TOP-UP OPERATION OF SPring-8 STORAGE RING WITH LOW-EMITTANCE OPTICS

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Abstract

We have succeeded in providing stable and three-times more brilliant x-ray beams to users by combining top-up operation with low-emittance optics. The optics with the low emittance of 3nmrad was firstly applied to the user operation in November 2002. Although the low emittance provided the brilliant x-ray, the extremely short beam lifetime much disturbed the precise experiments. Moreover, the aborted electron beam damaged the part of vacuum chamber at the beam injection section. The low-emittance operation was thus suspended in October 2003. By improving design of the vacuum chamber and introducing the top-up injection, the problems for the stable operation were resolved and then, the top-up operation with the low-emittance optics has been firstly achieved at SPring-8. This paper illustrates how we achieved this sophisticated operation by explaining the following three essential subjects: (1) our concept of increasing brilliance of x-ray beams and solution to some problems in realizing the low-emittance optics, (2) protection of vacuum chamber from aborted electron beam, and (3) introduction of top-up injection. The obtained performance is also described in the paper.

EMITTANCE REDUCTION

The 8GeV electron storage ring at SPring-8 was originally designed on the basis of the double-bend achromat cell structure. In November 2002 we released a new optics in which the achromat condition is broken and the emittance is lowered from 6nmrad to 3nmrad [1, 2].

When the achromat condition of the ring is broken and there exists finite dispersion at insertion devices (IDs), the emittance is not directly related to photon flux density available to experimental users. In such a case the important parameter is the effective emittance [3] defined by the phase-space volume of (x, x', y, y') at the photon source with finite momentum spread taken into account.

Figure 1 shows the case of the SPring-8 storage ring. The effective emittance ϵ_{eff} (circles and squares, left) and leaked dispersion at IDs (triangles, right) are plotted as a function of the natural emittance ϵ_0. In this figure ϵ_{eff} is plotted for two cases: when all of the gap of IDs are opened and when those are closed to their minimum values. Additional radiation damping by IDs reduces ϵ_{eff} by about 20% and the minimum value of ϵ_{eff} is about 2.9nmrad. In general the emittance reduction by breaking the achromat condition should be done by considering parameters of installed IDs, and systematic studies on this subject were carried out in Ref. [3]

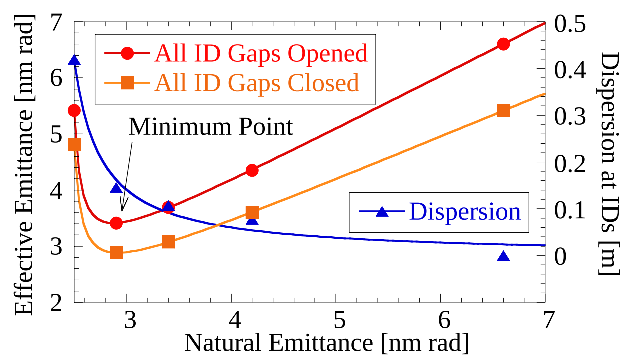

Figure 1: Effective emittance at SPring-8 storage ring.

LOW-EMITTANCE OPTICS AT SPRING-8

The SPring-8 storage ring was designed to keep high optics symmetry for on-momentum electrons, and the ring was initially composed of 44 CG unit cells and 4 straight cells with only bending magnets removed from the CG unit cell. The symmetry of the optics for on-momentum electrons was forty-eight, but the dispersion function was fourfold due to four straight cells in the ring. As a result, even when the dispersive arc is broken in a systematic way, the distortion is not forty-eight fold, but four fold with large peaks. At SPring-8 this was a serious hurdle for realizing the low-emittance optics when compared to ESRF and APS.

Let us assume that the ring has a matching section that connects two normal CG cells. We then consider a condition that the dispersion function determined from a unit CG cell also becomes a corresponding unit of a periodic structure of dispersion for the whole ring. This can be realized if the horizontal betatron phase advance over a matching section is $2\pi N$, where N is an integer, and the dispersion inside the matching section is periodic and closed completely. In the original design of the SPring-8 storage ring there was no room for making such matching sections using a straight cell and we could not realize low-emittance optics by the dispersion leakage.

In 2000 the lattice around the straight cell was modified locally to construct magnet-free long straight sections of about 30m [4]. At that time we adopted the phase-matching condition, and converted three CG cells including one straight cell into a matching section. The reason why we adopted the phase-matching condition was to keep the periodicity of cell structure, especially of sextupole field distribution along the ring for obtaining large dynamic aperture and large momentum acceptance [5]. Owing to this condition, it became possible to make the low-emittance optics by dispersion leakage.

