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AN e-p FACILITY IN THE SPS

by

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ABSTRACT

A 25 GeV electron (or positron) storage ring installed in the SPS tunnel above the proton synchrotron would provide e-p collisions with a luminosity in the range of 10^{31} to 10^{32} cm⁻²s⁻¹. The collisions would normally take place at an intermediate plateau of the SPS-cycle up to 270 GeV, and could be followed by acceleration and extraction of the proton beam for fixed target experiments. The feasibility of such a facility is demonstrated and the essential features presented.

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1. INTRODUCTION

Collisions of e^-p will provide new insights for high energy physics. To this end, such facilities have been considered by nearly all High Energy Physics laboratories^{1,2)}. The table below lists the energies of the beams and the available centre-of-mass energies of these proposed facilities.

TABLE 1
Comparison of facilities

		E_e (GeV)	E_p (GeV)	E_{CM} (GeV)
SLAC	PEP	15	200	110
Rutherford	EPIC	14	100	75
DESY	PETRA	15	120	85
BNL	ISABELLE	15	200	110
CERN	LSR	20	400	180
FNAL		40	1000	400
This report	{ nominal	25	270	165
	{ maximum	30	400	220

Colliding the 400 GeV SPS proton beam, circulating in a by-pass, with an electron beam of 5 GeV, stored in a separate small ring, was considered previously³⁾. The scheme advanced here is to house the e-ring in the SPS-tunnel above the synchrotron, thus permitting a higher energy at modest RF power. Furthermore, no by-pass is necessary and it is proposed to collide the two beams during an intermediate plateau at 270 GeV, where the SPS can run in a d.c. mode.

This yields a centre-of-mass energy of at least 165 GeV, a very respectable figure which, as seen from Table 1, would give CERN a leading position, since collisions of 40 GeV electrons with 1000 GeV protons in the doubler at FNAL cannot be expected in the near future. The enormous momentum transfer at these energies would open for CERN the realms where weak interactions dominate over electromagnetic interactions. It would extend with comparable effort the field of research which has been opened up by the 240 GeV muon beams in the SPS physics programme. The available centre-of-mass energy would increase by a factor 7.5 and the maximum momentum transfer by a factor 50.

Figure 1 shows a cross-section of the SPS tunnel with the electron storage ring positioned 75 cm above the beam orbit of the synchrotron. The electron ring has virtually the same geometry and lattice as the synchrotron except that the

elements are much smaller, need less power and probably no water-cooling at all. The lifetime of the electrons is many hours.

The collisions take place in the only free long straight section, LSS5, of the synchrotron where the electron beam is brought down into the plane of the protons to cross them horizontally with a very small angle. Near the interaction point, the tunnel has the normal cross-section, which limits the transverse dimensions of the detector system. However, with the moving centre-of-mass, a large fraction of the interesting physics lies within fairly small angles with respect to the proton beam, and could be studied with detectors of relatively small lateral extension²⁾.

The electron ring consists only of conventional elements which could be built rather quickly. Part of the installation could take place during normal shutdowns of the SPS, thus minimizing interference with SPS operation.

The proton ring does not need any modification except for a few elements in the interaction region. The long straight section LSS5 would be the natural choice, but LSS4 might also become available as a second experimental zone if one of the fast ejection systems were used as a beam dump.

The SPS cycle has to be extended somewhat to accommodate a plateau at 270 GeV where the two beams will be brought together. The SPS beam will contain 2×10^{13} protons grouped into 60 equidistant bunches. These high intensity bunches cannot be accelerated as quickly as normal bunches, which leads to an additional lengthening of the cycle by a few seconds. Figure 2 shows the example of an SPS cycle which provides a 50 % duty factor for e-p experiments. Fixed-target experiments using the extracted beams will still get, on average, 30 % of the protons of normal operation; in this comparison, it was assumed that normal operation will provide them with 2×10^{13} protons in ~ 6.8 s. Thus, this colliding-beam facility does not seriously impede physics in the North and West halls, nor does it require a complete halt over extended periods. These are important considerations which are properly accommodated by this mode of operation.

