BUNCHING THE BEAM IN THE ISR

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1. INTRODUCTION

Under normal circumstances the stacked beams circulating in the ISR are continuous, without any azimuthal structure. While this is likely to be satisfactory if not desirable for most colliding beam experiments there are some reasons why it may become desirable, occasionally, to bunch the stacked beam.

Two of these reasons are given below:

a) If the beams in both rings are bunched at the same frequency but with an adjustable phase between the two rings and if the bunch length is made smaller than half the distance between bunch centres one can make the particles of different rings miss each other completely at a given intersection point by adjusting the phaseshift between the rings. In other words, one can "turn off" the interaction between beams at this point - e.g. for checking background interactions - without changing the average beam orbit. This metod is, in fact, used with the Stanford electron storage rings.

b) It is desirable to be able to change the energy of the stacked beam instead of having to dump the beam and make a new stack every time one wants to carry out an experiment at a different energy.

The energy can be changed without bunching the beam by means of phase-displacement acceleration, employing the normal RF System. However, the efficiency of this type of acceleration is not very good and some dilution of beam density must be accepted if substantial energy changes are to be accomplished by phase displacement. If the beam can be bunched, normal phase-stable acceleration can be used which yields nearly unity efficiency.
In this report we shall discuss the possibility of bunching with
the two applications a) and b) in mind. Other possible applications of
bunching that require very tight bunches or high bunch frequencies will not
be discussed.

The difficulty of bunching the stacked beam lies essentially in
two facts:

Firstly, since the required RF voltage increases with the square
of the momentum spread to be contained in the bunches, very large voltages
tend to be required.

Secondly, because of the large magnitude of circulating current,
beam loading is likely to be severe.

In chapter III of this report we shall consider the use of the
normal ISR RF-system for bunching. Naturally this system, which is designed
for another purpose, can only cope with a fraction of the maximum ISR beam.

In chapter IV we present some preliminary design considerations
of a special bunching system that could be inserted in some of the spare
straight sections of the ISR. Spare-space has, in fact, been set aside
specifically for purposes such as this in the ISR project.

All numerical examples will be computed for the parameters pre-
presented in reference 1) and at 25 GeV total energy.

II. GENERALITIES

In all cases of practical interest the buckets generated by the
bunching system will be very nearly stationary, i.e. the stable phase
angle will be zero and the bucket will extend from $-\pi$ to $+\pi$.

The half width, in momentum, of a stationary bucket is given by

$$\left(\frac{\Delta p}{p}\right)_M = \frac{2eV}{\beta \pi \hbar E \left[\gamma^{-2} - \gamma_t^{-2}\right]}$$

where $V$ is the peak RF voltage, $e$ the elementary charge, $\hbar$ the
harmonic number, $E$ the total particle energy, $\gamma$ the particle energy
over the rest energy, $\gamma_t$ the same quantity at transition and $\beta$ the par-
ticle velocity over the velocity of light.

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The area, \( A \), of a stationary bucket, in a \((\Delta p/p, \varphi)\) plane where \( \varphi \) is measured in terms of the RF, is given by

\[
A = 3(\Delta p)_{M} \tag{2}
\]

It should be noted that \( A \) is the area of a single bucket in a \((\Delta p/p, \varphi)\) plane or the total area of all buckets in a \((\Delta p/p, \varphi/h)\) plane.

The bunches should be created by means of an adiabatic trapping process\(^*\). If this is done properly, the bunches are matched to the buckets and the bunch boundary is as well defined as was the original stack boundary prior to bunching.

The bunch half-width in momentum \((\Delta p/p)_{m}\), and the bunch area, \( a \), can be written in the form

\[
(\Delta p)_{M} = \mu (\Delta p)_{M} \tag{3}
\]

\[
a = \sqrt[\lambda]{A} \tag{4}
\]

where the coefficients \( \mu \) and \( \lambda \) depend on the bunch-length in phase. Values for \( \mu \) and \( \lambda \) for different bunch length have been computed by Cole and Morton\(^2\).

