Control of a cyclotron and an ECR ion source using Bayesian optimization method

THPO019

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Abstract

developed a tuning system that enables efficient tuning by using Bayesian optimization, one of the machine learning techniques, to learn and predict with a small amount of data. The auto tuning system using Bayesian optimization has been constructed in Python using the Python library 'GPyOpt' for Bayesian optimization, and 'EPICS' for the accelerator control. An auto tuning test has been done for the ECR ion source optimization with 4 parameters tuning and the auto system has work well. Another test for Low Energy Beam Transfer (LEBT) line with 14 parameters also has been carried and the transport has been well matched automatically to accelerator acceptance successfully.

Introduction

- Accelerator operation requires not only specialized knowledge, but also an understanding of habits through experience.
  - ➢ Operator-dependent fluctuations in beam conditions, poor reproducibility, and lack of operators during social implementation will occur.

Realize reproducible and automated operational tunings using machine learning.

Selection of machine learning methods to be used

Method	Advantage	Disadvantage
Deep neural networks	• High identification ability • Shortest tuning to the Solution	• Large amount of requested data • Reproducibility requirements for input/output
Reinforcement learning	• Tuning with hysteresis • Relatively short tuning time	• Large amount of requested data • Reproducibility requirements for input/output
Bayesian optimization	• Small amount of data requested • Responding to daily fluctuations	• Tuning without hysteresis • Tuning with hysteresis

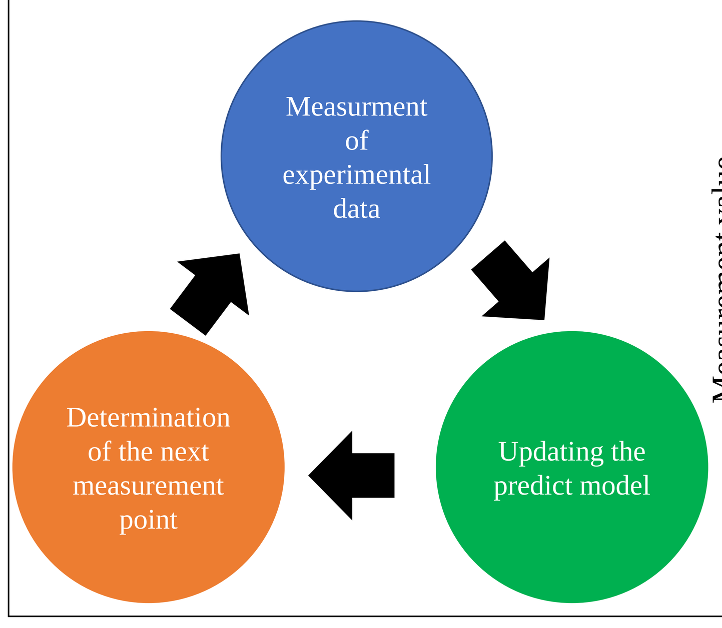
Especially in ion source tuning, the beam state can be affected by factors that cannot be tuned.

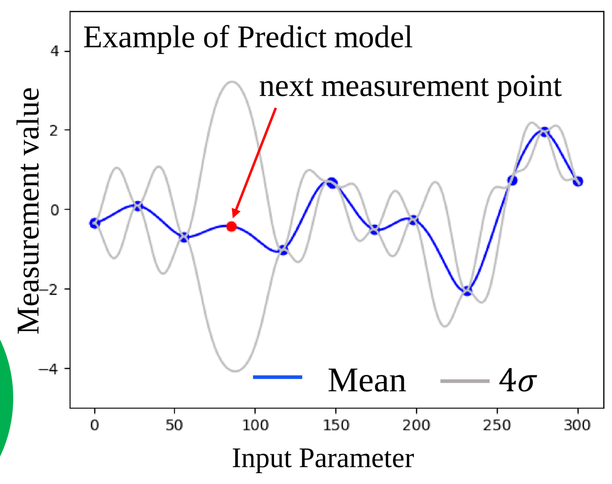
Performance is likely to deteriorate when conditions vary due to unmeasured factors.

