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		Reference: **B24-06135-MB**
		Project: ISEULT upgrade

ISEULT PROJECT:

TECHNICAL SPECIFICATIONS OF A NEW POWER CONVERTER

SUMMARY

The goal of this specification is to define the parameters, for the realization and delivery of a new 1500 A DC/DC power converter for the 11.7T MRI called ISEULT.

B	Official	23	Q.GUIHARD	A.SINANNA	J.BELORGEY	**Date:** **13/12/2024**
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PLAN

1. Purpose – Actors

1.1. Document purpose

Technical specification of a DC/DC power converter dedicated to the ISEULT project

1.2. Types of business

The tenderer will make a detailed offer for the realization, the tests and the delivery of a low voltage DC/DC power converter, which delivers 1500 A ±15mA DC to power the Iseult MRI superconducting magnet. This power converter will be designed with redundancy and modularity to guarantee the highest availability of the MRI magnet.

1.3. Actors

- Project owner : CEA/DRF/Joliot/NEUROSPIN
- Project manager : CEA/DRF/IRFU/DIS/LEIGE
- Final users : CEA/DRF/Joliot/NEUROSPIN/

1.4. Technical contacts

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2. CONTEXT

MRI equipment require a very stable magnetic field to operate optimally. Indeed, any fluctuation in the magnetic field amplitude is accompanied with a proportional change in the proton resonance frequency. Because the MRI technique precisely revolves around the measurement of that resonance, a change in the magnetic field “detunes” the whole system. Consequences are blurry, out-of-focus or shaky reconstruct images. Thereby, having a very stable magnetic field is paramount for MRI systems performance. The magnetic field of superconducting MRI magnets slowly decays over time. Most MRI systems operate in the so-called “persistent” mode in which the current decay is sufficiently slow to be not a major concern. However, the unique winding technique used for Iseult causes a faster field decay due to the large number of inner resistive joints. This is why the persistent operating mode was not an option for Iseult, which have to be actively stabilized to stay within a magnetic field drift < 0.05 PPM/h.

The Iseult magnet is equipped with two main components to reach the specification of a drift of less than 0.05 ppm/h:

1) a highly stabilized power converter (PCS) designed to maintain the current up to 1500 A in the magnet

Considering a current of 1470 A to reach the nominal magnetic field of 11.7 T in the magnet and the PCS full-scale long-term current stability of 10 ppm in 8 h, a drift of 0.05 ppm/h is not achievable by only using a highly stabilized power converter.

2) a filter resistor with a superconducting fault current limiter (FCL) (patented by CEA)

The first highly stabilized power converter (PCS) has been bought in 2012; this document details the technical specifications for replacing this power converter called **PCS**.

3. TECHNICAL SPECIFICATIONS

3.1. Environment

3.1.1. *Environmental conditions*

Technical room temperature	18 °C ≤ θ ≤ 25 °C
Relative humidity	50-70 %

3.1.2. *Electrical power network*

Mains supply	53 Vdc – 45 Vdc with battery back up
Power converter maximum consumption	8000 W
Grounding	Floating ground with insulation monitoring device

3.1.3. *Mechanical constraints*

The power converter is placed on a raised floor.

Dimensional constraints	
Maximal height	2200mm
Maximal depth	800mm
Maximal length	1200mm

All the electrical cables and water pipes pass through the rear bottom left of the cabinet.

Connector constraints	
Input cable	Positive polarity : 1x 150mm2 HIFLEX CY1000 Negative polarity : 1x 150mm2 HIFLEX CY1000
Output cables	Positive polarity : 6x 240mm² U1000R2V Negative polarity : 6x 240mm² U1000R2V
Earth cable	1x 50 mm² H07V-K

Cabinets should be equipped with removable lifting eye bolds and their bottom should be strong enough to permit the handling by a forklift.

