

## Engineering Specification

# THE HARDWARE INTERFACES BETWEEN WARM MAGNET INTERLOCK SYSTEM, NORMAL CONDUCTING MAGNETS, POWER CONVERTERS AND BEAM INTERLOCK SYSTEM FOR THE LHC RING

### *Abstract*

The LHC Machine Interlock System includes Powering Interlocks and Beam Interlocks to protect the equipment of the LHC [1]. The Powering Interlock System is designed to ensure the permission for powering the different electrical circuits with superconducting magnets and normal conducting magnets installed around the accelerator. For normal conducting magnets (in the following referred to as warm magnets), it protects equipment in case of a failure in the cooling or powering system and takes the appropriate action to minimise time for recovery.

This specification defines the hardware interfaces of the interlock system with warm magnets, power converters and the beam interlock system.

#### *Prepared by:*

**R. Schmidt AB/CO  
P.Dahlen AB/CO  
B. Puccio AB/CO  
M. Zerlauth AB/CO**

#### *Checked by:*

**O.Bruning AB/ABP  
V.Montabonnet AB/PC  
S.Ramberger AT/MEL  
G.Roy AB/OP  
H.Thiesen AB/PC  
D.Gerard AT/MEL**

#### *Approved by:*

**F.Bordry AB/PC  
K.H.Mess AT/MEL  
B.Frammery AB/CO**

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## 1. INTRODUCTION

The architecture of the Machine Protection System has been described in "Machine Protection for the LHC: Architecture of the Beam and Powering Interlock Systems" [1].

Two interlock systems have been proposed. The beam interlock system to be ready for the LHC start-up with first injection of beam in 2006 and one for the magnet powering system already required for hardware commissioning of LHC powering subsectors in 2005. The powering interlock system includes the interlocks for superconducting magnets that has been specified in [2], and the interlock system for the normal conducting magnets.

This specification describes the links of the powering interlocks for normal conducting magnets with magnets, power converters and the beam interlock system. It is based on the LHC layout version 6.402.

The superconducting magnets in the LHC are powered in so-called powering subsectors [3]. Other than the superconducting magnets, normal conducting magnets in one electrical circuit can be installed at both sides of one interaction point, powered in series by one power converter (for example, the D1 magnets in IR1 and IR5). The interlocks for all normal conducting magnets in one insertion are managed by one powering interlock controller. In IR4 no such controller is required since there are only superconducting magnets installed.

**Note:** The powering interlock controllers for normal conducting magnets will be hereafter referred to as the WIC (Warm magnet Interlock Controllers)

## 2. PURPOSE

- Definition of magnets and electrical circuits covered by this specification.
- Definition of the signals and cables between warm magnet interlock controllers, power converters and beam interlock system, including the detailed pin assignment.
- Assignment of each electrical circuit to an "interlock class" that determines the response of the warm magnet interlock system in case of a failure with respect to beam operation.
- Definition of the functionality of the interlock controller for the normal conducting magnets.

## 3. REMINDER

The interlock system for normal conducting magnets installed in the LHC ring and the associated power converters is separated from the interlock system of the normal conducting magnets installed in T12 & T18 (SPS to LHC transfer lines) and their associated power converters. The T12 & T18 transfer lines are considered SPS extension like. Therefore the interlock system of the normal conducting magnets installed in T12 & T18 and the associated power converters will strictly follow the same procedures as used in the SPS.

## 4. FUNCTIONALITY OF THE CONTROLLER: GENERAL ASPECTS

The warm magnet interlock system is required to avoid overheating of the normal conducting magnets. Risk of overheating is essentially due to the risk of a failure in the water cooling of such magnet. On each magnet several temperature probes in the form of thermo switches are installed. If the temperature exceeds a predefined value, the opening of the thermo switch is detected by the interlock controller, which then has the task of removing the permit for the power converter, thus stopping the converter. In order to start and operate the converter, all thermo switches need to be closed and the powering permit must be present.

The required response time for switching off the power converter to avoid overheating leading to equipment degradation is in the order of seconds. In general, normal conducting magnets have a large resistance and a low inductance. The time constant for the current decay is much less than for superconducting magnets, typically in the order of some seconds. Switching off such magnets could lead to beam loss within a very short time, for the D1 magnet already within a few turns [4]. After a fault is detected, a signal is immediately sent to the beam interlock controller that will trigger a beam dump. Only after a delay of around 1 second the power converter is switched off by the WIC to ensure that the beams are dumped before the current in the circuit is ramped down.

Some general requirements have to be considered when defining the functionality of the WIC:

- Protect the elements in the electrical circuits: In case of failure, the necessary steps should be taken to dump the beam (if required for this circuits) and stop the according power converter.
- Protect the beam: The system should not request beam dumps if this is not strictly necessary. Faulty trigger signals leading to a beam dump should be avoided.
- Provide the evidence: In case of failure, the messages should get to the operator. The system should support identifying the initial failure, also in case of multiple alarms (one initial failure that causes subsequent failures).
- Assist improving the operation: The diagnostics for failures should be easy. The status of the system must be clearly presented in the control room and should be transparent to the operator
- During accelerator operation, the controllers cannot be accessed. Full remote operation is required.

## 5. HARDWARE PLATFORM

The warm magnet interlock controllers are similar to those used in the SPS-LHC transfer lines. The powering interlock system will interface to power converters for 40 electrical circuits and 144 magnets as shown in Table 1 (the two main magnets of the ALICE and LHCb experiments are not under the responsibility of the machine interlock and as such not included in these numbers). There are in total 144 input signals, one for each magnet grouping all thermal switches for this magnet in series. 40 output signals will be transmitted by the system to the connected power converters (see Table 2 for a complete list of warm magnet types and the installed thermo switches). The required response time is in the order of several seconds. As for the interlock controllers for superconducting magnets, the controllers will be realised with industrial PLCs. The exchange of signals with the other systems is performed via deported input / output modules. For the PLCs, equipment from Siemens is selected (S7-300 safety serie for the PLC, 24 DI safety module for the input, 2 x 8 DO relay modules for the output), as this fully complies with the requirements.

