Developments of control system for ion source using machine learning

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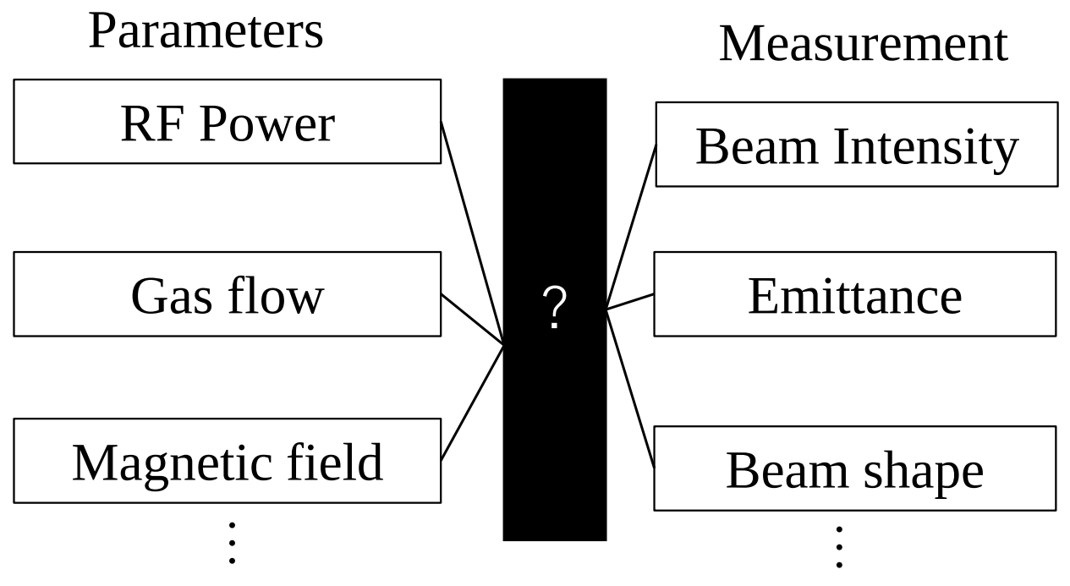
Abstract

Various factors influence each other in an ion source. Therefore, when operating an ion source, it is necessary to optimize and adjust various parameters such as the incident power of RF, the RF tuner and the flow rate of gas while observing the state of the beam. Since this adjustment is highly relies on the experience of the operator, the quantity, quality, and adjustment time of the beam are likely to vary depending on the operator. This time, we performed an experiment of automatic adjustment that maximizes the brightness of the beam using machine learning. A test bench experiment was showed and the feasibility of auto-adjustment was proven.

Introduction

- In an ECR ion source, multiple factors influence each other.
- At the time of adjustment, the black box part is supplemented by experience.
- There are variation in beam intensity and quality depending on the operator.



Parameters

RF Power
Gas flow
Magnetic field
⋮

?

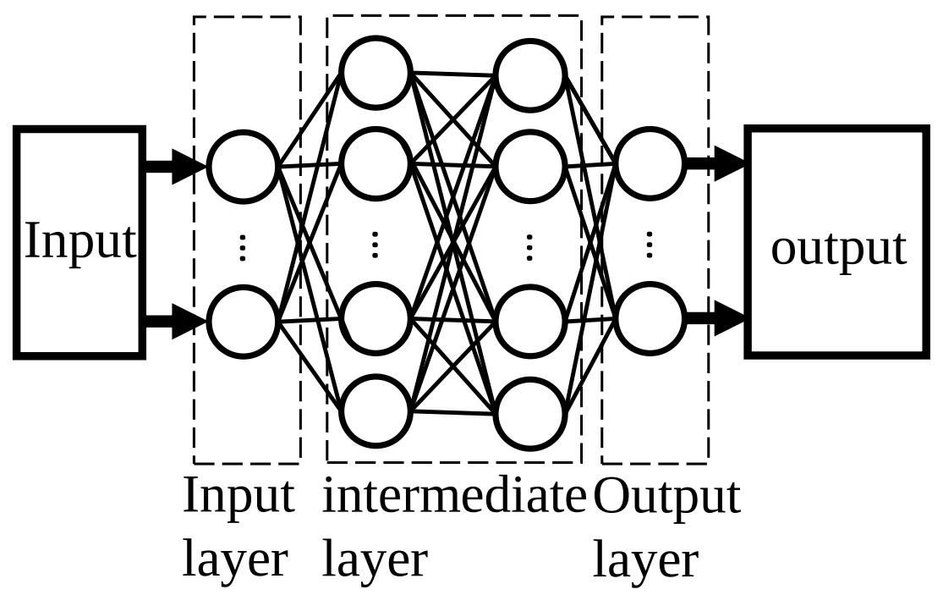
Measurement

Beam Intensity
Emittance
Beam shape
⋮

We aim to realize automatic control of multiple parameters using machine learning.

Neural network (NN) is a well-known machine learning method.
But NN cannot be used when reproducibility is low.

- ➢ Ion sources have low reproducibility over a long period.
- ➢ NN is not suitable for automatic ion source operation.



Neural network conceptual diagram

We try automatic adjustment using Bayesian optimization (BO).

