

Cryoplant of COMPASS-U

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This document is intended for companies who have shown interest in the Preliminary Market Consultations for COMPASS-U Cryogenic system to initiate discussion and have feedback on fabrication viability of the system. It will provide very basic information about the system which is in the Design Phase. Nothing in this document is legally binding.

Version	Published	Changes
1.0	20. 5. 2020	Initial revision
1.1	1. 7. 2020	Added system interfaces, environmental factors, inventory control
1.2	21. 7. 2020	Added page numbering, tender launch date
2.0	25. 9. 2023	New style, complete update
2.1	4. 2. 2025	Updated cooled parts definition

Scope of this presentation

This document describes boundary conditions for a cryogenic cooling system intended for the tokamak COMPASS-Upgrade. Since the design / construction of COMPASS-Upgrade is ongoing some conditions might change or are not yet defined in sufficient detail. This document serves as a starting point for discussions with potential suppliers of such a system in a public tender procedure.

Additional details about the COMPASS-Upgrade tokamak can be found at :

https://www.ipp.cas.cz/Compass_U/

https://www.ipp.cas.cz/o-ufp/Verejne_zakazky/

Questions and request for clarifications shall be sent to **compass-u-cryogenics@ipp.cas.cz**

Tokamaks are scientific devices designed and used to explore the thermonuclear fusion, using **strong magnetic fields**. Tokamak **COMPASS-Upgrade** (being built at IPP Prague) will **use copper coils** to create such magnetic fields. To reach high intensities of magnetic field for required time, **coils are cooled down** to lower their electrical resistance (which allows usage of higher electric current). COMPASS-U will have the coils cooled close to **temperature of liquid nitrogen**.

Because of physical constraints, tokamaks are inherently running in **pulsed regime** - it is not possible to run the experiment for longer period of time. For COMPASS-U, the single "pulse" will last maximally 10 seconds. During the pulse, current is run through the coils, causing them **to heat up**.

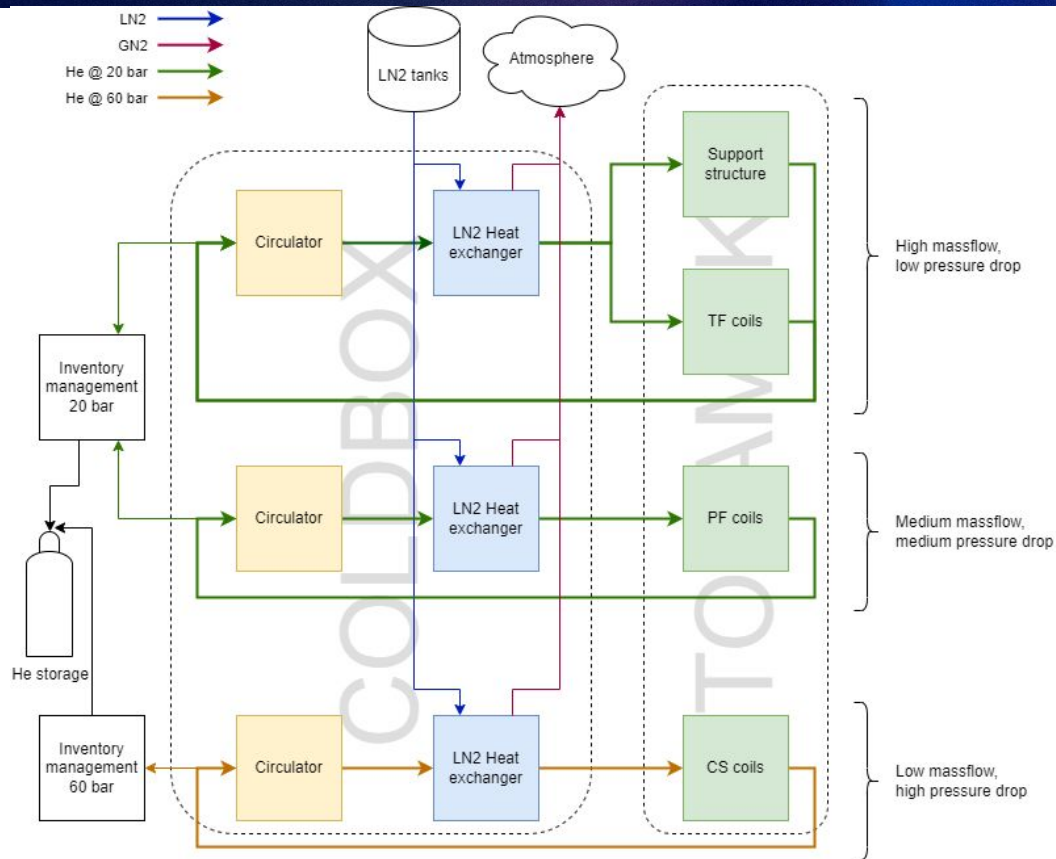
After the pulse is finished, time is given to prepare the tokamak for the next pulse. During that time, deposited heat must be extracted from the coils, reaching again the starting temperature. For COMPASS-U, **the target is to run the experiment / pulse each 15 minutes, 30 minutes at maximum**.