The maximum allowable sol-bearing limit is 500 kg/m^2

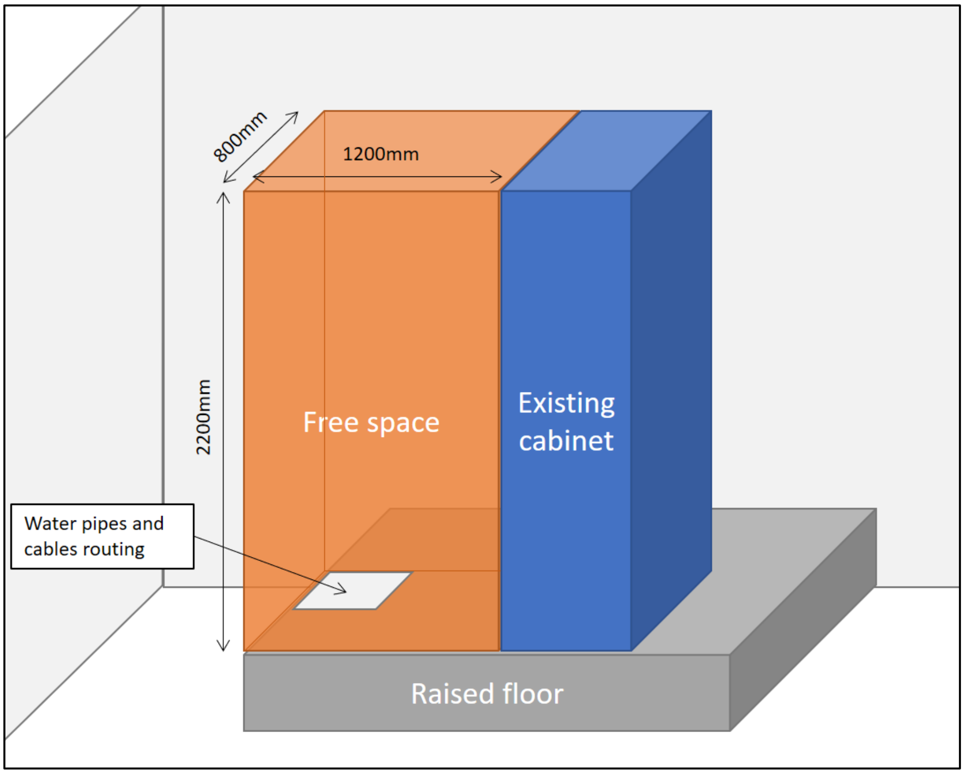

Fig. 1 : Layout view

3.1.4. *Cooling*

Cooling	De ionized water
Max pressure	5 bars
Max flow rate	6 l/min
Heat exchanger capacity	2500W (delta T = 10 °C)
Setting temperature	20 °C ≤ θ ≤ 30 °C
Temperature accuracy	< ±1 °C
Resistivity	< 1 MΩ, conductivity 10 µS mini

The cooling unit could be managed by CEA to fit the new power converter needs.

3.1.5. *Fringe field of the magnet*

The fringe field of the magnet near the power converter *PCS* is lower than 2 mT.

3.2. Load specifications

	Iseult magnet
Inductance (H)	311
Nominal current (A)	1470
Line resistance (mΩ)	1.5
Fast dump resistor (Ω)	2.3
Magnetic energy (MJ)	336

Table 1: ISEULT magnet parameters

Iseult MRI Magnet operates in driven mode, i.e. the magnet is permanently connected to a power supply, contrary to conventional MRI magnet. Furthermore, a stabilization circuit is added in parallel to the magnet (Fig. **3**), the aim is to reach a magnetic field drift lower than 0.05 ppm/h.
For the power converter design, tenderer will pay attention to the operation of the superconducting magnet with its stabilization circuit. Operating principle is described in paragraph 3.2.2

