Shaping of Magnetic Field Coils in Fusion Reactors using Bayesian Optimisation

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Introduction

The design of tokamaks is a complicated and high-dimensional problem that considers many physics and engineering challenges, often taking months and involving many stakeholders. Bluemira is a Tokamak design code that simplifies the initial design process by producing consistent tokamak designs in minutes using reduced physics and engineering models. Toroidal field (TF) coils are one such component of a tokamak that produces the magnetic pressure necessary to confine the plasma. Consequently, the design of TF coils is an essential factor in designing an efficient tokamak capable of producing electricity.

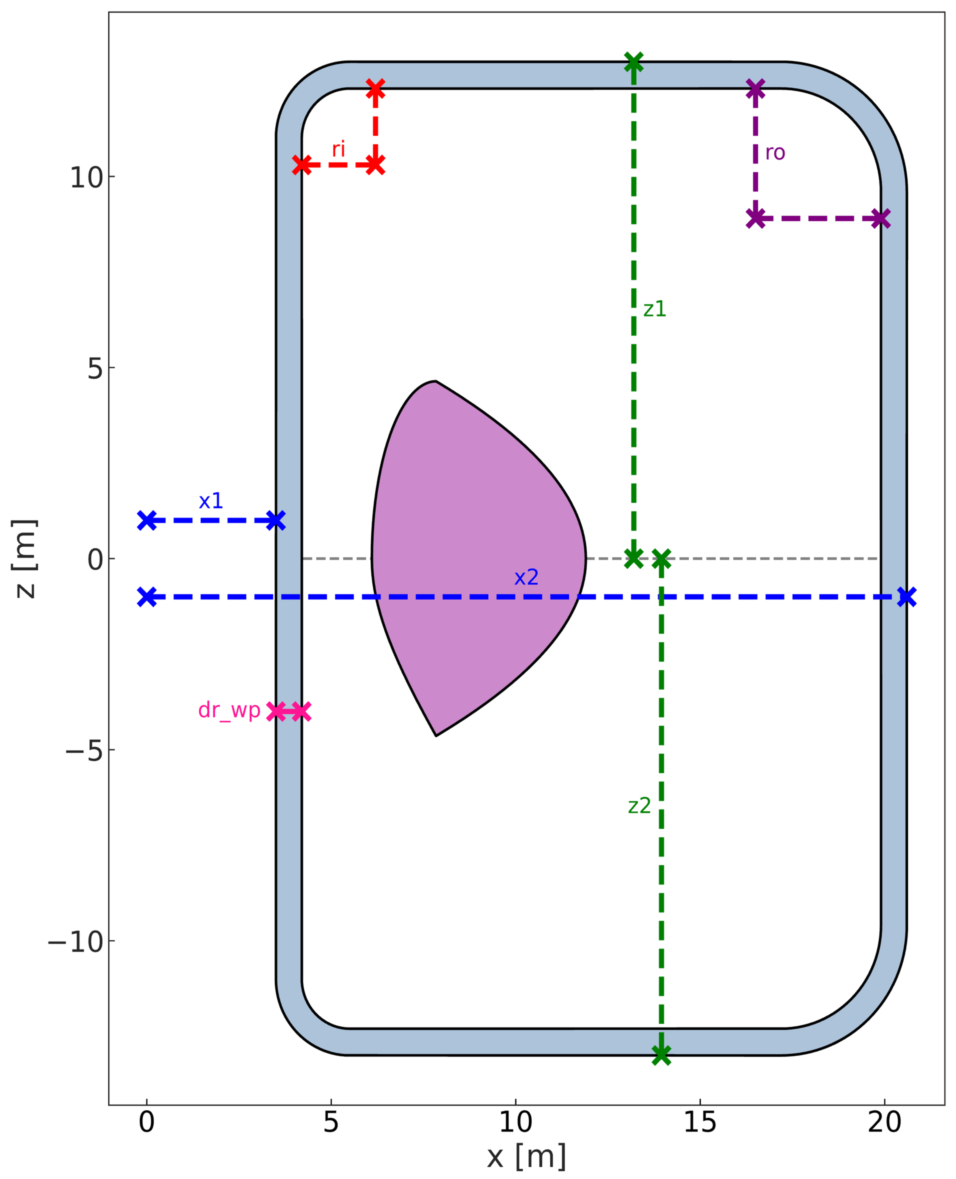
We present an AI-based method of exploration and optimisation for TF coil design. We deploy a Multi-Output Bayesian Optimisation (MOBO) algorithm over a Bluemira model to optimise the geometry of the coil. Benchmarking against conventional optimisation strategies demonstrates the efficiency of the MOBO approach and lays the foundation for deploying it over more complex design spaces.

