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Control of the MKQA tuning and aperture kickers of the LHC

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Summary

The large hadron collider (LHC) at CERN has been equipped with four fast pulsed kicker magnets in RA43 situated at point 4 which are part of the measurement system for the tune and the dynamic aperture of the LHC beam (Beam 1 and Beam 2). For the tune measurement 'Q', the magnets will excite oscillations in part of the beam. This is achieved by means of a generator producing a 5 µs base half-sine pulse of 1.2 kA [1] amplitude, superimposed with a 3rd harmonic to produce a 2 µs flat top. A kick repetition rate of 2 Hz will be possible. To measure the dynamic aperture 'A' of the LHC at different beam energies, the same magnets will also be driven by a more powerful generator which produces a 43 µs base half-sine current pulse of 3.8 kA. For the 'A' mode a thyristor is used as switching element inside the generator. A final third mode named 'AC dipole' will rely on the beam being excited coherently at a frequency close but outside its Eigen-frequencies by an oscillating dipole field. The beam is expected to oscillate at the exciter frequency of 3 kHz with a phase shift of π/2. The 'AC dipole' will use two 18 kW audio amplifiers capable of driving the magnets at 1 kHz(rms) around 3 kHz or between 2.7 kHz and 4 kHz. The complete system uses supervisory control implemented with Siemens PLC technology with added Siemens PROFIsafe safety feature to treat the various interlocks that have been introduced in the circuits and to assure a safe functioning and provide 'LOCAL' and 'REMOTE' control (via CCC) of the complete installation.

1. Tuning and dynamic aperture measurement with kickers

As reminder ‘Q’ denotes the tune function of the LHC accelerator and describes the particles trajectory oscillations during one revolution in the storage ring, these oscillations exist in transverse and longitudinal mode. Aperture ‘A’ or dynamic aperture is the maximum initial oscillation amplitude that guarantees stable particle motion over a given number of turns. The dynamic aperture 'A' which is the effective aperture for the beam after all the magnetic imperfections of the lattice have been taking in account is smaller than the physical aperture which is determined by the shape of the beam pipe and other physical obstacles such as collimators. The dynamic aperture is normally expressed in multiples of the RMS beam size (σ) and together with the associated number of turns. These are part of the LHC machine parameters linked to synchrotron beam dynamics which aid the machine physicist to setup the machine for optimum performance during operation and help determine the longitudinal and transverse dynamics of the beam. The MKQA kicker system will allow the measurement of tune and aperture via a standard excitation source (single kick, slow swept frequency). It will operate with all filling patterns and bunch intensities and be commissioned during the early start-up stages of LHC. The kicker approach will excite coherent oscillations in part of the beam with short kick pulses. The current specification calls for a 'Q' kicker generator [2] producing a maximum 9 µs base half-sine pulses with a superimposed 3rd harmonic which produces a square wave response. The length has been optimized to produce a kick onto 3x72 bunches with a limited disturbance on the neighboring batch. The dynamic aperture 'A' by kick method is based on a well know principle but may be hazardous at the 7 TeV LHC nominal energy as the damage limit could be approached or reached, even for a pilot bunch. This is why the dynamic aperture 'A' mode can only be true with LHC safe beam parameters and it was decided to increase the strength of the MKQA kickers to allow a possible maximum oscillation amplitude of 8 σ at 450 GeV (2σ at 7 TeV) whilst keeping a future upgrade to 7 TeV possible. This is the 'normal' way of measuring aperture by driving the beam to larger and larger amplitudes till it is lost. The problem with the LHC beam is it's 'rigidity' thus making it difficult to kick off its nominal trajectory due to its high momentum. The AC dipole principle uses the fact that the beam shows a large response to excitations at frequencies close to the tune and can generate large displacements in the LHC 'rigid' beam with relatively low power. Recent theoretical studies show the high potential of exciting a proton beam outside the Eigen-frequencies spectrum for the measurement of optic parameters (coupling, de-tuning and resonance driving terms). The principle is as follows: The beam is excited coherently at a frequency close but outside it's Eigen frequency by an oscillating magnetic field in a dipole magnet. Hence the name 'AC dipole' is given to the exciter system.

In the simplified model of a linear oscillator, the beam is expected to oscillate at the exciter frequency with a phase shift of π/2. The energy of the coherent oscillation does not couple with the incoherent oscillations of the individual beam particles and therefore there is no change in beam emittance. Inside the LHC, the revolution frequency is 11245 Hz. The fractional part of the tune is expected to be around 0.3 in both the horizontal and vertical planes. This means we can generate large transverse deviations in the beam if we power the dipoles with an oscillating frequency close to 3 kHz. A main advantage of an 'AC dipole' approach is that it causes virtually no emittance blow up in the beam so it can be reused many times over for different measurements if needed.

2. MKQA kicker magnets

The four magnets where built and designed on the basis of the design of the LHC beam dump system extraction kicker magnets. There are 2 units for horizontal deflection and 2 units for the vertical deflection which are orientated at 90˚. These are installed inside the point 4 of LHC in the RA43 between the Q5 and Q6 dipoles.

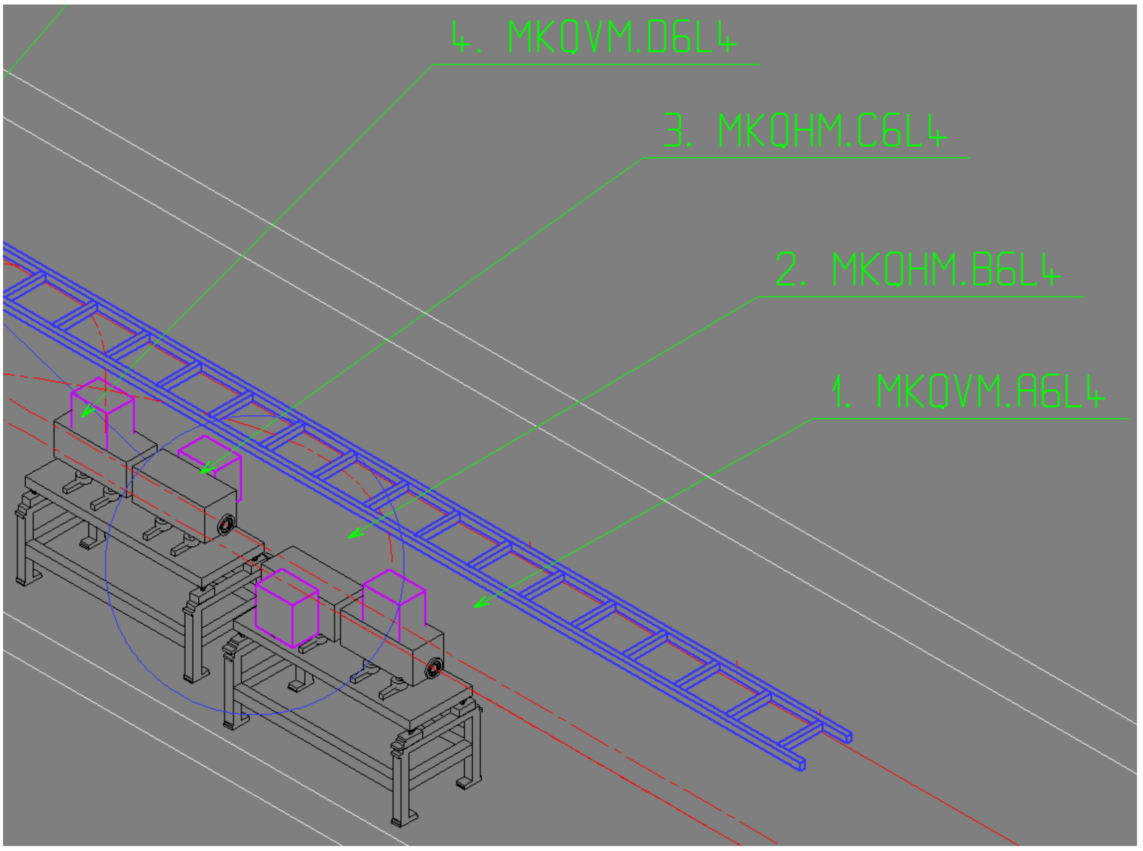

Figure 1 MKQA magnet tunnel position with corresponding nomenclature in RA43, point 4 LHC.

<u>MKQA RA43 magnet tunnel position configuration:</u>

- MKQVM.A6L4-> Beam 1 Vertical deflection.
- MKQHM.B6L4-> Beam 1 Horizontal deflection.
- MKQHM.C6L4-> Beam 2 Horizontal deflection.
- MKQVM.D6L4-> Beam 2 Vertical deflection.

Two magnets are installed on a support table for one ceramic chamber (1H and 1V). Each magnet has an entrance box (shown in red, fig.1) fed by 10 individual power cables + 1 spare (type CLP40). The entrance box is rectangular in shape, electrically isolated from the magnet and each have a protective cover. The 4 entrance boxes interconnect to the 4 generators that are situated in the adjacent UA43, which is where the control system for MKQA is installed [3].

The internal structure of the magnet is based around a stacked C core design. The internal coil is made of a single turn of solid copper to achieve a very low inductance. This has the advantage of guaranteeing a very fast response at the expense of requiring a large current to generate a strong magnetic field inside the beam pipe. The yoke of the magnet is made of stacked C cores, which are themselves made by winding 50 µm Si Fe tape for the toroid structure. By cutting out parts the C shape is achieved. The whole assembly can be split in half to allow easy mounting and dismounting without touching the beam pipe.

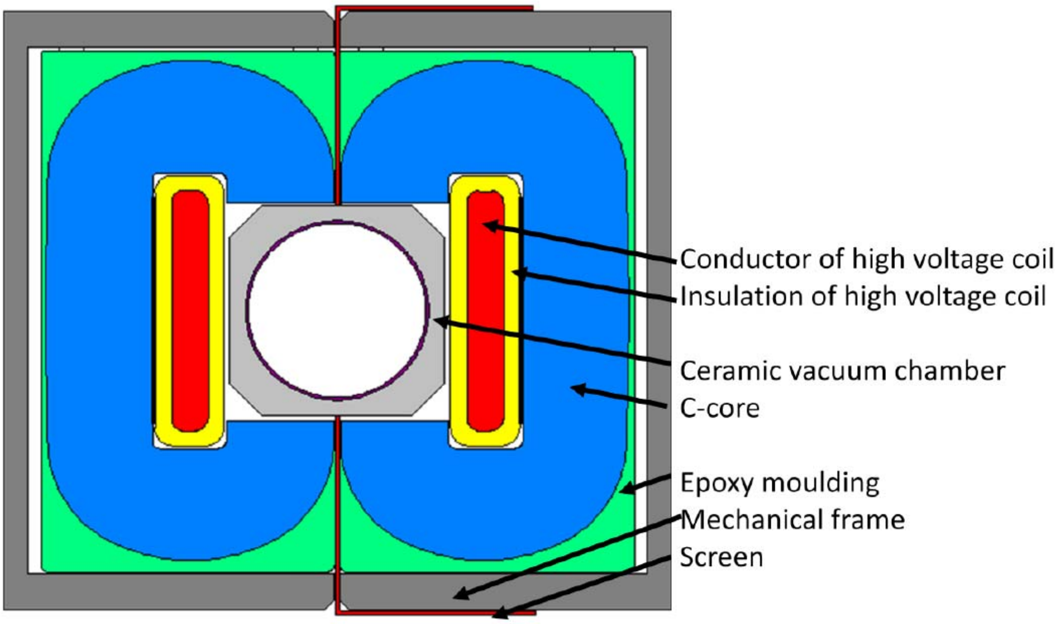

Figure 2 Side view cut of stacked C core magnet structure for the MKQA kickers

<u>Note: Each magnet is equipped with a Pearson pickup with the following characteristics:</u>
Pearson model 7546 output rated at 1mV/A +/-1 % into 50 Ohm; maximum 15As; output impedance 50 Ohms; usable rise time response 100ns; maximum droop rate 2 %/ms; low frequency +/-3dB cut-off 3 Hz; high frequency +/-3 dB cut-off 4 MHz.

3. MKQA HV generators

3.1 'Q' mode HV generator

The 'Q' kick generator is configured to produce a 5µs base half sine wave of 1.2 kA amplitude with a superimposed 3rd harmonic to render the pulse 'more square' and create a 2µs flat top, note that the total pulse response length is of the order of 9 µs. A kick repetition rate of 2 Hz during 20 minutes will be possible. The maximum beam oscillation amplitude corresponds to 0.41 σ at 7 TeV beam energy. The maximum generator voltage is 3.3 kV, with a dynamic range of around 20. A 5.2 kV WESTCODE press-pack capsule IGBT is used as switching element. There were several advantages of the press-pack IGBT construction with respect to conventional IGBT of which one is totally free from wire and solder bonds which helps to keep low the internal stray inductance on both the gate and emitter connections, these are small in comparison to conventional IGBT modules. The short circuit behavior is improved by the direct cooling on the emitter side of the chip. The IGBT is also equipped with an integral anti-parallel diode. A fast 30 A gate driver is used for triggering. The generator pulse current interruption is obtained with an extra-fast small recovery series diode. The IGBT has two power supply feeds, Q1 and Q2 power supplies (Heinziger PNCcap4000-10pos). Q1 is the generator full voltage and Q2 produces a pre-bias voltage to condition the turn-on characteristics of the IGBT. In laboratory conditions, 6.3 kA/µs dI/dt was achieved with a 200 ns turn-on delay. Careful adjustment of the Q2 voltage changes the turn on characteristic of the IGBT before firing, 10 kA/µs can be achieved. The superimposed 3rd harmonic is taken from a free-wheel diode that feeds back to the generator the negative baseline over damped peak of the pulse response.

