Beam halo losses reduction with simulation constrained Bayesian Optimization.

DE FRANCO Andrea on behalf of the IFMIF/EVEDA project team

5th ICFA Beam Dynamics Mini-Workshop on Machine Learning for Particle Accelerators

Linear IFMIF Prototype Accelerator (LIPAc)

Rokkasho Fusion Institute (BA Site)

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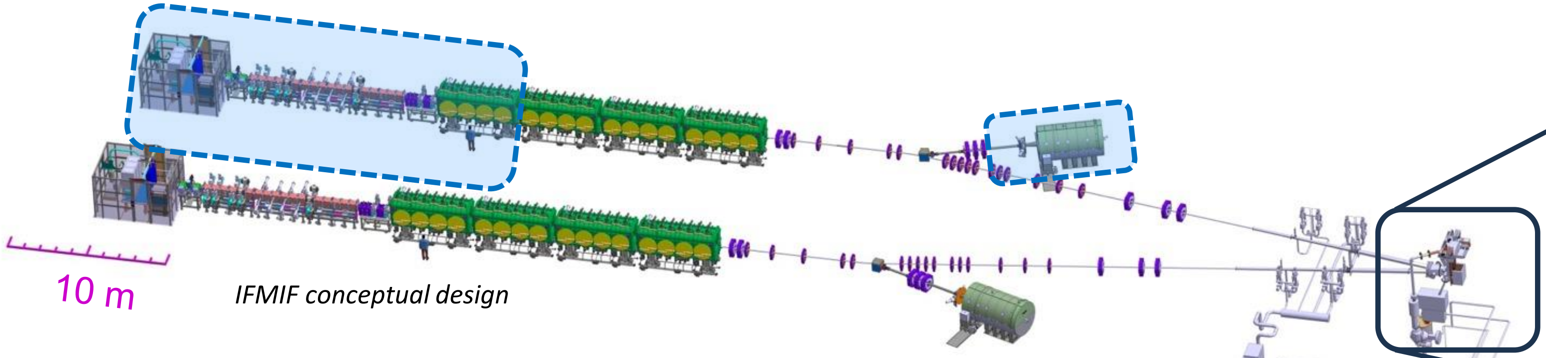
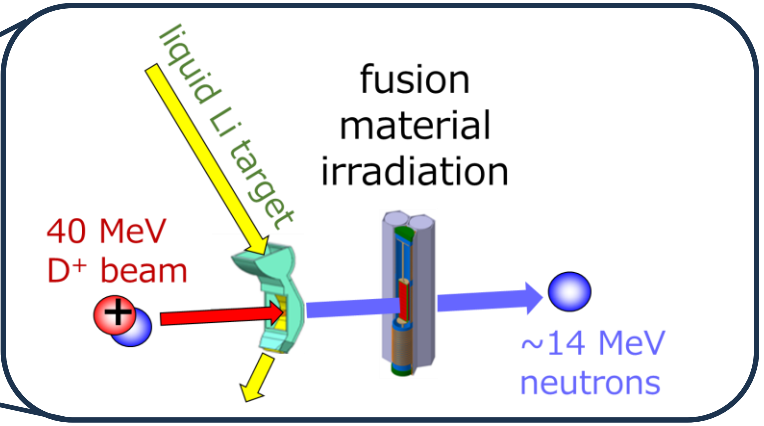
Linear IFMIF Prototype Accelerator

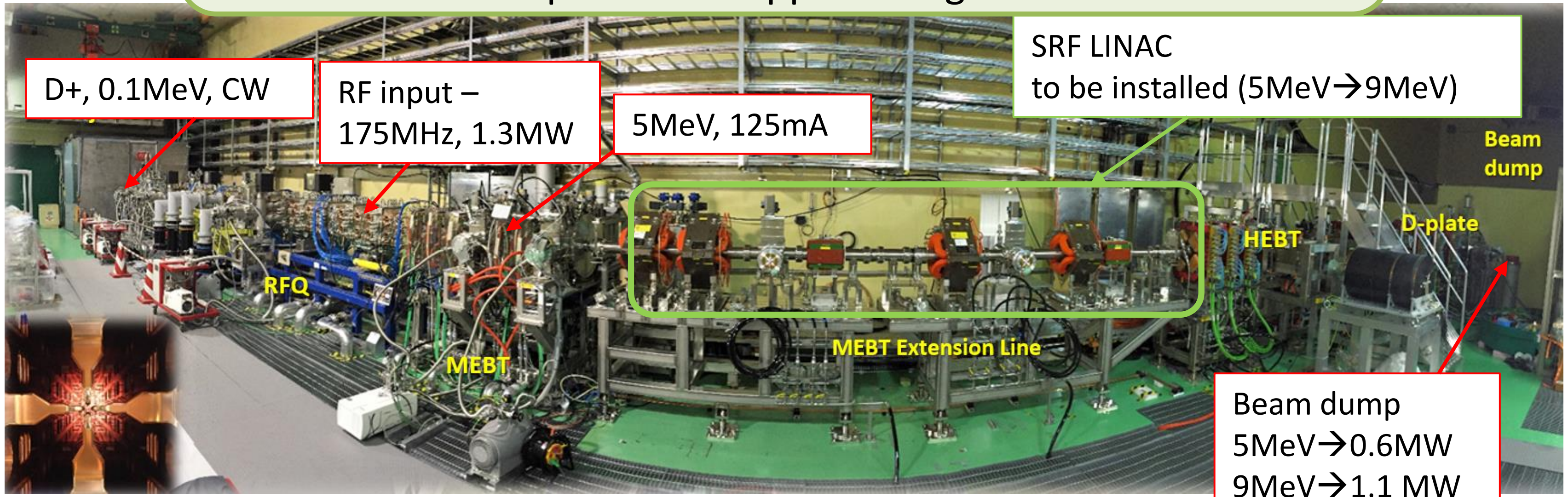
International Fusion Materials Irradiation Facility (IFMIF) will address the need of a neutron source for material tests toward future Fusion Power Plant