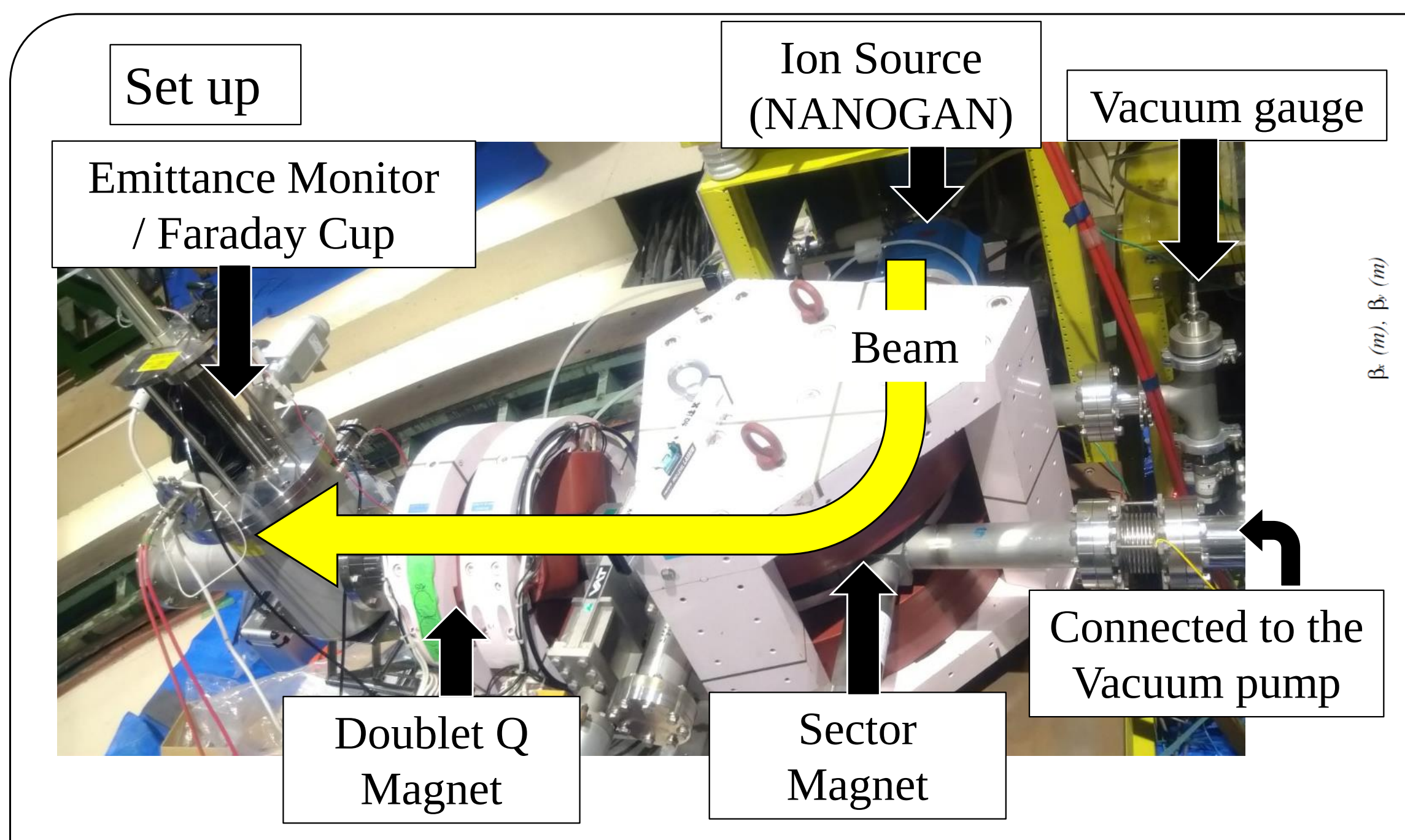
- BO can predict parameters using equation (1) that can give better results from the data points obtained.

$$P(X \mid D) = \frac{P(D|X)P(X)}{P(D)} \qquad (1)$$

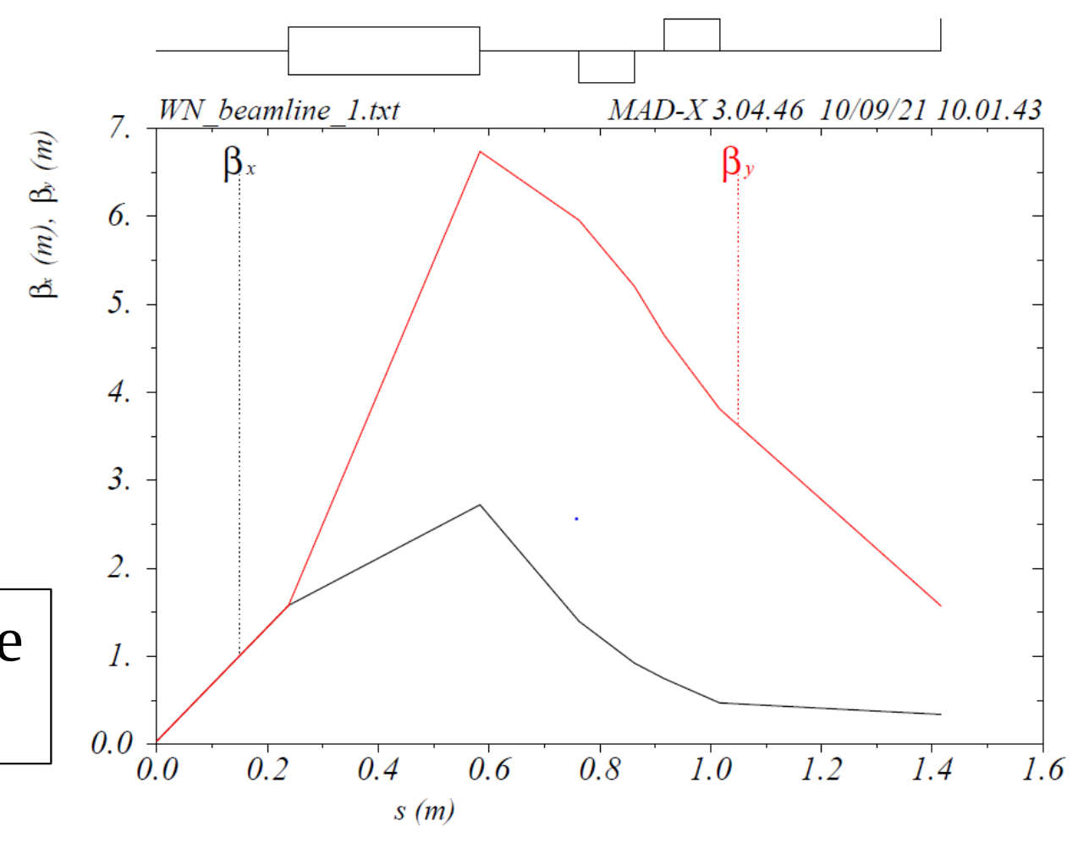
Merits

- Easy to get out of the local minimum.
- Even if the day or environment changes, it can be set to the optimum value at that time.
- It can adjust multiple parameters simultaneously in a short time.