Problem

Optimise the 'picture frame' geometric parameterisation of the TF coil in the X-Z plane, and the winding pack geometry.

- The thickness (Y) of the winding pack is a fraction of its maximum, ensuring no collisions without using constraints.
- Both height parameters (z_1 and z_2) have the same magnitude.
- The final parameter is the total number of coils.

Objective	Description	Rationale
Ripple	The maximum magnetic ripple experienced on the plasma's surface.	A higher ripple reduces plasma stability, leading to poor confinement and reducing the tokamak's efficiency.
Size	The volumetric sum of the TF coils.	Large coils cost more to produce and make the tokamak bigger, causing it to require more space.



Implementation

- We are implementing a multi-objective optimisation over an 8-dimensional design space.
- Initial sampling of the design space using the Sobol scheme.
- Then, run a prescribed number of Bayesian optimisation iterations.

The Bayesian optimisation is over a series of Gaussian Process (GP) surrogates, one for each objective metric:

- Noiseless observations ⇒ **Exact GPs**. • **Matern kernel**. • **Gaussian likelihood**. • **Length scale prior**.

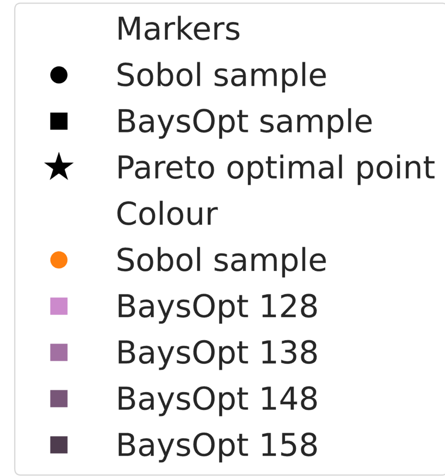
We fit the GPs by minimising the sum of the marginal log-likelihood across them. Finally, we transform the inputs onto the unit hypercube and standardise the outputs before fitting the GP; the standardisation occurs on every iteration. The Bayesian optimisation uses an **Expected Hypervolume Improvement** acquisition function.

Results

We present two experiments using the Sobol + Bayesian optimisation framework:

Expt #	Sobol Samples	Bayesian Samples	Size	Ripple
1	64	20	0.46	0.018
2	128	40	0.091	4.5e-4

