CONSIDERATIONS ON THE USE OF THE CERN STORAGE RINGS FOR

ELECTRON-PROTON COLLISIONS

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GENEVA
1966
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1. Introduction.

The use of the CERN concentric storage-ring system for electron-electron collisions has been discussed by the CERN Study Group on High-Energy Projects\(^1\). We consider the use of the storage rings for electron-proton collisions and in the following indicate some of the accelerator problems liable to be encountered and the physical processes which could be studied with the help of such an installation.

2. Instabilities in Electron Storage Rings and Likely Electron Current.

Electron storage rings are subject to a number of instabilities which can lead to a loss of beam in a time depending on the nature of the instability. If this time is of the order of the filling time a limitation of current will result.

2.1 Radial Anti-Damping.

The storage rings considered by the CERN Study Group consisted of separate bending magnets and quadrupole lenses, while the project now adopted\(^17\) is an alternating gradient structure. In AG structures the radial betatron oscillations are "anti-damped" and may build up to large amplitudes unless special precautions are taken to prevent this. This effect has been studied by Robinson\(^2,3\) and by Hereward\(^4\). These authors proposed several methods to avoid the anti-damping effect, e.g. coupling the various modes of oscillation by a tilted quadrupole or keeping the electron beam slightly displaced from the central orbit towards smaller radii. Robinson and Voss have further discussed the anti-damping problem in AG structures\(^5,6\) and have proposed a radial damping magnet for use with the Cambridge Electron Synchrotron employed as a storage- or colliding- beam facility. This magnet consists of several alternating-field alternating-gradient units intended to induce additional radiation loss by particles of lower energy and thereby transferring damping from synchrotron to radial oscillations. With such a device the authors estimate that it should be possible to store electron currents of 10 to 100 mA at 3 GeV in the CEA. It appears therefore that the electron anti-damping effect does not represent a fundamental difficulty in the use of AG structures for electron storage.
2.2 The Touschek Effect.

Another limitation of stored electron currents has been observed in the ADA storage ring at energies between 100 and 200 MeV by Bernardini et al.\(^7\). This so-called "Touschek Effect" consists of a loss of phase-stable electrons due to electron-electron collisions in a single beam. It has been analyzed by the authors who have established a relation between \(N\), the number of stored electrons and their lifetime \(\tau\) of the form

\[
\frac{1}{\tau} = \alpha E N + \frac{1}{\tau_c},
\]

for the case of a non-relativistic transverse motion.

In the ADA storage ring the parameter \(\alpha\) varied with energy according to \(\alpha E^{5.5}\) = constant.

The case of relativistic transverse motion has been considered by Gittelman and Ritson\(^{20}\) and by Berman et al.\(^{21}\). The latter authors show that for a beam current of 1 A in a proposed 3 GeV storage ring of 32 m radius and with an RF voltage of 0.87 MeV/turn the mean life of electrons due to the Touschek effect is a few hundred hours.

This effect will therefore not constitute a limitation of the beam lifetime at the currents and energies to be considered. In actual fact the enlargement of the beam by radial anti-damping will diminish any density-dependent effects. A similar conclusion has been reached by Collins et al\(^8\) in the study of electron-positron storage ring to be used with the Cambridge Electron Accelerator.

2.3 Other Effects.

However, in a further report Collins et al\(^{22}\) point out that there are other possible limitations due to coherent vertical and radial single-beam instabilities caused by wall effects and to coherent and incoherent double-beam instabilities. Double-beam instabilities are not thought to be serious in the CERN rings with a proton beam size of 6 x 1 cm\(^2\) (ref. 17; p. 67) and single beam coherent instabilities can be overcome by non linear elements\(^{22}\). Berman et al\(^{21}\) consider that scattering by the residual gas at pressures of order 10\(^{-7}\) torr of hydrogen and 10\(^{-9}\) torr of heavier gas constitute the most serious
limitation of the lifetime in the Stanford ring. Even this lifetime is of the order of some hours.

2.4 Likely Electron Current.

We envisage filling times of the order of a few minutes. Instabilities giving rise to beam loss over much longer periods therefore will not limit the stored current but may present drawbacks from the point of view of the use of the injector.

The present Stanford experiments, as reported by Gittelman\textsuperscript{9}) are being performed at a current of around 40 mA, corresponding to about $10^{12}$ electrons in the CERN storage ring. However, the Stanford currents are limited by phenomena in the electron-electron interaction region and appreciably larger currents were stored in a single ring. Taking account of the possible current and power limitations in the future CERN rings we shall assume that it will be possible to stack $10^{13}$ electrons, corresponding to a circulating current of 400 mA.


