Muon Collider Cryogenics:
R&D Plan, Resources and Cost estimate

Patricia Borges de Sousa on behalf of CERN TE/CRG

4th MuCol and IMCC Annual Meeting, 15th May 2025

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- Status update
- Key cryogenics-related challenges in the MC complex
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Status update

- **A lot of work done since 2021** (Evaluation report) and **a lot of work to do** (R&D Proposal)

- The full report is available at: [1] IMCC ESPPU Report · Indico and EDMS 3284682 – 10 pages backed by a **406-page document**

- Main contribution from Cryogenics this year was to the R&D plan for the ESPPU: we **identified the path, and the resources** needed to move forward **towards a conceptual design**

The Muon Collider
Input to the European Strategy for Particle Physics - 2026 update

The International Muon Collider Collaboration

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Abstract
Muons offer a unique opportunity to build a compact high-energy electroweak collider at the 10 TeV scale. A Muon Collider enables direct access to the underlying simplicity of the Standard Model and unparalleled reach beyond it. It will be a paradigm-shifting tool for particle physics representing the first collider to combine the high-energy reach of a proton collider and the high precision of an electron-positron collider, yielding a physics potential significantly greater than the sum of its individual parts. A high-energy muon collider is the natural next step in the exploration of fundamental physics after the HL-LHC and a natural complement to a future low-energy Higgs factory. Such a facility would significantly broaden the scope of particle colliders, engaging the many frontiers of the high energy community.

The last European Strategy for Particle Physics Update and later the Particle Physics Project Prioritisation Panel in the US requested a study of the muon collider, which is being carried on by the International Muon Collider Collaboration. In this comprehensive document we present the physics case, the state of the work on accelerator design and technology, and propose an R&D project that can make the muon collider a reality.

International MUON Collider Collaboration — MuCol — Funded by the European Union

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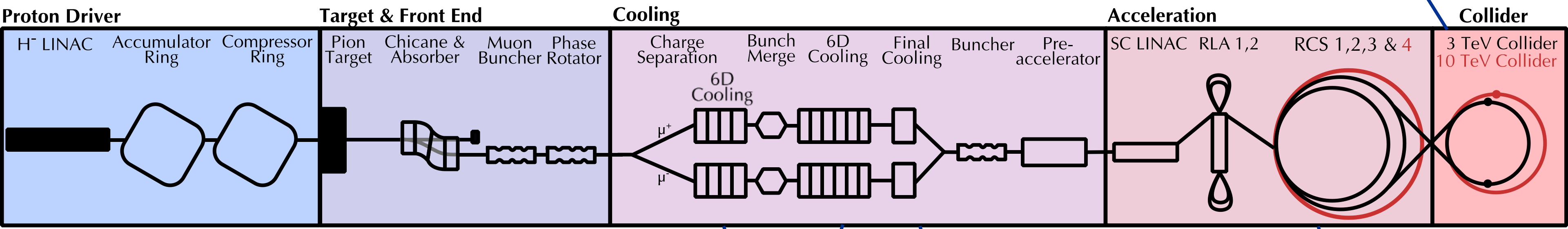
The Muon Collider complex

Key (cryogenics-related) challenges

So far, **no preliminary studies** have been carried out concerning **cooling requirements for SRF cavities**

High power deposition calls for **radiation and thermal shielding** in a complex radial build/crowded aperture; **interconnects** are **short** and required to be **flexible**



Most SC magnets in the complex are being designed for operation at **20 K** where possible – need **efficient** and **effective** cooling solution

High static heat loads due to mechanical supports

Local heat extraction remains a challenge

Cold-to-warm transitions and very short interconnects

R&D proposal

Cryogenics work package

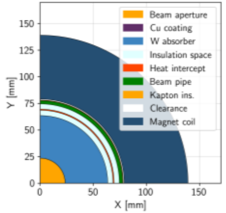
Objectives

- Investigate suitable cooling strategies for the several structures requiring a cryogenic environment, with special focus on **superconducting magnet structures operating at or around 20 K**, including defining integration studies and experimental validation as required. **Magnet structures requiring lower temperatures are extensively covered by HFM** and as such not repeated here.
- Provide **functional requirements for local heat extraction** on magnets, SRF cavities, and radiation shielding.

