Helmholtz
Zentrum Berlin

MECHANISMS FOR ACHIEVING THE SEALAB BEAM MODES

From modelling to optimisation strategies

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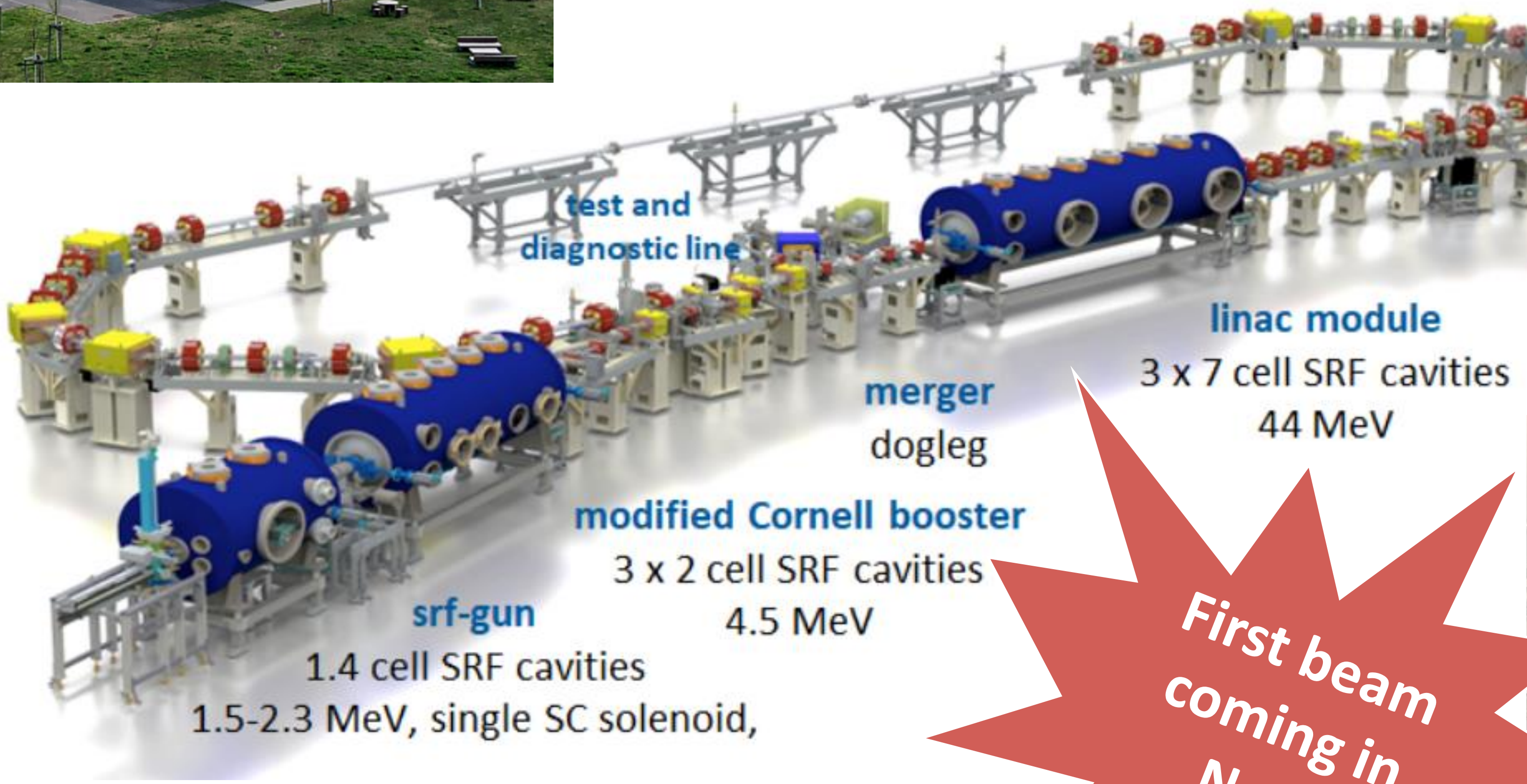
First beam coming in Nov!

The SEALab facility (bERLinPro successor)



srf-gun
1.4 cell SRF cavities
1.5-2.3 MeV, single SC solenoid,

modified Cornell booster
3 x 2 cell SRF cavities
4.5 MeV

merger
dogleg

linac module
3 x 7 cell SRF cavities
44 MeV

beam dump
6.5 MeV, 100 mA
= 650 kW

test and diagnostic line

First beam coming in Nov!

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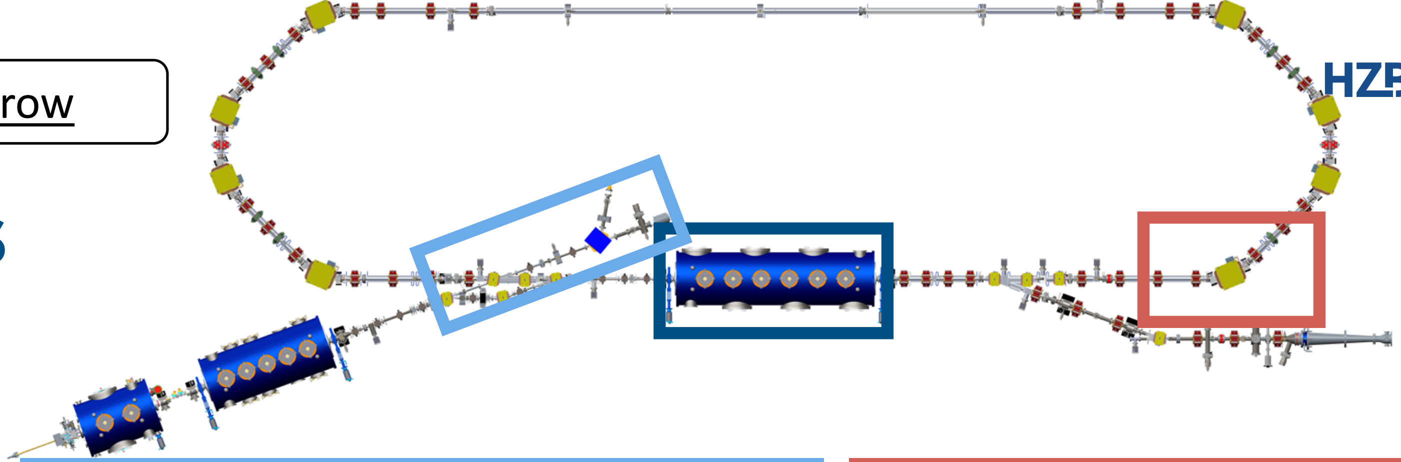
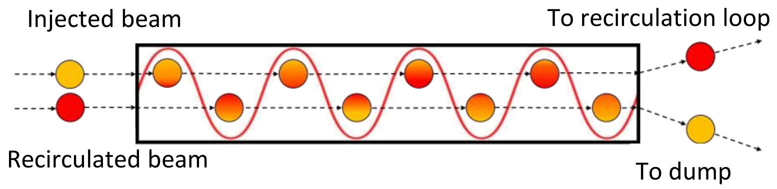
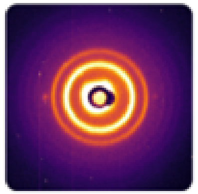
For more info, see Thorsten's talk tomorrow

Crucial Parameters

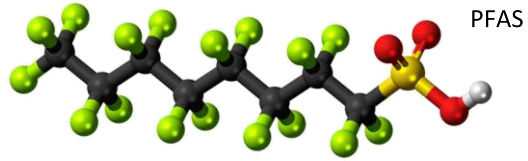




Energy Recovery Linac
Recycle recirculated beam energy for high-current operation and power saving



