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DEPLOYMENT AND COMMISSIONING OF THE CERN PS INJECTION KICKER SYSTEM FOR OPERATION WITH 2 GeV BEAMS IN SHORT CIRCUIT MODE

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Abstract

Within the framework of the LHC Injector Upgrade (LIU) project the feasibility and design of an upgrade of the existing CERN PS proton injection kicker system has been outlined in previous publications already. This paper describes the adjustments of final design choices, testing and deployment as well as the validation and commissioning of the new 2 GeV injection kicker system. The upgrade pays particular attention to the reduction of pulse reflections unavoidably induced by a magnet in short circuit mode configuration whilst keeping a fast 104 ns rise and fall time. An adapted thyratron triggering system to reduce jitter and enhance thyratron lifetime is outlined. Additionally, improvements to the magnet entry box and the elimination of SF6 gas in the magnet connection box and the associated pulse transmission lines are discussed.

INTRODUCTION

After several years, the upgrade project of the PS injection kicker system (KFA45) is finally facing its beam commissioning phase. The upgrade requirements were initially specified in [1] and further discussed in [2]. In 2015 a feasibility study was launched [3] and the first modifications were implemented during the yearly shutdown in 2016/17 [4]. Already at that time the initial plan of installing a new additional kicker module in the PS straight section 53 was challenged and the permanent short circuit (s/c) mode of the existing KFA45 was studied. Several measurement campaigns during run 2 in 2017 and 2018 were carried out to assess the system performance in s/c mode and a new beam-based measurement method was introduced [5–8], resulting in a re-tuning of the generator [9]. During the first few days of the Long Shutdown 2 (LS2), in January 2019, it was finally possible to measure for the first time the magnetic pulse waveform of the old magnet in the tunnel under the preliminary re-tuned configuration, to benchmark the assumptions that had been made based on the available pulse current waveform measurements up to that date [10]. The final upgrade plans were confirmed and comprised the complete upgrade of the Main Switch (MS) trigger system, the replacement of the old SF6 filled transmission (Tx) cables by standard CLP52.6 (RG220 like) cables, a new SF6 gas free magnet connection box (CB) and finally a new vacuum tank housing four redesigned magnet modules. In addition to the pulsed power systems a complete controls environment update as well as the renovation of the SF6 gas distribution and hydraulics was scheduled.

THE NEW KFA45 MAGNET

As outlined in [10, 11], the KFA45 magnet was initially designed for much lower beam energies and started to show saturation effects for LIU compatible pulse generator voltages above 56 kV (s/c mode) [3]. Figure 1 illustrates the magnetic measurements done on the new (blue) and old (red) magnet and clearly shows the up to 15% non-linearity of the old magnet design at full kick strength.

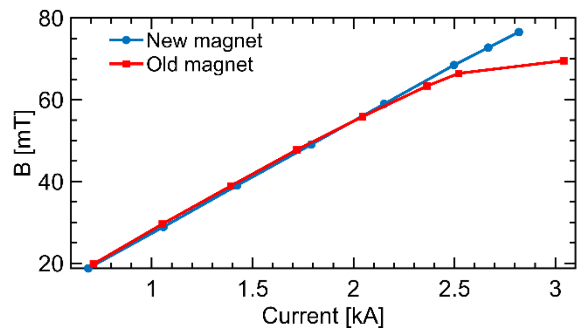

Figure 1: Measured saturation of the old (red) and new (blue) magnet.

Since the importance of the PS injection is evident the construction of a spare magnet was planned within the LHC Injector Upgrade (LIU) scope, and subsequently the opportunity was taken to redesign both, tank and modules.

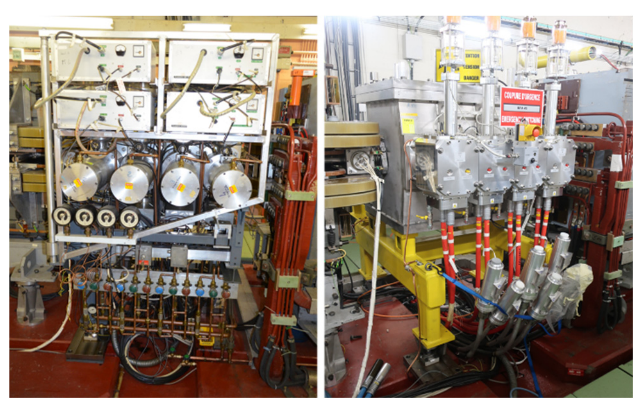

Figure 2: The old KFA45 magnet in the tunnel with s/c thyratron, TMR and oil cooling (left) and the new redesigned KFA45 in s/c configuration with the new SF6 gas free transmission cables (red) and a FC-77 filled connection box (right).