Large-scale cooling of accelerator magnets at 20 K is uncharted territory, experimental validation is vital regardless of chosen cooling scheme

Investigation of **thermal performance of a mock-up** of the collider radial build, of cold-to-warm transitions, will help **refine design** and heat load estimates

Early definition of functional specs to **steer magnet/cavity/cryostat design** in collaborative way



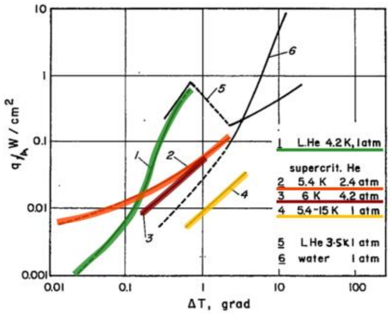
R&D proposal

Cryogenics work package

Strong development in industry based on **Turbo-Brayton cycle**, capable of reaching high refrigeration capacity soon

Cooling strategies for magnets and absorber structures

- Cooling schemes at **4.5 K** and at **20 K**
- Establish $(T, \dot{Q})$ **limits of He cooling**
- Evaluate **impact of low cryogen content**
- Cooling **strategy and choice of fluid for absorbers**

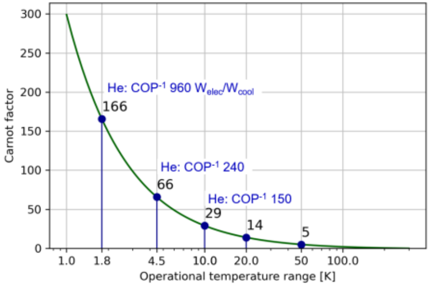


Functional requirements for design and integration

- **Local heat extraction studies**, optimization of materials and interfaces
- **Low thermal conduction supports** for absorbers in collider magnets
- Design and **integration of inner thermal screen** for collider magnets
- Mitigation of impact of **cold-to-warm transitions** in accelerator
- **Impact of movers** in cryogenic infrastructure
- Study of **compact re-cooling stations** at interconnecting regions

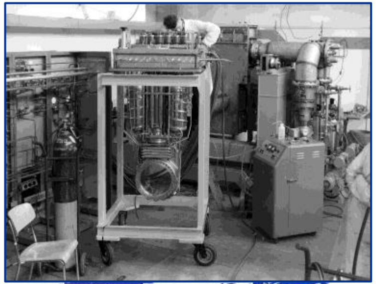
Optimization of cryogenic processes

- **Quantify potential energy savings** in developing cryoplants with **centrifugal compressors**
- Build and commission **pilot facility at CERN**



Hydrogen as a viable technical coolant

- Assessment of **safety implications** of using hydrogen in cooling channels in an accelerator magnet/tunnel
- **Study thermal performance** of forced-flow two-phase **hydrogen**
- Proof-of-principle **validation via small-scale test stand w/ hydrogen** as coolant



30 cm H_2 bubble chamber (CERN, CDS)

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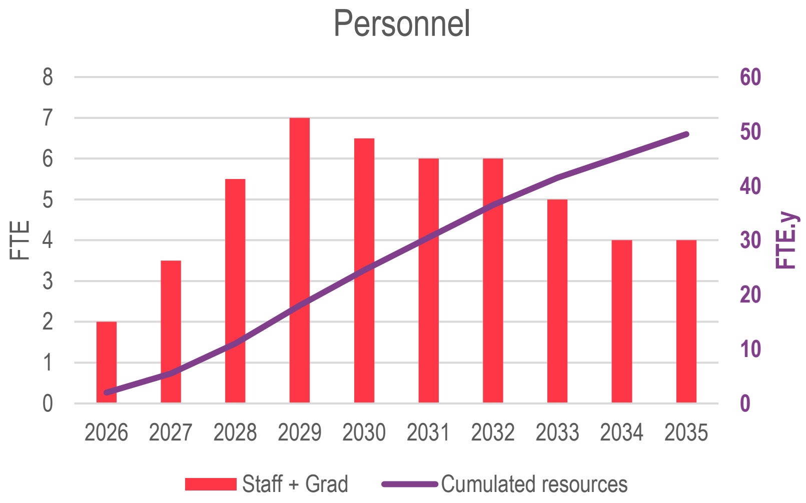
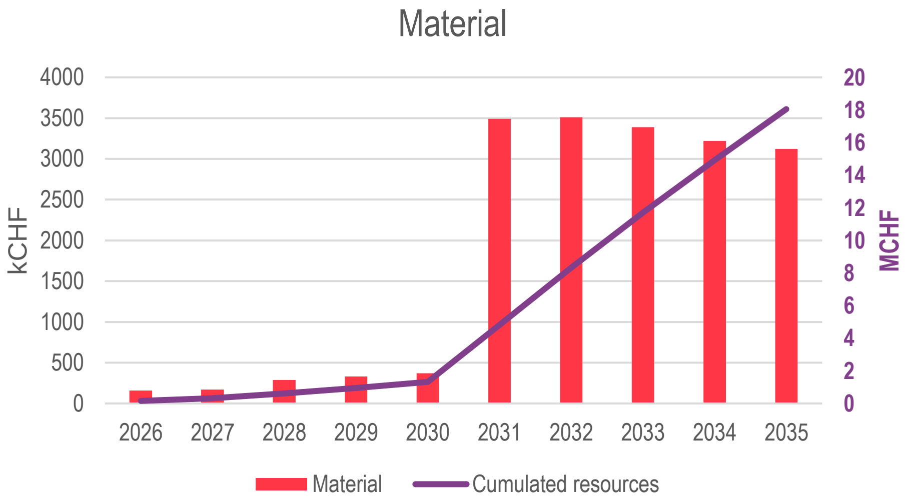
Timeline

