

Development of virtual accelerator environment for beam diagnostics*

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Abstract: For the proper operation of Dalian Coherent Light Source (DCLS) linac, measurement and control of the electron bunch is essential. In order to test control algorithms and high level physical applications, a virtual accelerator environment is constructed based on ELEGANT code and SDDS Toolkit. The required beam parameter measurement and orbit control tools are tested under this virtual environment and will greatly speed up the development of machine commissioning tools. The design concept and current development status are presented.

Key words: virtual accelerator environment; beam parameter measurement; high level application; orbit correction

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Dalian Coherent Light Source (DCLS) is a free electron laser user facility based on the principle of single-pass, high-gain harmonic generation scheme^[1]. During the commissioning of the linac section, beam parameter measurement is important, meanwhile, beam correction is indispensable for the stable operation of the machine. To expedite the design of measurement tools, Virtual Environment (VE) has been widely used on many facilities^[2-6]. Beam energy and energy spread are usually measured by a diagnostic system that consists of a bending magnet and the following beam profile monitor, and the transverse beam emittance is measured using the so-called “Quadrupole Scan” method. Beam orbit is measured by Beam Position Monitor (BPM) along the beamline and the orbit correction is implemented using the dipole correctors. Resolution and accuracy of the beam instrument should be specified during the design stage and analyzed during the commissioning stage.

In order to evaluate the feasibility of beam diagnostic systems, a virtual accelerator environment based on ELEGANT^[7] code and SDDS Toolkit is developed. With the tools and interfaces provided by this VE, the beam behaviours simulated by physics codes can be directly handled to High Level Applications (HLA), which will greatly speed up the development of machine commissioning tools.

This paper focuses on the concept of the virtual accelerator environment and its role during the communication between physics codes and high level applications. With the flexibility of this virtual environment, the energy and energy spread measurement tools have been designed, which can be used to find the proper RF phases before and after chicane. Also the beam emittance measurement tools based on VE is shown. Using these tools, the transverse parameters which give the information of the beamline can be derived. Finally the design of the beam orbit correction tool and the response matrices acquirement are shown both theoretically and experimentally.

1 Virtual accelerator environment based on ELEGANT and SDDS Toolkit

SDDS Toolkit and ELEGANT code have been used during the design of DCLS. Integrating physics codes

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into control system will give great potential to optimize the machine commissioning and operation. Hence we have developed a Virtual Accelerator (VA) code to provide tools for integrating and interfacing different simulation codes into the control system. The VA uses ELEGANT code as the simulator of beam dynamics to simulate the behaviour of electron beam, meanwhile, with the combination of SDDS Toolkit, the VA can also provide data pre-processing and exchanging for different simulation codes. As the control system is based on Experimental Physics and Industrial Control System (EPICS)^[8], the communication and data transfer are provided by using the EPICS portable Channel Access (CA), so a set of utilities for interfacing the VA and the high level control system have been developed. In this way, the VA will operate just like the real machine from the view of EPICS channel. The structure of the VA compared with a real machine is shown in Fig. 1.

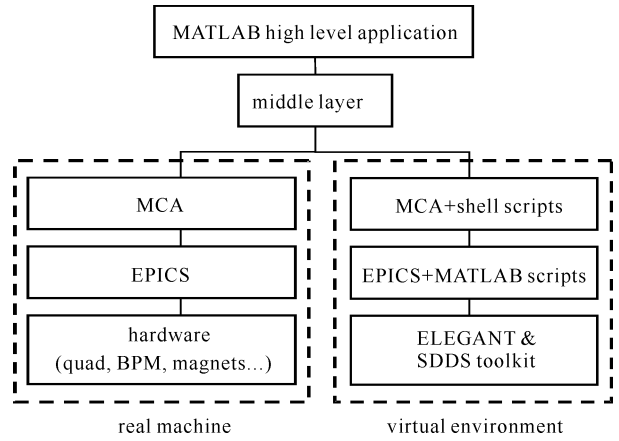


Fig. 1 Structure of the virtual environment compared with real machine

In the case of DCLS, the High Level Applications (HLA) including Graphical User Interface (GUI) has been designed on MATLAB platform. In order to enable the communication between HLA and the physics simulation codes, an I/O interface is developed which can convert files between SDDS format and MATLAB format. With the flexibility of the built-in functions in SDDS Toolkit, the SDDS format file can be loaded directly into MATLAB HLA. An example of reading and display the output beam distribution from simulation is shown in Fig. 2.

