Multi-parameter Bayesian optimisation of laser-driven ion acceleration in particle-in-cell simulations

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Particle Accelerators and Beams, University of Strathclyde

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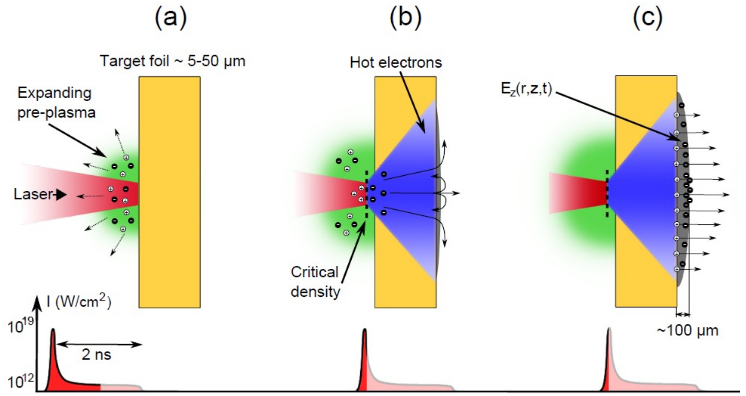
Optimising Sources of Radiation from Laser-Solid Interactions

- Radiation sources generated in laser-solid interactions have unique properties which are useful for applications.
- However, properties of these sources must be optimised before applications can be realised.
- However, these are highly non-linear interactions – very difficult to optimise for all input parameters!



Source of Multi-MeV ions with unique properties for applications!

Laser:
- **Intensity**
- **Energy**
- **Pulse Duration**
- Focal spot size
- Laser intensity contrast
- Polarisation

\+

Plasma:
- Energy conversion efficiency
- Fast electron divergence angle
- Z (scattering, resistivity)
- **Preplasma scale length**
- **Target Thickness**
- Incidence angle

→ Electric sheath field evolution → TNSA maximum proton energy ($E_{\max}$)

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Bayesian Optimisation of Laser-Plasma Accelerators

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Optimising in simulations

- Some interaction properties are difficult to measure experimentally but can be measured in simulations
- These properties define key source properties such as the maximum proton energy
- By optimising these properties in simulations, we can guide experimental conditions

Input — **Optimise** — Output

Peak laser intensity → Hot electron temperature ($k_B T_e$) → TNSA maximum proton energy (E_{max})

Optimising in experiments

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-020-20245-6 OPEN

Automation and control of laser wakefield accelerators using Bayesian optimization

R. J. Shalloo, S. J. D. Dann, J.-N. Gruse, C. I. D. Underwood, A. F. A... M. Backhouse, C. D. Baird, M. D. Balcazar, N. Bourgeois, J. A. Cardarelli, P. H... K. Krushelnick, S. P. D. Mangles, C. D. Murphy, N. Lu, J. Osterhoff, K. ... C. P. Ridgers, S. Rozario, M. P. Selwood, A. J. Shahani, D. R. Symes, A. G. R. Th... Z. Najmudin & M. J. V. Streeter

PHYSICAL REVIEW LETTERS **126**, 104801 (2021)

Bayesian Optimization of a Laser-Plasma Accelerator

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PHYSICAL REVIEW RESEARCH **5**, 013063 (2023)

Multi-objective and multi-fidelity Bayesian optimization of laser-plasma acceleration

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Automated control and optimisation of laser driven ion acceleration

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Input — Infer — **Optimise** Output

Peak laser intensity → ??? → TNSA maximum proton energy (E_{max})

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BISHOP code to facilitate Bayesian optimisation

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- Bishop is a platform for automatically generating PIC simulation data and applying machine learning techniques

1. Select a scan type:

Minimum – Maximum
Optimise

2. Simulation with inputs X_n is submitted to queue on a remote server

EPOCH
Open source PIC code developed by University of Warwick

3. Simulation data is transferred from remote – local server

4. The data is analysed by LPI-Py, providing evaluations, $f(X_n)$

Optimise

Next X_n values are guided by a GP surrogate model:

$UCB = \mu GP + \kappa \sigma GP$

LPI-Py
Project ID: 5304 Leave project
83 Commits 8 Branches 0 Tags 53.8 MB Project Storage
Python library for LPI physics models, experimental analysis and processing of numerical simulation data.