If the bunching is to be used for turning-off the beam-beam interaction the bunch-length can, at most, be \( \pm \pi/2 \). For this bunch-length one finds

\[
\mu = \frac{1}{\sqrt{2}} \tag{5}
\]

\[
\lambda = 0.423 \tag{6}
\]

Unless otherwise stated we shall use these values for the numerical examples given below. It should be remembered, however, that this does not include any safety factor for turning off the beam-beam interaction completely but it does include ample safety for phase stable acceleration where one may be permitted in principle to let \( \mu \) and \( \lambda \) approach unity.

\(^*\) Except the trivial case when the "stack" consists of a single CPS pulse and is held bunched by the normal ISR stacking system without ever being debunched.
We shall call "phase plane density", \( \rho \), the average particle density in a \((\Delta \rho_p, \varphi/h)\) phase-plane; averaged over the width of the stack or over that part of the stack that is to be bunched, i.e.

\[
\rho = \frac{\text{total number of stacked particles}}{2\pi \times \text{momentum spread of stack}}
\]  

(7)

It should be noted that the "stack" may consist of a single CPS pulse if so desired.

We shall call "nominal" phase-plane density that value of \( \rho \) that is arrived at in the prediction of ISR performance in reference 1, i.e.

\[
\rho_{\text{nom}} = 3.2 \times 10^{15}
\]

corresponding to \( 4 \times 10^{14} \) protons or 20 A beam current in a 2\(^0\)/o wide stack, and we assume for simplicity this to be independent of the number of stacked pulses. This value of \( \rho \) is, in fact, the best one can expect from present day performance of the CPS.

Nominal phase plane density will be assumed throughout chapters III and IV; in chapter V the consequences of a higher value of \( \rho \) will be discussed.

We assume that the bunching process is done completely adiabatically. Then the total number \( N \) of particles held in all \( h \) bunches is given by

\[
N = \rho a
\]  

(9)

The average beam current is given by

\[
I_{dc} = \frac{e \rho a^2 c}{2\pi R}
\]  

(11)

where \( c \) is the velocity of light and \( R \) the average machine radius.

The fundamental RF component of the beam current \( I_{rf} \), differs but little from the dc component. In the limit of very short bunches \( I_{rf} = 2I_{dc} \) but for bunches of \( \pm \pi/2 \) length uniformly filled with particles one finds that

\[
I_{rf} = 1.46 I_{dc}
\]  

(12)
Finally, another quantity of interest is the maximum total momentum spread of the stacked beam, prior to bunching, that can be bunched into bunches of area \( a \). This is given by

\[
u = \frac{a}{2\pi}
\]  

(13)

III. BUNCHING WITH THE NORMAL RF SYSTEM

The normal ISR RF system as described in ref. 1), operates at \( h = 30 \) and can generate a maximum peak voltage of 20 kV. Hence one finds a bucket half-width

\[
\left( \frac{\Delta n}{p} \right)_m = \pm 1.26 \cdot 10^{-3}
\]

and a bucket area

\[
A = 1.01 \cdot 10^{-2}
\]

With \( \pm \pi/2 \) bunch length one finds from the equations presented in the preceding chapter that

\[
\left( \frac{\Delta p}{p} \right)_m = \pm 0.89 \cdot 10^{-3}
\]

\[
a = 4.3 \cdot 10^{-3}
\]

\[
u = 0.68 \cdot 10^{-3}
\]

and, for nominal phase plane density,

\[
N = 1.37 \cdot 10^{13}
\]

\[
I_{dc} = 0.70 \quad A
\]

\[
I_{rf} = 1.0 \quad A
\]

As to beam loading the following can be said:

The final power amplifiers of the RF system are equipped with negative feedback so that the impedance which the cavity presents to the beam is very low. The total impedance that the beam sees across the gaps of all cavities is about 30 \( \Omega \). Hence, the peak beam induced voltage, about 30 V, is negligibly small compared with the 20 kV of RF-driven voltage. This is true so long as the RF beam current does not exceed the RF current of about 1.3 A peak delivered by the tube, a condition which is clearly satisfied. In fact, from this latter point of view beam currents in excess
of the tube current could still be handled by detuning the cavity to com-
penstate for the reactive beam loading.

Beam-cavity interaction at higher harmonics of the bunch fre-
quency is not likely to occur since the cavities are designed to present
a low impedance to the beam for frequencies up to several hundred
megahertz.