➢ We use Bayesian optimization.

Bayesian optimization

Bayesian optimization is a method that efficiently searches for the optimal solution while obtaining data each time.



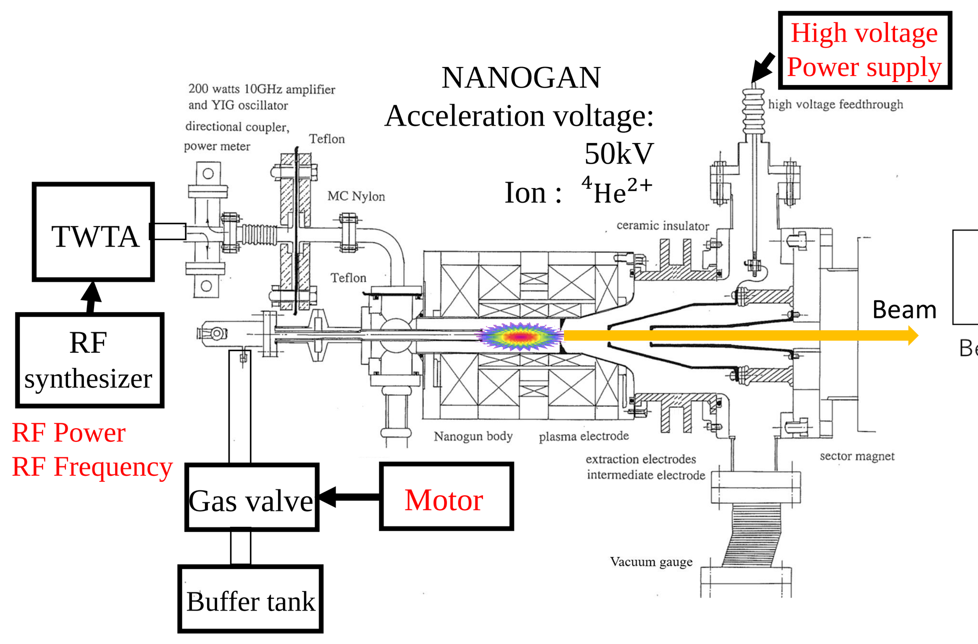


The prediction model has a prediction value and an error, the two of which determine the next point of measurement.

➢ The entire search can be performed in a small number of times.

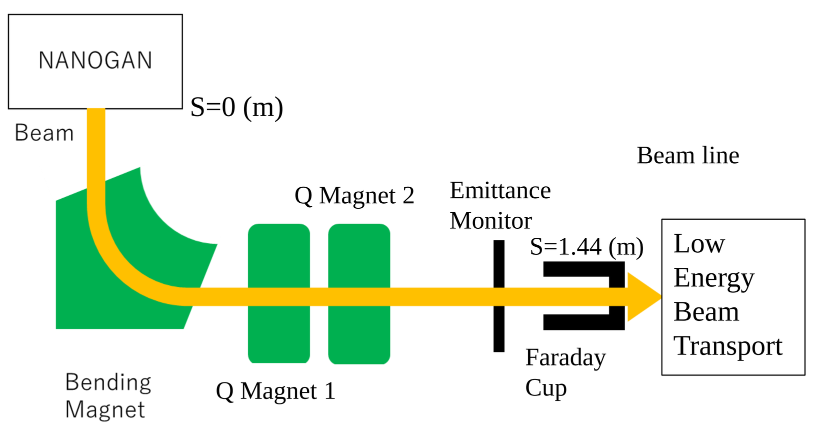
Set Up for Ion Source Test

The ion source tuning experiment used NANOGAN and was tuned to maximize the beam Brightness ($I/\varepsilon_x\varepsilon_y$) of $^4He^{2+}$ ions.



Setup of the brightness measurement that determines how good or bad the beam is

1. A bending magnet classifies ion species.
2. Focusing with two quadrupole magnets
3. Beam emittance ($\varepsilon_x, \varepsilon_y$) and intensity ($I$) are measured with a pepper pot emittance monitor and Faraday cup, and calculate Brightness ($I/\varepsilon_x\varepsilon_y$).

