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CRISP 72-57
ISABELLE Project

BNL 17065

RECEIVED BY TIC SEP 20 1972

BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York

ACCELERATOR DEPARTMENT
Informal Report

INTERSECTING STORAGE ACCELERATOR NOTES

A Measurement of the Proton-Proton Total Cross Section by Beam Attenuation

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August 2, 1972

ABSTRACT

A method for the measurement of the total rate of beam beam interactions in colliding proton beams is proposed. This technique, which directly measures a modulated beam attenuation far from the interaction region, can be combined with an independent luminosity determination to yield the proton-proton total cross section to better than 1%.

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A MEASUREMENT OF THE PROTON PROTON

TOTAL CROSS SECTION BY BEAM ATTENUATION

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A measurement of the pp total cross section (σ_T) and its s dependence constitutes a critical test of our ideas of the asymptotic behavior of the strong interactions. Some representative models and their predictions are listed below:

1) Simple Regge Pole models with the Pomeronchuk dominating the high energy region predict a constant $\sigma_T = 38.8$ mb

2) Regge Pole + Cut models predict a slowly rising σ_T which reaches 42 mb at 80 TEV lab equivalent energy

3) Complex Regge Pole models predict

$$\sigma_T = 38.8 - 4.3 \cos(.7 \ln s + 2) \simeq 36 \text{ mb at } 80 \text{ TEV}$$

4) Field Theoretical Models which saturate the Froissart bound predict $\sigma_T = 38.8 + C[\ln s/s_o]^2$. A recent analysis of cosmic ray data by Yodh et al fits such a $(\ln s)^2$ rise with C = 0.4. This predicts $\sigma_T = 52$ mb at 80 Tev. A 1% or better measurement of σ_T and its s dependence would be a useful step in deciding the validity of these models.

Basically there are two methods for measuring the total cross section with colliding proton beams. The first requires the detection of all interactions occuring in an intersection region. One then normalizes to the luminosity to obtain the total cross section. The difficulties with this method are obvious. One must cover all 4π steradians with no holes in the detector. This may be a serious limitation in that some unknown fraction of the interactions may produce secondaries which do not diverge appreciably from the proton beams. In addition one must carefully consider problems of accidentals and background due to beam-gas collisions, beam-wall collisions and general room background (e.g. slow neutrons) as well as deadtime effects.

The second method for measuring σ_T consists in measuring the proton beam attenuation in time. Here the difficulties are again the separation of beam-beam from beam-gas and beam-wall loss, and the fact that the relative attenuation is so small ($1/10^6$ per second at 10^{34} $cm^{-2}sec^{-1}$ luminosity). Here we propose a relatively simple method for measuring the total interaction rate which has good signal to noise (>99%) and which cleanly separates beam-beam from other sources of beam attenuation.

Let N(t) be the number of protons in one of the beams as a function of time, then

$$N(t) = N_o - \int_o^t \lambda(t)\ dt - \int_o^t \beta(t)\ dt$$

where $\lambda(t)$ is the rate of beam loss due to beam-beam collisions and $\beta(t)$ is the rate of loss on walls, residual gas and all other unspecified sources. The beam attenuation is then given by

$$\frac{dN(t)}{dt} = - \lambda(t) - \beta(t)$$

Consider the situation where one beam is caused to sinusoidally sweep across the other. If we study the attenuation of the <u>fixed</u> beam then

$$\lambda(t) = A \cos \omega t$$

$$\beta(t) = B$$

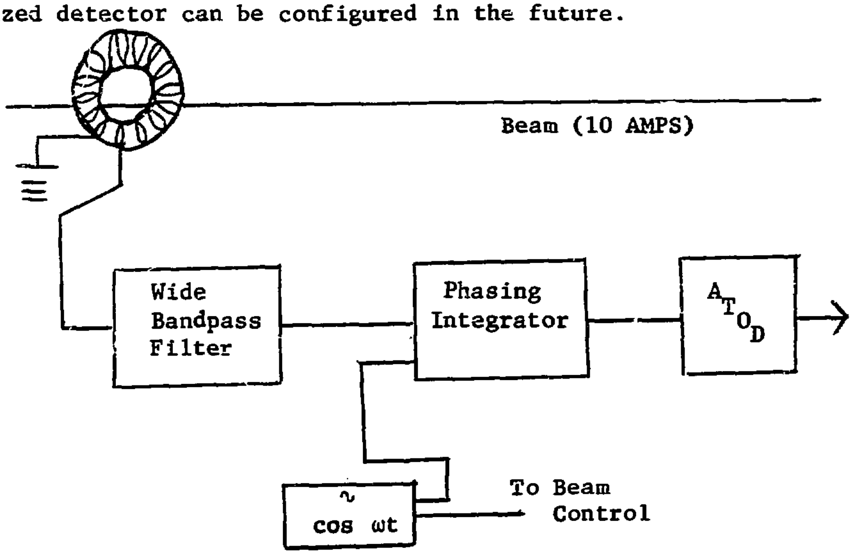
The beam-beam loss is periodic while other losses are to first order linear in time. The main point is that losses through processes other than beam-beam interactions are not periodic. If the sweeping beam were to completely cross the fixed beam then the peak to peak variation in $\lambda(t)$ gives the total beam-beam interaction rate.