Matt Alderton Talk – Thursday 14:20

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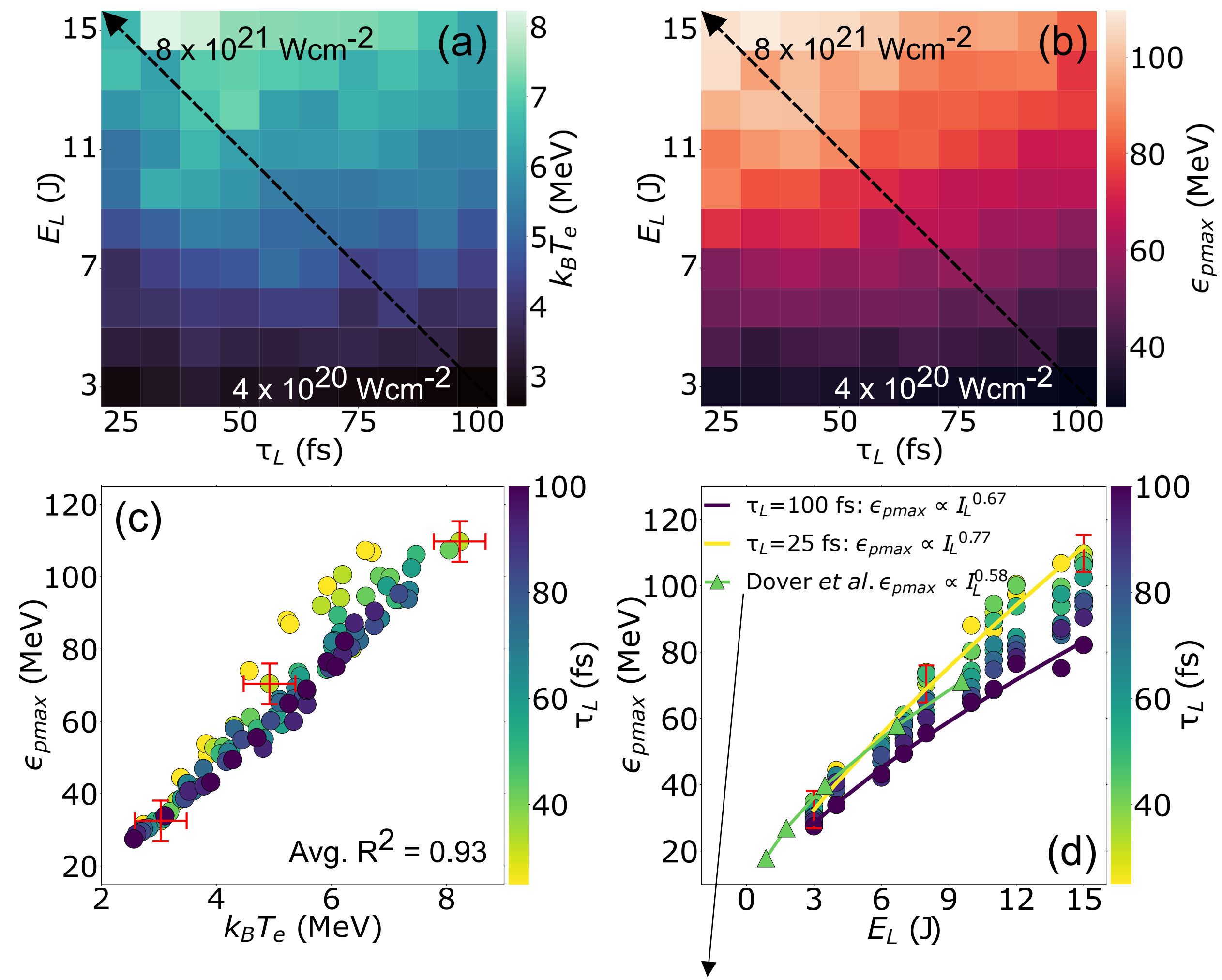
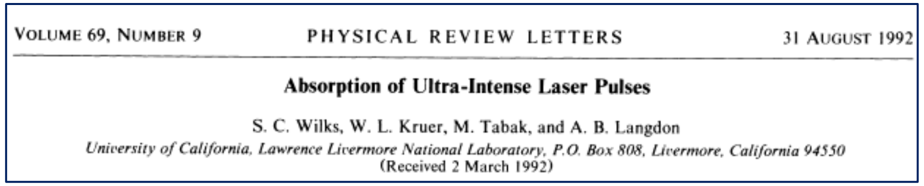
Conventional Optimisation using BISHOP

