
0.86836E-OI I
0.81728E-OI I
0.76620E-OI I
0.71512E-OI I
0.66404E-OI I
0.61296E-OI I
0.56188E-OI I
0.51080E-OI I
0.45972E-OI I
0.40864E-OI I
0.35756E-OI I
0.30648E-OI I
0.25540E-OI I
0.20432E-OI I
0.15324E-OI I
0.10216E-OI I
0.51080E-O2 I
-0.25029E-O7 I

```

Fig. 11

[illegible]

Fig. 12

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FIG. 13

BROOKHAVEN NATIONAL LABORATORY

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FIG. 14

$\phi = 200$

$\dot{\phi} = 100$

$\dot{\phi}$

ϕ

4.0

3.6

π

2.8

2.2

70 Millisec.

FIG. 15

BROOKHAVEN NATIONAL LABORATORY

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FIG. 16

BROOKHAVEN NATIONAL LABORATORY

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FIG. 18