






Design Strategies for Beam Impedance Reduction of Kicker Magnets in Particle Accelerators

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Abstract—In high-energy particle accelerators, kicker magnets are essential for injecting and extracting particle beams using fast-pulsed magnetic fields. A key challenge in their design is minimizing beam coupling impedance to maintain beam stability and reduce beam induced power losses while preserving the fast rise and fall times of the magnetic pulse. This paper presents innovative principles and mechanical approaches for reducing beam impedance in several kicker magnets operating under vacuum across the CERN complex. Kicker magnets use ferrite or laminated steel as a magnetic yoke, which is susceptible to beam-induced heating. The proposed techniques aim to screen the yoke, provide a low impedance path for the beam image current, and eliminate cavities that could generate resonances. Simultaneously, the screen must allow the passage of fast pulsed magnetic fields. Techniques include the insertion of ceramic chambers holding screen conductors, serigraphy of conductive paint, or thin metallization by sputtering. Bridges can eliminate cavities between adjacent magnets or vacuum vessels. The performance of these design strategies is evaluated through a combination of high-frequency simulations, laboratory impedance measurements, magnetic field assessments, and temperature monitoring of kicker magnets after installation in accelerators. The results demonstrate significant improvements up to 60-fold decrease, which are discussed in detail. This work establishes a foundation for further innovations in kicker magnet design, with the potential to enhance existing systems and guide the development for future accelerators such as FCC-ee, with shorter bunches, where the impedance is even more important.

Index Terms—Beam impedance, beam instabilities, design, kicker magnets, beam screen, serigraphy, chamber, vacuum, image current, CERN, particle accelerator.

I. INTRODUCTION

THIS study presents an overview of design strategies aimed at mitigating the beam coupling impedance of kicker magnets, within the CERN particle accelerator complex. Kicker magnets work at high voltage, are generally under vacuum at CERN, and are characterized by their field rise and fall times ranging from tens of nanoseconds to microseconds. The design and technology of individual kicker magnets vary across the CERN accelerator complex, depending on the specific requirements related to beam momentum, deflection angle, magnetic

field rise and fall time, aperture, and beam structure at the time of construction. Many of CERN's accelerators were originally designed decades ago, when beam intensities were relatively low and, as a result, beam coupling impedance was not a primary concern. However, especially for the High-Luminosity Large Hadron Collider (HL-LHC) with significantly higher beam intensities, sensitivity to impedance related effects has considerably increased. Consequently, beam impedance reduction techniques have been actively studied and implemented over the past years, both in the design of new kicker systems and the retrofitting of existing ones.

II. BEAM IMPEDANCE IN KICKER MAGNETS

In a particle accelerator, a beam of charged particles acts as a source of electromagnetic field, interacting with its surroundings. Whenever the beam faces a cross-section variation as well as a finite conductivity of the walls, it excites an electromagnetic field, which is left behind the source particle, called a wakefield. In the frequency domain, the wakefield is described by the so-called beam coupling impedance. Kicker magnets are considered significant sources of beam coupling impedance in particle accelerators, for example due to the presence of the lossy ferrite of the yoke. Ferrite presents dispersive behaviour, producing an impedance contribution which affects a broad range of frequencies. In addition, the kicker magnet can introduce structural discontinuities resulting in cavity-like resonators. If not properly matched or shielded, they can cause signal reflections and coupling effects, leading to beam energy loss and instabilities via both longitudinal and transverse beam coupling impedance [1], [2], [3]. Transverse beam coupling impedance contributions can affect beam stability: filters or improved termination matching have been demonstrated as mitigation solutions [4], [5], [6], [7].

This paper focuses on longitudinal beam coupling impedance and the mechanical solutions aimed at reducing the impedance contribution in the critical frequency ranges.

One of the most critical effects caused by the longitudinal beam coupling impedance is **beam induced heating**. This effect is dependent upon beam parameters, and results from the interaction of the real part of the longitudinal impedance with the beam spectrum [8]. This power deposition must be limited to avoid performance degradation, such as reaching the Curie temperature of the ferrite, excessive vacuum outgassing that can lead to high-voltage breakdowns, and general mechanical

