A modeling GUI for accelerator physics of the storage ring at SSRF

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Abstract In this paper, we report a MATLAB-based GUI tool, bodgui, which integrates functions of lattice editor, linear match, and nonlinear optimization, and visualized tracking functions for beam optics design. A user can switch his/her design procedures one to another. Flexibilities are provided for adjusting or optimizing the lattice settings in commissioning or operation of the accelerators. The algorithm of the linear match and nonlinear optimization, and the GUI windows including the main functions and running status, are presented. The SSRF storage ring was employed as a test lattice. Several optics modes designed and optimized by the GUI tools were used for commissioning the storage ring. Functions of bodgui tool are machine-independent, and it can be well applied to modern light sources being built in other parts of the world.

Key words MATLAB, AT, GUI, SSRF storage ring, Beam optics design

1 Introduction

A high performance light sources of the third generation is of reasonable lifetime and high injection efficiency, with lattices of low emittance and complex lower symmetry structures, though. Designing such a light source with a storage ring of larger dynamic acceptance needs nonlinear optimization, which has affected greatly the linear optics. In the physics design process, there used to be sequential steps of linear optics design, nonlinear optimization and investigation of the particle nonlinear behaviors, with frequent the renewals of a previous designing step. Nowadays, the design is in even more iterations of the steps[1], with different codes, to perform linear and nonlinear optimization, such as the MAD-X[2] for the former and the OPA[3] for the latter. This, however, requests compatibility of the codes, and an integrated tool is needed for doing the accelerator physics.

MATLAB language has been increasingly popular in accelerator physics modeling and simulation, and in developing high level application codes. As a matrix-oriented programming language, MATLAB provides an active variable workspace, a built-in math library, powerful graphics capabilities and on-going development of new software features. At Stanford Synchrotron Radiation Lightsource (SSRL), a collection of accelerator physics tools of Accelerator Toolbox (AT)[4] was developed for modeling particle accelerators and beam transport lines in the MATLAB environment. But there are some shortcomings with the AT, such as the lacks of linear match and nonlinear optimization functions, and the need of careful typing for coding the script file and inputting AT command with relevant parameters.

In developing our graphical user interface tool *bodgui* (beam optics design GUI) using MATLAB, and incorporated with some AT functions, we integrated different procedures of accelerator physics design to facilitate a designer to switch among the procedures of lattice editor, linear match, nonlinear optimization and visualized tracking. As a set of applications based on the GUI operations of buttons and menus, the *bodgui* tool provides a convenient way for especially an accelerator physics designer in novice, and it can be taken as a compensation for AT. The tool was developed for physics design and commissioning of Shanghai Synchrotron Radiation

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Facility (SSRF)[5], but as a machine-independent tool, it can well be used in other modern machines, too. In this paper, detailed descriptions of the *bodgui* tool are given and applications in commissioning the SSRF storage ring are summarized.

2 Functions of *bodgui* tool

2.1 Main window

When opening a lattice file by clicking the *File→Open* menu (Fig.1), the beta functions can be modeled and plotted, the elements can be mapped according to the LATTICE arrangement in different shapes and colors (which is shown here in grey scale), and the accelerator parameters (tune, natural emittance, natural chromaticity, natural energy spread, damping times, etc.) can be calculated and shown in the *Global Parameters* panel. Zoom operation are provided for looking about overview or detail. Another useful function offered in the main GUI is the quadruple editing panel, in which users can choose elements of different magnet families to edit the field strength. By pressing the *refresh* button to renew the work after the editing, the beta function and global parameters are re-plotted and recalculated. Functions include linear match, nonlinear optimization and tracking are offered in the menus of main window, which is linked to several subwindows.