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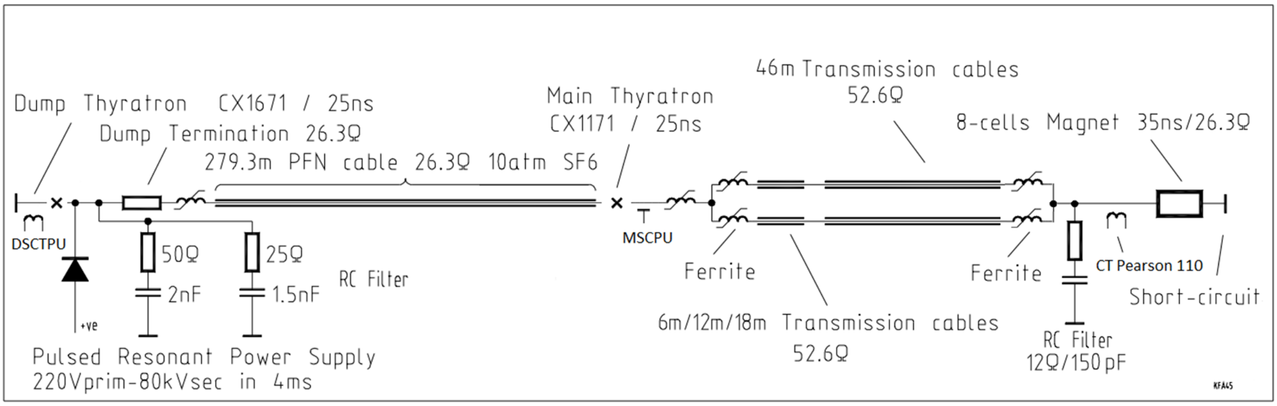

Figure 3: Schematic of the PS injection kicker system as installed with modified MS ferrites, dephasing cables, new Tx-cables, magnet CB ferrites and magnet CB filters.

Whilst the longitudinal length and aperture did not change, the magnet modules were vertically and horizontally enlarged to install 30 mm larger ferrites and thus prevent saturation at full current (80 kV equivalent). The extended ferrite volume drove the redesign of the interleaved high voltage (HV) and ground (GND) capacitor plates, the ceramic supports have been modified allowing an easier magnet assembly procedure and the HV and GND bar conductors have been adapted to improve the field uniformity.

Figure 2 shows the old magnet on the left and the newly installed KFA45 on the right. Clearly visible is the eradication of the terminating resistors and their oil cooling circuits as well as the s/c thyratrons which both massively ease maintenance and environmental protection aspects. The right image shows the new FC-77 filled magnet CB with the red CLP52.6 cables attached to it. For completeness Fig. 3 provides an overview schematic of the upgraded system.

Connection Box and Transmission Cables

The CB allows for the installation of two RC filters and up to 50 mm of ferrite rings around the high voltage Lemo® receptacles. Figure 4 shows the traces from the system tuning and the clear effect of the different RC filter values.

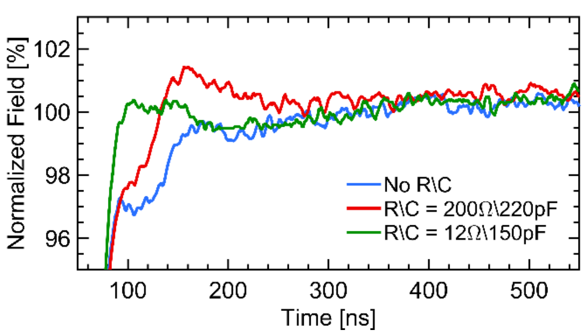

Figure 4: Measured field of the new magnet with different RC filters attached to the CB.

It was initially planned to have the s/c termination accessible in the CB but field measurements indicated that installing the s/c directly on the magnet improves the rise time by an invaluable 10 ns (Fig. 5). Consequently, the as built version is equipped with both feedthroughs but nevertheless is already s/c terminated on the magnet module directly. Inside the CB, one Pearson® 7308 current transformer and a capacitive pick up on the HV conductor are fitted for pulse monitoring.

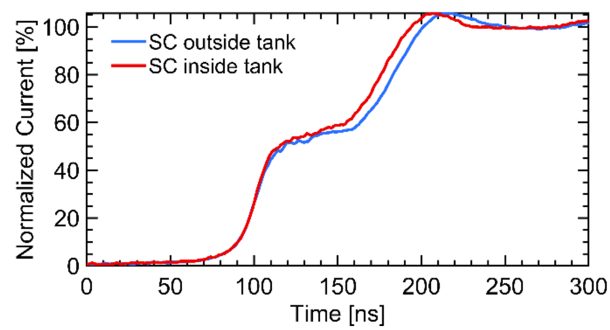

Figure 5: Measured current rise time of the new magnet with the s/c termination in the CB (blue) and directly at the module (red).

Another major improvement was the suppression of the SF6 gas filled Tx-cables as well as the SF6 gas in the CB. The replacement of the 40 kV Tx-cable was challenging in terms of the unique system impedance of 26.3 Ω in combination with the low attenuation of the so far installed SF6 gas filled cables. The found solution were two parallel custom made 52.6 Ω cables and a thorough preparation and validation in terms of accepting an increase in attenuation from 4.0 to 5.7 db/km (at 10 MHz). Simulations had already suggested that due to the short length (46.5 m) the impact is negligible, and this was finally confirmed by measurements on the installed system. Both, the elimination of SF6 gas for the magnet CB and Tx-cables and of the circulating oil between magnet and surface building are major steps in terms of environmental protection.

