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Experimentiermöglichkeiten mit Elektron - Proton - Strahlen in DORIS

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DORIS as an e-p Colliding Beam Facility

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Introduction

Studies [1, 2, 3] 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 accelerater physics relevant to electron-proton colliding beam machines [4], 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 beam bump 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 multiturn 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

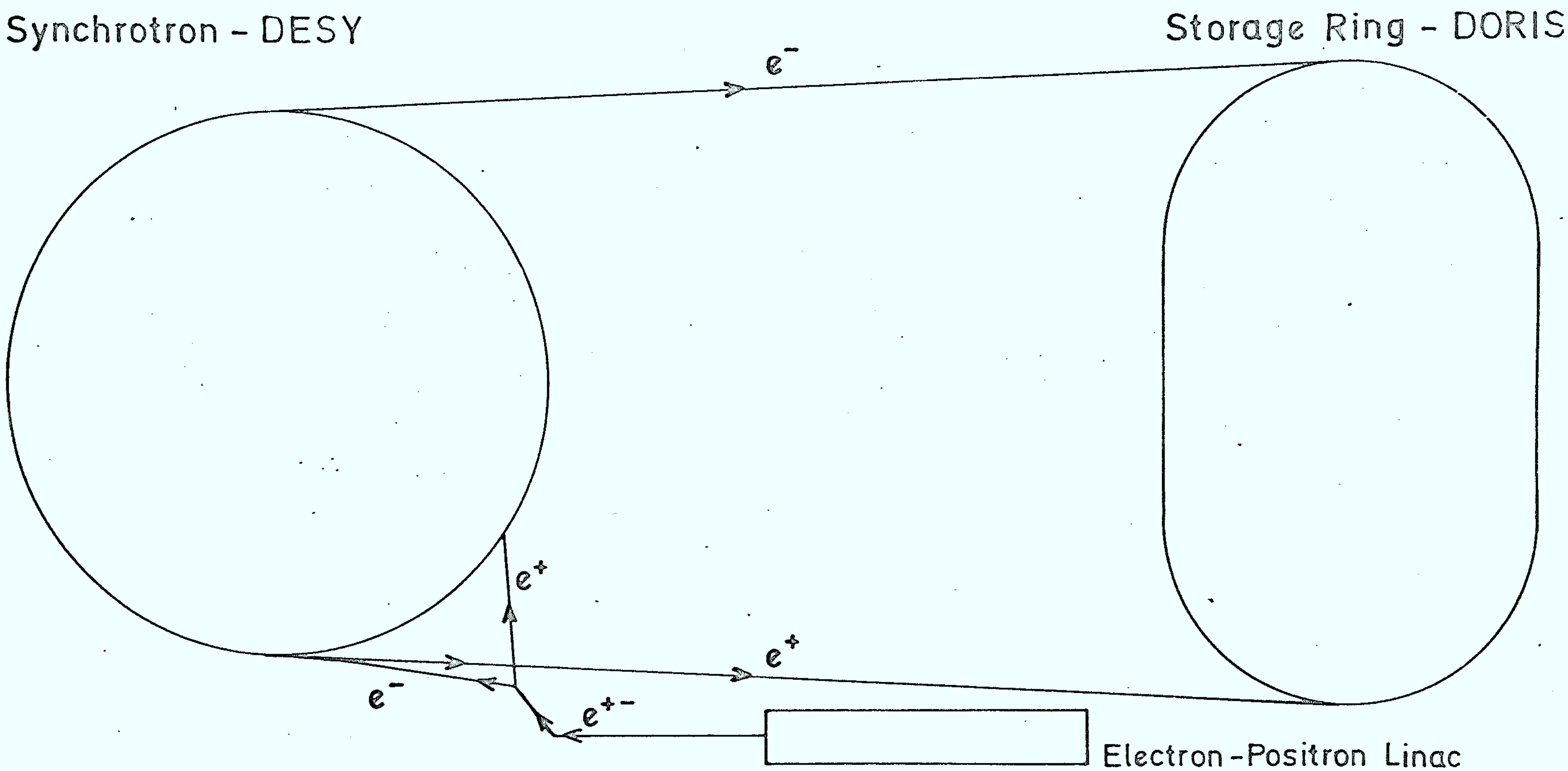

FIG. 1

Normal Operation

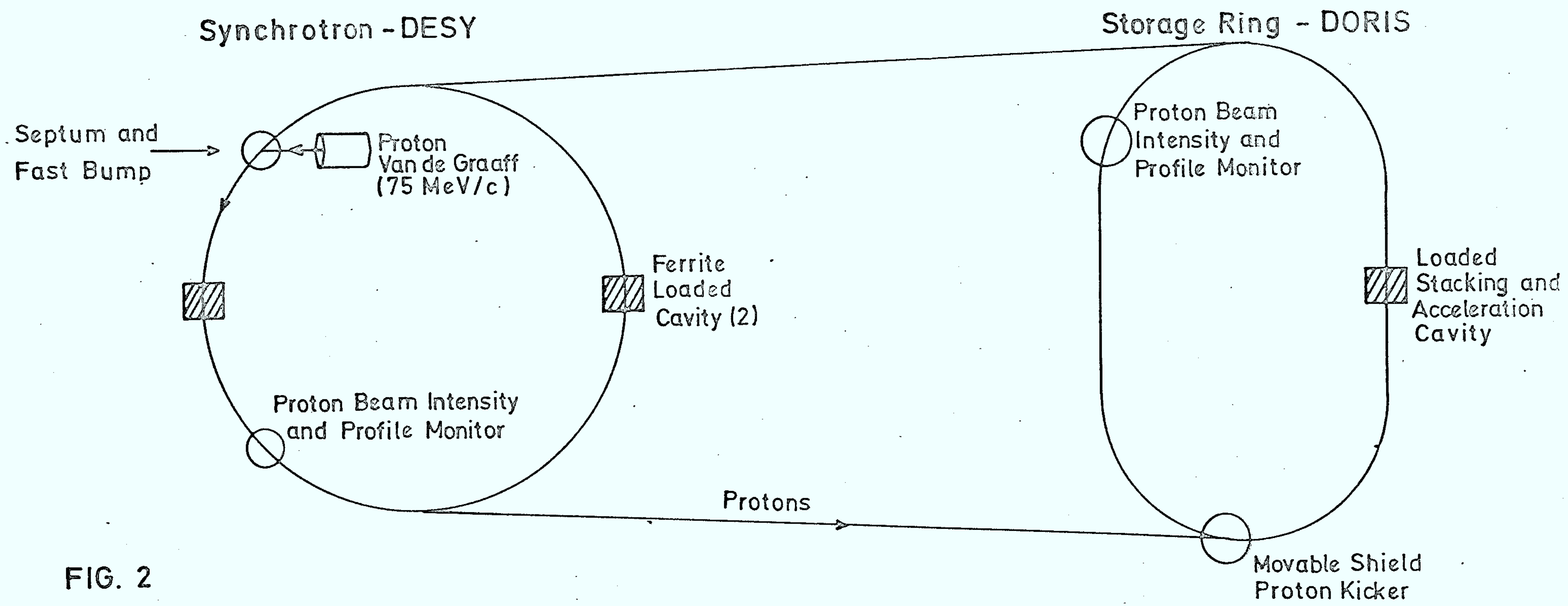

FIG. 2

Proton Operation

for electrons will be necessary. After injection of the maximum number of protons, space charge limited to less than 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. 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 homogeneously spread out [2)]. In addition the Touschek effect would require the beam holding cavities to produce excessive voltages 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 ($\varepsilon_H \varepsilon_V \beta^2 \gamma^2$) 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 [5] 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 [6]. The process is shown schematically in Figure 3. The bunched injected beam is placed onto an orbit of $\frac{\Delta p}{p} = + 0.41\%$ 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 $\frac{\Delta p}{p} = - 0.41\%$ (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.

