

RECENT IDEAS ON UPGRADING THE SLAC ACCELERATOR*

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In June 1971, the SLAC accelerator will have completed its first five years of operation. During this period, numerous publications (see for example Ref. 1) have described how the capabilities of the original two-mile machine have been expanded to satisfy the demands of the experimental physicists. The machine has recently achieved records of energy (22.1 GeV), peak beam current (82 mA at a 1.6 μ s pulse length) and average beam power (880 kW). The experimental particle physics program is flourishing in many diverse directions with the accelerator supplying as many as 6 interlaced beams of different characteristics. In spite of these achievements (or perhaps because of them), the demand for major accelerator innovations and improvements is becoming increasingly strong. The purpose of this paper is to summarize some of the recent ideas on this subject. As will be seen below, there are a variety of options. These can be divided into three categories: a) improvements and upgrading of the existing linac, b) energy and duty cycle increases by means of beam storage in a recirculation scheme, and c) various colliding beam devices. The first category includes increasing beam energy by addition of RF power or increasing duty cycle by modifying the modulators; it also includes an RF monochromatizer which could sharpen energy spectrum by a factor of 30. The second category involves a scheme which would increase beam energy by "storing" the electrons in a recirculator until they can be re-injected and reaccelerated by the accelerator a second time. The recirculator might also serve as a beam stretcher capable of substantially increasing the duty cycle. The third category comprises the possibility of colliding the linac beam with the beams stored in the SLAC storage ring (SPEAR) or of colliding the linac beam with itself. Some of these innovations can be viewed as ultimate goals or they may be considered as intermediate steps on the road to a superconducting 100 GeV, 6% duty cycle machine.²

Linac ImprovementsEnergy Increase to 35 GeV (Stage 1-1/2)

When the SLAC accelerator was first turned on, the klystron peak power output was 20 MW and the maximum electron energy that could be obtained was \sim 20 GeV. Recently, it has become possible to build 30 MW klystrons and these will gradually replace the existing 20 MW tubes as they fail. With this program (see SLAC' in Fig. 1), the accelerator will reach an energy of \sim 25 GeV in about 2-1/2 years.

Above and beyond this, provisions were made in the original design (Stage 1) of the SLAC accelerator to make it possible to double (Stage 1-1/2) or quadruple (Stage 2) the number of klystrons and thereby to increase the beam energy by a factor of $\sqrt{2}$ or 2, respectively. Because of the associated high costs, neither of these schemes is being seriously considered at this time. Recently, however, a modified version of Stage 1-1/2 has been thought of which will have a capability of up to 35 GeV and a maximum repetition rate of 180 pps. The reduction in repetition rate from the present 360 pps permits operation with no greater consumption of ac power and cooling water than the existing distribution systems can supply. On this basis, the cost of Stage 1-1/2 has been estimated to be roughly one-half of what it would be at 360 pps.

Two alternate ways of constructing Stage 1-1/2 are illustrated in Fig. 1. In Alternate A, two standard 30 MW

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klystrons are operated in parallel at each of the 245 stations. Their combined power output (60 MW) is transmitted through a hybrid junction into the existing waveguide system to the accelerator. The dc components in the present modulator at each station provide power to two parallel pulse forming networks, one existing and one which must be added. The existing regulating devices (DeQ'ing, etc.) in the modulator and the protection circuits (which sense reflected power and vacuum level in the waveguides, etc.) provide the same services for two tubes as they do at present for one. The second klystron is phased during installation so that there is \sim zero RF power in the fourth arm of the hybrid junction, i.e., the power in the third arm leading to the accelerator is maximized. Henceforth, only occasional manual adjustment of the input phase of the second klystron should be necessary. The automatic phasing system will simultaneously phase both of the paralleled tubes as it now phases the single tube at each station.

In Alternate B, the present 30 MW klystron at each station is replaced by a single \sim 60 MW tube. In this case, all of the devices now serving to monitor, protect or phase the present tube function in the same manner for the higher power tube. A possible advantage of Alternate B over Alternate A is that both the initial cost and the operating cost may be lower. It is too early to draw such a conclusion with any certainty since only a single developmental klystron producing \sim 50 MW now exists. The greatest uncertainty is the average lifetime of such higher power tubes.