$$k_B T_e = mc^2 \left(\sqrt{1 + a_L^2} - 1 \right)$$

$$E_{\max} = 2k_B T_{\text{hot}} \ln^2 \left(\tau + \sqrt{1 + \tau^2} \right)$$



N. P. Dover, et al., Phys. Rev. Lett. 124.8, 084802 (2020)



VOLUME 69, NUMBER 9 — PHYSICAL REVIEW LETTERS — 31 AUGUST 1992

Absorption of Ultra-Intense Laser Pulses

S. C. Wilks, W. L. Kruer, M. Tabak, and A. B. Langdon

University of California, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

(Received 2 March 1992)

VOLUME 90, NUMBER 18 — PHYSICAL REVIEW LETTERS — week ending 9 MAY 2003

Plasma Expansion into a Vacuum

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Centre de Physique Théorique (UMR 7644 du CNRS), Ecole Polytechnique, Palaiseau 91128 Cedex, France

(Received 27 September 2002; published 7 May 2003)

- 100 2D PIC simulations generated using BISHOP
- ε_{pmax} increases with electron temperature and peak laser intensity - good agreement with established models [S. Wilks 1992, P. Mora 2005]
- Bayesian optimisation has been used to optimise laser-plasma accelerators more efficiently!

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Bayesian Optimisation Example