Because electromagnetic forces are acting on the coils during the pulse, all tokamak coils are **held together with support structure** (made of massive stainless steel pieces), which is also cooled to same temperature as the coils.

- All parts will be cooled by **gaseous coolant**.
- Working gas: **Helium** (or Hydrogen).
 - Helium preferred due to safety advantages.
 - Hydrogen is meant as a secondary option in case detailed considerations show that with helium it is impractical or impossible to reach the goals.
 - Expected working gas pressure **20 and 60 bar** (see further)
- Target temperature of the appliance: **80 K**.
 - Being able to achieve lower temperatures is advantageous, but not required.
- Expected peak cooling power \geq **200 kW**.
 - Maximal expected delta T of coolant **< 40 K**
- Cold source: **LN2 evaporation**

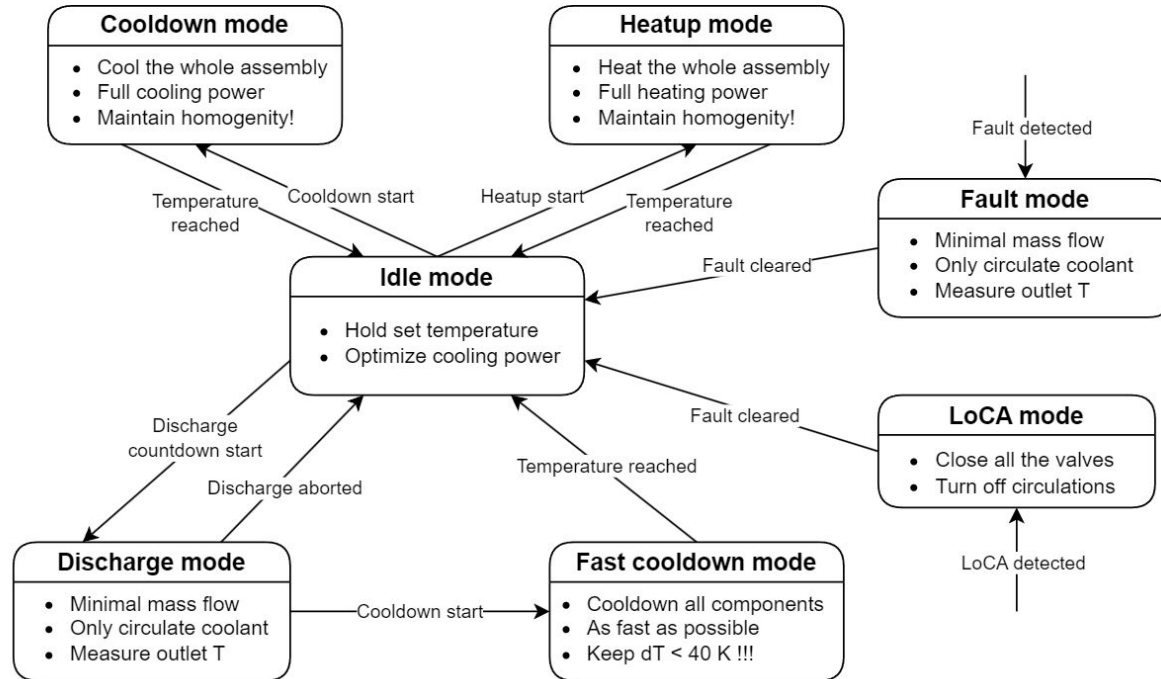
High level scheme proposal

- **3 cooling loops**
- Each loop contains
 - Circulator
 - LN2 heat exchanger
 - heater for controlled warmup
 - Cooled component
 - Auxiliary components
- LN2 heat exchangers might be combined / shared.



We expect 5 basic operation modes and 2 failure modes.