Increase in Duty Cycle

Various conventional schemes for increasing the duty cycle of the accelerator have also been considered.¹ In general, these schemes consist of modifying the pulse forming networks of the modulators to either 1) double the repetition rate, or 2) double the RF pulse length. To minimize cost, the peak power would, in each case, be reduced so as to keep the average power constant. The result would then be an increase in beam duty cycle by a factor of 2 (or \sim 2.5 in the case of doubling the RF pulse length) and a decrease in beam energy by a factor of $\sqrt{2}$.

Monochromatizer

The energy spectrum of the beam from the SLAC linear accelerator can be improved by a factor of about 30 by installing a traveling-wave RF separator³ in place of the energy defining slits in the beam switchyard, as shown in Fig. 2. The separator would be phased so that the center phase of the electron bunch is at the point in time when the transverse electric and magnetic fields vanish and the longitudinal electric fields, which are zero on the axis and vary linearly in the horizontal coordinate x , are maximum. The shunt impedance r_x of the separators built at SLAC is

$$r_x = \frac{\left[\frac{\lambda}{2\pi} \frac{\partial E_z}{\partial x} \right]^2}{-\frac{dP}{dz}} = 16 \text{ M}\Omega/\text{meter}$$

where E_z is the axial electric field and P is the power flow in the structure. The dispersion of a 20 GeV beam at the separator would be 27.5 MeV/cm. With two 6-meter separator structures connected in tandem and driven by a single klystron, the attenuation per section would be \sim 0.8 nepers and the power required would be 14.5 MW. The aperture of the

separator is about 4.5 cm which corresponds to an energy acceptance of 0.6%.

An important consequence of adding the monochromatizer is that the horizontal emittance of the beam is greatly increased. The monochromatizer rotates the beam in the x - p_x phase plane; thus, if the bunch is a δ -function in z , the transverse horizontal emittance increases by the same factor that the energy spread is reduced. However, the rf separator also shears the beam in the z - p_x phase plane and thus further increases the transverse horizontal emittance by a factor of 3 to 5. The table below shows the computed rms extent of the beam in each of the 6 dimensions of phase space at the input and output of the monochromatizer with the 12 meter long separator structure represented as four lumped elements spaced 3 meters apart:

	Input	Output
x (cm)	0.100	0.525
θ (mrad)	0.020	0.514
y (cm)	0.200	0.177
ϕ (mrad)	0.020	0.023
z (bunch length)(cm)	0.100	0.384
$\delta p_z/p_z$ (%)	0.200	0.006

waist waist

Energy and Duty Cycle Increases by Beam Recirculation

The energy of the accelerator could be greatly increased if the beam could be passed through the machine a second time. If the beam could be "stored" by recirculation during the entire 2.8 ms interpulse period, the energy could be doubled without any costly change to the RF system. The addition of only a short CW section would be needed to restore the energy lost by synchrotron radiation. A superconducting accelerator section is ideally suited for this purpose. The initial proposal of this scheme is described by Herrmannsfeldt.⁴ The beam stability and some basic parameters are further explored by Rees⁵ and Herrmannsfeldt.⁶ Much work on beam breakup and other instabilities remains to be done.

Consider a beam storage system such as that shown in Fig. 3. Rings of magnets at each end of the accelerator housing turn the beam back into a long straight drift line parallel to the accelerator. The total path length through the storage system is about 7500 meters so that the recirculating period is about 25 microseconds. Thus the beam would be stored for 112 periods.

Rings with dimensions as given in Fig. 3 are shown superimposed on the SLAC site in Fig. 4. At the west (injection) end of the accelerator, such a ring can be located almost on the surface of the existing grade in such a way that the beam can be recirculated through the entire length of the accelerator housing. At the east (research) end, the beam can be brought out through end station B in such a way that the same ring can be used for experiments involving e^-e^- collisions as described later in this paper.

The stored beam could also be used for high duty-cycle experiments at the recirculating energy. The duty cycle would be the ratio of the pulse length (1.5 microseconds) to the recirculating period (25 microseconds) or about 6%. A septum magnet would be used to extract about 1% of the original stored beam on each cycle.

