PERFORMANCE OF THE PS INJECTION KICKER SYSTEM SHORT CIRCUIT MODE UPGRADE FOR OPERATION WITH 2 GeV LIU BEAMS

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Abstract

In the framework of the LHC Injector Upgrade (LIU) project an upgrade of the existing PS proton injection kicker system for 2 GeV operation is in progress. The upgrade is based on the operation of the existing kicker system in short circuit mode. This paper briefly reviews the deployed modifications to the system to obtain the specified reduction of pulse reflections unavoidably induced by such a configuration. The implementation of improvements to the magnet entry box, transmission cables and the short circuit plug with integrated LC-filter are described as well as tests and measurements during the 2016/17 annual shutdown. The impact of the residual pulse shape structure on the beam performance for the reference LIU beam is discussed. The paper concludes with a performance analysis, a comparison of measurements vs. simulations and an outlook to the remaining modifications during the next long shut down.

INTRODUCTION

For the LHC Injectors Upgrade (LIU) project [1] several options for the injection of 2 GeV beams into the PS ring have been analysed [2]. Considering the updated kicker requirements [3] an upgrade of the existing injection kicker system (KFA-45) comprising operation in permanent short circuit (SC) mode has been developed. The challenges are the increased rise time in SC-mode caused by the pulse travelling twice through the magnet as well as the mitigation of higher ripple amplitudes.

Table 1: Nominal Voltage for Operation in SC-mode

Parameter	No. of Modules	Unit	Value
Voltage (1.4 GeV)	4	kV	40
	3	kV	53
	2	kV	80
Voltage (2.0 GeV)	4	kV	57
	3	kV	76

Nominal SC-mode voltage settings for the injection of 1.4 GeV and 2.0 GeV beams are outlined in Table 1 considering also failure cases (missing modules). In terminated mode the system provided a nominal kick angle of 4.3 mrad for 1.4 GeV beams when being pulsed at ~77 kV which corresponds to a current of 1.47 kA. For 2.0 GeV beams a current of 1.91 kA is needed which is provided by the upgraded system when being pulsed at 57 kV.

UPGRADE MODIFICATIONS

The KFA-45 upgrade consists of four major modifications: the permanent short circuit with integrated filter, the ferrite loaded connection box extension, the LEMO ferrites modification and the module dephasing. The simulations and development of the upgrade features have been described in [4] already.

SC-plug and Filter

Figure 1 shows the finally deployed oil insulated permanent SC-plug which short circuits the termination resistor (TMR) at the level of the former SC-mode thyratron. It features an integrated coil which serves as filter to mitigate the flat top ripple and has either two, three or four turns which can be exchanged for system tuning. As a fall back solution (until 2 GeV beams will be operational) the plug can be replaced by a blank flange turning the system back into terminated mode.

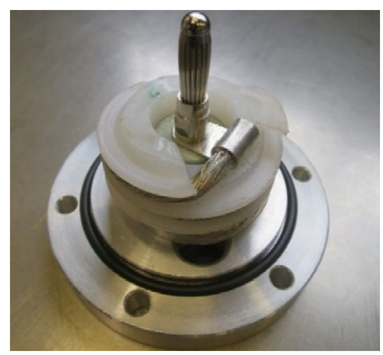

Figure 1: SC-plug with integrated filter coil.

Table 2: SC-plug: Measured Inductance for Two, Three and Four Turn Version

Parameter	No. of turns	Unit	Value
Inductance	2	nH	190
	3	nH	310
	4	nH	430

Table 2 indicates the measured coil inductance and is to be compared with the measured waveforms in Figs. 4-6. The modified magnet with the installed SC-plug instead of the SC-thyratron and thyratron auxiliaries is shown together with the new connection box extension in Fig. 2.

The orange box indicates the short circuited TMRs which are kept until LS2 for project risk mitigation. The removal of the TMR during LS2 will also allow to remove the oil distribution board and piping below.

Connection Box Extension

Each of the KFA-45 magnet modules is connected via two parallel 52.6 Ω SF6 gas filled coaxial high voltage cables. To house the intended ferrite rings a cylindrical SF6 gas filled extension of the magnet connection box was put in place for each of the eight cables. It houses one

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ferrite disc of 20 mm height and provides space for 2nd disc if needed. In total eight ferrite discs are installed.

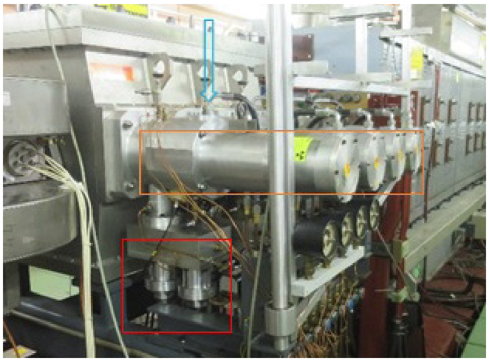

Figure 2: KFA-45 magnet after EYETS modifications: new magnet connection box extension (red), removed SC-thyratron and SC-plug (blue arrow) and TMR (orange).

