CHAPTER 10

PERFORMANCE AND LUMINOSITY

In this chapter we describe colliding-beam performance at 1000 GeV in the Energy Saver. For this purpose, we assume that beams of protons and antiprotons have been accelerated and are circulating in opposite directions so they collide in the center of the low-beta insertions at B0 and D0.

We assume the populations for the two beams are those required for a luminosity of 10^{30} $cm^{-2}s^{-1}$. Larger luminosity figures are also possible (see Table 1-I).

10.1 Beam Geometry

As an example, it is possible to create three bunches of antiprotons, each with 6 x 10^{10} particles and each with a longitudinal phase area of 3 eV-sec, which we define as the area including 95% of the population with a biGaussian distribution. To prepare the necessary number of antiprotons in the Accumulator will take a little more than 2 hours.

Similarly, we can assume that three proton bunches, each with 6 x 10^{10} particles and a longitudinal area of 3 eV-sec, coexist with the antiproton beam. Both beams have equally spaced bunches since the harmonic number 1113 can be divided by 3. In principle, there are therefore 6 equally spaced collision regions. We assume here that beams are not kept separated by electrostatic deflectors. We also assume that two sets of four rf cavities exist, giving orthogonal control of the two beams, as discussed in Sec. 8.5. In this mode of operation, there will be a total of 1.4 MV/turn for each beam.

Using the equations of Chapter 2, which apply to the Tevatron as well as to the Main Ring, we obtain the rms bunch length σ_e = 40 cm and the rms momentum spread σ_p/p = 1.2 x 10^{-4}. The area of the stationary bucket is 12.7 eV-sec, four times larger than the bunch area. Finally, the phase-oscillation period is T_s = 27 msec.

10.2 Beam Cross Section at the Collision Point

As a result of the transverse stochastic cooling in the Debuncher and Accumulator Rings, and because the two beams have roughly the same number of particles, the two beams have the same emittance in both horizontal and vertical planes. The normalized emittance is assumed to be 24 π mm-mrad. That is, $\varepsilon_V = \varepsilon_H$ = 0.0225 π mm-mrad at 1000 GeV (this includes 95% of the beam) distributions.

A low-beta figure of approximately 1 m is expected in both planes and therefore the rms beam radius is

$$\sigma = 0.06 \text{ mm}$$

or

$$\sigma^2 = 3.5 \times 10^{-5} \text{ cm}^2 .$$

Since the low-beta insertion has very small dispersion, there will be negligible contribution to the beam size from momentum spread. In Fig. 10-1 we show the variation of beta and the dispersion in the interaction region. Observe that the beta minima are about 10 cm apart. The dispersion is approximately 18 cm. For comparison in Fig. 10-1, we also show the longitudinal distribution of a bunch.

10.3 Luminosity

Because the low-beta value of 1 m is larger than the rms bunch length (0.4 m), a formula for luminosity valid for varying beam sizes is

$$L = \frac{N_p N_{\bar{p}} B f_0}{4\pi\sigma^2} K \quad , \qquad K = \int G(s)ds$$

where $N_p = 6 \times 10^{10}$ is the number of protons per bunch, $N_{\bar{p}} = 6 \times 10^{10}$ is the number of antiprotons per bunch, B = 3 is the number of bunches per beam, and $f_o = 4.77 \times 10^4$ Hz is the revolution frequency. This gives

$$L = 1.0 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1} .$$

The distribution G(s) of luminosity in the interaction region is shown in Fig. 10-2. It is approximately Gaussian with an rms value of 26 cm. This figure has already been adjusted by a factor 0.92 because of the variation of beta with bunch length[14]. This luminosity figure is clearly within reach with the methods and the techniques described in this report. Several alternative luminosity scenarios can be invented. For instance, it would be possible to replenish the Collider every hour with only one single bunch of protons and antiprotons with 10^{11} particles each, for the same luminosity of 10^{30} cm^{-2} sec^{-1}. This takes less filling time but requires an understanding of the bunch combination that we can achieve only with the collider at hand.

