REVIEW OF BEAM INSTABILITY STUDIES FOR THE SSC

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Abstract

Beam instability studies for the SSC during the period 1989-1993 are briefly reviewed in this paper. Various topics are covered: single bunch and multi-bunch, single beam and beam-beam, parasitic heating and active feedback, *etc.* Although the SSC will not be built, many of the results obtained from these studies remain as useful references to the accelerator community.

I. INTRODUCTION

Studies on beam instability problems for the SSC started in the early 1980s. A set of preliminary results were included in Reference [1]. Since the establishment of the SSC Laboratory in 1989, these studies have been further pursued and numerous new results have been obtained. In this paper we will briefly review these results. For details the readers are referred to Ref. [2] and the references therein.

The SSC is a low beam current machine. The beam intensity is primarily limited by the cryogenic system for absorbing the synchrotron radiation power. Generally speaking, therefore, collective effects — such as single bunch instability, parasitic heating and beam-beam interactions — do not present a threat to machine operations. However, the coupled-bunch instability may become a real concern, because the number of bunches is enormous (about 17000 per beam) and the transverse emittance is very small (1 π mm-mrad, rms, normalized).

II. IMPEDANCE BUDGET

A. Impedance budget of the baseline design

Each component in the vacuum, rf, diagnostic and injection/extraction systems have been carefully analyzed. Computer models for each component have been built. Measurements for some critical components (*e.g.,* the bellows and the liner) have been carried out. Two groups of simulation codes have been put in use. One is numerical, *e.g.,* MAFIA and HFSS.[3] Another is based on a boundary perturbation method and called BPERM, which was developed at the SSC.[4] The results obtained from different codes are in agreement.

The impedance budget is listed in Table 1, where $Z_{\|}/n$ is the longitudinal impedance and $Z_{\perp}$ the transverse one. There are several remarks about this budget.

1. Every effort has been made to make the beam pipe as smooth as possible: the bellows are shielded; the valves have rf fingers; the vacuum pump ports are screened; the transitions between two pipes of different sizes are tapered; and the ceramic pipes in the kicker sections are coated with thin metallic layers.
2. Table 2 lists the impedances of two different designs for the bellows rf shield. The reduction comes from a smaller gap and a smoother taper. The specification of the maximum lateral offset is 2.8 mm. Assuming a uniform distribution in misalignment, the resulting increase in impedance is also listed in Table 2.
3. In order to accommodate unforseen sources, the calculated total impedance is multiplied by a factor of two, which is then used in the safety margin estimate.

B. Impedance in the presence of a liner

A perforated liner inside the beam pipe would increase the impedance in two ways:

1. The holes or slots would introduce additional impedance. Below the cutoff, small holes/slots behave like a pure inductance. For a given pumping area, short slots give less impedance than circular holes. Above the cutoff, resonant peaks in the impedance spectrum are observed when the holes or slots are periodically placed. These peaks can be greatly suppressed when the periodicity is destroyed. It is thus concluded that randomly distributed short slots would be the choice for the pattern of the perforation.
2. The installation of a liner would also reduce the inner radius (ID) of the pipe. Consequently, the transverse impedance would increase.

For an area coverage of the holes on the liner surface 4%, the impedance increase is listed in Table 3.

C. Single bunch instability threshold and safety margin

The instability threshold impedances are listed in Table 1. The ratio of the threshold to the impedance budget, called the safety margin, is listed in Table 3. Several measures could be taken to increase this margin, *e.g.,* a larger liner ID, a bigger longitudinal emittance and a higher rf voltage at injection.

III. COUPLED-BUNCH INSTABILITY

In order to suppress the coupled-bunch instability, four types of rf cavities — multiple-cell and single-cell, superconducting (sc) and normal conducting (nc) — have been compared. The rf committee has endorsed the single cell, sc cavity as the choice for the SSC.

The higher order modes (HOM) may also be generated if the beam pipes in the dipole and quadrupole sections have different cross sections, which is called the trapped mode effect. The result could be a continuous beam emittance growth. Therefore, it was decided to use a beam pipe of uniform cross section throughout the entire cold region.