IFMIF conceptual design



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



Fisheye view of LIPAc

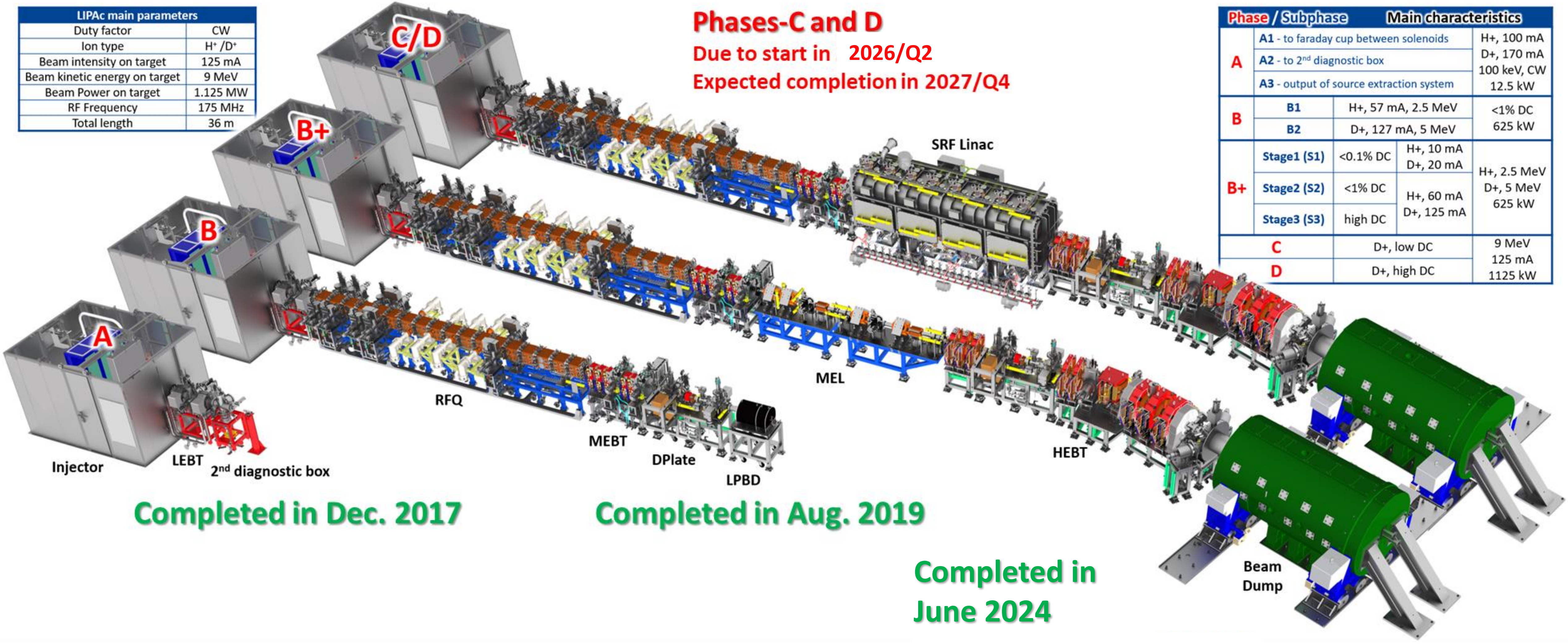
Status

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 2026/Q2
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

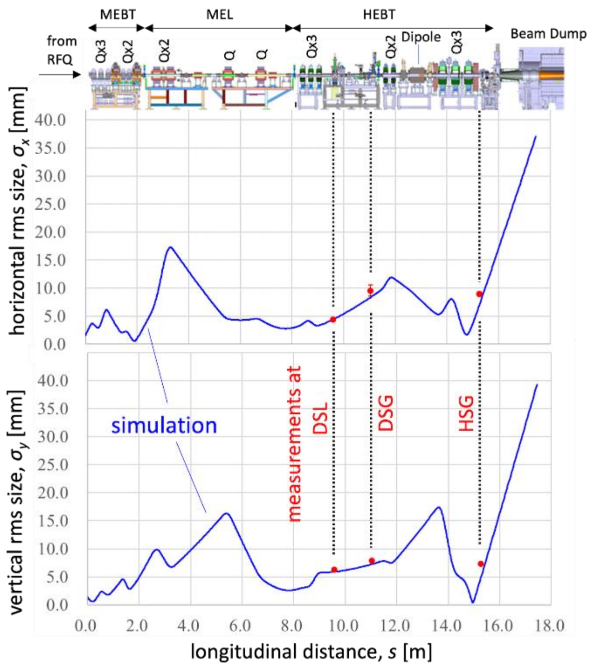
Beam losses optimization

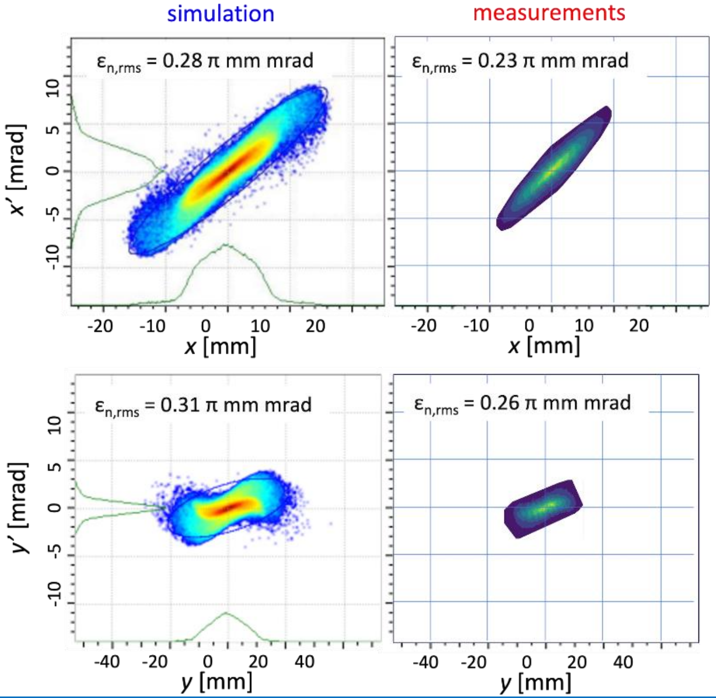
Fine optimization of beam losses is important because of the high intensity (1.1MW):

- Component integrity
- Quench prevention in SRF (10 W → 1e-5 losses!)
- Minimize activation for maintenance activity

Beam core-optics was verified and optimized at low duty cycle (<0.1 %)

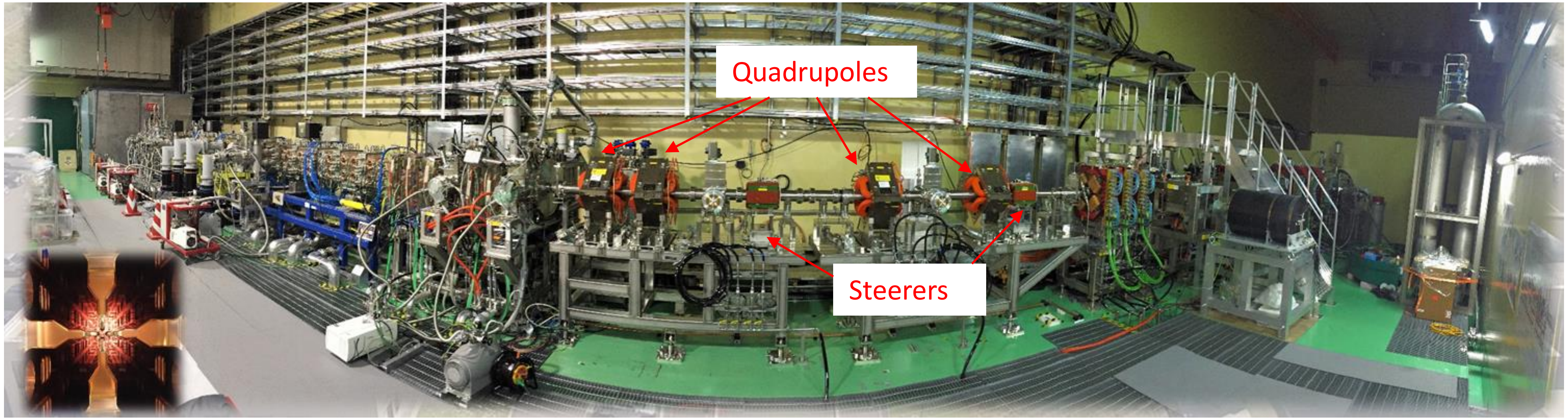
- Simulation model improved until good agreement obtained
- Optics/ cavity settings optimized until beam loss detectors barely respond





The challenge

When increasing duty cycle (~3%), vacuum pressure in transport line approached interlock level.
Hypothesis: vacuum pressure high because of losses
Losses from beam-core already optimized → how to reduce beam-halo losses?
Difficult to simulate because it requires precise knowledge of input beam distributions & all field perturbations.



IDEA:

Bayesian Optimization of optics (4x quads + 4x steerers) to minimize vacuum pressure?

Could work!!!