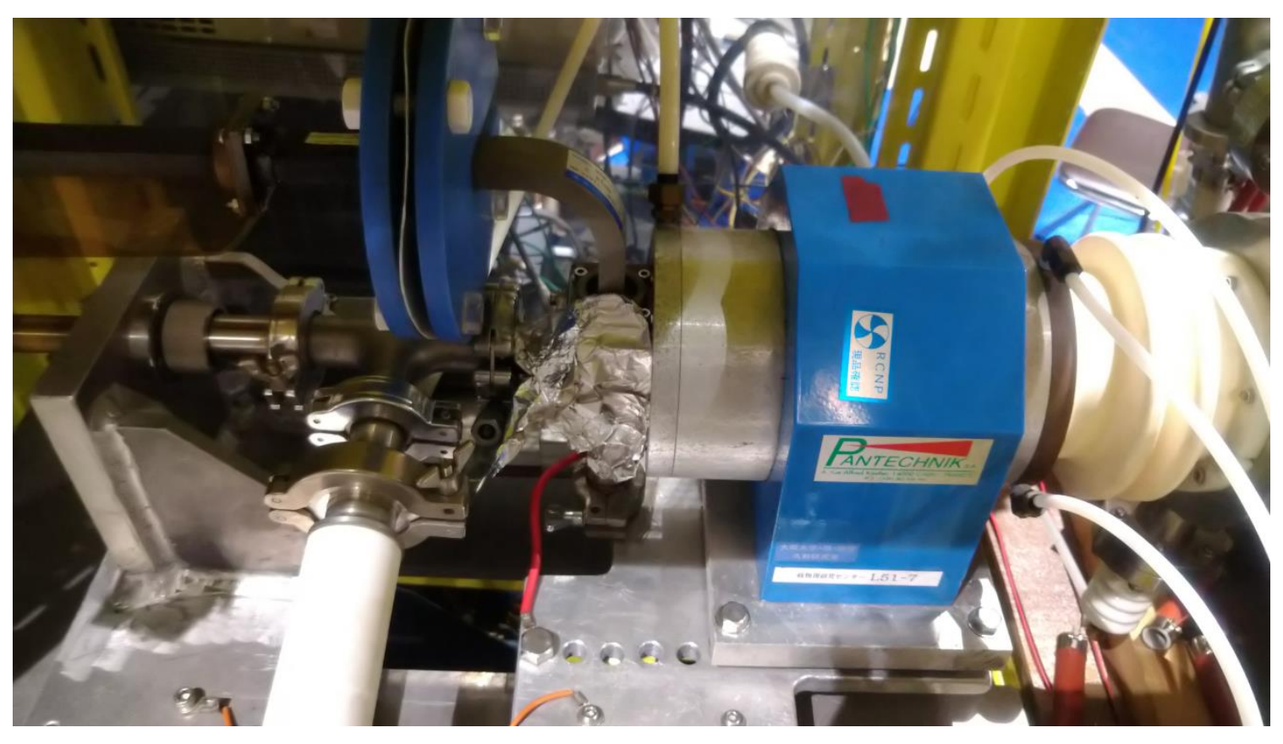
Set up

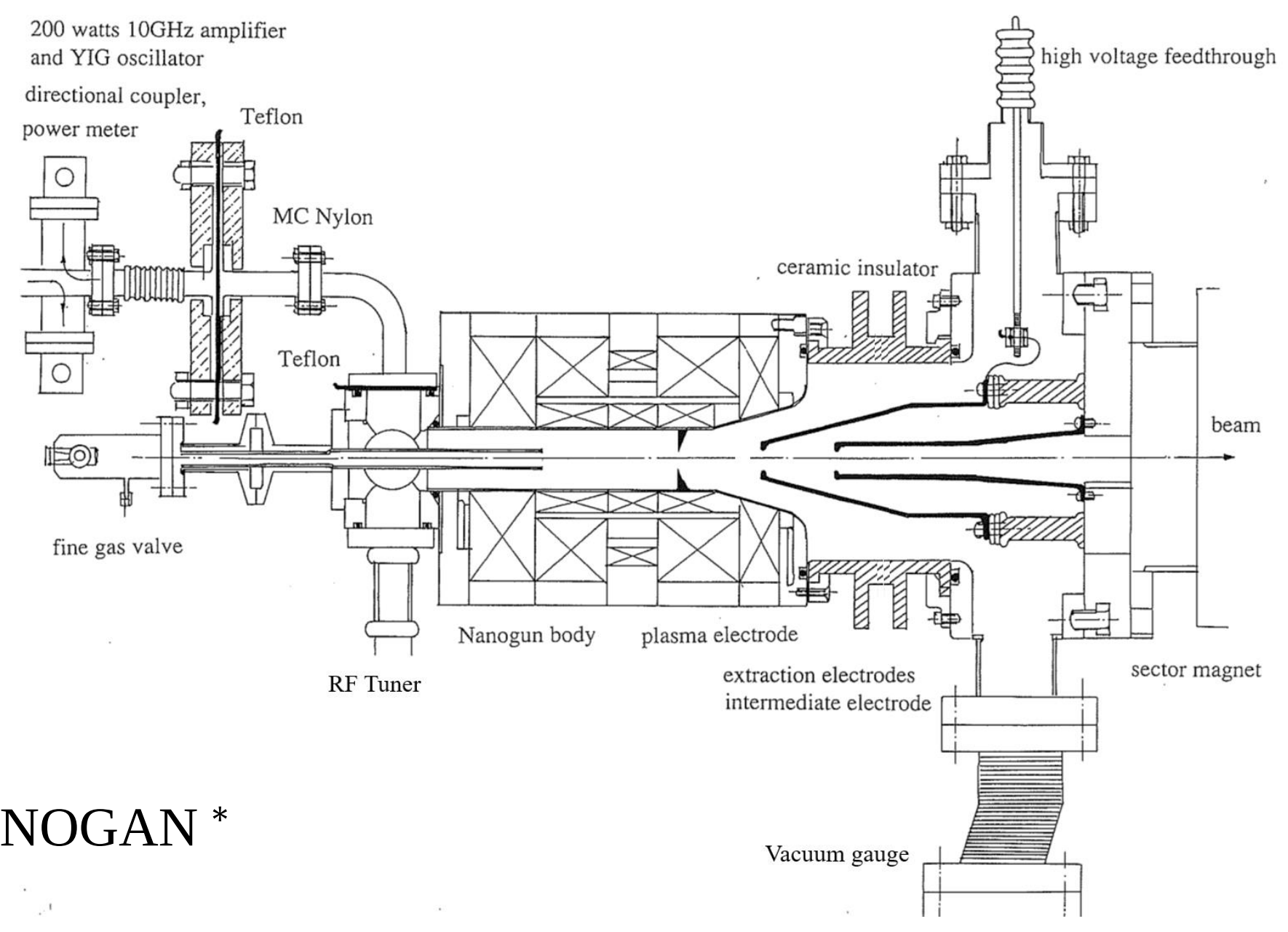


Test bench



Beam transport

