INJECTION AND STACKING IN THE LARGE STORAGE RINGS

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High current beams will be obtained in the storage rings by injecting many pulses from the main ring or doubler. Thirty-two pulses of 0.4 Amp/pulse would be necessary to obtain 10 Amp of circulating current in a 1.3 km ring and 62 pulses for the 2.5 km ring. The injection of these pulses would be done by momentum stacking as in the ISR. This injection process is described in detail in many ISR reports [1], only the basic idea is outlined here.

A pulse from the main ring would be single turn extracted, transported to the storage ring and then single turn injected on an off momentum orbit. The injection kicker used to put the beam on this orbit without coherent betatron oscillations would have a mechanically removable eddy current shutter which protects the beam already circulating in the ring from the magnetic field disturbance during the injection pulse. After a pulse has been injected the shutter is opened and the rf system decelerates the beam pulse to the stacking radius, where it is dropped and the process repeated.

The basic requirement on the rf system is that it does not dilute the longitudinal phase space during this process. At the injection time the storage ring rf must be phase locked to the injector ring and the ratio of the rf voltages in the two rings must be such that the phase space area is matched. At the time the new pulse enters the stack the rf bucket must be just the area of the beam phase space. Finally the rf cavity shunt impedance must be small so as to minimize beam-cavity interactions. Thus low cavity accelerating voltage is necessary if power levels are to be kept reasonable.

One major difference between the high energy storage rings and the 30 GeV ring or ISR is that $\Delta p/p$ of the adiabatically debunched beam is small even after stacking if dilution does not occur. The beam width caused by momentum spread is therefore small and adjustment of dispersion to zero in the interaction region may not be necessary. However the small momentum spread increases the probability of longitudinal instabilities for the first pulses in the stack and for the beam in the injector ring before it is extracted. It seems quite likely that considerable longitudinal phase space diultion will take place. Detailed study will be necessary and the following analysis does not attempt to account for this problem. One other difference in the high energy storage rings is that the amount of voltage on the cavities is determined by the time allowable for acceleration to the stacking radius and not by the bucket size necessary to contain the momentum spread of the injected beam.

Injection

The 1.3 km storage rings (Case 2) will obtain beam extracted from the main ring or doubler at straight sections A and B. In straight section A, equipment installed for single turn extraction to the experimental areas would also be used for the clockwise storage ring. The transport from A0 to the storage ring could be incorporated in an experimental area plan of the Q-line or it could be a branch off this line. The transport line is arranged to have only a small amount of bend and so does not require long strings of superconducting magnets or elaborate tunnel construction. Experimental areas and the storage rings probably would not be at the same elevation so some crossing of the storage rings with beam lines is also permissible.

A separate set of extraction equipment would have to be installed for the transport from B0 to the counterclockwise ring. This line could be used also for development of a new experimental area or extended for a main ring or doubler bypass. For injection at 1000 GeV the transport would have to be superconducting but is only about 2/3 of the length of a main ring sector.

The radius of the storage rings is larger than that of the main ring so the injected beam pulse will be slightly less than one turn and the fall time requirements of the injection kicker are very modest. The rf system can have a suppressed bucket scheme so that the stack is not diluted by the missing bunches[2].

Injection into the 2.5 km rings would be done from straight sections C and E. Long superconducting transports of the order of 1/3 of the length of the main ring would be necessary for high-energy injection. There would be plenty of straight section space available for injection however, and any number of injection configurations could be worked out. Because the circumference of the ring is 2.5 times that of the main ring probably two main ring or doubler pulses would be injected and then both accelerated to the stacking point.

The most efficient use of straight section length in storage rings with high order symmetry (8) is to use part of two interaction straight sections for injection rather than to build separate straight sections for this purpose. The straight sections in which injection takes place can also be used for experiments and the ones which do not have injection will have a longer total distance available for the manipulation of interaction region and experimental apparatus.

For the 1.3 km ring, the straight section length is rather limited (250 m) if the storage-ring bending magnet field is to be kept below 45 kG. The possible injection schemes are determined by the following limitations. Injection will be done by a pulsed septum magnet followed by a fast kicker. Both magnets will be horizontally bending and should be located in high horizontal-β regions separated by 90° betatron phase advance. If a straight section is composed of 4 straight FODO cells with betatron phase advance 90° per cell it would be natural to locate the septum and the kicker in 2 neighboring cells immediately after the F quadrupoles.

