TPS Engineering for Low-emittance and High Stability

The stringent requirements of users on the beam stability are critical to the related engineering issues in an advanced low-emittance synchrotron light source, such as Taiwan Photon Source. Any instability in the machine could destroy the high performance and high stability in beam position, beam size, bunch length and beam/bunch current. This article depicts the major engineering topics concerning the mechanical, electrical (and electromagnetic) and vacuum-related stabilities, which cover most low-emittance engineering issues of greatest concern to most of the users.

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The TPS accelerator-engineering system is composed of numerous complicated subsystems. The most advanced and reliable techniques are applied to fabricate the TPS subsystems. Any instability in the machine could destroy the high performance of a low-emittance machine. The instabilities are classifiable from perturbing environments, which are mechanical, electrical, vacuum and intra/inter-beam environments. To decrease the source of perturbations, desensitizing the sensitivity (amplification factor) on the transfer route from the source to the disturbed beam, and the use of control and feedback systems are three ways to improve the beam stability. Because of limited space here, this article concentrates on the major engineering topics concerning the problems and engineering solutions regarding the mechanical, electrical (and electromagnetic) and vacuum-related stabilities,[1-3] which cover most low-emittance issues in the frequency domain of greatest concern to most of the users.

I. Mechanical Stability

Not only should the performance of each TPS component be attained and maintained, but also the position of each sensitive component must locate at the exact position: no displacement is allowed. Fine positioning, stabilization of the temperature and suppression of vibration are three major mechanical issues concerning the low-emittance engineering of TPS.

To maintain the fluctuation of the intensity of a photon beam within 10 % ($\triangle I/I$ ~ 10 %) in a photon beam line, the criterion for the fluctuation of the beam orbit is generally set at 10 % of the beam size; this value is even smaller, 5 %, for some special experiments. An orbit fluctuation in the sub-micrometer range is thus necessary for a low-emittance machine, which has a typical vertical beam size ~ 5 μm or less (4.5 μm for TPS). An even stricter criterion is needed for the displacement of magnets due to the amplification of the lattice. The amplification factor, from the magnet displacement to the orbit fluctuation, is typically about 10 for the case of some magnets being grouped on one girder. The vibration of magnets in the light source should thus be decreased to a few tens of nanometers or less.

Temperature

Temperature stability constitutes the most basic engineering requirement of a low-emittance machine; the performance of components of a light source is strongly affected by the temperature of the atmospheric air and the cooling water. A temperature fluctuation ± 1 °C was set as the normal criterion for temperature of a synchrotron light source at the birth of the "first-wave" third-generation synchrotron light source, but it was soon recognized that this criterion is too loose for an advanced machine. A much smaller temperature fluctuation ± 0.1 °C is instead widely accepted as the criterion after years of operation experience. In the TPS utility system, high-resolution temperature sensors, high-resolution valves, variable-frequency controllers and methods to control the flow rate and pattern are applied to stabilize the fluctuations of air and water temperatures to within ± 0.1 °C. For some sensitive devices, a buffer tank is used to smooth further the temperature variation to < ± 0.01 °C.

Alignment

Besides the high quality of the magnetic field, all magnets must be aligned precisely to their designed positions in the ideal orbit. A displacement from that ideal position would cause the circulating beam to be "kicked" and result in a significantly distorted orbit. The amplification factor, which is the ratio of the rms value of the orbit distortion to the rms value of the magnet displacements, should be reasonably decreased. A decreased amplification factor diminishes not only the magnitude of the static distortion but also the fluctuations of the beam position from a dynamic disturbance. The amplification factor can be decreased on grouping the magnets in the same short straight section to be mounted on a single girder; TPS adopts this design. The use of this method enables the lateral displacements of the magnets on one girder to attain < 30 μm, rather than ~ 100 μm commonly used for individual magnets. The amplification factor in vertical/horizontal directions is decreased from 40.3/54.5 to 8.0/30.6 on grouping the magnets on a single girder for the TPS.

Advanced techniques are adopted at TPS to approach a concept of precision auto-alignment. The alignment error between two neighboring girders can be decreased significantly from ~ 100 μm on using conventional optical tools to a value < 10 μm through the use of mechanical touch sensors. In addition to these sensors for adjacent girders in an arc section, a laser-psd (psd: position-sensitive detector) alignment system was developed at TPS to align two girders at opposite sides of a long straight section. The experimental results showed an alignment error < 2 μm in 10 m to be achievable. With the mechanical touch sensors, the laser-psd alignment system, tilting sensors, cam-movers, together with an alignment method, automatic alignment of the TPS girder system is practicable. This system will save time for alignment and also offer a solution to the ground settlement. The simulation results showed that a global alignment error of < 30 μm is achievable for the TPS girders.