Task	Description	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
1.1	Studies on cooling schemes at or around 4.5 K		Profit from HFM studies	■	■						
1.2	Studies on cooling schemes at or around 20 K using either helium or hydrogen	■	■	■	■	■	■				
1.3	Establish limits of helium cooling	■	■	■	■						
1.4	Evaluation of impact of a reduced cryogen content cooling scheme					■	■	■	■		
1.5	Investigation of cooling strategies for the tungsten absorbers					■	■	■	■		
1.6	Summary of Deliverable 1									■	■
2.1	Study of local heat extraction between the cooling fluid and the magnet coil			■	■	■	■	■			
2.2	Investigation of low thermal conduction supports for tungsten absorber				■	■	■	■	■		
2.3	Design and integration study of inner heat intercept				■	■	■	■	■		
2.4	Study of impact and strategies to mitigate/reduce cold-to-warm transitions in accelerator ring on cryogenic heat loads							■	■	■	
2.5	Study impact of movers on collider ring on the cryogenic infrastructure							■	■	■	
2.6	Study on compact re-cooling stations at the interconnecting regions			Essential if forced He flow cooling scheme	■	■	■	■			
2.7	Summary of Deliverable 2									■	■
3.1	Quantify potential energy savings of replacing existing cryoplant technology with centrifugal compressors			■	■	■					
3.2	Construction and commissioning of a pilot facility using centrifugal compressors at CERN						Conditional to outcome of 3.1	■	■	■	■
4.1	Assessment of safety implications of using hydrogen as a coolant in cooling channels for accelerator magnets		■	■	■						
4.2	Studies on thermal performance of forced-flow of two-phase hydrogen in cooling channels				■	■	■				
4.3	Validation via small-scale test stand using hydrogen cooling in confined geometries, incl. upgrade of facilities						Conditional to outcome of 4.1 and 4.2	■	■	■	■

R&D proposal - Resources

Cryogenics work package





Resources over 10 years (2026-2035)

- 23 FTE.y for STAFF
- 26 FTE.y for graduates/students
- 18 MCHF for material

The presented resources **do not reflect present commitments** but express a projection of the resources needed (**not presently foreseen within TE/CRG**) for progressing on the cryogenics-related tasks to achieve a CDR in 10 years' time.