The maximum recirculating current will be limited by the available RF power as the energy of the stored beam increases. At lower recirculating energies, beam breakup will probably be the limiting factor. The final beam energy can be as high as the sum of the recirculating energy and the maximum energy of the full accelerator. By accelerating both a newly injected beam and the recirculating beam at the

same time, it may be possible to retain the present 360 pps repetition rate if beam breakup can be controlled. An off-axis injector would be needed along the accelerator to start a beam which would be recirculated at less than one-half the final energy.

The 30° reverse bends shown in Fig. 3 perform three functions:

- 1) they return the beam to the accelerator tunnel, thus saving the expense of additional tunneling;
- 2) they restore the bunch length which grows by about 3 centimeters per percent of spectrum width in each main bend ring, i.e., they provide the means to obtain any arbitrary setting of the momentum compaction parameter;
- 3) they provide a convenient means of adjusting the total path length to an integral multiple of the RF wavelength.

The drift sections near the 30° bends might be used to install an external damping system such as that proposed by Robinson and Voss.⁷ Without damping, the horizontal component of the transverse phase space can grow well beyond the admittance of the accelerator. Even the equilibrium value with damping is too large to get complete transmission of the initial beam at higher recirculating energies.

The main bend rings are patterned closely after the Cornell alternating gradient electron synchrotron. To build a less disruptive and less costly installation, it appears desirable to reduce the bending radius in the magnets to 85 m from the 100 m used at Cornell which then results in a 91.5 m radius for the actual loops, considering gaps between magnets. The total bending angle around the system is 480°. The table below summarizes the parameters for several different recirculating energies.

Beam Storage System Using a Superconducting Accelerator Section

E_0 (GeV)	U (MeV)	B (kG)	P_{RF} (kW)	σ_e/E_0 (%)	L_{sc} (m)	I/I_0 (%)
15	70	5.9	19	0.13	5	72
20	222	7.9	59	0.18	13	16
25	540	9.8	140	0.22	30	5

E_0	is the recirculating beam energy.
U	is the synchrotron radiation per 480° transit with $r=85$ m.
B	is the corresponding bending magnet field strength.
P_{RF}	is the beam power which must be contributed by the superconducting accelerator sections to a 5 mA recirculating beam.
σ_e/E_0	is the equilibrium value of the energy spectrum due to radiation damping.
L_{sc}	is the length of superconducting sections needed assuming 10 MeV/m gradient. It is assumed that the beam is passed through the structure in both directions. The total provides for the overvoltage needed for synchrotron phase stabilization.
I/I_0	is the fraction of the initial beam which can be transmitted through the accelerator after a storage period of 2.8 ms assuming no damping and the present focusing configuration. Improvements by factors of between 3 and 10 should be achievable by adding damping. Additional focusing along the accelerator may be needed also.

An alternative to the recirculation described here is to simply pass the beam through the accelerator a second time without storing it. In order to pulse the klystrons a second time after only 25 μ s, it would be necessary to divide the stored energy of the modulator system into two parts, one of which is pulsed during each transit of the beam through the accelerator. This can be done with relatively minor modifications to the modulators. The resulting beam energy would be limited to $\sqrt{2}$ times the present energy since the field strength on each pass would be only $1/\sqrt{2}$ times the full field strength.

Colliding-Beam Devices

Collisions Between 20 GeV Linac and SPEAR Beams

A method of achieving very high center-of-mass energies in electron collisions is to collide the 20 GeV linac electron beam against a positron or electron beam circulating in a storage ring.^{8,9} The center-of-mass energy would be 12.6 GeV for a stored-beam energy of 2 GeV and 15.5 GeV for a stored-beam energy of 3 GeV. These figures may be compared with a center-of-mass energy of about 28 GeV which will be available when a 400-GeV NAL proton strikes a stationary proton. In the proposed scheme, the linac beam would be brought to the storage ring (SPEAR) presently under construction at SLAC¹⁰ and caused to collide with the stored beam in one of the long experimental straight sections of the storage ring. At intervals, the linac would provide lower energy (1.5 GeV) particles for refilling the storage ring. The stored positrons or electrons would be concentrated into a single 50-MHz radiofrequency bunch which would be struck by three successive 1 nanosecond bursts of electrons from the linac (separated in time by the storage ring orbital period) during each linac pulse. Thus, all linac electrons would pass through the entire swarm of stored particles. Both beams would be focused down to a very small lateral extent at the collision point. The emittances involved permit dimensions of a small fraction of a millimeter. The length of the interaction region would be about one foot.

