Multi-Objective Bayesian Optimization of Electron Cyclotron Resonance Ion source

DE FRANCO Andrea for the LIPAc team

第21回日本加速器学会年会 - 31st July – 3rd August 2024

Linear IFMIF Prototype Accelerator (LIPAc)

Rokkasho Fusion Institute (BA Site)

Author list

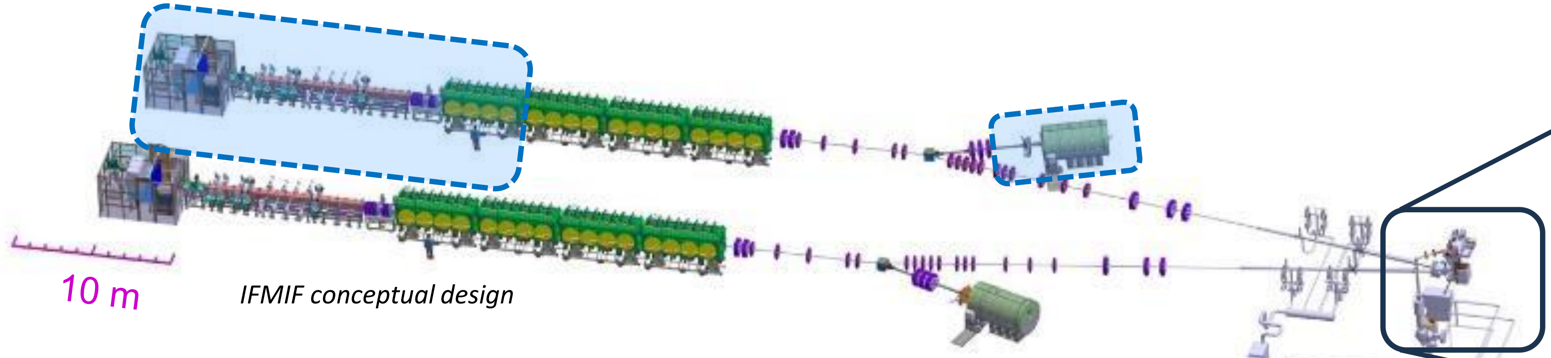
[1,3]DE FRANCO Andrea, [1,3]AKAGI Tomoya, [4,3]BOLZON Benoit, [2,3]CISMONDI Fabio, [4,3]CHAUVIN Nicolas, [2,3]DZITKO Herve, [1,3]ITAGAKI Tomonobu, [1,3]KONDO Keitaro, [1,3]MASUDA Kai, [1-6]IFMIF/EVEDA Integrated Team

[1]QST、[2]F4E、[3]IFMIF/EVEDA Project Team、[4]CEA、[5]CIEMAT、[6]INFN

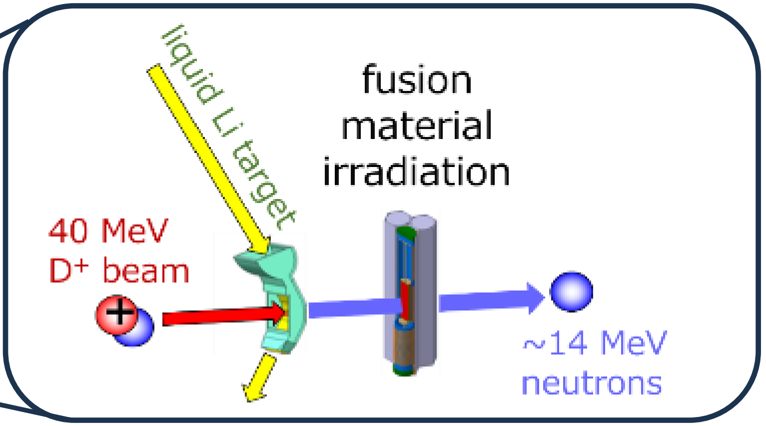
On behalf of the IFMIF/EVEDA project team

Linear IFMIF Prototype Accelerator

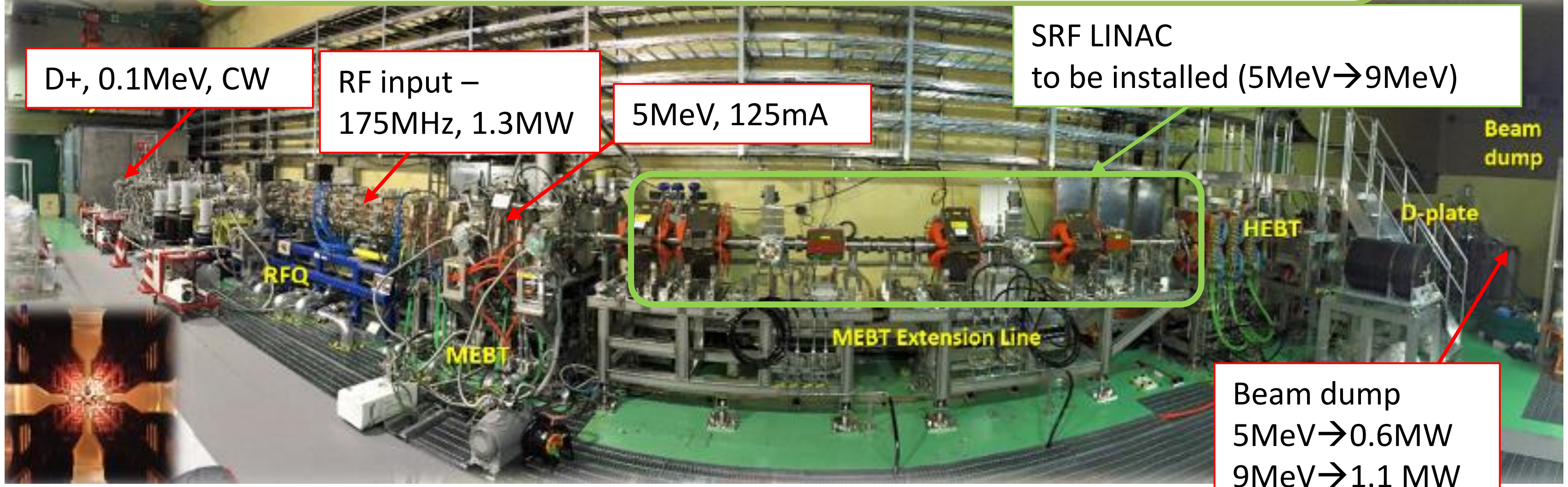
International Fusion Materials Irradiation Facility (IFMIF) will address the need of a neutron source for material tests toward future Fusion Power Plant



IFMIF conceptual design



Linear IFMIF Prototype Accelerator (LIPAc)
@QST in Rokkasho, Aomori, Japan
EU-Japan Broad Approach agreement



Fisheye view of LIPAc

More on LIPAc/IFMIF:

赤木: IFMIF原型加速器（LIPAc）の高デューティビーム試験結果

熊谷: IFMIF原型加速器における冷却水システムの保守に関する現状と課題

廣澤: 離調されたRF空洞を活用したパルス内振動測定の検討

蛯沢: A-FNS加速器HEBTの真空特性評価に関する実験的研究

金子: LIPAcにおけるBACnetベースの二次冷却水監視システムのEPICS統合(確認中)

増田: LIPAc現状2024（仮題）

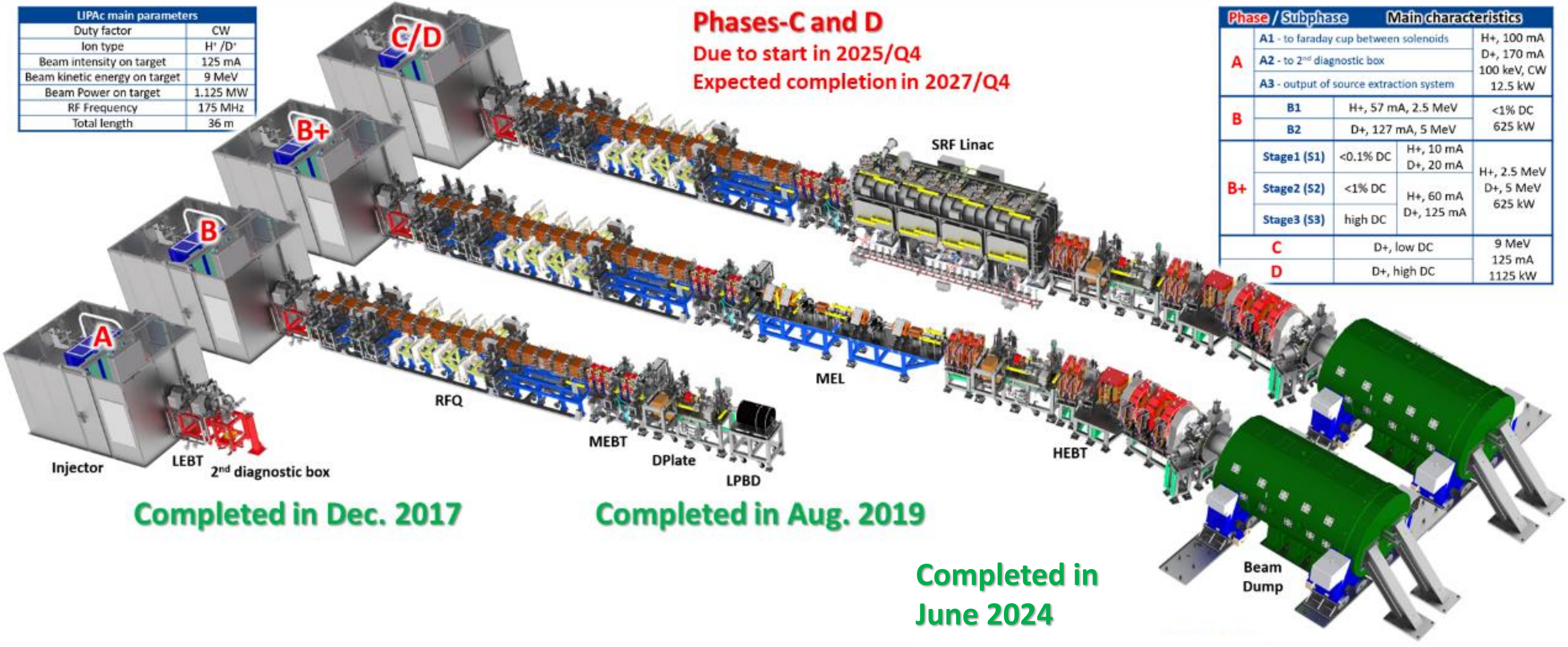
Status

5 Phases and 4 configurations

LIPAc main parameters	
Duty factor	CW
Ion type	H^+ /D^+
Beam intensity on target	125 mA
Beam kinetic energy on target	9 MeV
Beam Power on target	1.125 MW
RF Frequency	175 MHz
Total length	36 m

