© 1983 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

KAON FACTORY WITH TRIUMF AS INJECTOR

L. C. Teng
Fermi National Accelerator Laboratory*
P.O. Box 500
Batavia, IL 60510

Introduction

A kaon factory is defined as a proton accelerator in the energy range of 15-30 GeV and the average current range of 10-100 μA such that it can produce kaons copiously. A linear accelerator is certainly capable of this performance but tends to be rather costly. At the current unit cost of ~10 eV/$ a 15 GeV proton linac would cost well over one billion dollars

For a circular accelerator one can get higher beam current with fixed magnetic field. Fixed field alternating gradient (FFAG) accelerators have been studied exhaustively by the Midwestern Universities Research Association[1]. The microtron[2] also uses a fixed magnetic field to recirculate the beam many times through a linac. These studies indicate that for energies above 15 GeV all types of circular accelerators with fixed field are very difficult technically and would also be very costly. We are, thus, left only with the pulsed field circular accelerator, namely the synchrotron. This is not surprising if one remembers that historically the synchrotron was invented to extend the energy into the GeV range and the alternating gradient synchrotron made energies much higher than 10 GeV realistically attainable. The average beam current of 100 μA is just possible with a fast cycling synchrotron, say, pulsing at 30 Hz and with 2×10^{13} protons per pulse. The design of such a synchrotron with a linac injector (high current pulsed accelerator) is straightforward[3]. To obtain a long beam spill for experiments one needs a beam-spill stretcher ring which is a d.c. storage ring having the same radius and installed in the same tunnel of the synchrotron. Accelerated pulses of beam from the synchrotron are injected and stored in the stretcher ring to be spilled out uniformly in time by a resonant slow extraction system. The stretcher ring is an ideal application for superconducting magnets.

To use a CW accelerator, e.g. a cyclotron such as TRIUMF as injector one needs an accumulator ring which is an injection-energy d.c. storage ring, again having the same radius and installed in the same tunnel of the synchrotron. The CW beam from the injector is accumulated in the accumulator during one complete cycle of the synchrotron and is transferred to the synchrotron in one turn to be accelerated as one pulse. The timing between the 3 rings — accumulator, synchrotron and stretcher — is shown in Figure 1.

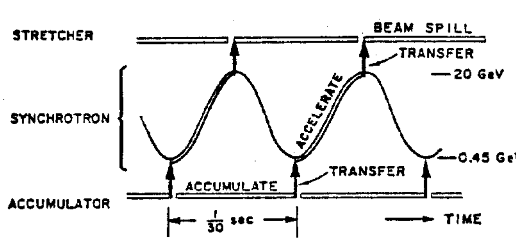

Figure 1 Timing between the accumulator ring, the synchrotron, and the spill stretcher ring.

*Operated by the Universities Research Association, Inc. under contract with the U.S. Department of Energy.

Beam Packet from TRIUMF

Stacking a large number of turns of beam during one synchrotron cycle is possible only with charge exchange injection. Thus, the beam must be extracted from TRIUMF as H^-. Even then, stacking in the accumulator is greatly facilitated by pre-stacking in TRIUMF on the extraction orbit. Approximately 100 turns of beam can be stacked in the longitudinal phase space (energy vs. rf phase) using either the rf stacking[4] or the field-bump stacking[5] schemes. The completed stack is then extracted vertically as one beam packet by a fast kicker. The parameters of the beam packet are:

Kinetic energy	450 MeV
Number of turns/packet	100
TRIUMF revolution frequency	4.6 MHz
TRIUMF harmonic no. = beam bunches/packet	5
Longitudinal emittance	
Phase spread $\Delta\phi$	±45°
Momentum spread $\Delta p/p$	±1/3%
Transverse emittance	
Horizontal	8π mm-mrad
Vertical	2π mm-mrad

Accumulator and Accumulation Scheme

We consider an accumulator (hence also synchrotron and stretcher) with a circumference 10 times that of the extraction orbit of TRIUMF and an rf harmonic number 100. The revolution frequency of the accumulator is then 0.46 MHz and the rf frequency is 46 MHz, twice that of TRIUMF. The injected beam bunches are synchronously captured into every other rf buckets. The scheme proposed for beam accumulation and injection is as follows.

