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Cryogénie pour le projet MINERVA

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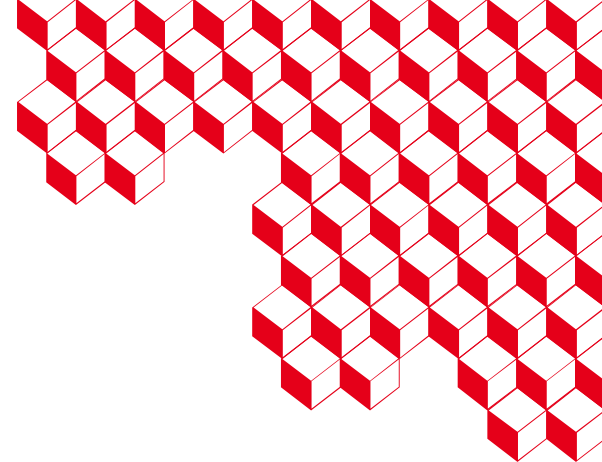
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Cryogénie pour le projet MINERVA

F. MICHEL, F. BONNE



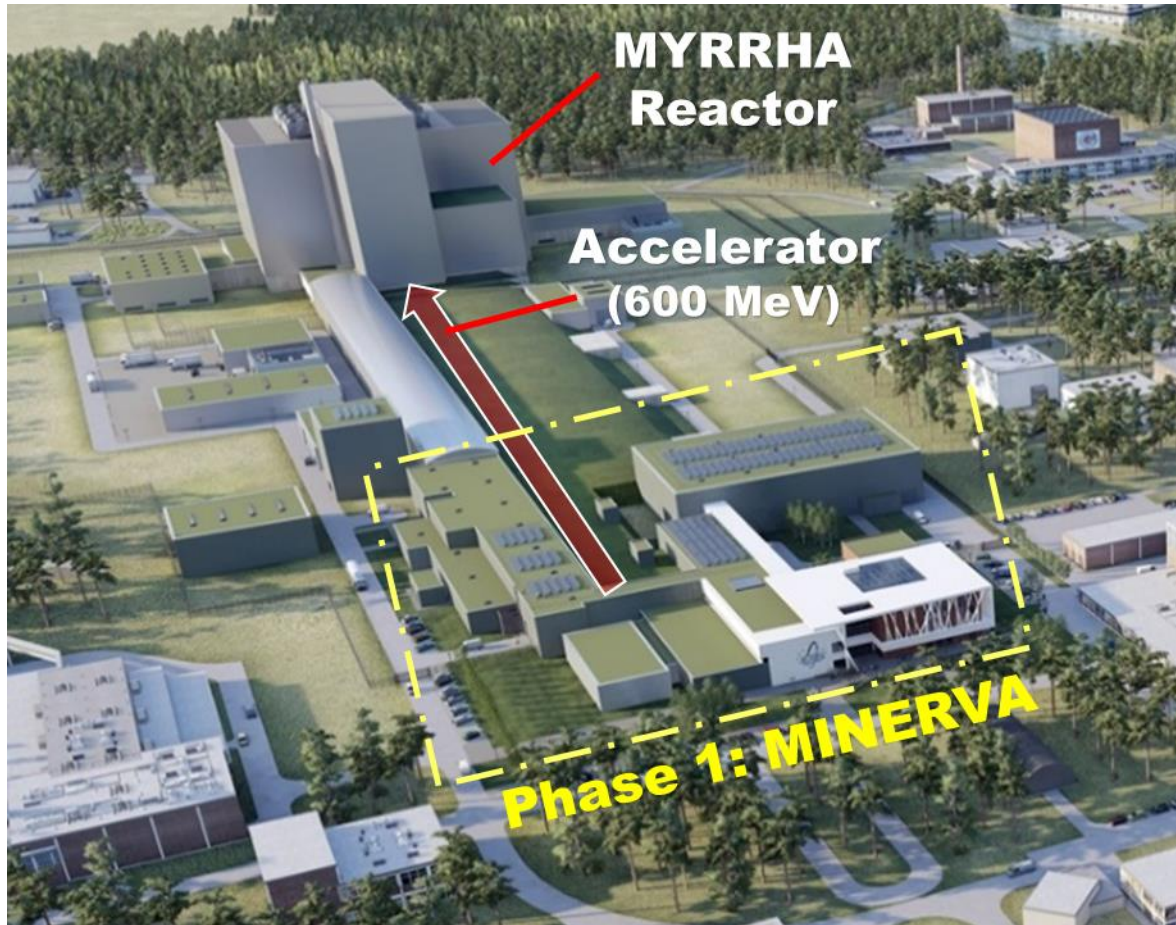
sck cen



<https://www.sckcen.be/fr/infrastructure/myrrha>

Introduction projet MINERVA : Phase 1 MYRRHA (1/2)

MYRRHA (fully implemented)



Objectifs projet MYRRHA: un réacteur piloté par accélérateur pour gérer les déchets radioactifs

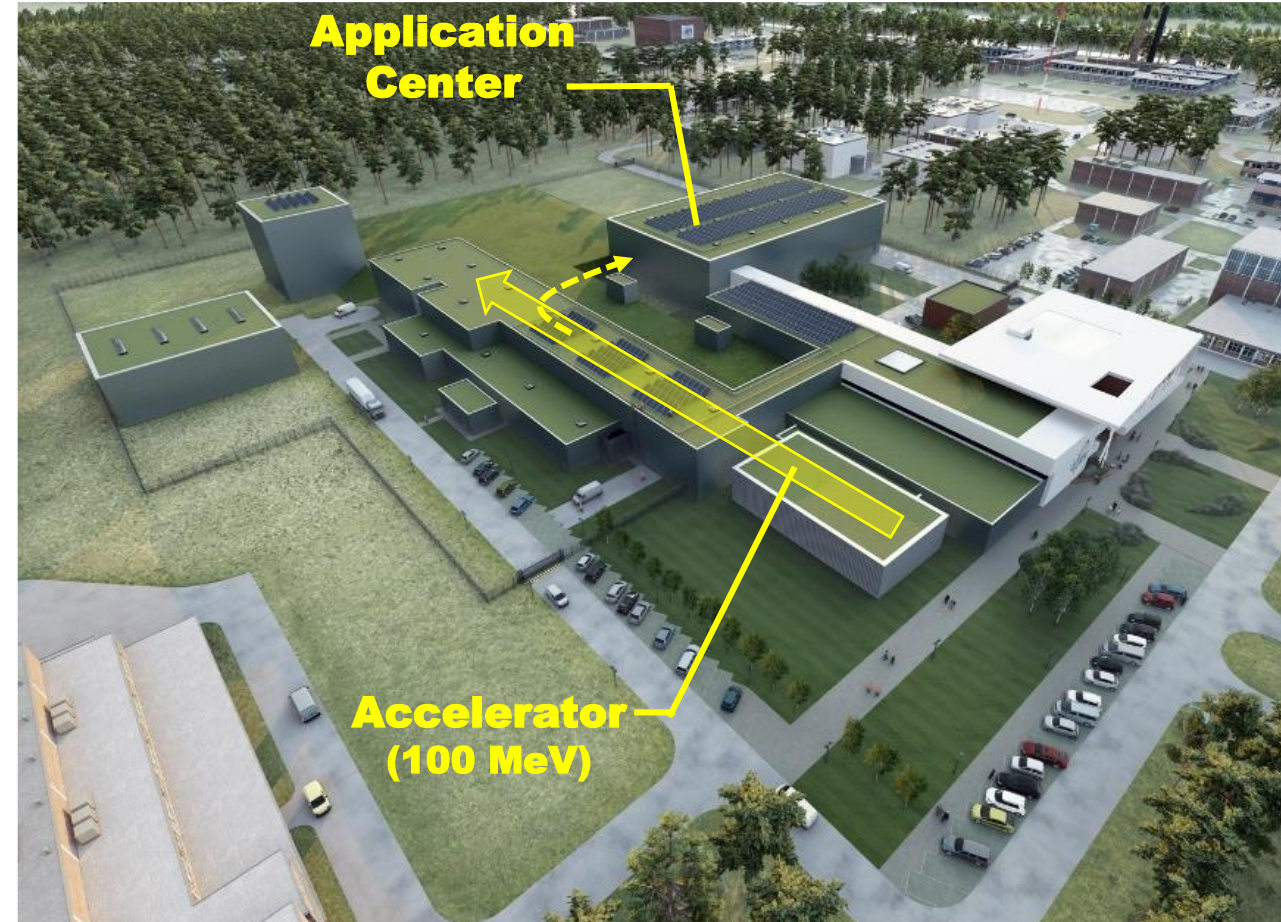
- SCK CEN a pour objectif de réaliser le 1er réacteur de recherche piloté par un accélérateur de particules sur le site de Mol (Belgique).
- MYRRHA sera un réacteur à neutrons rapides fonctionnant en régime sous-critique : les neutrons sont fournis par le bombardement par des protons d'une cible de spallation.
- L'objectif principal est d'étudier la transmutation de déchets radioactifs à vie longue en substances à durée de vie plus courte : facteur ~1000 !
- En parallèle, MYRRHA pourra produire des radio-isotopes pour la recherche et le médical.

