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CHART Scientific Report (Final Report for Phase 2)

Long term Coherent stability for the Future Circular Colliders

(FCC-hh and HE-LHC Stability)

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1. Introduction

In circular particle accelerators, particularly those handling positively charged particles, the formation of electron clouds (e-clouds) can significantly affect beam stability and performance. Mitigating e-cloud formation is crucial for the effective operation of modern accelerators, such as the Large Hadron Collider (LHC), and for future designs like the Future Circular Collider (FCC). These clouds, formed when electrons accumulate within the accelerator chamber, can cause detrimental effects such as transverse instabilities, particle losses, and increased heat loads. The first part of the study consists of identifying the parameters, in the range of the values of FCC-ee case, which play a significant role in the e-cloud formation. In the second stage, self-consistent beam stability simulations for the different arc elements with realistic e-cloud distributions obtained from build-up simulations will be performed based on the obtained results. In parallel, contributions to the benchmarking and improvement of the simulation tools based on laboratory and LHC measurements will be made.

2. Research Goal

The primary goal of this research is to tackle the challenges posed by electron cloud (e-cloud) formation and beam stability in circular accelerators. A key focus is on understanding and mitigating e-cloud effects by examining critical parameters, such as the Secondary Electron Yield (SEY) and surface treatments, particularly for the FCC-ee. The findings will directly influence material choices and treatments for the beam vacuum chamber, a decision with significant cost implications. The presence of e-clouds can drastically reduce the collider's luminosity due to severe instabilities, which may occur independently or in conjunction with flip-flop effects in colliding beams.

Another crucial objective is to develop predictive models for beam loss rates, unexplained beam losses (e.g., Unidentified Falling Objects), and instabilities in existing accelerators using machine learning techniques. These models are first being tested and validated on the LHC to benefit from experimental data, with the ultimate goal of applying them to the design of future accelerators. This approach will enable rapid, data-driven predictions of beam stability and particle loss rates, minimizing the reliance on time-consuming simulations.

3. Results

3.1 Electron Cloud studies:

The FCC feasibility study mid-term report serves as the baseline scenario, with a focus on the Z configuration, where the strongest e-cloud effects are expected due to the large number of bunches and minimal bunch spacing. Positron beams, more susceptible to e-clouds, are the primary concern. Since the FCC-ee is a top-up injection accelerator, understanding e-cloud behavior during charge accumulation is crucial. Bunch intensity was examined across a range from one-tenth to the nominal intensity of 2.15×10^{11} positrons per bunch (ppb).

A key aspect of e-cloud studies is identifying material constraints to prevent e-cloud avalanche multiplication (multipacting), which is governed by the Secondary Electron Yield (SEY). SEY multipacting thresholds have been calculated for various arc elements—drift spaces, dipoles, quadrupoles, and sextupoles—with quadrupoles and sextupoles being the most critical in e-cloud formation.

Table 2: SEY multipacting thresholds per arc element for the baseline scenario parameters.

Element	**SEY Threshold**	**25 ns**
Drift Space	nominal intensity	1.4
	all intensity below nominal one	1.2
Dipole (15.2 mT)	nominal intensity	1.4
	all intensity below nominal one	1.0
Quadrupole (1.45 T/m)	nominal intensity	1.1
	all intensity below nominal one	1.0
Sextupole (72.5 T/m^2)	nominal intensity	1.1
	all intensity below nominal one	1.0

Another key observation is that the most stringent SEY constraints occur at bunch intensities lower than the nominal value. Specifically, the critical intensities are 1.00 and 1.50×10^{11} positrons per bunch (ppb), as illustrated in Fig. 1 where we give an example for the electrons multipacting in dipole magnets.