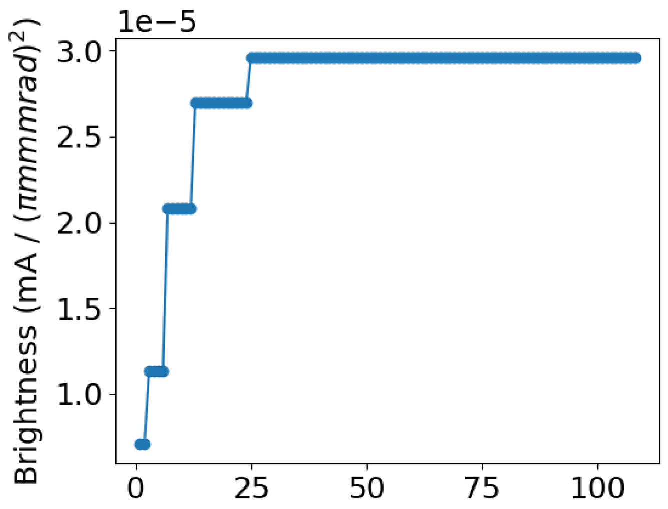


Result of Ion source Tuning

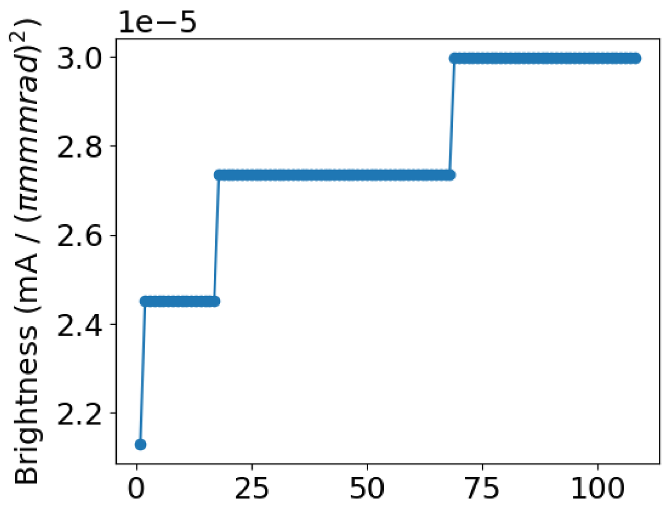
Experiment 1 Tuning with narrower range

Table : Parameter tuning range for Experiment 1

Parameter	Minimum	Maximum	1 tuning step
RF Power	-14.0 dBm	-10.0 dBm	0.1 dBm
RF Frequency	9.8 GHz	10.2 GHz	0.01 GHz
Gas valve (Motor)	11,500 steps	12,500 steps	100 steps
Intermediate electrode	15.0 kV	25.0 kV	0.1 kV



First Experiment



Second Experiment

Figure . Number of Parameter Tunings and Maximum Brightness

The same experiment was performed twice, but the number of times to find the optimal solution was different.

Table : Best parameters and brightness for each experiment

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

Optimal values have changed even for the same experiment with the same ion source.

High reproducibility confirmed!

Experiment 2 Tuning with wide range

Table : Parameter tuning range for Experiment 2

Parameter	Minimum	Maximum	1 tuning step
RF Power	-14.0 dBm	**-8.0 dBm**	0.1 dBm
RF Frequency	9.8 GHz	10.2 GHz	0.01 GHz
Gas valve (Motor)	11,500 steps	12,500 steps	100 steps
Intermediate electrode	15.0 kV	**30.0 kV**	0.1 kV

