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Automatic conditioning of the LHC injection kickers

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Abstract

The LHC injection systems, located near the interaction regions 2 and 8, comprise 4 fast pulsed kicker magnets (MKI) per ring to bring the beam onto the orbit. Each magnet is housed in a separate vacuum tank. Their nominal operating voltage is 54 kV, and the nominal pulse length 7.86 µs. To prepare these magnets for operation they are once assembled and baked out, gradually subjected to higher and higher voltages and greater pulse lengths, until their voltage holding capability is sufficiently beyond the nominal operating conditions. In the past this "conditioning" was carried out manually, and thus a manpower-intensive, and also technically not optimal procedure. To overcome these drawbacks a program has been developed, running in a Programmable Logic Controller (PLC), which has been used to condition the full suite of LHC injection kickers automatically.

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1. Injection kicker architecture

The two injection kicker (MKI) systems [1] near the interaction regions 2 and 8 of the LHC [2] will vertically deflect the beam to be injected onto the orbit of Ring 1 and Ring 2, respectively.

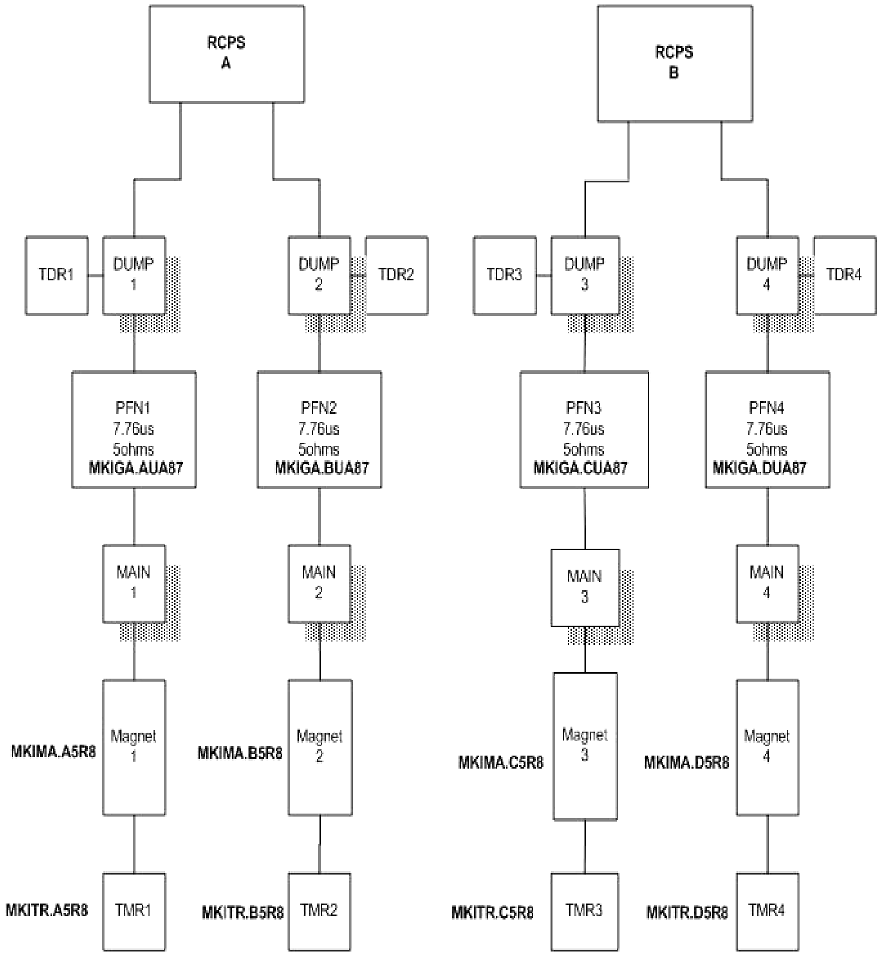

Figure 1: Injection kicker system block diagram.