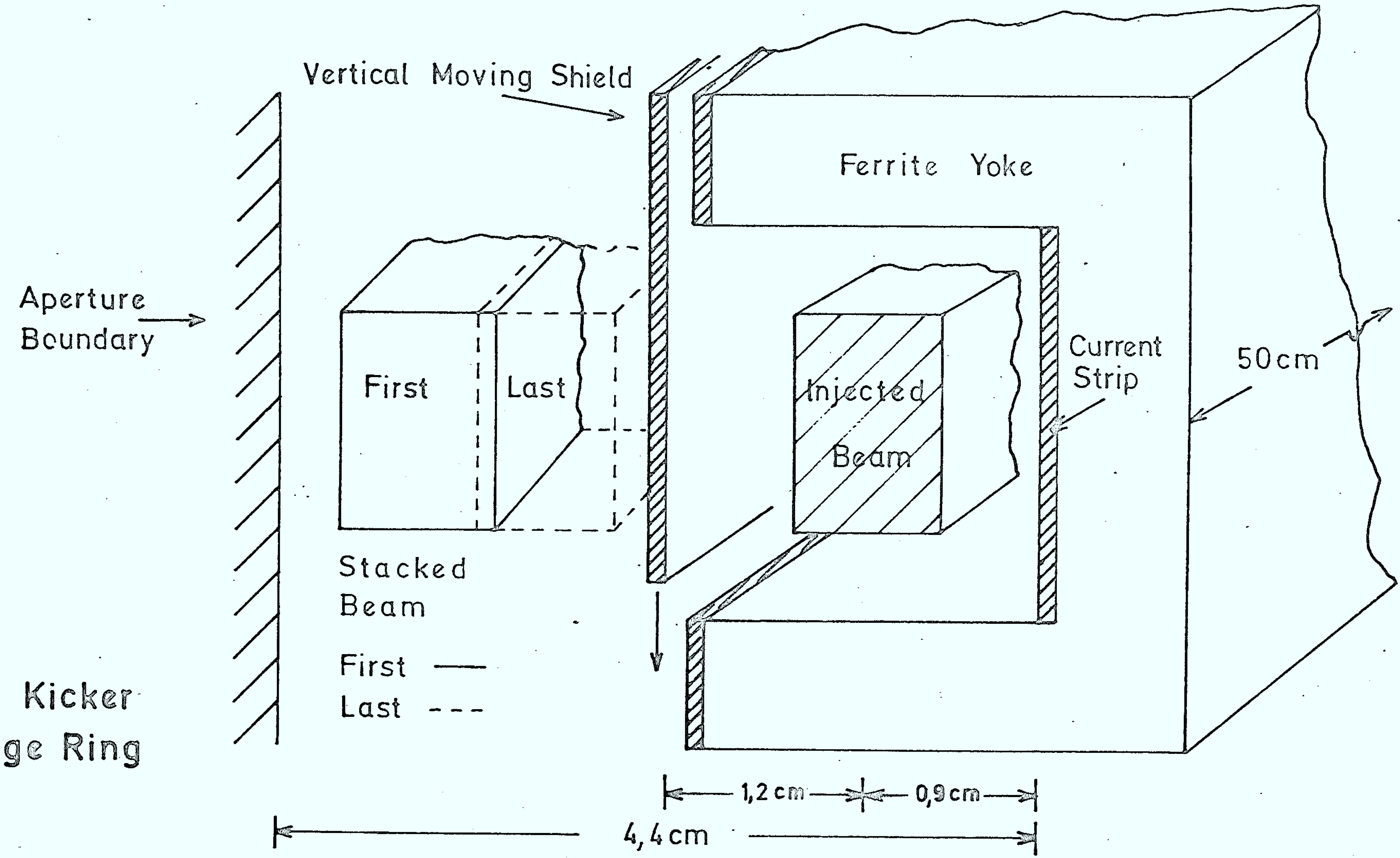

FIG. 3
Shielded Kicker
for Storage Ring

Beam Intensity Limits

Under proposed conditions for initial operation (i.e. beam momenta equal and ranging between 2 and 3.5 GeV/c, 3 MeV kinetic energy injection into the synchrotron), the strength of the electron beam is RF power limited while the fundamental limit on the intensity of the proton beam is believed to be the incoherent space charge limit in the synchrotron [4]. The beam-beam tune shifts are small, being less than 10^{-2} for the electrons and 10^{-3} for the protons. Longidudinal effects of the bunched electrons upon the protons recently studied by Augustin [7] and Rees [8] are small in the case under consideration [9]. If certain improvements are made, to be discussed under the heading of luminosity, the beam-beam limit for the allowed number of electrons may indeed become the fundamental limit at the lower end of the momentum range.