The design parameters of the septum and kicker can be easily estimated. If the septum is 25 m long and operates at a field of 15 kG, the injected beam at the entrance to the septum will be about 6 inches off the machine center line. This is sufficiently far out so that the injected beam will clear the conductor and superinsulation of the upstream F quadrupole. An injection channel will probably be necessary in the iron shield of that quadrupole.

The kicker magnet should be capable of compensating for a 1.5 cm displacement at the septum. If the average β at the kicker and septum positions is 75 m, the kicker must make a bend of 0.2 mrad. Parameters for the two magnets are listed below and would be equally applicable for the 2.5 km ring.

Septum

length ℓ	25 m
field at 1000 GeV	15 kG
angle θ	11.25 mrad
$\ell\theta/2$	5.6 inches

Kicker

length	11 m
field at 1000 GeV	0.625 kG
angle θ	0.2 mrad
$\beta\theta$	1.5 cm
gap	1/2 inch
current at 1000 GeV	2.5 kA (10 Ohm at 50 kV)

Stacking*

The maximum rf voltage required in the storage rings is determined by the time required to accelerate the beam from its injection orbit to the stack orbit. Assume that this displacement ΔR is of the order of 1 to 2 cm and that r_p, the mean momentum radius is given by $r_p = R/\gamma_t^2$ and $\gamma_t \simeq \nu$. (This last approximation is probably not a very good assumption and a precise lattice calculation is necessary to determine γ_t.) We have chosen 20 kV for the peak rf voltage and a synchronous phase angle consistent

*See the end of this section for a definition of symbols used throughout.

both with acceleration and final bucket shape. The length of time necessary for acceleration to the parked orbit is given in Table 1 and is consistent with the cycle time of the injector. Note that alternate pulses can be injected into the two rings.

During injection the beam is not being accelerated in either the main ring or the storage ring and at the transfer time the phase space ellipses in the injector and storage ring must match. This requires that $V/R(\frac{1}{\gamma^2} - \frac{1}{\gamma_t^2})$ be the same in the two rings. The necessary main-ring voltage V_{mr} is given in Table 1 for the storage-ring voltage of 20 kV and $\Gamma=0$. V_{mr} turns out to be about 50 kV. The main ring has a number of rather high-impedance cavities necessary for the acceleration rates of 100 GeV/s. (The doubler will also need rf voltage for about 40 GeV/s.) It remains to be seen if the main-ring beam can be adiabatically debunched to the 50 kV level without beam loading instabilities and phase space dilution. Higher transfer rf voltages may be necessary. The time, τ_{mr} necessary for debunching the beam from a high rf level to the extraction level without dilution is approximately equal to $1/f_s$, where f_s is the synchrotron frequency at the extraction voltage.[2] In no instance is this time critically long.

The longitudinal phase space area of the main ring beam must be known in order to carry out calculations of the momentum size of the beam in the storage rings and of the bucket area necessary at stacking time. Measurements in the main ring at high energy indicate a phase space area of 0.2 eV-sec/bunch. Fine corrections to the main-ring injection phase lock system can probably reduce this to 0.1 eV-sec/bunch, the number used in calculations here. The bunch area if spread uniformly over 20 ns would give a Δp of 5 MeV/c. The minimum conceivable momentum spread in the storage ring is just the ratio of the storage ring current to the current injected per pulse times 5 MeV/c. The momentum width of the stacked beam given by $\Delta r = r_p \, \Delta p/p$ can then be estimated. The design main-ring current is 0.4 Amps and a typical storage ring current would be 10 Amps. These numbers have been used to find $\Delta p/p$ and Δr in Table 1. A factor of 2 inefficiency in the stacking process has also been assumed. Note that the rf frequency must be critically controlled at the time the beam is released into the stack.

The rf parameters necessary for matching the bucket to the beam area at stacking time can be obtained from the following standard formulae [4]. The invariant phase space ellipse can be written:

$$\frac{W^2}{a^2} + a^2 \phi^2 = A/\pi \quad .$$

Where A is the invariant area per bunch,

$$W = \Delta E/2\pi f_{rf}$$

$$a^2 = \left(\frac{eV \cos \phi_s}{2\pi h} \frac{E}{\eta}\right)^{1/2} \frac{1}{2\pi f_{rf}} \quad .$$

The bucket area A_B is given by

$$A_B = 16\ a^2(\phi_s=0)\alpha(\Gamma)$$

where $\alpha(\Gamma)$ is evaluated in ref. 4.