A = beam-beam interaction rate.

We study the stationary beam to avoid any periodic loss not related to beam-beam collisions. Once A is determined an independent luminosity measurement gives the total cross section

$\sigma_T = \frac{A}{L}$ where L is the luminosity as determined by the methods discussed in CRISP 72-39.

In the following we propose a relatively simple, easily testable scheme for detection of the sinusoidal variations in beam attenuation. This detector, as proposed, is not optimized but presented in order to show feasibility. An optimized detector can be configured in the future.



We construct a toroid of high permeability material. This toroid has radius r, permeability $K\mu_o$ and cross sectional area Q. There are N turns of wire around the toroid so that the whole system acts as a transformer. The beam, which passes through the center of the toroid, has an AC component due to the sinusoidal variation in beam-beam interactions. This AC component induces an EMF in the toroid windings which is in phase with the driven oscillations of the other beam.

The magnetic field H due to the beam current in the toroid is

$\oint H \cdot d\ell = i_{free} \rightarrow H = \frac{i}{2\pi r}$ where we assume the coil diameter is less than the toroid radius, r.

The field, B, in the toroid is

$$B = K\mu_o H = \frac{K\mu_o i}{2\pi r}$$

so that the EMF induced in the winding is

$$EMF = -N\frac{d\phi}{dt} = -N\,Q\,\frac{dB}{dt} = -N\,\frac{Q\,K\mu_o}{2\pi r}\,\frac{di}{dt}$$

The time derivative of the beam current is proportional to the rate of beam loss

$$\frac{di}{dt}\ \alpha\ \frac{dN}{dt} = \lambda(t) - A\cos\omega t$$

so that
$$\frac{di}{dt} = i\,\frac{A}{N_o}\cos\omega t$$

where A is the rate of beam-beam collisions and N_o is the total number of protons in the fixed beam. Thus the induced EMF is

$$EMF = \frac{N\,Q\,K\mu_o}{2\pi r}\; i\;\frac{A}{N_o}\cos\omega t$$

We can measure the part of this EMF in phase with the sinusoidal beam deflecting voltage ($\cos\omega t$) and we can measure

$$i = e\,\frac{N_o c}{2\pi R}$$ where R is the radius of the storage ring.

This gives for the induced EMF

$$EMF = \frac{N\,Q\,K\mu_o\,ec\,A\cos\omega t}{(2\pi)^2\,rR} = \frac{N\,Q\,K\mu_o\,ec\,L}{(2\pi)^2\,rR}\cdot\sigma_T\cos\omega t$$

The coefficient of cos wt is measured and all component factors are known except σ_T.

In order to estimate the size of this signal we consider the case of a luminosity of 10^{34} cm^{-2} sec^{-1}.

Then $i = 10$ AMPS

$A/N_o \sim 10^{+8}/10^{14} = 10^{-6}$ for a 40 mb total cross section

We consider a toroid and coil with

$$N = 10^3$$

$$Q = 3 \text{ cm} \times 3 \text{ cm} \sim 10^{-3} \text{ m}^3$$

$$K = 10^5 \qquad \mu_o = 4\pi \times 10^{-7}$$

$$r = 3 \text{ cm} = 3 \times 10^{-2} \text{ m}$$

then

$$\text{EMF} = 10 \cos \omega t \text{ microvolts}$$

Such an AC signal can certainly be detected with phasing techniques since it has a well defined frequency modulation. With a better designed coil (e.g. higher K, more turns) the signal level could be increased.

We must still consider the question of signal vs. noise; that is, our circuitry will pick up random noise as well as the desired AC signal. We must ask how long this signal must be sampled to achieve a good signal to noise ratio. This ratio should certainly be better than 1%. If such a ratio cannot be achieved in a reasonable sampling time then many systematic drift problems will have to be considered as difficult corrections.