Ultrafast Electron Diffraction
Snapshots of atomic processes on femtosecond timescale



Electron Beam Water Treatment
Break down water pollutants using electron beams

Spec	ERL	UED	EBWT
Rep rate	1.3 GHz	100 kHz	1.3 GHz
Emittance	<1 µm	10^-3 µm	1-6 µm
Pulse length	2-3 ps	1 fs	2-10 ps
Bunch charge	77 pC	0.1 pC	77-500 pC
Av current	100 mA		20-100 mA
Kinetic energy	44 MeV	3.5 MeV	7 MeV

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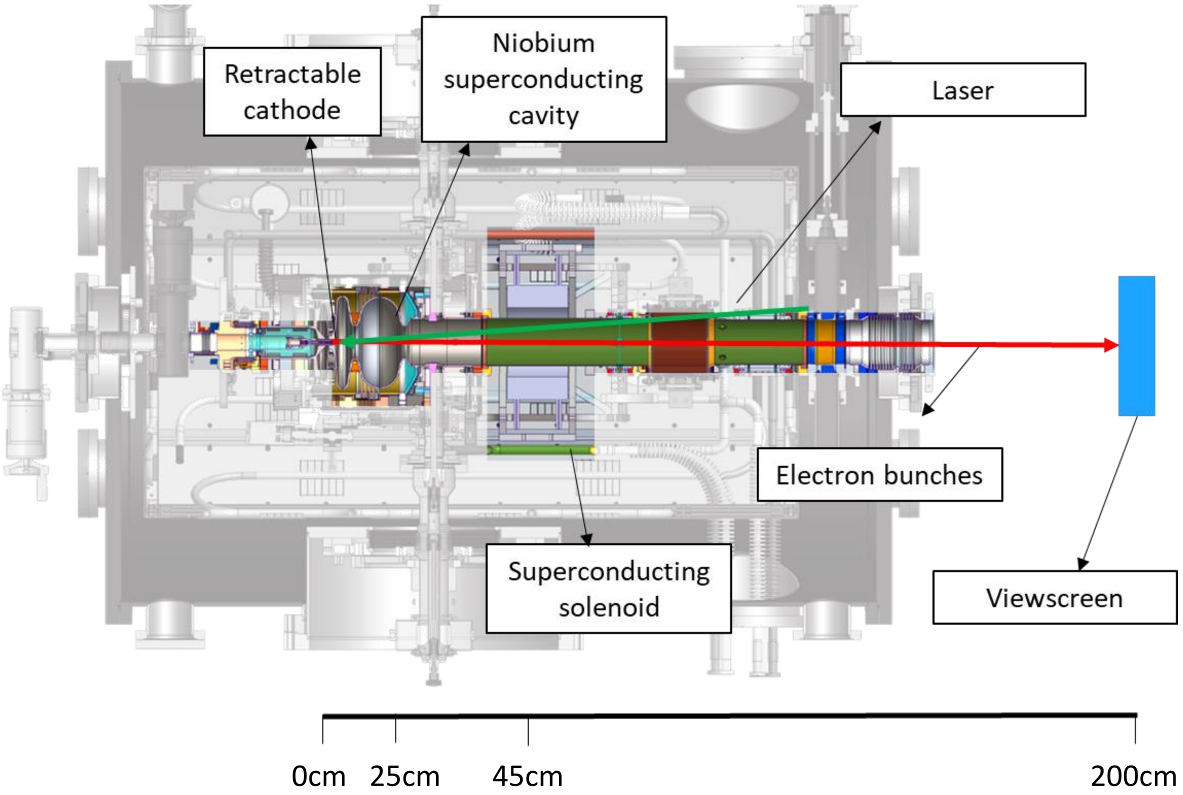
SEALab Models for the SRF Gun and First Metre



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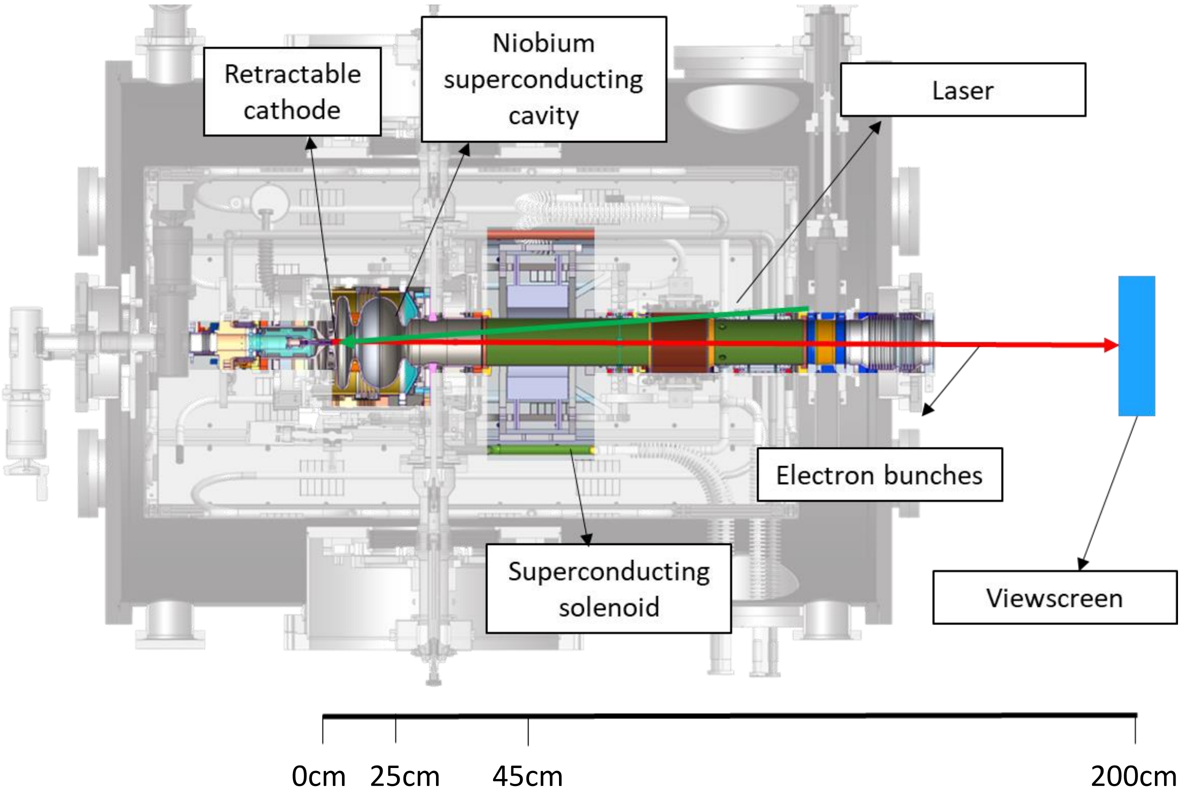