Introduction projet MINERVA : Phase 1 MYRRHA (2/2)

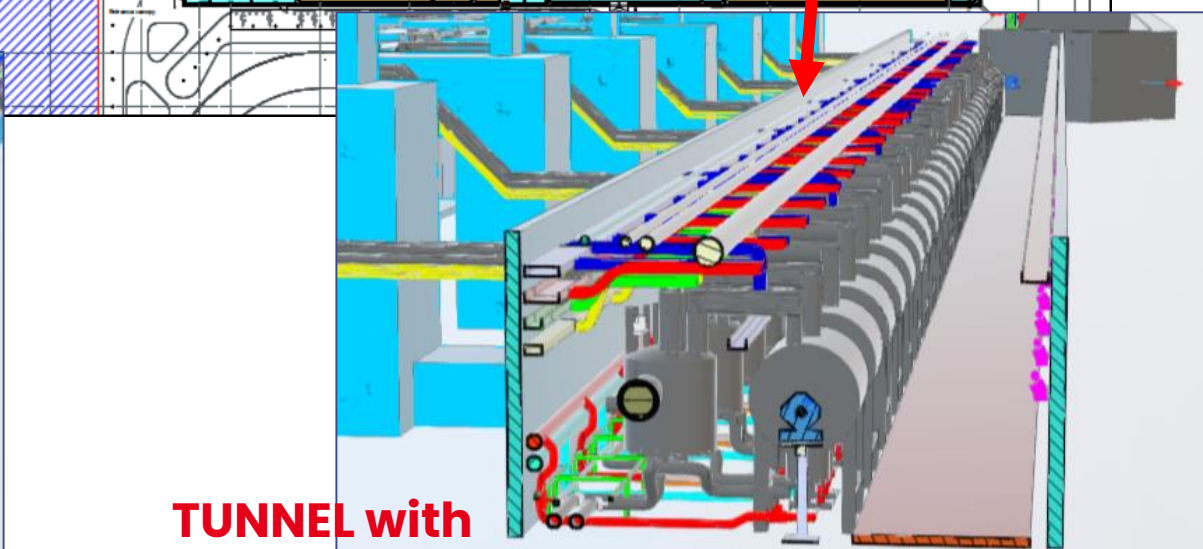
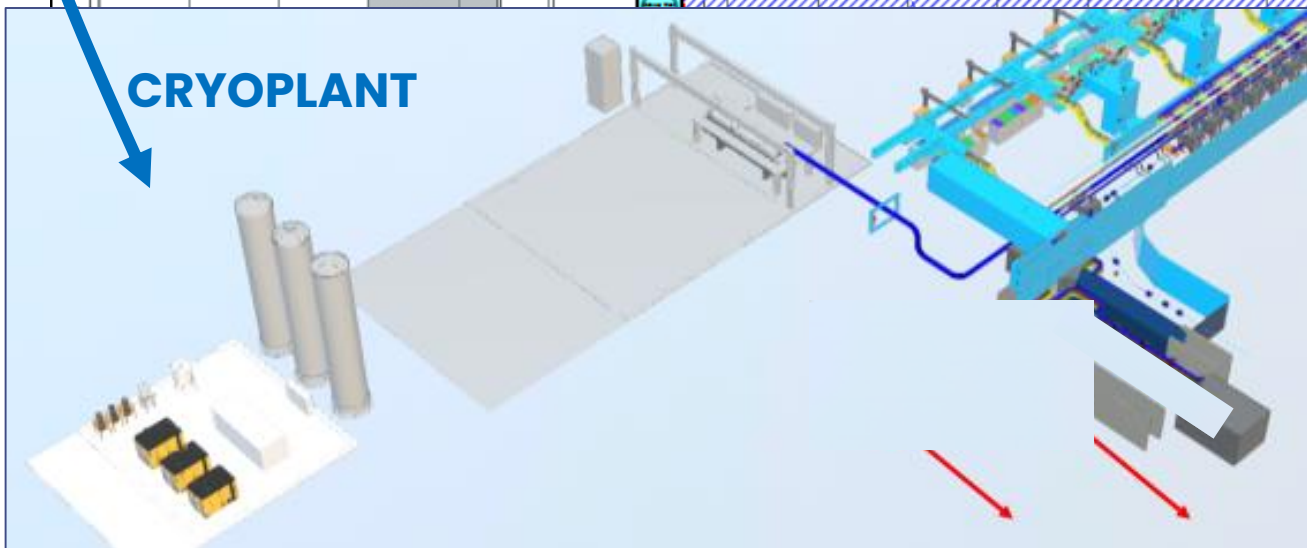
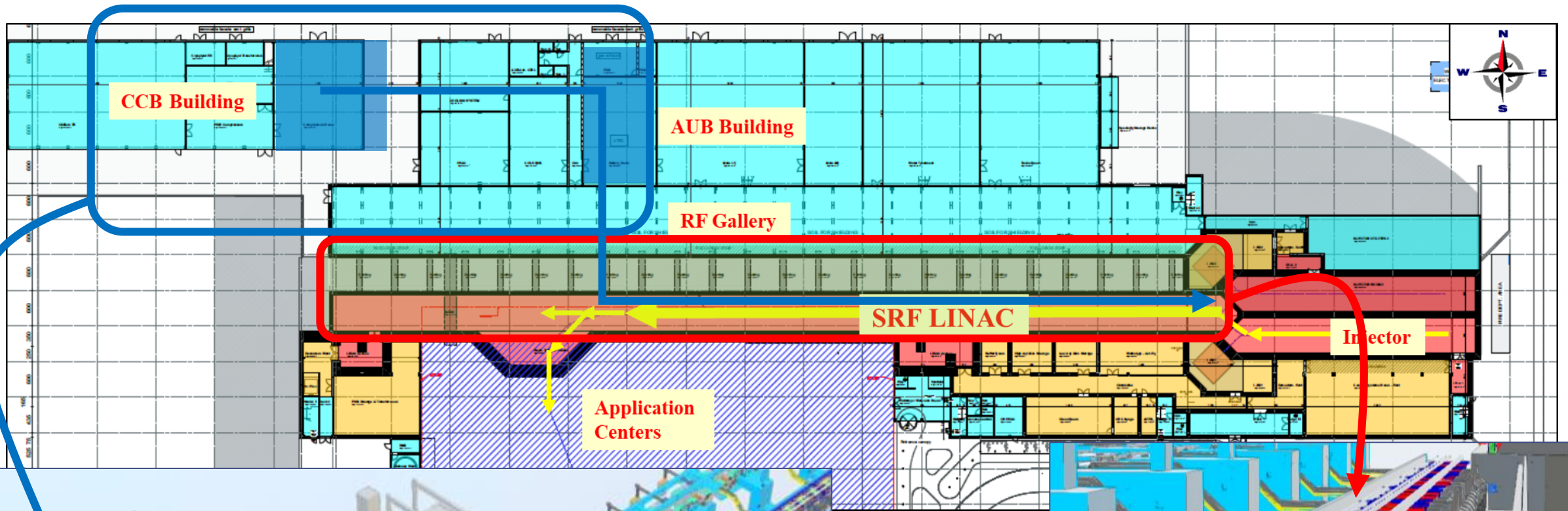
Objectifs projet MINERVA: Accélérateur linéaire 100 MeV

- Fortes exigences de disponibilité et de fiabilité de l'installation
- 60 cavités supraconductrices en Niobium installées dans 30 cryomodules (énergie du faisceau de 16,6 MeV à 100 MeV)
- Cavités refroidies à 2 K par de l'hélium superfluide saturé.
- Longueur accélérateur ~100 mètres.
- Puissance à 2 K dissipée dans chaque cavité ~ 5 W/cavité

MYRRHA Phase 1 (= MINERVA)