3.2.1. *Electrical diagram*

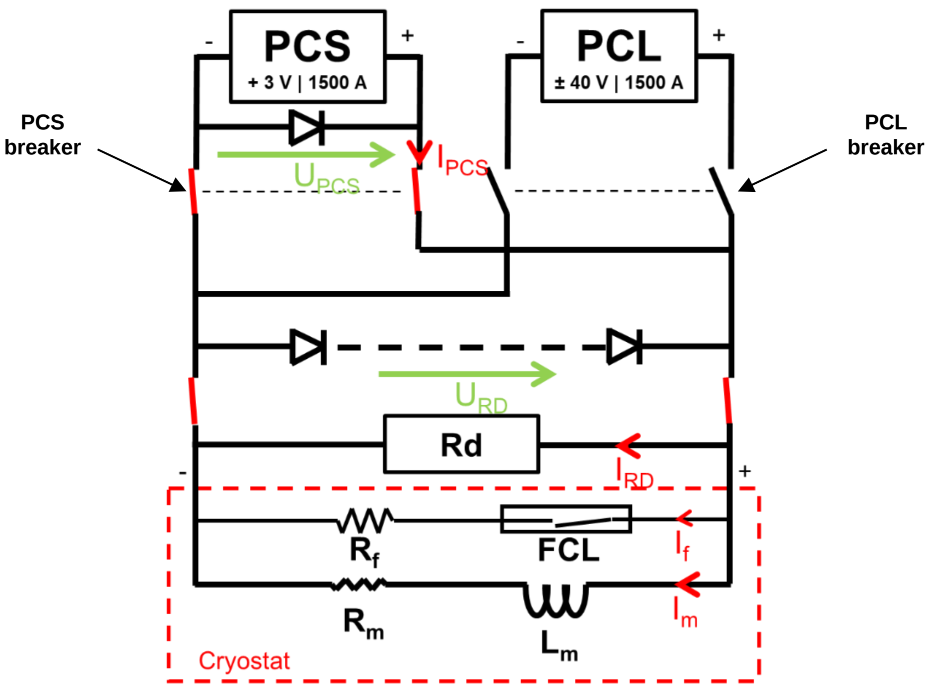

Fig. 2 : Electrical diagram

Rm	240 nΩ	Residual resistance of the superconducting magnet
Lm	311 H	Inductance of the magnet
Rf	24 uΩ	Resistance of the low pass filter
Rd	2.3 Ω	Resistance used to discharge the magnet
FCL		Fault Current Limiter; how it works is explained in paragraph 3.2.3.
PCS		Power converter for stabilization ; purpose of this specification
PCL		Power converter used to load the magnet with 40V

Table 2: Electrical diagram parameters

The operation of the electrical circuit to operate the Iseult magnet is as follows:

1) Closing the PCL breakers to connect the power converter for loading (PCL)
2) Loading the magnet to the nominal current of 1470A at 40V ; the FCL is opened due to the voltage across the magnet (see the 3.2.2)
3) Waiting for PCL to reach the current set point ; the FCL stays opened because of the voltage ripple of this power converter
4) Switching from PCL to PCS following this steps :
    a. Closing the PCS breaker
    b. Turning off the PCL ; the current is flowing through the PCS free wheel diodes
    c. Opening the PCL breakers
    d. Turning on the PCS with a current set point closest to the magnet current to take back control of the current
5) Adjusting the current in the magnet following the Imaging Team measurement ; **a set point resolution of 10mA is needed**
    a. When the set point is reached, the FCL closes automatically because of the low voltage ripple of PCS
    b. If the current is not at the right value and the FCL is closed, PCS can generate a pulse of 50A during 200ms to open the FCL and adjust again the current
6) Adjusting the current in the FCL to stabilize the current with PCS ; the value of current to add is about 14A
7) Staying at 1470 A + 14 A (Im + If ; Magnet current + FCL current) during 1 year without interruption ; annual maintenance is planned
8) To unload the magnet, the operation is the same as for the loading.

During the operation of loading and unloading the magnet, only one power converter is ON (PCL or PCS) but during a short time (<500ms), their output impedances are connected to each other; Especially the capacitors banks that can cause some oscillations.

The free wheel diodes at the output of PCS is composed of 8 air cooled Schottky diode MBRA801100CT from daco semiconductor.

3.2.2. *Field stabilization circuit*

This circuit includes a superconducting fault current limiter *FCL* in series with a 24 µΩ resistor R_F. The *FCL* behavior is like a variable impedance, R_{FCL} is the resistance of *FCL*. Stabilization circuit diagram is given in Fig. **3**. *L* and *R* are respectively the inductance and residual resistance of the magnet. R_D is the 2.3 Ω resistor of dump circuit. Let us call I_{PS} the current supplied by the power converter *PCS*, Kirchhoff's current law is given by equation (1).

$$I_{PS} = I_{RD} + I_{FCL} + I_0 \tag{1}$$

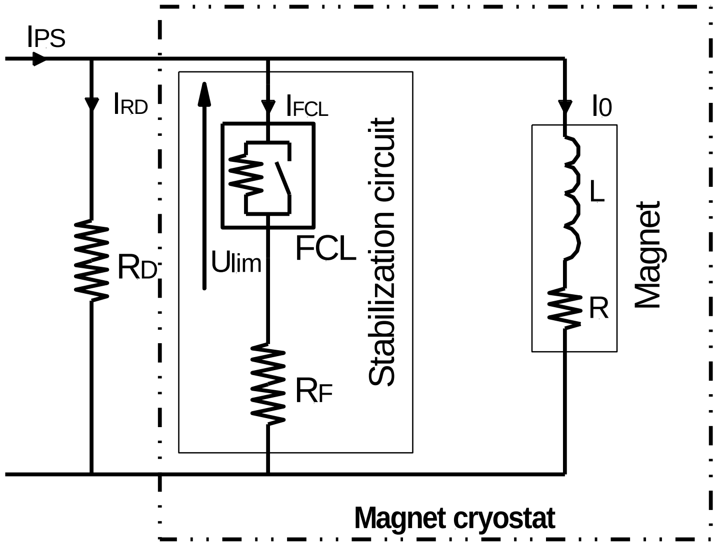

Fig. 3 : Stabilization circuit

Fault current limiter (FCL) designed for Iseult MRI magnet is wounded as a non-inductive coil (<5mH) and operates at cryogenic temperature (1.8 K). The coil is made with NbTi superconducting wire and its critical current *Ic* is assumed lower than 50 A in an operating condition.

