and circular with n = 0.12 giving focusing. The section is C — Shaped with the yoke on the out-side.

A short pulse (10 nanosec) of protons ejected from the PS falls on a target in the ring. Pions of momentum 1.3 GeV/c are concentrated forward by a magnetic horn and make 1 turn before again hitting the target assembly. During this time(50 nanosec) about 20% of the pions decay and the forward emitted muons have almost exactly the same momentum. They can therefore remain in the ring. Some of the muons however have slightly less momentum, which causes the orbit to contract inwards away from the horn. These muons can therefore fall into permanently stored orbits. We thus use the $\pi - \mu$ decay process to inject, and do not need an electromagnetic inflector. Using 1/20th of the P. S. beam (1 of the 20 r. f. bunches) we expect to store on each cycle ~ 1500 muons with 95% polarization.

When the muon decays in flight the decay electron must have less energy and therefore emerges on the inside of the ring, where it will be detected by a series of lead glass Cherenkov counters. By demanding a large pulse height we ensure that only high energy ($E > 750$ MeV) electrons are detected, and these can come only from *forward decay.*

As the muon precesses according to eq. [1] the counting rate will therefore be modulated allowing the frequency ω_a to be measured. The figure also shows the thick concrete needed to protect the counters from direct radiation from the target during injection.

Fig. 2 is a photograph of the ring during assembly. Fig. 3 is a close up showing the magnet gap with the windings emerging vertically through a slot in the yoke.

Fig. 4 shows the magnetic field obtained with a region of linear gradient, $\eta = 0.12$, obtained after some shimming of the predesigned pole shape which was not completely correct. Variations of field in azimuth have been corrected by introducing aluminium foil spacers in the yoke and the median plane can be controlled by adjusting the supports. We now have a field which is suitable for storing muons, and reproducible in shape from day to day to ~ 30 ppm.

Fig. 5 shows the counters being installed; the cheese shielding them from the target area can be seen on the right.

Fig. 6 shows the layout with the ejected beam crossing the South Hall to the storage ring on the left.

The statuts now is that we are ready to run, and hope to see some stored muons in the near *future.*

REFERENCES

(1) G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens and A. Zichichi: Nuovo Cimento, *37*, 1241, 1965.

μ-MESON AND ANTIPROTON TRAP AT SLAC *

D. Green, F. Lobkowicz and J. Tinlot

Department of Physics and Astronomy, University of Rochester, Rochester, New York (USA)

(Presented by F. Lobkowicz)

The Stanford 2-mile linear accelerator will provide an intense source of muons having energies from a few BeV up to nearly the maximum primary electron energy. Clement and Kessler (1) have calculated the muon yields from Lithium and Lead. Interpolating their values for copper, one finds that there will be 2×10^{-7} μ/BeV/c per electron at 10 BeV produced in a thick ($\geqslant$ 3 r.l.) target. The assumed primary energy is 20 BeV. 80% of these muons will emerge at less than 1° with respect to the electron beam. Assuming an electron beam of 30 μA, one thus gets 2.5×10^7 μ/sec in a $\pm$ 4% band around 10 BeV/c. This beam can be quite efficiently purified by filtering through a low-Z absorber of some 15 nuclear mean-free-paths. The energy loss by ionisation (3-4 BeV) and multiple scattering (5-10 mrad) are quite tolerable as long as the final muon energy is to be greater than 5 BeV. Somewhat paradoxically, it is very difficult to make use of the full achievable intensity of such a beam. This is due mainly to the very poor duty cycle of the linear accelerator (a few hundredths of a percent). In addition, some experiments require that the muon energy be restricted within

* Supported by U. S. Atomic Energy Commission.

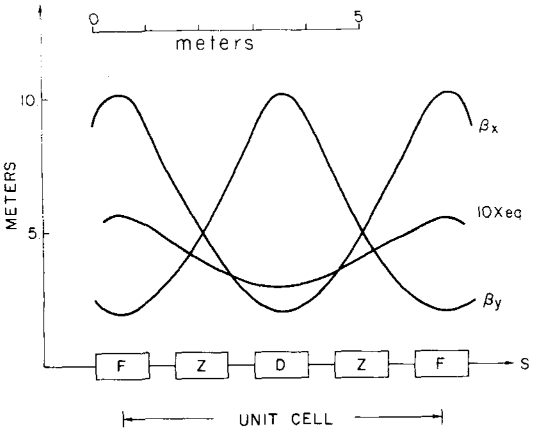

Fig. 1 - Betatron function behavior in the unit cell of the storage trap. β_x is the horizontal, β_y the vertical betatron function. X_{eq} is defined as the deviation of the closed orbit for off-momentum particles per unit $\Delta p/p$.

