THE APPLICATION OF THE OPTIMIZATION ALGORITHM IN THE COLLIMATION SYSTEM FOR CSNS/RCS

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Abstract

The robust conjugate direction search (RCDS) method, which is developed by X. Huang from the SLAC National Accelerator Laboratory, has high tolerance against noise in beam experiments and thus can find an optimal solution effectively and efficiently. In this paper, the RCDS method is used to optimize the beam collimation system for Rapid Cycling Synchrotron (RCS) of the China Spallation Neutron Source (CSNS). A two-stage beam collimation system was designed to localize the beam loss in the collimation section in the RCS. The parameters of secondary collimators are optimized with RCDS algorithm based on detailed tracking with the ORBIT program for a better performance of the collimation system. The study presents a way to quickly find an optimal parameter combination of the secondary collimators for a machine model for preparation for CSNS/RCS commissioning.

INTRODUCTION

The China Spallation Neutron Source (CSNS) is designed to provide a proton beam with beam power of 100 kW [1, 2]. The accelerator complex consists of an 80 MeV Linac and a 1.6 GeV Rapid Cycling Synchrotron (RCS) [3, 4]. In the RCS, the proton beam is accumulated through an anti-correlated painting scheme within 200 turns, and accelerated to 1.6 GeV in about 20000 turns [5, 6].

For the RCS, the space charge forces are strong and have a large impact on beam dynamics. The emittance growth and halo generation induced by space charge could lead to unacceptably high beam loss [7, 8]. Considering the requirements for hands-on and safe maintenance of the machine, the average particle loss should be controlled to a low level of 1 W/m [9]. To meet this requirement, a two-stage collimation system was designed to localize the beam loss in the collimation section in the RCS [10, 11].

The transverse collimation system consists of one primary collimator and four secondary collimators. The layout of the transverse collimation system and the optical parameters are shown in Fig. 1.

In the RCS, the aperture of each secondary collimator can be varied by adjusting the positions of four movable blocks. Now the RCS is under construction, and the collimation efficiency with different sets of collimator parameters is evaluated with numerical simulation in this study. The collimation process in the presence of space charge is simulated with the Objective Ring Beam Injection and Tracking (ORBIT) code [12, 13]. Moreover, we introduce an algorithm, the Robust Conjugated Direction Search (RCDS) method, in the optimization. This method is effective in optimizing a multi-variable objective online and it has both high tolerance to noise and high convergence speed [14]. It has been used for online optimization of machine performance when the objective function can be measured [14-16].

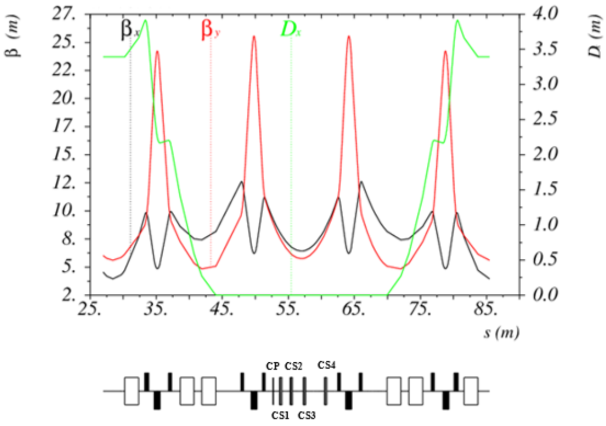

Figure 1: Optical functions along a ring super period of the RCS, and the layout of the transverse collimation system. CP represents the primary collimator. CS1, CS2, CS3 and CS4 represent four secondary collimators in sequence, respectively).

PHYSICS ANALYSIS AND MODELING

To implement the application of the RCDS method in the optimization of the RCS collimation system, the model of an ORBIT instance to simulate the collimation process were determined.

Physical Variables

In this study, the acceptance of the primary collimator is fixed to 350 πmm·mrad all the time, and the secondary collimators are tuned to optimize the performance of the collimation system.

The structure of a secondary collimator is shown in Fig. 2. Each of the secondary collimators is composed of four movable copper blocks with thickness of 200 mm. Two of the blocks are in the vertical direction and the other two, downstream of the vertical blocks, are in the

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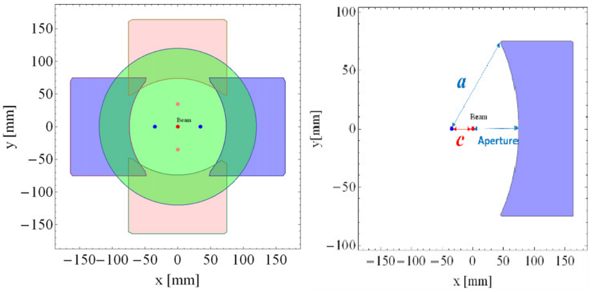
horizontal direction. All the blocks can be adjusted individually.

Each block has a circular surface based on the equation,

$$\frac{\left(x\cos(\frac{\pi\theta}{180^\circ})+y\sin(\frac{\pi\theta}{180^\circ})\pm c\right)^2}{a^2}+\frac{\left(-x\sin(\frac{\pi\theta}{180^\circ})+y\cos(\frac{\pi\theta}{180^\circ})\right)^2}{a^2}=1, \qquad (1)$$

where θ = 0° or 90° corresponds to the horizontal or vertical direction of the block, a is the radius, and c is the distance between the beam center and the geometric center of the block, which can be changed from 34.8 mm to 68.8 mm determined by the mechanical design.



