SSC-N-230

BEAM CURRENT LIMITATIONS IN THE SSC
A Review of Section 4.5 of the CDR

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ABSTRACT

Section 4.5 of the CDR on beam current limitations in the SSC is reviewed. The various estimates of impedance are discussed, and the stability of the beam is computed with the program BBI. The results are in very good agreement with earlier estimates. The most severe limitation appears to be the longitudinal coupled bunch instability, for which feedback stabilization or coupling out of higher modes in the RF cavities has been considered. However, increasing the energy spread at injection by only a small amount will stabilize these modes sufficiently without any additional measures.

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1. Introduction

The calculation of collective effects in the SSC has been performed by a number of people[1] and has more recently been completed and summarized by S. Chattopadhay in the CDR.[2] The stability limits were obtained from estimates of the impedances[3] of various components in the SSC vacuum chamber, using the computer program ZAP recently developed by M. Zisman at LBL. Further estimates of the growth rates of unstable modes and the required feedback systems[4] for stabilization were made by D. Hartill using the program DOSCIL written by R. Siemann at Cornell.

During my stay at LBL, I have tried to verify and extend these estimates using the program BBI (Bunched Beam Instabilities) which was written at CERN several years ago[5] and of which I had brought a copy with me on tape. However, this program was originally written for CDC computers, and only recently converted for use on IBM. The effort of further converting the program to VAXes, which are the main computers at LBL, did not appear justified in particular since ZAP already exists for these machines. However, with the help of T. Knight at SLAC it was possible to get the program running on the SLAC IBM, and D. Groom showed me how to address this machine directly from LBL. In this somewhat round-about manner we finally obtained results which agree quite well with those described in the CDR.

In this report I will thus mainly discuss some open questions on the impedance estimates, and propose a way to stabilize the beam at injection energy when it is the most unstable.

2. Impedance Estimates

In addition to the discussion of the impedance of various components of the vaccuum chamber in chapter 4.5 of the CDR,[2] a more detailed account of the derivation of these estimates is given in the report of the SSC Impedance Workshop.[3] Proceeding in the order of presentation in the CDR, I shall comment on the various components of the SSC vacuum chamber expected to have an appreciable impedance acting on the beam.

2.1 RF Cavities

At present, there is no consistent cavity design for the SSC. The CDR shows the 358 MHz PEP cavity and lists its (computed) higher modes, but the RF frequency of the SSC is listed as 374.7 MHz. Evidently, the cavity must be redesigned, or at least be scaled, so that the fundamental frequency is correct, and then the higher modes can be calculated. The large beam ports of 5 cm radius reduce the number of trapped modes in the PEP cavity to below 20 for both m=0 (rotationally symmetric) and m=1 (dipole) modes. Since the vacuum chamber in SSC has only 1.65 cm radius, the beam ports are also likely to be smaller, or a transition piece to the large radius tube has to be made which will have its own impedance to be calculated.

The calculation of energy loss due to the higher modes in the cavities[6] shows that it is important to keep those modes sufficiently far away from multiples of the bunch frequency (62.5 MHz). Scaling the PEP cavity in all dimensions does fulfill that criterion, but for an independent, new cavity design this should be taken into consideration.

The spread of the higher modes frequencies in the 40 RF cavity cells is due to variations of dimensions, temperature or tuner positions (which keep the fundamental frequency constant). It has been taken into account in the CDR by reducing the quality factor Q (typically about 40000 for copper cavities) by a reduction factor to about 2000, corresponding to a typical frequency spread of 5×10^{-4}. Since R/Q for each mode is a geometrical invariant, the impedance R must be reduced by the same factor 20, resp. the single cell impedance must be increased by a factor of 2, since the number of cells is 40.

In recent, still unpublished measurements of the LEP cavity cells, it was found that there the frequency spread is only of the order of 1×10^{-4}. Therefore special measures have to be taken, such as variation of dimensions or of the cooling water temperature from cell to cell. For the calculation of coupled bunch mode stability the exact value of the reduction factor for the quality factor is very important, and it should be taken into consideration for the detailed cavity design.

