Electron - Proton Collisions in Storage Rings

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1. Introduction

In a recent report[1)] attention was drawn to the possibility of studying electron-proton collisions in the CERN Intersecting Storage Rings (ISR) by storing protons in one ring and electrons in the other. Since the publication of the report the successful demonstration of electron storage in an alternating-gradient structure[2)] and the progress in the study of beam instabilities in storage-rings[3)] have clarified certain aspects of the proposal. The technical implications of electron storage in the ISR have been summarized by Johnsen[4)]. We have made a more detailed study of the experimental possibilities of an electron-proton colliding beam system and are presenting a summary of the results.

2. Electron Proton Kinematics

The centre of mass energy U* of two colliding particles of rest mass m_i (i = 1, 2), kinetic energy E_i, total energy U_i and momentum Pi is

$$U^* = \left[m_1^2 + m_2^2 + 2(U_1 U_2 + P_1 P_2) \right]^{1/2} \qquad (1)$$

The total equivalent energy U_{e1} of a moving particle 1 striking a stationary target 2 and giving the same CMS energy as two particles undergoing a head on collision while moving with velocities $\beta_1 c$ and $\beta_2 c$ is

$$U_{e1} = m_1 \gamma_1 \gamma_2 (1 + \beta_1 \beta_2) \qquad (2)$$

The related CMS kinetic energy E* and the laboratory equivalent kinetic energy E_{e1} are shown in fig. 1 for collisions between protons of energy E_1 = 25 GeV and protons (curves a) and electrons (curves b) of kinetic energy E_2.

Figures 2 and 3 refer to elastic scattering between protons of energy E_1 = 25 GeV and electrons of energy E_2. Fig. 2 gives the angular correlations between the proton and electron lab scattering angles Θ_3 and Θ_4. Θ^* is the CMS scattering angle. Fig. 3 reproduces part of fig. 2 on an enlarged scale and indicates the four-momentum transfer q, which for small transfers at large CMS energies is given by

$$q \approx U_1 \tan\theta_3, \qquad (3)$$

independent of U_2. In the range of values covered by fig. 3 q and Θ_3 are proportional.

Other interesting kinematic quantities are the derivatives of the angles or momenta of the scattered particles to the inelasticity of the interaction, as expressed by a change in the outgoing mass m_3. E.g. the variation of the momentum P_4 of the scattered electron with m_3 is

$$\frac{1}{P_4}\frac{\partial P_4}{\partial m_3} \approx \frac{1}{U_4}\frac{\partial U_4}{\partial m_3} = -\frac{m_3}{U_4^* U^*} \approx -\frac{2m_3}{U^{*2}} \qquad (4)$$

For m_3 = 1 GeV and U* = 15 GeV this quantity is about 1% per GeV.

3. Electron Energy and Current

The choice of electron energy is largely determined by the radiofrequency power which can be supplied to the circulating electron beam. It turns out that 10^{13} electrons of 3 GeV stored in the CERN ISR will require about 46 KW of RF power. Fig. 1 shows that electrons of this energy colliding with 25 GeV protons have a CMS kinetic energy of 16.6 GeV, i.e. twice the value ultimately attainable with the Stanford SLAC at its peak design-energy of 40 GeV. The equivalent electron energy for a stationary proton target is 166 GeV.

We envisage that electrons of the chosen energy would be injected into the ISR system from a separate electron-synchrotron or, if the change over from proton to electron acceleration can be performed sufficiently rapidly, from the CERN PS fitted with an electron injector.

Alternately the electron energy can be raised after the ring has been filled, as e.g. in the Adone project[5)].

Robinson and his collaborators at the CEA have shown that the effects of radial anti-damping of electrons in an alternating gradient structure can be overcome by the use of a system of damping magnets coupling the damped synchrotron oscillations with the anti-damped radial betatron oscillations. (See e.g. reference 2).

We believe therefore that the principal limitation of the luminosity of the system will come from the beam-beam instability first observed at the

Stanford 500 MeV electron storage rings[6].