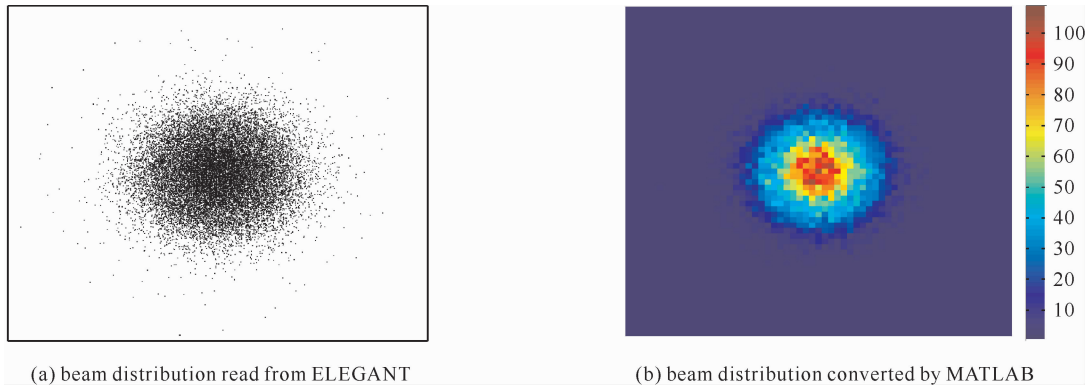


Fig. 2 Simulated and converted beam distributions

In the reverse process, the parameters and configurations from HLA can be converted to physics simulation codes via specified functions. The conversion processes between machine quantities (e. g. current in ampere) and physics quantities in simulation codes (e. g. quadrupole strength K in m^{-2}) are carried out and stored in advance so that the VA can operate like an online machine.

2 Beam parameter measurement in longitudinal direction

With the flexibility of VA environment, we can measure and tune the longitudinal beam parameters for the DCLS linac. According to the design layout, beam energy and energy spread measurement are routinely carried out at three beam diagnostic locations; at the exit of RF gun, at the exit of ACC2 and at the linac end. The basic layout of bending magnet system is shown in Fig. 3.

The beam energy can be evaluated from the magnetic field of the bending magnet as described in Eq. (1),

$$E/\text{MeV} = 299.8(B/T)(\rho/m) \tag{1}$$

where ρ is the bending radius which is fixed by the geometric distance between profile and bending magnet, B

is the magnetic field of the bending magnet which is controlled by current^[9]. In order to simulate the general procedure of energy measurement, in the calculation of the beam distributions using simulation code, each location is equipped with one “watch point” element, by which we can get the theoretic 3D beam distribution. As the beam energy distribution is characterized by analyzing the transverse profile collected on a profile, only the x - y plane beam information is handled to reconstruct the beam transverse distribution. The beam shape and center are fitted using Gaussian fit method and shown on the HLA panel. As described in Eq. (1), the beam energy can be determined as long as the current of bending magnet is measured.

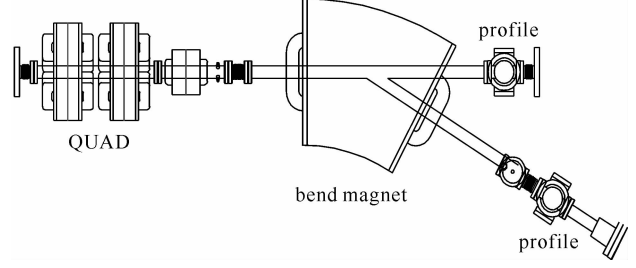


Fig. 3 Basic layout of bending magnet system

The energy spread measurement is carried out in a similar way. The energy spread is derived by measuring the beam size at the profile screen and acknowledging the local dispersion^[10]. The transverse beam size $\sigma_{\text{beam}} = \sqrt{\sigma_{\beta}^2 + \sigma_{\delta}^2}$ is measured in a dispersive location with two sources, where $\sigma_{\beta} = \sqrt{\epsilon\beta}$ is the beam betatron’s size and σ_{δ} is the size caused by dispersion. Thus, the energy spread is $\sigma_E = \sigma_{\delta}D/E_{\text{beam}}$, where D is the dispersion. When $\sigma_{\beta} \ll \sigma_{\delta}$, the betatron contribution can be ignored, then the energy spread can be dominated by transverse beam size and dispersion. Using the strategy above, the upstream quadrupoles are optimized to get the minimum betatron contribution after 30° bending magnet, then the corresponding energy spread is determined^[11]. The final energy spread measurement interface is shown as Fig. 4.

