AI/ML for the MAX IV accelerators

Magnus Sjöström, MAX IV Laboratory

Outline

Overview

MAX IV accelerators

Possible AI applications @ MAX IV

Machine-learning based accelerator tuning

AI-based or aided accelerator lattice design methods

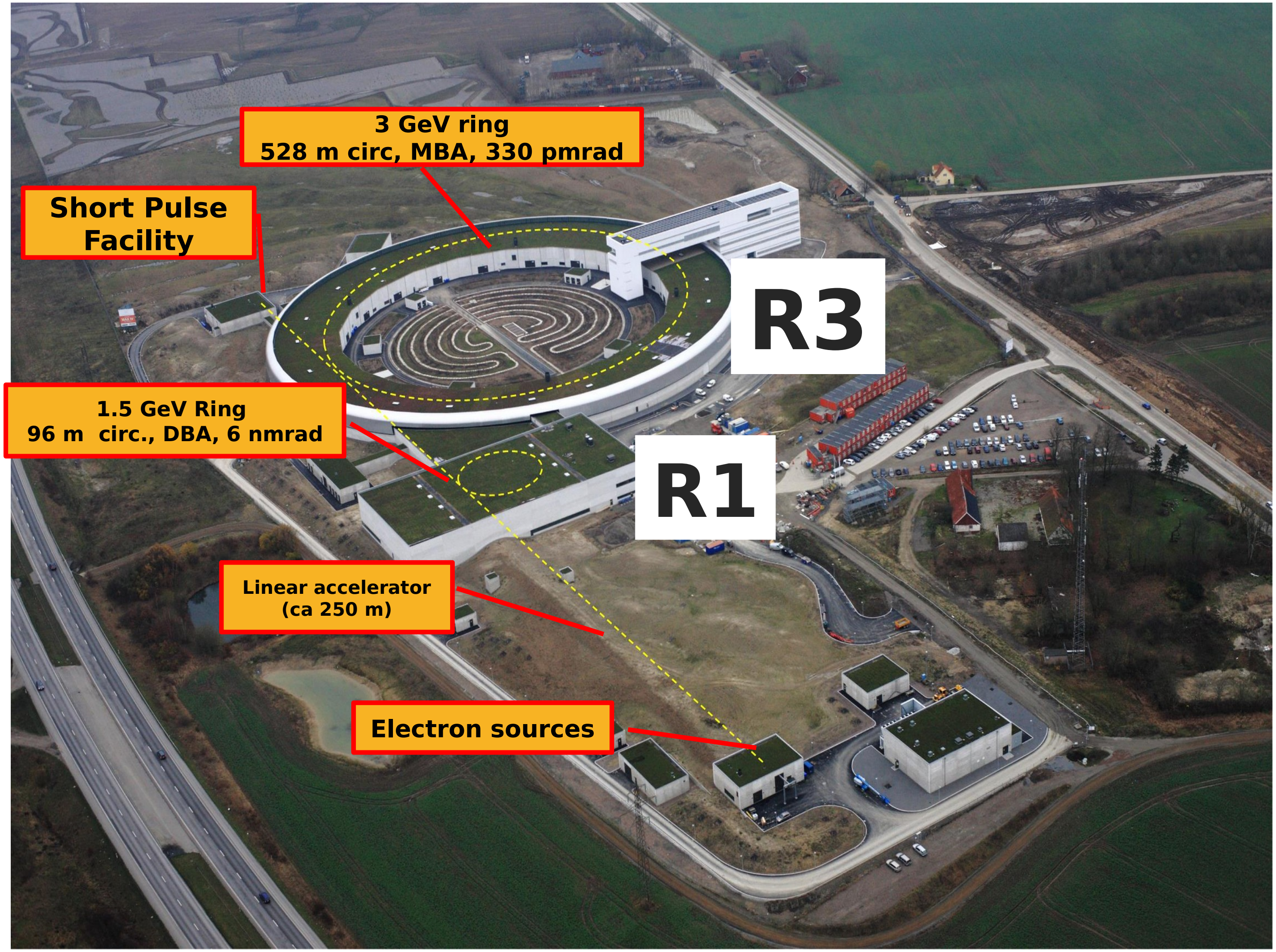
Virtual Diagnostics

MAX IV accelerators

Synchrotron Light Sources are research infrastructure.