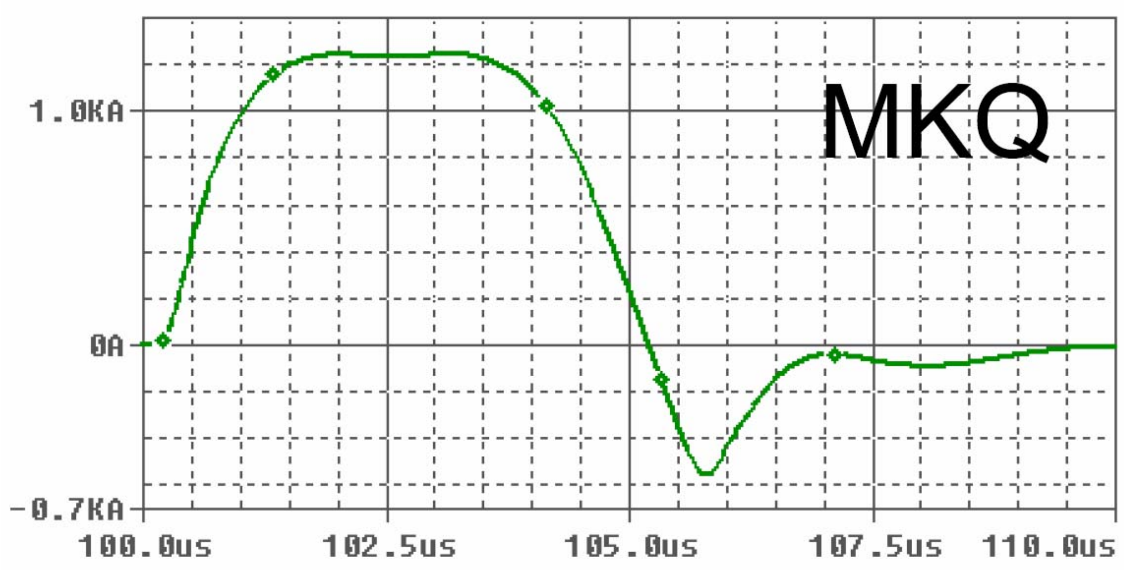

Figure 3 MKQA 'Q' generator pulse output (PSpice circuit simulation)

3.2 'A' mode HV generator

To measure the dynamic aperture of the LHC in the horizontal and vertical plane at different beam energies, the same magnets will also be driven by a more powerful generator which produces a 43 µs (1/2 turn of LHC) base half-sine current pulse of 3.8 kA which corresponds to a maximum beam oscillation of 1.4 σ at 7 TeV. The maximum generator voltage is 890 V and the dynamic range of this system is about 10. A fast 2 kV thyristor is used as switching element. The slow kick repetition rate is 10 minutes. For reliability reasons, AVX self-healing type capacitors are employed in both generators. Various interlocks have been introduced in the circuits to assure a safe functioning and rely on Siemens PROFIsafe modules for monitoring of safe parameters.

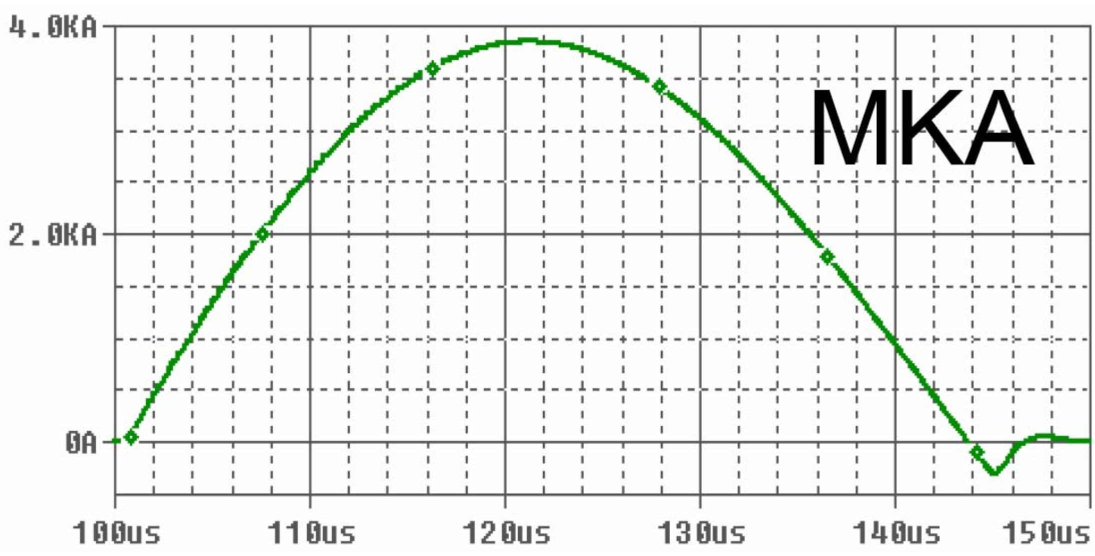

Figure 4 MKQA 'A' generator pulse output (PSpice circuit simulation)

Table 1

Comparative table of 'Q' and 'A' mode beam parameters for the LHC machine

MKQA system	Tune (Q)	Dynamic Aperture (A)
Magnet current pulse type	half sine + 3rd harmonic	half-sine
Duration	5.1 µs	43 µs
Pulse repetition rate	2 Hz for 20 minutes	1 pulse for 10 minutes
Oscillation amplitude 450 GeV 7 TeV	 1.62 σ 0.41 σ	 5.0 σ 1.4 σ
Max.generator current	1.2 kA	3.8 kA
Max. generator voltage	3.3 kV	890 V

3.3 Q' mode HV generator hardware

The 'Q' generator has a basic arrangement using one IGBT with a series WESTCODE blocking diode to setup initial dynamic conditions onto the IGBT gate via the Q2 power supply (typ. 1.5 kV/DC min). Q1 sets the operating voltage of the generator (typical range of 300 V-3.5 kV). Each generator is equipped with analogue d'Arsonval movement meters on their front panel to indicate the capacitor charging voltage. Read back of the HV dividers on Q1 and Q2 is acquired through the analogue acquisition system via PLC I/O's. A capacitor bank is charged up and due to voltage inversion during the characteristic 'Q' mode pulse, a free-wheel diode system recuperates the energy from the 3rd harmonic and injects it back into the system. The generator is equipped with a manual earthing switch system to safely ground the capacitor bank when the generator is not in use and also and electrical earthing switch which is automatic. When the 'Q' mode is selected, the capacitor bank is switched onto the HV circuit via a final Ross relay which closes the complete HV circuit. The IGBT is triggered through a trigger circuit which receives a signal coupled via a fibre optic link from a driver circuit placed before it.

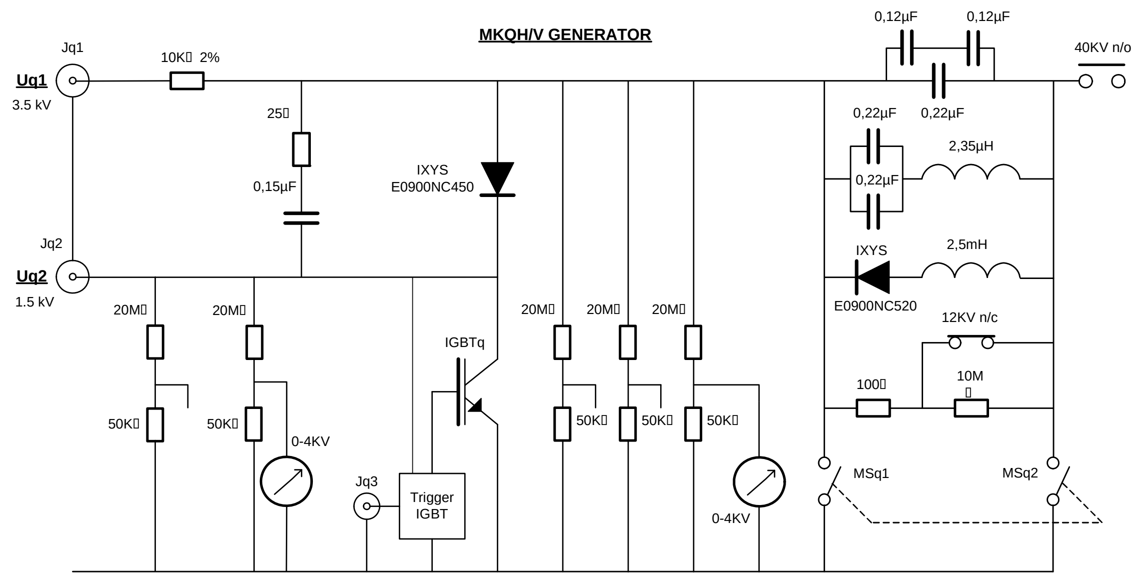

Figure 5 Simplified electronic layout of the 'Q' generator

3.4 'A' mode HV generator hardware

The 'A' generator has a basic arrangement with one thyristor power switch. Ua1 sets the operating voltage of the generator (Heinziger PNCcap1000-10pos). The generator is equipped with an analogue d'Arsonval movement meter on the front panel to indicate the voltage of the main charging capacitor. Read back of the HV dividers of Ua1 is acquired through the analogue acquisition system via PLC I/O's. Multiple capacitors are charged up (13x6 µF & 2 µF) and due to the voltage inversion of the characteristic half-sine 'A' mode pulse of 43 us, a free-wheel system recuperates the energy from the capacitor and injects it back into the system.

The generator is equipped with a manual earthing switch system to safely ground the capacitor when the generator is not in use and also and electrical earthing switch which is automatic. Finally the capacitor bank is switched onto the HV circuit via a Ross relay which closes the complete HV circuit. The thyristor is triggered through a galvanically coupled trigger circuit.

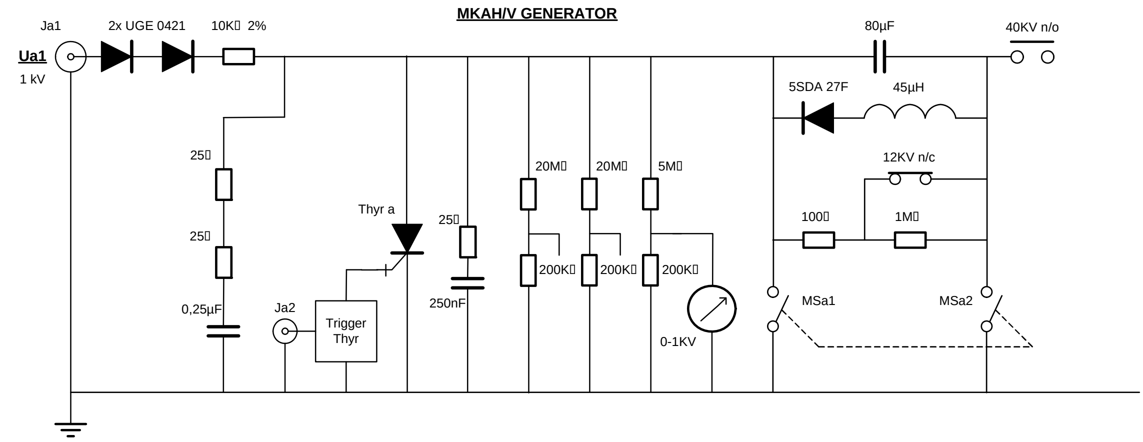

Figure 6 Simplified electronic layout of the 'A' generator

3.5 'AC dipole' mode generator & hardware

The 'AC dipole' generator will be used for tune and aperture measurement purposes but will also be used for measuring the β function and other beam optics parameters. The technology used is derived from a commercially available high power audio amplifier. This system is fitted below the 'Q' and 'A' generator electronics due to the fact it came as an 'after-thought' and as a complementary idea to the existing MKQA hardware. The amplifier used is a DIGAM Powersoft K20 DSP [4] and is located at the bottom right inferior part of the 'Q' and 'A' generator housing. An independent power distribution system solely for the AC dipole system had to be implemented due to the design coming after the conception of 'Q' and 'A' generators. An integrative approach for the slow control of the system allows the 'AC dipole' mode to be partially controlled via the same PLC interface as the 'Q' and 'A' generators so it is controlled in a similar way except for generator parameter settings and timing control. The 'AC dipole' amplifier adjunction required an added 'Ross' relay inside the generator housing to switch it into the generator circuit and isolate it from the other modes ('Q' & 'A' modes respectively).