Cost Estimate

for Cryogenics in the CERN implementation

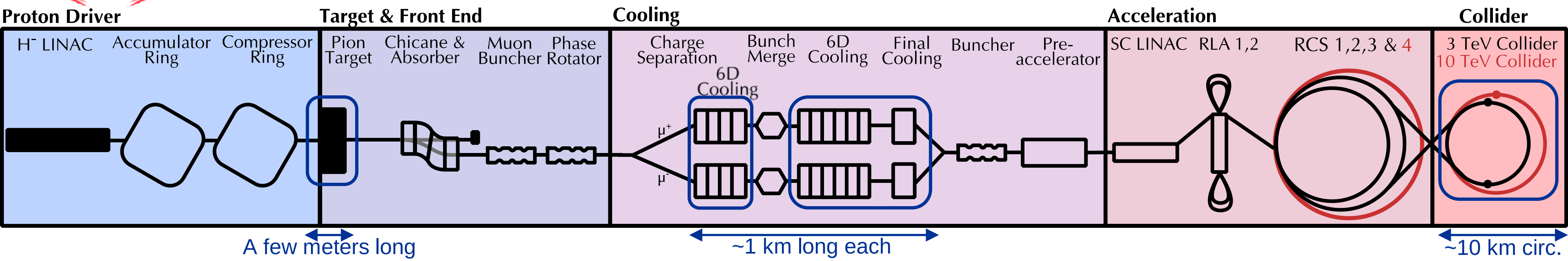
- In the framework of the input for the ESPPU, we were requested to provide an estimate for **power consumption** and **cost** for the cryogenic infrastructure.
- We made this estimate considering only the cryogenic needs for the **superconducting magnets**; superconducting RF, LH_2 absorbers, and detectors are **not included**.
- Cryogenic cooling scheme is **not yet defined**
- **Multiple areas** of complex require cryogenic infrastructure
- Heat loads at three different temperature levels, high level of **uncertainty**

} Challenging task!

Our approach: make a "magnet catalogue" and collect expected heat loads and temperature requirements, estimate required installed power without adding distribution

See details in backup slides

Magnet heat load table (preliminary) – 3.2 TeV option



Complex	Description	# magnets /type	Total magnet length [m]	Cold mass temperature [K]	Average heat load to cold mass [W/m]	Integrated heat load [kW] @ *T*	Thermal screen temperature [K]	Average heat load to thermal screen [W/m]	Integrated heat load [kW] @ *T*	Comments
Target	Target coils	23 solenoids	-	20	-	**4.1 kW @ 20 K**	80	-	**0.2 kW @ 80 K**	(1)
Cooling	6D channel 1	3030 solenoids	849	20	40	**33.96 kW @ 20 K**	80	300	**254.7 kW @ 80 K**	(2)
	6D channel 2	3030 solenoids	849	20	40	**33.96 kW @ 20 K**	80	300	**254.7 kW @ 80 K**	(2)
	Final cooling 1a	x solenoids	72	20	40	**2.88 kW @ 20 K**	80	300	**21.6 kW @ 80 K**	(3)
	Final cooling 1b	x solenoids	18	4.5	40	**0.72 kW @ 4.5 K**	80	300	**5.40 kW @ 80 K**	(3)
	Final cooling 2a	x solenoids	72	20	40	**2.88 kW @ 20 K**	80	300	**21.6 kW @ 80 K**	(3)
	Final cooling 2b	x solenoids	18	4.5	40	**0.72 kW @ 4.5 K**	80	300	**5.40 kW @ 80 K**	(3)
Collider	3.2 TeV option	1200 dipoles	6000	4.5	6.8	**40.8 kW @ 4.5 K**	80	10	**60 kW @ 80 K**	(6)

- No SC magnets in Accelerator!
- Collider uses Nb_3Sn magnets

Heat load and power consumption using He cryoplants 3.2 TeV option

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If using He cryoplants for all temperature levels:

- 85 kW cooling power @ 4.5 K_{eq} over the complex (distribution in table to the right)
- Considering HL-LHC cryoplant data (COP^{-1} 230 W_{el}/W, see slide "assumptions"), this corresponds to 19.5 MW energy consumption
- Extra heat loads and resulting power consumption associated to a specific cooling scheme, or generated by the distribution line itself, are not included.
- See next slide for spatial distribution of suitably sized cryoplants/cryo-islands with associated cost estimate

Complex	Description	Integrated heat load @ *T* [kW]			Equivalent heat load @ 4.5 K [kW]	Required electrical power [MWel]
		@ 4.5 K	@ 20 K	@ 80 K		
Target	Target coils		4.1	0.2	**0.9**	**0.2**
Cooling	6D channel 1		33.96	254.7	**17.9**	**4.1**
	6D channel 2		33.96	254.7	**17.9**	**4.1**
	Final cooling 1a		2.88	21.6	**1.5**	**0.35**
	Final cooling 1b	0.72		5.4	**0.9**	**0.2**
	Final cooling 2a		2.88	21.6	**1.5**	**0.35**
	Final cooling 2b	0.72		5.4	**0.9**	**0.2**
Collider	3.2 TeV option	40.8		60	**43.3**	**10**
				TOTAL	**84.9 kW**	**19.5 MW_{el}**

