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The DESY Synchrotron as a Proton Injector for DORIS

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Introduction:

Preliminary studies [1,2] have shown that it would be desirable to store protons in DORIS to serve as a target for both electron and positron beams. Under favourable conditions it is estimated that a luminosity in excess of 10^{30} $cm^{-2}sec^{-1}$ may be achieved [2]. Such an accomplishment would be useful both for physics directly and as a prototype for a much larger electron proton colliding beam facility. Because of its role as electron and positron injector for DORIS it seems natural to consider the DESY synchrotron also as an injector of protons. All investigations to date have indicated that with minor additions the DESY Synchrotron is eminently suited to this task, thereby offering a great saving in manpower, time and money as compared to the construction of an auxiliary synchrotron for this purpose, as previously propsed [1,2].

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1) Gerke et al., DESY Interner Bericht H-72/22

2) Wiedemann + Wiik, DESY Interner Bericht F 35-72/3

Summary of Required Synchrotron Modifications

Enabling the DESY synchrotron to accelerate protons in addition to electrons and positrons will require certain additions and minor modifications: A source of protons must be provided, some means for providing the necessary magnetic field wave form must be arranged and a frequency modulatable accelerating device must be added. Provision for multi-turn injection as well as proton beam size measuring equipment will also have to be made.

As proton source it is proposed to use a 3 MeV Van de Graaff accelerator since such sources have been used successfully as injectors for several synchrotrons [10)] and are commercially available from two sources [11)], and - as seen above - possess adequate brightness [12)]. It turns out that the rate of rise required of the magnetic field, and therefore also the accelerating voltage is determined by the need to minimize gas scattering of the beam at low momenta. The requirement that we suffer less than 20% emittance increase, coupled with the existing synchrotron vacuum of 10^{-7} torr and 75 MeV/c injection momentum, demands that the beam be accelerated at a rate of 4 GeV/c per second for the first 200 milliseconds or so. The acceleration rate during the remainder of the cycle may be slower if desirable. Such a magnetic field cycle, with the necessary precision,

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10) J.J.Livingood, Cyclic Particle Accelerators, Van Nostrand 1961 pp. 156,7

11) National Electrostatics Corp., Middleton, Wisconsin and High Voltage Engineering Corp., Burlington, Massachusetts

12) The instantoneous beam intensity required for 2 turn injections is about 3 ma, far below currently attained valves op. cit. 4,5,6,7,

may be achieved by programming the existing ignitron controlled d c power supply. A small precision power supply of some 25 amperes capacity will be added to provide a suitably stable injection field. To avoid undesirable transient effects some minor switching equipment will also be added. This switchgear will automatically remove certain a.c. components from the magnet circuit during proton acceleration. This system should allow a total cycle time of 2 seconds to be achieved giving a nominal filling time for the storage ring of 191 x 2 sec. $\cong$ 6 minutes.

Taking the above mentioned acceleration rate together with the momentum spread of the injected beam and the anticipated jitter in the injection field level of 2 parts in 10^4, the R F voltage requirement is still only a modest 10 K v. This value should be readily achieved even over the frequency range (0.83 to 9.4 MHz) needed [13]. Because of this rather large frequency range and the absolute necessity for maintaining the longitudinal phase space density two cavities will be needed to cover the frequency range, transfer of acceleration from one to the other being done adiabaticly under phase lock control at a suitable point in the cycle.

To effect proper injection of the Van de Graaff beam a new septum will be required and a beam bump installed. Additionally some analysing equipment for the Van de Graaff beam and the beam circulating in the synchrotron must be provided and the necessary equipment for exciting and synchronizing the R F system and magnet power supply obtained. It is expected that extraction of the proton beam will be carried out in

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13) Cavities in the CERN Booster give 15 k V over a frequency range of a factor of 3. U.Bigliani et al., IEEE Transactions NS 18,3 (1971) p. 233 ff.

exactly the same manner and with exactly the same equipment as in the case of electron and positron beams. Thus no additional equipment or modification will be required in this sector.

A rapid overview of the additional equipment required can be had by reference to figure 1. Exlusive of possible linac and Van de Graaff costs, the provisioning of the DESY synchrotron with the auxiliary equipment necessary for proton acceleration will cost 2 Million DM and take between 19 and 29 months, depending upon the source of the Van de Graaff injector. A breakdown of cost and time schedule appears at the end of this report.

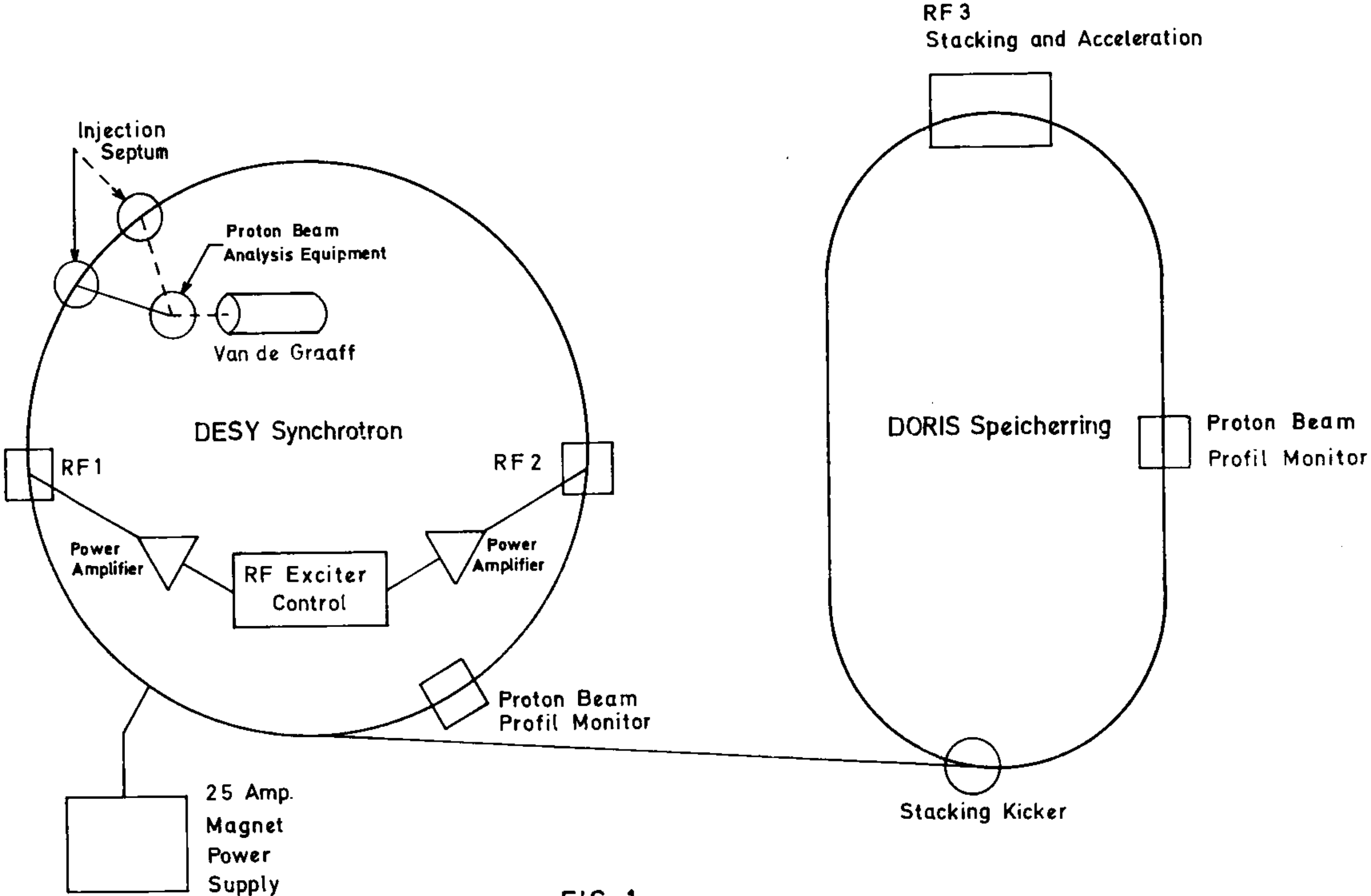

FIG. 1

Principal Additional Equipment Required for Proton Operation

TECHNICAL DETAILS

In this section we shall attempt to justify the numbers presented in the foregoing introduction and to describe in more detail the modifications and additions required in the synchrotron. The presentation will be divided into ten sections, named as follows:

Beam Brightness Limits, Instabilities

Synchrotron Peak Energy

Operating Point

Vacuum Requirements

Magnet Power Supply

R F System

Injection

Ejection

Controls and Monitors

Time Scale and Costs

Beam Brightness Limits, Instabilities

The most basic limitation on the number of protons that can be stored within the useful phase space volume in the storage ring is the Laslett space charge limit for that volume, evaluated at the energy of injection of protons into the storage ring. To evaluate this limit we must know the average proton beam dimensions in the storage ring. Optimum use of the proton beam as a target for the $e^{\pm}$ beam is had when the proton beam has the same width (emittance) as the $e^{\pm}$ beam. Thus we will choose the proton beam width equal to the radiation controlled width of the electron beam at an operating energy of interest for purposes of estimation.