A particularly attractive feature of this scheme is that these high-intensity proton bunches need only live over one, somewhat extended, SPS cycle and not over many hours, thus relaxing long-term stability requirements for intense, bunched proton beams.

This report deals mainly with operation at $25 \times 270 \text{ GeV}^2$, since 270 GeV is the highest energy at which the SPS can run in d.c. mode. However, without any changes in the installation, the facility will operate at reduced average luminosity up to $30 \times 400 \text{ GeV}^2$, yielding a maximum centre-of-mass energy of 220 GeV.

2. THE INTERACTION REGION

Since it is important not to exclude the possibility of working with either electrons or positrons, elements common to the electron and proton beam must be avoided. This excludes schemes with a zero crossing angle. On the other hand, the crossing angle should be very small to get the maximum luminosity. The angle is determined by the required beam separation at the entrance of the septum magnet, which bends the electrons away from the protons to get enough separation at the first focusing elements.

Since the horizontal emittance is larger than the vertical in both rings, the finite crossing angle does less harm if the crossing occurs in the horizontal plane. The installation of the elements is also simpler in this case.

Figure 3 shows a possible layout for a crossing angle of 5 mrad. The geometry is such that the vertical and horizontal ring separation can be accommodated within the normal cross-section of the SPS tunnel. After the detector, the beams are separated horizontally by septum magnets; the first of the septa, in two sections, has a stepped field increasing from ~ 0.1 T to 0.2 T to soften the synchrotron radiation directed towards the detector and onto the counter-rotating protons. The first focusing elements are special septum quadrupoles which fit between the two beams. Figure 4 shows the sketch of such a quadrupole.

Figures 5 and 6 give the layout of the quadrupoles in the insertion and the structure functions along the insertion. It should be stressed that the p-insertion is fully matched to the SPS structure, i.e. the rest of the SPS is unperturbed to first order. The e-insertion is also matched into the electron ring except for a small residual vertical dispersion (~ 10 cm) which would be removed in a more detailed study.

There is a strong interest in rotating the transverse radiative polarization of the electrons into the longitudinal direction at the crossing point, in order to facilitate the separation of weak and electromagnetic interaction phenomena. The electron beam geometry on one side of the crossing point is fully compatible with this requirement; on the other side, some modifications to the bending geometry, not yet studied in detail, will be required⁴⁾.

The following table gives the principal parameters of the insertions.

TABLE 2
Parameters of insertion

	Proton ring	Electron ring
β_x^*	6.5 m	1.5 m
β_x^*	0.6 m	0.3 m
$\alpha_{px}^* = \alpha_{py}^*$	0	0
Crossing angle 2ϕ	5 mrad	
Free length for detector	± 5 m	
Max. quad. gradient	21 T/m (400 GeV)	13 T/m (30 GeV)
Half-aperture for beam	$5\sigma_{xp} = 2.5$ mm	$10\sigma_{xe} = 15$ mm
Septum + closed orbit distortions	12.5 mm	
		at entrance of first septum

3. GENERAL PARAMETERS

Given the energies, the proton emittances and total number of protons, and taking into account constraints such as crossing angle, β -values at the crossings, maximum tune shifts and bunch length, one obtains the rest of the parameters after some iteration. The formulae for luminosity and tune shift are shown in the Appendix.

