THE EFFECT OF DUTY CYCLE ON THE RESEARCH POTENTIAL OF PION FACTORIES (*)

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(Presented by R.P. Haddock)

The research program of a pion factory is chiefly concerned with 2 or 3 particle final states; e.g. elastic scattering or single pion production in π-P, P-P, and N-P scattering. Scintillation counter techniques are well suited to the detection of these processes; so, counter systems are the principle particle detectors used in medium energy pion physics; and therefore, duty cycle is an important consideration to the experimentalist.

Until a few years ago many experiments at synchro-cyclotrons were "duty cycle limited" and not flux limited. We mean by this that the correlated-to-random coincidence ratio was unfavorable at full machine current, but became favorable at a lower current (sometimes 1-10% of the available current), for which a correspondingly longer running time was required. By various techniques, the peak current has been reduced by increasing the macroscopic duty factor (CERN: stochastic dee, Berkeley: auxiliary dee and Nevis: vibrating target).

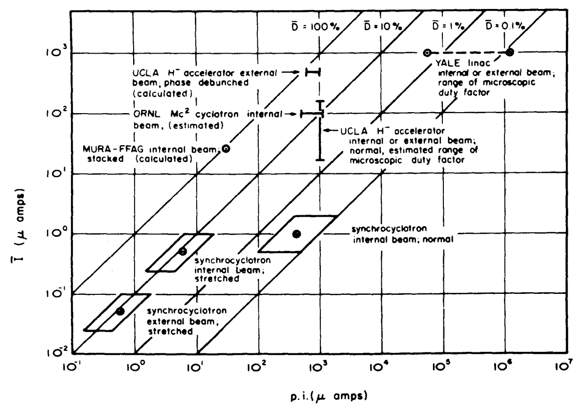

Fig. 1 Relation between average current $\bar{I}$ and peak current p.i. for various machines.

Fig. 1 is a plot of the average current, $\bar{I}$, versus the peak current, p.i., for synchro-cyclotrons and proposed pion factories. The ratio $\bar{I}$/p.i. will be called the effective duty factor, $\bar{D}$. For step-function pulses $\bar{D}$ is the product of microscopic duty factor, m.d.f., and macroscopic duty factor, M.D.F. Fig. 1 shows parallelograms representing an estimated range of operating conditions for synchro-cyclotrons under the following conditions: a) a normally accelerated internal beam; b) a stretched (second dee) internal beam and; c) a stretched external beam (10% average extraction efficiency). If we take the operating point for a stretched internal beam as corresponding to the peak current at which the afore-mentioned experiments were not duty cycle limited then a machine with $\bar{D}$ = 100% would be restricted to an average current of about 6 μA.

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Positive and negative ion isochronous cyclotrons are shown for the following conditions: a) the internal beam of a positive ion cyclotron having an estimated phase acceptance of 10^{o}-20^{o}; b) the internal or external beam of a negative ion cyclotron having an estimated phase acceptance between 5^{o} and 90^{o}; and c) the internal or external beam of a negative ion cyclotron using phase debunching for which a limit of 500 μA has been set on the average beam due to radiation considerations. Fig. 1 shows that the peak current of the normally accelerated beams of frequency modulated and isochronous cyclotrons are about the same. The horizontal bar for the linac represents the range of effective m.d.f.; when, a) the m.d.f. is determined by the linac, and when, b) the m.d.f. is determined by a counter system with a 1 ns time resolution (full width, half maximum). A counter system with a 5 ns resolution will wash out the micro structure leaving only the macro structure which is determined at present by power dissipation.

The finite velocity spread of external beams may also affect the effective m.d.f. for sufficiently low velocities or long flight paths. Fig. 2 shows the required flight path, L, to produce a time difference of one oscillator period, as a function of oscillator frequency, f, for different momentum spreads in the beam. A 750 MeV proton beam with a 1% momentum spread requires a $\frac{1}{2}$ km flight path at 200 Mc/s; so, this effect does not appear useful from a practical standpoint for the primary proton beams. On the other hand, low energy beams with a 10% momentum spread may be effectively debunched in less than a 50 m flight path at 200 Mc/s.

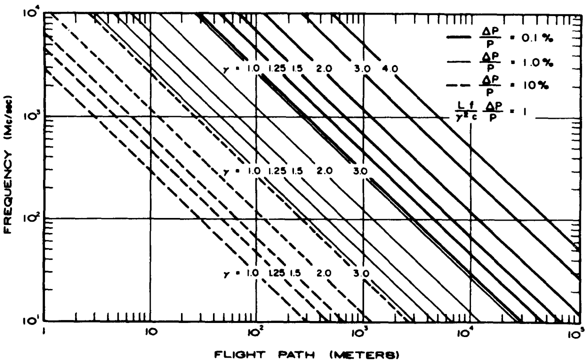

Fig. 2 Flight paths required to eliminate the micro-structure in a beam.