We can then compute the width of the proton beam in the storage ring at the energy of injection by using Liouvilles theorem. Because of the existance of coupling between horizontal and vertical motions through intra beam coulomb scattering and lattice imperfections it would seem unwise to make the vertical emittance of the proton beam much different from the horizontal emittance. For that reason we set them equal in this calculation. Thus the order of the space charge limit calculation is as follows: From the "natural" radiation controlled width of the electron beam at a colliding beam operating energy of interest compute the invariant emittance. This number will be the desired invariant emittance of the proton beam in both planes. Now find the proton beam emittance at injection energy for the proton beam. From the optics of the storage ring lattice under injection conditions compute the proton beam average half width and half height. Insert these dimensions into the Laslett formula and obtain the space charge limit at the injection momentum.

As a typical colliding beam operating momentum we choose 3 GeV/c. With a betatron amplitude function, $\beta(0)$, of 0.1 meter in the interaction region we have, at 3 GeV [14),]

$$2\,\sigma_H = 480\mu$$

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14) H. Nesemann, Private Communication (8.72) und Vorschlag zum Bau eines 3 GeV Elektron-Positron Doppelspeicherrings für das Deutsche Elektronen-Synchrotron (1967) - Abb. 31
The theoretical value for $2\sigma_H$ is subject to change as the optical structure of the storage ring is optimized. For example one of the structures being intensively studied at present (1.73) gives $2\sigma_H$ = 653μ . When $\beta(0)$ = 0.1 meter at the interaction point. In the case of 2σ beam widths larger than the 480μ used in our estimates the Laslett limit will be higher by roughly the square of the beam width ratios.

where σ_H is the standard deviation of an assumed Gaussion distribution of betatron oscillation amplitudes. To include 87% of the beam particles rather than the 67% included within $\pm\sigma_H$ we take W_H, the horizontal width of the beam as

$$W_H = 2 \times 1.5\ \sigma_H = 720\mu \quad \text{at 3 GeV/c}$$

Using the relation [15]

$$W_H = 2\left(\varepsilon_H \beta_H(0)\right)^{1/2}$$

we have then $\varepsilon_H(3\ \text{GeV}) = 1.295 \times 10^{-6}$ radian meter. Setting this equal to the proton beam vertical and horizontal emittance we obtain $\varepsilon_H(\text{proton, 1 GeV)c}) = \varepsilon_V(\text{proton, 1 GeV/c}) = 1.295 \times 10^{-6} \times 3\ \text{GeV/c}/1\ \text{GeV/c}$ $= 3.885 \times 10^{-6}$ rad.meter

Likewise at 2 GeV/c $\varepsilon_H = \varepsilon_V = 1.94 \times 10^{-6}$ rad.meter.

From the DORIS injection envelope [16] we find the beam average half height $\bar{b}$ and average half width $\bar{a}$ to be

$$\bar{b} = 1.33\ \text{cm} \quad \text{and} \quad \bar{a} = 2.72\ \text{cm}.$$

for emittances of 8 mm-mrad and 80 mm-mrad respectively. For our proton beam then we will have

$$\bar{b} = 1.33\left(\frac{3.78}{8}\right)^{1/2} = 0.914\ \text{cm}\ ; \quad \bar{a} = 2.72\left(\frac{3.78}{80}\right)^{1/2} = 0.591\ \text{cm}$$

at 1 GeV/c

and likewise

$$\bar{b} = 0.655\ \text{cm} \quad ; \quad \bar{a} = 0.424\ \text{cm at 2 GeV/c}$$

The space charge limit is [17]

$$N_p \cong \frac{\pi\ \bar{b}\ (\bar{b} + \bar{a})\ B\ Q_V\ \Delta Q_V}{r_p\ R\ F}\ (\beta^2\ \gamma^3)$$

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15) See for example K.Steffen, High Energy Beam Optics, Wiley (1965) p.172

16) DESY drawing H5-SP-OPT-Nov. 27, 1972

17) See for example C.Bovet et al. CERN/MPS-SI/Int. DL/70/4 - A selection of formulae and data useful for the design of AG Synchrotrons

where

B = bunching factor [18] $= 2/\pi$

Q_V = vertical betatron wave number [16] $\simeq 8.25$

ΔQ_V = distance to next lower betatron resonance $\simeq 0.25$

$r_p = 1.53 \times 10^{-18}$ meter

R = average bending radius = 45.8 meter

β, γ = relativistic factors appropriate to injection momentum

F = image force factor [17]

$$= 1 + \frac{\bar{b}\,(\bar{b} + \bar{a})}{h^2} \left\{ \varepsilon_1 \left[1 + B(\gamma^2 - 1) \right] + \varepsilon_2 \left[B\,(\gamma^2 - 1)\, h^2/V^2 \right] \right\}$$

h = vacuum chamber half height $\simeq$ 3 cm

V = magnet gap $\simeq h$

ε_1, ε_2 = image force coefficients [17] = 0.17, 0.41 respectively

$F \simeq 1.15$ for both momenta

Evaluation of the formula at the two injection momenta gives

$$N_p \simeq 1.2 \times 10^{13} \quad - \quad 1.0 \text{ GeV/c}$$

$$N_p \simeq 3.8 \times 10^{13} \quad - \quad 2.0 \text{ GeV/c}$$

The limit we have just estimated is the so called incoherent limit. An extention of the same image force theory [19] gives also a coherent instability limit. Using the formula for this limit as given in reference 17 we obtain

$$N_p(\text{coherent}) \simeq 13 \times 10^{13}$$

so in our case the incoherent limit is the more restrictive, as usual [18].

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18) D.Möhl, CERN MPS/DL/nov.-72-6, p. 5

19) L.J.Laslett L.Resegotti, The space charge intensity limit imposed by coherent Oscillation of a Bunched Synchrotron beam, Proc. IV Acc.Conf. CEAL 2000 Cambridge (1967)

To achieve such a large stored beam multiple pulse injection into the storage ring will be needed. Therefore some method for stacking multiple pulses in DORIS is required. Because of its notable success in the ISR the R F stacking method recommends itself highly for this purpose [8,9]. To evaluate the practicality of using the DESY synchrotron to fill DORIS in this manner we must know the amount of aperture available in DORIS for momentum stacking, the momentum spread to be expected in an individual beam pulse from the synchrotron and the number of protons per individual pulse from the synchrotron. The storage ring aperture available for stacking will be the total aperture less the aperture required by the finite betatron emittance of stacked and injected beams and less the aperture required by the kicker shield and reasonable errors in beam manipulation. At a reasonable position for the fast proton kicker, approximately 15.5 meter downstream from the DORIS septum [20] the available horizontal aperture is 4.4 cm, $\beta(s)^{1/2}$ is about 2.46 $m^{1/2}$ and the dispersion is about 3.2 meter [21]. The combined betatron width of stacked and injected beams at 2 GeV/c is thus $2 \times 2.46 \times 1.94$ mm $\cong 0.7$ cm. If we now introduce a sufficient number of beam pulses that the total stacked proton beam has a momentum spread of 0.25 percent, a further $.25 \times 10^{-2} \times 3.2 \times 10^{2} = 0.8$ cm will be required. We are left then with $4.4 - 1.5 = 2.9$ cm for the shield thickness and manipulation and lattice errors which seems conservative. As shown earlier (p.3) this stacking aperture, together with the known properties of Van de Graaff machines gives an expected stacking capacity

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20) Suggested by K.Steffen

21) op.cit. 16 and G.Mülhaupt, Techn.Notiz H5-24 Nov. 1972

of 191 pulses from the synchrotron provided that we inject at 75 MeV/c momentum into the synchrotron and inject into DORIS at 2 GeV/c. Higher injection energy into DORIS would of course give smaller relative momentum width of the proton beam and thus the possibilities of a higher stacking capacity.

The emittance of the ejected proton beam could be substantially worse than predicted if signifigant non-linear resonances exist in the synchrotron and are crossed and recrossed due to time dependant field errors and synchrotron oscillations [22]. The unusual narrowness of the injected proton beam momentum spread and the high quality of the DESY synchrotron magnet give hope that such will not be the case. Only experiments with protons will sufice for evaluating this effect thus putting a premium on early injection of protons into the ring.

The number of protons per synchrotron pulse is also ultimately limited by the Laslett space charge limit appropriate to the synchrotron at the injection momentum of 75 MeV/c.

