

DIPOLE POWERING FAILURE CRITICALITY AND MITIGATION FOR FCC-ee

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Abstract

The electron-positron Future Circular Collider (FCC-ee) will initially operate at the Z-pole energy of 45.6 GeV with beams composed of 12 000 bunches, storing a total energy of 17.5 MJ per beam. Combined with small emittances, this results in extremely high beam energy densities that pose a significant damage risk to accelerator components. A comprehensive assessment of powering failure scenarios is therefore essential to ensure safe machine operation. This study evaluates the impact of a powering failure in one of the main dipole circuits using the Local Chromaticity Correction (LCC) lattice configuration. Multi-turn bunch tracking simulations are performed to determine the beam response and assess failure criticality. We interpret these novel results with respect to previously established results for the Global Hybrid Correction (GHC) lattice. Horizontal orbit excursions are found to develop over a significantly longer timescale than for the GHC lattice. The underlying physics of this behaviour is analysed in detail, with emphasis on the role of the modified sextupole configuration in the arcs. Based on these findings, the implications for machine protection system design, including interlocking requirements and detection strategies, are discussed and mitigation measures are proposed.

INTRODUCTION

The stored beam energy of the electron-positron Future Circular Collider (FCC-ee) at the Z-pole energy (45.6 GeV) reaches 17.5 MJ per beam, with very small transverse emittances ($\epsilon_x \approx 0.7$ nm and $\epsilon_y \approx 1.4$ pm). The resulting beam energy density is therefore exceptionally high, and fast beam losses carry a significant damage potential for accelerator components [1]. Hence, a systematic assessment of powering failure scenarios is a prerequisite for the design of adequate machine protection systems.

Two optics configurations are considered for FCC-ee: the Global Hybrid Correction (GHC) optics [2] and the Local Chromaticity Correction (LCC) optics [3]. The criticality of a main dipole circuit powering failure for the GHC lattice has been established in Ref. [4], demonstrating that orbit excursions of up to 11σ can develop within three turns in the worst-case scenario. The present study extends this analysis to the LCC lattice, providing a systematic physics-based comparison of the failure dynamics in both configurations,

and investigating an alternative powering scheme that exploits a specific design property of the LCC optics.

LATTICE CONCEPTS AND POWERING SCHEME

The FCC-ee ring comprises eight arcs separated by four experimental and four technical straight sections [5]. In both the GHC and LCC lattices, the main dipoles are twin-aperture magnets powered in series per half-arc, yielding 16 independent circuits with an identical time constant:

$$\tau = \frac{L_{\text{dipole}}}{R_{\text{dipole}}} = \frac{0.184 \text{ mH}}{0.62 \text{ m}\Omega} \approx 300 \text{ ms}. \quad (1)$$

Following a power converter trip, the current decays as $I(t) = I_0 e^{-t/\tau}$, reducing the bending field by approximately 0.1 % per machine revolution (300 μ s).

The two lattices differ fundamentally in their optics design. The GHC arcs consist of pure FODO cells, with chromaticity corrected globally by strong sextupole families distributed around the ring. The LCC arcs are based on a hybrid FODO design (HFD) [3], inspired by synchrotron light source lattices, in which arc sextupoles are weaker and fewer, with chromaticity correction predominantly performed locally in the straight sections using strong higher-order magnets (octupoles, decapoles). The smaller arc beta functions of the LCC lattice ($\langle \beta_x \rangle \approx 85$ m vs. ≈ 105 m for GHC) translate directly into a larger physical aperture relative to the beam size. The foreseen horizontal collimation cut for the two lattices is $\sim 10\sigma$. Given the extremely high beam energy density, collimators can only be designed to intercept a small fraction of the total beam energy before sustaining permanent damage [1], making any orbit excursion reaching the collimation cut immediately critical.