TABLE 3
Performance

			Protons	Electrons
Luminosity (peak) L	cm ⁻² s ⁻¹		0.5 × 10 ³²	
Energy E	GeV		270	25
Total number of particles	N		2 × 10 ¹³ ≡ 150 mA	1.5 × 10 ¹³ ≡ 100 mA
Number of equidistant bunches k _b			60	60
Circumference 2πR	m		2π 1100 m	2π 1100.013 m
Emittances	$\left\{ \begin{array}{l} E_x/\pi \\ E_y/\pi \end{array} \right.$	radm	20 × 10 ⁻⁶ /(βγ)	7.7 × 10 ⁻⁸
		radm	10 × 10 ⁻⁶ /(βγ)	0.35 × 10 ⁻⁸
Beam size at	$\left\{ \begin{array}{l} \sigma_x^* \\ \sigma_y^* \end{array} \right.$	mm	0.34	0.34
crossing point		mm	0.072	0.032
Bunch length	σ _s	mm	300	33
Energy spread	σ _E /E		0.8 × 10 ⁻³	0.8 × 10 ⁻³
Beam-beam	$\left\{ \begin{array}{l} \Delta Q_x \\ \Delta Q_y \end{array} \right.$		0.01	0.006
tune shifts			0.01	0.014
RF	MHz		200	200
Polarization time	h		---	1.7

For historical reasons, different definitions of emittance are in use:

$$E_x/\pi = 4\sigma_x^2/\beta_x \quad \text{for protons}$$

$$E_x/\pi = \sigma_x^2/\beta_x \quad \text{for electrons ,}$$

where σ stands for the r.m.s. beam size.

The energy spread and bunch length of the protons, quoted above, are derived from the final bunch area which is larger than at injection for stability reasons. Normally, it is assumed that the beam-beam tune shift suffered by the protons ΔQ_p should not exceed 0.005. Here, this permissible tune shift was increased to 0.01 in view of the fact that the protons have to sustain it for only ~ 10 s and not for hours as in a storage ring. During acceleration, the two beams will be separated vertically by a local closed orbit bump to avoid excessive proton tune shifts at low energies.

The electron tune shifts are safely below the generally accepted maximum of 0.05, i.e. the number of protons could be increased by a factor 3 once one has learned to handle such an intensity. The luminosity would then increase by the same factor.

4. THE ELECTRON RING

The lattice of the electron ring is very similar to that of the SPS. Its median plane is 0.75 m above the SPS median plane. In order to synchronize the electron bunches with the proton bunches, the average radius of the electron ring is about 13 mm larger than the SPS radius and the protons must be displaced 10 mm inwards at 145 GeV and 10 mm outwards at 400 GeV, in terms of average radius. The electron beam must remain centred to maintain radiation damping for all oscillation modes.

In some of the long straight sections, the space above the SPS is obstructed by special equipment such as RF feeders, etc. However, moving the e-ring outwards in these straight sections by 0.6 m clears all obstructions. The minimum distance from the e-orbit to the tunnel wall is still 0.6 m. The displacement is achieved by moving the two missing dipoles, which are located at the beginning of the long straight section, one cell earlier. The orbit will lengthen by 9.2 mm per displaced straight section which can be compensated easily in the arcs.

Table 4 gives parameters of the electron ring derived from the lattice including the apertures required by the beam in the lattice.

TABLE 4
Parameters of the e-ring at 25 GeV

Circumference	$2R\pi = 2\pi \ 1100.013 \text{ m}$
Bending radius	$\rho = 740 \text{ m}$
Tune	$Q = 28$
Momentum compaction	$\alpha = 1.66 \times 10^{-3}$
Energy loss due to synchr. radiation	$U_o = 49 \text{ MeV/turn}$
Emittances $\left\{ \begin{array}{l} E_x/\pi \\ E_y/\pi \end{array} \right.$	$\sigma_x^2 / \beta_x = 7.7 \times 10^{-8} \text{ m}$ $\sigma_y^2 / \beta_y = 0.35 \times 10^{-8} \text{ m}$
Coupling coefficient	$\kappa = E_y/E_x \cong 0.05$
Bunch length	$\sigma_s = 33 \text{ mm}$
Energy spread	$\sigma_E/E = 0.8 \times 10^{-3}$
Required apertures	D-quadrupole $w = \pm 12 \text{ mm} \quad h = \pm 25 \text{ mm}$
without closed	F-quadrupole $w = \pm 40 \text{ mm} \quad h = \pm 9 \text{ mm}$
orbit distortions	Bending magnet $w = \pm 40 \text{ mm} \quad h = \pm 25 \text{ mm}$
Pipe dimensions	$w = \pm 45 \text{ mm} \quad h = \pm 30 \text{ mm}$

