OVERVIEW OF SINGLE PASS FEL DESIGNS TECHNICAL SUGGESTIONS FOR STABILITY IMPROVEMENT

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Abstract

The single pass FEL based SASE is only one realistic candidate to generate intense coherent radiation at X-ray wavelength. To achieve high gain amplification of FEL signal, we need to provide a high density electron beam with low transverse emittance and maintain its trajectory in precisely straight line along the fairly long undulator, typically, 100 m or even longer. To do beam based alignment or simply guide the beam, the machine has to be very stable, with low pulse-to-pulse jitter and slow drift. This paper will provide some technical suggestions to improve today's linear accelerator to meet the above demand.

INTRODUCTION

The FEL: free electron laser using a high energy electron beam running in an undulator as an active media has been realized and used for various applications in infrared wavelength. However, when the requested wavelength becomes short, the interaction of the electron beam with the undulator radiation becomes weaker, since the energy exchange is performed through transverse motion of the beam along sinusoidal trajectory in the undulator, and its amplitude is inversely proportional to the beam energy, thus FEL becomes harder to be realized in shorter wavelength. Additionally, bellow 200 nm wavelength, no efficient mirror material is available as the cavity reflector, and all mirror material becomes weaker against intense radiation circulating in the FEL resonator.

To avoid this difficulty, the X-ray free-electron laser (FEL) based on linear accelerator technology using the principle of self-amplified spontaneous emission (SASE) appears to be the most promising approach. SASE does not require the resonator, instead it amplifies the spontaneous signal associated with the incoming electron beam, for several decade of magnitude, until it reaches to saturation condition along a fairly long undulator.

To realize this type of new FEL, we have to establish the following two major technologies.

(1) Generation of high density electron bunch with a peak intensity at a few kA, at the same time the beam emittance has to be very low, typically 1 π.mm.mrad for transverse, and 10^{-4} energy spread.

(2) Transport above electron bunch fairly straight trajectory in the long undulator line. The alignment tolerance is typically 10 to 50 micron-meter for each Q-magnet in X-ray FELs.

To perform these requirements, in many accelerator laboratories, new R&D programs for X-ray FEL have been started in these years. Up to now, R&D's are mostly focused on the development of low-emittance electron-source using photo-cathode RF-gun, or HV gun using thermionic cathode. Recently, very promising results are reported from those R&D's at FEL2004 conference.

To achieve the high peak current in a bunched beam, we currently believe the magnetic chicane type bunch-compressor will be capable of handling the low emittance beam without emittance dilutions. There are a large number of studies on this subject, and can be found elsewhere.

However, on the second issue, not many studies have been carried out, because this is not a single subject and the target cannot be clearly specified, since it varies on boundary conditions of each detail designs. The issue is widely cross-related between, undulator technology, beam optics, electron beam monitoring, and X-ray beam detection.

In this paper, the author wishes to illuminate machine stability issues behind each of these technical details. To perform the beam based alignment on undulator beam line, machine has to provide fairly stable beam during iteration process: measuring beam position carefully with changing the beam energy. Also on tuning the chicane magnet, we need careful measurement on bunch length v.s. energy or CSR noise radiation from the beam line. Every tuning and beam study will request stable beam and quiet environment (low electro-magnetic radiation from power supplies).

In this paper, we compare machine stability of the linear accelerators with storage ring and discuss various aspects of machine stability. The author will also try to provide some technical suggestions on improving the machine stability.

STABILITY COMPARISON

Table-1 compares various aspects related to the machine stability of the storage ring and linear accelerator (pulse mode). In the storage ring, machine runs mostly in steady state condition, while the pulse mode linear accelerator runs in transient condition, this cause the major difference of the machine stabilities in two types.

The electron beam trajectory in a storage ring is a "closed orbit", which is an eigen vector of the wave-function (ring optical matrix). Therefore, even with different initial conditions, in practice with beam injection errors, beam converges to unique closed orbit (eigen vector) after damping. On the other hand, in the linear accelerator, the trajectory is not an eigen vector, it is an open single-pass trajectory, which varies with initial conditions, in practice, injection error. Therefore, the stability of the electron source is very important in the linear accelerator.