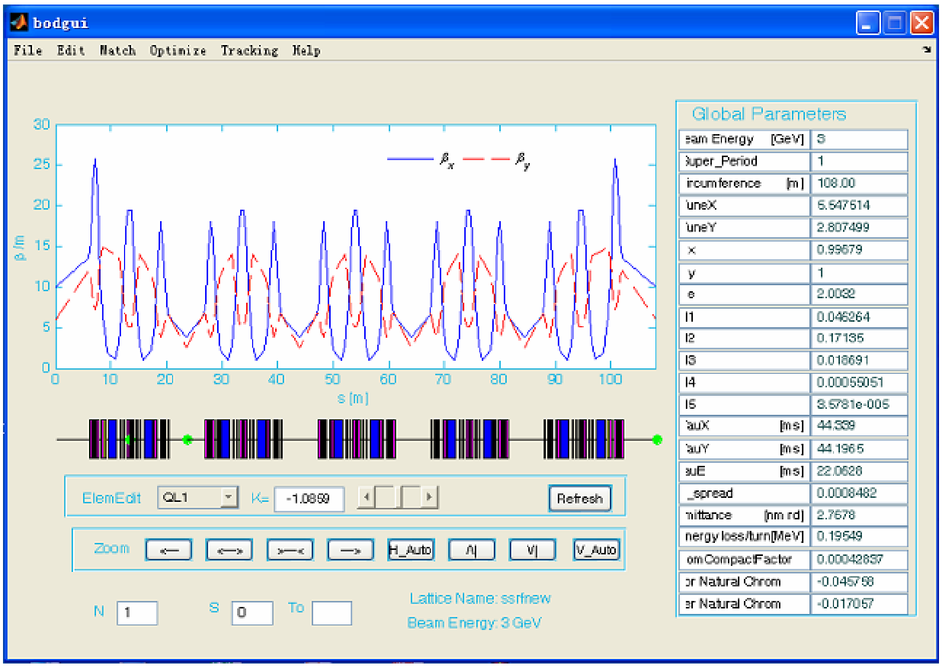

Fig.1 The main window of *bodgui* tool.

2.2 Lattice editor

In AT, lattice can be established from the lattice file with a MATLAB function or user-coded script. It is a sequence of commands that construct a special variable of *THERING* describing a lattice in MATLAB workspace. The *bodgui* provides a graphic way for the users to build lattice files by the *lattice editor*, with relevant functions to create new elements, edit existing elements, create new lattice cell from existing elements, and edit existing lattice cell or lattice ring. Fig.2 shows the main window of *lattice editor*. Existing elements and cells can be edited in the editing boxes by clicking an item in the popup windows in Fig.2. New element can be built from the *Element-Input* wizard (Fig.3) by pressing the button *NewElement*. Different elements of specific properties are offered for choices, such as bend, quadruple, sextuple, and corrector etc. Pressing the *Create* button after inputting the properties, the element can be created with the background process and stored in the MATLAB data area. In the *Cell-Input* wizard (Fig.3), cells or super periods of lattice can be established by incorporating existing elements and cells from the list boxes *Elements* and *Segments*. The lattice can be saved as an m-file by clicking the menu *File→Save* or a data file. For an existing lattice file, the *lattice editor* can load all the elements and cells in the list boxes when click the *File→Open* menu.

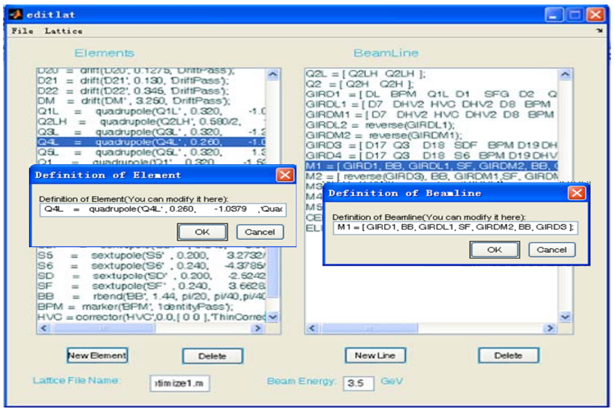

Fig.2 The main window of lattice editor.

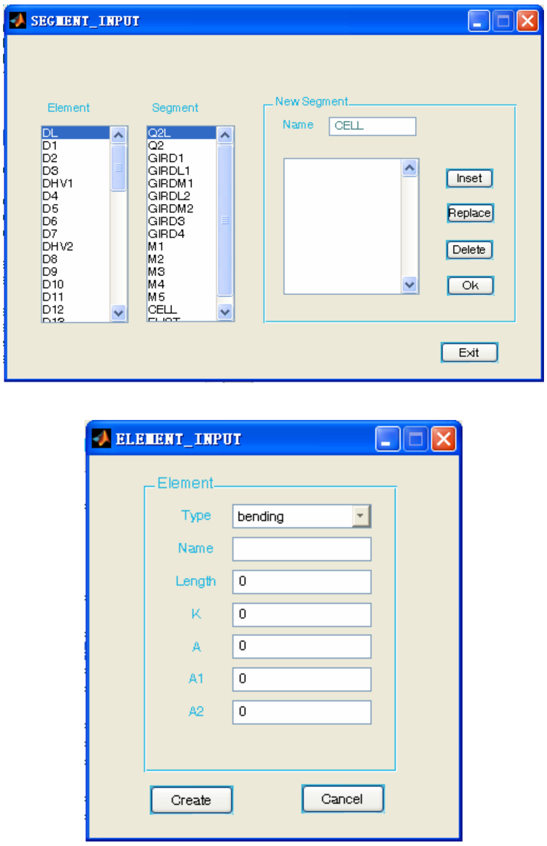

Fig.3 Element-input and cell-input wizards.

