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0350

MATCHING AND SYNCHRONIZATION DURING TRANSFER FROM BOOSTER TO MAIN RING AT 8 GeV

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We shall discuss the following problems:

1. Phase space bunch shape matching.
2. RF phase and frequency matching.
3. Momentum matching.
4. Booster beam gap cogging.

We assume that at least one booster pulse has already been injected into the main ring and is held in stationary buckets of the main ring rf.

1. Phase space bunch shape will be matched if the booster and main ring rf bucket shapes are matched at transfer, when $\gamma = 9.52646$, $\beta = 0.994475$. Both will be approximately stationary buckets with phase spread of $\pm\pi$. The $\left(\frac{\Delta p}{p}\right)_{max}$ of a stationary bucket is given by

$$\left(\frac{\Delta p}{p}\right)_{max} = \frac{2}{\pi h} \frac{1}{\beta^2 \gamma \Lambda} \frac{eV}{mc^2} \tag{1}$$

where

$$\Lambda \equiv \frac{1}{\gamma^2} - \frac{1}{\gamma_t^{\,2}}$$

and V is the rf voltage amplitude. All other symbols are conventional. For $\left(\frac{\Delta p}{p}\right)_{max}$ to be the same for the booster (subscript

b) and the main ring (subscript m) we must have

(γ_{tb} = 5.44595, γ_{tm} = 19.61246)

$$\frac{V_b}{V_m} = \left|\frac{h_b \Lambda_b}{h_m \Lambda_m}\right| = 0.203 \tag{2}$$

Assuming

$$V_m = 1.5 \text{ MV} \tag{3}$$

we have

$$V_b = 0.305 \text{ MV} \tag{4}$$

As V_b tapers off toward the transfer time it reduces to 0.305 MV at about $t = -4$ msec ($t \equiv 0$ at $\dot{B}_b = 0$). At that time it should be smoothly flattened out to 0.305 MV. The values of V_m and V_b are not critical. An accuracy of ±5 % is adequate.

With these voltages the bucket size is

$$\pm (\Delta\phi)_{max} \text{ x } \pm \left(\frac{\Delta p}{p}\right)_{max} = (\pm\pi) \text{ x } (\pm 3.39 \text{ x } 10^{-3}) \tag{5}$$

and the phase oscillation wave numbers given by

$$\nu_s{}^2 = \frac{h}{2\pi} \; \frac{\Lambda}{\beta^2\gamma} \; \frac{eV}{mc^2} \tag{6}$$

are

$$\begin{cases} \nu_{sb} = 0.00324 \\ \nu_{sm} = 0.0159 \end{cases} \tag{7}$$

with the corresponding frequencies and periods

$$\begin{cases} F_{sb} = 2.04 \text{ kHz} \\ F_{sm} = 0.754 \text{ kHz} \end{cases} \qquad \begin{cases} \tau_{sb} = 0.491 \text{ msec} \\ \tau_{sm} = 1.326 \text{ msec} \end{cases} \tag{8}$$

At transfer the beam bunch area gives

$$\Delta\phi \; \frac{\Delta p}{p} = 0.232 \times 10^{-3} \tag{9}$$

For stationary bucket the matched shape is given by

$$\frac{\Delta p}{p} \Big/ \Delta\phi = \frac{1}{2}\left(\frac{\Delta p}{p}\right)_{max} = 1.70 \times 10^{-3} \tag{10}$$

The bunch size is, therefore,

$$\pm(\Delta\phi)_{bunch} \times \pm\left(\frac{\Delta p}{p}\right)_{bunch} = (\pm 0.370) \times (\pm 0.627 \times 10^{-3}) \tag{11}$$

The accuracy of placement of a beam bunch into a bucket should be better than, say, 20 % in each dimension, namely

$$\begin{cases} |\delta\phi| < \frac{1}{5}\,(\Delta\phi)_{bunch} = 0.074 = 4.2^{\circ} \\ \left|\frac{\delta p}{p}\right| < \frac{1}{5}\left(\frac{\Delta p}{p}\right)_{bunch} = 1.25 \times 10^{-4} \end{cases} \tag{12}$$

There are three reasons for wanting to keep V_m and V_b high at transfer;

a. So that the phase oscillation frequency F_{sb} is fairly high and adjustments can be made adiabatically without taking too much time.

b. So that $\left(\frac{\Delta p}{p}\right)_{bunch}$ is fairly large and the tolerance $\left|\frac{\delta p}{p}\right|$ for the placement of beam bunches into buckets not too tight.

c. So that there is enough rf to manipulate the booster beam for matching rf phase and frequency (problem (2)) fairly rapidly.

