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BEAM BEHAVIOR AND LUMINOSITY IMPROVEMENT IN THE TRISTAN MAIN RING

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Abstract

This paper describes the present knowledge of the beam behavior, directly related to the luminosity improvement. The stored current limits at the injection energy and the problem restricting the luminosity are discussed.

1. Introduction

The commissioning of the TRISTAN main ring started in October 1986[1]. The most important objective of the accelerator group was of course to start the physics run operation as soon as possible. For this purpose, most of the accelerator study time was devoted to the tuning of the accelerator, including the development of a lot of programs for the operation. The rest of that was used for the investigation of the beam behavior, directly related to the improvement of the luminosity.

The operation group gained and accumulated the understanding for the physics run, and became skillful enough for keeping the stable operation. In the end of the last operation cycle the luminosity reached 70 % of the designed value.

This paper describes the present knowledge gained by the investigation of the beam behavior. Two important subjects are discussed. The first is several limits of the stored current at the injection energy. The second is the improvement of the luminosity. Discussion is made on the present method for improving the luminosity as well as on the restriction of the luminosity.

2. Current limits at injection

The present injection optics, which is used for the physics run operation, was found by time-consuming tune surveys. This optics is supposed to be the best one among a lot of optics ever investigated. The beam is injected from the accumulation ring at 7.4 GeV in the last operation cycle. Wiggler magnets are used at the injection energy. They play an important role in stabilizing the stored beam. They make the radiation damping time shorter, and make the bunch length longer at the same time. Table 1 shows the beam parameter in the present injection optics with and without the wiggler magnet.

It is desired that an injection optics have to satisfy the conditions that the injection efficiency is high enough and the maximum current is high. The present optics, however, is not satisfactory. The typical injection efficiency is at most 50-70 %. The reason of the low efficiency is owing to the small aperture in the main ring. The geometrical aperture was surveyed by making local bump orbits everywhere along the whole ring to find unexpected obstacles. No such thing was found at all.

The acceptance was measured with a kicker magnet. The stored beam was deflected by the kicker magnet horizontally. The maximum coherent oscillation amplitude without beam loss shows the acceptance. The maximum amplitude measured at the symmetry point where the oscillation detector locates is about 15 mm, when the beam current is low, for example, less than 0.5 mA. The geometrical useful aperture at that point is more than 50 mm. If the beam current increases, the acceptance becomes smaller. This means that the acceptance is dependent on the beam current.

If one observes oscillation amplitudes after kicking the beam, the amplitude decays very rapidly within 20 turns, or 0.2 ms, which is much smaller than the radiation damping time. It is found that the decay rate depends on the initial coherent oscillation amplitude. The decay time for the small initial amplitude is longer than that for the large amplitude, which is due to strong dependence of the betatron tunes on the betatron amplitude. This fact is explained by the non-linearity of sextupole magnets used for chromatic corrections, as a computer tracking program shows.

Table 1
Injection Parameters (Optics 'LBJUL07')

$\nu_x = 32.30$	$\nu_y = 38.61$	
$\beta_x^* = 6.4m$	$\beta_y^* = 0.4m$	
$E = 7.4GeV$	$V_c = 25MV$	$f_s = 6.4kHz$
$Wiggler$	$1.2T$	$0T$
$\tau_\epsilon(msec)$	28.7	69.3
$\tau_x(msec)$	57.4	138.6
$\sigma_z(cm)$	1.24	0.45
$\epsilon_0(m)$	1.3×10^{-7}	1.1×10^{-8}
$U_0(MeV/Turn)$	2.59	1.07

The strong non-linearity was once accused of the small aperture. In order to prove the prediction, strengths of the sextupole magnets were adjusted so that the betatron tunes may depend weakly on the amplitude. The correction of the non-linearity,however, did not lead the improvement of the acceptance.

Another observation is that the acceptance becomes large with increasing the beam energy. Therefore the acceptance seems to be limited by an intensity-dependent phenomena. No reasonable explanation of the small acceptance has been found and proposed.

The maximum single bunch current is 3.2 mA, above which the beam life is very short. This problem will be treated in a later section. The maximum current is dependent on the RF voltage. The highest current is obtained when the voltage is about 25 MV. Below this operating voltage the maximum current decreases as the RF voltage is lowered. However, if the voltage is increased further above 25 MV, the beam behavior changes abruptly. The current is limited at a much smaller intensity, for example, less than 1 mA. It is believed that the beam current is limited by another instability under this condition.