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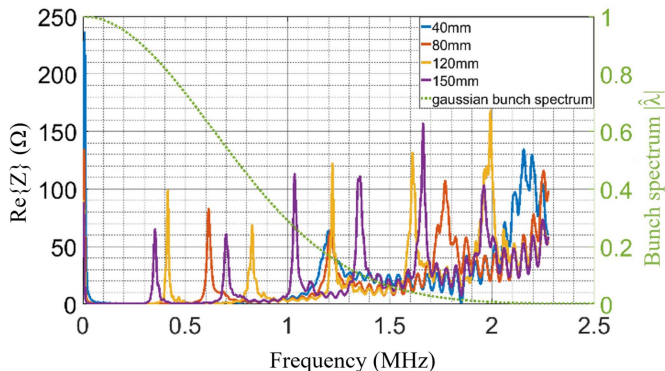


Fig. 1. LHC beam bunch spectrum with a study of different lengths of capacitive coupling of screen conductors for the injection kicker (MKI) to shift the real part of longitudinal impedance towards higher frequencies where the beam spectrum carries less power [2].

damage [1], [9]. Another important impedance-induced effect is **beam instabilities**.

In the ideal case of a new design, both problems are addressed by providing a continuous path for the beam image current, effectively **screening** the lossy ferrite yoke from wakefields, and ensuring a continuous and smooth **transition** flange to flange so that no resonance is excited in gaps that may act as cavity resonators [10], [11]. Reduction of the power deposition is achieved by shifting impedance peaks in the spectrum of the kicker magnet towards higher frequencies where there is less power in the beam spectrum. This technique is illustrated in

Fig. 1 and developed in Ref. [2].

Electromagnetic simulations are carried out at the design stage to optimize mitigation strategies. Beam coupling impedance measurements are performed before and after the implementation of impedance reduction solutions to validate the simulation results. Eventually, temperature measurements within the kicker magnets, during operation with beam, provide the conclusive outcome.

III. SCREENING

The screening solution depends on the pulse rise time, from a uniform resistive layer for slower cases [12] to interdigitated fingers [13] or capacitively coupled conductive comb [14] for faster ones, known as conductive stripes. It generally requires the insertion of a ceramic chamber into the magnet aperture, both as mechanical support and as electrical insulation from the kicker magnet [2], [9], [15]. However, this reduces the available beam aperture and may not be feasible for retrofittings.

A. Ceramic Chambers With Resistive Coating

Kicker magnets with field rise/fall time in the microsecond range are typically lumped inductance magnets and can efficiently be screened by continuous resistive coating [16]. Titanium sputtering is commonly used at CERN for this purpose on Al_2O_3 ceramic chambers. This technique offers controllable surface resistivity through thickness, strong adhesion to the ceramic substrate, excellent compatibility with ultra-high vacuum, and

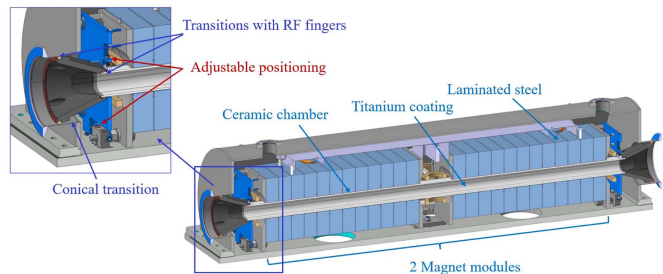


Fig. 2. Beam screen study for the SPS dump sweeping kicker MKDH.

a low Secondary Electron Yield (SEY). The thickness of about $2\ \mu\text{m} \pm 20\%$ is selected to ensure that eddy currents induced by the pulsed magnetic field do not degrade the rise and fall times by more than 10%, depending on the application [2], [16].

For the LHC dump kicker (MKD), impedance mitigation was integrated from the design stage. A ceramic chamber coated with Ti serves as the vacuum pipe, with the magnet assembled around, outside vacuum. The Ti layer of $0.15\ \Omega/\text{sq}$ increases the magnetic field rise time by less than $1\ \mu\text{s}$ for a nominal rise time of $3\ \mu\text{s}$ [3], [16]. A similar coating was added for the PS Booster bumpers (KSW), which were already built around a naked ceramic vacuum chamber [17].

For retrofit applications, where aperture limitations exist, the ceramic chamber geometry must be optimized. Currently, a beam screen is being studied for the beam dump sweeping kicker (MKDH) of the SPS [18]. Although the magnet yoke is constructed from laminated magnetic steel, the impedance mitigation principles remain the same. A Ti-coated ceramic chamber, approximately 1.5 meters in length, is being designed (see Fig. 2). A major challenge is to limit the aperture reduction due to the insertion of this chamber into the two series-connected magnet modules. The Ti coating will be connected to the vacuum tank flanges to ensure continuity of the beam image current path, as discussed later in Chapter IV. Conical-like connecting components will be terminated by lamellar flexible contacts, RF fingers, to accommodate any mechanical imperfections, tilts, and misalignments of the tank flanges without imposing mechanical stress on the ceramic chamber.

