FEASIBILITY STUDY OF THE FAST SPS ION INJECTION KICKER SYSTEM

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Abstract

As part of the upgrade project for ions the rise time of the injection kicker system into the SPS needs to be improved. The changes being studied include the addition of a fast Pulse Forming Line in parallel to the existing Pulse Forming Network for the fast kicker magnets MKP-S. With the PFL an improved magnetic field rise time of 100 ns is targeted. Two different configurations utilizing a 2nd thyratron or two fast diode stacks have been outlined in the past. This paper presents the recent progress on the analogue circuit simulations for both options as well as measurements carried out on a test system. Modelling, optimization and simulation of the entire system with diodes and a second configuration with two thyratron switches are outlined. Measurement results are given and the feasibility of the upgrade is discussed.

INTRODUCTION

Different options for a low inductance connection of the existing Pulse Forming Network (PFN) with a new required Pulse Forming Line (PFL) have been outlined in previous papers [1, 2]. Two proposed solutions are shown in Fig. 1. Configuration 1 uses two diode stacks to separate PFL and PFN whilst the same functionality is obtained in configuration 2 by the utilization of a 2nd thyratron. Both configurations introduce extra elements at the main switch tank level and lead to a more complex and larger connections between each of the pulse forming systems and the thyratron(s). It was expected that this modification would slightly reduce the system performance in terms of rise time as well as in flat top stability. However, the introduction of new filters and the optimization of the already installed ones, could have enough margin to achieve all system specifications.

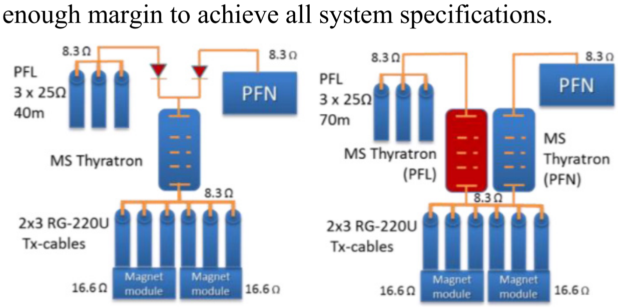

Figure 1: MKP 100 ns test configurations: Configuration 1 with diode for separation between PFL and PFN (left) and configuration 2 with one thyratron per branch (right).

Previous measurements carried out on the test system in configuration 1 with only the PFL branch connected showed a significant increase of rise time well above the 100 ns goal [2].

TEST SYSTEM PERFORMANCE

In order to validate previous measurements and to collect additional data for further performance analysis and optimization, new tests were carried out. Only the PFL branch was connected during these tests. The PFL used comprised of three 50 Ω F&G cables, of which one end was connected to the anode of the E2V CX1171A thyratron, located in the main switch. The spare MKP-S magnet was terminated with a matched load (hereafter called TMR) and is connected to the main switch cathode by three 5 m long RG220 coaxial cables. In order to house the diode stack (six ABB 5SDA 27Z13 multichip diodes in series) and the RC filter for configuration 1, an old MKA switch tank (already containing the thyratron) was modified.

Figure 2 presents the measured current waveform for both configurations. The upper plot, showing the system in configuration 1 indicates a significant slower dI/dt at the rising edge compared with configuration 2 which shows significant flat top ripple to be optimized. Subsequently the diode configuration has a largely increased rise time due to a distortion located at the end of the rising edge. Table 1 summarizes the measured rise times for the different configurations and rise time definitions.

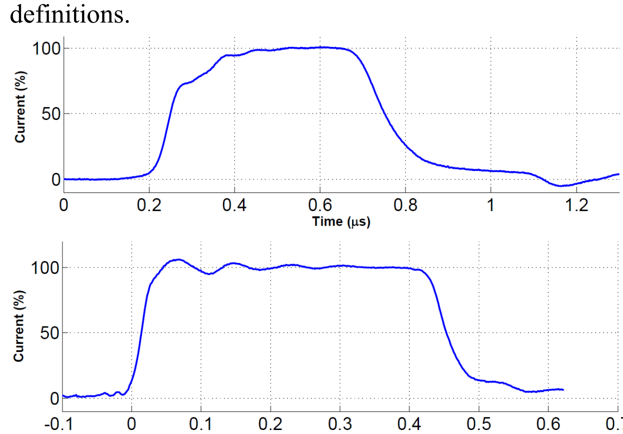

Figure 2: Measured current waveform at the TMR. Upper figure, MKP-S system with configuration 1. Lower figure, MKP-S system with configuration 2.

In configuration 2, despite the higher dI/dt at the rising edge, the system is not close to the specifications as the

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oscillation along the flat top is too large. Proper filter tuning might mitigate this effect and damp the oscillation but will likely also lead to a slower rising edge.

