AN ELECTRON TARGET FOR NAL

T. L. Collins
National Accelerator Laboratory

The electron target is an intense beam of stored electrons with a few GeV energy, sufficient so that when directed in opposition to the main-ring circulating beam there will be reactions with a high center-of-mass energy. The protons are simply the normal accelerator current, not stored, which is of course different from a proton-electron storage ring and accounts for the name. The electron target will intercept very few protons and will run in conjunction with other (or all) experiments of the normal experiment program. Most of the data will be collected during acceleration, from say 100 GeV and up. In the case of fast extraction any flat-top will provide additional data at the higher energies but slow extraction flat-top will be less useful. The electron target will be inserted in one of the main-ring long straight sections, suitably modified to provide a reduced proton beam cross section. Its operation should not be noticeable except for the impact of its results.

The primary result from the first experiments with the electron target will be a study of "scaling" in inelastic proton-electron scattering over a much enlarged momentum range. There is no need for me to emphasize the great general interest in such experiments. One notes the number of proposals currently under development for electron-proton storage ring facilities which hope to do this experiment very well indeed. It is not my intention to impede progress towards such a facility--I hope one is built, and at NAL where protons and space are available--but NAL needs more timely answers to simple questions concerning scaling than these facilities will supply. This is not to say that physics must proceed on some timetable but rather to say that the order of experiments can greatly effect their efficiency. I believe the planning and execution of NAL's experiment program can be greatly influenced by such answers, but only if the answers are forthcoming in the next few years.

The electron target will provide timely answers to questions on scaling. It works because the internal proton beam of the NAL main ring, at 200 - 500 GeV, has a high current density. It can be assembled quickly because an excellent source of multi-GeV electrons, the Cambridge Electron Accelerator, now could be available for re-installation at NAL.

These notes provided some background for the electron target idea. Essentially they are bits and pieces from which one can construct proposals with different degrees of optimism and ambition. Because I am most interested in simple but timely results I will tend to look for the easiest way. I have no doubt that others will want more ambitious programs. The trick is to provide the opportunity for both--a developing program that tries to avoid future roadblock.

Some Experimental Background

I provide a diagram for a particular pair of energies, 4 GeV and 300 GeV. This is but one of many diagrams. It is intended to give a sense of scale, not to define limits to the energies. The diagram refers to inelastic electron scattering and plots Q^2 vs ν where

$$Q^2 = 2M\nu + M^2 - W^2,$$

with W being the invariant mass of the products. The sloping line represents elastic scattering and the vertical line represents completely backward scattered electrons. For a complete description one should refer to the fine report "Particle Physics with Position-Electron-Proton Colliding Beams," April 1972, SLAC-146 or LBL-750.

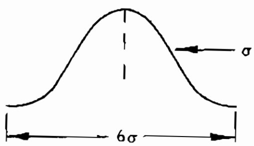
Please concentrate on the lower part of the diagram, say $Q^2 = 1000$. The angles and energies of the scattered electrons are shown and they are friendly. The luminosities are more difficult, however an initial experiment at $L = 10^{30}$ would provide valuable information up to about $Q^2 = 1000$. Obviously a development to 10^{32} would make the whole program very attractive.

Duty Factor

The luminosities above and throughout these notes do not include duty factors. This is not to make the numbers big but simply because the relative value of parts of the main-ring cycle varies with the experiment. For a demonstration of scaling, data between 100 and 500 GeV are all useful and so the lower part of the $Q^2 - \nu$ diagram has a duty factor of 0.5. In addition one must judge the fraction of time that the accelerators are operating, thus 100 days represents at least one year of operation. This is not prohibitive because the experiment is completely parasitic.

Proton Current Density

Measurements on the main-ring beam at higher energies show that it has a cross section in the horizontal (and most probably also in the vertical) which is a very good gaussian out to 3σ. Our electron beam will also have a gaussian distribution so it will be convenient to define the emittance in terms of σ.



