Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) – France

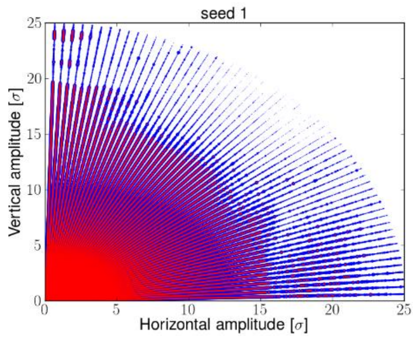
ADVANCED AND ARTIFICIAL INTELLIGENCE TECHNIQUES TO MITIGATE LINEAR AND NON-LINEAR IMPERFECTIONS IN FUTURE CIRCULAR COLLIDERS

DESCRIPTION (EN)

After the discovery of the Higgs boson at the LHC, particle physics community is exploring and proposing next accelerators, to address the remaining open questions on the underlying mechanisms and on the constituents of the present universe. One of the studied possibilities is FCC (Future Circular Collider), a 100-km-long collider at CERN [1][2]. The hadron version of FCC (FCC-hh) seems to be the only approach to reach energy levels far beyond the range of the LHC, in the coming decades, providing direct access to new particles with masses up to tens of TeV. The electron version of FCC brings a tremendous increase of production rates for phenomena in the sub-TeV mass range, making precision physics studies possible.
A first study [1][2] has shown no major showstopper in the colliders' feasibility but has identified several specific challenges for the beam dynamics: large circumference (civil engineering constraints), beam stability with high current, the small geometric emittance, unprecedented collision energy and luminosity, the huge amount of energy stored in the beam, large synchrotron radiation power, plus the injection scenarios.
This thesis will focus on the optimization of the hadron option of the future circular collider against linear and non-linear imperfections (i.e. magnets alignments and their field quality).
A key point of this thesis is the comparison of current advanced correction schemes to techniques based on machine learning. The application of these techniques to accelerators is one of current hot topics in the field and pursued worldwide (see for example [3]).

WORK PLAN

The efficiency of the used correction scheme directly bounds the corrector needs and magnet tolerances. A first specification of the linear and non-linear correctors' fields and tolerances for magnets misalignments and field quality already exists, based on the LHC standard NbTi technology [4][5] and traditional (LHC design) correction schemes of linear and non-linear imperfections.
Firstly, the student will apply the correction techniques, currently employed in the operation of the LHC. Then he/she will include the residual linear errors in the computation of Dynamic Aperture (DA), which is the area of stable motion for the particles travelling in the accelerator. The DA is the figure of merit for the evaluation of the non-linear correction schemes and quantifies the impact of non-linear errors [6] on the long-term stability of the machine.



Stable particles (red) among all simulated particles (blu), for one configuration of dipole field errors in the accelerator.

Secondly, the student will develop Artificial Intelligence (AI) based techniques and compare the obtained performances and specifications to the previous techniques.
Currently, accelerator physicists perform the linear correction and specify the correctors by using gradient descent or Single Value Decomposition methods [7]. A first application of AI is to propose alternative minimization techniques in order to improve the correction efficiency.
A second application will be to find an interpolating function of the DA for a set of multipole field errors (imperfections). Currently, tracking simulations, which are time consuming, are the only way to evaluate the DA. Accelerating the computation of the DA will enable to better specify the magnet tolerances and to improve the statistics. Other advanced techniques using Echo State Network or Recurrent Neural Network [8] could also predict the evolution of the DA with the number of turns. The direct consequence would be to speed up the calculation by reducing the number of required turns.
Finally, the peaks in the frequency spectrum of the turn-by-turn beam positions in the BPMs (Beam Position Monitors) identify the resonances. A better accuracy of this spectrum is essential in the identification of the higher order resonances and thus their corrections. The student will exploit the possibility to use neural networks to filter noise on beam based measured quantities, to improve the

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ratio signal over noise and to reduce the error bars on the non-linear contributions.
Where possible, the student will also apply the new developed techniques to other accelerators, like FCC-ee, muon colliders, or IOTA [9].

Bibliography

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Working environment

The thesis will take place within the Department of Accelerators, Cryogenics and Magnetism (DACM) at CEA Saclay. DACM has a strong potential in the design of charged particle accelerators within the LEDA laboratory ("Laboratoire d'études et de *développements pour les accélérateurs*").

Collaborations

The student will collaborate with CERN accelerator physics group for applications related to LHC and to perform (and participate in) experiments in LHC.
The work related to artificial intelligence will be also discussed in a multidisciplinary CEA team (named "InTheArt"). It involves about 100 researchers from the LSCE laboratory ("*Laboratoire des Sciences du Climat et de l'Environnement*"), to software developers of the DEDIP department ("*Département d'Electroniques, des Détecteurs et d'Informatique pour la Physique*"), including also people of DEN ("*Direction de l'Energie Nucléaire*"), DRT ("*Direction de la Recherche Technologique*"), CNRS and Paris-Saclay University.
Mathematical aspects will be discussed with the Laboratory for Modeling and Scientific Computing of *"Politecnico di Milano"* (Italy).

Doctoral contract financing

CFR

Training and required skills

Master in Physics or Applied Mathematics or Engineer with good knowledge in Machine Learning techniques, analytical calculations and affinity for theoretical studies.

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