	Controller			Number of		Magnet Types
	Nbr	Name	Location	Converters	Magnets	
IR1	1	CIPW.LR1	US15	1	12	MBXW(2x6)
IR2	2	CIPW.LR2	UA23	3	3	MBXWT(x2), MBWMD
IR3	3	CIPW.LR3	UJ33	3+12	44	MBW(x12), MCBWH(x4), MCBWV(x4), MQWA(x20), MQWB(x4)
IR5	4	CIPW.LR5	USC55	1	12	MBXW(2x6)
IR6	5	CIPW.LR6	US65	2	30	MSDA(2x5), MSDB(2x5), MSDC(2x5),
IR7	6	CIPW.LR7	UJ76	3+12	40	MBW(x8), MCBWH(x4), MCBWV(x4), MQWA(x20), MQWB(x4)
IR8	7	CIPW.LR8	US85	3	3	MBXWS(x2), MBXWH

Table 1: List of warm interlock controllers in the LHC insertions and the protected warm magnets

Magnet type	Description	Thermo Switches / magnet	Total <sup>1</sup>
MBW	Separation dipoles Cleaning Insertions	6	120
MBXW	Separation dipoles Experimental Insertions	6	144
MBXWH	LHCb main dipole central compensator	6	6
MBWMD	Alice main dipole central compensator.	6	6
MBXWS	Short compensation dipole LHCb	2	4
MBXWT	Short compensation dipole Alice	2	4
MCBWH	Horizontal correction dipoles	6	48
MCBWV	Vertical correction dipoles	6	48
MQWA	Twin aperture quadrupole Cleaning Insertion	8	320
MQWB	Twin aperture quadrupole Cleaning Insertion	8	64
MSDA	Septum extraction dipole type A	4	40
MSDB	Septum extraction dipole type B	5	50
MSDC	Septum extraction dipole type C	6	60
			<b>914</b>

Table 2: List of warm magnet types and installed thermo switches

Note: all thermo switches are of the type Elmwood 3106 T117 and open at 65°C but choice for MBWMD needs to be confirmed.

## 6. OVERVIEW ON THE HARDWARE INSTALLATIONS FOR THE LHC

The figures given in the Annex (Figure 4 to Figure 10) show the installations for each insertion of the LHC.

- On each magnet several thermo-switches are installed. The switches are connected in series with one NE04 cable to a patch panel in the vicinity.

<sup>1</sup> These numbers do not take into account thermo-switches installed on spare magnets, but represent the total number of switches installed for the current optics layout 6.402.

- In the patch panel the signals from the NE04 cables for several magnets are combined and routed via a multi-wire cable to the PLC that is installed in an underground area in the vicinity. For each magnet, two signals will be read by the PLC.
- From the PLC, cables are routed to the power converters and to the closest beam interlock controller. Power converters for MQWB, MCBWH and MCBWV in IR3 and IR7 are installed in UJ33 and UJ76 respectively (being conventional 600A converters), while all other power converters (thyristor converters) are installed in SR surface buildings. For IR3 and IR7 an additional patch panel is required to route the cables from the PLC to the power converters in the underground areas.
- The connection between PLC and power converters on the surface is via a multi-wire cable, with another patch panel installed in the surface building that routes the signals to the power converters.

## 7. ASSIGNMENT OF AN INTERLOCK CLASS

Most of the normal conducting magnets in the LHC are essential for continuous beam operation and any failure in the magnet powering should result in an immediate beam dump. Only after the beams are dumped, the powering permit of the according power converter is removed. Similar as for the interlock controller of the superconducting magnets in the LHC ring, the assignment of a parameter to decide whether or not to dump the beams in case of failure will allow for flexibility during operation. If the functionality of a circuit is inevitable for beam operation it is defined to be an 'essential circuit', and the assigned parameter will be '1'. In case of smaller corrector circuits, the circuit is defined to be an 'auxiliary circuit' and the assigned parameter is '0'. A failure of any circuit will provoke the signal AUXILIARY\_CIRCUITS\_OK to become inactive (connected to the mask-able beam dump input of the beam interlock controller). Only a failure in a circuit considered essential for beam operation will in addition force the signal ESSENTIAL\_CIRCUITS\_OK to become inactive (connected to the non-mask-able beam dump input of the beam interlock controller) and as such immediately dump the beam.

The following initial assignment has been chosen for the electrical circuits powering normal conducting magnets, but might be changed during commissioning, first injection tests for sector 78 or later operation scenarios:

Circuit Types	Essential for beam operation
RD1	YES
RBWMDV	YES
RBXWTV	YES
RD34	YES
RQ4	YES
RQ5	YES
RQT4	YES
RQT5	YES
RCBWH	NO
RCBWV	NO
RMSD	YES
RBXWH	YES
RBXWSH	YES

Table 3: Circuit classes with respect to their importance for beam operation

## 8. HARDWARE SIGNALS BETWEEN THE WARM INTERLOCK CONTROLLERS AND OTHER SYSTEMS

- **MAGNET\_OVERTEMP:** The signal corresponds to the series of thermo-switches installed on each magnet and is an input for the WIC. A flowing current in the loop and as such an active signal indicates a magnet temperature below the limit of 65°C. If one of the thermo-switches opens, the loop is broken and the signal becomes inactive.
- **MAGNET\_OVERTEMP\_Test:** This signal will be generated by the WIC and will allow a remote test of the interlock loop and will thus simulate the opening of a thermo-switches. This test will be able to be carried out only apart from the normal operation.
- **PC\_FAST\_ABORT:** This signal is generated by the WIC and sent to the power converter. A flowing current in the loop permits the power converter to start ("green light"). When the current in the loop is broken by opening of the relay contact by the WIC (for example after a contact of a thermo-switch opens), the power converter opens the primary circuit breaker and goes OFF. The current in the circuit will be forced into the free-wheeling diode and decay with the natural time constant of the electrical circuit.
- **POWERING\_FAILURE:** In case of a failure noticed by the power converter, the loop is broken by the converter and the loss of current is detected by the WIC. Such faults include failures of the power converter itself, failures in the supply (water, electricity), etc. Sending of the **POWERING\_FAILURE** signal is requested since the warm interlock system is in charge of dumping the beams in case of failure.
  - a) If the **POWERING\_FAILURE** signal is not activated (no current in the loop):  
The PC is OFF (or is in the process of switching OFF) and cannot be switched on.  
**Note:** An inactive **POWERING\_FAILURE** signal is no guarantee for zero current in the circuit!
  - b) If the **POWERING\_FAILURE** signal is activated (current is flowing in the loop):  
The power converter can be either ON or OFF. It means that the signal does not include the ON/OFF status of the PC.
- **AUXILIARY\_CIRCUITS\_FAILURE:** Failures in any of the electrical circuits will provoke the signal **AUXILIARY\_CIRCUITS\_FAILURE** to become inactive (no current in the loop). The signal is connected to the mask-able beam dump input of the adjacent beam interlock controllers and triggers a beam dump if decided by the BIC. The WIC always sends this signal to one of the beam interlock controllers in the insertion.
- **ESSENTIAL\_CIRCUITS\_FAILURE:** In case of failures in an electrical circuit considered essential for beam operation, the WIC will force the signal **AUXILIARY\_CIRCUITS\_FAILURE** and the signal **ESSENTIAL\_CIRCUITS\_FAILURE** to become inactive (no current in the loop). The signal is connected to the non-mask-able beam dump input of the beam interlock controller and will in any case result in a beam dump by the beam interlock controller. The WIC always sends this signal to one of the beam interlock controllers in the insertion.
- **PC\_DISCONNECT:** Flowing current and as such an activated **PC\_DISCONNECT** signal indicates a correctly connected cable in between the WIC and the corresponding power converter. If the cable is disconnected at either side, the loop is broken.