- **Cooldown from room temperature**
 - Cooling down whole assembly from RT to 80 K
 - Focus on temperature homogeneity
- **Idle**
 - Keep the components at set temperature
 - Helium circulation optimized to save power
- **Tokamak discharge**
 - Circulate with small mass flow through all the channels, **not heating or cooling**
 - Read object temperature.
- **Cooldown after tokamak discharge**
 - Cool down all the components to set temperature as fast as possible.
 - Limit $(T_{\text{object}} - T_{\text{coolant}}) \leq 40 \text{ K}$
- **Heat up**
 - Heat the assembly up back to RT.
 - Focus on temperature homogeneity



System has a large amount of a **diverse cooling channels!** Nomenclature is **important!!!**

Tree-like schematic with 4 levels. Each level has some specifics

- **Cooling loop**
 - **Cooled object**
 - **Object cooling bus**
 - **Object cooling channels**

This means **for example**

- **Cooling loop:** High mass flow, low pressure drop
 - **Cooled object:** Toroidal field coils lower limb+core
 - **Object cooling bus:** Toroidal field coils lower limb+core bus 1
 - **Object cooling channels:** Single toroidal field coils channel

or **for example**

- **Cooling loop:** medium mass flow, medium pressure drop
 - **Cooled object:** Poloidal field coil PF4U
 - **Object cooling bus:** Poloidal field coil PF4U bus
 - **Object cooling channels:** Poloidal field coil PF4U first cooling channel

Why we chose such 4 level scheme? Each level has its **specifics** and **necessities**!

- **Cooling loop**
 - Several different cooled objects are connected to one cooling loop.
 - One cooling loop - one circulator - one heat exchanger.
- **Cooled objects**
 - Helium inlet temperature to all **object cooling busses** of a single **cooled object** must be same
 - Temperature gradient in each **cooled object** must be ≤ 40 K
 - This implies $\text{abs}(T_{\text{inlet}} - T_{\text{outlet}}) \leq 40$ K for each **cooled object**
- **Object cooling bus**
 - **Object cooling busses** can be quite different. For PF coils, only 1 - 5 long **object cooling channels** will be connected to one **object cooling bus**. For TF coils, ~50 short **object cooling channels** will be connected to one **object cooling bus**.

- **TF coil**
 - 1 cooled object
 - $16 \times 7 \times 2 = 224$ short channels of two types connected in parallel to 4 busses
 - Channel length 5 - 8 meters
- **PF coils**
 - 10 cooled objects, 2 - 5 cooling channels / object
 - Channel length 60 - 80 meters
- **CS coils**
 - 5 cooled objects, 1 - 2 cooling channels / object
 - Channel length ~ 90 meters
- **Support structure**
 - 1 cooled object,
 - Large amount of cooling channels, 4 busses
- **Auxiliary channels**
 - Thermal anchors, CS tie tube cooling

Coil	Count	Cooling channels		Coil weight <i>(only copper)</i>	Maximal energy to extract <i>(per coil)</i>
		Diameter	Lengths		
PF1a	2	7 mm	61 m, 64 m	201 kg	4.5 MJ
PF1b	2	7 mm	70 m, 74 m	231 kg	5.1 MJ
PF2	2	7 mm	80 m, 83 m	261 kg	5.8 MJ
PF3	2	7 mm	83 m, 84 m, 87 m	406 kg	9 MJ
PF4	2	9 mm	90 m, 90 m, 90 m, 75 m	840 kg	18.7 MJ

10 (2*5) separate coils made of solid conductor with inner hollow channel.

Maximal deposited energy to PF coils during a tokamak discharge (in total, all 10 coils) ~ **20 MJ**

Coil	Count	Cooling channels		Coil weight <i>(only copper)</i>	Maximal energy to extract
		Diameter	Lengths		
CS1	1	6x8 mm, elliptical	88 m, 88 m	714 kg	16.0 MJ
CS2	2	6x8 mm, elliptical	86 m	349 kg	7.8 MJ
CS3	2	6x8 mm, elliptical	88 m, 88 m	714 kg	16.0 MJ

Central solenoid (CS) coils are stack of 5 coils with same design as for PF coils (hollow copper conductor). Two coils (CS2U, CS2L) are smaller with singular cooling channel, three coils (CS1, CS3L, CS3U) are bigger with cooling channel divided in half.

Maximal deposited energy to CS coils in one tokamak discharge (in total, all 5 coils) ~ **30 MJ**

Part	Count	Cooling channels		Maximal energy to extract (per channel)
		Diameter	Length	
TF core + lower limb	112	6x10 mm, elliptical	9.2 m	1.75 MJ
TF upper limb	112	6x10 mm, elliptical	7.7 m	0.48 MJ

One huge coil (112 turns) made out of copper plates with brazed-on pipe.