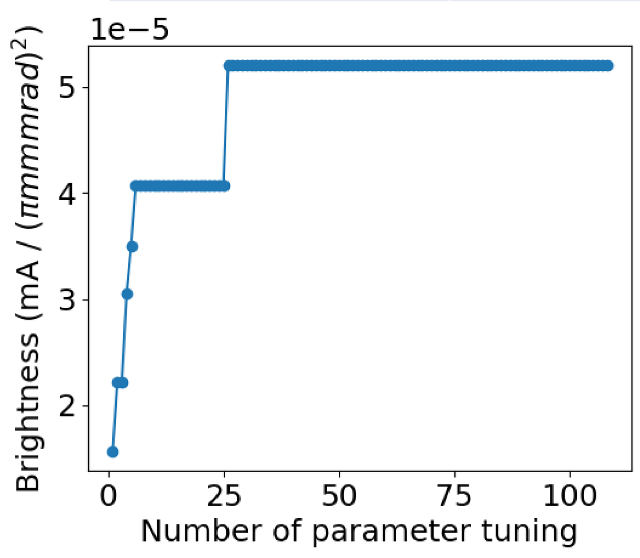


Table : Best parameters and brightness

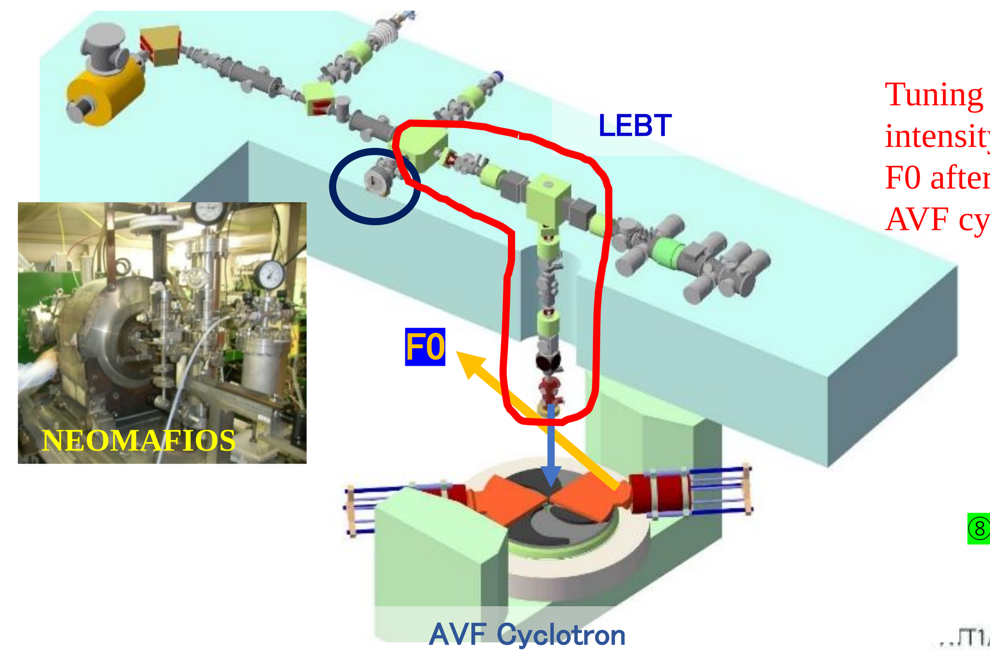
Parameter	Set value
RF Power	-9.3 dBm
RF Frequency	10.18 GHz
Gas Valve	12,100 steps
Intermediate electrode	15.1 kV
Brightness	5.2×10^{-5} mA/(mm · mrad)^2