It may be concluded that beams up to 0.7 A at nominal phase
plane density can be bunched into bunches of $\pm \pi/2$ length by means of the
normal ISR stacking system without any additional expense. The bunching
increases the peak to peak momentum spread from $0.68 \cdot 10^{-3}$ to $1.8 \cdot 10^{-3}$.

Since one has to keep the bunch matched to the bucket whose width
cannot be increased without increasing the voltage, shorter bunches can
only be obtained by making the bunch area smaller i.e. by bunching a smaller
amount of beam. Below a bunch length of $\pm \pi/2$ the shape of the bunch in
phase space is nearly an ellipse so that the bunched beam intensity de-
creases approximately with the square of the bunch length.

IV. A SPECIAL BUNCHING SYSTEM

1) Basic parameters

We assume that the maximum permissible peak to peak momentum
spread of the bunched beam is $2.5^\circ$ which is close to the maximum spread
that can be held in the ISR aperture. Hence $(\Delta p/p)_m = \pm 1.25 \cdot 10^{-2}$ and
the necessary bucket half-width for $\pm \pi/2$ bunch-length is given by

$$\left(\frac{\Delta p}{p}\right)_m = \sqrt{2} \left(\frac{\Delta p}{p}\right)_M = \pm 1.77 \cdot 10^{-2} \quad (14)$$

From this one finds, always with nominal phase plane density,
that

\[
\begin{align*}
a & = 6.0 \cdot 10^{-2} \\
u & = 0.96 \cdot 10^{-2} \\
N & = 1.9 \cdot 10^{-4} \\
I_{dc} & = 9.7 \quad \text{A} \\
I_{rf} & = 14 \quad \text{A}
\end{align*}
\]
Hence, given only the limitation of 2.5\% maximum permissible momentum spread, one can bunch about half of the maximum nominal current of 20 A in bunches of $\pm \pi/2$ length. The peak to peak momentum spread before bunching and after adiabatic debunching is about 1\%. For the remainder of this chapter we shall discuss a bunching system for this beam.

Since the voltage required to obtain a given bucket-width is proportional to the harmonic number $h$ a special bunching system, whose parameters one is free to choose, should work at $h = 1$ i.e. at the revolution frequency of 318 kHz. With $h = 1$ and $(\Delta p/p)_M = \pm 1.77^{\circ}/o$ one finds that

$$V = 131 \text{ kV}.$$ 

It is true that the shunt impedance per unit length of RF structures tends to increase with frequency but this increase will never be sufficient to justify any other choice but $h = 1$.

2) Beam loading

Since there is no acceleration the beam current is $\pi/2$ out of phase with the bunching voltage. The corresponding reactive power

$$\frac{VI_{\text{rf}}}{2} = 0.93 \text{ MVA}$$

(16)

for maximum beam current and maximum voltage. Under the same conditions there is an apparent susceptance across each RF cavity of

$$\frac{I_{\text{rf}}}{nV} = n \cdot 1.1 \cdot 10^{-4} \Omega^{-1}$$

(17)

where $n$ is the number of cavities.

While it may not be entirely out of question to supply the reactive beam-power from tubes (ten or twenty cavities each fed from a very large power tube may be a possibility) such a solution would be very expensive. Instead, following a proposal made by M.G.N. Hine, the reactive power can be covered by detuning the RF -cavities in such a way that the susceptance of the detuned cavity cancels the susceptance presented by the beam.
In order to maintain this cancellation at all levels of beam loading and voltage the cavities should be equipped with an automatic tuning system of the kind that is usually employed in accelerating cavities. In such a system a phase detector measures the phase between the cavity voltage and the input voltage of the power tube. If the phase differs from zero the phase detector produces an error signal that controls a tuner—most likely consisting of saturable ferrite loading of the cavity—in such a way as to restore zero phase.

The tuning system assures that the impedance presented to the tube remains real, independent of beam current. In addition the impedance remains constant so long as the beam current remains exactly \( \pi/2 \) out of phase with the voltage (and so long as the cavity losses are not altered by way of adjusting the tuner).

Small in-phase components of the beam current might occur during the bunching process or while one adjusts the phase of one storage ring with respect to the other. It is advisable, therefore, to equip the power amplifier with a system for automatic amplitude control (AGC).