Maximal deposited energy to TF coil in normal tokamak shot (in total) ~ **250 MJ**

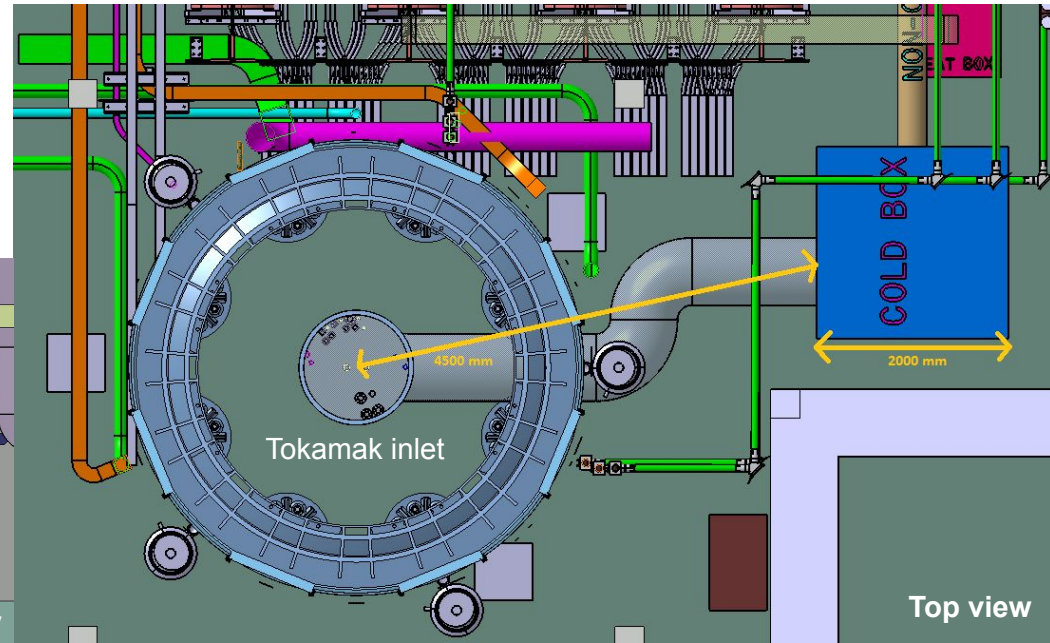
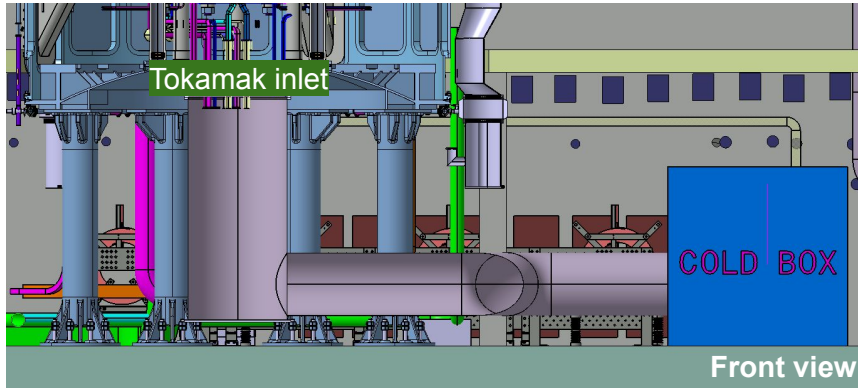
TF coil have 4 busses (2 for TF core + lower limb, 2 for TF upper limb)

- channels are divided to two halves and connected to busses.

As said on previous slide, mainly copper coils will be cooled to cryogenic temperatures. However several others parts must be cooled. Those are

- **Support structure**
 - Huge metallic (SS316) structure holding all coils in place, weight ~ 250 tons
 - Actively cooled during initial cooldown
 - Same coolant loop as TF coils (base pressure 20 bar)
 - Expected pressure drop 0.1 bar, helium massflow 0.5 kg/s (at RT) - 1.2 kg/s (at 80 K)
- **Coil “busbars”**
 - Copper conductors, connecting coils to power sources. Thermal anchor (@160 K) is required not to get them overheated.
 - May be cooled by “waste” helium.
- **CS Tie tube**
 - Metal tube (cut to 4 pieces) holding mechanically preloaded central solenoid stack. Cooling is needed because of thermal expansion.
 - May be cooled by “waste” helium.