The apertures were calculated according to

$$w = \pm 10 \left[\frac{\sigma_x^2}{\beta_x} \beta_x + \left(\frac{\sigma_E}{E} \alpha_{px} \right)^2 \right]^{\frac{1}{2}}$$

$$h = \pm 10 \left[\frac{\sigma_x^2}{\beta_x} \beta_y \right]^{\frac{1}{2}} .$$

Adding 1 cm for closed orbit distortions, the aperture required by the beam yields the aperture of the beam pipe; its dimensions should not vary around the ring in order to reduce parasitic power losses.

Figure 7 shows the cross-section of a quadrupole, and Fig. 8 the cross-section of a dipole magnet. Table 5 gives some of the magnet parameters.

These conventional magnets, which are rather small and not very heavy, would be suspended from the ceiling to avoid interference with the survey of the SPS elements and to allow independent access to the components of the two rings. The dissipated power is very moderate and air-cooling would be sufficient with a modest rise of temperature ΔT above ambient. Besides avoiding extra cost and complexity of water-cooled magnets (hollow conductors and insulators), the magnet system could be installed without the need to break into the existing water circuits.

TABLE 5
Magnet parameters for the e-ring

		Quadrupole	Dipole
Length	m	3.17	6.25
Overall width	mm	300	280
Overall height	mm	300	140
Bore $\emptyset$ / gap height	mm	78	64
Field at pole (25 GeV)	T	0.047	0.113
Field at pole (5 GeV)	T	0.01	0.023
Weight per magnet	t	2	2
Peak excitation current	A	1440	1440
Number of turns / magnet		2	4
Total ring voltage	V	30	572
Total power dissipation	kW	42	823
ΔT above ambient	$^{\circ}C$	5	20
Power supply voltage	V	750	
Power supply current	A	1440	

To avoid costly bus-bar systems, the dipoles and quadrupoles are designed to be excited in series at the nominal machine tune. A small number of trimming quadrupoles in the region of the long straight sections could be used to provide tune variations. The total main magnet system could then be powered in series by a single supply of the same output capability as one of the present SPS quadrupole power supplies. With this arrangement, the maximum voltage to ground would never exceed 400 V.

The RF-system is assumed to operate at a frequency of 200 MHz, the same frequency as in the SPS, where CERN has plenty of expertise. However, other frequencies could be considered if there were valid reasons. In order to minimize losses in the cavity, the RF-structure should be long, but should fit into one long straight section. Hence, we assume a total length of about 100 m. For the shunt impedance, we take 15 M Ω /m, a value obtained by scaling from PEP and SPEAR.

Table 6 summarizes the RF-parameters.

It is assumed that the RF-system of the electron ring is installed in LSS3 together with the already existing 200 MHz system for the protons. The available space for power feeder lines in the pits is restricted. While it seems possible to accommodate the feeder lines for 25 GeV operation, the space available for feeding a 30 GeV RF-system seems to be very marginal.

TABLE 6
RF-parameters at 25 GeV (30 GeV)

f_{RF}	200		MHz	RF-frequency
I_e	100		mA	electron current
q	1.31	(1.28)		overvoltage factor for 10 h quantum lifetime
U	61	(124)	MV	RF-peak voltage
Q_s	0.044	(0.056)		synchrotron tune
f_s	1.9	(2.4)	kHz	synchrotron frequency
P_s	4.9	(10)	MW	power loss into syn- chrotron radiation
P_c	2.5	(10)	MW	power dissipation into fundamental mode of cavity
Z	15		M Ω /m	shunt impedance
l	100		m	cavity length
σ_t	0.1		ns	bunch length
τ_E	12		ms	damping time of synchro- tron oscillations