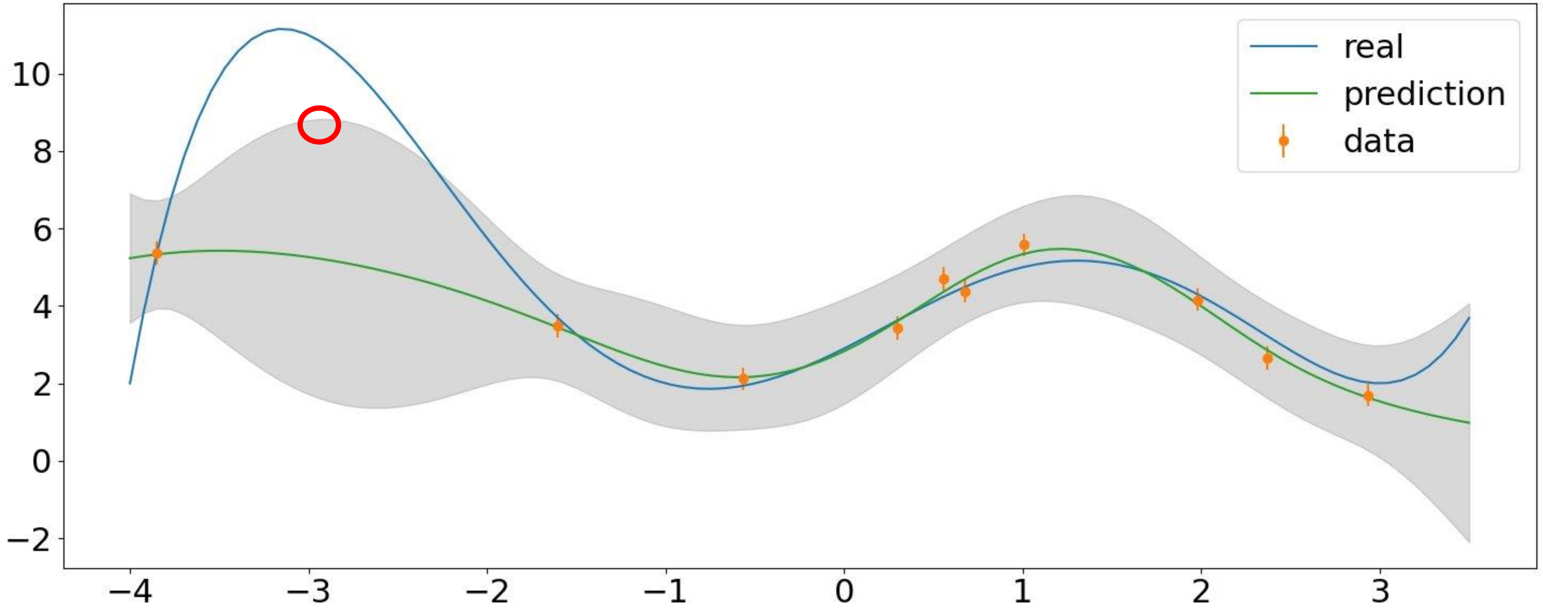
The “standard” algorithm (maximise ex.)

Surrogate model → Acquisition function → Optimization of acq. function

Vac(q1,…,q4,s1,…,s4)
μ: Mean
σ: uncertainty

UCB (q1,…,q4,s1,…,s4)
$\mu + \beta\,\sigma$

Find where UCB is maximum.
ADAM, L-BFGS, etc.



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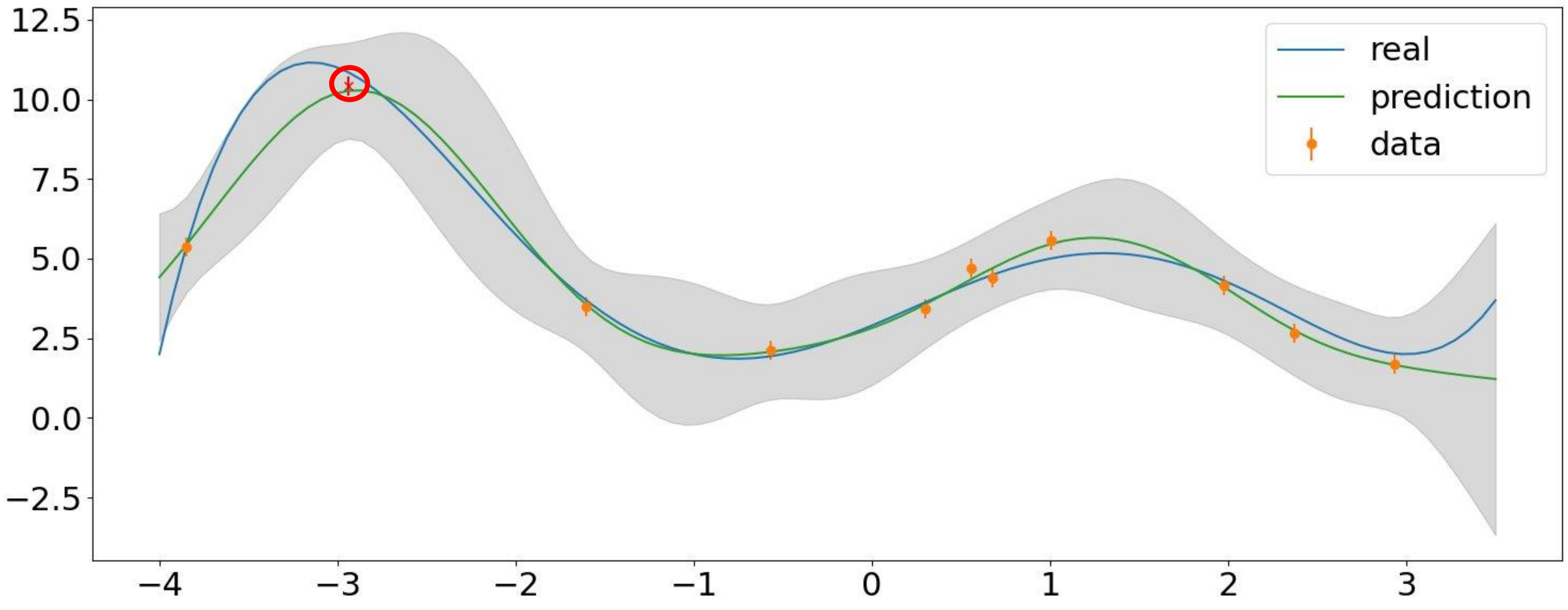
↓

Measure Vac at:
candidate *q1,…,q4,s1,…,s4*



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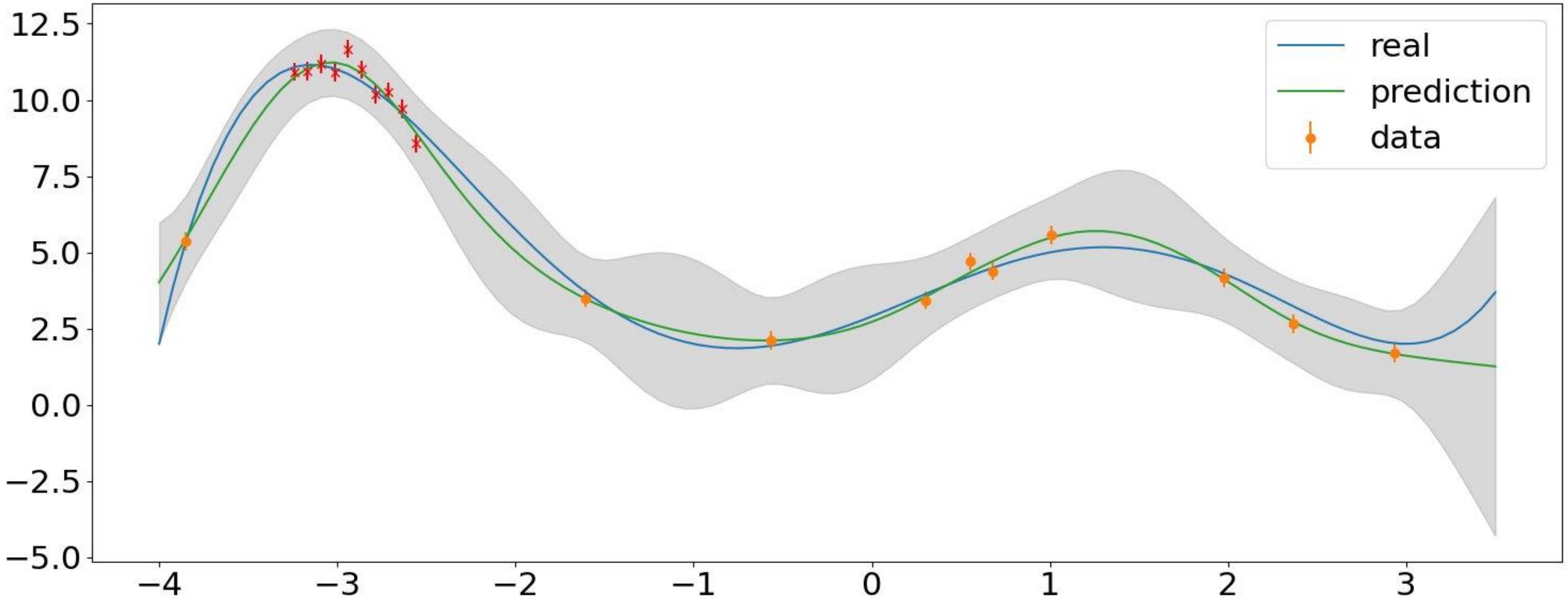