Dephasing

The concept of dephasing the individual modules such that the flat top ripple seen by the beam (ideally) cancels out has been described in [4]. The calculated cable length has been verified by VNA measurements and all cable length have been fitted with connectors after high voltage testing and chemical analysis of the dielectric. The length installed for each cable pair per module is shown in Table 3. The dephasing cable installation required a resynchronization of the main and dump switch in order to not compromise the rise and fall times. As the reflections travel several times through the dephasing cables the intended effect is still present even if the main switch trigger is moved by the additional cable length (in time).

Table 3: Dephasing Cables: Required and Measured Length

Module No.	Required length [m]	Measured length [ns]	Measured length [m]
1	3.5	-	3.54, 3.54
2	5.4	29.45, 29.77	5.39, 5.45
3	8.4	46, 45.86	8.43, 8.4
4	11.13	60.8, 60.8	11.14, 11.14

LEMO Ferrite Modification

The initial upgrade program included a modification of the ferrite loaded LEMO connectors close to the main switch.

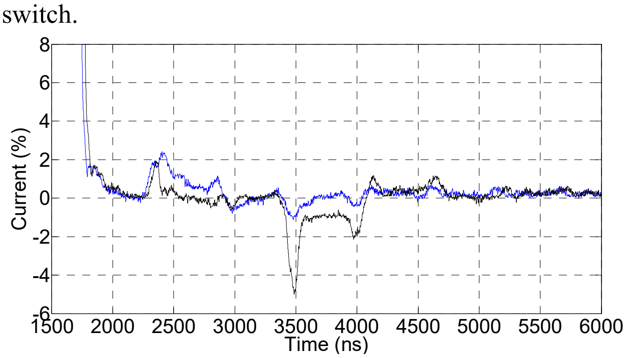

Figure 3: Measured post pulse ripple current of module 1 with five (blue) and three (black) LEMO ferrites.

Analogue circuit simulations suggested a slight reduction of flat top ripple when removing part of these five pulse steepening ferrite rings whilst the increase in rise time stayed stable and acceptable. Measurements showed however that taking out three of the five ferrite rings results in a considerable post pulse ripple excursion (Fig. 3). It was decided to keep all LEMO ferrites installed also in view of a faster rise time.

UPGRADE PERFORMANCE

An intensive test program has been performed to verify the hardware availability and performance after the modifications.

Methodology

The assessment of the kicker performance is not straight forward. The kicker itself provides no means for direct field measurements and for inserting a field probe one of the adjacent main bending units would need to be removed. Consequently only current measurements on the magnet modules output have been performed and are compared with expectations from current and field simulations. For definitive verification beam based measurements are being developed [5] and are planned for the PS start up period.

SC-plug and Filter

Different filter coils have been produced as outlined. They have been tested in module four and behave as predicted by analogue circuit simulations. Figure 4 illustrates the measurement results which clearly show the advantage of the filter coil and the decreasing ripple with increasing coil inductance.

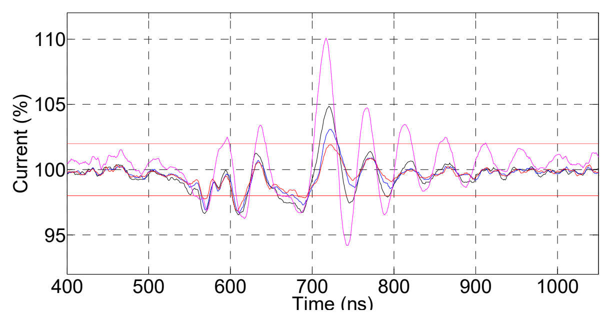

Figure 4: Measured current at the output of module 4 for different coils with two (black), three (blue) and four (red) turns mounted to the SC-plug and a direct SC (magenta).

Figure 5 shows the rising edge indicating an overshoot mitigation as expected. The undershoot does not decrease in the same way which is explained by the low pass characteristic of the filter. The same effect can be seen on the falling edge (Fig. 6) extending the fall time with increasing inductance. Therefore the filter is beneficial for flat top ripple mitigation but has potential impact on the system rise and fall times. In favour of faster rise & fall time parameters and because the flat top ripple is further mitigated by the dephasing concept the two turn coil has been chosen and was installed on all four modules.