B. Conductive Stripes

Kicker magnets with field rise times faster than a microsecond are generally of transmission line type, made of fast cells [3]. Resistive coatings compatible with the fast-travelling field wave typically do not provide sufficiently screening. In such cases, capacitively coupled conductive stripes are used as an alternative solution [9]. This method can achieve a significant reduction in beam coupling impedance over a broad frequency range [13], [19] without negatively affecting the field rise time. Nevertheless, the final design of the screen is the result of several iterations to optimize the beam-coupling impedance and the HV behaviour [20]. In addition, the stripes may introduce resonances, which must be carefully studied during the design process. For example, in SPS injection, the frequency range around 40 MHz had to be avoided as detailed in Ref. [19].

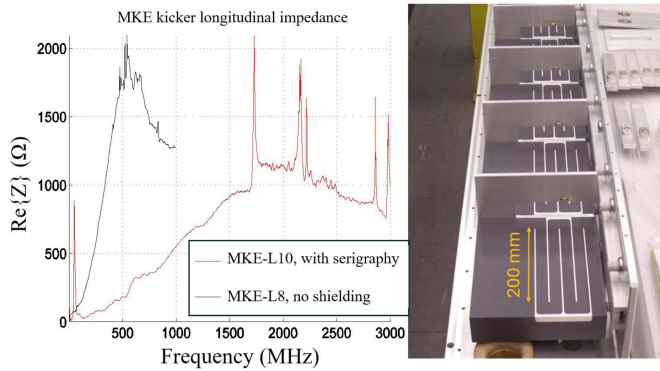


Fig. 3. Upgraded MKE kicker's real part of longitudinal impedance, with 200 mm long serigraphy, compared to the frequency range before serigraphy.

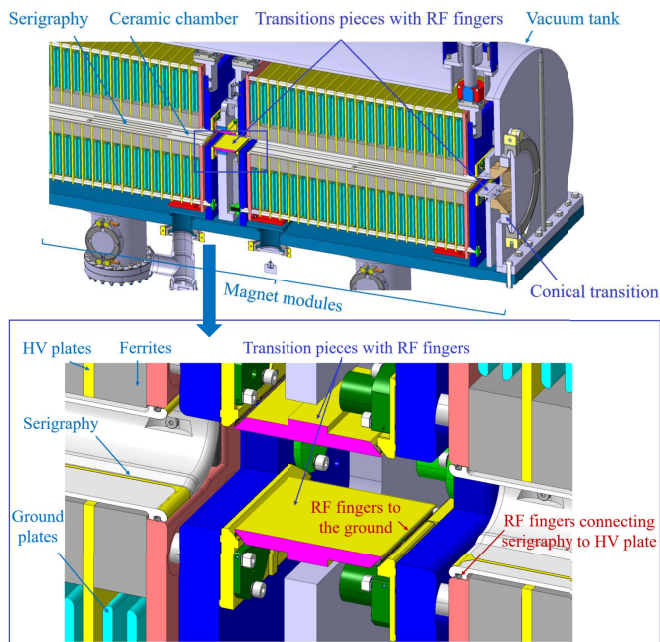


Fig. 4. Fully equipped SPS injection kicker MKP-L with impedance reduction transitions and beam screens.

Conductive stripes can be created using silver-based conductive paint, by serigraphy, either directly applied onto the ferrite blocks or onto a ceramic support (Fig. 3). After application, the paint is sintered in air at 850°C. Alternatively, conductive wires, referred as screen conductors, may be used within a ceramic chamber (Fig. 5). To minimize the risk of electrical discharge between stripes and further reduce the SEY, a Cr_2O_3 coating can be applied to the ceramic surface. This approach has been successfully implemented in injection kickers in both the SPS and LHC [19], [21].

1) *Serigraphy*: The stripe pattern (spacing, width, and length) is carefully designed based on impedance simulations tailored to each specific kicker [22]. Proper application is critical and requires uniform paint thickness, without droplets or irregularities, which could otherwise create sharp edges and present high-voltage breakdown risks.