Each system comprises 4 vacuum tanks containing one magnet each. Vacuum valves around each tank allow to separate the tanks from each other if needed, and to transport magnets under vacuum but furthermore they serve to uphold the vacuum conditioning and high voltage conditioning made inside the test laboratory, this also helps vastly in reducing the lead time when changing a magnet, a few days instead of a few weeks usually. The associated 2 high voltage (HV) pulse generators (in the following called "generators") are located in the adjacent underground galleries (UA23 & UA87). A block diagram of the HV circuitry of one injection kicker system is given in Fig 1. The quasi-rectangular pulse exiting the magnet is created by a resonant charging power supply (RCPS) followed by a pulse forming L-C network (PFN), and transferred to the magnet through a set of parallel transmission cables. Each magnet is fed by a separate PFN; two PFNs are charged simultaneously from one RCPS. The start of the pulse is defined by the closure of the main switch (MS) thyratron. After having travelled through the magnet, the electrical energy is absorbed in a terminating magnet resistor (TMR). The pulse duration is adjusted by the closing of the dump switch (DS) thyratron which discharges part of the energy stored in the PFN through the terminating dump resistor (TDR). The nominal operating voltage is 54 kV, the design voltage is 60 kV. The maximum pulse length to be used during operation is 7.86 μs, the maximum pulse length which can be delivered by the generators is close to 10 μs. The field rise time is 0.9 μs, the fall time is about 3 μs.

To obtain a high bandwidth, ensuring the desired quasi-rectangular pulse shape, the PFN's are composed of multiple L-C cells; the magnet is a multi-cell travelling wave magnet. The complete HV circuit is impedance matched, with a characteristic impedance of Z = 5 Ω to avoid reflections which would lead to unwanted distortions of the pulse shape. The nominal beam deflection per system (4 magnets) is 0.85 mrad.

2. Kicker magnet design

The kicker magnet design is based on a travelling wave magnet topology and is composed of 33 cells. The nominal inductance of the ferrite C-core is 101 nH per cell and the cell capacitance, obtained using ceramic capacitors is 4.04 nF. The magnets are operated in vacuum of the order of 10^{-11} mbar. The complete magnet is baked out at 300 ^{o}C before HV conditioning. The bake out is necessary to eliminate any impurities inside the magnet vacuum chamber which would affect high vacuum quality and contribute to the out-gassing of the surfaces, specifically H_2O. The kicker magnet has a C-shaped ferrite yoke and 2 ceramic matching capacitors mounted between high voltage and ground plates. The relatively long field rise time allows building a magnet of 2.2 m length. The capacitance of 4.04 nF per cell is achieved by means of high voltage/high frequency grade 1 ceramic plate capacitors. The magnet is housed in a cylindrical vacuum tank of 600 mm diameter.

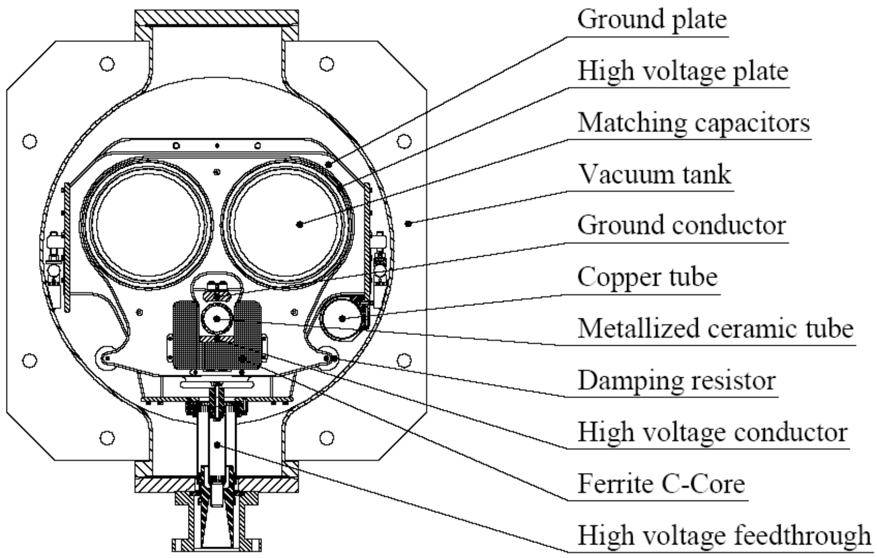

Figure 2: Cross section view of the MKI kicker magnet.

The LHC beam, which has high peak currents alters the impedance of the ferrite yokes and can provoke significant beam induced heating, even above the Curie temperature. To limit the beam coupling impedance a beam screen is placed in the aperture of the magnet. The screen consists of a ceramic tube with conductors on the inner walls. The conductors provide a path for the image current of the high intensity LHC beam and screen the ferrite against the Wakefield's.

3. HV conditioning

Many high voltage equipments need to be conditioned to avoid sparking on their electrical surfaces, klystrons, RF cavities, magnets. Furthermore equipment with high vacuum needs to be conditioned with more care. The SPS kicker magnets where conditioned with DC generators, sometimes with a positive and negative DC high voltage. This implied using a DC generator in-situ (shorter power cable hence charge limiting) and to let the process to be run by itself with increments in voltage steps done manually by an operator. DC conditioning is a fairly rapid process and can be achieved over a relatively short period of time. Historically the kicker magnets designed for SPS and LEP were constructed differently to the current MKI kicker internal structure; inter-cell capacitance had smaller values than the current design.