In the storage ring, there is a synchrotron damping effect, which is a combined effect of synchrotron phase stability phenomena on rf-voltage and radiation damping effect. Thanks to this effect, the initial condition error or some temporal error excitations are damped, and the beam trajectory approaches to the steady state closed-orbit. But, in the linear accelerator, there is no phase-stability phenomena, therefore no negative feedback acts on the beam in natural, and also there is no synchrotron radiation damping. Thus, we do not have any helpful phenomena on beam stabilization in the linear accelerator, and the beam accumulates error during its acceleration from the electron source to the undulator, until it is damped.

According to the beam quality issue, i.e., shape of the beam distribution function, in the storage ring, beam tails are cleaned up during many turns by quantum excitation due to the synchrotron radiation, and by limited rf-bucket height or collision to the beam aperture, finally it approaches to the Gaussian shape. In the linear accelerator, there is no such natural beam cleaning effect. Additionally, we have the dark-current emission from metallic surface in high-field at the rf-gun and also in the linear accelerating structure. In order to clean up and avoid contamination, we have to prepare beam collimators in proper locations, where we carefully need to study the wakefield effect associated to non continuous change in beam aperture.

The state of the art achievement on stability has been made recently in storage rings after introducing the "Top-up mode" operation[1]. The beam intensity (or beam current) stability reached to 2 x 10^{-4} level, and the beam energy stability is in the range of 10^{-5} to 10^{-6}. for period of a day(the beam energy spread is 10^{-3}). There is no question to all synchrotron radiation users being satisfied with these beam stabilities. For example, protein crystallography, can be smoothly performed if the beam energy stability at <10^{-3} level.

On the other hand, today's linear accelerator has much poorer performance, unfortunately. The charge stability from electron gun and after acceleration is in the order of 10^{-2} in single bunch mode. The energy stability is about 10^{-3}, which depends on the power supply stability, especially the line-type pulse modulator power supply stability is in 10^{-3} level. The author believes that there is much rooms of improvement on the machine performance.

The super conducting accelerator technology will solve a part of the jitter problem.

The X-ray FEL based on SASE mode will be used for very wide applications, among them; unique applications will be the basic study on high field phenomena in condensed matter, and imaging of single molecular or nano-structure by single shot. In such applications the intensity stability of 10^{-2} level and 10^{-3} energy stability will be good enough. However, the beam trajectory inside the undulator line has to be stable within 10 to 50 micronmeter (depends on design choice) for 100 m long undulator line in X-ray FELs.

Change in energy will cause trajectory deviation with dispersion in focusing system, or bunch compression factor change in chicane magnet. The charge variation will cause energy variation through beam loading effect, and bunching ratio change through space charge repulsive force, or betatron phase shift through radial space charge force. Those parameters are closely related in complex manner, so it is not simple to specify the beam stability requirement, and not be described further in this paper. The author instead will try to provide suggestions on improving the machine stability by introducing today's advancing technology in industries.

JITTER AND DRIFT SOURCES

The possible jitter sources of pulse-to-pulse change in intensity, energy, timing, etc., and sources of long-term parameter change are listed below.

(1) AC line voltage and phase fluctuation.
(2) Power supply fluctuation (due to temperature, or other reasons).
(3) Switch-tube pulse-to-pulse jitter. Residual ON-voltage and delay time variation of thyratron tube in pulse modulator power supply for the high power klystron.
(4) EM noise interfere from switching power supply of modulator and inverter type power supply.
(5) AD, DA digitising and quantized resolution noise.
(6) Temperature fluctuation on all hardware components.
(7) Ground motion of natural and human activity.

We need to cure all these sources of fluctuation. In an ideal machine, thermal noise will define all the residual

Table-1. Stability comparison.