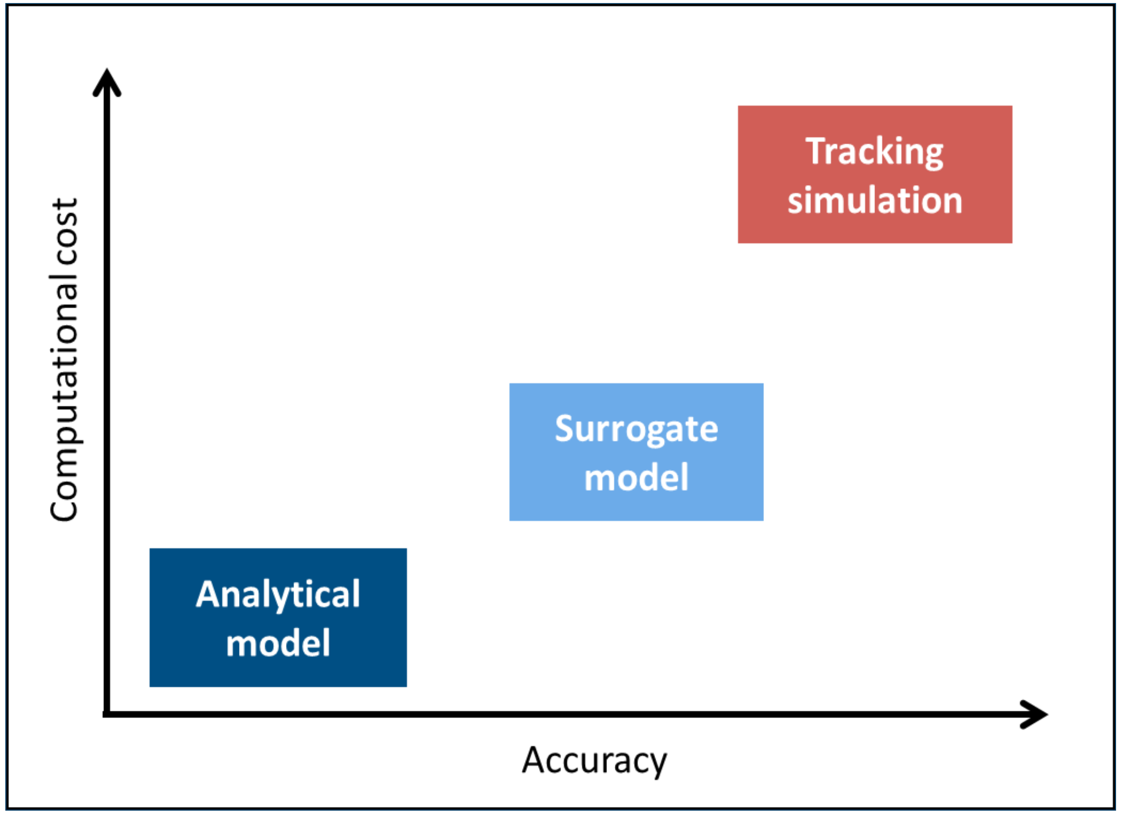

Computational cost

Accuracy

Tracking simulation

Surrogate model

Analytical model

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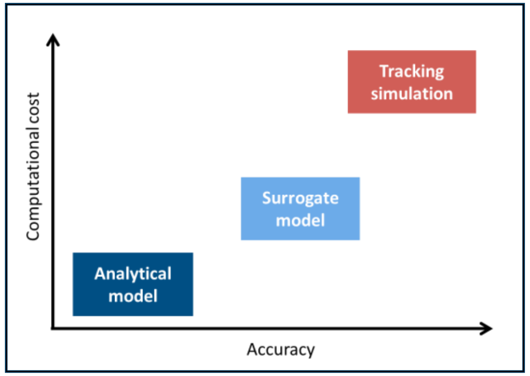
6-Dimensional Analytical Model

$$\begin{bmatrix} x_f \\ x'_f \\ y_f \\ y'_f \\ dE_f \\ dt_f \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & 0 & 0 \\ M_{21} & M_{22} & M_{23} & M_{24} & 0 & 0 \\ M_{31} & M_{32} & M_{33} & M_{34} & 0 & 0 \\ M_{41} & M_{42} & M_{43} & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & M_{56} \\ 0 & 0 & 0 & 0 & M_{65} & M_{66} \end{bmatrix} \begin{bmatrix} x_i \\ x'_i \\ y_i \\ y'_i \\ dE_i \\ dt_i \end{bmatrix}$$

Final values

Transfer matrix

Initial values



Properties:

- Fast, closed-form solutions from simplified dynamics
- First-order, linear approximations of beam behaviours in response to condition changes

Application in SEALab:

- Initial commissioning
    - Setting initial parameters
    - Control system setup
    - Important controls/observables
- Beam matching
    - Match transverse properties at each stage of the accelerator

Based on K.-J. Kim,
‘Rf and space-charge effects in laser-driven rf electron guns’

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Longitudinal Analytical Model

$$\boxed{\begin{bmatrix} dE_f \\ dt_f \end{bmatrix} = \begin{bmatrix} M_{55} & M_{56} \\ M_{65} & M_{66} \end{bmatrix} \begin{bmatrix} dE_i \\ dt_i \end{bmatrix}}$$

Cavity electric field: $A_z(z,t) = A_0 \cos(kz) \sin(2\pi f t + \phi_0)$

Force: $\boldsymbol{F} = m\ddot{z} = -eA_z(z)\hat{e}_z$

Energy gain: $\dfrac{dE_f}{dt} = \mathbf{F} \cdot \mathbf{v}$

Field amplitude

Electric field strength: $\alpha = \dfrac{eA_0}{2mc^2k}$

Wavenumber

Exit phase   Initial phase

Exit phase: $\phi_e = \phi_0 + \dfrac{1}{2\alpha \sin(\phi_0)}$

Exit kinetic energy: $E_f = \alpha mc^2(n\pi \sin(\phi_e) + \cos(\phi_e))$

Number of cells

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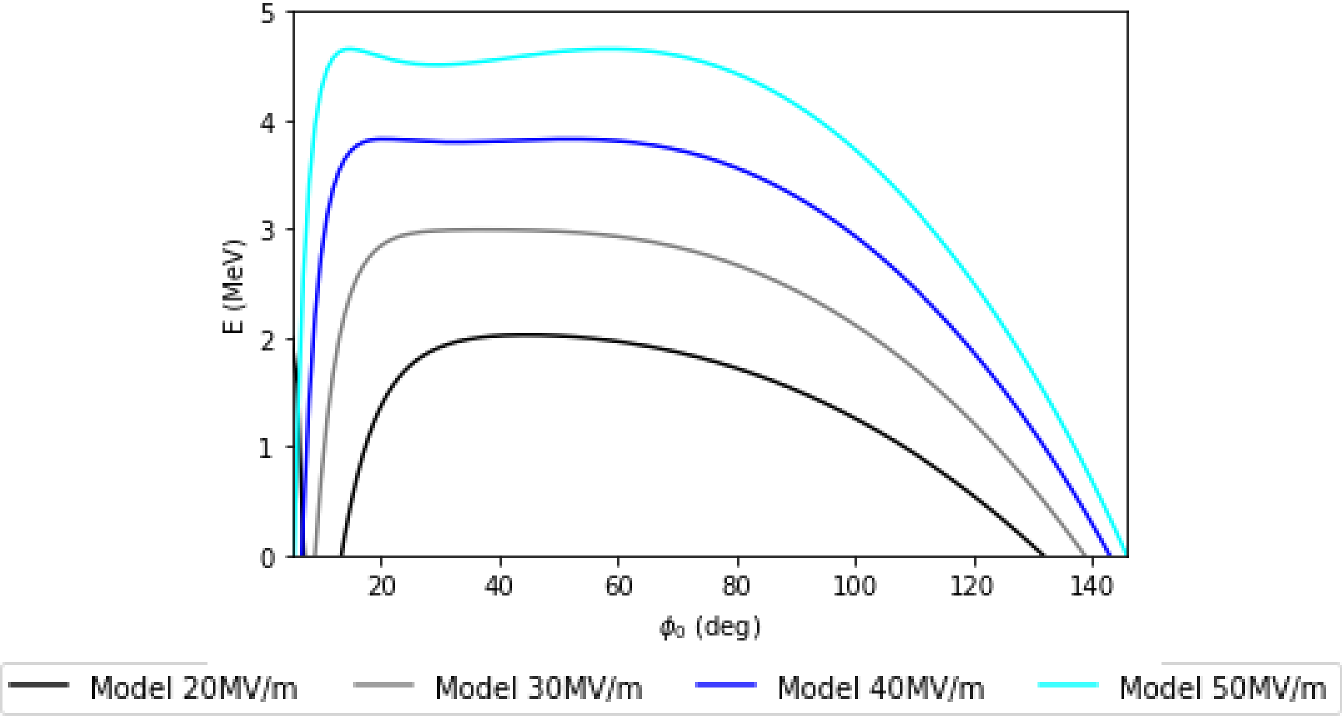