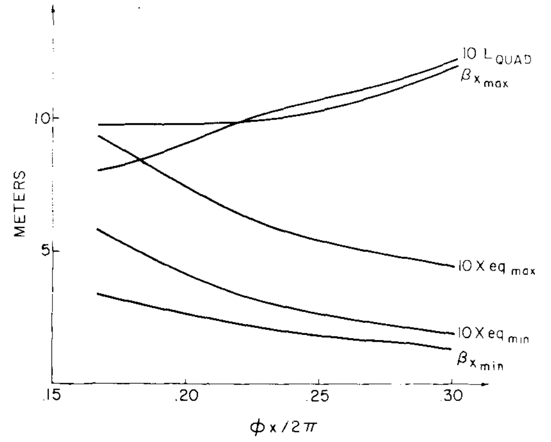

Fig. 2 - Behavior of the pertinent parameters in the cell structure as function of the phase advance per cell. L_{quad} is the length of the quadrupole magnets. The length of the bending magnets is fixed at 1 m.

a band of a few percent; this is usually only achievable with a large loss of intensity.

According to Drell (2), the same accelerator will also be an extremely good antiproton source. According to his estimate, 30 μA of electrons of 20 BeV will give a peak antiproton intensity of about 5×10^5 $\bar{p}$/sec. mst. BeV/c at 15 BeV and somewhat more at 10 BeV. This is a very useful beam; but unfortunately it is badly contaminated by pi-s, μ-s and K-s. The only purification scheme nown is mass separation, which will reduce the intensity by at least one order of magnitude.

The device described here is designed to trap muons or antiprotons of 5-10 BeV/c in stable orbits. The trap consists of two semicircles of quadrupoles and bending magnets, connected by 40 m long straight sections. One of the two straight sections will be used for injection, while the other will be used as experimental station. Each straight section has a 16 m long magnet-free central section and two shorter sections partially occupied by momentum compensating magnets. A target (~ 1.5 g/cm^2 of liquid H_2) is placed in a convenient point of the experimental straight section; the trapped particles traverse the target many times.

The duty cycle is limited only by the lifetime of the muons (220 μsec at 10 BeV) and by loss through outscattering for antiproton. For mu-mesons, taking into account losses due to multiple scattering and energy degradation of the trapped beam (which then leaves the momentum acceptance of the trap) a crude estimate is that 1 event/sec corresponds to a cross section of 10^{-32} cm^2 in Hydrogen. The duty cycle is then 3%. All the antiprotons interact and thus one has about 5×10^5 events/sec for a total cross section of 50 mb, or 1 event/sec for 10^{-31} cm^2. Both these interaction rates are at 10-100 times better than anything presently available. Both beams can be made very pure, as we will see in a while.

To achieve this rate, one has to have a trap with a momentum acceptance of at least ± 4% and a phase space acceptance of at least 15 cm-mrad in each direction. The available site also limits the mean radius to a value $\leq$ 50 m.

Translated into machine parameters, the phase space acceptance can be written

$$A = \frac{a^2}{\beta_{max}}$$

where a is the limiting half-aperture and β_{max} the maximum betatron function. The momentum acceptance, defined as the value of $\Delta p/p$ for which the phase space acceptance drops to 1/2 maximum, is:

$$\left.\frac{\Delta p}{p}\right|_{1/2} = \frac{0.3\ a}{X_{eq}\ \mathrm{max}}$$

where X_{eq} is the closed orbit excursion per unit $\Delta p/p$.

This means that with our chosen a of ~ 7.5 cm in both directions, β should be $\lesssim$ 15 m and X_{eq} $\lesssim$ 0.5 m. Just for comparison let me mention here that the Brookhaven AGS has a maximum β of 24 m and an X_{eq} of 2 m.

We have up to now investigated several basic schemes for the unit cell of the trap: A low guidefield A. G. system, a high guide field A. G. system and a separate function system, where roughly $^1/_2$ of the magnets are zero gradient bending magnets and the rest quadrupoles. We used the SYNCH program developed by Garren and Eusebio (3).

As can be seen from Table I, only the separate function system fulfills the requirements. Since the interaction rates for mumesons are proportional to $((\Delta p/p)^2$ (once for the number of trapped muons and once for the amount of material traversed before the mumesons leave the momentum band of the ring) the small momentum acceptance of the A. G. systems is their main drawback.

