Characterization of Losses in the SMH16 Septum Magnet for PS Extraction

Thibaut Lemercier
Supervisor : Lucien Porta

September 24, 2025

Abstract

The SMH16 magnetic septum is a pulsed magnet used for fast extraction from the CERN Proton Synchrotron (PS). Due to its high-current operation and exposure to intense beam conditions, understanding and quantifying energy losses within the magnet is critical for both performance and reliability. This report presents a detailed study of the different loss mechanisms in the SMH16, including copper losses, iron losses, and eddy current effects. Analytical models, finite-element simulations, and experimental measurements are combined to provide a coherent picture of the magnet's loss characteristics and their thermal consequences.

1 Introduction

The PS extraction system relies on two complementary elements: the kicker, which provides a fast initial deflection, and the septum magnet, which bends the extracted beam into the transfer line. The SMH16 septum magnet, installed at the SS16 straight section, has been in service since the mid-1990s and remains a key component for extraction toward TT2. Its pulsed operation (tens of kiloamperes within microseconds) makes it particularly sensitive to electromagnetic and thermal losses.

With the increasing number of extractions, the effective lifetime of the SMH16 is approaching two years. Since maintenance operations must be performed in a high-radiation environment, frequent replacement is undesirable. To address this issue, a new magnet based on a different topology, known as an **eddy current septum**, has been developed.

An eddy current septum operates by driving high-current pulses through a conductor in such a way that rapidly varying magnetic fields induce eddy currents in the septum blade. According to Lenz's law, these currents generate an opposing magnetic field that shields the field-free region where the circulating beam passes. This design makes the septum more mechanically robust and extends its expected operational lifetime. However, because shielding relies on fast magnetic transients, the device must operate at significantly higher frequencies than conventional septa. This shift in operating regime amplifies the importance of accurately understanding loss mechanisms, especially those related to skin effect and eddy currents.

The objective of my work during this summer was to characterize the different loss mechanisms in the magnet to identify and quantify potential sources of overheating.

2 Loss Mechanisms in Pulsed Septum Magnets

At higher frequencies, the current distribution in conductors is affected by the skin effect, which confines the current to a thin surface layer and consequently increases the effective resistance of the conductors. In the laminated yoke, alternating magnetic fields generate iron losses, primarily in the form of eddy currents and hysteresis. Eddy current losses arise from circulating currents induced within the iron laminations, similar to the phenomenon observed in induction heating, while hysteresis losses are caused by the repeated magnetization and demagnetization cycles of the steel. Additionally, small mechanical vibrations may occur due to magnetic forces, though these mechanical losses are generally negligible when compared to electrical and magnetic losses (even if the forces are high the displacement is very small).

3 Modeling and Simulation

3.1 Finite Element Method (FEM)

Finite Element Method (FEM) simulations were conducted in COMSOL to evaluate the induced losses in the SMH16 geometry. Iron losses were estimated using the generalized Steinmetz method. For detailed methodology and calculations, refer to the document *"SMH16cf Analysis of Electromagnetic Losses"* available on the EDMS platform.

3.2 2D Losses in Laminations

Two types of laminations were considered: Di-Max and GOES. GOES laminations are thinner, which results in lower iron losses. Tables 1 and 2 summarize the integrated losses over a pulse for different waveform conditions.

Table 1: Integrated losses for **Di-Max** material under different waveform conditions ($\mathrm{W\,s\,m^{-1}}$)

Waveform	Method	Iron	Coil 1	Septa	Coil 2	Backplate	Total
Sinusoidal	Temporal	38.95	66.85	63.15	53.03	42.60	264.58
Flat Top (23/07)	Frequential*	39.12	60.91	57.57	48.25	38.78	244.63
Flat Top (23/07)	Temporal (GES)	34.41	60.91	57.57	48.74	38.78	240.41

* Iron losses simulated using the Frequential (Steinmetz) method.

Table 2: Integrated losses for **GOES** material under different waveform conditions ($\mathrm{W\,s\,m^{-1}}$)

Waveform	Method	Iron	Coil 1	Septa	Coil 2	Backplate	Total
Sinusoidal	Temporal	13.19	67.12	63.51	53.07	42.64	239.53
Flat Top (23/07)	Frequential*	24.55	61.04	57.76	48.25	38.80	230.40
Flat Top (23/07)	Temporal (GES)	11.94	61.16	57.76	48.26	38.79	217.91

* Iron losses simulated using the Frequential (Steinmetz) method.

3.3 3D Losses in Di-Max

3D FEM simulations were also conducted using Di-Max laminations. The skin effect in the coil was not considered in the 3D model, which explains minor discrepancies compared to 2D results. Table 3 shows the dissipated power for a flat-top waveform.

Table 3: Integrated losses for **Di-Max** material with the 3D model ($\mathrm{W\,s\,m^{-1}}$)

Waveform	Method	Coil 1 & 2	Septa	Backplate	Iron
Flat Top	Temporal	21.76	52.87	30.46	39.38

The total dissipated power in 3D ($144.47\,\mathrm{W\,m^{-1}}$) is consistent with the 2D results, confirming the validity of the 2D approximations.

4 Thermal Consequences

Electrical and magnetic losses ultimately manifest as heat within the SMH16 structure. Thermal simulations indicate that the temperature distribution is dominated by the interface between the septa blade, where heat is extracted, and the iron core. Insufficient thermal contact at this interface can lead to localized overheating of the iron core.

5 Experimental Measurements

Direct electrical measurements were performed on the magnet. These measurements revealed losses approximately ten times higher (2.314J) than those predicted by simulations.

6 Investigation

To understand this significant discrepancy, a series of experiments was conducted. A dedicated test bench was constructed to evaluate the behavior of the laminations under various stresses, including applied pressure, contact with screws, and induced electrical shorts. These tests, performed at $0.2\,\mathrm{T}$ (approximately five times lower than the operating field of the magnet), showed only minor variations in the measured losses.

Further insight was obtained by removing the septa blade from the magnet and performing additional electrical measurements. In this configuration, the measured losses decreased to approximately one fifth of their previous value, a reduction that was not anticipated by the simulations.

A detailed inspection revealed multiple defects contributing to the elevated losses. Some screws were in direct electrical contact with the laminations and the septa blade, and the electrical connections of the septa circuit were poor. Additionally, manufacturing burrs and threading imperfections created localized shorts on the septa blade.

The excitation history of the magnet was also analyzed. During initial testing, the magnet required progressively higher currents to maintain the same magnetic field. Even after correcting for potential leakage, the magnet did not return to its original current behavior. Circuit simulations indicate that this behavior is consistent with a progressive increase in losses, suggesting that the magnet experienced early-stage degradation. This degradation, likely caused by electrical sparks (possibly creating connections between laminations), resulted in irreversible local damage and excessive losses in multiple regions of the magnet.

These findings indicate that a rebuild of the SMH16 is necessary, with particular attention to eliminating shorts and ensuring robust electrical contacts. A deeper study of lamination aging is also required to fully understand the phenomena that can create interlamination shorts. With careful design upgrades, assembly and inspection, the losses of the SMH16 can be significantly reduced, bringing them closer to simulation predictions.

7 Conclusion

The characterization of the losses led us through an interesting process of cross-correlation between experimental measurements and simulations. The results revealed that the problem is more complex than initially anticipated, involving degradation, shorts, and localized effects.

On a personal note, this project has been highly engaging, presenting numerous challenges that provided valuable learning opportunities. I am very grateful to my tutor, Lucien Porta, for his guidance and support throughout this project.