Preliminary verification of online optimization of the luminosity of BEPCII by using the robust conjugate direction search method*

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Abstract: The robust conjugate direction search (RCDS) method has high tolerance to noise in beam experiments, and it is an efficient experimental technique for online optimization with multi-dimensional variables. In our study, this method is applied on BEPC-II, an electron-position collider, to optimize the luminosity, which can be considered as a multivariable function. Several variables are considered, including horizontal displacement, horizontal angular deviation, vertical displacement and vertical angular deviation at the interaction point. To verify the feasibility and practicability of the online optimization at the collider, the objective function, optimization time and experimental applications require careful consideration. Results from numerical simulation and online optimization experiments with RCDS are presented. The effectiveness of this method in online optimization at a collider is preliminarily verified.

Key words: online, optimization, RCDS, luminosity, a multivariable function

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I. Introduction

A particle accelerator is a complex system that consists of many components, e.g., beam transport, control, diagnostic, acceleration systems. There are many variables can be tuned, which are usually coupled. To meet the design requirements of the machine, it is necessary to perform optimization in a multi-dimensional variable space, in different stages: design, commissioning, and operation.

In the design phase, a variety of programs (such as Mad [1], SAD [2], Elegant [3], AT [4]) and algorithms (such as genetic algorithms [5], multi-objective genetic algorithm [6]) have been proposed to model the system and to optimize the expected machine performance. Nevertheless, for an existing accelerator, optimization algorithms are rarely used, due to the fact that many kinds of errors cause some differences between the theoretical model and the actual conditions. As a result, the optimized parameters from theoretical analysis and numerical calculation may not work very well in real operation. Actually, in most cases, to optimize the objective, physicists usually do optimization in a manual manner, namely, repeatedly tune and scan parameters according to the actual situation of the accelerator observed directly, starting from theoretical design values.

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Although this method usually works, it is time-consuming and the effectiveness decreases with the number of parameters increases. It is noted that, along with the unceasing development of computer technology and optimization algorithms, applications of online optimization algorithms of multi-dimensional variables on accelerators have become imperative and feasible.

Several optimization algorithms have been proposed for different purposes in different accelerator labs, for instances, slow feedback systems [7], downhill simplex method [8-10], rotation rate tuning [11], random walk optimization [12], robust conjugate direction search method [13]. Among these methods, the algorithm RCDS has high tolerance to noise in beam experiments and high convergence speed, which can reduce effects of noise and lead to optimal solution (see [13] for more detail). RCDS method can be used as an online optimization algorithm to optimize the performance of an accelerator and it is effective in optimizing a single-objective function of several variables with a certain level of noise. This method has been successfully applied to the SPEAR3 storage ring for realistic accelerator optimization problems, including the minimization of the vertical emittance with skew quadrupoles and the optimization of the injection kicker bump match. In this study, we apply this method to automatic online optimization of the luminosity of BEPCII, which is the most important measure of performance of colliders.

Up to now, the maximum luminosity of BEPCII is $8.0\times10^{32}cm^{-2}s^{-1}$. It is an essential subject for current physics study of BEPCII to achieve the design peak luminosity, $1.0\times10^{33}cm^{-2}s^{-1}$, by further optimization of parameters. Luminosity depends on more than 20 variables, such as the transverse offset in position and angular deviation (x, x', y, y') and optical parameters at the interaction point (IP), the x-y coupling parameters (R1, R2, R3, R4), tune, RF parameters. At present, operators mainly tune and scan parameters manually. So it makes sense to set up an online optimization process based on the RCDS method. It is expected to contribute to increasing the peak luminosity and to establish a standard operation system for optimization of luminosity of BEPCII by scanning parameters in a standardized and routine way by using the online algorithm, which would not only reduce operators' work, but also increase the operation efficiency.

The numerical simulation is presented in Sec. II and the experimental applications are given in Sec. III.

