STORAGE RING INJECTION

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Introduction

Multiturn injection is an essential step in generating high power beams for heavy ion fusion. Systems have been proposed that use a hundred turns of injection or more,[1,2,3] which must be done with minimal beam losses. To cause the stored beam to miss the back side of the inflector, adequate separation is required between the stored and incoming beams. This dilutes the phase space density, but the allowable dilution is also constrained by the limits on the brightness of the linac beam and the final focussing requirements set by the size of the fusion fuel pellet. The injection problem is thus bracketed by the constraints of beam loss on the one hand and phase space density on the other.

The most commonly proposed scheme to accomplish many turns of injection has been to inject N_1 turns into the horizontal plane of a ring used expressly for injection, transfer this accumulated beam to a storage ring after first interchanging the horizontal and vertical phase planes, and repeat the process N_2 times for a net multiplication of the linac current by $N_1 \times N_2$. For convenience, we assume $N_1 = N_2 = N$ and write $N^2 = S$, the total number of turns injected into the first ring and destined for any one final storage ring.

Investigation of injection schemes at ANL has begun to incorporate detailed space charge effects using numerical simulation.[4] The results so far confirm the expectation that space charge effects complicate the injection problem, and more dilution seems necessary to avoid excessive beam loss. The means to increase the dilution allowance are, however, very limited.

Allowed Dilution

The dilution allowance may be written

$$D = \frac{\varepsilon_{SR}}{\varepsilon_L \, (S)^{1/2}}$$

where ε_{SR} = the emittance of the stored beam and ε_L is the emittance of the linac beam. The total number of injected turns is also the ratio of the overall current of the beam stored in the ring (I_{SR}) to that out of the linac (I_L). The average stored current, based on the space charge limit, is

$$I_{SR} = K \cdot \Delta\nu \cdot \varepsilon_{SR} \cdot (\beta\gamma)^2 \cdot \overline{B} \cdot BF \qquad ,$$

where the value of K is about 100 if the average magnetic field ($\overline{B}$) is expressed in Teslas and the emittance is expressed in mr-cm. The expression gives the same average current for a given fill and different azimuthal beam distributions (i.e., bunching factors, BF) as long as the corresponding value of the tune shift is used.

The dilution may now be written

$$D \sim \left(\frac{I_L}{\Delta\nu \cdot B \cdot BF}\right)^{\frac{1}{2}} \frac{\varepsilon_{SR}^{\frac{1}{2}}}{\beta\gamma\ \varepsilon_L} \qquad .$$

The variables in this expression are subject to numerous constraints. As noted above, ε_{SR} is constrained by the final focussing requirements. Much consideration of the normalized linac emittance ($\beta\gamma\ \varepsilon_L$) has led to rough agreement about the minimum feasible; though reductions are not impossible, they are expected to be very difficult. Multiple front ends and other concepts have raised the linac current to the point where economics may be the limiting factor. The tune shift and bunching factor should not be too small to achieve cost effectiveness in the storage rings. Thus, a small average field, or large ring radius, may be the most useful possibility for increasing the dilution allowance.

If there were a more important reason for keeping the ring radius small, this means of providing a larger dilution allowance could not be used. From the results of the storage ring group at the workshop, it appears that such a reason could be avoidance of the longitudinal microwave instability. The potential conflict stems from the dependence of the Keil-Schnell threshold current[5] for this instability on the momentum spread of the stored beam, which is related to the ring radius in the following way.

As the ring circumference is increased, so tends to be the length of the beam contained in it. This requires increased longitudinal compression to reach the final beam length determined by the short pulse duration needed to drive fusion pellets to ignition. Additionally, efficient focussing constrains the momentum spread in the compressed beam to some upper limit; and for a given upper limit, conservation of phase space in the longitudinal plane requires that the momentum spread before the final compression must decrease as the amount of compression is increased. Thus, enlarging the circumference of a ring tends to require storing beam with smaller momentum spread, raising the concern that the stored beam will be unstable.

