ELECTRON BEAM STABILIZATION EXPERIENCES AT THE ESRF

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Abstract

Since the construction and operation of the ESRF, significant efforts have been made to improve the e-beam stability. These include ground vibration measurements, identification and elimination of internal and external vibration sources, girder design optimisation, development and implementation of a vibration damping system for magnet girder assembly. These achievements on mechanical vibrations are beneficial for the machine and e-beam stabilisation. Global and local feedback has been also implemented. Significant improvement on e-beam stability has been achieved.

INTRODUCTION

The e-beam stability is one of the most important requirements for 3rd generation synchrotron light sources. The ESRF had a design target of emittance growth related to the stability of less than 20%. Significant efforts have been made during the construction and the operation of the ESRF machine to minimize internal and external vibration sources as well as the vibration responses of the girders and quadrupole magnets. Ground vibration has been being permanently monitored with a seismic recording network implemented at the ESRF since the construction phase [1]. A great amount of vibration measurements have been made to identify vibration sources. Countermeasures have been taken to suppress them or reduce their impact. These efforts resulted in an emittance growth of a few percent [2]. Since the operation of the ESRF, the horizontal emittance has been reduced from 6.2 to 4 nm.rad, the vertical emittance has been reduced from a design target value of 0.62 to 0.025 nm.rad – a routine operation value [3]. With the reduction of the beam size, beam stability has become a more and more important parameter. Damping devices have been developed to attenuate the resonant vibration of the quadrupoles and girders. A damping device, the so-called ‘damping link’, has been developed and installed in the ESRF storage ring. The fundamental resonant vibrations of the magnet girder assemblies have been effectively attenuated by a factor of 5.8 [4, 5]. The electron beam stability is significantly improved. This paper reviews stability related activities at ESRF: ground vibration, vibration source identification, mechanical design consideration, damping device for machine girder, and electron beam motion and feedback.

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GROUND VIBRATION

The ground vibration is usually divided into three frequency ranges: low (f<1 Hz), intermediate (1-100 Hz) and high (f>100 Hz) frequency ranges. In the lower frequency range (f<1 Hz), vibrations are essentially due to ocean waves and micro earthquakes. They are characterised by two peaks centred at 0.14 Hz and 0.07 Hz. The peak around 0.07 Hz is considered to be due to the action of ocean waves on coasts. The peak around 0.14 Hz is due to the pressure from standing ocean waves, which may be formed by waves travelling in opposite directions in the source region of a storm or near the coast. This mechanism generates seismic waves with a frequency twice that of ocean waves [6]. With a typical wave propagation speed of 700 m/s in a sand-gravel soil, the wavelength is about 5 km and 10 km. The good spatial coherence of this micro-seismic noise within a couple of hundreds of meters results in a negligible differential vibration at any two points in a modern synchrotron radiation facility (diameter<500m) [7]. The intermediate frequency range (1-100 Hz) is the most interesting one for the synchrotron radiation facility because the fundamental resonant frequency of the mechanical components is usually in this frequency range. Therefore the accelerator machine is sensitive in this frequency range. Vibration sources are road and train traffic, the operation of heavy machines, the water flow and wind, and so on. In the higher frequency range (f>100 Hz), the ground vibration level is much smaller than in the intermediate frequency range because this vibration, mainly generated by smaller

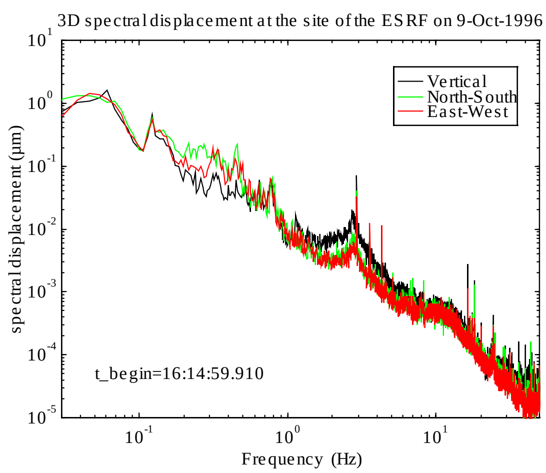

Figure 1: 3D Spectral Displacement of the ground vibration at the ESRF site.