Simulations follow the methodology described in Ref. [4]: matched 6D Gaussian bunches are tracked with XSuite [6], with synchrotron radiation enabled and ideal tapering, to compensate for local energy variations through the optimisation of individual dipole strengths, applied [7]. The physical aperture is modelled as a 3 cm-radius circular cross-section; the collimation insertion, experimental solenoids, and beam-beam effects are not included. The failure is simulated by applying a time-dependent field decay to all dipoles of the failing circuit.

FAILURE DYNAMICS: GHC VS. LCC

Figures 1a and 1b show the evolution of the orbit excursion throughout the machine during the worst-case dipole

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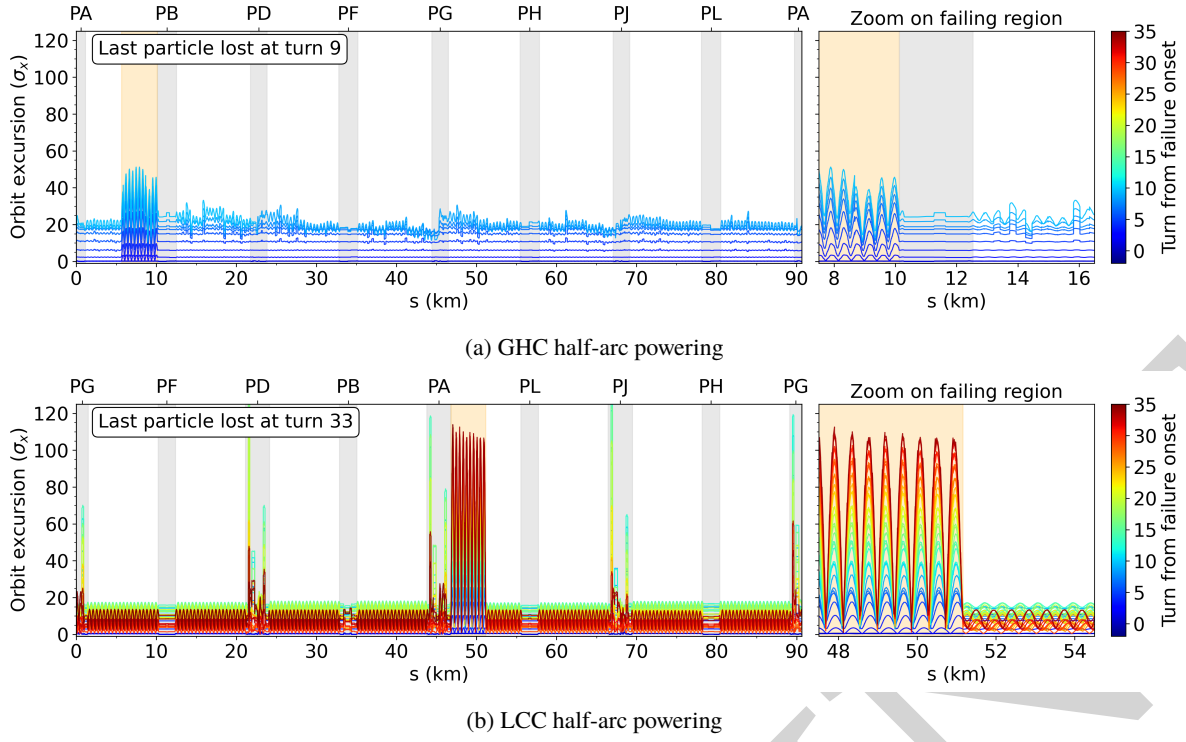


Figure 1: Orbit excursion throughout the machine for the GHC lattice (a) and the LCC lattice (b), for the worst-case dipole powering failure. The orbit excursion leakage at the edge of the failing arc (highlighted in orange) is shown (right). The colour scale represents the turn number from failure onset.

powering failure, i.e., the one leading to the fastest orbit excursion outside the failing arc, for the GHC and LCC lattices in case of half-arc powering. For GHC, the orbit excursion outside the failing arc grows rapidly and irregularly, reaching more than 10σ within a few turns (4–9 depending on the half-arc), with all particles lost in the physical aperture after 9–12 turns. All the orbit excursion shown in the plots lie within the physical aperture of the machine. The losses occur because the closed-orbit growth outside the dynamic aperture of the machine, leading to beam losses as the beam particles are driven towards the physical aperture. For LCC, the excursion outside the failing arc reaches 10σ within 5–24 turns, but subsequently remains comparatively contained without the explosive growth observed in GHC, while very large oscillations—up to 110σ —develop inside the failing arc before all particles are lost after 31–37 turns.