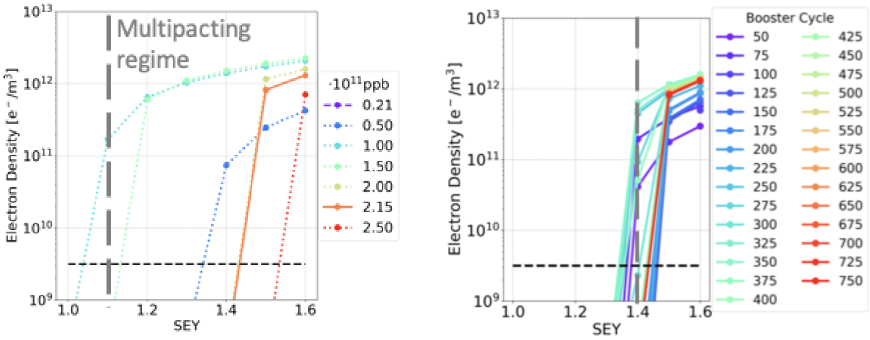

Fig. 1: The results pertain to the dipole magnets. The initial e-cloud density is indicated by the horizontal dashed black line. The SEY multipacting threshold, considering different bunch intensities during the charge accumulation phase, is shown by the vertical dashed grey line. (Left) Total e-cloud density in the vacuum chamber

versus SEY for different bunch intensities, represented by different colours (with the nominal bunch intensity shown in a solid line). (Right) Total e-cloud density in the vacuum chamber versus SEY for different booster cycles during the charge accumulation phase, represented by different colours.

One technique to obtain larger SEY multipacting thresholds is to use filling schemes with larger bunch spacing to reduce the avalanche effect by letting the electrons decay before the second bunch passes. A bunch spacing of 50 ns results in SEY multipacting thresholds that are larger than or equal to 1.3 for all the considered arc elements. However, increasing the bunch spacing requires increasing the bunch intensity to maintain a constant beam current and constant performances in terms of luminosity. Larger bunch intensities could lead to issues with other collective effects, such as beam-beam and wake-fields and coupling impedance, as shown in recent studies presented at the FCC week 2024 [9,10].

Another idea to have less tight material constraints involves using larger bunch spacing when the bunches reach the critical bunch intensities, with special filling schemes during the charge accumulation phase. This approach allows the SEY multipacting threshold, considering the full charge accumulation phase, to be equal or close to the SEY multipacting threshold for the nominal bunch intensity.

If electron cloud formation cannot be avoided then the collider has to deal with some effects and we have computed their impacts in terms of heat-loads and instability thresholds.

The total additional heat loads in the arcs due to e-cloud are in the order of a percentage of the synchrotron radiation power (50 MW) in case of multipacting, and they are negligible compared to the synchrotron radiation power if there is no multipacting.

Secondly, the e-cloud could trigger instabilities as the beams pass through the e-clouds and they receive transverse kicks [12]. The e-cloud density stability thresholds have been assessed by means of the theoretical equation [13]. These thresholds have been verified through simulations for drift spaces (see Fig. 2) and dipole magnets. These simulations are computational intensive, with the computational time depending on numerical parameters such as the number of longitudinal slices, the average number of bunch MPs per slice used to model the positron bunch, the number of MPs used to model the e-cloud at each interaction, the configuration of the transverse grids used to compute the fields generated by the beam and by the electrons through the Particle In Cell (PIC) method, and the number of e-cloud interactions (kicks) along the ring. After a preliminary convergence study, the numerical parameters were chosen and every multi-core simulation took around 4 weeks to simulate 4,800 turns.

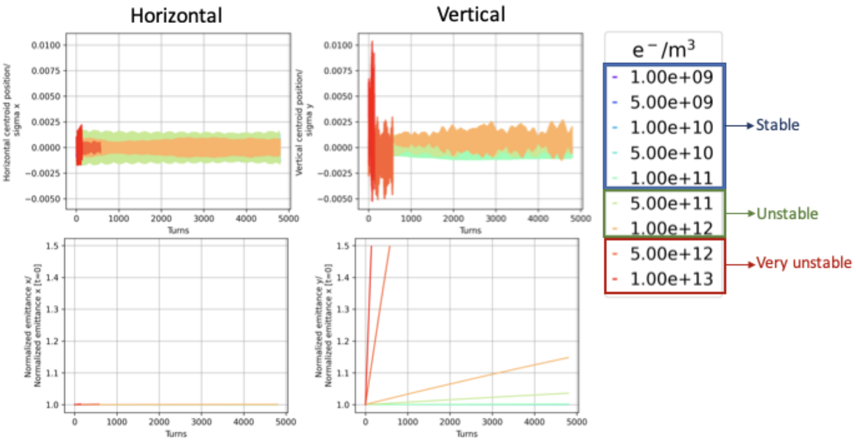

Fig. 2: The first row shows the transverse centroid versus turns. The second row displays the normalised emittance divided by the initial normalised emittance versus turns. The horizontal and vertical planes are shown in the first and second columns, respectively. Different e-cloud densities are represented by different colours.

