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ON-LINE TUNE MEASUREMENTS IN THE AGS

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Introduction

The need for an automated betatron tune measurement system on the AGS has in the past always been marginal. However, with the upcoming program to accelerate polarized protons on an operational basis, knowledge and control of the tune will become vital. Since the tune and the chormaticity will be carefully programmed throughout the acceleration cycle, constant monitoring of the tune variation will be necessary.

With the advent of H^- injection in the fall of 1982, more careful control of the tune at low energy may be necessary to take full advantage of increased current that can be injected. Also, in conjunction with the new ionization profile monitors [1] it should be possible to test various tune operating points as a function of time in the acceleration cycle so as to minimize transverse dilution. Both of these programs would benefit from a readily available tune monitoring system.

It is the purpose of this report to describe the elements necessary for such a system, including two possible options, either of which could readily be implemented on the AGS and to list some of the required design parameters.

Coherent Excitation

It is always assumed that the integer part of the tune is known and also whether the fractional part q is > or < 0.5. Then to obtain q one generally measures the frequency $(1-q)f_o$ or qf_o where f_o is the rotation frequency which must also be measured. If the latter is not available as in the case of a d.c. beam, then both the coherent frequencies can be measured and added. [2] In order to measure q, coherent transverse motion of the beam must be induced. This can be in the form of an impulse or fast kick lasting for one revolution period or less or so-called rf knockout where a sinusoidal deflection signal at one of the frequencies $f_m = |m-Q| f_o$ is applied. Both options have been used in the AGS in the past.[3, 4, 5] However, for on-line measurements in a machine like the AGS where at low energies f_o is changing relatively rapidly with time, rf excitation is not really suitable. In any event, at higher energies above transition ($\gamma_{tr} \approx 8.5$) where the natural horizontal chromaticity becomes large, detection of the coherent signal is very difficult unless the entire beam is excited. Hence, full aperture kicker magnets for both planes as are employed in many other accelerators[2, 6, 7] are desirable.

The shape of the kicker pulse will determine the relative amplitudes of the signal at q, (1-q), (1+q), (2-q) etc., times f_o that will be seen by position sensitive pick-up electrodes.[8] Generally, it is the two lowest sidebands mentioned above that have the largest amplitude for reasonable kicker pulse shapes. In particular, for a half-cosine shape or a trapezoid of width $1/f_o$ the amplitude will range between 0.5 and 1 for a unit kick, i.e., if the maximum deflection which is given by

$$y_p = \sqrt{\beta_p \beta_k} \quad \theta_k$$

is one mm, then the amplitude of the filtered pick-up electrode signal at $(1-q) f_o$ for $q > 0.5$ will be in the range of that calculated for a 0.5 to 1 mm deflection.[8] The trapezoidal or approximate square pulse is superior to the half-cosine for equal values of θ_k the deflection angle but is generally more expensive to generate. Hence, unless there is a severe limit on available aperture for the kick, the half-cosine pulse can be used.

Frequency Determination

The frequency to be measured then is either $q\ f_o$ or $(1-q)f_o$. In the AGS $q \geq 0.5$ in both planes for normal operation so the $(1-q)f_o$ line is preferable since the amplitude of the qf_o line would range from 0.25 to 0.45 for the same unit kick. In order to insure that a single frequency is presented for measurement, the pick-up electrode signal must at some point be filtered. Hence, a bandpass filter covering the range of $0.05\ f_o$ to $0.45\ f_o$ with a rejection of 40 db or greater at $0.5\ f_o$ and above will be required. Since the rotation frequency changes from 210 KHz to 371 KHz during the acceleration cycle, this filter must be programmable. Under certain conditions, i.e., when the chromaticity is large and the momentum spread is large, the coherent signal can rapidly die out (in less than 100 μsec). Thus, the transient response of the filter must be considered when the measurement is performed. If the lower frequency filter proves to be too slow (say a 25 μsec or greater response time) then one should consider measuring the qf_o line. Then a larger kick or more sensitivity for the signal channel will be required. The fastest and most accurate frequency measurement can be made with an automatic counter such as the HP 5345A or 5335A. The former for short gate periods is capable of several hundred measurements per second while the latter can make ten or more per second. For 100 μsec gates, their potential accuracy is $\pm 2 \times 10^{-5}$ but in reality the measurements will be limited by the signal to noise ratio present at the input to around $\pm 10^{-3}$ or better (see below). Since they have HP-IB (Hewlett-Packard Interface Bus) capability and are fully programmable, they can readily be incorporated into an automated system.