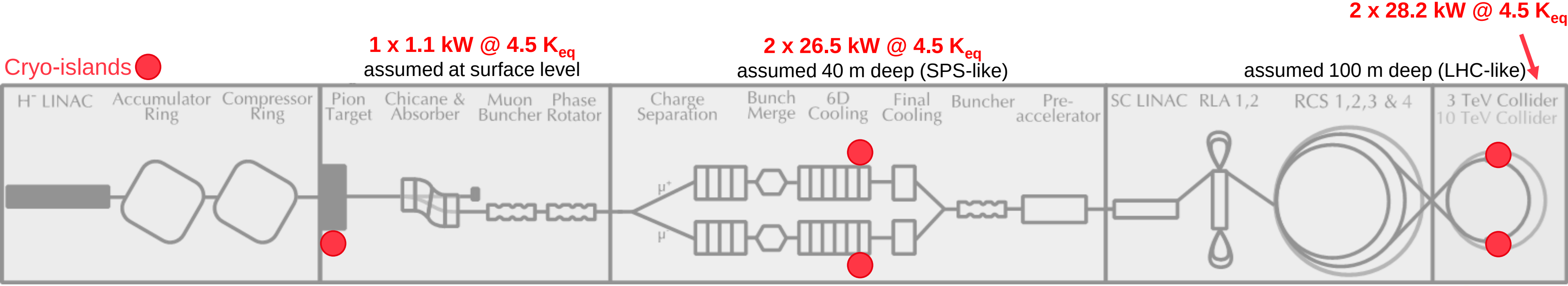
Heat load and power consumption using He cryoplants
3.2 TeV option

Complex	Eq. heat load @ 4.5 K [kW] (calculated)	Electrical power [MWel] (calculated)	Cryoplant # and capacity @ 4.5 K_{eq} (installed)	Associated cost estimate [MCHF]*
Target	0.9	0.2	**1 x 1.1 kW**	**4.7**
Cooling	40.7	9.3	**2 x 26.5 kW**	**65.1**
Collider	40.8	10	**2 x 28.2 kW**	**71.3**
	84.9 kW	**19.5 MW_{el}**	**110.4 kW installed**	**141.1 MCHF***

* 25.4 MW_{el}

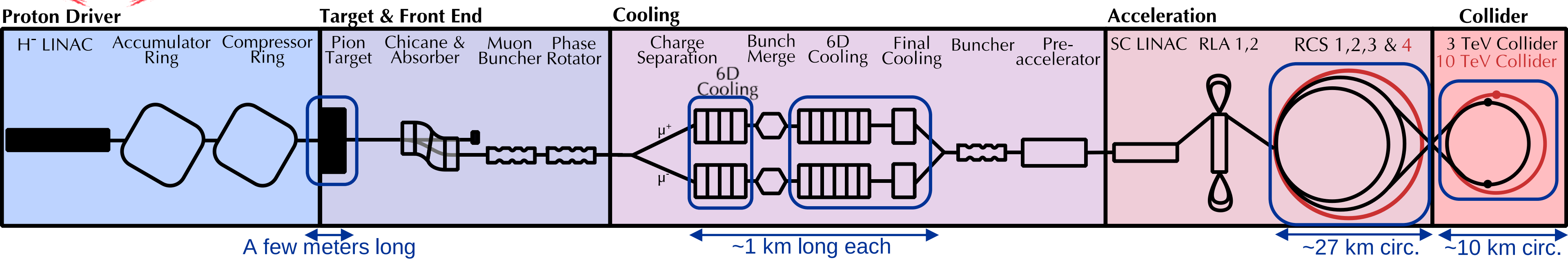
*** Assumptions:**

- Price given in [MCHF_2023], where a 2023-updated cost index was used to scale the different costs data from 1998 and compiled for LHC/HL-LHC project.
- Estimate **includes** the cost of the cryoplants, dryers, vertical shaft transfer lines to indicated depth, and interconnection boxes.
- Estimate **does not include** gas or liquid storage, cryogen inventory, instrumentation and control, warm piping, distribution