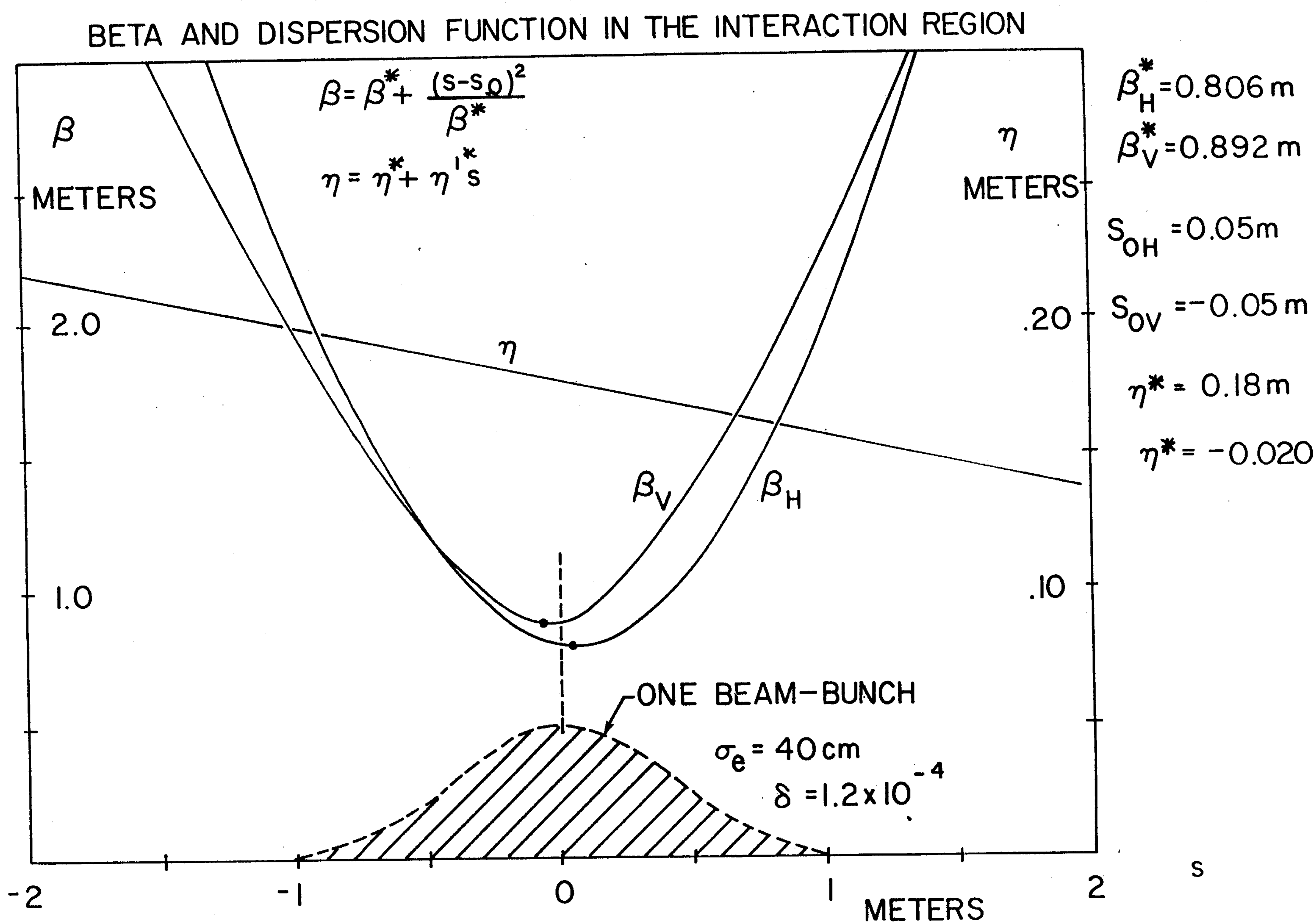

BETA AND DISPERSION FUNCTION IN THE INTERACTION REGION
β= β*+ (s-s0)²/β*
η = η*+ η'*s
β
METERS
2.0
1.0
η
METERS
.20
.10
β*H=0.806 m
β*V=0.892 m
SOH =0.05m
SOV =-0.05 m
η* = 0.18 m
η* = -0.020
βV
βH
ONE BEAM-BUNCH
σe = 40 cm
δ =1.2 x 10-4
-2
-1
0
1
2
METERS
s

