Mechanical stabilized schemes of position sensitive components in the synchrotron facility

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Abstract

In the synchrotron facility, many components such as magnets, beam position monitor, girder and beamline components need high mechanical stability to one micron or better. For the long term stability, the common factor is the thermal stress from air temperature, cooling water temperature and beam heating and their interplay. In this paper we will describe some schemes in the design consideration and their test results.

1. Introduction

In a synchrotron facility, there are many components need the requirement of high position stabilization to a level of micron or better, such as magnet, beam position monitor and mirror related components. From the classification in the frequency domain, one is vibration issue and another is thermal drift. Here, we are focusing on the thermal stability with period in minutes or longer, displacement in micron or better.

Thermal stability is a must-have requirement for a precision component. There have been some papers about precision optical components [1], but the real thermal input or installation situation may be not the same as that in the synchrotron facility. From the viewpoint of thermal stability, we need to know the reference point of this component, thermal input of this system and interplay of nearby components. For example, if the reference point is ground then all the related subsystem from ground to this component have to be considered. It may include many components and become too complex. Adopting suitable mechanical design can simplify and release the thermal stress and reduce the displacement to tolerated value.

In this paper we will review the concept of thermal stabilization, and give some examples in the storage ring and beamlines.

2. Design consideration of thermal stabilization

Many important thermal properties often appear in thermal equations. Such as thermal conductivity (k), heat capacity (c), density (ρ), thermal diffusivity (D), heat flow per area (q).

Let's consider the simplest case of steady heat flow in one dimension. From the Fick's first law,

$$q = \frac{k\theta}{l} \tag{1}$$

θ is the temperature above ambient, l is the length of the rod. If the system is linear, the average temperature of this rod is $\theta/2$. The increase of length is

$$dl = \alpha \frac{\theta}{2} l = \frac{\alpha q l^2}{2k}. \tag{2}$$

To reach a low displacement, dl, we prefer a low value of α/k, a well-known parameter in the mirror material selection.

For the transient response, from the Fick's second law, heat equation in the one dimension is

$$\frac{d\theta}{dt} = \frac{k}{c\rho}\frac{d^2\theta}{d^2x} \tag{3}$$

k/cρ is called thermal diffusivity, it can be found in most textbook. With high diffusivity means a rapid stabilization after a change in thermal stimulus. To express it in displacement, we can use $dl=\alpha*d\theta*l$ to give

$$\frac{dl}{dt} = \alpha D l \frac{d^2\theta}{d^2x} \tag{4}$$

This equation indicates a transient parameter, αDl, related to the length change response. In some applications we prefer a high rate, so the unstable time elapsed can be shortened like the case in mirror thermal deformation. In other case, if the thermal impulse is small we may prefer small rate, using small D to smooth the thermal spike such as deformation of magnet girder.

Equations 2 and 4 give a guideline of the steady state and transient response in the thermal stability. α, k, c, ρ, are classified as material properties; l is structure factor; q is external or internal heat source. In the real condition the thermal transfer is more complex than the 1 D conduction assumption and some non-linearity in the joints may happen. When the structure is made of two material bimetal effects have to include. Designer can modify either the thermal or structure parameters to meet the goal.

3. Storage ring

In general the amplification factor of quadrupole magnet displacement on the electron orbit is in the order of ten. It means to keep orbit stable within a micron order the position stability is required to sub-micron level. Magnets and chambers are usually seated on a common girder. Thermal input of whole system is heating from magnet and chamber; cooling is by water and air. Some examples and discussion are in the following section.

1.1. Effect of periodic air temperature variation on girder

Girder can be treated as the lumped thermal capacity system, i.e. heat transfer of heat convection from air to girder interface is smaller than the conduction in the steel girder. A criterion is Biot number, ht/k, less than 0.1. h is the convection coefficient, t is thickness of girder plate. Now we show how the steel girder temperature (*Ts*) changes as a function of air temperature (*Ta*).

$$\frac{Ts-Ta}{To-Ta}=e^{-\frac{t}{tc}}$$

To is original temperature of steel and air, time constant $tc=\frac{\rho Vc}{hA}$, *V* is volume; *A* is the area of heat convection.