It is well known that the current is limited by a fast head-tail instability in large electron storage rings[2]. The instability is excited by large transverse impedance which originates in RF cavities and vacuum chamber components, such as bellows. The fast head-tail instability is identified by a large betatron tune shift comparable with the synchrotron oscillation tune. In the main ring this instability was observed first in a low-emittance optics, which has a larger beta-function in the RF section than that in the present injection optics. The maximum stored current was 2.8 mA with the RF voltage of 20 MV. Under this condition the frequency spectrum of the horizontal betatron oscillation showed a large tune shift, and two peaks, corresponding m=0 and m=-1 modes, being close to each other. This indicated the presence of the fast head-tail instability. When the voltage was decreased to 18 MV, some part of the beam was lost. This is explained by the fact that reducing the RF voltage makes the synchrotron tune smaller with a smaller tune difference between the two modes, and that the threshold current where the tune difference becomes zero is lowered.

In order to understand the stability of the stored current, the transverse impedance was calculated with the TBCI program[3]. The transverse impedance sources are RF cavities and several types of bellows. Inner shields were inserted into race-track bellows in the arc section, to make their impedance as small as possible. Otherwise the bellows could limit the current at a lower value. The measurement shows that the design is working well. The betatron tune shifts in the horizontal and vertical directions are almost the same with each other. The inner shields successfully reduce the transverse impedance of the race-track bellows, which could induce a much larger tune shift in the vertical direction than in the horizontal direction without the shield. As the result the RF cavities and the circular bellows, which have not an inner shield, by the cavity are considered in the estimation of the impedance. The circular bellows contribute to the tune shift by only several per cent. The predicted threshold current in the low-emittance optics is 3.2 mA which is consistent with the observation.

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In the present injection optics the theory predicts that the threshold current is 4.2 mA, while the beam is unstable above 3.2 mA in the experiment. If one observes the current just after the beam is injected into a bunch with the maximum stored current, the beam current exceeds 4.0mA, close to the predicted threshold current, and decreases rapidly within 20 turns. Although the two peaks in the frequency spectrum of the betatron oscillation do not appear, the stored current is probably limited by the fast head-tail instability.

One of the methods to raise up the threshold current is increasing the RF voltage and making the tunes of the two modes far apart. When the threshold was estimated in designing the main ring, the synchrotron tune at injection was assumed equal to that at the flat top energy. During the acceleration the synchrotron tune was to be kept constant. The present injection voltage is, however, lower than that expected. When the voltage is raised above the normal operating voltage of 25 MV, the beam becomes unstable even with low intensities. This instability was observed when the injection energy was 6.5 and 7.0 GeV in the early stage of the main ring operation. The problem deserves to be solved for increasing the stored current.

In the physics run operation the total current is not restricted by the fast head-tail instability. Two electron bunches and two positron bunches are needed for the physics run. Usually the positron bunches are filled first and then the electron bunches. Each bunch is filled with two shots of the injection from the accumulation ring. When the total current exceeds about 7 mA the beam life time becomes short. Because it takes several minutes to perform one cycle of the accumulation ring, the life time as short as half an hour really restricts the total current. It is supposed to be related to the beam-beam effects. Although preliminary investigation of this phenomena was done, the satisfactory explanation of the short life time has been unknown.

3. Luminosity improvement

During the acceleration the betatron tunes are kept constant while the strength of the wiggler magnet decays gradually. On the other hand, the synchrotron tune has to be increased in order to hold the beam at the flat top energy. At the flat top the injection optics, which has the same beta-functions as in the injection energy, is changed into a colliding optics having low beta-functions at colliding points.

Three of the four colliding points are occupied by large physics detectors with solenoid fields. The solenoid field couples the horizontal and vertical emittances with each other. The coupling makes the vertical beam size larger at the colliding point and then reduces the luminosity. For the compensation of the solenoid field three pairs of skew quadrupole magnets are installed near each colliding point. The strength of the skew quadrupole magnet is adjusted in such a way that no vertical closed orbit distortion appears when symmetric and anti-symmetric horizontal bump orbits are made at the colliding point. The compensation is done at every colliding point independently of the other sections. The horizontal and vertical beta-functions at the colliding point in the last operation was 1.8 m and 0.1 m, respectively. Table 2 shows the parameters in the collider operation. In order to understand how the luminosity depends on various parameters, valuable formulae related to the luminosity are listed in Appendix.

In the main ring the luminosity is not limited by the beam-beam effect. At present the beam current is limited at the injection. The beta-functions at the colliding point, which are important parameters for determining the luminosity, have already reached the designed values, below which the sextupole correction becomes difficult. Under these boundary conditions the formulae show a fair way to increase the luminosity. The horizontal emittance must be as small as possible. At the same time the coupling between the horizontal and vertical emittances should be decreased. One method for the lower emittance is to develop a low-emittance optics having a small dispersion function along the curved section. The construction of such optics failed by the reason that it was hard to transform the injection optics into a colliding optics without beam loss.

