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RF system noise considerations

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Introduction:

In a previous report[(1)] the effects of rf system noise on the bunched beams in the storage mode were evaluated assuming an active phase loop and high Q (i.e., bandwidth < f_0 the rotation frequency) cavities. However, it is now planned to have about 45db of local feedback around each cavity so that the bandwidth will be of the order of 700 kc or about 9 f_0. In addition, it has been suggested[(2)] that the rf system be operated with the phase loop open during the storage mode as has been done at the Tevatron. The source of the rf frequency would be a low noise frequency synthesizer operating around 200 Mhz. Two commercial models are under consideration; the HP8662A and the Marconi 2040 series. The single sideband phase noise of these two units at 200 MHZ is shown in Fig. 1. (The Marconi plot is extrapolated from the 2GHz plot and additional references.) In this report we calculate the bunch area growth rate for gold ions at 26^+ and 100 GeV with rf voltage of 2 and 6 mV assuming bunch areas of .35 and .7 evsec/AMU due to the phase noise expected from each synthesizer.

Bunch Diffusion Rate:

Again[(1)] we consider only the diffusion due to phase noise and neglect any effects due to amplitude noise. Take $\overline{X} = \overline{J}/\hat{J}$ as a measure of the bunch emittance where $\hat{J}$ is the action on the bucket boundary and $\overline{J}$ on the bunch boundary. J itself is the action of a single particle and $\overline{J}$ the average over the bunch.[(3)] Then for small t (but many phase oscillatance) one can write[(3)]

$$\overline{X} = \overline{X_0} + S_1(\overline{X_0})\,t \tag{1}$$

so that the time required to double the bunch area would be

$$\tau = \overline{X_0}/S_1(\overline{X_0}) \tag{2}$$

Now one can write $S_1(\overline{X})$ as[(4)]

$$S_1 = \frac{\omega_{so}^2}{4}\left(\frac{2K}{\pi}\right)^{-4}\frac{\pi^2}{k^2 4B}\sum_{m=1,3,5} m^4 \sum_n \frac{S_\phi(m\omega_s + n\omega_o)}{\cosh^2(m\nu)} \tag{3}$$

where S_φ is the power spectral density of the phase noise at the cavity gap, n = 0, ± 1, + 2..-, K and B are an elliptic functions of $k^2 = \sin^2(\Phi/2)$ where Φ is the peak phase excursion for a given $\bar{X}$, $\omega_s = \omega_{so}\,\pi/2K$ is the synchrotron frequency corresponding to $\bar{J}$ and$\nu = \pi K'/2K$ with K′ also an elliptic function. Thus, in order to evaluate τ for a given bunch area one must calculate the various coefficients in equation 3 for a given bunch area and determine the values of S_φ from the plots of single sideband phase noise for those values of m and n that give significant contribution to the summation.

At V = 2mV and γ = 26 for gold ions the bucket area is 0.68 evsec/AMU and f_s = 189 Hz. For a 0.35 evsec/AMV bunch $(\Phi/2) = 50.4^0 = .88$ rad. Since η/γ at 100 GeV (γ = 108.4) is the same as at γ= 26 these values remain the same. We have then $k^2 = \sin^2(\Phi/2) = .594$, K = 1.9432, K′ = 1.782, B = .8632, so that $\nu = .917\ \pi/2 = 1.44$ rad, $\cosh^2(1.44) = 4.968$, $\cosh^2(3\nu) = 1413$ $\cosh^2(5\nu) = .44 \times 10^6$. Now we consider first n = 0 and require $S_\varphi = 2L(f_m)$ for m = 1,3,5 or the single side band phase noise $L(f_m)$ for 189, 567 and 945 Hz. We choose the Marconi unit first where L(189) ≅ -115db, L(567) ≅ -125db, L(945)≅ -130db, this lead to

$$2(.201x10^{-11.5}+.0573x10^{-12.5}+1.656x10^{-3}x10^{-13}) = \sum_{n=0\,m=1,3,5} S_\phi$$

or 1.31×10^{-12}. We can then write

$$S_1 = \frac{148 f_{so}^2 1.31x10^{-12}}{(1.9432)^4 x.5937x.8632} = .948x10^{-6}sec^{-1}$$

for the contribution from the n=0 line. In principal we should also consider the contributions from the lines n = ± 1, ± 2... for m = 1,3,5... but we see from Fig. 1 that these will all be of the order of $10^{-14.8}$ i.e., about -148 db, the noise floor for this unit, and hence will not really alter the value of S_1. Hence, using equation 2 and the relation $\bar{X} = k^2 B$ we obtain a doubling time of