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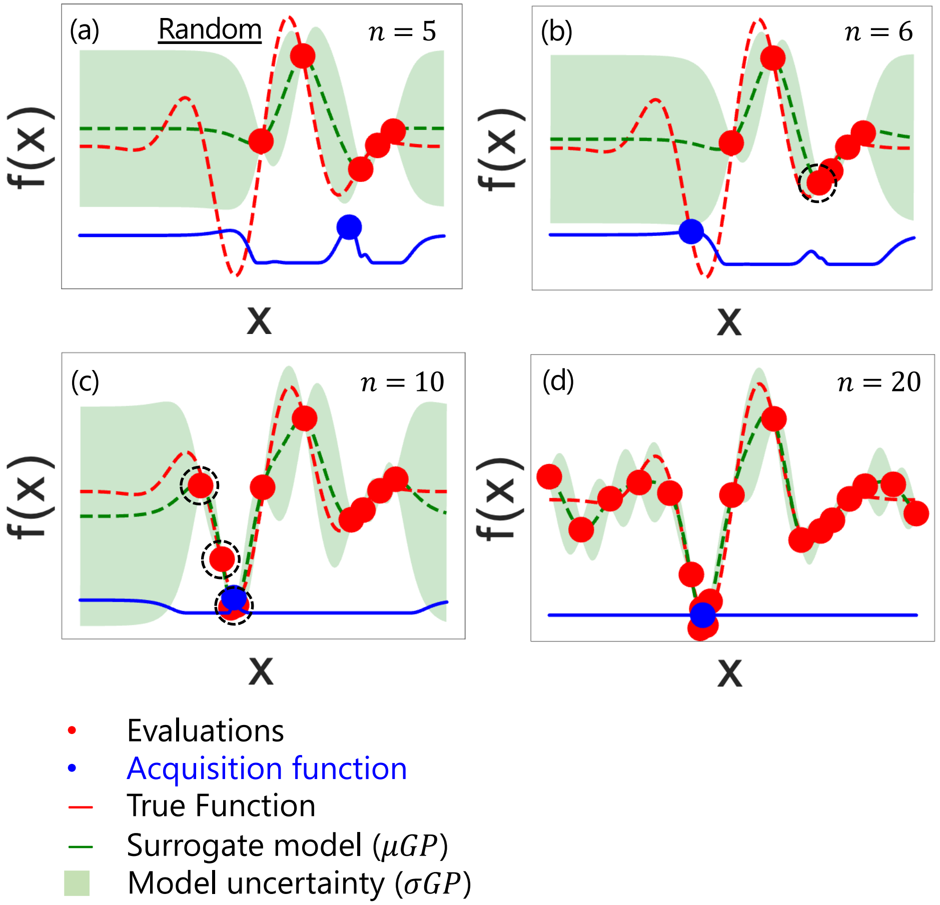
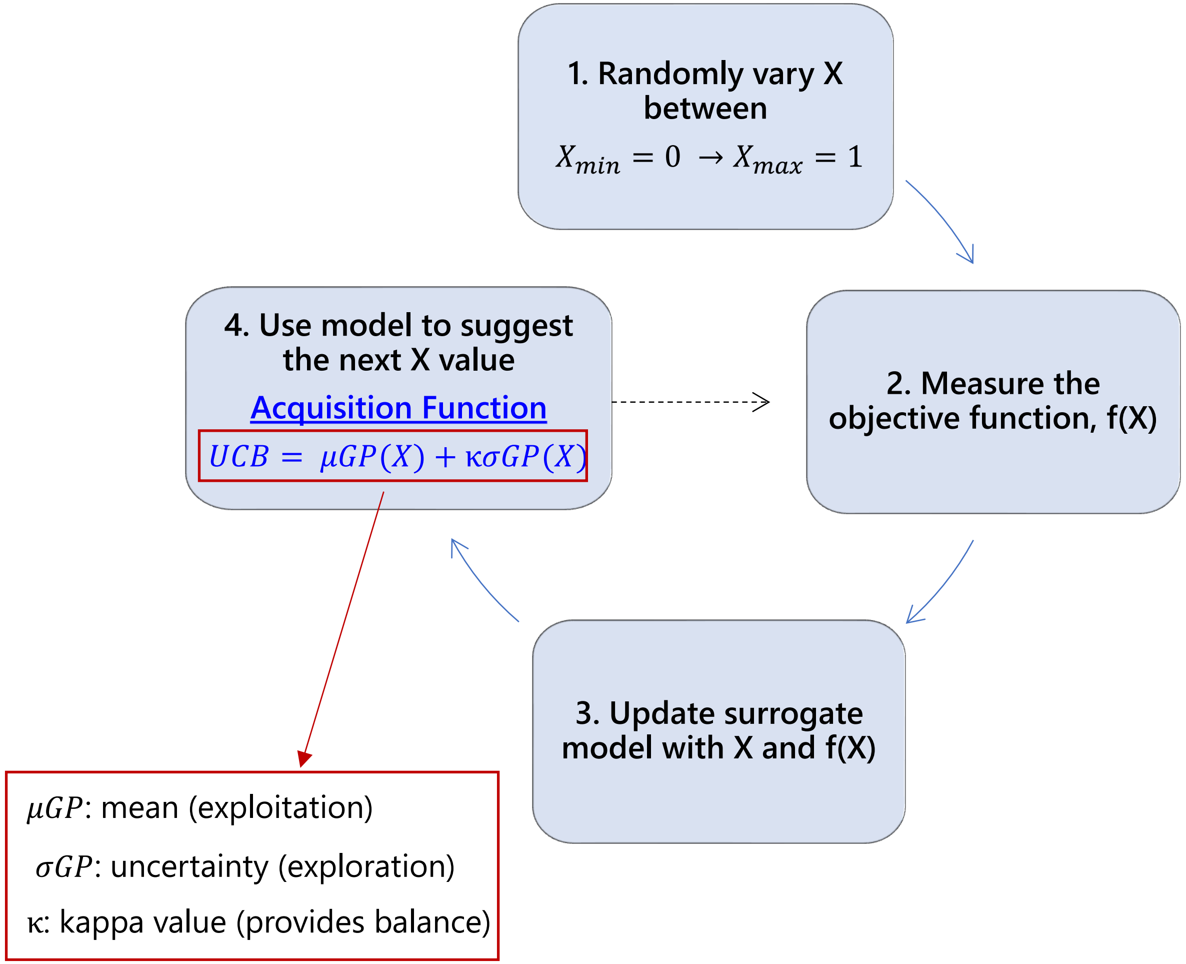
We can optimise a noisy and expensive function with **limited data!**