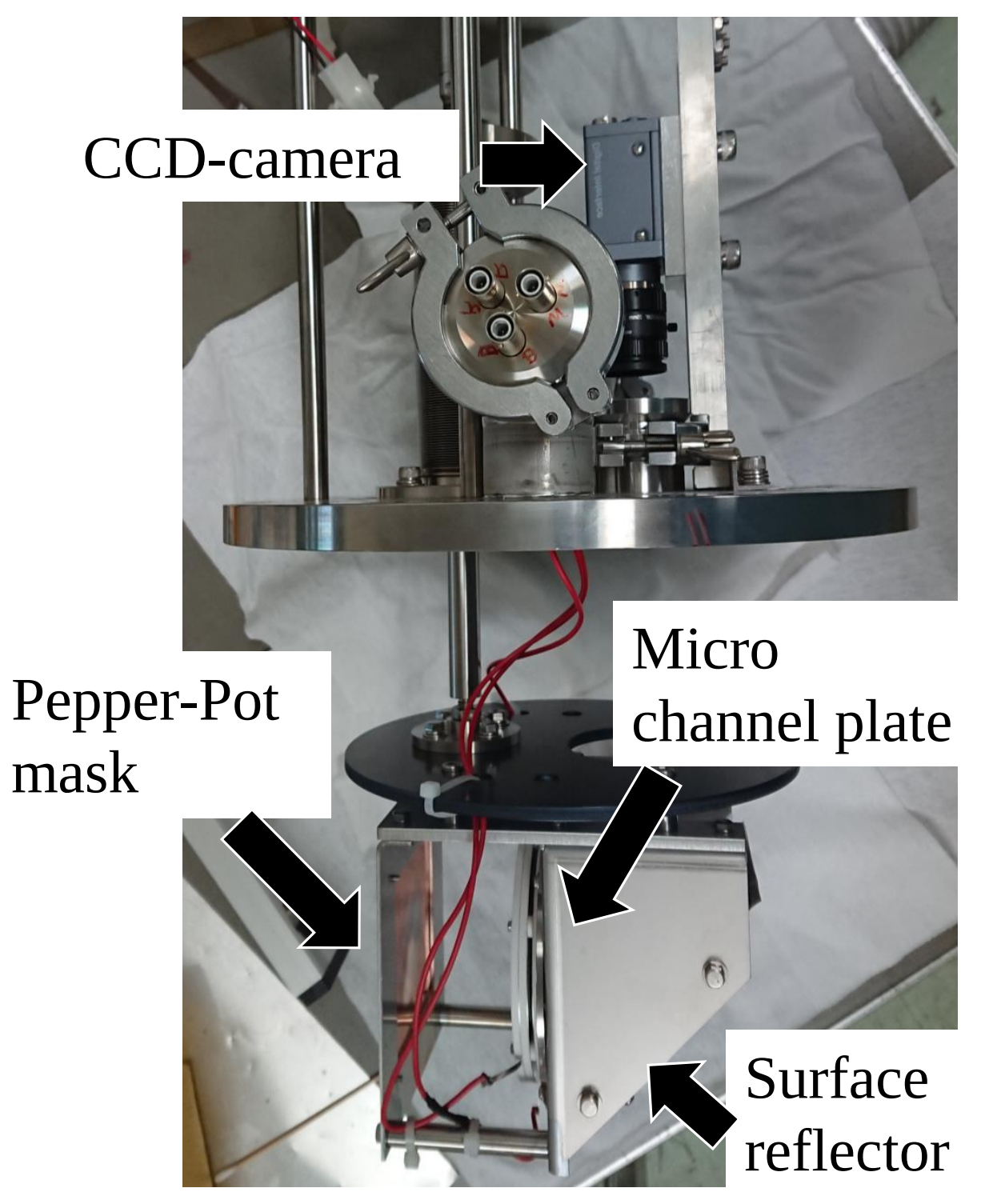




NANOGAN *

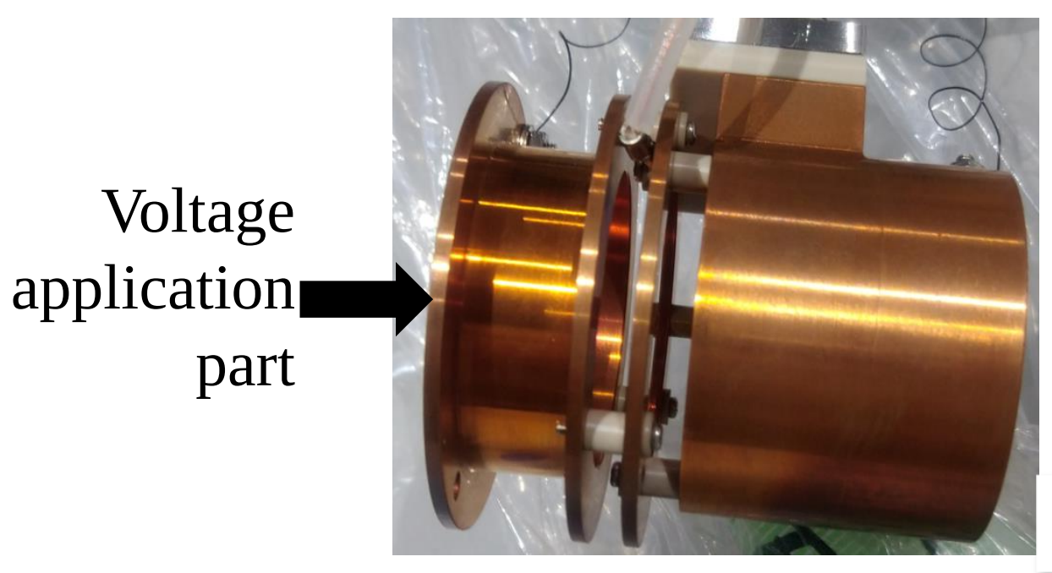
Measurement systems

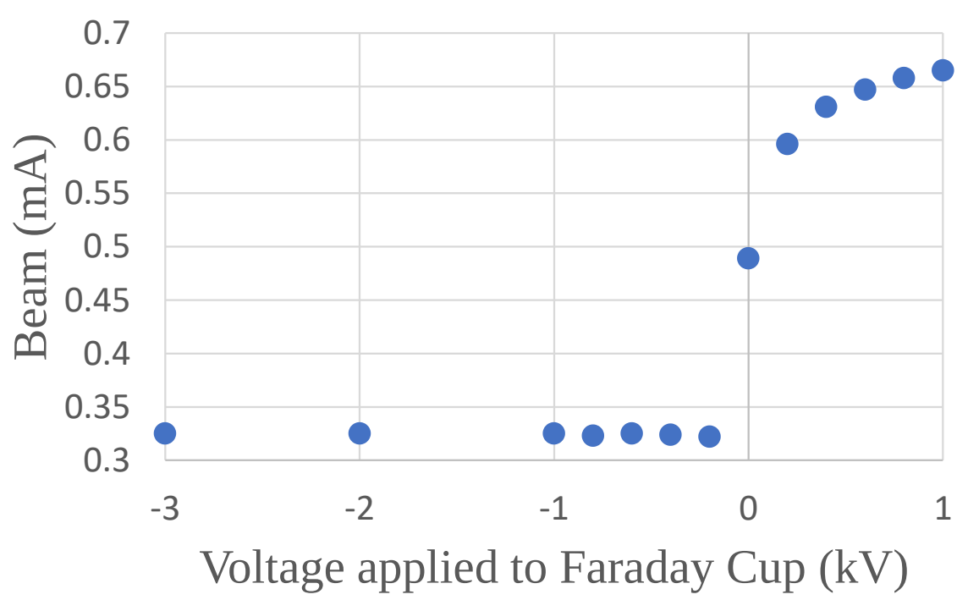