The coincidence method imposes a fundamental limitation on the instantaneous rate that may be used for a given correlated-to-random coincidence ratio, $r = C/R$, and effective resolving time. This restriction is well known in $\beta - \gamma$ coincidence experiments and is stated as follows for two counter systems in coincidence: $r = C/R = \bar{D}/2\tau\bar{I}$; where $\bar{I}/\bar{D}$ is the average instantaneous source rate and 2τ is the effective resolving time. In this expression it is assumed that each counter system is designed to count only particles of the correct species; so that the ultimate limitation is due to uncorrelated <u>real</u> events. If R_1 and R_2 are the individual average rates of the two counter systems then $R_1R_2/\bar{I} = C$ where R_1 and R_2 are linearly related to $\bar{I}$ through the solid angle, efficiencies, momentum acceptance, and the nature of the process being detected. Let $R_1 = \alpha_1\ \bar{I}$, and $R_2 = \alpha_2\ \bar{I}$; so that $C = \alpha_1\alpha_2\bar{I} = N/T$, where N is the number of correlated counts obtained in a time T. Finally we obtain

$$\bar{D}\alpha_1\alpha_2 = 2\tau r N/T.$$

We will use this relation to investigate the effect of duty cycle on the research potential of pion factories. Such a discussion must be drastically simplified. First, we will neglect the complications of microstructure and and $\bar{D}$ is simply the fraction of time beam is "on". The time resolution is then determined by the electronic resolving time of the counters, which are assumed to be in fast coincidence; so that $2\tau = 1$ ns.

There are two cases that are likely to arise. The first we will call the "precision-measurement" case and we assume that a 1% measurement of N is to be made in a day or less of data taking, with a 10:1 correlated-to-random ratio, then $T\bar{D}\ \alpha_1\alpha_2 = 10^{-4}$. We will assume reasonably good geometry and energy resolutions whenever necessary for this case, i.e., $\Delta\Omega = 5$ msterad, ΔE or Δ Pc = 5 MeV. The second case we will call the "discovery" case, and assume that 100 counts in a month or less are to be obtained with a 1:1 correlated-to-random ratio, then $T\bar{D}\ \alpha_1\alpha_2 = 10^{-7}$. Whenever necessary we assume a poor geometry and no energy resolution; i.e. $\Delta\Omega = 2\pi$ sterad.

Geometry I. A geometry that is frequently used to measure cross-sections consists of a counter system in front of a target to define the beam and another counter system to record an event; then $\alpha_1 = 1$, and $\alpha_2 = n\sigma$ (assuming 100% efficiencies). If we use a 1 gram/cm^2 hydrogen target, then $\alpha_2 = 6 \times 10^{23}\sigma$. Fig. 3 is a plot of σ(mb) versus T(sec) for different duty factors. We can in principle investigate processes with cross-sections of the order of 10^{-33} cm^2 and 10^{-37} cm^2 in the precision and discovery cases respectively, assuming a 100% duty factor. Fig. 3 also applies to differential cross-sections where $\sigma = [d\sigma/d\Omega][\Delta\Omega]$, so for $\Delta\Omega = 5 \times 10^{-3}$ sterad we can measure precisely a $d\sigma/d\Omega$ of 10^{-29} cm^2/sterad. Similarly energy spectra in inelastic scattering, $\sigma = [\frac{d^2\sigma}{d\Omega dE}]\ [\Delta\Omega\Delta E]$, of about 10^{-28} cm^2/sterad MeV can in principle be measured, whereas the energy spectra in single pion production have cross-sections about 10^{-30} cm^2/sterad MeV. While it is doubtful that this geometry will be used for cross-section measurements at pion factory intensities, because it effectively limits beam intensities to less than 10^8 particles/sec, the geometry does correspond to that used in many of the analysis techniques. The following experiments are typical. The arrangement used to analyze the polarization of scattered nucleons, where α_2 is frequently 2×10^{-3};

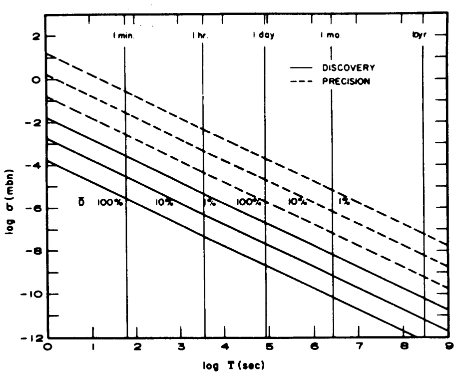

Fig. 3 Minimum cross-sections σ that can be determined during a running time T for different duty factors.

magnetic spectrometers with counters at the entrance and focal plane, where $\alpha_2 = \frac{d^2n}{d\Omega dP/P} \Delta\Omega \frac{\Delta P}{P}$, while $\frac{d^2n}{d\Omega dP/P}$ is the spectral shape to be measured normalized to unity, and $\Delta\Omega \frac{\Delta P}{P}$ is the transmission of the instrument; bent crystal spectrometers used in mesic X-ray experiments with transmissions of about 10^{-8}. In the latter case $\bar{D}T = 10^4$, when a beam telescope is used in coincidence with the γ ray counter in order to reject background, so that at best one precise measurement per day is possible.