In Table 2 are listed solutions for the rf voltage of the minimum bucket for different rates of acceleration Γ; also listed are the synchrotron frequency and the energy spread at half height. Measurements at the ISR show that the stacking efficiency gets less as Γ increases. In our case, however, this effect is probably small compared with other diluting effects which will take place throughout the debunching in the main ring and deceleration in the storage ring.

In conclusion, rf parameters are generally more favorable in the 1.3 km storage ring. The filling time is shorted and shorter acceleration times at lower synchronous phase angles are possible. Final rf voltages and shunt impedances are higher.

The longitudinal stability criterion[5] usually given for the shunt impedance of a system is:

$$\frac{Z}{n} \leq \frac{m_o c^2}{e} \frac{\eta}{I\gamma} \left(\frac{\Delta pc}{m_o c^2} \right)^2 \equiv \frac{Z_{max}}{n}$$

where $m_o c^2$ is the rest energy of the proton, n is the harmonic of the rotational frequency which is of interest, and Δpc is the full width at half maximum of the momentum spread. During stacking I and Δp are approximately proportional. The first pulses are therefore the most unstable unless their phase space is blown up. Z_{max}/n and $Z_{max}(h/n)$ are given in Table 2 for $\Delta pc = \Delta E$ and $I = 0.4$ Amp. Obviously a closer look must be given to this problem, cavity and resistive wall impedences calculated, and a more reasonable longitudinal phase space dilution factor arrived at.

Finally, rebunching the storage ring beam to attain higher luminosities at low beam currents is probably not reasonable because of the large amount of rf voltage required.

References

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Definitions

E	storage ring energy
ΔE	half energy spread
R	ring radius
$r_p = \frac{1}{\gamma_t^2} R$	momentum compaction radius
γ_t	transition γ
$\gamma = E/m_o c^2$	
$\eta = \left\lvert \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} \right\rvert$	
ν	number of betatron oscillations around the ring(tune)
ϕ_s	rf synchronous phase angle
$\Gamma = \sin \phi_s$	
ϕ	half phase-angle width
f_{rev}	revolution frequency
f_{rf}	rf frequency
h	f_{rf}/f_{rev} = harmonic number
V	rf voltage

Table 1 RF Parameters for injection and acceleration in the storage rings.

ΔR distance between the injected and stacked orbits

ΔE_{acc} change in energy between the injected and stacked orbits

t_{acc} time necessary for acceleration

τ_{mr} debunching time necessary in the main ring

$\Delta p/p$ the momentum spread of the stacked beam assuming a factor of 2 dilution in the phase space during the stacking process. Injection pulse intensity 0.4 Amp, storage ring intensity 10 Amp, injection pulse phase space 0.1 eV-sec/ bunch.

Δr momentum width of the stacked beam

Storage ring	Case 1		Case 2	
E (GeV)	300	1000	300	1000
R (km)	2.48		1.26	
f_{rev} (kHz)	19		38	
$r_p \approx R/\gamma_t^2$ (m) ($\gamma_t \approx \nu$)	0.6		1.2	
ΔR (cm)	1		2	
ΔE_{acc} (GeV)	5.0	16.7	5.0	16.7
V (kV)	20		20	
$\Gamma = \sin\phi_s$	.8		.5	
dE/dt (GeV/s)	0.31		0.40	
t_{acc} (sec)	16	54	13	42
V_{mr} (kV)	75		38	
τ_{mr} (sec)	0.06	0.11	0.08	0.16
$\Delta p/p$	0.83×10^{-3}	0.25×10^{-3}	0.83×10^{-3}	0.25×10^{-3}
Δr (mm)	0.58	0.18	1.17	0.35

Table 2 RF parameters for stacking. Values for a full bucket with a single bunch phase space area of 0.1 eV-sec

V_f final rf voltage

ΔE final bucket 1/2-height

f_s final synchrotron frequency

Z_{max} maximum allowable shunt impedance

Storage ring		Case 1			Case 2	
E (GeV)	300	1000	1000	300	1000	1000
$\Gamma = \sin\phi_s$	.5	.5	.8	.5	.5	.8
h		2800			1400	
γ_t		65			33	
V_f (kV)	.54	.17	2.1	1.1	.34	4.2
ΔE (MeV)	7	7	12	7	7	12
f_s (Hz)	.25	.14	.22	1	.55	.9
Z_{max}/n (Ohm)	.1	.03	.1	.4	.14	.4
$Z_{max}(h/n)$ (Ohm)	310	95	280	630	200	560