electro-mechanical structures, is not powerful enough to induce significant ground vibrations. At the ESRF, ground vibration is permanently monitored in the intermediate frequency range and occasionally extended to low frequency range. Figure 1 shows a typical spectral displacement in vertical, North-South, East-West directions for the frequency range of 0.033-50 Hz. The vibrations in the three perpendicular directions are quite similar. Only some differences around the peak of 3 Hz and between 0.2 and 0.4 Hz can be observed. The peak of 3Hz is very characteristic for the ESRF site (Grenoble) and can be frequently observed. In fact, advanced geophysical studies show that there is a fundamental resonant frequency of 0.3Hz in the central part of the Grenoble basin, and another resonant frequency at 3Hz assigned to a thin surface layer of the ground [8, 9]. The peak around 3 Hz and between 0.2-0.4 Hz is due to the resonance of the ground in the Grenoble basin.

The ESRF is located in Grenoble, between two rivers (Isère and Drac) and two motorways. Road traffic and industrial activities generate considerable vibration noise, which varies with time. Figure 2 shows the peak-to-peak displacements versus time at four points around the storage ring for a period of one month. Each value of peak-to-peak displacements was calculated in the bandwidth of 1-100 Hz over a window of 8.192 seconds. The vibration level varies clearly with time. Generally, the vibration level increases during the day and decreases at night as a shape of sine with a period of 24 hours. The week-end is quieter than the five working days. There is a relatively quieter period between 12:00-13:30 - lunch break during the working day. It can be remarked that the vibration at cell 28 is significantly higher than at other places. In the next section, we will see that the high vibration at cell 28 was due to the road traffic on Avenue des Martyrs near cell 28. The road was repaired in December 1996, and since then the vibration level at cell 28 is comparable with other locations on the ESRF site.

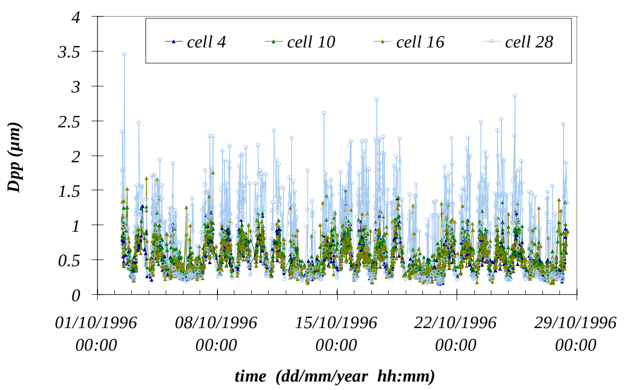

Figure 2: Peak-to-peak displacement of the ground vibration on the ESRF site during one month.

VIBRATION SOURCES

To keep the stability within the tolerance criteria, the ground vibration level at the ESRF should not be increased. The vibration sources, both internal and external, have been intensively studied during the construction and the operation of the ESRF. Vibration sources were first identified. Countermeasures were then designed, tested and implemented.

External sources

Many external vibration sources near the ESRF have been studied: speed bump at the exit of the motorway, bridges across the two rivers, speed bumps on site, traffic (due to trains, buses, trucks, trolley-bus,…), heavy machines (compressor, pumps, electric-heat co-generator,…).