For the MKI magnets, DC conditioning was not a viable solution because of the inter cell capacitors (4.04 nF) that would store too much energy under DC conditioning. The internal sparking under DC conditioning could be very destructive due to the high amount of energy stored inside the capacitors. Hence a pulsed conditioning system or AC conditioning was opted due to its short pulse width (1 to 10 µs) and long mark-to-space ratio (more or less 10 s). These characteristics allow for a 'soft' conditioning approach and reduce greatly the internal HV breakdown energy. Also pulse conditioning is required to test and condition the screen conductors (DC conditioning would not induce a voltage on the screen conductors). The major drawback of AC conditioning is that is becomes a lengthy operation and requires an operator to be constantly monitoring the progress. In a manual conditioning process, the operator had to survey the vacuum on all magnet tanks, monitor the out-gassing and record the number of peak events of out-gassing, take decisions on whether to place in standby the process to give the system some rest time before starting the conditioning again and this had to be decided depending on certain vacuum thresholds. In the end, the HV conditioning by human operator had become a complex algorithm and was part of a process that required quick thinking and constant attention, something a human cannot achieve as well as a computer. This gave the need for a fully automated AC conditioning system that could automatically increment voltage and pulse width, cause the system to stop according to well know pre-defined parameters for vacuum interlock thresholds and also count the numerous sparking events at different vacuum thresholds.

4. HV conditioning mechanics

A kicker magnet inner structure for the MKI system has 33 cells consisting of HV plates with capacitors to ground (delay line type magnet) and a screen to shield the ferrite magnet for optimising beam impedance. The HV bus bars and capacitors and screens contribute actively towards internal HV breakdown. Kicker magnet conditioning is a process in which it is necessary to prepare the magnet for an optimum operating voltage condition. Normally at all voltages the electric fields are uniform across the surfaces of the magnet electrodes except when dust or contaminants increases locally the field. To enforce the cleaning of the surface and contribute towards electrical field uniformity, a voltage must be applied in slow incremental steps and progressively. Failure to apply this process can result in internal magnet sparking and out gassing which can in turn damage the magnet structures and change the high vacuum inside the chamber ($\approx 10^{-11}$ mbar). Conditioning of the inner magnet chambers with high voltage is also a means to eliminate surface impurities on the high voltage plate and ground plate structures of the magnet. Typically, contaminants such as dust can contribute to creating small electrode formations that can inherently disturb the internal electric fields inside the magnet chamber and form unwanted arc points. A contaminant particulate on a high voltage plate structure can increase the E field in a region where the ground plate has an accumulation of nano layers from other contaminants, such as residual ions distributed on its surface. Without conditioning, HV breakdown can occur between two electrode formation points thus creating a discharge path between both structures. The conditioning process allows for this unwanted effect to be overcome with slow and carefully controlled appliance of voltage increment steps and pulse width adjustment, thus creating internal micro discharges to 'clean' and 'flash burn' residual contaminants which would otherwise create a threat to the clean surfaces of the magnet chamber inner structures. As previously mentioned contaminants can be found on the surfaces of the magnet chambers, these can be by-products from the vacuum bake out process (usually carbon related contaminants). Failure to not condition the magnets can cause strong HV sparking inside the chambers and hypothetically damage components, increase contaminants, disturb the geometry and topology of chamber structures and cause long term damage to the magnets therefore increasing machine down time. The HV breakdown also affects the ultra high vacuum by producing out-gassing and also causes pulse reflections back to the thyratron tubes. Another additional risk is loss of magnetic field during the sparking which can cause the proton beam to badly steer or increase the chance of hitting a vacuum chamber causing hypothetical structural damage by spraying the machine with ionising particles and cause short term high radiation levels in areas that would not normally do so.

5. MKI control hardware

The complete installation state control is based on SIEMENS automation systems for slow control and to some extent manages also the fast control (thyratron erratics, missing pulses and magnet sparking).

The master CPU is based on a SIEMENS S7-400 master Programmable Logic Controller (PLC) which is linked via two groups of identical PROFIBUS-DP segments to the various equipment controllers (resonant charging power supply controller, thyratron heater controller, terminating resistor controller, pulse generator controller). These are connected either as deported I/O’s or decentralised I/Os when low-level intelligence is required. A third profibus-DP segment is used to interface the resources common to the two generators of one injection scheme such as electrical distribution and temperature measurements. The master PLC has also a TCP/IP connection for communication with the various control applicative layers.