Phases-C and D
Due to start in 2025/Q4
Expected completion in 2027/Q4

Phase / Subphase		Main characteristics		
A	A1 - to faraday cup between solenoids			H+, 100 mA D+, 170 mA 100 keV, CW 12.5 kW
	A2 - to 2nd diagnostic box			
	A3 - output of source extraction system			
B	B1	H+, 57 mA, 2.5 MeV		<1% DC 625 kW
	B2	D+, 127 mA, 5 MeV		
B+	Stage1 (S1)	<0.1% DC	H+, 10 mA D+, 20 mA	H+, 2.5 MeV D+, 5 MeV 625 kW
	Stage2 (S2)	<1% DC	H+, 60 mA D+, 125 mA	
	Stage3 (S3)	high DC		
C		D+, low DC		9 MeV 125 mA 1125 kW
D		D+, high DC		



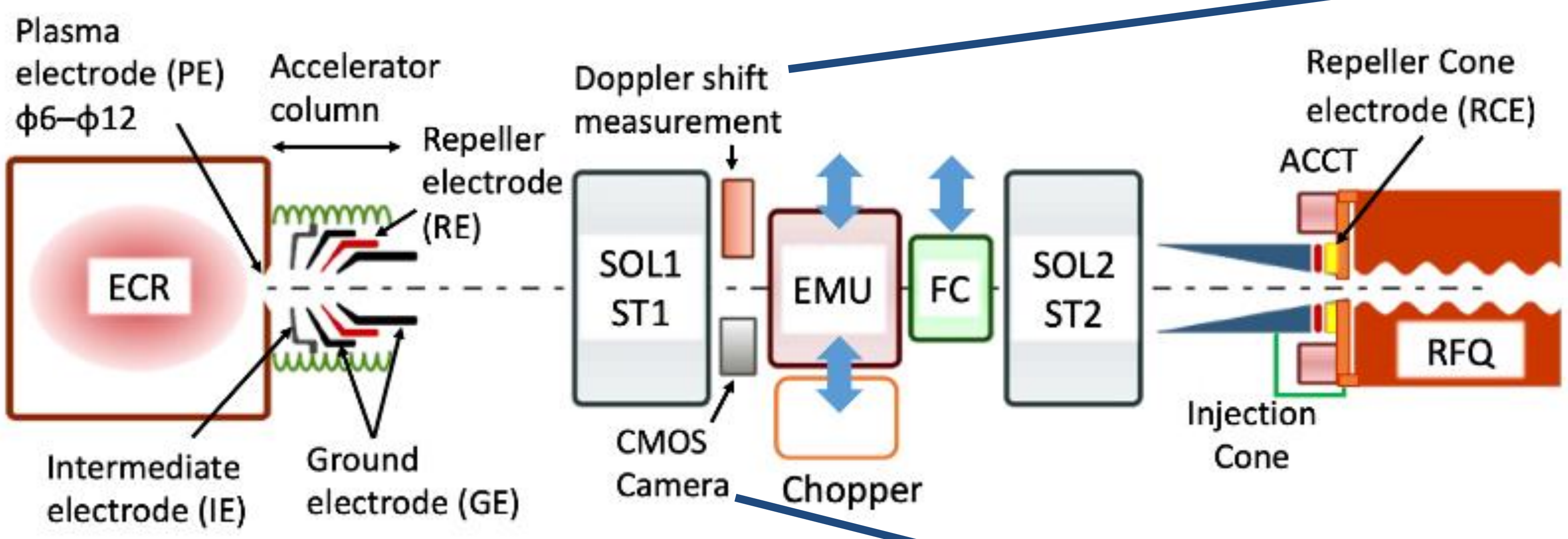
Completed in Dec. 2017

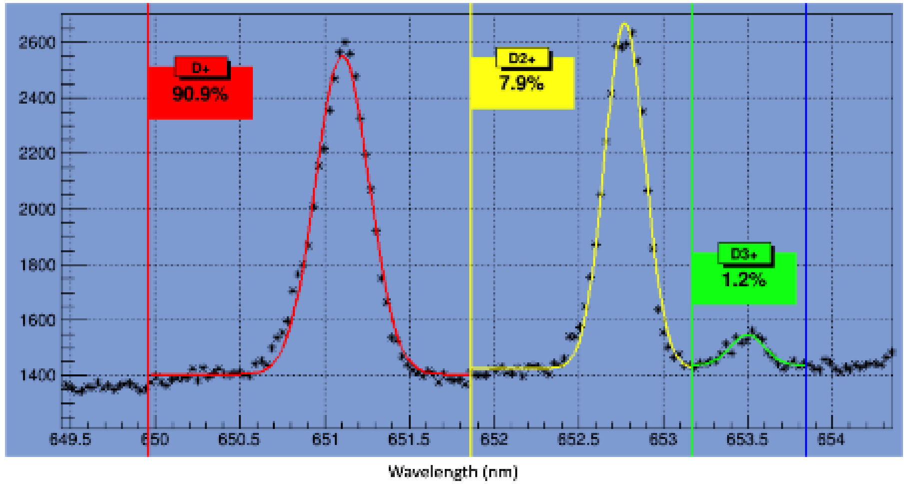
Completed in Aug. 2019

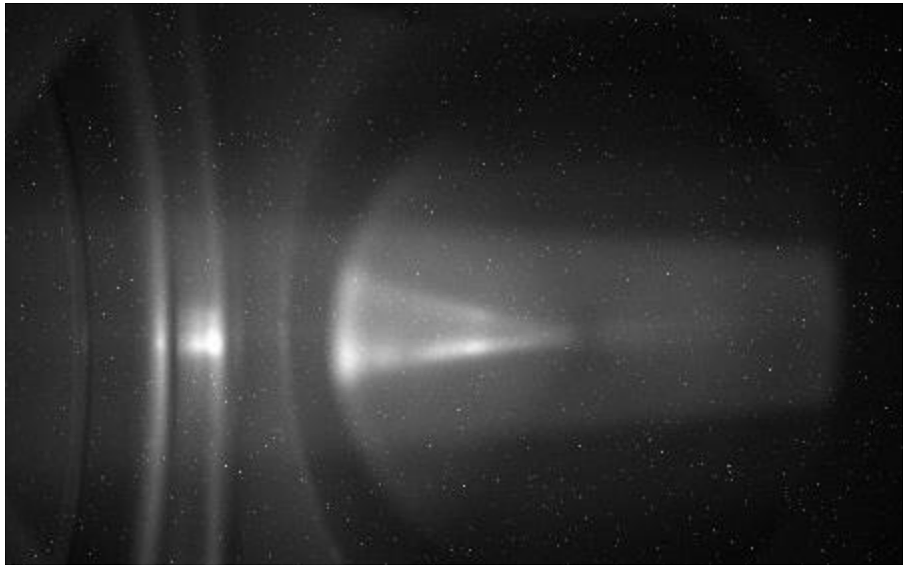
Completed in June 2024

LIPAc injector overview

ECR ion source (2.45 GHz), designed by CEA/Saclay based on SILHI





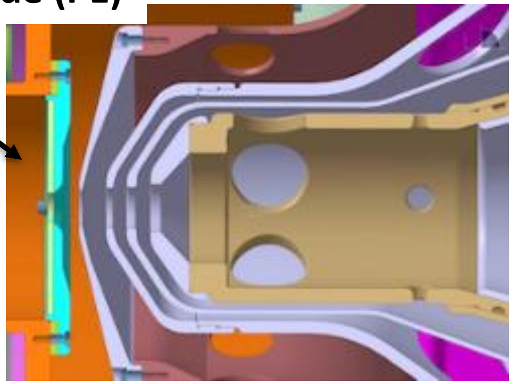


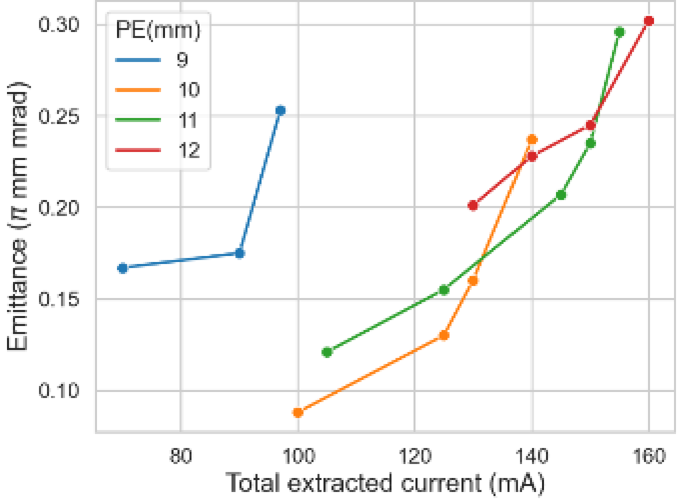
Requirements

Particle type	D^+ (H^+)
Beam energy	100 keV
D^+ Beam current	140 mA
Beam current noise	1% rms
Normalized rms emittance	0.25 π mm mrad
Operation mode	Pulse/CW