This FCL is designed to work in two operating modes:

⇨ acting as a current low pass filter when the FCL is superconductive;

In this "filter mode", almost all the current ripples coming from PCS pass through the filter resistance branch and not in the magnet branch due to the huge difference of impedance between the two branches. In this mode, the load impedance can be considered as a short circuit of **1.5mOhm and 4mH.**

⇨ No acting when the FCL is resistive.

In this "open mode", FCL is resistive and all the current can pass through the magnet to increase or decrease the magnetic field.
In this mode, the load impedance can be considered as **a highly inductive impedance of 311 H in series with a resistance of 1.5mOhm**

The conditions of switching between the two operating modes are also important:

- **"filter mode" ➔ "open mode"**: it happens when the FCL critical current is reached (pulse of 50A or when AC losses are too high).
- **"open mode" ➔ "filter mode"**: it happens when **the magnet loading voltage is very low and stable enough (Ripple and noise < 10 mV p to p ; see Fig.4**)

For more information, you can check the following reference:

SINANNA, A (2010). *"Field Stabilization of the Iseult/Inumac magnet operating in Driven Mode"*

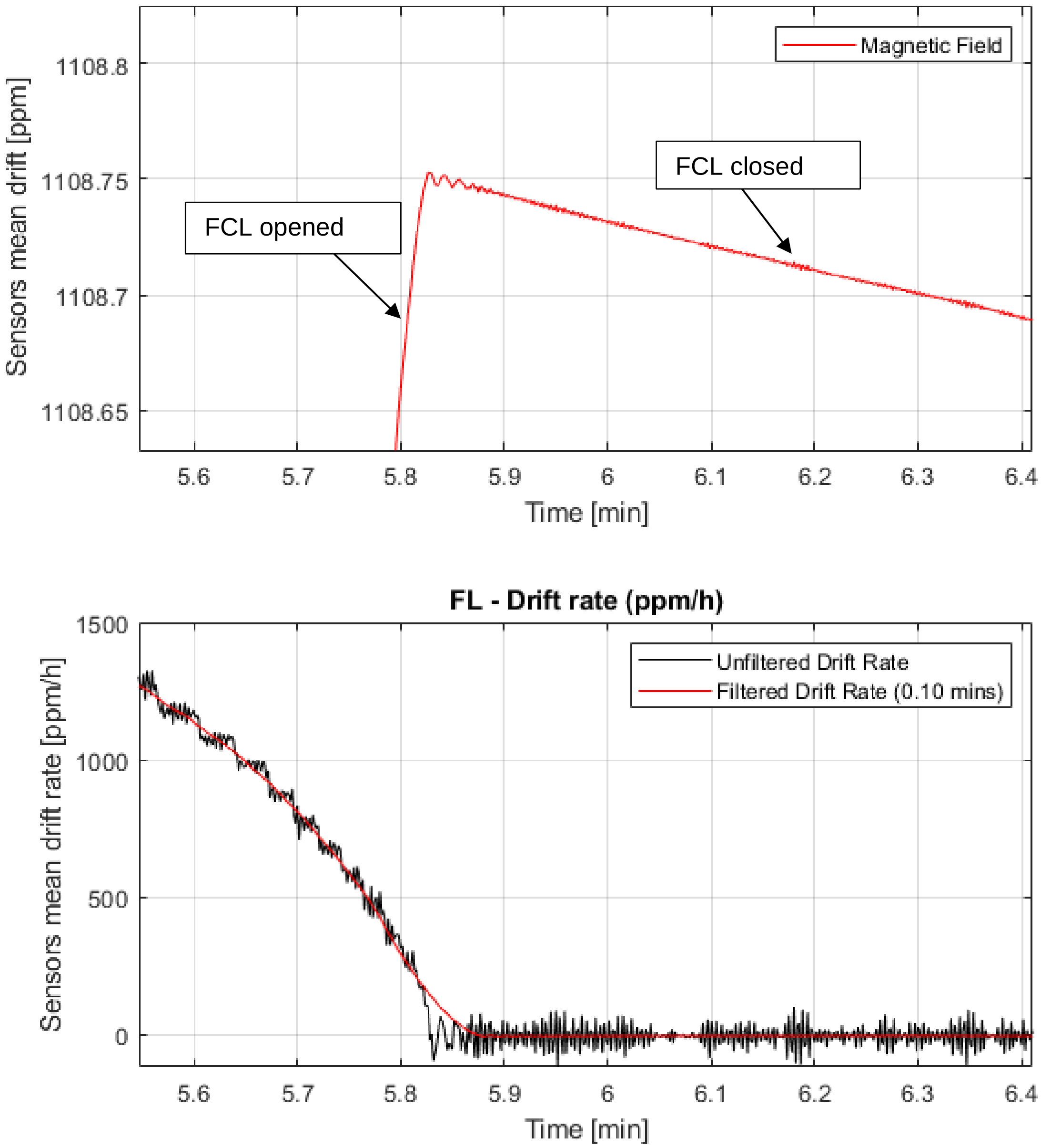

Fig. 4 : FCL closing: a transition between the “open mode” and the “filter mode”

3.3. Power converter specifications

3.3.1. *Performances*

Maximum output current (I_{max})	1500 A