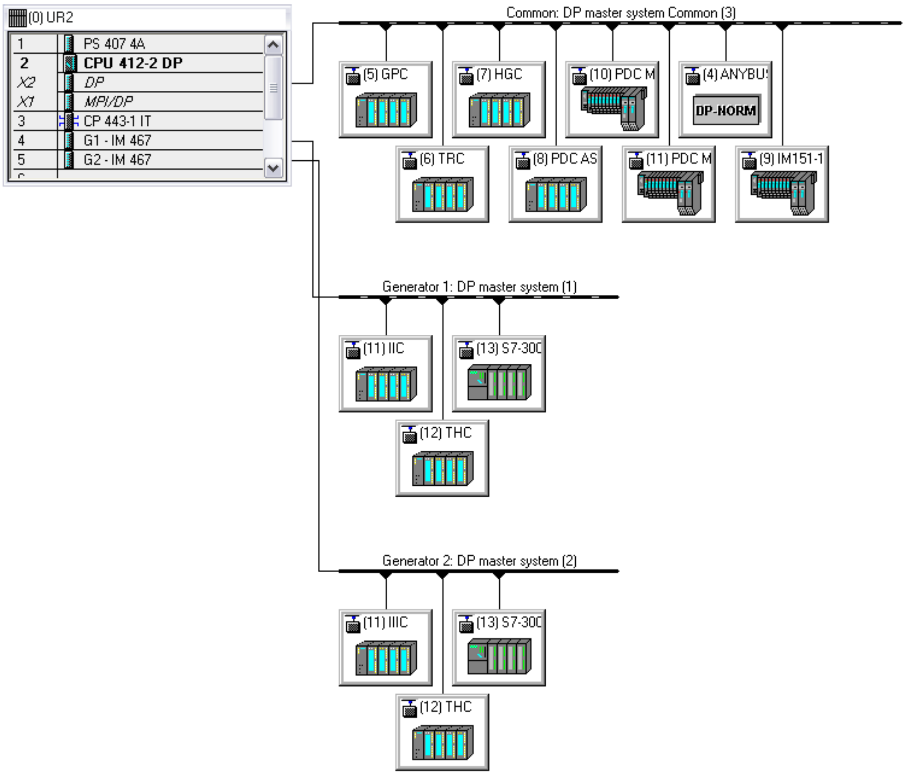

Figure 3: MKI block diagram of injection kicker PLC distributed I/O's.

The MKI injection process control consists of a LynxOS VME power PC Front-End Computer (FEC) including three 1ns resolution digital delay modules which are used for trigger pulse generation that are in phase with the injected and circulating beam and are also used for fine timing adjustments, a 12 bit DAC/ADC module for kick strength settings and measurements and one standard LHC timing module (CTRV) for synchronisation with the machine timing. All of these components assembled together constitute the distributed timing of the installation. The management of the different operational settings during the injection process is based on a real-time task running front-end which shares it resources with the FESA control database for parameter setting and control of the MKI installation.