The use of the CERN PS for electron acceleration has been considered by the CERN Study Group, but we assume that for proton-electron collisions a separate electron accelerator may be required. If such an accelerator is necessary its cost will be a limiting factor; another will be the synchrotron radiation losses of the electrons in the storage ring.

In table I we list the energy loss per turn in a CERN storage ring and the approximate cost of a strong-focusing electron synchrotron injector as function of the electron energy. The cost-estimate is based on published figures for the Cornell and Desy machines\textsuperscript{10}) during their construction. In fact the cost of the Desy laboratory, estimated at 66 MSfrs in (10), amounted to 120 Msfrs in 1964\textsuperscript{18}), but one may note that this includes provision for experimental halls and equipment. We also indicate in table I the centre-of-mass energy $E^*$ of electrons of energy $E_2$ colliding with protons of kinetic energy $E_1 = 25$ MeV and the equivalent energy $E'_e$ of an electron accelerator designed to give the same centre-of-mass energy in collisions with stationary protons. $E^*$ and $E'_e$ are plotted as function of $E_2$ and for $E_1 = 25$ GeV in fig. 1, which also gives the equivalent data for collisions of protons of 25 GeV with protons of
energy $E_2$, i.e., for asymmetric proton-proton collisions.

<table>
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<tr>
<th>$E_2$ (GeV)</th>
<th>$\Delta E$ (Kev per turn)</th>
<th>Cost of injector (MSfrs)</th>
<th>$E^*$ (GeV) for $E_1 = 25$ GeV</th>
<th>$E_e$ (GeV)</th>
</tr>
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<tr>
<td>1</td>
<td>1.12</td>
<td>2.2</td>
<td>9.28</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>8</td>
<td>13.5</td>
<td>111</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>18</td>
<td>16.6</td>
<td>166</td>
</tr>
<tr>
<td>6</td>
<td>1450</td>
<td>70</td>
<td>24.0</td>
<td>332</td>
</tr>
</tbody>
</table>

These data suggest the following comments:

1) The RF system at present foreseen for the storage rings is designed for 20 kV peak voltage and for 18 kW of RF power per ring. It would limit the electron energy to a value below 2 GeV and its mode of operation will have to be modified for electron storage. $10^{13}$ stored electrons of 3 GeV would require an RF power of at least 46 kW to balance radiation losses. Additional power will be required to provide a sufficient peak voltage. It would therefore be necessary to foresee additional accelerating stations for electron storage or the possibility of modifying the ones now planned, and this will add to the cost of the project.

2) The cost of an electron injector of more than 3 GeV becomes an appreciable fraction of 300 MSfrs, the total cost of the storage ring project.

3) A 3 GeV electron beam would double the centre-of-mass energy attainable with the Stanford machine at 40 GeV.

It appears that a 3 GeV electron beam would at present constitute a worthwhile step from the point of view of the centre-of-mass energy and would not add considerably to the cost or the complexity of the storage ring project. Provision of electrons of about 6 GeV would amount to a major undertaking.
4. Electron-Proton Kinematics.

The kinematics of the elastic collisions of protons of kinetic energy \( E_1 = 25 \text{ GeV} \) with electrons of different energies \( E_2 \) are illustrated in fig. 2 and 3. Fig. 2 shows the lab. scattering angles of the protons and electrons at various centre-of-mass scattering angles \( \theta^* \). The case of small momentum transfers \( (q \ll \text{ centre-of-mass energy}) \) is shown in more detail in fig. 3. For small \( q \) the proton lab. angle \( \theta_3 \) depends only on the proton energy \( E_1 \) and is independent of the electron energy \( E_2 \). The protons emerge under small angles and could be analysed by the ring magnet sectors foreseen for small angle pp scattering \(^{11}\). The electrons emerge at larger angles and would require separate analysing magnets.

5. Interaction Rates.

As in the case of proton-proton elastic scattering the cross-section for elastic proton-electron collisions at large momentum transfers becomes too small to hope for an observable rate of events. The main interest of elastic scattering lies therefore in the possibility of studying small transfers at different centre-of-mass energies.

This leaves the field of inelastic interactions (class B experiments of ref. \(^{17}\), p. 13) which here take the form of the electro-production of known and possible new particles and the study of electromagnetic processes at high centre-of-mass energies. Here the fact that the centre-of-mass is not at rest in the laboratory becomes of importance. Secondaries from such events emitted with low energies in the centre-of-mass would be grouped close to the direction of the incident proton, which would probably somewhat increase the problems of detection, identification and distinction from background compared with those encountered in collisions of protons of equal energy.