From an accelerator perspective they are ***photon factories***

R3: hard X-rays
R1: soft X-rays
SPF: short X-ray pulses



MAX IV accelerators

The accelerator complex at MAX IV is a set of photon factories. As such:

- a SCADA DCS (TANGO) is used to control and monitor the equipment
- production is prioritized so significant effort is put into maximising MTBF, minimising downtime and MTTR, and ensuring the product is up to specifications. This means:
  - regular maintenance and tuning
  - efficient troubleshooting (requires alarm system logs, archived sensor data, etc.)
  - 24/7 operations (maximise output, maintain thermal stability, etc.)
  - maintaining photon source stability (emittance, position/angle/time/energy, charge) → removal of noise sources and deployment of feedbacks
  - providing information to beamlines to allow data filtering (injection signals for gating, beam current for normalization, etc.)
- Interest to cut costs, improve performance/product quality; this means:
  - R&D into new accelerator technology (e.g. permanent magnets)
  - R&D into decreasing electron beam emittance and preserving energy spread (6D dimensions) as it improves resolution; this is set by the magnetic lattice (e.g. MAX 4U)

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ML-based accelerator tuning

USE CASES @ MAX IV

Injection trimming

- Drifts cause injection efficiency to drop over time
- Depends on both linac and storage ring; usually only former possible to trim
- Enable online trimming during top-up injections (few shots every 10 minutes) to maintain high injection efficiency

Beam focus trimming for the SPF

- Drifts causing beam size variations in the FemtoMAX insertion devices
- Experts/skilled operators not always available
- Enable online trimming, likely relying on virtual diagnostic

Calibration of Insertion Device (ID) orbit feed-forward compensation (ongoing)

- Insertion devices generate the photons using the electron beam, but will perturb the latter globally as the photon energy is adjusted
- Orbit perturbations require feed-forward compensation which needs time-consuming tuning
- Online re-training compensation scheme possible?

ML-based accelerator tuning

Being investigated at several labs. In general:

- Human operators only able to monitor and trim a single or a few parameters at the same time
- Human operators cannot react as quickly
- Human experts not always available

→ *desire for automated, robust, and online solutions to tune as needed*

Example collaboration: KIT and DESY, "Machine Learning Toward Autonomous Accelerators".

Stated (ambitious) end goal is autonomous start-up, whereas subgoals have included tests of AI/ML to control the bunch profile at two similar accelerators, to test transferability.

Sample published articles

A. Eichler, "First steps toward an autonomous accelerator, a common project between DESY and KIT"

G. Mitsuka et al., "Machine-learning approach for operating electron beam at KEK electron/positron injector linac", Phys. Rev. Acc. Beams 2024.

Virtual Diagnostics

Background

Particularly for the linac some diagnostic instruments are destructive, i.e. they block or divert the beam during the measurement. This makes such sensors “costly” to use and limits the use of feedbacks. ML can be used to estimate such sensor data based on non-destructive sensors measurements

MAX IV use cases:

Virtual bunch length measurement (ongoing, coming slides)

Virtual FemtoMAX focus beam size measurement

Examples from other facilities:

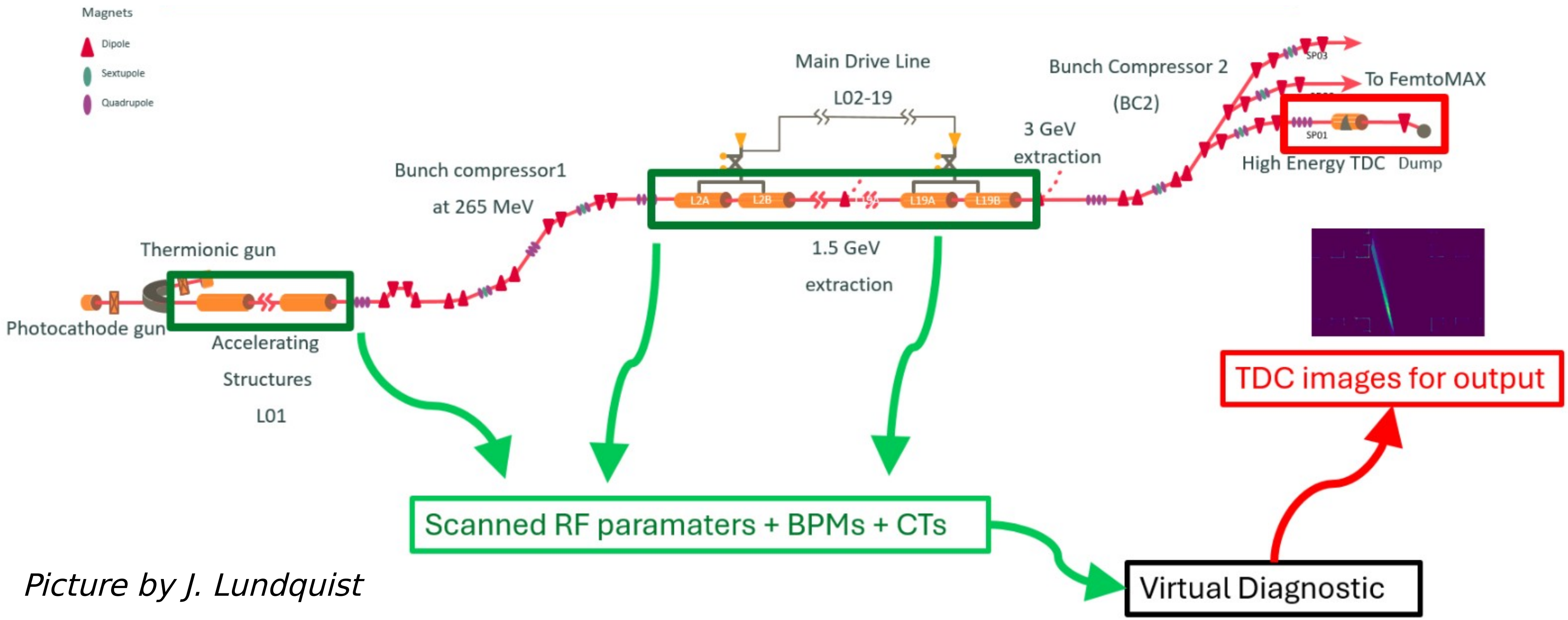
C. Emma et al., “Machine learning-based longitudinal phase space prediction of particle accelerators”, Phys. Rev. Acc. Beams 2018

