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CONTROL OF A CYCLOTRON AND AN ECR ION SOURCE USING BAYESIAN OPTIMIZATION METHOD*

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Abstract

An enormous number of parameters are tuned during accelerator operation. The tuning is ultimately dependent on the operator's knowledge and experience. Therefore, there is a risk that tuning time and accuracy may vary depending on the operator. This tuning difficulty is an extremely important issue when implementing accelerometers in society, such as in medical applications. In this study, we developed an automatic tuning method using Bayesian optimization, one of the machine learning technique. The aim is to realize a tuning method that can supply beams in a short time with good reproducibility and comparable to manual tuning.

BAYESIAN OPTIMIZATION

Bayesian optimization [1] is a method that can efficiently utilize Gaussian process regression. The most important feature of Gaussian process regression is that it can calculate the expected value of the forecast (μ) and its variance (σ) from the obtained data. In general methods, the model is trained with a huge amount of data, and the next action is decided based only on the calculated predictions. Therefore, when the number of data is insufficient, the prediction may be inaccurate, and there is the problem of being trapped in local maxima. Bayesian optimization has the advantage that it can be used even with a small number of data because the model is less complex. Also, since the next action is determined from the mu and sigma calculated by Gaussian process regression, it actively adopts regions with a small number of data and is less likely to be trapped in local maxima. For example, in Lower Confidence Bound (LCB), the next action is determined from the acquisition function as shown in Eq. (1).

$$L_{LCB} = \mu + \alpha\sigma \quad (1)$$

where α is a constant. When this α is large, the error is more important and is less likely to be trapped in the local maxima. On the other hand, if the error is considered important, the number of searches increases, and the number of times required to find the optimal solution is likely to increase. Therefore, it is necessary to select a value that is somewhat appropriate for the problem. In this study, experiments were conducted with α = 4 fixed.

TUNING TEST FOR ECR ION SOURCE

Set Up

First, we developed an automatic tuning system using Bayesian optimization for tuning ion sources. In this experiment, a 10 GHz ECR ion source 'NANOGAN [2]' manufactured by Pantechnik was used as the ion source, and He ions were extracted at 50 kV acceleration. A schematic diagram of the test bench is shown in Fig. 1.

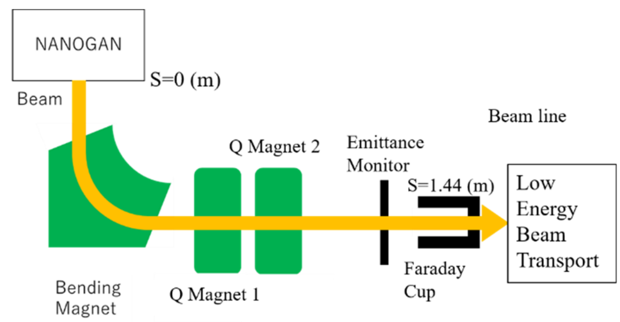

Figure 1: Schematic diagram of the test bench.

After extraction, the beam was bent 90° by a bending magnet to analyze the ion species, and then the beam emittance (ε) and beam intensity (I) were measured with a Pepper-pot emittance monitor (PPEM) [3] and Faraday cup (FC), respectively, using two quadrupole magnets. Beam brightness ($I/\varepsilon_{x-x'}\varepsilon_{y-y'}$) was calculated from the PPEM and FC measurements and adjusted to maximize brightness.

Tuning Experiments

In this experiment, four of the tuning parameters of the ion source were tuned: RF frequency, RF power, gas valve, and intermediate electrode voltage. The RF power was tuned by fixing the amplification factor of the Traveling Wave Tube Amplifier (TWTA) and varying the signal source power. The gas valve had a motor attached to the knob of the needle valve, and the amount of opening and closing was controlled by the amount of rotation [4]. The tuning range and minimum change for each tuning parameter are shown in Table 1. In this experiment, the number of parameter tuning was set to 108 times: 8 times for initial conditions and 100 times for tuning by Bayesian optimization. This is the number of tuning cycles that would take approximately 1.5 hours to complete.