The physical mechanisms underlying this contrast are as follows. The beam centroid displacement Δx in the arc sextupoles of strength k_2 generates a quadrupolar feed-down $\Delta k_1 = k_2 \cdot \Delta x$ at each sextupole location. The relevant figure of merit for comparing the two lattices is the total integrated feed-down strength, weighted by the beta function and summed over all arc sextupoles:

$$\int k_2(s) \beta_x(s) ds \approx \sum_i k_{2,i} \cdot L_i \cdot \beta_{x,i}. \quad (2)$$

This can be decomposed into a pure hardware contribution $\sum_i K_{2,i} = \sum_i k_{2,i} \cdot L_i$ and a beta function weighting. For GHC, the arc sextupoles have an average normalised strength $\langle k_2 \rangle \approx 0.951 \text{ m}^{-3}$ over a length $L = 1.3 \text{ m}$, with $N = 584$

sextupoles per beam, giving:

$$\sum_i K_{2,i} \Big|_{\text{GHC}} \approx 722 \text{ m}^{-2}. \quad (3)$$

For LCC, the arc sextupoles have an average normalised strength $\langle k_2 \rangle \approx 0.243 \text{ m}^{-3}$ over an average length $\langle L \rangle = 0.4 \text{ m}$, with $N = 1632$ sextupoles per beam, giving:

$$\sum_i K_{2,i} \Big|_{\text{LCC}} \approx 159 \text{ m}^{-2}. \quad (4)$$

The hardware contribution alone is therefore approximately 4.5 times larger in GHC than in LCC. Notably, the LCC lattice has a larger number of arc sextupoles than GHC, but this is more than compensated by the much weaker integrated strength per magnet. Applying the beta function weighting—with $\langle \beta_x \rangle \approx 105 \text{ m}$ for GHC vs. $\approx 85 \text{ m}$ for LCC—amplifies this difference by a further factor of ~ 1.2 , bringing the total ratio of the feed-down integral to approximately 5.6.

This intrinsic lattice property directly governs the strength of the phase advance drift during the failure, and enters the perturbation to the machine tune which evolves as Δx changes turn by turn:

$$\Delta Q \approx \frac{1}{4\pi} \oint k_2(s) \Delta x(s) \beta_x(s) ds. \quad (5)$$

The resulting difference in ΔQ —calculated as 0.155 for GHC vs. 0.057 for LCC five turns after failure onset—is consistent with this estimate. While the tune perturbation represents the global effect on the orbit, the local beta beating

induced by the distributed quadrupolar error drives a local phase advance perturbation:

$$\frac{\Delta\beta(s)}{\beta(s)} = \frac{1}{2\sin(2\pi Q)} \oint \Delta k_1(s') \beta(s') \cos(2\Delta\phi - 2\pi Q) ds', \quad (6)$$

with $\Delta\phi = |\varphi(s) - \varphi(s')|$. Integrating this beta beating across the failing half-arc yields the local phase advance perturbation:

$$\Delta\mu_{\text{arc}} = - \int_{\text{arc}} \frac{\Delta\beta(s)}{\beta(s)^2} ds. \quad (7)$$

The degree to which the orbit bump is closed—and therefore the amount of orbit excursion leaking outside the failing arc—depends on the coherent sum of the distributed bending field errors across the half-arc, weighted by $\sqrt{\beta_x(s)}$ and the local betatron phase. As $\Delta\mu_{\text{arc}}$ changes during the failure, this coherent sum evolves continuously, alternating between configurations that confine the distortion within the arc and those that allow significant leakage around the ring. The more-open states can lead to orbit excursions of several sigma in a single turn, as visible in the zoom region of Fig. 1a. For the LCC lattice, the factor of approximately 5.6 reduction in the total feed-down integral significantly reduces $\Delta\mu_{\text{arc}}$ compared to GHC, producing the more regular, slowly evolving orbit excursion pattern observed outside the failing half-arc (Fig. 1b).