2.2 Resistive Wall of Vacuum Chamber

New results for the impedance of two-layer beam pipes have been reported recently by J. D. Jackson and should be used to update the estimates.

2.3 Space Charge

The almost perfect cancellation of electric and magnetic fields in a relativistic beam yields the factor $1/\gamma^2$ which makes this contribution usually negligible in high-energy storage rings. However, any perturbation of this equilibrium, like for example a small neutralization due to collision of the beam with the rest gas, or the "curvature" effect discussed by R.Talman[7] could easily increase its value by orders of magnitude.

2.4 Bellows

In large storage rings the transverse impedance of bellows can often become a dominant contribution to the single beam "transverse mode-coupling" instability. This is due to the large number of bellows required to compensate for thermal expansion of the vacuum chamber, and is enhanced by the fact that the bellows convolutions are usually rather close to the beam ($Z_T \sim a^{-3}$). In order to alleviate this limitation, bellows have been shielded in all recently built, large elctron storage rings.

In proton machines with many, long and weak bunches like in the SSC the transverse mode-coupling instability is less dangerous. However, the contribution of the bellows "cavities" to the impedance driving coupled bunch modes is not negligible, and it was therefore proposed to shield also the SSC bellows by two concentric tubes sliding one in the other. Naturally, this also makes a cross section variation which is even closer to the beam than the original bellows and care has to be taken to make the thickness of the inner tube as small as practically possible. The present example of 2 mm appears rather on the high side. In LEP, there are elastic "finger" contacts foreseen with a thickness of 0.7 mm. This solution also avoids leaving a small gap between the sliding parts which can couple to the bigger cavity formed by the bellows behind them.

2.5 Beam Position Monitors

The unexpectedly high contribution of these[3] is due to their large number and the particular design (stripline). If this impedance is really as big as assumed (transverse 11MΩ/m), a different design of pick-ups might be considered. However, a more careful evaluation of this impedance should be done first.

2.6 Injection and Abort Kickers

Kicker tanks usually contribute a considerable amount of impedance, but in the CDR this seems relatively small (1.4MΩ/m). The number of tanks is not stated in this section of the CDR, but is quoted as only 6 injector and 9 abort kicker tanks in the Impedance Workshop. Ferrite is used in the kickers, but its effect on the impedance is not discussed - I would expect it to be rather large. Tank resonances may be damped by high frequency losses in the ferrite, but then the HOM loss could become large. However, due to the low peak current and the small average power of the beam, heating of the ferrite is probably no problem.

2.7 Coherent Synchrotron Radiation

This impedance should be strongly suppressed by the presence of the surrounding vacuum chamber of high conductivity. It will contribute only at extremely high frequencies in the infrared, where the assumption of good conductivity breaks down. The radiation is then already mainly incoherent, so it might be better to call this section simply "radiation impedance", or neglect it altogether.

2.8 Collimators

Computations of their wake potentials have been done by Huan Lee using the program TBCI, which is not very accurate for this geometry. However, low frequency inductance agrees well with results from the program RSTEP by S. Kheifets with which we compared it for mode m=0.

2.9 Higher-Order Mode Loss

Energy loss is mainly due to higher modes in the RF cavities; it was calculated by M. Furman and H. Lee using a broad band approximation. Summation of an infinite series for Gaussian (Hermite modes) permits a calculation also for narrow-band resonances.[6] Losses depend critically on the exact mode frequencies. The exact RF cavity design must keep them away from harmonics of the

bunch frequency 62 MHz, and this can be done by scaling PEP cavity equally in all dimensions. Energy loss is not critical in warm elements like RF cavities; only the resistive wall has to be kept low - not recalculated yet. Energy loss during injection is enhanced due to "box car" stacking which excites many more harmonics than the evenly filled ring, but only at reduced current: if "de-Q-ing" by factor 20 is used in the calculation, losses increase by only 50%. Energy loss could be (somewhat) larger if more than one (higher) mode resonance is exactly at the same frequency in different cells.