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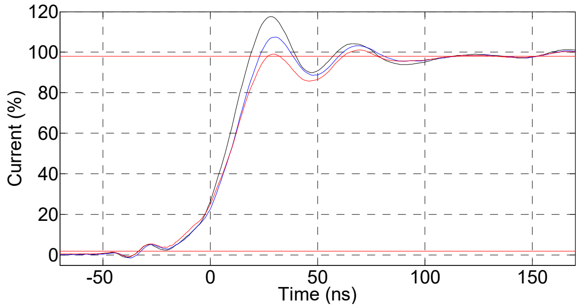

Figure 5: Current rise time measured at the output of module 4 for different coils with two (black), three (blue) and four (red) turns mounted to the SC-plug.

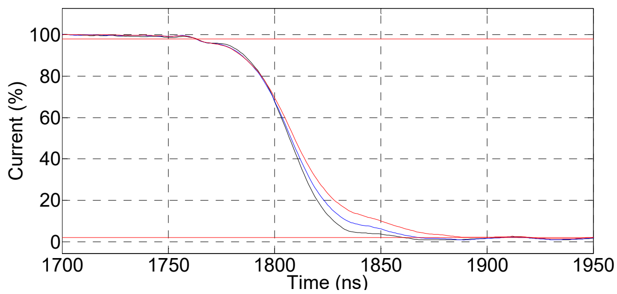

Figure 6: Current fall time measured at the output of module 4 for different coils with two (black), three (blue) and four (red) turns mounted to the SC-plug.

Rise Time

Current measurements (Fig. 5) show a rise time of 80 ns (5-95%) respectively 150 ns (2-98%) mainly due to the undershoot no. 2 falling again below the 98% level. Simulations indicate that the transmission line magnet structure will smooth this (current) ripple and the actual field rise time will be within the 105 ns specification.

Flat Top Ripple

The upgraded system shows a reduced current flat top ripple of 2.6% peak (Fig. 7). Again it is expected that the magnet will further smoothen this ripple regarding the field seen by the beam.

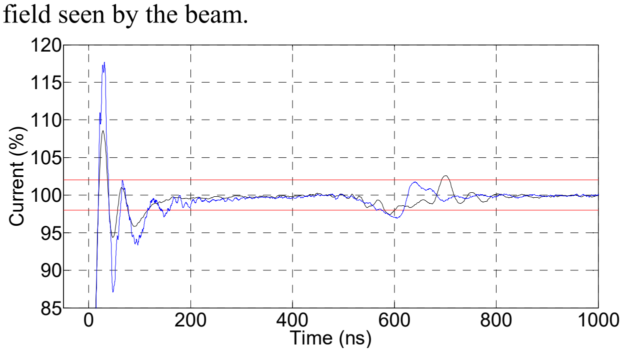

Figure 7: Measured current (sum signal) in 2015 (blue) and 2017 (black).

Post Pulse Ripple

Especially the installation of the ferrite loaded connection box was intended to reduce the post pulse ripple (PPR). The improvement is clearly visible in Figure 8 showing that the upgraded system features only half the ripple amplitude. During beam commissioning wrong settings lead to too long flat top requests. It was clearly visible that the PPR amplitude increases with very long flat top settings (>2 µs). This dependence of the PPR on the flat top length has not been observed before and needs further analysis.

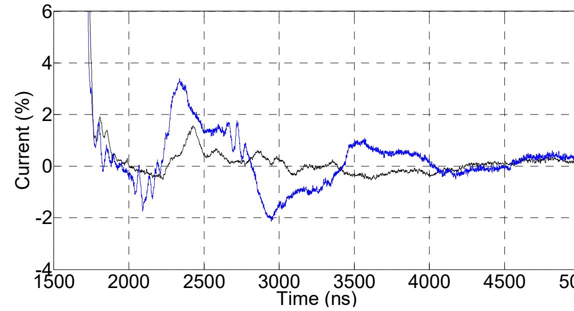

Figure 8: Measured PPR (current) before (blue) and after (black) the EYETS upgrade.

OUTLOOK

A spare magnet will be built allowing to modify the modules to prevent ferrite saturation at high current. The removal of the TMR during LS2 will require a modification of the magnet entry box which will be used at the same time to replace the gas filled transmission cables by conventional RG-220 type cables. Efforts are also being taken to replace the 80 kV gas filled pulse forming cables. Only recently an alternative design without SF6 gas was deemed to be acceptable for prototyping in terms of voltage hold off and attenuation values.

Table 4: Characteristic Values for the Measured Output Current (Sum of all Modules)

Parameter	Unit	Value
t_r (2-98%, 5-95%)	ns	150, 80
t_f (98-2%)	ns	105
Flat top ripple	%	2.6
Post pulse ripple	%	< 2

CONCLUSIONS

The proposed upgrade for the KFA-45 has been deployed during the past EYETS. For the correct assessment of the performance either direct field measurements or precise beam based measurements of the waveform are crucial. However, only current measurements could be taken during the EYETS to preliminary assess the performance and compare with simulations whilst beam based measurements are planned for the PS start-up. Table 4 summarizes the measured characteristic current pulse parameters which are widely according to expectations and simulations.

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