The storage ring parameters generated at the workshop use relatively high average magnetic fields, apparently to avoid the instability by maintaining adequate momentum spread in the ring. As shown in Table I, however, these designs may be easily adjusted to larger ring radius, lower magnetic field, fewer turns of injection, and larger allowed dilution without changing the momentum spread (or the final compression factor). The changes are made by adjusting the bunching factor, tune shift at the space charge limit, number of rings, and number of bunches per ring. As seen in Table I, all of the changes that have been made are non-controversial.

Discussion

The revised parameters show that phase space dilutions by more than a factor of 2.5 can be provided for the systems considered at the workshop. Initial studies of injection in the presence of strong space charge forces[4] permit optimism that the allowance of this much dilution will result in acceptably small beam loss. In fact, the ease of reducing the injected turn requirement to a relatively small number suggests that one or more of the other significant parameters of the systems are not optimal and invites consideration of further parameter changes. Alternatively, one could simply rejoice at the prospect of an easier injection task, and that it is not mandatory to employ schemes that call for additional rings for injection, multiple ring filling ejection, and transfer, etc. Nevertheless, these schemes appear to be technically realistic, if confined to reasonable limits, and the most immediate question may not be technical feasibility but cost. Thus, it could be profitable to return to a higher degree of difficulty for the injection problem, if this allows changes that significantly reduce the overall cost.

In the systems studied, the linear accelerator is the obvious subject for cost reduction attempts. Most obviously relevant to the injection problem is the beam current, which was taken to be 0.3 A. For cases B and C, the peak power needed to accelerate the beam is 3 GW. A reasonably optimistic unit cost for rf power is 0.1 \$/W. The resultant \$300 M price for the beam power component of the rf requirement suggests that it may be advisable to lower the current to cut the cost, and accept the corresponding increased difficulty in the injection problem.

Reducing the total accelerating voltage of the linac would not only reduce the rf costs, but all other linac costs as well. In the context of the fusion pellets considered at the workshop, one would keep the ion kinetic energy and shorten the linac by increasing the ion charge state.

Table II compares some parameters for a Case B system (3 MJ, 10 GeV) using U^{+2} with the previous U^{+} system. Halving the linac cost and increasing the cost for rings probably brings the total cost down.

In addition to the space charge effects or charge state that were regularly considered before the workshop, the effect of the charge state on the longitudinal instability must also be taken into account. The systems studies at the workshop were guided by the dependence of the Keil-Schnell threshold current, which varies inversely with the charge on the ions. It appears, however, that the Keil-Schnell threshold criterion is irrelevant for HIF storage rings because of the low velocity of the ions, which results in a large capacitive contribution to the complex inpedance. This makes the stored beams unstable with a modest resistive impedance component.[6] The amount of momentum spread required for stabilization would result in excessive chromatic aberration in final focussing and/or impractical ring parameters. Stabilization by providing compensating inductive impedance also appears inapplicable. Because the impedance provided by any physical feature of the ring will depend on the frequency, such compensation would not stabilize all of the relevant modes.[7] Therefore, the risetime of the instability rather than the threshold current appears to be the governing consideration.

Fenster[6] finds that the risetime may be expressed for the purposes of systems studies in the following convenient form

$$t_{rise} = \left(\frac{2R}{\Delta\nu\varepsilon_{SR}}\right)^{\frac{1}{2}} \frac{Z_0}{2\pi Z_r \beta^2 c} \qquad \text{(sec)}$$

Z_r is the resistive contribution to the longitudinal impedance ($\Omega\ m^{-1}$) and $\Delta\nu$ is the tune shift at the space charge limit. In the examples given in Table I and Table II, the problem has been looked at in terms of the values of Z_r needed to achieve $t_{rise} = 0.01$ sec. Since the beam is accumulated in a fraction of this time (about 2 msec), the values of Z_r given in the tables should substantially overestimate the requirement.

Summary

Some basic issues involved in injecting the beam into storage rings with the principal parameters of those studied at the workshop have been considered. The main conclusion is that straightforward adjustments of the storage ring parameters makes injection easy. The largest number of injected turns is fourteen, and the phase space dilution allowance seems adequate to ensure very small beam loss during injection. The adjustments also result in lower bending magnet fields, and high field superconducting magnets (e.g., 5 Tesla) are not necessary. The design changes do not necessarily affect the Keil-Schnell criterion for stability of the longitudinal microwave instability, although that criterion appears to be irrelevant. Because the beams are expected to be unstable, but with slow growth rates, the vacuum chamber impedances required to give equal risetimes for the various designs are compared for systems posing various degrees of difficulty for injection.