Minimum output voltage (V_{min})	+3 V
Peak output current during FCL pulse (I_{peak})	1550 A
Peak output voltage during FCL pulse (V_{peak})	5 V
Setting range of the output current	from 0 to I_{max}
Long term current stability (8h)	< 10 ppm
Current setting resolution	< 5 ppm
Current accuracy	< 20 ppm
Current reproducibility	< 20 ppm
Ripple and noise	< 10 mV p to p
Ambient temperature coefficient	< 5 ppm/°C
Maximum electrical consumption	8000 W

3.3.2. *Ramps*

The current ramp up and down should be adjustable from 1 mA/s to 1000 mA/s.

When turning on the power, with a current setting at 0, the output current should not exceed 0.1% of the maximum current.

The output current overshoot should not exceed 0.1% of the maximum current at the end of ramping.

3.3.3. *Catch up current*

PCS is mainly use when the magnet is already loaded by the PCL power converter.
Consequently, PCS should be design to be able to catch up the magnet current without fault.

3.3.4. *Extra-feature to open the FCL*

PCS should be able to generate a pulse of current with the followings specifications:

Maximum output current (ΔI)	50 A
Maximum Pulse duration	1000 ms

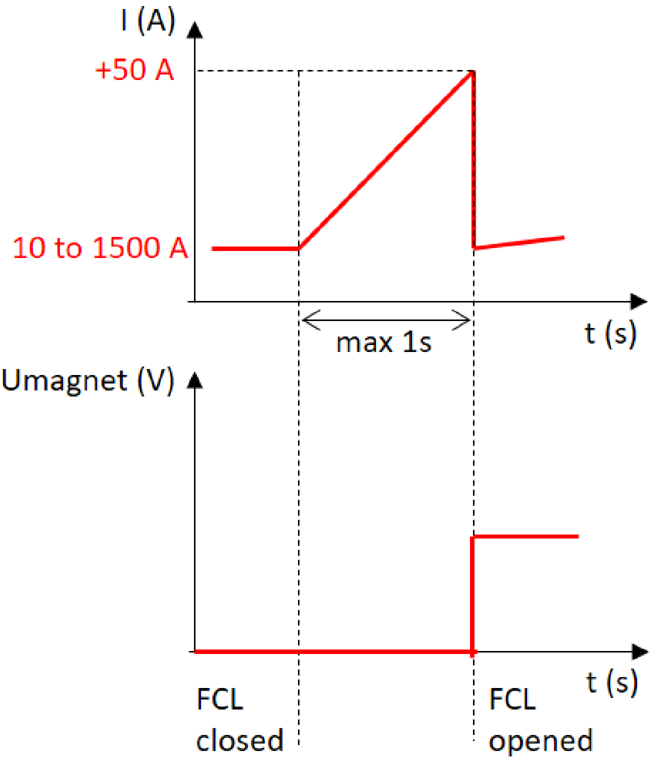

Fig. 5: Pulse FCL example

This pulse is only use when the FCL is close to open it and be able to change the current in the magnet. The pulse should not disturb the DC current regulation of PCS.

3.3.5. *Control*

The power converter should be controlled in local mode through a local panel and in remote mode using Profibus DP.