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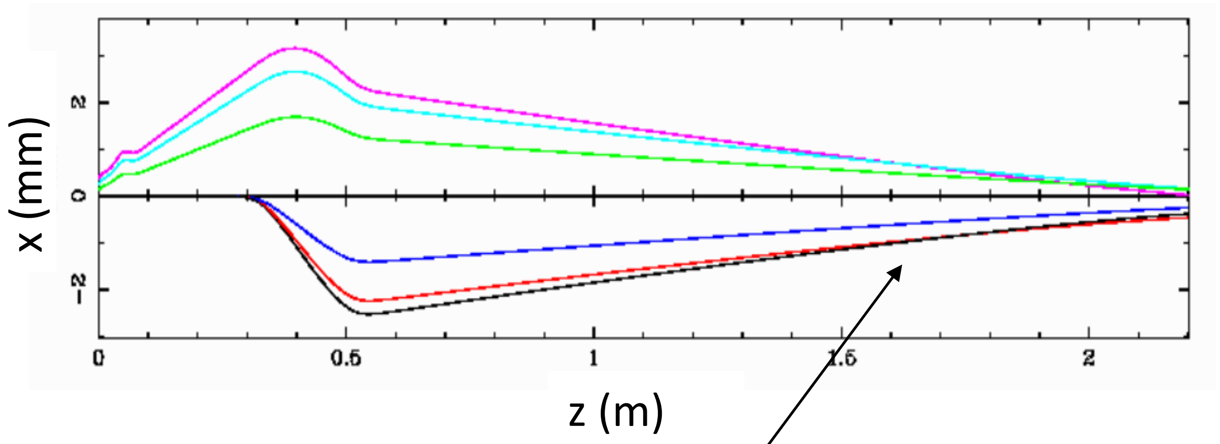
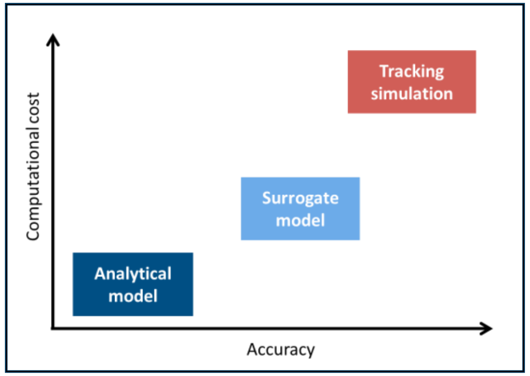
Tracking Simulations (ASTRA)



x-position of 6 particles, 3 started with non-zero x positions, 3 started on axis with y-offset.



Properties:

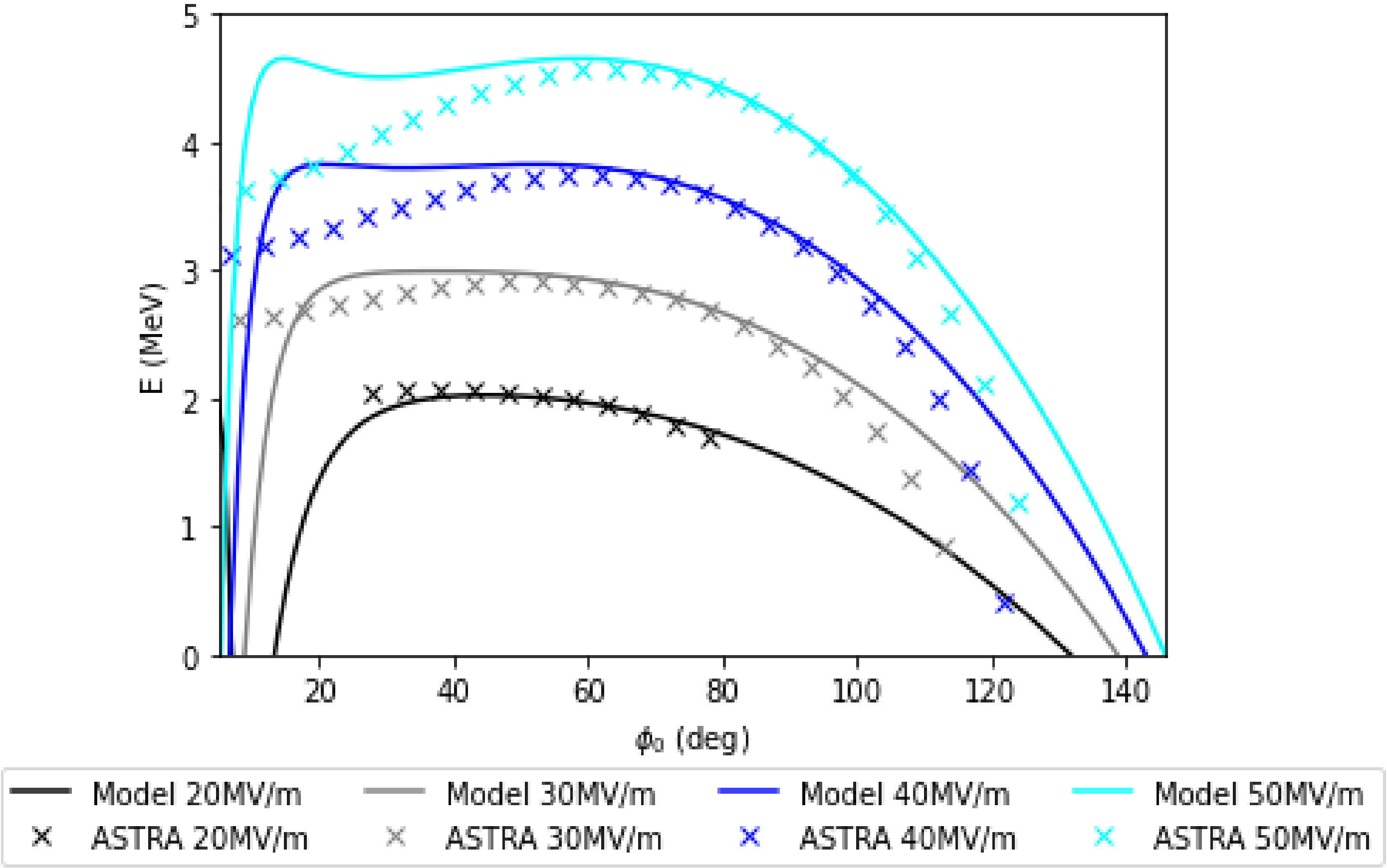
- Slow, precise numerical solutions to complex beam dynamics
- Incorporates higher order effects like space charge and non-linear field components

Application in SEALab:

- Detailed beam dynamics studies
  - Understanding under realistic conditions
  - Modelling through the gun
- Higher-order effects
  - Modelling of space charge forces and halo generation
  - Design of gun solenoid for emittance compensation

ASTRA, DESY

Tracking Simulations (ASTRA)



