PAUL SCHERRER INSTITUT

PSI

Philipp Dijkstal (FEL Beam dynamics, PSI) on behalf of the collaboration

LEAPS collaboration between PSI, DESY, and EuXFEL on **Virtual Longitudinal Diagnostics**

LEAPS plenary meeting, 20th October 2023

Applying ML methods to large FEL facilities

- Despite the great Machine Learning hype in approximately the past 8 years, and many papers demonstrating and highlighting the value of ML methods for operation of large FEL facilities in particular, **actual daily applications of ML at these facilities are so far almost non-existent**. We continue to believe in the potential of ML and think that a **fresh start** is needed.
- New collaboration between DESY, European XFEL GmbH and PSI started as part of the LEAPS working group 2.0 on photon sources. The idea is to make use of ML methods in particular for **virtual diagnostics at FEL user facilities**.
- What are virtual diagnostics? They **replace destructive measurements**, using **ML methods such as surrogate models** in combination with **non-invasive, online measurements.**
- Examples of invasive measurements are electron beam LPS diagnostics (linac side), or grating-based FEL spectrum measurements (photon side).
- Examples of non-invasive, online measurements are rf phases and OTR-based current profile measurements (linac side), and gas-based FEL spectrum measurements (photon side).
- These virtual diagnostics have to be **developed and benchmarked** with the help of all measurements available. ML methods can also be applied to **improve the fidelity of all available diagnostics**. This would be useful in any case.

In-person workshop, 28-29 Sep. 2023, DESY

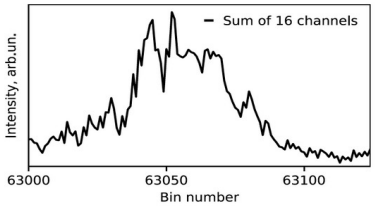
- Organized by Christopher Arrell (PSI) and Jan Grünert (EuXFEL). 13 participants: 3 from PSI, 3 from EuXFEL, 7 from DESY. Most of them **accelerator physicists and photon diagnostics experts** heavily involved in the development and **daily operation of FEL user facilities**.
- The workshop included **presentations** on already existing virtual diagnostics under development, comparisons of diagnostics available at both machines, and ideas for collaboration. **Most time was spent on discussions**.
- The workshop was appreciated, and the information exchange was beneficial. We confirmed the interest within PSI, DESY and EuXFEL to pursue demonstrative virtual diagnostics / ML projects / combined systems.
- **Dedicated support by controls and ML experts will be needed**.
- Common themes identified:
  - Building a **complete model of the FEL** (linac+undulator) as a basis for virtual diagnostics, and beyond.
  - Full implementation of **virtual diagnostics** into FEL operation as a **running, usable, and maintainable system.**
  - **Fidelity augmentation** of X-ray spectrum and electron beam LPS measurements.

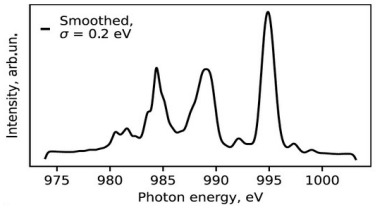
The participants

(Christopher Arrell took the photo.)

Next slide: Example for an already existing application of ML methods for virtual diagnostics at EuXFEL.

An example of virtual diagnostics at EuXFEL





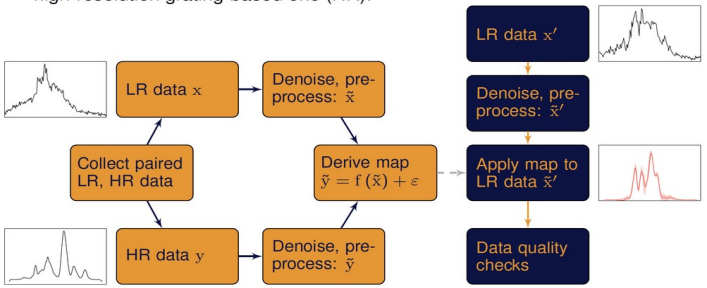
Photoelectron spectrometer.