The effect of this instability on the intersecting proton beams in the CERN ISR has been estimated[7]. For proton currents of 20A stored in ribbons of 6cm width and 1cm height the eight intersections produce a shift $\Delta\nu = 2 \times 10^{-3}$. For electrons of about 3 GeV the effect would be about ten times as large, and therefore still tolerable. While theories have tended to underestimate the effect, a vertical spreading of the electron beam will not lead to an immediate loss in interaction rate since it will be smaller than the proton beam. We therefore assume that it will be possible to store about 10^{13} electrons in the presence of 10^{14} protons in the other ring. With a proton beam height of 1cm, an electron beam of smaller height and an intersection angle of 0.3 radiaus we would obtain a luminosity of 2×10^{28} s^{-1} cm^{-2}. Recent work (see e.g. Courant et al[19]) suggests that proton currents of some hundreds of ampere may be possible and that the effect of the beam-beam instability may be less serious than thought previously. An increase of luminosity by a factor of ten may therefore be hoped for.

4. Comments on Possible Experiments

The processes which suggest themselves for study with colliding proton and electron-beams are (i) elastic scattering, (ii) quasi-elastic scattering and (iii) inelastic processes in general.

(i) Elastic Scattering

Here fairly detailed predictions are possible since the theory, as expressed in the Rosenbluth formula[8], appears to be valid up to momentum transfers of $q^2 = 10$ $(GeV/c)^2$ [9-11]. For the case of large CMS energies and small momentum transfers the Rosenbluth formula can be approximated by

$$\frac{d\sigma^*}{d\Omega^*} \approx \text{const.} \times \frac{U^{*2}}{q^4} \left[G_E^2 + \frac{q^2 G_M^2}{4M^2} \right] \qquad (5)$$

Here G_E^2 and G_M^2 are form-factors, which depend only on q^2, and M is the proton mass. (5) is valid for $q^2 \ll 4M^2$ and $M^2 \ll U^{*2}$. We use it to extrapolate known cross-sections to higher CMS energies.

Using e.g. the data of Wilson[12] and Engler[13] and extrapolating them with the aid of (5) to collisions between 4 GeV electrons and 25 GeV protons we obtain cross sections of about 2×10^{-31} cm^2/ster for $q^2 = 0.62$ $(GeV/c)^2$ and of 5×10^{-32} cm^2/ster for $q^2 = 0.95$ $(GeV/c)^2$.

With a luminosity of 2.10^{28} cm^{-2} s^{-1} one would require a detection system of 0.1 steradian aperture to get an event in a few hours.

Elastic scattering can therefore only be studied at small momentum transfers.

(ii) Quasi Elastic Scattering

Quasi-elastic processes such as

$$e + p \rightarrow e + X$$

where x could be a nucleon resonance, could be rewarding even at small momentum transfers. Bellettini et al[14] have compared pp and ep quasi-elastic scattering data and have shown that they lead to different mass-spectra. It seems tempting to extend this comparison to collisions in pp and ep storage rings. However, formula (5) shows that the sensitivity of the electron momentum P_4 to the mass m_3 of x is extremely small. In addition the momentum spread of the stored particles will be such as to make small changes P_4 undetectable.

(iii) Inelastic Events

These would take the form of the electro-production of known and possible new particles and the study of electro-magnetic processes at large CMS energies. It is obviously of the greatest interest to compare these to the corresponding strong interactions observed in proton-proton collisions.

Only order of magnitude estimates of cross sections can be made at present, based on available electro- and photon-production data. E.g. Crouch et al[15] give the total photo-production cross section of $\pi^+\pi^-$ pairs on protons as 80μ at 1 GeV, while the ratio of the photo- and electro-production cross sections[16,17] at 750 MeV is about 100. A similar ratio for photo and electro-production cross sections has been predicted by Kessler[18].