Some 150 packets of H^- extracted from TRIUMF are stacked in the transverse phase space by charge exchange stacking to form a "box-car" of protons. All during this time the proton beam travels on an orbit in the accumulator which passes through the stripper foil (the stacking orbit). The completed box-car is then switched onto and stored on another orbit in the same accumulator which does not pass through the foil (the storage orbit). Ten box-cars are sequentially strung end-to-end to fill the entire storage orbit. The train of beam box-cars is then fast transferred to the synchrotron in one turn. For this scheme to work one must check first that the foil scattering during the stacking of a box-car is not excessive. Secondly, one has to show that two separate closed orbits can be simultaneously contained in the same ring. In principle, one can always use a second ring instead of the second orbit. But the addition of a fourth ring may be economically or emotionally untenable.

Foil Scattering

To obtain a good stripping efficiency (>98%) we need a 200 μg/cm^2 thick carbon foil stripper[6]. The number of beam packets to be stacked in one box-car is 4.6 MHz/(100x10x30 Hz) ≑ 153. The first protons will have made ~1530 revolutions by the time the last protons enter the accumulator. On the average each proton will pass through the foil 1530/2 = 765 times or a total thickness of 0.153 g/cm^2. This is actually an overestimate because after having been blown up by foil scattering the p beam will be larger than the foil

0018-9499/83/0800-2016$01.00© 1983 IEEE

which is just the size of the initial H^- beam. Hence protons in the beam will not pass through foil every turn. The rms scattering angle due to multiple Coulomb scattering in 0.153 g/cm^2 of carbon (radiation length = 42.7 g/cm^2) at 450 MeV (pv = 754 MeV) is

$$\theta = \frac{14.1\ \text{MeV}}{754\ \text{MeV}} \sqrt{\frac{0.153}{42.7}} \left(1+\frac{1}{9}\log\frac{0.153}{42.7}\right) \doteq 0.8\ \text{mrad}.$$

If the ring magnet lattice amplitude function at the foil is $\beta_{foil} \doteq 10$ m this scattering angle will add only $\pi\beta_{foil}\ \theta^2 \doteq 7\pi$ mm-mrad in quadrature to the transverse emittance. Since the space charge limit for 2×10^{13} protons/pulse requires an emittance larger than ~20 π mm-mrad this increase in emittance is inconsequential.

Formation of Two Closed Orbits in the Accumulator Ring

For the accumulator which has a circumference of 478.8 m we assume a simple magnet lattice made up of 32, 88° separated function FODO cells. The choice of lattice is not crucial. We only need a specific example for ease of discussion. The only parameters we will use are

Half cell length	ℓ = 7.48 m
Length of dipole in half cell	ℓ_B = 3 m
Phase advance per cell	μ = 88°
Number of cells	N = 32
Betatron tunes	$\nu_h \doteq \nu_v \doteq \nu$ = 7.82
Maximum amplitude function	$\beta_{max} \doteq$ 25 m
Minimum amplitude function	$\beta_{min} \doteq$ 4.5 m

To form two orbits in a horizontal plane we place a separator at a horizontally focusing quadrupole where $\beta \equiv \beta_s = \beta_{max}$ = 25 m. The separator is an electrostatic septum 60 cm long and producing fields of ±22 kV/cm on opposite sides. One can also use a current septum of the same length producing magnetic fields of ±100 G. The separator kinks the orbits on opposite sides by angles θ_s = ±1.75 mrad. The two distorted orbits will both have betatron invariant (relative to the undistorted central orbit)

$$W = \beta_s \left(\frac{\theta_s}{2\sin\pi\nu}\right)^2 = 68\ \text{mm-mrad}.$$

The maximum excursions of the orbits are

$$(\Delta x)_{max} = \pm\sqrt{W\beta_{max}} = \pm 41\ \text{mm}$$

and occur diametrically opposite the separator. At the separator the excursions are

$$(\Delta x)_s = (\Delta x)_{max} \cos\pi\nu = \pm 35\ \text{mm}.$$

This is enough to accommodate the half-widths of two 30 π mm-mrad emittance beams with ample clearance for the separator septum. The cross-sectional geometry of the septum and the beams is shown in Figure 2.