	Storage Ring Machine	Linear Accelerator (Pulse Mode Machine)
Machine condition	All hardware are in the steady state condition.	Transient condition (less stable)
Trajectory	Closed-Trajectory (Eigen-vector)	Open-Trajectory (Not Eigen vector)
Damping	Synchrotron damping	No Damping Effect
Beam cleaning	During many turns, synchrotron excitation and beam tail loss make Gaussian beam.	Single pass. No natural beam cleaning exists. Dark-current contamination is a big problem.
Noise bandwidth	~ 1 kHz Narrow tune resonance.	~GHz. Bunched electron beam samples all the noise in wide frequency spectrum.
Energy and intensity stability	10^{-5} ~ 10^{-6}	10^{-2} ~ 10^{-3}

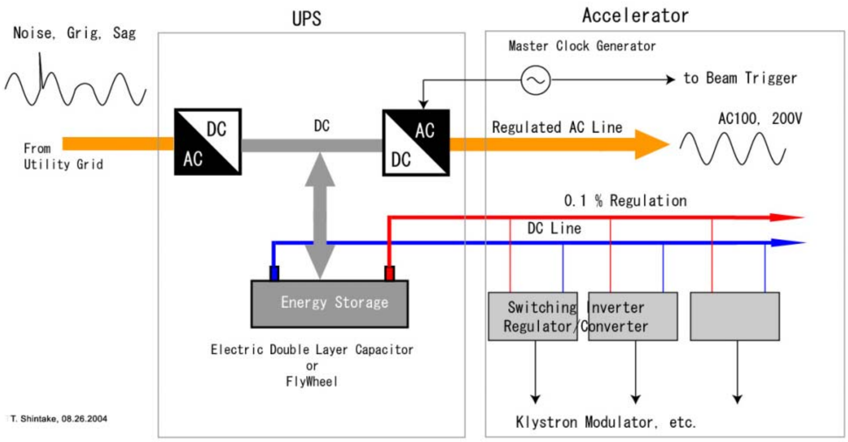

Fig. 1. UPS as an energy storage and power regulation.

fluctuations, however practical machine is far from such ideal conditions. From the following section, possible cure to these fluctuations will be discussed.

AC Line stabilization

AC line provides all the energy to the accelerator, thus it is one of the most important fluctuation source. Today's power generator plants form a network connection and exchange energy to compensate variation of energy consumption in a day or a week, and also regional unbalance between a city and industrial zone. Therefore, voltage and phase are always changing (AC phase is artificially used to control power flow in the network).

Also, in spring and summer seasons, lightning in thunderstorm causes short-term power glitches, sags or power down, resulting in beam loss, or vacuum pump down. On the other hand, in pulse mode operation of the normal conducting accelerator, machine runs at 10 to a few hundred pps, in which, after firing each pulse, the power supplies need to be re-charged within a cycle, thus system creates pulse power loading to external power grid.

In order to avoid the power down, and also prevent the system to sending the pulse loading to external site, the accelerator should be equipped with UPS (uninterruptible power supplies). A small UPS system has been used to backup the computer power in important network servers, where mostly the small size chemical batteries were used. For large scale application, such as in a hospital or semiconductor fabrication line, a diesel engine was used, but it runs limited time only after the AC power down, and can not be used continuously. An advanced system using flywheel energy storage [2] and IGBT switching power controller can be found in large scale applications, such as semiconductor fabrication line.

UPS system using lead acid battery also used in a large system, however, it needs frequent maintenance on the battery with careful treatment of acid. The lead acid battery is also massive.

In electric car development, a new type of energy storage using "double layer capacitor" appears to be the most promising battery [3]. The energy to mass ratio is ten times higher than the lead acid battery, and does not use the chemical process to store the electric charge, therefore the life time is much longer. The USP system capable of handling 400 kW using this type of capacitor is already on market [4].

Fig. 2 shows a possible UPS power regulation system. The key points are

(1) The double layer capacitor store energy for UPS function.
(2) The switching inverter converts DC power to AC power with high regulation and its cycle is locked to a clock generator in the accelerator.
(3) The AC power from external grid is converted to DC power through active rectifier on the double layer capacitor, and regulated.
(4) The DC power is also directly distributed to accelerator, and used for various voltage through switching converter. In this scheme, we can simplify each power supply by eliminating AC-DC converter parts.
(5) Pulse loading effect in the linear accelerator is almost perfectly compensated by the energy storage in UPS.

Detail information of the double layer capacitor can be found in ref. [3].