Manual tuning : About 4.5×10^{-5} mA/(mm · mrad)^2

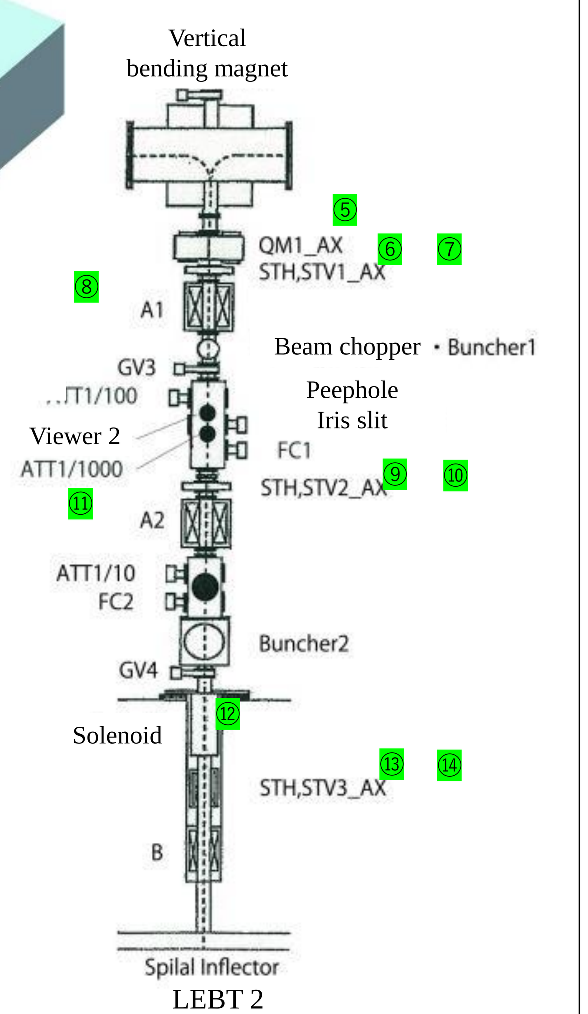
It is important to understand the characteristics of the ion source, beam transport line, and accelerator in advance, because there is a risk that the tuning will not converge if the tuning range is extended too far.

Set Up for LEBT Test

Tune the LEBT, which transports the $^4He^{2+}$ beam from a separate ion source test to the AVF cyclotron.

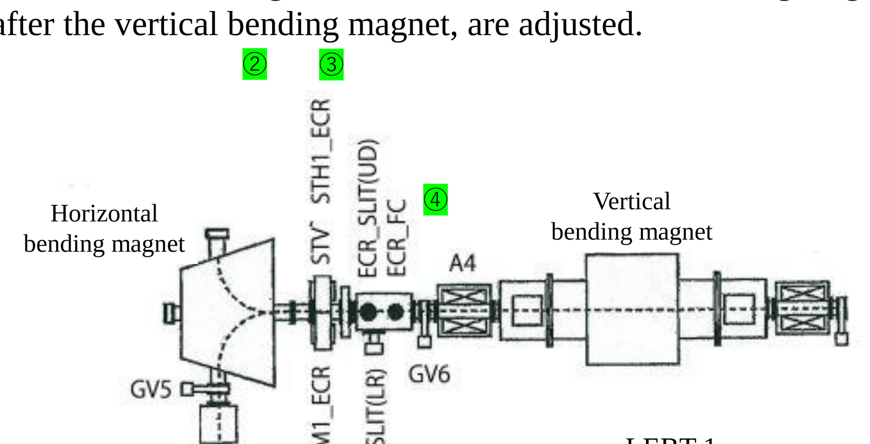


Tuning is judged by the beam intensity of the Faraday cup F0 after acceleration by the AVF cyclotron.



LEBT 2
(From Vertically Modified Magnet to AVF Cyclotron Injection)

A total of 14 electromagnets, 4 before to the vertical bending magnet and 10 after the vertical bending magnet, are adjusted.



LEBT 1
(From ion analysis magnets to vertical change magnets)