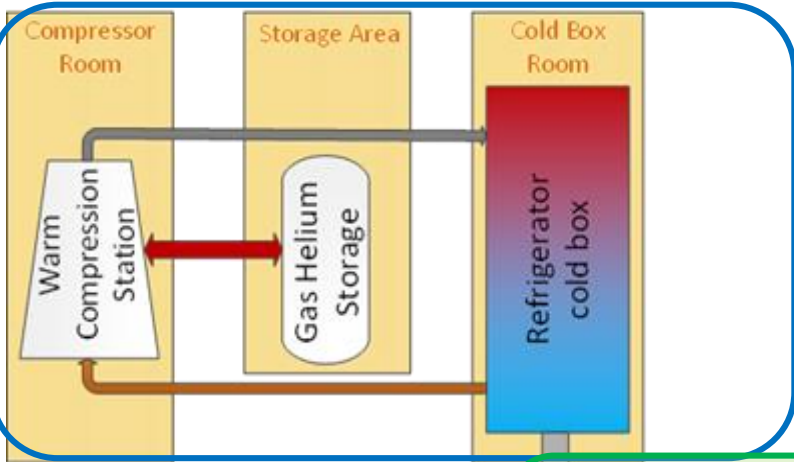


PLAN DU SITE MINERVA



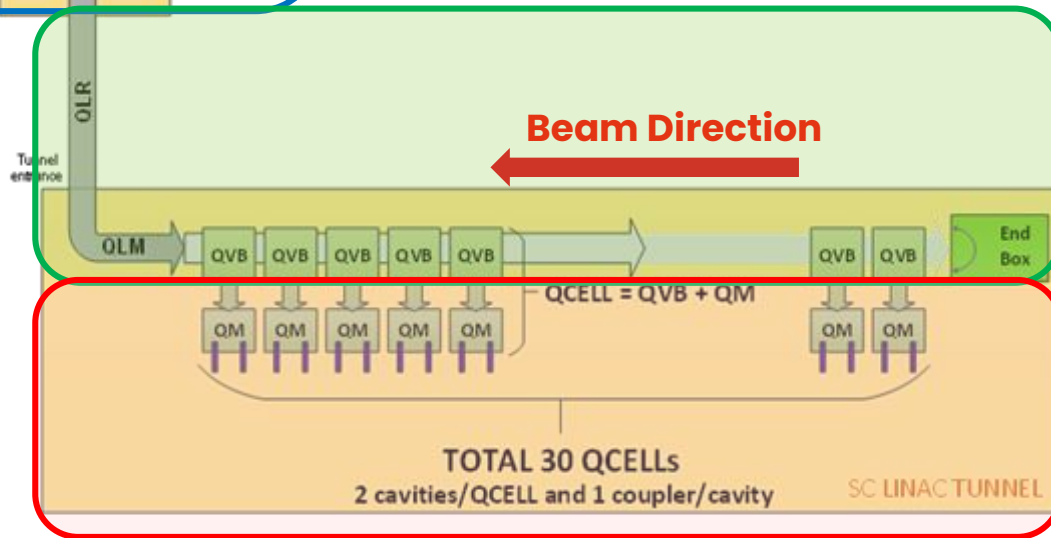
**TUNNEL with
QCELL=QVB+QM**

MINERVA CRYOGENIC SYSTEM BLOC DIAGRAM



- **CRYOPLANT**

- Warm Compressor Station (LP-HP compressors + VLP- LP compressors)
- Refrigeration Cold Box (with Cold Compressors)
- Gas Helium Storage (700 kg of helium to store)



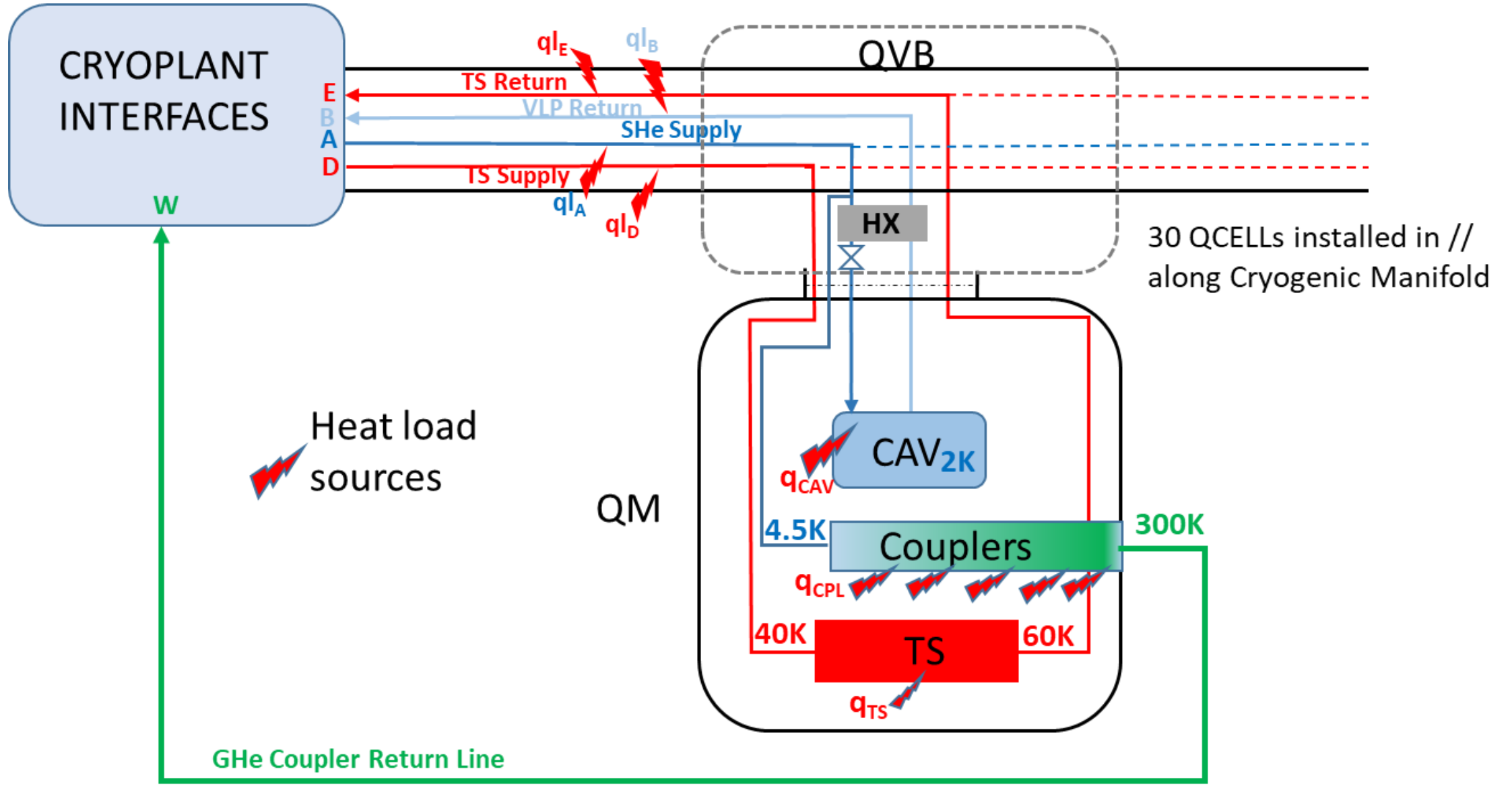
- **CRYOGENIC DISTRIBUTION**

- Cryogenic lines
- Cryogenic Valve Boxes (QVB)
- End Box (QVE)