- **MAGNET\_DISCONNECT:** Flowing current and as such an activated **MAGNET\_DISCONNECT** signal indicates a correctly connected cable in between the WIC and the corresponding normal conducting cable. If the cable is disconnected at either side, the loop is broken. In order to reduce the number of inputs at the PLC level, a grouping of the signal for one electrical circuit already at the level of the patch panel is possible.

## 9. DESIGN CONSIDERATIONS FOR THE HARDWARE INTERFACES

The exchange of hardware signals is performed using fail-safe logic. Nominal operation of the system is represented by an active signal. An active signal corresponds to a flowing current in the loop, while a deactivated signal or a loss of the supply results in a safe state of the system. High reliability is required after a detection of magnet overheating since the power converter of the corresponding circuit needs to be shut down (via the removal of the **PC\_PERMIT** signal by the WIC) to avoid damage or degradation of the normal conducting magnet.

Requirements for the design of the hardwired interfaces have been defined as follows:

- The interfaces should be reliable
- The interfaces should be simple
- The cost of the implementation should be considered

The considerations to design a safe system led to the design of signal loops for the exchange of information as shown in Figure 1 and Figure 2. By definition, the system requesting a signal provides the current in the loop. The loops will be driven by a voltage between 15 V and 24 V. The current should be between 10 mA and 20 mA. The **PC\_FAST\_ABORT** loop, the **POWERING\_FAILURE** loop and the **PC\_DISCONNECT** loop represent a one-to-one connection between the power converters and the WIC. The normal conducting magnets are connected via the **MAGNET\_OVERTEMP** loop and the **MAGNET\_DISCONNECT** loop to the WIC.

## 10. RELIABILITY AND REDUNDANCY

To design a reliable system, several ideas to add redundancy and reliability to the system have been considered. The finally chosen principles should be transparent for the user and will not influence the hardware interfaces described in this document.

- For redundancy, part of the thermo-switches on a magnet could be connected in series via one cable as a first signal and the second part of the thermo-switches as a second (and thus redundant) signal via another cable. For each magnet, the two signals are connected to two different PLC input channels. The choice should take into account that certain thermo-switches reach the critical temperature earlier because of the direction of water-flow.
- To assure switching off the power converter, two output relays of different WIC output modules could be connected in series.
- Replacing the controller and I/O modules of the warm interlock controller by a safety PLC and the corresponding I/O modules increases the reliability of the system at an acceptable increase of cost.
- Watchdogs or additional software interlocks on the supervision level will monitor the proper functionality of the PLC process. In case of failure, a remote

reset of PLC and I/O modules or the forcing of all outputs to a safe state could increase the overall reliability of the system.

## 11. QUESTIONS

A number of open questions still needs to be discussed in between the involved groups before approval of this document, namely:

- *PC ON/OFF status. Current SPS interlock system experience and practice (P. Dahlen), established over many years, have shown to be quite useful, even though not essential, to have PC ON/OFF status signal on the magnet interlock system side. Piquet service and normal intervention on the magnets interlock system are facilitated. Unfortunately ON/OFF status signal is not foreseen on actual defined interfaces and protocol.*
- *Choice of thermo switches for MBWMD (Norbert Siegels comment that 65 Celcius too large for this magnet type)*
- *Installation of interlock cable – radiation*
- *Send abort signal via software – redundant way*

## 12. REFERENCES

- [1] F.Bordry et al.: The Architecture of the Machine Protection System of the LHC. LHC Project Note 521
- [2] B.Puccio et al.: The hardware interfaces between powering interlock system, power converters and quench protection system, EDMS Doc.Nr.: 368927
- [3] B.Puccio, R. Schmidt: Powering Subsectors, EDMS Doc.Nr.: 361532
- [4] V.Kain: Power converter failure of the normal conducting D1 magnet at the experiment insertions IR1 and IR5, LHC-Project-Note-322

### 13. APPENDIX A: INTERFACE BETWEEN WIC AND PC

#### Hardware Interface – Cable ID: WIC-PC

A 10-wire cable (NE10) has been chosen for the interface between power converter(s) and WIC for each electrical circuit. The type of the connector at each end of the cable is a 12 male poles Burndy connector, type 12BPMB with the following pin assignment:

<u>Name</u>	<u>PC side or WIC side</u>	<u>NE 10 Wire</u>
POWERING_FAILURE +	Pin 1	1
POWERING_FAILURE -	Pin 2	2
Spare	Pin 3	3
Spare	Pin 4	4
PC_DISCONNECT +	Pin 5	5
PC_DISCONNECT -	Pin 6	6
PC_FAST_ABORT +	Pin 7	7
PC_FAST_ABORT -	Pin 8	8
Spare	Pin 9	
Spare	Pin 10	
Spare	Pin 11 <sup>2</sup>	9
Spare	Pin 12 <sup>2</sup>	10

### 14. APPENDIX B: INTERFACE BETWEEN WIC AND MAGNETS

#### Hardware Interface – Cable ID: WIC-MAGNET

A 4-wire cable (NE4) has been chosen for the interface between each normal conducting magnet and WIC. The type of the connector at each end of the cable is a 4 male poles Burndy connector, type 4BPMB with the following pin assignment:

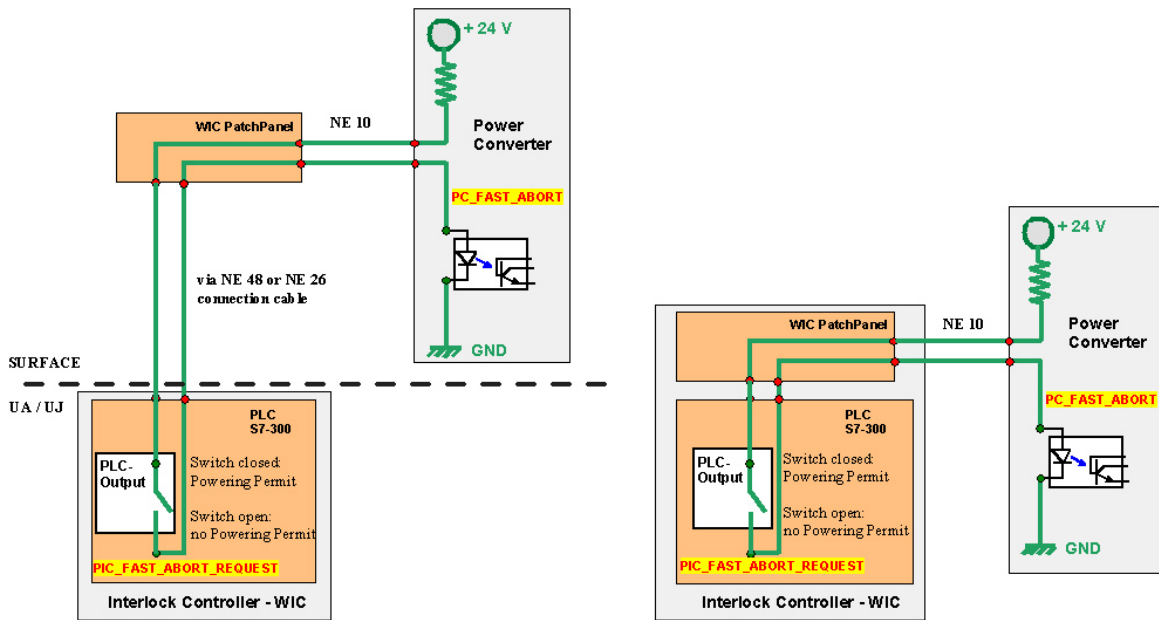
<u>Name</u>	<u>Magnet side or WIC side</u>	<u>NE 4 Wire</u>
MAGNET_OVERTEMP +	Pin 1	1
MAGNET_OVERTEMP -	Pin 2	2
MAGNET_OVERTEMP_Test +	Pin 3	3
MAGNET_OVERTEMP_Test -	Pin 4	4