Result of CW campaign

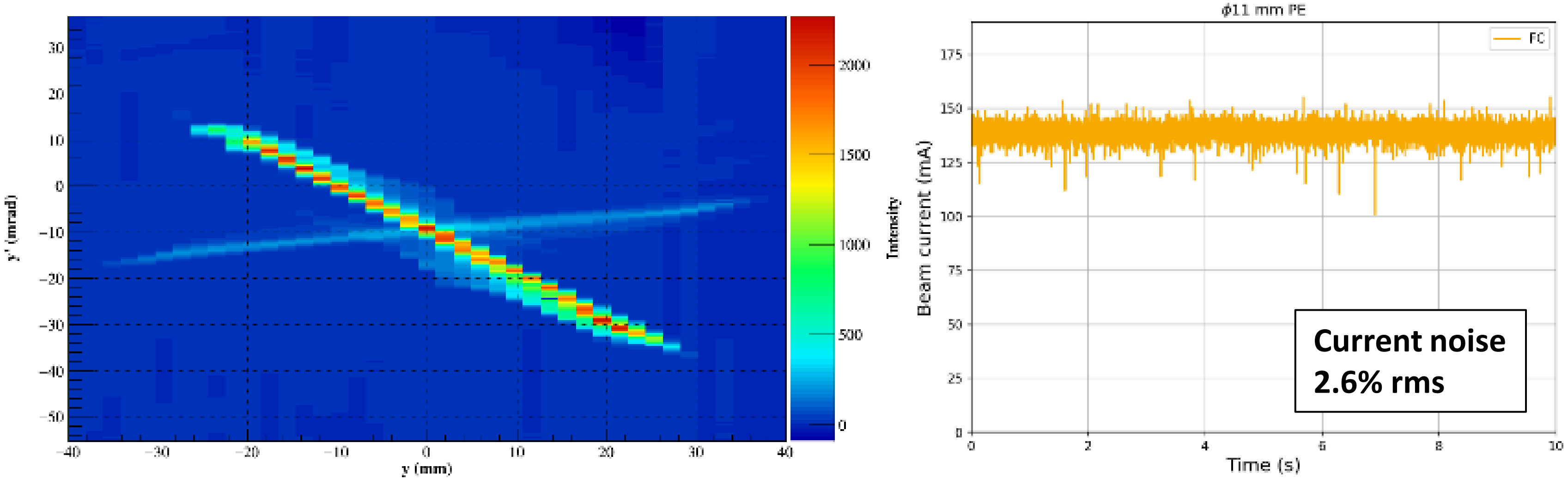
Plasma Electrode (PE)



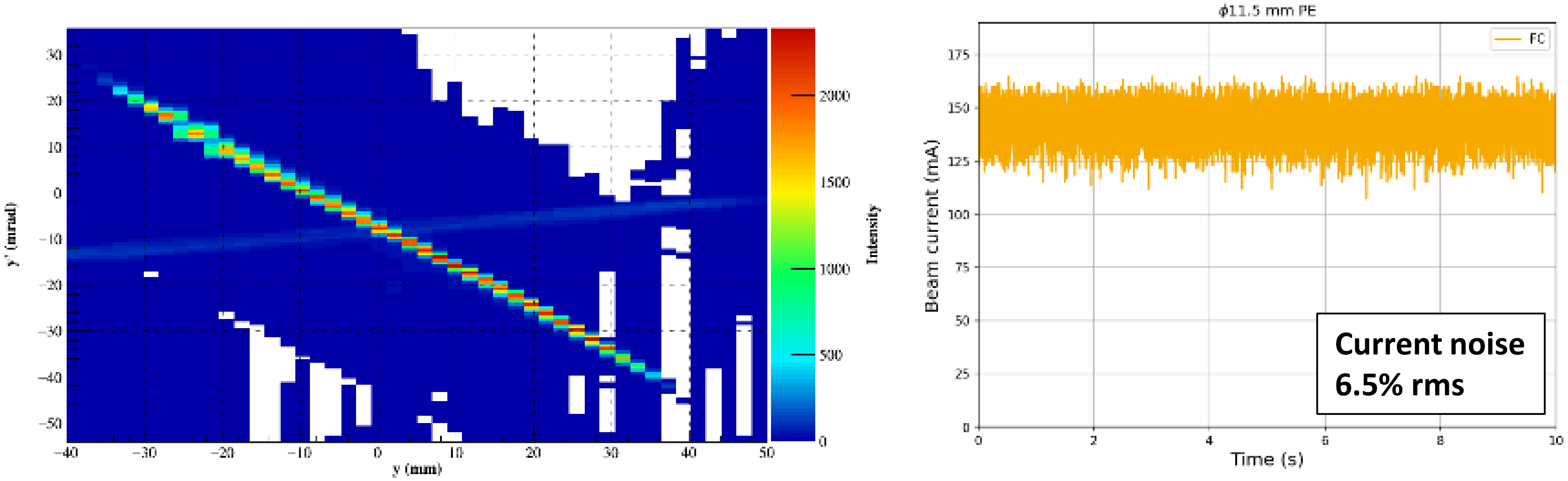


Optimization of source configuration to obtain maximum beam current while meeting the required quality and stability is ongoing.

ϕ11 mm PE: ε=0.24 π mm mrad for Iext=150 mA ± 3.9 mA



ϕ11.5 mm PE: ε=0.19 π mm mrad for Iext=155 mA ±10mA



Machine Learning?

Is this problem suitable for Machine Learning?

- ✓ Complex physics, cannot be modeled/simulated to the desired precision
- ✓ Human can become experts with a lot of training (patterns and correlations exists)
- ✓ Expect plenty of local maximums
- ✓ Expect the need to retune while following duty cycle, after maintenances, with ageing

Goals:

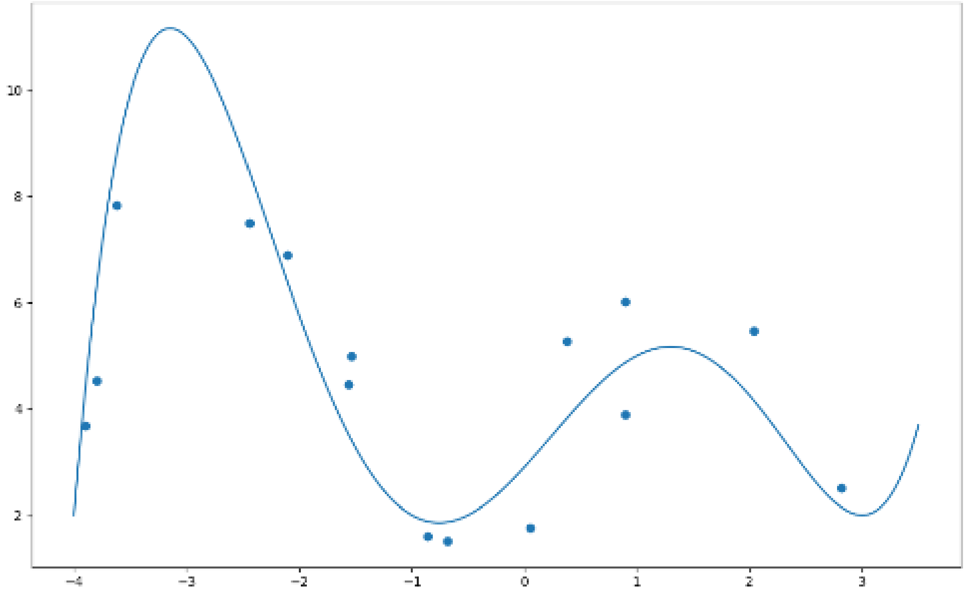
- tool to assist the expert to return quickly the ECR when necessary
- provide a surrogate model to reveal patterns and develop semi-analytical models

Proposed solution:

Bayesian optimization (Gaussian process, Gaussian regression, etc.)