A qualitatively different effect arises in the LCC interaction regions. The strong high-order magnets used for local chromaticity correction generate large local orbit excursions when the beam centroid arrives with a non-zero offset Δx . Octupoles (k_3) and decapoles (k_4) produce kicks scaling as $k_3 \Delta x^2$ and $k_4 \Delta x^3$ respectively, so even moderate orbit offsets propagating from the failing arc produce very large local deflections—reaching up to $\sim 200\sigma$. By design of the LCC correction these excursions partially cancel over the length of the correction region [3], but their local amplitude within the experimental insertions is a concern for synchrotron radiation emission (background to the detectors, heat load) and for beam stability. Their precise effects must be studied. If they are too critical, mitigations and dedicated protection solutions must be implemented.

To compare the failure criticality for the different lattices, the turn-by-turn evolution of the orbit excursion is shown in Fig. 2. The orbit excursion evolution during the failure is studied at different locations: in the straight sections (maximum), inside the failing region (mean) and in the non-failing arcs (mean). The orbit excursion grows rapidly both inside and outside the failing region for both lattices. The maximum in the straight sections is limited during the failure for GHC but becomes very large for LCC when the phase advance is unfavourable. The principal figures of merit are summarised in Table 1. The ranges reflect the variability of the failure dynamics across different half-arcs: the number and arrangement of magnets differ between circuits, modifying both the nominal phase advance and the sextupole feed-down contribution to $\Delta\mu_{\text{arc}}$, and therefore the degree

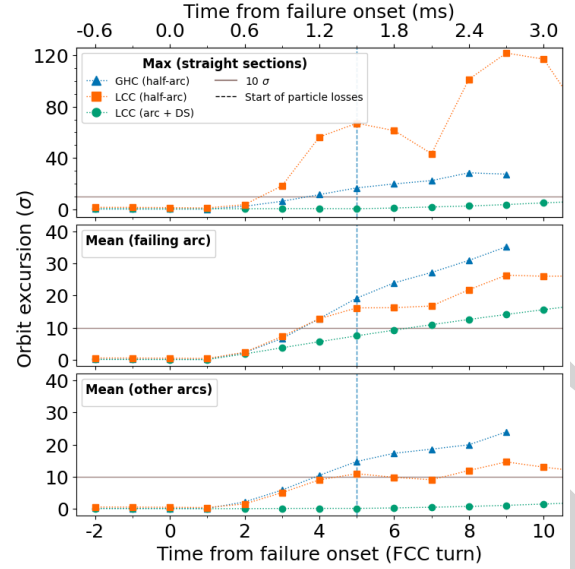


Figure 2: Turn-by-turn orbit excursion—maximum in the straight sections, mean in the failing region and mean in the others arcs—for the three configurations (half-arc dipole powering for both GHC and LCC, and full arc + dispersion suppressor powering for LCC). The vertical dashed lines mark the onset of particle losses in the physical aperture.

Table 1: Failure Dynamics for GHC and LCC

Observable	GHC	LCC	LCC
	Half-arc	Half-arc	Arc+DS
Turns to exceed 10σ			
in failing arc	3–5	3–4	6
outside	4–9	5–24	28–31
Turns to lose all particles	9–12	31–37	32–36

of orbit leakage outside the arc. This half-arc-to-half-arc variability precludes a reproducible failure signature and requires the machine protection system to be dimensioned for the worst-case scenario in both lattices.