We represent the voltage input to the phasing integrator as

$$V(t) = V_1(t) + V_o \cos \omega t$$

where $V_1(t)$ is the noise component with a random time distribution, V_o is the amplitude of the signal due to beam-beam attenuation. The output of the phasing integrator is calculated by folding V(t) with the modulating signal cos wt.

$$R = \int_o^T V(t) \cos \omega t \, dt = \int_o^T V_1(t) \cos \omega t \, dt + V_o \int_o^T \cos^2 \omega t \, dt$$

$$R = \int_o^T V_1(t) \cos \omega t \, dt + \frac{V_o T}{2} \quad \text{where T is the sampling time}$$

To evaluate the first term we must have a model for the noise $V_1(t)$. If we require a long sampling time compared to the reciprocal of the modulating frequency $\qquad T \gg 1/w$

then we can, to first order, say that the noise averages to zero in the sampling time except over one cycle of the modulating signal. With this model

$$\int_0^T V_1(t) \cos \omega t \, dt = V_{rmx} \int_0^{2\pi} \cos \omega t \, dt = V_{rms} \cdot \frac{2\pi}{w}$$

where V_{rms} is the mean amplitude of the noise. With these assumptions (which we use only to estimate the magnitude of the sampling time).

$$R = \frac{V_o T}{2} + V_{rms} \frac{2\pi}{w}$$

If we require a ratio of signal to noise from the phasing integrator to be 100/1 then this should be the ratio of the two terms above.

$$\frac{V_o T}{2} = 100 \, V_{rms} \frac{2\pi}{w}$$

$$T = \frac{V_{rms}}{V_o} \cdot \frac{400\pi}{w} = \frac{V_{rms}}{V_o} \cdot \frac{200}{f}$$

We must choose the value of w so that the drift in this modulating signal, Δw, is much less than the sampling time so that phase relations are maintained

$$\frac{1}{\Delta w} \ll T$$

We choose, for example, $f = w/2\pi \sim 5KC$ as a possible driving frequency. The rms value of the random noise is unknown but for the sake of discussion we choose $100 \ \mu v = V_{rms}$. Hopefully one can reduce such noise below this level, but as we shall see it is quite possible to test the system under realistic conditions in order to learn the feasibility of working at such a level. With these numbers we calculate a sampling time T to reach a 1% noise to signal level as

$$T = .4 \text{ sec}$$

This time scales as V_{rms} so that even a noise level of 1mv allows a measurement time which is adequately short compared to drift times. We see that within the constraints of our admittedly crude analysis it seems feasible to consider a measurement of σ_T by modulated beam attenuation methods.

There are several potentially serious problems as well as more sophisticated techniques which have thus far been ignored. These problems include beam associated noise, beam fluctuations (both short term and those comparable to our integration time) and collective beam-beam loss. In addition there is the questions of corrections due to those amplitudes which contribute to the total cross section but which do not scatter particles out the beam phase space. In some cases, for example, a proton is coulomb scattered out of only one beam. For a given set of β functions there is a minimum scattering angle above which a scattered proton leaves the beam before reaching the toroid. In principle the determination of this angle is a straightforward calculation in beam dynamics since one need not consider machine resonances which take more than a fraction of a turn in order to remove a scattered particle from the beam. By varying the β functions one could perform the equivalent of the classical total cross section measurement where the limit of $\beta \to \infty$ is analogous to the extrapolation to zero solid angle.

Collective beam loss may be handled by a correlated attenuation measurement of both beams in that such a measurement limits the allowable time of such effects to a fraction of a turn. In addition such effects vary with luminosity and so a series of measurements at different luminosities should help separate the particle-particle total cross section from collective beam effects. Another possibility whose feasibility we have not yet understood is a correlated attenuation measurement on both beams without modulating the signal by beam oscillations. If the signal could be extracted in this situation one may avoid problems due to instabilities introduced by the driven beam oscillations. We are currently trying to understand the effects of such sophistication on our design.

We must also mention the ease in making first order tests of the detection system proposed here. The system is designed to detect oscillations of one part per million in the kilocycle frequency range in a current of 10 amps. This sensitivity can be tested on the bench by proper modulation of an electric current in a wire going through the toroid. To get some idea of the noise discrimination in the working environment of an accelerator the device can be tried near a running machine like the AGS or even the ISR to get some feel for beam associated noise. Such simple tests may help define realistic operating requirements for the electronic components of the detection system.