$$\tau = \frac{.5937x.8632}{.948x10^{-6}sec^{-1}} = .54x10^6 sec = 150 Hrs$$

Next, let us take V = 6mV so that for gold ions the bucket area becomes 1.18 evsec/AMU and f_s = 327 Hz. Then $\Phi/2$ = .648 rad and k = .6035, k^2 = .3643, K = 1.7536, K′ = 1.9903, B = .8271 and ν = 1.7828 rad. We have $\cosh^2(\nu) = 9.347$, $\cosh^2(3\nu) = 11.05x10^3$, $\cosh^2(5\nu) = 3.27x10^6$ and need the single sideband phase noise for 327, 981, and 1635 Hz. For the Marconi generator we obtain L(327) = -121db, L(981) = -131db, L(1635) = -137.2db which gives

$$2(.107x10^{-12.1} + .0073x10^{-13.1} + .19x10^{-3}x10^{-13.7} = .171x10^{-12}$$

Again, we can write

$$S_1 = \frac{148x327^2.171x10^{-12}}{(1.7536)^4.3643.8271} = .952x10^{-6}sec^{-1}$$

and

$$\tau = \frac{.8271x.3643}{.952x10^{-6}sec^{-1}} = 1.267x10^6 sec = 88Hrs$$

Finally, let us double the bunch area to 0.7 evsec/AMV and keep the 6MV voltage. Then ($\Phi/2$) = 54.9^0 or k = .818, k^2 = .6694, K = 2.0326, K′ = 1.7569, B = .8779 and ν = 1.3577. Then $\cosh^2(\nu)$ = 4.2945, $\cosh^2(3\nu)$ = 862.9 $\cosh^2(5\nu)$ = 196,753 and we can write

$$2(.233x10^{-12.1} + .094x10^{-13.1} + .0032x10^{-13.7}) = .385x10^{-12}$$

then

$$S_1 = \frac{148x327^2.385x10^{-12}}{(2.0326)^4.6694x.8779} = .608x10^{-6}sec^{-1}$$

which gives

$$\tau = \frac{.6694x.8779}{.608x10^{-6}sec^{-1}} = .966x10^6 sec = 268Hrs$$

Returning to Fig. 1 we now evaluate τ for the HP8662A and the above choice of voltage and bunch areas. For 2mV and 0.35evsec/AMU we need L(189) = - 121.5db, L(567) = - 128.5db, L(945) = - 130db which gives for the n = 0 line

$$2(.2x10^{-12.15} + .0573x10^{-12.85} + 1.66x10^{-13}) = .3x10^{-12}$$

However, we must also consider the contributions for n = ± 1, ± 2 and ± 3 for m = 1,3,5 since the noise floor is around -135.7db at 78kc and -137.15 at 160kc. For n = ± 1 we obtain $2x2x10^{-13.57}$ $(.2+.0573+1.66x10^{-3}) = .027x10^{-12}$, for n = ± 2, $(4x10^{-13.71}x.259) = .02x10^{-12}$ and for n = ± 3 $(1.036x10^{13.92}) = .0124x10^{-12}$. In the case of n = 3 we multiply by .82 since at 234kc one is at .67 of the cavity bandwidth. Hence, the rotation lines will contribute $.052x10^{-12}$ and the n = 0 line $.3x10^{-12}$ for a total of $.352x10^{-12}$. This would result in a doubling line of (1.31÷.352)x150 = $558x10^3$ Hrs.

For 6mV and 0.35evsec/AMU we find L(327) = -126.4db, L(981) = -130db, L(1635) = 132.8db which gives

$$2(.107x10^{-12.64} + .0073x10^{-13} + 10^{-3}x.19x10^{-13.28}) = .0505x10^{-12}$$

Now for the lines at n = ± 1 we assume the same noise level and obtain $2x2x10^{-13.57}$ $(.107+.0073+.19x10^{-3}) = .012x10^{-12}$. Similarly for the n = ± 2 line $2x2x10^{-13.71}x.1145$ $= .0089x10^{-12}$ and n = ± 3, $4x10^{-13.92}x.82x.1145 = .0045x10^{-12}$. The total is then (.0505x.0254) $x10^{-12} = .076x10^{-12}$ which would give a doubling time of (.171÷.076)x88 = 198 Hrs. For double the bunch area at 6mV we find for the n = 0 line

$$2(.233x10^{-12.64} + .094x10^{-13} + .0032x10^{-13.28}) = .125x10^{-12}$$

and for the n = ± 1 line $4x10^{-13.57}$ x .33 = $.0355x10^{-12}$ and the n = ±2 lines 4 x $10^{-13.71}x.33$ = $.0257x10^{-12}$ and finally for the n = ± 3 lines $4x.82x10^{-13.92}x.33 = .013x10^{-12}$. The grand total for S_φ is then $.20x10^{-12}$ giving a doubling time of (.3858÷.20)x268 = 516 Hrs.