As done previously for DORIS, we compute the beam dimensions in the synchrotron at the injection momentum using the required emittance and theoretical lattice parameters. This information is then inserted in the Laslett formula to give the limiting number of protons per pulse. Using the beam emittance computed at 3 GeV we first form the invariant four dimensional emittance:

$$\varepsilon_H \ \varepsilon_V \ (\beta\gamma)^2 = (1.295 \times 10^{-6})^2 \times 10.2 = 17.1 \times 10^{-12} \ \text{rad.}^2\text{meter}^2$$

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22) See for example Green and Courant, Proton Synchrotrons in Handbuch der Physik, XLIV p. 315 - Springer (1959)

At 75 MeV/c we have then

$$\varepsilon_H \varepsilon_V \text{ (75 MeV/c)} = \varepsilon_H \varepsilon_V \, (\beta\gamma)^2 \; / \; (\beta\gamma(75 \text{ MeV/c}))^2$$

$$= \frac{17.1 \times 10^{-12}}{6.36 \times 10^{-3}} = 2.69 \times 10^{-9} \text{ rad.}^2\text{meter}^2$$

For the DESY synchrotron the computed admittance is [23]

$$A_H A_V = 8.43 \times 10^{-9} \text{ rad}^2 \text{m}^2$$

where $A_H = 172 \times 10^{-6}$ radian meter, $A_V = 49 \times 10^{-6}$ rad.meter. If we posit that we may use 2/3 of the vertical admittance and let χ be the horizontal admittance that we may fill we can write

$$\chi \cdot 2/3 \, A_V = 2.69 \times 10^{-9} \text{ rad}^2\text{meter}^2$$

$$\chi = 82.3 \times 10^{-6} \text{ rad.meter}$$

or some 48% of the DESY synchrotron theoretical horizontal admittance. Since the average value of $\sqrt{\beta(s)}$ in the synchrotron is 3.21 $m^{1/2}$ in both vertical and horizontal dimensions we have the average beam half height and half width as

$$\bar{b} = 3.21 \, (2/3 A_V)^{1/2} = 1.84 \times 10^{-2} \text{ m}$$

$$\bar{a} = 3.21 \, (\chi)^{1/2} = 2.91 \times 10^{-2} \text{ m}$$

Putting these numbers into the incoherent limit formula given previously we obtain

$$N_p\text{(Synch., 75 MeV/c)} \cong 1.7 \times 10^{11} \text{ for } \Delta Q = 1/4$$

The image force factor based on synchrotron magnet dimensions [24] is ca. 1.4. The corresponding coherent limit is more than a factor of two larger.

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23) G.Hemmie, Enveloppen and Dispersionsbahnen, DESY - Stand 1.11.72

24) H.Kumpfert, Jahresbericht 1968, DESY Interner Bericht DESY S1-69/3

In our space charge calculations we have tacitly assumed that there is no neutralization of the electric component of the field of the beam due to electrons trapped in the potential well of the beam. While the neutralization of the beam self-defocusing force might at first glance seem beneficial it is known that the ion-beam system can become unstable leading to large proton beam oscillation amplitudes [25,26].

We will show that with a continuous beam of 75 MeV/c momentum i.e. the anticipated injection condition, one might expect such an instability but that by the artifice of introducing a notch in the beam azimuthal charge distribution, all instabilities of this sort can be avoided. Using the formulas of ref. 26 and taking approximate account of the periodic beam shape variation around the orbit, one finds the threshold for beam-electron instability at a neutralization of slightly more than one percent, i.e. one electron for every hundred protons. The rate of ionization by the beam is

$$I \simeq \frac{dE}{dx} \cdot \frac{1}{W} \cdot \rho \cdot \beta c$$

where dE/dx is the energy loss per gram per cm^2 in the residual gas, assumed to be air, W the energy loss per ion pair created, ρ the gas density and βc the protn beam velocity. Taking an operating gas pressure of 10^{-7} torr, dE/dx = 100 MeV/gm/cm^2 at a proton energy of 3 MeV [27] and W [27] = 34 eV per ion pair

$$I \sim 1.1 \times 10^3 \ sec^{-1}$$

Since the revolution period at 3 MeV kinetic energy is about 13 μsec this rate of ionization leads to complete neutralization in about 70 revolutions. The characteristic kinetic energy for the ions will be in the

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25) D.Möhl, A.M.Sessler, Proton-Electron Coupling Instability of Debunched Beams, LBL-ERAN-186

26) op. cit. 8 p 48

27) H.Bethe and J.Ashkin, in Experimental Nuclear Physics, vol I ed by E.Segrè Wiley (1953) p.188

28) op.cit. 27 p. 233

electron volt range [29]. With an energy of one eV, an electron would strike the vacuum chamber wall in less than 0.1 μsec. were it not for the field of the beam. Thus a notch in the beam of less than one microsecond should suffice to allow the electrons to escape. After bunching at 800 kHz such notches will automatically occur. Prior to bunching such a notch may have to be artificially introduced. Because of the narrow energy spread of the beam and the low momentum compaction a one microsecond notch would maintain itself for about 10^4 revolution giving plenty of time for bunching to take place. Such a notch would have the further advantage of introducing an a c component for beam monitoring purposes.

There can, of course, be other instabilities of the beam-enviornment interaction type. One can however draw considerable comfort from the success of the CERN PS in which 2×10^{12} particles per pulse has been accelerated. This number corresponds rather well to the prediction of the Laslett incoherent limit for the PS [30]. Other instabilities that have been encountered at higher energy in the PS have been successfully countered by the addition of modest multipoles, a step already planned for the DESY synchrotron in any case.

One unique difference between the PS and the DESY synchrotron is the presence of the high shunt impedance electron acceleration system in the DESY ring. Because the proton velocity will be different from light velocity and varying with time the interaction between the protons and the electron cavities should be rather small except at discrete values of velocity, namely at those velocities where the phase between a circulating proton and any 500 MHz engendered in the cavities by the beam

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30) op.cit. 18 p. 2

29) M.E.Rudd et al., Phys.Rev. 151 p.2o (1966)

can shift a multiple of 2π radians in the time it takes the proton in question to travel from one cavity to the next. One may write this relationship as

$$\beta_{resonant} = \frac{U}{16\lambda n}$$

where U is the orbit circumference, λ is the 500 MHz wavelength and n is an integer. The "width" of one of these synchronisation resonances is given by the change in β necessary to make the phase of a given test particle with respect to the 500 MHz in a given cavity shift by $\pi/2$ per revolution. Evidently the situation will be worst at high energy where the β changes slowly and the beam current is at a maximum. At that time $\beta \simeq 1$ so that the condition that the change in β required to make the relative phases slip by a quarter wave length per revolution is

$$\Delta\beta \sim \frac{1}{4} \times \frac{1}{528} \sim \frac{1}{2} \times 10^{-3}$$

where 528 is the harmonic number for $\beta = 1$ particles with respect to the 500 MHz system. The change of β per revolution is given by

$$\Delta\beta/\text{rev.} = \Delta T/\text{rev.} \cdot \frac{1}{\beta\gamma^3 m_o c^2}$$

At an acceleration rate of 4 GeV/c sec., the change in kinetic energy per revolution, ΔT, is about 4 KeV. At a peak beam momentum of 2 GeV/c then

$$\Delta\beta/\text{rev.} \sim 0.5 \times 10^{-6}$$

so it takes to about 10^3 revolutions or 10^{-3} sec. to cross a resonance. If the risetime of significant interaction between the proton beam and electron accelerating system is less than or of the order of 10^{-3} sec. the beam will be destroyed. One can hope to reduce the interaction impedance of the electron accelerating cavity system through negative feed back similarly to what has been done at the ISR [31].

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31) op.cit. 8, p. 15

Experiments with coasting electron beams are now planned to test this idea. In extremis remotely controlled short circuiting sleeves could be installed to take the electron accelerating cavities completely out of the circuit.

Synchrotron Peak Energy

As seen above the synchrotron peak energy has a strong bearing on the number of protons that can be stored in DORIS. This dependence came about both through the Laslett limit cubic energy dependance and through the increase of effective momentum stacking aperture which, in principle, increases linearly with the momentum of injection into the storage ring. These two considerations as seen above indicate that an injection momentum above 1 GeV/c is necessary that the charge storage capacity of DORIS be equal to or larger than the capacity of the synchrotron to inject protons. Above 2 GeV/c [32] the capacity of the storage ring begins to outstrip the injection capability of the synchrotron even at 15 MeV injection energy into the synchrotron so that the only advantage of operating above 2 GeV/c would be that one could load directly at the operating energy of interest, thereby avoiding beam acceleration. There are two further considerations which establish rather rigid upper and lower bounds to the synchrotron peak energy. The upper limit is given by the transition energy of the synchrotron which is slightly above 5 GeV. One can, of course, pass through the transition energy. However such passage results in substantial phase space dilution, e.g. a factor of 6 in energy spread in the PS [33] at CERN. In the future it is possible that tricks for

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32) B.Barbalat, MPS-DL-Note 71-16 CERN

33) The present transport system between synchrotron and storage ring has a momentum capability of 2.2 GeV/c.

passing transition will be developed so that this difficulty can be circumvented. The lower limit on the transfer momentum is established by the vacuum in the storage ring. Computing the lifetime due to multiple scattering diffusion to the walls from an approximate solution to the Fokker-Planck equation [34)] we find