We may therefore assume that a total cross section of order 1μb is typical of the electro-production processes in the GeV region. With a detection system covering a large solid angle and a luminosity of order 10^{28} cm^{-2} s^{-1} one may therefore expect to observe an electro-production event every few minutes.

In comparing the experimental possibilities of e-p beams with those of p-p beams one notes that the general picture is similar: There are restricted possibilities for elastic scattering experiments, and the main interest will be found in the observation of particle production at very high CMS energies

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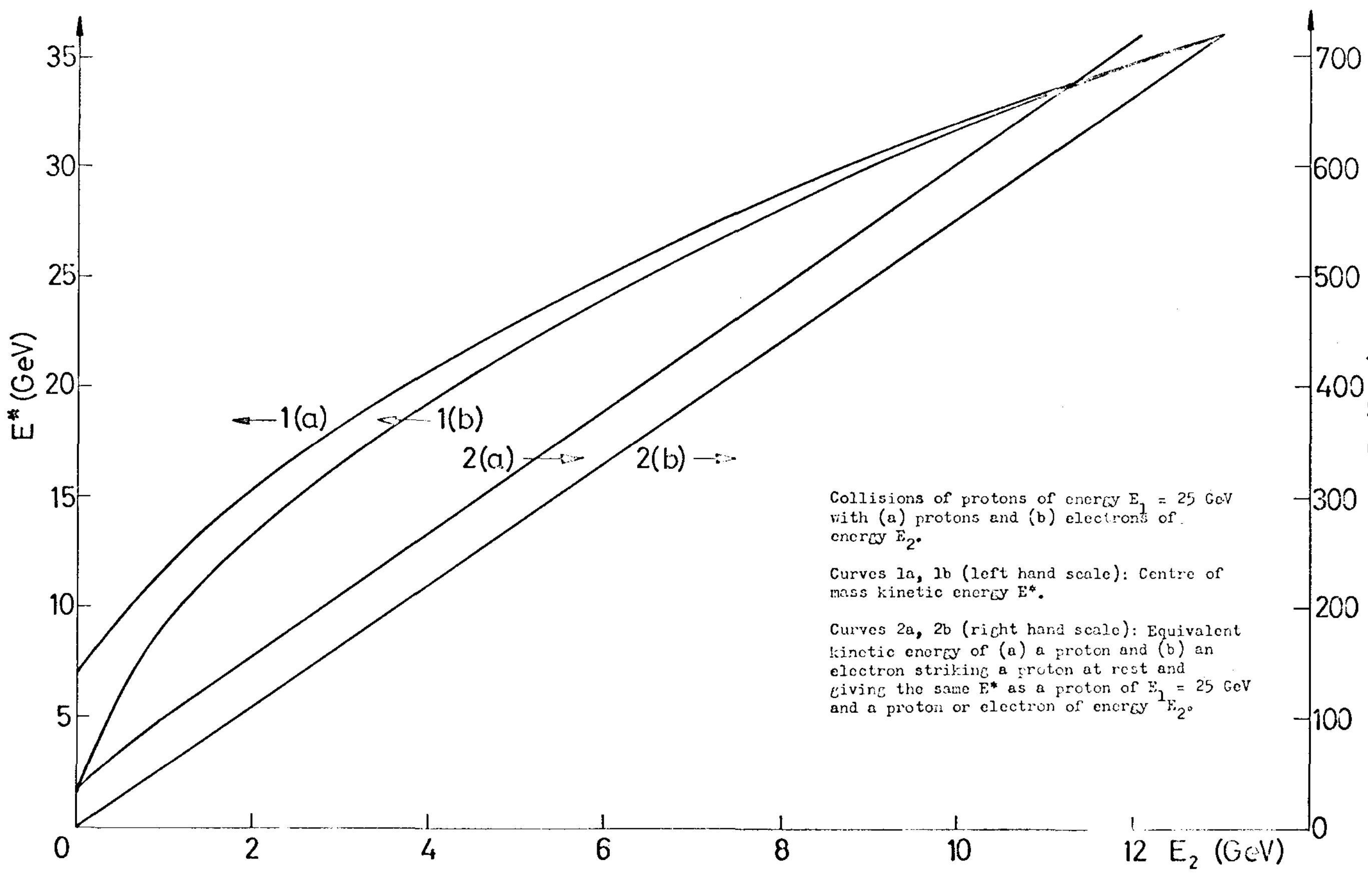