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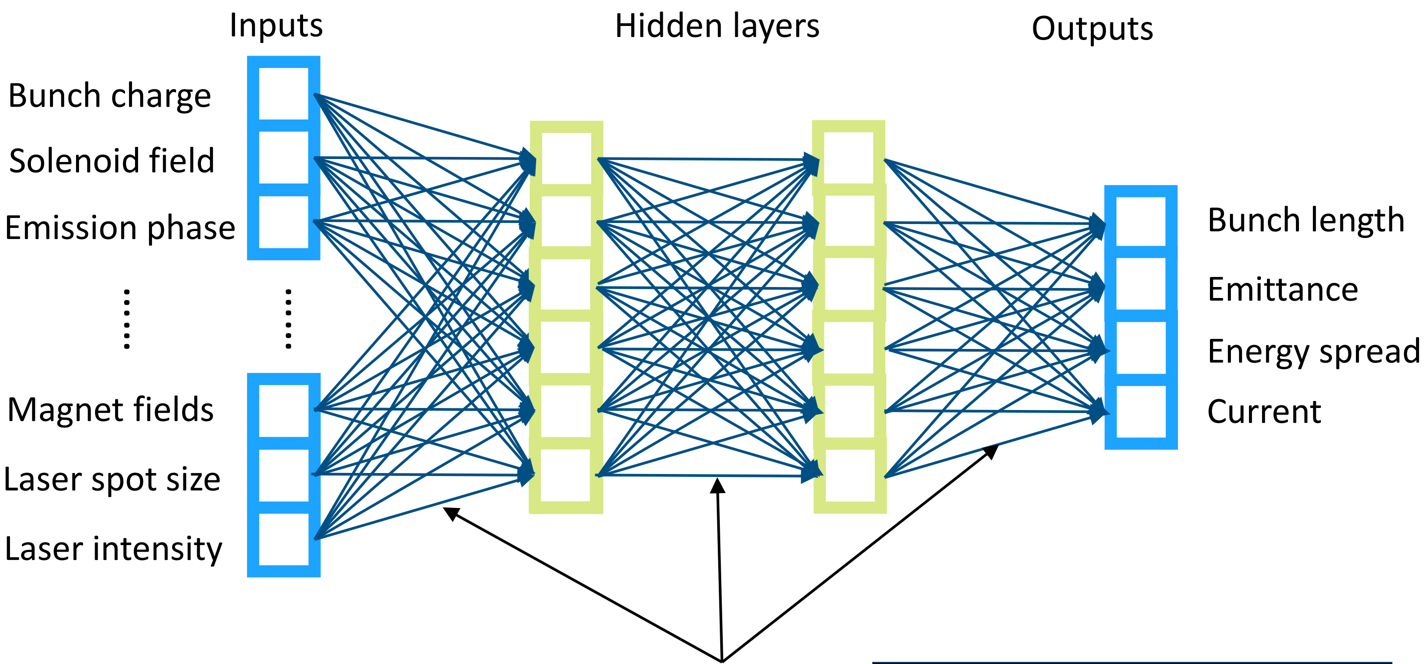
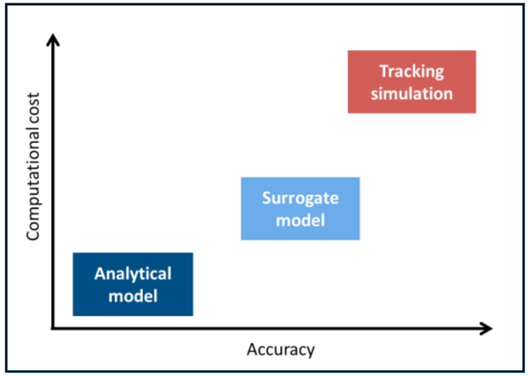
Surrogate Model



```
MLPRegressor(solver="adam",
alpha=0.01, activation="relu",
hidden_layer_sizes=(2000,500,150,20))
```



Properties:

- Fast estimates of computationally expensive simulations
- Require training (computationally expensive) but only once

Application in SEALab:

- Real-time corrections
  - Quickly estimate beam properties
  - Predict beam parameter response to non-linear machine changes
- Online control system
  - Can be integrated into feedback loops and optimisation strategies
  - Enable fast decision-making

Based on B Esuain PhD thesis

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Surrogate Model

Knobs

Control knob	Range
Bunch charge	7pC or 77pC
RMS laser time	[1e-3,10e-3] ns
RMS laser size	[0.5,2] mm
Emission phase	[-20,20] deg
Gun field amplitude	[10.25] MV/m
Solenoid amplitude	[0,0.05] T
Quadrupole gradients (x5)	[-0.1,0.1] T/m

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Observables

Observable
Longitudinal emittance
Bunch length
Energy
Energy deviation
Transverse spot size (x5)
Emittance (x5)
Divergence (x5)

19

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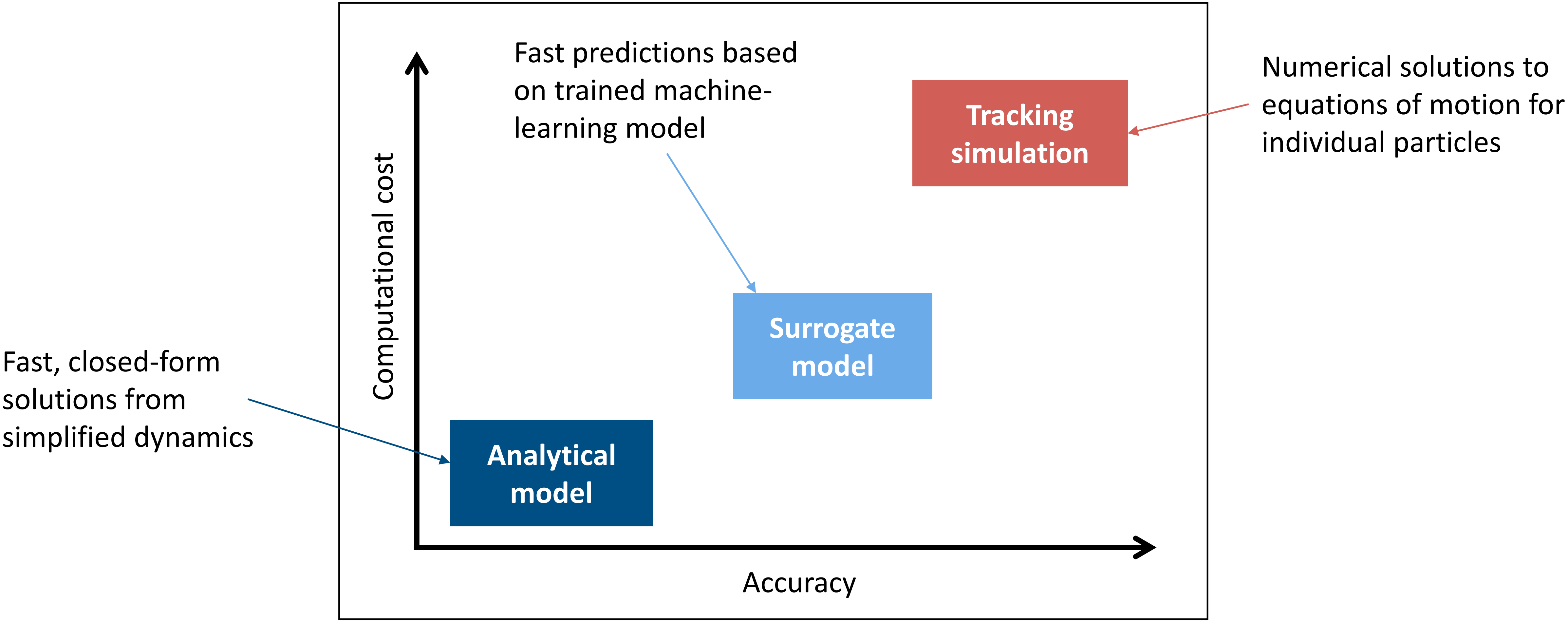
SEALab Models