Bayesian Optimization in a nutshell

What we often do in data analysis



Acquire several data points
Assume a model

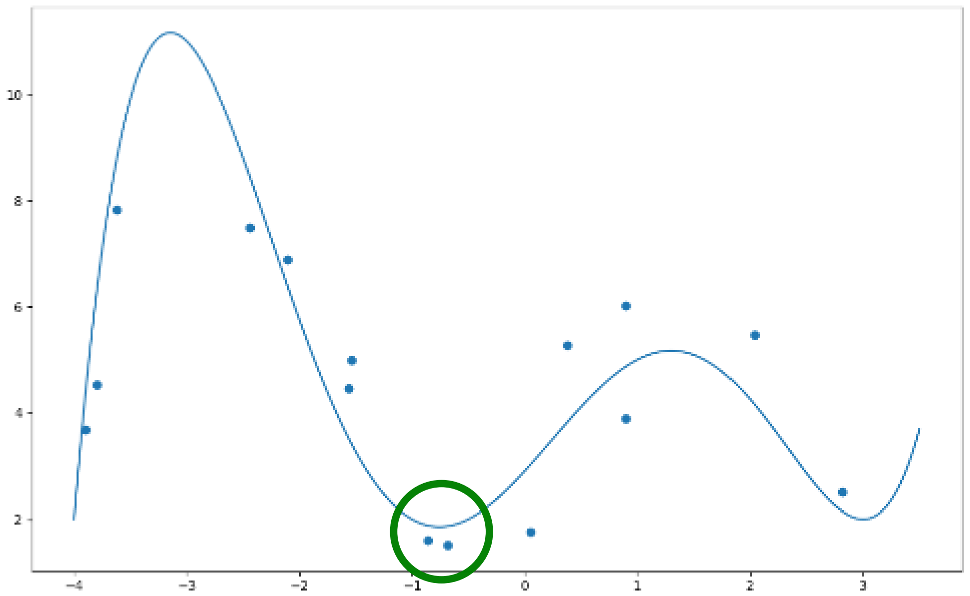
$$y = ax^5 + bx^4 + cx^3 + dx^2 + ex + f$$

Find the function parameters that best describe our data.
a,b,c,d,e and *f*

CHALLENGE: which function do we assume?

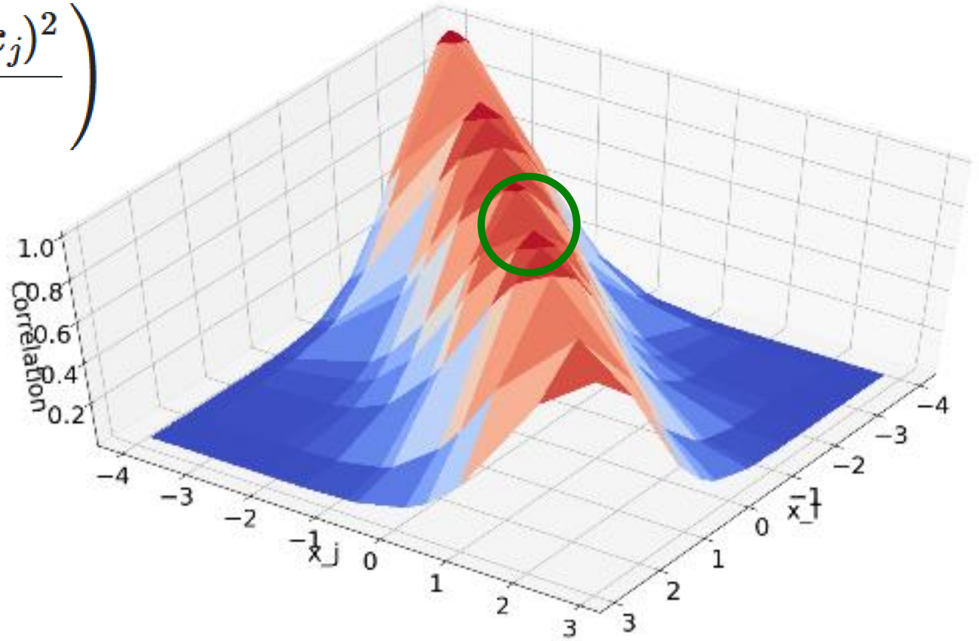
Bayesian Optimization in a nutshell - II

What else we can do?



Acquire several data points
Assume outcome y for any variable x is the mean of a multivariate gaussian weighting several (infinite) model distributions
Assume that the closest two x are, the closer the outcome y will be.
Quantify the correlation, for example:

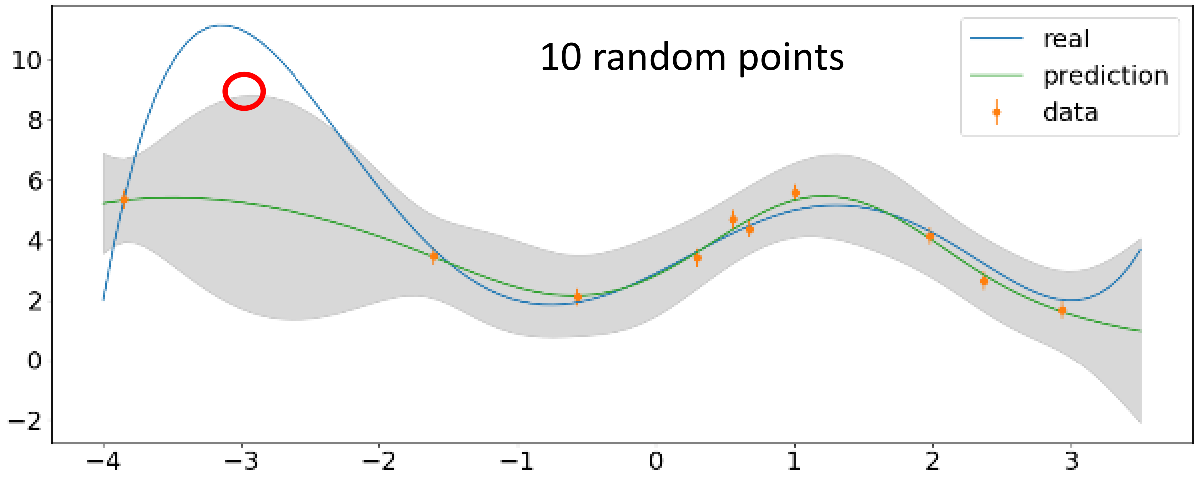
$$k(x_i, x_j) = \exp\left(-\frac{d(x_i, x_j)^2}{2l^2}\right)$$



From a small sample of y(x) find the multivariate gaussian
→
we have an expectation for $y_{mean}(x) \pm y_{std}(x)$

Bayesian Optimization in a nutshell - III

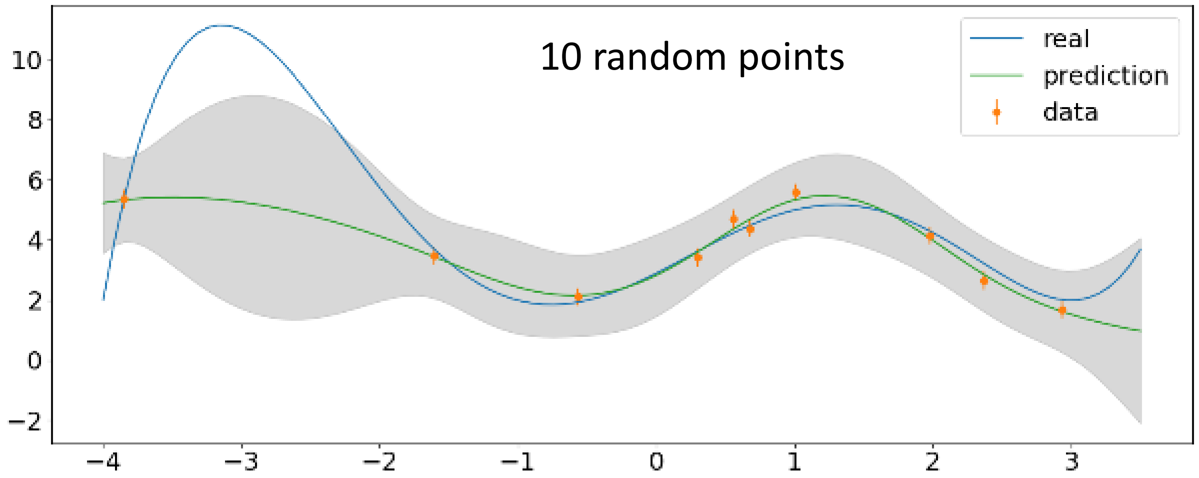
Example: seek global max with 1 dimension x variable