The longer particle survival time in LCC (31–37 turns vs. 9–12 for GHC) is primarily a consequence of the larger physical aperture relative to the beam size—particles sustain very large orbit excursions inside the failing arc for many turns before being lost on the vacuum chamber wall, as visible in Fig. 2—rather than due to the slower growth of excursions outside the arc. However, the failure is equally critical in both lattices from a protection point-of-view as an excursion of 10σ is reached outside the failing arc within as few as 4 to 5 turns. Mitigation strategies are therefore essential, as this time is deemed too short for reliable beam-based detection followed by a safe extraction of the beam.

FAILURE MITIGATION

The half-arc-to-half-arc variability and the uncontrolled orbit excursion leakage observed in the half-arc configuration motivate the study of an alternative powering scheme. A distinctive feature of the LCC optics is the transparency condition between each arc and the adjacent straight sections:

the lattice is constructed such that perturbations originating in a given arc are naturally contained within that region. Extending the powering circuit to cover a full arc including the dispersion suppressors (DS) at both ends is a natural approach to exploit this property.

In this configuration, a bending field error distributed over a full arc including the DS is equivalent to a local momentum offset in that region. Since the DS boundaries are designed to coincide with zero-dispersion points ($D \approx 0$), the perturbation has a predominantly dispersive character. The closed orbit response is then governed by the dispersion function $D(s)$ and the momentum compaction factor α_p :

$$x_{co}(s) = D(s) \cdot \delta_{\text{eff}}, \quad \delta_{\text{eff}} \approx \frac{1}{N \alpha_p} \cdot \frac{\delta B}{B}, \quad (8)$$

where $N = 8$ is the number of arcs. In the failing arc, the bending field error induces a large orbit offset, amplified by the large dispersion in the arcs ($D \approx 0.4\text{--}0.5\text{ m}$). In the straight sections, the DS suppresses the dispersion to near zero, strongly confining the orbit response to the failing arc. This is illustrated in Fig. 3, which shows the bunch centroid's horizontal position $x_{co}(s)$ around the machine at turn 17 ($B_f = 0.983 B_0$): the mean orbit offset reaches $\sim 6\text{ mm}$ inside the failing arc, while remaining at $\sim -1\text{ mm}$ in all other arcs to compensate the effective momentum offset δ_{eff} . The dominant response is determined by the momentum compaction factor, a global machine parameter, which strongly reduces the arc-to-arc variability observed in the half-arc case discussed above.

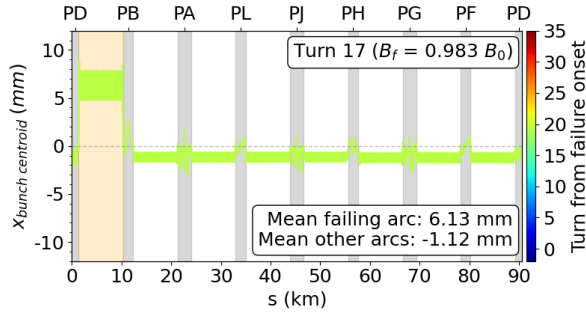


Figure 3: Bunch centroid horizontal position $x_{co}(s)$ around the machine during a dipole powering failure for the LCC lattice with a full arc + DS circuit.

Figure 4 shows the orbit excursion evolution for this configuration. The orbit oscillations inside the failing region are limited to $\sim 50\sigma$ amplitude compared to $\sim 100\sigma$ for the half-arc powering. The orbit excursion grows linearly and predictably while the transparency condition holds (see Fig. 5). Outside the failing region, the growth is limited and the linear regime persists until the orbit offset becomes large enough to break the confinement, at which point leakage into the straight sections begins. The high-order corrector magnets then drive large local oscillations, and the orbit excursion transitions rapidly to an exponential growth regime leading to particle losses (from turn 31–34). This two-phase behaviour—clean linear growth followed by a sudden expo-

nential blow-up—contrasts sharply with the irregular leakage that begins almost immediately after failure onset in the half-arc cases shown in Fig. 2. Figure 6 clearly illustrates the different behaviour between the half-arc powering and the full arc powering with the dispersion suppressor. Quantitatively, the mean orbit excursion outside the failing arc reaches 10σ after approximately 4 turns for the half-arc configuration, compared to approximately 28 turns for the full arc with DS. The last particle is lost after a comparable number of turns in both cases (~ 32 turns), as the aperture limit inside the arc is reached regardless of the powering configuration.