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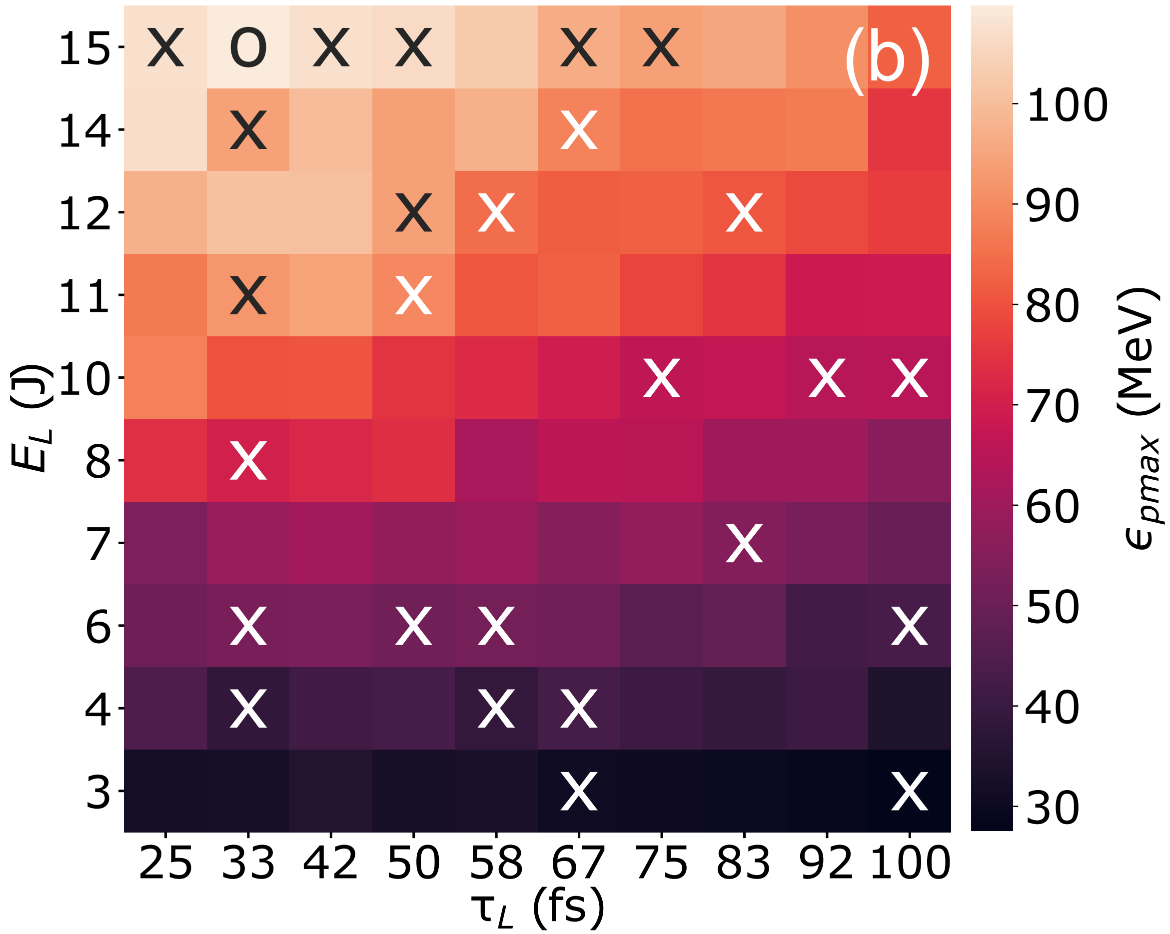
Bayesian Optimisation using BISHOP



The optimum maximum proton energy was identified after ≈ 23 simulations - **4x more quickly** than by grid search for 2 input parameters