IV. RESISTIVE WALL INSTABILITY

The beam tube of the Collider is made of stainless steel, which is coated on its inner surface with a thin copper layer in order

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Table 1. Impedance Budget (per ring)

Component	Number	Impedance	
		$Z_{\parallel}/n$ (Ω)	$Z_{\perp}$ (MΩ/m)
RF cavity (HOM)	8 × 5-cell	0.036	0.016
Transition (tapered)	4	0.004	0.003
Bellows (shielded)	6000	0.12	10
BPM (15 cm, 55°)	968	0.05	4.6
Weldment	12000	0.002	0.2
Valve (shielded)	128	1E-4	0.01
Pump port (screened)	650	0.02	2
Flange gap	12000	TBD	TBD
Resistive wall		0.02	1.7
Scrapers		1.8E-4	0.02
Collimators		2.6E-4	0.08
Injection Lambertson (laminated)		1.5E-3	1.4
Abort Lambertson (solid iron)		–	–
Injection kicker		0.06	2.0
Abort kicker		0.2	4.7
Joint to Lambertson		TBD	TBD
Conical section near IP		–	–
Total		0.51	27
Impedance budget = Total × 2		1.0	54
Instability threshold:			
At 2 TeV		4.0	270
At 20 TeV		16	1200

Table 2. Comparison of Bellows (shielded) Impedance

Case	$Z_{\parallel}/n$ (Ω)	$Z_{\perp}$ (MΩ/m)
Baseline design	0.12	10
New design		
No misalignment	0.03	2.5
Max lateral offset 2.8mm	0.06	6.5

Table 3. Transverse Impedance with/without Liner

Case	$Z_{\perp}^{(liner)}$ (MΩ/m)	$Z_{\perp}^{(others)}$ (MΩ/m)	$Z_{\perp}^{(total)}$ (MΩ/m)	Safety Margin
Baseline	–	54	54	5
With liner	37	94	131	2

Table 4. Resistive Wall Impedance Budget

Component	$Z_{\perp}$ (MΩ/m)	
	2 TeV	20 TeV
Cold beam pipe	4300	4300
Warm beam pipe (stainless steel)	1300	1300
Graphite shadows:		
Upstream to abort Lambertson	7.1	7.1
Upstream to collimator	10	323
Scrapers (copper)	1.4	46
Collimators (stainless steel)	7.7	250
Abort Lambertson (solid iron):		
Symmetric	22	22
Asymmetric	4.6	4.6
Total	5700	6300

to have low electrical resistivity. The resistive wall instability growth time can be approximately written as

$$\tau_{\rm w} = \left(\frac{2\pi\gamma\ \nu_\beta\ b^3}{N_{\rm tot}\ c\, r_{\rm p}}\ \frac{\mu\omega}{2} \right) \sigma_e \Delta \tag{1}$$

where γ is the relativistic energy of the particles, ν_β the betatron tune, b the beam tube radius, μ the vacuum permeability, ω the angular frequency, $N_{\rm tot}$ the total number of particles, c the velocity of light, $r_{\rm p}$ the classical radius of proton, σ_e the wall conductivity, and Δ the coating layer thickness. The specification is $\sigma_e\Delta \geq 1 \times 10^5\ \Omega^{-1}$, which corresponds to a wall impedance of 4300 MΩ/m in the cold region. Table 4 is a list of the wall impedance budget, which gives a growth time of 25 ms, or 88 turns, during the about one hour injection period.

An alternative is to use an aluminum beam tube. There are several reasons for considering this option: saving the coating cost, solving the vacuum problem without a liner, and avoiding the adhesion problem in a bi-layer tube. The quantity $\sigma_e\Delta$ remains about the same.

V. FEEDBACK SYSTEMS

The feedback systems serve four different purposes:

1. Correction of the injection errors — The feedback must have enough power to kick the beam back to the orbit before any significant decoherence occurs.
2. Damping of the resistive wall instability — Because this is a fast beam blowup, a feedback system with a large gain is needed.
3. Damping of the coupled-bunch instability — The feedback system needs a wide bandwidth.
4. Control of emittance growth — This feedback system must have very low noise level. The emittance growth rate due to the feedback noise is:

$$\frac{1}{\tau_{\rm noise}} = 0.64\, f_0 \left(\frac{x_{\rm N}}{\sigma_\beta}\right)^2 \Delta\nu^2 \qquad (2)$$

   in which f_0 is the revolution frequency, $x_{\rm N}$ the noise level at the pickup, σ_β the rms beam size and $\Delta\nu$ the total tune spread. The theoretical limit of the pickup resolution due to the thermal and electronic noises, Δx, is also calculable. In designing a feedback system, Δx must be smaller than $x_{\rm N}$, which is determined by a specified allowable growth rate $1/\tau_{\rm noise}$.