Since for configuration 1 the only changed element is the diode, it was considered to be the main source of the performance degradation and subsequently further investigations were launched.

DIODE CHARACTERIZATION

All diodes need some transient period to be fully conductive after they are switched on. This phenomenon is known as a forward recovery and is especially noticeable in switched and pulsed power applications [3]. During this transient time a voltage overshoot, directly proportional to the applied dI/dt, develops across the diode. Any apparent negative effect that the diode stack may have on the targeted fast rise time for the ion injection cannot be overlooked. In order to better understand the forward recovery time impact on the system performance, several diode tests were carried out. A fast pulse generator was used to pulse one single diode multichip wafer with currents up to 1 kA. A low inductance set up was realized to minimize undesirable effects and to clearly evaluate the diodes turning on transients.

Figure 3 shows the measured forward voltage. As previously commented, the diode represents relative high impedance only at the beginning of the conduction period. As soon as the diode substrate becomes more conductive, the resistance across the diode decreases until the steady state condition is achieved. With this data, a diode model was obtained and included in the MKP system simulations.

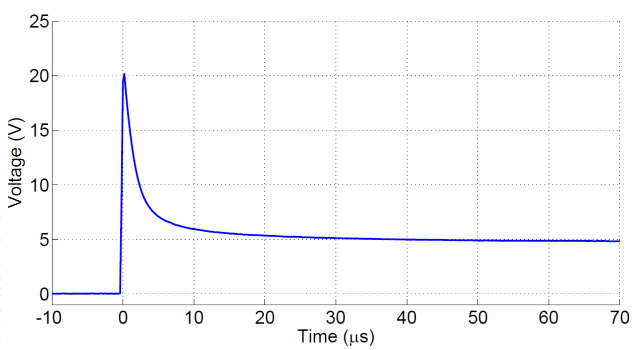

Figure 3: Measured diode forward voltage of ABB 5SDA 27Z1350.

Several elements are needed to model the diode behaviour. The nonlinear steady state V-I curves of a diode can be represented using an ordinary PSpice diode model. To include the forward recovery behaviour a bulk resistor needs to be added. During the forward recovery phase this resistor causes the observed voltage overshoot. It is possible to model the bulk resistor with a dependent voltage source driven by an exponential source. To make the voltage source acting like a real resistor, the diode current dependence needs to be added. This can be realized by adding a transimpedance source. To conclude the model, an 30 nH inductance per diode was added. Figure 4 shows the schematic of the described diode model.

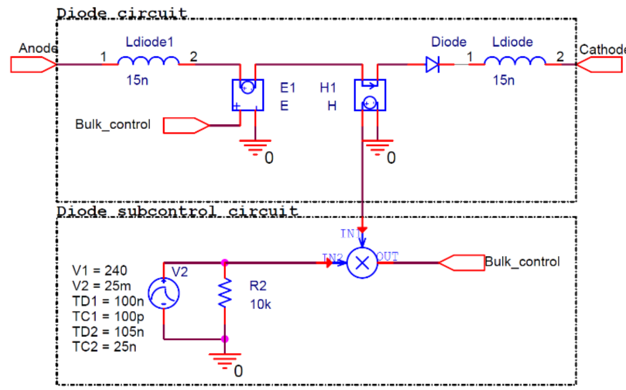

Figure 4: Developed diode model.

SIMULATIONS

A model for both possible MKP configurations was developed. Passive circuit elements, main switch tank filter or the MKP magnet were described in this model. Modifications to the main switch to accommodate the diode stack were also modelled by adding 720 nH of inductance representing the connection between thyratron anode, diode and PFL.

This model allowed to reproduce the current waveform previously observed in measurements.

The current through the system was measured at the terminating resistor. Since it is a calibrated element, the current can be easily measured avoiding uncertainty, bandwidth limitations and noise often added by a current transformer.

Simulations pointed out that the inductance added by the diode assembly influences the rise time. For this reason new simulations with less inductive connections were also carried out. Figure 5 shows the simulated current at the TMR for configuration 1, configuration 1 with a 50% less inductive connection (hereafter called configuration 3) and configuration 2.

The simulated current of configuration 1 shows a good agreement with the measured waveform with the same range of dI/dt at the rising edge. It is also observed that the dI/dt ratio decreases at the end of the rising edge in almost the same manner, contributing to the waveform distortion and substantially increasing the rise time. The simulation also shows how the variation of the inductance has a big impact on rise time.