The injection into the e-ring is below nominal energy and a fast cycling electron synchrotron is needed. In order to demonstrate feasibility, we assume that the electron injector has the same features as NINA, the electron synchrotron in Daresbury, U.K., with a maximum energy of 5 GeV and a cycling rate of 53 Hz. If its radius is increased by 4.5 %, we obtain a convenient revolution-frequency ratio:

$$f_{rev} (NINA) = 30 f_{rev} (e SPS) .$$

A concomitant increase of NINA's radio frequency by 1.8 % yields

$$f_{RF} (NINA) = 2 f_{RF} (e SPS) .$$

Hence, two equidistant bunches in NINA are just in the right place to load two of the 60 buckets in the e-ring which have to be filled. Since one NINA bunch carries 3.8×10^8 electrons, it takes about 7 min to fill all the 60 buckets provided one has installed a wiggler magnet⁵⁾ in the electron ring to reduce the betatron damping time to 0.6 s. Such a wiggler magnet requires a field of 1.7 T and has a length of 7.5 m.

To get a sufficient number of positrons in a limited number of bunches is a common problem with high energy e^+e^- machines and several schemes have been proposed to minimize the positron filling time. The application of these methods to the present proposal has not yet been studied in detail.

The lifetime of the electron beam is dominated by bremsstrahlung on the residual gas. Distributed ion pumps keep the pressure at 10^{-9} Torr at 25 GeV which yields a lifetime of 50 h. At 12 GeV, their efficiency is diminished due to the lower field and the pressure is around 10^{-8} Torr which reduces the lifetime to 5 h. At 5 GeV, the injection energy, the distributed pumping has ceased altogether; the conductance of the pipe in the magnets will then determine the pressure, expected to be around 10^{-7} Torr. This reduces the lifetime to 30 min, sufficient, however, for injection.

The lumped pumps at the ends of the magnets must each have a pumping speed of at least 20 l/s. One could also consider connecting the system to the manifolds of the SPS.

5. BEAM HANDLING IN THE PS AND THE SPS

The SPS is supposed to be filled by three PS-pulses each consisting of 20 bunches having the right size to fit into one SPS-bucket at the injection energy of 10 GeV. Each PS-pulse will consist of $\sim 0.7 \times 10^{13}$ protons, which is comfortably within the present performance of the PS.

Before ejection from the PS can take place, the bunches have to be shortened to make them fit into the 5 ns long SPS buckets. The principle of the method is shown in Fig. 9. After a jump of the unstable fixed point to the centre of the bunch, the latter expands along one branch of the separatrix; once the required shape has developed, the bucket is again centred on the bunch which will have rotated into the correct position for ejection after $3/8$ of a phase oscillation period.

This approach was tried out recently in the PS, in particular to find out whether the procedure would suffer from instabilities. The results were positive and a bunch length of less than 5 ns was achieved⁶⁾.

Ejection from the PS is accomplished by the full-aperture kicker of the PS (FAK) whose 12 modules are grouped to form four independent kickers. Each kicker is operated by a system which reduces its deadtime to ~ 20 μ s. Such a system has already been designed and tested in the PS⁷⁾. Assuming we number the bunches, then the following ejection sequence will put the 20 bunches into the proper buckets of the SPS:

After every ejection of a batch of four bunches, the SPS-beam makes one revolution ($21 \mu\text{s}$) to give the kickers time to recover. The total ejection time T_e for 20 bunches becomes, including these four recovery pauses

$$T_e = \frac{1089}{20} T_0 \cong 114 \mu\text{s} ,$$

where T_0 is the revolution time in the PS. After three PS-cycles, 60 equidistant bunches are obtained in the SPS.

The injection kicker in the SPS must have a rise and fall time of less than 350 ns. The present kicker does not fulfil this requirement, but the new kicker proposed in connection with the multi-pulsing of the PS will have a characteristic time of $\leq 120 \text{ ns}$ ⁸⁾.