Figure 10-1

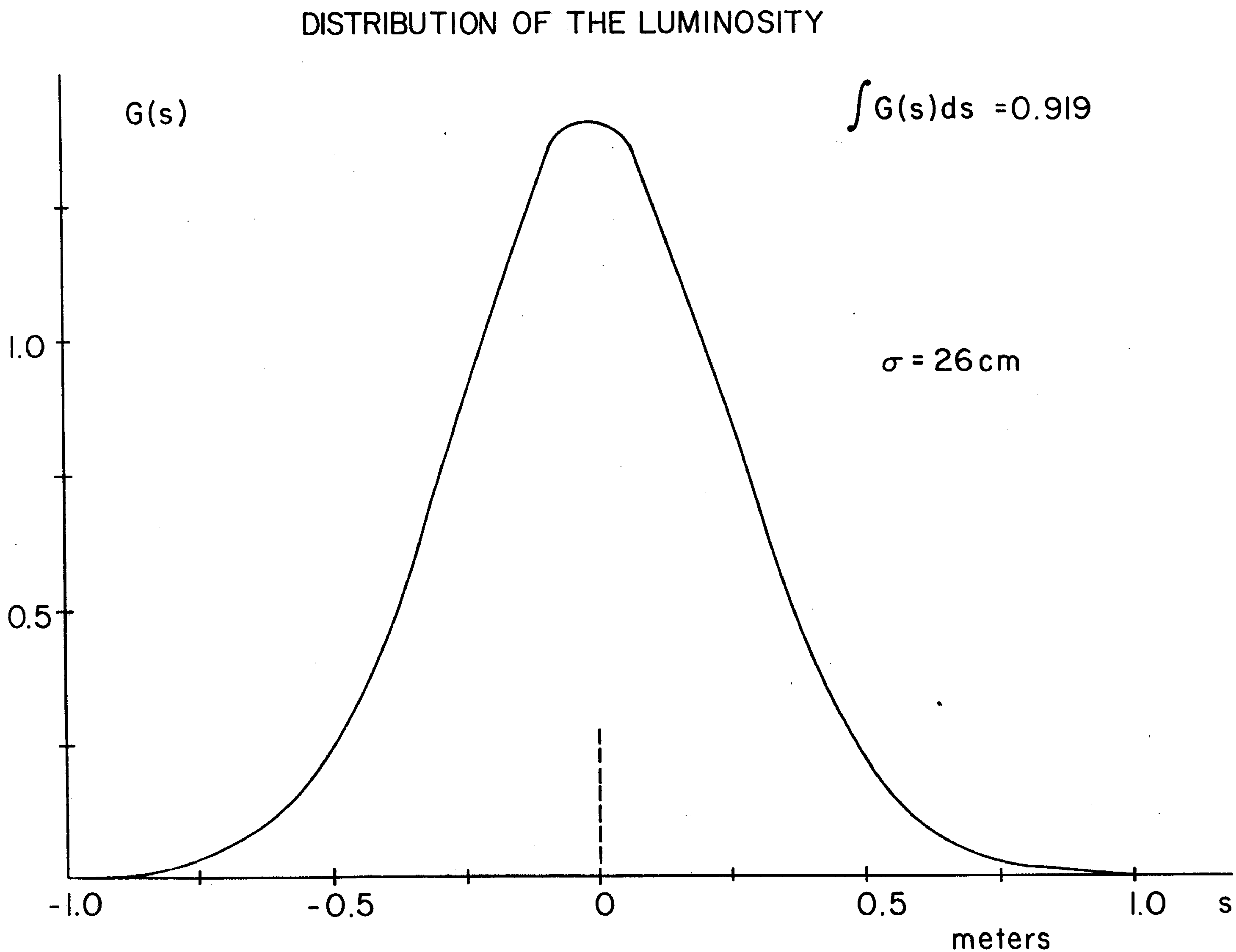

DISTRIBUTION OF THE LUMINOSITY
G(s)
∫G(s)ds =0.919
σ = 26 cm
1.0
0.5
-1.0
-0.5
0
0.5
1.0
s
meters

Figure 10-2

Higher luminosity figures can also be expected, as high as 6×10^{30} $cm^{-2}sec^{-1}$ (see Table 1-I), by improving either the stochastic cooling (a factor of two), or the beam intensity in the Main Ring and Tevatron (also possibly by a factor of two) or with 6 bunches per beam instead of the 3 assumed here.

10.4 Beam-Beam Tune Shift

Collisions are head on, the emittances of both beams in both planes are all equal, and the lattice functions are approximately the same in both planes. The beam-beam tune shift is therefore the same for both beams, is independent of the beam energy, and does not depend on the lattice functions. The linear beam-beam tune shift is given by

$$\xi = \frac{3\ N r_0}{2\varepsilon_N},$$

where $N = 6 \times 10^{10}$ is the number of particles per bunch, $\varepsilon_N = 24\pi$ mm-mrad is the normalized emittance and $r_o = 1.535 \times 10^{-18}$m is the classical proton radius. We have

$$\xi = 0.0017/\text{crossing}$$

Even with a low-beta insertion, the beam cross-section in the other five collision regions with normal β values is round and the contribution to the beam size from the momentum spread is negligible. The tune shift per crossing is therefore the same at each crossing so long as the collision is head-on, or at least at an angle $\theta \ll \sigma/\sigma_e$. If there is a total of 6 crossings, the total tune-shift per turn

$$\xi_{tot} = 6\ \xi = 6 \times 0.0017 = 0.01.$$

10.5 Single-Beam and Luminosity Lifetime

We have investigated four possible sources of lifetime deterioration in the Tevatron: scattering by the residual gas, intrabeam scattering, beam-beam effects and beam-beam cross sections. An analysis of periodic or random crossings of nonlinear resonances has also been carried out[15]. This will help to determine not only possible limits on the nonlinearities in the Energy Saver superconducting magnets, but also on the amount of coherent and incoherent noise amplitude allowable.

10.5.1 Effects of Residual Gas[1]. The following effects have been investigated:

(i) Multiple Coulomb Scattering

(ii) Single Coulomb Scattering

(iii) Nuclear Scattering

The first effect causes a beam-emittance growth, which leads both to a luminosity decay and a single-beam lifetime in a finite aperture. The single-beam lifetime due to multiple Coulomb scattering is very long and this effect is quite negligible. The second and third effects cause an intensity decay, but the third effect is more important than the second[1].

The average vacuum pressure expected in the Tevatron is 10^{-8} Torr in the warm regions and 5×10^{-11} Torr in the cold regions with the gas composition:

warm region: 60% H_2 and 40% CO
cold region: 75% H_2 and 25% He

The intensity decay per beam due to single Coulomb and nuclear scattering is

$$\frac{1}{I}\frac{dI}{dt} = -1.07 \times 10^{-6}/\text{sec} . \qquad (10.1)$$

The emittance growth due to multiple Coulomb scattering is

$$\frac{1}{\varepsilon}\frac{d\varepsilon}{dt} = 1.3 \times 10^{-6}/\text{sec} . \qquad (10.2)$$

These effects combined lead to a luminosity decay of

$$\frac{1}{L}\frac{dL}{dt} = -3.44 \times 10^{-6}/\text{sec} ,$$

giving a loss of 23% of the luminosity in 20 hours.