Possible cryo-island distribution/placement

Magnet heat load table (preliminary) – 10 TeV option



Complex	Description	# magnets /type	Total magnet length [m]	Cold mass temperature [K]	Average heat load to cold mass [W/m]	Integrated heat load [kW] @ *T*	Thermal screen temperature [K]	Average heat load to thermal screen [W/m]	Integrated heat load [kW] @ *T*	Comments
Target	Target coils	23 solenoids	-	20	-	**4.1 kW @ 20 K**	80	-	**0.2 kW @ 80 K**	(1)
Cooling	6D channel 1	3030 solenoids	849	20	40	**33.96 kW @ 20 K**	80	300	**254.7 kW @ 80 K**	(2)
	6D channel 2	3030 solenoids	849	20	40	**33.96 kW @ 20 K**	80	300	**254.7 kW @ 80 K**	(2)
	Final cooling 1a	x solenoids	72	20	40	**2.88 kW @ 20 K**	80	300	**21.6 kW @ 80 K**	(3)
	Final cooling 1b	x solenoids	18	4.5	40	**0.72 kW @ 4.5 K**	80	300	**5.40 kW @ 80 K**	(3)
	Final cooling 2a	x solenoids	72	20	40	**2.88 kW @ 20 K**	80	300	**21.6 kW @ 80 K**	(3)
	Final cooling 2b	x solenoids	18	4.5	40	**0.72 kW @ 4.5 K**	80	300	**5.40 kW @ 80 K**	(3)
Accelerator	RCS 3	288 dipoles	5680	20	14	**79.52 kW @ 20 K**	80	10	**56.8 kW @ 80 K**	(4)
Collider	10 TeV option	1200 dipoles	6000	20	12	**72 kW @ 20 K**	80	10	**60 kW @ 80 K**	(5)

- Collider uses HTS magnets

Heat load and power consumption using He cryoplants 10 TeV option

If using He cryoplants for all temperature levels:

- 79 kW cooling power @ 4.5 K_{eq} over the complex (distribution in table to the right)
- Considering HL-LHC cryoplant data (COP^{-1} 230 W_{el}/W, see slide “assumptions”), this corresponds to 18.1 MW energy consumption
- Extra heat loads and resulting power consumption associated to a specific cooling scheme, or generated by the distribution line itself, are not included.
- See next slide for spatial distribution of suitably sized cryoplants/cryo-islands with associated cost estimate

		Integrated heat load @ *T* [kW]			Equivalent heat load @ 4.5 K [kW]	Required electrical power [MWel]
Complex	**Description**	**@ 4.5 K**	**@ 20 K**	**@ 80 K**		
Target	Target coils		4.1	0.2	**0.9**	**0.2**
Cooling	6D channel 1		33.96	254.7	**17.9**	**4.1**
	6D channel 2		33.96	254.7	**17.9**	**4.1**
	Final cooling 1a		2.88	21.6	**1.5**	**0.35**
	Final cooling 1b	0.72		5.4	**0.9**	**0.2**
	Final cooling 2a		2.88	21.6	**1.5**	**0.35**
	Final cooling 2b	0.72		5.4	**0.9**	**0.2**
Accelerator	RCS 3		79.52	56.8	**19.3**	**4.5**
Collider	10 TeV option		72	60	**17.9**	**4.1**
				TOTAL	**78.8 kW**	**18.1 MW_{el}**

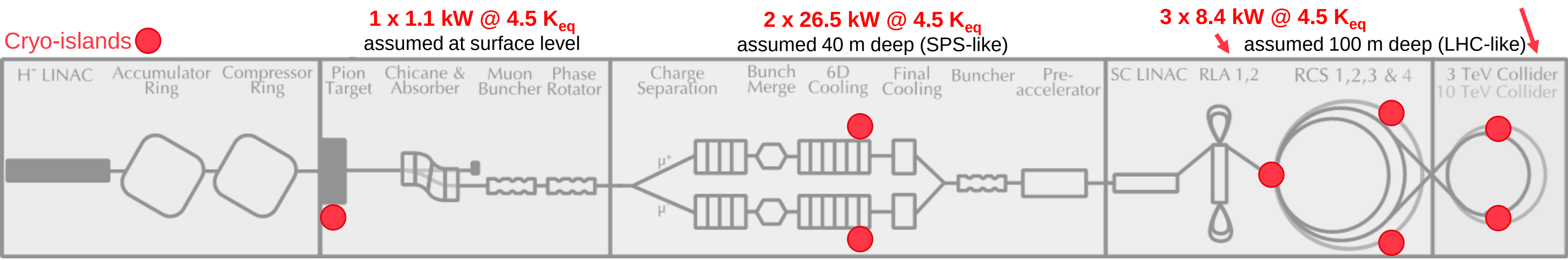
Heat load and power consumption using He cryoplants
10 TeV option

