THE PROPOSED DESY PROTON-ELECTRON COLLIDING BEAM EXPERIMENT

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Summary

It is proposed to store protons as well as electrons and positrons in the DESY storage ring, DORIS. The techniques planned for accomplishing this and the hoped for results are described.

Introduction

Preliminary studies[1,2] have shown that if one ring of the DESY $e^\pm$ double ring storage ring, DORIS, were filled with protons some useful $e^\pm$ - p scattering experiments could be done. Additionally such a facility would provide a device for studying accelerator physics relevant to very high energy electron-proton colliding beam machines, e.g., transverse phase space stacking and longevity of tightly bunched proton beams. With an unbunched proton beam injected by means of momentum stacking, it is expected that a luminosity in excess of 10^{30} cm^{-2}sec^{-1} can be achieved.

General Scheme

Figure 1 shows a schematic layout of the DESY synchrotron, storage ring and injector linac. Normally, to fill the storage ring with electrons or positrons, a pulse of electrons or positrons is injected by the linac into the synchrotron, accelerated to an energy in excess of 2 GeV in the synchrotron, ejected in a single turn by a fast kicker and septum system, transported over a system of quadrupoles and bending magnets to the storage ring and injected by a septum and fast kicker system. After radiation damping of the initial betatron oscillations in the storage ring the next injection can be carried out. Above 2.2 GeV the damping time is such that a new electron pulse may be inserted, every 20 msec. Subsequently the other ring of the storage ring can similarly be filled with a counter rotating beam.

A somewhat similar process is envisioned for proton injection as can be seen from Figure 2. Protons from a 3 MeV Van de Graaff machine are multi turn injected into a dc field in the synchrotron. The frequency modulatable RF accelerator is then gradually turned on to provide adiabatic trapping. Subsequently acceleration is initiated by programming the existing ignitron controlled dc supply to give a ramp wave form to the magnetic field and at the desired momentum (also 2 GeV/c or greater) single turn extraction is effected with the same equipment used for electrons or positrons. The anticipated acceleration time in the synchrotron is about one-half second for 2 GeV/c. Having been accelerated and ejected the protons are conducted to the storage ring over the electron or positron channel already provided and injected into the storage ring. Because of the absence of radiation damping, an injection method different from that used for electrons will be necessary. After injection of the maximum number of protons, space charge limited to about 4×10^{13} protons at 2 GeV/c, the beam can be loosely bunched by a small RF system and, together with the counter rotating beam of electrons or positrons injected earlier, slowly accelerated to the operating energy of interest. Alternatively the beam could be injected directly at the operating energy of interest. Both possibilities are under study.

Proton Beam Stacking in the Storage Ring

The phase space brightness of the Van de Graaff beam is good enough in all dimensions that in principle one could stack the beam in either transverse phase space or momentum or both. It is hoped to try all methods to investigate their potential and their peculiar problems. It is evident, however, that in the case at hand momentum stacking is the simplest approach for a first step. Because of the inequality of proton and electron velocities at DORIS momenta, bunched proton operation is limited to discrete energies only. Further, owing again to the velocity differences, to achieve the same luminosity, a significantly higher spatial density of protons is required when the protons are bunched than when they are homegeneously spread out.[2]