### 15. APPENDIX B: INTERFACE BETWEEN WIC AND BIC

#### Hardware Interface – Cable ID: WIC-BIC

The beam dump requests of the WIC will be provided as simple PLC outputs within the WIC rack to the installed beam interlock client interface (BICI box). No additional cable has to be foreseen as the transmission of signal to the BIC is managed by the beam interlock system.

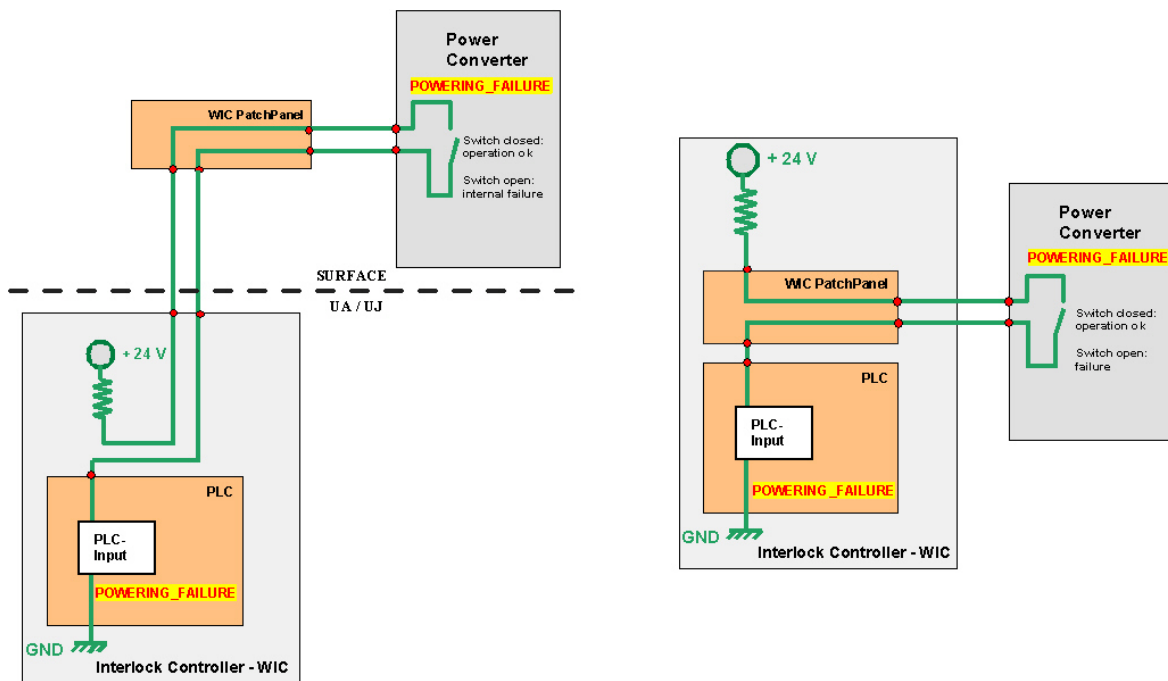
<sup>2</sup> The PC Permit signal required for a start up of the PC will be strapped at the level of the cable's connector (at the converter side). The WIC will always require a fast power abort of the converter via pins 7 & 8 of the connected cable.