2.3 Linear match

In physics design and online control of an accelerator, a match of the twiss parameters is required frequently. For the simulation mode, the purpose of adjusting the twiss parameters can be achieved by the match calculation when target values of the twiss parameters have been set and the adjustable quadrupoles have been chosen. For the online mode, the beam parameters can be calculated by the methods based on the real time parameters, such as beam energy and current of quadrupoles. For example, the beta functions can be calculated by the online measurement tool *BetaMeas*. So the control of the twiss parameters can be accomplished by setting the shift current to the quadrupoles after match from the real time functions to the required values.

The sub-window *Matchgui* (Fig.4), called by clicking the *Match→Matchgui,* performs the linear match of the transfer beamlines and the storage ring. Family names of quadruples and fit points are listed for choices. A pop-up panel controlled by the *Set* button in the *FitPoint* area is provided for setting the target functions of the chosen fit points. The callback function of the *Match* button participate the main processing of the match function. We note that position and number of the fit points are different from lattice to lattice. Generally, three points, which locate the centers of two straight sections and the arc cells, are enough to flexibly adjust the global parameters while maintaining the symmetry and periodicity of the liner optics for the SSRF storage ring, and DIAMOND[6] and TPS[7] storage rings as well.

The matching algorithm is based on the Single Value Decomposition (SVD) and the Gauss-Newton descent method. A parameter vector constituted by local functions (twiss functions, dispersions, phase advances for instance) at the fit points is:

$$\overline{A}=\left(A_1, A_2, A_3, \ldots, A_N\right) \tag{1}$$

The distance between the target and the initial vector is defined as

$$\chi^2=\left|\overline{A}_{\text{tar.}}-\overline{A}_{\text{init.}}\right|^2 \tag{2}$$

Eq.(2) gives a measure of the matched level. This quantity is minimized by the Gauss-Newton descent method that involves fitting strengths of the chosen quadrupoles. It needs a Jacobin matrix with dependence of the parameter vector on the chosen quadrupole strengths (k):

$$M_{ij}=\frac{\partial A_i}{\partial k_j} \tag{3}$$

and the new setting of the chosen quadrupole strengths is derived by:

$$\overline{k}_{new} = \overline{k}_{init.} + M^{-1}\Delta\overline{A} \tag{4}$$

where M^{-1} is a matrix inverted by means of SVD from M. The inversion can be easily done in MATLAB (inv (M)). As the dependence of the parameter vector on quadrupole strengths is weak nonlinear, the procedure should be iterated until a convergence is reached. If the number of the adjustable quadrupoles is larger than the number of the restricting parameters, the inverted matrix is over determined, but this can be solved by the MATLAB command pinv (M).

Commonly, for storage ring lattice at SSRF, and for those similar to SSRF, the matched parameters of the point in the center of the long straight section include β_x and β_y for adjusting beam cross section and dynamic aperture of injection point, η_x for tuning the natural emittance or momentum compactor of short bunch operation mode, and the phase advances for optimizing the tunes. The ones in the center of the standard straight section include β_x and β_y for adjusting beam cross section, and α_x, α_y and η_x' set to zero for maintaining the symmetry of the linear optics, and reaching the largest or smallest values of β_x, β_y and η_x. An easier way to do these is by chromatic compensation.