From long periods of measurement observations (as shown in Fig.2), it was found that more than 95% of strong vibration events (peak-to-peak displacement >1.5 µm) on site are induced by the passage of trucks or buses over irregularities such as sewer covers on the Avenue des Martyrs, a local road. Various vibration measurements have been carried out to identify these vibrations sources. By placing 10 geophones along the Avenue des Martyrs in the section near the ESRF site, vibration measurements were carried out simultaneously with the triggering of the geophone at its normal position at cell 28. The temporal displacement of a typical event is shown in Fig.3. The

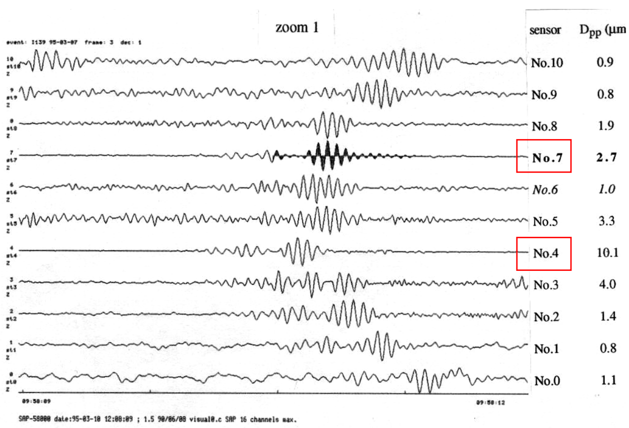

Figure 3: Temporal displacement of a typical event when a truck or bus passes over a sewer cover on the avenue des Martyrs. All sensors were placed along that road in the section near the ESRF site except sensor No7.

sensor No7 is the geophone at its usual position in cell 28 around storage ring and used for triggering measurements. The measurements showed that the perturbation started near the sensor No4 and propagated to the other sensors with a decrease in amplitude. This clearly suggested that the vibration sources came from near sensor No4. Further investigations revealed the clear correlation of these vibrations with the passage of trucks or buses over a

sewer cover on the road near sensor No4. Once this identification was established, a technical proposal for road repairs was submitted to the relevant authority. After road repair and re-arrangement of lanes, the vibration near cell 28 has been reduced to a level comparable to other place on the ESRF site.
Vibration impacts of speed bumps near the ESRF site were also investigated. Some of them inducing significant vibrations at the ESRF site were modified or suppressed.

Internal sources

Vibrations generated by various accelerator components have been intensively studied. The virtual internal sources were the High Quality Power Supply (HQPS), power supply and transformer, the cooling water flow of magnets and thermal absorbers, operating front-end shutters, the air conditioning units, and the overhead-crane.
With the surrounding Alps, Grenoble has frequent thunderstorms during the Summer months. Fluctuations or micro-interruption of the mains caused by the thunderstorms can lead electron beam loss. An HQPS system [10] was installed at the ESRF to smooth these micro-interruptions. The HQPS consists of ten units of 1MW each with rotating equipment: an alternator, an accumulator and a diesel engine. The vibrations induced by the functioning of these powerful alternator-diesel engines have been carefully controlled. Isolation systems for the engines and for the buildings have been implemented to reduce the vibration. Measurements have been made and results show that the vibration amplitude at 30 m from the HQPS building is less than 1.3 µm peak-to-peak, compared to the 1.0 µm when all units are off. The vibration influence on the accelerator machine located at least 100 m far from the HQPS building is negligible.
To ensure temperature stability, a great number of air conditioning units have been installed in the storage ring tunnel and in the experimental hall. The air conditioning units in the experimental hall and in the central building generate a very sharp peak at 16.4 Hz. The contribution of this peak in the wide band (1-100 Hz) displacement is negligible.
The vibrations induced by a 6 tons overhead-crane in motion are significant in the frequency range 30-80 Hz for both the storage ring and experimental hall slab. The amplitude in this frequency range is at maximum 10 times higher than the ambient noise. In addition, the quasi-static deformation of the floor under the weight of the crane might affect some experiments on beamlines. However, the use of the overhead-cranes is simply not allowed during machine operation and beamline experiments.
Rubber dampers were used at the fixations of the cooling water tubes to limit the vibration induced by the cooling water flow. Cooling water flow in magnets and thermal absorbers generates vibrations above 20 Hz. Fortunately, this is far from the first natural frequencies (7-13 Hz) of the magnet girder assembly. Although the vibration amplitude of magnets above 20 Hz is much higher than the ground vibration, it was still about 10 times lower than the peak at the first natural frequency (Fig.4) before the installation of damping links.