10.5.2 Intrabeam Scattering[2] To estimate intrabeam scattering diffusion rates for the colliding-beam mode, we have used the same computer code we used to estimate intrabeam scattering for the Accumulator. For our estimate, we have used the actual Tevatron lattice with the low-beta insertion. From this calculation, we have found empirical formulas for diffusion rates, which apply to a bunched beam at 1000-GeV. Define

$$\Delta\delta = \sigma_p/\sigma_{p_0}$$

$$\Delta\varepsilon = \varepsilon/\varepsilon_0 ,$$

where σ_p is the rms momentum spread and $\varepsilon = 2\sigma^2/\beta$ is the rms betatron emittance; σ_{p_0} and ε_0 are the initial values. Then

$$\frac{d\Delta\delta}{dt} = \frac{\tau_p^{-1}}{(\Delta\delta)^{m_p - 1}\ (\Delta\varepsilon)^{r_p}} \qquad (10.3)$$

$$\frac{d\Delta\varepsilon}{dt} = \frac{2\tau_x^{-1}}{(\Delta\delta)^{m_x}\ (\Delta\varepsilon)^{r_x - 1}} \qquad (10.4)$$

Here r_p, r_x, m_p and m_x are empirically determined exponents. There is actually damping of the vertical betatron emittance.
For σ_{e_0} = 40 cm, $N_0 = 6 \times 10^{10}$, ε_0 = 0.0077 mm-mrad and $\sigma_{p_0}/p = 1.2 \times 10^{-4}$,

$$m_p = 2.2 \qquad r_p = 1.4$$

$$m_x = 0.7 \qquad r_x = 2.0 .$$

We obtain as initial diffusion times

$$\tau_p = (63.5 \text{ hours}) \frac{N_0\, \sigma_e}{N\, \sigma_{e_0}}$$

$$\tau_x = (24.0 \text{ hours}) \frac{N_0\, \sigma_e}{N\, \sigma_{e_0}}$$

There is a loss of luminosity caused by intrabeam scattering diffusion in the horizontal betatron oscillation. We assume that there is also diffusion of the vertical emittance at the same rate caused by nonlinear coupling of the type induced[16] by beam-beam effects and chromatic/sextupole effects. It has been found that the CERN-SPS-Collider performance is limited to a luminosity lifetime of about 16 hours mostly because of intrabeam scattering. The calculations made to explain the experiment are very similar to the ones here.

10.5.3 Beam - Beam Effects. Beam-beam effects have been extensively simulated on the computer. Several issues have been discussed, studied, and, we hope, resolved.

A systematic search for Arnol'd diffusion for the Tevatron parameters has given negative results.[3,4] We have been able to simulate in some cases up to 20 minutes real time of collisions. From our data, we can extrapolate beam-beam lifetimes of several days. We believe the stability of the system arises from the "roundness" of the beam geometry and of the lattice functions.[5]

We found that the addition of the nonlinear beam-beam interaction to a system already affected by external random noise (such as gas scattering) causes an enhancement of the diffusion rates.[6] The largest enhancement encountered was a factor 6 for a beam-beam tune shift of 0.06 in proximity to a fourth-order resonance. This is well above the tune shift we can expect, as shown in section 10.4.

We have investigated beam-beam interactions with the beam centers offset or oscillating around each other.[7] This could be caused by either a dipole oscillation or a finite dispersion in the collision region coupled to the momentum oscillation. We have not found any effect of significance.

Of more serious concern are the effects created by betatron tune oscillations. If proper care is not taken, it is possible to cause an emittance growth of a factor two in a few minutes.[8] Fortunately, we have found a threshold and the growth can be tuned out by either adjusting the betatron tunes or by improving the power-supply regulation to better than 10^{-4} and flattening the lattice chromaticity.

This latter effect has been clearly observed in the CERN Collider[17]. But, once a better tune of the machine was available, this effect, even for a tune-shift of 0.004, did not cause a significant effect compared with intrabeam scattering[18].

We have also investigated multiple crossings per revolution, 2 or 6 instead of 1, with similar results. The emittance growth due to the beam-beam effect has been modeled by the equation

$$\frac{1}{\varepsilon_0}\frac{d\varepsilon}{dt} = \frac{\sqrt{n_c}}{\tau_{BB}}\;\frac{N/N_0}{\varepsilon/\varepsilon_0} \qquad (10.5)$$

with n_c the number of crossings and τ_{BB} = 100 hours for $\Delta\nu$ = 0.0017, which fits observations in the CERN SPS.[18]