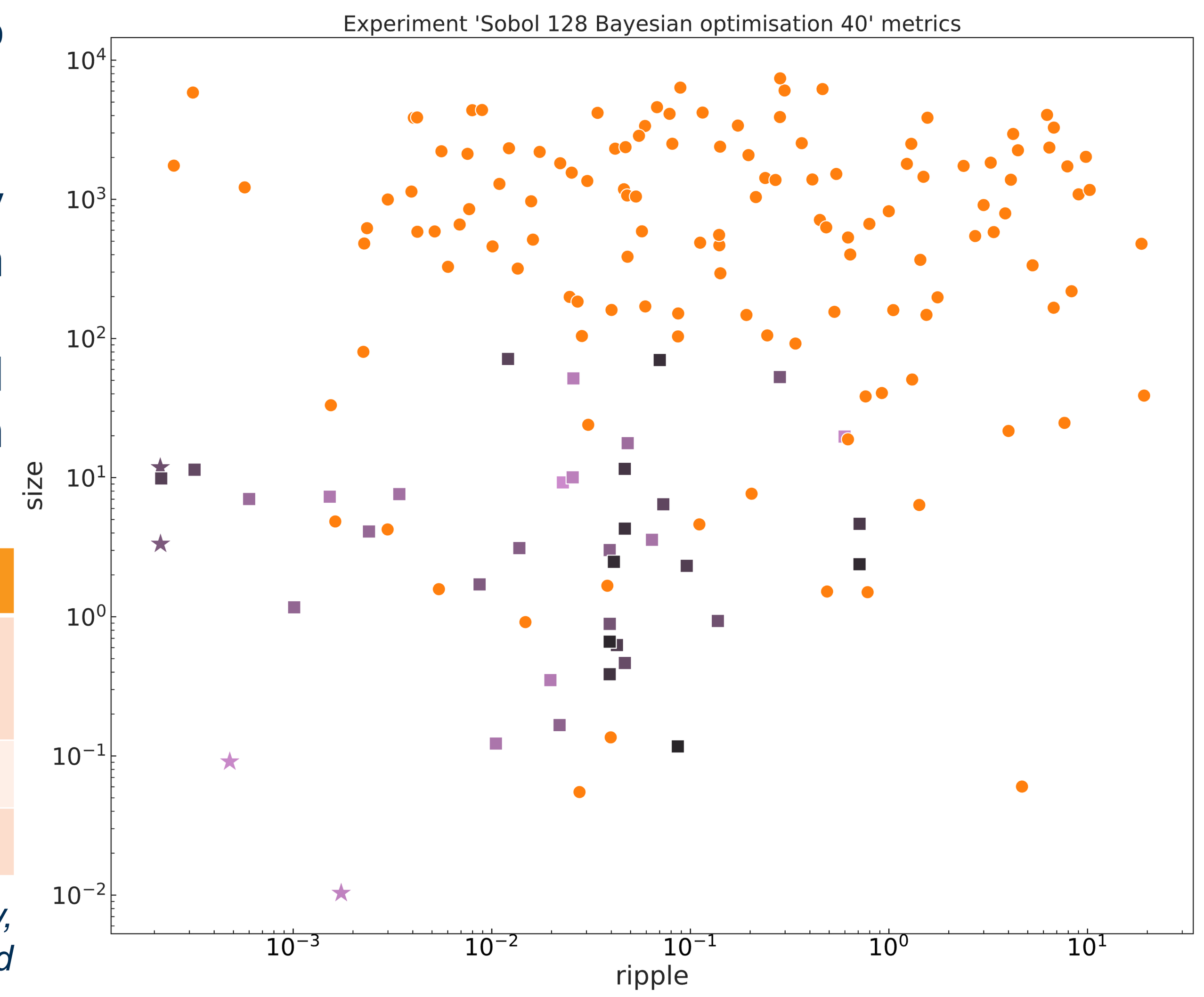
Experiment 2 gets closer to the true Pareto frontier by several orders of magnitude. A log-log plot of Experiment 2, including its Pareto frontier, is shown below.



We benchmarked the MOBO approach to two standard methods currently employed in the industry:

- pure (quasi-)Monte Carlo sampling using **Sobol**.
- multi-objective evolutionary algorithms, specifically Non-dominated Sorting Genetic Algorithm (**NSGA-II**).

The comparison is against the quality of the returned design points and the time taken to arrive at such design points.



Method	Size	Ripple	Time (s)
MOBO Baseline (Experiment 2)	**0.091**	**4.5e-4**	**872**
Sobol	**0.055, 0.43**	**0.028, 5.9e-3**	**691**
NSGA-II	**89.1**	**0.19**	**786**