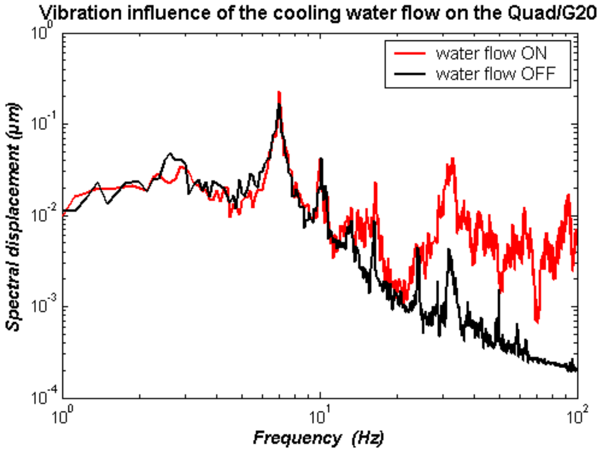

Figure 4: Spectral displacements of a Quadrupole magnet with and without cooling water flow before the installation of damping links

The opening and closing of the front-end shutter by fast pneumatic valves induced very strong vibrations on the magnets and on the girder. The peak-to-peak displacement of a quadrupole may be increased from 3.2 µm (noise) to 74 µm in the lateral direction, and from 0.9 µm (noise) to 21 µm in the vertical direction during the fast closing (50 msec). It was seen that the fast closing affects the e-beam stability, especially in the case of single bunch mode. The slow closing (200 msec) generates a vibration amplitude on the quadrupole six times lower than the fast closing. This mode was implemented. Analysis of the vibration response of the quadrupole G20 during the fast closing of the front-end shutter showed that the magnet-girder assembly was excited in the lateral direction at 7 Hz, which was the first natural frequency. The excitation lasts about 5 seconds. The modal damping ratio has been roughly estimated at 1.6%, which is very low. After the installation of the damping links and modification of the opening and closing mechanism of the front-end shutter, the vibrations induced by the action of these shutters were significantly reduced. It should be noted that the opening and closing action is occasional, the vibration impacts are limited both in duration and in the vicinity of the shutter.

MECHANICAL DESIGN CONSIDERATION

In parallel to the efforts deployed in the ground vibration monitoring and the identification and control of vibration sources, stability issues have also been considered in the design of mechanical components for the machine and beamlines. As the ground vibration decreases quickly with the increase of the frequency, a general guideline for the mechanical design is to have a fundamental natural frequency of the structure as high as possible, for example larger than 50Hz. The fundamental natural frequency f_0 of the structure is calculated by

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (1)$$

where m and k are respectively mass and stiffness. To have a high natural frequency f_0, the mass should be small and the stiffness should be large. In practice, the system is quite complex, Finite Element Analysis (FEA) is necessary to calculate the natural frequencies of the system. More advanced FEA, such as harmonic response analysis and PSD response analysis, can be used to simulate the dynamic response and transfer function of the system [11, 12].

To have high stiffness and high fundamental natural frequency of the system, non-necessary adjustments should be avoided: jacks, translation and rotation stages. Flexor hinges [13, 14] are interesting devices affording adjustment and controlled stiffness.

The fixation of the system should be carefully designed.

Different supports or tables have to be used for system generating vibrations and systems very sensitive to vibrations in order to avoid direct excitation of the sensitive system.