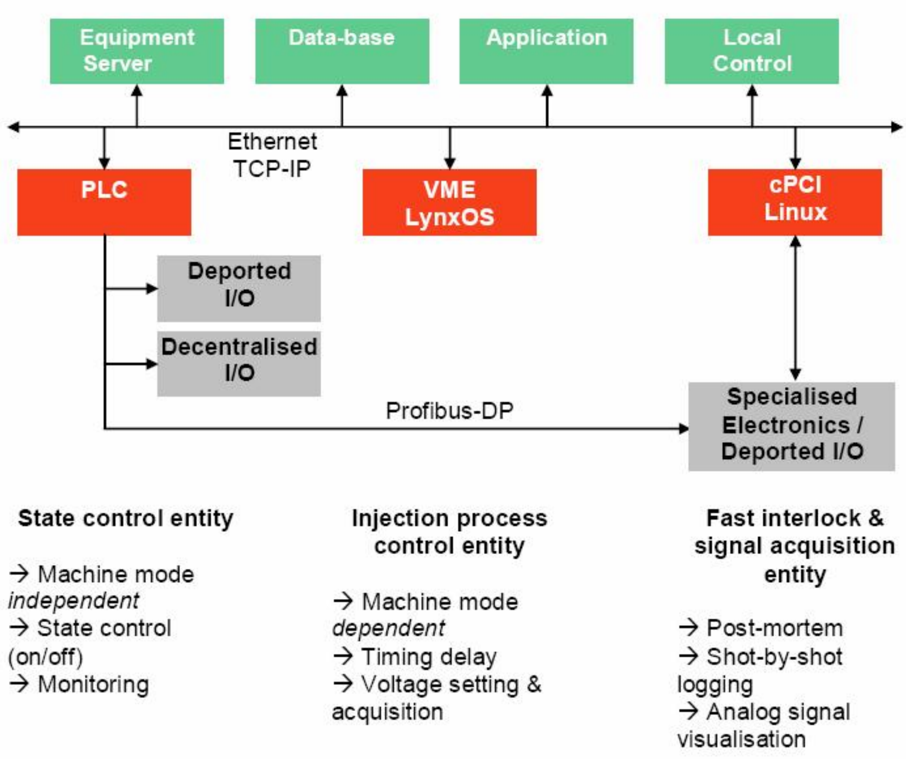

Figure 4: Layout of control and applicative layer.

6. Software

The software architecture is divided into three different layers, the controller software, the front end and applicative layers. Controller and front end layers communicate through the standard PROFIBUS-DP protocol and are implemented through commercially available packages (STEP7, WinCC V6.0, WinCC flexible, Pro Tool, ASIMON). The application layer software consists of applications and operations and expert programs connected to the front end layer through the FESA control software.

7. MKI functionalities

The MKI state transition management and state acquisition are implemented through a finite state machine running in the master PLC level. The "standard" operating mode is designed into a stepped sequence using the principle of a finite state machine. The step sequences are the following:

1) Validation of emergency stops
2) Validation of ASI thermal protection
3) Thyratron tube heaters ON
4) Resonant charging power supply ON
5) PFN network ON
6) Automatic Magnet Conditioning MODE (if used)
7) Dual charging power supply ON
8) Timing ON
9) Injection permit & Beam permit (Remote only)

These steps are executed for each functional block or performed automatically with an ON/OFF/STANDBY actuation command. The system is operable in LOCAL mode in which the system expert can operate and test the system in-situ and the REMOTE mode is for the operation's functionality of the system which is controlled from the CCC.

Most of the system parameters can be adjusted from an operator panel such as the TMR settings, thyratron heater settings, TMR hydraulic group settings, local timing parameters, kick strength, TDR and TMR fluid levels, HV connection boxes fluid alarm thresholds and more. Other features of the SCADA interface to the system are the range of operating parameters and settings for the automatic conditioning system.

8. Automatic conditioning operator control interface

An operator can follow closely the process of automatic conditioning. The magnet strength reference is taken from a pick up from the PFN's, and is represented by an average over the four PFN's. Each magnet displays kick strength and vacuum values. A magnet spark counter is indicated and can show recorded spark events for both weak and strong sparks, these are associated with the following interlocks:

PSHH=very high pressure (MKI at 1EP^{-08P} mbar)
PSH=high pressure (MKI at 2EP^{-09P} mbar)
PSLL=very low pressure (MKI at 1EP^{-12P} mbar)

These interlocks each provoke an action. The PSHH stops the timing, the PSH interlock will stop voltage incrementation and starts a user defined timer after PSHH action and will continue the conditioning process after the timer has ended, hence forcing the system to automatically recover vacuum activity and start a new cycle of voltage conditioning when vacuum levels have regained their satisfactory values. The PSLL interlock will stop the conditioning and display a system failure. The PSLL values are very low and are more likely to be provoked by a faulty Balzer vacuum gauge that has gone into saturation or has a cable disconnected. Other information displayed are the total pulse count during the conditioning process, the kick length reference during kick length enlarging mode and individual pulse counter steps for each ramping profile.

