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SUMMARY REPORT - INJECTION GROUP

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1. Introduction

The injector group attempted to define and address several problem areas related to the SSC injector as defined in the Reference Design Study (RDS). It also considered the topic of machine utilization, particularly the question of test beam requirements. Details of the work are given in individually contributed papers, but the general concerns and consensus of the group are presented within this note.

The group recognized that the injector as outlined in the RDS was developed primarily for costing estimates. As such, it was not necessarily well optimized from the standpoint of insuring the required beam properties for the SSC. On the other hand, considering the extraordinary short time in which the RDS was prepared, it is an impressive document and a good basis from which to work.

Because the documented SSC performance goals are ambitious, the group sought an injector solution which would more likely guarantee that SSC performance not be limited by its injectors. As will be seen, this leads to a somewhat different solution than that described in the RDS. Furthermore, it is the consensus of the group that the new, conservative approach represents only a modest cost increase of the overall project well worth the confidence gained and the risks avoided.

2. The Injector Parameters

The injector to the SSC as described in the RDS is made of three components: a linac, the Low Energy Doubler (LEB) and the High Energy Booster (HEB). The linac consists of an H^- source, an RFQ, a drift-tube linac, and a side-coupled linac. The final energy is 1 GeV. The normalized emittance for 95% of the beam population is assumed to be 1.1 π mm-mrad up to the drift-tube linac (125 MeV). A modest dilution is assumed in the side-coupled linac so that at 1 GeV the emittance is 1.3 $\pi\pi$ mm-mrad. The beam current is 25 mA (average) over a pulse whose length must be at least five times the circumference of the LEB, about 20 μsec. The issues of beam stability over this period of time (how constant the beam emittance, momentum spread, and central momentum can be maintained along the pulse length) have not been addressed in the Reference Design. The pulse is quite long and the beam tightly bunched; the ratio of the bunch-to-bunch separation to the bunch length of more than one hundred. The total momentum spread of 1 GeV is taken to be 0.1%.

We were concerned about the time required for the beam to "debunch", given by:

$$\tau_{deb} = \frac{\gamma^2}{2f_o\Delta p/p}$$

where f_a is the frequency structure in the beam, not necessarily the linac frequency. In the case that one linac bucket out of ten has a beam width determined by f_o = 0.13 GHz, τ_{deb} = 16 μsec. This is about three turns of the *LEB*. This represents a considerable period of time and one must worry about possible space charge tune depression during injection into the LEB.

The Reference Design Study assumes that the beam emittance at 1 GeV injection into the *LEB* is diluted from 1.3 to 4 π mm-mrad (95% of the beam). It does not specify how this is accomplished though and one can question how one can control the amount of dilution with external means. The probable intent is to let the beam dilute itself under the effect of the space charge forces. The figure of 4 π mm-mrad is crucial for the design since only a factor of 1.5 increase is allowed during acceleration to 1 TeV and transfer from the LEB to the HEP. At injection into the SSC the emittance is 6 π mm-mrad. No safety factor is allowed during transfer and capture in the SSC and no other safety factors are allowed during acceleration and operation in colliding-beams mode. We believe that the allowed figure of 1.5 for the beam emittance growth beyond injection into LEB is not adequate. Some of us feel that it should be twice that or even more. An analysis of possible dilution mechanisms is required and a comparison with what is (or could be) observed at Fermilab and in the SPS in CERN would be extremely important.

Let us turn now to the issue of the tune depression caused by space charge (the Laslett tune shift). An expression for this, which applies to a beam bunch with Gaussian distribution in all dimensions is

$$\Delta\nu_{s.c.} = \frac{3}{2}\frac{r_p}{\beta\gamma^2}\frac{NB}{6\pi\epsilon_N}FG. \qquad (1)$$

This expression is similar to (4.9.1) in the Reference Design. The normalized emittance $6\pi\epsilon_N$ in the denominator is for 95% of the beam *population* and is given in πm-mrad units.

There are two factors in Eq. (1) which nevertheless did not appear in the Reference Design: the *form factor F which* for β << 1 is close to unity,

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DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED but could be significantly larger than 1 for $\beta \sim 1$, as is the case at 1 GeV. It represents the image effects at the wall. The form factor G is an average over the lattice defined by:

$$G = \frac{1}{2\pi R} \int \frac{ds}{1 + \sqrt{\beta_H/\beta_V}}$$

For a beam with the same emittance in both planes $G = 0.5$. If the beam is flat (i.e. the emittance in the vertical plane is smaller than ϵ_N), then $G \approx 1$. If we take a flat beam, which is likely the assumption of the Reference Design, we see that for $6\pi\epsilon_N = 4\pi$ mm-mrad and a bunching factor $B = 2$, $\Delta\nu_{s.c.} \sim 0.25$.