To estimate the rate of events for given currents of protons and electrons we use the formula given by Schoch \(^{12}\) for the interaction rate

\[
I.R. = \frac{2\alpha N_1 N_2}{h_1 a}
\]

where \( h_1 = \text{height of proton beam}, a = \text{intersection angles}, N_1 \) and \( N_2 \) line densities for protons and electrons respectively.
The height of the electron beam is likely to be less than that of the proton beam, but the interaction rate is not affected by this since it only depends on the particle density in the larger beam. We find for $N_1 = 10^9$, $N_2 = 10^8$ per cm (corresponding to $10^{13}$ circulating electrons) $h_1 = 1$ cm and $\alpha = 0.3$ radians:

$$I.R. = 2 \times 10^{28} \sigma (\text{cm}^2 \text{ events/sec}).$$

A cross-section of 100 $\mu$b would then give 2 events per second. To estimate the order of magnitude of the cross-sections to be expected in electron-proton interaction we note that present-day data on the photoproduction for multiple pion events on hydrogen suggest a total cross-section of about 100 $\mu$b between 1 and 4 GeV$^{13}$. The cross-section for electro-production of pions appears to be about two orders of magnitude less$^{14}$. One could therefore hope to observe about one electro-production event per minute.

6. Comments and Conclusions.

In an evaluation of a project of this type one might note that possible future proton accelerators of 200 to 300 GeV will permit the production of electron beams by conversion of gamma rays. These beams will be weak and less pure than those obtainable at the Stanford 40 GeV machine but will be of much higher energy. Using Burhop's$^{15}$ estimate of photon fluxes to be expected from a 300 GeV machine one may hope to obtain electron beams of order $10^7$ particles per 1% momentum band around 150 GeV per millisteradian and per $10^{12}$ interacting protons. For corresponding electron beams of about 100 GeV the flux would be one to two orders of magnitude larger. Again a proton accelerator of 300 GeV would be capable of producing very clean muon beams of order $10^6$ particles per $10^{12}$ protons in a momentum band of 1% around 150 GeV and of about $10^8$ particles around 100 GeV. Apart from the study of the muon itself such muon beams may be more suitable for certain types of investigation than electron beams. Muon or electron beams of $10^6$ particles per pulse traversing a hydrogen target of 150 cm give an interaction rate which is about 100 times as large as that estimated above for proton-electron interactions in the CERN storage rings with $10^{13}$ stored electrons.
If proton accelerators of more than 200 GeV are constructed in the not-too-distant future we therefore tend to believe that the use of the CERN Storage Rings for proton-electron collisions would be mainly justified for electrons of 5 GeV or above which, in collision with 25 GeV protons, correspond to 300 GeV electrons striking protons at rest. Furthermore, if the realisation of tangent accelerators\textsuperscript{16}) proves possible, they could be usefully applied to electron-proton collisions in flight.

With these possible provisos it appears to us from this preliminary analysis that the idea of electron-proton collisions in storage rings might merit some further consideration from the point of view of its practicability. If the conclusions are favourable the provision of an electron-injector for the CERN storage rings would, in our opinion, add to its scientific interest. Conversely, if the construction of an electron accelerator is considered, it would add to its scientific value if it were built near a proton storage-ring system. It is evident that such a combination would also facilitate the study of electron-electron or electron-positron interactions discussed by the CERN Study Group\textsuperscript{1}).

We are indebted to Drs. H.G. Hereward, K. Johnsen, A. Schoch, P. Marin, J.V. Allaby for advice, criticisms and comments. We thank Mr. B. Mouellic for help with the kinematic calculations and Dr. F. Ploquin for checking them by means of a computer programme\textsuperscript{19}).
References

1. AR/Int.SG/62-11, sections 9 and 17.
10. CERN 60-4.
15. E.H.S. Burhop, AR/Int.SG/63-42, Fig. II.3.
20. B. Gittelmann and D. Ritson, HEPL 291.
Figure captions

Fig. 1 - Centre of mass energy $E^*$ and equivalent electron accelerator energy $E_e$ for collision of electrons and protons of kinetic energy $E_2$ with protons of $E_1 = 25$ GeV.

Fig. 2 & 3 - Angular correlations for elastic collisions of electrons of energy $E_2$ with 25 GeV protons.

$\Theta^*$ = centre of mass scattering angle.

$E_1 = 25$ GeV.
Collisions of protons of energy $E_1 = 25$ GeV with (a) protons and (b) electrons of energy $E_2^*$.

Curves 1a, 1b (left hand scale): Centre of mass kinetic energy $E^*$.  

Curves 2a, 2b (right hand scale): Equivalent kinetic energy of (a) a proton and (b) an electron striking a proton at rest and giving the same $E^*$ as a proton of $E_1 = 25$ GeV and a proton or electron of energy $E_2^*$.  

FIG.1