Measure Vac at:
candidate *q1,…,q4,s1,…,s4*

Repeat until satisfied

The "standard" algorithm

Surrogate model

Vac(q1,…,q4,s1,…,s4)
μ: Mean
σ: uncertainty

Acquisition function

UCB (q1,…,q4,s1,…,s4)
$\mu + \beta \sigma$

Optimization of acq. function

Find where UCB is maximum.
ADAM, L-BFGS, etc.

Measure Vac at:
candidate *q1,…,q4,s1,…,s4*

What if some settings leads to high core losses?

Option 1: Trust that Vacuum is ALWAYS a good estimate for losses (also core ones) and constraint the Opt. of acq. Func. to select candidates within safety boundaries

Option 2(this work): Use reliable simulation information for core losses and assume halo-losses are not severe enough to cause problems

Include info of Core Losses

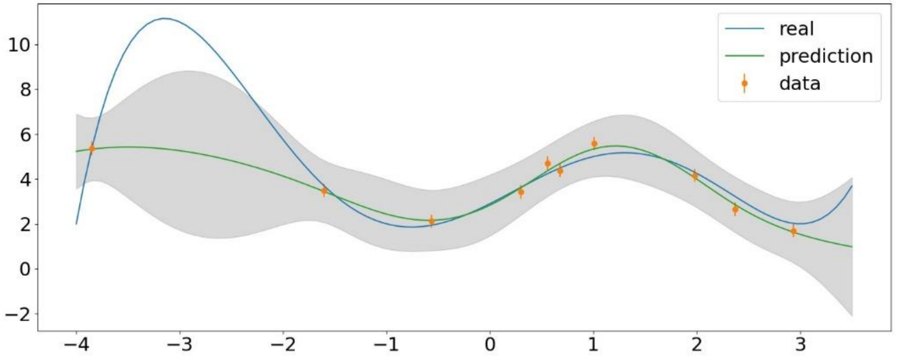
Surrogate model

Simulations core losses

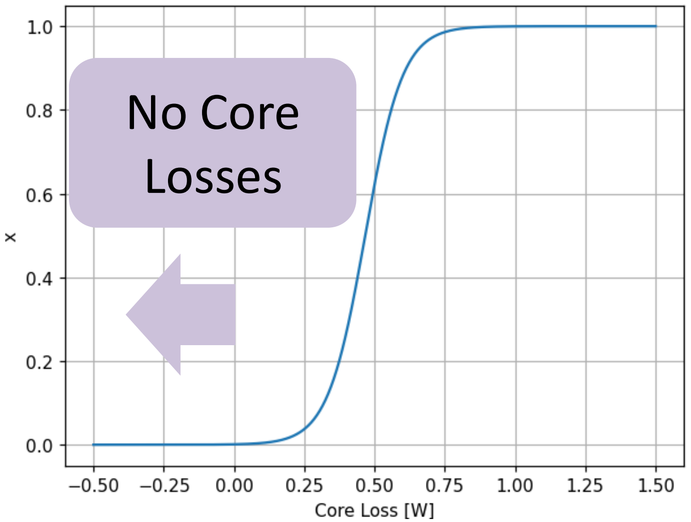
Vac(q1,…,q4,s1,…,s4)

CoreLoss(q1,…,q4,s1,…,s4)
From TraceWin code

Acquisition function



$$UCB(Vac) - 10^2\left(\frac{1}{1+e^{(-CoreLoss+\alpha)}}\right)$$



Simulation Core Losses – computational limitation

Optimization of acquisition func. typically requires O(100) of evaluations
Value of core losses required at each evaluation. But…

Envelope simulations are fast (<1s) but not precise enough because of strong space charge.
Particle tracking simulations requires O(100s) for 1 setting…

IDEA: pre-train a Bayesian surrogate model offline with ~5k simulations with random combinations of quadrupole, steering settings (~1 week)

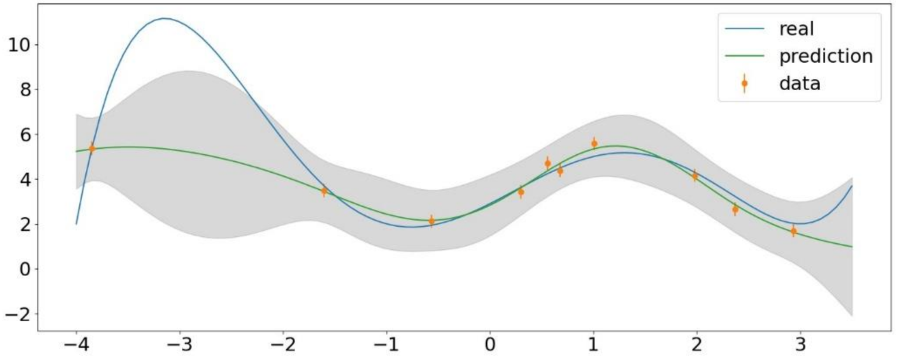
Core Losses – Surrogate core losses model

Surrogate model + Surrogate Simulations core losses

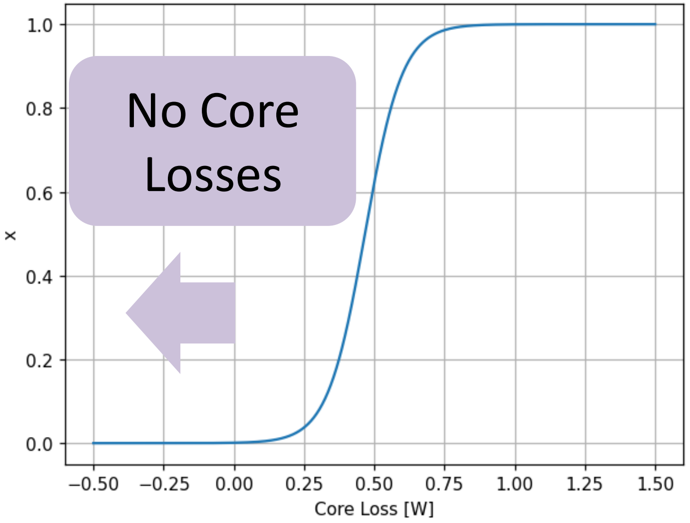
Vac(q1,…,q4,s1,…,s4)

CoreLoss(q1,…,q4,s1,…,s4)
From TraceWin code

Acquisition function



$$UCB(Vac) - 10^2\left(\frac{1}{1+e^{(-UCB(CoreLoss)+\alpha)}}\right)^{x}$$



BO with simulation constraints

Surrogate model

Vac(q1,…,q4,s1,…,s4)

+

Surrogate Simulations core losses

CoreLoss(q1,…,q4,s1,…,s4)