**Interface between power converter in the surface building and WIC: PC Fast Abort Loop**

**Interface between power converter in the underground area (UA / UJ) and WIC: PC Fast Abort Loop**

Figure 1: Interfaces between power converters and WIC: PC Fast Abort Loop



**Interface between power converter in the surface building and WIC: Powering\_Failure Loop**

**Interface between power converter in the underground area (UA / UJ) and WIC: Powering\_Failure Loop**

Figure 2: Interfaces between power converters and WIC: Powering Failure Loop

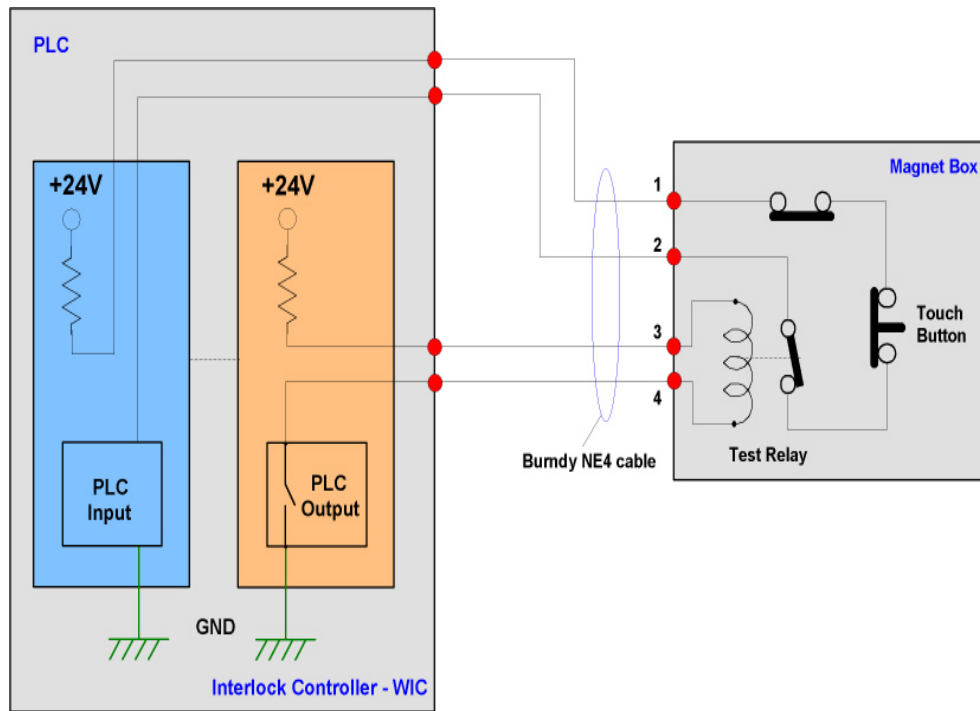