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Table 1: The Tuning Range and Minimum Change for each Tuning Parameter

Parameter	Minimum value	Maximum value	Minimum change
RF Frequency	9.8 GHz	10.2 GHz	0.01 GHz
RF Power	-14.0 dBm	-10.0 dBm	0.1 dBm
Gas valve	11,500 steps	12,500 steps	100 steps
intermediate electrode	15.0 kV	25.0 kV	0.1 kV

Table 2: The Tuning Range and Minimum Change for each Tuning Parameter

Parameter	Experiment 1	Experiment 2
RF Frequency	10.0 GHz	10.0 GHz
RF Power	-13.7 dBm	-13.5 dBm
Gas valve	11,900 steps	12,100 steps
intermediate electrode	16.8 kV	15.5 kV
Beam Brightness	3.0×10^{-5} mA/(mm · mrad)^2	3.0×10^{-5} mA/(mm · mrad)^2

We performed the tuning experiment twice, changing only the first setting in this range. The results of these two experiments are shown in Table 2.

The results show that the beam can be extracted with good reproducibility. In addition, the experiment was conducted again with a wider tuning range for some parameters. The parameter ranges and tuning results for those parameters are shown in Tables 3 and 4. Figure 2 shows the maximum beam brightness and the number of parameter tuning cycles.

By expanding the tuning range, we were able to arrive at even better parameters. From these results, we believe that a wider tuning range is necessary to achieve higher intensity beam brightness, while considering the time required for tuning.

Table 3: The Tuning Range and Minimum Change for each Tuning Parameter

Parameter	Minimum value	Maximum value	Minimum change
RF Frequency	9.8 GHz	10.2 GHz	0.01 GHz
RF Power	-14.0 dBm	-8.0 dBm	0.1 dBm
Gas valve	11,500 steps	12,500 steps	100 steps
intermediate electrode	15.0 kV	39.0 kV	0.1 kV

Table 4: The Tuning Range and Minimum Change for each Tuning Parameter

Parameter	Experiment 1
RF Frequency	10.18 GHz
RF Power	-9.3 dBm
Gas valve	12,100 steps
intermediate electrode	15.1 kV
Beam Brightness	5.2×10^{-5} mA/(mm · mrad)^2

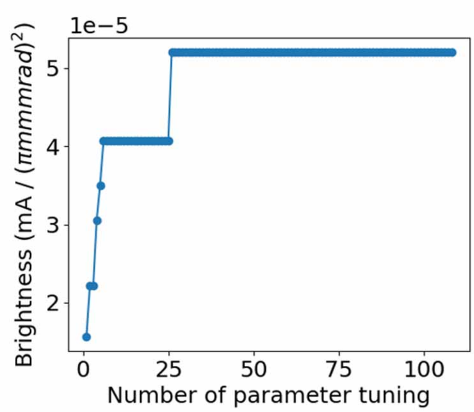

Figure 2: The maximum beam brightness and the number of parameter tuning cycles.

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TUNING TEST FOR LEBT

Set Up

Next, we experimented with fine-tuning the Low Energy Beam Transport (LEBT). In this experiment, we fine-tuned 14 electromagnets (two quadrupole magnets, four solenoid magnets, and eight steerer magnets) installed in the LEBT. Each electromagnet was set to a range of 10 steps of tuning based on the operator's prior tuning history. The settings for the AVF cyclotron, which is the trailing accelerator, were fixed, and a Bayesian optimization was constructed to maximize the beam intensity at the Faraday cup (F0) after acceleration. A schematic of the tuned LEBT is shown in Fig. 3.

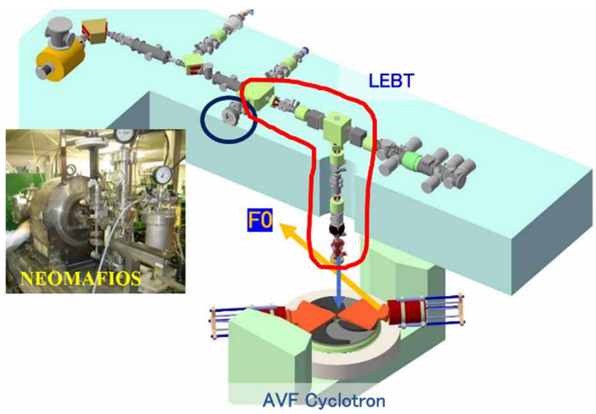

Figure 3: Schematic diagram of the LEBT, F0 is the Faraday cup that measures the beam intensity at the position after the accelerator.