The two servo-systems for phase and for amplitude should take care of the beam load so that the bunching process can be conducted simply by turning on the reference voltage of the AGC system. As long as the bucket width is still small compared with the momentum spread of the original unbunched stack the voltage can be increased rather rapidly. Only after the bucket width has become comparable to the stack width must the bunching be conducted adiabatically. Hence the bunching time need not be very much longer than the phase oscillation period of 33 ms which corresponds to full voltage.

The net RF beam current can be expected to remain small till the bucket width has become comparable to the stack width and then to increase rather rapidly. Fortunately the time scale is again set by the phase oscillation frequency of about 30 Hz, and it should not be difficult to make the automatic control systems for phase and amplitude very much faster than that.
The bunching frequency must probably be taken from an external oscillator until the bunching is nearly completed, then one may switch to phase-lock.

So long as the bunches are not much shorter than $\pm \pi/2$ the beam does not carry very high harmonics of appreciably amplitudes. In spite of this beam cavity interaction at higher harmonics may present a problem. The least one can say is that the cavities should not have higher order resonances at those higher harmonics of the revolution frequency that are contained in the beam current. This may not be so easy to avoid because of the large tuning capacitors that are required in a 300 kHz cavity.

Finally the amount of stored energy and the range of the automatic tuning system remains to be discussed:

Above transition energy, where the bunching system would be used most of the time, the beam loading is inductive i.e. a cavity that is tuned to resonance without beam appears to be inductive with beam.

The RF cavities will probably consist of lumped capacitors and inductors and the tuning will be inductive by means of saturable ferrite loading of the coaxial inductors.

In the absence of RF beam current the inductance must be reduced to its minimum (i.e. the saturating field must be maximum) and the capacitance must yield resonance with this minimum inductance at 318 kHz. When the beam current increases the inductance must be increased (i.e. the saturating field must be decreased) so that the resulting excess of capacitive susceptance cancels the inductive susceptance presented by the beam.

If the inductance could be increased to infinity the total reactive power in all tuning capacitors at full beam load would at least have to equal the reactive beam power. In practice the reactive power in the tuning capacitor must be somewhat larger to account for the finite maximum inductance. If the ratio of maximum to minimum inductance is $m$ the required capacitance $C_n$ across each of the $n$ cavities is given by

$$\omega_n C_n = n \frac{m}{m-1} \left( \frac{I_{RF}}{V_{max}} \right)$$  \hspace{1cm} (18)
Unfortunately it is not sufficient to insert the maximum voltage and maximum RF beam current in equation (18), not even if the system is to be used solely for bunching the full beam, since
\[(I_{rf}/V)_{\text{max}} > I_{rf\, \text{max}}/V_{\text{max}}\] i.e. \(I_{rf}/V\) tends to be larger during the intermediate stages of the bunching process than at its end.

In the absence of better knowledge we assume that the maximum ratio \(I_{rf}/V\) occurs when the growing buckets have just become large enough to hold all particles. At that point, and for uniform phase plane density, one finds that
\[I_{rf} = \frac{2}{3} I_{dc}\] (19)
and
\[V = 0.179 V_{\text{max}}\] (20)
so that, according to eq. (18) and with \(m = 3\) \(C_n\) should be equal to \(n \cdot 2.1 \cdot 10^{-10}\) F. This is the minimum value that will be certainly required but it may be somewhat too small if the maximum of \(I_{rf}/V\) does not occur where it has been assumed. For this reason we prefer to include a safety factor of 1.5 so that
\[C_n = n \cdot 3.1 \cdot 10^{-10}\] F (21)

The total reactive power in all capacitors at full voltage is
\[\frac{V_{\text{max}}^2 \omega C_n}{2n} = 5.35 \text{ MVA}\] (22)
which is, of course, independent of \(n\).

If a smaller beam current with a correspondingly smaller momentum spread is to be bunched the voltage scales, other things equal, with the square of the current so that the susceptance presented by the beam tends to increase proportionally to the inverse beam current. Fortunately the bunching system will consist of a fairly large number of identical cavities so that it becomes possible to "switch off" a certain number whenever a smaller than maximum current is to be bunched.
If the number of active cavities is made proportional to the beam current one size of tuning capacitor is sufficient for all intensities down to the point where only one cavity is left. At this point the normal ISR RF system can take over.