Emittance $\epsilon = \sigma^2/\beta$

Thus emittance must be multiplied by π to obtain a phase space area and by 4 or more to obtain the usual emittance which contains at least 90% of the beam (2-3σ).

The current density of a beam is

$$J = \frac{I}{2\pi(\epsilon\beta_x)^{1/2}(\epsilon\beta)_y^{1/2}} \exp\left\{-\frac{1}{2}\left(\frac{x^2}{\epsilon\beta_x} + \frac{y^2}{\epsilon\beta_y}\right)\right\},$$

where I is the total current.

$$J_{max} = \frac{0.16\ I}{(\epsilon\beta)_x^{1/2}\ (\epsilon\beta)_y^{1/2}}.$$

Measurements in the last two weeks with 4×10^{12} proton/pulse at 300 GeV give

$\sigma = 2/3$ mm at $\beta = 79$ m (wire device) or $\epsilon = 0.56 \times 10^{-6}$ cm

$\sigma = 3/2$ mm at 98 m (CERN device) or $\epsilon = 0.57 \times 10^{-6}$ cm

with the vertical slightly smaller. This gives a dc max density $J = 1.4$ A/cm^2 at long straight section $\beta_x = \beta_y = 70$ m. Note 5×10^{13} p/pulse = 382 mA dc. (I use centimeters because we want to end up with cm^{-2}sec^{-1}.)

The problem is to estimate the emittance at 5×10^{13}. I will use at 300 GeV

horizontal $\epsilon_x = 6 \times 10^{-6}$ cm

vertical $\epsilon_y = 1.5 \times 10^{-6}$ cm

dc $J_{max} = 2.9$ A/cm^2 at $\beta_x = \beta_y = 70$ m.

These values agree well with the booster parameters and show only a factor of two increase in current density over present actual performance.

The current density and emittances will vary inversely with the energy. The actual current density is increased by rf bunching. The important point is that these are quite respectable currents and current densities.

Electron Emittances

The horizontal size of electron beams in a synchrotron or storage ring is determined by the balance between "noise" from the satistical nature of synchrotron radiation, which blows-up the beam, and damping from replacing the average energy loss in synchrotron radiation. The vertical is much smaller. For a storage ring with the size of CEA (bending radius 25 m)

$\epsilon_H = 8.5 \times 10^{-6}$ cm at 3 GeV

$\epsilon_v = 0.4 \times 10^{-6}$ cm (guess).

The emittance will increase with the square of the energy, that is beam size increases linearly, for a fixed bending radius.

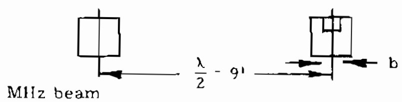
Actually the very small vertical size of the beam may be a nuisance. This small size (much smaller than the proton beam) does not increase the luminosity but does increase the tune-shift for small amplitude protons. Various strategems are available to increase it, the preferred one may reduce the horizontal emittance at the same time.

Bunch Structure

The proton beam is bunched at a frequency of 53.1052 mH at high energies (2.5 kH lower at 100 GeV). The wavelength is 564 cm or 18.5 feet. Measurement at 300 GeV show that all the beam is in a bunch b = 2 feet long with an rms of less than 1 foot.

The frequency of CEA is almost exactly 9 times and can be made so (present 475.9 MHz, $9 \times 53.105 = 477.9$ MHz). The bunch length is determined by quantum fluctuations in the synchrotron radiation and should be about 0.1 λ or 2.5 inches. If we choose to change to 53 MHz, the bunch length should increase to 7.5 inches.

If two 53 MHz beams collide head on, collision regions are spaced 9 feet. The length of each region is one bunch long but each particle sees the other beam for b/2.



If a 477 MHz beam and 53 MHz beam collide, the interaction regions are 1 foot apart (unless we leave some buckets empty). The interaction regions are essentially b/2 long and thus are almost continuous.

