VARIABLE BUNCH SPACING IN SUPER COLLIDER

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Abstract

This paper suggests a variable bunch spacing instead of a fixed value in the SSC. This will give a higher luminosity for a given beam current and provide more flexibility in machine operations. Two possible schemes for varying the bunch spacing, namely, bunch coalescing and beam chopping, are studied and compared. Some of these discussions may be useful to future accelerators.

I. INTRODUCTION

When the beam-beam tune shift limit is not reached, the luminosity $\mathcal{L}$ is proportional to the bunch spacing S_b:

$$\mathcal{L} = \left(\frac{\gamma}{4\pi c \cdot e^2}\right) \frac{I^2}{\beta^* \cdot \epsilon_{\rm N}} \cdot S_b \qquad {\rm cm^{-2}s^{-1}} \tag{1}$$

in which γ is the relativistic factor, c the velocity of light, e the electron charge, β^* the β-function at the interaction point, I the average bunch current, and ϵ_N the normalized rms transverse emittance. The average number of events per crossing is:

$$n = \frac{\mathcal{L} \cdot \sigma_{\rm inel}}{c} \cdot S_b \tag{2}$$

in which $\sigma_{\rm inel}$ is the inelastic pp cross section. The baseline parameters are: $\gamma = 21316$, $I = 71$ mA, $\beta^* = 0.5$ m, $\epsilon_{\rm N} = 1$ mm-mrad, and $S_b = 5$ m. They correspond to $\mathcal{L} = 1 \times 10^{33}$ and $n = 1.7$.

The parameters I, β^* and $\epsilon_{\rm N}$ were chosen based on the limitations of accelerator technology and the costs, whereas the choice of S_b was made by the detector requirement that n should be close to 1. In the following sections, we investigate the merits and penalties of a larger bunch spacing — a multiple of 5 meters — and the means to implement it.

II. MERITS AND PENALTIES

It is seen from Eq. (1) that, when all the other parameters are fixed, a larger bunch spacing will directly translate to a higher luminosity. This fact can be exploited in two different ways: (a) In the first few years during the commissioning stage, we will be on a learning curve. A larger bunch spacing can speed up the pace to reach the design luminosity. (b) When the machine operation is matured, a larger bunch spacing provides one of the easiest ways for a luminosity upgrade.

On the detector side, a larger bunch spacing would be beneficial to the electronics and instrumentation. This is because a lower collision frequency implies simpler electronics, easier synchronization of subsystems and easier bunch crossing identification. Moreover, a larger S_b is preferred by the detectors should the luminosity be below the design value, because it will bring n close to 1. Even when the luminosity reaches the design value, a larger S_b may still be preferred in order to get a higher luminosity in the n-for-$\mathcal{L}$ trade off.

A larger bunch spacing will also have certain negative impact on the pattern recognition of detector subsystems if it results in multiple events per crossing. The main concern is the tracking detector, which is most sensitive to an increase in pile-up per crossing, while the performance of the muon system, the electromagnetic calorimeter and hadron calorimeters will remain unchanged.

It is interesting to note that all the three LHC detectors — ATLAS, CMS, and L3P — claim they can deal with a n much larger than unity.[1-3]

III. IMPLEMENTATION

Assume $\mathcal{L}$ is fixed and S_b increased by a factor of 6. Then n will also be increased by the same factor. Below are two possible scenarios to achieve this bunch spacing.

A. Bunch coalescing

Assuming the coalescing be carried out in the MEB at the flat top (200 GeV), a new 10 MHz rf system (in addition to the main 60 MHz rf) is required. The longitudinal emittance ϵ_L will be increased by a factor of about 6. Because the baseline design includes an intentional ϵ_L blowup by a factor of about 50 when the beam is accelerated from 200 GeV to 20 TeV, the coalescing blowup factor can be absorbed in this process so that the final ϵ_L at 20 TeV will remain unchanged.

The reasons to choose the flat top in the MEB for coalescing are the following:

- The two cold machines, HEB and Collider, are excluded because of the possible quenching that could be caused by the lost particles during coalescing.
- The LEB is a fast cycling machine (10 Hz). It is thus difficult to incorporate the coalescing scheme.
- At the flat bottom (12 GeV), the beam lifetime due to gas scattering is poor, and the rf voltage required to generate the necessary size of the buckets to capture the coalesced bunches is high. In addition, a coalesced bunch with large longitudinal emittance represents a concern during the transition crossing.