Vibration

To suppress the sources of vibration, generated from motor-vehicle traffic and utilities and from vibrations along transfer routes to a sensitive device, and to construct a girder insensitive to a source of vibration are two major topics concerning vibration suppression.

A girder with a large natural frequency is always sought because the noise amplitude decreases rapidly with increasing frequency. The natural frequency of a mechanical structure is inversely proportional to the square root of mass and directly proportional to the square root of the stiffness. It becomes effective to increase the natural frequency of a magnet-girder assembly by decreasing the mass of the magnets. TPS increases the stiffness of the girder to increase the resonance frequency of the magnet-girder assembly. With a wider, shorter structure, a light frame, a lower position of the center of mass, more numerous supporting points, use of a locking mechanism, etc. are helpful to increase the natural frequency of a girder.

An innovative "extended kinematic mount" design is used for the TPS girder to improve the stiffness of the kinematic mount from 3-point to 6-point support without sacrificing the flexibility of adjustment. A further increase from ~ 24 Hz to 30 Hz for the first natural frequency was achieved after using locking wedges for the TPS girder prototype. The natural frequency obtained is almost twice that of a machine with a flexible adjustment mechanism. Furthermore, the fluctuation of the electron beam could be correlated with the vibration of the vacuum chamber because of the eddy-current effect from the magnet fields. At TPS, it is designed to decrease the rate of water flow, to smooth the piping curvature, and to rigidly fix the vacuum chamber so that the vibration of the vacuum chamber is minimized.

For equipment in the facility, the frequency of vibration typically locates in a range ~ 10 Hz to ~ 100 Hz. A basic requirement is that machines must be dynamically balanced. The uses of dampers underneath a heavy machine and pipeline dampers at the outset of a pipeline are popular mechanisms of solution. Although these effects might be effective (decrease 10 to 100 times), they are insufficient. Further suppression along transfer routes is necessary to decrease the level of vibration. Locating facility equipment as far from sensitive components as practicable is effective. At TPS, rubber pipes are used at the pipe lines near the storage ring to further decrease the level of vibration transferred from the source to the accelerator elements. A decrease factor ~ 10 was attained at TLS with a similar design.

The vibration level at the TPS site was found to be significantly large (> 50 nm, 4-100Hz) in the daytime. Vibration from motor-vehicle traffic, in a frequency range of Hz to tens of Hz, is due primarily to the coincidental start/stop acceleration of all vehicles when the traffic signal changes and to an irregular surface of roads near the site, such as at bridges, steps, sewer covers, speed bumps. To smooth the road surface, decreasing the speed or detouring heavy vehicles is effective in diminishing such vibration from traffic.

II. Electrical Stability

Electrical noises could degrade the beam stability mainly through degrading the performance of some sensitive instruments. The noises primarily arise from the ripple of line voltage, surge noise (from lightning, switching on/off, electrostatic discharge, etc.), noises generated by the switching-mode power supplies, noise (electromotive force) induced by electromagnetic (EM) radiation, fluctuations in the ground voltage, current leakage due to the coupling from stray capacitances or an improper handling of equipment, EM radiation generated from a transmission line (mismatched or with an improper inductance), and the signal reflected from a region of mismatched impedance. These noises co-exist with the real signals in the daily operation of an accelerator.

A low-noise electrical environment is essential for TPS. The electrical issues that will degrade the quality of signals and lead to misjudging the beam parameters are of great concern at TPS. Several measures are performed to overcome these electrical stability issues at TPS. Fundamentally, a reliable electricity supply system is designed. An electric SCADA system and false-recording monitors are established. AC switchgear has on-line sampling of voltage, current, harmonics, etc. A power incident will trigger the false-recording function to capture the transient waveform. The origin source of the failure could then be traced back and pinpointed. Second, a good grounding network with a resistance < 0.2 Ω is designed. About 50 copper rods, each of length 30 m, are buried uniformly and separately underneath the storage-ring building. Those grounding rods are linked to each other to form a grounding network, which can easily carry away the currents that flow into the network and minimize the fluctuations in grounding potential.