The only reliable way of switching off an unused cavity appears to be by way of a low impedance short right across the gap, e.g. in the form of a pair of metal jaws driven by hydraulic or pneumatic actuators.

3) Tentative design

We assume that three long straight sections per ring can be made available for the bunching system and that the total free length available there is 3 x 9 m. We assume further that there are 21 individual cavities of 1.28 m length each so that there is 6.25 kV maximum peak RF voltage across each accelerating gap. The latter assumption is rather arbitrary but most basic design considerations depend on the total length of RF structure rather than the number of individual cavities.

Neglecting for a moment the problem of tuning out the beam load, one may, at first, think of air cored coaxial resonators with capacitive loading across the gaps. Making the rather optimistic assumption that the coaxial line part of the resonators fills 80% of the total length and has a characteristic impedance of 100Ω we obtain a total reactive power of 590 MVA i.e. the capacitance across each gap is 0.73 μF at 9.1 kA RF current. This is much more than is required to handle the beam load and is, in fact, scarcely practicable.

In order to reduce the stored energy the cavities should be filled with magnetic material, most likely ferrite. The ferrite loading also provides the tuning facility required to compensate the beam current.

With ferrite loading it is not difficult to reduce the stored energy down to the limit given by the beam loading. In other words, the value of the tuning capacitor across each resonator is the one given by eq. (21) i.e. it is 6.5 nF with n = 21. The reactive current through each capacitor at full voltage is 83 A peak. This is quite feasible.
In spite of the ferrite loading the coaxial part of the resonator is likely to be short enough to present a lumped inductance which is given by

\[ L = \frac{\mu_0 l_f}{2\pi} \mu \ln \frac{r_1}{r_2} \]  

(23)

where \( l_f \) is the total length of ferrite per cavity (i.e. the sum of the thickness of all ferrite rings), \( r_1 \) and \( r_2 \) are the inner and outer radii of the ferrite rings, \( \mu \) is the RF permeability and \( \mu_0 = 1.26 \times 10^{-6} \text{ Vs/Am} \).

As a possible design one may choose \( r_1 = 12 \text{ cm} \), \( r_2 = 24 \text{ cm} \)

\( l_f = 78 \text{ cm} \) or about 60\% of the total available length. In choosing \( l_f \) we have taken into account the cavity end plates, vacuum flanges and bellows and the thickness of the metal discs which one may have to sandwich between the ferrite rings for cooling. The total weight of ferrite per storage ring is 11 tons.

The inductance per resonator at no beam load must be 38 \( \mu \text{H} \) which, according to eq. (23) requires an RF permeability \( \mu_{\text{min}} \) of 350. This is the minimum permeability associated with maximum saturating field.

One can hope to find a suitable ferrite with an initial permeability of about 1000 at least which would confirm in retrospect the assumption that \( m = 3 \). With such a ferrite the maximum required saturating field may be of the order of 100 A/m which would not be difficult to provide and to control.

The peak RF flux density at the inner radius of the ferrite rings is given by

\[ B_{\text{rf}} = \frac{V}{r_1 \omega n l_f \ln \frac{r_2}{r_1}} \]  

(24)

With the chosen parameters and full voltage

\[ B_{\text{rf}} = 480 \text{ Gauss}. \]
This is a rather high value at which all available ferrites exhibit appreciable hysteresis losses. Unfortunately the only parameter affecting $B_{rf}$ for which one has some freedom of choice is the total ferrite-length $n l_f$. Keeping the RF flux density to a reasonable value has, in fact, been the only reason for making the total length of RF structure as long as 27 m.

In order to keep hysteresis losses as low as possible one would like to choose a ferrite of the low resistivity (manganese-zinc) type (e.g. some variety of Ferroxcube type 3, Siferrit 1100 N2, Stanferit SA 400). This type of ferrite would also yield the high desired initial permeability.

From the somewhat sketchy data available about ferrite-losses at high flux density it can be inferred that one may have about 250 mW/cm$^3$ total magnetic loss at the given maximum flux density and frequency. Averaging from $r_1$ to $r_2$ under the assumption that the specific loss scales with the 5/2th power of the flux density yields 108 mW/cm$^3$. Since the total volume of ferrite in our design is 2.2 m$^3$ the total magnetic RF power loss is

$$240 \text{ kW}$$

per storage ring, or about 12 kW per station, which is quite reasonable. It is interesting to note in passing that the corresponding Q-factor is about 20.