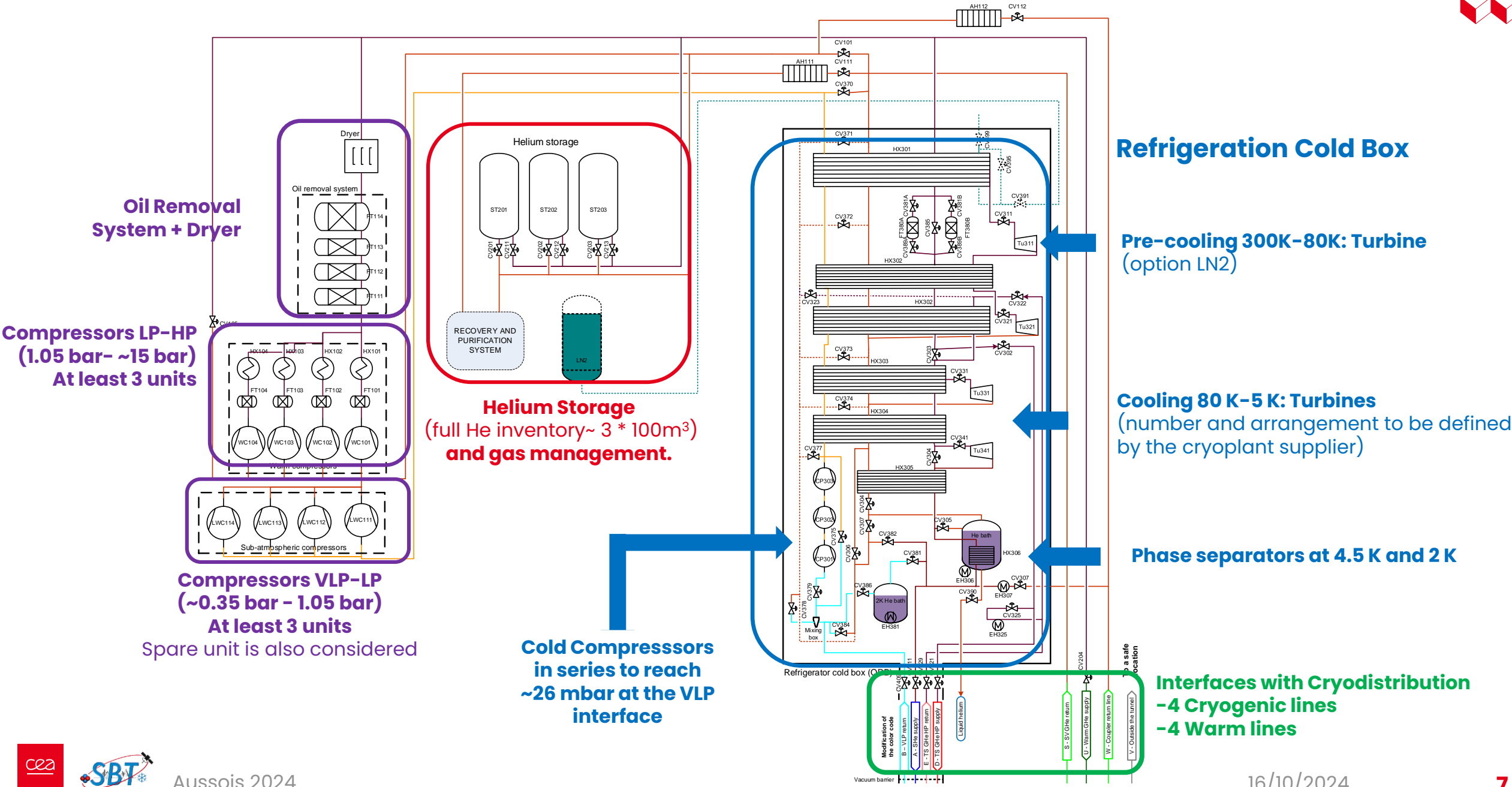
- **CRYOGENIC USERS**

- Cryomodules (QM), each with:
 - **2 superconducting RF cavities submerged in a 2 K bath**
 - **2 RF couplers cooled at 5 K – 300 K**
- Thermal Shields at 40 K – 60 K

MINERVA CRYOGENIC USERS



THE CRYOGENIC PLANT FOR MINERVA



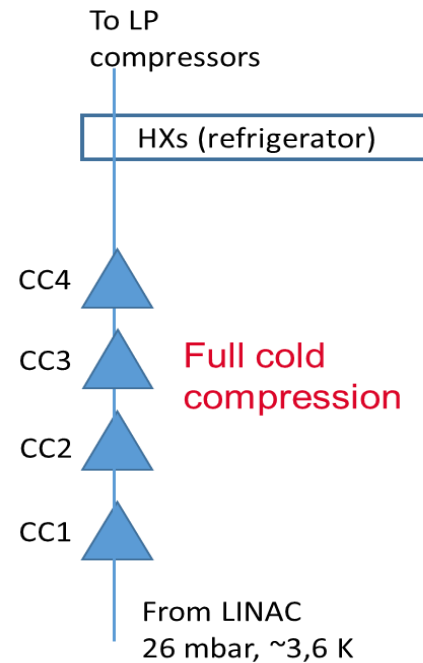
THE SUB-ATMOSPHERIC COMPRESSION SELECTION

Comparison of 3 VLP configurations

Requirements:

- Suction pressure at **26 mbar** (~ 31 mbar required at cryomodules for 2 K bath)
- Max/Min mass flow: 45/17 g/s **ratio ~ 3** at 2K operation

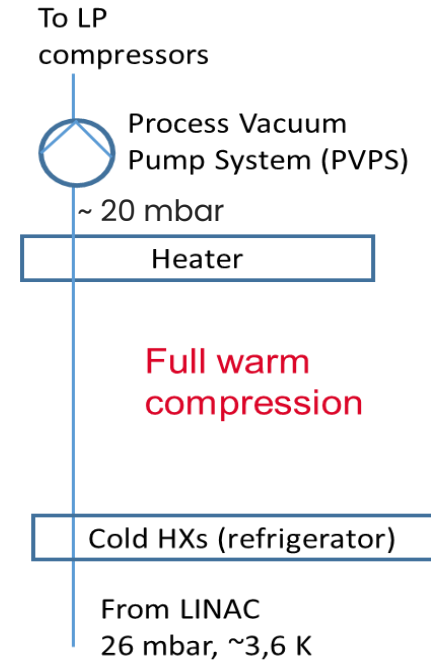
(Equipment cost is not discussed here)



Smallest (no need of PVPS)

~ 0.9 MW

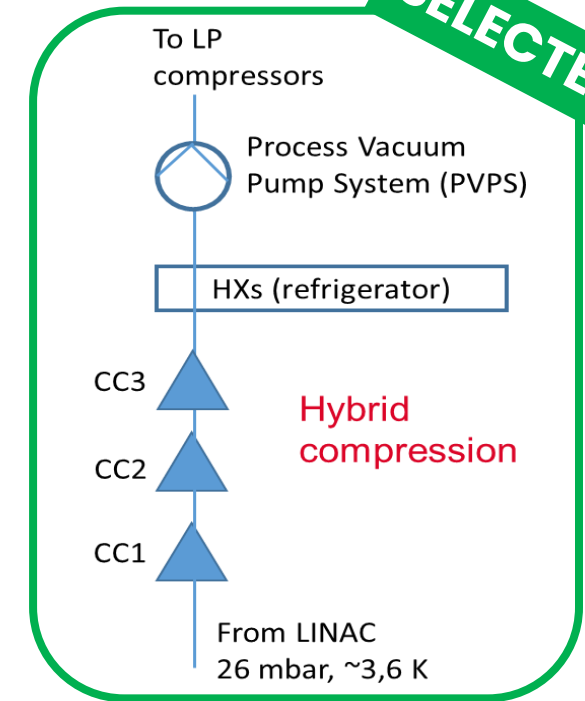
Less flexible (limited by narrow operation range of the CC train)



Largest (due to large PVPS)

~ 1.9 MW (difficult enthalpy recovery)

Flexible (thanks to wide operation range of PVPS)



Intermediate (requires smaller PVPS)

~ 0.9 MW

Flexible (« combines » avantages of both methods.)

Key aspects:

Footprint

Expected electrical consumption (for compressors)

Flexibility of operation for large mass flow ratios

THE OPERATION MODES



- **Design modes at 2K:**

Main steady-state modes	LINAC configuration	Heat loads and margins
2 K nominal mode (Design Point)	For 30 cryomodules	Static + Dynamic (includes margins)
2 K stand-by mode (Min Turndown)	For 24* cryomodules	Static only (without margin)

* Minimal staged installation (hypothetical). Only 24 Cryomodules installed at the beginning

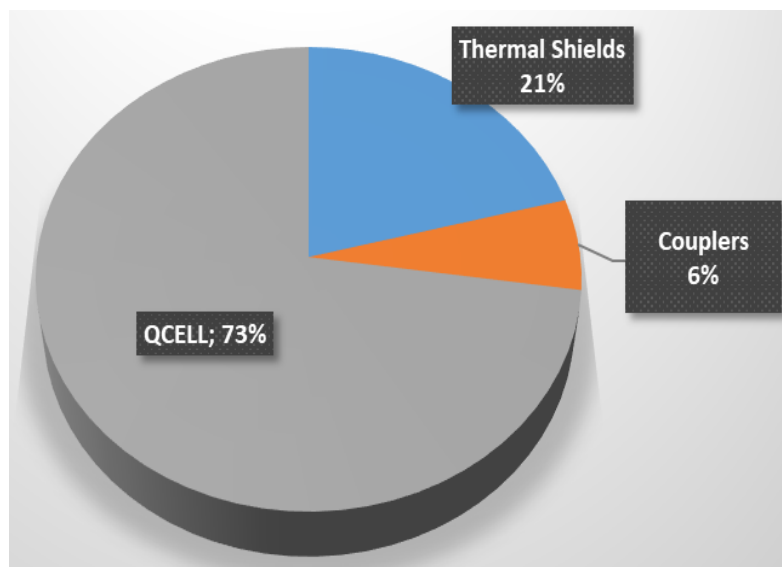
Note:

Dynamic heat loads correspond to RF and resistive losses at cavities and power couplers.