Requirements for the integration of 'AC dipole' with MKQA where:

- Connector logistics.
- AC dipole amplifier presence safety switches.
- Mechanical modifications.
- Partial control.
- Amplifier interlocking.
- Additional hardware channels for the PLC I/O's.
- Modifications to certain cables and patch panels.
- A basic assumption of machine protection for the operation of the 'AC dipole' based around a similar logic as the MKQA system.

The 'AC dipole' amplifier choice was based around the following criteria's:

- Immediate availability.
- Small budget.
- Rugged construction.
- High Power (2x18 kW).
- Good match to the frequency range.
- Proven technology.

The design of the 'AC dipole' amplifier started with the calculation of the integrated field strength inside the magnet chamber necessary to generate a transverse displacement Δz using an AC dipole generator, these are:

Bl(max) = 17.5 mT.m is achievable with I(max) = 1700 A (Ipk) and **I(rms)** = 1200 A rms

These quantities equate to driving a conservative value of 1000 A(rms) at 3 kHz into the magnets. An exciter frequency of 3 kHz precludes using a superconducting magnet or a steel magnet which was to inductive to be driven with the AC dipole system. To be able to drive 1000 A(rms) in the magnet with two 18 kW audio amplifiers, the AC dipole generator takes the advantage of a parallel resonant circuit. To create the resonant circuit, a capacitor bank is placed in parallel with the magnet. This capacitor bank is located between the audio power amplifiers and the "Ross" relay, in order not to conflict with the others generators (MKQ/A). Due to differences in beam characteristic in the horizontal and vertical axis, resonance frequencies for vertical and horizontal deflection generators are slightly different: 3148 kHz for the horizontal and 3485 kHz for the vertical. Therefore, there are two capacitor bank configurations (Bulk+bit4+bit3 for horizontal generators and bulk+bit3+bit2 for vertical generators).

In order to achieve the required nominal current in the magnet, two amplifiers are used per generator. The amplifier's outputs are connected in series trough two transformers (see fig.7). The transformers are not only used to connect the amplifiers in series, but also to match impedance seen by each of them. The DIGAM K20 DSP from Powersoft can deliver its maximal power of 18 kW into a 4 Ω load. Thus the turn ratio of the transformers is 4:1. To obtain as much current as possible in the RLC circuit, the amplifier are configured in "bridge mode". This means that each stereo channel of the amplifier takes the same input signal, but one of them is phase shifted by 180 degrees. Then the output of each channel is connected to the load. Doing so, the output voltage is doubled.

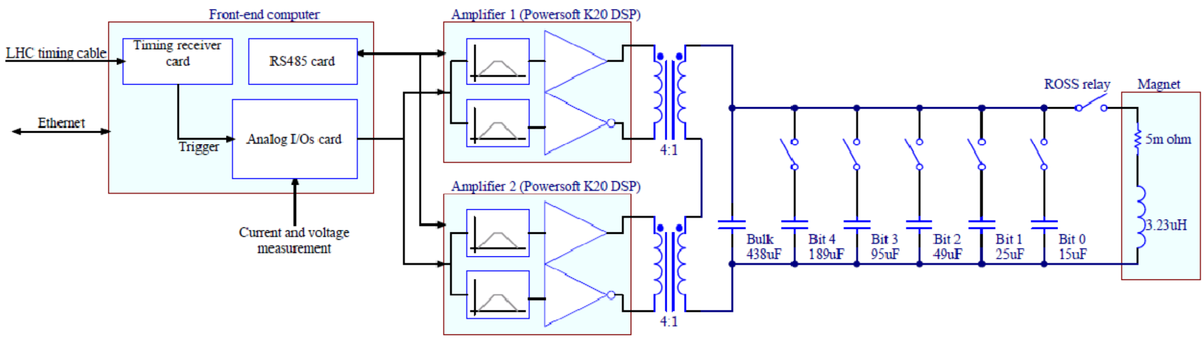

Figure 7 AC dipole generator layout

4. MKQA system control hardware

The complete MKQA system hardware and control is placed in the adjacent UA43 tunnel, parallel to the RA43 section that contains the 4 MKQA magnets. The complete row of rack cabinets and generators are placed onto a copper ground strip to guarantee a good earth connection and thus reducing potential earth loops. The basic layout is depicted in fig.8:

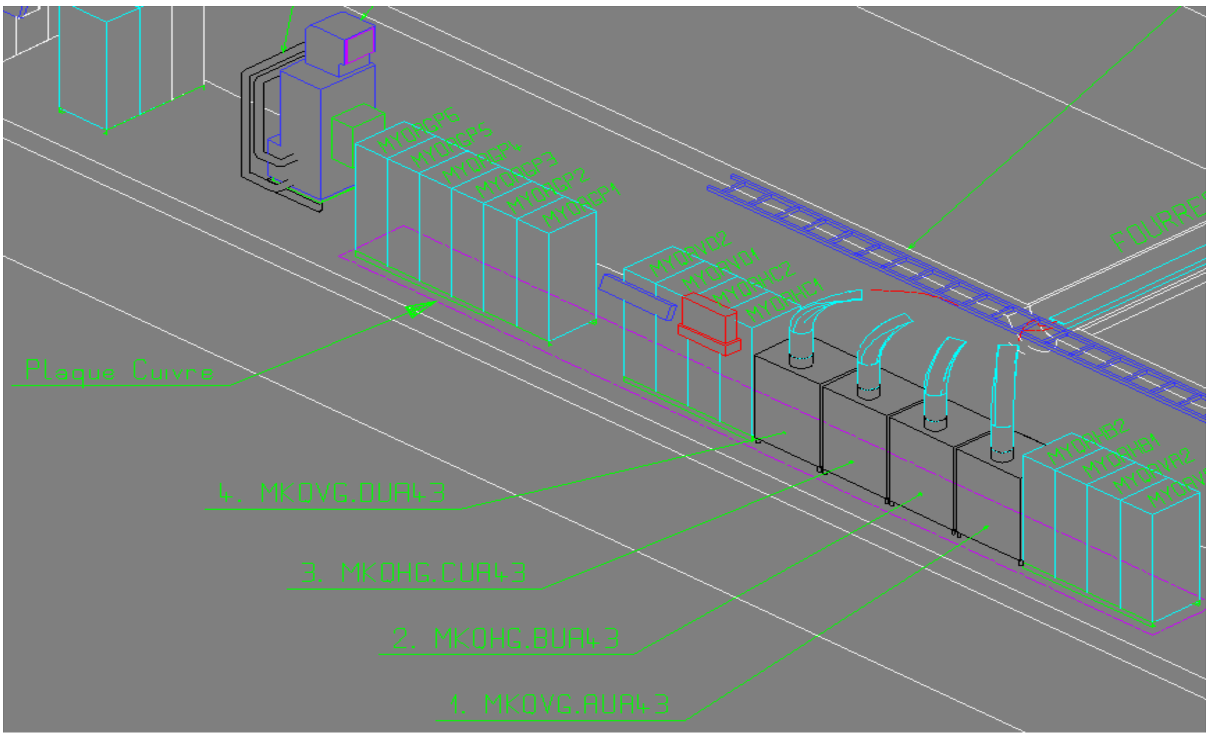

Figure 8 View of the MKQA generators and control hardware inside the UA43 gallery

The system comprises the following equipment:

4 Kicker generators containing a subset of modes, 'Q' mode, 'A' mode, 'AC dipole' mode:

- MKQVG.AUA43 coupled to magnet MKQVM.A6L4-> Beam 1 Vertical deflection.
- MKQHG.BUA43 coupled to magnet MKQHM.B6L4-> Beam 1 Horizontal deflection.
- MKQHG.CUA43 coupled to magnet MKQHM.C6L4-> Beam 2 Horizontal deflection.
- MKQVG.DUA43 coupled to magnet MKQVM.D6L4-> Beam 2 Vertical deflection.

Generator control racks containing the generator PLC controllers, power supplies and generator trigger systems:

- MYQAVA1 contains the trigger system for MKQVG.AUA43.
- MYQAVA2 contains PLC controllers and power supplies for MKQVG.AUA43.
- MYQAHB1 contains the trigger system for MKQHG.BUA43.
- MYQAHB2 contains PLC controllers and power supplies for MKQHG.BUA43.
- MYQAHC1 contains the trigger system for MKQHG.CUA43.
- MYQAHC2 contains PLC controllers and power supplies for MKQHG.CUA43.
- MYQAVD1 contains the trigger system for MKQVG.DUA43.
- MYQAVD2 contains PLC controllers and power supplies for MKQVG.DUA43.

Control racks containing the power distribution, system timing distribution, measurements systems, computer hardware, external systems are:

- MYQAGP1 -> Power Distributor Controller (PDC).
- MYQAGP2 -> Operator touch panel for LOCAL control, PLC master controller, patch panels.
- MYQAGP3 -> Timing modules for pulse production, Front-End VME control crate.
- MYQAGP4 -> Timing modules for pulse production, CIBU system, Front-End compact PCI.
- MYQAGP5 -> LOCAL/REMOTE hardware, computer.
- MYQAGP6 -> Oscilloscope, signal distributor.

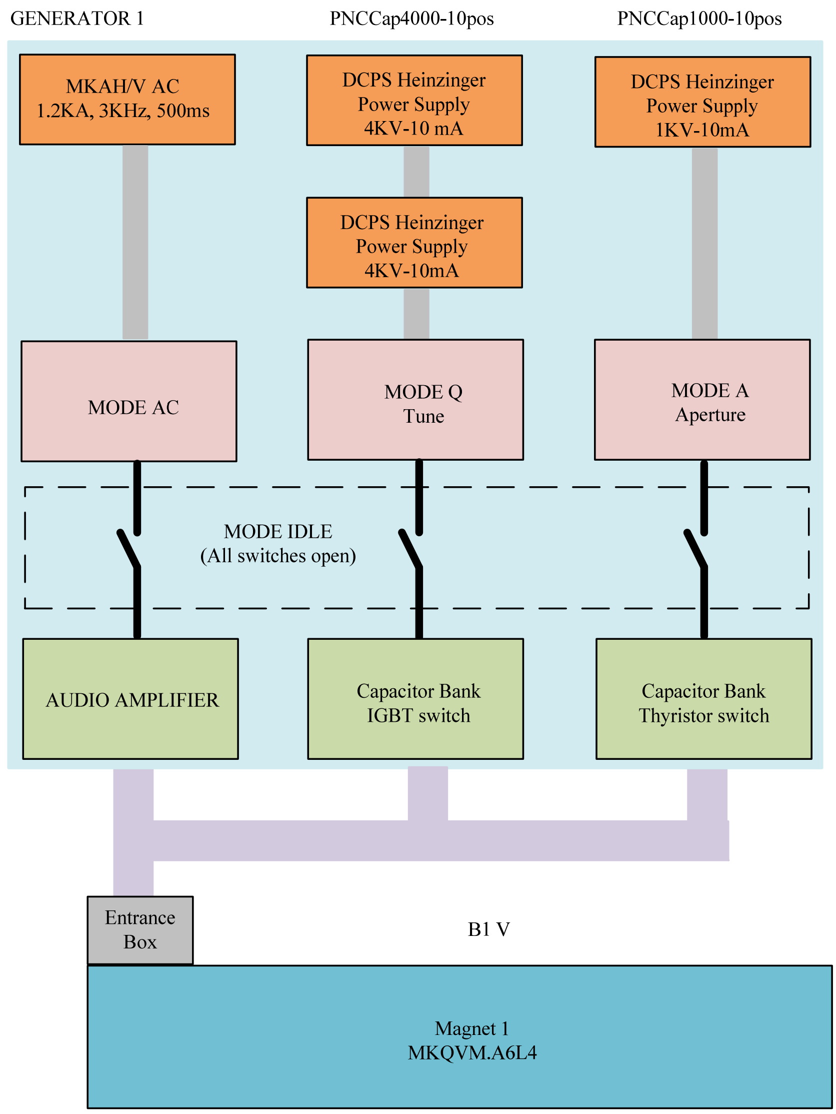

Figure 9 Block diagram representing the MKQA power system layout (the system shown is Beam1 Vertical only)

4.1 MKQA detailed rack equipment description

The following section explains in detail the different elements of the control system. Fig.10 displays the general control system racks with its individual elements referenced:

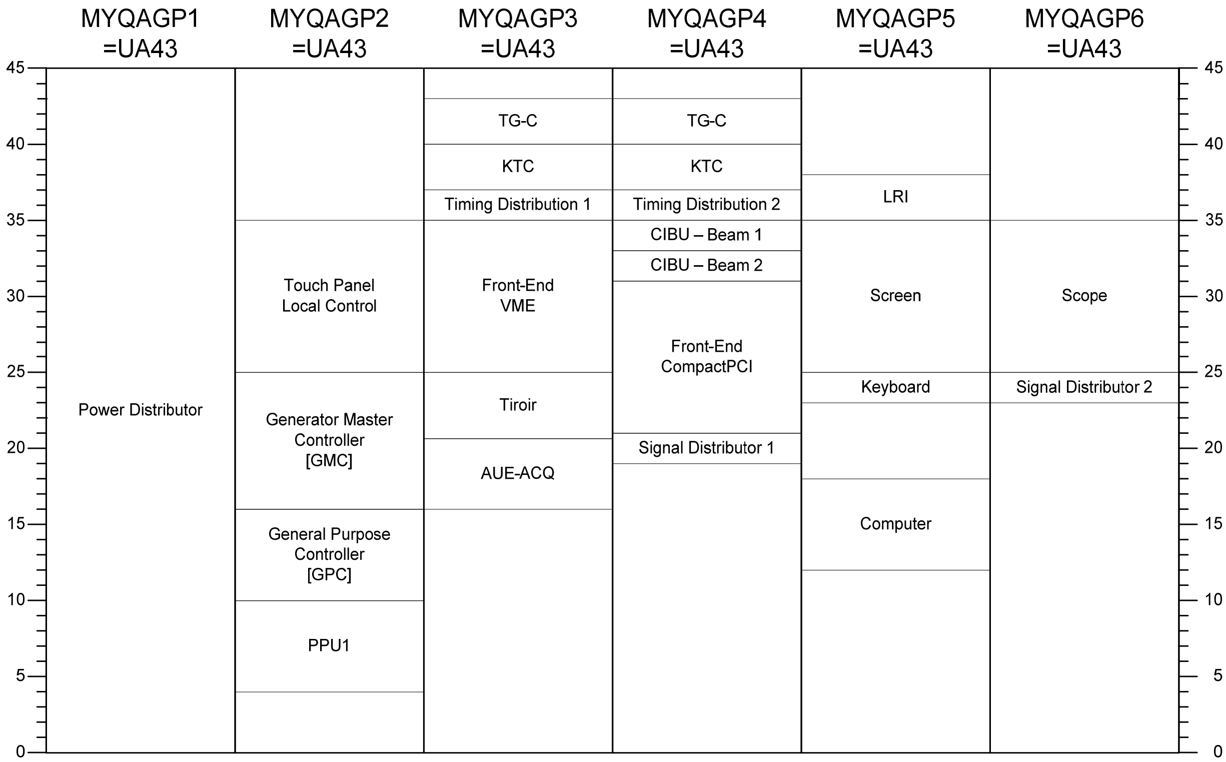

Figure 10 Rack equipment layout of MKQA control system

- **RACK MYQAGP6 content:**

-One Lecroy oscilloscope Wave surfer 434 which allows in-situ surveillance of the signal pulses coming from the generator and magnets.
-A signal distributor panel (SD2) that routes the magnet Pearson pickups signals to the oscilloscope and also the timing prepulse signals.

- **RACK MYQAGP5 content:**

-L/R (LOCAL/REMOTE) module. This is where the LOCAL/REMOTE controller is, this action is initiated by turning a hardware switch into the desired position.
-COMPUTER SYSTEM (CWE-UA43-PC). This computer serves multiple purposes and is on the CERN TN (Trusted Network) domain. The most common use for this machine is the running of FESA applications, OASIS system check and Web navigator Wincc V7.0 SCADA.

- **RACK MYQAGP4 content:**

-Contains the TG-C modules for LOCAL timing distribution of the system prepulse, (HB2 and VB2 only), the same modules also generate the complex REMOTE timing produced via external triggering.
-The CIBU beam interlocking system from the AB/CO group.
-A compact PCi front-end containing the acquisition cards (DC265, 500MS/s, 150 Mhz) for the OASIS remote viewing system.

- **RACK MYQAGP3 content:**

-Contains the TG-C modules for LOCAL timing distribution of the system prepulse, (HB1 and VB1 only), the same modules also generate the REMOTE timing produced via external triggering.

-The AUE chassis that manages the emergency STOPS of the system.

-The FEC (CFV-UA43-MKQATIM) with VME bus backplane containing the following set of electronic cards:

- System CPU.
- RF/RXO electronic card, RF signal (Circulating beam 1 & 2) via optical link and output to ECL format.
- PCV card, this receives the ECL signal of the circulating beam 1&2 and converts it to LVTTL which then goes into the V850 digital delay cards.
- V850 Digital delay cards (2 of), allows adjustment of prepulse trigger with respect to beam synchronization.
- CTRV (4 of). These cards distribute the timing triggers to the MKQA which are synchronized to the circulating beam signals.

- **RACK MYQAGP2 content:**

- One touch panel screen (OP370 Siemens) for local manual operator control of the installation containing the SCADA for the supervisory software system (WinCC flexible).

-The Generator Master Controller PLC system (GMC), which contains the master CPU unit and associated modules and is also the main controller for the deported I/O's.

- The General Purpose Controller chassis (GPC) interfacing the acquisitions and controls of signals that are common to all four generators.

- **RACK MYQAGP1 content:**

-PDC (Power Distributor Controller), contains the low voltage distribution system derived from a CERN standard 380 V/AC mains arrival.

4.2 MKQA generators control racks

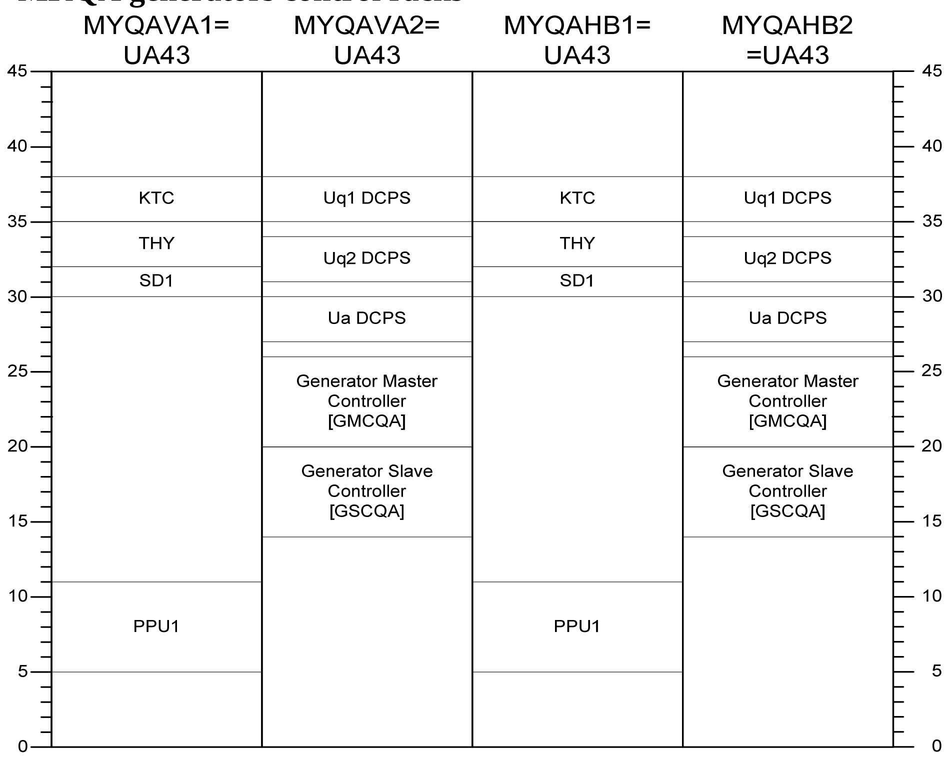

Figure 11 Rack equipment layout of generator control

Note: We shall only treat MYQAVA1 and MYQAVA2 since these are replicated three more times for the other generators, MYQAHB1, MYQAHB2, MYQAHC1, MYQAHC2, MYQAVD1, MYQAVD2.

- **RACK MYQAVA1 content:**

-KTC: IGBT trigger system (EDA-01733), this system receives the trigger pulse for the 'Q' mode generator and it's output is routed via optic fibre to the IGBT trigger card inside the generator.
-THY: thyristor trigger system, (SPS 5069-14), this system receives the trigger for the 'A' mode generator and outputs it galvanically to the thyristor driver card inside the generator housing.
-SD1: (Signal distribution patch panel).
-PPU1: (Controller patch panel).

- **RACK MYQAVA2 content:**

-Uq1 DCPS Heinzinger PNCcap4000-10pos power supply for Uq1 voltage control.
-Uq2 DCPS Heinzinger PNCcap4000-10pos power supply for Uq2 voltage control.
-Ua DCPS Heinzinger PNCcap1000-10pos power supply for Ua voltage control.
-GMCQA (Generator Master Controller) Siemens I/O's that controls the power supply.
-GSCQA (Generator Slave Controller) based on Siemens Profisafe I/O's that controls the generator various interlocks.

4.3 The CIBU system

The CIBU (Controls Interlocks Beam User) [5] is a sub system of the Beam Interlock System (BIS). This was conceived and designed for the LHC machine protection scheme. The BIS meets the SIL3 safety standard. The CIBU system is a unique user interface that allows for BEAM permit according to certain conditions constrained to it. The CIBU has two configurations, CIBUS for single beam and CIBUD for double beam connection. To meet the stringent SIL3 requirements the system is completely redundant and it is achieved by 2 separate channels (named 'A' and 'B'). Two separate BEAM_PERMIT inputs are required from the user system, these are labeled 'USER_PERMIT A' and 'USER_PERMIT B' and these are connected to separated isolated pieces of hardware controller.

4.4 Interlocking the LHC beam with the MKQA system

The aim for the Beam Interlock System is to generate BEAM_PERMIT signals for the two LHC circulating beams. Here are the basic conditions:

When BEAM_PERMIT is TRUE, the beam can circulate and when BEAM_PERMIT is FALSE, a beam cannot circulate. During a BEAM_PERMIT transition (TRUE to FALSE), a beam dump is done. In the LHC, the CIBU's role is to take the two USER_PERMIT signals and transmit them to the nearest Beam Interlock Controller in a safe and reliable manner; in return the 'Users' receive a BEAM_PERMIT_STATUS giving an indication of the availability of the whole LHC machine for beam operation.

The MKQA system has the following logic with the BIS:

- 'Q' mode in REMOTE = BEAM PERMIT always TRUE
- 'A' mode in REMOTE = BEAM PERMIT always FALSE
- 'AC dipole' mode in REMOTE = BEAM PERMIT always FALSE
- 'Q', 'A' and 'AC dipole' in LOCAL mode = BEAM PERMIT FALSE

The MKQA system follows these set of rules for interlocking the BIS CIBU system with the LHC beam (this is summarized in table 2 and 3):

Table 2

BEAM1 BIS configuration for MKQA

MKQA BEAM1	**Beam mode**	**Beam permit status**
MKQA REMOTE	Safe-beam	No LHC beam permit
AC dipole REMOTE	Safe-beam	No LHC beam permit
MKQ REMOTE	LHC beam	Beam permit OK
MKQA LOCAL	No beam	No LHC beam permit
AC dipole LOCAL	No beam	No LHC beam permit
MKQ LOCAL	No beam	No LHC beam permit

Table 3

BEAM2 BIS configuration for MKQA

MKQA BEAM2	**Beam mode**	**Beam permit status**
MKQA REMOTE	Safe-beam	No LHC beam permit
AC dipole REMOTE	Safe-beam	No LHC beam permit
MKQ REMOTE	LHC beam	Beam permit OK
MKQA LOCAL	No beam	No LHC beam permit
AC dipole LOCAL	No beam	No LHC beam permit
MKQ LOCAL	No beam	No LHC beam permit

Note: Safe-beam can me masked from the CCC when required via the safe machine parameters. In ‘AC dipole’ and ‘A Mode’ BEAM PERMIT can be masked within the Machine Protection System under SafeBeam flag conditions.

When MKQA is in 'Aperture' or 'AC dipole mode', the machine can only inject a safe-beam (i.e. low intensity pilot bunch). It is considered far too risky and dangerous to use these modes at full amplitude LHC beam (7 Tev). However in 'Q' mode full LHC beam will be allowed. For safety reasons, when the installation is in 'LOCAL' mode for test purposes, no beam can circulate into the machine and hence no beam injection.

4.5 KEY mode selector chassis

When the MKQA is set in 'LOCAL' mode, the system user can choose and select the operating mode of the installation via the operator console, these modes are the 'Q', 'A' and 'AC' dipole mode and a fourth mode named 'IDLE' (All mode selection switches are open, hence MKQA does not operate). For 'REMOTE' operation of these modes, a specific PLC based chassis located in the CCR allows an operator to select the MKQA functional modes via a key switch system. Depending on which selection the key switch is set, a diode indicates which mode is selected.

Figure 12 Frontal view of Key mode selector chassis

This system was devised to be a safe and secure way of selecting operating modes for the MKQA kickers in 'REMOTE' mode.