The luminosity of this colliding beam system is limited by the periodic but quasi-stochastic disturbance of the stored particles by the linac pulses, which results in a dilation of the stored beam. The luminosity which can be achieved in the face of this phenomenon has been estimated in Ref. 9. For the SLAC storage ring operating at 2 GeV with a stored current of 2 amperes (10^{13} electrons), and for a linac current of 3×10^{11} electrons per pulse (see the next section), a luminosity, $L = 2.4 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$, should be achievable. For example, counting rates of the order of several per hour for the final states $\mu^+\mu^-$, $\pi^+\pi^-$ and e^+e^- should be expected for such a luminosity.

Only minor modifications would be required to use the SLAC storage ring presently under construction in this colliding-beam system. However, a new high-energy, high-power electron beam line would have to be established to bring the linac beam to the storage ring. The luminosity is independent of the linac beam energy and the center-of-mass energy increases as the square root of linac beam energy. Therefore, the stored beam can be thought of as a target containing heavy positrons or electrons.

20 GeV Colliding Beams

The recirculating scheme described above presents an interesting feature: the loop at the downstream (east) end can perhaps be used for a 20 GeV colliding beam facility as suggested by S. S. Brodsky at SLAC. The principle can be understood by referring to Fig. 5. Two regular SLAC bunches [1] and [2] belonging to the same pulse and spaced roughly $1 \mu\text{s}$ (or 1000 ft) apart are accelerated by the linac. When they reach the loop, bunch [1] is deflected along one path and bunch [2] along the other. The interaction region where the collision is to occur is located as shown. The luminosity of the interaction is given by

$$L = \frac{kNn^2}{A}$$

where k is the pulse repetition rate, N is the number of pairs of bunches per pulse, n is the number of electrons/bunch and A is the cross-sectional area of the bunch in the interaction region. Because of the very low reaction cross sections, one must be able to achieve luminosities of the order of $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. Such a result might, for example, be obtained for $k = 360 \text{ pps}$, $N = 1$, $n = 10^{11}$ electrons/bunch and $A = \pi(10^{-3})^2 \text{ cm}^2$. Choosing $N = 1$ makes use of the best presently known

beam breakup limitations (~ 20 nanocoulombs in one short pulse). The $\sim 1 \mu\text{s}$ spacing between bunches is selected to give time for the beam loading and beam breakup fields to decay. The most difficult parameters to attain are n and A . Bunches with 10^{11} electrons are two orders of magnitude above present SLAC injector performance. While there is evidence from LRL-ERA experience with their field emission gun that these currents (50 to 100 amperes) can be generated within the proper phase space [$\sim 0.03 \pi(\text{cm})(\text{MeV}/c)$], it remains to be verified that emittance growth, beam loading and spectrum broadening can be kept within tolerable limits along the accelerator. A preliminary experiment done at SLAC with $\sim 10^9$ electrons/bunch indicates, by linear extrapolation, that beam loading could be of the order of 5 GeV for 10^{11} electrons/bunch. The value of the cross section A requires that the bunches be focused down to a waist of 10 microns in the interaction region. This in turn places very stringent requirements on the linearity and chromaticity of the focusing system. Assuming an interaction region between quadrupoles of 15 meters and incoming bunches with $\sim 1 \text{ cm}$ radii, the maximum deviation from linearity must be of the order of 10^{-4} . These are some of the parameters which must be examined in future feasibility tests.

Conclusions

The gradual up-grading of the SLAC accelerator by replacement of the existing 20 MW klystrons by 30 MW tubes is presently under way and will be completed in the next $\sim 2\text{-}1/2$ years as the present lower power tubes fail. Upon completion, the maximum accelerator energy will be ~ 25 GeV. During approximately the first half of this period, research programs will be continued on superconducting accelerators, high power (~ 60 MW) klystrons, various types of recirculation schemes and colliding beams. The relative success of these programs, the associated costs, and the potential physics payoff from each will determine which of these will lead to definite proposals. At this point it is only possible to give examples of future actions.