EM NOISE

The traditional design of the line type pulse power supply (modulator) generates strong EM noise. The rush current in thyratron switch is usually 1000A or more, the voltage swing across the switch is 20 to 50 kV, and the switching speed exceeds order of 10 kV/100 ns. If the circuit is not properly designed, the switching circuit will radiate EM noise in wide frequency spectrum at DC to a few tens MHz. Once this radiation spreads out to envi-

Fig. 2. Klystron pulse modulator for SCSS project. All HV components are installed in metallic shield tank, and filled with oil.

ronment of accelerator system, its runs along the power line or control line, finally cause various effects on the system. Most sensitive part is the beam diagnostics, and user experiments.

In order to cure this noise, we have to design the noise source not to radiate to outside, or to keep the rush current within the closed circuit. To do this, the Faraday cage concept provides best guideline on hardware design. As shown in Fig. 2, if the switching circuit is perfectly surrounded by a closed metallic boundary, no EM field will can leak out. But weed to make holes to provide in and out power feeds, or control lines. We can stop the noise leakage through these holes and wires by properly choosing filter, so called, common-mode choke. Today, such filters can be easily found in market.

Fig. 3 shows the klystron power supply developed in SCSS project based on Faraday-cage concept. All of the switching device and high voltage components of the modulator are installed into a metallic shield box made by stainless panels, and filled with oil to prevent the circuit from high voltage discharge. The stainless panels are standard components designed for water supply, so it is not expensive. This design is also desirable to isolate high voltage circuit from the environmental change, i.e., the humidity, temperature, or dust contamination.

The same guideline can be applied to all the circuit components in liner accelerators.

ASIC DEVICE

ASIC: Application Specific Integrated Circuit is widely used in rf, wireless and optical fiber communications, and also electrical test equipments [5]. This technology is based on silicon and germanium integrated circuit, which suitable to design frequency up- and down- converting mixer and amplifier in rf-detector and modulator, or BPM detector. In linear accelerators, rf: radio-frequency power is used as the energy source of particle acceleration, or beam monitoring signal. There are basic functions of

(1) Signal modulation of rf-carrier and de-modulation.
(2) Frequency up and down conversion.
(3) Local frequency generation using PLL.
(4) Level adjustment according to the beam intensity.

All of those functions can be integrated into a chip based on ASIC technology. We may also realize those circuits via traditional design like circuit boards in a shielding box. With ASIC, we may eliminate shielding box, since the chip size is much smaller than the typical wavelength of signal, thus it is in-sensitive to noise environment. Also it is easy to utilize the laser trimming technique to adjust the balance of mixers, or the amplifier gain, thus it is fairly easy to produce repeatable parameter for many number of circuit in mass production, which resulting in reducing the fabrication cost.

Additionally, standardization of basic functions listed above by means of ASCI design will make easier to share the circuit design between each accelerator design groups, which will enhance the R&D efficiency.

THE MECHANICAL STRUCTURE

Mechanical support structure of accelerator component is also important subject for stability issue. Since the X-FEL requires very small electron beam emittance: 1 π.mm.mrad, the beam size in the undulator becomes about 100 micron-meter or smaller. We need to keep overlapping of the electron beam and X-ray radiation through undulators, therefore, the position stability of focusing component has to be very stable.

Traditionally we use a support structure made by steel framework to support Q-magnet, and position of the beam pipe is about 1 m high from floor. Since the heat capacitance of the steel framework usually not so big, the framework temperature always follows the air temperature. If the room temperature changes 1 deg.C, the steel framework will expand 12 micron-meter, which is already close to the tolerance limit of the alignment.

If the temperature distribution around the steel framework is not uniform, it will cause transverse displacement. If there is forced air flow inside tunnel, or a heat source located nearby (a lump or cooling water), this type of displacement becomes not negligible.

The author would like to suggest the following design for support structure in X-FEL.

(1) Locate beam height as low as possible. Lower structure makes vertical and transverse displacement due to thermal expansion smaller, and also provides higher stiffness.
(2) Use low thermal expansion material.
(3) Use massive volume structure rather than frame work. Larger heat capacity makes sensitivity to ambient temperature change smaller. Larger mass makes vibration amplitude from external force smaller.

