**SC magnets**

# TO PERFORM PROCESS FUNCTIONS. To generate the rated magnetic field with reduced joule losses: the energy consumption of the magnet system shall be small compared to other plant systems [1]

## To confine the plasma by means of the toroidal field (*🡪* **control system**) TF coil system

### To ensure the required current in the coils

#### To electrically connect two conductor lengths with low electrical resistance (joints/terminations)

##### To let the current flow from one conductor to another

##### To guarantee a low electrical resistivity

##### …

#### To transfer the current from the power supply to the coils with low electrical resistance

##### To transfer the current from room to cryogenic temperature (current leads)

##### To transfer the current from outside the cryostat to the coils (busbar)

##### To cool the electrical lines connecting the coils to the power supply in order to reduce the Joule losses below a given threshold

###### To guarantee adequate inlet thermodynamic conditions (🡪 **cryoplant/cryodistribution**)

To guarantee the proper inlet temperature in the different sub-systems (magnets, BB, CL, …)

##### …

#### To avoid shorts and arcs

##### To electrically insulate the turns

###### To withstand the maximum voltage foreseen on the coil

###### To guarantee the required mechanical strength of the insulation

##### To electrically insulate the coil

###### To electrically insulate the coil from the cooling pipes

###### To electrically insulate the coil from the other coils

###### To electrically insulate the coil from other system components

##### To electrically insulate the CL

##### To electrically insulate the BB

##### …

#### …

### To maintain a constant magnetic field (peak up to 13 T in the superconductor) during the plasma pulse [1]

#### To control the current to a constant value in the TF WP (🡪**control system, PES**)

##### To prevent FD

###### To prevent quench

###### To prevent spurious FD

##### To measure the current

##### To transfer the measured current value to the control system

##### …

#### …

### To guarantee a magnetic field ripple smaller than 0.6% [1]

#### To provide mechanical support to the magnets at cryogenic temperature for their proper positioning

##### To withstand the Lorentz forces on cable (jacket/RPs/casing/intercoil structures)

##### To provide mechanical support to the coils against gravity (gravity support)

##### To limit the coil relative movement due to dynamic Lorentz forces

##### …

### …

## To provide adequate magnetic field to control/drive the plasma current (🡪 **control system, PES**) (CS and PF coil system)

### To ensure the required current in the coils

#### To electrically connect two conductor lengths with low electrical resistance (joints/terminations)

##### To let the current flow from one conductor to another

##### To guarantee a low electrical resistivity

##### …

#### To transfer the current from the power supply to the coils

##### To transfer the current from room to cryogenic temperature (current leads)

##### To transfer the current from outside the cryostat to the coils (busbar)

##### …

#### To avoid shorts and arcs

##### To electrically insulate the turns

###### To withstand the maximum foreseen voltage on the coil

###### To guarantee the required mechanical strength of the insulation

##### To electrically insulate the coil

###### To electrically insulate the coil from the cooling pipes

###### To electrically insulate the coil from the other coils

###### To electrically insulate the coil from other system components

##### To electrically insulate the CL

##### To electrically insulate the BB

##### …

#### …

### To allow current/magnetic field variations to initiate the plasma (break down), ramp up and ramp down

#### To withstand current variations

#### To withstand magnetic field variations

##### To limit inductive effects

##### To limit heat generation from AC losses

###### To limit coupling losses in the SC

###### To limit hysteresis losses in the SC

###### To limit eddy currents in the stabilizer

###### To limit eddy currents in the jacket

###### To limit eddy currents in the casing

##### …

#### To withstand cyclic mechanical loading

#### To provide mechanical support to the coils at cryogenic temperature for their proper positioning

##### To withstand the Lorentz forces on cable (jacket/pre-compression tie plates)

##### To provide mechanical support to the coils against gravity (supports)

##### To limit the coil relative movement due to dynamic Lorentz forces

##### …

#### …

### To allow current/magnetic field variations to generate a magnetic flux that enables a pulse length of 2h at nominal plasma current (peak up to 13 T in the superconductor) [1]