If the development of superconducting accelerators leads to the realization of maximum expectations including high gradients, excellent stability, and reasonable costs, there will undoubtedly be a strong interest in pushing for complete conversion of the SLAC accelerator to a 100 GeV, 6% duty cycle, superconducting machine.² In this case the other up-grading alternates will probably be deemphasized or dropped completely from further consideration. A more modest degree of success in the superconducting accelerator work may tend to discourage the idea of a complete superconducting conversion but may be more than adequate to make beam recirculation (energy doubling) feasible. A negative conclusion in the superconducting program or a significant delay in achieving definite results would tend to favor either the single recirculation scheme (which does not employ superconducting sections) or Stage 1-1/2.

The technical and economic feasibilities of operating with two paralleled 30 MW klystrons or a single 60 MW klystron at each station are the principal factors influencing the future of the Stage 1-1/2 concept. These factors can be understood only by operating a substantial number of stations for a significant period of time in these configurations. It may be possible to draw some tentative conclusions in this area during the next 1 to 1-1/2 years. It now seems most realistic to plan Stage 1-1/2 with a large initial complement of stations each having two 30 MW tubes plus a smaller number of stations with 60 MW tubes. The time scale for complete conversion of the machine to one of these configurations would depend upon their relative success.

The decision to construct one of the colliding beam alternates discussed above is to a large degree technically independent of which of the energy upgrading schemes is carried out. Such a decision is expected to depend principally upon the demands and preferences of the high energy particle

physics programs at SLAC, especially with respect to high center-of-mass energies.

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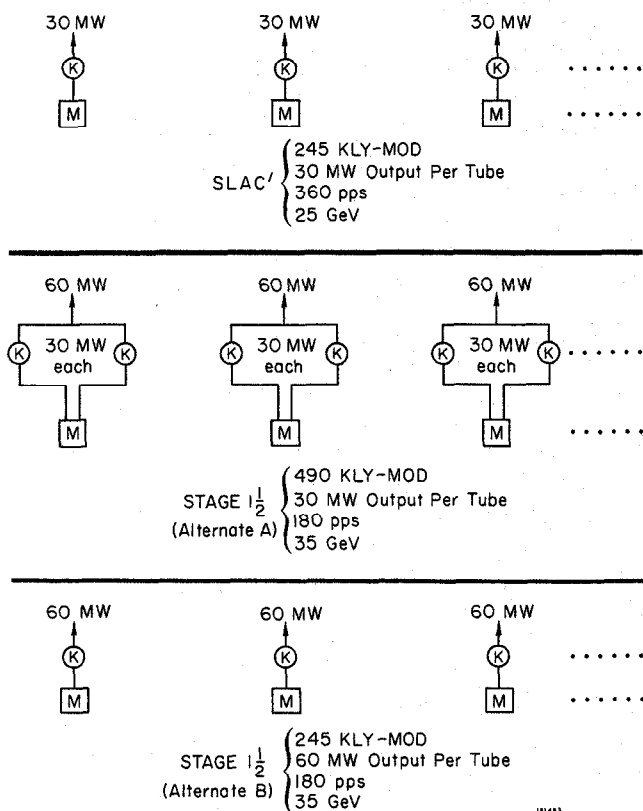


FIG. 1--Klystron-modulator arrangements in SLAC' and Stage 1-1/2.

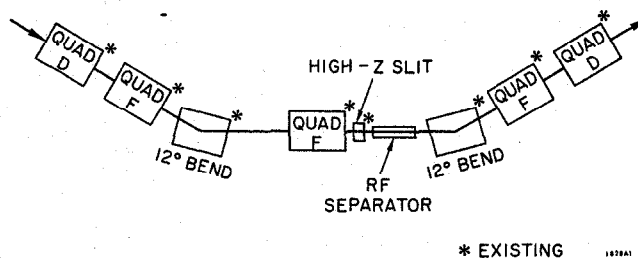


FIG. 2--Monochromatizer consisting of present momentum analyzing beam line with high power slits removed and an RF separator installed in their place.

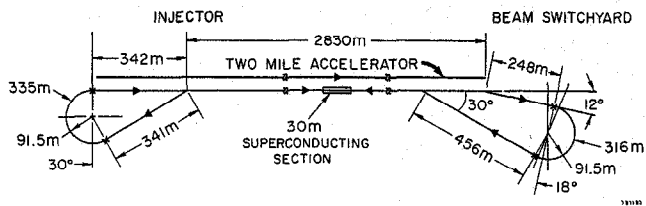


FIG. 3--Proposed layout of a SLAC recirculator. The beam would be stored for 112 cycles before being re-jected into the accelerator for a second acceleration.