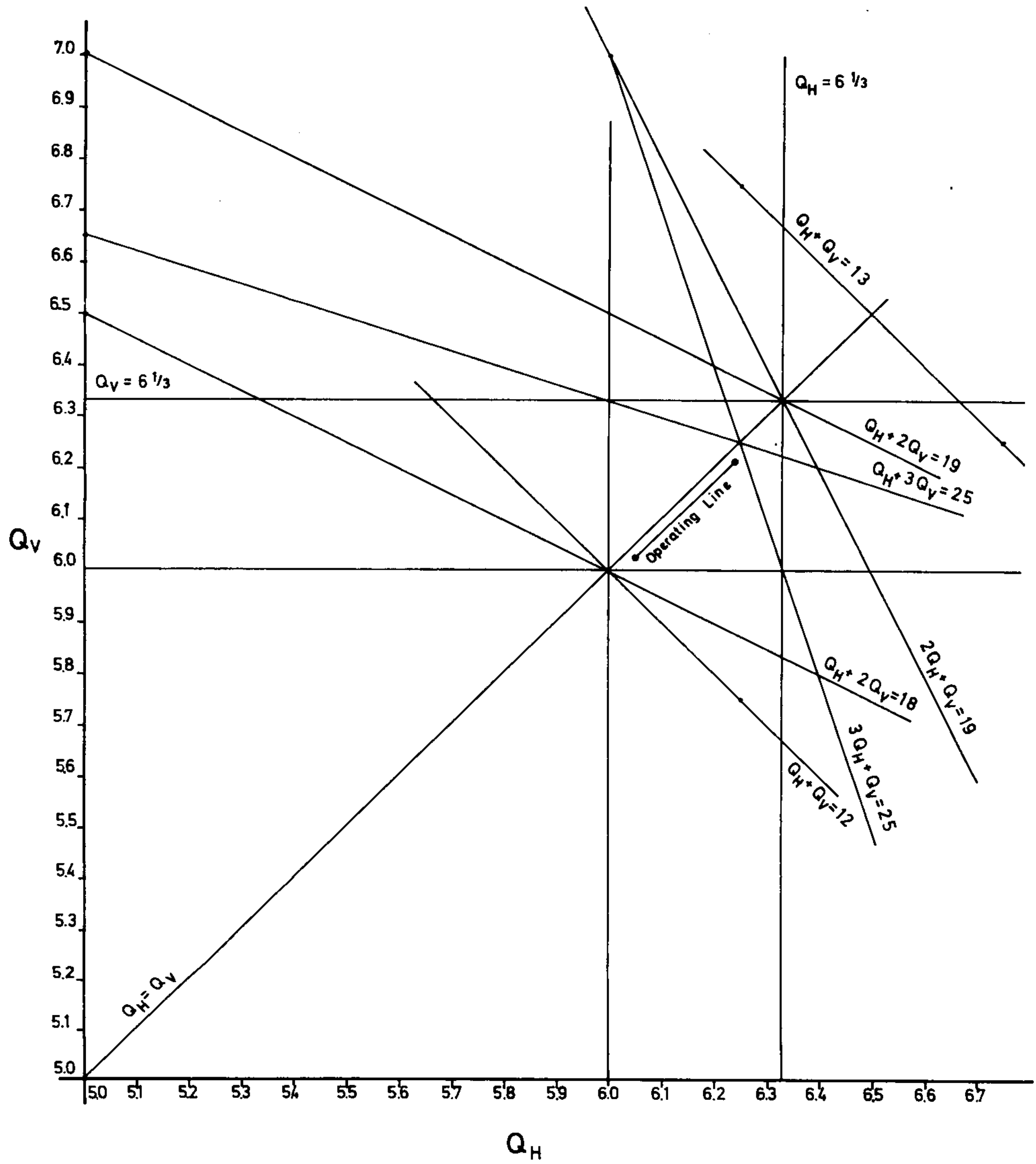
$$\tau(\text{protons in DORIS}) \simeq 0.5 \text{ hours at } 1.0 \text{ GeV/c}$$

Since this life time is proportional to $\beta^3\gamma^2$ we will have a diffusion life time of five times longer or 2.5 hours at a momentum of 2 GeV/c. We have estimated above a filling time of the order of 6 minutes. Comparing the filling time to the expected lifetime it is clear that 1 GeV/c is the lower limit for useful injection momentum.

Operating Point

Because the space charge detuning will have a profound effect on the operating point and because we want to preserve the beam brightness we need to work away from non-linear resonances as well as the usual linear resonances. At any Q_H, Q_V the beam will occupy an area rather than a point in the Q_H - Q_V diagram. This spreading will be due to the multipole moments of the lattice (single particle effect) and of the proton charge distribution (collective effect). The most important component of lattice non linearly is the sextupole moment which gives a chromaticity of -11 and -3.5 for horizontal and vertical directions respectively. For the planned momentum spread at injection $\Delta p/p$ = 5×10^{-4}, we have $\Delta Q_H \simeq 0.006$ and $\Delta Q_V \simeq 0.002$. From amplitude dependant betatron oscillation measurements one can say that higher multipoles will not contribute more than $\Delta Q_{HV} \sim 0.01$. These spreads will probably

34) W.Hardt, CERN ISR-300/GS/68-11



Q_V
Q_H
7.0
6.9
6.8
6.7
6.6
6.5
6.4
6.3
6.2
6.1
6.0
5.9
5.8
5.7
5.6
5.5
5.4
5.3
5.2
5.1
5.0
Q_V = 6 1/3
Q_H = 6 1/3
Q_H = Q_V
Q_H + Q_V = 13
Q_H + 2Q_V = 19
Q_H + 3Q_V = 25
Operating Line
2Q_H + Q_V = 19
Q_H + 2Q_V = 18
3Q_H + Q_V = 25
Q_H + Q_V = 12

be small compared to the spread introduced through non-uniformity of the beam charge distribution which in principle can give a spread almost as large as the maximum space charge detuning. This spread, which can only be measured by experiment and which will depend upon the injection trajectories, will determine the extent to which the full ideally allowable space charge detuning can be utilized. Fig. 2 shows an operating diagram for the synchrotron and an ideal operating line for a perfectly uniform beam with sharp edges. The end point at the upper right represents the operating point for single particles while the end point of the lower left gives the operating point for the fully loaded machine before acceleration has taken place.

Vacuum requirements

Due to the strong multiple scattering of the low energy proton beam by the residual gas the time permitted for acceleration is severly limited. This time constant determines the required characteristics of the magnet power supply and R F system.

Assuming a gaussian distribution of the injected beam and a linearly rising magnetic field during acceleration we may write the change in the invariant emittance of the beam [34] as

$$\Delta(\varepsilon\beta\gamma) \simeq 0.32 \frac{\lambda\, p\, \tau}{\beta_f\, \gamma_f} \cdot \frac{1}{\beta_o}$$

where $\lambda = R/Q = \frac{50.4}{6.25}$ meter

p = residual gas (air) pressure in torr
τ = acceleration time in seconds
$\beta_f\gamma_f$ = $\beta\gamma$ at peak momentum = 2.13 for 2 GeV
β_o = v/c at injection = 0.08 (75 MeV/c)

For purposes of establishing limits let us say that we will permit a phase space dilution of no more than 20%. We take as the basic invariant emittance that value given by the storage ring electron beam at 3.0 GeV.

$$(\varepsilon\ \beta\ \gamma) \simeq 4.1 \times 10^{-6} \text{ rad.meter}$$

so that $\Delta(\varepsilon\beta\gamma) \leq 0.83 \times 10^{-6}$ rad.meter. Inserting and solving for τ we find

$$\tau \leq 0.55 \text{ sec for } p = 10^{-7} \text{ torr}$$

This requirement demands that acceleration between 3 MeV and a few hundred MeV take place at a rate of

$$\frac{2 \text{ GeV/c}}{1/2 \text{ sec}} = 4 \text{ GeV/c/sec}$$

Experience has shown that a residual gas pressure of 10^{-7} is practical to achieve without significant effort. Because the capability of the individual components of the vacuum system is substantially better than this value ($< 10^{-8}$ for the ceramic chambers for example) one might be able to improve the average operating pressure by at least a factor of 2. To be conservative, however, we shall use 10^{-7} torr as our working number.

Another important parameter is the amount of time allowed for "adiabatic" capture of the beam at injection. Because the injected beam is unbunched we should like to be able to turn on the R F slowly to capture a large fraction of the beam. Unfortunately the worst scattering by the residual gas takes place at injection time so we have a very limited time for capture. Under conditions of constant momentum we use our scattering formula above with $\beta_o = \beta_f$ and find, for $\Delta(\varepsilon\beta\gamma) = .10(\varepsilon\beta\gamma)$, $p = 10^{-7}$ torr an allowed capture time of 10^{-2} sec. which corresponds to about 750 revolutions.

As we shall see later this time will allow more than 10 synchrotron oscillations to take place during capture even with slow turn-on of the R F so it should be entirely adequate.

Magnet Power Supply

In as much as the DESY synchrotron magnet normally operates in an almost fully based condition (a c current = d c current) the d c power supply can manifestly operate the magnet at a field corresponding to more than 3.5 GeV/c. Further, as this d c supply is ignitron controlled, one should be able to generate any current waveform consistant with the inductance and resistance of the magnet and with the maximum d c voltage of the supply. To compute the limiting performance that might be achieved with the present power supply we take the total inductance and resistance of the magnet itself, 1.39 henry and 0.825 ohm together with the maximum d c supply voltage for normal operation [35], 1060 volts. If the full supply voltage is applied to the magnet, the field will rise to a momentum equivalent value of 2.4 GeV/c in 0.6 sec after application of the voltage. It at 0.6 sec, this voltage is reversed, the field will pass through zero at just over 1.0 sec measured from the initital application of voltage. The waveform thus obtained is shown roughly in Fig. 3 and would correspond to a minimum cycle time of about 1 sec. If instead of reversing the voltage at 2.4 GeV/c it were merely brought to zero and the current permitted to decay by dissipation in the magnet coils the field would decay to a momentum equivalent of 75 MeV/c in about 5 1/2 sec. after turn off giving a minimum cycle time of about 6 seconds. A value somewhere in bet-

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35) G.Bothe, Private Communication

ween could be achieved also without reversing the supply voltage by switching in a water coold resistor bank with transistors at the appropriate time. Of course, the highest cycling rate practical should be employed because the amount of time necessary for proton beam tune-up is directly related to the cycling rate.