Unfortunately, the ferrites that exhibit small hysteresis losses and high permeability also tend to have a low resistivity and a high dielectric constant. It remains to be seen whether these properties can be rendered tolerable by means of a suitable cavity design or whether they basically preclude the use of those ferrites in a high voltage cavity at 300 kHz.

If the latter should turn out to be the case one would have to employ high resistivity (nickel-zinc) type ferrites (e.g. Ferroxcube 4A, Stanferit SB 700). These ferrites have a lower initial permeability (about 600 maximum) so that the size of the tuning capacitor had to be increased and a larger saturating field would be required. This would
be undesirable but acceptable and one would be rewarded by an increase of the maximum tolerable beam load.

More serious is that the hysteresis losses of this type of ferrites would tend to be several times higher than those of the low resistivity type so that the total power consumption would approach one megawatt, if one attempted to hold the same voltage.

Fortunately the uncertainty about the specific ferrite loss is not too disturbing at this point. Since the total loss scales faster than the square of the voltage (though not as fast as the cube) while the voltage in turn scales with the square of the beam current to be bunched an uncertainty of as much as a factor 4, say, in the specific ferrite loss at a given voltage reflects itself only in an uncertainty of about 1.3 in the maximum bunched beam current.

The same argument also goes to show that the assumed initial momentum spread of 1\(^0/\circ\), leading to bunches of 2.5\(^0/\circ\) width and \(\pm \pi/2\) length, is at the limit of feasibility, even if there were room in the ISR aperture for a larger momentum spread.

Finally we shall try to give a rough cost estimate for the system, assuming a total RF power of 300 kW per ring. The cost is given in megatswiss-francs for two bunching systems, one per storage ring. It goes without saying that the figures given are but order of magnitude estimates.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (MFS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42 cavities, complete with tuning capacitors,</td>
<td>2.0</td>
</tr>
<tr>
<td>ceramic vacuum seals, bake-out facility for ultra-high vacuum, short-circuiting devices, ferrite tuning and ferrite cooling facility but without ferrite</td>
<td>&quot;</td>
</tr>
<tr>
<td>22 tons of ferrite</td>
<td>2.2</td>
</tr>
<tr>
<td>42 RF amplifiers 14 kW each, complete with drivers</td>
<td>1.8</td>
</tr>
<tr>
<td>Power supplies, 1.2 MW total</td>
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</tr>
<tr>
<td>Ferrite tuning amplifiers</td>
<td>0.6</td>
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<tr>
<td>Low level electronics</td>
<td>0.4</td>
</tr>
<tr>
<td>Development and engineering, models</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\[9.6 \text{ MFS}\]
4) Conclusions

One may conclude from the preceding discussion that it is probably possible to bunch a $10^4$ beam of $1^\circ$ initial momentum spread into bunches of $\pm \pi/2$ length at 318 kHz and $2.5^\circ$ momentum spread. However, one may also conclude that such a bunching system is at the limit of practicability and quite expensive, of the order of 10 MFS.

It should be noted that the bunches are unlikely to have a sharply defined boundary so that a nominal bunch length of $\pm \pi/2$ is really too long if the beam-beam interaction is to be turned off completely at some point around the ISR circumference.

Shorter bunches can be made only if the initial momentum spread is reduced, approximately as the square of the desired bunch length. Hence, at a given phase-plane density the bunchable beam current is approximately proportional to the square of the bunch length. There is the additional difficulty that the maximum ratio of RF beam-current to voltage occurring during the bunching process tends to scale with the inverse beam current so that the size of the tuning capacitors must be increased unless it is possible to switch-on cavities in succession during the bunching process.

It is interesting to see by how much the size and cost of the bunching system could be reduced if one reduced ones exigences as to the maximum bunchable beam current. In discussing this we shall again, assume constant phase plane density so that beam current and momentum spread are proportional.

One way of scaling is to reduce both the number of cavities and the voltage per cavity proportionally to the beam current. In this case the ratio of beam current to RF voltage stays constant so that the basic design of the cavity, as characterized by the size of the tuning capacitor and the permeability of the ferrite loading, remains the same. The total RF power consumption scales faster than the cube of the beam intensity as long as hysteresis losses in the ferrite are still predominant and with the cube of the beam size eventually, when the RF flux density has become so small that only residual ferrite loss remains appreciable.