The experiment involved the transport of $^4He^{2+}$ ions extracted from the ECR ion source 'NEOMAFIOS'. Two tuning experiments were conducted, one with the same amount of time as the operator and the other with less than half amount of the time as the operator, to verify the practicality and usefulness of the tuning by comparing the beam intensity with that of the operator's tuning.

Tuning Experiment

The number of tunings and measurement time after each tuning for the two experiments are shown in Table 5.

Table 5: The Number of Tunings and Measurement Time After each Tuning

	Initial data	Number of Tuning	Measurement time
Experiment 1	16	200	5 seconds
Experiment 2	16	600	2 seconds

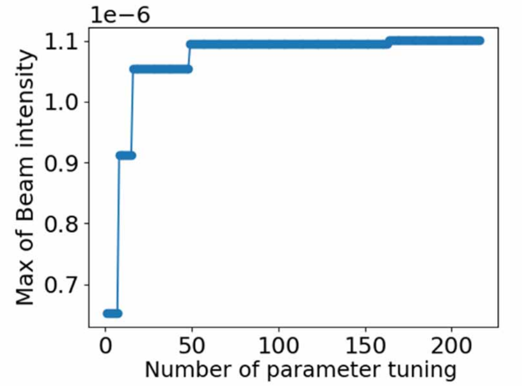

Figure 4: The number of tuning cycles and the maximum beam intensity for Experiment 1.

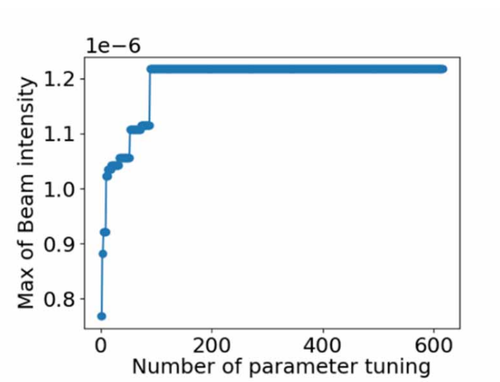

Figure 5: The number of tuning cycles and the maximum beam intensity for each experiment.

Figures 4 and 5 show the number of tuning cycles and the maximum beam intensity for each experiment. Although the maximum beam intensity values in the two experiments were different, both experiments showed a gradual finding of good points and improvement of the beam intensity.

The beam intensity at F0 after each experiment and when tuned by the operator before the experiment are shown in Table 6.

The results in Table 6 show that by using the same amount of time as the operator, the same beam intensity as the operator could be achieved. In addition, the beam intensity could be reached to more than 90% of the operator's beam intensity in one-third of the operator's time. The results show that the settings can be flexibly changed to meet the user's requirements during actual operation. For example, in medical accelerators, tuning time is important, and it is possible to set the required beam intensity and tune in a short time without pursuing the maximum beam intensity. On the other hand, in scientific experiments, it is possible to use as much time as is available and to request the beam intensity to be as close to the maximum as possible.

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Table 6: Comparison of Beam Intensity and Tuning Time After Tuning

	Beam Intensity	**Tuning time**
Experiment 1	1.1 μA	20 minutes
Experiment 2	1.2 μA	60 minutes
Operator tuning	1.2 μA	60 minutes

CONCLUSION

In this study, Bayesian optimization was used to automate the tuning of the ion source and LEBT.

In the tuning of the ion source, four parameters were tuned, and the tuning that maximized the beam brightness within the tuneable parameter range without prior information was achieved in about 1.5 hours.

In tuning the LEBT, 14 electromagnets were fine-tuned. By spending the same amount of time as the operators, we were able to provide the same beam intensity as the operators. It was also possible to provide nearly 90% of the beam intensity in one-third of the operator's time. These results show that the tuning time and beam intensity can be changed depending on whether the tuning time or beam intensity is more important for the application, and that a short tuning time is sufficient to provide a usable beam.

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