The e-cloud density stability threshold is higher than the e-cloud density above the SEY multipacting threshold, before the bunch passage and close to the vacuum chamber centre, for all the considered elements, except for the sextupole magnets. In other words, if the material constraints are not met, the e-cloud could lead to beam instabilities. Several mitigation techniques as non-uniform filling schemes are under investigation with the goal to provide more relaxed constrains on the inner vacuum chamber SEY. Preliminary results and a new operational filling scheme will be proposed.

3.4 Additional contribution to the e-cloud formation process given by the photoemission

The previous results do not take into account the photoelectrons. The photoelectrons are the primary electrons produced by the circulating beams by means of the photoemission from the chamber's wall due to the synchrotron radiation emitted by the beam. Synchrotron radiation emitted by electron and positron beams represents a major loss source in high energy circular colliders, such as the lepton collider FCC-ee [14]. Therefore, it is important to assess the impact of the photoelectrons on the e-cloud formation process.

In PyECLOUD, the parameter $K_{pe,st}$ represents the number of photoelectrons to be generated per beam particle (positron) and per unit length. Taking into account the photoemission in the e-cloud formation process, the e-cloud density saturation value could be reached in less bunch passages and it could be larger. Moreover, the gap length, needed to clean the vacuum chamber, could be larger (see Fig.3).

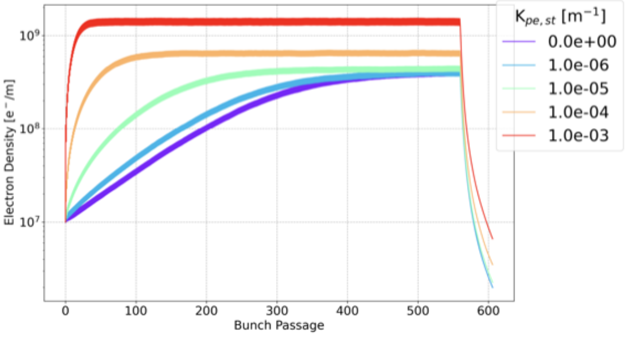

Fig. 3: E-cloud density versus bunch passage for different values of $K_{pe,st}$ in different colours.

Furthermore, the central e-cloud density before the bunch passage could exceed the e-cloud stability threshold even below the SEY multipacting threshold. For this reason, high values of $K_{pe,st}$ should be avoided. Another important property of the beam chamber surface is the photoelectron yield Y, which depends on $K_{pe,st}$ and the photon flux. From preliminary ray-tracing simulations, the photon flux, except in the absorber areas, is in the order of 10^{13} - 10^{14} photons/(cm^2 ·s) and, therefore the photoelectron yield should be smaller than 3% - 3‰. This constraint on the material is very tight, and in the absorber areas the photon flux is expected to be even higher. For this reason, some solutions are under development by the vacuum group. One solution is the design of a new synchrotron radiation absorber with a sawtooth profile along the primary facet, i.e., the facet where the primary synchrotron radiation photons hit. With the sawtooth profile oriented in a specific way, only a much smaller fraction of the impinging photons are actually reflected. This solution results in a much larger deposition of synchrotron radiation in the absorber areas, necessitating efficient cooling methods [15]. Additionally, the presented results consider a uniform generation of photoelectrons per segment of the vacuum chamber surface. Next step will be to use a more realistic distribution of photoelectron generation using ray tracing codes, allowing for a better simulation of the e-cloud formation process. Another point is that the e-cloud affects the two beams differently. The effects of the e-cloud are more severe for the positron beam than for the electron beam. This discrepancy could lead to other side effects that require further investigations, such as the beam-beam flip-flop phenomenon, which is sensitive to the asymmetry between the two beams [18].

3.6 Nested Magnets

Nested magnets are under exploration by overlapping dipole fields with arc quadrupoles and sextupoles in order to increase the dipole filling factor and reduce the synchrotron radiation power [16]. Preliminary e-cloud studies on nested magnets have been conducted.