10.5.4 Total Cross Section. As the two bunched beams interact with each other, there is a continuous loss of luminosity due to particles being removed by single events or as the beam size grows under the effect of multiple scattering. The total cross section is built from four pieces,[19] diagramaticlly shown in Fig. 10-3. If σ is the cross section in mb and p the momentum in GeV, the following equations apply, where x' is the transverse momentum transfer normalized to the longitudinal momentum:

for elastic:

$$\frac{d\sigma}{dx'^2} = 18p^2\sigma\, e^{-18p^2x'^2} \qquad (10.6)$$

for single-diffraction and a given beam particle:

$$\frac{d\sigma_{SD}}{d\delta\, dx'^2} = \frac{6.1p^2}{\delta}\, e^{-9p^2x'^2} \qquad (10.7)$$

for double-diffraction

$$\frac{d\sigma_{DD}}{d\delta\, dx'^2} = \frac{5.3p^2}{\delta}\, e^{-9p^2x'^2} \qquad (10.8)$$

and for the core:

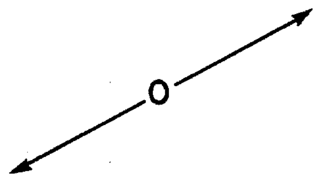
$$\sigma_{CORE} = 26.3 \text{ mb} . \qquad (10.9)$$

10.5.5 Luminosity Lifetime[13,14]. All the effects discussed before have been taken into account to estimate the luminosity lifetime. In Fig. 10-4 we show the variation of the emittance and the momentum spread with time. The luminosity variation with time is shown in Fig.10-5 for an initial value of 10^{30}cm^{-2}sec^{-1}, which corresponds to the case discussed in the previous sections. The luminosity lifetime is about 20 hours. As we have

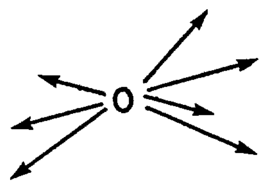
CROSS SECTIONS

THE TOTAL CROSS–SECTION IS BUILT FROM FOUR PIECES:

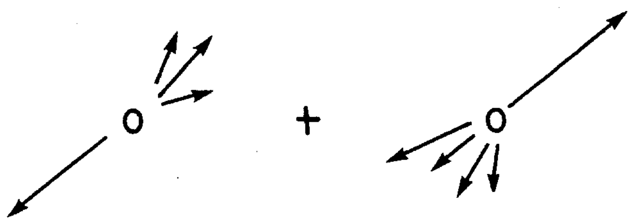
ELASTIC



CORE



SINGLE DIFFRACTIVE



DOUBLE DIFFRACTIVE

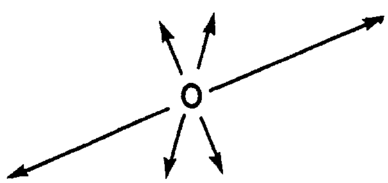
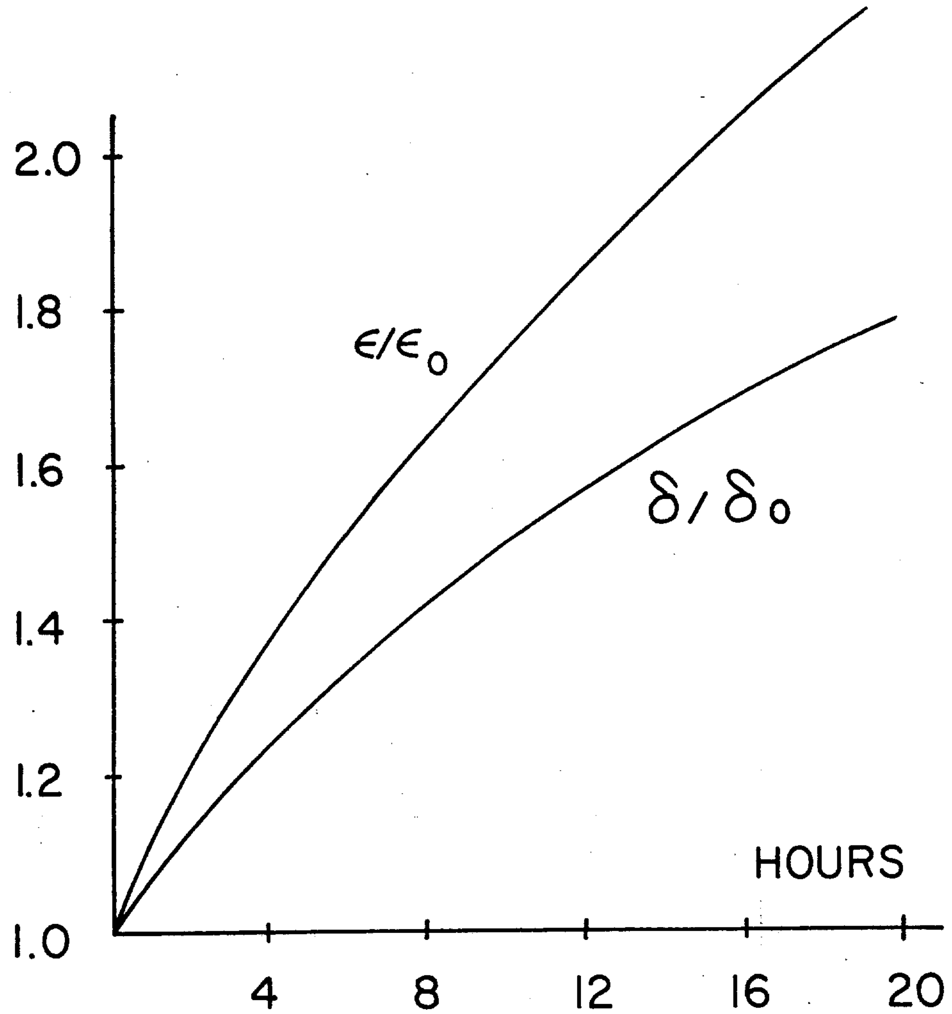