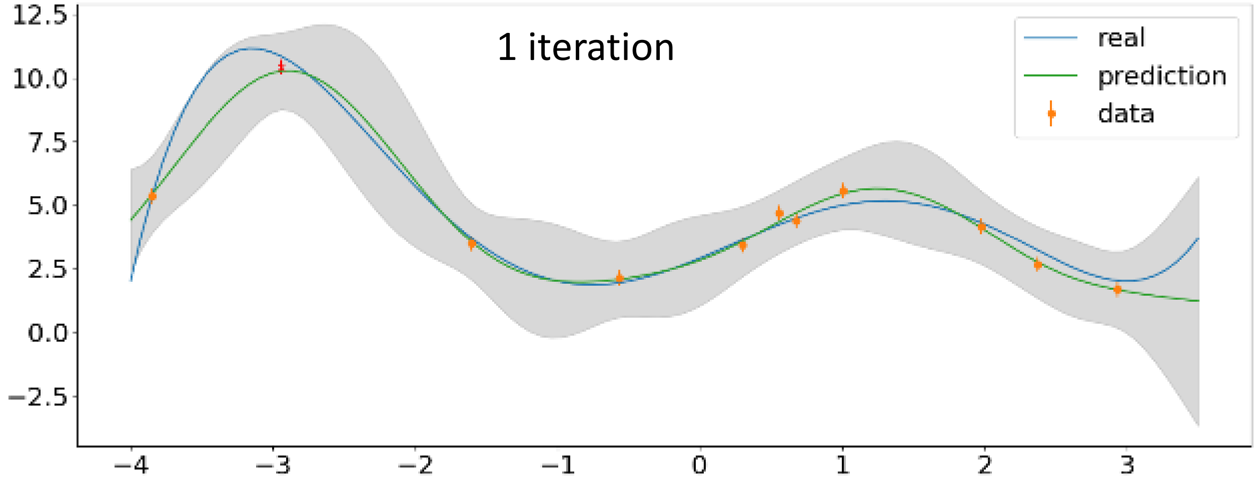


Measure next where $mean_y + \beta \cdot \sigma_y$ is maximum

Bayesian Optimization in a nutshell - III

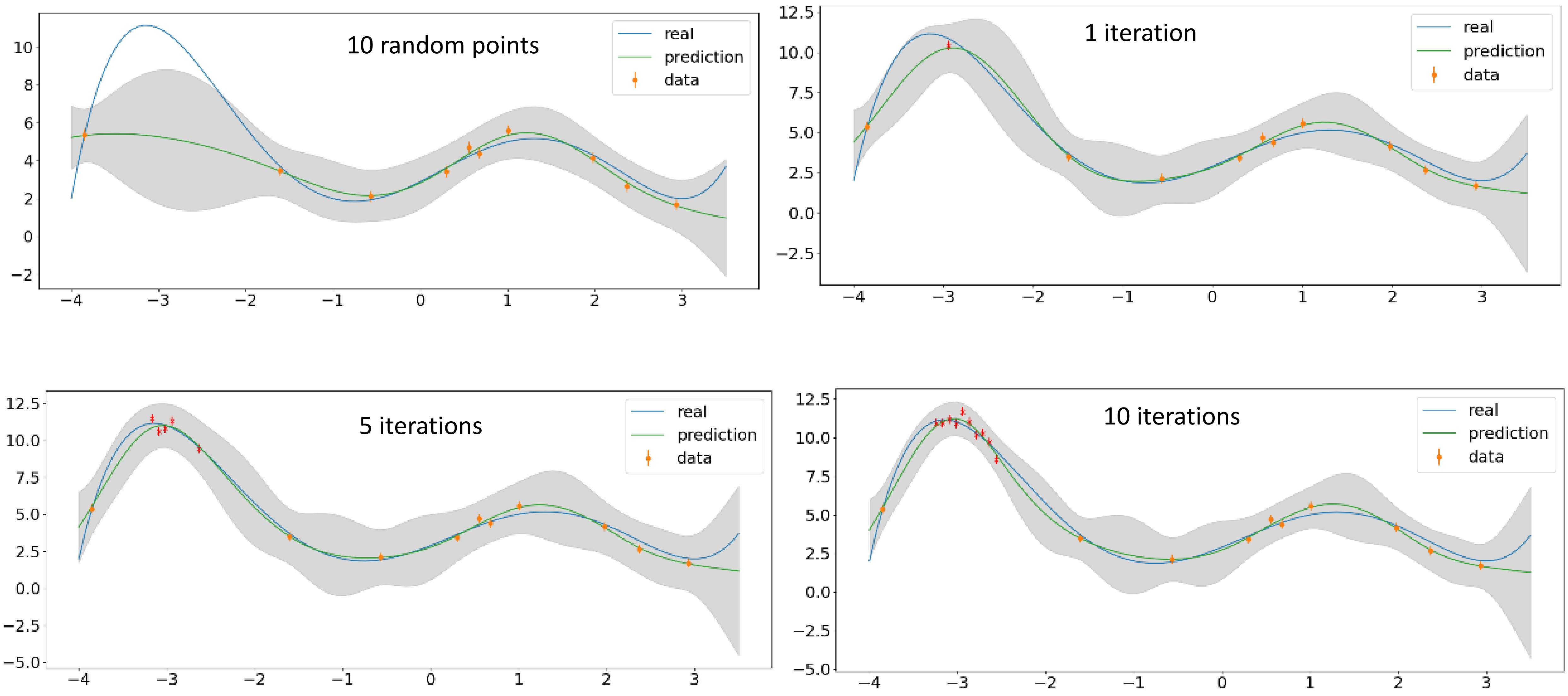
Example: seek global max with 1 dimension x variable