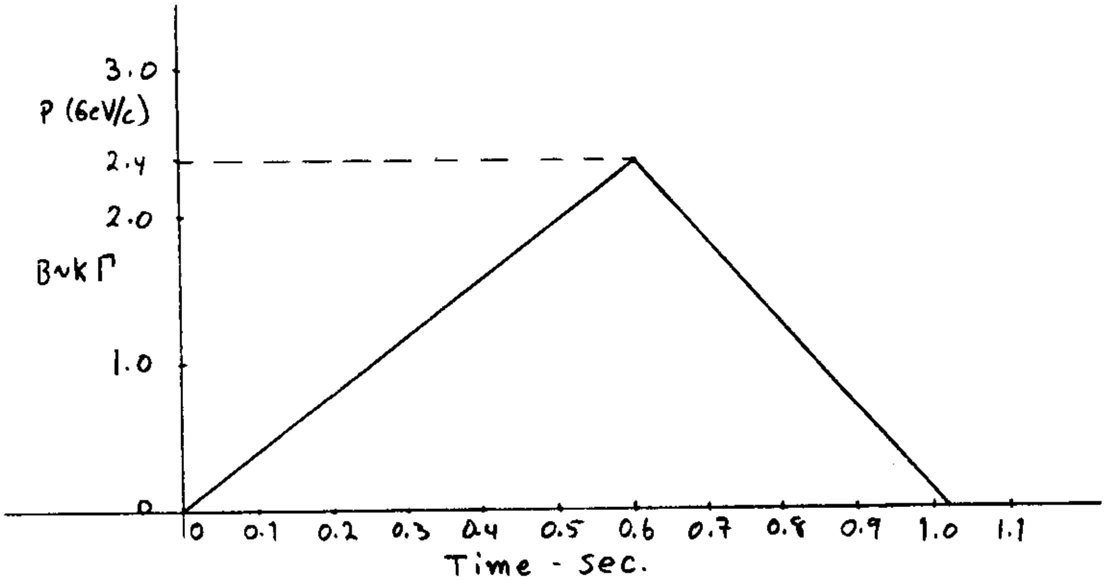

Fig. 3

Under normal a c operating conditions the magnets are also interconnected with the chokes and resonating capacitors. The chokes add substantial inductance and resistance. The presence of the resonating capacitors and capacitance to earth of the distribution cables could also lead to unpleasant transient effects when the d c supply voltage is applied. It is therefore proposed,if necessary, to install automatically controlled and interlocked switches in the ring tunnel to switch these components out of the circuit during porton operation. The part of the circuit affected is shown in Fig. 4

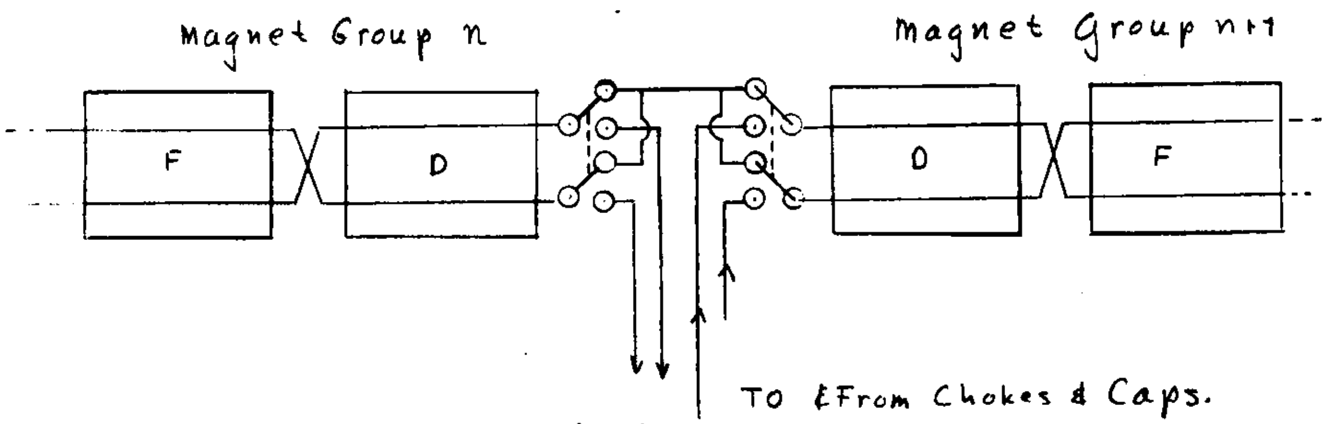

Fig. 4

The switches are shown in the positions appropriate for proton operation.

As will be seen when we examine the R F requirements the value of the injection field level needs to be held stable to 2 parts in 10^4 to avoid excessive R F voltages. That being the case, the regulation problem could be made considerably easier if a small precision power supply were diode added with the main supply. The magnet current required for 75 MeV/c momentum is only about 12.5 amp. so this extra supply would be small. If the voltage of the main supply is reversed to bring the current rapidly to zero, the power supply adding diode will have to be an SCR.

With a symmetrical wave form such as figure 3 and a peak current of 400 amps which corresponds to 2.4 GeV/c, the total average power dissipated in the magnet coils will be about 66 Kw.

The magnetic field cycle can be summarized as follows. With the pedestal of 12.5 amps being supplied by the small injection supply the injector is pulsed. The beam coasts at this field level for about 5 milliseconds while the R F is turned on and the beam begins to bunch. At the end of this period the main magnet power supply is brought on uniformily from zero to full voltage in the course of another 10 milliseconds or so to avoid excitation of significant synchrotron oscillations. The full voltage is held constant until the desired peak field level is reached at which time the voltage is either reversed or brought to zero and damping resistors switched in to return the magnet current to the injection value. The early part of the acceleration cycle is depicted schematically in Fig. 5

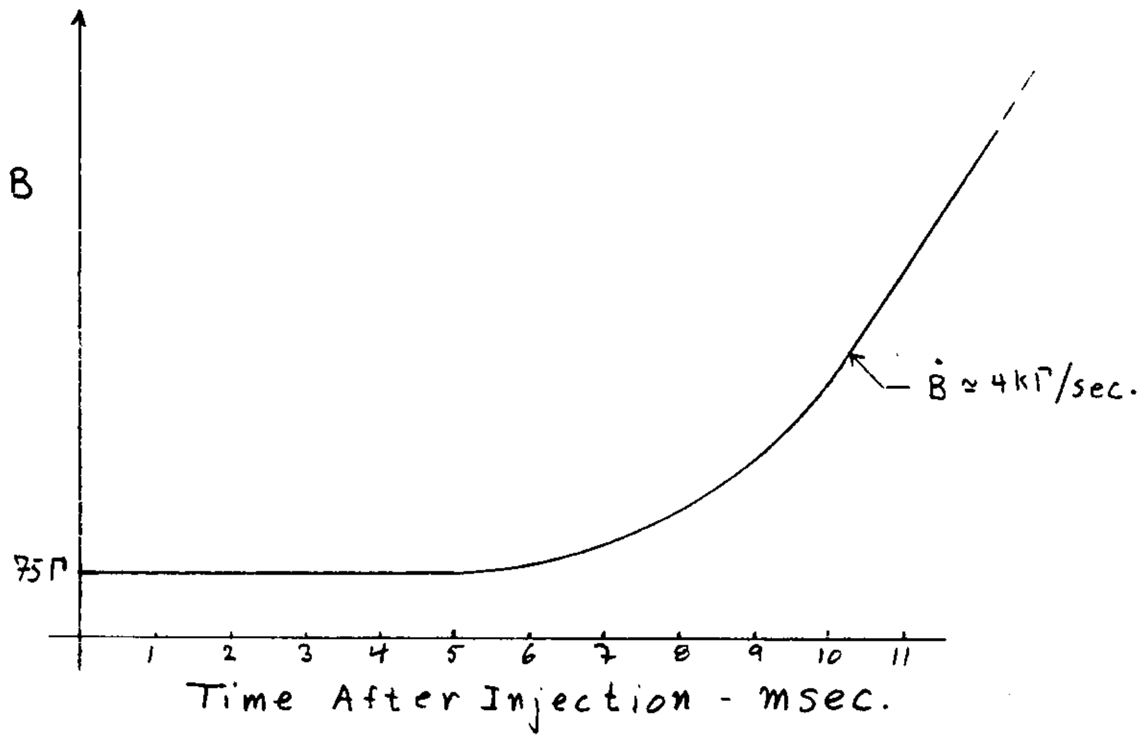

Fig. 5

R F System

The basic parameters of the R F system - frequency and voltage - depend in the first case on the relationship of the synchrotron and storage ring circumferences as well as their absolute values and in the second case upon the rate of rise of the magnetic field (and thus the vacuum) and the energy spread in the injected beam and precision of the field value at injection.