Pepper-Pot Emittance Monitor (PPEM) **



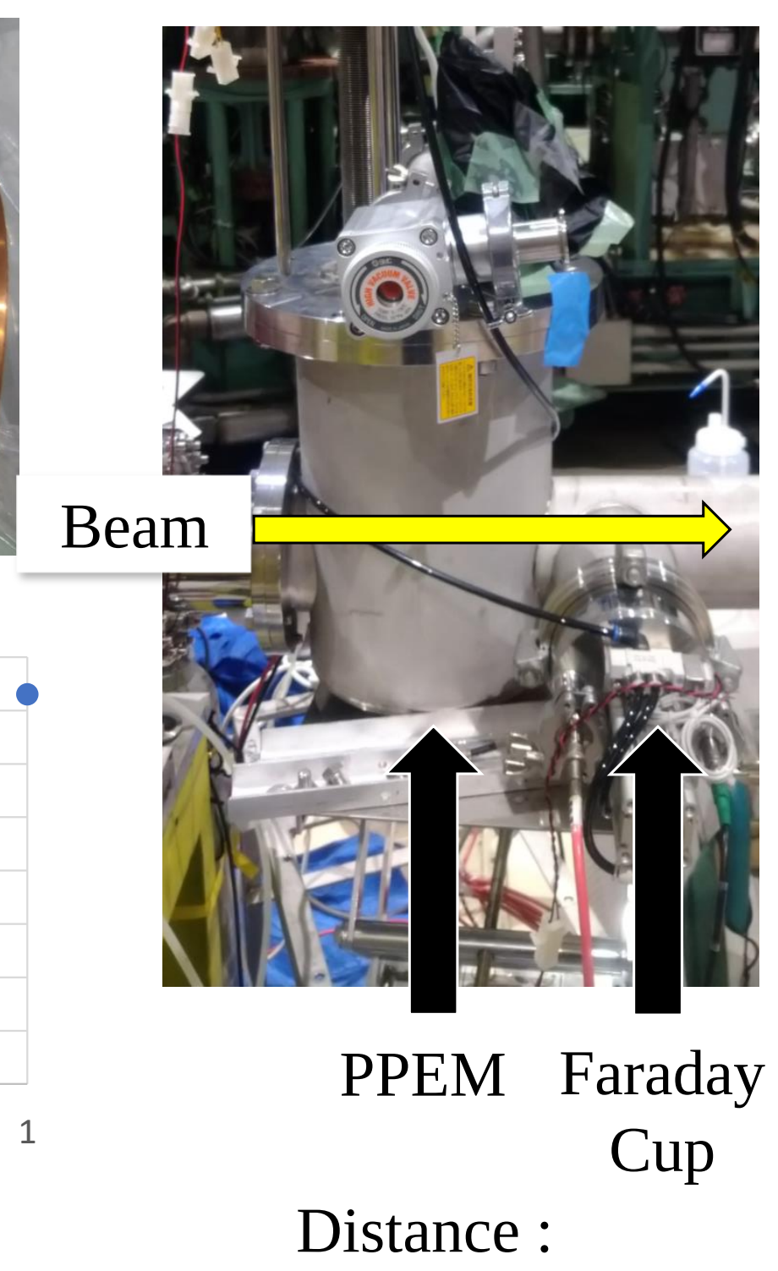
Insert on the beamline only during measurement.