Fig. 1 Centre of Mass and and Equivalent Kinetic Energies for protons of 25 GeV colliding with protons or electrons of energy E_2.

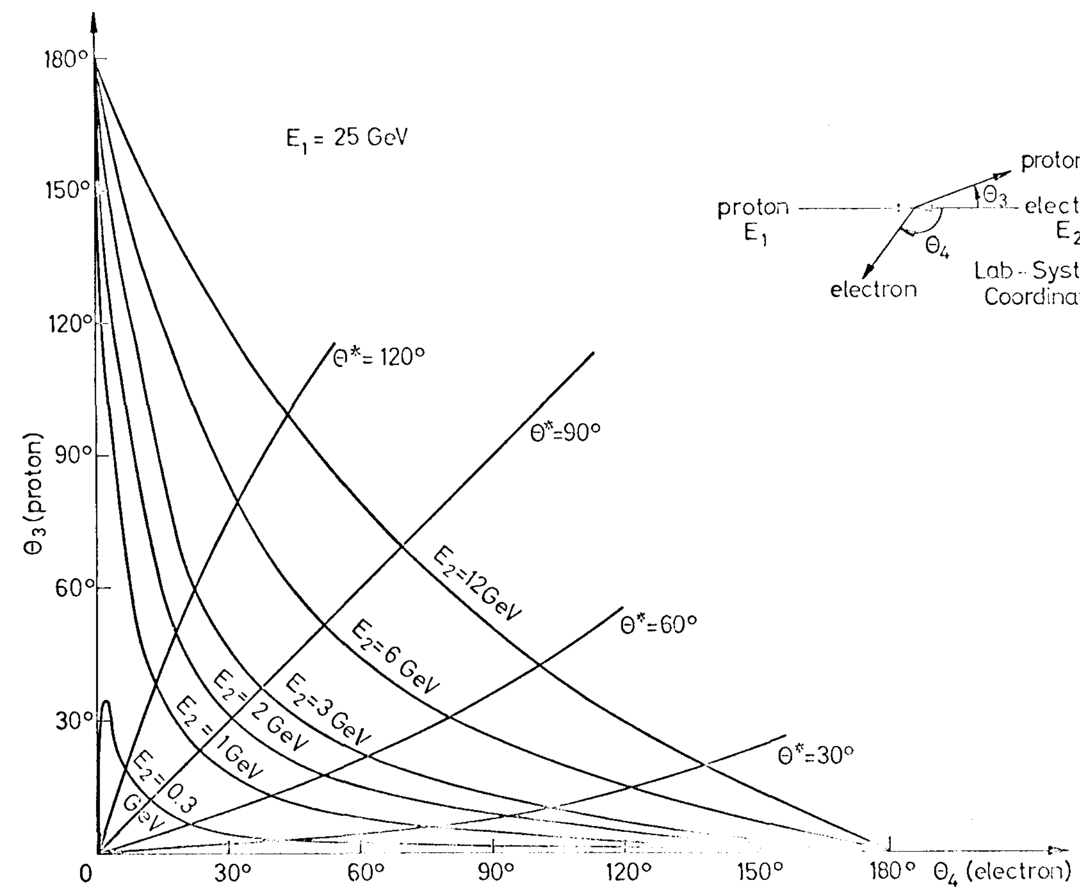

Fig. 2 Angular Correlations for electron-proton elastic scattering.