In principle, one would need at least two such counters, one to measure the filtered betatron frequency and another to measure f_o the rotation frequency or in reality 12 f_o in the AGS since the rf accelerating frequency is readily available. At the expense of reduced accuracy, one could use the B/A ratio (i.e., the ratio of the counts in the two input channels) mode and only one counter. In this case, the B input, which is the reference time base, would be the rf frequency. The filtered input would go to the A input and one then obtains the ratio B/A which can easily be converted to give the value of q. In addition to the trigger error which we take to be $\leq \pm 10^{-3}$ the least significant digit error would be $\approx \pm 2 \times 10^{-3}$ (for the 5345 A) if we assume a gate length of 200-110 μsec, i.e., 500 cycles of f_{rf} the reference frequency. One could improve this if f_{rf} were multiplied by ten say, to $\pm 2 \times 10^{-4}$ for the LSD (least significant digit) error since one would have 5000 cycles in the same period. The number of measurements per second should be the same in this mode also. If this choice of a single counter is made, one would have to insure that the coherent signal input was always above 75 mv p.p. for the minimum peirod required to accumulate the desired number of clock pulses.

A second method of measuring q would be to use FFT (Fast Fourier Transform) techniques. As first implemented on the CERN PS [9] a filtered coherent signal is digitized every revolution. One, of course, always works with the frequency that is $\leq 0.5\ f_o$. Then a discrete Fourier transform is performed with the data points (256 eight-bit words from a Biomation unit was used). [9]

Here the sampling rate defines the reference period and one obtains a determination of q or (1-q) directly. Using this method, one can obtain in addition to the Q value, an estimate of the tune spread and can detect the presence of linear coupling and even determine phase oscillation frequencies.[10]

It is not necessary to have a filtered signal to digitize and for the case where the coherent oscillation rapidly decays due to Landau damping, filters are not desireable due to their finite response time. At KEK[10] the signal from a single kicked bunch is integrated and then digitized every revolution. In either case, one obtains N samples in as many revolutions and after the FFT is performed, one has N/2 lines spaced 1/N apart between $f_{min} = 1/N$ and $f_{max} = 1/2$. Hence, in principle the accuracy is $\leq \pm 1/2N$ for determining q or (1-q). However, it is possible to improve on this without increasing N when the tune spread in the beam is such that Δq is $\gtrsim 1/2\,N$ (assuming a Gaussian distribution $\exp(-\,\delta Q^2/2\,\Delta q^2)$).[9] After performing the discrete FFT, one then does a least squares fit to the points in the neighborhood of the maximum. From this it is possible to obtain q and Δq for the distribution assumed. The value of q is found relatively insensitive to the distribution[9] while Δq is much more sensitive. An accuracy of 10^{-3} or better is possible for an N = 256 for example.

If the tune spread is considerably less than half the line spacing, then one must increase N to increase the accuracy. Smaller tune spreads will, of course, result in the coherent signal lasting for a longer time which would permit more samples to be obtained for a given bit resolution of the digitizer. This, of course, assumes the memory is available and that the tune does not vary significantly over the period, compared to the desired accuracy of measurements. The FFT method will be much slower than the counter measurements, particularly if a fitting routine is included. It should be possible to take several measurements during a single machine cycle and store the data for later processing. A dedicated FFT processor could be employed if some speed is deemed necessary.