Consider the form factor, F, given by

$$F = 1 + \frac{b(a+b)}{h^2} \{\epsilon_1 [1 + \frac{\gamma^2 - 1}{\beta}] + \epsilon_2 \frac{\gamma^2 - 1}{B} \frac{h^2}{v^2} \}, \quad (2)$$

where h and v are the half width and half height respectively of the vacuum channel and of the magnet gap $h/v \approx 1$); a and b are the mean horizontal and veritcal beam axis assuming a uniform distribution; and ϵ_1 and ϵ_2 are the so called Laslett image coefficients. It the vacuum chamber is perfectly circular $\epsilon_1 = 0.411$.

Again, for a flat beam ($b < a$) and assuming a partially filled vacuum chamber ($ba/h^2 \sim 0.5$) we can observe that the second term at the right-hand side of Eq. (2) can be as large as 1/3 and his would make $\Delta\nu_{s.c.}$ as large as $1.3 \times 0.25 = 0.33$. A more careful examination is required of the factor $[b(a+b)/h^2]$. If the vacuum chamber is rectangularly shaped (as perhaps it should be) then $\epsilon_1 \sim 0.1$ and with the same assumption $\Delta\nu_{s.c.}$ could approach 0.36. Obviously there are uncertainties in calculating the tune shift and one can only be cautious about the problem. For instance, the coherent tune shift should also be summed though we do not expect a contribution larger of 0.01 if the beam is perfectly centered. Possible closed orbit distortions may bring the beam closer to the walls and cause this term to increase.

The group was also concerned that the assumed bunch factor, $B \approx 2$, is too small. It corresponds roughly to stationary rf buckets full of beam. It is true that this is about the configuration in the Fermilab Booster, but as the beam is accelerated B increases at a faster rate than the kinematic factor $\beta\gamma^2$ and one observes losses later in the cycle. It is important that an rf accelerating program is designed to guarantee that acceleration is possible so that the factor $B/\beta\gamma^2$ does not exceed the intial value. This may take a considerable amount of time (the total LEB cycle is already a long three seconds). Thus, the beam must spend a considerable length of time at low energy and one might wonder whether a tune depression of 0.25 is too large. In a fast-cycling machine, such as the Fermilab Booster, this could be acceptable as it would represent a transient, but we do not believe it is possible to maintain a large tune spread (0.25) over a time as long as a considerable fraction of a second.

Another question was that of beam behavior during the first few turns in the LEB while it is still tightly bunched (from the linac). The tune shift $\Delta\nu_{s.c.}$ as calculated with Eq. (1) is also a measure of possible disruptive effects during one turn. If we assume $F = G = 1$, $\sigma\pi\epsilon_N = 6\pi$ mm-mrad and $N = 0.6 \times 10^{12}$ (corresponding to one-turn injection) we predict $\Delta\nu_{s.c.} = 0.03$ B. For an initial bunching factor of ~ 100 this gives $\Delta\nu_{s.c.} \sim 3$. It is important that the beam is injected with considerably less bunching. One solution would be the addition of a "debuncher" between the linac and the LEB. A debuncher not only would reduce the bunching factor, b, but can also be used as a feedback device to stabilize the central momentum value of the beam and the other characteristics along the pulse length. Slower filling (i.e. longer injection at less current)

An approach to injector parameterization suggested and originally developed by C. Ankenbrandt represents a systematic procedure which addresses many of the group's concerns. Briefly, the procedure is:

- determine the beam brightness as specified by acceptable beam-beam tune shift at 20 TeV
- specify a cascade of accelerators which (at least) preserves this brightness and maintains conservative acceleration ratios and other parameters.

The distinctive character of following such an approach is the need for a third, low-energy synchrotron and the use of a lower energy linac.

Several other issues were discussed by the group. For examples:

- Is the apparent simplicity and cost effectiveness of the proposed bi-directional operation of the HEB such a good idea? It requires more complicated rf, diagnostics, dampers, and beam dumps.
- Can the Fermilab booster's diagnostics (or some other) be upgraded to investigate emittance blowup in detail?

3. Machine Utilization

J. Cooper studied the requirements for test beams. His paper anticipates additional performance capabilities (slow spill, etc.) which must be designed into the SSC injector systems.

4. Other Items

A.G. Ruggiero's studies of how a $\bar{p}$ source might be implemented at the SSC are, fortunately, consistent with the proposed new sequence of accelerator steps. This, plus the study of $\bar{p}$ production limitations (G. Dugan), are important for $\bar{p}$ capability in the SSC.

In addition, alternative booster schemes and techniques using superferric magnets and suggested by R.R. Wilson's talk have been submitted by individual authors.

5. Summary

Several aspects of the SSC injector system have been studied. Potential shortcomings of the RDS outlined scheme have been identified, and one possible systematic approach toward specifying a SSC injector have been made.