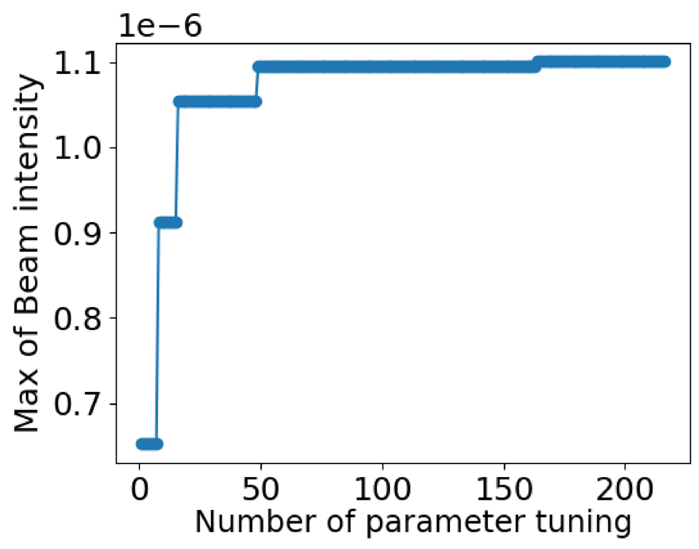
Result of LEBT Tuning

A total of 14 units (2 quadrupole magnets, 4 solenoid lenses, and 8 steerer magnets) were each tuned from 10 different values within the range of fine tuning.

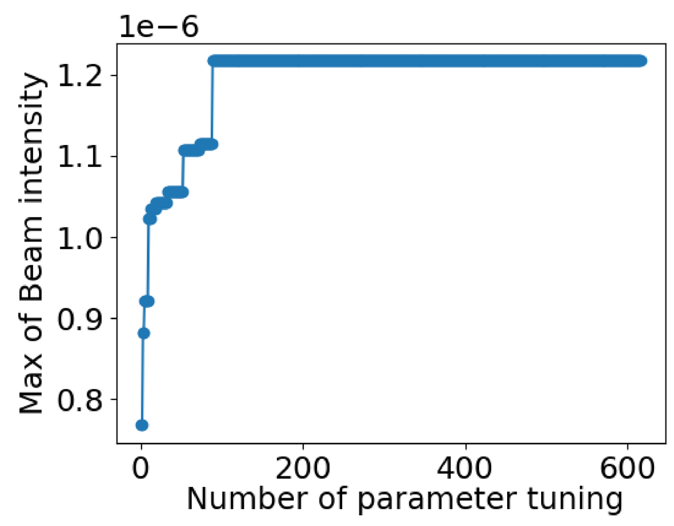
➢ There are a total of 10^{14} different parameter combinations!

Table : Conditions for Tuning Experiments

	Initial data	Maximum number of parameter tuning	Approximate tuning time	Waiting time
Experiment 1	16	200	20 minutes	5 seconds
Experiment 2	16	600	60 minutes	2 seconds



Experiment 1



Experiment 2

Figure . Number of Parameter Tunings and Maximum Beam Intensity at F0

Increasing the number of tuning cycles slightly increased the beam intensity, but did not significantly improve it.
It can be used to provide a reasonable beam intensity in a short period of time or maximum beam intensity with a longer time.

Table : Tuning Result

	Approximate tuning time	Beam Intensity at F0
Experiment 1	20 minutes	1.1 μA
Experiment 2	60 minutes	1.2 μA
Operator tuning	60 minutes	1.2 μA

The system is fully practical, with performance comparable to that of a skilled operator.

Conclusion

- We have developed an automatic tuning system using Bayesian optimization for ion sources and LEBT.
- In the ion source tuning, four parameters (RF power, RF frequency, gas valve, and intermediate electrode voltage) were tuned, and beam brightness comparable to that of manual tuning was achieved in 1.5 hours.
- LEBT tuned 14 parameters to achieve the same beam intensity in the same amount of time as a skilled operator.
  In addition, we were able to increase the beam intensity to a level that was usable even in a short period of time.

Future work

1. **Consideration of conditions for terminating tuning**
   There is potential to improve tuning stability and reduce time by changing termination conditions.
   Optimal termination conditions for each condition are currently being investigated.
2. **Development of a system for automatic determination of the adjustment range**
   - The range is determined by matching the initial set value and its beam condition with the past optimum value.
   - Development of Neural Network that classifies conditions based on initial settings and environmental information
3. **Realization of super multi-parameter tuning**
   Tuning multi-parameters in low-dimensional space by compressing dimensions using Variational Autoencoder, Principal Component Analysis, etc.
   ➢ Development of a comprehensive system for adjusting ion sources and LEBT