The Effects of Linear Coupling

If the zeroth harmonic of any skew quadrupole field is not compensated, then there will be some linear coupling present. This coupling can affect the tune measurements in a manner that depends upon the method used. For a system using a counter to determine the frequency, significant errors can occur when the tunes in both planes are close to each other for one then has a signal that contains two different frequencies[5, 9, 10] since the energy from the motion in the kicker plane is transferred back and forth to the other plane. Hence, this system is not suitable for automatic measurements when the Q's are close together unless the linear coupling is corrected. However, on the AGS, such correction is readily available[5] and can be easily implemented.

The FFT method would, of course, reveal the presence of more than one frequency in the signal input Hence, it could be used to detect the presence of coupling.[10] If a fitting routine is used, then one would have to work in general with the sum of two distributions.[9]

The Effects of Tune Spread

We consider only the effect of momentum spread on the coherent frequency f_m that is to be measured. It is easily shown that

$$\Delta f_m = \frac{\Delta p}{p} f_o \left[1m - Q/\eta - \xi Q_o\right]$$

with $\eta = \frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2}$ and $\xi = (dQ/Q_o)/(dp/p)$

where $f_{mo} = f_o Q_o$ when $\Delta p = 0$. Now ξ, which is often called the chromaticity, varies in the AGS over a wide range in both planes from injection to the maximum energy of ≈ 30 GeV.[3] This variation at low fields is due primarily to eddy currents in the vacuum chamber and hence is dependent on $\dot{B}/B$. Another source of sextupole fields are end effects in the alternating gradient magnets and these become dominant at intermediate and high fields.

A typical value for ξy is -0.8 at injection, passing through zero around 18 GeV and becoming $+0.9$ at 28.1 GeV. ξ_x on the other hand can be around -1.8 near injection, -2.5 at ≈ 18 GeV, -3.2 at 28 GeV and -4.4 at ≈ 30 GeV/c. Let us calculate Δf_m for the lowest frequency mode in the horizontal plane for two values of the energy, i.e., $\sqrt{3}\ \gamma_{tr} E_o = 13.8$ GeV and $E = 28$ GeV. We take as the bunch area 0.56 evsec which is a typical value for intensities in the AGS of 3×10^{12} or <u>less</u> if transistion dilution has been minimized. Assuming $V_{rf} = 280$ kV we obtain a $(\Delta p/p)$ of 1.3×10^{-3} at the lower energy and 0.73×10^{-3} at the higher energy. For large values of ξ and considering only the lowest frequency mode, the contribution of the first term in the expression for Δf_m is negligible. We find $\Delta f_{mx} = f_o\ 1.77 \times 8.65 \times 1.3 \times 10^{-3} = 0.02\ f_o$ at 13.8 GeV and $\Delta f_{mx} = f_o\ 3.2 \times 8.65 \times 0.73 \times 10^{-3} = 0.02\ f_o$ at 28 GeV.

Now the effect of a tune spread is to cause the amplitude of the coherent oscillation of the center of charge to decay with time. In order to determine the decay rate, we must chose a suitable expression for the momentum and hence tune distribution in the beam. We shall assume a parabolic shape of the form $[1 - (\delta Q/\Delta Q)^2]$ where ΔQ is the half width at the edge of a bunch. Then one can show that after the beam is kicked so that all of the particles receive the same initial unit deflection, the motion of the center of charge will be given by

$$\bar{X}(t) = \frac{3 \sin Q_o w_o t}{(\Delta Q w_o t)^2} \left[\frac{\sin \Delta Q w_o t}{\Delta Q w_o t} - \cos \Delta Q w_o t \right]$$