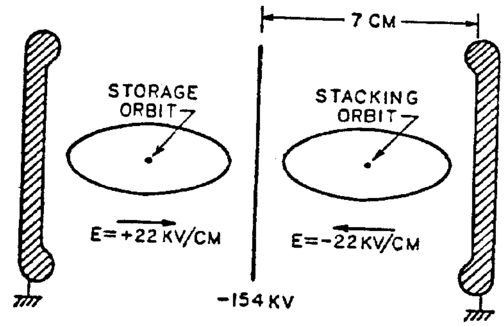

Figure 2. Cross-sectional geometry of the separated orbits and beams at the location of the electrostatic septum. The transverse emittances of the beam are taken to be 30 π mm-mrad.

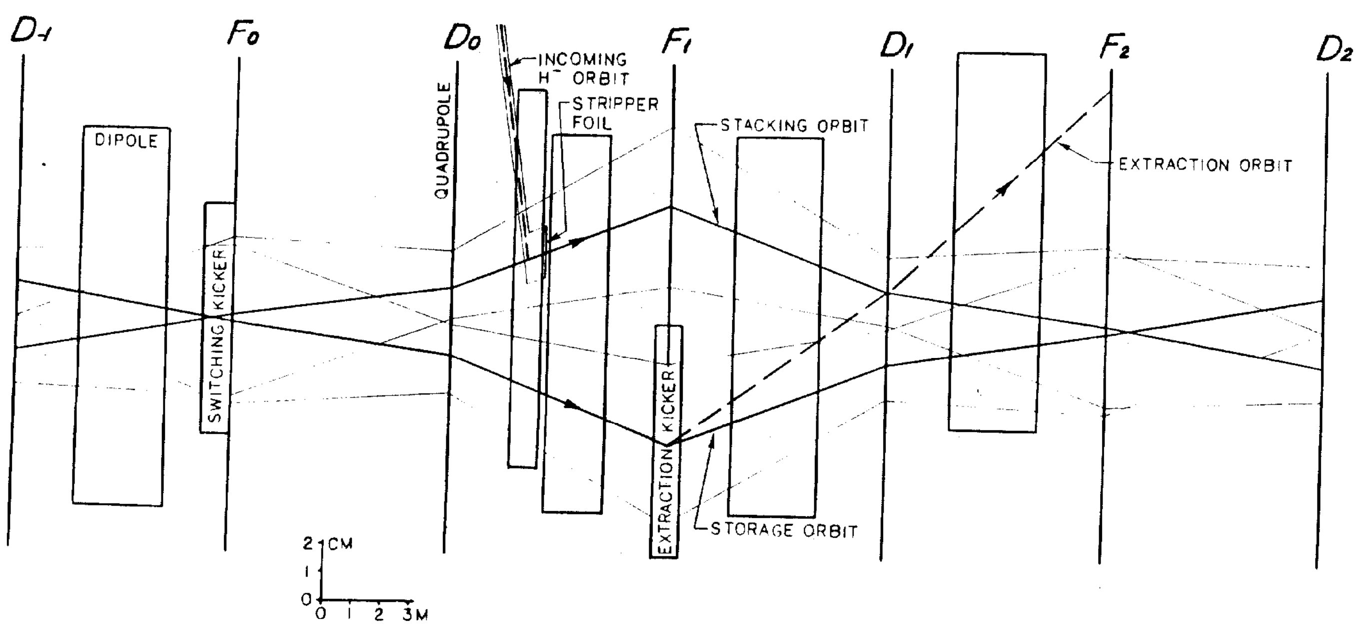

Figure 3. Geometry of the stacking and the storage orbits and beams at a location diametrically opposite to the separator, showing the charge-exchange stripper foil, the orbit-switching kicker, and the extraction kicker. The quadrupoles are assumed to be thin and the beam envelopes are approximated by straight lines.