#### To allow high negative current

##### To withstand forces in opposite direction during a transient

##### …

#### To withstand current variations

#### To withstand magnetic field variations

##### To limit inductive effects

##### To limit heat generation from AC losses

###### To limit coupling losses in the SC

###### To limit hysteresis losses in the SC

###### To limit eddy currents in the stabilizer

###### To limit eddy currents in the jacket

###### To limit eddy currents in the casing

##### …

#### To withstand cyclic mechanical loading

#### To provide mechanical support to the coils for their proper positioning

##### To withstand the Lorentz forces on cable (jacket/pre-compression tie plates)

##### To provide mechanical support to the coils against gravity (supports)

##### To limit the coil relative movement due to dynamic Lorentz forces

##### …

#### …

### To stabilize and control the plasma position [1]

#### To allow high negative current

##### To withstand forces in opposite direction during a transient

##### …

#### To withstand current variations

#### To withstand magnetic field variations

##### To limit inductive effects

##### To limit heat generation from AC losses

###### To limit coupling losses in the SC

###### To limit hysteresis losses in the SC

###### To limit eddy currents in the stabilizer

###### To limit eddy currents in the jacket

###### To limit eddy currents in the casing

##### …

#### To withstand cyclic mechanical loading

#### To provide mechanical support to the coils for their proper positioning

##### To withstand the Lorentz forces on cable (jacket/pre-compression tie plates)

##### To provide mechanical support to the coils against gravity (supports)

##### To limit the coil relative movement due to dynamic Lorentz forces

##### …

#### …

## To transport the current in SC mode

### To guarantee a minimum temperature margin in the conductor of 1.5 K [1]

#### To remove the heat generated in the superconductor

##### To guarantee a sufficient coolant flow (🡪 **cryoplant/cryodistribution**)

###### To limit the pressure drop (space for coolant flow with low hydraulic impedance)

###### To confine the magnet coolant flow (jacket)

To guarantee leak tightness of the coolant supply/return pipes / circuit components (🡪 **cryoplant/cryodistribution**)

To guarantee leak tightness of the coolant inlets/outlets

To guarantee leak tightness of the conductor jacket

…

###### …

##### To guarantee adequate inlet thermodynamic conditions (🡪 **cryoplant/cryodistribution**)

###### To guarantee the proper inlet temperature in the different sub-systems (magnets, BB, CL, …)

##### To guarantee adequate heat transfer coefficient

##### To guarantee a sufficient thermal capacity of the cable

##### To guarantee a sufficient thermal capacity of the coolant

##### …

#### To remove the heat deposited in the structures

##### To guarantee a sufficient coolant flow (🡪 heat transfer coefficient)

###### To limit the pressure drop (space for coolant flow with low hydraulic impedance)

###### To confine the magnet coolant flow (jacket)

To guarantee leak tightness of the coolant supply/return pipes / circuit components (🡪 **cryoplant/cryodistribution**)