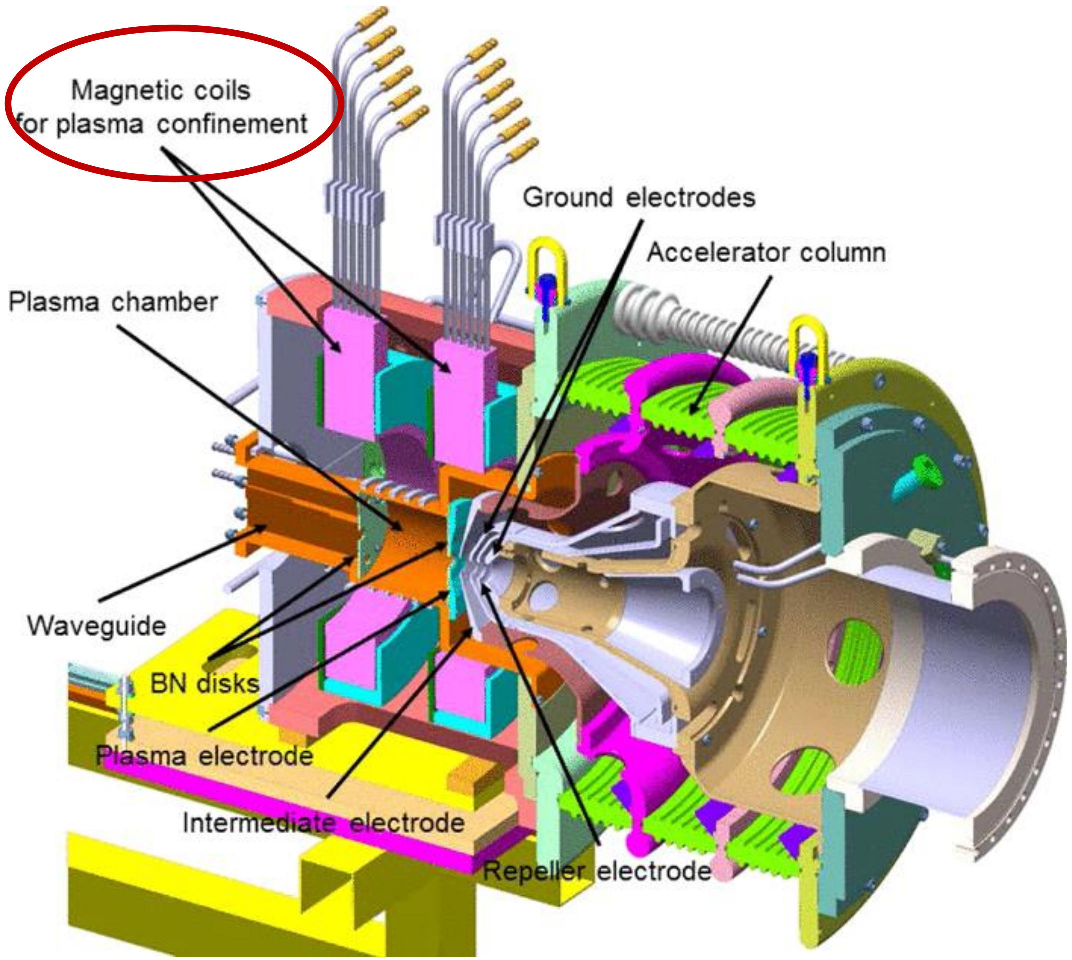


Bayesian Optimization in a nutshell - III

Example: seek global max with 1 dimension x variable



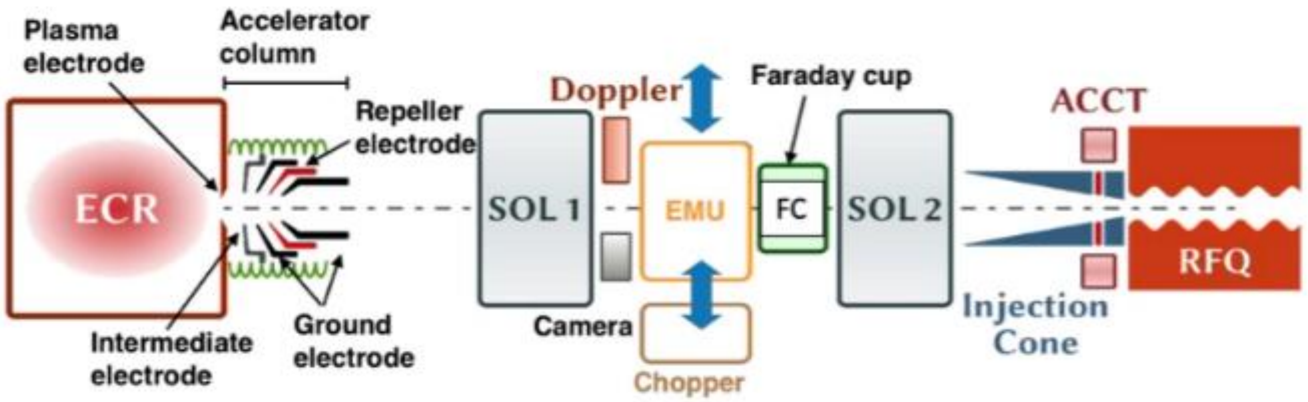
ECR BO: walk before you run



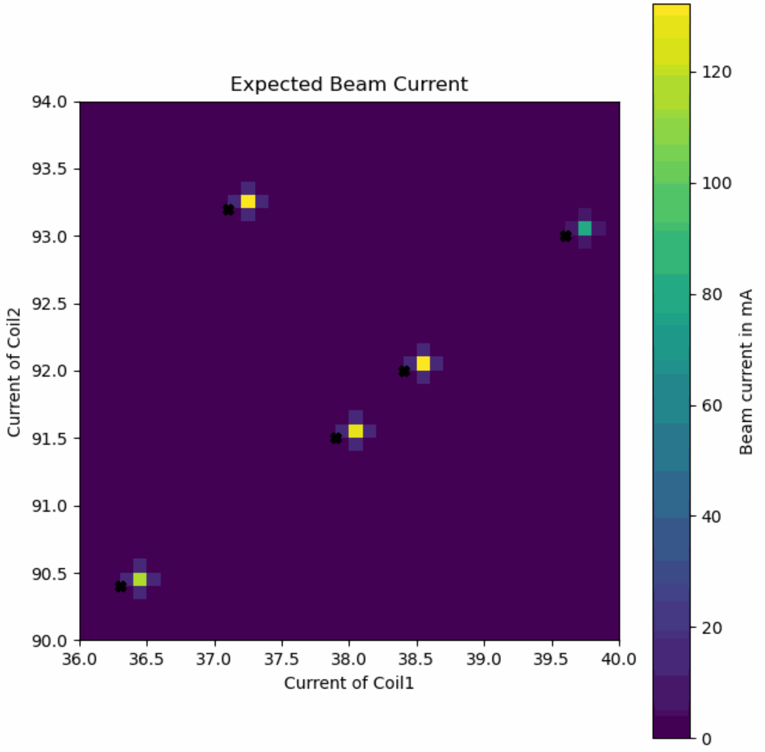
Test on Mar 2022 with D+ beam.

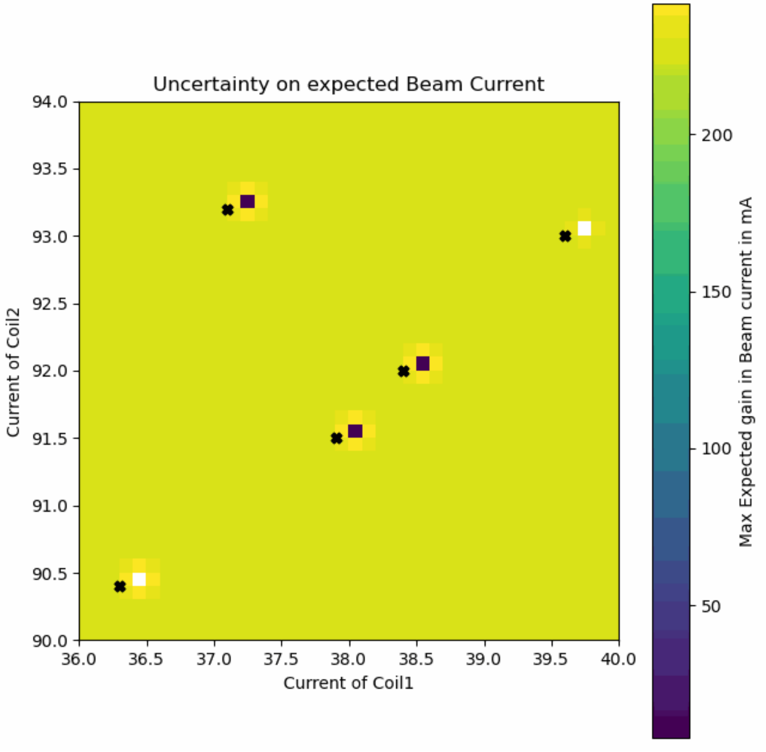
Tuning parameters:
Field of 2 magnetic coils

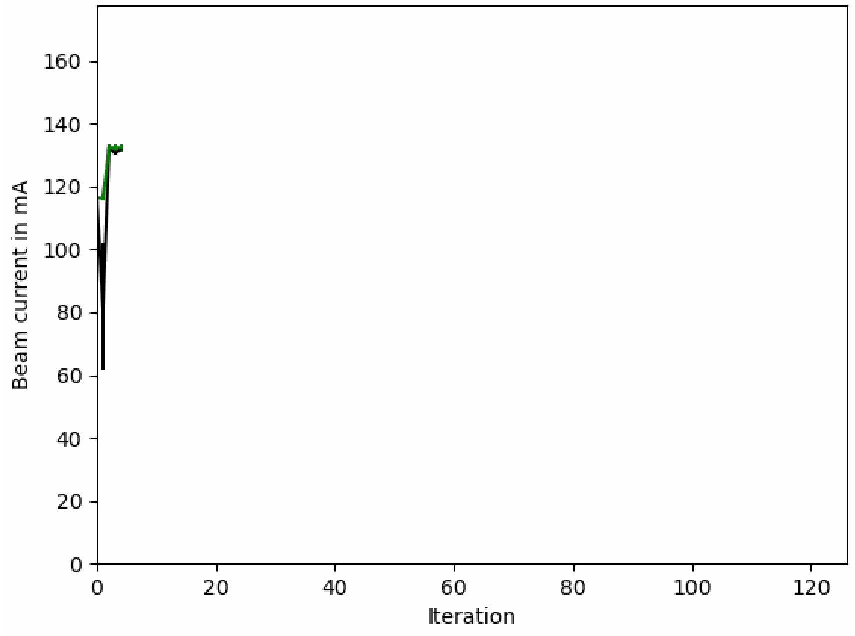
Target:
Max beam current measured at faraday cup



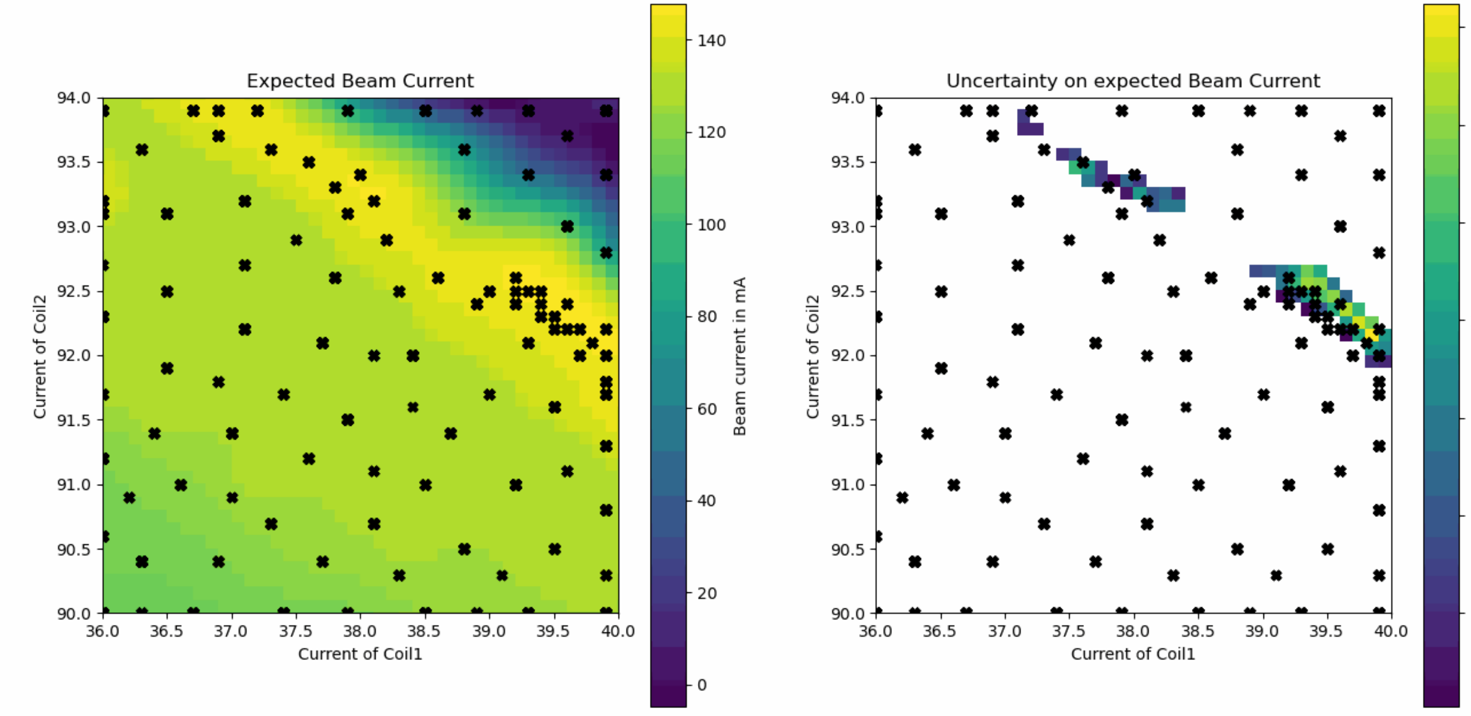
First Results

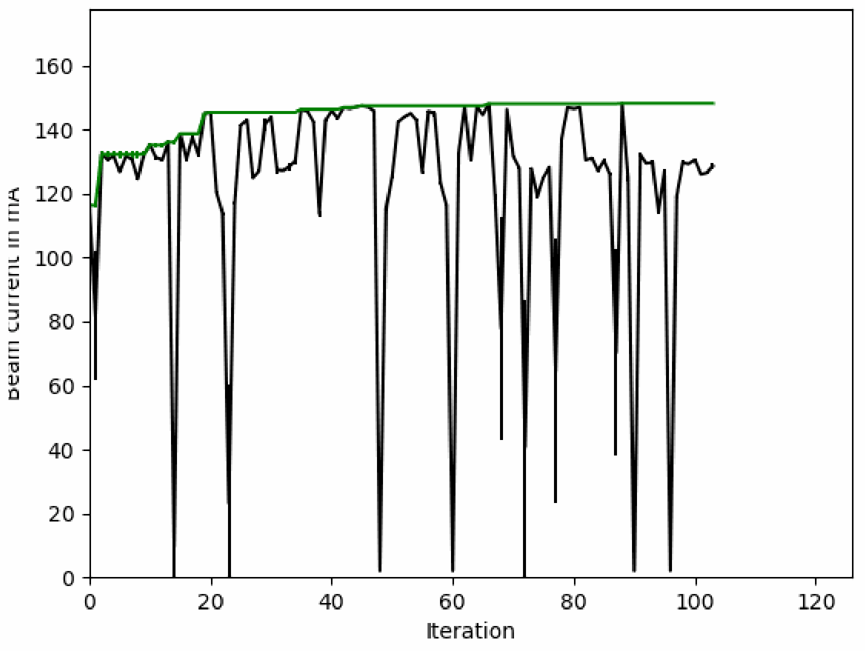






Next step: more variables & include stability





<u>Next step:</u>

Variables: 2 (Sol1, Sol2) → 4 (RF power, gas flow, 2x RF tuners)