R. Sharankova, “Diagnostics for linac optimization with machine learning”, FermiLab

Virtual Diagnostics

MAX IV example: TDC bunch length measurements

To measure the very short electron bunch lengths (~10 fs) for the Short Pulse Facility a Transverse Deflecting Cavity (TDC) may be used. Unfortunately this diverts the beam from the FemtoMAX beamline.



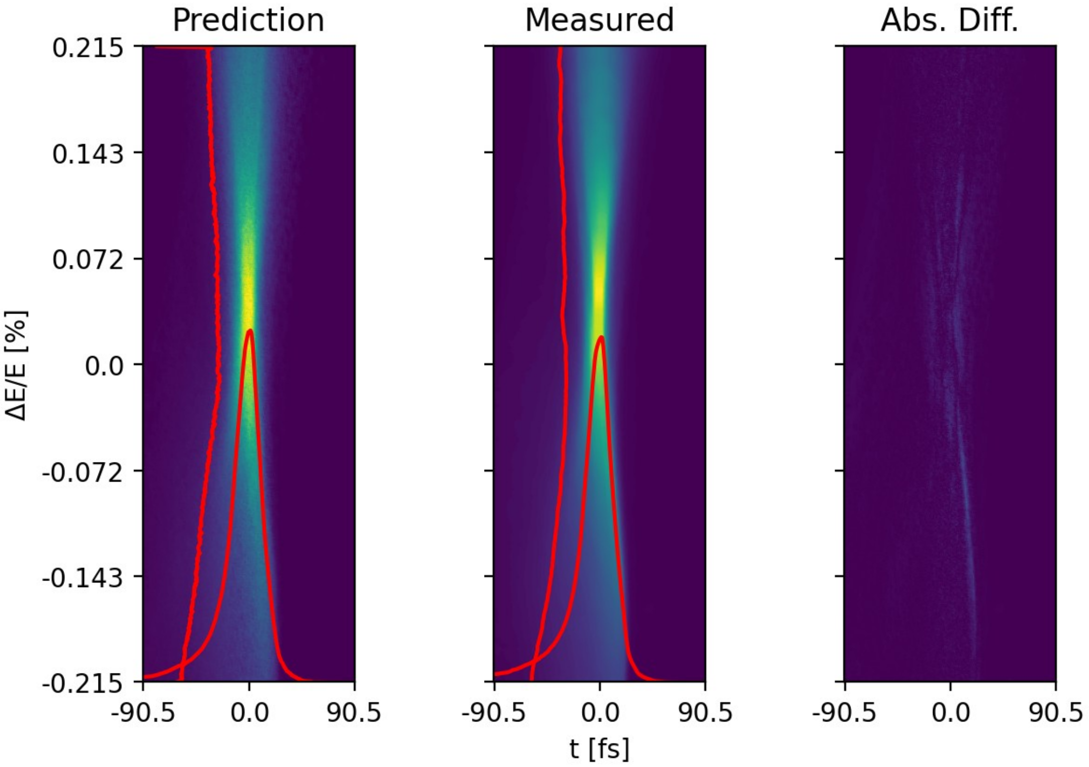
Picture by J. Lundquist

Virtual Diagnostics

TDC bunch length measurements

Number of open questions remaining such as deterioration of prediction quality over time, etc.

Goal is to enable feedback control of the accelerating RF phase and amplitude, in order to stabilize the delivery parameters: bunch length and energy



Data and graph by J. Lundquist

AI-based or aided accelerator lattice design methods

Key accelerator parameters, e.g. emittance, Dynamic Aperture (DA), and Momentum Acceptance (MA) are determined by the particle beam optics, i.e. the magnetic lattice.

Over the last several decades computer aided optimization using Multi-Objective Genetic Algorithms (MOGA) has been used to find optimum solutions given constraints.

However:

a) vast parameter space to search

b) calculation of DA and MA is very expensive

c) error robustness need to be considered → each parameter combination requires many evaluations

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Machine learning has been used to significantly speed up MOGA runs by evaluating DA and MA using a neural net periodically retrained during the run.

Y. Lu et al., “Enhancing the MOGA optimization process at ALS-U with machine learning”, Proc. of IPAC’21

Thank you for your attention!