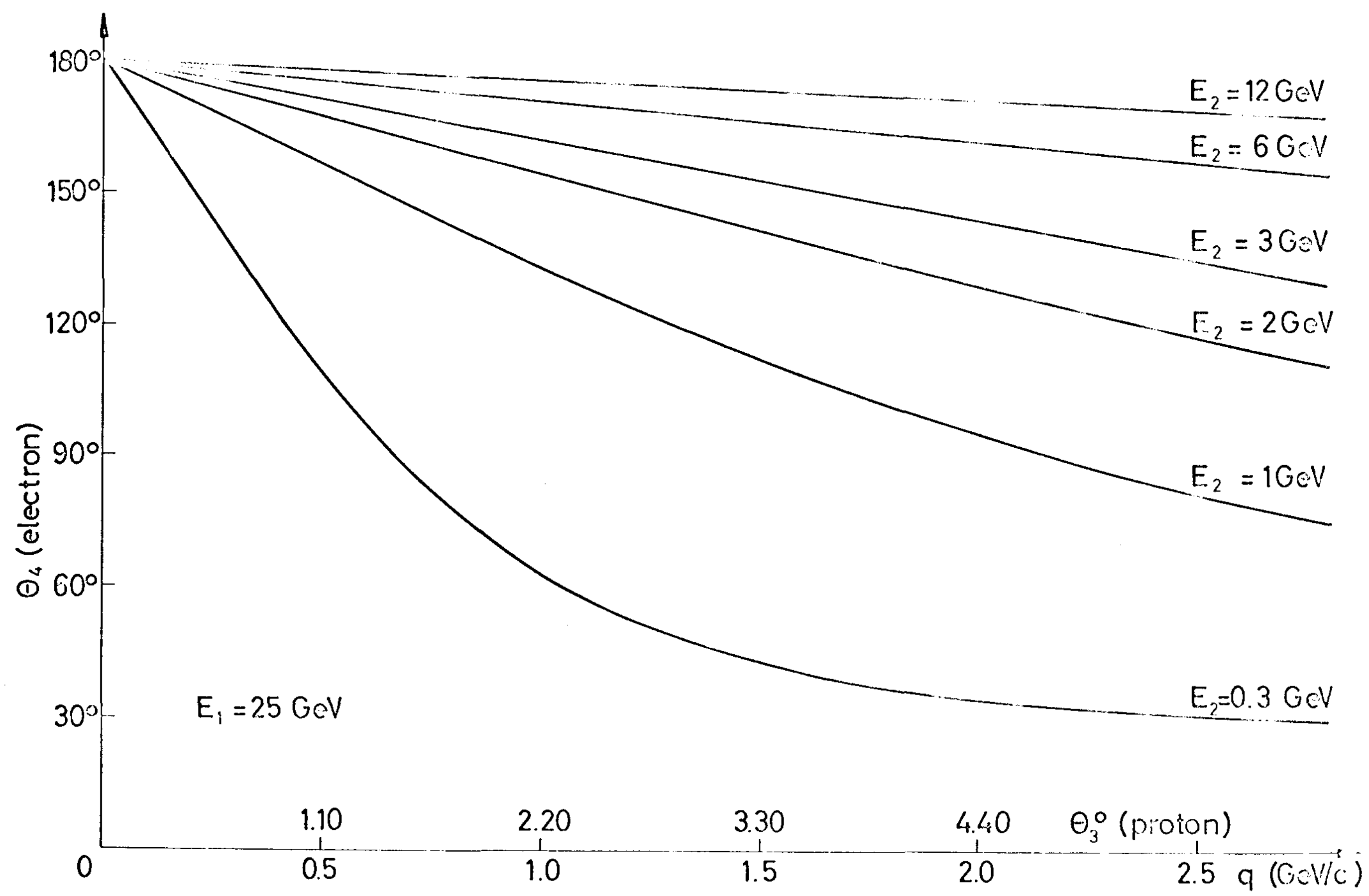

Fig. 3 Angular Correlations and Momentum transfer for small angle electron proton scattering.