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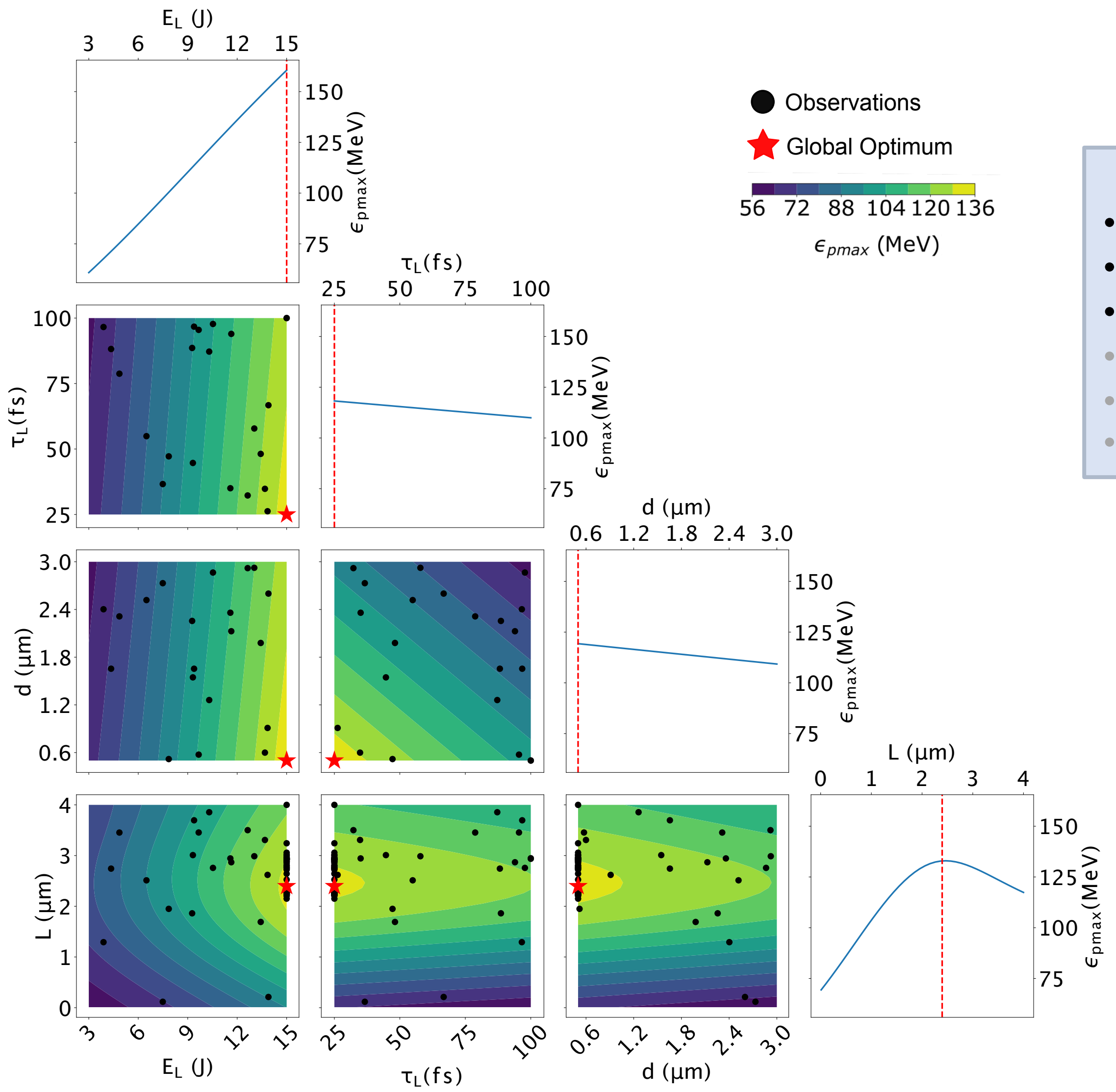
Optimising for Laser AND Target Parameters



Laser:
- **Intensity**
- **Energy**
- **Pulse Duration**
- Focal spot size
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- Polarisation

Plasma:
- Energy conversion efficiency
- Fast electron divergence angle
- Z (scattering, resistivity)
- **Preplasma scale length**
- **Target Thickness**
- Incidence angle

Optimised TNSA maximum proton energy (E_{max}) in **50 simulations** as a function of **4 laser-target parameters**