To guarantee leak tightness of the coolant inlets/outlets

To guarantee leak tightness of the conductor jacket

…

###### …

##### To guarantee adequate inlet thermodynamic conditions (🡪 **cryoplant/cryodistribution**)

##### To guarantee adequate heat transfer coefficient

##### …

#### To limit the heat load

##### To limit the AC loss

###### To limit coupling losses in the SC

###### To limit hysteresis losses in the SC

###### To limit eddy currents in the stabilizer

###### To limit eddy currents in the jacket

###### To limit eddy currents in the casing

##### To limit the static heat load

###### To limit the radiative heat load (thermal shield)

###### To limit the conductive heat load (gravity support, CS and PF supports)

To guarantee a suitable coolant temperature at the CL inlet

…

###### …

##### To limit the nuclear heat load (neutron shield)

##### …

#### To guarantee proper performance of the coil (TCS)

##### To guarantee performance of the virgin conductor

##### To maintain performance during cyclic mechanical load

##### To maintain performance after cyclic thermal load

##### To avoid damages due to neutron irradiation (DPA)

###### To shield the neutron flux

###### …

##### …

#### …

# TO PROVIDE PROTECTION OF INVESTMENT. To protect the integrity of the magnet system and other tokamak subsystems

## To prevent damage to magnet system components

### To avoid mechanical damages to the magnets

#### To avoid mechanical overloads due to electro-magnetic forces

##### To control the current in the coils

###### To measure the current

###### To transfer the measured current value to the control system

##### To control coil displacements

###### To measure the coil displacements

###### To transfer the measured coil displacement values to the control system

##### …

#### To avoid thermo-mechanical overloads

##### To ensure cooling

##### To prevent quench

##### To avoid spurious FD

##### …

#### To allow controlled FD

##### …

#### To monitor the magnet displacements

##### To measure the magnet displacements (strain gauges)

##### To transfer the measured magnet displacement values to the control system

#### To avoid damages due to neutron irradiation (DPA)

##### To shield the neutron flux

##### …

#### …

### To support the magnet mass against gravity

#### To accommodate movements during operation

#### …

### To avoid thermal overloads

#### To avoid thermal overloads due to plasma instabilities / mis-positioning

##### To allow safe plasma shutdown if required [2]

###### To withstand current variations

###### To withstand magnetic field variations

To limit inductive effects

To limit heat generation from AC losses

To limit coupling losses in the SC

To limit hysteresis losses in the SC

To limit eddy currents in the stabilizer

To limit eddy currents in the jacket

To limit eddy currents in the casing

…

###### …

##### …

#### To avoid quench

#### …

### To avoid abnormal electrical interference between the coils

#### To avoid shorts / arcs

##### To ensure suitable insulation between the coils

##### To ensure suitable insulation within the coils (turn/pancake/layer insulation)

##### To ensure suitable insulation to ground (ground insulation)

##### To ensure vacuum in the cryostat

###### To confine the magnet coolant

To guarantee leak tightness of the coolant supply/return pipes / circuit components (🡪 **cryoplant/cryodistribution**)

To guarantee leak tightness of the coolant inlets/outlets

To guarantee leak tightness of the conductor jacket

…

###### To confine the thermal shield coolant

To guarantee leak tightness of the coolant pipes / circuit components (🡪 **cryoplant/cryodistribution**)

…

###### …

##### To prevent abnormal tension

###### To measure the tension

###### To transfer the measured tension value to the control system

###### To avoid spurious FD

###### …

##### …

#### …

## To prevent damage to other system components (vacuum vessel, penetrations, primary cooling system, vacuum pumping system, …)

### To avoid mechanical failure of the magnets on the other system components

#### To avoid mechanical overloads due to electro-magnetic forces

##### To control the current in the coils

###### To measure the current

###### To transfer the measured current value to the control system

##### To control coil displacements

###### To measure the coil displacements

###### To transfer the measured coil displacement values to the control system

##### …

#### To avoid thermo-mechanical overloads

##### To ensure cooling

##### To prevent quench

##### To avoid spurious FD

##### …

#### To allow controlled FD

##### …

#### To monitor the magnet displacements (strain gauges)

##### To measure the magnet displacements (strain gauges)

##### To transfer the measured magnet displacement values to the control system

#### …

### To support the vacuum vessel mass against gravity

#### To accommodate vacuum vessel movements during plasma current variation

#### …

### To avoid overpressure in the cryostat

#### To confine the magnet coolant

##### To guarantee leak tightness of the coolant supply/return pipes / circuit components (🡪 **cryoplant/cryodistribution**)