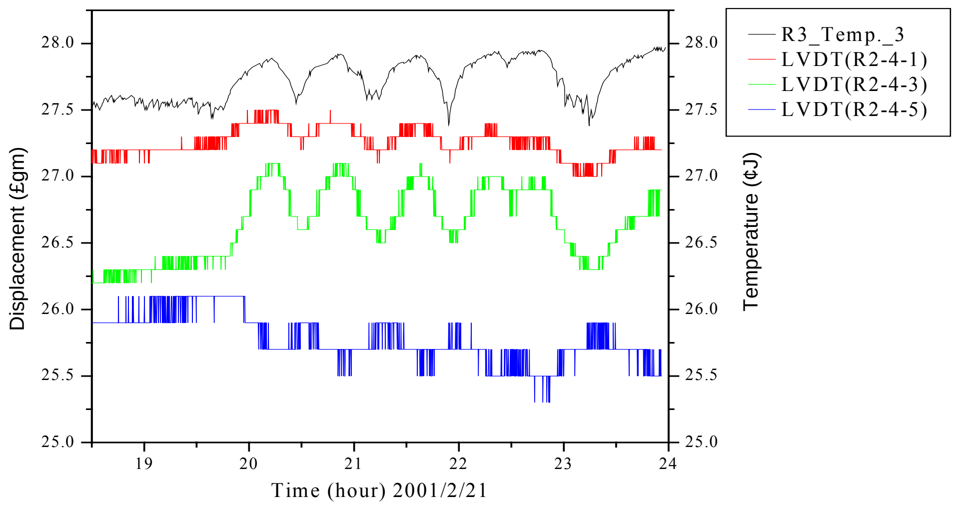

Fig. 1: Girder height changed with the air temperature variation

Fig.1 shows a girder height changed by the air temperature variation [2]. We can see the girder height changed periodically with the air temperature variation. Girder height measured at 3 different points along beam direction is not same, it seemed the thermal deformation is not isotropic. In the first hour of Fig. 1, the period of temperature variation is shorter than the rest time and the girder height change is smoother. The concept of period and time constant is discussed in the following.

For a general condition h is about 200W/(m^2K), thickness of steel of girder is about 2cm. We can get time constant, tc, is 350sec. If we set To is 25 °C, Ta is 25.2 °C, in the Table 1 we can find after 0.1 tc elapsed Ts can keep 25.02 °C.

Table1: The transient response of Ts as a function time elapsed.

Time elapsed	0 tc	0.1 tc	0.2 tc	0.5 tc	1 tc	2 tc
Ts (°C)	25.0	25.02	25.04	25.08	25.13	25.17

From Table 1 we can see to increase the time constant of steel girder or decrease the period of air temperature variation is good for Ts, mechanical stability. One simple scheme to increase the time constant of girder is feeding the girder or pedestal with water. Because water has 10 times the heat capacity more than steel, so it is easy to increase the time constant of girder to 10 times as original.

1.2. Effect of insulation of the girder by a periodic sinusoidal variation of air temperature

Let air temperature Ta=A sin (2πt/P), A is variation amplitude, P is period. Then temperature of insulation at x thickness is

$$Tx = Ae^{-Bx} \sin(\frac{2\pi t}{P} - - Bx) \tag{5}$$

$$B = \sqrt{\frac{\pi}{DP}} \tag{6}$$

From equation 5 we can see if we put some insulation on girder then the steel girder temperature will varied as a factor e^{-Bx} lower than that of air temperature variation.

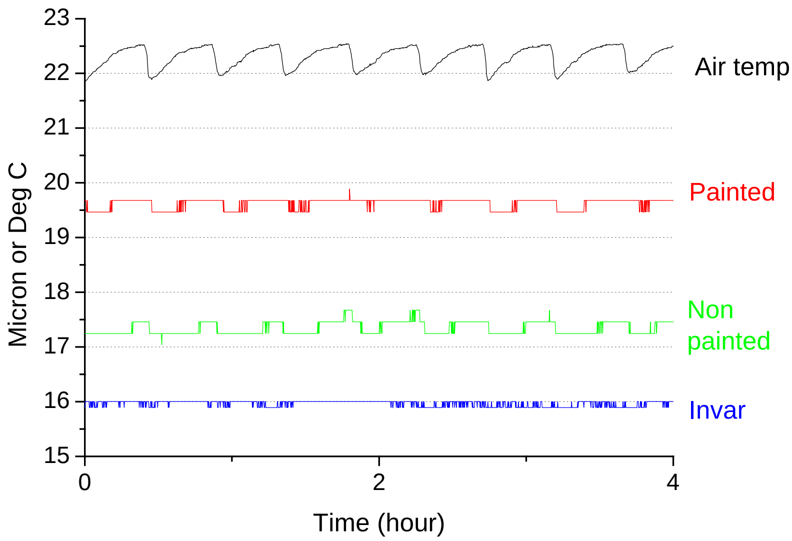

Fig. 2 The length change of 20mm diameter rod with air temperature in different insulation.

Fig.2 shows the length change of three rods in different insulation. Two steel rods and one invar rod with diameter 20mm were fixed to a big steel support. We can find even a thin painting can have some effect. If we adopt better insulated foamed sponge with D=0.5mm^2/s, P=5 minutes, and x=16mm, then Tx can reduced 10 times lower than surface temperature T0, at x=11mm Tx can reduce 5 times.

Insulated schemes have been reported three times improvement in the mechanical stability of girder in the NSRRC [3].