Figure 10-3

STANDARD

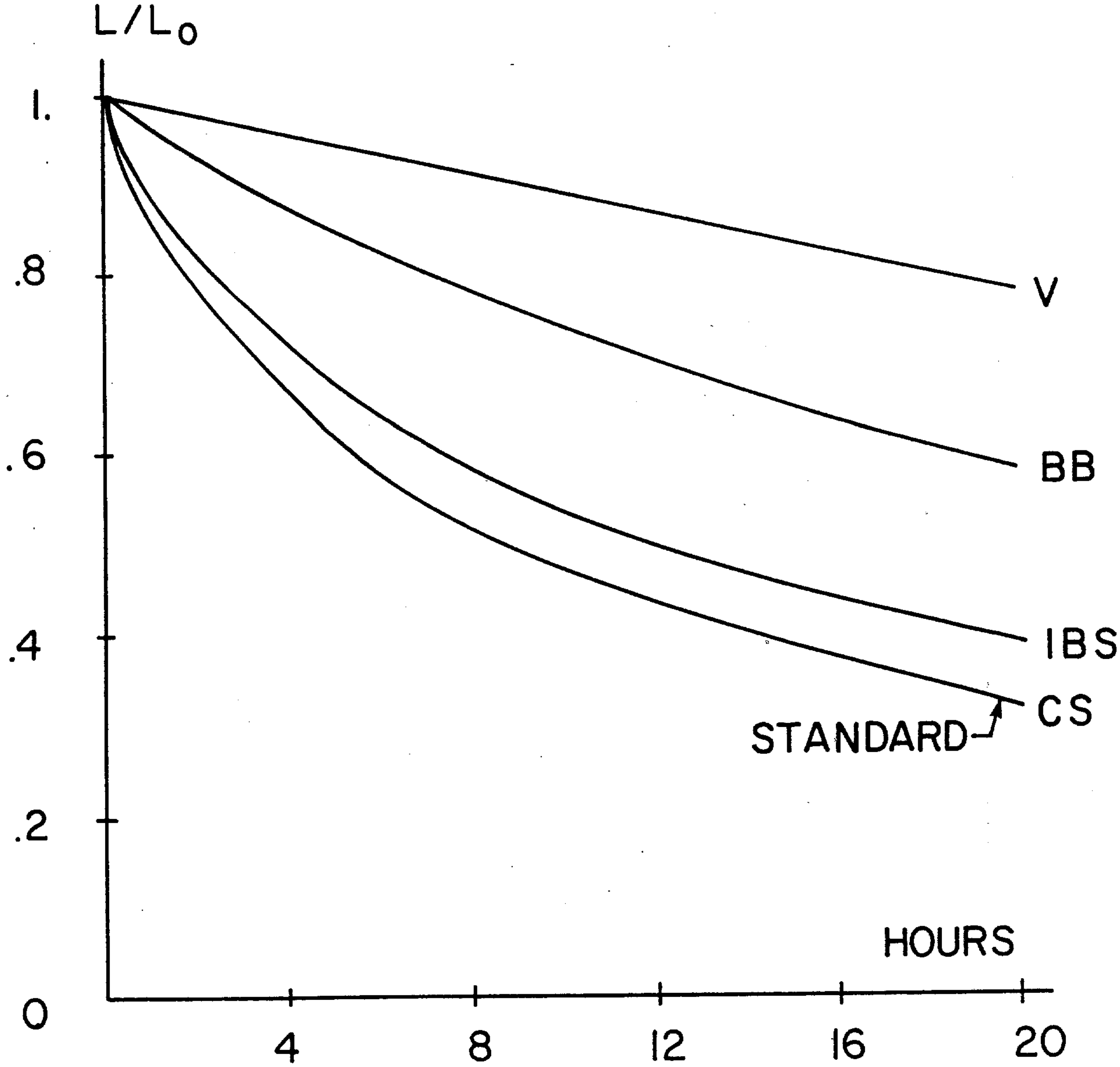


$$\frac{1}{\epsilon_0}\frac{d\epsilon}{dt} \sim \frac{1}{9.2h}$$

FROM INITIAL SLOPES

$$\frac{1}{\delta_0}\frac{d\delta}{dt} \sim \frac{1}{13.6h}$$

Figure 10-4



V	VACUUM EFFECTS ONLY.
BB	BEAM-BEAM EFFECTS ADDED TO ABOVE.
IBS	INTRA BEAM SCATTERING ADDED TO ABOVE.
CS	CROSS-SECTIONS ADDED TO ABOVE.