In order to chirp the bunch during the longitudinal compression process, the linac has to be operated at off-crest phase. In practice, the accelerating phase is indicated by the offset of minimum energy spread from maximum energy spread from maximum energy^[12]. Using the energy and energy spread data acquired by the previous measurements, the required RF phase of subsequent accelerate modules can be found out at the point where the energy spread is the smallest, as shown in Fig. 5.

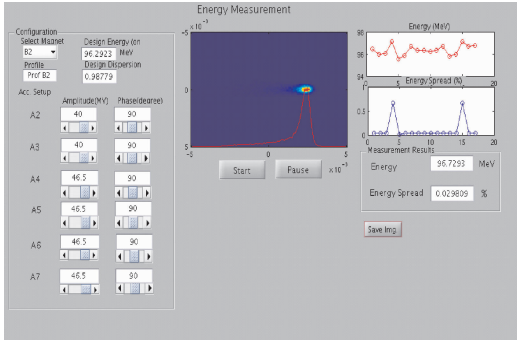


Fig. 4 Energy spread measurement interface

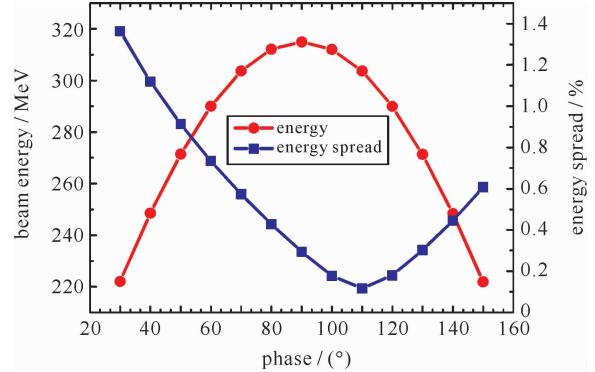


Fig. 5 Scanning process of the required RF phase for subsequent accelerating modules

3 Beam emittance measurement in transverse direction

As one of the most important judgments of beam quality, projected emittance measurement is crucial for optics matching in linac. Many different ways have been studied to measure the beam emittance, in the case of DCLS, an automatic measuring tool is developed based on VA using “Quadrupole Scan” method^[13]. During the scanning, with the thin lens approximation, the correlation between σ_s^2 and KL_q is given as Eq. (2).

$$\sigma_s^2 = A(KL_q)^2 - 2AB(KL_q) + (AB^2 + C) \quad (2)$$

where σ_s is the root mean square (RMS) beam size on the profile screen, L_q is quadrupole length, K is the normalized quadrupole strength, A , B and C are coefficients that can be fitted by the second order polynomi-

al fitting. The normalized projected emittance ϵ_n can be written as $\epsilon_n = \sqrt{AC}/L_d$. Where L_d is the length of drift between quadrupole and profile screen. There are five reserved diagnostics locations for emittance measurement and each location is equipped with one profile, after scanning the upstream quadrupole, the emittance measurement tool can extract the transverse beam size on profile and estimate the transverse beam emittance at the entrance of the scanned quadrupole. The emittance will be determined on both horizontal and vertical plane simultaneously. At the same time, Twiss parameters at the entrance of scanned quadrupole can also be measured. Space charge forces are not included in the emittance analysis and should have no significant impact on the final measurement results^[14]. During the tracking in ELEGANT, 100 000 particles are used. When the beam image converted from beam distribution is loaded, it is shown in a 10 mm×10 mm area, the pixel calibration is 10 $\mu\text{m}/\text{pixel}$. In order to remove the influence of background noise, an averaged background image is subtracted from each beam image in MATLAB processing. When the emittance measurements are performed sequentially at each diagnostic location, the transported beam emittance information along the linac can be obtained^[15].

Fig. 6 indicates an example of the software interface and result of emittance measurement, in which the scanned quadrupole values with observed beam size square are measured and then fitted. Finally the emittance of 1 mm • mrad were determined from the fitted curves for both horizontal and vertical planes.