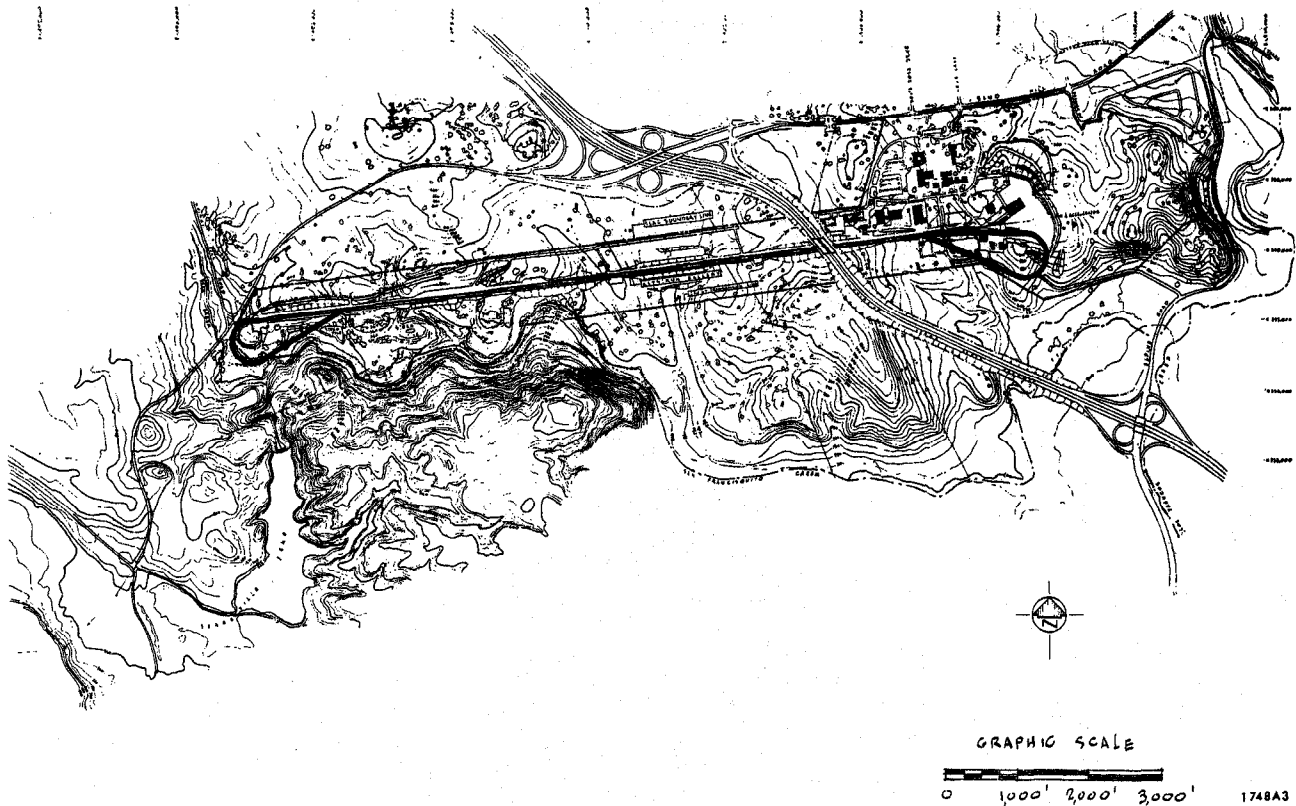


FIG. 4--The layout of Fig. 3 is shown superimposed on the SLAC site. No existing structures are affected and the recirculating beam line can be located very close to the existing grade except where the new line intercepts the existing tunnel.

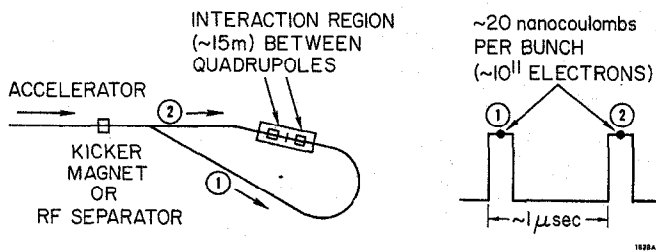


FIG. 5--20 GeV colliding beams.