(a) (b)

Figure 2: The structure of a secondary collimator. (a) A second collimator has four blocks (pink: vertical blocks, blue: horizontal blocks) and has a cross section with the ring (green: vacuum chamber of the RCS). (b) The relationship between the parameter c and the aperture of the acceptance of the collimator.

The parameter c of each block is closely related to the acceptance of the collimator, so this parameter is selected to be the variable for the optimization. Considering the symmetry of beam distribution in simulations, the parameter c of the blocks on the same direction of each secondary collimator are same. Then there are eight variables to be tuned for four secondary collimators, i.e., (c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8), as shown in Fig. 3.

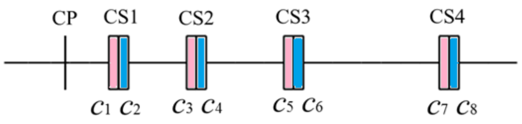


Figure 3: The variables to be tuned in the optimization of the RCDS collimation system.

Objective Function

The goal of the optimization of the collimation system is to localize the beam loss with a high shielding efficiency, and meanwhile, to have a low uncontrolled beam loss, a high cleaning efficiency of the system [17], a high collimation efficiency and a low beam loss around the RCS.

In our study, a single objective function is constructed to measure the performance of the collimation system, which is in the form of

$$f=-\eta_{\text{system}}\cdot R_{\varepsilon_{xm}}\cdot R_{\varepsilon_{ym}}\cdot R_{\varepsilon_{add}}\cdot R_{\varepsilon_{flag}}, \qquad (2)$$

where a minus sign is added to form a minimization problem, η_{system} is the cleaning efficiency of the system, $R\varepsilon_{xm}$, $R\varepsilon_{ym}$, $R\varepsilon_{add}$ and $R\varepsilon_{flag}$ are the weight factors [18].

OPTIMIZATION RESULT

In order to confirm the optimization of the performance of the collimation system, we fixed the particle distribution for the input of the acceleration process. A realistic distribution of macro particles was obtained with the acceptances of secondary collimators being set to 500 πmm·mrad due to the transverse acceptance of the ring. The horizontal 99% emittance of the beam distribution is 193 πmm·mrad and the vertical is 219 πmm·mrad.

In the following, the performance of the collimation system during the acceleration process is presented and analyzed. By running an instance with the beam being accelerated for 2000 turns (a series of numerical simulations have been performed to determine the parameters of model [18]) repeatedly, the noise level of the cleaning efficiency was calculated to be 0.7%, and this value was used as the noise of the objective during the optimization. The initial acceptances of secondary collimators were set to 420 πmm·mrad. Based on the optical functions, the initial values of the variables were calculated and listed in Table 1.

Table 1: The Initial Values of the Variables

variables	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
value / mm	52.8	51.6	57.9	55.7	59.5	56.6	50.6	48.2

Having configured the parameters of RCDS and given the initial values of the variables, the simulation was performed to optimize the collimation system for the RCS. Figure 4 shows the objective function for all trial evaluations and the best evaluations. The objective was optimized from −92.8% to −98.2% with the product of the weight factors set to 1. Table 2 shows a comparison of the parameters reflecting the performance of the collimation system between the initial state and the optimal result. The cleaning efficiency, η_{system}, was optimized to 98.2%. The total beam loss along the ring was acceptable for shielding, although it was a little higher than that of the initial state. The uncontrolled beam loss of 1.7×10^{-4} of the total beam was lower. Considering even larger beam loss might be caused by various kinds of errors in the actual conditions, it is more important to reduce the uncontrolled beam loss.

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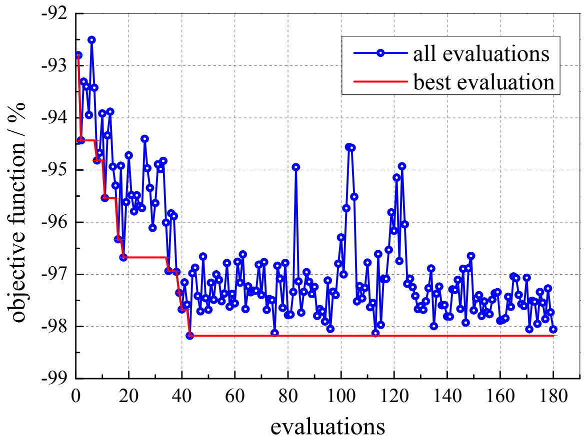

Figure 4: History of all evaluations and the best evaluations during the optimization of the collimation system with the RCDS method.

Table 2: Comparison of parameters reflecting the performance of the collimation system between the initial state and the optimal result. The parameter η_{system} is the cleaning efficiency, η_{co} is the collimation efficiency of collimators, λ_{un} is the uncontrolled beam loss of total beam outside the collimation section during the acceleration, λ_{total} represents the total beam loss as a percentage of total beam along the ring during acceleration, and ε_x (ε_y) is the 99% horizontal (vertical) emittance of the beam.

parameters	η_{system} / %	λ_{un} / 10^{-4}	η_{co} / %	λ_{total} / %	ε_x /πmm·mrad	ε_y /πmm·mrad
initial state	92.8	4.9	91.9	0.7	193	219
optimal result	98.2	1.7	96.3	0.9	193	215

SUMMARY AND DISCUSSIONS

In this paper, we have implemented the RCDS method to optimize the collimation system of CSNS/RCS. The uncontrolled beam loss of the total beam during the acceleration can be reduced to 1.7×10^{-4}, which is lower than that obtained by previous optimization [11]. As a result, an approach was established to efficiently give an optimal parameter combination of the secondary collimators for the present machine model.

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