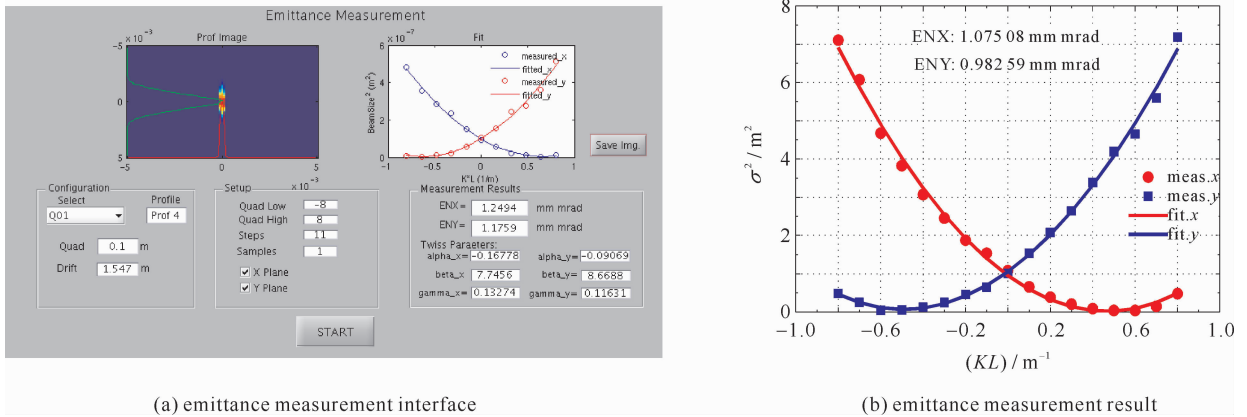


Fig. 6 Emittance measurement software interface and result example

4 Beam orbit correction

With the existence of element misalignments, the orbit needs to be corrected. Usually, a common used Singular Value Decomposition (SVD) based orbit algorithm like Global method is applied on the linac. Beam orbit correction is accomplished using BPM readings and in turn correct the orbit with dipole magnets. Correction tools has been developed and debugged under the VA environment. This algorithm relies mainly on a so-called Response Matrices which maps the orbit changes due to the corrector kicks. The main issue when applying orbit correction is how to get the according response matrices for both planes. The theoretical response matrices can be computed by ELEGANT and imported into a MATLAB Orbit Correction tool. Experimentally, the response matrices can be determined by measuring the BPM readings while varying the current of each dipole corrector. Compared with the time consuming experimental measurement, using the theoretical response matrices is much faster and can be applied to the orbit control system without affecting the facility operation, considering the demand of verifying the consistency between the theoretical and experimental model.

Fig. 7 shows the typical improvement in beam position at each BPM achieved by the correction tool. In this example, each quadrupole is assumed with 100 μm transverse offset with respect to a straight line. In the horizontal plane the RMS error is reduced from 0.41 mm to 0.06 mm while in the vertical plane the RMS

error is reduced from 0.52 mm to 0.05 mm.

5 Conclusion

A set of beam parameter measurement and orbit control tools based on virtual accelerator environment have been developed. The VA environment provides flexible data process interfaces with physics simulation codes. The theoretical model from simulation can be directly imported into high level applications or through EPICS channel access. Different beam measurement procedures and correction methods can be tested and verified using this VA environment. Successfully integrating this VA environment into the control system will greatly improve the machine performance in the DCLS commissioning.

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束流诊断虚拟加速器环境开发

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摘要: 为了更好的测试控制方法和开发上层控制软件,本文提出了一种基于 ELEGANT 和 SDDS Toolkit 的虚拟加速器环境。在这个虚拟环境下,可以将底层物理模拟软件与上层控制软件通过 EPICS 控制通道及 Matlab 脚本进行数据分析及处理。本文描述了在该虚拟加速器环境中束流参数测量和轨道控制等软件的开发和测试,并探讨了该虚拟加速器的设计理念和未来可能的应用。

关键词: 虚拟加速器环境; 束流参数测量; 上层控制软件; 轨道校正

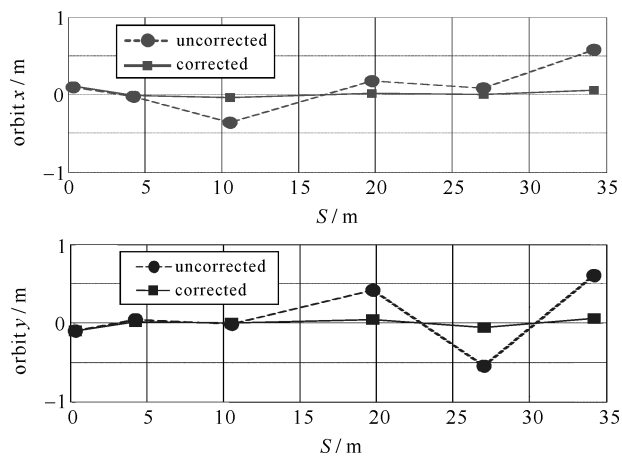


Fig. 7 Improvement after orbit correction for both vertical and horizontal planes