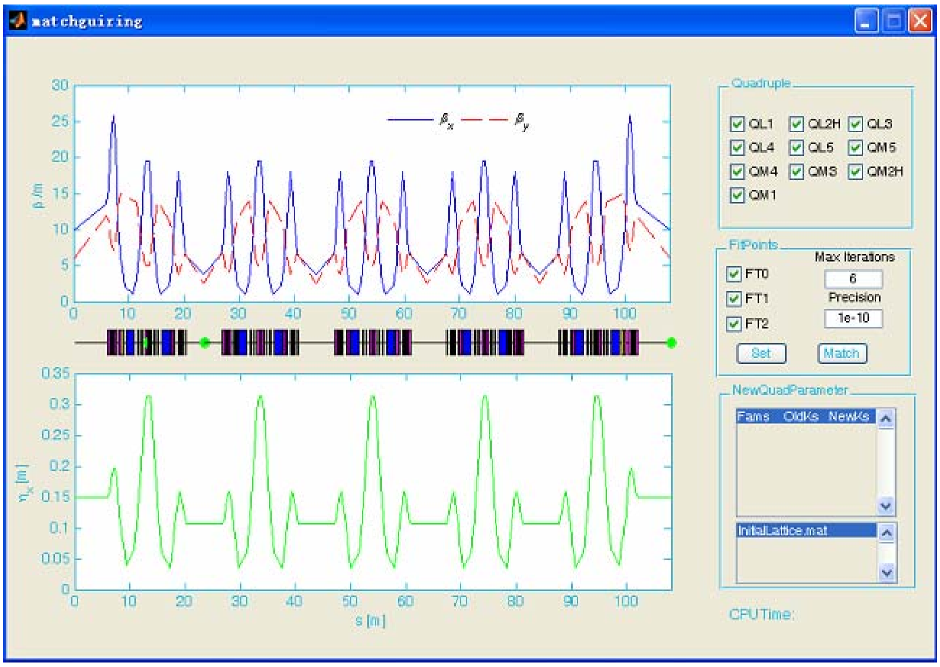

Fig.4 Sub-window *Matchgui*.

This matching method depends on the initial model. If the discrepancy between the initial model and the target model is large, it is better to divide the procedure into several steps to minimize the discrepancy. For example, if the tune difference between the initial and the target model exceeds the linear structural resonances, some middle state will drop into the stop-bands and the optics is unstable[8], and the matching will fail. So, the tune must be changed in the *LATTICE* editor to span these linear structural resonances by experience.

2.4 Nonlinear optimization

In the storage ring of a third generation light source, nonlinear optimization is an indispensable course to obtain ample dynamic acceptances and achieve high injection efficiency and long beam lifetime. The algorithm is based on the single resonance approach, which takes relative weight and initial Harmonic Sextupole Integral Strength (HSIS) as search variables.

The *NonlinearOptimize* window is opened by clicking the *Optimize*→*NonlinearOptimize* menu. To use the *NonlinearOptimize* function, a lattice containing sextupoles should be preloaded. The initialization also includes: setting the weight values of driving terms, about which five geometric terms (h_{21000}, h_{10110}, h_{30000}, h_{10200} and h_{10020}) and three linear tune shift terms ($\partial \nu_x/\partial J_x$, $\partial \nu_{x,y}/\partial J_{y,x}$ and $\partial \nu_y/\partial J_y$) are of concern;

setting the start value of *Ws* and mesh *Wm*, and the end value *We* of relative weight for scanning; and setting the start value of *Ss* and mesh *Sm*, and the end value *Se* of initial strength of the sextupoles.

After the initialization, press the button *Optimizing* to start the calculation. In the callback function, the program calculates all the initial values from the GUI, and sets them to the relevant variables. A function scan is done by a dual loop, in which the cycle variable outer is the relative weight increased by the mesh *Wm* and the cycle variable inner is the initial strength of the sextupoles increased by the mesh *Sm*.

In every change in initial strength of the sextupoles, the program sets the focusing sextupoles (S1, S3 and S5 at SSRF) with the same integral strength (a, for example), and the defocusing sextupoles (S2, S4, and S6 at SSRF) will be set with the same integral strength ($-a$). Then the iteration begins based on the Gauss-Newton descent method. On reaching the convergence of the penalty function, the dynamic aperture tracking module is called, and the tracking result and the strength of sextupoles are recorded. After each inner cycle, the biggest dynamic aperture is picked out from several tracking results, and after all the outer cycles, the results of good dynamic apertures and the relevant strength of sextupoles are saved and shown in the result window. As Fig.5 shows, the program can renew the values of each driving term and sextupole to the GUI when the values change in the calculation.