Figure 3: Interfaces between WIC and Magnets: Remote test

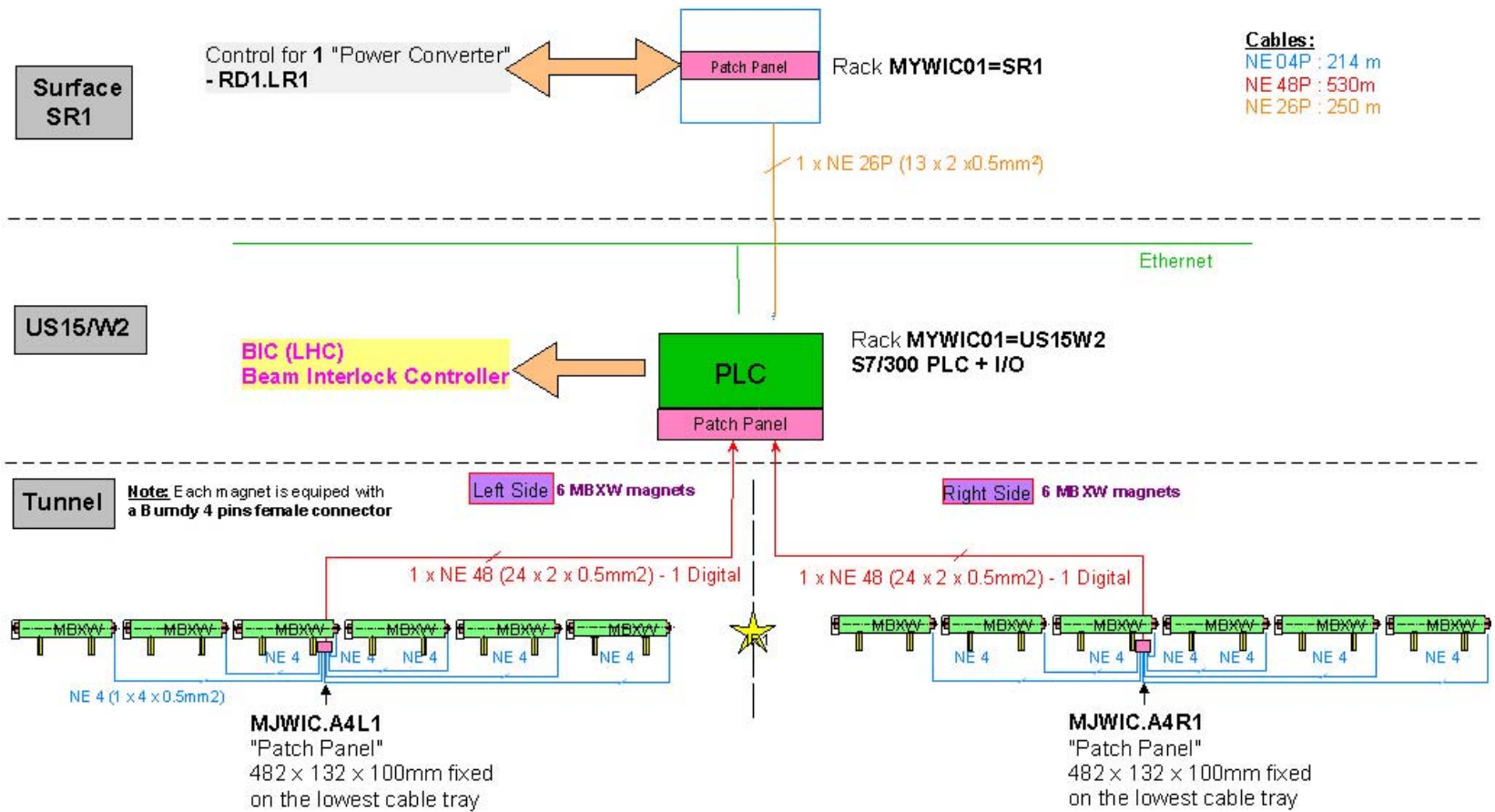


Figure 4: Principle of the warm magnet interlock system for IR1 in the LHC

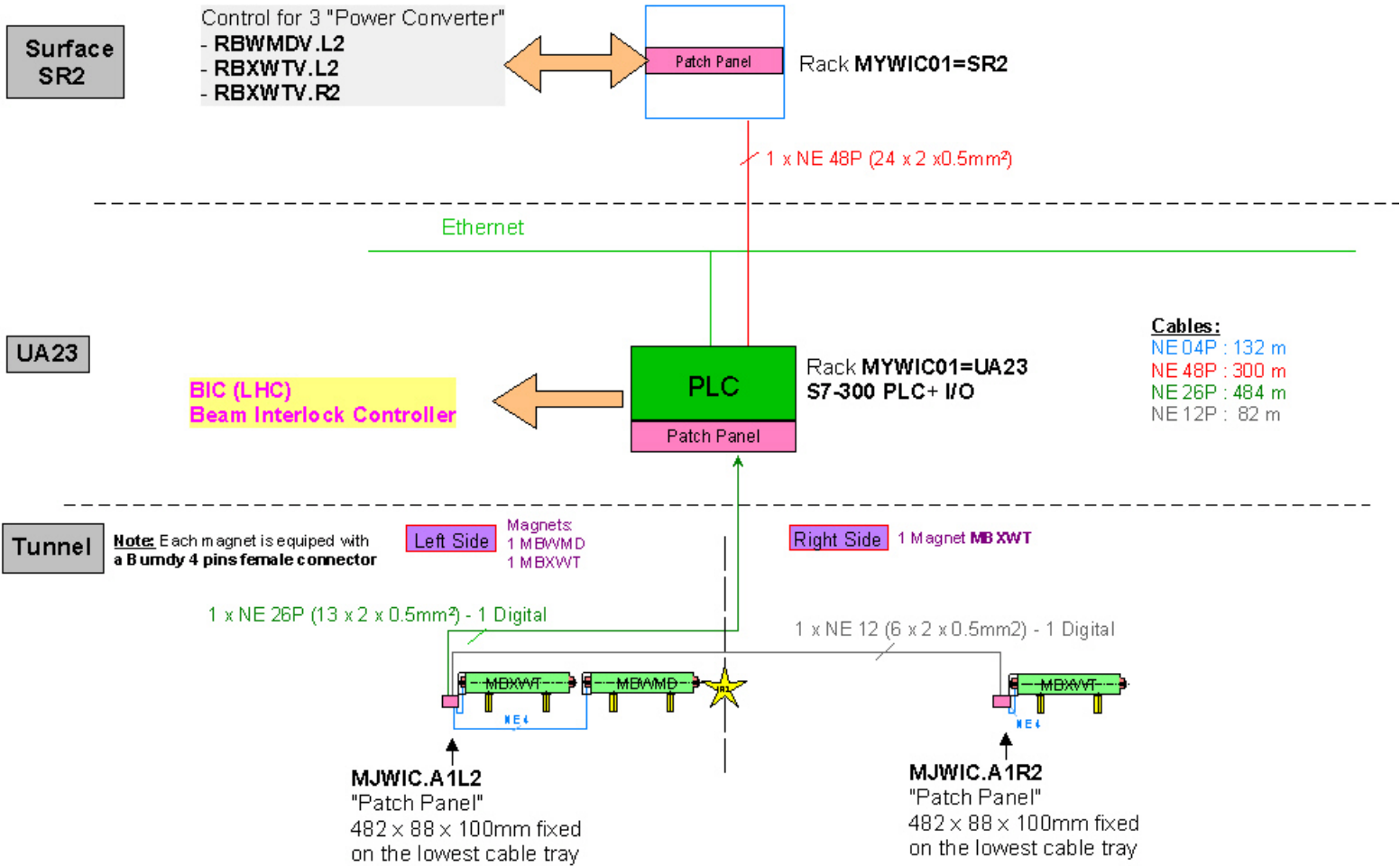


Figure 5: Principle of the warm magnet interlock system for IR2 in the LHC

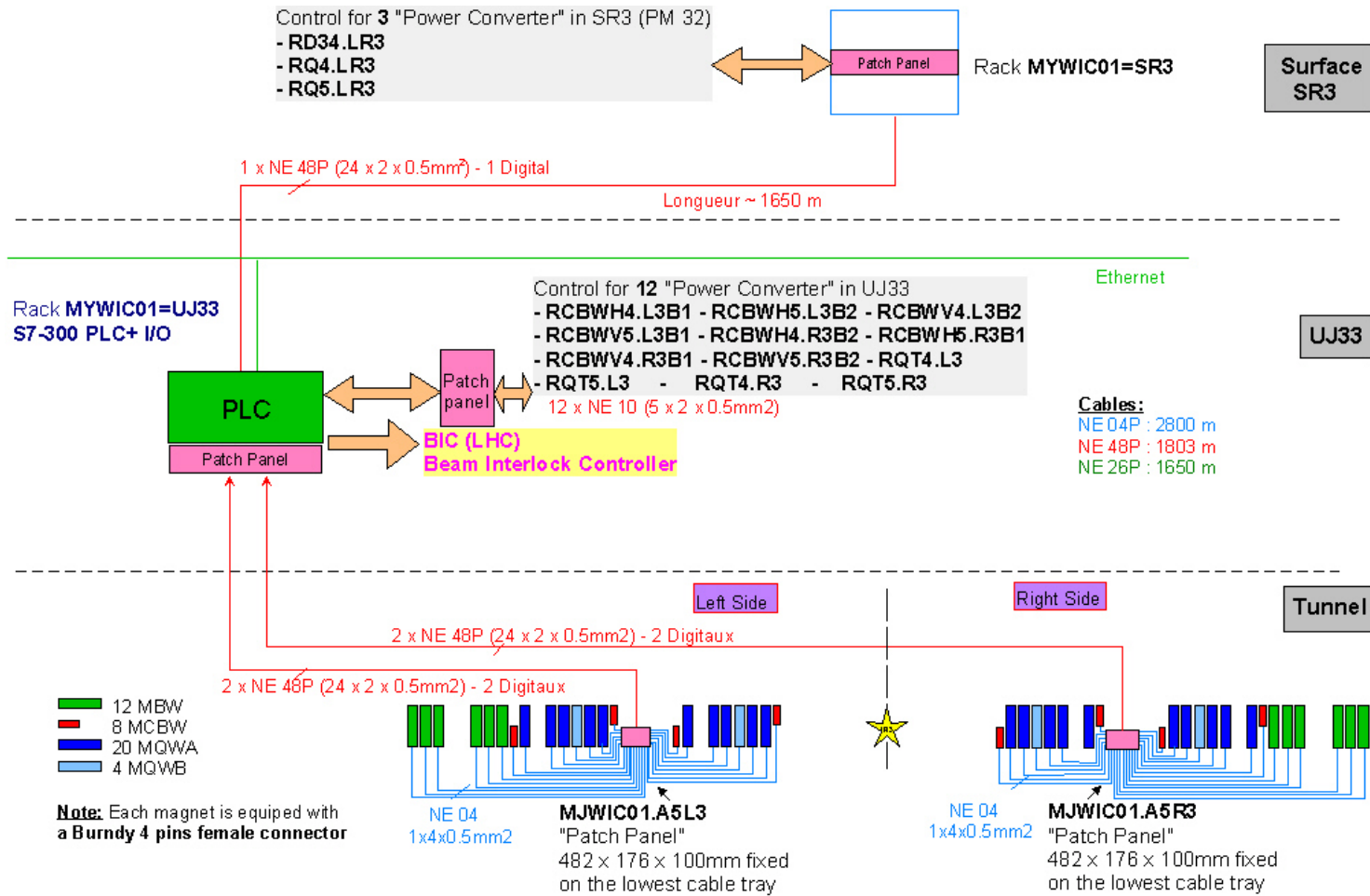


Figure 6: Principle of the warm magnet interlock system for IR3 in the LHC

(Note! Layout change in Version 6.5 due to new collimation layout affecting orientation and location of normal conducting magnets)