In addition the Toushek effect would require the beam holding cavities to produce of the order of a million Volts to achieve reasonable life times. For these reasons it has been decided to propose initial operation with a homogeneous proton beam. Under operating conditions of interest the useful invariant admittance volume of the storage ring ($\epsilon_H \epsilon_V \beta^2 \gamma^2$) is about 17×10^{-12} rad^2-meter^2 while the relative momentum spread that could be used for stacking is about 2.5×10^{-3}. The equivalent transverse emittance volume for the Van de Graaff is 2.5×10^{-12} rad^2-meter^2 and if strict adiabaticity is preserved the relative momentum spread in the beam at 2 GeV/c will be 1.3×10^{-5}. Thus under ideal conditions 6 injector pulses could be stacked in betatron phase space while some 190 pulses can be stacked in momentum space. Given the intensity limit[3] per injector pulse of about 1.6×10^{11} particles it is clear that we must choose momentum stacking to come close to saturating the space charge limit of the storage ring under unbunched beam operation. The stacking would be carried out exactly as at the ISR[4]. The process is shown schematically in Figure 3. The bunched injected beam is placed onto an orbit of $\Delta p/p =$ + 0.41 % by means of a septum, beam bump and the fast kicker shown in the figure. Single turn injection is employed. The beam is there "received" by an RF system of appropriate frequency and bucket size and, after the shield has been lifted, carried to a lower energy orbit of $\Delta p/p = - 0.41$ % (first pulse only). This is done by slowly lowering the cavity frequency during which process the RF amplitude is gradually decreased to spill the beam out onto the desired orbit. The shield is lowered again to protect the stacked beam from being disturbed by the next kicker pulse and another proton pulse is injected. If Δp is the momentum displacement of the first parking orbit (.41 % of p_o here) and δp is the momentum spread of the injected pulses then the second pulse is decelerated to a parking orbit characterized by $-\Delta p + \delta p$, the third pulse to $-\Delta p + 2\,\delta p$ etc. until the available aperture is full. In DORIS the dispersion at the movable shield kicker is about 3.2 meter in an aperture of 4 cm.

Proton Beam Intensity Limits

It is believed that under possible operating parameters for DORIS the ultimate limit on useful proton beam intensity is given by the single particle Laslett space charge limit. At planned operating conditions the beam-beam betatron detuning is small as is the longitudinal effect, recently studied by Augustin[5] and Rees[6], of the bunched electron beam on the continous proton beam. At 2 GeV/c momentum for injection into DORIS the Laslett limit within the useful volume determined by the electron beam size is about 4×10^{13}. For a proton beam of this size, 3 GeV operating energy, a crossing angle of 6 mr and a beta at the center of the interaction region of 10 cm we find a Q shift for the electrons of about 8×10^{-3}. The number of electrons at 3 GeV is RF power limited to about 5×10^{12} giving a detuning of the protons of about 1×10^{-3}. To estimate the size of the longitudinal effect we can think of the electron bunches as little accelerators, giving a longitudinal impulse to the protons passing through-proportional to the phase angle between the proton and the center of the electron bunch. For electrons against protons, the protons being below transition, the electrons tend to bunch the protons about the center of the electron bunches. Making use of the impulse formula of 5 we can write the equivalent bucket half height, H/2, for this acceleration process as

$$\frac{H}{2} \left(\frac{\delta p}{p} \text{units} \right) \sim \frac{1}{\pi \sigma_\ell} \sqrt{\frac{N_e \lambda r_p}{h} \gamma_p}$$

(below transition)

where N_e is the number of electrons per bunch, λ is the wave length of the RF for the electrons, r_p is 1.5×10^{-18} meter, h is the harmonic number of the electrons' RF system and σ_ℓ is the root mean square length of the electron bunches. This formula gives only a crude upper limit for the true bucket height because the accelerating voltage goes to zero when the phase exceeds the physical extent of the electron bunch. Putting in the numbers for 3 GeV/c protons and 5×10^{12} electrons we find a half bucket height of $\delta p/p = 10^{-4}$ which is only 10 % of the momentum spread planned. At the proton momenta being considered it is possible to pick many operating momenta where the protons are rather far from synchronism with the electrons so that the effect of the longitudinal impulse is much diluted, thereby giving a convenient mechanism for the study of the effect should it be important.

Less fundamental instabilities may also plague us in attempting to achieve a beam intensity comparable with the space charge limit. If it is legitimate to scale from the ISR experience we should be able to avoid transverse resistive wall instabilities and the head tail effect by applying a chromaticity of $Q' = \Delta Q/\Delta p/p \sim 7$ by means of the DORIS sextupoles. We have assumed here that the resistive wall instability is dominant[7] and that the Q' required to supress it[8] goes like γ^{-3} for small γ. With regard to longitudinal instabilities the situation is not clear. Using formulae for allowed coupling impedances such as given by Keil and Zotter[9] we come out with values comparable with those estimated for the ISR. Certainly one will have to apply negative feed back to the accelerating cavities as per the ISR[10]. Another problem which is receiving attention at the present time but is as yet unresolved is the sweeping out of the electrons created at the proton beam by ionization of the residual gas. Reported experience with the ISR makes clear the need for this step.