1.3. Thermal displacement of beam position monitor (BPM)

BPM position is required mechanical stable and is usually fixed rigidly on a girder or a magnet. It is generally welded on the vacuum chamber with flexible bellows on both sides. Kinematic mounting is effective to reduce the thermal deformation of the chamber. In some case, there is no enough space to accommodate bellows or the bellows is not flexible enough. Some over constraints and thermal stress on the chamber would dislocate the position of BPM. Fig. 3 shows an old BPM support moved by the deformation of chamber as beam current decayed. A new mounting adopted a parallel mechanism, it allowed BPM move in longitudinal direction but keep the vertical and horizontal position stable [4]. It can also eliminate thermal stress of chamber transmitting to the girder, the position stability of magnet is also better.

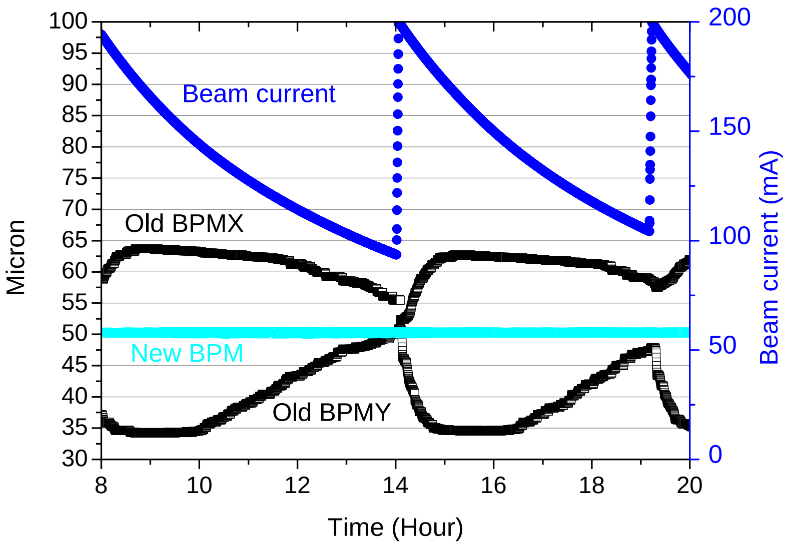

Fig.3 The mechanical stabilities of old BPM support and new one.

1.4. Beamline components

The first vertical mirror on the beamline reflects and focuses the synchrotron light to entrance slit. If the mirror angle change then the intensity pass through the slit may vary, then the user would sense the intensity fluctuate. For a common user's requirement, 0.1% intensity variation, the angle change of mirror is expected to be stable down to sub micro radian. This small amount is not easy to measure by common instrument.

Fig.4 shows a mirror angle changing with the temperature variation of the chamber. There were some points need to improve in this system. 1.The mirror was directly mounted on the chamber. 2. Part of horizontal beam impinged directly on the chamber, no independent heat absorber. 3.No good stress relief mechanism was designed. We adopted another mirror mounting mechanism as shown in Fig. 5 for the point 1. and 3. An independent heat absorber was also designed for the problem 2. After improvement the angle stability of mirror could achieve sub micro radian.

It is interested to note that the mirror manipulator is directly mounted on the ground and only a welded bellows is linked with chamber. Welded bellows have very low stiffness (spring rate) than that of formed bellows [5], it is easy to reduce the transmitting of thermal stress.

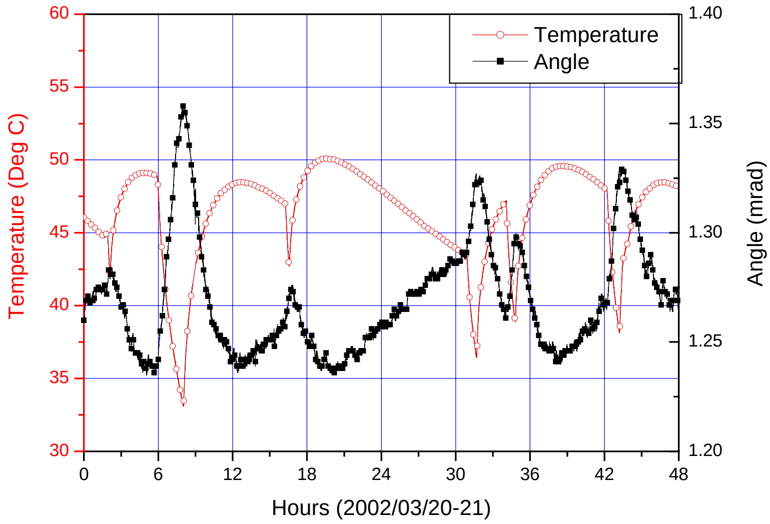

Fig.4 The angle variation of chamber with chamber temperature.

4. Summary

We introduced design considerations in the steady state and transient response of temperature variation on the mechanical stability. To achieve high mechanical stability we should consider material parameters, structure type, mounting methods and thermal transfer route. In the storage ring we presented schemes of girders insulation and a flexure BPM support to reduce the interplay between deformation of chamber and magnets. In the beamline an independent mirror manipulator was designed to decouple chamber-induced deformation with mirror.

5. Reference

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