→ **Acquisition function**

$$UCB(Vac) - 10^2\left(\frac{1}{1+e^{(-UCB(CoreLoss)+\alpha)}}\right)$$

→ **Optimization of acq. function**

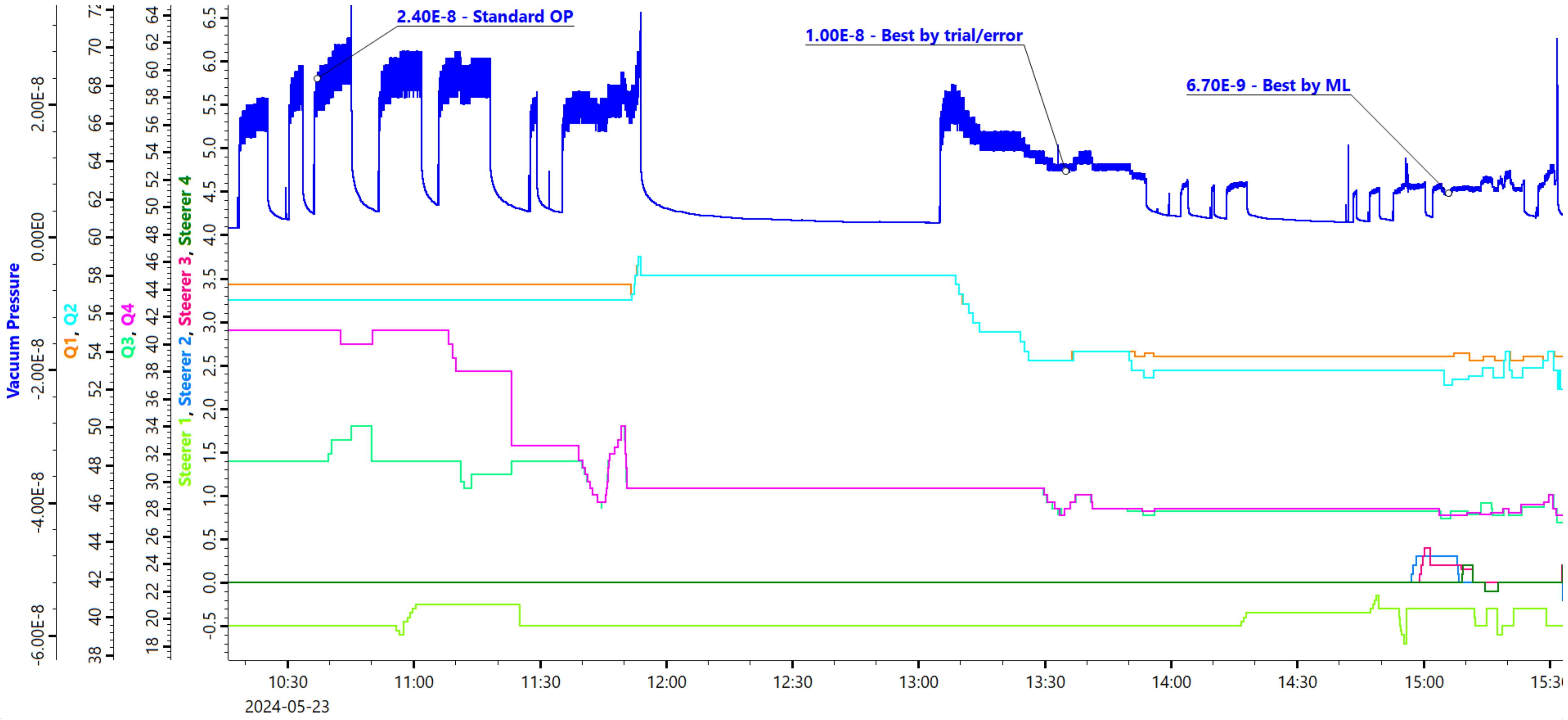
Find max of acq. Func. (ADAM)

↓ **Measure Vac at: candidate *q1,…,q4,s1,…,s4***

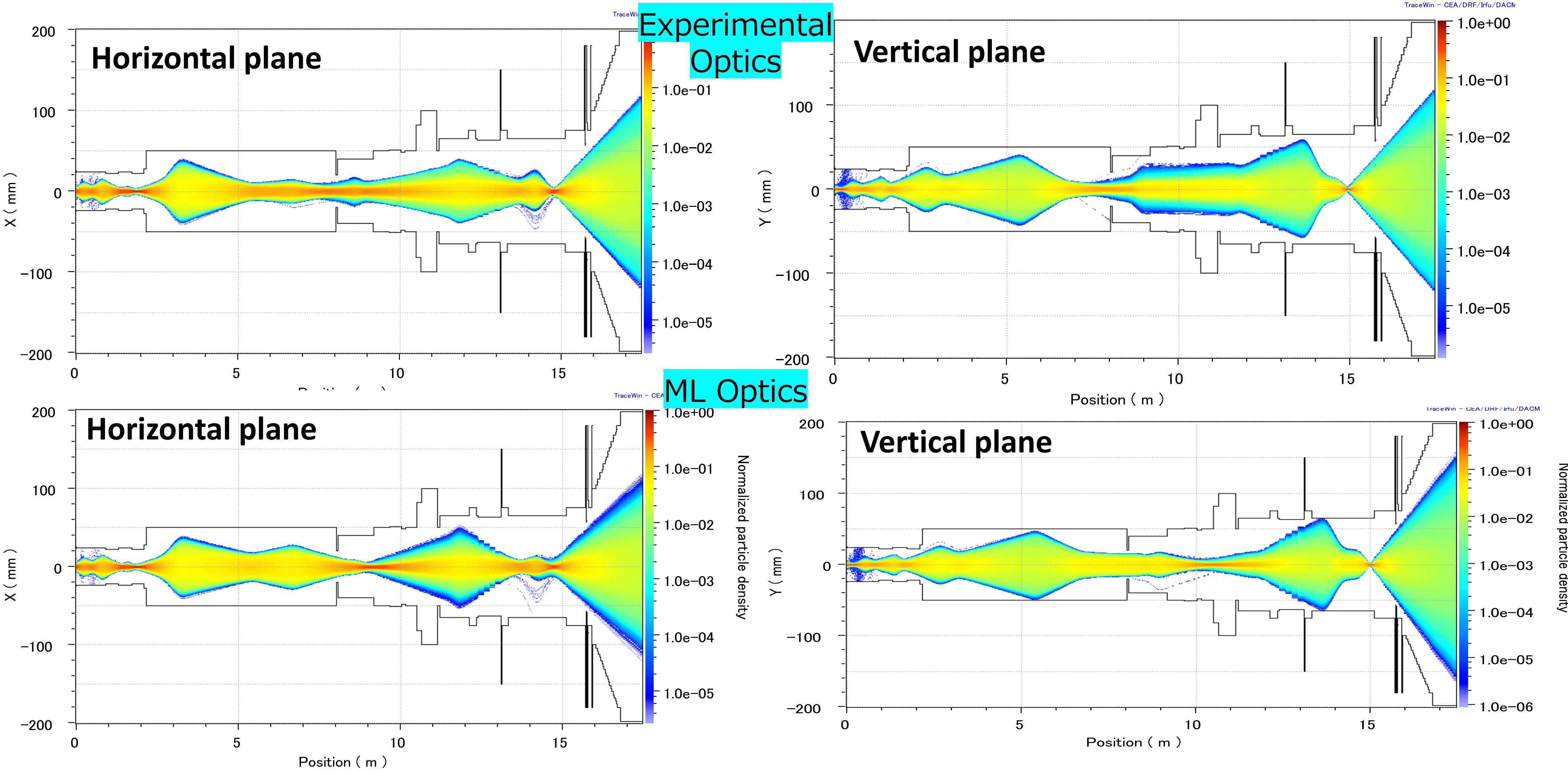
↓ **Repeat until ~~satisfied~~ time allows**

Library used: BoTorch with custom development for acquisition function and optimizer.

