Physics Issues of the Synchrotron Radiation Intercept at the Superconducting Super Collider

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Abstract

The synchrotron radiation is a main concern in the design of the Superconducting Super Collider (SSC). One solution to this problem is to install the intercepts to absorb radiation at a temperature above that of liquid helium. This paper discusses several physics issues associated with the intercepts, including the rf impedance, vacuum, etc. Various types of intercepts are compared in these respects.

I. Introduction

The synchrotron radiation has been studied for years in electron accelerators. For proton machines it was never an issue. However, the approval of the 20 TeV SSC project has changed the picture. The SSC will be the first proton machine of which the performance will closely be related to the synchrotron radiation.

The radiation leads to two types of problems. One is the heat load, which accounts for about one third of the total cryogenic power at the nominal operation of the SSC, and goes up linearly with the beam current. Another problem is the vacuum, which may become intolerable when the gas molecules produced by the photon-induced-desorption accumulate in the surface of the beam tube that serves as a cryopump. These absorbed molecules will give a catastrophic pressure rise when a monolayer is built up at a temperature near 4 K (the magnet temperature). They can also easily be re-desorbed by the scatterd photons (the secondary desorption).

One solution is to install the radiation intercepts inside the beam tube. These intercepts will absorb the radiation power at a temperature above that of the liquid helium, say 20 K or 80 K. Therefore, the Carnot efficiency of the refrigerators will be much higher. The intercepts will also help to solve the vacuum problem, because they can substantially reduce the secondary desorption of the previously absorbed gas molecules.

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There are several proposals for the intercept design. We will mainly study the liner (or the screen as in CERN's glossary). The ridge type and the dog-ear type intercepts will be dicsussed for the purpose of comparison.

II. The Liner

Figure 1 shows the generic shape of a liner. The outside is the bore tube. It is at the liquid helium temperature ($T_0 \sim 4$ K) and serves as a cryopump. The inside is the liner. Its temperature is higher ($T = 20$ K or 80 K). The principal function of the liner is to decouple the beam from the bore tube. The slot is for the pumping purpose. There will be cooling tubes, supports and probably getters in between the bore tube and the liner. They are omitted in the figure for simplicity.

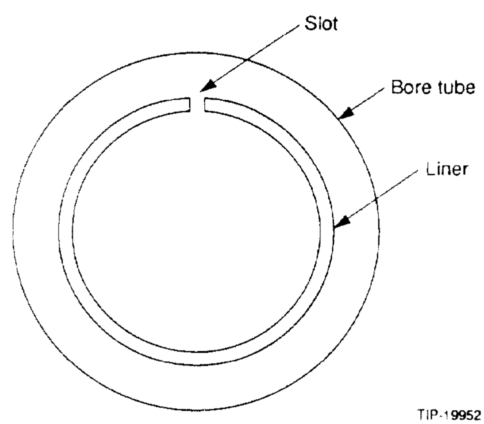

Figure 1. The generic shape of a liner.

When the synchrotron radiation hits the liner, the heat will be absorbed by the wall and carried away by the gas helium in the cooling tubes that are attached to the liner. The ratio of the refrigerator efficiency, between with and without the liner, is roughly T/T_0, which is 5 ($T = 20$ K) or 20 ($T = 80$ K). In other words, with a liner, the SSC would be able to operate at a beam current intensity that is 5 (or 20) times higher than the designed value (72 mA) without the need to upgrade the cryogenic system. This

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is certainly desirable. Because not only can a larger beam current make the luminosity upgrading possible, it will also help to ease the requirements on other parameters (the brightness of the beam and the betatron function at the interaction region) in order to reach the nominal luminosity (10^{33} cm^{-2}s^{-1}). Furthermore, the gas molecules (mainly H_2) desorbed from the wall of the liner by the synchrotron radiation will be pumped out through the slots and absorbed by the inner surface of the bore tube. The liner will prevent these absorbed molecules to be re-desorbed by the scattered photons, which are confined in the liner. One may also install getters in the space between the liner and the bore tube to avoid the formation of monolayers on the tube wall.