Table-2. Material Properties for Support Structure

	Units	Steel	Alumina	Granite	Concrete	Anocast™	Cordierite	Fused Silica
Chemical formula		Fe(C)	Al_2O_3			Epoxy resin quartz	$2MgO$-$2Al_2O_3$-$5SiO_2$	SiO_2
Thermal expansion	10^{-6} /C	6~15	7	5 ~ 15	7 ~ 13	17	1~0.1 * 1.7 **	0.45**
Thermal conductivity	W cm/°C	0.8~2	0.17~0.29	0.02	0.01	0.24	0.03	0.014
Specific heat	Cal/g°C	0.1	0.19	0.2	0.24~0.3	0.23~0.26	0.35	0.16
Density	g/cm^3	7.8	3.8	2.6~2.7	2.4	2.32	2.6	2.2
Compressive strength *	MPa	1000-2000	~2000	130	30~100	110-117	350	650-1100
Tensile strength *	MPa	1800	260-300		-	15.2	25.5	48

* room temperature - **~25ºC through ±1000ºC

Table 2 compares several materials for support structure. Among them, candidates for the support structure will be cordierite ceramic or fused silica. In industrial ceramic factory, the cordierite has been used as high-voltage bushing operating at high temperature in a dust cleaning chamber at the power generation plant. Therefore, technology to fabricate meter-size cylinder with cordierite and fixing to metal flange exists in ceramic factory [6]. We may employ the cordierite ceramic tube as the stable support with reasonable cost. Fig. 3 shows our ceramic support for SCSS project, on which focusing Q-magnet and BPM will be installed in the undulator line. The outer surface of the ceramic is covered by soft polymer sponge (black color) for protection. Inner volume is filled with sand to damp mechanical vibration. With careful measurement, we found the thermal expansion ratio was 1.9×10^{-6} (1/C).

The same concept can be applied to large scale magnetic device, such as the undulator. In the undulator, linear arrays of permanent magnet generate periodic transverse field. Since the field is fairly uniform in transverse plane, we do not need precise positioning of the undulator. However, the field intensity is a strong function of the gap size of two magnet arrays, we need to precisely maintain the relative position of the gap, tolerance is order of 1 micron-meter.

In the undulator design, steel structure have been used to hold the magnetic array. However, as mentioned above, the steel frame work does not have enough heat capacity, thus it changes the dimension with ambient temperature change.

The author would like to suggest the granite table as the support structure for the magnet array of the undulator. From the thermal expansion point of view, cordierite will

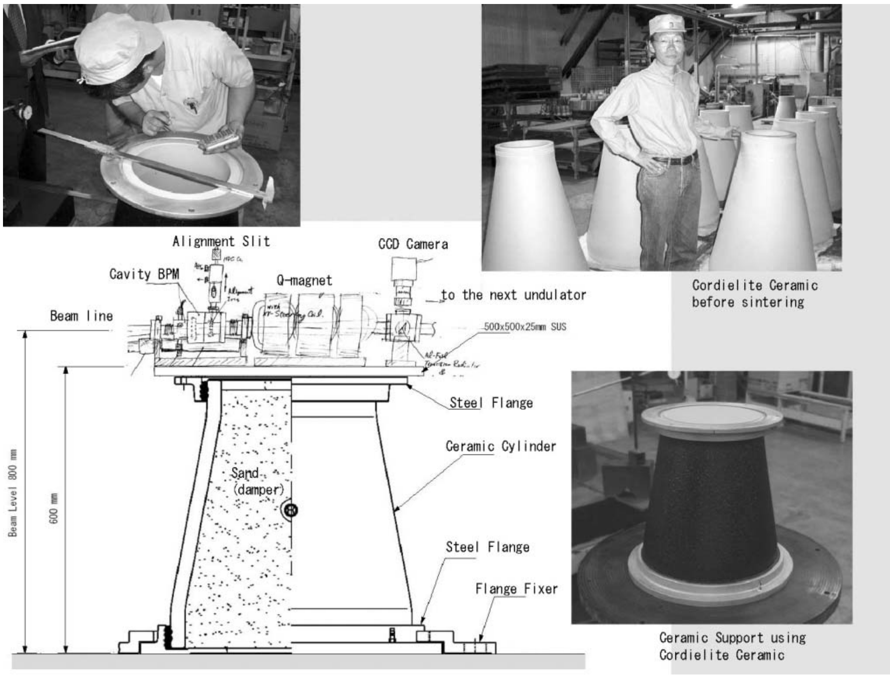

Fig. 3. Ceramic material is suitable to stable support for accelerator component.