- Coldbox will be located approximately 4.5 meters from the center of tokamak bottom lid. **There is space 2x2x2 m allocated for the coldbox itself.**
- In current stage of design, all pipes are routed to one location on the bottom lid of tokamak cryostat.
- Supplier will also supply vacuum piping connecting the tokamak to coldbox.
- Coldbox should include all sensors (coolant thermometers, flowmeters, pressure sensors) and all needed control/isolation valves.
- There can be multiple coldboxes.



- Available interfaces will be
 - **Electricity**
 - 400 V
 - Available power for cryogenics ~ 100 - 200 kW
 - **Water / glycol cooling**
 - Cooling power ~ 100 kW
 - Base temperature ~ 10 °C
 - **Demineralized water cooling**
 - Cooling power ~ 10 kW
 - Ultra pure, nitrogen buffered, continuously measured conductivity
 - **Liquid nitrogen**
 - ~ 100 m³ storage onsite
 - **Compressed air**
 - 10 bar

- Cryogenic control system should be a **stand alone system**.
 - This should include interlocks, fault handling, process variable logging, etc.
 - Interface will be present to connect cryogenic system to tokamak central control system.
 - Setting operation modes / temperatures, overviewing current state / faults...
- Most sensors will be part of the tender
 - Except temperature sensors inside cryostat (coil/structure/etc temperature sensors) will be supplied by IPP and cryosystem must be able to interface them.
 - Sensors need to have **sufficient precision** to obtain requested limits (max 40 K difference between coolant and cooled part, cooldown in 30 minutes, etc...) - we think that **thermometer precision 1 - 2 K is sufficient**.
- All actuators will be part of tender
 - During tokamak operation (during shot itself), stray magnetic field will be present. If any electromagnet-actuated valve is used, it must be verified that this stray field will not affect its performance.

- Cryogenic system will include **inventory control system** which will
 - Automatically **fill or discharge medium** during operation to keep pressure in set range.
 - **Compress medium back** to reservoir for system maintenance periods.
- System should include precautions to keep medium purity
 - Chance of contaminants to **cause blockage** in one of the cooling channels must be **minimized!**
 - Cooling channels will include **ceramic brakes** to electrically insulate coils from rest of cryogenic system. Working voltage across those insulation gaps will be 1 kV. Attention must be paid to any contaminants possible to **short out this isolation barrier!**
 - Circulator bearings **doesn't have to be oil-free**, if proper filters are introduced in system.

- In the tokamak hall, **neutron flux** during discharge will be present.
 - Total neutron dose ~ up to 5 000 Sv per year.
 - We don't require absolute neutron protection, however radiation should not cause "expensive" faults like destruction of circulator or tokamak.
 - It is possible to locate sensitive components (high power circulator drivers, etc...) out of tokamak hall. Distance from shielded space to coldbox is ~10 meters.
- **Stray magnetic field** will be present during the tokamak discharge.
 - Magnetic field intensity < 60 mT.
 - Presence of magnetic field should not cause any destructive fault of electronics or uncontrolled opening of valves.

- Cryogenic system will be supplied by **one supplier**.
- Tender will be public, according to Czech legislation
- Cryogenic system will include
 - Coldbox and all sensors / actuators
 - All piping up to requested interface
 - Circulators, cold sources, heat exchangers
 - Coolant inventory management system
 - Control system
- Interfaces will be in detail described in tender
 - Interface to **tokamak** will be **between cryostat and coldbox**.
 - Interface to **building systems** will also **be specified** in tender.
- System documentation (drawings, etc...) will be part of the tender
- **Source codes of all software** used in cryosystem will be **required!**
 - With appropriate NDA or IP agreement.
 - This is mainly to prevent vendor lockdown and ensure longevity of system.

Questions for potential manufacturers

- Regarding tender
 - Do you have and are you willing to prove (by disclosing the customer) the experience with cryogenic helium loop design and production with temperature of $<100\text{ K}$ and cooling power $>10\text{ kW}$?
- Regarding contract
 - What is the expected price of the described cryogenic system? ($\pm 10\%$)
 - What are suggested advance (zálohy) / partial (částečná plnění) payments?
 - What is suggested time schedule for delivery?
 - Design, manufacturing, installation, commissioning?
- Regarding design
 - Is space for coldbox adequate? What space will be needed around the coldbox itself for reasonable maintenance?
 - What efficiency of LN₂ - He heat exchangers shall be specified? Is 90% ok?
 - How to specify required flows and energies to extract better?
 - Shall complete scheme of pipework (including busses) be included?
 - How fast is it possible to divert turbocirculator to bypass?
 - How dangerous is loss of pressure for running circulator?