The installation of a liner will entirely change the beam environment. Several issues have been studied as follows.

1. The slot size. It should be large enough to meet the vacuum requirement but still small enough to avoid rf penetration through it. For a beam life time, τ, of 150 hours, the residual gas density is

$$n = \frac{1}{\tau\sigma c} = 0.6 \times 10^{15} \quad 1/\mathrm{m}^3 ,$$

in which $\sigma = 100$ mb is the inelastic cross section of the p–H_2 collision at 20 TeV, c the speed of light. This gas density corresponds to 1.7×10^{-8} Torr at 300 K. The pumping rate of the slot is

$$\begin{aligned} S_1 &= n \cdot \frac{1}{4}\bar{v} \cdot w \cdot P \\ &= 2.2 \times 10^{16} \cdot \sqrt{T} \cdot w \quad 1/\mathrm{s} \cdot \mathrm{m} , \end{aligned}$$

in which w is the width of the slot, P the Clausing factor (the probability of passage) of a rectangular duct (about 0.7 when the slot width is comparable with the wall thickness of the liner), and

$$\begin{aligned} \bar{v} &= \frac{2}{\sqrt{\pi}} \cdot \sqrt{\frac{2k_BT}{m_{H_2}}} \\ &= 102.5 \cdot \sqrt{T} \quad \mathrm{m/s} , \end{aligned}$$

the average velocity of the H_2 molecules at temperature T. The photon induced desorption rate is

$$S_2 = \eta \cdot N_\gamma ,$$

in which η is the desorption coefficient, which is 0.02 molecules/photon at the beginning and will decrease as the photon dose is accumulated.

$$\begin{aligned} N_\gamma &= \frac{5}{2\sqrt{3}} \frac{\gamma}{137} \cdot \frac{I}{\rho \cdot e} \\ &= 1 \times 10^{16} \quad \mathrm{photon/s} \cdot \mathrm{m} \end{aligned}$$

is the mean number of photons emitted in a unit length by a current I (72 mA) circulating on a circle of radius ρ (10187 m), e the electric charge of a proton. By equating S_1 and S_2, we get

$$\begin{aligned} w &= \frac{13.4}{\sqrt{T}} \quad \mathrm{mm} \\ &= \begin{cases} 1.5 \ \mathrm{mm} & T = 80 \ \mathrm{K} ; \\ 3.0 \ \mathrm{mm} & T = 20 \ \mathrm{K} . \end{cases} \end{aligned}$$

2. The rf impedance associated with the liner. Preliminary estimation by means of simulation codes (such as MAFIA [1]) shows that, for a liner with a long slot, the impedance is tolerable provided that the width of the slot is small. The results are given in Table 1.

Table 1. Impedance of the Liner with Slots

Width w	$Z_\parallel/n$		$Z_\perp$	
mm	mΩ	% †	MΩ/m	% †
1	0.05	0.01	0.04	0.2
2	0.4	0.1	0.4	2
3	1.2	0.35	1.5	7.5

† The percentage of the total impedance of the SSC.

This table is computed for a liner with the inner radius b be 1.65 cm. If a smaller radius is adopted, the transverse impedance of the liner may increase significantly ($\sim b^{-3}$). It should be pointed out that more careful analysis together with measurements will be necessary in order to assure that there would be no rf coupling between the inner and the outer parts of the liner by the slots for frequencies as high as the upper bound of the bunch spectrum.

3. The resistive wall instability. The conductivity of copper at 20 K does not change significantly from that at 4 K. But at 80 K, the conductivity reduction factor is about 4. In order to keep the growth rate of the transverse multiple bunch instability due to the resistive wall at the same level, one has to increase the thickness of the copper layer. The proposed 80 K liner is made of pure copper of thickness 0.5 mm. This can be compared with the beam tube without the liner, which is made of stainless steel coated with a 0.1 mm copper layer. With this design, the equatorial pressure during magnet quenching also remains about the same.