2. To lock the booster rf phase and frequency to those of the main ring rf we can use the booster radial position feed-back system. The booster is adjusted so that its rf frequency crosses the constant main ring rf frequency at about one phase oscillation to $\dot{B}_b = 0$ time, say, -0.5 msec. (See Fig. 1.) At that time the signal to this feed-back system is switched from Δx to $\delta\phi \equiv \phi_{rfb} - \phi_{rfm}$ with appropriate scale factor. The response time of the feed-back system should be slowed down to approximately the phase oscillation period (frequency band width reduced to ~2 kHz) so that the adjustment is adiabatic. With proper operation $\delta\phi$ and $\delta f = f_{rfb} - f_{rfm}$ should be reduced to below tolerance ($|\delta\phi| < 0.074$ $\left|\frac{\delta f}{f}\right| < 10^{-6}$) within two phase oscillations, namely, at < 0.5 msec.

The frequency content of the booster horizontal aperture (at $x_{p\ max} = 3.19$ m) is given by

$$\frac{\Delta f}{f} \Big/ (\Delta x)_{max} = \frac{\Lambda}{x_{p\ max}} = -0.0071 \times 10^{-3}\ \text{mm}^{-1} \qquad (13)$$

To catch up 1 rf oscillation in, say, $\tau = 0.5$ msec with a cosine Δf curve

$$\Delta f \propto 1 - \cos 2\pi \frac{t}{\tau} \qquad 0 < t < \tau \qquad (14)$$

we get

$$\begin{cases} (\Delta f)_{max} = \frac{2}{\tau} = 4 \times 10^3\ \text{sec}^{-1} \\ (\dot{\Delta f})_{max} = \frac{2\pi}{\tau^2} = 25.1 \times 10^6\ \text{sec}^{-2} \end{cases} \qquad (15)$$

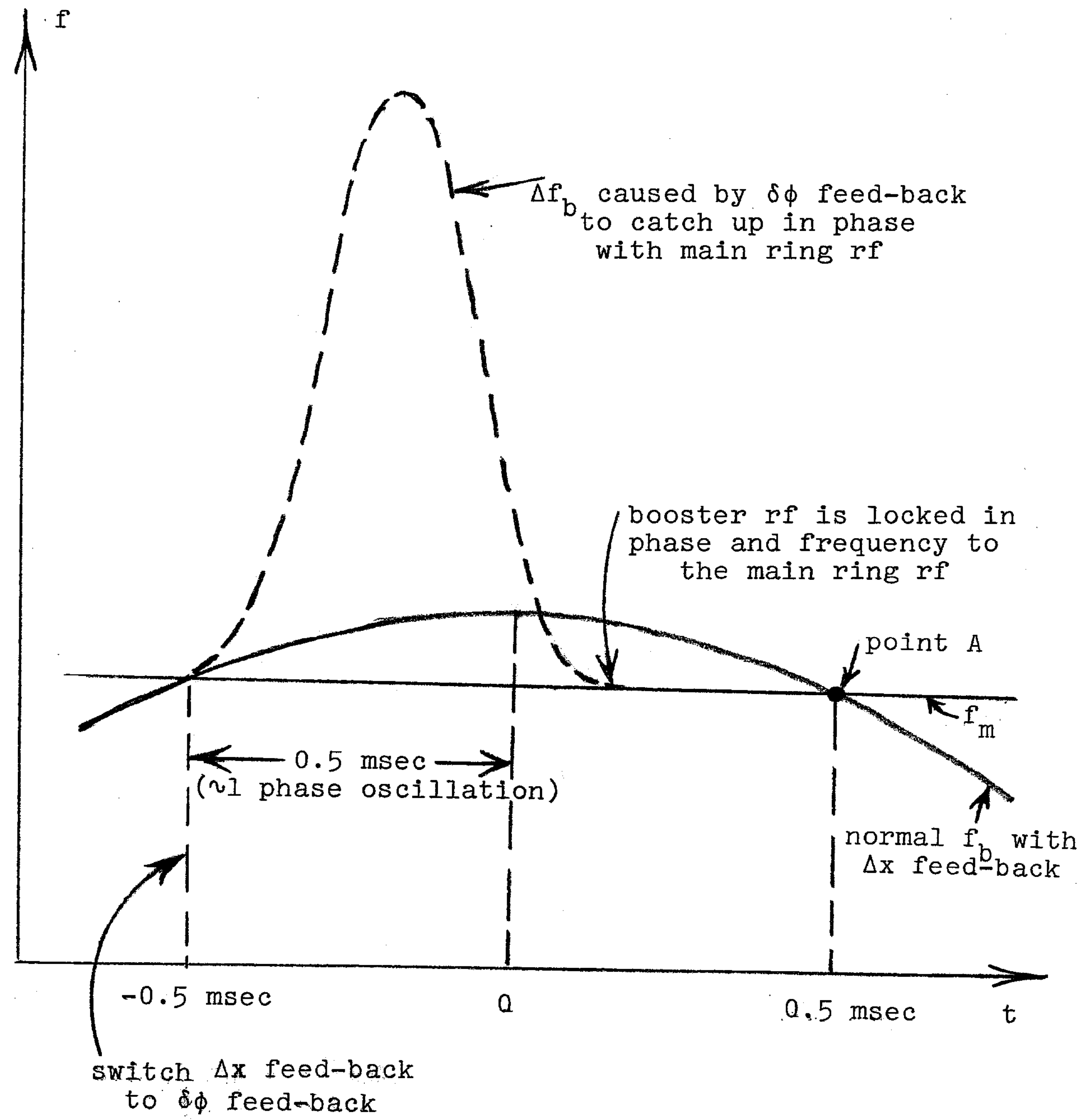
f
Δf_b caused by $\delta\phi$ feed-back to catch up in phase with main ring rf
booster rf is locked in phase and frequency to the main ring rf
point A
f_m
0.5 msec
(~1 phase oscillation)
normal f_b with Δx feed-back
-0.5 msec
0
0.5 msec
t
switch Δx feed-back to $\delta\phi$ feed-back