II. The numerical simulation of optimization of the luminosity of BEPCII using the RCDS

The numerical simulation is performed to verify the feasibility of the luminosity optimization by using the RCDS method, and to identify some possible constraints in experimental applications.

First, the luminosity is modeled as an objective function of 8 variables, i.e., (x, x', y, y', R1, R2, R3, R4) at the IP. To simulate the effect of each variable on the performance of BEPCII, for each one, the function relation is

$$F(x_i) = e^{-\frac{(x_i-a_i)^2}{\sigma_i^2}} \frac{J_0(\frac{x_i-a_i}{\delta})+\Delta}{\Delta+1}, \tag{1}$$

where a_i is the variable x_i which corresponds to the maximum function value and $F(a_i)=1$, σ_i determines the changing rate of the function value with the deviation $|x_i-a_i|$, δ determines oscillation frequency of the Bessel function, $\Delta > 0.5$ leads to a function value greater than 0 and changing Δ is to regulate the changing rate of the function value. The effect of the arguments to the function is shown in Fig. 1. Bessel functions are used to study the convergence ability and efficiency for multivariable functions with local optima. The luminosity here is calculated as the production of functions for 8 variables,

$$Lum(x_1, x_2, ..., x_n) = L_{\max} \prod_{i=1}^{n} F(x_i), \tag{2}$$

where $L_{\max}$ is the maximum luminosity corresponding to $x_i = a_i$ for each variable and for simplicity, $L_{\max}$ is set to 100. Values assigned to the arguments of the corresponding function of each variable are listed in Table 1 based on experience.

Secondly, for each set of variables, the corresponding luminosity is the calculated value [from Eqs. (1) and (2)] plus a random number. The random number is subject to Gaussian distribution to simulate the effects of noise on luminosity in actual condition due to various errors. Then RCDS optimization can be performed. Fig. 2 shows the process of the luminosity optimization. By adding the minus sign to the luminosity, the optimization becomes searching for the minimum of objective value. The objective value changes with variable scanning. As shown in Fig. 2, we get the optimization result after about 300 evaluations of the luminosity.

To explore the dependency of the RCDS method on the noise, we optimize the luminosity 20 times with a certain noise level. The initial sets of variable values are different in each optimization process. We then change the noise level and repeat the optimization process. The optimization results are shown in Table 2. The results show that the optimized value of the luminosity doesn't decrease with the increase of the noise level. Instead, larger noise level may be useful to reach a higher luminosity, because it is easier for the variable scans to get over the local barrier caused by the Bessel function in the model formula.

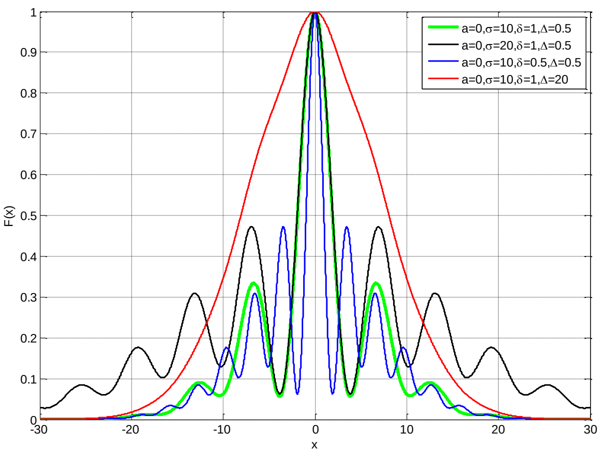

Fig. 1. (color online) The effect of the arguments (σ, δ, Δ) to the function.