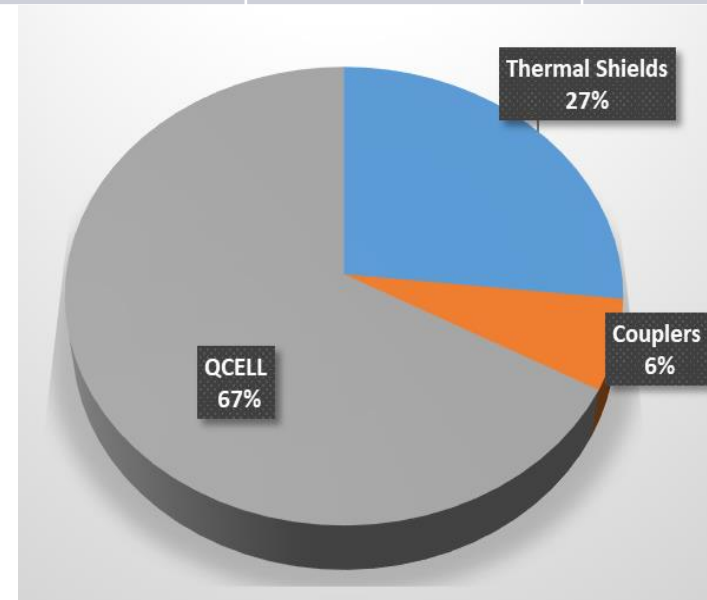
HEAT LOAD REQUIREMENTS FOR MINERVA CRYOPLANT



Mode	Isothermal Heat Loads (W)	Non-Isothermal Heat Loads (W)				Equivalent Refrigeration Power @4.5 K (W)
		VLP Return Line	SHe Supply Line	TS (40-60 K)	Couplers 5 K-300 K (g/s)	
2 K Design point	900	40	20	8600	2	3430
2 K Min Turndown	340	30	10	5100	1	1490



Nominal Design Point 2K
Total eq@4.5 K - 3430 W

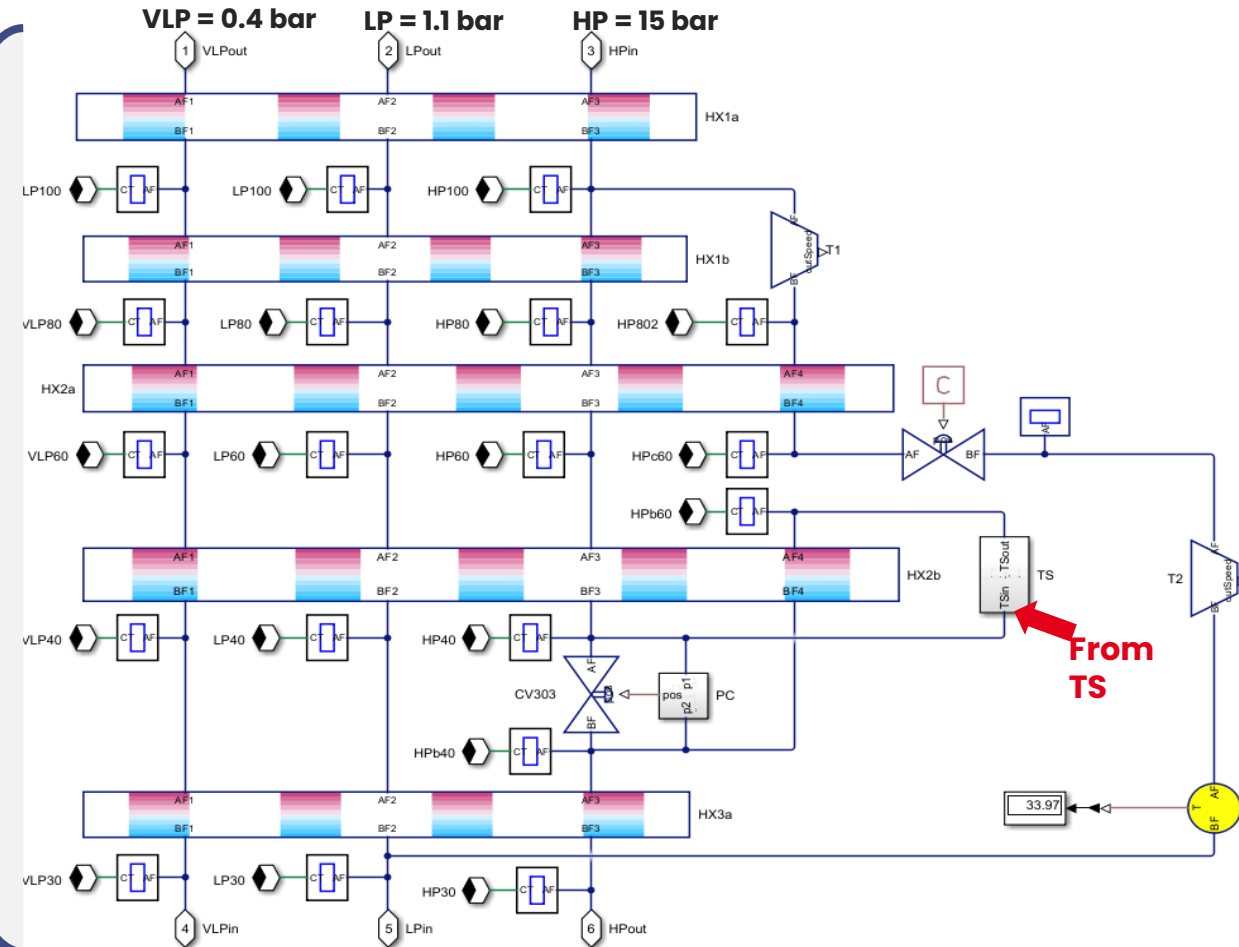
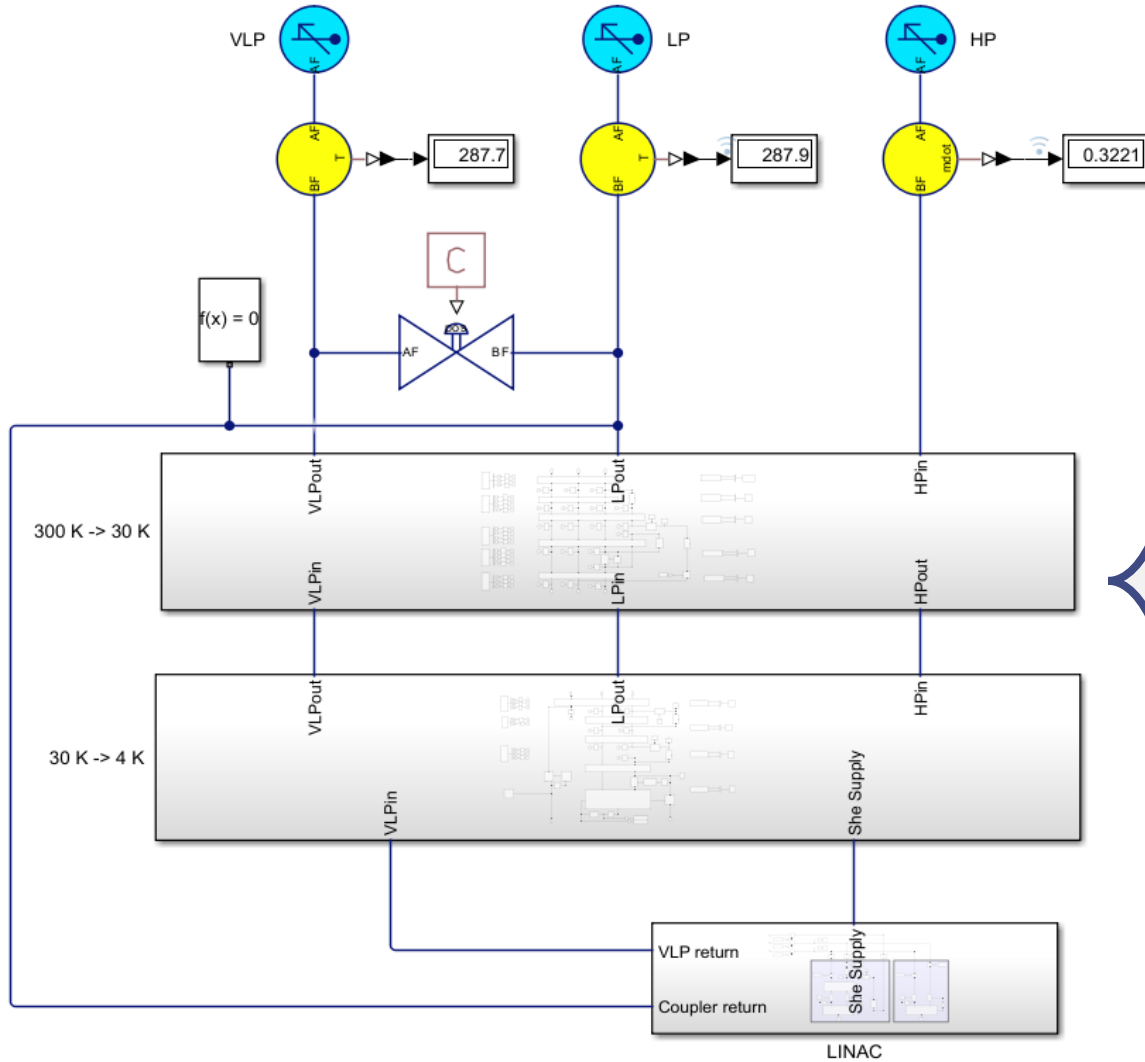