The bunch coalescing has been a routine operation at Fermilab (Main Ring) and CERN (PS) for many years. The new features of the MEB coalescing are: (a) Unlike the Main Ring, all the buckets are filled in the MEB; (b) Unlike the PS, more bunches (six) need to be merged.

The procedure is: (a) reduction of the bunch momentum spread by either adiabatic debunching, or rf phase jump, or rf amplitude jump; (b) adiabatic capture and compression by the subharmonic rf system; (c) bunch rotation; (d) recapture of the coalesced bunches by the main rf system; (e) extraction. The simulations show that when coalescing 6 bunches using this scheme, the particles leaking into adjacent buckets are less than 0.5%.

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B. Beam chopping

This is to chop a gap in a sequence of micro-pulses of particles, i.e., to create a macro-structure. This has to be done when the beam energy is low, namely, in the linac, in order to avoid the radiation problem.

The injection from the linac to the LEB is a 4-turn process. In each turn, there are 9 micro-pulses injected into each LEB bucket. All the buckets are full. To change the bunch spacing from 5 m to 30 m, one has to chop out a gap of 25 m in the linac pulse sequence and fill up only every 6th bucket in the LEB. Meanwhile, each filled bucket has to contain more particles (a factor of 4, see Table 1) in order to maintain the luminosity. The number of injection turns has to be increased accordingly. The transverse emittance will also have to be blown up (by a factor of 3) due to the space charge. Four schemes have been studied:

1. The transverse deflector:
   This is a pulsed electrostatic deflector consisting of a number of pairs of plates. The voltage is applied to the plates sequentially at a rate that matches the beam velocity as a slow wave structure. In the AGS Booster, it is placed after the RFQ where the beam energy is 750 keV. Its length is about 1 m.[4] In the SSC linac, the beam exit energy from the RFQ is 2.5 MeV. Therefore, the deflector would have to be longer. The main concern of this scheme is that the no-focusing long drift space occupied by the deflector will cause a significant transverse emittance growth.
2. The energy chopper:
   This is a new idea proposed by D. Swenson. It is based on the fact that the Low Energy Beam Transport (LEBT) and RFQ are energy-selective. When the beam energy is 35 keV, the transmission in the RFQ is about 90%. When the energy error is ± 6 keV, the transmission is reduced to almost zero. Therefore, if one lowers the ion source energy down to 30 keV and installs a small acceleration device between the ion source and RFQ to provide alternatively $+5$ keV and -1 keV to the beam, then one can chop the beam by switching this device on and off. The device suggested by Swenson is a Betatron using a high permeability ferrite ring. It needs to provide the rise and fall times of 2-3 ns and the peak pulse length 21 ns. The difficulty is that the ferrite must have both high permeability and high frequency response. In the preliminary measurements using the commercial products CMD5005 and CN20, the rise and fall times of the primary are 200 ps, and that of the secondary are 25 ns (CMD5005) and 5 ns (CN20), respectively. The difference comes mainly from the geometry rather than the material. But the voltage of the pulse generator is too low (several volts) to draw any conclusions from the measurements.
3. The rf switch in the ion source:
   To meet the requirement of the neutron spallation source, V. Smith at LANL proposes to pulse the electrically-isolated collar in the Penning source to chop the H^- beam. The goal of the rise and fall times are on the order of 10 ns, which is still too slow compared with 2-3 ns required by the SSC linac.
4. The laser stripper:
   This is based on the observation that the binding energy of the second electron on the H^- is 0.75 eV and can be stripped by a laser beam of wavelength 1.06 μm (corresponding to a photon energy of 1.18 eV). The photoneutralization cross section is large (35 mega-barns). A pair of parallel mirrors of 5 cm length that reflects the laser beam 40 times can give rise to neutralization over 99%. However, if one wants to use this technology to chop 45 out of every 54 micro-pulses, the costs seem prohibitively high.

C. Comparisons

The advantages of the bunch coalescing method are:

1. For the same beam current, it gives more luminosity than that by the chopping method, because it does not have to sacrifice the transverse emittance.
2. For the same luminosity, it can ease the space charge problem in the LEB, because the number of protons per bunch is smaller.
3. It is a proved technology.

The advantages of the beam chopping method are:

1. It is flexible. In principle, it can create any macro-structure in the beam as needed. This is in contrast to the coalescing method, which requires a specific subharmonic rf system for a specific coalescing scenario.
2. It can decrease the current per bunch. This feature will be particularly useful during commissioning.
3. It can reduce the radiation at the LEB extraction.