≈ 1000 x faster than by grid search

E_{max} = 220 MeV, for E_{L} = 15 J, τ_{L} = 25 fs, t = 500 nm, L = 2400 nm

≈ **2x increase in E_{max}** compared to varying 2 parameters

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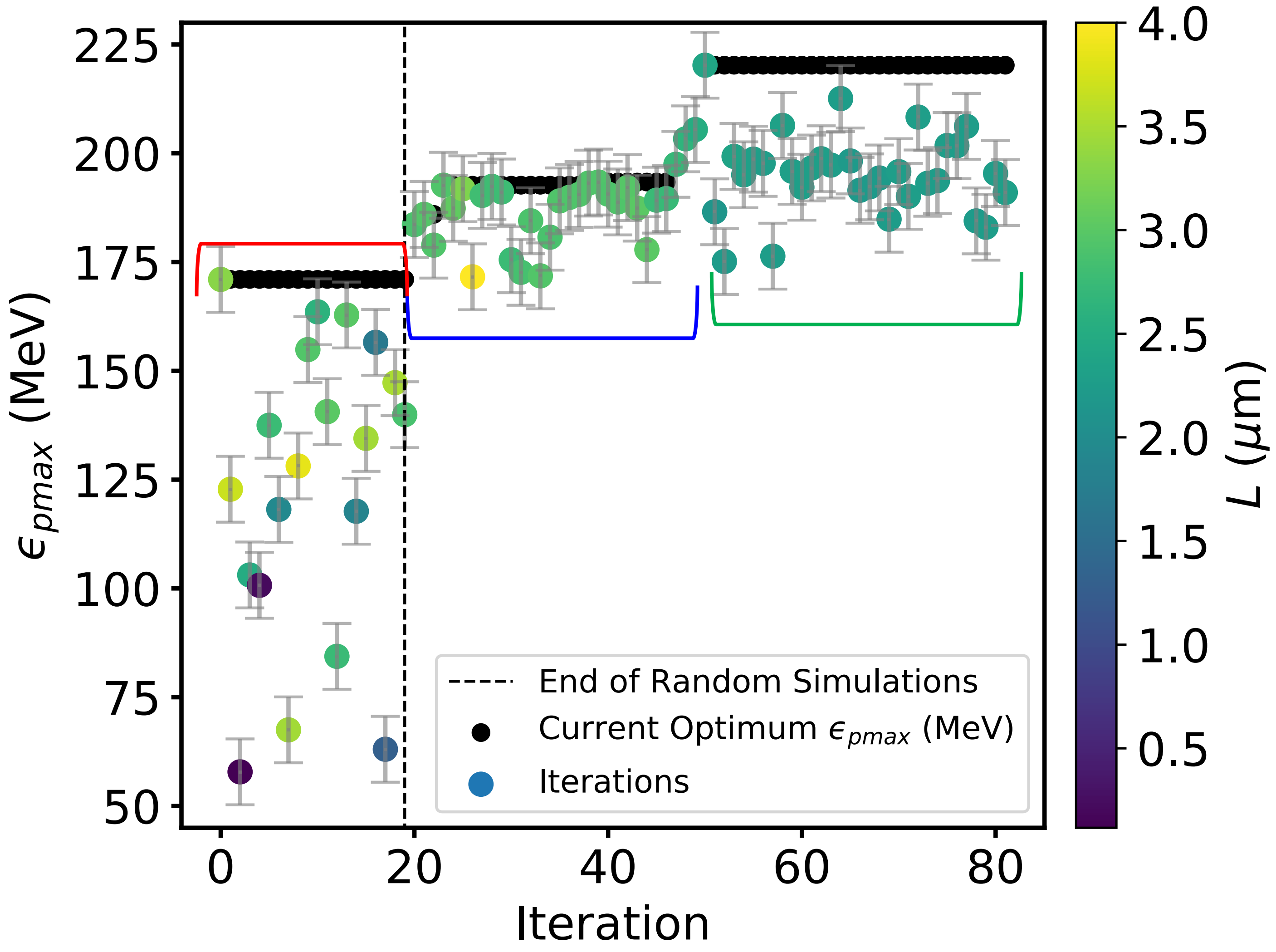
Bayesian Optimisation Process



Inputs for each parameter are randomly varied to initialise the model

Model is created and is confident that optimal conditions for laser energy, pulse duration and target thickness have been found

Model focuses on varying scale length from ~ L = 2.7 µm - L = 4.0 µm

Model focuses on varying scale length from ~ L = 2.1 µm - L = 2.4 µm

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Key Results of Proton Optimisation Work

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- BISHOP platform generates a large dataset of expensive PIC simulations with minimal user input – significantly speeding up the process
- Using Bayesian optimisation, we identify an optimum configuration for a TNSA driven proton source 4x more quickly, and using 4x less resource compared to conventional grid search
- Optimised laser-driven ion acceleration as a function of 4 input laser-target parameters ≈ 1000x more quickly compared to conventional grid search resulting in a 2x improvement in maximum proton energy
- Identified non-trivial optimum condition for front surface density scale length