Minimal Turndown 2K
Total eq@4.5K - 1490 W

SIMCRYOGENICS MODEL and SIMULATION of THE CRYOPLANT



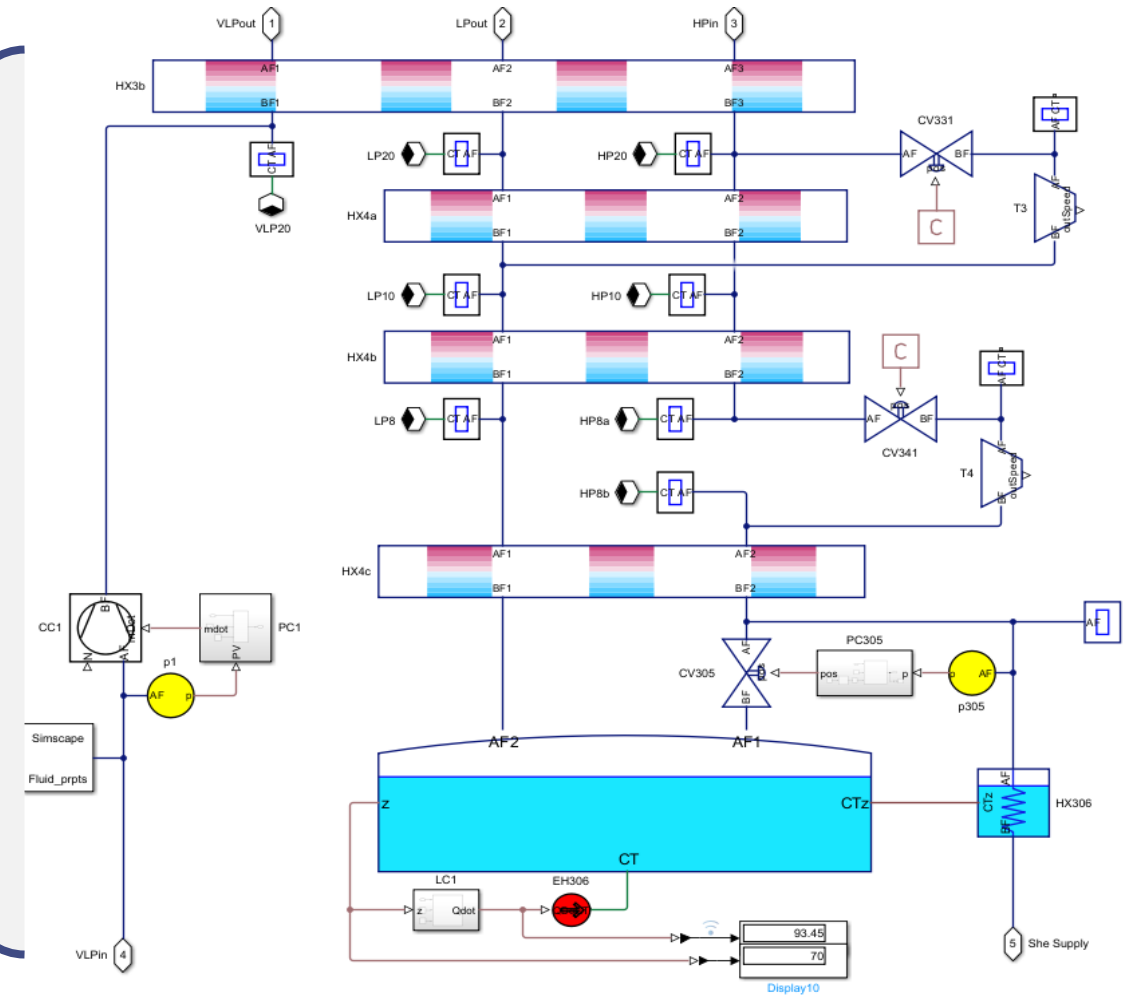
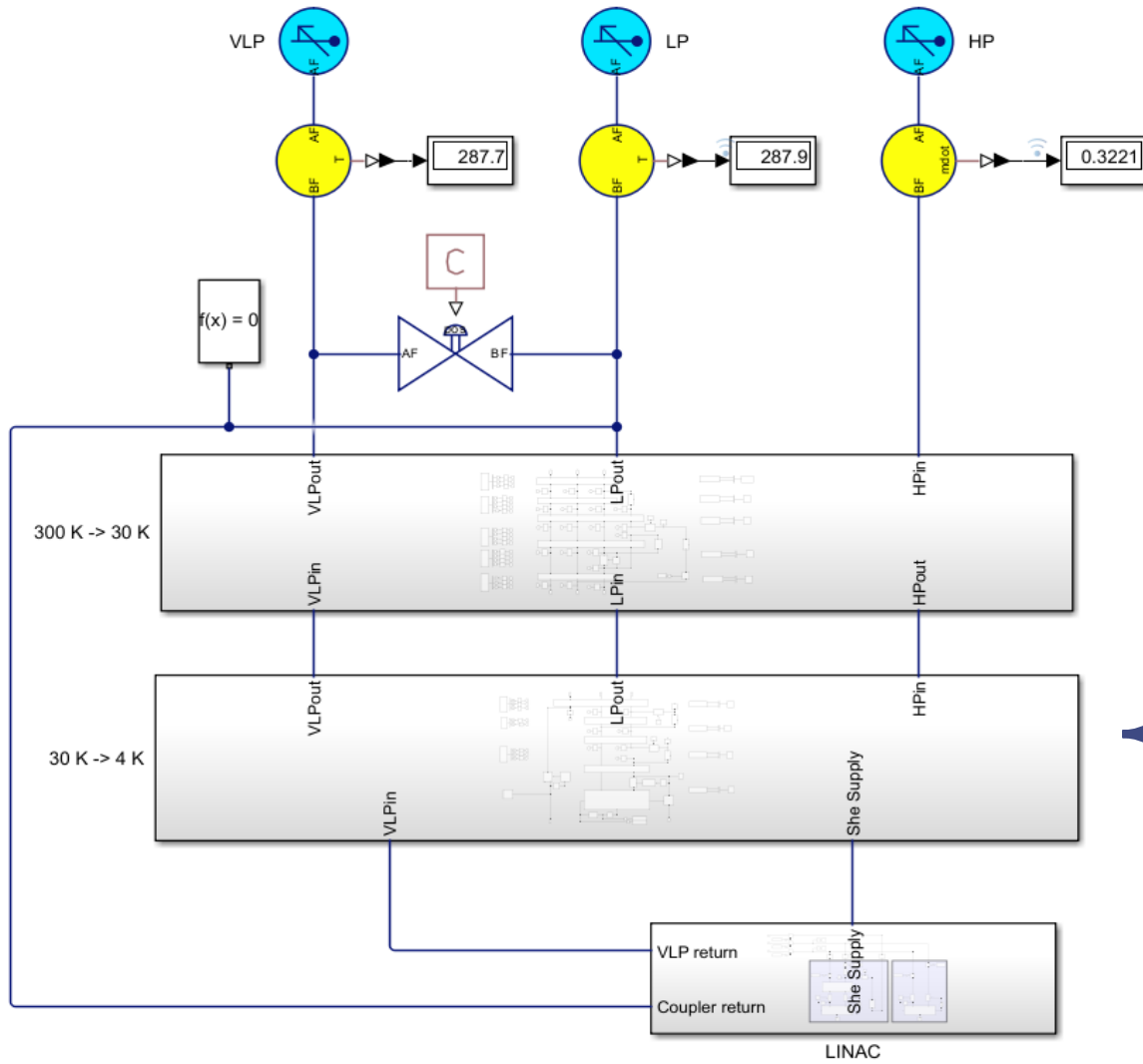
Model for 300 K-30 K stage