The system whose parameters are given here is actually the better of two separate function systems investigated. Its basic structure is 1/2 FZDZ 1/2 F (Fig. 1). Another system investigated was 1/2 FZZDZZ 1/2 F, where the bending magnet length/cell is twice the quadrupole length/cell. Such a system has a tolerable maximum betatron function of 15 m, but an impossible maximum X_{eq} of 2 m. The reason is simply that for good momentum compaction one is not allowed to bend the beam too much between quadrupoles.

Fig. 2 shows the important parameters of the 1/2 FZDZ 1/2 F cell as functions of the phase advance per cell. In order to make X_{eq}, the most critical parameter, small, one needs as large a phase advance as possible. However, this leads to a very small minimum horizontal β, and this in turn gives rise to a blowup of the beam in the straight section, as discussed below. The bending field is 20 kG and there are 48 cells in the whole ring.

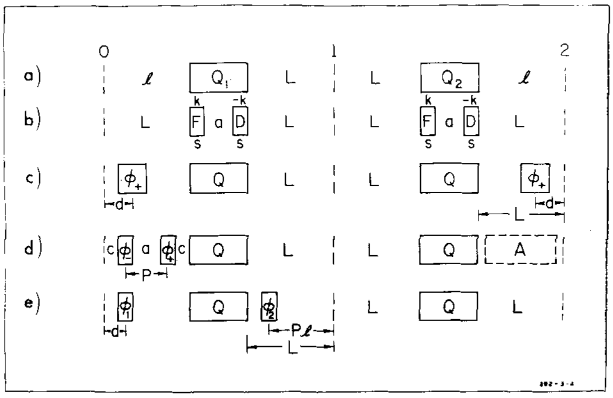

Fig. 3 - Schematic diagram of Garren straight section design. *a) Basic Garren straight section; b) The chosen* particular straight section; c) Garren's scheme for off-momentum compensation. Ø ± are bending magnets (+ signifies bending inwards); d) Momentum compensation for the injection straight section. A is the injection kicker magnet; e) Momentum compensation for the experimental straight section. $\varnothing_2$ is the experimental magnet.

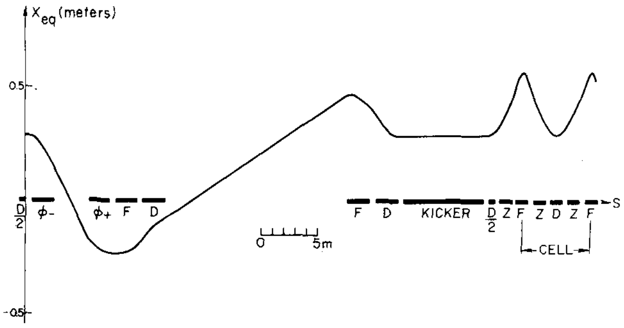

Fig. 4 - Behavior of the betatron functions in the straight sections.

TABLE I

Comparison of the low guide field A. G. system (L. G.) the high guide field A. G. system (H. G.) and the separate function system (S. F.)

		H.G.	L.G.	S.F.	
β_{horiz} maximum		12.8	20.2	10.2	m
β_{vert} maximum		12.5	20.1	10.1	m
Effective Aperture	Horiz.	6	10	7.5	cm
	Vert.	3	5	5	cm
Phase space acceptance	Horiz.	28	50	55	cm mrad
	Vert.	7.2	12.4	20.7	cm mrad
Momentum acceptance		± 1.1	± 1.6	± 3.9	%
Radius of Ring		33	49	48	m
Bending field		13	8	20	kG
Field gradient		0.48	0.25	1.6	kG/cm

The straight sections should have a long (at least 10 m) magnetfree portion, so that one can iniect and perform experiments with high energy muons or antiprotons. This rules out a Collins straight section, which by definition is unable to match exactly the betatronfunctions and their derivatives to the cell values. Unless one wants to increase drastically the overall betatron function, one has to limit the fieldfree region of a Collins straight section to 5 m or less.

The Garren straight section (4) does not have these drawbacks. Consider Fig. 3. If one has the system shown in Fig. 3a, where Q are some arrangements of quadrupoles, one can write down very simple relations between' the four matrix elements of Q1 and Q2 in *one* direction in order that the total transfer matrix of the system becoems - I in *both* directions, i. e. the total phaseadvance is π. In particular one can choose both Q1 and Q2 to be equal to an FD doublet (Fig. 3b). One can also choose an FDFD structure, etc. If one wants one can write down a similar set of equations for a total phase advance of 2π. Then a triplet as Q is the simplest structure and Q1 and Q2 are no longer identical. For all these simple structures the lengths l and L become equal. These sections can in principle be made arbitrarily long.