The e-cloud transverse distribution before the bunch passage has been compared for different configurations of nested magnets with single element magnets (e.g., dipole magnet, as shown in Fig. 4) to observe how the central e-cloud density is affected. Changing the polarity of the quadrupole (focusing and defocusing) in nested magnets with only a dipole, and adding also a sextupole, inverts the left-right symmetry of the e-cloud transverse distribution, but it does not alter the central e-cloud density, similar to observations for single quadrupole magnet. In a configuration with a dipole, a quadrupole, and a sextupole magnet with a positive gradient, the electrons are pushed away from the vacuum centre (see Fig. 4 bottom left). This phenomenon does not occur with a sextupole magnet with a negative gradient (Fig 4 bottom right).

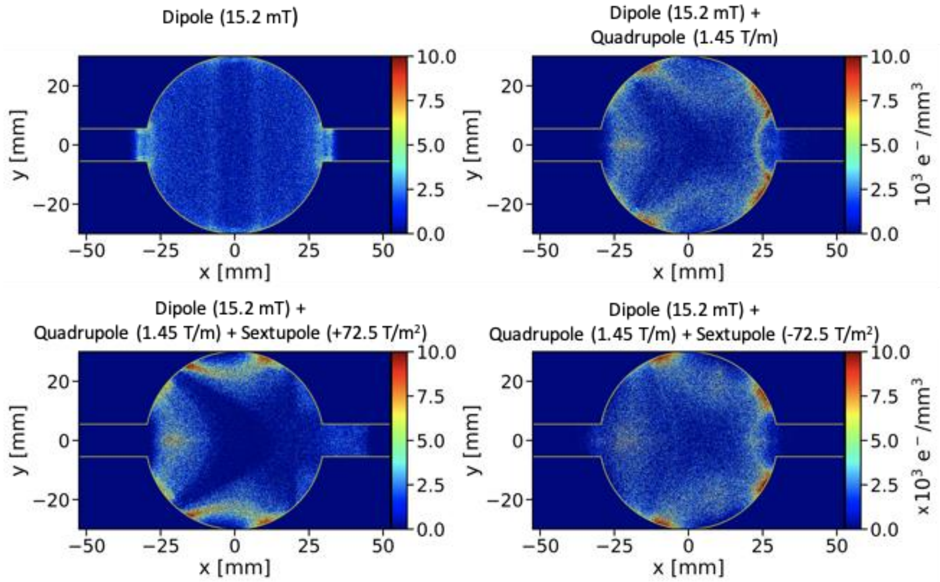

Fig. 4: E-cloud transverse distribution before the bunch passage for different magnetic elements. First row: (from left to right) dipole magnet, dipole and quadrupole magnet. Second row: (from left to right) dipole, quadrupole, and sextupole magnet with positive and negative gradient.

The SEY multipacting thresholds, for the nominal bunch intensity, are lower in case of nested magnets compared to a single dipole magnet. This phenomenon could be explained as follows: the quadrupole and sextupole gradients trap the electrons for a longer period inside the vacuum chamber, increasing the e-cloud density even at lower values of SEY. The central e-cloud density values before the bunch passage are of the same order of magnitude for both dipole magnets and nested magnets, except in the case of a configuration with a dipole, quadrupole, and sextupole with a positive gradient. The SEY multipacting thresholds for the nominal bunch intensity are nearly the same in the case of a quadrupole magnet and some configurations of the nested magnets, particularly a dipole plus a quadrupole, and a dipole plus a quadrupole plus a sextupole with a negative gradient. As aforementioned, in the nested magnet configuration with dipole, quadrupole, and sextupole with a positive gradient, the electrons are pushed away from the vacuum chamber centre. Furthermore, the nested magnet with quadrupole and sextupole exhibits a particular transverse distribution. In this configuration, a large number of electrons are trapped in an off-centre cross shape (see Fig. 5), positioned to the right or left of the vacuum chamber centre depending on the combination of the gradient sign of the quadrupole and sextupole. Consequently, the central e-cloud density in this nested magnet configuration is much lower compared to that of a single quadrupole magnet.

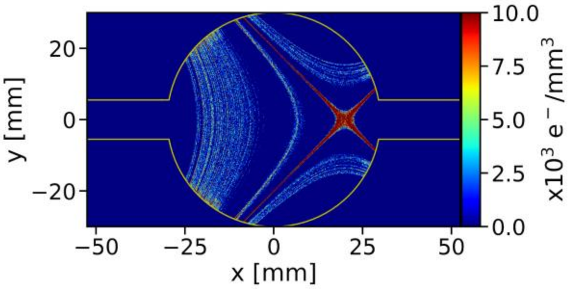

Fig. 5: E-cloud transverse distribution before the bunch passage for a nested magnet with quadrupole and sextupole.