Faraday Cup





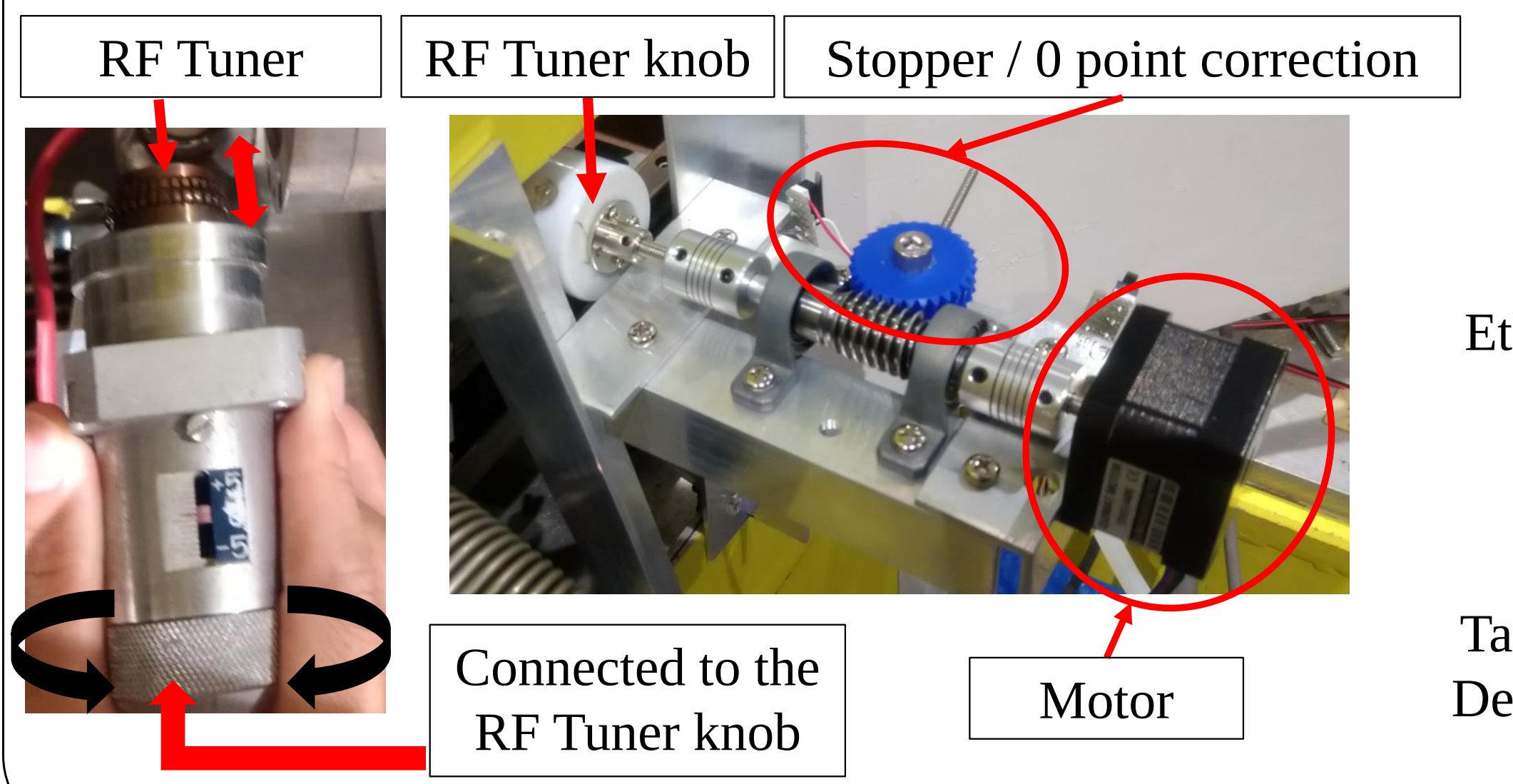
Apply 0.2 kV during measurement



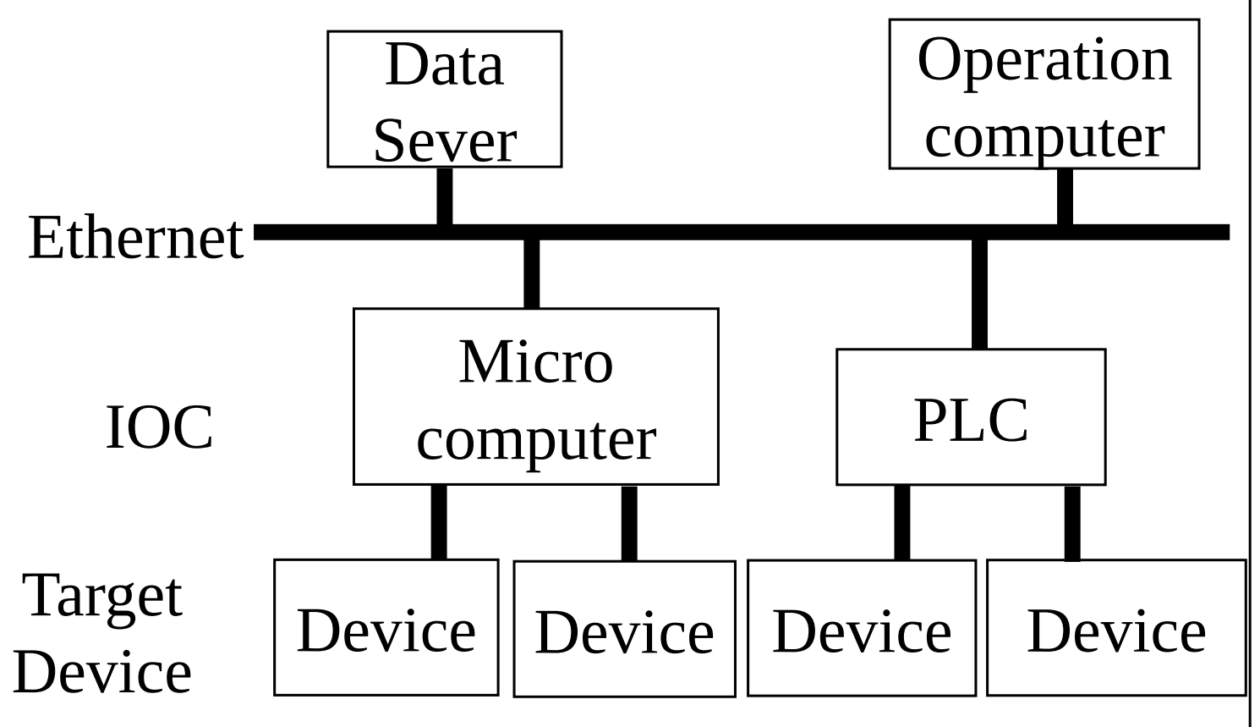
Distance : about 20 cm

Parameters and their range of change

Parameters	Min	Max	
Power of RF synthesizer	-14 (dBm)	-11 (dBm)	4W-8W in plasma chamber
RF Tuner	0 (pulses)	32000 (pulses)	} Control by the amount of rotation of the motor
Gas Valve	0 (pulses)	24000 (pulses)	
RF Frequency	9.8 (GHz)	10.2 (GHz)	NANOGAN is a 10GHz ion source
Intermediate electrode voltage	0 (V)	15 (V)	



Parameters are changed by controlling PLC and microcomputer using EPICS.

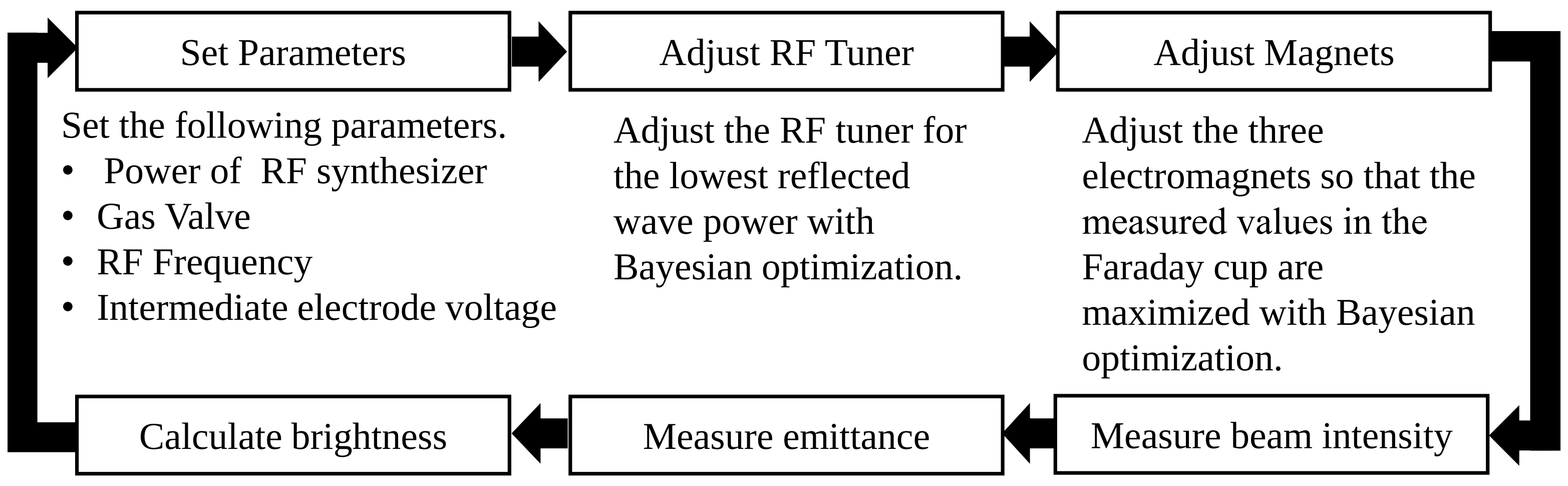


Data Sever
Operation computer
Ethernet
IOC
Micro computer
PLC
Target Device
Device
Device
Device
Device

EPICS conceptual diagram

How to adjust

Bayesian optimization was performed using GpyOpt, a library for Python.



Set Parameters

Set the following parameters.

- Power of RF synthesizer
- Gas Valve
- RF Frequency
- Intermediate electrode voltage

Adjust RF Tuner

Adjust the RF tuner for the lowest reflected wave power with Bayesian optimization.

Adjust Magnets

Adjust the three electromagnets so that the measured values in the Faraday cup are maximized with Bayesian optimization.

Measure beam intensity

Measure beam intensity using Faraday Cup. After the measurement, insert PPEM.

Measure emittance

Measure 90% emittance on the x-x' plane and y-y' plane using PPEM . After the measurement, evacuate PPEM.