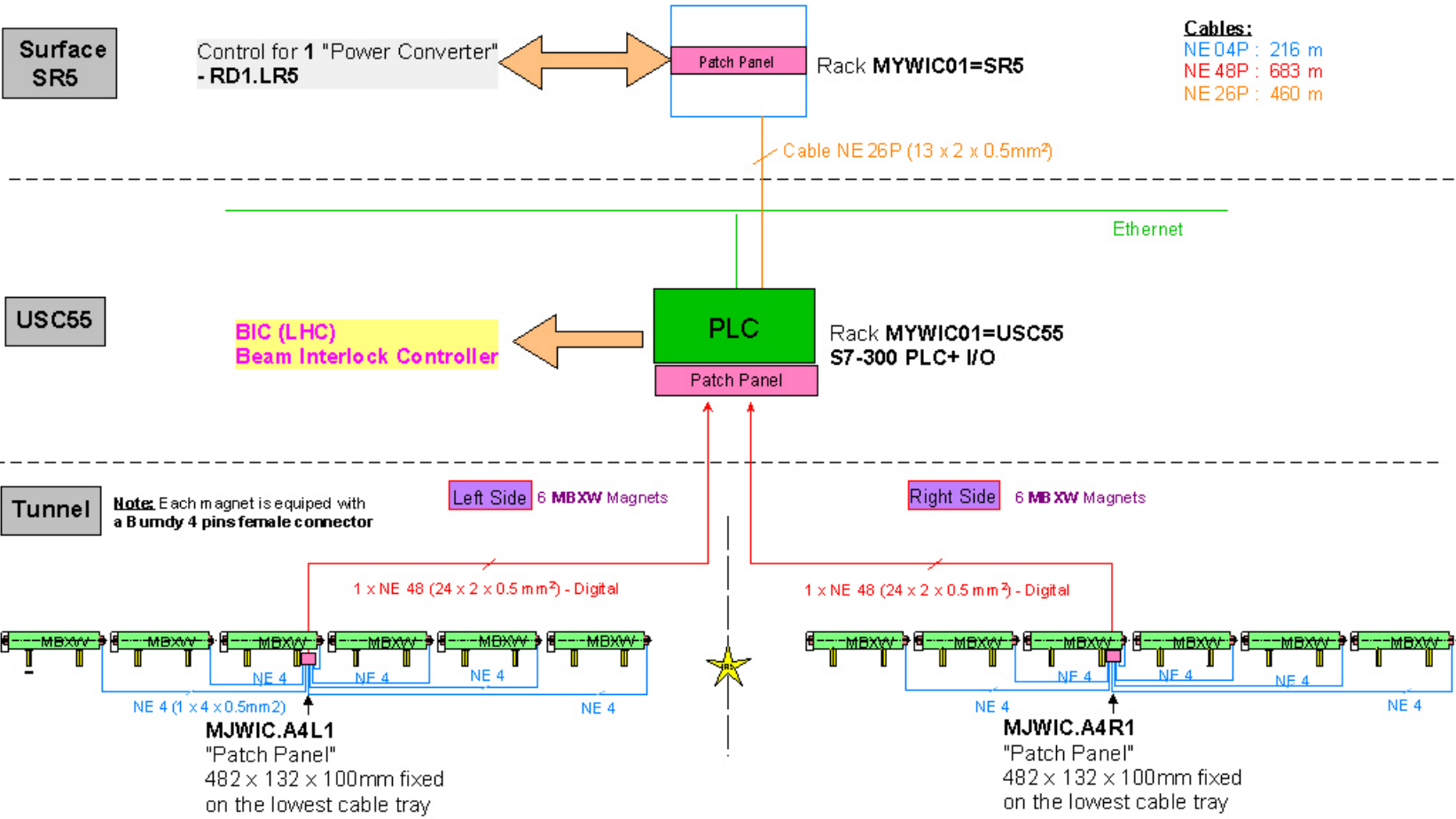


Figure 7: Principle of the warm magnet interlock system for IR5 in the LHC

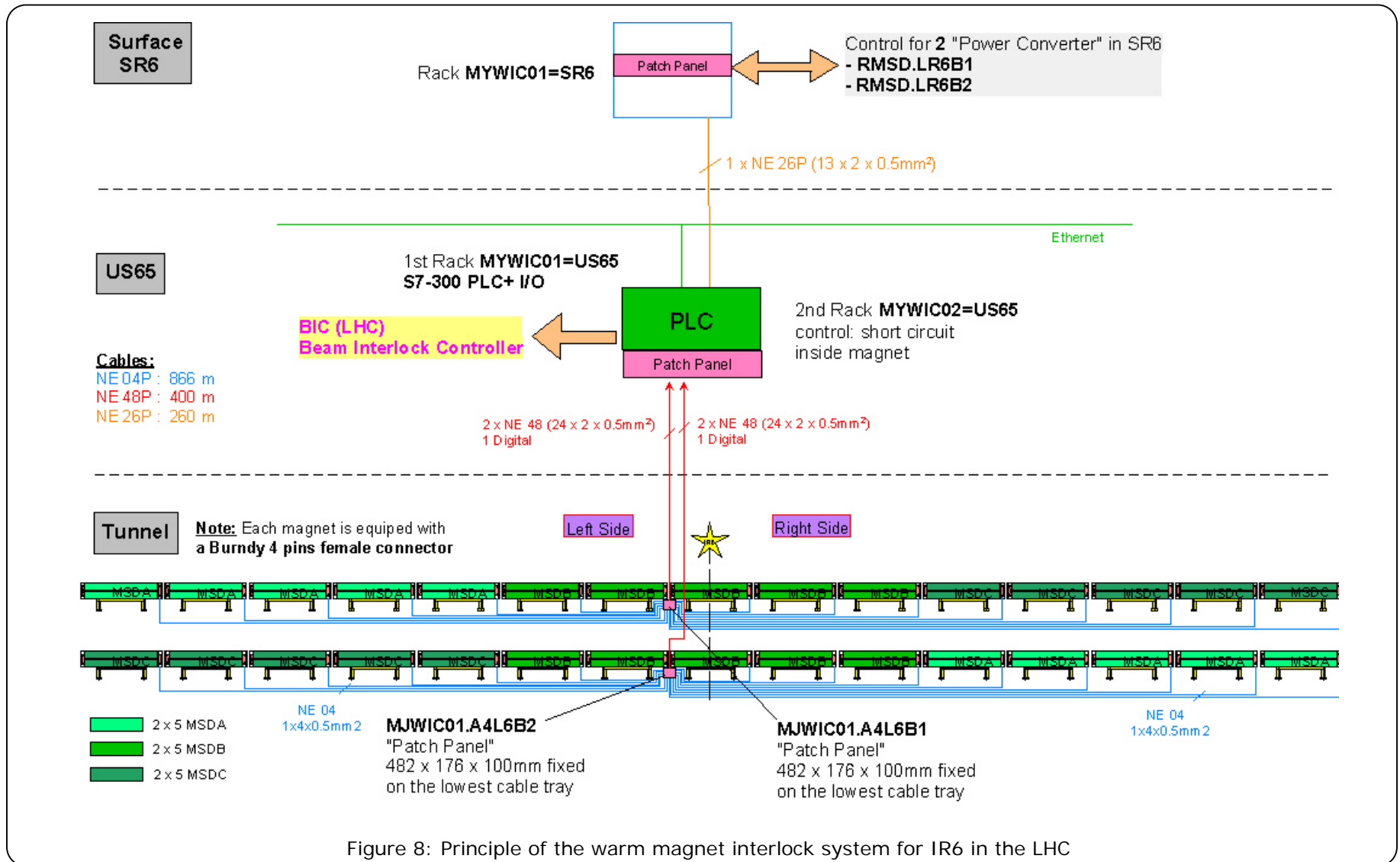


Figure 8: Principle of the warm magnet interlock system for IR6 in the LHC

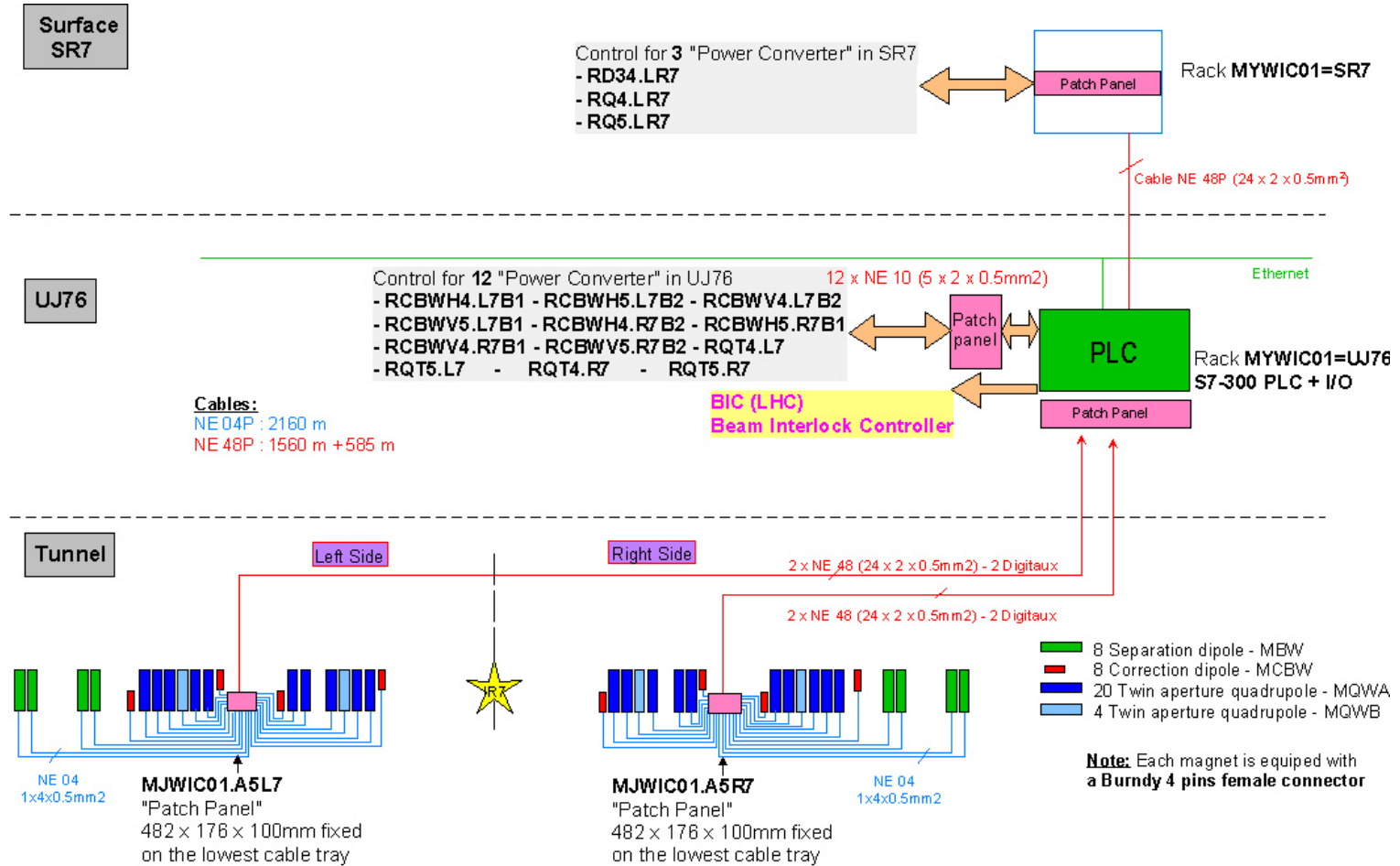