Fig. 1

This $(\Delta f)_{max}$ corresponds to a $(\Delta x)_{max\ max}$ of only 10.7 mm. Neglecting the small contribution to $\Delta\dot{f}$ from $\dot{B}$ this value of $(\Delta\dot{f})_{max}$ corresponds to a maximum energy gain per turn of

$$\left(\frac{dE}{dn}\right)_{max} = 0.294\ \mathrm{MeV}/_{turn} \tag{16}$$

The assumed V_b = 0.305 MV is just barely enough to supply this. But presumably only in rare extreme cases do we need to catch up one whole rf oscillation.

3. The central (synchronous) momentum of the beam is related to the frequency and the magnetic field by

$$\frac{\Delta f}{f} = \Lambda \frac{\Delta p}{p} + \frac{1}{\gamma_t^2} \frac{\Delta B}{B} \tag{17}$$

For the booster and the main ring at transfer these are

$$\left\{\begin{aligned} \left(\frac{\Delta f}{f}\right)_b &= -22.7 \times 10^{-3} \left(\frac{\Delta p}{p}\right)_b + 33.7 \times 10^{-3} \left(\frac{\Delta B}{B}\right)_b \\ \left(\frac{\Delta f}{f}\right)_m &= 8.4 \times 10^{-3} \left(\frac{\Delta p}{p}\right)_m + 2.6 \times 10^{-3} \left(\frac{\Delta B}{B}\right)_m \end{aligned}\right. \tag{18}$$

After the rf phase and frequency are matched $\left(\frac{\Delta f}{f}\right)_b = \left(\frac{\Delta f}{f}\right)_m$, and for $\left(\frac{\Delta p}{p}\right)_b = \left(\frac{\Delta p}{p}\right)_m$ we must have

$$\left(\frac{\Delta B}{B}\right)_b = 0.208 \left(\frac{\Delta B}{B}\right)_m - 110 \left(\frac{\Delta f}{f}\right)_m \tag{19}$$

If the main ring is so well regulated that $\left(\frac{\Delta B}{B}\right)_m << 5 \times 10^{-4}$ and $\left(\frac{\Delta f}{f}\right)_m << 10^{-6}$ we get from Eq. (19) $\left(\frac{\Delta B}{B}\right)_b << 10^{-4}$ which together with $\left(\frac{\Delta f}{f}\right)_b = \left(\frac{\Delta f}{f}\right)_m << 10^{-6}$ will lead only to an error in $\frac{\Delta p}{p}_b << 10^{-4}$. In this case we may just forget about $\left(\frac{\Delta B}{B}\right)_b$ and extract the beam from the booster at point A (Fig. 1).