This expression in brackets has its first zero at $\Delta Q w_o t \cong 1.43\ \pi$ and rises to a value of less than 0.08 at $\Delta Q w_o t \cong 2\pi$. For a $\Delta Q = 0.02$ with $w_o = 2\pi \times 371$ KHz, we find $t \cong 96$ μsec for the first zero or about 36 revolutions. Measurements made using the E-15 kicker at the above energies with a $(1-q)\ f_o$ filter resulted in signals that exhibit essentially this behavior when the linear coupling is compensated. That is the oscillations decay rapidly to a few percent of their initial value, typically in 90 to 150 μsec. Since the dynamic range of the HP 5345 is 30 db, a useful signal would be available over most of this period (allowing for the filter transient response to decay). We note that since the counter records the number of zero crossing of the input signal, one should terminate the measurement before the amplitude modulation term reaches its first zero.

One could, of course, digitize the filtered signal and perform an FFT to obtain an estimate of q and Δq. If we assume eight-bit accuracy, then the dynamic range of amplitudes would be 128:1 or ≈ 42 db. The idealized signal described above would remain within this range for $\Delta Q w_o t \approx 6\pi$ or ≈ 400 μsec. However, the real signal will die out sooner since the bunches will not in general have sharp edges. Thus, for N = 256, many of the samples will be zero.

One can still obtain an acuracy of 10^{-3} for this value of N, as long as q is no closer than 0.05 to an integer or half integer by the fitting procedure referred to above. This is because this type of signal is time limited [11] and the sampling period is such that no leakage can occur and errors due to aliasing are avoided by our restriction on the range of q that can be measured accurately.

In the discussion above we have ignored any effects due to synchrotron oscillations. This omission is valid for the horizontal signal since it dies out in a time short compared to a synchrotron period, which above transition in the AGS is of the order of 5 msec or greater. Even for the vertical coherent signal which can decay very slowly at higher energies, a 256 point sample would take only about 1/7 of a period. Hence, the effects of frequency modulation at w_s would be negligible. Of course, if one wished to resolve the spectrum, including the synchrotron sidebands, the sample time would have to include at least one period of the synchrotron frequency. This also presupposes that the coherent signal either does not completely die out or reappear during the sampling period. Such behavior has been observed in the AGS [3, 4] and earlier in the CERN PS. [12]

Measurements made at low energies where the synchrotron period can be as short as 250 μsec, could of course be significantly affected whether one uses the counter or FFT methods. For the counter scheme it might be wise to make the gate length equal to a synchrotron period if one wishes to minimize any error caused by the presence of sidebands. Similarly with the FFT approach, although there is less flexibility here since one is usually tied to 2^{ℓ} samples. An analysis of the errors involved if the measurement period is not adjusted for this effects, plus some form of averaging several measurements, will be necessary if the accuracies stated earlier are to be realized.

Other Effects

In general, the coherent frequency will be intensity dependent. This arises from the interaction of the beam with its surroundings, i.e., the vacuum chamber and any structures therin and at low frequencies (where the skin depth is greater than the wall thickness) the magnets themselves. Included in this, of course, would be the transverse dampers[13] which could be driven into saturation by the coherent oscillations exicited by a kicker used to measure the tune. This could lead to beam blow up and loss at low energies, and must be considered in implementing an operational system. In principle, one could excite large oscillations at high energies (where the present damping system is not effective) but so far such behavior has not been observed.

Of course, any radial position change during the measurement period or fluctuation from cycle to cycle can also produce measurement variations. Hence, monitoring of the radial position, as well as the beam intensity and energy, should be part of the overall tune measurement program.

Some Design Considerations

At present, tune measurements are made using a set of the original pick-up electrodes. It would be preferable to retain these since they have a larger sensitivity than the new electrodes and also have a much better low frequency response. The latter is needed in measuring $(1-q)\ f_o$ when the tune is near nine, as is often the case at low energy. These electrodes have a differential sensitivity of at least 80 MV/cm per 10^{12} protons. The one sided signal is around 300 MV times the buncing factor at 10^{12}. Hence, very large peak signals can be developed at 10^{13} protons, particularly in the neighborhood of the transition energy. For this reason, a low pass filter will be necessary between the pickups and the input circuit. In order to improve the signal-to-noise ratio for low intenstiy measurements, the difference amplification should be done locally on the ring. This has been done for the transverse damping system electronics[13] with no difficulties arising from radiation damage to the components.