ML4FCC project: Accelerating Beam-Dynamics studies for FCC

To understand the non-linear beam dynamics and factors behind beam losses in circular accelerators, the concept of Dynamic Aperture (DA) is crucial. DA defines the phase-space region within which a particle's motion remains bounded. Calculating DA involves tracking multiple initial conditions over many turns, which is computationally demanding, especially for large accelerators like the LHC or FCC.

Over the last two years, we developed machine learning models, specifically a Deep Neural Network (DNN), to quickly and accurately predict DA for unknown machine configurations. This was trained on a large dataset of simulated initial conditions, effectively capturing the relationship between accelerator parameters and DA. In 2023, we introduced a Multilayer Perceptron (MLP) model to predict DA, trained using simulated configurations of the 2023 LHC lattice at injection energy. The model achieved a Mean Absolute Error (MAE) of 0.34 beam σ, with accurate predictions shown in a 2D histogram.

Additionally, we incorporated an error estimator using Monte Carlo dropout, allowing the model to assess uncertainty in DA predictions. This was integrated into an Active Learning (AL) framework, prioritizing new simulations based on predicted error. This approach accelerates DA estimation and expands the dataset efficiently.

The model's computational efficiency is a key achievement. For a batch of 1024 samples, DA prediction takes 1.41 ms per inference using a GPU, compared to the traditional particle tracking method, which takes up to 30 hours for 1000 configurations. Once trained, the model can be up to 200 times faster than conventional methods. This allows for almost online predictions of loss rates for the LHC and a much faster and efficient design and/or optimization if a future collider as the FCC-ee. The next step is indeed to continue and instead of focusing on reducing the error in optimizing DA proposing a possible innovative scenario for the FCC-ee. Preliminary results are very promising but further studies are needed to pursue this investigation and possibly apply it to the LHC operation and/or the design of the FCC.

4. List of Presentations

- Presentation at FCC Week 2024 2024/06/12
  https://indico.cern.ch/event/1298458/contributions/5978306/attachments/2873359/5035736/2024_06_12_FCC_week.pdf
- Presentation at FCCee Optics Design Meeting 2024/05/28
  https://indico.cern.ch/event/1416849/contributions/5957937/attachments/2866454/5017388/2024_05_28_FCC-ee_Accelerator_Design_Meeting.pdf