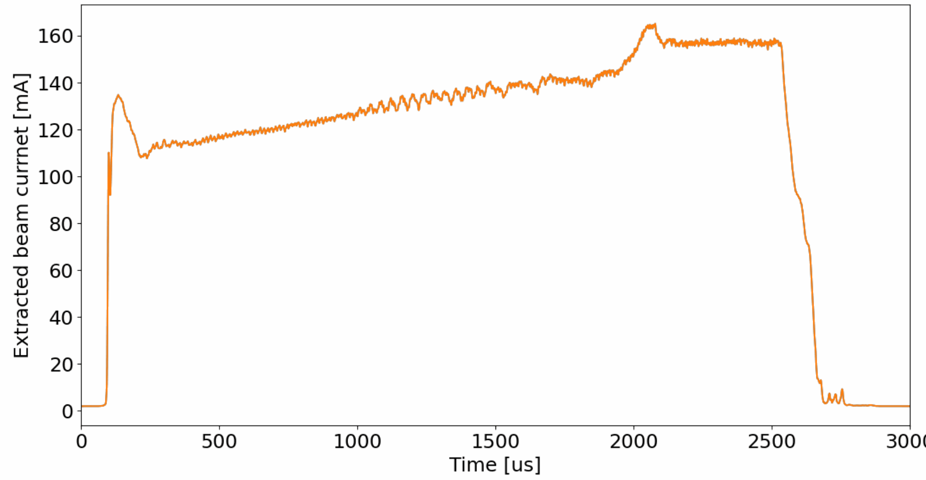
Some settings lead to very unstable extraction

→ create 2 models: Avg current; Std current over 30 shots

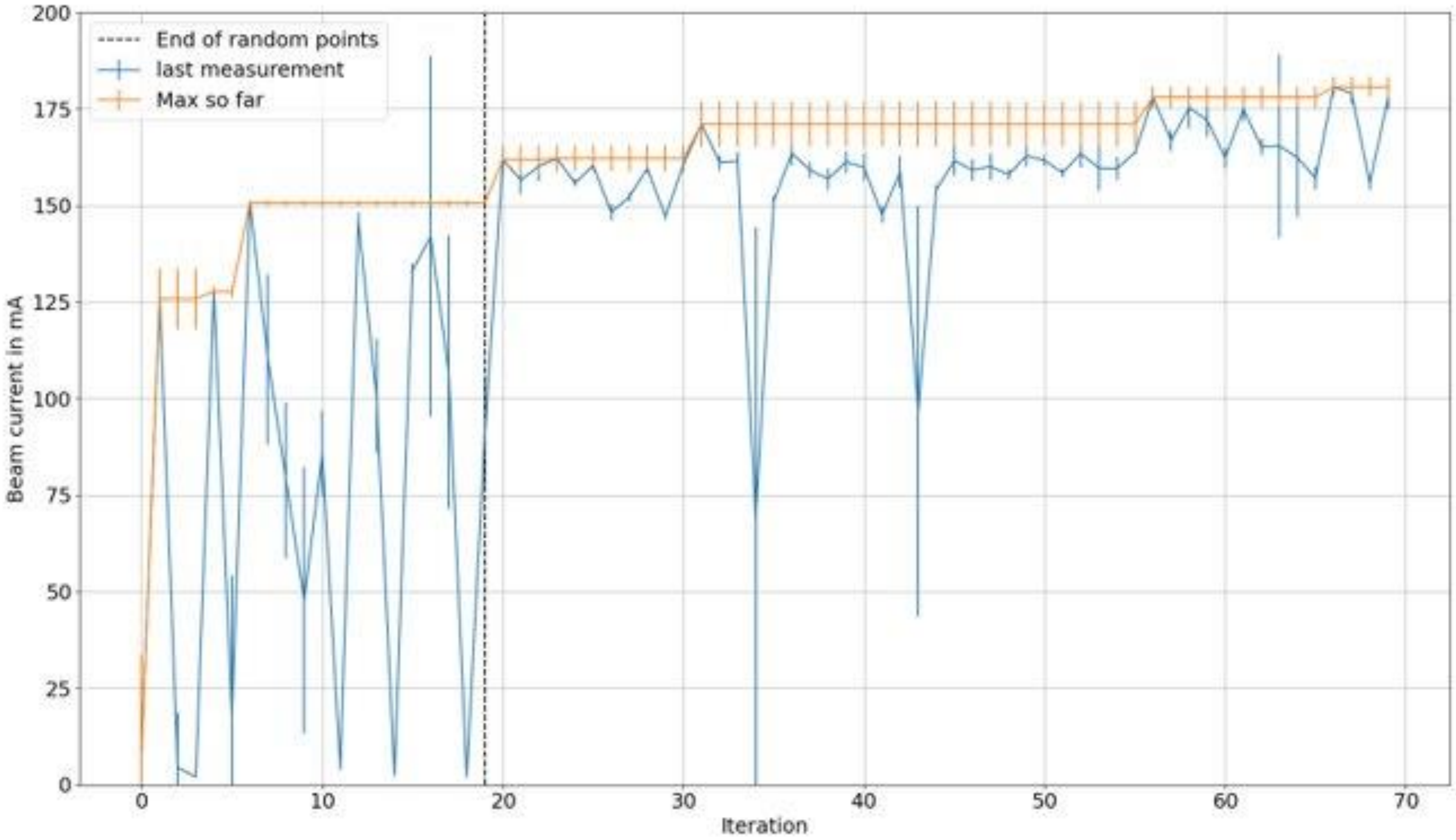
Acquisition function:

Select where Std - $\beta_{std} \cdot \sigma_{std} < 3$ mA

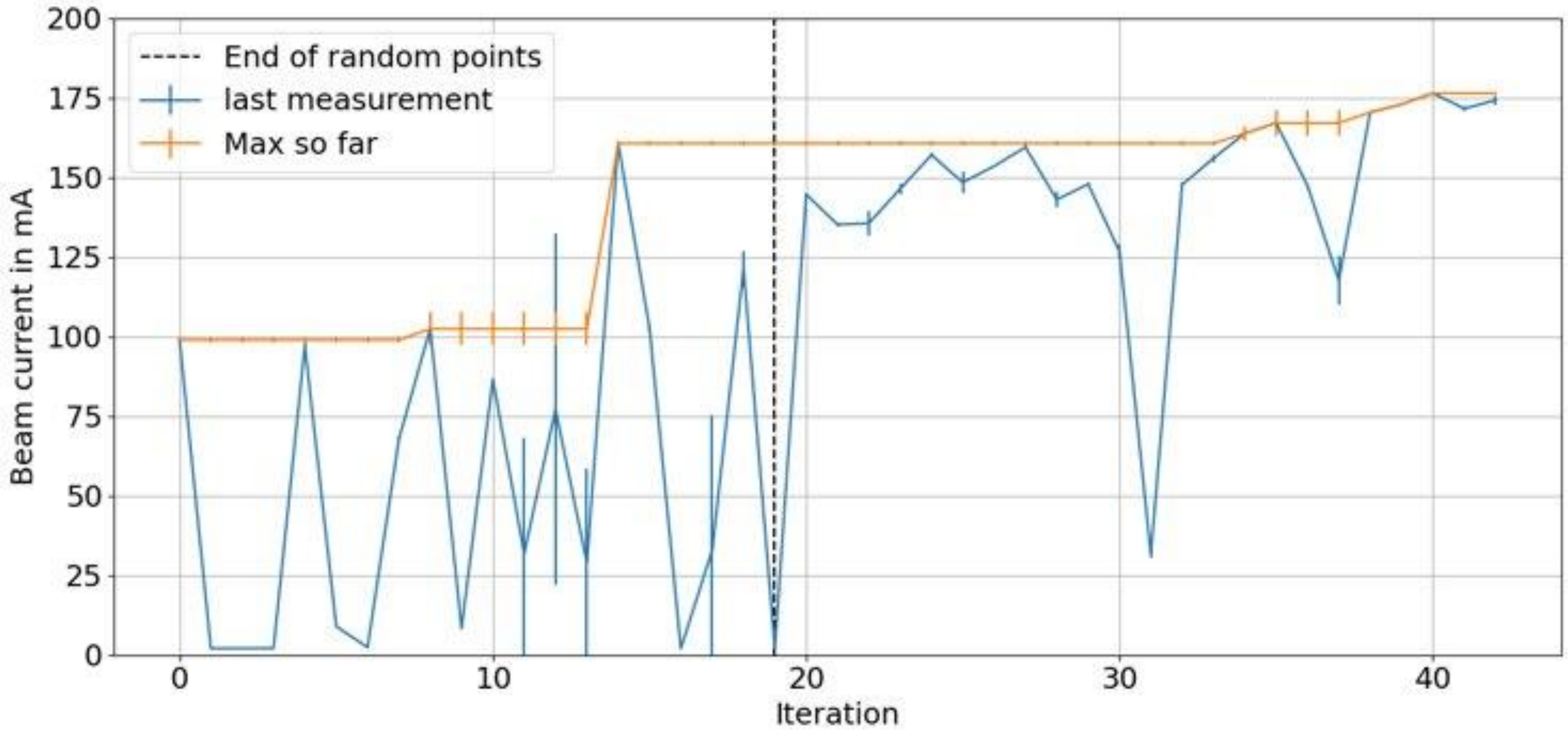
In this space Max(Avg + $\beta_{avg} \cdot \sigma_{avg}$)