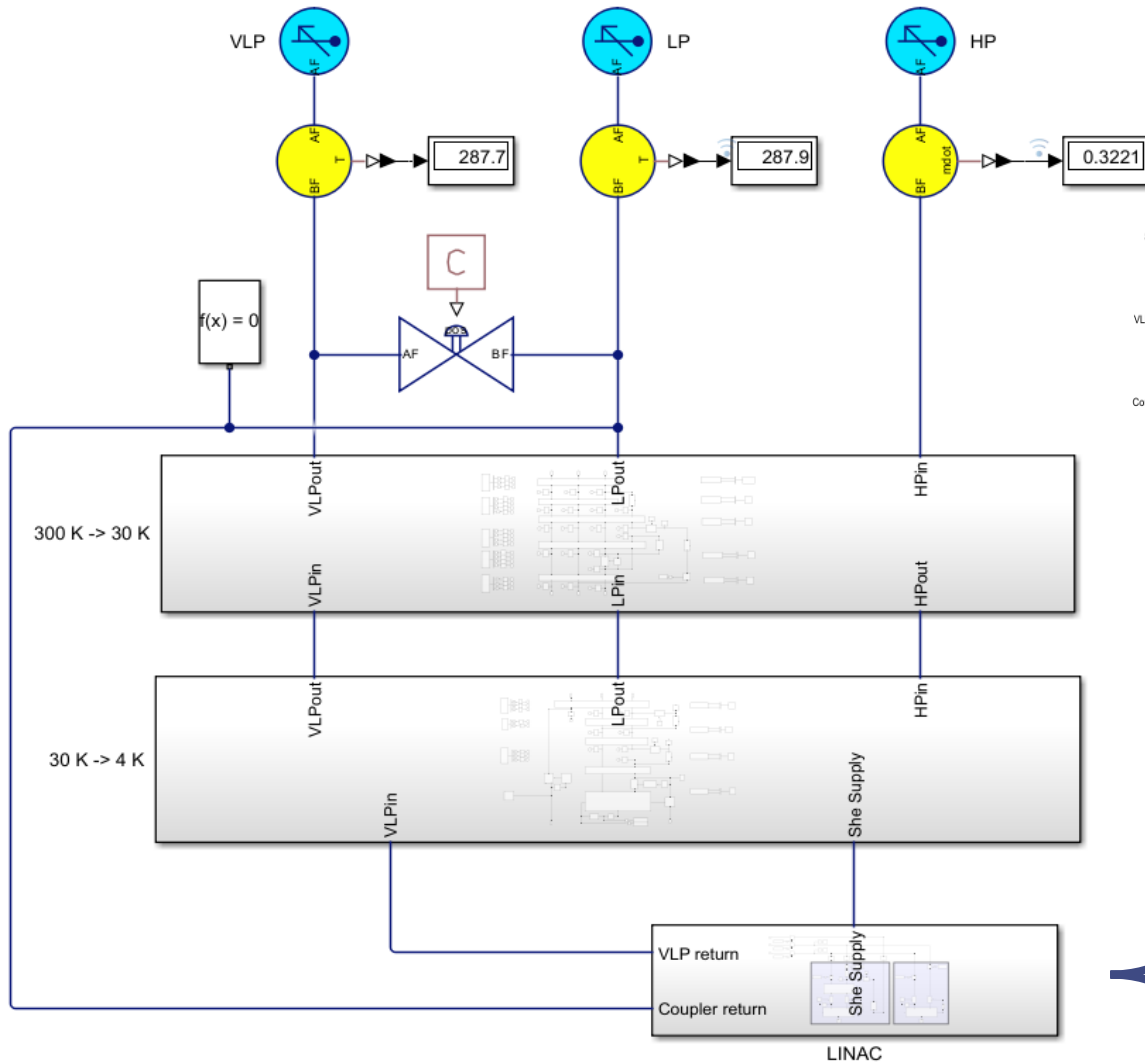
SIMCRYOGENICS MODEL and SIMULATION of THE CRYOPLANT



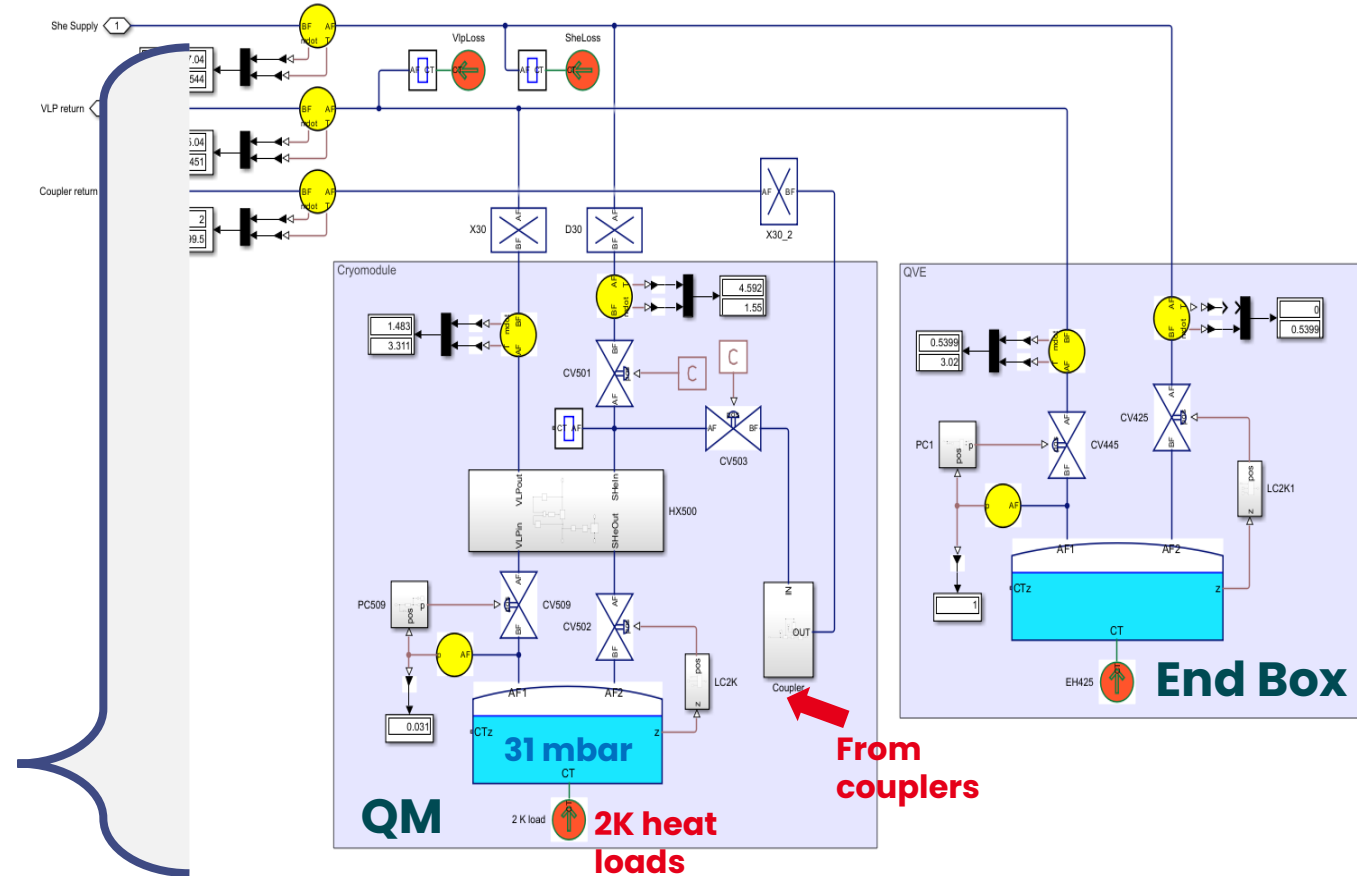
Model for 30 K-3 K stage



SIMCRYOGENICS MODEL and SIMULATION of THE CRYOPLANT



Model for LINAC (simplified with 1 QM x30 + End Box)