Diode codes are the following:

- Aperture -> ORANGE
- Tune -> GREEN
- AC dipole -> BLUE

5. MKQA power distribution system

The power distribution system for the MKQA installation is split into two main sections, one is fully dedicated towards powering the 'Q' and 'A' mode of the installation and the other is dedicated to managing the 'AC dipole' equipment. The power distribution system relies on two essential components, low voltage electrical distribution equipment and PLC modules for control purposes. Once grouped, these entities form the PDC (Power Distributor Controller). Both systems are housed inside rack MYQAGP1 of the UA43.

5.1 PDC for 'Q' and 'A' mode generator

The PDC for 'Q' and 'A' generators has the following set of design parameters:

Table 4

Design parameters for the MKQA power distribution.

Components	**Intensity**	**Power**
	A/Mono	**kVA**
Generator1 / Q20	3.12	0.75
Generator2 / Q21	3.12	0.75
Generator3 / Q23	3.12	0.75
Generator4 / Q24	3.12	0.75
AUX1 / Q30	3	0.7
AUX2 / Q31	3	0.7
AUX3 / Q32	3	0.7
AUX4 / Q33	3	0.7
AUX5/Q45	3	0.7
AUX6/Q46	3	0.7
AUX7/Q47	3	0.7
AUX8/Q48	3	0.7
Total	36.48	8.6

A worst case figure of 36.48 A and 8.6 kVA was obtained which determined the selection of the PDC low voltage components.

5.2 PDC hardware components layout for 'Q' and 'A' mode generator

The low power system (400 V/ac max.) is derived from the EDB1/43 (Q135) EN/EL electrical distribution (3x400 V + N + PE) rated at 10 kVA.

The PDC components are the following:

Table *5*

The PDC component table for MKQA

Name	Description	Reference
Q10	400 V , 4 poles, 50 A, C curve	General circuit breaker
F20	Phase Detector	
F21	Trigger by voltage loss 24V	
SD10	Circuit breaker status	
CA10	Circuit breaker status + Fault detection	
Q1	1 pole, 230 V, 20 A	UPS system circuit breaker
Q20	10 A, 2 pole, NO	Generator 1 circuit breaker
Q21	10 A, 2 pole, NO	Generator 2 circuit breaker
Q22	10 A, 2 pole, NO	Generator 3 circuit breaker
Q23	10 A, 2 pole, NO	Generator 4 circuit breaker
SD20	Circuit breaker status	
SD21	Circuit breaker status	
SD22	Circuit breaker status	
SD23	Circuit breaker status	
K20	Contactor	Generator 1 contactor
K21	Contactor	Generator 2 contactor
K22	Contactor	Generator 3 contactor
K23	Contactor	Generator 4 contactor
CA20	Contactor status	
CA21	Contactor status	
CA22	Contactor status	
CA23	Contactor status	
Q5	AC, 2 pole, 2A, C curve	AC distribution circuit breaker
SD50	Circuit breaker status	
Q30	10 A, 2 pole, NO	Auxiliary circuit breaker
Q31	10 A, 2 pole, NO	Auxiliary circuit breaker
Q32	10 A, 2 pole, NO	Auxiliary circuit breaker
Q33	10 A, 2 pole, NO	Auxiliary circuit breaker
SD41	Circuit breaker status	
SD42	Circuit breaker status	
SD43	Circuit breaker status	
SD44	Circuit breaker status	
Q45	10 A, 2 pole, NO	Auxiliary circuit breaker
Q46	10 A, 2 pole, NO	Auxiliary circuit breaker
Q47	10 A, 2 pole, NO	Auxiliary circuit breaker
Q48	10 A, 2 pole, NO	Auxiliary circuit breaker
SD45	Circuit breaker status	
SD46	Circuit breaker status	
SD47	Circuit breaker status	
SD48	Circuit breaker status	

The PDC is equipped with PLC control which fulfils the following functions:

PLC commands	PLC acquisitions
K20	F20
K21	SD10
K22	SD20
K23	SD21
	SD22
	SD23

Here is a view showing the 'Q' and 'A' PDC system topology with its front mounted low voltage distribution components:

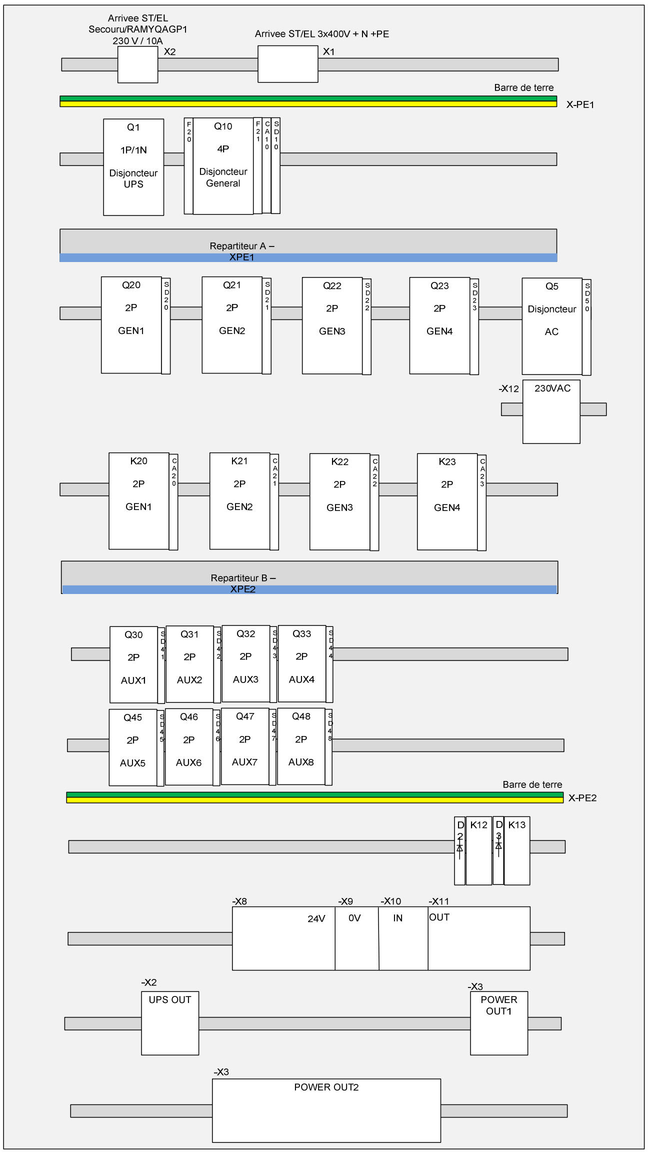

Figure 13 PDC (Power Distribution Controller) simplified block view of frontal components

The inner panel of the PDC frontal view is covered and protected with vitronite type plates for safety reasons (no hand of metallic object can find it's way on live terminals). The K12 and K13 relays are there for driving the ON/OFF status lights on the front of the PDC rack door. The PDC rear fixture contains all the PLC hardware that controls the PDC functionalities. Below the PLC distributed I/O's is mounted the 'AC dipole' PDC unit.

5.3 PDC hardware layout for AC dipole mode generator

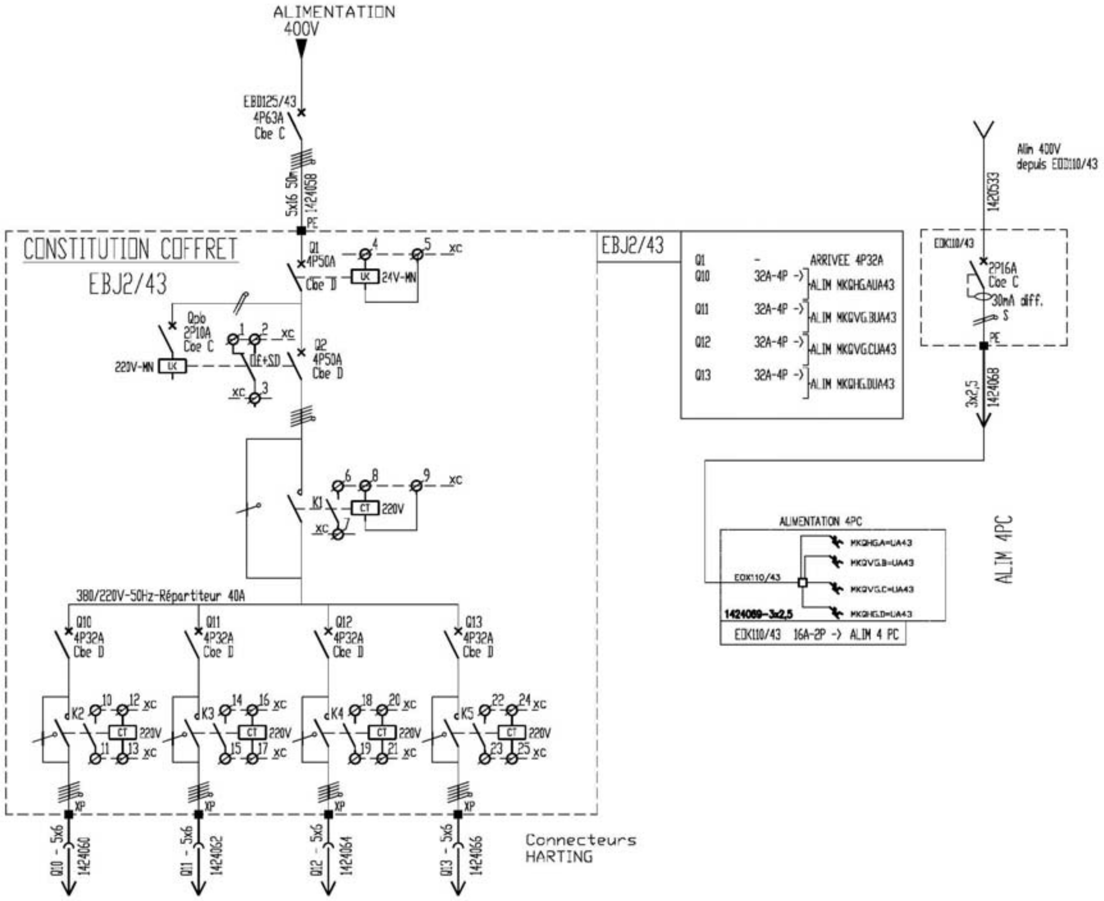

Figure 14 AC dipole power distribution schematic

Table *6*

AC dipole power distribution elements

1	Q1	Main circuit breaker + MN 24V	D32A 4P + MN 24V	Legrand
2	QPb	Circuit breaker inductor protection MN pos. 3	C60N C10A 2P	Merlin Gerin
3	Q2	Circuit breaker " triggered by loss of network voltage" + OF + MN 230V	C60N D32A 4P + OF + MN 230V	Merlin Gerin
4	K1	Contactor "consignation dipoles"	LC1-D32M7	Télémécanique
5	K2	Contactor "dipoles power GEN MKQHG.AUA43 "	LC1-D32M7	Télémécanique
6	K3	Contactor "dipoles power GEN MKQVG.BUA43 "	LC1-D32M7	Télémécanique
7	K4	Contactor "dipoles power GEN MKQVG.CUA43 "	LC1-D32M7	Télémécanique
8	K5	Contactor "dipoles power GEN MKQHG.DUA43 "	LC1-D32M7	Télémécanique
9	Q10	Amplifier power MKQHG.AUA43	C60N D32A 4P	Merlin Gerin
10	Q11	Amplifier power MKQVG.BUA43	C60N D32A 4P	Merlin Gerin
11	Q12	Amplifier power MKQVG.CUA43	C60N D32A 4P	Merlin Gerin
12	Q13	Amplifier power MKQHG.DUA43	C60N D32A 4P	Merlin Gerin

The AC dipole PDC is interfaced with the 'Q' and 'A' PLC control which fulfils the following functions:

Table 7

AC dipole PDC commands and acquisitions

DEVICE	PLC command	PLC acquisitions	Hardware control
K1	No	No	K1 is controlled by the Q10 action of the Q and A PDC system
K2	Yes	Yes	
K3	Yes	Yes	
K4	Yes	Yes	
K5	Yes	Yes	
Q1	No	No	Q1 is controlled by AUL action
Q2	no	Yes	

6. Siemens PLC distributed system for the MKQA generator control

The complete installation state control is implemented using SIEMENS automation systems for slow control. The PLC's are based around the Simatic technology and the PROFIsafe technology. The master CPU is a SIEMENS S7-400 master Programmable Logic Controller (PLC) which is linked via two groups of PROFIBUS-DP segments to the various equipment controllers. The equipment controllers are connected as deported I/O’s. The master PLC has also a TCP/IP connection for communication with the various control applicative layers (FESA, Web Navigator WinCC).