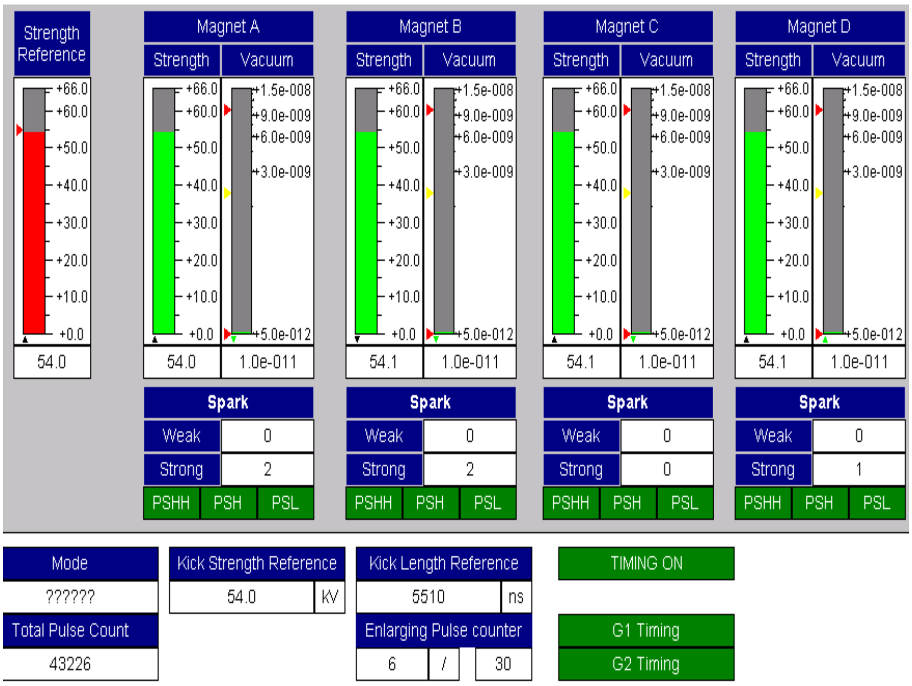

Figure 5: Main control window of the automatic conditioning system.

8.1 Trends view

This feature allows the operator to follow and monitor in real time events of the vacuum condition on all four magnet tanks. It is a tool that allows visualisation of magnet sparking due to high voltage breakdowns. These can be measured, recorded and help to further the understanding of the conditioning process. Multiple graphical curves can be overlaid for analysis; these can include vacuum levels, voltage increment steps, pulse width increments and pulse counts.

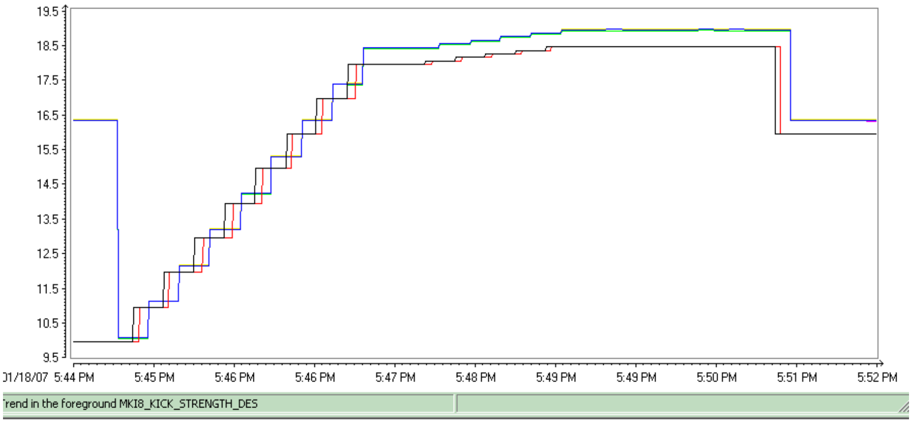

Figure 6: Automatic conditioning voltage trend view window.

8.2 Interlock settings

Prior to launching the automatic conditioning program, the user can set various parameters inside the process. These are the numerous interlock thresholds (PSHH, PSH and PSLL), vacuum spark detection thresholds for both strong and weak spark count together with voltage reduction percentage. Also a maximum allowable voltage ceiling interlock, a pulse detection tolerance window and a counter timer setting after a PSHH interlock occurs.

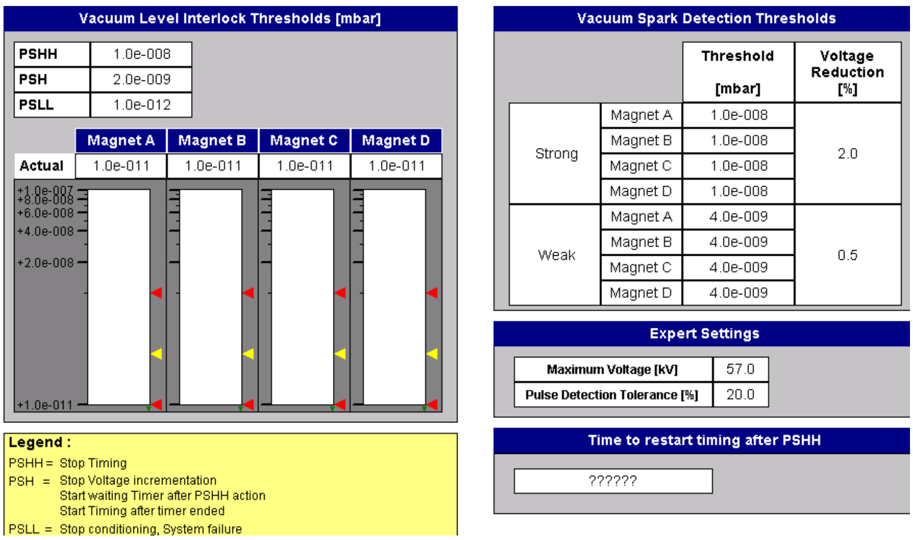

Figure 7: Interlock settings window.