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 [10] and that the Q' required to supress it [11] 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 [12] 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 [13].

While theoretical estimates and scaling from the ISR experience make it seem likely that ion effects will be ameliorated sufficiently by the presently planned DORIS ion sweeping system, past experiences with stored protons [10, 14] have shown that it is impossible to predict all the effects one might expect with the existing theory. Thus one may need to effect an improvement in the ion-sweeping system.

Lifetime of Protons

Multiple scattering on the residual gas provides a rather severe limit on the lifetime. Using an approximate formula [15] we find that the expected lifetime due to this process varies from 0.5 hr. at 1.0 GeV/c to 8.3 hr. at 3.5 GeV/c when the residual gas pressure is 10^{-9} Torr (air equivalent). It is possible that intrabeam scattering induced diffusion into non-linear resonances or perhaps Arnold diffusion might limit the lifetime. Simple scaling from the ISR would predict no problem, however, the theory is not yet on a firm experimental foundation [16, 17] and should these phenomena prove important the herein proposed e-p colliding beams will provide an ideal instrument for their study.

Luminosity

In computing the luminosity we use the expression given by Sands [18], based on the physical situation shown in Fig. 6

$$\simeq \frac{2}{\pi} \frac{N_e N_p f}{\bar{W} \delta l} \qquad \text{(two interaction regions)}$$

N_e = number of electrons

N_p = number of protons

f = revolution frequency of electrons

$\bar{W}$ = RMS beam width averaged over the effective interaction length (2σ)

l = orbit circumference

2δ = beam crossing angle

The proton beam is assued uniformly spread around the ring (no bunches). In the momentum range of interest, that is 2.0 to 3.5 GeV/c per beam, the number of electrons is limited by available RF power, the number of protons being limited by space charge detuning in the synchrotron under proposed conditions of operation [4]. Under these conditions, should we inject directly at the operating energy, the number of protons in the storage ring will rise linearly with energy. This rise is cancelled by the approximately linear rise in $\bar{W}$, the radiation controlled electron beam width, with energy. Thus the luminosity scales with energy as does the number of electrons. For a given optics of the storage ring, in particular the momentum compaction factor, the number of electrons allowed at a given energy is determined solely by the RF power. This number can be computed using the power balance equations [19] and the result is shown in Fig. 4. The luminosity implied by these numbers of electrons is given in Fig. 5 (a). The parameters that were used in the computation are shown in Table 1 and are based upon some reasonable assumptions about the final storage ring optics.

Should preliminary results with the ep-colliding beams make it seem attractive, several strategems could be employed to increase the luminosity. First, and most easily effected, one could operate with positrons and protons so that by placing vertical bending magnets on either side of the interaction point the crossing angle can be made arbitrarily small [2]. As shown in reference 2, it doesnt' pay to go below a crossing angle of six milliradian because the interaction region becomes too long. At a crossing angle of six milliradian the luminosity is a factor of two higher than at 16 mr. The expected luminosity

TABLE I :

List of parameters used in obtaining Figures 4 and 5.