##### To guarantee leak tightness of the coolant inlets/outlets

##### To guarantee leak tightness of the conductor jacket

##### …

#### To confine the thermal shield coolant

##### To guarantee leak tightness of the coolant pipes / circuit components (🡪 **cryoplant/cryodistribution**)

##### …

#### …

### To avoid thermal overloads due to plasma instabilities / mis-positioning

#### To allow safe plasma shutdown if required [2]

##### To withstand current variations

##### To withstand magnetic field variations

###### To limit inductive effects

###### To limit heat generation from AC losses

To limit coupling losses in the SC

To limit hysteresis losses in the SC

To limit eddy currents in the stabilizer

To limit eddy currents in the jacket

To limit eddy currents in the casing

###### …

##### …

#### …

### To avoid electro-magnetic overload on other system components (VV)

#### To control the current in the coils below a threshold

##### To measure the current

##### To transfer the measured current value to the control system

#### To control coil displacements

##### To measure the coil displacements

##### To transfer the measured coil displacement values to the control system

#### …

### To avoid abnormal electrical interference with other system components

#### To avoid arcs to other system components

##### To insulate electrically the coils from other system components

##### To avoid overpressure in the cryostat

###### To confine the coolant

###### …

##### To prevent abnormal tension

###### To measure the tension

###### To transfer the measured tension value to the control system

###### To avoid spurious FD

###### …

##### …

#### …

## To manage the magnetic energy

### To prevent the discharge of the magnetic energy in the coil

#### To prevent quench

#### To allow controlled FD

##### …

#### …

### To control the current in the coils

#### To measure the current

#### To transfer the measured current value to the control system

#### …

### …

# TO ENSURE SAFETY. To avoid the exposure of workers, public and environment to hazards

## To limit the occupational exposure to 200 mT over an 8-hour non-stop working day [2]

### To monitor the magnetic field where workers and public are expected to be present

### To limit the magnetic field below the threshold value where workers and public are expected to be present

#### To control the current in the coils below a threshold

##### To measure the current

##### To transfer the measured current value to the control system

#### To control coil displacements

##### To measure the coil displacements

##### To transfer the measured coil displacement values to the control system

#### …

### To keep the workers away from areas with magnetic fields higher than the allowed threshold

### To shield the magnetic field where workers and public are expected to be present

#### …

## To avoid the exposure to electrical risks

### To avoid electric shorts and arcs where workers and public are expected to be present

#### To ensure suitable insulation on the room temperature power supply (🡪 **PES**)

#### To prevent abnormal tension where workers and public are expected to be present

##### To measure the tension

##### To transfer the measured tension value to the control system

##### To avoid spurious FD

##### …

#### …

### To keep the workers and public away from areas with electric fields higher than the allowed threshold

### To shield the electrical field where workers and public are expected to be present

#### …

## To prevent damage to other safety system components related to radiological/chemical risk (VV, penetrations, primary cooling system, vacuum pumping system, cryostat…)

### To avoid mechanical failure of the magnets on the other system components

#### To avoid mechanical overloads

##### To control the current in the coils

###### To measure the current

###### To transfer the measured current value to the control system

##### …

#### To avoid thermo-mechanical overloads

##### To ensure cooling

##### To prevent quench

##### To avoid spurious FD

##### …

#### To allow controlled FD

##### …

#### …

### To support the vacuum vessel mass against gravity

#### To accommodate vacuum vessel movements during plasma current variation

#### …

### To avoid overpressure in the cryostat

#### To confine the magnet coolant

##### To guarantee leak tightness of the coolant supply/return pipes / circuit components (🡪 **cryoplant/cryodistribution**)

##### To guarantee leak tightness of the coolant inlets/outlets

##### To guarantee leak tightness of the conductor jacket

##### …

#### To confine the thermal shield coolant

##### To guarantee leak tightness of the coolant pipes / circuit components (🡪 **cryoplant/cryodistribution**)

##### …

#### To ensure the proper operation of the cryostat pressure relief systems (burst disk)

#### …

### To avoid thermal overloads due to plasma instabilities / mis-positioning

#### To allow safe plasma shutdown if required [2]

##### To withstand current variations

##### To withstand magnetic field variations

###### To limit inductive effects

###### To limit heat generation from AC losses

To limit coupling losses in the SC

To limit hysteresis losses in the SC

To limit eddy currents in the stabilizer

To limit eddy currents in the jacket

To limit eddy currents in the casing

###### …

##### …

#### …

### To avoid abnormal magnetic interference with other system components

#### To control the current in the coils below a threshold

##### To measure the current

##### To transfer the measured current value to the control system

#### To control coil displacements

##### To measure the coil displacements

##### To transfer the measured coil displacement values to the control system

#### …

### To avoid abnormal electrical interference with other system components

#### To avoid arcs to other system components

##### To insulate electrically the coils from other system components

##### To ensure vacuum in the cryostat

###### To confine the coolant

To confine the magnet coolant

To guarantee leak tightness of the coolant supply/return pipes / circuit components (🡪 **cryoplant/cryodistribution**)

To guarantee leak tightness of the coolant inlets/outlets

To guarantee leak tightness of the conductor jacket

…

To confine the thermal shield coolant

To guarantee leak tightness of the coolant pipes / circuit components (🡪 cryoplant/cryodistribution)

…

…

###### …

##### To prevent abnormal tension

###### To measure the tension

###### To transfer the measured tension value to the control system

###### To avoid spurious FD

###### …

##### …

#### …