Injection Geometry

We denote the focusing quadrupole diametrically opposite to the separator by F_1 and the downstream quadrupoles sequentially by D_1, F_2, D_2 etc. The stripper foil could be placed between D_0 and F_1, across the outside orbit (stacking orbit) as shown in Figure 3. The 3 m dipole should be cut up into 2 sections 1 m and 2 m in length respectively and the foil is placed in a 25 cm spacing between the two sections. The incident H^- beam clears D_0 on the outside and is deflected onto the stacking orbit by the 1 m section of dipole. At the stripper we have $\beta_h \cong 10$ m and $\beta_v \cong 13$ m. The cross-sectional dimensions of the H^- beam, hence also of the stripper foil are 18 mm(h) x 10 mm(v). But in order to support the foil it may have to be larger. As discussed earlier these β values at the foil yield acceptable emittance growths due to foil scattering.

The fully stacked beam box-car is switched over to the storage orbit by a fast kicker magnet placed just upstream of F_0 where the two orbits cross and where $\beta_k = \beta_{max}$ (Figure 3). The angle to be kicked is

$$\theta_k = 2\sqrt{\frac{W}{\beta_k}} = 3.3 \text{ mrad.}$$

The kicker should be 1 m long, and have a peak field of 113 G and a rise time shorter than the separation between rf bunches in TRIUMF, namely 2 accumulator rf periods or 43 nsec. It may be better to stack 153 (10/9) = 170 beam packets in one box-car and string only 9 box-cars together with gaps 3 accumulator rf periods long. The rise time of the kicker could then be 65 nsec. Clearly by reducing the number of box-cars further one can accommodate even longer kicker rise times. This kicker should flat-top for ~180 nsec and should operate at a pulse rate of ~300 Hz.

Extraction from the Storage Orbit

The extraction kicker should be located at F_1 (see Figure 3). It can span both the stacking and the storage orbits, but the separation between the beams at F_1 is large enough to accommodate the side frame of a kicker which spans only the storage orbit. The specifications of this kicker could be the same as those of the orbit switching kicker, except the flat-top should be ~2.2 μsec. The kick angle of $\theta_e = \theta_k$ = 3.3 mrad at F_1 will give a horizontal displacement at F_2 of

$$(\Delta x)_e = \beta_{max}\,\theta_e \sin\mu = 83 \text{ mm.}$$

This is ample for the beam to clear a current septum and enter an extraction channel which further deflects the beam out of the accumulator. It is convenient to leave out the dipole in this half-cell F_2 to D_2. To cancel the dispersion caused by this omission we should omit another dipole half a wave length or 2 cells up- or down-stream, i.e. in either half-cell F_0 or D_0 or half-cell F_4 to D_4. To obtain the minimum 2-fold symmetry in the ring geometry one should omit also the diametrically opposite dipoles. These empty half-cells provide convenient locations for rf cavities.

The ring magnets of the accumulator will naturally have to have a wide aperture. Good field aperture of 14 cm(h) x 6 cm(v) is adequate. This aperture will accommodate beams with 30 π mm-mrad transverse emittances. Aside from the special problem created by injection from a cyclotron, TRIUMF, the design of the fast cycling synchrotron and of the superconducting stretcher ring is standard and needs no elaboration.

References

1. K.R. Symon, D.W. Kerst, L.W. Jones, L.J. Laslett and K.M. Terwilliger, Phys. Rev. 103, No. 6, pp. 1837-1859 (1956)
2. See e.g. A. Roberts, Ann. of Phys. 4, pp. 115-165 (1958)
3. See e.g. L.C. Teng, Proc. of the Workshop on Nuclear and Particle Physics at Energies up to 31 GeV (January 1981) p. 477, Los Alamos Scientific Laboratory Report LA-8775-C
4. W. Joho, Particle Accelerators 6, 41 (1974)
5. R. Laxdal, R. Lee, G. Mackenzie, TRIUMF design note TRI-DN-82-10; M.K. Craddock, TRIUMF design note TRI-DN-82-11
6. R. Baartman, R. Laxdal, G. Mackenzie, "Kaon Factory-Neutral Beam Injection", TRIUMF draft design note (22 October 1981)