With regard to the frequency one notes that the synchrotron to storage ring circumference ratio is 1.1. Thus if the R F frequencies in the two devices are to be the same, as seems advisable, the lowest frequency that will do is the 11th harmonic of the rotation frequency in the synchrotron. At injection time, T = 3.0 MeV (75 MeV/c)

and $f_{o,i} = .075505$ MHz

while at 2.0 GeV/c $f_{o,f} = .856837$ MHz

so $\frac{f_f}{f_i} = 11.34$

and the 11th harmonics are F_{11}(injection) = 0.830 MHz

F_{11}(end of cycle) = 9.425 MHz

We assume that these frequencies will be used as they are in a resonable range for ferrite loaded cavities.

Assuming a linear rise in the field, the R F voltage required will be constant for constant synchronous phase.

$$e\,V \sin \phi_s = 10^{-3}\, C\, \dot{p}$$

eV = maximum energy that can be obtained by passing through cavity

C = circumference of orbit-(meters) = 317 meter

$\dot{p}$ = rate of rise of momentum (eV/c) $\simeq$ 2 GeV/c x 2 $\sec^{-1}$

eV $\sin \phi_s$ = 4.23 KeV

Now to determine ϕ_s we need to know the bucket area required to hold the inejcted beam. To calculate the area required we need to make an assumption about the magnetic field wave form and about its stability. We shall assume that the magnetic field is held constant at injection value until the Van de Graaff is through, a time duration of up to 66 μsec. At that time the acceleration period begins. From the vacuum calculations we know that we have 10 msec to begin accelerating at the full rate. Thus during the first 10 msec we must slowly increase the rate of acceleration until at the end of 10 msec more than half of the full rate of 4 GeV/sec is achieved. While the rate of acceleration is being increased the R F voltage is also increased from 0 to its full value in 10 msec. These functions are shown in Fig. 6.

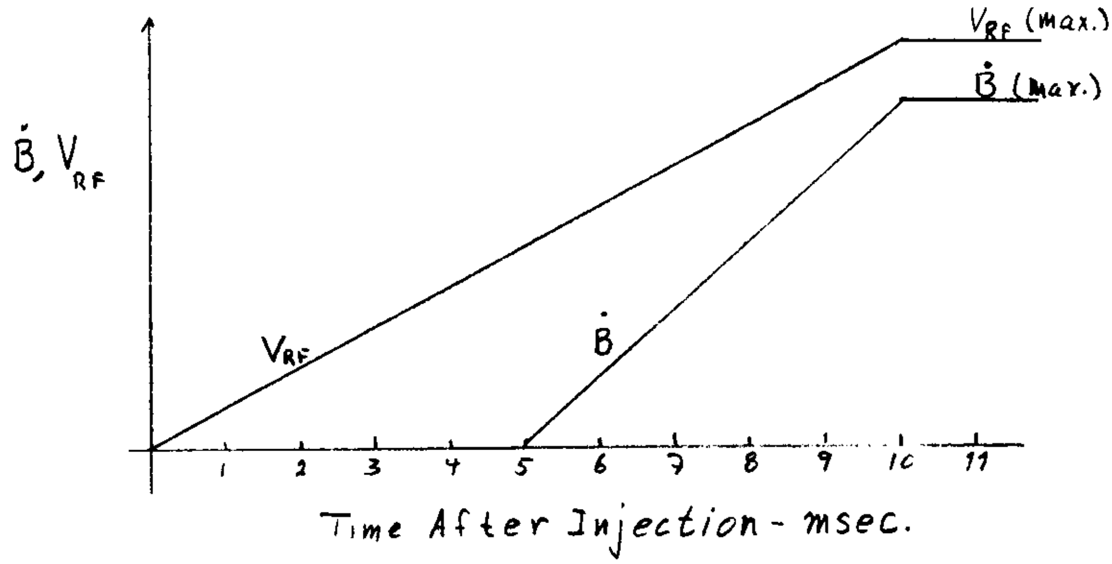

Fig. 6

We can say more about the quantitative aspects of the wave forms by computing the voltages and synchrotron frequency. The spread in kinetic energy from the Van de Graaff machine will be

$$\Delta T \simeq 2 \text{ KeV} \qquad \text{so} \quad \Delta T/T \simeq 0.66 \times 10^{-3}$$

and since

$$\Delta p/p = \frac{1}{2} \frac{\Delta T}{T} \text{ for } v < < c \text{ we have}$$

$$\frac{\Delta p}{p} \simeq 0.33 \times 10^{-3}$$

as the momentum spread of the beam. To this must be added any error in the magnetic field at injection time. Let us assume that we can control

$$\Delta \left(\oint_{ORBIT} B \cdot dl \right) \Big/ \oint_{ORBIT} B \cdot dl$$

at injection to a band of width 0.17×10^{-3} or less so that

$$\left(\frac{\Delta P}{P}\right)_{equivilent} = 0.5 \times 10^{-3} \ ; \quad \left(\frac{\Delta T}{T}\right)_{equivilent} = 10^{-3}$$

Thus the bucket half-height after adiabatic capture will be

$$\frac{H}{2} = \frac{1}{2} \times 10^{-3} \times 3 \text{ MeV} \times \frac{\pi}{2} = 2.35 \text{ KeV}$$

Using formula 3.2.1 of ref. 17 we can solve for the required cavity voltage when $\phi_s = 0$ (adiabatic capture).

$$2.35 \text{ KeV} = \left(11 \text{ eV}\right)^{1/2} \times 1.41 \times \frac{8 \times 10^{-2}}{11} \left(\frac{941 \times 10^{3}}{\pi}\right)^{1/2}$$

$$\text{or } eV = 16 \text{ eV}$$

the theoretical voltage required after adiabatic capture has been completed. We must preserve the bucket area corresponding to this voltage. Using the bucket area formula of ref. 17 corresponding to the height formula used above

$$A_{bucket} = 2.35 \times 16 \times \frac{1}{\sqrt{2}} \times \frac{1}{\sqrt{2}} = 18.8 \text{ KeV - radian}$$

The quantity to be preserved is

$$\sqrt{eV} \ \alpha(\Gamma), \text{ when } \alpha(\Gamma) = 1, \ eV = 1.265 \sqrt{KeV} \times 10^{-1}$$

so we solve the transcendental equations

$$\sqrt{eV}\ \alpha(\Gamma) = 1.265\ \sqrt{KeV}\ \times 10^{-1}$$
$$eV \sin \phi_s = 4.21\ KeV$$

simultaneously, using the graph on p. 31 of ref. 17. The result is that

$$eV_{RF} \simeq 6.0\ KeV, \quad \phi_s \sim 45^{o}$$

Thus 10 KV seems a reasonable choice for cavity voltage.

Without giving the arithmetic we note that if we were to relax our tolerances on magnet errors from $.2 \times 10^{-3}$ to $.6 \times 10^{-3}$ the $\frac{\Delta p}{p}$ equivilent would increase by a factor of two which - as the relationship works out - means a factor of two more R F voltage required. It is important to emphasize this point because experience with recently constructed proton accelerators tells us [13] that 10 keV is a reasonable figure for cavities of the size we can put into DESY. If we need 20 kV it is likely that two cavities in parallel will be necessary. Thus there is clearly a premium on controlling the magnet to high tolerances.

Having estimated the voltages required we can now give the requirements for bringing on the magnetic field. The synchrotron oscillation frequency at 10 kV on the cavity is [17]

$$V_s \simeq .95\ MHz \left(\frac{11 \times 10 \times 10^{-6}}{2\ \pi \times .935}\right)^{1/2} \simeq 4.1\ kHz$$

so we have ca. 4 cycles/millisecond or 40 cycles in 10 milliseconds. Since the criterion for successful adiabatic capture is that the R F be turned on over the course of many synchrotron oscillations while ϕ_s is very small, we should be able to do reasonably well in the 10 milliseconds we are allowed. If the R F voltage is up to at least 1/2 of its full value after 5 msec then the rise of accelerating voltage will have taken of the order of 10 cycles of synchrotron oscillation before significant acceleration began. That ought to suffice to give reasonable adiabatic capture (ca. 50%).

Next we must check if the momentum swing of the particles will use up an appreciable fraction of the aperture. The swing in momentum can be computed from the bucket height H/2 = 2.35 keV,

so $$\frac{\Delta E}{E} = \frac{2 \times 2.35 \text{ KeV}}{3 \text{ MeV}}$$

and $$\frac{\Delta p}{p} \simeq \frac{1}{2} \frac{\Delta E}{E} \simeq 0.8 \times 10^{-3}$$

now $$\frac{\Delta R}{R} \simeq \alpha \frac{\Delta p}{p} \simeq 0.03 \times 0.8 \times 10^{-3}$$

hence $\Delta R \simeq 50 \times .03 \times .8$ mm = 1.2 mm peak to peak

so we could tolerate even more phase oscillation if necessary.