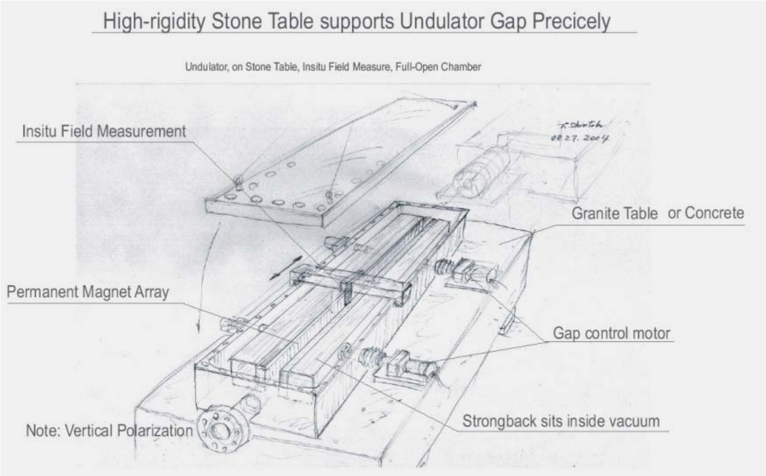

Fig. 4. Granite table as the support structure of the undulator magnet. Massive granite will provide high rigidity against various deformation forces. In-situ field measurement will be performed by movable probe, whose linear guide has to be integrated into the chamber.

be the best choice, but ceramic factory can not handle a few meter long structure. If we chose granite, we can find a few meter long solid block with reasonable cost. Casted concrete, with steam heat treatment, may be alternative candidate, but we need a careful study on slow dimension change with drying for few years.

Fig. 4 shows illustration of the idea. Massive granite will provide high rigidity against various deformation forces. The assembly and field tuning will be made in a laboratory, the we transport the undulator to the tunnel. During this transport, various external forces will be applied and also internal force due to temperature change will cause deformation. Therefore, the support structure has to have high rigidity.

In the X-ray FEL, since the field tolerance is very tight, while the beam quality will not be good as one in the storage ring, and also dark-current emission from the linear accelerator cause degradation of magnetic property.

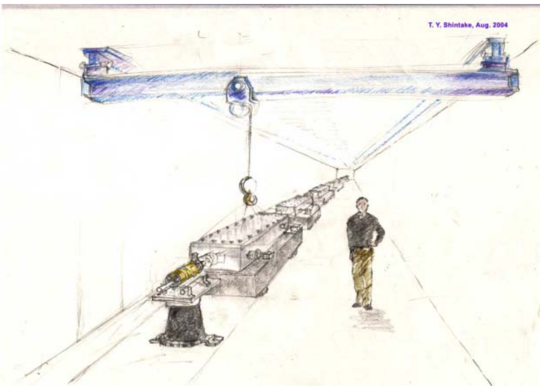

Fig. 5. Accelerator tunnel image. Focusing elements sit on the ceramic cylinders, and undulators are on the granite table.

Therefore, in-situ field measurement will be non evitable process and scheduled measurement has to be repeated once per year, for example. As shown in the figure, in-situ field measurement will be performed by a movable probe, whose linear guide will be integrated into the chamber.

When we install the focusing elements and undulators, the tunnel becomes as Fig. 5. Beam line height will be 1m or lower, the undulator will be accessible from top cover. The total length of undulator line will be 100m or longer in X-FEL.

CONCLUSION

The X-ray FEL based on SASE mode request revolutionary improvement on accelerator performance. The super conducting accelerator technology will solve a part of the jitter problem, but at the same time it may introduce new type of difficulties. Now, the X-FEL is a big challenge to the accelerator community. Continuous persevering efforts in each detail will be requested.

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