Geometry II. Elastic cross-sections may be measured by counting the two final-state particles in fast time coincidence. The particles are exactly spatial related as well as time related if a mono-energetic beam is initially incident on the target. Here, $R_1 = R_2 = C = \bar{I} = I_0 n \, [d\sigma/d\Omega] \, \Delta\Omega$; so that $\alpha_1 = \alpha_2 = 1$ and $\bar{D} = 2\tau rC$. The maximum correlated rate is determined once the duty factor, the correlated-to-random rate and the resolving time are fixed, and this in turn places a limit on the maximum incident beam intensity, I_0, the number of scattering centers, and the cross-section that can be investigated. For our precision geometry $I_0 \, d\sigma/d\Omega = 5.6 \, \bar{D} \, \mu A$ mb/sterad, so that for a differential cross-section of 1.0 mb/sterad, I_0 must be less than $5.6 \, \bar{D} \, \mu A$. This case is clearly the same as that of two counters in the same beam or between two counters in a scattering counter system due to the exact spatial correlation. However, it is a necessary technique when compound targets, such as those in polarized hydrogen targets, are used.

When an angular correlation is to be measured by a pair of counter systems, counting only particles of the correct species, the above expression is modified to $r = \bar{D} \, F(\vartheta)/2\tau \, \bar{I}$, and $C = \bar{I}\epsilon_1 \Delta\Omega_1 \epsilon_2 \, \Delta\Omega_2 F(\vartheta)$; where ϵ_1 and ϵ_2 are efficiencies and $F(\vartheta)$ is the angular correlation factor.

We now consider the effect of the microstructure on a pair of counter systems in fast time coincidence. Fig. 4 shows a delay curve for two counters in the stripped negative ion beam of the UCLA 50 MeV cyclotron showing a real coincidence spike together with a succession of random coincidences spaced by the period of the RF. The resolving time of the equipment was about 10 ns (full width, half maximum). The relevant features of this curve are: a) there are no counts between the RF bursts; indicating that only fast beam-beam coincidences are involved and b) the random rate agrees with that computed from the individual rates and corresponds to a resolving time of 2 ns or about the width of the burst. This is typical of the situation where the counter resolution is faster than the RF period but is not as fast as the beam burst. Clearly, for counting during the pulse, and for counting between pulses, one requires opposite extremes in microscopic structure

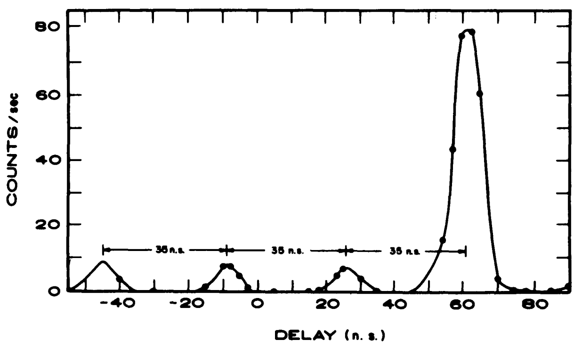

Fig. 4 Time structure of the stripped negative ion beam of the UCLA 50 MeV cyclotron.

Delayed coincidence experiments require a sufficient period between bursts. The pion and muon mean lives are 25.6 ns and 2.21 μs respectively. A 10 Mc/s oscillator will allow 4 pion mean lives between pulses, but a muon mean life is 22 RF bursts.

Our conclusions are that: a) the macrostructure should be as near 100% as possible; b) a flexible microstructure is indicated, i.e. change in width of bursts and spacing between bursts; c) some of the experiments envisaged for a pion factory are dangerously close to the ultimate limit of the coincidence method so that strict attention to shielding and resolving time problems will be necessary.

DISCUSSION

HUGHES : Sandweiss has considered a beam transport system in which the microstructure of the linac can be eliminated by making the length of the trajectory dependent on the energy of the particle. It looks fairly reasonable and involves some 30 ft of magnet. Secondly, I want to remark that the phase spread of the linac is somewhat variable. Teng has written a paper about this in the 1962 Brookhaven Conference on linacs. The figures given in our report are not the only possible ones.

HADDOCK : It would be very interesting to hear more about the system of Sandweiss.

HUGHES : I think that in a general analysis of limiting counting rates one must take into account, that one would often put additional requirements on the energy or polarization of the particles that are counted. In this case the rates would be much lower.

SCHMIDT : When the resolving time of your coincidence circuit is smaller than the time difference between the beam pulses, but larger than the burst width, the calculated coincidence rate is not the rate that you give here. It is rather the product of the rates in each of the two counters multiplied by the time interval between two pulses.

HADDOCK : That is correct.

HUGHES : In experiments involving stopped mesons the energy spread of the mesons and the length of the path over which they are stopped often destroys the microscopic duty cycle.

HADDOCK : I agree that one can think of several cases where 2τ is not the resolving time of the RF nor of the electronics, but is determined by velocity spread or other effects.