- Non-invasive.
- Pulse-resolved.
- Low-resolution.
- Complex calibration.

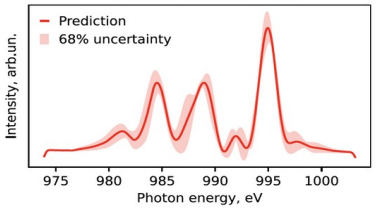
Grating-based spectrometer.

- Invasive.
- Train-resolved.
- High-resolution.
- Simple calibration.

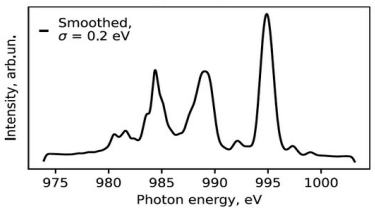
Idea. Map the low-resolution photoelectron spectrometer (LR) to the high-resolution grating-based one (HR).



Derived from LR data.

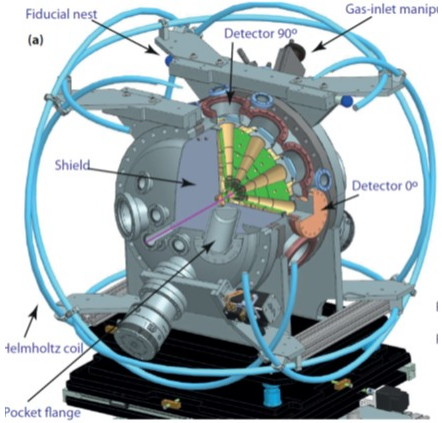


Corresponding HR data.



Virtual spectrometer.

Non-invasive:	During inference the input is LR data only.
Pulse-resolved:	During inference the input is LR data only.
Improved resolution:	1.8 eV in this example vs. 0.2 eV for the HR.
Simple calibration:	Automated, only HR data are calibrated.



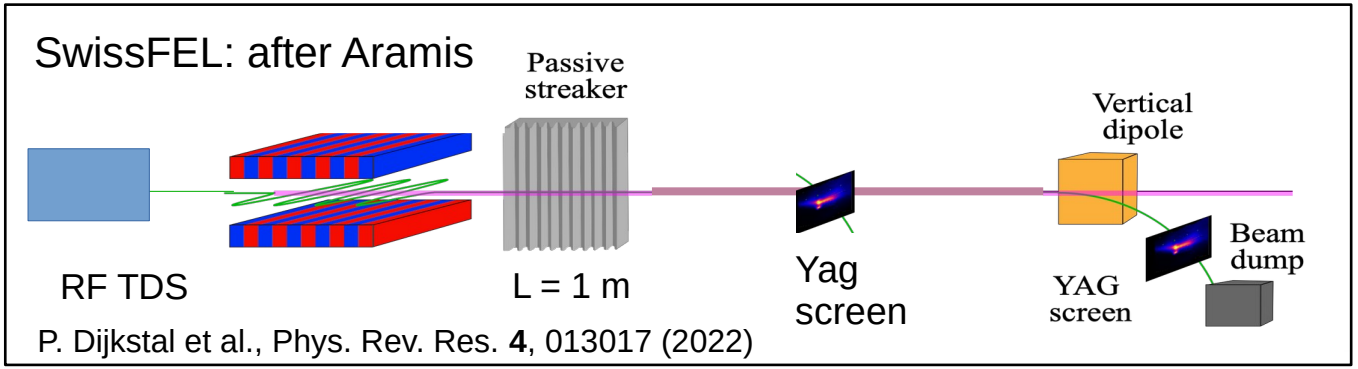
On-demand, standard diagnostics for the soft X-ray SASE3 beamline.