THE KFA45 MAIN SWITCH UPGRADE

A full upgrade of the pulse generator was not foreseen. However, during beam-based measurements in 2017 a significant jitter of the pulse was identified. Figure 6 illustrates measurements on the MS output current w.r.t to the timing signal and shows a 15 ns jitter (peak to peak) for all

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modules as well as occasional pre-fire events of up to 40 ns. Consequently, the MS triggering scheme has been fundamentally changed from priming Grids to "Double Pulsing" [12]. This included the removal of the external faraday cages for floating trigger signal, grid bias, reservoir and heater voltage supply of the CX1171 thyratron. Instead, a 100 m long delay line coil was installed in the switch tank to delay the Grid 2 pulse by 500 ns with respect to Grid 1. Additionally, separate HV insulated transformers for remote control of heater and reservoir voltage were placed in the switch tank as well as blocking ferrites around the cathode heater and reservoir supply leads.

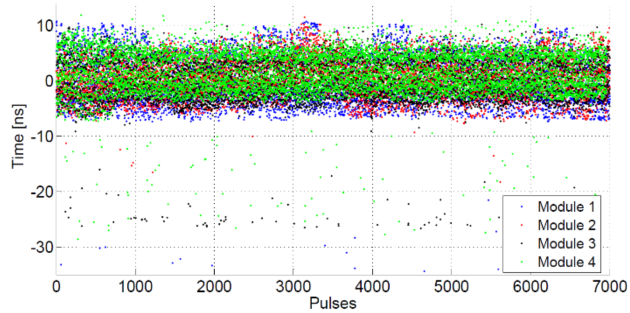

Figure 6: Jitter measurement of all KFA45 modules during operation at 54 kV in 2017.

Jitter measurements on the upgraded MS (Fig. 7) outline an excellent improvement in jitter (~1 ns) but also indicate that there are still occasional pre-fire like events at an unusual stable level of about -20 ns. Their origin has been further investigated and it can already be excluded that they are related to the MS thyratron itself. It is currently believed that the ferrites in the MS CB [13, 14] are occasionally left in a different remanent state depending on events occurring at the dump switch side. Further research is needed to fully understand and mitigate this issue.

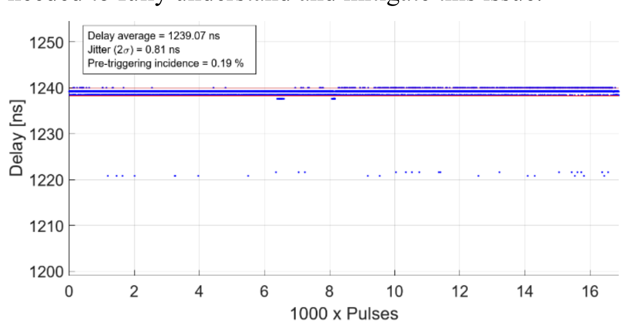

Figure 7: Jitter measurement on one module of the new MS triggering system pulsing at 60 kV.

Together with the switch renovation a new control system has been introduced allowing for full remote control and monitoring of the complete system. The first two months of KFA45 operation have already demonstrated the benefits of the new controls features as well as a remarkable system reliability.

Parameters of the magnetic field waveform of a single module, measured using a newly designed probe [15] are summarized for different tuning configurations in Table 1 and have been benchmarked by numerical simulation for compatibility in terms of emittance growth of future LIU beams.

The resulting system flat top ripple is being further reduced by the dephasing of the four modules for which short cables between MS CB and the TX cables have been installed which provide 60 ns, 120 ns and 180 ns delay to module 2-4. Compared to values measured pre-LS2 [7, 8], the quoted R/C filter configuration (Table 1), together with the steepening ferrites provide a good gain in rise and fall time (t_r/t_f) in the order of 20 ns.

Table 1: Measured Pulse Parameters (Integrated Magnet Field) for one Module at 60 kV at two Different Tuning Configurations of RC-filters and Ferrite Load

Configuration	t_r / t_f (2-98%/ 98-2%)	Flat Top (<±2%)	Post Pulse (<±2%)
No R/C MS 150 mm + CB 0 mm	179/ 94 ns	+6.5%	±4%
R/C 12 Ω/150 pFMS 210 mm + CB 30 mm	89/ 106 ns	+5%	±1.8%

CONCLUSIONS

The new PS injection kicker system has been fully deployed and successfully hardware commissioned. The system is already injecting 2 GeV beams at nominal working conditions without any magnet saturation effects. The deployed modifications have been outlined and resulting performance improvements concerning jitter and rise time have been highlighted. The full performance with respect to beam operations still needs to be evaluated during advanced beam commissioning. Further investigations will be conducted concerning the occasional pre-fire events and mitigation of the flat top spike. The newly available laboratory test stand will, therefore, be a key element in develop optimized tuning setpoints.

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