The first implementation of serigraphy was carried out on the SPS extraction kicker MKE [13]. The kicker's design, which

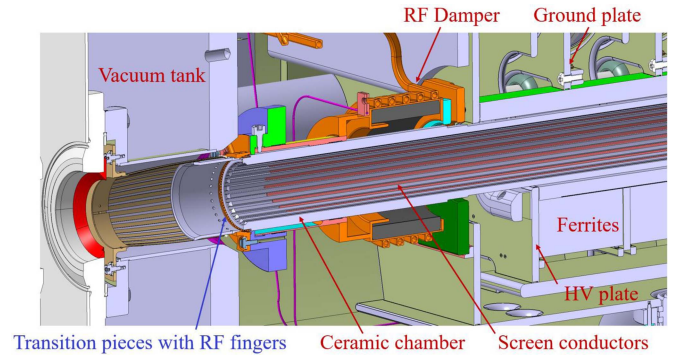


Fig. 5. Screen conductors implemented in the 3-meter-long LHC injection kicker MKI.

includes long ferrite cells, made it feasible to apply the paint directly to the ferrite blocks, as shown in Fig. 3. This resulted in a significant reduction of the longitudinal beam impedance and a decrease in induced heating by a factor of 5 [13], with 200 mm long serigraphy fingers [23] without affecting the beam aperture [3]: this length of fingers was chosen before appropriate electromagnetic software was available. The length of the serigraphy was subsequently further optimized to 180 mm, giving an additional reduction of beam induced heating by a factor of 2, with 25 ns beam [24].

For the SPS injection four-module kicker MKP-L, shown in Fig. 4, the short magnetic cells required the use of a ceramic chamber per module as a substrate for the serigraphy to ensure suitable capacitive coupling between adjacent stripes. The design of the stripe pattern is presented in Ref. [19], which also compares the longitudinal beam coupling impedance of the new design with the original configuration. The design includes transitions between modules to ensure the continuity between modules and with the tank. During the first scrubbing run in 2023-year, operational data confirmed approximately a twelve-fold reduction in beam-induced temperature rise [15].

2) *Screen Conductors*: In long kicker magnets, applying serigraphy inside long tubes is challenging due to the access and the voltage induced by the fast magnetic field gradient between adjacent metallized surfaces: the sharp edges of 20 μm thickness of the painted stripes lead to high-voltage discharges in vacuum [25]. For this reason, 0.9 mm thick rounded screen conductors were developed as an alternative and successfully improved the voltage by at least one order of magnitude in the 3-meter-long LHC injection kicker MKI, [21], [26], [27], [28], [29], [30], as shown in Fig. 5. This approach uses solid wires with an elliptical cross-section, inserted into grooves that are extruded along the inner surface of the ceramic tube. Nevertheless, extensive studies were required to achieve good high-voltage performance [31]. The adjacent screen conductors are then insulated from each other by the ceramic wall. The design required tight tolerances over the full length to ensure the correct position of each wire. It is complemented by RF ferrite absorbers, so called RF Dampers. The final configuration resulted in a successful reduction in induced power heating by a factor of 60 [21], [27], [32], [33].

IV. TRANSITION PIECES

Any discontinuities within the beamline vacuum system can act as a geometrical resonator, contributing to impedance peaks at low frequencies and lead to beam instabilities [26]. These resonant modes are particularly problematic when they coincide with beam harmonics. The beneficial effect of adding transition pieces to interconnect individual kicker magnet modules was already demonstrated in the 70's [10], [11]. The PS complex has continued efforts to reduce beam impedance, with all PS Multi-Turn Extraction kickers now equipped with transition pieces at the interface between their last modules and the vacuum tanks [34].

In the case of **longer magnets** equipped with beam screens, it is especially important to suppress resonances at transitions and to establish a continuous conductive path between the beam screens and the vacuum tank. This continuity is typically achieved using metal cones or plates with flexible lamellar contacts, referred to as RF fingers, maintained by dedicated supports. These assemblies are designed to provide sufficient contact pressure across a range of operating temperatures, which sometimes includes bakeouts to 300°C, and to tolerate mechanical misalignments or geometric imperfections.

When retrofitting existing devices, transition piece design poses additional challenges such as preserving beam aperture and avoiding localized high electric fields that could lead to high voltage discharge. High radiation activation may also restrict accessibility and design choice. Transitions often feature adjustable mechanical supports to compensate for small positional variations between magnet modules. When disassembly is possible, individual gaps between modules are measured and custom-fitted transitions are manufactured. Transition piece geometry to the vacuum tank is generally optimized to ensure a smooth connection between the rectangular aperture profile and the circular tank inlet or outlet, often incorporating RF fingers on both sides. Additionally, amorphous carbon (a-C) coatings may be applied to the transition surfaces to reduce the SEY and thus mitigate the risk of partial discharges [25].