4 Variables → Max(Avg I) & Std I < 3mA

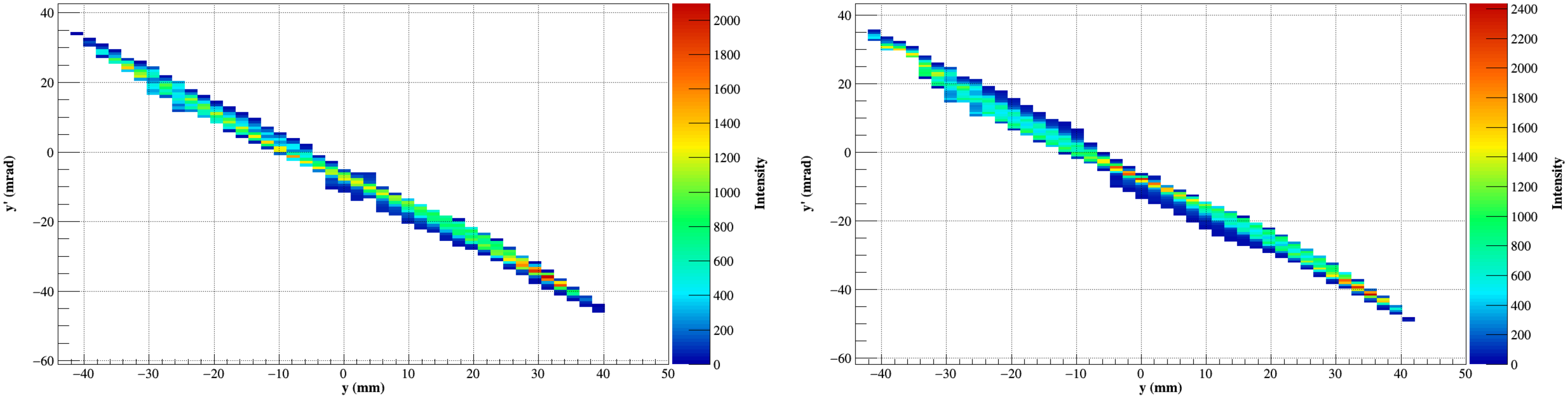


6 Variables → Max(Avg I) & Std I < 3mA



Emittance?

153 mA – 0.31 π mm mrad → ML opt → 173 mA – 0.42 π mm mrad

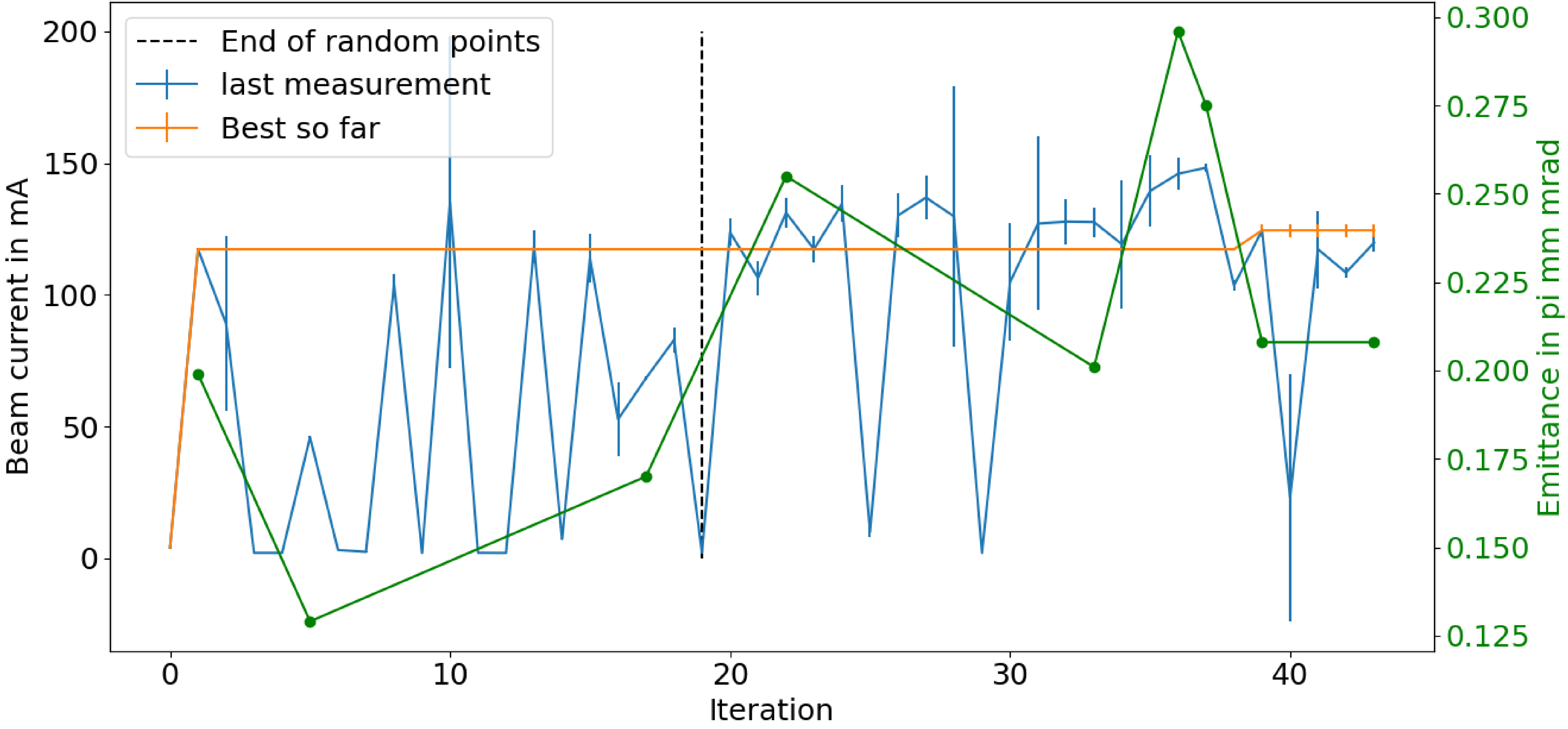


Significantly improved extracted current, but emittance is too large…

→ include a 3rd model for emittance

sample acquisition function where emittance < threshold

6 Variables → Max(Avg I) & Std I < 3mA & Eps < 0.25 π mm mrad



Ongoing works

ECR ML optimization

- multi-fidelity Bayesian Optimization
- adaptive emittance measurement
- identify pareto front of current, stability, emittance compromise
- semi-continuous live optimization (change of duty cycles, every morning, etc.)
- interpretation of physical patterns in surrogate model
- develop semi-analytical physical models

Other uses of ML for LIPAc/IFMIF:

- Optimization of LEBT optics for RFQ transmission with BO (real data)
- Optimization of HEBT optics for best energy spread measurement’s resolution with Genetic Algorithm (in simulation)
- Optimization of MEBT optics to minimize vacuum pressure with BO (real data + constraint from simulations)
- Reconstruction of longitudinal phase space with Neural Networks
- …

Personal opinion on ML

Trends:

- Presence is the accelerator community growing exponentially. (In Japan: 加速器機械学習フォーラム)
- Sexy topic with potential multi-disciplinary collaborations.
- In 10+ years every major facility will very likely use it many ways.

Clear communication/expectations:

- We should not expect order of magnitude better performances. Tools to saves expert time is a good achievement.
- It requires a step-wise approach, early attempts are useless use-cases, but necessary stepping-stones. (First teach yourself how to teach to a machine…).
- Superior pattern recognition could lead to physics/science insights.

Our approach:

- Start with simple models and later move to blacker and blacker boxes libraries.
- Seeking multi disciplinary and diverse group collaborations.
- Never forget the physics!

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- Seeking multi disciplinary and diverse group collaborations.
- **Never forget the physics! Never forget the physics! Never forget the physics!**

Conclusion

- The 6 main variable parameters of LIPAc's ECR ion source have been optimized with Bayesian optimization to achieve high extracted beam current with low fluctuations and small transverse emittance.
- Committed to compare surrogate models with simulations and develop physics interpretations.
- LIPAc/IFMIF team is committed to continue and expand the applications of ML to support experts in operations, tuning, data analysis and physics interpretation.
- We welcome new collaborations: proposal of ML for LIPAc ; our tools/experience in ML for your machine.

ありがとうございました！

This work was undertaken under the Broader Approach Agreement between the European Atomic Energy Community and the Government of Japan. The views and opinions expressed herein do not necessarily state or reflect those of the Parties to this Agreement.