This same consideration tells us what the frequency tolerance on the R F must be. If the bucket total height is 0.8×10^{-3} then

$$\frac{\Delta f}{f} < \alpha \frac{\Delta p}{p} = 0.03 \times 0.8 \times 10^{-3} = 2.4 \times 10^{-5}$$

So if frequency error of the R F is to be an inconsequential factor in setting the bucket width then

$$\frac{\Delta f}{f} \rightarrow 10\% \quad \text{of bucket height}$$

or $$\frac{\Delta f}{f} \sim 2 \times 10^{-6} \quad \text{at injection.}$$

On the basis of the above information one can say something about the accelerating device. First, it seems clear that the device will have to be a resonant cavity because of the voltage requirement. It is probable that a one turn ferrite transformer could be used to produce voltages of the order of 1 kilovolt over the required frequency range. Ten kilovolts is out of the question because of the limit on peak current of available transmitting tubes of reasonable output capacitance.

Because the cavity must be resonant it will have to be tuned by magnetizing the loading ferrite. To cover the large band of frequencies encountered, it will probably be necessary to use two separate cavities operating in two overlaping bands with suitable synchronization. It appears possible that a ferrite (designated CM 2002) from Ceramic Magnetics may allow one to cover both bands with minimum tuning current, however, its dielectric and loss properties are as yet not fully known. Some toroids are on order for testing. Failing this we can of course fall back on the design and ferrite used successfully for a slightly smaller frequency band in the CERN Booster [13]. In any event a $\lambda/2$ ferrite loaded coaxial cavity of about one meter active length will result.

To summarize we can write a list of parameters characterizing the R F system required in the DESY Synchrotron for proton acceleration.

Harmonic number	11
frequency at injection	0.830 MHz nominal
frequency at ejection	9.425 MHz nominal
frequency ratio	11.34
accuracy and stability of injection magnetic field	2×10^{-4}
accuracy and stability of injection frequency	2×10^{-6}
peak gap voltage	10 kV
bucket half height after adiabatic capture	2.35 keV
number of cavities	2
length of adiabatic capture period	5×10^{-3} sec
rise time to full accelerating rate of 4 GeV/sec	10×10^{-3} sec
Synchrotron frequency just after adiabatic capture	4 kHz
individual cavity length	1 meter
type of cavity	$\lambda/2$ coaxial

Injection

As envisioned, the beam from the proton injector will be conducted through a suitable analysing and matching system from the point of origin to the synchrotron. The beam will be introduced into the synchrotron aperture through a thin septum. The non-conservative element which will allow the beam to miss the septum on successive revolutions will be a fast beam bump created by some air core coils or back leg windings appropriately placed. Multi-turn injection is planned.

As stated previously we expect no more than a 2 keV spread in the injector beam kinetic energy. This energy spread arises from four sources, only two of which have significance in this case. The most fundamental limit is the energy dispersion in the beam extracted from the duo-plasmatron ion source which is typically [36] of the order of 40 eV and thus negligible. The second is the spread due to fluctuations in energy loss while the low energy beam traverses the accelerating column high pressure region near the ion source. Experimental evidence and rough theoretical estimates predict that this spread amounts to a few hundred eV at most. The principal known reasons for the observed spread are fluctuations in the terminal potential and sag of the terminal poential due to discharge of the terminal capacitance during the pulse. The latter effect can be easily estimated. If we make the conservative assumption that 0.25 of the charge leaving the terminal is finally captured in the synchrotron then the change in terminal charge during a given injection pulse will be

$$\Delta q = 4 \times 1.7 \times 10^{11} \times 1.6 \times 10^{-19} = 10.9 \times 10^{-8} \text{ coulomb}$$

From the physical dimensions of common 3 MeV Van de Graaff machines [7] one can say that the diameter of the terminal will not be much different from one meter which corresponds to a terminal capacitance of about 56 picofarad. Thus

$$\Delta V_{\text{Terminal}} \cong \frac{\Delta q}{C} = 1.2 \text{ kV}$$

which is comparable with the allowed energy spread. This means that this sag will probably have to be compensated by pulsing an insulated liner within the Van de Graaff tank during the injection pulse, standard practice with Van de Graaffs used as accelerator injectors [4,5]. Having thus compensated the pulse sag it remains necessary to regulate the terminal voltage through a feedback system which controls the charging rate of the belt. The measuring element in this system is a well regulated analysing magnet through which the beam passes followed by a slit at a point of high dispersion. The slit has insulated jaws so that the current intercepted by each jaw can be fed to one side of a differential amplifier whose output is used to govern the charging rate. Because the duty factor of the pulsed current is so low, the feed back system actually works on the "dark" or leakage current from the ion source which is continously being accelerated. By such means the PPA [4] injector was controlled so that the final energy spread was 1 keV, a factor of two better than we have assumed in estimating R F requirements.

The absolute value of the injected beam momentum as well as the momentum spread is important because it determines the injection field in the synchrotron and the R F required to capture the beam with minimum synchrotron oscillation amplitude. Therefore it is important that the analyser magnet field and the geometrical relation among the slits, magnet and Van de Graaff output be as stable as possible. Sufficient stability of the analyser field can be obtained by using a nuclear resonance magnetometer-frequency discriminator combination to control the magnet current.

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36) Current Veeco and High Voltage Engineering Ion Source Catalogs

While there are several possible locations for the Van de Graaff machine, at present it appears most advantageous to use the so called"inner experimental area". This room, inside the synchrotron ring near straight section 21, has adequate floor space and good access and permits a rather short transport path between the Van de Graaff and synchrotron. The present arrangement of straight section equipment is compatible with placement of injection septa in straight sections 19, 21, or 22 so that injection in either direction is possible. Because it is radiation shielded from the synchrotron this location would also allow tune-up and operation of the proton injector during normal electron operation of the synchrotron, thereby saving time in the switch over from electron to proton operation.

The required properties of the Van de Graaff injector can be summarized as follows:

<u>Van de Graaff Specifications</u>

Beam Energy	3 MeV
Beam energy spread	$\leq$ 2 keV
Beam phase space area	$\leq 20\,\pi \times 10^{-6}$ meter radian
Total number of protons accelerated per pulse	$\geq 6.8 \times 10^{11}$
Repetition rate	1 Hz
Pulse length	13 to 62 μsec.

As seen above it may be necessary to spread the beam from the Van de Graaff in betatron phase space. The emittance of the Van de Graaff beam is smaller than that required for optimum luminosity (p. 3) whereas the Laslett limit was computed for the largest possible allowed emittance. This means that in principle the coherent Laslett limit could be exceeded locally within the unspread Van de Graaff beam leading perhaps to uncontrolled blow up of the inected beam. This point will have to be checked experimentally. Should spreading prove necessary a modicum of controlled gas scattering just prior to injection should serve the purpose. The computation goes as follows. We planned to fill a vertical admittance of 33×10^{-6} rad.meter in the synchrotron whereas the Van de Graaff beam is expected to occupy 20×10^{-6} rad.meter. We use the formula

$$\langle \theta^2 \rangle = \frac{\Delta\varepsilon}{\beta(s)}$$

where $\langle \theta^2 \rangle$ is the mean square angle of scattering and $\Delta\varepsilon$ is the increase of emittance engendered in a lattice with amplitude function $\beta(s)$. The $\Delta\varepsilon$ required is $(33-20) \times 10^{-6} = 13 \times 10^{-6}$ rad.meter. So if we could make controlled scattering of

$$\langle \theta^2 \rangle \simeq \frac{13 \times 10^{-6}}{10} \quad \text{rad}^2.$$

just prior to injection we would fill the vertical emittance. Since we want to fill 82×10^{-6} m.rad. horizontally, we will need 2 or 3 turn injection, again something that will have to be experimentally tested. Using the multipule scattering formula [37)]

$$\langle \theta^2 \rangle = \left(\frac{21 \text{ MeV}}{\beta \ c \ p}\right)^2 \frac{x}{X_o} = 1.3 \times 10^{-6} \text{ rad.}^2$$

where x is the scatterer thickness and X_o is the radiation length of the scattering material. We find $x/X_o \sim 10^{-7}$ when p = 75 MeV/c. For a thin film of carbon (X_o = 30 cm) for example, this corresponds to a thickness of 300 Å which is too thin to be practical. Therefore a gas cell can be used.

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37) B.Rossi, High Energy Particles, Prentice Hall (1952), p. 68.

If the effective length of the cell is 50 cm and air (X_o = 23.7 x 10^4/P(Torr)) is the scattering gas we find that P = 48 x 10^{-3} Torr which should not be difficult to maintain by differential pumping. There will be an energy loss which accompanies this scattering. If this energy loss is too large the fluctuations in energy loss could give an unacceptably large momentum spread to the beam. The scatterer's thickness is about 4 x 10^{-6} g/cm^2 and since dE/dx = 100 MeV/g/cm^2, ΔE = 400 eV. For such an energy loss at this kinetic energy the expected fluctuation [38] is 5% of ΔE so the spread caused by straggling is completely negligible.