Fast predictions based on trained machine-learning model

Numerical solutions to equations of motion for individual particles

Fast, closed-form solutions from simplified dynamics

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Introducing MOBO (Multi-Objective Bayesian Optimisation)

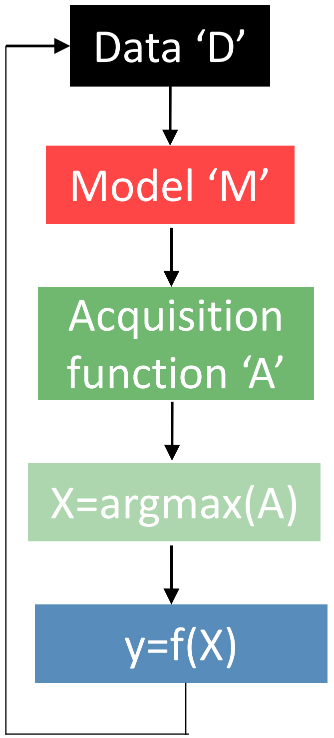
Optimisation algorithm which uses Bayesian methods to iteratively sample the optimal solutions to problems with competing objectives

Well-suited for high-dimensional problems with competing objectives

Balances exploration of new parameter space with exploitation of already known promising areas

Probes the set of non-dominated solutions (Pareto Front) efficiently and widely

Introducing MOBO (Multi-Objective Bayesian Optimisation)

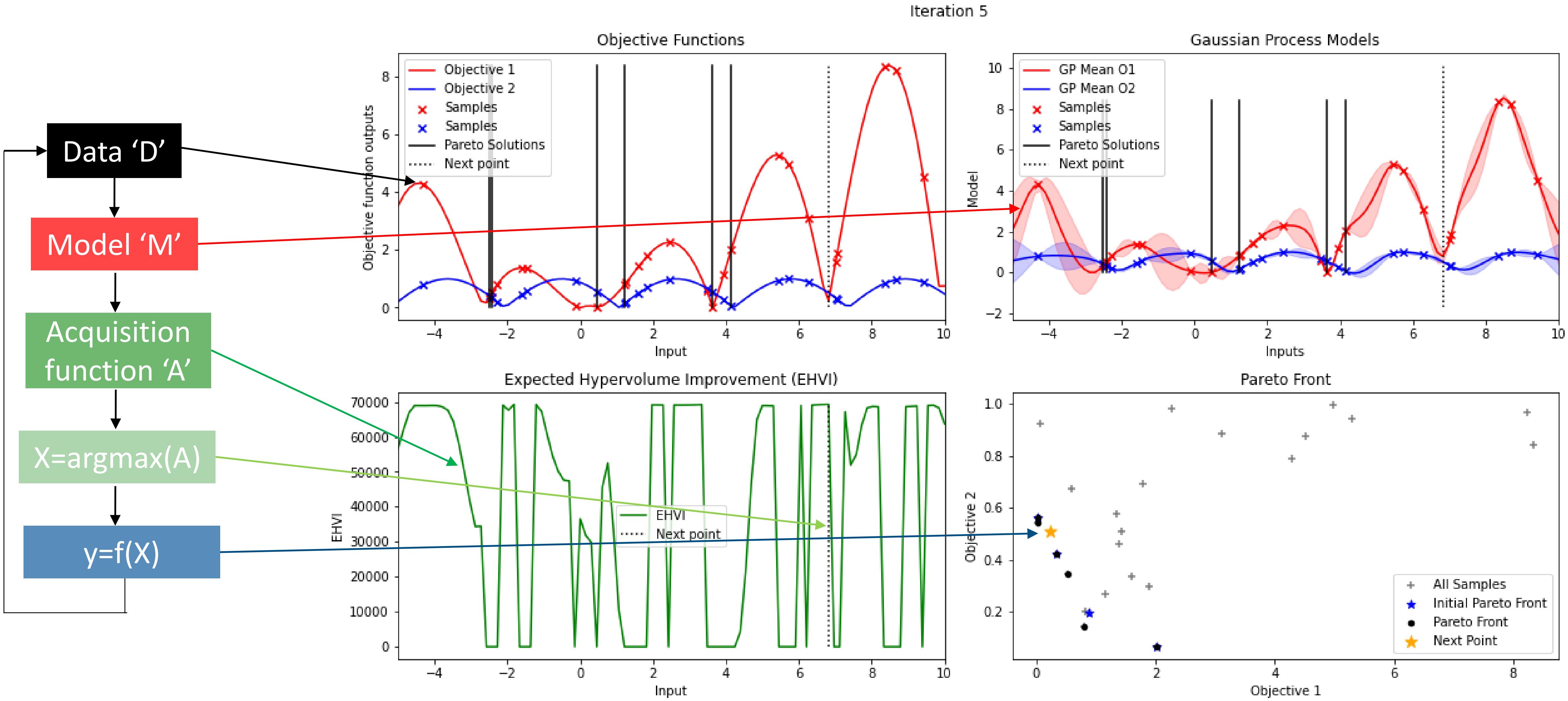


Optimising an accelerator often requires finding a trade-off between two competing objectives (eg. minimise emittance and minimise bunch length)

MOBO aims to find the optimal trade-off possibilities

1. Define objectives to optimise
2. Sample initial points
3. Use Gaussian Process modelling to fit the data
4. Evaluate the next point to sample at using an acquisition function
5. Sample at new point and add this to the dataset
6. Iterate until termination criteria is met

Introduction to MOBO



Data ‘D’

Model ‘M’

Acquisition function ‘A’

X=argmax(A)

y=f(X)

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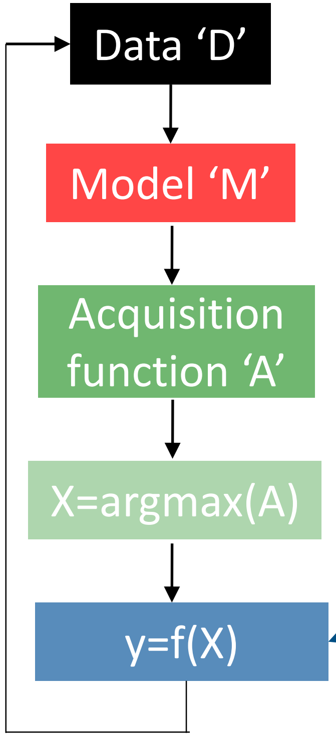
Introduction to MOBO