Table 1. Values assigned to the arguments of the corresponding function $F(x_i)$ of each variable in the numerical simulation

Variables	a	σ	δ	Δ
x_1 (x)	44.5 μm	60 μm	0.3	10
x_2 (y)	13.7 μm	10 μm	0.2	0.8
x_3 (x')	8.4 mrad	100 mrad	0.5	15
x_4 (y')	2.3 mrad	100 mrad	0.5	15
x_5 (r_{11})	0.12	68	0.2	20
x_6 (r_{12})	0.07	95	0.2	20
x_7 (r_{13})	0.03	68	0.2	20
x_8 (r_{14})	0.39	95	0.2	20

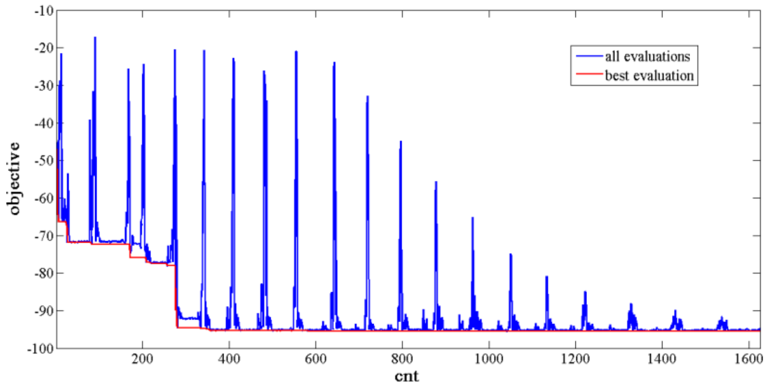

Fig. 2. The process of the luminosity optimization in a numerical simulation. The image shows the recorded objective value of all evaluations. The value of the luminosity is optimized from 60 to 95.

Table 2. Statistical analysis of the optimization results in numerical simulation

Noise σ_f	Aver.	Sigma
0.5	89.8	11.0
0.2	85.0	12.0
0.1	84.4	11.4
0.05	84.0	14.2
0.01	84.1	13.3
0.001	85.6	8.61
0.0001	85.1	9.70

III. Experimental application of RCDS for the optimization of the luminosity of BEPCII

The online control program at the BEPCII is SAD, which is a computer program complex for accelerator design and operation. So we coded the RCDS algorithm in SAD. A flowchart of the data stream between the RCDS and operation of BEPCII is shown in Fig. 3. Set the initialization parameters and start the application. Then we get the luminosity from the database of BESIII. As needed, the value of objective function is calculated from the luminosity and introduced into the

RCDS method to start the main loop. The iteration continues with the data transmission between the RCDS method and operation of BEPCII. The set of parameters values produced by the RCDS method is used to set up the collider till the luminosity is optimized.

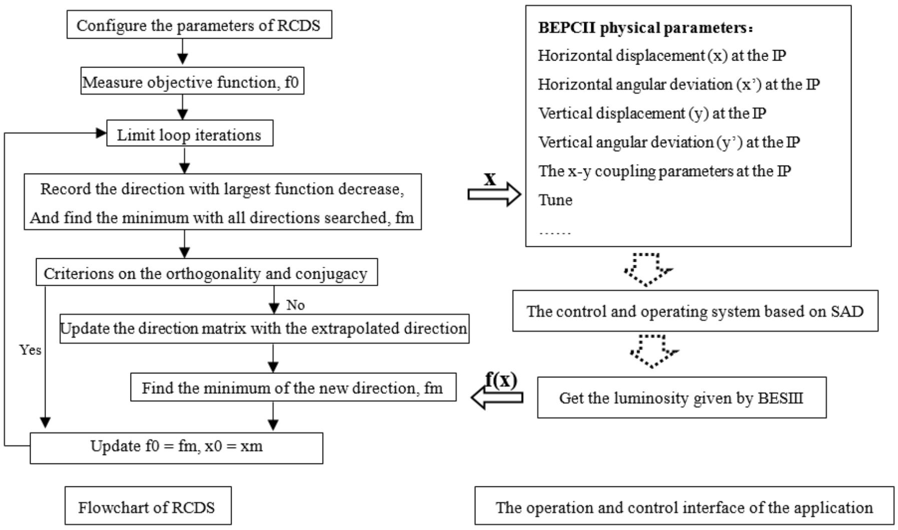

Fig. 3. Flowchart of RCDS for online optimization of the luminosity of BEPCII and the data stream between the RCDS method and operation of BEPCII.