Complex	calculated Eq. heat load @ 4.5 K [kW]	calculated Electrical power [MWel]	installed Cryoplant # and capacity @ 4.5 K_{eq}	Associated cost estimate [MCHF]*
Target	0.9	0.2	**1 x 1.1 kW**	**4.7**
Cooling	40.7	9.4	**2 x 26.5 kW**	**65.1**
Accelerator	19.3	4.4	**3 x 8.4 kW**	**54.8**
Collider	17.9	4.1	**2 x 11.6 kW**	**43.4**
	78.8 kW	**18.1 MW_{el}**	**102.5 kW installed***	**168 MCHF***

* 23.6 MW_{el}

*** Assumptions:**

- Price given in [MCHF_2023], where a 2023-updated cost index was used to scale the different costs data from 1998 and compiled for LHC/HL-LHC project.
- Estimate **includes** the cost of the cryoplants, dryers, vertical shaft transfer lines to indicated depth, and interconnection boxes.
- Estimate **does not include** gas or liquid storage, cryogen inventory, instrumentation and control, warm piping, distribution



Possible cryo-island distribution/placement

Option using He cryoplants @ 4.5 K + TB @ 80 K

shown only for 10 TeV option

If using He cryoplants for 4.5 K and 20 K levels, and a turbo-Brayton machine for the 80 K loads:

- 50.3 kW cooling power @ 4.5 K_{eq} over the complex (distribution in table below)
- Considering HL-LHC cryoplant data (COP^{-1} 230 W_{el}/W) and TB data (COP^{-1} 7.5 W_{el}/W) , this corresponds to 11.6 MW + 5.2 MW = 16.8 MW combined energy consumption
- Extra heat loads and resulting power consumption associated to a specific cooling scheme, or generated by the distribution line itself, are not included.
- See next slide for spatial distribution of suitably sized cryoplants/cryo-islands with associated cost estimate

		Integrated heat load @ *T* [kW]		Equivalent heat load @ 4.5 K [kW]	Required electrical power [MWel]	Integrated heat load @ *T* [kW]	Required electrical power [MWel]
Complex	**Description**	**@ 4.5 K**	**@ 20 K**			**@ 80 K**	
Target	Target coils		4.1	**0.9**	**0.2**	0.2	w/ LHe cryoplant
Cooling	6D channel 1		33.96	**7.2**	**1.7**	254.7	4.2
	6D channel 2		33.96	**7.2**	**1.7**	254.7	
	Final cooling 1a		2.88	**0.6**	**0.14**	21.6	
	Final cooling 1b	0.72		**0.72**	**0.17**	5.4	
	Final cooling 2a		2.88	**0.6**	**0.14**	21.6	
	Final cooling 2b	0.72		**0.72**	**0.17**	5.4	
Accelerator	RCS 3		79.52	**17.0**	**3.9**	56.8	0.5
Collider	10 TeV option		72	**15.4**	**3.5**	60	0.5
				50.3 kW	**11.6 MW_{el}**	**680 kW**	**5.2 MW_{el}**

For LHe cryoplants — For TB machine

Option using He cryoplants @ 4.5 K + TB @ 80 K
shown only for 10 TeV option

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He cryoplants @ 4.5 K

Complex	Eq. heat load @ 4.5 K [kW]	Electrical power [MWel]	Cryoplant # and capacity @ 4.5 K_{eq}	Associated cost estimate [MCHF]*
Target	0.9	0.2	**1 x 1.1 kW**	**4.7**
Cooling	17.1	3.6	**2 x 11.1 kW**	**38.7**
Accelerator	17	3.9	**3 x 7.3 kW**	**51.1**
Collider	15.4	3.5	**2 x 10 kW**	**40**
	50.3 kW	**11.6 MW_{el}**	**65.4 kW installed***	**134.5 MCHF***