While it appears possible in principle to put several times 10^{13} protons into the storage ring, in practice we shall probably be limited by the space charge limit in the synchrotron coupled with the various inefficiencies of beam transfer. With the 3 MeV injector, taking into account the space charge limit of the synchrotron and efficiencies for injections and ejection[3], one estimates a possible stored intensity of 1.6×10^{13} protons. Should it prove desirable at a later date a higher energy injector can be provided for the synchrotron to allow acceleration of more charge per pulse therein.

Lifetime

Multiple scattering on the residual gas provides a rather severe limit on the lifetime. Using an approximate formula[12] we find that the expected lifetime determined by this process varies from 0.5 hr. at 1.0 GeV/c to 8.3 hr. at 3.5 GeV/c when the residual pressure is 10^{-9} Torr air equivalent. Possible ion effects and intra beam scattering into non-linear resonances are being examined also as possible limits to the lifetime.

Luminosity

Taking figure 4 as our model with the boundaries shown being taken to mean the envelope of the root mean square particle distribution function and assuming a Gaussian distribution, the luminosity for the case of two interaction regions is[13]

$$L \simeq \frac{2}{\pi} \frac{N_e N_p f}{\bar{w} \delta \ell}$$

where f is the revolution frequency, $\bar{w}$ the average beam width in the interaction region (rms), l is the machine circumference and 2 δ is the crossing angle (vertical) of the beams. For 10^{13} protons, 5.7×10^{12} electrons at 3 GeV, $\bar{w}$ ($\beta_{o\lambda}$ = 10 cm) = 0.63 mm, l = 388 meter, f = 1 MHz and δ = 8 mr $L_o = 0.24 \times 10^{31}$ cm^{-2}sec^{-1}. At the space charge limit of DORIS (2 GeV/c injection momentum) the luminosity would then be about $4L_o$ or about 10^{31}. For positrons against protons one can make the crossing angle smaller easily by use of magnetic dipoles on either side of the interaction point[2] and obtain further gain in luminosity. Below a crossing angle of 6 mr further decrease of the crossing angle doesn't bring much more as $\bar{w}$ begins to grow correspondingly. With a crossing angle of 6 mr and 4×10^{13} protons then one might achieve a luminosity of $L = 2 \times 10^{31}$.

Experimental Utility

As can be seen from fig. 5, a luminosity of between 10^{30} and 10^{31} would permit e-p scattering in and just above the kinematic neighborhood of present e-p coincidence experiments. Thus one has the opportunity, relatively rapidly and inexpensively, to do some interesting experiments while simultaneously getting a feel for the detection problems associated with e-p colliding beams. Additionally, the proposed project would provide an opportunity for relatively rapid and low cost tests of the possible accelerator physics problems of e-p colliding beams.

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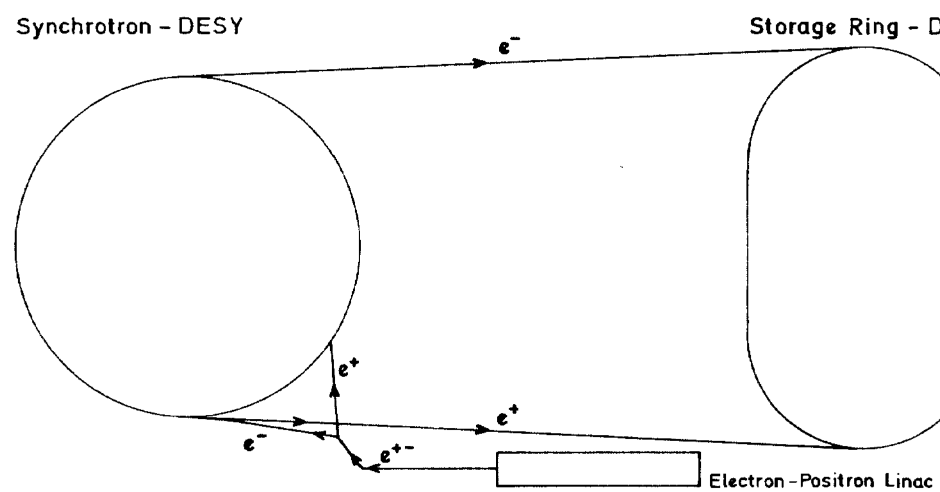

Fig. 1. Normal operation.