An alternate method is to raise the RF frequency. The nominal frequency of 508.5808 MHz is increased by about 2.5 kHz, which reduces the horizontal emittance to a half of the original value. For keeping the quantum beam life time sufficiently long and unchanged, however, it requires a more RF voltage than that in a case without the frequency increase. For example, if the frequency is increased by 2.5 kHz at the 26 GeV operation, an RF voltage of more than 30 MV has to be added to the total voltage of about 220 MV.

Table 2
Colliding Parameters (Optics 'LBJUL07')

$\nu_x = 32.28$	$\nu_y = 38.56$	
$\beta_x^* = 1.8m$	$\beta_y^* = 0.1m$	
$E = 26.0GeV$	$U_0 = 163.8MeV/Turn$	
$f_{RF}(MHz)$	508.5833	508.5808
$V_c(MV)$	252	221
$\tau_q(sec)$	1.3×10^5	1.3×10^5
$\tau_\epsilon(msec)$	3.0	1.6
$\tau_x(msec)$	1.7	3.2
$\sigma_z(cm)$	1.5	1.2
$\epsilon_0(m)$	7.0×10^{-6}	1.4×10^{-5}
$f_s(kHz)$	9.4	8.3

The correction of the coupling between the horizontal and vertical emittances is a controversial problem. The coupling due to the solenoid field, one of various coupling sources, is successfully compensated for by the skew quadrupole magnet, which is easily verified by making a closed bump orbit at the colliding point. On the other hand, no reliable information has obtained on the coupling which could be induced by vertical orbit distortions at sextupole magnets or by unexpected non-linear elements. Because of lack of a monitor sensitive to the vertical emittance it is impossible to measure the coupling directly.

Luminosity monitors are useful for the estimation of the coupling parameter. At each colliding point a luminosity monitor is installed. The counting rate of the luminosity monitor is, however, so low that it takes a lot of time to tell the luminosity with reasonable statistical errors. Therefore the luminosity monitor is not useful for the measurement of the short-term change in the coupling. The coupling is also estimated by the betatron tune shift due to a beam-beam effect[4]. For the luminosity optimization the tune shift is only a good measure for the coupling parameter, provided that the beta-functions at the colliding point are equal to those given by the optics[5].

For the physics run operation the colliding optics has to satisfy at least three conditions. The coupling should be as small as possible for realizing the high luminosity. The noise level due to straying energetic particles or synchrotron radiation are bearable for every detector. The beam life time is long enough. Discussion of the life time due to the vacuum pressure is found in this conference[6].

Careful fine tunings of the betatron tunes are always very important for the stable colliding operation. Attention should be paid to the movement of the tunes whenever the orbit correction is done. A small shift of the orbit through sextupole magnets brings about noticeable changes in the betatron tunes. The vertical orbit correction in the whole ring, sometimes called a global orbit correction, is important because the vertical orbit distortion through sextupole magnets produces the coupling of the emittances. A fine orbit correction in both the horizontal and vertical directions at every colliding point is sometimes very effective in keeping low noise level. Noise sources have not been fully identified. Therefore the removal of the noise is always a time-consuming tuning in the beginning of a collider operation cycle.

Experience gained in the physics run shows that making vertical bump orbits at every symmetry point improves the vertical tune shift, supposed to be directly related to the luminosity. The reason why the bump orbits were made there is that the vertical bump orbits through sextupole magnets may compensate for the remaining coupling. Symmetric and anti-symmetric bumps were made. The size of the bump was about 5mm. These bumps were adjusted so that the coupling parameter becomes as small as possible. The maximum luminosity was $7.2 \times 10^{30} cm^{-2} sec^{-1}$ with the total current of 8.7 mA. At that time the coupling parameter was 2.2 % with $\xi_y = 0.032$. Fig.1 shows the measurement of the beam-beam parameters. The measured coupling parameter was closely related to the luminosity as expected. The long-term luminosity was indeed improved by the method described here, and was consistent with the estimation. Provided that the coupling parameter is 2 %, the vertical beam size at the colliding point is 20 μm . This beam size is a good measure for discussing what restricts the luminosity in the main ring.

A problem of the method is, however, that the measurement gives the real coupling parameter, the ratio between the horizontal and vertical emittances, only if the head-on collision is expected. Otherwise the measured coupling includes the effect of the vertical separation between the two beams at the colliding point as well as the real coupling. It is impossible to separate the two effects in the measurement.