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Thus, the total cost of the installation goes down rather rapidly at first but soon the point is reached where almost all the remaining cost is for hardware and ferrite. From there on cost is roughly proportional to beam intensity.

Another way of scaling, and probably a more attractive one, is to reduce only the number of cavities keeping the design voltage per cavity constant and equal to the maximum one considers feasible. If in addition the size of the tuning capacitors is also kept constant, it is obvious that the total cost scales directly with the number of cavities (except a small fixed amount for low level electronics) while the maximum bunchable beam intensity scales only with the square root of the number of cavities.

For instance one may consider a system of 7 cavities of the type discussed in the preceding section. This would occupy one long straight section and may cost about 3 to 4 NSF. Such a system could bunch a beam of 5.6 A and 0.56°/o initial momentum spread into bunches of ± 90° length. The same system could also bunch a beam of 3.2 A and 0.32°/o initial momentum spread into bunches of ± 70° length without an increase of the tuning capacitors and without having to turn on cavities in succession during the bunching.

V. HIGHER PHASE-PLANE DENSITY, IMPROVED CPS

So far all calculations have been done for what we have defined as "nominal" phase plane density. This was arrived at in reference 1) by assuming that the output from the CPS is $9 \times 10^{11}$ protons/pulse, which is close to the present maximum intensity, and that the total dilution of phase plane density from the CPS injection to the stack in the ISR is 50°/o.

One may ask whether the improvement programme for the CPS may not make it possible to increase the phase plane density beyond the nominal one. Unfortunately these are good reasons for not relying upon this to occur. In fact, already at the present maximum intensity blow-up due to space
charge forces starts to occur in the neighbourhood of transition. There are methods by which it should still be possible to avoid such a blow-up at present intensities and, therefore, good reasons for assuming the "nominal" intensity to be obtainable. However, these methods may fail to work efficiently at higher intensities where space charge forces would become predominant over external focusing forces.

Even then it should, at least, be possible to avoid a decrease of phase plane density with increasing intensity, for instance by creating a deliberate blow-up prior to passing transition so as to avoid excessive longitudinal charge density. However, there is, at present, no guarantee that the CPS improvements will ever lead to an increase of phase plane density, let alone an increase proportional to intensity.

Nevertheless one may assume for a moment that the blow-up in the CPS could be completely cured such that an intensity of, say, $9 \times 10^{12}$ per pulse would lead to ten times the "nominal" phase plane density. We shall discuss the possibility of bunching under this assumption. It should not be forgotten, though, that these considerations are purely hypothetical at the moment.

With ten-fold increased phase plane density the maximum bunchable beam of 1% total momentum spread amounts to about 100 A average current, which is in the neighbourhood but not necessarily above the space charge limit.

The bunching system described in chapter IV of this report can bunch this beam provided the size of the tuning capacitors is increased by a factor of ten. This also implies that the ferrite permeability has to be lowered by the same factor and that the strength of the saturating field may have to be increased. All this is cumbersome and may involve additional expense but it is not impossible and, in fact, well in keeping with many other problems involved in stacking and handling a 100 A beam.

A more modest possibility is that of the beam of $0.7 \times 10^{-3}$ total momentum spread that can be bunched by the 20 kV of the normal ISR stacking system. With ten times nominal phase plane density this beam amounts to 7 A average, or 10 A peak RF at $\pm \pi/2$ bunch length. The current
is more than the current obtainable from the RF amplifier presently under design. However, the stored energy in the cavity is so large that 70/o detuning is sufficient to compensate for the beam load.

Even without installing an automatic tuning system one could put the stored energy to use by detuning the cavity manually to the point where half of the beam current is compensated. Then the cavity appears to be capacitive without beam and inductive with beam by equal amounts, so that the peak RF current from the amplifier has to be increased to about 5 A which is perfectly feasible.

It may be easier, though, to leave the amplifier as it is and to equip the cavity with a ferrite tuner. This may be a separate saturable ferrite reactor which is connected to the cavity via a short transmission line. Such a tuner should not be very expensive and it could be added to the system whenever the need arises.

REFERENCES


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