These results demonstrate that this alternative powering scheme constitutes an effective mitigation strategy for the dipole powering failure. Beyond the mitigation of these catastrophic failures, a powering configuration aligned with the LCC transparency condition makes the orbit response to any deviation from the nominal current proportional, predictable and reproducible — which is advantageous for orbit monitoring and early fault detection during routine operation. This powering scheme is compatible with the hardware design of the power converters as the voltage required to power the dipoles is low enough [8].

MACHINE PROTECTION IMPLICATIONS

The results presented confirm that a main dipole powering failure is a highly critical failure mode for FCC-ee, irrespective of the lattice choice. In the half-arc configuration, the bending field error combined with the quadrupolar feed-down induced by the centroid offset in the arc sextupoles can lead, in the worst case, to orbit excursions larger than the collimation cut within 3–4 turns with both GHC and LCC optics. When powering a full arc with DS in the LCC optics configuration this is extended to 28 turns but still makes source-based interlocking, such as a Fast Magnet Current change Monitor (FMCM) [9], an essential element of the FCC-ee machine protection system.

All simulations presented assume a conservative, pure RL circuit; the real powering circuit will include a capacitance for current ripple control, making it RLC with a slower current decay. Realistic capacitance values lead to a gain of ~ 5 turns at the beginning of the decay. However, even with very fast source-based detection, the interlock communication, dump trigger, and full beam extraction requires a minimum of 3 turns. Furthermore, these studies do not include magnetic errors and misalignments, the effect of the injected beam — which is offset by a few sigma — or beam-beam effects, all of which are expected to worsen the failure dynamics. In addition, the capacitance can be bypassed in the event of a power converter diode short-circuit, removing the benefit of the slower decay. The full arc with dispersion suppressor powering configuration therefore constitutes an essential mitigation, substantially improving the machine protection outlook. The linear growth regime and the reproducible orbit response provide a well-defined detection window for Beam Position Monitor (BPM) and/or Beam

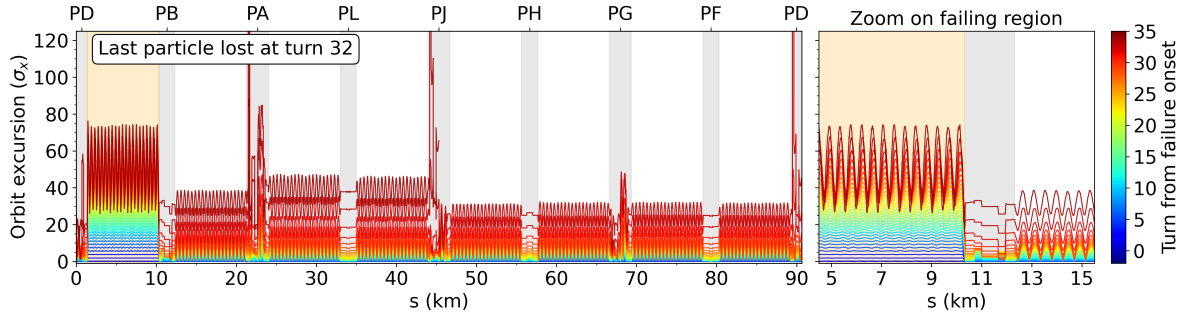


Figure 4: Orbit excursion during a dipole powering failure for the LCC lattice with full arc and dispersion suppressor powering (left). The orbit excursion leakage at the edge of the failing arc (highlighted in orange) is shown (right). The colour scale represents the turn number from failure onset.