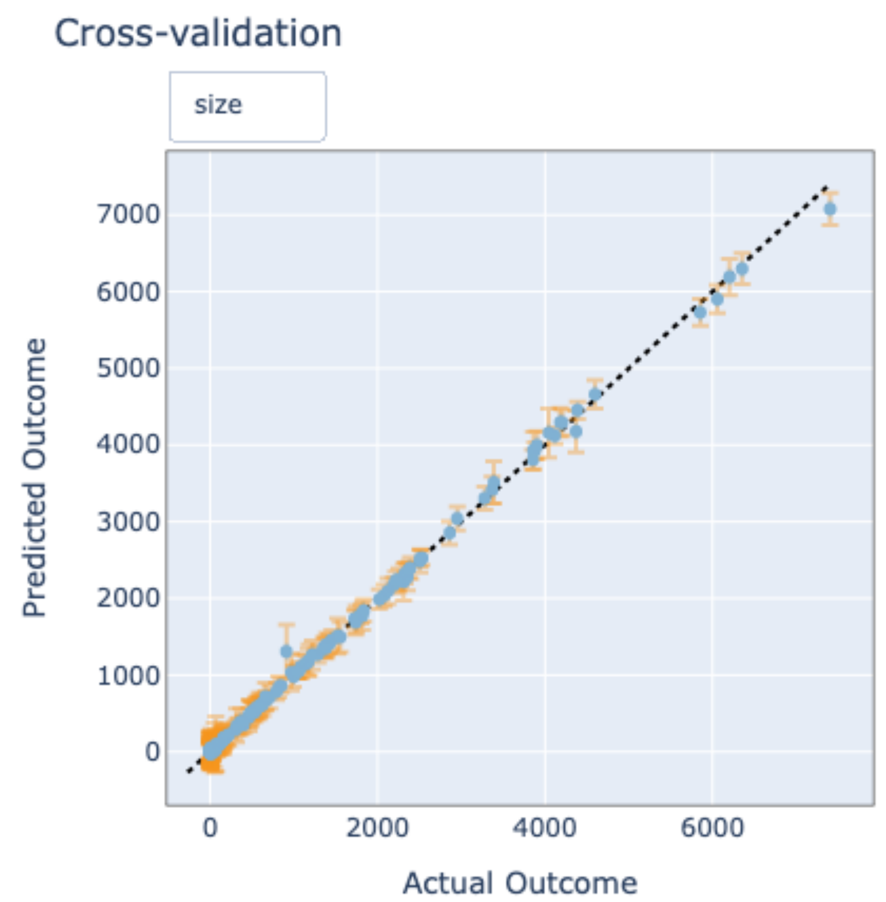
Where multiple Pareto optimal points are deemed to be of equal quality, we present them comma delimited

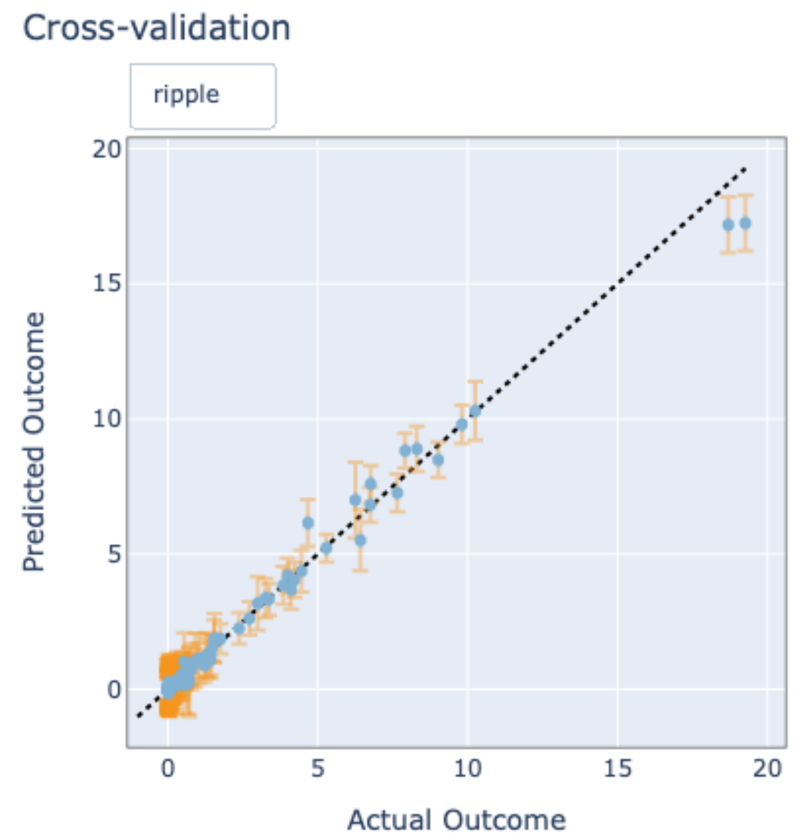
Key Takeaways

- The **Sobol Pareto frontier is worse** than that of the MOBO; however, it still provides decent design points.
- Qualitative analysis of the Experiment 2 samples shows **Sobol samples are generally orders of magnitude worse**.
- **Sobol is ~23% faster** but would **require more runs** to get to a frontier of comparable quality.
- **NSGA-II performs extremely poorly**, which is attributed to the curse of dimensionality. NSGA-II would likely require many more samples to perform comparable to Sobol or MOBO.

Future Work

- Further constraining the TF coil to produce an optimal design that is physically feasible by taking into account other physical effects.
- Consider applications of this technique to the design of other reactor magnets such as the Poloidal Field coils and Central Solenoid coils, considering their effects on the plasma equilibria.





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