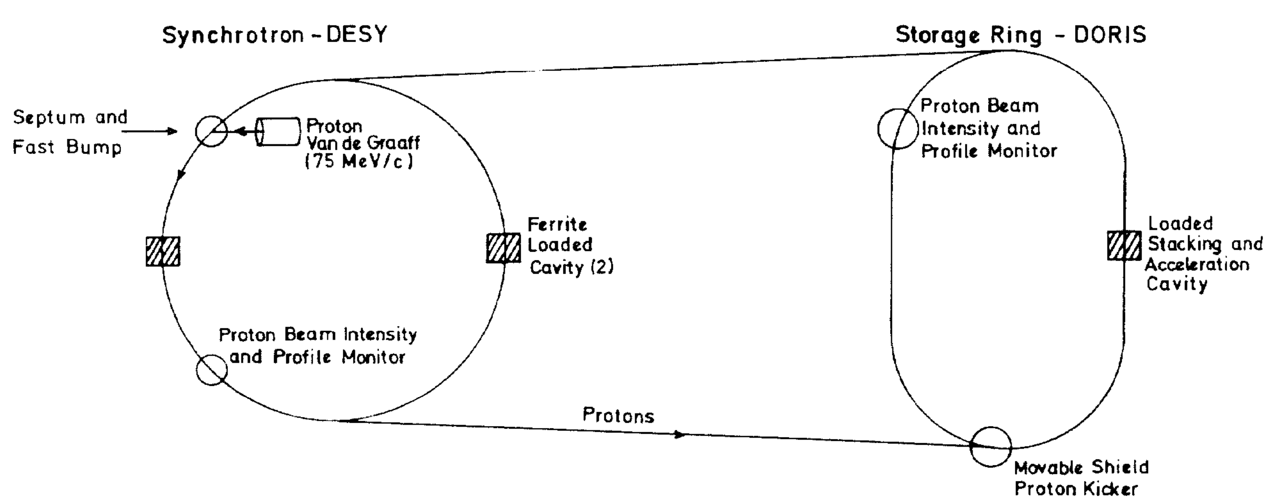

Fig. 2. Proton operation.

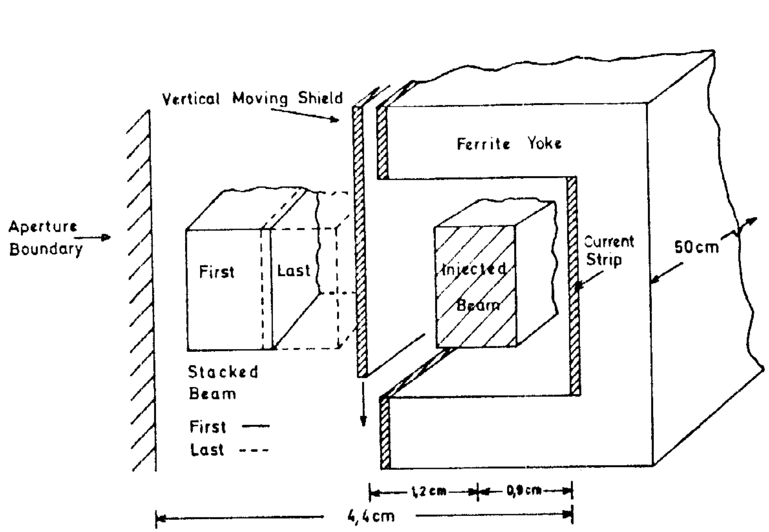

Fig. 3. Shielded kicker for storage ring.