The specifications of the power, bandwidth, gain and noise level of the feedback systems can be found in [2].

VI. PARASITIC HEATING

The parasitic heating can be calculated by

$$P = k \frac{I_{\rm av}^2}{M f_0} \qquad (3)$$

where $I_{\rm av}$ is the average beam current, M the number of bunches, and k the loss factor, which is

$$k = \frac{c^2 R}{2\pi b} \int_{-\infty}^{\infty} \tilde{\lambda}^2(\omega)\ R_{\rm s}(\omega)\ d\omega \qquad (4)$$

in which R is the machine radius, $\tilde{\lambda}(\omega)$ the bunch spectrum. In order not to exceed the heat load budget (which is 1 kW per ring for the parasitic heating), the surface resistance must be kept below a certain level. To estimate $R_{\rm s}$ correctly, one should consider the co-existence of three extreme conditions:

- Low temperature (4 K).
  The low temperature resistance is described by RRR, the residual resistance ratio. But it is meaningful only at low frequencies and low magnetic field.
- High magnetic field (6.8 T).
  The magnetoresistance can be studied using a Kohler plot. At 6.8 Tesla, the RRR value is about an order of magnitude lower than that at zero field.
- High frequency (1 GHz and above).
  Because of the anomalous skin effect, the surface resistance ratio $R_{\rm s}(300\ {\rm K})/R_{\rm s}(4\ {\rm K})$ at high frequencies is significantly lower than the dc value.

The measurement of $R_{\rm s}$ under these conditions was started but not completed.

VII. BEAM-BEAM EFFECTS

A. Strong beam-beam interactions

1. Inelastic scattering:
   The particle loss rate is ˇ$\sigma_{\rm inel}$, which is $10^8\ {\rm s}^{-1}$ per interaction point (IP). The corresponding luminosity lifetime is $180/N_{\rm IP}$ hours.
2. Elastic scattering:
   This contributes to the emittance growth:

$$\frac{d\epsilon}{dt} = \frac{N_{\rm B}\, f_0}{4\pi\epsilon} \sigma_{\rm el} \sigma_\theta^2 \qquad (5)$$

   in which $N_{\rm B}$ is the number of particles per bunch, $\sigma_{\rm el}$ the elastic cross section, σ_θ the rms values of pp elastic scattering angle in the center of mass system. This gives about 4.6×10^{-17} m-rad/s per IP.

B. Electromagnetic beam-beam interactions

1. Incoherent effects:
   (a) Tune shift and tune spread:
   The most significant beam-beam effect is the slow diffusion caused by high order betatron resonances. The budget of the total tune spread (head-on + long-range + nonlinear magnetic field) is 0.02. The calculated tune spread is well below this value.
   (b) Orbit distortion:
   This is induced by long-range interactions. The calculated values are small compared with the beam size at the IP's (less than 10% σ_β).
2. Coherent effects:
   The rigid dipole modes (π- and σ-mode) and high order multipole modes are studied. There are enough stability regions in the (ξ, ν_β) space.
3. Pacman effect:
   There are seven injection gaps (1.7 μs each) and one abort gap (4.1 μs) in the bunch train. Bunches near the edge of the gaps may miss collisions at some IP, thus experiencing an irregular collision sequence. This makes the orbit and tune correction difficult. But simulations show that there is enough working area in the tune space to accommodate this Pacman effect.
4. Synchro-betatron resonance due to crossing angles:
   Computer simulations show that this is not a serious problem. Because the three parameters that determine the strength of the resonance are all small: (a) the beam-beam parameter $\xi = 0.0009$, (b) the synchrotron tune $\nu_s = 0.0012$, and (c) the normalized crossing angle $\alpha\sigma_s/\sigma_\beta = 0.45$.

References

[1] "*SSC Conceptual Design*," SSC-SR-2020, SSC Laboratory (1986).
[2] W. Chou, SSCL-680, SSC Laboratory (1994).
[3] MAFIA is developed by T. Weiland and his associates, HFSS by Hewlett-Packard Company.
[4] T. Barts and W. Chou, SSCL-MAN-0035, SSC Laboratory (1994).