Figure 9: Principle of the warm magnet interlock system for IR7 in the LHC

(**Note!** Layout change in Version 6.5 due to new collimation layout affecting orientation and location of normal conducting magnets)

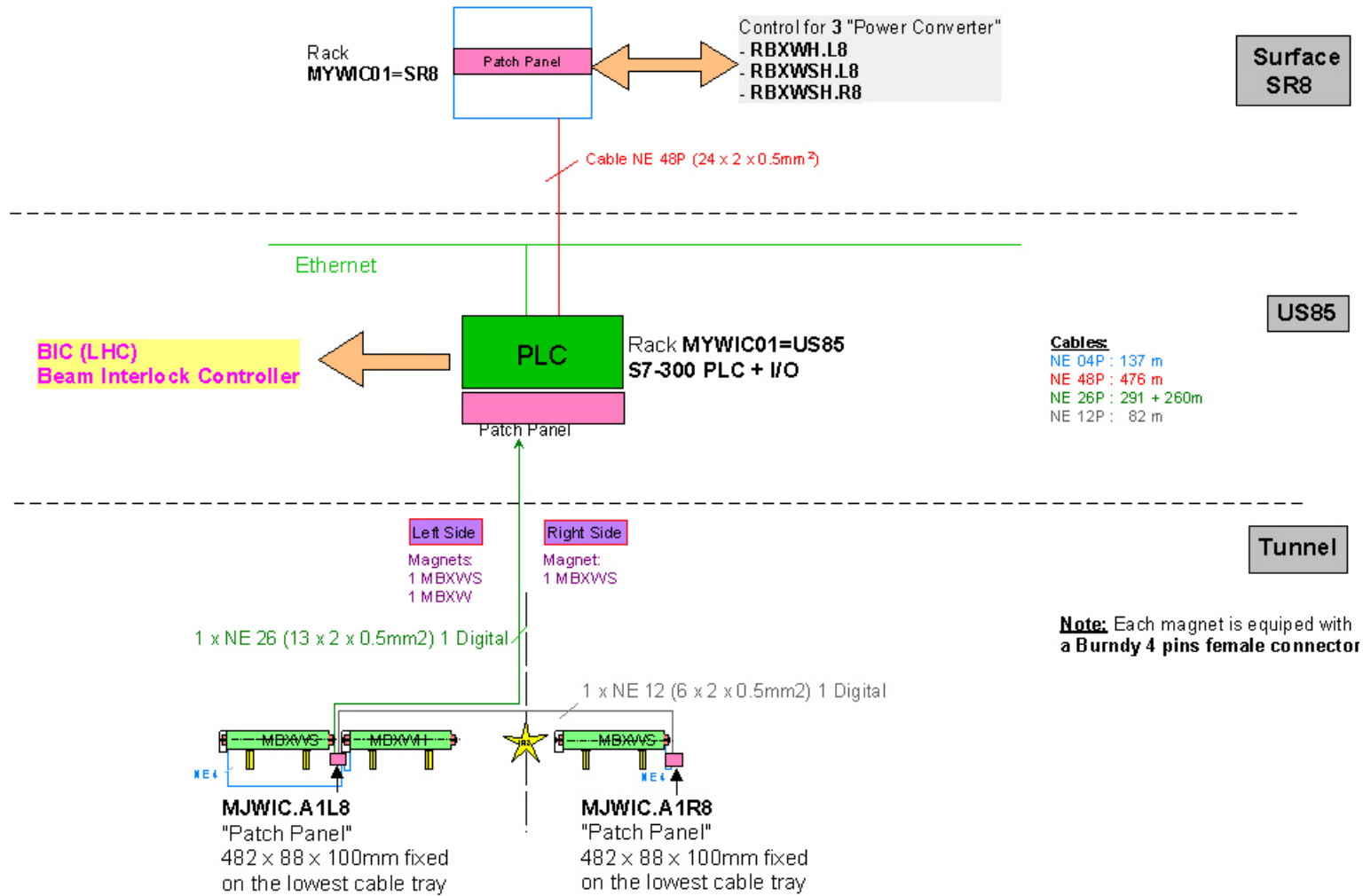


Figure 10: Principle of the warm magnet interlock system for IR8 in the LHC