3.3.5.1. Local mode

Informations	Main power ON Auxiliary "ON" Power "ON/OFF" Local/remote Power converter inner fault 1st fault (memorized) Voltage readout Current readout
Commands	Power "ON/OFF" Open FCL Local/remote Fault clear "RESET" Current setting Ramp up and ramp down setting Output current limitation Output voltage limitation

The local panel and the information available will be discussed between the manufacturer and the CEA, to take into account specificities of the manufacturer control interfaces.

3.3.5.2. Remote mode

The power converter *PCS* is remotely controlled through a Profibus DP interface in slave mode with the following specification:

- Refresh rate = 500ms max
- Lag time = 500ms max

If the Profibus DP interface is not the standard protocol of the power converter, the use of gateways should be limited and a detailed diagram of the communication network should be delivered.

The Profibus DP connector will be a sub-D9 female on the power converter PCS.
Pin numbers used by CEA for Iseult project are given in Table 3.

Table 3: CEA Sub-D9 of profibus DP interface

Pin no.	Signal	Significance
1	Shield	Shield or functional ground
3	TXD+/RXD+ (B)	Received/transmitted data - P
5	DGND	Data reference potential output
6	VP	Power supply voltage output
8	TXD−/RXD− (A)	Received/transmitted data - N

This interface will have the same functions as the local control panel. It should memorized the fault which has turned off the power converter, called "1st fault memorization".

3.3.5.3. Regulation Parameters

The regulation parameters used to control the current and voltage loop need to be accessible and editable by CEA in an “expert mode” accessible using a password.
The FCL pulse settings should also be accessible by CEA.
In case of analog regulation, a procedure should be delivered.

3.3.5.4. Interlocks inputs

The interlock input have to shut down the output of *PCS* safely.
The Interlock input specification are given below:

- “Magnet discharge”, digital input
  - Close contact ➔ PCS output ON
  - Open contact ➔ PCS output OFF

- “Interlock PCL/PCS”, digital input
  - Close contact ➔ PCS output ON
  - Open contact ➔ PCS output OFF

3.3.5.5. Auxiliary contacts

- “Power ON”, 2x relays contacts without voltage
- “Power OFF”, 2x relays contacts without voltage
- “Power converter fault”, relay contact without voltage

The rated voltage is 24 V and the rated current is 20 mA for relay contact.

3.4. Redundancy and modularity

To be able to guarantee the highest availability of the MRI magnet, the power converter should be design with redundancy and modularity.

The redundancy should be achieved using more power output modules than needed, for example:
  - 4 modules of 500A in parallel;
  - 16 modules of 100A in parallel;

In case of a module failure, the power converter should be able to continue with the remaining modules.

The modularity should be achieved using modules that can be easily replaced without specifics skills in electronics.

4. TESTS

4.1. Factory acceptance tests (FAT)

The factory acceptance tests must include all tests usually performed by the contractor as well as the tests in the paragraph 4.1.1. The report must include the results, test conditions and measurement devices used. CEA reserves the right to request the certificate of calibration of each measurement device and to visit the contractor during the completion of the FAT.

4.1.1. *Electrical tests*

The output of the power converter have to be fully load to deliver their maximum current and voltage. The following measurements have to be done after 2 hours of warm-up

4.1.1.1. Current measurements

With an appropriate measuring device, the following data have to be measured:

- The output current with the maximum set point;
- The current stability on an 8h timespan;
- The measurement of the current ramp in three points between the maximum and the minimum.

4.1.1.2. Voltage measurements

With an appropriate measuring device, the following data have to be measured:

- The output voltage with the maximum set point on a resistive load;
- The ripple and noise (20 MHz) voltage.

4.1.1.3. Power consumption tests

With an appropriate measuring device, the consumption have to be measured with a power network of 48 VDC.

4.1.1.4. Temperature Measurement

Doors closed and with an appropriate measuring device, the hot spot of the power converter has to be found and be measured. The datas of the cooling unit and environment temperature should also be recorded.

4.1.1.5. Functional tests

All the necessary functions to meet this specification document have to be tested and reported.

4.1.2. *Redundancy tests*

By shutting down a power module, the power converter should continue to supply the 1500A to the loads and continue to satisfy all the specifications.

4.1.3. *Pulse current tests*

With an appropriate measuring device, the pulse current have to be performed with the maximal output current, the following data have to be recorded during the pulse:

- The output current;
- The output voltage;
- The inrush current;
- The mains voltage.

4.1.4. *Remote control tests*

Connected to our control system, the protocol of communication will be fully tested by CEA in your facility, especially; all the commands and informations listed in 3.3.5 should be functional.