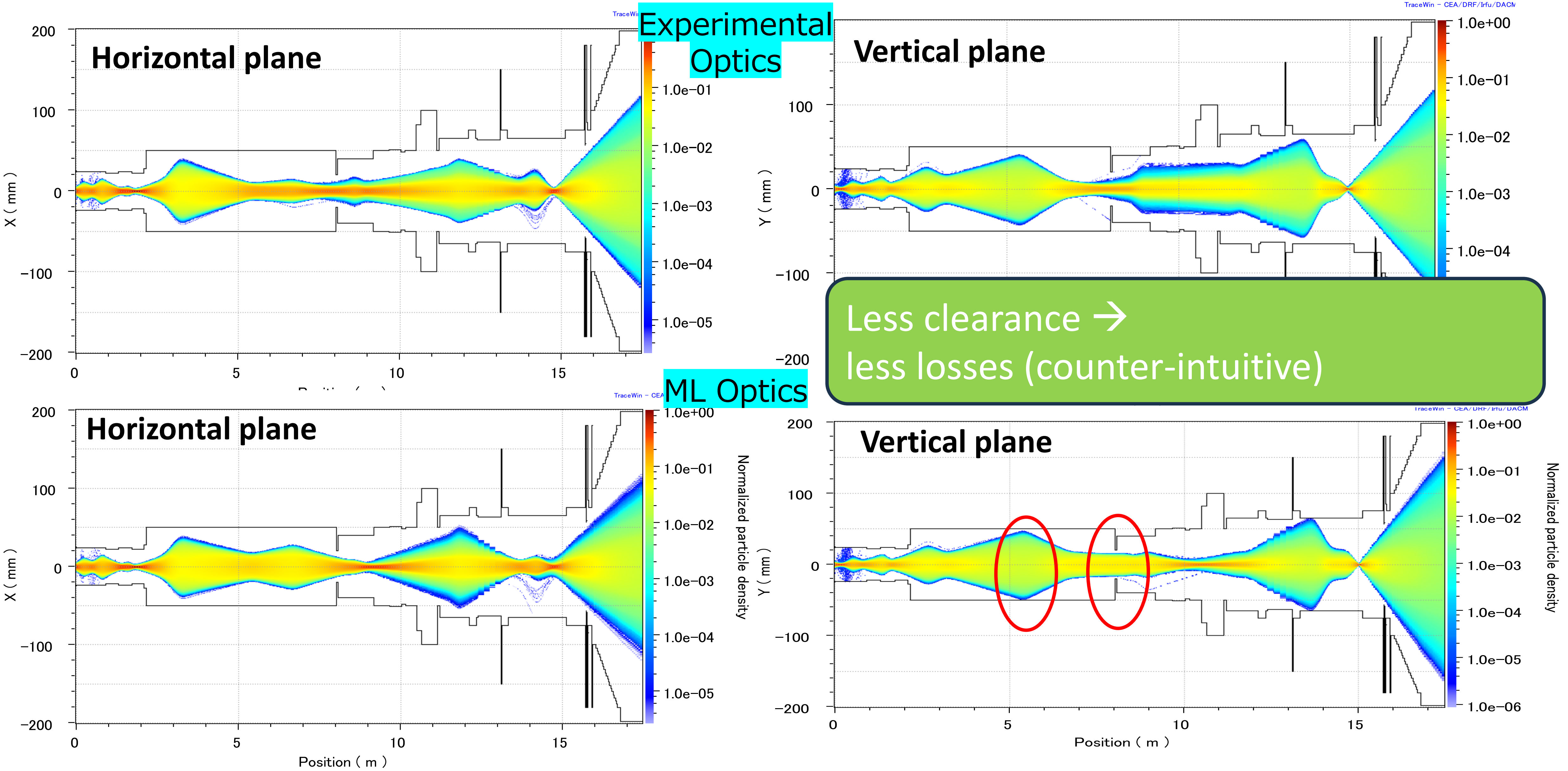
Test results



Look into beam dynamics - 1

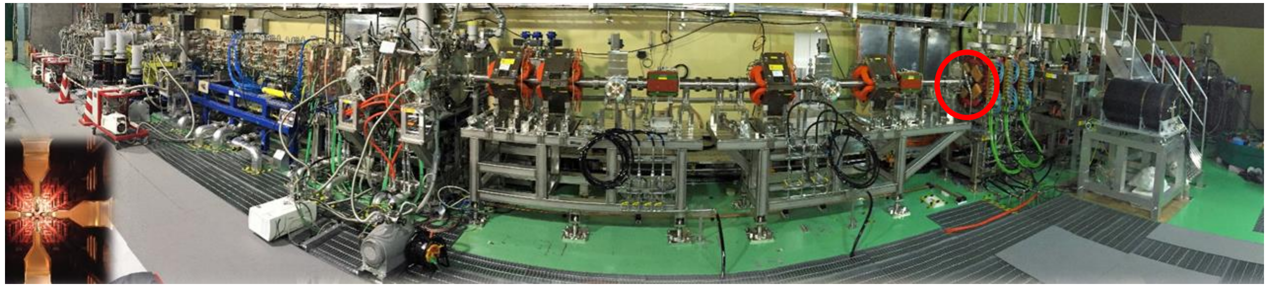


Look into beam dynamics - 1



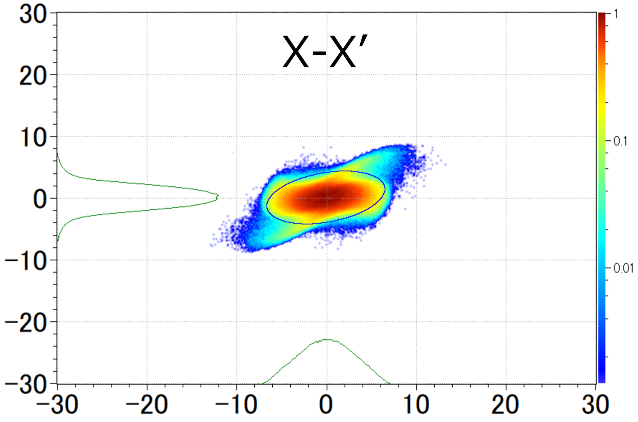
Less clearance →
less losses (counter-intuitive)