Luminosity and Beta

Luminosity is the number (dimensions cm^{-2}/sec) which multiplied by the reaction cross section yields the reaction rate. The luminosity may be evaluated by adding up, for each particle in one beam, the particle density along the interaction length with the other beam, and multiplying by the repetition rate. In terms of currents one expression is

$$\mathcal{L} = \frac{2}{e^2 c} I_1 J_2 \ell ,$$

where ℓ is the length of the interaction region, and J_2 is the appropriate average. One can replace J_2 by I_2/A where A is an average area. One can use dc currents because bunching will simply average out. A special case is the single bunch interaction region where one uses $\lambda/2$ for ℓ instead of the interaction length (which is only one bunch long). This latter arrangement is very attractive for the experiment and is generally used.

The current density can be increased by a local reduction in $\beta^{1/2}$, the parameter giving the envelope of the beam. There is a limit to this process because β is a parabola in free space.

If β_0 is a minimum then $\beta = \beta_0 + S^2/\beta_0$ where S is the distance. Generally one finds that the optimum β_0 is one half the interaction length so that β is double at the ends. It is also difficult to make long free regions with small central β for the same reason.

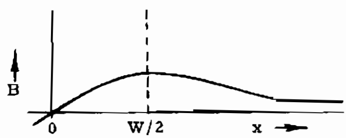
For gaussian distributions one finds on integrating

$$A = 2\pi \left[(\beta\epsilon)_X + (\beta\epsilon)_x \right]^{1/2} \left[(\beta\epsilon)_Y + (\beta\epsilon)_y \right]^{1/2} ,$$

where XY is one beam and xy is the other. If β varies significantly one uses the average value of 1/A.

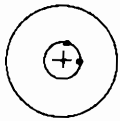
Tune Shift

When a particle of one beam passes near or through the other beam it is deflected. Because the velocities are c and in opposite directions the electric and magnetic forces will be equal and will add. As shown, the center of the beam provides a gradient or a linear tune shift, but the edge and outside is very nonlinear. If the current density exceeds a limiting value, the nonlinear forces cause a rapid growth of the betatron amplitude of the particle and therefore a loss of luminosity. Unfortunately one has not been able to treat this phenomenon analytically, however, operating electron rings have shown that the linear tune shift is a fair measure of the seriousness of the effect with a limit of about



0.05. The limit for a proton passing through an electron beam has not been measured but is thought to be smaller because of the lack of damping.

For a simple head-on collision we can easily calculate the tune shift. The field at a small radius r is $\pi rJ/5$; r in cm, J in A/cm^2. The gradient is $\pi J/5$. The focal power p (1/focal length) is $G\ell/(B\rho)$ which must be doubled to include the electric field. Finally a thin lens added to a ring where one originally had β will shift the tune $\Delta\nu = p\beta/4\pi$ provided we are not near a stop band. So



$$\Delta\nu = J\beta\ell / 10(B\rho).$$

For a bunched beam, the linear current density if $I\lambda/b$ where I is the dc current and b is the bunch length. The interaction length on an individual particle is b/2. For a gaussian distribution

$$J = 0.16\ I/(\beta\epsilon)_x^{1/2}\ (\beta\epsilon)_y^{1/2},$$

so

$$\frac{\beta_1}{\beta_x^{1/2}\ \beta_y^{1/2}} \le \frac{120\ (B\rho)_1\ (\epsilon_x\ \epsilon_y)^{1/2}}{\lambda}\ \ \frac{\Delta\nu}{I}\ .$$

Consider a 3-GeV electron and a 300-GeV proton beam with emittances as given.

$(B\rho) = 10^7$ gauss-cm for electrons
$(B\rho) = 10^9$ gauss-cm for protons.