SIMCRYOGENICS MODEL and SIMULATION of THE CRYOPLANT

Energy Balances

- 4 Turbines with T1/T2 in series (No nitrogen precooling), 9 heat exchangers
- 3 Branches (VLP, LP, HP)
- Simplified model for cryogenic users (Thermal Shields, Cryomodules)
- Energy balance performed at the cold box interfaces: Comparison of heat sources vs extracting power

Enthalpy Difference (inlet-outlet)	Irreversibility (DT HX, DP,...)	4995			
Heat loads	2 K	893			
	QVE	10	Turbine power extraction (W)	T1	3786
	TS	8505		T2	11368
	Couplers	3118		T3	5437
"Margin"	Phase separator heater	94		T4	1215
Cryodistribution Losses	Cryoline VLP	34			
	Cryoline Supply	11			
	Cold Compressors	4147			
Total (W)		21 806	Total (W)		21 806

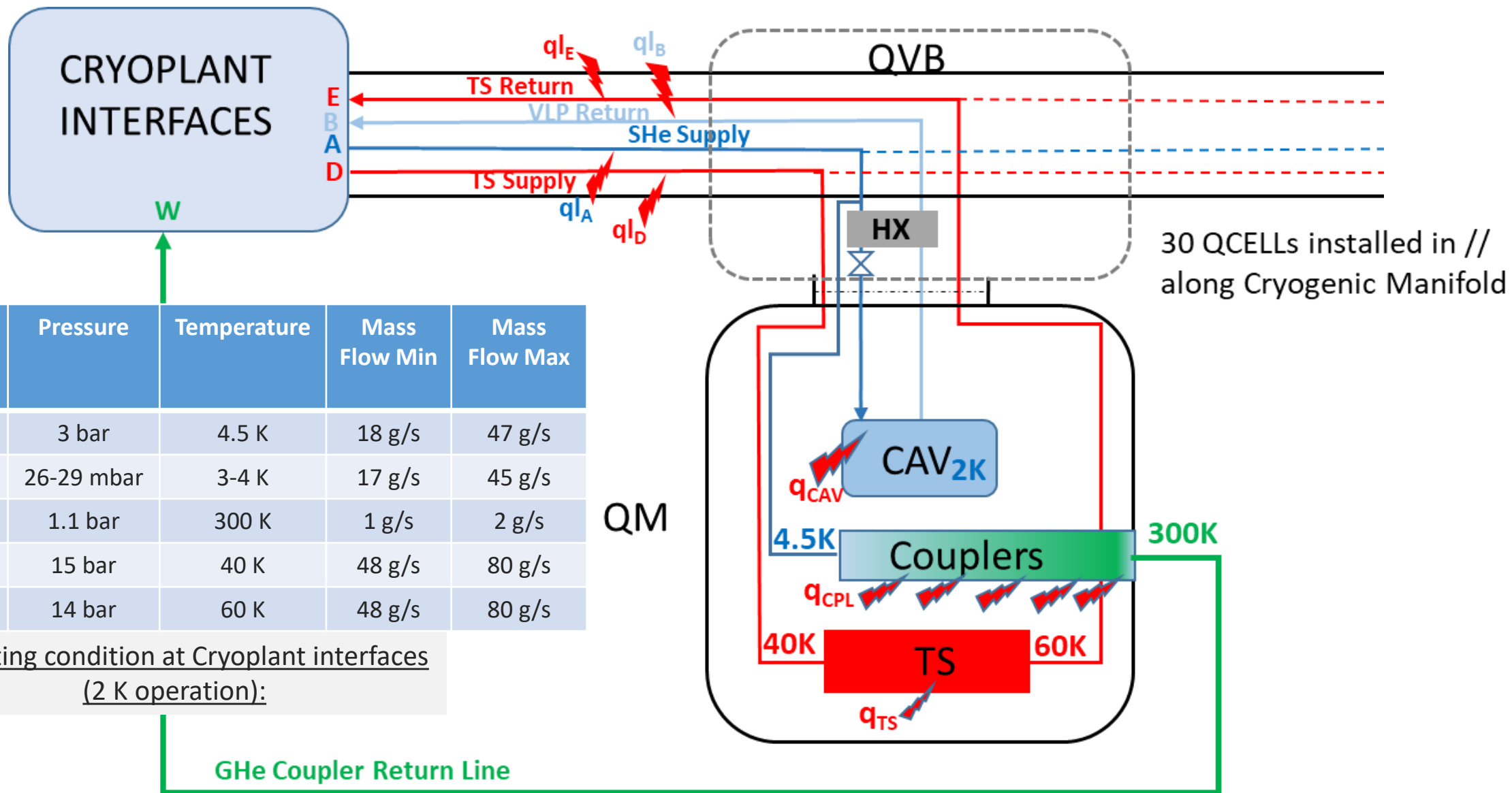
Conclusion

- The installation of the MINERVA Cryogenic System (Cryoplant, Cryogenic distribution, Cryomodules) is set between 2027 and 2029 at the SCK-CEN site in Mol, Belgium.
- The cryogenic users and the main cryogenic requirements are defined.
 - For the Cryoplant, the required total refrigeration power at 4.5K is **approximately 3.5 KW**.
 - The 60 superconducting cavities with **900 W @ 2 K** contribute to more than **70%** of the total heat loads eq.@4.5K.
 - An **hybrid sub-atmospheric compression** has been selected for its efficiency and flexibility in covering nominal and turndown modes.
 - SIMCRYOGENICS model of the MINERVA cryogenic system had been developed to study the cryogenic system and to prepare the technical specification for the Cryoplant
 - The study results were consolidated using **two industrial pre-studies** performed by Linde Kryotechnik and Air Liquide Advanced Technologies.
- The technical specifications for the Cryoplant is finished; **tendering phase....**

Additional slides



HEAT LOAD REQUIREMENTS FOR MINERVA CRYOPLANT



Cryoplant Interfaces	Pressure	Temperature	Mass Flow Min	Mass Flow Max
A	3 bar	4.5 K	18 g/s	47 g/s
B	26-29 mbar	3-4 K	17 g/s	45 g/s
W	1.1 bar	300 K	1 g/s	2 g/s
D	15 bar	40 K	48 g/s	80 g/s
E	14 bar	60 K	48 g/s	80 g/s

Operating condition at Cryoplant interfaces
(2 K operation):

GHe Coupler Return Line

SPECIFIC REQUIREMENTS FOR MINERVA CRYOPLANT

Key operational requirements

- High operational reliability with a limitation of thermal cycles (full warm-up every 5 years)

To improve the cryoplant availability the following specifications are considered:

1. Number of compressor units: **≥ 3 for LP-HP compressors**
Allows reduced operation even in case of failure or maintenance on one unit.
2. VLP configuration: **Hybrid VLP Compression**
For cold compressors, **magnetic bearings** are required for high reliability.
For VLP-LP compressors, **≥ 3 units + additional unit** is also under consideration.
3. Maintenance and repair strategy: **Preventive maintenance and spare-part policy**
Strategy to consider preventive maintenance and on site capital and operational spare parts to allow maintenances and repairs.
4. Helium storage: **Full inventory on site** (incl. +20 % margin to cover for leaks)
To mitigate risks related to helium supply chain.

THE OPERATION MODES (2/2)



- **Transient modes**

- Considers 11 Tons of cold masses (<5 K), 10 Tons at TS temperature (40 K–60 K), and a speed average for cool-down/warm-up of 4 K/h.
- **Cool-down** (Total duration of 5 days, including 3 days to reach 4.5 K)
 - Cool-down 300 K to 50 K.
Refrigeration power from ~ 13 kW@300 K to 10 kW@50 K, peak value ~ 17 kW@200–150 K.
 - Cool-down from 50 K to 4.5 K.
Refrigeration power on the TS ~ 8.5 kW and on the colder masses from 1.2 kW at 50 K to ~ 650W below 30 K.
 - Liquid Helium filling: ~ 2800 liters of liquid helium in cryomodules.
 - 2 K stage: Cool-down of 2 K cavity circuits (starts of VLP compressors)
- **Warm-up** (Main expected phases)
 - Warm-up to 4.5 K: Stop of the Very Low Pressure Compressors
 - Evaporation of the Liquid helium baths
 - Warm-up from 4.5 K to 300 K (speed average of 4 K/h)