Table 1: Measured rise times

Tr[ns]	Config. 1	Config. 2	Config. 3
Tr (2-98%)	271	93	261
Tr (5-95%)	217	46	171

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Table 2: Simulated rise times

Tr[ns]	Config. 1	Config. 2	Config. 3
Tr (2-98%)	217	77	157
Tr (5-95%)	154	48	106

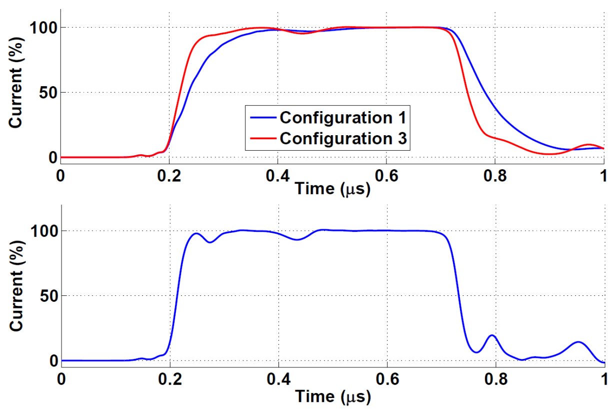

Figure 5: Simulated current at the TMR. Upper figure, configuration 1 and configuration 3. Lower figure, configuration 2.

VALIDATION OF SIMULATIONS

Simulation results and characterization test showed that the diode does not have such a relevant role in terms of the dI/dt ratio as expected. Since the diode quickly becomes conductive, the impact on the pulse rise time is small. It was noticed, that the modifications to accommodate the diode stack were highly inductive causing the reduced dI/dt ratio. For this reason a new test was performed bypassing the diode stack with the inductive connection remaining as before. Figure 6 shows a comparison between configuration 1 with and without diode bypass. It is clearly noticeable that both traces are very similar. This test shows that the simulation is valid and the constraining element is indeed the inductive connection set up.

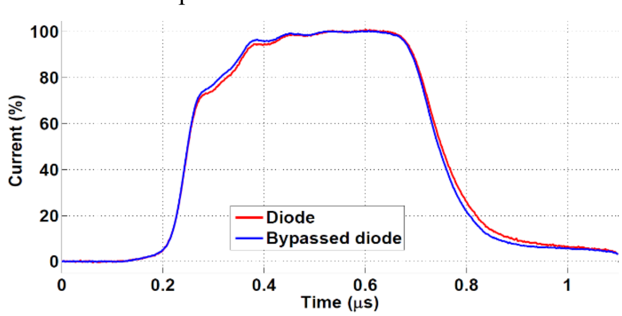

Figure 6: Measured current waveform at the TMR

OPERATIONAL PERFORMANCE

The SPS injection kicker systems are composed of 16 magnets distributed in four different tanks. The first three tanks contain 12 fast magnets, also known as S-type. These are able to achieve a rise time of 145 ns. The fourth tank contains four L-type magnets with a larger rise time of 225 ns.

In order to reduce the batch spacing, a new configuration was tested in 2015 using only the first 3 tanks principally allowing for a faster rise time [4]. Before this, all four tanks were normally used during ion injection allowing a rise time of 225 ns. The missing kick in the new configuration was delivered by a bump created with correctors. At first attempt of ion injections the beam was straight away dumped. A jitter of ±30 ns at the MKP trigger electronics was found as the reason for high beam losses and the consequent dump trigger. Once the triggering issues were solved, the replacement of one slow thyratron suffering from ageing and then proper synchronization of all the magnet modules, the injection of ions into the SPS with 150 ns batch spacing was successfully achieved.

CONCLUSIONS

The target of 100 ns rise time is challenging. Two PFL configurations have been analysed and tested. Both need to be improved to finally reach the 100 ns and ±1% flat top ripple requirement. The observed rise time degradations have different reasons for each configuration. In configuration 1, both rising and falling edges have low dI/dt, measured as simulated. As outlined in this paper the diode forward recovery phenomenon could not explain this performance degradation. An extra inductance added and representing the diode connection better matches the simulation to the measured waveforms. Indeed the diode assembly needed relatively long connections to fit into the available space. Also, this additional inductance creates an impedance mismatch between the PFL and the main switch, causing the chain of reflections towards the PFL and afterwards reflected again into the magnet. Even if the system fall time is not critical this effect leads to post pulse ripples up to 4.5 µs which need to be improved. To mitigate this problem, a new low inductance connection needs to be designed.

Configuration 2 rising edge is much faster compared with configuration 1, but not properly damped oscillations at the flat top still need to be addressed. A filter was already installed to soften this effect, but tuning is still needed. The feasibility of configuration 2 seems better whilst configuration 1 would be the less complex solution. For both variants a low inductance connection to the existing PFN needs to be developed.

Finally, the operational achievements with the existing system, improving the batch spacing from 225 ns to 150 ns however make the 100 ns SPS ion injection upgrade less attractive.

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