As an example, figure 5 shows two optic tables for beamlines [15]: one optic table with an aluminium frame and a stiff pedestal air pad, another with a granite frame and a not very stiff commercial air pad. The table with the granite frame was a very early design. The fundamental natural frequency is 16 Hz. This table amplifies the ground vibration by a factor of 4 in the bandwidth of 4-100 Hz. The aluminium frame optical table is a new design. The mass of the assembly is reduced by a factor of 3.6. The specifically designed air pad was also more stable than the commercial one. The fundamental natural frequency is increased to 85 Hz. The ground vibration is only amplified by a factor of 1.05 (5% increase). Compared to the fundamental natural frequency and the ratio of the mass of these two tables, one can deduce that the stiffness of the aluminium frame, stiff pedestal air pad table is about 28 times that of the granite frame, commercial air pad table. This example clearly shows the beneficial effects of the high stiffness, low mass and carefully designed support for optics.

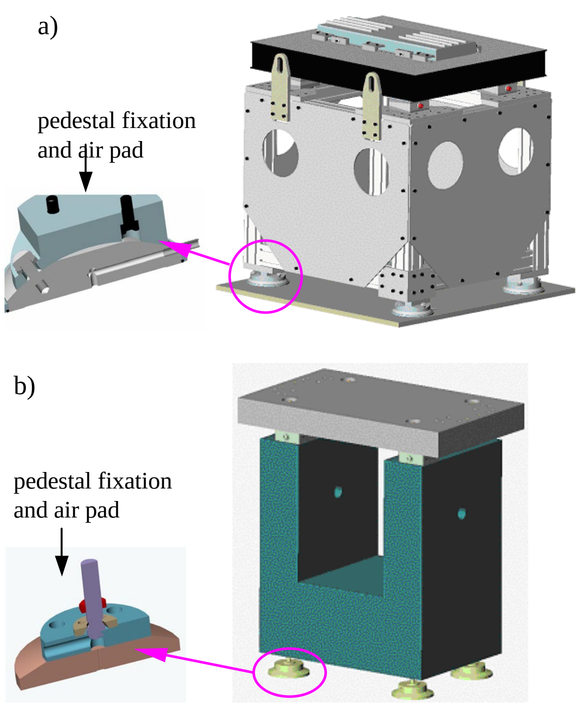

Figure 5: a) optic table with aluminium frame and stiff pedestal fixation and air pad, b) optic table with granite frame and not very stiff pedestal fixation and commercial air pad.

DAMPING DEVICES FOR MACHINE GIRDERS

The fundamental resonant vibration mode of the ESRF quadrupole magnet girder assemblies was a horizontal rocking motion at about 7 Hz [11, 12]. This was the origin of the dominant motion of the e-beam, and of the X-ray beam instability. A damping device, the so-called 'damping link', has been developed to attenuate the vibrations of the magnet girder assemblies.

The damping link design consists of adding a ViscoElastic link between the girder and the floor. It consists of three parts (Fig.6): (1) a sandwich structure with aluminium plates and ViscoElastic Material (VEM) (Al + VEM + Al), (2) a girder mounting fixture (GMF) links the sandwich structure to the girder, (3) a floor mounting fixture (FMF) links the sandwich structure to the floor. The idea was to use the sandwich structure with VEM to absorb the dynamic strain energy of the MGA related to the rocking motion. The damping links were installed on the two extremities of the girder and floor (as shown in Fig.6) in parallel with the existing jacks. Therefore the required lateral stiffness was maintained. This installation allowed attenuation of both lateral rocking motion (1st mode) and horizontal rotation around the vertical axis at the centre of the girder at about 13.6 Hz (3rd mode) [11, 12]. The mounting fixtures (GMF, FMF) should both accommodate the environment in the tunnel and be stiff enough to transmit maximal dynamic strain energy of the MGA to the VEM layer which then dissipates this energy. The VEM sandwich was optimised to attenuate the 1st resonant vibration with an operation condition tolerating up to 2 mm shear displacement in the vertical direction. This 2mm displacement corresponds to the maximum possible accumulated stroke required by alignment for two years. Test results show that the MGA with the