The present coupling parameter of 2 % is still larger. In order to understand whether the luminosity is restricted by the coupling or by the beam separation, computer simulations were done. The effect of the vertical bump orbit on the coupling and the separation was estimated. The simulation predicts that a 5 mm symmetric bump orbit at the symmetry point between Fuji and Nikko experimental areas produces the coupling of about 0.5 %. The simulation shows another interesting effect of the bump orbit. When the symmetric bump orbit is made, vertical closed orbits of the electron and positron beams are no longer the same with each other. The separation at Tsukuba colliding point is 7 μm, which is not small compared with the assumed beam size. The separation of the closed orbits is probably explained by the fact that the two beams have different energies along the whole ring. Main reasons of the large energy difference between the two beams are that the energy loss per revolution is large, for example, 0.6 % of the beam energy at 26 GeV, and that the RF acceleration stations are not distributed symmetrically.

A conclusion derived from the above discussion is as follows. The vertical bump orbit at the symmetry point induces the vertical orbit separation between the two beams at the colliding point as well as the coupling between the horizontal and vertical emittances. Both effects can be important causes restricting the luminosity. In the collider operation the luminosity was improved by making vertical bump orbits at every symmetry point. The probable reason of the luminosity improvement is that the bump orbits compensated for the remaining coupling, or for the remaining vertical separation at the colliding point, or fortunately for the both simultaneously. Before the bump orbits were made, the luminosity was thought to be restricted by a large coupling parameter or large separations. For further improvement of the luminosity it is necessary to separate and understand the two effects. For this purpose computer simulations as well as accelerator studies are needed and to be performed.

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Appendix

If the beam current is kept constant, the luminosity L is related to the beam size $\sigma_{x,y}$ at the colliding point as

$$L \propto \frac{1}{\sigma_x \sigma_y} .$$

The beam size is derived from the emittance $\epsilon_{0,x,y}$, the coupling parameter κ and the beta-functions.

$$\sigma_x = \sqrt{\epsilon_x \beta_x^*} = \sqrt{\epsilon_0 \beta_x^*}, \quad \sigma_y = \sqrt{\epsilon_y \beta_y^*} = \sqrt{\kappa \epsilon_0 \beta_y^*} ,$$

$$\kappa = \frac{\epsilon_y}{\epsilon_0} \simeq \frac{\epsilon_y}{\epsilon_x} .$$

Then we have

$$L \propto \frac{1}{\sqrt{\beta_x^* \beta_y^*}} \frac{1}{\epsilon_0 \sqrt{\kappa}} .$$

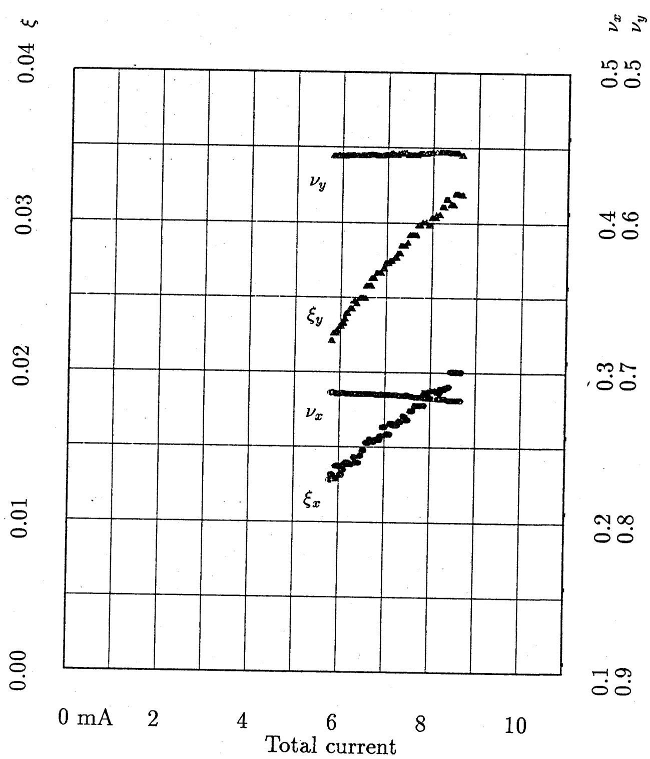

Fig.1 Measurement of the beam-beam parameter.

The measured tune shift is almost close to the beam-beam parameter $\xi_{x,y}$, which is expressed under the condition, $\sigma_y \ll \sigma_x$, as

$$\xi_x \propto \frac{\beta_x^*}{\sigma_x^{*2}} , \; \xi_y \propto \frac{\beta_y^*}{\sigma_x^* \sigma_y^*} .$$

From the measurement we can get

$$\kappa = \frac{\beta_y^*}{\beta_x^*} \left(\frac{\xi_x}{\xi_y} \right)^2 .$$

The luminosity is proportional to the vertical beam-beam parameter:

$$L \propto \frac{\xi_y}{\beta_y^*} .$$

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