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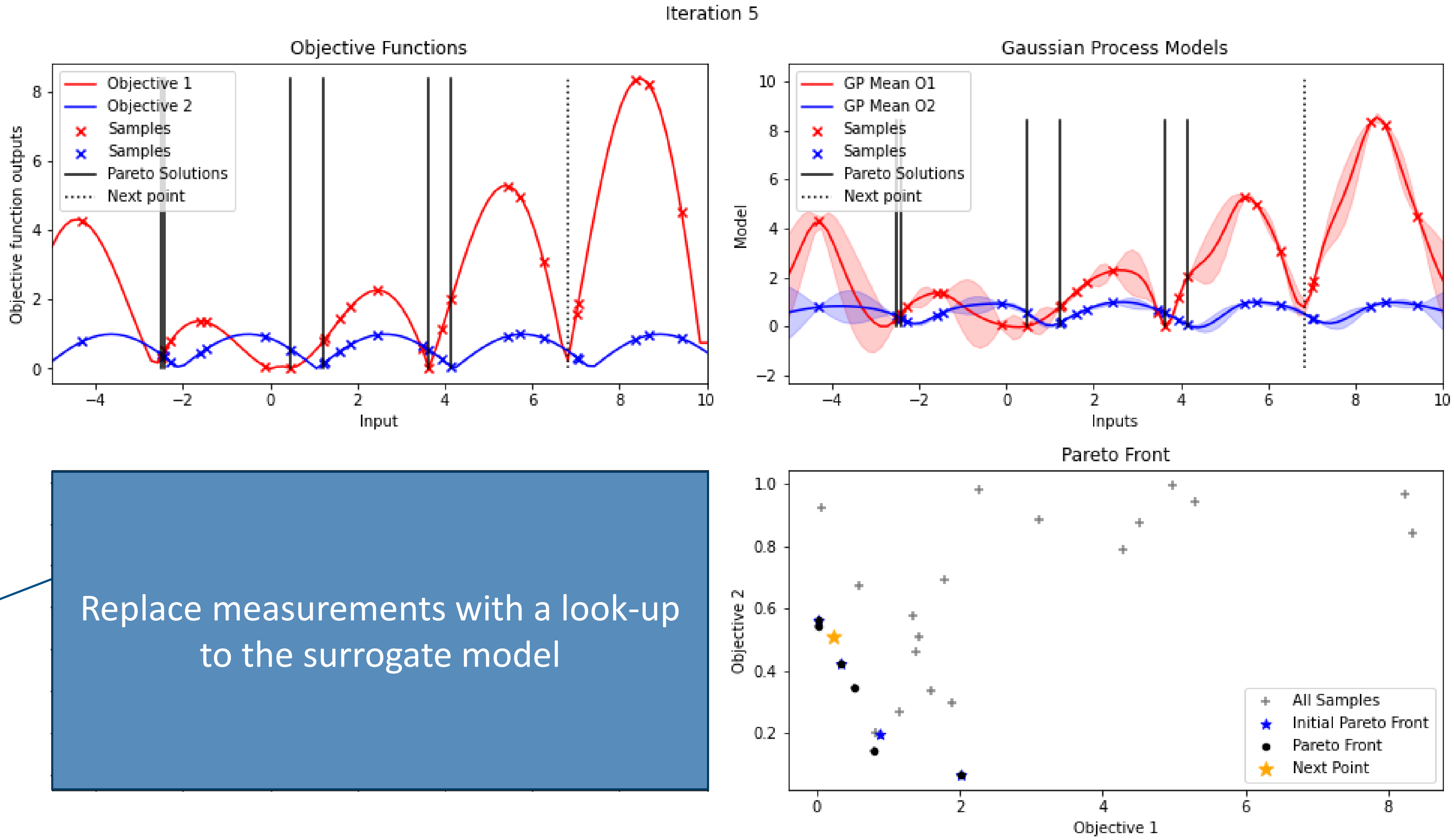

Replace measurements with a look-up to the surrogate model

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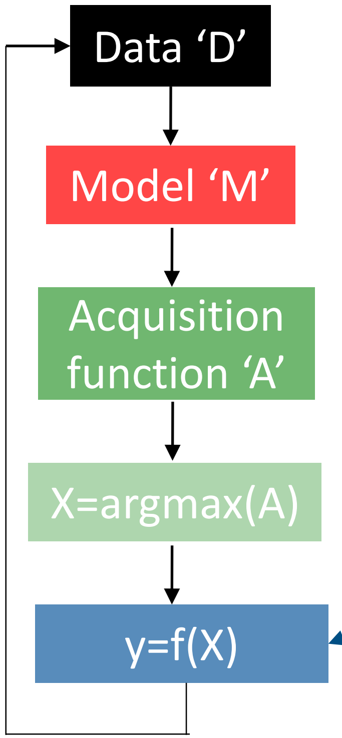
Introduction to MOBO



Data ‘D’

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Acquisition function ‘A’

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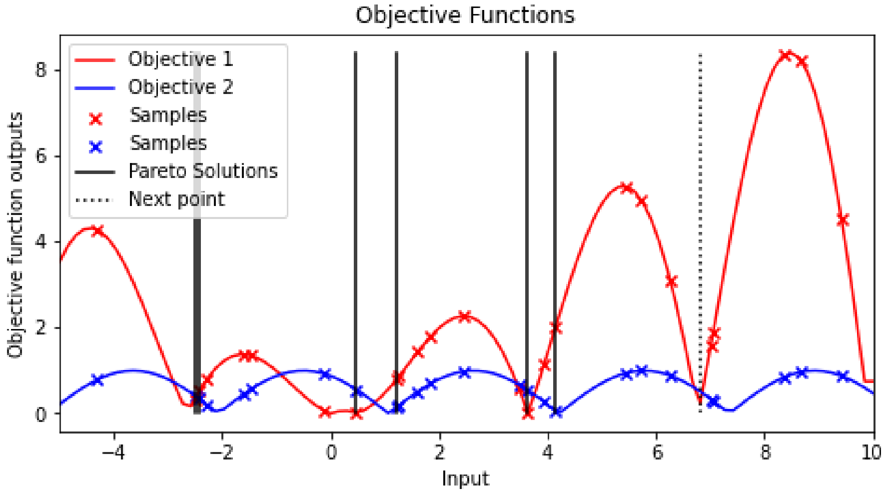
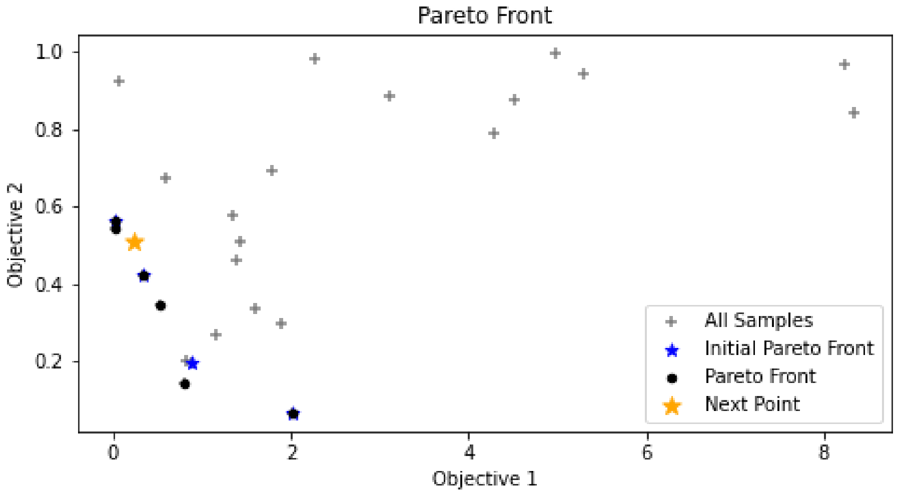
Iteration 5



The many modes of SEALab require many controls and observables
This makes it a high-dimensional optimisation problem
MOBO is great for this!