Figure 10-5

seen, each beam is made of three bunches, each with 6×10^{10} particles and a longitudinal area of 3 eV-sec. The beam intensities, both average and peak, are very modest. A considerable effort has been made in the recent past to estimate the longitudinal stability of each beam for both individual bunch and bunch-to-bunch modes.[9,10] The beam-wall impedance expected in the Tevatron was estimated[11] to be $|Z_n|/n \sim 1$ ohm. In Fig. 10-7 we give an estimate of the longitudinal-coupling impedance verses the harmonic number. Every contribution from the vacuum-chamber equipment has been included except for the major rf system. Because of the small longitudinal beam density, we believe the beams are quite stable. Moreover, a longitudinal damper operating on each individual bunch is planned.

Fewer calculations have been done for the case of transverse instabilities. But again we do not foresee major problems. In addition, a transverse active damper has been proposed[12] that will be fast enough to operate on individual bunches in both radial and vertical modes of oscillation.

10.6 Collider Filling Strategy.[13,14]

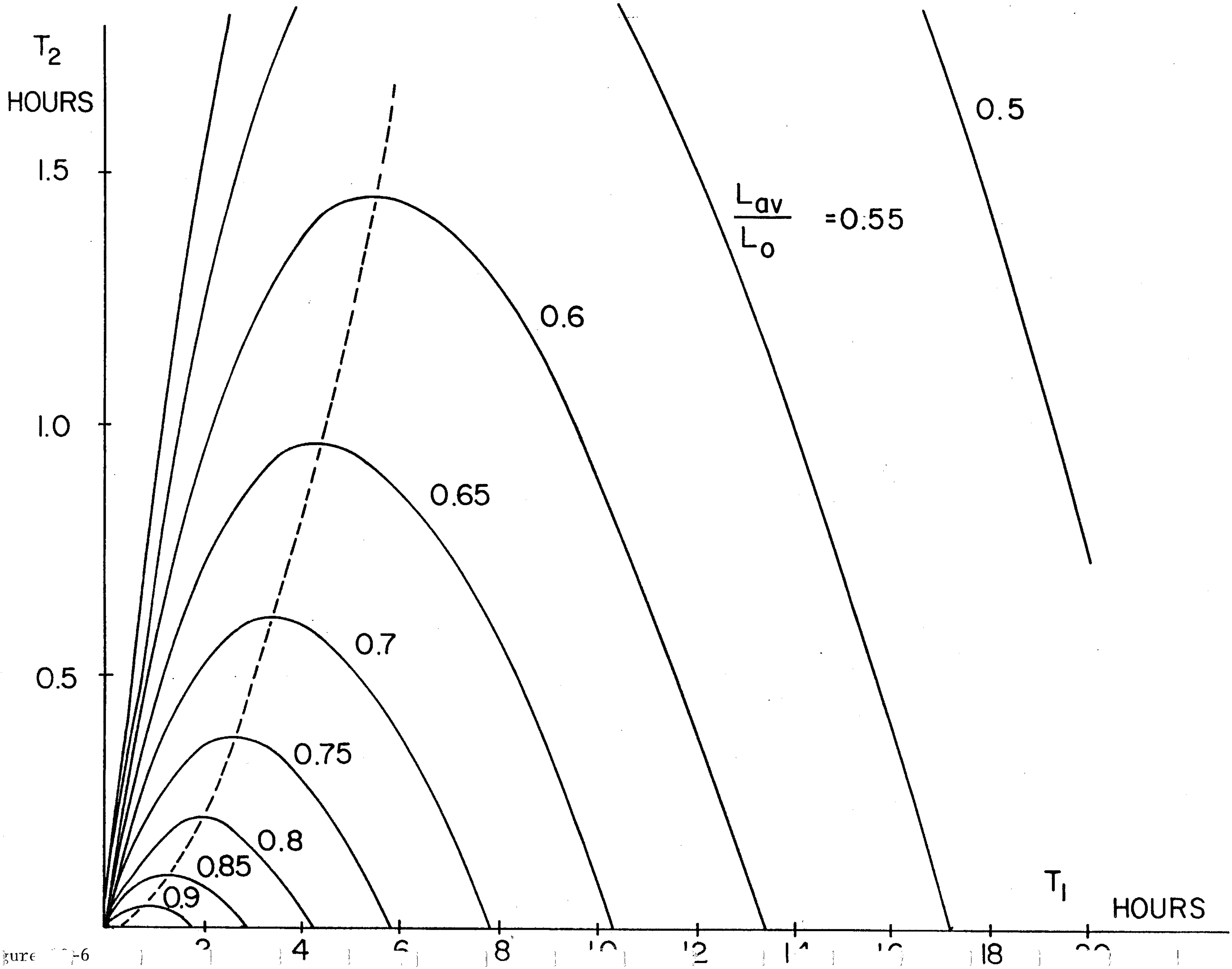
Because of the luminosity deterioration as a function of time, the refilling of the Tevatron I Collider with fresh beams of protons and antiprotons can be thought of as follows.