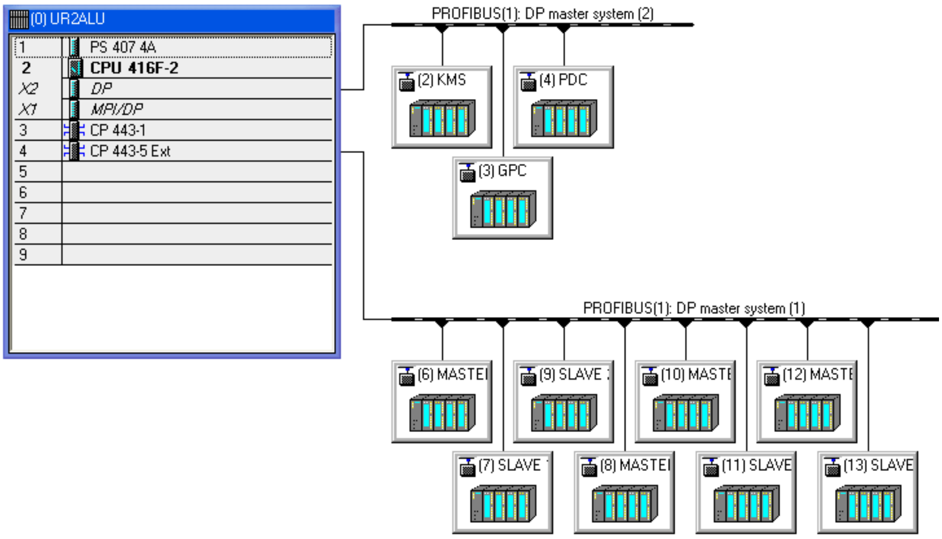

Figure 15 MKQA PLC hardware block diagram with distributed I/O's

Table 8

MKQA PLC châssis description

MASTER chassis UR2ALU	This is the master CPU controller for the complete system (with PROFIsafe features), it is combined with a TCP/IP communication module for REMOTE operation of the installation.
KMS (Key Mode Selector)	The KMS is a chassis that is housed in the CCR and allows generator mode selection when the system is in REMOTE configuration. The system is coupled to its Profibus by an optical fibre link in mono-mode due to a lengthy communication distance (approx.6.3 km).
PDC (Power Distribution Controller)	These are the controllers that manage the low voltage electrical distribution system.
GPC (General Purpose Controller)	The GPC controls all the system parameters common to all four generators, these are: -Timing ON status -Locale/Remote status -Beam permit status -Emergency buttons acquisitions (AUE) -Magnet temperature
MASTER (4 of)	The master manages the generator parameters such as: -HV 'ON' status -U mon and I mon acquisitions -Uref and Iref outputs -HV 'ON' command
SLAVE (4 of)	The slave manages a subset of generator signals and these are integrated within the PROFIsafe framework for added safety feature, these are: -Electrical discharge switch, manual earthing switch status -Rack door status - HV cable presence status -AC dipole 'ON' status and thermal interlock -Operational switch status -Voltage acquisition -Operational switch and electrical discharge switch command

6.1 The PROFIsafe distributed I/O's

The SLAVE chassis and MASTER F-CPU incorporates the SIEMENS PROFIsafe technology for industrial safety compliance. The choice was orientated towards safety critical signals.

These components respect the EN 61508 norms and SIL3 standard. PROFIsafe components encompass the following principles:

1) First communication standard according to safety standard IEC61508
2) The PROFIsafe profile supports safe communication for the open standard industrial buses PROFIBUS and PROFINET.
3) The PROFIsafe profile is designed to prevent the potential faults such as address errors, delays and the loss of data by the consecutive numbering of the PROFIsafe data, watchdog technique, authentification by unique address with additional CRC protection.

PROFIsafe faces the possibilities of errors at the message transfer level such as falsification of the addresses, data loss, delay, and more. Between a fail safe CPU (F-CPU) and a fail-safe slave (F-Slave) status and control information's are exchanged next to the used data. The F-slave is able to report incorrect telegrams to the F-CPU. F I/O data consists of the following series of data segments, one byte is allocated for user data, the next byte is the sequence number, then a byte with a 2 byte or 4 byte CRC makes up the complete telegram which can be up to 122 bytes long. Each message sent out has a reply frame with consecutive numbering and CRC check which ensures the level of safety into the data transmission. The program structure is based around time-diversity redundancy also. The system processes two paths to derive the same result but each path is processed differently. The output will be the same if no divergence exists between the two paths. One path is the user side and the other path is the system side. Historically, a fail safe PLC controller was based around the principle of structural hardware redundancy. Two or more controllers execute the same program and the outputs are compared. SIMATIC S7 safety related systems are based around the concept of time redundancy and diversity. The S7 distributed safety controls are based on standard CPU's of which the operating system has been expanded with three different protection mechanisms to enable the processing of safety orientated user programs. Error detection and error controlling are performed by the safety program in the CPU in connection with their autonomous failsafe periphery modules. The F-modules are built up internally dual channeled, they contain their own self tests and recognize both, internal and external failures. The communication between periphery modules and the CPU proceeds by PROFIBUS DP. The safety orientated data are transmitted by the standard field bus according the PROFIsafe profile. Finally, check modules embedded by the generation of the safety program guarantees that failures in hardware and software are recognized and creates the reaction that forces and keep the F-system into the fail-safe mode.

In the MKQA system the following signals are monitored within the fail-safe PROFISAFE protocol:

- The electrical discharge switches of the generators.
- The manual earthing switches of the generators.
- The HV cable presence connections.
- The operational switches for each generators.

Status and operation is monitored, all inputs are doubled up to ensure redundancy, discrepancy time between two position events will create a safety related fault and finally the system 'freezes' when a safety related fault occurs (a faulty sensor state which inhibits the 'ON' command of the system state machine). When a fault occurs the PROFIsafe technology is in a faulty state and the I/O's card are passivated during that time. An operator must identify the fault, take the correct measures to repair the fault and then proceed to reintegrate the safety functions by acknowledging the fault over the operator console so to unlock the system from it's frozen state and resume operation. This procedure is clear and explicit on the operator consol screen.

7. MKQA slow control and SCADA interface

The MKQA system uses a SIEMENS OP370 touch screen panel to allow for the slow control GUI interface of the system. Replicas of these views are also replicated via a WinCC V7 SCADA interface through a web navigator environment. An additional FESA based applicative layer permits for the REMOTE operation of MQKA via the CCC and interfaces with higher order applicative layers of 'tune' and 'aperture' software.

7.1 System state machine

The general layout for the slow control system has the following flow diagram structure:

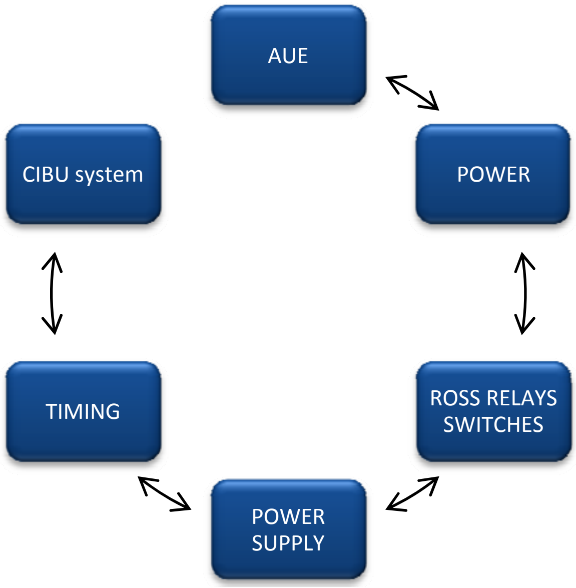

Figure 16 MKQA state machine start-up sequence

To operate the MKQA kicker, the operator must validate each step that represents a sub-state function of the whole system and in consequence initiate the start-up sequence of the installation. First the emergency buttons (AUE) must be released and reset, this automatically validates the emergency stops stage. The power distribution must be turned on, making sure no interlocks prevents this and correct status readings are met. The Ross Relay Switches (fig.17) stage 3 is interlocked with the DCPS's interlocks, the system cannot be turned on if any of these are not in the correct ‘fault free’ state. To enable the power and Ross Relay switches, DCPS and timing stage the user must verify correct interlocks and status readings and press the START command for each sequence. The beam permit (CIBU) is not inherently part of the state machine but is an outside component that interlocks the timing of the system.

The table below gives a descriptive view of the system sequential functions together with associated interlocks and status readings but also depicts the state value for each step whether actuated or not actuated:

Table 9

MKQA state machine of one single generator

FUNCTION	INTERLOCKS	STATUS	COMMANDS	STATE ACTUATED	STATE NOT ACTUATED
AUE	AUE gen1		**ENABLED ON RESET**	FAULTY	FAULTY
	AUE gen2				
	AUE gen3				
	AUE gen4				
	AUE timing racks				
	AUE RA43				
POWER	F20 Phase presence	K20 Main contactor	**START/STOP**	FAULTY	OFF
	SD10 Main circuit breaker	Q2 phase presence AC dipole			
	SD20 Main contactor	K1 contactor AC dipole			
		K2 contactor AC dipole			
SWITCHES	DCPSq1 Over-voltage	DCPS interlock thresholds	**START/STOP**	STANDBY	FAULTY
	DCPSq1 Over-Current				
	DCPSq1 Short-circuit				
	DCPSq2 Over-voltage				
	DCPSq2 Over-Current				
	DCPSq2 Short-circuit				
	DCPSqa Over-voltage				
	DCPSqa Over-Current				
	DCPSqa Short-circuit				
	DCPS rack door				
	DCPSq1 HV cable generator				
	DCPSq2 HV Cable generator				
	DCPSa HV cable generator				
	AC dipole HV cable generator				
	Manual earthing switch				
DCPS			**START/STOP**	FAULTY	FAULTY
TIMING		Timing ON MKQ	**START/STOP**	ON	FAULTY
		Timing ON MKA			
BEAM PERMIT			**INHIBITS TIMING PULSE**		

The MKQA state machine is not solely dependent of a step wise approach for turning the complete sequence of the system ‘ON’, this would be laborious to proceed this way with all four generators, however their are extra commands 'ON/OFF/STANBY' that allows for each generator to automatically go through the step sequence and deals with interlocks ‘RESETS’ in a transparent way. This automatic start-up sequence of the system is used by the CCC or operator to allow for a faster and simpler approach for the MKQA state machine start-up sequence.

Other important system state parameters can be read from the operator control panel, these are:

- Readout values of the HV divider resistors inside the generators housing.
- The magnet temperature data, upstream and downstream.
- The mode selection, ‘IDLE’, ‘Q’,’ A’ and ‘AC dipole’.
- The generator DCPS settings and read back of these settings.
- Recipe inputs to allow for different generator voltage settings.
- A PLC safety module acknowledge screen to allow card 'depassivation' with acknowledge request.
- A switch status page that indicates graphically the correct position for each relay switch and is also a tool for troubleshooting the equipment in case of a fault.

A typical view of the MKQA generator operator control panel. The top part contains the following functions:

- User logging window
- Locale/Remote status
- Generator state
- Generator mode
- Time and date

Centre part:

- System state depiction for each generator
- ON,OFF,STANDBY commands

Bottom menu provides navigation control for the various sub-screens:

- DCPS settings
- HV divider values
- Mode selection
- Switch status
- Magnet temperature
- Recipe settings
- Safety settings