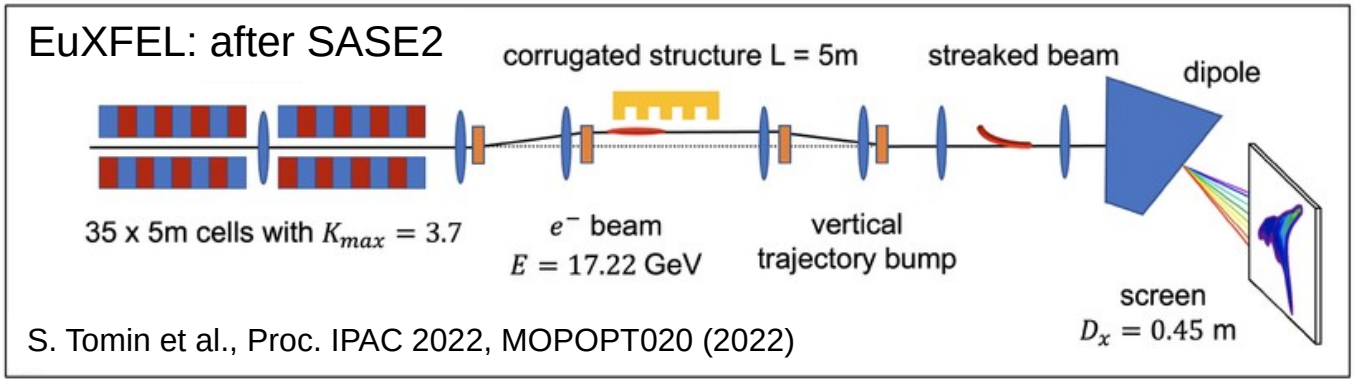
Next steps for our collaboration

- **Small groups** start to work on selected topics, with **results hopefully within the next 12 months**.
  1) Building a surrogate model of the FEL to predict X-ray pulse properties.
  2) Phase and temporal FEL pulse reconstruction based on photon spectra and electron beam LPS measurements.
  3) Improve analysis of online diagnostics, for example of photon spectrometer measurements.
  4) Improve electron beam LPS and FEL power profile measurements from passive wakefield streakers.
- We will try to collaborate successfully and use that to **acquire funding** through LEAPS (or other sources).
- Another in-person meeting in early 2024.
- Next slides show **more details about selected topic 4**. Project between myself and Sergey Tomin (DESY, MXL).

Passive wakefield streakers at SwissFEL & EuXFEL

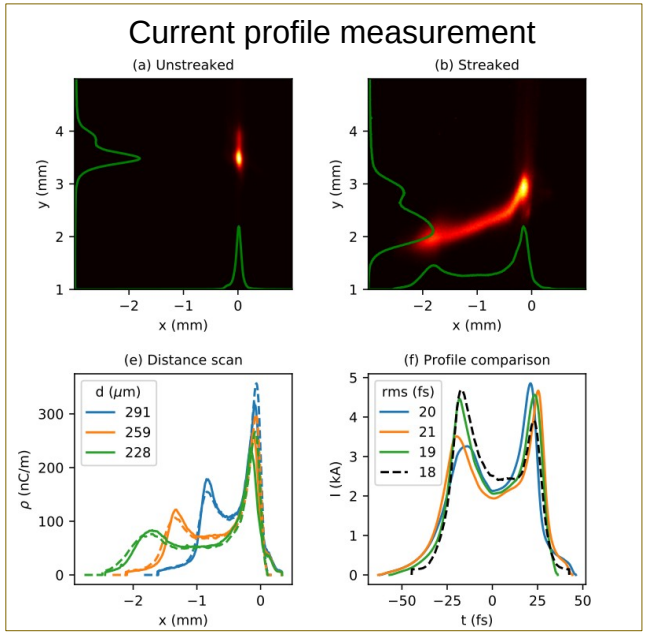
- Passive streaker diagnostics are a **cost-efficient** and self-synchronized **alternative** to rf deflector (TDS) diagnostics.
- They will be needed to benchmark future virtual longitudinal diagnostics after some of the EuXFEL and SwissFEL beamlines.