If $\left(\frac{\Delta f}{f}\right)_m$ and $\left(\frac{\Delta B}{B}\right)_m$ are large they must be measured, say, at $t = 0$, $\left(\frac{\Delta B}{B}\right)_b$ calculated using Eq. (19), and the beam extracted when $B_b = B_{b\ \text{design}} \left[1 + \left(\frac{\Delta B}{B}\right)_b\right]$. Note that to meet the required tolerance of $\left|\frac{\delta p}{p}\right| < 1.25 \times 10^{-4}$ given by (12) $\left(\frac{\Delta f}{f}\right)_m$ and $\left(\frac{\Delta B}{B}\right)_m$ have to be measured to accuracies better than 10^{-6} and 5×10^{-4}, respectively. Hopefully, the main ring regulations will be such that this complication can be avoided and the beam can be extracted always at point A.

4. For the booster beam gap cogging we will adopt the scheme proposed by L. Klaisner. In this scheme the fact that the main ring circumference is 13-1/4 times that of the booster is utilized to precess the beam gap by 1/4 booster turn per main ring turn until at the proper moment when the tail of the pulse train in the main ring is at the proper azimuth the gap in the booster beam is less than 1/4 turn before the extraction point. The beam is then extracted when the gap arrives at the extraction point. The head of the pulse train injected into the main ring in this manner will then never be more than 1/4 booster turn behind the tail of the previous pulse train. Hence, we can inject a minimum of $\frac{13.25}{1.25}$ >10 booster pulses, which is only slightly less than the maximum of 13 booster pulses possible.

In this scheme one may have to precess the beam gap in the booster by a maximum of 3/4 turn, i.e., one may have to wait for 3 main ring turns which amounts to 63 μsec or ±31.5 μsec.

This corresponds to an uncontrollable error in $\left(\frac{\Delta B}{B}\right)_b$ around point A (0.5 msec after $\dot{B}_b = 0$ time) of

$$\left(\frac{\Delta B}{B}\right)_b = \pm\frac{1}{2}\,(30\pi \times 0.5 \times 10^{-3})\,(30\pi \times 31.5 \times 10^{-6})$$
$$= \pm 0.70 \times 10^{-4}$$

which by itself gives, from Eq. (18)

$$\left(\frac{\Delta p}{p}\right) = \pm 1.04 \times 10^{-4}$$

Compared to the conditions given in Eq. (12) this error is just barely tolerable. This also indicates that there is no point in trying to pin point B_b from $\left(\frac{\Delta B}{B}\right)_b$ given by Eq. (19) to better than, say, $\pm 0.5 \times 10^{-4}$.

In summary, the recipe for the scheme is as follows:

A. Adjust the injection field of the main ring B_m to a (constant) value such that f_b crosses the (constant) f_m at about -0.5 msec. This also defines the proper transfer values p and B_b. Hopefully, we can hold B_m and f_m to within $\pm 5 \times 10^{-4}$ and $\pm 10^{-6}$, respectively, over the whole injection time.

B. Set V_m = 1.5 MV to within ±5 % and at ∿ -4 msec flatten V_b smoothly to 0.305 MV to within ±5 %.

C. At about -0.5 msec when f_b crosses f_m switch the signal to the radial position feed-back system of the booster from Δx to $\delta\phi = \phi_{rfb} - \phi_{rfm}$ with appropriate scale factor. The response time of the feed-back system at that time should not be much faster than 0.5 msec. The phase and frequency of the booster rf should be locked to those of the main ring rf at $t < +0.5$ msec.

D. Again assuming that B_m and f_m are held to much better than $\pm 5 \times 10^{-4}$ and $\pm 10^{-6}$, respectively, start the cogging interrogation at 31.5 μsec to point A (+468 μsec). Depending on the initial position of the beam gap one may have to wait for 0, 1, 2, or 3 main ring turns to extract the beam from the booster and inject into the main ring.

If all goes well conditions (12) should be met and the beam bunch shapes should be matched to ±5 %. This procedure is repeated 9 times to inject 10 booster pulses into the main ring.