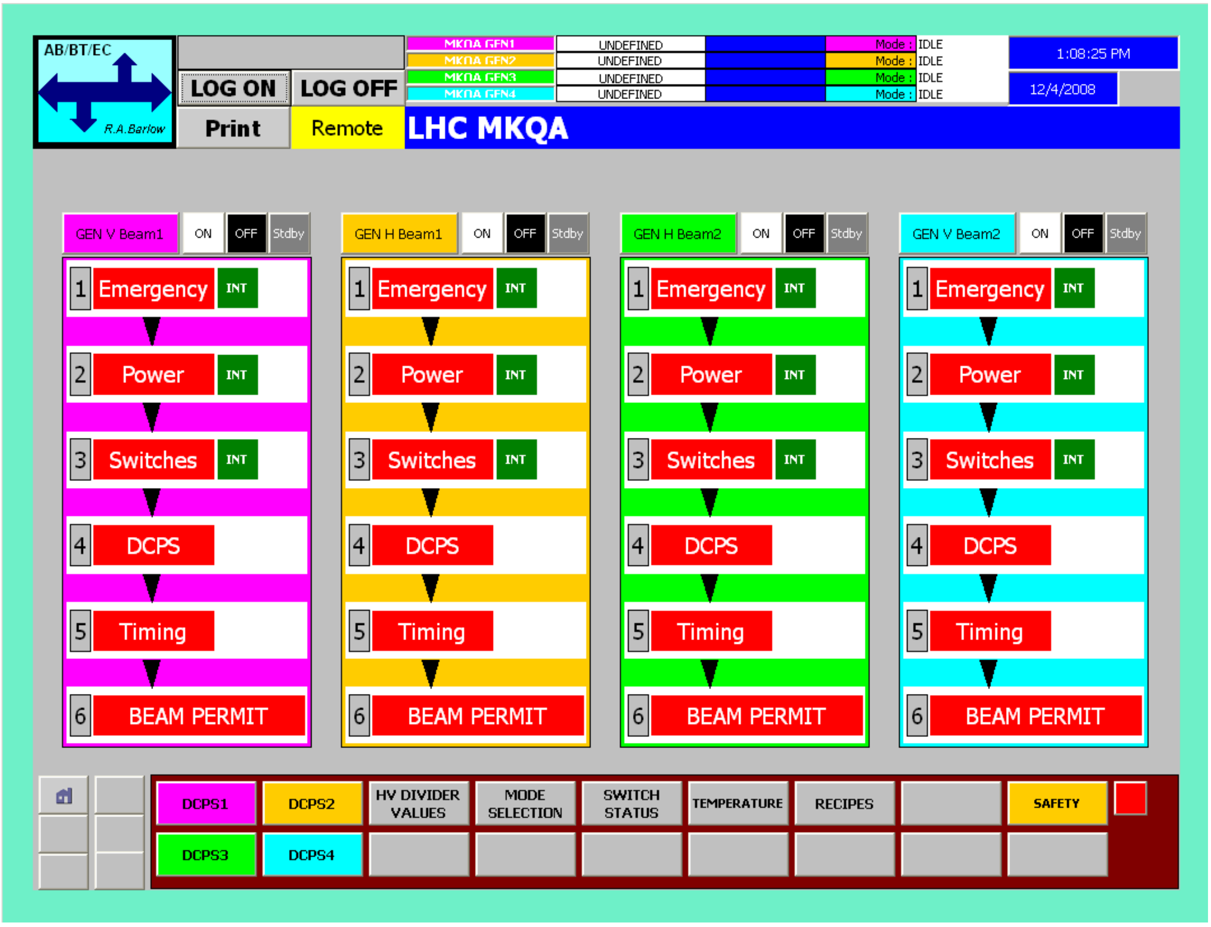

Figure 17 SCADA home page view of the MKQA system operator console

7.2 MKQA alarm loggings

To allow remote control of the MKQA via a similar interface as the operator panel within the WinCC flexible environment, a web navigator version was designed using WinCC V7.0 The control has been kept very similar and the control layout is basically the same. However minor differences exist of which the alarm logging window. The decision to implement this as remote viewing serves the purpose to timestamp the alarms to further provide a useful aid for diagnostics.

A typical ALARM logging window for MKQA is shown in fig 18 below:

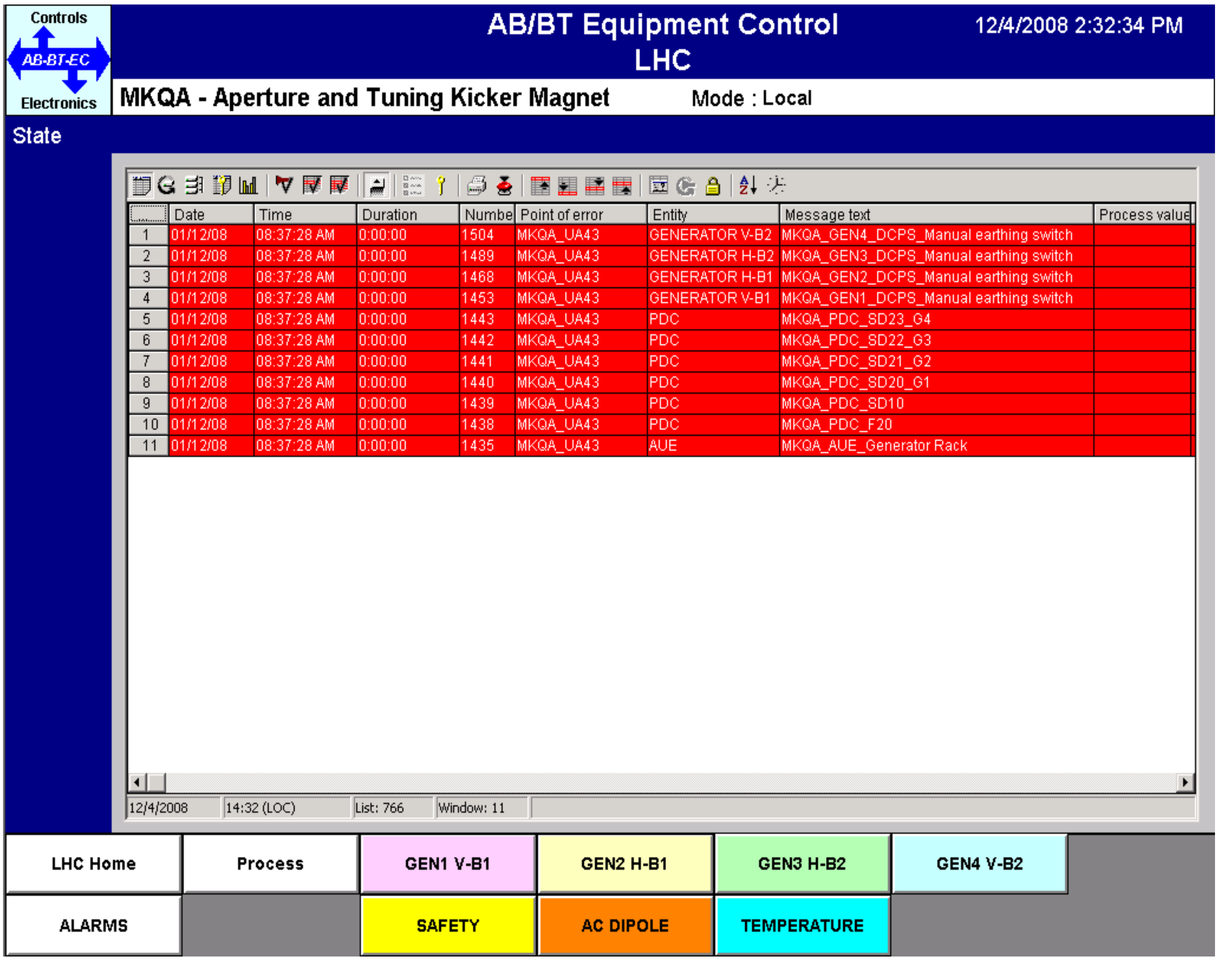

Figure 18 WinCC web navigator console view of alarm logging window

7.3 FESA applicative layer for MKQA remote control

The final control software layer is via the FESA framework. Features from the REMOTE control is brought forward inside a IEPLC class that communicates with the FESA PLC class and applicative layer class (FAPP). This interface is mainly used by the CCC operators and is often linked towards other applicative layers (typically Java language based) for finer parameter control, sequencer application and the RBAC (Role-based access control) safe LHC parameters. The ultimate and finite tuning and aperture measuring software is linked to the FESA class deployed for MKQA, taking parameters from the STATE and TIMING control.

Below is a typical FESA window showing the STATE class of the MKQA installation:

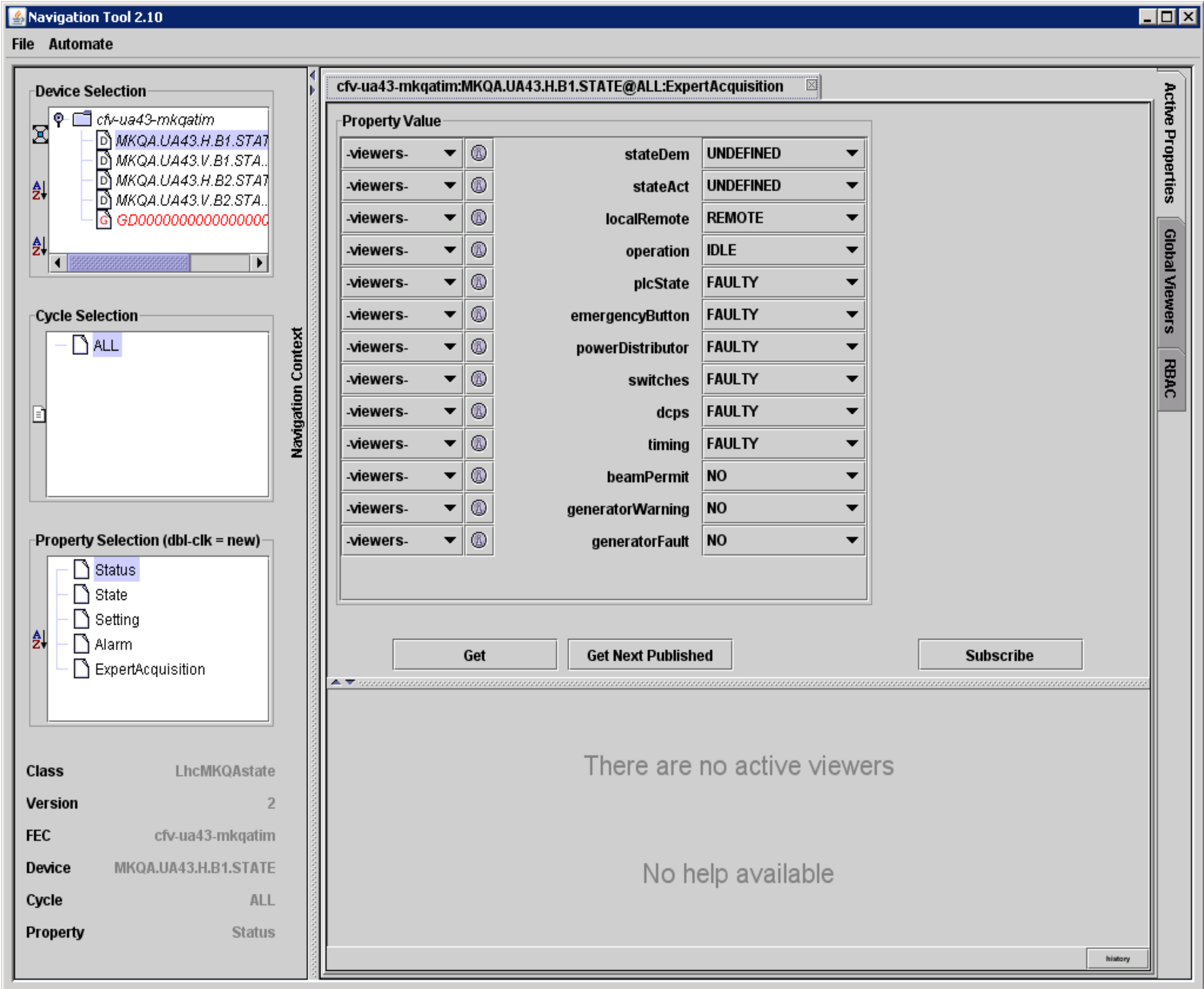

Figure 19 FESA navigation tool view of the MKQA state control

All the MKQA machine parameters can be found and identified via the FESA navigator interface, the four generators are listed with their associated fields of interest such as status, settings, state and expert acquisitions.