A. Safety and efficiency of the experimental application

It is necessary to ensure the safety and reliability of the online application. Before start the online application, according to the real-time running state, we calculate the adjusting range of the parameters to be tuned, and give warnings for unreasonable sets. It will confirm the limitation of the magnets to check for the valid range of the physical variables.

Both the current of electron beam and positron beam decay in time due to the limit beam lifetime in BEPCII. So the status of the machine also changes with time. Time between two injections is limited, which means time for optimization is also limited. Thus shortening optimization time becomes very important.

It is very critical to choose an appropriate objective function in order to achieve high optimization efficiency. The luminosity of BEPCII measured by the BESIII End-cap Electro-Magnetic Calorimeter is actually an integral average value of luminosity in 30 seconds. So it has a long response time. Moreover, the decrease of beam current has a significant effect on the luminosity, and so the same parameter set may lead to different luminosity values over time, which will directly affect the efficiency of optimization. Theoretically, luminosity can be expressed as

$$L\left[cm^{-2}s^{-1}\right] = L_0 R = 2.17\times10^{34}(1+r)\xi\frac{E\left[GeV\right]k_b I_b[A]}{\beta_y^*[cm]}R \quad , \tag{3}$$

where L_0, r, ξ, E, k_b, I_b, β^*_y represent the nominal luminosity, the aspect factor, the beam-beam parameter, the energy, the number of bunches, the bunch current, and the value of the vertical beta function at IP, respectively. R is a reduction factor which may come from a non-zero horizontal crossing angle, coupling, tune and so on.

It is expected that the optimization algorithm can find an optimized set of parameter values, which can lead to a higher luminosity value with the factor R closer to 1. So we have to choose another objective function which can well represent the collision luminosity, has a short response time and would be less affected by the decrease of beam current.

So we select the so-called specific small-angle luminosity as the objective function (adding the minus sign) which is given by

$$L_{SpeLumP} = \frac{L_{ZeroLumP} / \mathrm{N}_{bCollide}}{\frac{I_{BER}}{N_{bBER}} * \frac{I_{BPR}}{N_{bBPR}}} \quad , \tag{4}$$

where $L_{ZeroLumP}$ is the small-angle luminosity given by a zero-degree detector [14], $N_{bCollide}$ is the number of the collision bunches, I_{BER} and I_{BPR} are the electron and positron beam current, N_{bBER} and N_{bBPR} are the number of electron bunches and the number of positron bunches.

Although the effect of the decay of beam current on the specific small-angle luminosity is not completely eliminated, it is small enough to be acceptable for the preliminary application.

Besides the data acquisition speed of the objective value from the database, the optimization time depends primarily on the response speed for setting parameters, both of which in fact determine the time needed to get an evaluation. Because the luminosity of BEPCII is sensitive to the vertical displacement, we estimate the response time requirement by setting the y offset to a fixed value. Based on the data analysis results, it takes about 7 seconds to complete an evaluation. We also take the objective function value as an average of three readings in applications. Above all, it takes about 10 seconds to get an evaluation.

B. Optimization results

As stated above, the specific small-angle luminosity is used as the objective function (with the minus sign), and it takes about 7 seconds to get an evaluation. According to the numerical simulation results, about 300 values of the luminosity are taken to get the optimization result with 8 tuning parameters. For simplicity, we apply the RCDS method for 4 parameters (x, x', y, y') at the IP.

With long time running and tuning, BEPCII has been in good status and operators have saved some optics models of the machine to be set. We set one of these as the reference standard, where the offset is a set of (x=0 mm, x'=0 mrad, y=0 mm, y'=0 mrad) and the objective function value is about -51.