4.2. Saclay acceptance tests (SAT)

The Saclay acceptance tests will allow validating the power converter on the magnet load at the nominal current (1485 A).

4.2.1. *Electrical tests*

Connected to the magnet, to the 48VDC power network and to the cooling unit, the following measurements will be done after 2 hours of warm-up

4.2.1.1. Current measurements

With an appropriate measuring device, the following data have to be measured:

- The output current with the maximum set point;
- The current stability on an 8h timespan;
- The measurement of the current ramp in three points between the maximum and the minimum.

4.2.1.2. Voltage measurements

With an appropriate measuring device, the following data have to be measured:

- The output voltage with the nominal value;
- The ripple and noise (20 MHz) voltage.

4.2.1.3. Power consumption tests

With an appropriate measuring device, the consumption have to be measured.

4.2.1.4. Temperature Measurement

Doors closed and with an appropriate measuring device, the hot spot of the power converter has to be found and be measured. The data of the cooling unit and environment temperature should also be recorded.

4.2.1.5. Functional tests

All the necessary functions to meet this specification document have to be tested and reported.

4.2.2. *Pulse current tests*

Connected to the magnet, to the 48VDC and to the cooling unit, at the nominal current, the current pulse have to be measured and check that the FCL is opened

4.2.3. *Catching current tests*

Connected to the magnet, to the 48VDC and to the cooling unit, at the nominal current, a switch from PCL to PCS will be performed to see if PCS is able to catch up the current.

4.2.4. *Redundancy tests*

By shutting down a power module, the power converter should continue to supply the 1485A to the magnet and continue to satisfy all the specifications.

4.2.5. *Remote control tests*

Connected to our control system, the protocol of communication will be fully tested by CEA in our facility, especially, all the commands and information listed in 3.3.5 should be functional.

5. IDENTIFICATION, CLEANING, PACKING, SHIPPING

5.1. General requirements

The following general requirements apply to every components delivered by the contractor. The contractor shall receive CEA's approval before shipping. Once the power converter successfully passed theirs FAT and received CEA's approval, the contractor shall deliver it to CEA.

The Contractor shall transport the power converter, and more generally all materials and equipment necessary for performance of the Contract, to the required location.

The power converter packaging shall be secured to protect them from any damages during handling and shipping.

Below is a list of the contractor responsibilities regarding the shipping and transport:

- power converter preparation prior to loading onto the transportation vehicle;
- power converter loading onto the transportation vehicle;
- power converter inside the transportation vehicle;
- inspection of power converter inside their transportation vehicle;
- transport of power converter from the Contractor's site to CEA;
- inspection of power converter inside their transportation vehicle at CEA site;
- delivery and unloading in the determined CEA's premises.

5.2. Packaging restrictions

All wood packaging material have to comply with International Standards For Phytosanitary Measures No. 15 (ISPM 15)..

6. TENDER CONDITIONS

6.1. Tender Phases Description and Acceptance Criteria

6.1.1. *Scope of the contract*

The contract is split into 3 main phases:

- **PHASE 1:** Validation of the power converter

The power converter topologies and specifications will be validated during the phase 1. The integration studies and the electrical drawings will be validated during this phase too.

- **PHASE 2:** Realization and tests of the power converter

The power converter will be realized, integrated and tested in factory during the phase 2.

- **PHASE 3:** Saclay acceptance tests of the power converter

The power converter will be fully tested in CEA connected to the MRI magnet during the phase 3.

6.1.2. *Kick-off Meeting*

A kick-off meeting, gathering both the Contractor and CEA representatives, is organized to start the Design Validation Phase. During the meeting, the Contractor and CEA representatives shall come to a common understanding about how they will communicate during the project. They introduce their main collaborators and verify that they agree on the present specifications document and on the project schedule.
During the meeting, the Contractor shall also provide to CEA the following documents:

- a pre-study of the power converter;
- a detailed diagram of the communication network;
- some information about all other equipment including the integration and the tests planned;
- a detailed project schedule;

To prepare the kick-off meeting, a document package composed only of computer readable files, shall be sent to CEA two weeks before the meeting is held. The document package shall include the contractor's Quality Assurance Plan, and demonstrate that the contractor has a correct understanding of the performance that the power converters design shall reach, and that he has a viable project schedule and risk management plan in place. The kick-off meeting shall take place at CEA Saclay.
A visit of the MRI facility will take place during the Kick-off meeting especially to show and explain to the Contractor how it works with the actual PCS.