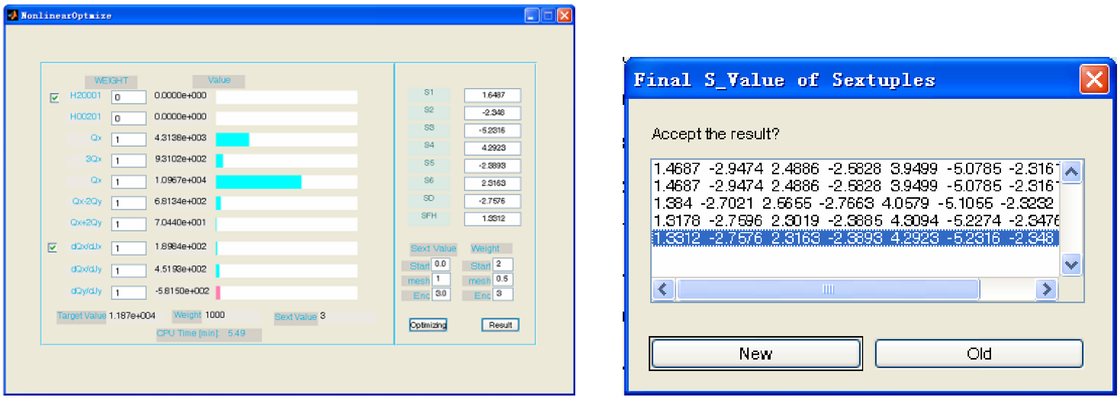

Fig.5 Sub-window *NonlinearOptimize*.

2.5 Tracking

In *bodgui*, the tracking of particles becomes visualized because of the GUI tools *PhaseSpace* and *DynamicAperture*. With similar layout, the tools have a set of panels placed in the bottom right area to provide settings to edit start point, scan mesh and turn number etc, and three axes to show the relevant tracking results. The callback functions in the background call the tracking modules based on the AT function *ringpass* with the configured parameters.

3 Applications in the SSRF storage ring

The *bodgui* tool was used for designing and optimizing the lattice of SSRF storage ring. One of the operational modes was the nominal mode with the tunes of 22.22/11.29 (H/V)[9]. After the linear match and nonlinear optimization by using the *bodgui* tool, the beta function was restricted within 25 meters, and the periodicity of lattice could be well maintained (Fig.6). The nonlinear optimization could provide a sufficient dynamics acceptance, such as a horizontal dynamic aperture of ±30mm (Fig.7) and an energy acceptance of ±6%, so as to reach a high injection efficiency and long beam lifetime. The strengths of the quadrupoles and the sextupoles are showed in the GUI.

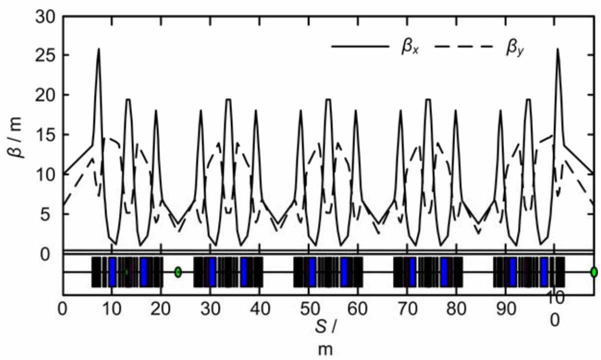

Fig.6 Beta functions of the nominal mode.

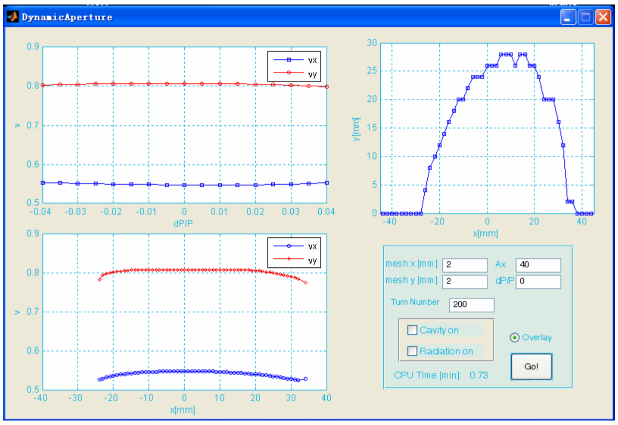

Fig.7 The dynamic aperture of the nominal mode

It has been proved in commissioning the storage ring and transfer lines at SSRF that the *bodgui* tool is of convenience for the physicists and operators in the in-time correction of measurement errors (such as the effective length error), and in the design and optimization, in advance, of weak-focusing mode for the storage ring commissioning and different operational modes for commissioning and operating SSRF.

4 Conclusion

The *bodgui*, is a straightforward and comprehensive tool for beam optics design, facilitates the physicists and operators to switch conveniently among the functions of lattice design, linear optics design, nonlinear optimization and particle tracking. It can be considered as a compensation of the popular toolkit AT. With the GUI-based tool, operations can be simple. The match and optimization methods are reliable and effective, proved in its application in designing and commissioning the storage ring at SSRF. Functions of the *bodgui* tool are machine-independent, and it can be applied to modern light sources to be built in other parts of the world.

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