3. Coupled Bunch Oscillations

Comparison of results by different computer programs

The parameters used are *not* exactly the same, since those in CDR are slighlty different from the ones used earlier in ZAP, (see Table 1) but not by far (17280 rather than 16600 bunches, 1.75×10^{-4} rather than 1.5×10^{-4} for energy spread.) The growth rates for longitudinal dipole mode are of the same order, quadrupole mode (just) damped. Transverse coupled bunch oscillations damped by small (10^{-3}) tune spread. There is a discrepancy in mode-number of most unstable mode; appears to be just the complementary number (number of bunches - mode number); sign error in imaginary part of frequency shift in one of the programs, of little importance for multi-bunch machines. BBI has been converted only recently, hence not fully tested - maybe just physics convention for exponentials $\exp(-i\omega t)$ rather than engineering convention used at CERN, $\exp(+j\omega t)$.

4. Stabilization by Enhanced Landau Damping

Longitudinal coupled bunch oscillations are almost stable; a small increase in damping is enough to keep also the dipole mode stable. Landau damping depends on the *fifth* power of bunch length resp. energy spread. This can be seen from the simplified stability criterion: frequency shift < frequency spread. The frequency shift is proportional to the *inverse third* power of bunch length or bunching factor $B = L/2\pi R$, while the spread is proportional to its *square*,

$$\Delta\omega = j\frac{m\omega_{so}}{(m+1)}\frac{I_b}{3B^3hV\cos\phi_s}\left(\frac{Z}{n}\right)_{eff}^{m,n}$$

$$S = \frac{m\omega_s}{2(m+1)}\frac{\pi^2}{48}\left(\frac{3+2\sin^2\phi_s}{\cos^2\phi_s}\right)(hB)^2$$

where

$$\left(\frac{Z}{n}\right)_{eff}^{m,n} = \sum \frac{Z(\omega_{m,n})}{\nu_{m,n}} h_m(\omega_{m,n})$$

$\omega_{m,n} = (kp + n + m\nu_s)\omega_o$ are the spectral frequencies, and $h_m(\omega)$ the normalized mode power density such that $\Sigma h_m(\omega_{m,n}) = 1$.

Increasing the energy spread (at injection) to 2×10^{-4} is sufficient to give stability for all longitudinal modes with the impedances assumed (0.23 Ω broad-band impedance, fundamental mode of RF cavity and its second harmonic de-Q-ed by 20.) Since the longitudinal bunch area needs to be blown up anyhow during acceleration,[9] it is reasonable to inject already with a larger energy spread as long as it fits into the aperture and noise diffusion is not too large. If the impedance estimate is too low, even larger energy spreads could be injected - the fifth power makes the required increase very small! Alternative means to increase Landau damping are higher harmonic cavities or a lower RF frequency.

5. Conclusions

1. By slightly increasing the energy spread of the injected beam from 1.75×10^{-4} to 2.0×10^{-4}, the expensive longitudinal feedback system against the coupled bunch dipole mode can be avoided.
2. No special mode killers are required in the RF cavities if the higher mode frequency spread can be held at several times 10^{-4}.
3. Higher order mode loss can be kept small by keeping the strongest higher modes in the cavities away from multiples of the bunch frequency 62 MHz.
4. Transverse coupled bunch modes and single bunch instabilities do not seem to present a problem in the SSC unless different modes of operation are seriously considered.

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Table 1.

BBI Output – growth rates & spreads

σ [cm]	δ_E [10^{-4}]	m	$1/\tau$ [sec^{-1}]	S [sec^{-1}]	stabil.?
6	1.75	1	2.09	1.33	U
		2	1.93	1.78	U
6.8	2	1	1.26	1.74	S
		2	0.71	2.32	S
8	1.75	1	0.56	1.66	S
		2	0.09	2.21	S

SSC with 17,280 bunches

using $Z/m = 0.23$ BB

1st + 2nd modes of RF cavity

(374 and 528 MHz)

de-Q-ing by factor 20

(the frequency spread S (5th col.) is defined on p.6)

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42-381 50 SHEETS 5 SQUARE
42-382 100 SHEETS 5 SQUARE
42-389 200 SHEETS 5 SQUARE
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