PROTECTION OF CHAMBER WALL

In October 2003 there was a trouble that vacuum leakage occurred at an injection section during beam operation in the low-emittance optics. This occurred just after aborting a stored beam by cutting off the RF power. We thoroughly investigated the vacuum chamber and concluded that an aborted electron beam (8GeV, 100mA) hit thin chamber wall of 0.7mm thick, and generated electromagnetic shower melted the wall. In the SPring-8 storage ring most part of the vacuum chamber is made of aluminum alloy, but this thin part of injection section is made of SUS to ensure necessary mechanical strength. When compared to aluminum, SUS has lower heat conductivity and the atomic number of material is larger. Then, the energy density deposited in this part became high and the wall was melted.

In Fig. 2 we show pictures of the injection chamber after this trouble. The cross section is shown at several longitudinal positions from an injection point. We can see the evidence that the chamber was melted by an 8GeV electron beam and solidified again as it gets cold.

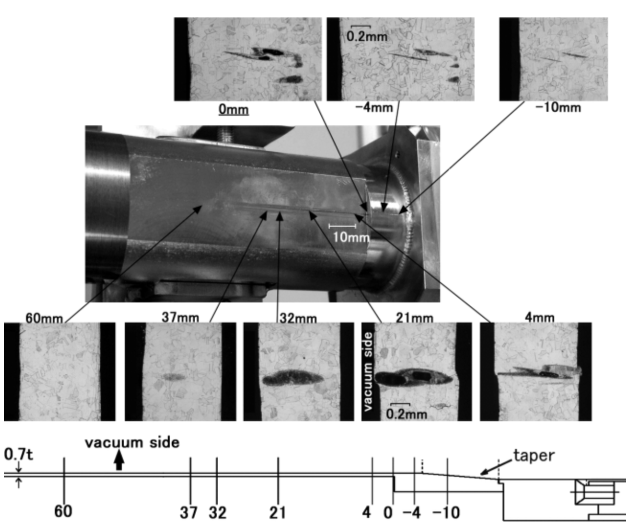

Figure 2: Injection chamber damaged by electron beam.

We then tried to find the reason why an aborted beam hits the injection chamber in the low-emittance optics not in the achromat one. The answer was as follows: To lower the emittance we changed the distribution pattern of linear dispersion along the ring, and as a result of this, distribution of non-linear (high order) dispersion [6] was also changed and a beam-loss point shifted.

In Fig. 3 we show calculated beam trajectories on the horizontal plane after cutting off the RF power. We see that in the low-emittance optics the aborted beam follows a trajectory very different from one in the achromat case, and it quickly approaches to the wall of the injection chamber as it goes around the ring. A physical aperture of the injection chamber is narrower than other places and the aborted beam eventually hits the wall of this chamber.

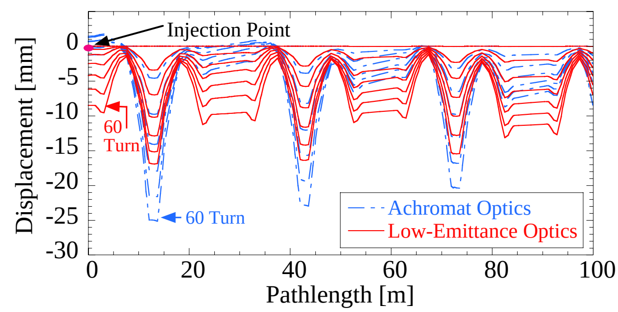

Figure 3: Calculated horizontal beam trajectories at 1, 10, 20, 30, 40, 50 and 60 turns after cutting off the RF power.

After this trouble we suspended the low-emittance operation. We then designed a new chamber on the basis of computer simulations. In the newly designed chamber a block of aluminum is put upstream of the injection section as a damper so that an aborted beam hits it first. Generated shower is then spread and the energy density deposited in chamber is drastically reduced. To ensure the protection, we set the damper 1mm inside from the inner wall of the chamber. Moreover, the thin chamber wall (0.7mm thickness) was modified as thick as possible. To increase the thickness of chamber wall, we reduced the thickness of magnetic shield of a neighboring septum magnet as much as we could. The maximum thickness of the new chamber wall is 5mm. This new chamber was installed in 2005, and it was confirmed that the aborted beam indeed hits the damper by measuring radiation level.

TOP-UP OPERATION

To make a profit of low-emittance operation as much as possible, it is necessary to introduce the top-up operation because the Touschek beam lifetime becomes shorter. In order to introduce the top-up injection, oscillation of a stored beam at injection must be suppressed. This is, however, not easy if there exist sextuploe magnets in an injection part of the ring because the oscillation is induced by nonlinear kicks due to sextupole magnets inside the bump orbit.