Since the bunch area is 0.01 rad at an intensity of 0.7×10^{13} protons in the PS, the acceptance of the SPS RF-system is sufficient. However, the initial acceleration must be slow to avoid spill-out of the particles as during normal operation. The bunch area is given in units of $\Delta\beta\gamma$, $\Delta\phi_{\text{RF}}$.

The beam loading becomes important during acceleration and will reduce the effective RF-voltage which can lead to bucket reduction and, as a consequence, to particle loss. Beam loading with only 60 buckets filled will be substantially different from the case where all buckets are filled due to the low stored energy of the accelerating tanks. Each bunch enters the cavities before they could be refilled with RF-power after the passage of the preceding bunch; nevertheless, it seems that enough stored energy could be made available provided the losses around the ring into higher modes do not turn out to be prohibitive. This problem is already under investigation since the beam loading will determine the maximum acceleration rate in general. If the available RF-power were to be increased in order to cope with the higher proton intensity for normal operation, the beam loading problem for this new mode of operation would be alleviated and we may assume that the RF-system would provide an effective voltage of 5 MV.

An important factor is the longitudinal stability of these high-intensity bunches. Current theory indicates that the bunches will grow above transition, driven by the longitudinal instability. It is assumed that the bunch area will grow from 0.21 rad to 1.2 rad* at 270 GeV, stabilizing itself in this way. However, an RF-voltage of 5 MV is enough to create a bucket which contains the bunch at all energies provided that $\sin \phi_s$ does not exceed 0.4. These low values of

* Note that the area of a single bunch in this definition is dependent on RF-frequency. Hence, a bunch area of 0.01 rad in the PS becomes 0.21 rad in the SPS.

$\sin \phi_s$ will also avoid an excessive reduction of the RF-voltage under strong beam loading. The low $\sin \phi_s$ will in turn somewhat lengthen the cycle. However, this increase is estimated to be smaller than 3 s, not very dramatic for a cycle which is about 20 s long. This increase in acceleration time has been taken into account in the cycle sketched in Fig. 2.

At transition, special measures are indicated to prevent an excessive energy spread of the bunches. This problem certainly needs further study, the more so since it is common to all operational modes of the SPS which require bunches of high intensity.

Single bunch, transverse instabilities, which are equally dangerous, are expected to be suppressed by positive chromaticity and/or octupoles as is done in the PS and SPEAR.

Multi-bunch instabilities will be weak due to the long distance between the bunches and due to the fact that all high Q-resonators are damped in the SPS, which avoids cross-talk between the bunches. The remaining effect can be easily cured by a feedback system.

In general, one can say that machine experimentation in the SPS and the desirable measures for increasing its performance in normal operation will also be beneficial to its use in colliding-beam modes.

6. PERFORMANCE AT OTHER ENERGIES

The emittances of the electron and proton beams depend on energy. If this natural variation is accepted, then the beam sizes become mismatched leading to a loss in luminosity. If a wiggler system⁹⁾ or variable tune¹⁰⁾ is used in the electron ring such that the performance is optimized at all energies, a considerable improvement is possible as shown in Figs. 10 and 11. These figures indicate that to reach centre-of-mass energies below the nominal value, it is better to reduce the electron energy, while to increase the centre-of-mass energy, it is better to increase the proton energy. The luminosity variation has been calculated ignoring the small crossing angle which may slightly alter the behaviour without changing the fundamental features. It has been assumed that the number of electrons is limited by the available RF-power (7.4 MW) above 25 GeV. Table 7 gives the parameters and peak luminosity for the nominal and a few selected cases where natural electron beam size has been used. If more RF-power were installed, it would be possible to maintain constant luminosity up to higher electron energies.