RF power per ring	750 KW
Number of cavities per ring	12
Shunt impedance per cavity	$3 \times 10^6\ \Omega^{+,\ ++}$
β_x (horizontal betatron function at interaction point)	10 cm
2δ (crossing angle)	16 mr
$2\sigma_x$ (3.0 GeV)	635μ
Orbit circumference	288 m
ϕ_s (all energies)	17.5^o
number of protons (2.0 GeV)	1.6×10^{13}
injection energy of protons into storage ring	operating energy
injection energy of protons into synchrotron	3 MeV
$\eta_{protons}$ (dispersion at interaction point)	0

\+ see ref. 19 for definition

++ cavity assumed matched at each value of electron current

with positrons and protons colliding is given in Fig. 5 (b). Second, one might increase the number of electrons allowed by connecting the transmitters associated with the proton ring (where they are not needed) in parallel with the transmitters driving the electron ring. This could in principle give a factor of two in power and essentially double the beam. Simultaneously one could increase the energy of proton injection into the synchrotron to 15 MeV allowing the acceleration of about 3 times as many protons as with 3 MeV injection. Thus at 3.5 GeV/c per beam the increase in proton injection energy would allow an increase of a factor of 3 in the luminosity. At 2.5 GeV/c there would be little if any improvement as the space charge limit of the storage ring itself would limit the number of protons. The luminosity resulting from this simultaneous increase in the number of electrons and positrons is shown in Fig. 5 (d). Third, if the two rings of the storage ring could be wired independantly, one might preserve the energy available in the center of mass by running the proton beam energy as high as possible and lowering the electron energy to obtain a higher electron current. We are thus helped by three factors:
At lower energy for the electron beam the radiation loss is less so we may have more electrons for a given power; in addition lower energy for the electrons means a narrower beam; on the proton side, higher energy means more protons stacked into the storage ring. Putting these things together and assuming a 4 GeV/c momentum for the proton beam we find an improved luminosity as shown in Fig. 5 (c).

Ultimately the limit on the electron beam tolerable is the beam-beam limit for the detuning of the protons by electrons. Recent work [16, 17] has made it seem likely that a tune shift for protons between .001 and .005 is the maximum allowed. The approximate boundary for ΔQ (protons) = 2×10^{-3} is shown also in Fig. 2.

Conversion of the DORIS - DESY Synchrotron System to Proton Operation

Conversion of the synchrotron to proton operation has been discussed elsewhere [5]. Conversion of DORIS to proton operation with momentum stacking for filling involves principally three things. First a moving shield kicker must be installed such as described above, second an RF system for effecting the momentum stacking is required and third, a means for measuring the intensity and profile of the beam must be provided. Fig. 7 shows a suitable space for the moving shield kicker [20] which can be used with minimal interference with planned e^+e^- operations. In addition to the moving shield the kicker magnet itself must be movable so that it can be withdrawn during e^+e^- operation to avoid aperture restriction and induced heating effects in the ferrite.

The strength required for the kicker is given by the formula [+)]

$$\theta_k = \frac{X}{(\beta_s \cdot \beta_k)^{1/2}}$$

Assuming that the septum and kicker are (2n + 1) 90^o apart in betatron phase and that injection is parallel to the equilibrium orbit at the septum, then θ_k is the angle by which the beam must be kicked to place it on the correct equilibrium orbit. X is the distance from the center of the injected beam outside the septum to the equilibrium orbit while β_s and β_k are the betatron amplitude functions at the septum and kicker respectively.

$X = W_s + 2\,W_c + W_B$ where W_s is the septum thickness, W_c is the clearance that must be allowed between beam and septum and W_B is the beam width at the position of the septum. We assume no dispersion at the septum and that the emittance of the beam injected into the synchrotron is 82 x 10^{-6} radian meter at 75 MeV/c. In addition we take $2\,W_c + W_s$ = 7 mm so that

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+) For this to be correct the derivative of β with respect to distance along the orbit evaluated of the septum or kicker must be zero.