There is another kind of liner that deserves serious consideration – the perforated liner. Instead of a long, narrow slot, a small portion (1-2%) of the liner surface is perforated with tiny holes ($\sim$ 1 mm in diameter) for the pumping purpose. This is mechanically more preferable than the slot type. The main concern is its rf impedance. There is difficulties in pursuing numerical simulations due to the large aspect ratio of the geometrical dimensions. Investigations are under way.

III. Other Types of Intercepts

There are several other conceivable types of intercepts. One is the ridge type, as shown in Figure 2. The ridges absorb the synchrotron radiation at an incident angle 90° (compared with 2 mrad without the ridges). Thus, the scattered photons will be reduced to the minimum. Furthermore, these ridges can be detatched from the beam tube and be kept at a higher temperature with their own cooling system. Therefore, the radiation heat load problem will also improve. The disadvantages of the ridge design is two-fold. (a) The rf impedances are considerably greater than the liner. Even with the best design of ridges (tapered edges, small dimensions, symmetrically positioned), the transverse impedance will account for up to 50% of the total machine impedance. The detailed computations can be found in reference [2]. (b) The capacity of the ridges to absorb the synchrotron radiation power is smaller than that of the liner.

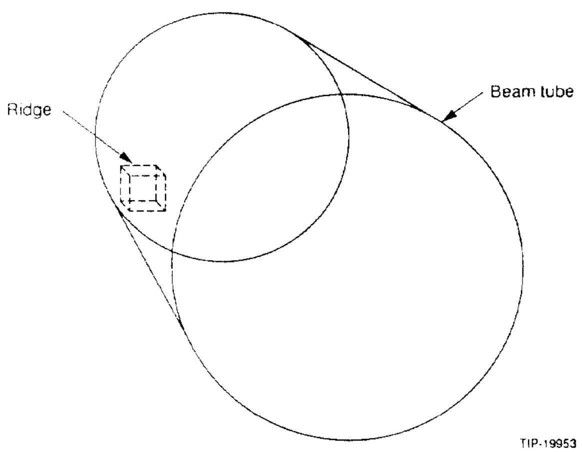

Figure 2. The ridge type of intercepts.

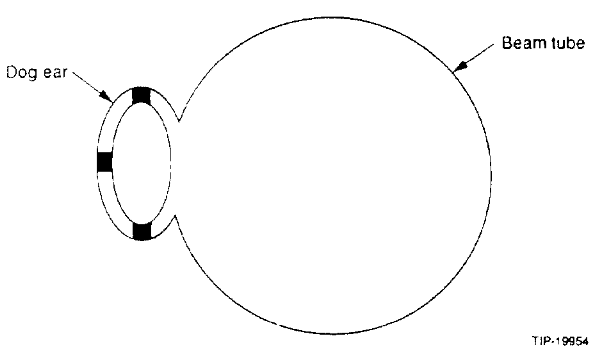

Figure 3. The dog-ear type of intercepts.

Another type of the intercepts is the dog-ear design shown in Figure 3. The cooling tubes in the dog-ear side may provide a greater capacity to absorb the radiation. The coupling impedance is also very small [2]. But it may not be able to solve the secondary desorption problem. The complex, non-circular shape is also difficult to implement in the engineering design.

IV. Conclusions

The synchrotron radiation of the circulating current in a cold beam pipe at liquid helium teperature brings out a series of important physics problems, such as the vacuum and the power loss. With the intercepts inside the pipe, these problems may get resolved. Meanwhile, new problems will arise with the introduction of the intercepts, for example, the rf impedance, the overall machine reliability, etc. It seems that a liner with long narrow slots may give the best performance, whereas the perforated liner may be another candidate only if its rf impedance appears not to be a problem.

References

[1] MAFIA codes are developed by T. Weiland and his group in collaboration with several US and European laboratories.

[2] W. Chou, Proc. of the Fourth Advanced ICFA Beam Dynamics Workshop on Collective Effects in Short Bunches, KEK, Japan, Sept. 24-29, 1990, p. 161, KEK Report 90-21 (February 1991).