Calculate brightness

Calculate brightness by

$$B = \frac{I}{\varepsilon_x \varepsilon_y}\ .$$

I : Beam intensity
ε_x : Emittance on the x-x' plane
ε_y : Emittance on the y-y' plane

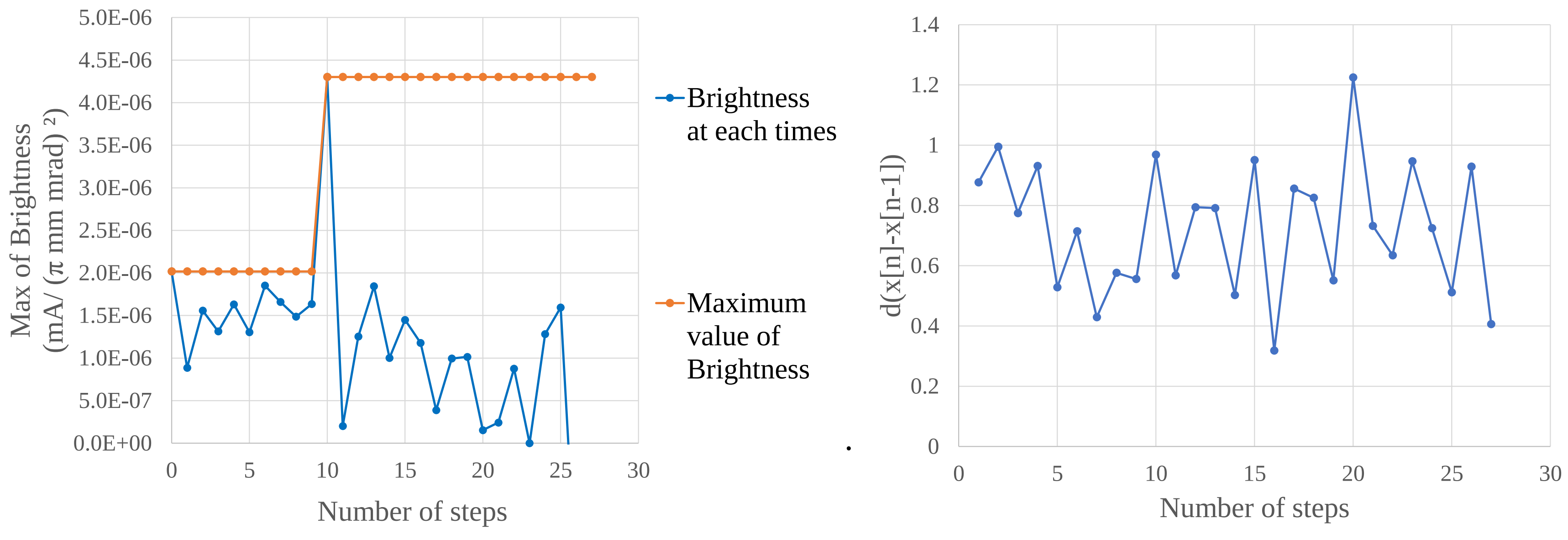
If machine learning determines that no improvement can be expected, or if the set number of loops is exceeded, set the parameter to the value that recorded the highest value and finish the adjustment.

Experiment

Plasma electrode voltage	Beam ion	Vacuum degree before operation	Adjustment range of the gas valve
30 kV	$^4He^{2+}$	1.7×10^{-4} Pa	5000 – 6000 palses

- Since it was confirmed that the temperature of the cooling water increased with the passage of time, the electromagnet was adjusted every step.
- The upper limit of the adjustment range of the gas valve was set so that the degree of vacuum during beam extraction don't exceed 2E-3Pa in consideration of the effects of discharge and the like.
- The 90% emittance, which corresponds to the area occupied by 90% of the entire beam on the x-x' (or y-y') plane, was measured as the emittance.

Results



(a)

(b)

(a) shows the beam brightness at the time of all 28 adjustments and the maximum value up to that point.

(b) shows the magnitude of the parameter change.

$$d(x[n]-x[n-1]) = \sqrt{\left(\frac{x_{RF}[n]-x_{RF}[n-1]}{RF_{max}-RF_{min}}\right)^2 + \cdots + \left(\frac{x_{Voltage}[n]-x_{Voltage}[n-1]}{Voltage_{max}-Voltage_{min}}\right)^2}$$

The value of $d(x[n]-x[n-1])$ would be decreased if optimum value is find and there is no need to search.

Parameters at maximum brightness

Power of RF synthesizer	Gas Valve	RF Frequency	Intermediate electrode voltage
-12.9 dBm	5400	9.87 GHz	4.8 kV

Beam state at the parameters at maximum brightness

Beam intensity	ε_x	ε_y	Brightness
0.138 mA	170 π mm mrad	188 π mm mrad	4.32×10^{-6} mA/(π mm mrad)^2

Discussion

- In previous study***, the adjustment of 2 parameters was completed in about 30 steps.
- In this experiment, it is hard to say that it converges in about 30 steps, but there is a possibility that the best parameter search can be done by increasing it to 50 steps and 100 steps.
- This experiment took about 8 hours, but it is expected to reduce to about 1 to 2 hours by reviewing the adjustment method of the electromagnet and tuner.
- After this experiment, it was confirmed that the bellows of the RF tuner was damaged.
- ➢ We think that it is necessary to have a highly durable device and devise to prevent wear when using machine learning.

Summary

- We performed a test bench of automatic adjustment experiment using machine learning method.
- We confirmed the feasibility of automatic adjustment using machine learning.

Future

- Repeat the same experiment to verify the accuracy of the adjustment.
- Examine how each parameter interacts and affects beam intensity and emittance.
- Develop techniques to minimize device wear.

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* T. Itahashi, et al., 'Performance of the NANOGUN™ electron cyclotron resonance ion source applied for nuclear astrophysics', Rev. Sci. Instrum. 71, 1075 (2000),
** Y. Morita, et al., 'Developments of real time emittance monitors', Rev. Sci. Instrum. 91, 043303 (2020),
*** Y. Morita, et al., Proceedings of PASJ in 2021. WEP005.