PhD position in artificial intelligence and accelerator physics

Interpretable Surrogate Modeling of Collective Effects in the FCC-ee High-Energy Booster

Description:

The High-Energy Booster (HEB) of the FCC-ee is an important part of the collider complex. Its task is to accelerate beams from 20 GeV at injection to the top energies required by the collider (45.6–182.5 GeV depending on the operation mode) and deliver them with the stability, emittance, and intensity demanded by precision electroweak physics. Yet this apparently routine task hides a major challenge. The FCC-IS feasibility study [1–3] has underlined that, beyond optics design and ramping strategy, the collective effects arising at injection energy represent one of the most critical challenges for the HEB.

At low energy, the beam is most vulnerable. Resistive-wall impedance, unavoidable in the vacuum chamber, is sufficient to trigger coupled-bunch instabilities. Higher-order modes (HOMs) in the RF system exacerbate the problem. FCC-IS analyses [2] showed that without active mitigation, instability growth times are shorter than damping times, making bunch-by-bunch feedback mandatory. Such dependency illustrates how essential robust feedback systems will be to ensure reliable beam delivery under varying operating conditions.

Today, the only way to study these effects is through multi-turn, multi-bunch tracking simulations. Codes like BLonD and PyHEADTAIL (XSuite today) have been the backbone of collective-effects research at CERN for two decades. Their fidelity is not in question. Their speed, however, is a critical barrier. To sweep across beam currents, RF voltages, chromaticities, HOM parameters, and feedback gains requires thousands of runs. Even with modern HPC clusters, these studies take weeks. As the FCC design matures and options multiply, this bottleneck will become unsustainable. Here is where surrogate modeling enters the stage. The idea is straightforward: use the heavy simulations to train fast, interpretable neural networks that can predict beam stability in seconds. But the ambition goes beyond speed. By designing the surrogate as a segmented graph, where each subsystem of the HEB (optics, resistive wall, HOMs, RF cavities, dampers, kickers) is represented by its own neural block, we create a framework in which digital twins can be plugged in at will. If tomorrow the RF group delivers a high-fidelity twin of the 400 MHz cavities including Lorentz force detuning, we can swap out the surrogate RF block and drop the twin in. If the impedance team develops a detailed DT of the vacuum chamber with coatings and tapers, it can replace the RW block. The surrogate framework thus becomes the glue that binds together multiple twins into a single predictive machine.

This modularity is not only pragmatic but strategic. It ensures that the framework remains sustainable as the FCC-ee design evolves. It also enables interpretability: each block can be analysed in isolation, with observer heads predicting hidden physical quantities such as effective impedance or chromatic tune spread. In this way, the surrogate is not a black box but a physics- informed partner to design and operation. This programme does not start from scratch. The doctoral research of Emmanuel Gouttière at IJCLab [7,8], focused on the ThomX compact light source, has already demonstrated the feasibility of segmented neural surrogates for accelerator modeling. In that work, the LINACNET architecture was introduced for cloud-to-cloud propagation of particle distributions, while the INODE framework addressed discontinuity-aware dynamics such as kicks and regime changes. These methods successfully reproduced beam evolution with strong fidelity and offered interpretability through modular, physics-informed designs. The research also delivered a reduced cavity model including Lorentz force detuning, bridging machine-learning surrogates and physics-based reduced models. Building on this foundation, the proposed FCC-ee HEB programme will extend these approaches to multi-bunch, multi-turn collective effects, and will be carried out in close collaboration with CERN, IJCLab, and LISN.

Expected skills:

Applied physics, accelerator physics, data science
Softwares : Python, XSuite, MADX, PyHEADTAIL

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1. **FCC-IS Feasibility Study**, Deliverable D2.3: *HEB Collective Effects at Injection*, CERN, 2024.
2. Quartullo, D. et al., *Collective Effects in the FCC-ee High-Energy Booster*, FCC Week 2023.
3. **FCC-IS Final Report**, March 2025.
4. CERN **XSuite Documentation**, https://xsuite.readthedocs.io
5. Biancacci, N. et al., *XSuite–PyHEADTAIL Interoperability for Impedance Modeling*, FCC Week 2024.
6. Alexahin, Y. et al., *Synchrotron Radiation and Collective Effects in e^+e^- Rings*, Phys. Rev. Accel. Beams, 2022.
7. Goutierre, E., *Utilisation de Méthodes d'Apprentissage pour la Modélisation d'un Accélérateur de Particules*, PhD Thesis,
Université Paris-Saclay, 2024.
8. Goutierre, E. et al., *Reduced Model of a Superconducting Cavity Including Lorentz Force Detuning*, Phys. Rev. Accel. Beams
24, 2021.