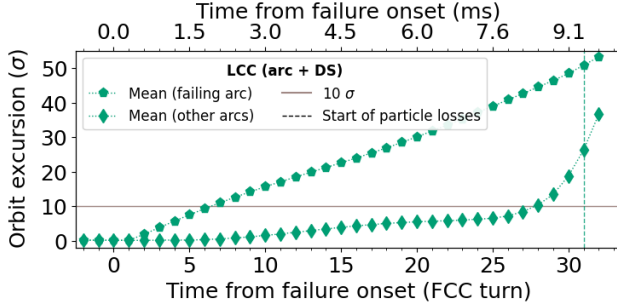


Figure 5: Turn-by-turn orbit excursion for the LCC lattice with full arc+DS powering.

Loss Monitor (BLM) interlocks [10] as a second protection layer, while the confinement of the perturbation to the failing arc avoids uncontrolled losses elsewhere in the machine.

CONCLUSION AND OUTLOOK

The main dipole powering failure has been studied for the LCC lattice and compared to established GHC results [4]. For the standard half-arc powering, the failure is highly critical in both lattices: 10σ orbit excursion is exceeded in the collimation region within 4 to 5 turns independently of the lattice choice. The qualitative difference in failure dynamics originates in the sextupole configuration: the strong global families of GHC generate rapidly growing, irregular orbit excursions around the full ring through quadrupolar feed-down and dynamic phase advance drift, while the weaker arc sextupoles of LCC limit this propagation. The longer particle survival time in LCC is a consequence of the larger physical aperture relative to the beam size rather than a slower global orbit growth. The large orbit excursions driven by the high-order chromaticity correction magnets in the LCC interaction regions are identified as an additional concern whose criticality must be studied.

For the LCC lattice, powering a full arc including its dispersion suppressors is shown to produce a clean, predictable, and reproducible failure signature, with a factor of seven reduction in orbit leakage outside the failing arc, leading to a 10σ orbit excursion after approximately 28 turns compared to the 4–5 turns of the half-arc powering scheme. This configuration exploits the LCC transparency condition and

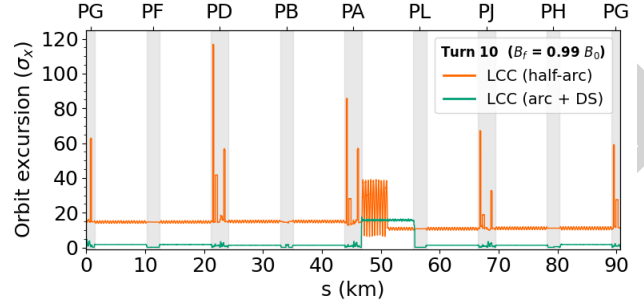


Figure 6: Orbit excursion comparison 10 turns after the failure onset for the two powering schemes of the LCC lattice. is identified as a promising mitigation strategy for a main dipole powering failure.

A number of elements remain to be studied before being able to fully define the machine protection system requirements to protect against this failure. The feasibility of the full arc with DS powering configuration must be fully assessed; should this prove incompatible with the machine design, alternative mitigation strategies—such as increasing the circuit time constant—will need to be explored. Tracking studies including beam-beam effects, magnetic errors, misalignments, and the effect of the injected beam must be performed to determine their effect on the failure criticality. Beyond the beam dynamics, the full chain of failure consequences on the machine equipment remains to be assessed. This includes, for example, the shift of the synchrotron radiation fans induced by the rapid orbit excursion inside the failing arc, which could expose unprotected surfaces to intense radiation loads, but also the thermal and mechanical response of vacuum chamber components, absorbers, and other machine elements.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support and fruitful discussions with many colleagues, in particular J. Bauche, S. Kostoglou, S. Pittet, G. Roy and N. Zamorano, whose contributions were essential to this work.

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