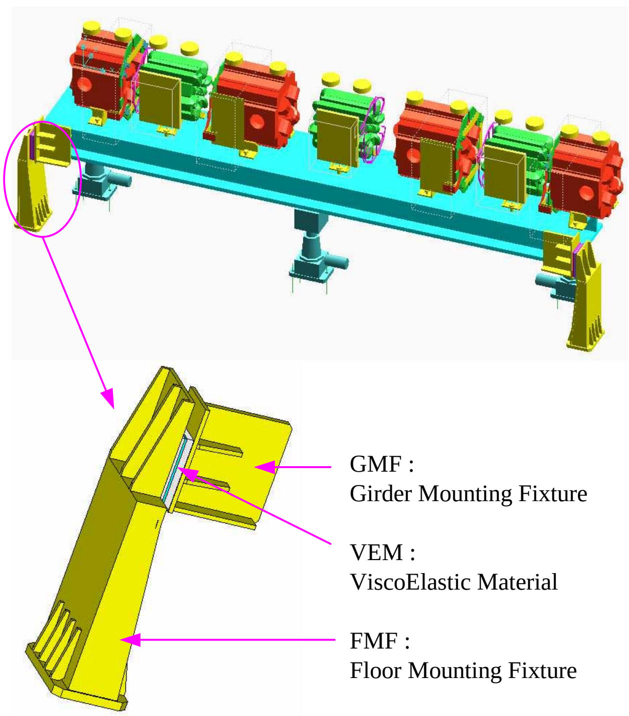

Figure 6: Damping link and installation on a G20 magnet girder assembly in the ESRF storage ring

damping links could be adjusted 2mm in vertical and lateral directions, and that the damping performance is not degraded by this amount of adjustment. The damping links are fully compatible with the alignment operation [16].

A complete installation of damping links in the ESRF storage ring was made after the March 2001 shutdown. The fundamental resonant vibrations of the magnet girder assemblies have been effectively attenuated by a factor of 5.8 [5]. The RMS displacement of the electron beam in the horizontal direction has been reduced from 10 to 2.7µm in the bandwidth of 4-12 Hz. Power Spectral Density (PSD) of the horizontal displacement of the electron beam is shown in Figure 7. Before the installation of the damping links, there was a huge peak at 6.8 Hz in the horizontal displacement PSD. When the storage ring was totally equipped with damping links, the peak at 6.8 Hz in the PSD was dramatically attenuated by a factor of 49. A wide peak around 30 Hz was also observed on the PSD. The damping links have no effect on that peak. This is because the wide peak around 30 Hz in the PSD of the electron beam motion is due to the lateral rocking motion of the quadrupole QF2 (or QF7) relative to the girder. The resonant motion of the quadrupoles QF2 and QF7 at 30 Hz are excited by the water flow in the cooling circuits. As the girder does not move for this vibration mode, the damping links are therefore not effective for the vibration of the quadrupoles, as well as for the motion of the electron beam around 30 Hz. Some countermeasures to reduce the vibrations of quadrupoles QF2 and QF7 have been studied by finite element simulation, and could be very effective.

E-BEAM MOTION AND FEEDBACK

After the installation of the damping links, displacement PSD of the electron beam in horizontal direction was compared with the PSD of the quadrupole magnet for three cases of the operation of the booster (Fig. 8). The measurements of the e-beam motion and quadrupole vibration in each of the three cases were made simultaneously. Spectral results show sharp peaks at 10 and 20 Hz in the e-beam motion when the booster was in operation (ON), a smaller peak at 10 Hz when the booster was in low power mode (ECO: ECOnomic mode). This 10 and 20 Hz component was not observed in the motion of quadrupoles. Therefore, this e-beam motion results probably from magnetic perturbations induced by the