To test the validity of the optimization algorithm, we set the offset of the machine to Δ, Δ= (x=-0.6 mm, x'=0.15 mrad, y=0.002 mm, y'=0.2 mrad), right from the reference standard. The objective function value is about -17. The corresponding state of machine will be the initial state of the optimization program. It is expected that the optimization result is about –Δ. Fig. 4 shows objective function values during an optimization run. The objective function value changes as parameters are scanned. After 2 iterations, the optimization result is about -52, lower than the initial value, -17. The offset is optimized to (x=0.5898 mm, x'=0.1911 mrad, y=-0.0022 mm, y'=-0.1354 mrad) relative to the initial state of the program, which is closer to –Δ except the horizontal angular deviation. It is because the luminosity is not so sensitive to the horizontal angular deviation within the present scanning range (more than 9 consecutive objectives with small fluctuation in Fig. 4). During the optimization process, the objective function values have a tendency to go lower, which means the luminosity is indeed being optimized. Enough time is left to ensure the luminosity is the corresponding result of a set of parameters. So it takes about 2068 seconds to get 137 evaluations. It is a little longer.

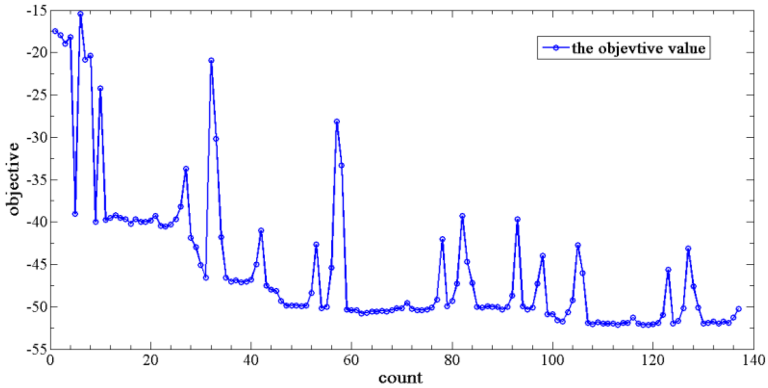

Fig. 4. The objective function values during the optimization.

(The application optimizes the luminosity by scanning the parameters (x, x', y, y') sequentially within the first few iterations. About 50 evaluations are taken in every iteration.)

To further verify the effect of optimization, another experimental application is conducted. From experience, the luminosity of BEPCII is sensitive to the vertical displacement. So we deliberately increase the vertical displacement to Δ=0.025 mm to reduce the initial luminosity. At this point, the specific small-angle luminosity is only 4.3. We widen the range of the vertical displacement from the preceding $4\sigma_y$ to $20\sigma_y$ (σ_y=5 μm), and optimize the luminosity online. Fig. 5 shows the objective function values during optimization. In the second iteration, one can see a sudden drop in the objective function value when the vertical displacement is scanned. It is actually a sudden rise of the specific small-angle luminosity. The optimization result is about -50 with y offset to be -0.0273 mm, which is close to the expected negative deviation, -Δ. Moreover, by optimizing the way of getting an objective function value, the optimization time of the application is shortened. On the condition of good optimization effect, taking138 evaluations spends about 1435 seconds. It takes less time than the injection period. So we can perform the online optimization within available time. The change process of the luminosity given by BESIII is shown in Fig. 6. We finally reset the initial parameters, and see a corresponding decrease in the luminosity (inside the red square in Fig. 6). The recovery of the luminosity given by BESIII further verifies the effectiveness of the online optimization.