Let us take $\beta_x = \beta_y$ (probably not the actual choice) and the proton current = 382 mA.

$$\frac{\beta_p}{\beta_e} \ge 1.2 \text{ for } \Delta\nu = 0.05 \text{ for electrons}$$

$$\frac{\beta_p}{\beta_e} \le 3.9/i \text{ for } \Delta\nu = 0.01 \text{ for protons, } i \text{ is electron current.}$$

A high luminosity can be achieved with β_p = 1 meter and β_e = 0.5 meter, and an electron current of 1 amp. These values satisfy the tune shift limits above. The overlap area

$$A = 2\pi\ (600 + 425)^{1/2}\ (150 + 20)^{1/2} \times 10^{-6} = 2.6 \times 10^{-3}\,\text{cm}^2.$$

(Note that β does not change much in 15 cm.)

So

$$L = 1.3 \times 10^{27} \times \frac{0.382 \times 1}{2.6 \times 10^{-3}} \times 564 = \underline{\underline{1.1 \times 10^{32}}}.$$

This is a great number. There are two difficulties which suggest that we can reach it as a second step.

CEA as a Storage Ring Accelerator

A brief description of CEA as an accelerator is:

5.5 GeV (rf limited)
48 gradient magnet units, 24 F, 24 D
average radius 118 ft or 36 m
bending radius 26 m
200-kW rf power at 475.8 MHz
250-MeV linac injector
more than 29-mA current at 60 cycles.

In use as a storage ring, current is injected on a series of cycles using the synchrotron radiation damping at the high end of cycle to shrink the beam so it is not lost at subsequent lows. After filling, the magnet shifts slowly to dc at the high value. This process is somewhat complicated by the necessity of "bumping" the high energy beam into a "damping" magnet which redistributes the radiation properly among the three modes.

The stored current is probably limited to 100 mA or so. There are 3 factors: the low injection energy, the curious wall impedance of a ceramic chamber, and probably the nonlinearities of the "damping" magnet.

The CEA on reinstallation would be simply modified to provide straight sections and an interaction region. The magnet girders and bending radius would not be changed. For use as a storage ring, the long straight sections would allow a much improved "damping" magnet.

Improved Electron Density

An electron target with only 0.1 A would become minimal after a time. The obvious improvement program is to increase the injection energy to the storage device. One way is to construct a dc storage ring in the same tunnel as CEA and to use CEA as a high energy injector. In this case the electron current would probably be rf limited.

For a ring with the same bending radius one finds for the synchrotron radiation per turn:

GeV	MeV/turn
3	0.28
3.5	0.51
4	0.87
4.5	1.4
5	2.1

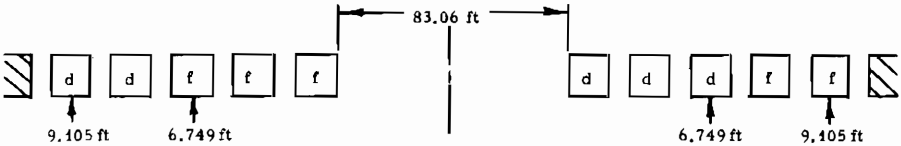
The rf power required is somewhat less than twice the current x MeV/turn. There are sufficient CEA rf cavities to provide the desired shunt impedance. In addition the synchrotron radiation power must be absorbed by the vacuum chamber. This latter problem will limit the maximum current even if sufficient new rf power is purchased, possibly to 1 A at 4 GeV or the equivalent power.

The magnets for a separated function storage ring for 5 GeV at 26 m bending radius are 6.5 kG bending and 1 kG/in. for 12 in. long quadrupoles. Power supplies and ultra-high vacuum equipment are available from CEA. This option, without expanded rf, may be a good move in the initial reinstallation of CEA. In this case the improvement of electron density means largely the purchase of rf power and operational improvement of the vacuum, a process which should not require further downtime for the main ring.

Low Beta for Protons

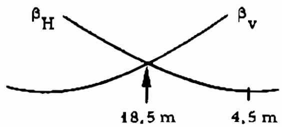
The design of a low beta insertion (1 m) for the main ring has not been done. Such designs do take some time but should be possible; however it is clear that considerable changes will be necessary. I would suggest that a first experiment might use inserted quadrupoles which when turned off would leave the main ring exactly as before. This would allow positive proof of the noninterfering parasitic nature of the electron target under circumstances which should reassure other experimenters.