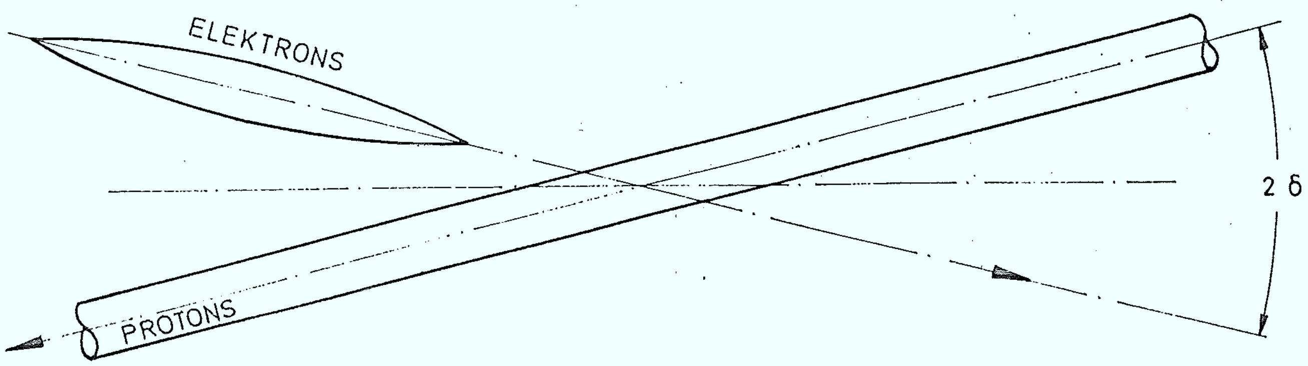

Fig. 6 Symbolic Vertical Cross Section Near Interaction Point

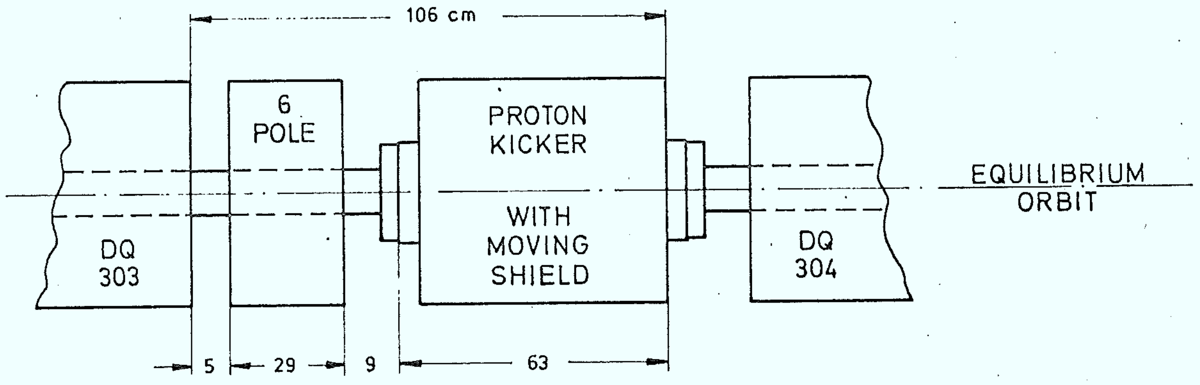

Fig.7 Position of Proton Kicker in **DORIS** Lattice

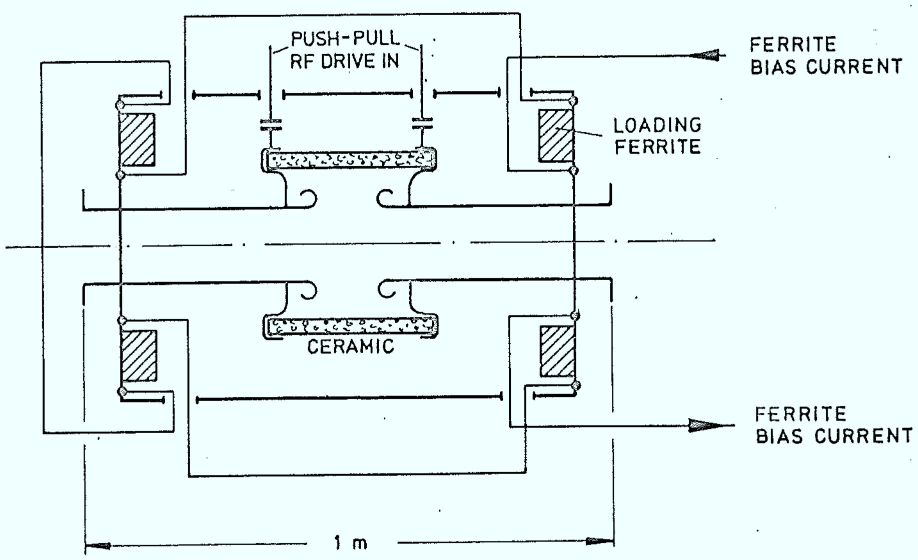

Fig.8 Schematic of Storage Ring Stacking and Manipulation Cavity

β_s being taken as 15.3 meter [21)]