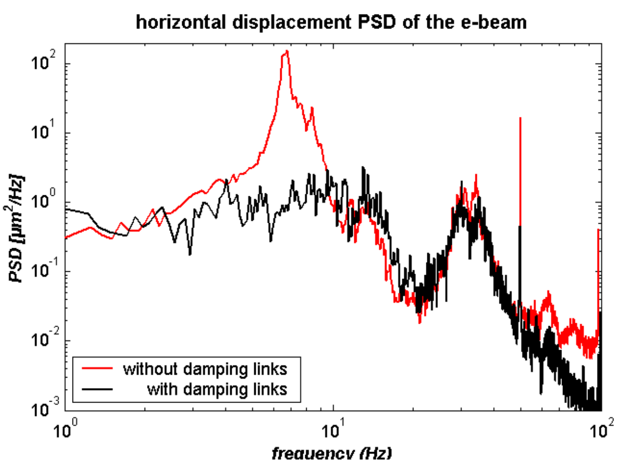

Figure 7: Horizontal displacement PSD of the electron beam before and after the installation of the damping links in the storage ring.

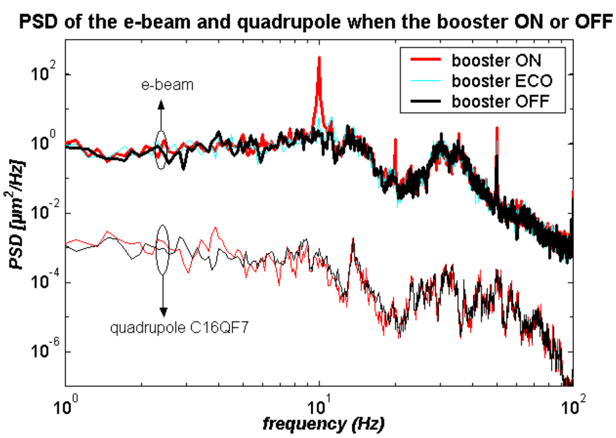

Figure 8: Displacement PSD of the e-beam and quadrupole C16QF7 when booster was ON/ECO/OFF.

operation of the booster. This is also consistent with the fact that the ESRF booster is a 10 Hz fast cycling synchrotron. The booster is in operation during the beam injection and during the weekly day of Machine Dedicated Time (MDT), when studies with the booster were frequently carried out. The operation of the booster and the motion of the electron beam at 10 and 20 Hz have no impact on the experiments with X-rays, since the booster is switched off during the operation of USM (User Service Mode). From Fig.8, one observes that the PSD value of the e-beam horizontal motion is about 1000 times that of the quadrupole C16QF7. In other words, the RMS displacement of the e-beam is about $\sqrt{1000} = 31.6$ times RMS displacement of the quadrupole. This consistent with the theoretical estimation.

In addition to the slow orbit correction (every 5 minutes), a fast global feedback system [17] was implemented to correct, in the vertical direction, the fast orbit distortion caused by quadrupole magnet vibrations. Sixteen Beam Position Monitors (BPMs) and sixteen correctors were used in the feedback system which performs corrections at a rate of 4.4 kHz in an efficient frequency range of 0.01 – 100 Hz. A global feedback system to correct horizontal orbit distortion is planned to be implemented using 32 BPMs and 24 correctors.
For the beamlines (X-ray user experimental station) requiring particularly stability of the beam, a local feedback system [18] was installed on a straight section of the storage ring. The synopsis of the system is shown in Fig.9. The function of the local feedback system is similar to the global feedback system but acts locally to improve the horizontal stability of the electron beam – the source of the X-ray beam. The electron beam position was measured at both ends of the 5 m long straight section using two low noise BPMs. A resolution of 1μm of the position was achieved in a bandwidth of 1 kHz. Four fast steerers are used to produce the closed orbit bumps for the correction. The feedback is effective in the frequency range of 0.01 – 100 Hz. The local feedback system has been installed in five straight sections and for five beamlines.