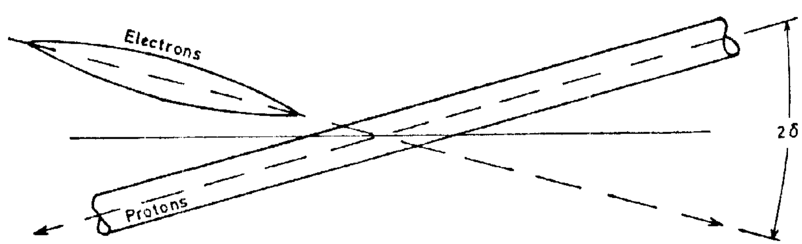

Fig. 4. Symbolie vertical cross section near interaction point.

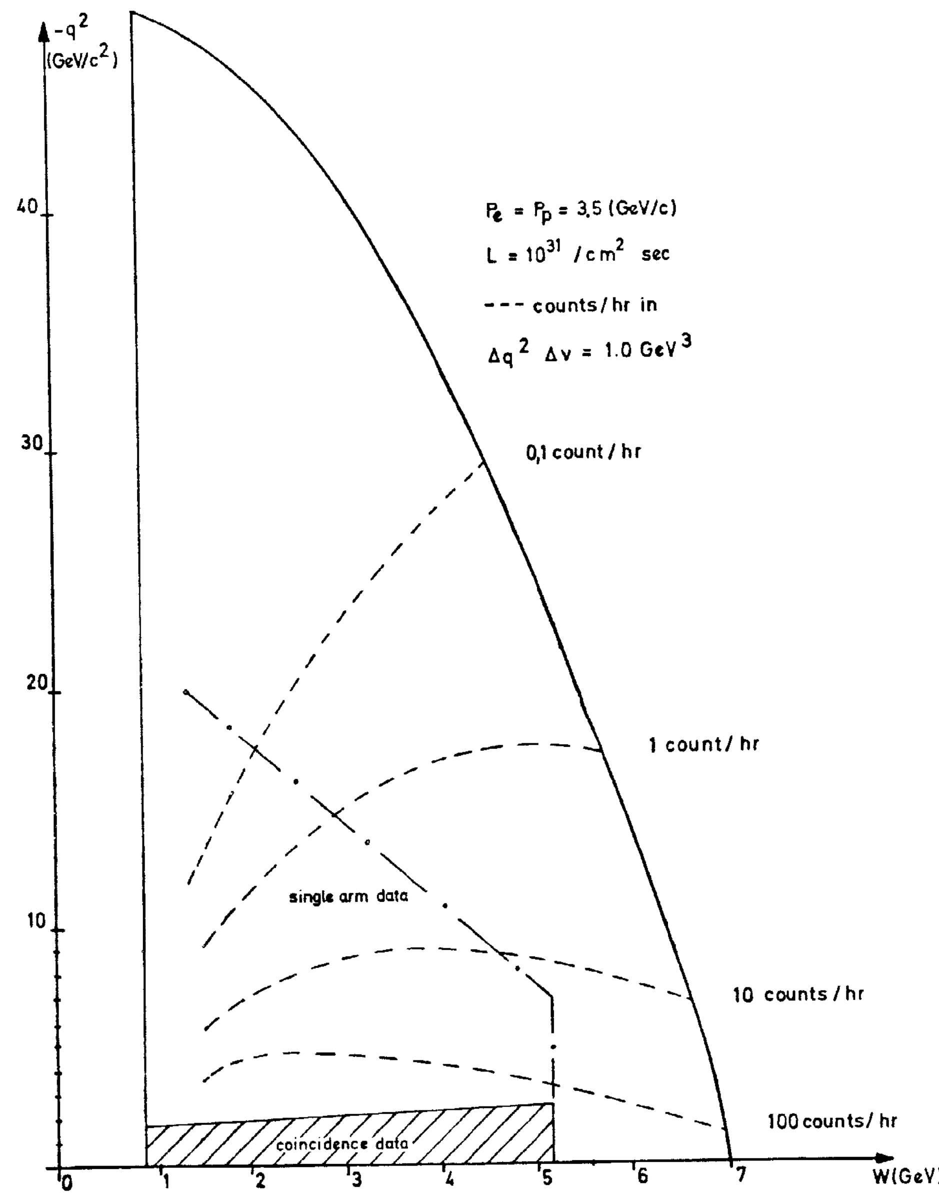

Figure 5.