Besides, designs are also focused on decreasing the interferences among the accelerator subsystems. Sources of noises are decreased on raising the quality of connecting points (a resistance of tens μΩ or less should be attained), matching the impedance of the components to minimize signal reflections (and also to decrease the generation of EM noise) in a transmission line. One example is the electric feed-through of the electron beam-position monitor for TPS. The reflection coefficient is controlled below 0.03 with carefully designed structure and manufacturing techniques. It is also highly concerned at TPS to reduce the noise generated from the high power devices. For high power devices, such as kickers and septa, a mismatch in impedance not only cause the reflection noise in the real signal but a high intensity EM noise will radiate into the space and flow into the grounding network. The interference of this EM noise to the instrumentation nearby could be fatal. The position of some sensitive transmission line is fixed to decrease the fluctuation of the inductance and the stray capacitance. Various cable trays are designed for different cables to decrease the cross-talk between two separate transmission lines. For the cables for an analogue signal, the cable tray is specially covered with metal conductors to shield from the potential EM interference. A shorter current loop (including the ground loop) is a major design principle for every electrical device; this concept is also adhered to at TPS, all CIA (in which instrumentation racks are installed) are located as near their load as possible.

An independent voltage line feeder is constructed for each major subsystem, especially for high power systems. Conventional facility loads (motors, HVAC, lighting, etc.) and technical loads are separated. The transformer in each main branch plays a role of basic isolation of the line-voltage fluctuation. All power supplies and controllers are required to introduce a minimal total harmonic distortion (< 5%) to the line voltage. Methods are developed to verify the quality of each power supply/controller. If the level is too high, the power supplies/controllers will be requested to install a filter to meet the requirement. The leakage current to the ground will be monitored for each major branch. In case of an abnormal leakage current, a circuit breaker will be triggered to cut off the branch to protect other instruments from interference, and also for personnel protection. In many locations, systems to monitor electricity and grounding are installed.

III. Vacuum Environment

In addition to the basic mechanical and electrical stabilities, environmentally, the vacuum system should offer a "very clean" (gas-free) environment for the beam to circulate and also to offer a "very smooth" wall structure to transmit the image-charge current (of the circulating beam). Any scattering of the circulating beam with the residual gas or ions in the beam duct will enlarge the beam size and beam divergence and even cause a severe beam loss. Any disturbance (due to the alteration of the beam-duct structure) to the image current will "drag" the circulating beam and induce beam instabilities.

Based on aluminum technology established at NSRRC as well as many benefits of aluminum material in vacuum performance, such as a small rate of outgassing, small weight, easy machining and extrusion, large thermal conductivity, aluminum is chosen as the material for the vacuum chamber of TPS. Many studies with surface analysis through AES, SIMS, XPS and NRA have been conducted at NSRRC to decrease gas desorption from vacuum surfaces. The developed techniques, such as oil-less CNC machining, ozonized water cleaning, extremely dry venting, are applied to fabricate the vacuum chambers for TPS. A static vacuum 10^{-11} Torr was obtained at the prototype TPS vacuum system. Regarding the dynamic vacuum in TPS, ozonized water cleaning is used, which yields a hundredth of the photon-induced desorption coefficient. Much fewer gas molecules will be desorbed during the beam operation; the gas/ion scattering with the circulating beam will thus be much decreased to maintain the high-beam quality in the storage ring.

One mechanism, the dust trapping effect, could drop the beam current abruptly. The dust in a light source vacuum system is easily charged up by the scattering photons and electrons when beam circulating. The charged dust can be trapped by the electric potential formed by the circulating beam. The circulating beam could easily hit the large-size (much larger than molecules) and slow-motion dust; under such circumstance, the beam current will be reduced abruptly. All the welding and assembly processes for TPS vacuum are performed in the clean room (or a clean booth) to reduce the dust contamination in vacuum. Furthermore, turbo-molecular pumps are designed to evacuate the large amount of photo-desorption gas molecules out of the chamber for the first two years' operation of the machine when the gas desorption coefficient and thus the gas load on the ion/getter pumps is high. With such design, the powders formed in the ion/getter pumps are much reduced. Slow venting process when breaking the vacuum is also necessary to avoid "stirring up" the dust from the pumps to the beam duct, so that the dust trapping events can be minimized.

In addition to the surface treatment and pumping methods necessary to attain a small gas pressure, tremendous manufacturing techniques, such as precision machining, automatic TIG welding, laser-beam welding, precision supporting, different-material joining, coating and sliding-finger rf contact techniques, have also been developed to fabricate the complicated TPS vacuum chamber and components. A major purpose of their development is to decrease the rf-impedance in the vacuum duct seen by the circulating beam. To diminish the rf-impedance in the TPS vacuum, the number of bellows, flanges and sector gate valves are decreased as much as possible. Only two bellows and two flanges (about 1/5 of the numbers used at TLS and other light sources) are designed in the arc section of each super period. Discontinuities (steps and gaps) in the TPS vacuum duct are controlled within 0.3 mm. RF shielding is also used at the sector gate valves, bellows and flange gaps, which have a large unavoidable discontinuity. Each pumping port is also carefully designed to attain a small impedance value. Under such design and carefully fabrication, the stringent requirement of a low-impedance vacuum structure is achieved for TPS.

References

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