Ejection

It is anticipated that for the most part fast ejection of protons can be carried out exactly as in the case of electrons and positrons destined for injection into the storage ring. That is, at the instigation of a trigger signal, a fact kicker fires and steers the circulating beam into a septum from whence it leaves the machine. (Alternatively, near the peak of the cycle one might bump the beam near to the septum to ease the job of the kicker). Since we wish to R F stack the extracted beam we must be careful to minimize the pulse to pulse difference in the momentum of the ejected beam. In order to keep the R F requirements resonable we should try to achieve a pulse to pulse momentum difference of no more than the expected momentum spread in the individual beam pulses. This individual beam pulse momentum spread will depend upon the R F con-

38) Op. Cit. Rossi p. 32

ditions used for transfer from one ring to the other. For purposes of estimate we may take $(\Delta p/p)_{ejection} \simeq 5 \times 10^{-5}$. Due to its basic simplicity and known reliability one would like to trigger the beam extraction from a peaking strip biased to fire at about 2.4 KGauss. Peaking strips are known to be capable of a resolution [39,40] of better than 0.03 Gauss. Thus at a field of 2.4 kGauss the relative field error will be

$$\frac{\Delta B}{B} = \frac{\Delta p}{p} = \frac{.03}{2.4 \times 10^{3}} = 1.2 \times 10^{-5}$$

Clearly this method is, in principle, more than adequate. An additional source of spreading has to be considered if we use the peaking strip. Since the field will be rising during extraction a difference in momentum will exist between the particles first extracted and those last extracted. This difference will be $\dot{p}\Delta\tau$ where $\Delta\tau$ is the extraction time duration or 1.2 μsec at 2 GeV/c. Since $\dot{p}$ may be as high as 4 GeV/c per sec at $p \simeq 2.4$ GeV/c then the fractional momentum spread engendered through this process is

$$\frac{\Delta p}{p_{max}} \simeq \frac{4}{2.4} \times 1.2 \times 10^{-6} \simeq 2 \times 10^{-6}$$

which is of the order of 20% of the natural momentum spread of the beam, an acceptable value. This computation also shows that jitter in the firing time of the ejection kicker of 1 μsec will result in $\sim 2 \times 10^{-6}$ $\Delta p/p$ error. Thus such jitter should be kept to 1 μsec or less if possible.

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39) E.J.Rogers et al. RSI 24, 9 (1953) p. 848

40) K.Endo and H.Sasaki - A Modified Peaking Strip Method for Measurements of slowly varying low Fields. SJC-A-70-S - Institute for Nuclear Study, University of Tokyo.

One can summarize by pointing out that to effect proper ejection of protons from the synchrotron one need add only a peaking strip with associated electronics to trigger the normal extraction equipment.

In the transport system between synchrotron and storage ring there exists equipment for measuring the $e^{\pm}$ beam emittance. As the emittance of the proton beam is approximately the same as that anticipated for the positron beam we may expect that this measurement equipment will suffice for protons as well. Because of its narrowness, it will not be practical to measure the momentum spread of the proton beam independent of the storage ring.

Controls and Monitors

The significant control problems are the synchronization of injection, acceleration, extraction and stacking processes both internally and with each other. The philosophy of connection between the synchrotron and storage ring under proton operation should clearly be as similar as possible to that pertaining to electron operation.

Since power supply ripple voltages will be synchronized to the line frequency it is absolutely necessary that the master clock used for synchronization under proton operating conditions be started by a line synchronous gate, thereby ensuring that injection will be line synchronous. In addition, another enabling gate for the master clock will be required. This gate, signaling the completion of stacking, must be derived from the storage ring. Power supply ripple will also limit ejection and stacking processes. For this reason we should like these processes to be line synchronous too. However, we have already proposed to initiate ejection and stacking from a peaking strip signaling a certain B value. These two conditions are not incompatible provided that the magnet supply voltage is held stable enough. For example we wish to find the condition under which the firing of the ejection equipment does not jitter significantly with respect to power supply ripple. If the ripple is well filtered its principal fourier component will be 6 x 50 Hz. Therefore if the time of which B_{max} is reached does not vary by more than a small fraction of 3.3×10^{-3} sec. then for all practical purposes we are operating synchronously with the line. Since the acceleration time is of the order of 1/2 sec the precision of dB/dt must then be better than $3.3 \times 10^{-3}/.5 = 6.6 \times 10^{-3}$. Thus if the magnet power supply voltage (which sets B) is held constant to 0.1% ejection will be practically line synchronous. The return of the magnetic field to injection values at the end of the cycle and resetting of the master clock can be carried out with respect to the master clock itself or be initiated from the peaking strip signal. The use of the peaking strip may allow a more accurately reproduced magnetic cycle.

Injection control has already been mentioned briefly under the paragraphs about injection and magnet power supply. The question whether dynamic regulation of the injection field on the basis of a field measurement will be necessary or whether simple regulation of the excition current will suffice has to be investigated in detail. The most substantive question of control has to do with the R F system where the frequency, amplitude and phase must be under rigorous control at all times. The control philosophy and methods used successfully with the CERN Booster [41] R F system recommend themselves for the purpose at hand. In general one programs the variable in question from a fixed program, accurate to a few percent, and then uses active feed back to correct the fixed program. The active feed back in the frequency program case derives its correction signal from the beam. The amplitude feed back uses the comparision of actual cavity voltage with theoretical values to generate the error signal and the phase feed back is arranged so that phase shift between oscilator and cavity voltage is constant. Having picked and stabilized by various means the injection energy and ejection energy, the two corresponding revolution frequencies are known and can be established to quarz crystal accuracy by use of a programmable frequency synthesizer. At the beginning of the cycle for example the master voltage controlled oscillator (VCO) can be phase locked to the synthesizer. When acceleration begins the VCO is unlocked from the synthesizer to follow a pre-determined analog program corrected by active feed back using beam position signals. At the end of the cycle the VCO can again be adiabatically brought into phase lock with the synthesizer whose frequency has been appropriately raised during the acceleration period. Simultaneously the stacking cavity in the storage ring is also phase locked to the ejection R F frequency.

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41) U.Bigliani, The Beam Control System for the CERN PS Booster, IEEE Trans.on Nuclear Science, NS-18,3 (1971) p. 352 (1971 Chicago Accelerator Conference)

Stacking may well require the use of several precise but adjustable frequencies also. The same synthesizer should be used. Without a synthesizer the fixed frequencies could be supplied by a number of quarz crystal oscillators constructed so that they can be pulled by electronic means to allow empirical adjustments. The remaining control problems can be handled in a straight forward manner with very standard techniques.

Monitoring can be largely carried out with existing electron beam equipment. The principal exception is the measurement of the beam profile. Because we shall be wanting to push the intensity of the beam to its ultimate limit, suitable instruments must be at hand for analysis of beam instabilities at injection and during acceleration. A method of determining the beam charge distribution dynamically gives one a direct method for observing the instability in detail. Such detectors have been built and used with good results at Argonne National Lab. [42] and at CERN [43, 44]. Such a detector will certainly also be required for monitoring the d c beam in the storage ring.

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42) W. De Luca, Beam Detection Using Residual Gas Ionization IEEE, Trans.on Nuclear Science (1969 Washington Acc.Conf.) NS-16, 3 p 813

43) C.Johnson and L.Thorndahl, The CPS Ionization Beam Scanner, IEEE Trans.on Nuclear Science (1969 Washington Acc.Conf.) NS-16, 3 p. 909

44) H.Kozoil and K.H.Reich, Beam Diagnostics at the CPS Booster IEEE Trans.at Nuclear Science (1971 Chicago Acc.Conf.) NS-18,3 p. 347

COST ESTIMATE

Item		Cost kDM
Injection		
Van de Graaff Machine		*
Installation		50
Beam Transport		200
Beam Analysis		20
Septum Magnet		90
Driver		50
Beam Bump		20
	Sub Total	430
Synchrotron Magnet Power Supply		
Additional Supply (25 A)		40
Switching Equipment		150
Controls and Cabling		20
Modify Present Supply		50
	Sub Total	260
Synchrotron RF System		
Cavities		430
Final Amplifiers		180
Intermediate Amplifier and Frequency Source		260
Controls and Cabling		130
	Sub Total	1000
Synchrotron Beam Monitors		
Beam Profile Scanner		10
Read-out and Display Electronics		50
Intensity Monitor		20
	Sub Total	80
Main Controls		
Remote Injector Controls		100
Automated Switchover from e to p Operation		100
Triggering and Synchronization		30
	Sub Total	230
	Grand Total	2 Million DM

* cost not included

TIME SCHEDULE ESTIMATE +

1973 · 1974 · 1975

F M A M J J A S O N D | J F M A M J J A S O N D | J F M A M J J A S O N

Van de Graaff Purchase Construction* (High Voltage Engineering)	Approval → Construction →
(National Electrostatics)*	Approval → Construction →
Van de Graaff Shipping, Installation and Test (High Voltage only shown)	→
Synchrotron Magnet Power Modification	Design Measurement → Installation and Test (Work carried out during normal maintenance periods) →
Synchrotron RF System	Design&Prototype → Construction & Test →
Injection Equipment	Design → Construction →
Controls and Monitors	Design Prototype → Construction →

\+ Based upon Van de Graaff delivery time and the equivalent of 2 Engineers and 3 Technicians full time for design and prototype work.

* Based upon rough estimates given by the Companies.