Finally, the impact of the parameters on cost is noted, and a system is considered that cuts the length of the linac in half by using doubly charged ions. Aside from the possible net decrease in cost, the system using doubly charged ions required fewer injected turns (due to the same changes made for the other revised systems) and a slightly lower resistive impedance per unit of length than the comparison U^+ system.

TABLE I

Comparison of Revised Parameters (NEW) with Those Suggested at Conclusion of Workshop (WS)

$A = 238$, $q = +1$, $I_L \approx 300$ mA, $\beta\gamma\varepsilon_L = 1.5$ µm-rad,
$\Delta p/p = 2.8 \times 10^{-4}$ (FWHM, beam stored in ring)

	CASE A		CASE B		CASE C	
	NEW	WS	NEW	WS	NEW	WS
E (MJ)	1		3		10	
T (GeV)	5		10		10	
$B\rho$ (T-m)	158		224		224	
t_f (ns)	20		40		70	
I_{aV} (kA)	10		7.5		14.3	
l_b (m)	1.25		3.485		6.1	
Total Compression, LC	49		49		49	
$\Delta\nu$	0.25	.068	0.25	.115	0.25	0.19
BF	0.5	1.0	0.5	1.0	0.5	1.0
ε_{SR} (µm-rad)	57	60	55	60	61	60
N_{SR}	4	7	3	3	9	6
h	8	5	6	3	4	2
N_b	32	35	18	9	36	12
R (m)	156	49	326	81.6	382	95.1
t_{rise} (sec)	0.01		0.01		0.01	
Z_r (Ω m^{-1})	2.14	2.24	1.63	1.15	1.68	.968
$\bar{B}$ (T)	1.01	3.2	0.69	2.7	0.59	2.4
I_{SR} (S.C.L.) (A)	6.4	5.8	8.5	17	8.1	4
I_{SR} (avg) (A)	3.2	5.8	4.25	17	4.1	24.3
I_{SR} (exit) (A)	45	41	60	120	57	170
S	10	20	14	57	14	81
D	2.6	1.9	2.98	1.61	3.3	1.35

TABLE II

Comparison of 3 MJ System for U^{+2} with U^{+} System from the Workshop

q	+2	+1
E (MJ)	3	
T (GeV)	10	
$B\rho$ (T-M)	112	224
$\overline{T}_f$ (nsec)	40	
I_{aV}(kA)	15	7.5
l_b (m)	3.485	
LC	50	49
$\Delta\nu$	0.25	.115
BF	0.5	1.0
ε_{SR} (μm-rad)	57	60
N_{SR}	12	3
h	2	3
N_b	24	9
$(N_b)_{min}$	15	6
R (m)	112	81.6
t_{rise} (sec)	0.01	
Z_r (Ωm^{-1})	.93	1.15
$\overline{B}$ (T)	1	2.7
I_{SR} (SCL) (T)	12.5	17
I_{SR} (avg) (A)	6.3	17
S	21	57
D	2.5	1.6

Definition of Symbols

$\overline{B}$ = average magnetic bending field = $\frac{B\rho}{R}$

BF = bunching factor in storage ring

D = maximum allowable dilution per 2-D phase plane during injection

h = number of bunches from each storage ring

I_{aV} = nominal beam current on target

I_L = linac beam current

I_{SR} (S.C.L.) = peak stored current at space charge limit

I_{SR} (avg) = average current of stored beam

I_{SR} (exit) = peak beam current at extraction

LC = total compression of beam bunches beyond their length when stored at the space charge limit

l_b = final length of each beam bunch

N_b = total number of beams on target

$(N_b)_{min}$ = number of beams required by transport power limit

N_{SR} = number of storage rings

S = total injected turns per storage ring

R = average radius of storage ring

t_f = nominal duration of beam pulse on target

t_{rise} = risetime of longitudinal microwave instability

Z_o = 120 π

Z_r = resistive impedance of storage ring vacuum chamber per unit of length

ε_L = emittance of linac beam

ε_{SR} = emittance of beam stored in ring

ν = betatron tune of storage ring

References

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