- Presentation at Electron Cloud Studies for FCC-ee EPFL-LPAP 2024/05/07 https://indico.cern.ch/event/1412362/contributions/5936229/attachments/2851871/4988907/2024_05_07_FCC_ecloud_meeting.pdf
- Presentation at FCCIS WP2 Workshop 2023/11/13 https://indico.cern.ch/event/1326738/contributions/5650208/attachments/2750643/4787790/2023_11_13_FCCIS_WP2_Workshop_2023.pdf
- Presentation at FCCee Optics Design Meeting 2023/11/02 https://indico.cern.ch/event/1335891/contributions/5630850/attachments/2744965/4776359/2023_11_02_FCCee_Optics_Design_Meeting.pdf
- Presentation at CHART Workshop 2023/10/11 https://indico.psi.ch/event/14732/contributions/44276/attachments/26092/48432/2023_10_11_Chart_workshop.pdf
- Presentation at Electron Cloud Studies for FCC-ee EPFL-LPAP 2023/09/12 https://indico.cern.ch/event/1324913/contributions/5575351/attachments/2713113/4711737/2023_09_12_FCC_ecloud_meeting.pdf
- Presentation at FCC Week 2023 2023/06/06 https://indico.cern.ch/event/1202105/contributions/5390895/attachments/2659031/4607694/2023_06_06_FCC_week.pdf
- Presentation at ABP-CEI Section Meeting 2023/06/01 https://indico.cern.ch/event/1281953/contributions/5385854/attachments/2657397/4602982/2023_06_01_CEI_section_meeting.pdf
- Presentation at Electron Cloud Studies for FCC-ee EPFL-LPAP 2023/05/15 https://indico.cern.ch/event/1287085/contributions/5408619/attachments/2647970/4583936/2023_05_15_FCCee_ecloud_meeting.pdf
- Presentation at FCCIS 2022 workshop 2022/12/07 https://indico.cern.ch/event/1203316/contributions/5125374/attachments/2562368/4416763/2022_12_07_Sabato_Luca_FCCIS_2022_Workshop.pptx
- Presentation at 159th FCC-ee Optics Design Meeting 2022/11/10 https://indico.cern.ch/event/1205924/contributions/5080961/attachments/2544998/4382481/2022_11_10_Sabato_Luca_FCC-ee%20Optics_Design_Meeting.pdf
- Presentation at ECLOUD22 workshop 2022/09/25 – 2022/10/01 https://agenda.infn.it/event/28336/contributions/176811/attachments/97052/133885/2022_09_26_Sabato_Luca_ECLOUD22.pptx
- Presentation at EPFL-LPAP Activity Meeting 2022/09/23 https://indico.cern.ch/event/1200207/contributions/5046762/attachments/2514699/4323463/2022_09_23_Sabato_Luca_EPFL-LPAP.pdf
- Presentation at CHART Workshop 2022 2022/06/09 https://indico.psi.ch/event/12727/contributions/35124/attachments/21949/37860/2022_06_09_Sabato_Luca_CHART_Workshop.pptx
- Presentation at EPFL-LPAP FCC-ee Software Framework Meeting 2022/05/11 https://indico.cern.ch/event/1160125/contributions/4872192/attachments/2441680/4182938/2022_05_10_Sabato_Luca_FCCweek.pdf
- D. Di Croce, "Accelerating Beam Dynamic Simulations". FCC Week 2023. London, 08.06.2023.
- D. Di Croce, M. Giovannozzi, T. Pieloni, M. Seidel and F.F. Van der Veken, "Optimizing Beam Dynamics in LHC with Active Deep Learning", in Proc. 68th ICFA ABDW on High-Intensity and High-Brightness Hadron Beams, 2023.

5. List of Publications

- Sabato L, Pieloni T, Mether L, Iadarola G, "Electron Cloud Build-up Studies for FCC-ee", "Electron Cloud Build-up Studies for FCC-ee", Journal of Physics: Conference Series,

Volume 2687, Beam Dynamics and EM Fields, IOP, DOI 10.1088/1742-6596/2687/6/062029.
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- Mether L, Sabato L, et al., "The Electron Cloud and its Impact on LHC and Future Colliders", 15th Int. Particle Accelerator Conf. (IPAC24), Nashville, Tennessee, USA, 2024. https://accelconf.web.cern.ch/ipac2024/pdf/WEZD2.pdf
- Sabato L, Pieloni T, Mether L, Iadarola G, "Electron Cloud Build-up Studies for FCC-ee", 14th Int. Particle Accelerator Conf. (IPAC23), Venice, Italy, 2023. https://www.ipac23.org/preproc/pdf/WEPA092.pdf
- Mether L, Sabato L, et al., "Electron cloud observations and mitigation for the LHC Run 3", 14th Int. Particle Accelerator Conf. (IPAC23), Venice, Italy, 2023. https://www.ipac23.org/preproc/pdf/WEPA091.pdf
- D. Di Croce, "Accelerating dynamic aperture evaluation using deep neural networks". IPAC 2023. Venice, 10.05.2023.
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- D. Di Croce, "Designing Future Colliders". Artifact Workshop 2023. Paris, 28.11.2023.
- D. Di Croce, M. Giovannozzi, T. Pieloni, M. Seidel and F.F. Van der Veken, "Accelerating dynamic aperture evaluation using deep neural networks", in Proc. 14th Int. Particle Accelerator Conf. (IPAC'23), pp. 2870–2873, JACoW Publishing, Geneva, Switzerland, 2023.
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- G. Iadarola et al., "Xsuite: an integrated beam physics simulation framework", in Proc. 68th ICFA ABDW on High-Intensity and High-Brightness Hadron Beams, 2023.
- Thomas Pugnat, D. Di Croce, M. Giovannozzi,F. F. Van der Veken, "Analysis Tools for Numerical Simulations of Dynamic Aperture With Xsuite", in Proc. 68th ICFA ABDW on High-Intensity and High-Brightness Hadron Beams, 2023.

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