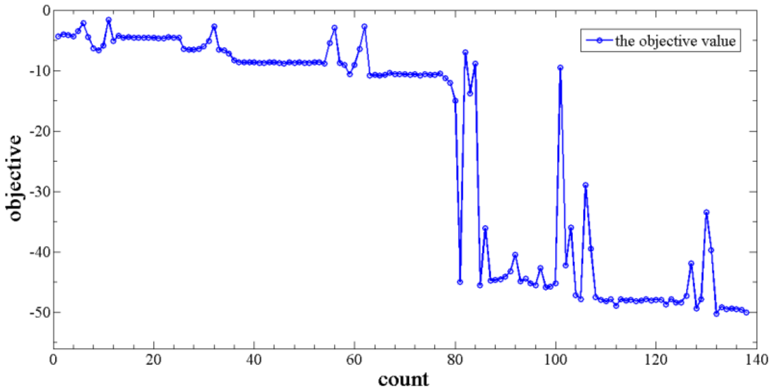

Fig. 5. The objective function value during the optimization.
(The application optimizes the luminosity by scanning the parameters (x, x', y, y') sequentially within the first few iterations. About 50 evaluations are taken in every iteration.)

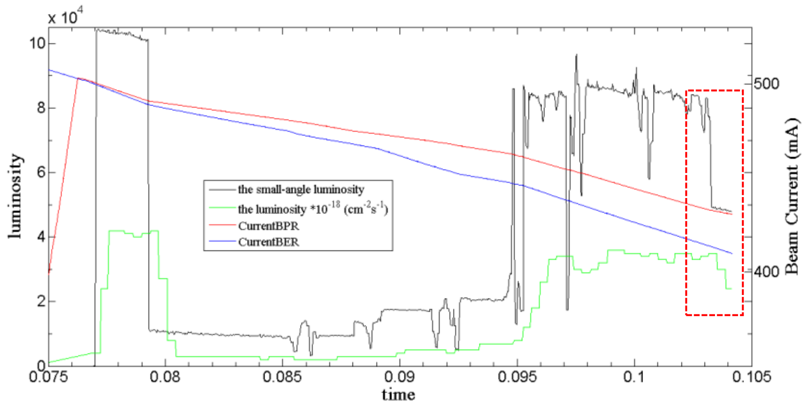

Fig. 6. (color online) The change process of the luminosity given by BESIII
(The horizontal axis shows the time range with serial time numbers.)

IV. Conclusion

As an online optimization algorithm with high tolerance to noise, the RCDS method has been experimentally and successfully applied to the light source. In this paper, we explore optimization of the luminosity by using the RCDS method in numerical simulation and experimental application at the collider BEPCII. The effectiveness of the online optimization is preliminarily verified by the recovery of the luminosity with offset being tuned, even with a wide range of parameters. The result shows that it is possible to further optimize the luminosity online with more parameters at the collider.

References

1 Grote H, Iselin F C. The MAD Program Version 8.19 User's Reference Manual, CERN/SL/90-13 (AP), 1996
2 SAD, Strategic Accelerator Design. http://acc-physics.kek.jp/SAD/index.html
3 Borland M. Report No. APS LS-287, 2000

4 Terebilo A. Accelerator Toolbox for MATLAB, SLAC-PUB-8732, 2001
5 Hajima R, Takeda N, Ohashi H, Akiyama M. Nucl. Instrum. Methods Phys. Res., Sect. A, 1992, **318**:822
6 Bazarov I et al. Proceedings of the Particle Accelerator Conference'05, Knoxville, TN, 2005
7 Hendrickson L et al. EPAC2000, Vienna, Austria, 2000, p.1897
8 Emery L et al. PAC03, Portland, Oregon, 2003
9 Nelder J, Mead R. Computer Journal 7, 1965, 308
10 Funakoshi Y et al. EPAC2008, Genoa, Italy, 2008, p.1893
11 Scheinker A et al. Phys. Rev. ST Accel. Beams, 2013, **16**: 102803
12 Aiba M et al. IPAC2012, New Orleans, Louisiana, USA, TUPPC033
13 Huang X, Corbett J, Safranek J, Wu J. Nucl. Instrum. Methods Phys. Res., Sect. A, 2013, **726**: 77-83
14 Xue Zhen et al. Chinese Physics C, 2011, **35**(1): 1-5