TABLE 7
Performance at different energies without wiggler magnets

E_p (GeV)	E_e (GeV)	E_{CM} (GeV)	σ_{xp} (mm)	σ_{xe} (mm)	N_e	L (peak) ($\text{cm}^{-2}\text{s}^{-1}$)
270	25	164	0.34	0.34	1.5×10^{13}	0.5×10^{32}
400	25	200	0.28	0.34	1.5×10^{13}	0.6×10^{32}
270	27.8	173	0.34	0.38	1.0×10^{13}	0.1×10^{32}

7. CONCLUDING REMARKS

An e-p facility with 25 GeV electrons colliding with 270 GeV protons at a peak luminosity of $0.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ appears to be feasible, and offers even higher energies at reduced luminosities. The electron ring would be housed in the SPS tunnel just above the proton synchrotron. The beams would collide in one interaction region during a plateau in the SPS cycle before subsequent acceleration or extraction of the beam. Thus, the normal physics programme will not be stopped or seriously restricted apart from some reduction in the average number of protons received. The electron ring itself consists of conventional elements, whose technology is well known. It could certainly be installed without serious interference with the SPS physics programme. Finally, one can note that the possibility exists of colliding a bunched proton beam in the e-ring with that in the SPS. Such a scheme would require some geometrical changes in order to preserve bunch synchronism; we have not yet studied such schemes in detail. The e-p facility would provide CERN within a relatively short time with a new probe whose power would open a new field in particle physics beyond the reach of all other existing machines.

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APPENDIX

The luminosity for horizontal crossing is given by¹¹⁾

$$L = \frac{f N_e N_p}{2\pi k_b} \frac{1}{\sqrt{(\sigma_{yp}^2 + \sigma_{ye}^2) [\sigma_{xp}^2 + \sigma_{xe}^2 + (\sigma_{sp}^2 + \sigma_{se}^2) \phi^2]}} . \quad (1)$$

The tune shift suffered by the particles i due to the other beam j can be calculated from the following formulae¹²⁾ which neglect the long-range tune shift:

$$\Delta Q_{xi} = \frac{r_i \beta_{xi}}{\gamma_i} \frac{1}{2\pi k_b} \frac{N_j}{\sqrt{\sigma_{xj}^2 + \sigma_{sj}^2 \phi^2} (\sigma_{yj} + \sqrt{\sigma_{xj}^2 + \sigma_{sj}^2 \phi^2})} , \quad (2)$$

$$\Delta Q_{yi} = \frac{r_i \beta_{yi}}{\gamma_i} \frac{1}{2\pi k_b} \frac{N_j}{\sigma_{yj} (\sigma_{yj} + \sqrt{\sigma_{xj}^2 + \sigma_{sj}^2 \phi^2})} , \quad (3)$$

where:

- N = total number of particles
- k_b = number of bunches
- σ = r.m.s. beam size at crossing point
- 2ϕ = crossing angle
- β = beta-function at crossing point
- $r = e^2/mc^2$
- $\gamma = E/mc^2$.

Fig. 1 Cross-section of the SPS-tunnel at the quadrupoles with the electron ring installed above the proton synchrotron.

Fig. 2 Example of an SPS-cycle with $\sin \phi_s = 0.4$ including a flat top at 270 GeV

FIG. 3 GEOMETRY OF HALF INTERACTION REGION

FIG. 4 FIELD CONFIGURATION IN A SEPTUM QUADRUPOLE

Fig. 5 Structure functions along the matched insertion of the proton ring

Fig. 6 Structure functions along the matched insertion of the electron ring

Fig. 7 Cross section of a quadrupole in the electron ring

Fig. 8 Cross-section of a dipole in the electron ring

before phase jump of RF

after phase jump

end of bunch shaping

bucket re-centred on bunch

after rotation by $135^\circ \equiv$ ejection

Fig. 9 Bunch compression in the PS by bunch shaping on the unstable fixed point

Fig. 10 Luminosity variation for 25 GeV electrons against protons of different energies

Fig. 11. Luminosity variation for 270 GeV protons against electrons of different energies