Let T_1 be the running time, that is, the period when colliding beam experiments are usefully done, and let T_2 be the period without beams in the storage ring. One can also include in T_2 the average failure time. The useful average luminosity L_{av} normalized to the initial luminosity L_0 is

$$\frac{L_{av}}{L_0} = \frac{1}{T_1+T_2}\int_0^{T_1} \frac{L(t)}{L_0}\, dt\,, \qquad (10.10)$$

where L(t) is the actual luminosity as a function of time as given in Fig. 10-5.

For a given ratio L_{av}/L_0 one can derive from Eq. (10.10) the pause T_2 as a function of the running period T_1. This is shown in Fig. 10-6. For instance, with the present accumulation scheme, except at the first filling, one can produce enough antiprotons for the goal luminosity of $10^{30}\text{cm}^{-2}\text{sec}^{-1}$ in less than 2 hours. It is therefore conceivable to run for a period of 2 hours and rest, for refilling and other interruptions, for 6 minutes. This would correspond to an average luminosity of 80% of the initial value. To do better than this would require a larger production of antiprotons.



T_2
HOURS
1.5
1.0
0.5
0.5
$\frac{L_{av}}{L_o}$ =0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
4
8
12
18
T_1
HOURS

gure -6

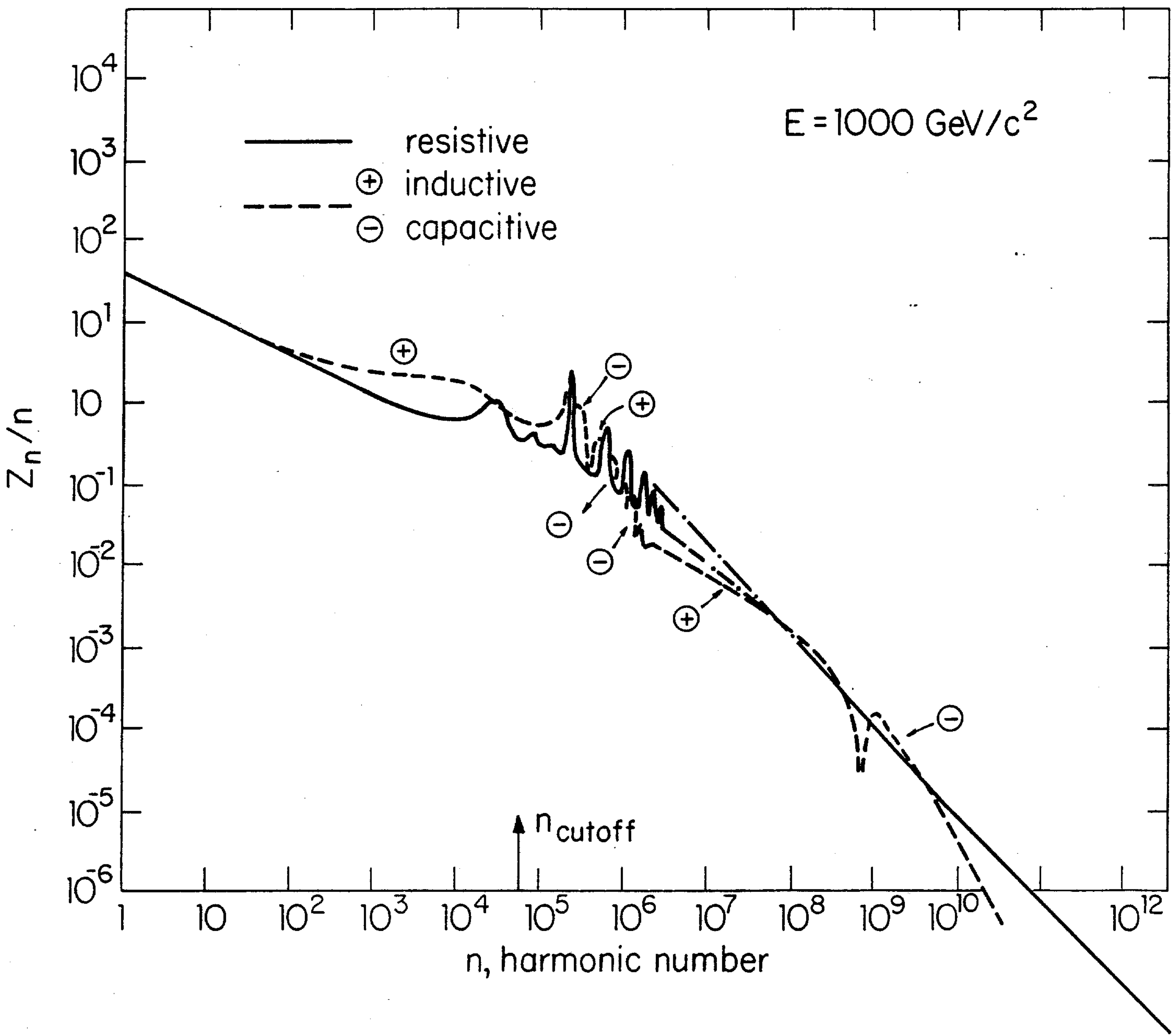

E = 1000 GeV/c²
resistive
⊕ inductive
⊖ capacitive
Z_n/n
n_cutoff
n, harmonic number
10⁴
10³
10²
10¹
10
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
1
10
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹²

Figure 10-7

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