We note that largest difference between the two units occurs at 2mV where the lower synchrotron frequency favors the HP8662A. At the design value of 6mV which is required for efficient rebucketing and a 60% survival rate (due to IBS) of 10 Hrs. the difference is about a factor of two. However, during storage at 6mV the Au bunches will fill the buckets in less than one hour due to intra beam scattering. Thus, it is really the effects of rf noise on a full bucket that is of chief interest. In principal the lifetime of the particles due to noise diffusion can be determined if the dependence of S_1 on the synchrotron amplitude is known.[(3)] The most simple case would be if $S_1(X)$ were a constant. We see from the two cases at 6mV that S_1 decreased as the bunch area doubled S_1 decreased for both units. In order to check on this trend we calculated S_1 for the case where $\omega_s = \omega_{so}/2$ which corresponds to a bunch ≈320^0 wide i.e., for $k^2 = .97$ with K = 3.155, K′ = 1.5828 and v = .7876. Here the bunch occupies 93% of the bucket area. For the Marconi unit $S_1 = 2.55x10^{-6}$ and for the HP8662A $S_1 = .945x10^{-6}$. Hence S_1 is increasing as the bunch nears the separatrix. This is easily seen in Fig.1 where $L(f_m)$ rise rapidly at low frequencies. Since equation 3 is an approximation it is not valid near the bucket boundary and thus we cannot obtain an upper limit on the noise which one could use as a "constant" value in order to obtain a lower limit or the lifetime of a full bucket due to rf noise. (Also the value of $L(f_m)$ below 10 Hz is not available.)

Now referring again to Fig. 1 we see that the slope of the HP8662A curve is clearly less than that of the Marconi at frequencies less than 100Hz. Hence, it would seem to be the best choice to insure that the rf noise contribution to the beam lifetime is negligible even with no phase loop present.

<u>References</u>

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2. M. Brennan: BNL Private communication.

3. G. Dome: Theory of RF Acceleration and RF Noise, CERN SPS/84-14 (ARF) and CERN Accelerator School Proceedings of Sept. 1983.

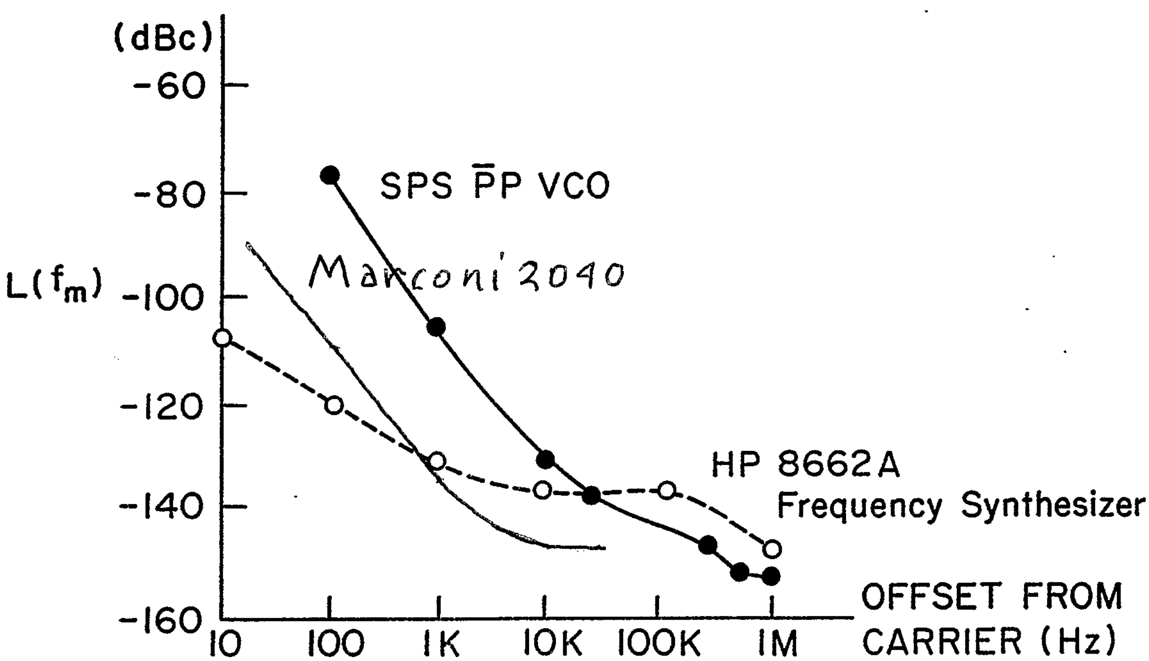

Figure 1. Single Sideband Phase Noise.