One can also compensate the Garren straight section for the off momentum excursion, using only its ends and thus leaving the center section free.

For the injection straight section we put both compensating magnets on one side, since the other short section is used for the injection kicker (Fig. 3d and Fig. 4). To be able to compensate with reasonable magnets, one has to cut the cell structure at a position where X_{eq} is a minimum, i. e. in the middle of a D magnet. But this means that the horizontal betatron function is also minimal at the ends of the straight section. Unfortunately this has the consequence that the betatronfunction within the straight section itself becomes very large (Fig. 5). The reason is very simple: The phase advance in the straight section can be written

$$\pi = \Delta\psi = \int \frac{ds}{\beta}$$

and a large portion of this integral is used up at the ends. Thus in the center the integrand has to be very small, i. e. the betatron function large. As a rule of thumb one can say that the maximum betatron function in the straight sections will be proportional to its length and inversely proportional to the betatron function to be matched.

In the experimental straight section one of the momentum compensating magnets should be the experimental magnet. Here one would like to have a large variation in field and length of this magnet and still be able to compensate. This can be done, to a limited amount, by installing one or two magnets in the end sections. However, once one has chosen one experimental situation and designed the ring around it, the overall bend and displacement of the beam should be kept always the same. Thus for any new experimental setup one has four conditions to fulfil: X_{eq} and dX_{eq}/ds have to match and the overall bend and displacement of the beam should be kept the same. This is possible with reasonable magnets only if the experimental manet is still somewhere in the center straight section. That is, the experimental magnet is part of the ring and while it can be moved (and its field varied somewhat), it cannot be taken out without repositioning all other magnets.

Now a few words about targeting and injection. The muon beam is produced in a 10 r.l. water-cooled copper target. About one quarter of the initial beam power or about 150 kW, escapes from the target in form of low energy photons and electrons. The muon beam is taken off at 0°, caught in a triplet and twice brought into a focus of roughly the original target spot size (8 mm diameter). Into each focus an absorber is istalled to eliminate strongly interacting particles. The only dangerous background are antiprotons (or protons), since pions and kaons will decay very quickly in the ring and electrons will lose sufficient energy by synchrotron radiation to get lost after some 40 μsec. Multiple scattering of the mumesons in the target and in the absorbers will add about 40% to the original phasespace of 7 cm mrad in each direction. If we add 50% for injection errors and transport system misalignments, we arrive at the previously mentioned minimum acceptance of 15 cm mrad for the ring.

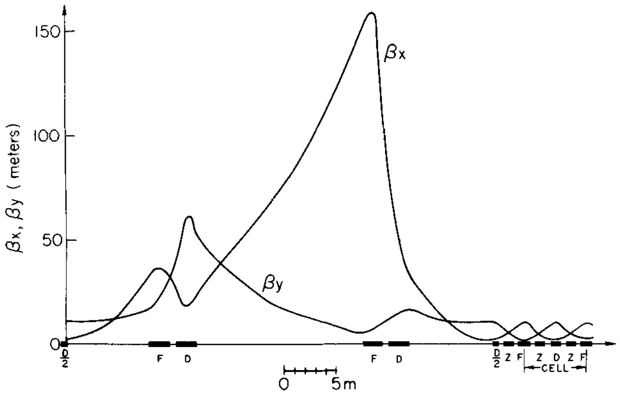

Fig. 5 - The off-momentum deviation X_{eq} in the injection straight section.

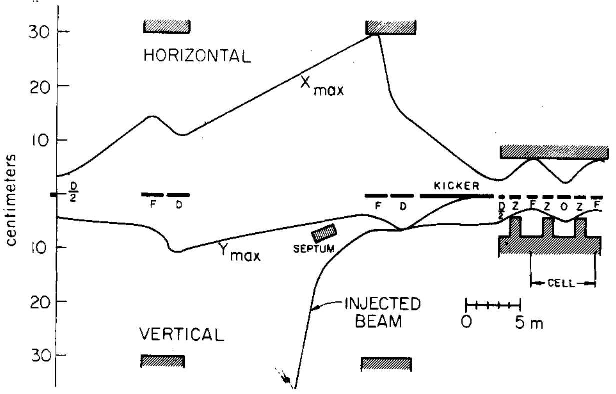

Fig. 6 - Beam envelope and path of injected beam in the injection straight section. The shaded areas show the magnet apertures.