X (2 GeV/c injection) $\simeq$ 2.1 cm

X (4 GeV/c injection) $\simeq$ 1.7 cm

If for β_k we now take 5 meter [21)] we have

$$\Theta_k \text{ (2 GeV/c injection) } \simeq 2.4 \text{ mr}$$

$$\Theta_k \text{ (4 GeV/c injection) } \simeq 2 \text{ mr}$$

For a kicker length of 50 cm then, the kicker magnetic field will be

$$B_k \text{ (2 GeV/c injection) } \simeq 320 \text{ Gauss}$$

$$B_k \text{ (4 GeV/c injection) } \simeq 533 \text{ Gauss}$$

Both of which are relatively modest numbers and should present no exceptional problems in their achievement.

The requirements on the cavity system are substantially less than in the case for proton acceleration the synchrotron in terms of frequency range. The voltage requirements for acceleration are comparable. Between 2 and 4 GeV/c the velocity of the proton increases by about 7% so that the maximum tuning range of the cavity need be only 7%. During stacking where both the momentum and radius change

$$\frac{\Delta f}{f} = \left(\frac{1}{\gamma^2} - \alpha \right) \frac{\Delta p}{p}$$

and we assume the optics is set so that

$$\alpha = \gamma_{TR}^{-2} \ll \gamma^{-2} \text{ so that}$$

$$\frac{\Delta f}{f} \simeq \frac{1}{\gamma^2} \frac{\Delta p}{p} \approx \frac{1}{10} \times 10^{-2} = 10^{-3}$$

for a one percent change in momentum during stacking. In principle then, if injection took place at the operating energy so that no acceleration were necessary, then the electronic tuning range could be restricted to about 10^{-3} with some form of mechanical tuning being used for changing operating energy. This would allow minimal loading by the (inevitably) lossy tuning element and result, in principle, in a much higher shunt impedance. The voltage requirements set by stacking are considerably lower than those required by acceleration. In order to obtain efficient stacking the RF buckets in the storage ring should fit tightly around the bunches ejected from the synchrotron. This condition is roughly equivalent to having the bucket heights equal in the two machines. In terms of the conventional proton synchrotron nomenclature [22)] then

$$V_{SR} = V_{Syn} \frac{\gamma^2 (\Gamma)_{Syn}}{\gamma^2 \ (\Gamma)_{SR}} \cdot \frac{h_{SR}}{h_{Syn}} = 10 \text{ KV} \times \left(\frac{.91}{1.41} \right)^2 \times \frac{10}{11} = 3.8 \text{ KV}$$

For acceleration the RF buckets in the storage ring must be large enough to allow for adiabatic capture. The actual acceleration voltage necessary is very small being about 30 volts for an acceleration rate of 100 Gauss per second. The cavity voltage is then that required to adiabatically capture the stacked beam with a momentum spread of 2.5×10^{-3} which corresponds, after adiabatic capture at 2.0 GeV/c to a bucket half height of 4.2×10^{-3} in $\Delta p/m_o c$ units. The voltage required to produce this bucket size using the 10 th harmonic of the revolution frequency (necessary to match the synchrotron RF) is $V_{SR} \simeq 4.8$ KV. With the large number of particles anticipated however, there is a substantial space charge repulsive force tending to weaken the phase focussing of the RF, Parametrizing this in the standard way [23)] we have

$$\Lambda \quad A_{sp.c} = 4\pi \ h \ g_c \ E_o \ r_o \ N \ / \ \text{ReV} \ \gamma^2$$

where h = harmonic number of the RF

g_c = 1 + 2 ln (chamber diameter / beam diameter)