Replace measurements with a look-up to the surrogate model



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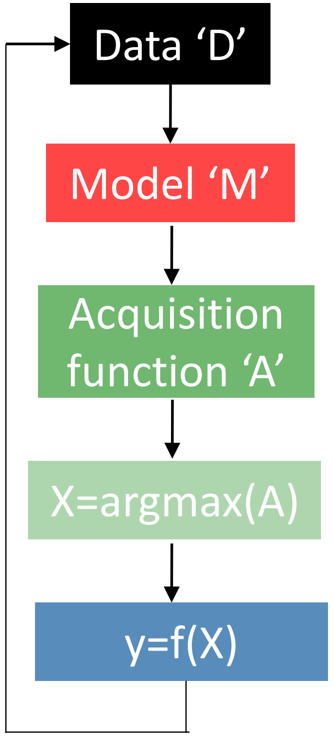
MOBO with ASTRA

10 initial data points
4 input parameters
2 objectives
5 iterations

Problem: maximise kinetic energy and minimise bunch length



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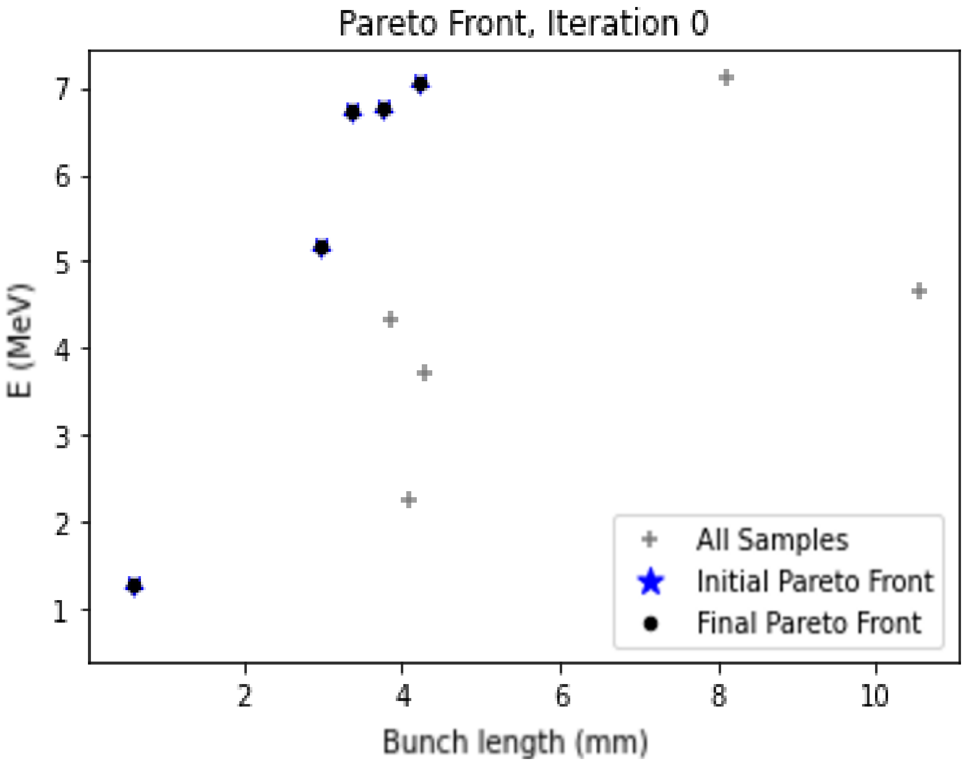

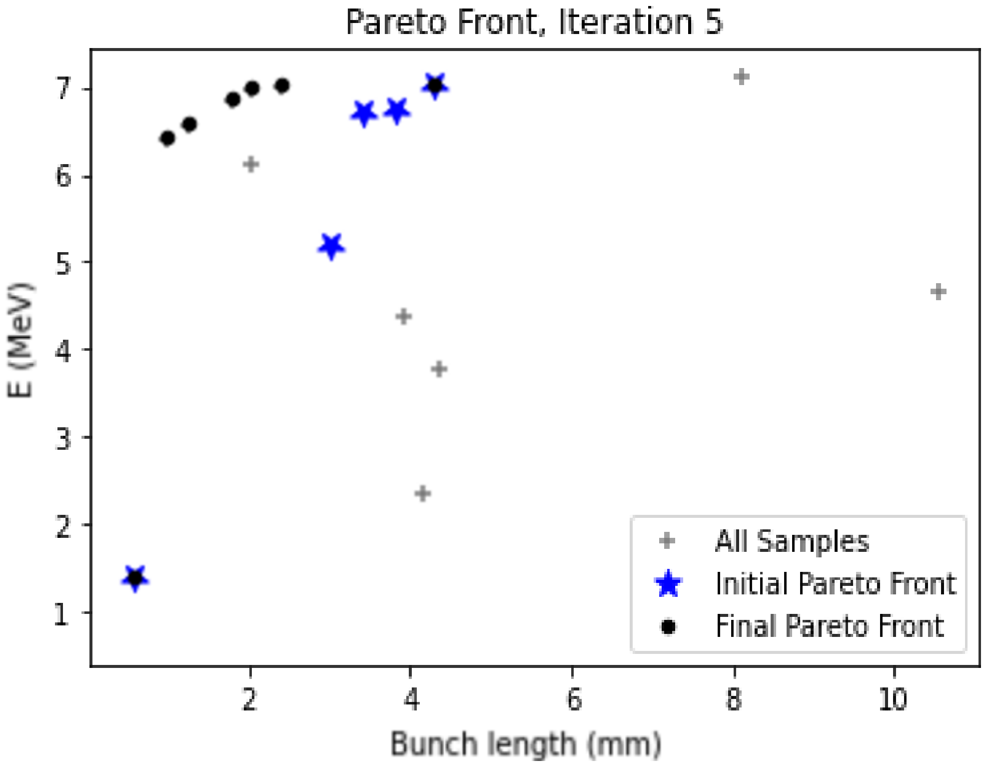

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Key takeaways

SEALab has many diverse applications.
This requires a flexible machine

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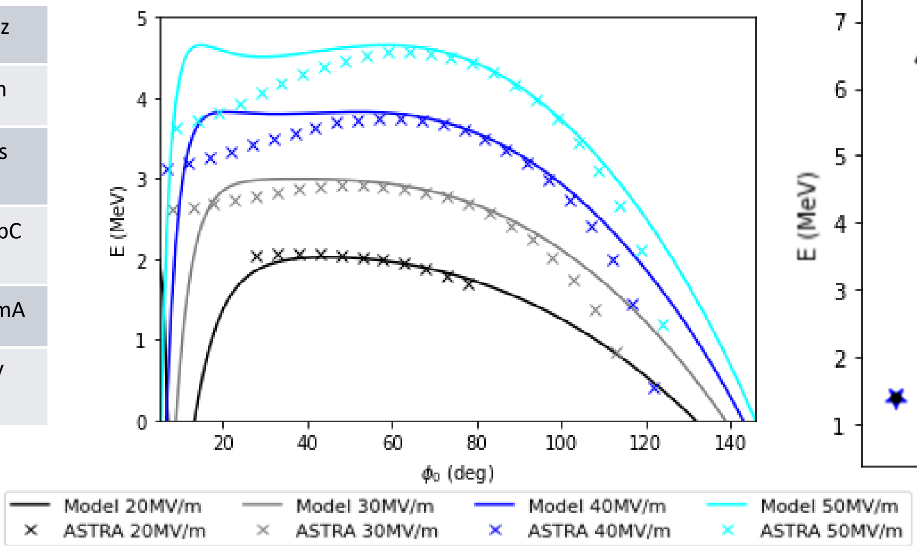
Rep rate	1.3 GHz	100 kHz	1.3 GHz
Emittance	<1 µm	10^-3 µm	1-6 µm
Pulse length	2-3 ps	1 fs	2-10 ps
Bunch charge	77 pC	0.1 pC	77-500 pC
Av current	100 mA		20-100 mA
Kinetic energy	44 MeV	3.5 MeV	7 MeV

Modelling and optimisation allow us to efficiently find solutions complex problems



MOBO provides a solid foundation for advanced, scalable optimisation strategies and has been tested on tracking simulations