With a gain of 40, we can obtain $\approx$ 200 MV/mm 10^{12} on the ring and at low frequencies about 150 MV in the Control Room. Allowing for at most a 0.5 reduction for the amplitude of the $(1-q)\ f_o$ line gives 75 mV peak signal or twice the minimum required for the HP5335A and 2.5 times that needed for the 5345A. One can easily push the sensitivity down into the low 10^{11} proton range, but measurements at the expected intensities for polarized protons, i.e., 10^{10} or less, will take special effort. However, development of electronics for radial position signals, derived from a pair of "old" pick-up electrodes, to be used in accelerting the polarized protons is under way.[14] Most likely, these circuits could be employed in a separate amplifier for very low intensity measurements.

Considering the signals available from a one mm displacement, it is reasonable to specify at least twice this value in determining the amount of kick required. Using the expression for δy given above and assuming

$$\sqrt{\beta_{min}\,\beta_{max}} = \overline{\beta} = R/Q,$$

we obtain $\theta = 2 \times 10^{-3}/12.85 \div 8.75 = 0.136$ mrad. This is more than five times less than the old full aperture C-15, E-15 kicker magnets could produce at 29.4 GeV/c. At the maximum current of 5,000 Amps, they were rated at 30.5 KG inch. Hence, one of these units with a 1 KAmp supply would be suitable for horizontal excitation. If the other old full aperture unit were to be used for a vertical kicker, a new coil would have to be designed. If we keep the same 6" horizontal aperture, at least 25% more current will be required for the same deflection assuming both kickers are at horizontal β_{max} and the PUE's are at horizontal β_{min}. The latter is true for the remaining old electrodes and the former would be true if two of the free 5-6 straight sections are used for the kickers.

Other factors to be considered in the power supply design are the cycling rate and the current pulse shape. The latter should be well formed with less than 10% overshoot or ringing. If we keep the pulse length fixed and assume the shape is a half cosine wave of duration 1/371 KHz or 2.7 μsec, then at injection energy where f_o = 200 KHz, the coherent signal for the same angular kick and the (1-q) f_o frequency will be about 1/3 the maximum deflection. One can, of course, compensate by using a larger amplitude or requiring greater sensitivity in the detection system. In any event, a variable pulse length is not really required. The need for multiple kicks during one acceleration cycle could, of course, increase the cost of the supply. Such a requirement would need strong justification.

Conclusions and Recommendations

An on-line tune measurement system can be implemented with a relatively modest amount of effort. The cost and time required would depend upon the final specifications for accuracy, resolution, sensitivity and rate at which measurements would be made. Several of the required components are already on hand and no significant engineering problems need to be solved in developing the remaining pieces.

We propose that the gated counter method be used with the clock frequency being some multiple of the rf frequency. This system is deemed more suitable for routine operational checks. We also propose that an FFT capability be added to be used for machine studies. We assume that filtered coherent signals will be available and that one of the LeCroy 2256A digitizers (eight bit, 1024 words, max. 20 MHz sampling rate) will be used at all times to digitize these signals. One can use a divided by M circuit from fr_f to choose the sampling rate. For a FFT measurement M = 12 and N = 256 samples, but for monitoring purposes, one will chose N = 1024 and a smaller value for M. This signal displayed on a terminal could then be used to optimize the counter gate timing and duration, and as a check on the presence ofa suitable waveform for the measurement.

Of course, a control and monitoring program incorporationg these as well as other elements such as radial position, beam energy, intensity, and the currents in all quadrupoles and sextupoles will be required.

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