8. MKQA system timing distribution

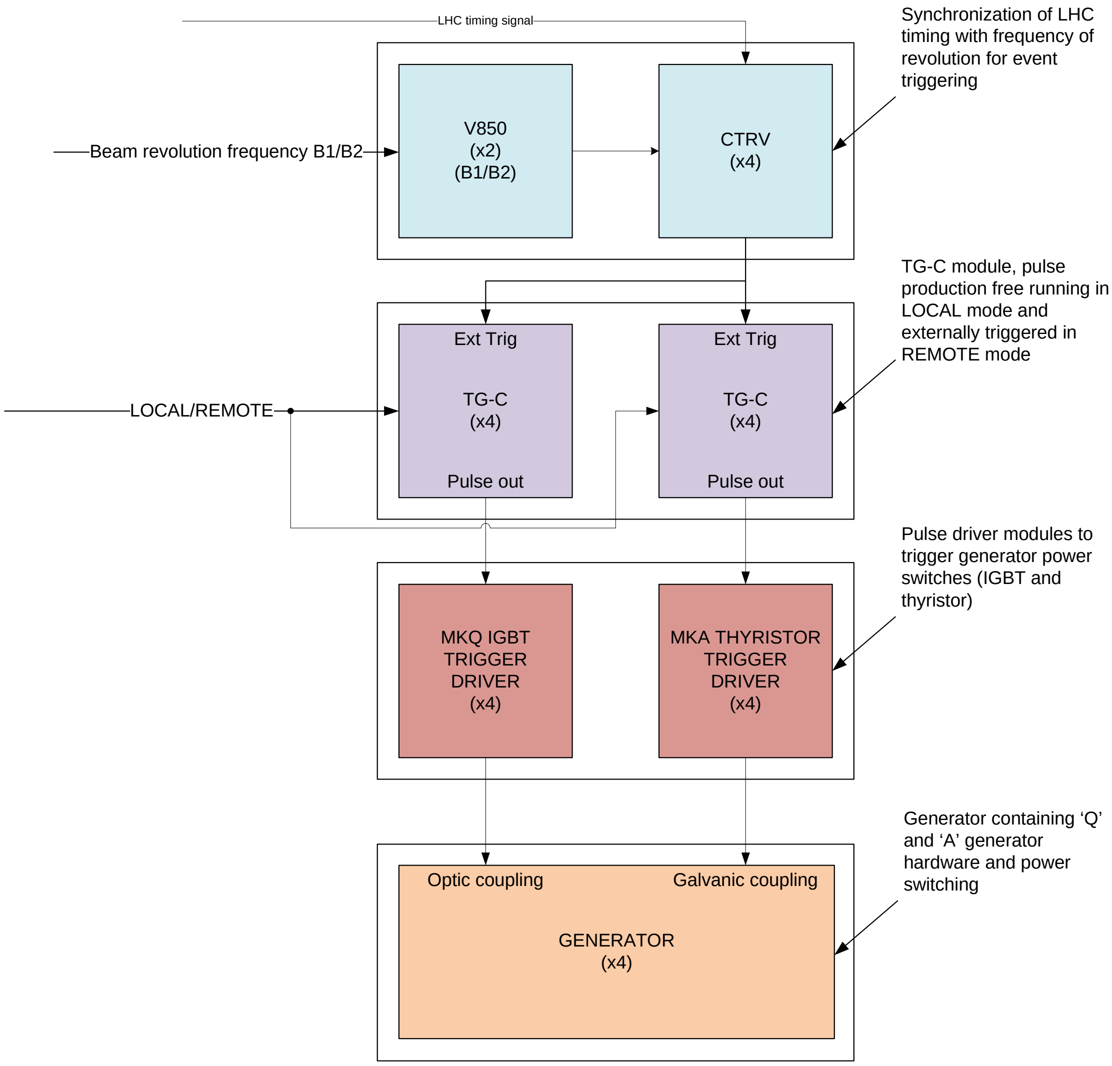

Figure 20 Simplified block diagram view of MQA timing distribution

The MKQA timing distribution scheme consists of several modules which each have specific functions but are combined to form the complete timing distribution. Due to its specific position, the kicker triggers depend on the LHC timing distribution protocol and the beam revolution frequencies. These signals are synchronized so to enable accurate triggering of the magnets. In LOCAL mode, the system is almost free running and relies solely on the TG-C modules that produce pulse trains with user defined intervals by a thumbwheel on the front panel. The signals coming from the TG-C (8 of) are distributed to two different drivers, one drives the generator MKQ IGBT via optic coupling and the other drives the MKA thyristor trough a galvanic connection.

In REMOTE mode, the installation is pulsed according to machine specific parameters. The machine frequency of revolution comes through a V850 (digital delay card) and is adjusted accordingly to the LHC timing distribution managed via the CTRV (Control Timing Receiver VME) card. This is entirely parameterized from the MKQA timing class inside the FESA framework. The CTRV then drives the external trigger outputs to TG-C cards and hence produce the correct pulses synchronized in time that are distributed to the rest of the pulse trigger driver systems.

The following table summarizes the timing distribution parameters:

Property	Field	Units	Cmd
Expert settings	strength Q2	Volts	FIXED
	strength Q1_min	Volts	Set/Get
	strength Q1_max	Volts	Set/Get
	strength Q2_min	Volts	Set/Get
	strength Q2_max	Volts	Set/Get
	strength A_min	Volts	Set/Get
	strength A_max	Volts	Set/Get
A & Q settings	reservation token	String	Set/Get
	reservation time out value	Seconds	Set/Get
	enable	Boolean	Set/Get
	kick delay	ns	Set/Get
	kick delay min	ns	Set/Get
	kick delay max	ns	Set/Get
	synchroDelay	ns	Set/Get
	synchroDelayInc	Integer	Set/Get
	synchroDelayInc_min	Integer	Set/Get
	synchroDelayInc_max	Integer	Set/Get
	strength	Volts	Set/Get
	strength min	Volts	Set/Get
	strength max	Volts	Set/Get
Expert acquisition	operation	Operational mode	Get
	local remote	Local/Remote	Get
	hardware error	True/false	Get
	plcerror	True/false	Get
	trigger time stamp Q	Seconds	Get
	trigger count Q	Integer	Get
	enable Q_dem	OFF/ON	Get
	enable Q_act	OFF/ON	Get
	kick delay Q_dem	ns	Get
	kick Delay Q_act	ns	Get
	synchrodelay Q_dem	ns	Get
	synchrodelay Q_act	ns	Get
	strength Q1_dem	Volts	Get
	strength Q2_act	Volts	Get
	strength Q2_meas	Volts	Get
	trigger time stamp A	Seconds	Get
	trigger count A	Integer	Get
	enable A_dem	OFF/ON	Get
	enable A_act	OFF/ON	Get
	kick delay A_dem	ns	Get
	kick delay A_act	ns	Get
	strength A_dem	Volts	Get
	strength A_act	Volts	Get
	strength A_meas	Volts	Get

Most of the settings parameters for the MKQA timing are self explanatory. Note that the strength of the Q2 setting is frozen inside the software for hardware protection reasons. Q2 must remain constant and unchangeable by the CCC user (only the software expert), this ensures protection of the thyristor diode stack and the thyristor. In the 'A' and 'Q' settings, a token number is allocated to the operator so that only one designated person at a time can change the system settings. The token reservation time out value is set so that if the system remains latent and unattended for some while, a time out prevents overwritten the system parameters till a new reservation token is summoned. The kick delay is triggered from the abort gap event and can be adjusted with respect to the abort gap to ensure a kick at specific parts of the circulating beam. The synchrodelay allows for multiple kicks with delay incrementation so that a kick can target each proton batch of the machine and hence produce a tune scan over the entire length of the beam. The synchrodelaying is set to the accorded number of batches the user wants the MKQA to kick. Inside the expert acquisition window, hardware and plc errors can be monitored. A plc error will indicate a loss of communication between the PLC system and applicative layer control software and the hardware error can indicate faulty electronic cards inside the FEC, for example a faulty V850 or CTRV card. The trigger time stamp variable indicates the length of time the system has been pulsing and the trigger count indicates the total pulse count.

8.1 AC dipole timing distribution and control

A PCI based front-end computer is used to control the AC dipole generator. It contains three different modules: a timing receiver card (CTRI), an analogue I/O card and a RS485 card. The RS485 card is used to remotely configure the amplifiers settings. The timing receiver card reacts on a timing event sent on the LHC timing network and produces an output pulse to trigger the analogue I/O card, which generates the signal for the amplifiers. In addition, the analogue I/O card reads current and voltage measurement at different points in the AC dipole system.

The generated waveform is a sine-wave modulated by a trapezoid (see Figure 21).

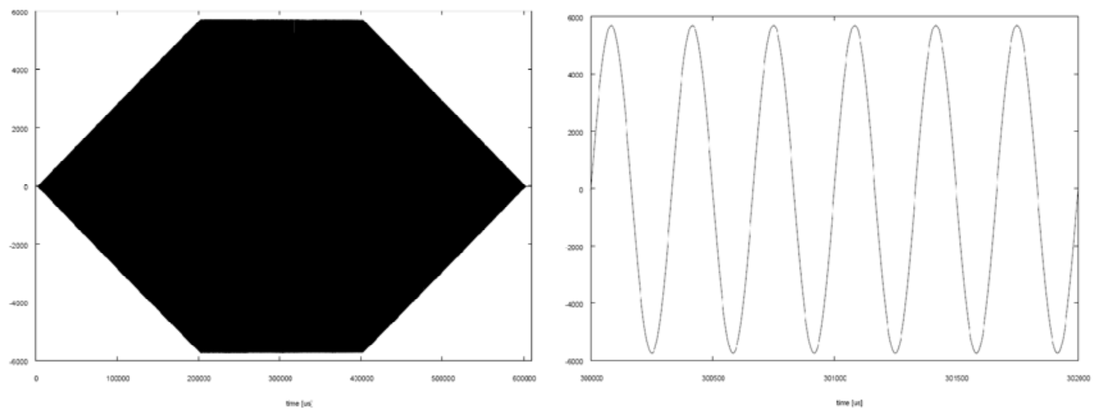

Figure 21 Magnet current waveform with AC dipole generator

The AC dipole is controlled by a high level java application in the control room, which communicates with a FESA class in the front-end computer. When the system is started, the FESA class is in "unloaded" state. As soon as the wanted sine-wave frequency and the flat-top amplitude are selected, it goes to "loaded" state. Note that the system can't generate any couple of frequency and amplitude. All generators as been characterized and the FESA class will reject a frequency-amplitude couple that is not possible to obtain with a given configuration.

Then the operator should arm the system (will go to "armed" state). At this moment, the system is ready to receive a trigger and generate the programmed waveform. When a trigger comes, it then goes to "busy" state and will stay there for one minute. This is a safety feature to avoid accidentally triggering the system too quickly after an excitation. Finally it goes back to "loaded" state, where new values for frequency and amplitude can be sent to the system.

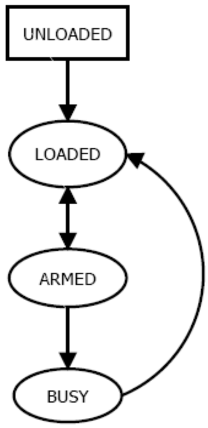

Figure 22 AC dipole FESA class state diagram

9. The OASIS remote acquisition viewing system

As previously mentioned this is a compact PCi front-end containing the acquisition cards (DC265, 500 MS/s, 150 Mhz) which makes up the OASIS remote viewing system. The OASIS system requires external triggers corresponding to each generator triggers with their corresponding modes, ‘Q’ or ‘A’ and finally ‘AC dipole’. These triggers are issued from the CTRV card and routed to the card which also monitors the magnets Pearson signals and the circulating beam for synchronization action.

Figure 23 OASIS remote viewing window depicting 'Q' mode magnet pulse response

10. Conclusion

The MKQA system underwent extensive testing during its commissioning stage and performed as expected in 'Q', 'A' and 'AC dipole' mode. The simple interface and user friendly control has contributed to this success. The system has only been truly tested in 'dry run' mode and due to the LHC setbacks of October 2009 the system could not be fully exploited for tune and aperture measurements. We are hoping to get first results during the current year of 2010 when the LHC will be started up again. It will be imminent to measure the tune and aperture of the beam at the early stage of LHC commissioning run.

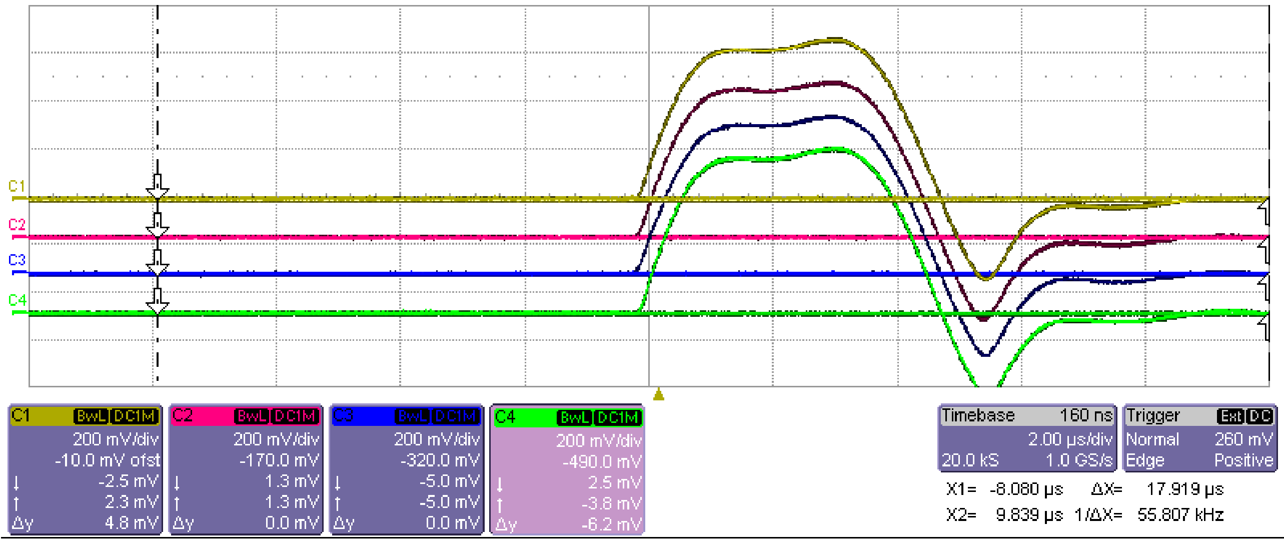

Figure 24 Magnet pulse shape measured with MKQA set to 'Q' mode

11. Acknowledgements

The author would like to thank Javier Serrano for helping out concerning the AC dipole mode of the system and finally Michel Laffin who although not directly assigned to work on this project helped me with many of the hardware aspects of this project.

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