E_o = M_oC^2 (proton)

r_o = 1.5×10^{-18} meter

R = Average radius of storage ring

eV = cavity voltage

γ = Lorentz factor of protons

Putting in the numbers for 2 GeV/c protons

$$\Lambda A_{sp.c} = \frac{4\pi \times 10 \times 2.4 \times .938 \times 10^9 \times 1.5 \times 10^{-18} \times 1.6 \times 10^{13}}{46 \times 5 \times 10^3 \times 5.5} = 5.4$$

yielding a bucket shrinkage of about 30% ($\phi_s \simeq 0$, see Fig.III.3.2.2 of ref.23) which means that the voltage must be increased to

$$V \simeq (1.3)^2 \times 4.8 \text{ KV} = 8.1 \text{ KV}$$

Thus an approximately 10 KV capability is required also for acceleration in the storage ring. As noted above one could in principle take advantage of the narrow tuning range and make a very lightly loaded cavity of high shunt impedance. There are two reasons for not doing so for the initial operation as discribed above. Firstly, at these frequences (λ = 30 m), it is mechanically difficult to realize high shunt impedance in a limited space and secondly a shunt impedance of more than a few thousand ohms is dangerous from the point of view of beam-enviornment instabilities. This last point is particularly true of modes other than the fundamental which normally have also a relatively high shunt impedance in a lightly loaded cavity and against which feed back at the fundamental can do nothing. For these reasons it seems wisest to begin with a relatively heavily ferrite loaded cavity even though the tuning range is not needed. This ferrite is then in intimate electromagnetic contact with the gap and provides an excellent damper for the higher modes. Later experiments with tightly bunched proton beam may require special cavities. A cavity of the type proposed for initial operation is shown very schematically in Fig. 8. This is simply a half-wave cavity where enough ferrite is installed to foreshorten the guided wavelength to the available dimensions. ($\lambda_g \sim 2$ meter in this case). In a practical case there will be some loading capacitance associated with the gap which will also shorten the cavity and reduce the shunt impedance. For one meter of ferrite and a typical gap-associated capacitance of about 10^{-10} farad, the required μ of the ferrite is about 26. Should we select the same ferrite used in the CERN PS Booster cavities [24] Phillips 4L2, we know that the ferrite figure of merit, μQf, is greater than 0.8×10^{10} near to 10 MHz [25]. These figures then lead to an expectation for Q of about 30.6. Since, to a good approximation

$$Q \simeq \omega R_s C$$

where C is the gap loading capacitance and R_s is the shunt impedance we have

$$R_s \sim \frac{30.6}{2\pi \times 10^7 \times 10^{-10}} \sim 4.9 \times 10^3 \Omega$$

so that the power required for 10 KV gap voltage is

$$P = \frac{V^2}{2R_s} = \frac{10^8}{2 \times 4.9 \times 10^3} \sim 10 \text{ KW}$$

which could be handled nicely by a pair of 4 CX 15000's in push pull. For stacking the power is much more modest, being only 1.6 KW for 4 KV.

In addition to the special kicker and cavity some beam measurement devices will be necessary. Single particle orbits can of course be studied with a low current bunched beam and normal inductive pickups. These can also be used with a high intensity beam by means of RF scanning [6]. However, some means of intensity and profile measurement will be necessary for the undisturbed cossting beam. A "DC transformer" type of detector can be used for intensity measurements. In such a device one measures the state of magnetingation of a ferromagnetic ring surrounding the beam through measurement of the inductance of a secondary winding or similar scheme. For the profile measurement a residual gas ionization scanner such as those used at Argonne [26)] and CERN [27)] suggests itself.

As cost estimate for conversion of the DESY synchrotron to proton operation was given in Ref. 5. Below in Table 2 is a list of the estimated costs for conversion of DORIS for protons.

TABLE II :

Costs for Converting DORIS to Proton Operation

Item:	costs (KDM)
1. Shield kicker with power supply and pulser	250
2. RF System	400
3. Beam Detectors	120
4. Controls and Cabling	200
total	970

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