This oscillation can be suppressed [7] if we impose an additional constraint on the strength of sextupole magnets inside the bump orbit. However, since in the low-emittance optics the dispersion exists all along the ring, sextupole magnets for chromatic correction and for harmonic correction cannot be treated separately anymore as in the achromat optics. We then developed a computer code to treat such an optimization procedure and obtained sufficiently large dynamic aperture for high injection efficiency and sufficiently large momentum acceptance for long beam lifetime.

We then performed beam injection tuning in a similar manner to the achromat optics: suppression of residual oscillation of a stored beam by correction kickers [8], beam collimation in the transport line for high injection efficiency [9], etc. In Fig. 4 we show oscillation amplitude of a stored beam at beam injection in horizontal (H) and vertical (V) directions. The data was taken by using turn-by-turn beam position monitors. The oscillation amplitude in the low-emittance optics is well suppressed to the same level as in the achromat optics.

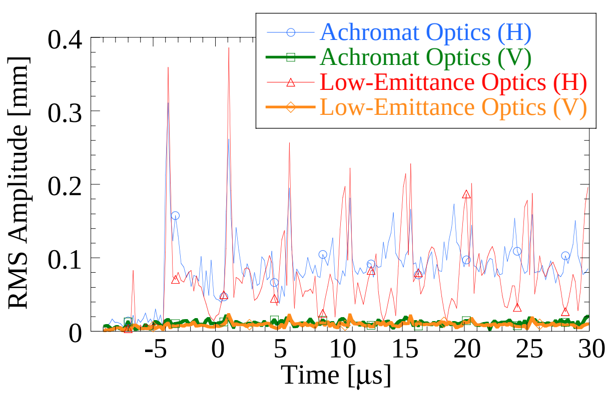

Figure 4: Oscillation of a stored beam at beam injection. Revolution period is 4.8μs.

ACHIEVED PERFORMANCE

After the improvements and careful tuning, we started the top-up operation with the low-emittance optics in user-time from September 2005. Stability and performance of the beam is at the same level as achieved in the previous achromat optics: (1) Temporal fluctuation of the total current is lass than 0.1%. (2) Maximum deviation of bunch current in a several-bunch filling mode is less than 10%. (3) Horizontal oscillation amplitude of a stored beam at injection is less than one-third of the horizontal beam size and vertical one is less than a half of the vertical beam size. (4) Impurity of an isolated single-bunch is less than 5×10^{-9}. In addition to these, the brilliance in user-time has now become about three times that in the achromat optics.

In Fig. 5(a) we show calculated brilliance in the achromat and low-emittance optics. We also show experimental photon flux density in Fig. 5(b), where we plotted monochromatized photon flux observed in BL19LXU long-undulator beamline. This shows that the experimentally observed brilliance is about 2.7 times that in the achromat optics and this agrees with calculations.

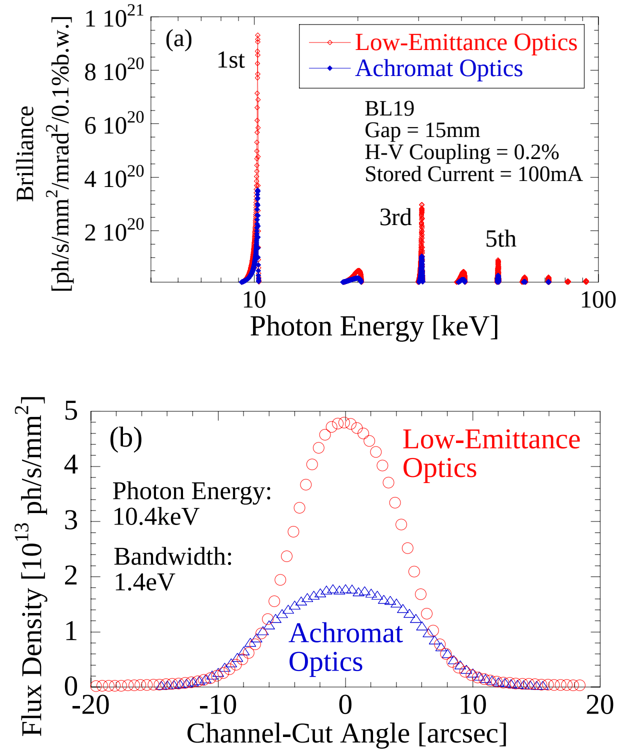

Figure 5: Comparison of brilliance and flux density. (a) Calculated brilliance and (b) observed flux density in BL19LXU long-undulator beamline.

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