Published Manuscript

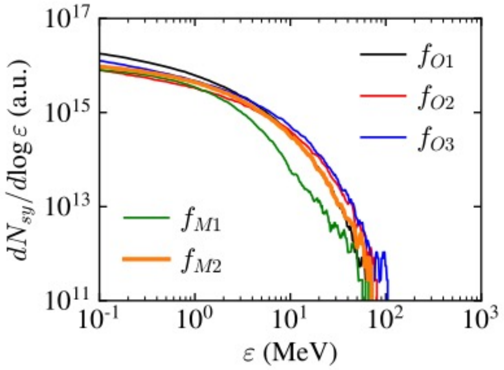
Multi-parameter Bayesian optimisation of laser-driven ion acceleration in particle-in-cell simulations

E. J. Dolier et al 2022 New J. Phys. 24 073025

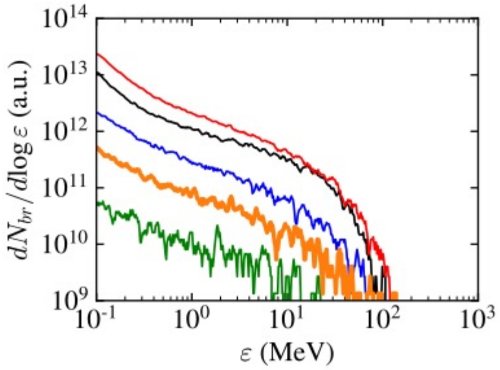
What Next?

- Applying Bayesian optimisation to a more complex regime with more input parameters – synchrotron emission!

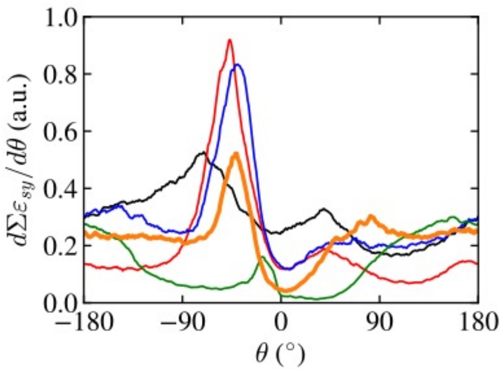
Synchrotron Emission



Bremsstrahlung Emission



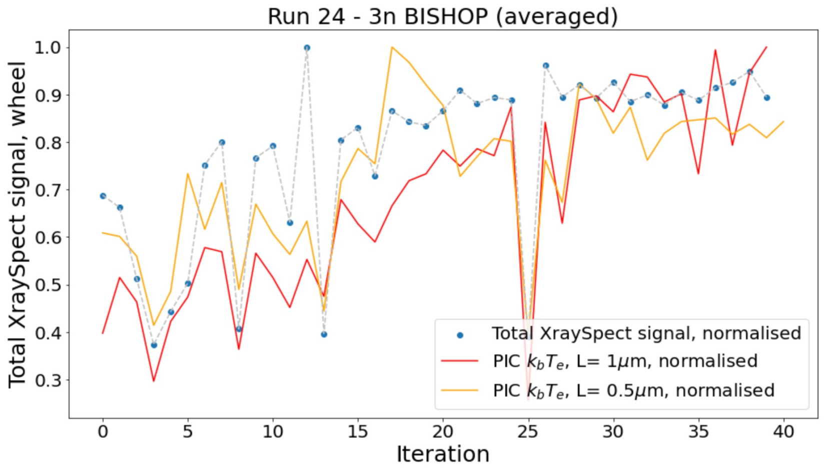
Angle-resolved synchrotron Emission



Published Manuscript

Goodman, J., et. al, 2023. Optimisation and control of synchrotron emission in ultraintense laser-solid interactions using machine learning. HPLSE, pp.1-17.

- Using BISHOP, Bayesian optimisation and LPI-Py to guide experiments - ongoing analysis of two experiments and more scheduled soon!



See Poster by Maia Peat from Thursday

Simulation guided Bayesian optimisation of fast electron temperature in laser-solid interactions

See Talk by Matthew Alderton from Thursday

Commissioning experiment on laser-driven proton acceleration on SCAPA

E. J. Dolier, et al., New J. Phys. 24.7, 073025 (2022)

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Thank you for your time!

Any Questions?

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