6.1.3. *Phase 1: Design validation and integration studies*

The contractor is responsible for the studies, the realization, the integration and for the delivery to CEA Saclay of the power converter that meets all the requirements defined in the present technical specifications.

The design validation and integration studies shall include:

- the detailed performances and topology of the power converter meeting the specifications;
- the delivery of a 2D drawing of the integration.
- the delivery of electrical drawings of complete and functional 19" cabinets;
- the Integration and Test Plan (ITP).

The Contractor shall deliver to the CEA a Final Design Report, two weeks before the Final Design Review.

The Final Design Report is a document package composed only of computer readable files. It shall demonstrate that each kind of power converter meet the specifications. It shall also demonstrate the contractor's ability to realize complete and integrated power converter that meets the present technical requirements. The ITP shall describe how FAT will be done on the power converter. The Final Design Report shall also cover all the work previously described. The Final Design Review shall take place at the Contractor's premises.

CEA may request the contractor to cover additional specific subjects for the review if necessary. CEA will allow the contractor to proceed, with the realization phase, after successful completion of the FDR.

6.1.4. *Phase 2: Realization Phase*

After the successful Final Design Review, the contractor shall begin the realization and integration of the power converter. The power converter shall be realized and quality controlled by the documents and procedures reviewed and approved by CEA during the Final Design Review.

The realization work shall include:

- the procurement of materials and components;
- the fabrication of the complete power converter cabinets;
- the FAT of the power converter;
- the packing and shipping of the power converter to CEA Saclay;

After FAT, the contractor shall proceed, after CEA's approval, to the delivery of the power converter.

6.1.5. *Phase 3: Final Tests Phase*

After the completion of the Factory Acceptance Tests and the delivery of the power converter, the contractor and the CEA shall begin the Saclay acceptance tests of the power converter.

The Final tests phase shall include:

- the implementation of the power converter in the technical room;
- the wiring of the power converter;
- the SAT of the power converter;

During the phase 3, the Contractor shall be at Saclay to perform the implementation, the wiring and the SAT.

After validation of the SAT by CEA, an acceptance report will be delivered to the Contractor.

6.2. Quality Assurance

6.2.1. *Process and quality control plan*

The Contractor shall provide CEA with a detailed quality plan (QP) two weeks before the kick-off meeting. This QP shall be effective for all the phases of the contract, including design, procurement, realization, integration, inspection and test of the power converter.

Quality assurance standard

The Contractor shall inform in written form the CEA of any change in the validity of its ISO 9001 (or equivalent) certification during the contract. The Contractor shall demonstrate that its suppliers and subcontractors are currently ISO 9001 (or equivalent) certified. The Contractor shall ensure that each of his suppliers and subcontractors has a similar Quality System or a suitable alternate system, or, failing this, he will undertake all the necessary actions to establish and maintain the quality in their premises.

Change Request (CR):

During the contract's implementation, the contractor may propose to have the scope of the power converter specification modified through a Change Request.

A CR shall include the following information:

- motivation for the change of scope;
- objective of the change of scope;
- description of the proposed scope modification;
- description of the impact of the change of scope on the project execution;
- verification that the change of scope objective is reached after the implementation of the proposed modifications.

An CR shall be reviewed and approved by the contractor's quality control representative and sent to CEA for approval prior to proceeding with the proposed changes of scope.

After approval by CEA of the CR, the contractor can resume his activities by implementing the new scope. It is the responsibility of the contractor to check the results of the scope modification, compare them to the CR objective, record them in the CR and report them to CEA.

CEA reserves the right to visit the Contractor's and its sub-Contractors' facilities at any time during the execution of the project for the purposes of making inspections of the work and project related activities.

CEA will provide the Contractor with reasonable advanced notice of any site visits or inspections that are not already planned and required by the specifications. Such visits or inspections will be done during normal business hours unless other arrangements that have been mutually agreed on are made.

6.2.2. *Visits by CEA representatives*

The Contractor shall arrange for CEA representatives a free access to its sub-Contractor's premises during all the phases of the contract. Mandatory and optional inspections shall be carried out in accordance with the Quality Plan (QP). The contractor shall send a list of the sub-contractors involved in the project so that CEA can review and validate it.

The Contractor shall also arrange other visitors to have free access, when invited by CEA to visit the Contractor's or sub-Contractor's premises, review the progress of the work and discuss the results of the inspections and controls.

CEA shall have the right to take photographic and video records of the work in progress on all aspects related to operations and components included in the deliverables for this contract. This shall also apply to any subcontractor's premises.

The Contractor is responsible for providing a safe working environment that meets CEA safety standards.