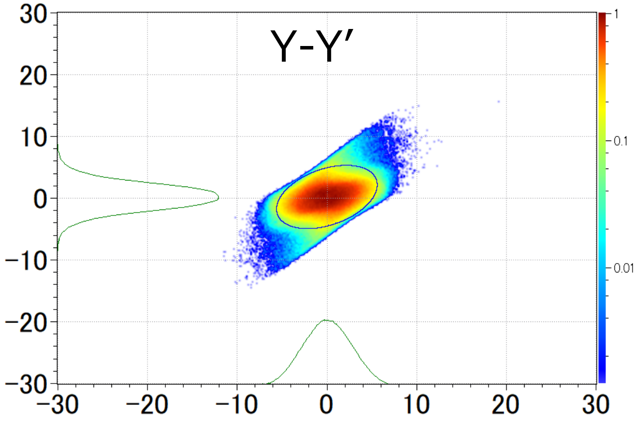
Look into beam dynamics - 2

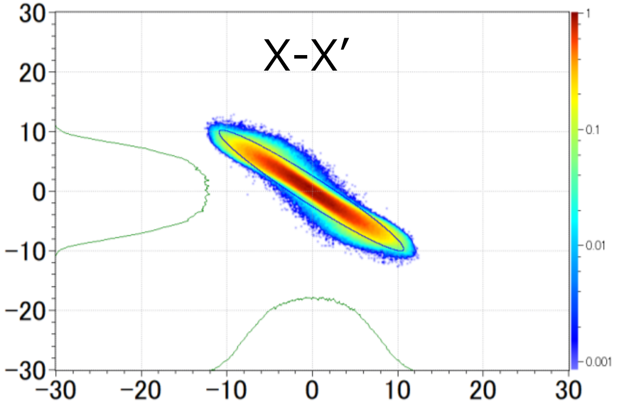


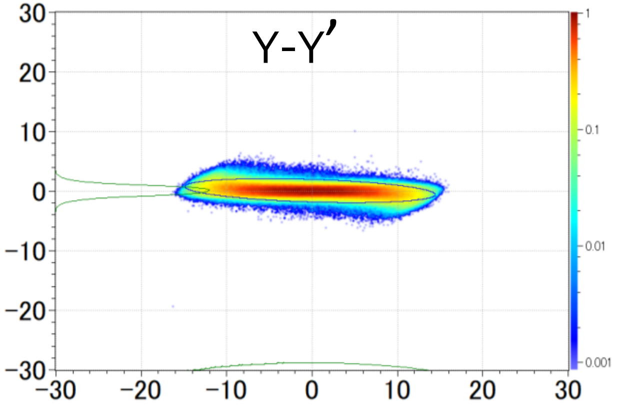
Experimental Optics

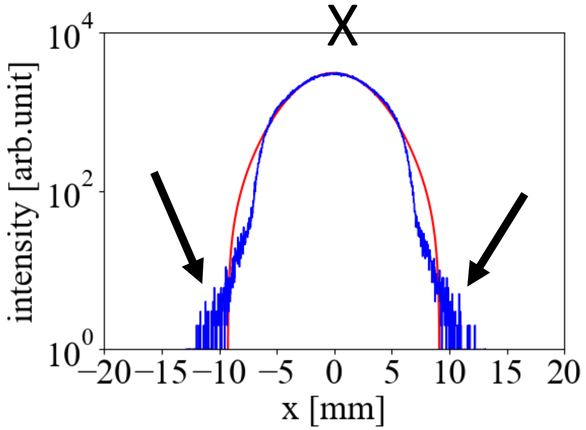
ML Optics

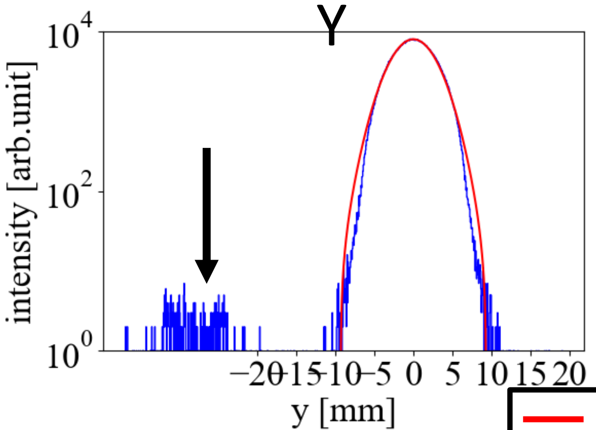


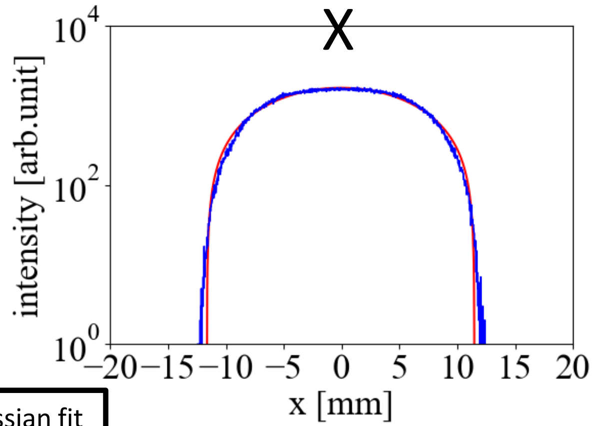


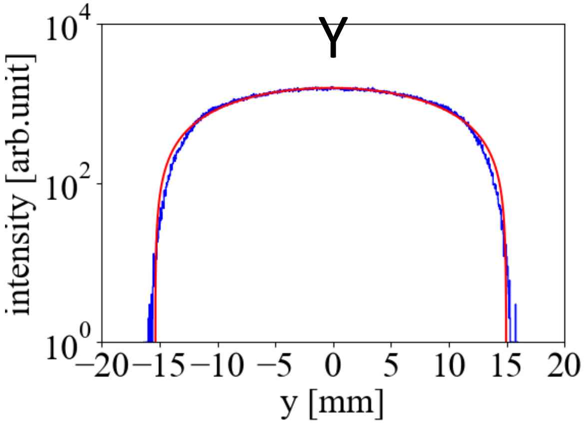






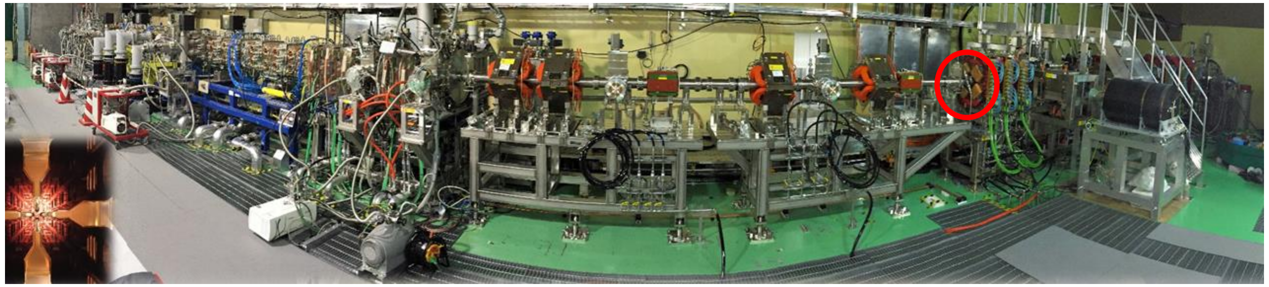






: Gaussian fit

Look into beam dynamics - 2



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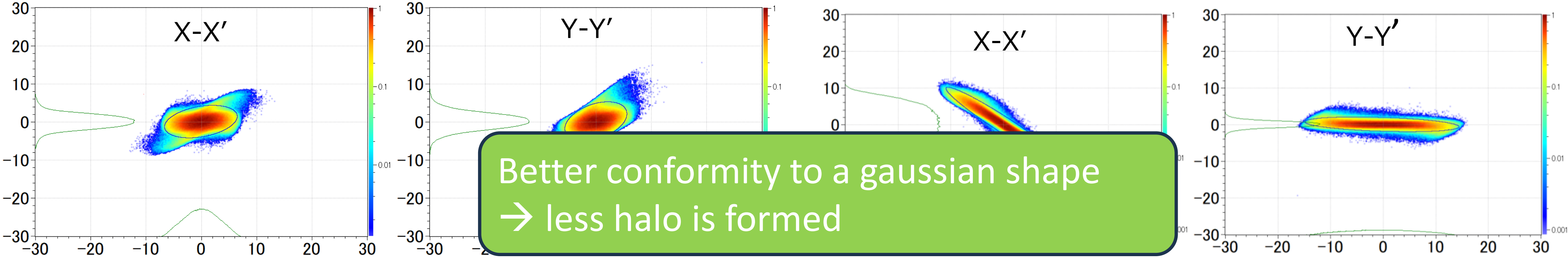
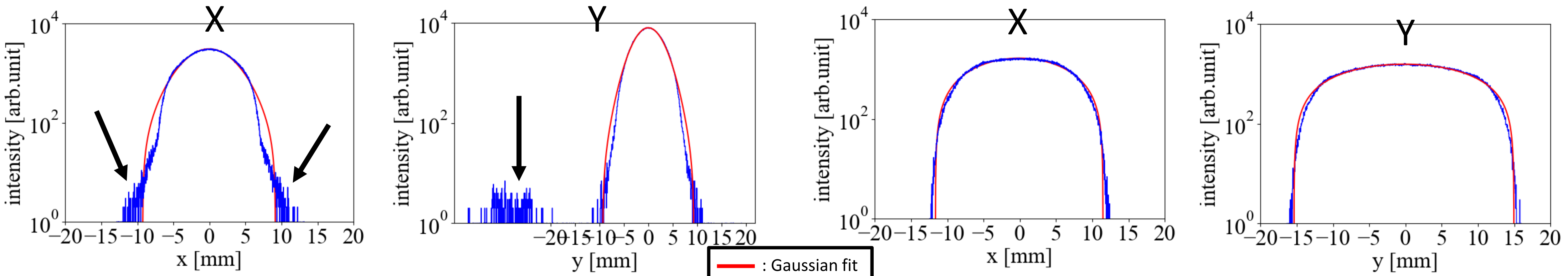