8.3 Voltage ramping settings and pulse enlarging settings.

The ramping window allows for parameterisation of each step necessary for the automatic conditioning profile. Initial kick strength can be input from the start of the conditioning ramp and various count pulses for each voltage increment steps. The ramping mode can have a long plateaux or a short brief one. When nominal voltage is reached, a decrement step prepares for the following stage, the pulse width widening process.

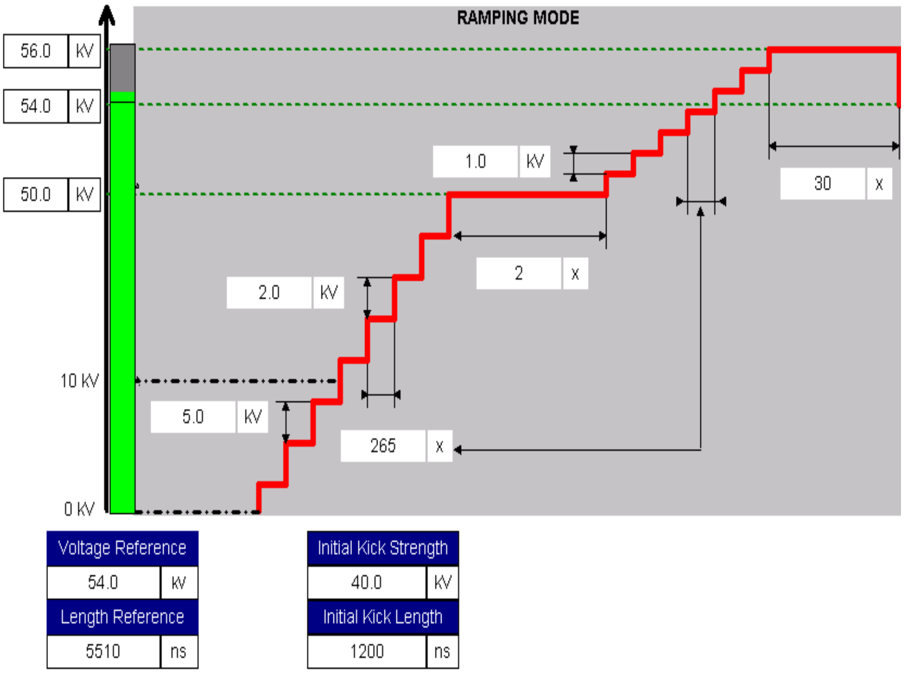

Figure 8: Voltage ramping setting window.

Similar to the voltage ramp, the enlarging mode can be set with an initial kick length which can then be widened over several steps to a nominal operating pulse width. Once this value is attained and no interlock has disturbed the process, the automatic conditioning system comes to a halt and ends.

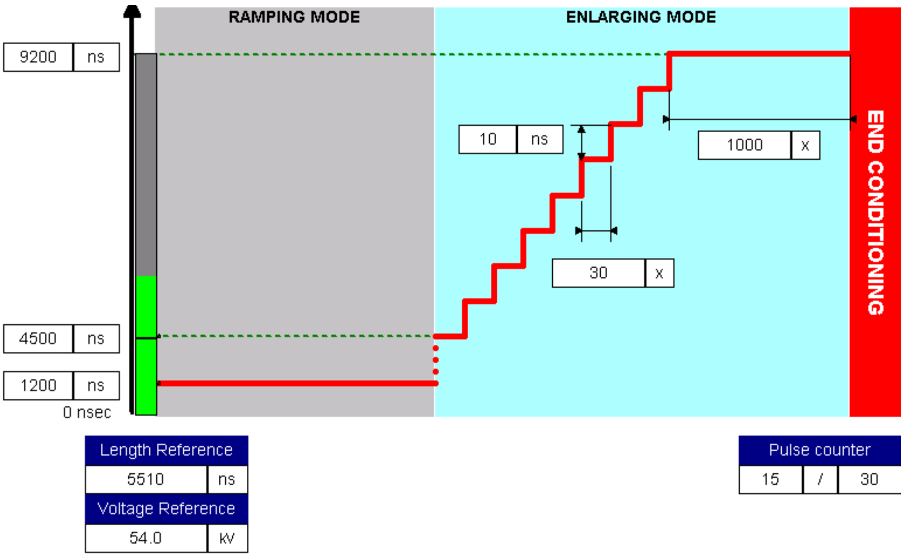

Figure 9: Pulse width widening setting window.