An initial insertion which satisfies these conditions is a set of main-ring quadrupoles in the presently available 160 ft long straight section.



Except as noted all quads are 7 ft long (std.) and spaces are 1 ft.

Beta is not a minimum at the center but at about 26 ft past the center. Actually, the product $\beta_H \beta_v$ is a minimum of $(15.8\,\mathrm{m})^2$ at 21.4 ft from the center. Thus there is a long region of approximately constant current density.



The clear space of 83 ft is ample for the electron portion of the interaction.

A Lower Limit Luminosity

Let us assume for an initial installation the simple 18 m insertion above and an electron current of 1/8 A interacting with only one proton bunch. The electrons can have a considerably smaller β (5 m or less) and will interact with the center of the proton beam. The proton density will be

$$\frac{70}{18.5} \times 2.9 = 11\ \mathrm{A/cm^2},$$

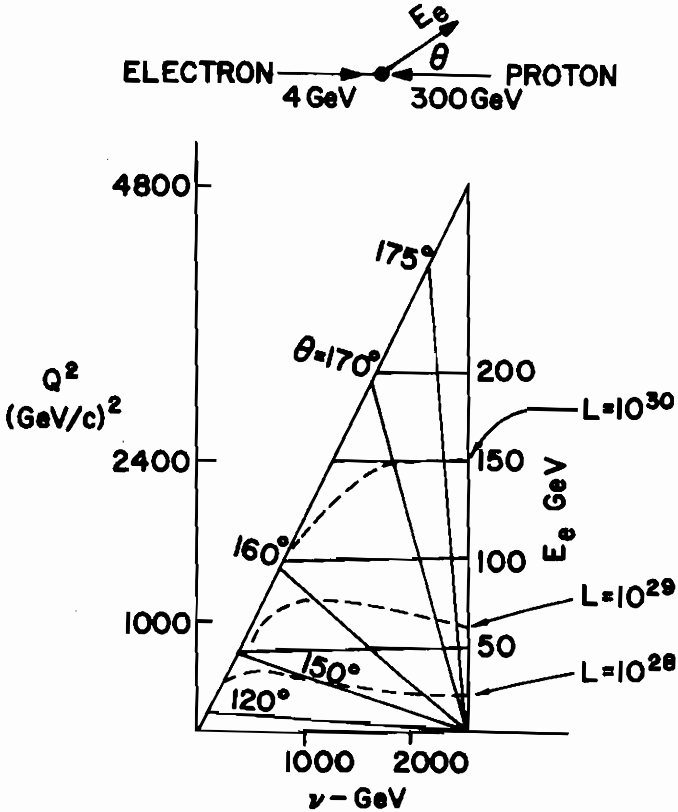
and the luminosity is

$$0.125 \times 11 \times 564\ \mathrm{cm} \times 1.3 \times 10^{27} = 10^{30},$$

which is sufficient to demonstrate the proper working and extreme value of the electron target. If continued at this level for one year the electron target should provide a demonstration of scaling, if true, to about $Q^2 = 1000$. In addition, it can provide very important information on colliding electron-proton beam-design parameters.

Intensification of the Electron Target

By a lower beta insertion, increase of electron injection energy, and increase rf power, in such steps as seem best at the time, we can approach a luminosity of 10^{32}. This allows a detailed investigation of electron scattering and perhaps some results on weak interactions. If indeed one could just show to a reasonable probability that the "weak" interaction does become stronger than the electromagnetic at large Q^2 then one could argue vigorously for ISABELLE or PEP or ISAPEP--on--Eola.



DOTTED LINES ARE DECADE STEPS IN RATE. ONLY A FEW (2 OR 3) EVENTS WOULD BE ABOVE THE LINE AFTER 100 DAYS AT INDICATED LUMINOSITY L, IF SCALING WORKS.