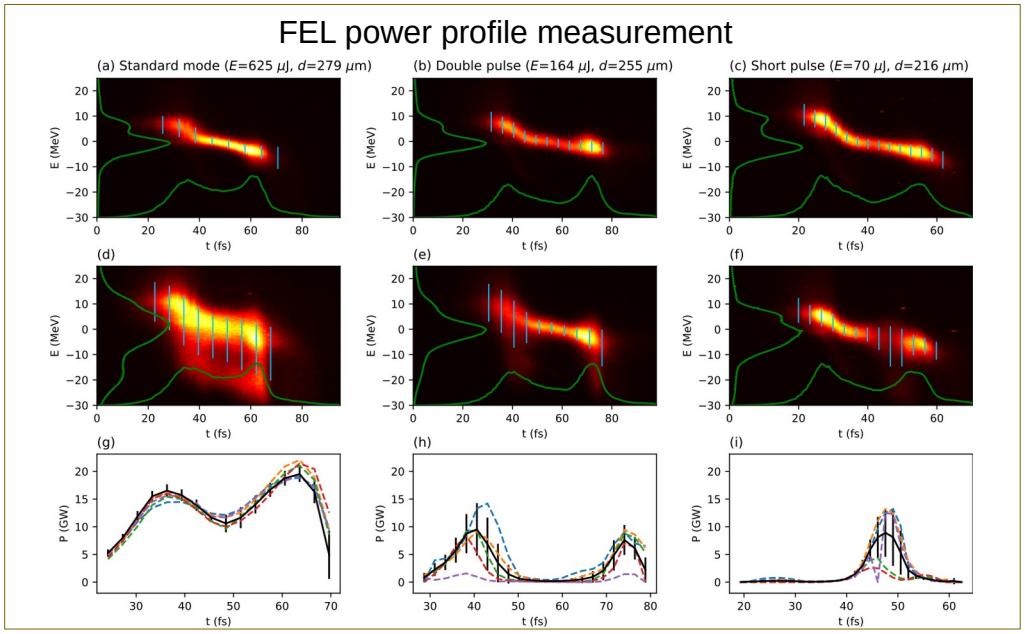




Current state of measurement analysis

- Iterative algorithms from P. Dijkstal et al., Phys. Rev. Res. **4**, 013017 (2022) are used at both facilities to measure the electron beam LPS and the **FEL power profile and pulse duration**, with good success.
- But these algorithms are certainly not perfect. Instead of incremental progress through more tinkering, I would prefer the development of a **fresh analysis approach employing ML methods**.





Outline of ML-enhanced measurement analysis

Bunch properties:
- Mostly current profile
- But also transverse properties
  - Beam size / optics
  - Tansverse alignment / tilt

+

Passive streaker properties:
- Corrugation geometry (known)
- Most importantly distance between beam and plate (initially unknown).
- Possibly also trajectory angle.

+

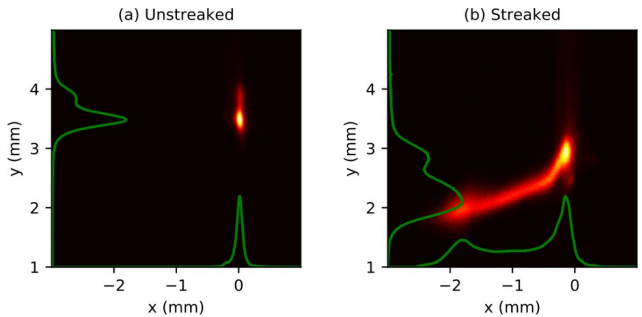
Analytical WF model: K. Bane et al., PRAB **19**, 084401 (2016)

Forward simulation =

Beam monitor image, i.e., transverse (2D) projection of the 6D particle distribution.
Beam monitor is usually dispersive.

- Need to “invert” the forward simulation process, input the measurements, and obtain the beam properties!
- Need support from ML specialists. We already reached out to an expert at PSI / ETH Zurich and hope to attract a master student for this topic.

Measurements



In a distance scan, we measure the unstreaked beam, the maximally streaked beam, and everything in between.

Thank you for your attention