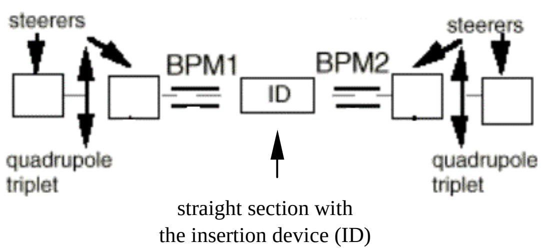

Figure 9: The synopsis of the local feedback system in one straight section and for one beamline

The electron beam motion in vertical and horizontal directions is summarized in Table 1 for the cases without damping links, with damping links, and with local or global feedback. It is also indicated in the table the electron beam size at the middle of an high-β (β_x = 35.4m) straight sections. In the frequency range of 4-12 Hz, the damping links reduce the horizontal e-beam motion by a factor of 3~4. The local feedback again reduces this vibration by a factor nearly 10 in the horizontal direction, the global feedback reduces the vibration by a factor of three in the vertical direction. The electron beam stability requirement at the ESRF is that the emittance growth should be less than 20%:

$$\Delta\varepsilon/\varepsilon < 20\% \qquad (2)$$

This corresponds to approximately 10% of the apparent beam size growth and 10% of beam divergence increase. The electron beam stability requirement is thus that the RMS displacement ΔRMS of the electron beam should be smaller than 10% of electron beam size RMS:

$$\Delta\text{RMS} < 10\%\text{RMS} \qquad (3)$$

The results in Table 1 show that the stability requirement (3) is satisfied for both horizontal and vertical directions. The damping links and feedbacks significantly improve the electron beam stability.

Table 1: Beam motion in vertical and horizontal directions in three cases: without damping links, with damping links, with local feedback in the horizontal direction or global feedback in the vertical direction

ΔRMS $_{horizontal}$ ***(μm)***	4-12 Hz	4-200 Hz
without damping links	10	12
with damping links	2.7	4
damping links + H-local feedback	0.28	1
horizontal beam size RMS $_{horizontal}$	*402 μm (high-* β_x *=35.4m)*	

ΔRMS $_{vertical}$ ***(μm)***	4-12 Hz	4-200 Hz
with damping links	0.5	1
damping links + V-global feedback	0.17	0.6
vertical beam size RMS $_{vertical}$	*8 μm (* β_z *=2.5m)*	

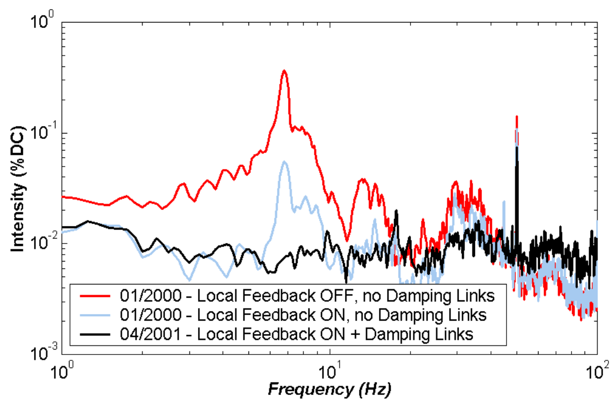

Figure 10: Spectra of the X-ray beam intensity variation measured with the ID14-EH1 beamline at the ESRF

The significant enhancement of the electron beam stability was also observed on the X-ray beam. As an example, Figure 10 shows the spectra of the X-ray beam intensity variation measured with ID14-EH1 beamline. The spectra are expressed as a percentage of the DC value. The fluctuation of the intensity should be as small as possible, therefore the spectral value should be significantly smaller than 1. The peak at 6.8 Hz in the X-ray beam intensity spectra was totally removed after the installation of the damping links in the storage ring. It should be noted that a local feedback on the electron beam was able to significantly reduce the intensity variation around the peak frequency 6.8 Hz, but the peak was still visible. This example shows that the damping links and local feedback are complementary and both effective.

CONCLUSION

Constant efforts made at the ESRF to monitor ground vibrations, to identify and cure the vibration sources, to integrate stability considerations into the mechanical design phase, to develop and implement damping devices and feedback systems, improve the electron beam stability as well as the performance of the light source. All these activities are necessary and complementary.

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