If antiprotons are to be stored, a 2 r.l. carbon target is used and antiprotons are taken off at an angle of about 2°. The absorbers are omitted. Otherwise the transport system to the ring itself is nearly identical. Purity of the beam is achieved by simply waiting.

Injection into the ring is a difficult problem. One-turn injection is intended. The injection has to be such that the phase space as well as the off momentum deviation of the injected beam are matched to the ring acceptance. Since the phase space acceptance of the ring is much larger horizontally than vertically, one needs a smaller injection kicker for vertical injection, which was therefore selected. Even then one needs a total kick of 4 kG meters. The injection is of the usual $\pi/2$ type; the septum magnet (Fig. 6) is in the center of the long section. The septum magnet will have to be horizontally focussing to properly match the phase space acceptance. Since X_{eq} and dX_{eq}/ds is very small at the septum exit, while the horizontal betatronfunction is large, the off momentum compensation at injection is not very difficult. A slight horizontal bend (~ 1.5°) has to be built into the magnet preceding the septum.

The risetime (or really decaytime) of the injection kicker has to be 0.3 μsec or less in order to fill the whole ring. This is not an easy problem. The desired kick and aperture of the kicker corresponds electrically to a current of 10,000 Amps in an inductance of 8.5 μH. If one would use the usual simple schemes for such kickers, the necessary voltage would be:

$$V = \frac{L \cdot J^2}{\tau} \sim 280\,\text{kV}$$

and peak power

$$P = \frac{L \cdot J^2}{\tau} \sim 3\times10^9\,\text{W} = 3000\,\text{MW}$$

However, one notes that the risetime of the kicker can be large, as long as the decaytime is small. Consider Fig. 7. The inductance is made into a distributed line with a characteristic impedance of about $R = 4\Omega$. Then the risetime, assuming that the pulseforming network is a simple voltage source, is 2.1 μsec. If one wants to turn the magnet off, one shorts the input and turns on a series of switches, each going to ground over a resistor R′. Thus we have suddenly a lossy line with no input voltage. The current will decay exponentially with a decaytime

$$\tau_D = 2\frac{R'C}{n}$$

where n is the number of damping resistors and C the total capacitance of the line of ~ 0.5 μF. Thus choosing $R' = 8\Omega$ and $n = 40$ one gets a decay time of 0.2 μsec. None of the switches except S1 and S2 will have to conduct more than 5000 A peak current, something achievable with present day thyratrons. S1 will have to be a bank of ignitrons, while S2 probably should be two thyratrons in parallel. The pulseforming network has to deliver 40 kV and a peak power of only 400 MW. The average power is about 400 kW.

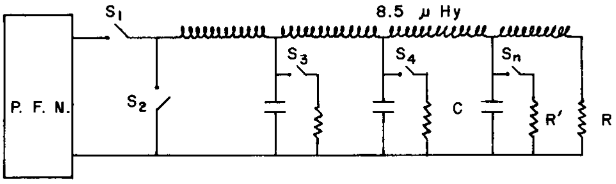

Fig. 7 - Electrical analogon of the injection kicker magnet. To turn the current on, one closes S_1, leaving the other switches open. To turn the current off, $S_2 - S_n$ are closed.

The disadvantage of the present system is that all the power is destroyed. Possibly a combination of the present scheme and the system proposed for the SLAC electron storage ring might be the best solution (5).

We would like to thank the Staff of SLAC, in particular Drs. W. Panofsky, J. Ballam and M. Sands for their generous hospitality during the summer of 1965 and many fruitful discussions.

REFERENCES

(1) G. Clement and P. Kessler: Nuovo Cimento *37*, 876 (1965).
(2) S. D. Drell: Int. Symp. Hamburg, 1965 and SLAC-PUB-118 (1965).
(3) A. Garren and T. Eusebio: UCID - 10153 - AS/Theoretical/03, (1965).
(4) A. Garren: UCID - 10129 - AS/Theoretical/02 (1964).
(5) M. Richter: Private communication.

DISCUSSION

Ammn: May I ask for details on the experimental straight section?

Lobkowicz: We have not yet frozen the design; the experimental building will be about 20×40 m, the floor will be some 2 m below beam height.

Bernardini C.: Do the electrons coming from muon decay in flight constitute an appreciable background?

Lobkowicz: Most of the electrons will not be in the acceptance of the ring. This will be the main background, but not a very serious one.