In essence, the system has to achieve two main important processes, a voltage increment of the kicker pulses achieved in multiple steps with a plateau on each step followed by a pulse widening program close to the nominal operating voltage or at nominal voltage that allows the kick pulse length to be stretched to its maximum width. These two processes must also recognise vacuum level interlocks, count sparking events and allow for a soft start when an interlock occurs, all these goals have been achieved with the automatic conditioning program.

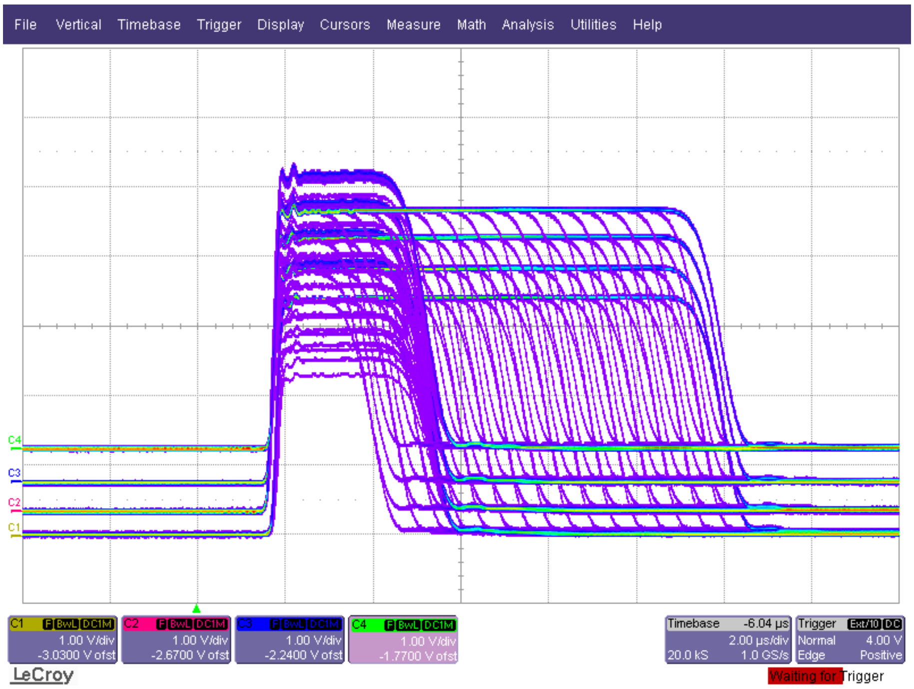

Figure 10: Pulse measurements on a TMR showing voltage increment and pulse width increments by automatic conditioning.

9. Conclusion

To this day the system has proven to be efficient and reliable and widely appreciated by the operators and engineers. The performance of the system relies on a good knowledge of the kicker magnets characteristics, the installation power electronics and control system comprising all sub-systems. This system is implemented for both injection kicker magnet installations (MKI8 and MKI2) and might also be implemented for other automatic magnet conditioning projects. The system has allowed furthering the understanding of the operating points for nominal kick voltages and has vastly contributed to reducing the time and effort that is normally associated with a manual conditioning approach. This project has been achieved with the use of industrial components which has also helped to reduce the development time and cost of the project and has the full advantage of a system based on industrial standards. The system performs well and is now recognised as an essential tool for kicker magnet conditioning.

10. Acknowledgements

The author (*R.A. Barlow*) is grateful towards Michael J. Barnes for fruitful discussion and contribution towards this document.

11. References

[1] L. Ducimetière et al., “Design of the Injection Kicker Magnet System for CERN’s 14 TeV Proton Collider LHC, Proc 10th IEEE Int. Pulsed Power Conf., Albuquerque, USA, 1995.

[2] O. Brüning et al. (eds.), LHC Design Report – Vol. I: The LHC Main Ring, CERN-2004-003, CERN, 2004.

12. Glossary

FEC: Front End Computer
FESA: Front End Software Architecture
PLC: Programmable Logic Controller
CCC: CERN Control Centre
SCADA: Supervisory Control And Data Acquisition