A representative example is the SPS extraction kicker (MKE), where the installation of transition pieces at the extremities reduced low-frequency impedance peaks by factor a of 3 to 4 [36], [37]. The fully upgraded four-module SPS injection kicker (MKP-L), shown in Fig. 4, also includes transition pieces between modules consisting of flat surfaces with RF fingers on adjustable supports, allowing for misalignment compensation while maintaining good electrical continuity.

For **short magnet modules**, transitions between each module and between the module and the vacuum tank are generally sufficient to suppress undesirable impedance without a full beam screen. In the case of the Proton Synchrotron (PS) injection kicker (KFA45), shown in Fig. 6, transition pieces with RF fingers were mounted between ground busbars as close as possible to the aperture as part of the LHC Injector Upgrade project.

More recently, impedance mitigation studies were conducted for the PS fast-extraction kickers KFA79 and KFA71, targeting primarily low-frequency peaks in relation to the accelerator's overall impedance threshold [38], [39]. In these magnets, the optimal solution of connecting ground busbars close to the

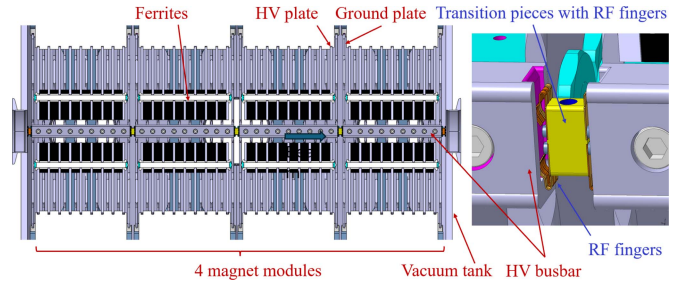


Fig. 6. Transition pieces with RF fingers provide a link close to the aperture for the PS injection kicker KFA45.

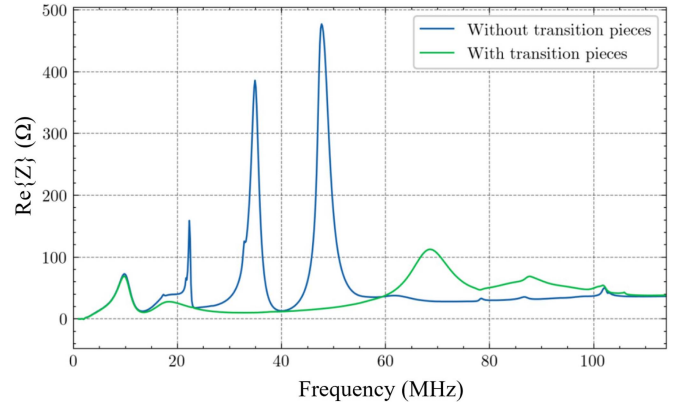


Fig. 7. Wire impedance measurements on spare KFA79 with transition pieces [40].

aperture could not be implemented due to sequential inversion of module orientation, which placed the ground busbar adjacent to the high-voltage busbar of the next module. Simulations, however, predicted that transition pieces placed at the level of the ground plates, approximately 150 mm away from the aperture, would sufficiently reduce low-frequency impedance. Adjustable wedges with RF fingers were inserted into a full spare unit, and wire measurements confirmed a significant reduction in the real part of the impedance, see Fig. 7. Based on these results, KFA71 and KFA79 kicker magnets will be equipped with similar transition pieces.

V. CONCLUSION AND OUTLOOKS

A significant reduction of the beam coupling impedance of kicker magnets for high intensity beams has been achieved through dedicated design approaches. The extensive experience accumulated has enabled the development of several effective impedance mitigation strategies, guided by high frequency simulations. These approaches have been validated through laboratory impedance and field measurements as well as temperature monitoring during operation with high intensity beams.

Ideally the impedance reduction techniques should be integrated in the early design phase for a seamless integration.

Looking ahead, the importance of beam impedance control increases in the context of next-generation accelerator projects such as the Future Circular Collider (FCC), with very short beam size and an associated spectrum which can extend to several tens of GHz. The techniques and lessons learned at CERN provide a

strong foundation for developing kicker magnets able of meeting the stringent demands of future high-intensity machines.

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