IV. ACCELERATOR ISSUES

Table 1 lists the changes of the beam parameters when the bunch spacing is increased from 5 m to 30 m by the two different methods. The luminosity is fixed at 1×10^{33} cm^{-2}s^{-1} in these calculations.

1. Space charge in the LEB:
   When the chopping method is used, one has to put about 4 times more particles into a bunch. But this should be okay when one allows ϵ_N to be increased by a factor of 3. The simulation results are supported by the Fermilab Booster measurement data.
2. Injection efficiency in the LEB:
   When the chopping method is used, only a portion of the LEB buckets are to receive particles from the linac. The particles may leak into the neighboring empty buckets and create satellites or cause particle loss. Therefore, one needs to modify the rf voltage profile and inject 7 micro-pulses in each turn instead of 9. Simulation shows the particle loss will be less than 3%.
3. Dynamic aperture in the Collider:
   When ϵ_{N} is 3 times larger, the dynamic aperture, expressed in terms of the beam size σ, will be reduced. The values listed in Table 1 are obtained by a scaling formula. More accurate data by long term tracking (10^5 turns) gives 9σ.
4. Single bunch instability threshold:
   This should not be a serious problem because there is a relatively large safety margin (about 6) in the design. Furthermore, this margin can be improved by redesigning the longitudinal emittance budget.
5. Beam-beam interaction:
   The head-on tune shift is increased because there are more

Table 1. Beam Parameter Dependence on Bunch Spacing

Parameter	S_b = 5 m $\epsilon_{\rm N} = 1 \times 10^{-6}$	S_b = 30 m $\epsilon_{\rm N} = 1 \times 10^{-6}$ Coalescing	S_b = 30 m $\epsilon_{\rm N} = 3 \times 10^{-6}$ Chopping
Events per crossing n	1.7	10	10
Time interval between crossings Δt (ns)	17	100	100
Events per second (s^{-1})	10^8	10^8	10^8
Average current I (mA)	71	29	48
Protons per bunch $N_{\rm b}$ ($\times 10^{10}$)	0.81	2.0	3.3
Number of bunches M	17424	2904	2904
Head-on tune shift $\Delta\nu_{\rm HO}$	0.0038	0.0094	0.0053
Long range tune shift $\Delta\nu_{\rm LR}$	0.0067	0.0027	0.0046
Long range tune spread $\delta\nu_{\rm LR}$	0.0020	0.0008	0.0041
LEB space charge tune shift $\Delta\nu_{\rm SC}$	0.38	0.16	0.53
Synchrotron radiation $P_{\rm s}$ (kW/beam)	9.0	3.7	6.1
Parasitic heating $P_{\rm loss}$ (kW/beam)	1.3	1.3	3.6
Instability threshold $Z_{\parallel}/n$ (Ω)	3.7	1.5	0.9
$Z_{\perp}$ (MΩ/m)	250	100	60
Resistive wall instability $\tau_{\rm wall}$ (turns)	106	260	155
Dynamic aperture during injection (σ)	13	13	8.0
Dynamic aperture at IR (σ)	11	11	6.2
Beam-beam luminosity lifetime $\tau_{\mathcal{L}}$ (h)	78	32	54
Intrabeam scattering lifetime $\tau_{\rm x}$ (h)	211	86	516
$\tau_{\rm z}$ (h)	120	49	109
Luminosity reduction factor $R_{\rm r}$	0.91	0.91	0.97

particles in a bunch, whereas the long range tune shift is decreased because of a larger S_b. The total change is small and the sum is well below the tune shift budget of 0.02.

6. Synchronization during beam transfer:
   When the chopping method is used, the linac and LEB need to be phase locked. In addition, the beam transfer must be bucket-to-bucket. The SSC synchronization scheme assures that these can be done.
7. Instrumentation:
   The specifications (dynamic range, bandwidth and accuracy) of the orbit and phase measurements need to be revised in order to serve variable bunch spacing.
8. Other issues:
   (a) The average beam current becomes smaller, whereas the peak current becomes larger.
   (b) The synchrotron radiation is proportional to the average beam current. Therefore, it is also decreased.
   (c) The parasitic heating is proportional to the product of the average and peak beam current. It remains the same (in the case of coalescing) or is increased (in the case of chopping). This term may become a dominant loss term if more and more charges are put in a bunch for luminosity upgrades.
   (d) The beam-beam luminosity lifetime becomes shorter because the number of protons is smaller.
   (e) The total number of bunches is reduced by a factor of 6. This will make the machines more stable.

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