Better conformity to a gaussian shape
→ less halo is formed

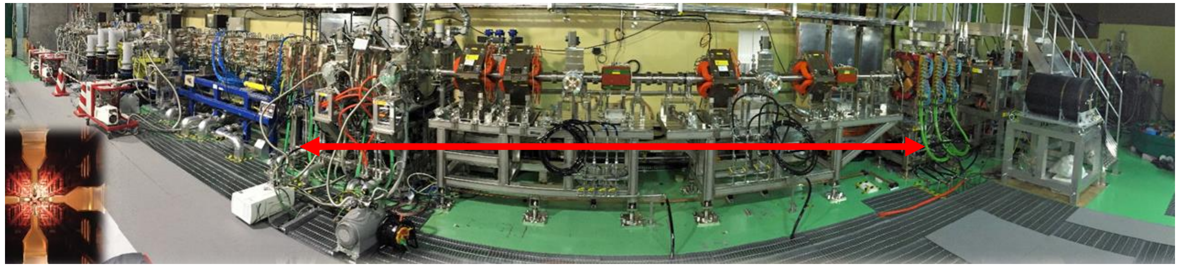


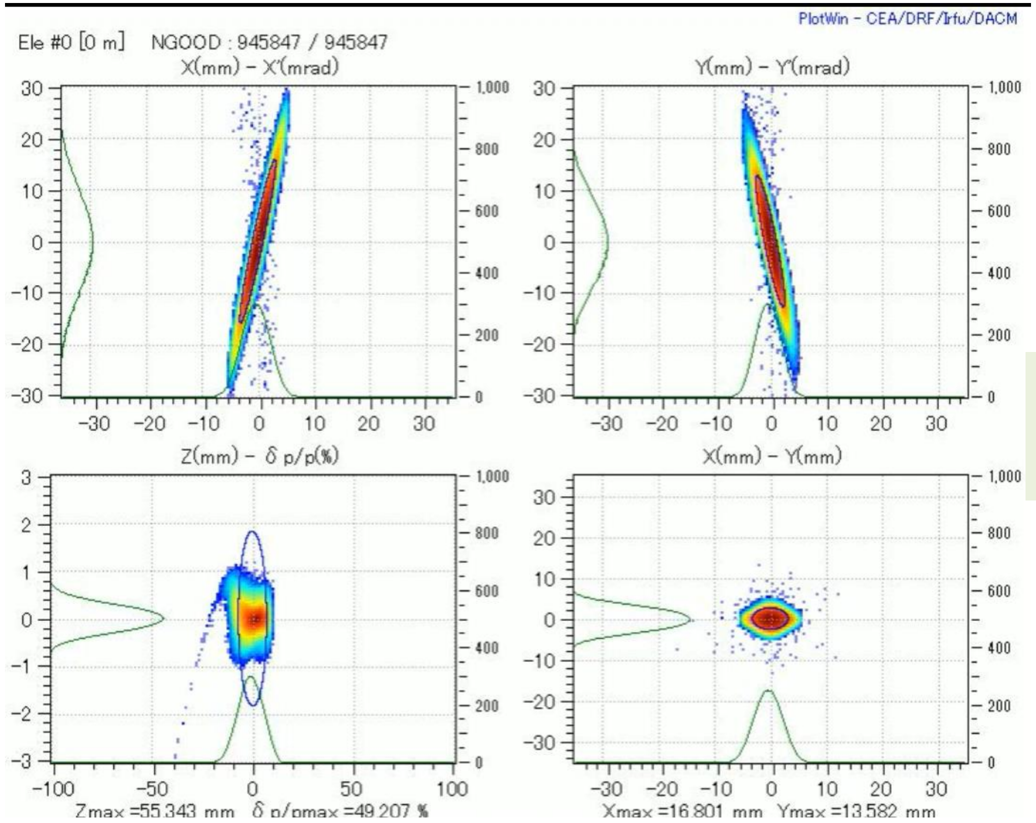
: Gaussian fit

Look into beam dynamics - 3

Physics interpretation of choices ML did

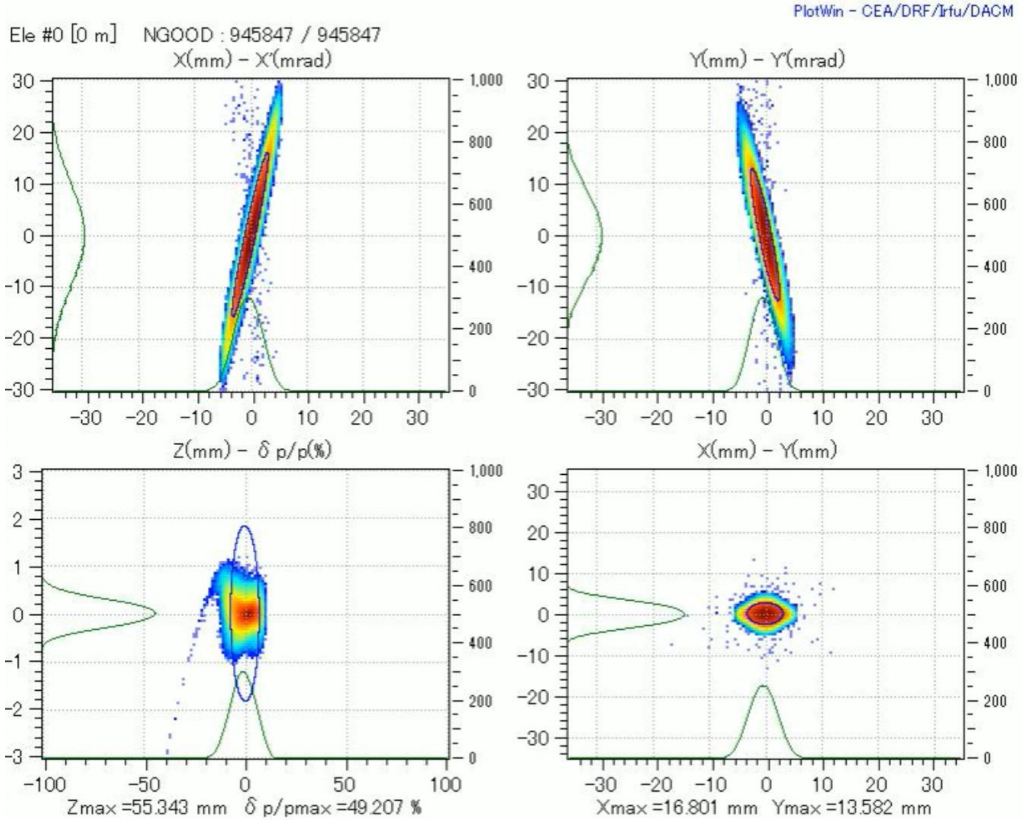
1. Weaker focusing → larger beam → less halo formation
2. Compromise of transport between halo & core





←Before

After ML →



Conclusion

- BO was successful to tune transport optics (4 quads+4 steerers) to reduce beam halo induced losses
- Vacuum pressure used as indicator of beam losses
- Simulations were used as constraints to avoid optics that leads to core losses for safety reason

Thank you very much!

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.