* 15 MW_{el}

Turbo-Brayton He-Ne @ 80 K

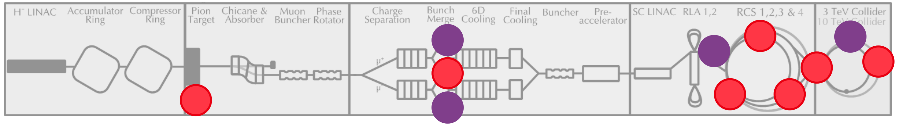
Complex	Eq. heat load @ 80 K [kW]	Electrical power [MWel]	TB # and capacity @ 80 K_{eq}	Associated cost estimate [MCHF]
Target	0.2	w/ LHe cryoplant	**N/A**	**Under investigation with specialized industry; not currently existing at CERN**
Cooling	563.4	4.2	**2 x 300 kW**	
Accelerator	56.8	0.5	**1 x 60 kW**	
Collider	60	0.5	**1 x 60 kW**	
	680.4 kW	**5.2 MW_{el}**	**720 kW installed**	

*** Assumptions:**

- Price given in [MCHF_2023], where a 2023-updated cost index was used to scale the different costs data from 1998 and compiled for LHC/HL-LHC project.
- Estimate **includes** the cost of the cryoplants, dryers, vertical shaft transfer lines to indicated depth, and interconnection boxes.
- Estimate **does not include** gas or liquid storage, cryogen inventory, instrumentation and control, warm piping, distribution

He cryoplants

TB cryoplants



Summary

- ✓ Clear R&D plan as **'roadmap towards CDR + demonstrator'** defined, with estimate for **resources** (material and personnel) as input for the ESPPU

- ✓ **First estimate of power consumption** for magnet structures within the complex has been carried out; further refinement must come from **definition of cryogenic layout**, peak power demand, more **mature conceptual design** esp. on cooling channel where static heat loads dominate

- ✓ **Superconducting RF cryogenic needs should be added** to the overall estimate, with definition of operating temperature(s)

- ✓ **R&D effort requires the requested manpower to advance!**

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Thank you for your attention!

Backup slides

Comments to magnet heat load tables

1) Integrated heat load for cold mass and thermal shield. Input: L. Bottura, S. Fabbri

2) Average heat load to cold mass 15 W/m (static + dynamic losses, incl. 1 pair of current leads per solenoid) + 25 W/m (transient due to ramping losses). The conservative value of 15 + 25 = 40 W/m is taken to size installed power in the cryoplant, but a value close to 15 W/m can be used when estimating yearly electrical power consumption. The heat loads at 80 K are conservatively estimated at 300 W/m, considering 1 pair of current leads per solenoid, thermal screen, and cold-to-warm mechanical supports for the solenoids. An option in which the solenoids are supported between each other using cold-cold transitions can reduce this value but is not yet mature. Input: M. Statera, L. Bottura, S. Fabbri

3) Final cooling solenoids are divided into those at 20 K and those at 4.5 K, with the same heat load assumptions as stated in (2).

4) The heat load for the cold mass is estimated at 14 W/m: 11 W/m is load induced by the beam, 3 W/m estimated as static heat loads from supports, radiation, etc. The contribution from eventual cold-to-warm transitions is not included.

5) Values estimated for a collider ring operating at 10 TeV. For magnets at 20 K the agreed absorber thickness is 30 mm and resulting beam-induced load is 8 W/m. Static losses are estimated at 4 W/m, bringing the total heat load to the cold mass to 12 W/m. Heat load at 80 K is estimated at 10 W/m incl. supports and radiation. Input: P. Borges de Sousa based on [2]

6) Values extrapolated from a 10 TeV collider where beam losses are 3.2/10 of the 10 TeV value. For magnets at 4.5 K the agreed absorber thickness is 40 mm and resulting beam induced heat load is 3.2/10 x 4 W/m = 1.3 W/m. Static losses are estimated at 5.5 W/m, bringing the total heat load to the cold mass to 6.8 W/m. Input: P. Borges de Sousa based on [2]

[2] Patricia Borges de Sousa *et al.* *“Cryogenic options for future accelerators: case study for the Muon Collider ring”*. In: Proceedings of the 29th International Cryogenic Engineering Conference and International Cryogenic Materials Conference 2024. Submitted for publication on 10/12/2024

Assumptions for cost estimate

- This estimate **only considers the cryogenics needs for the magnets**. Required cryogenic infrastructure for **experiments**, superconducting **RF** and **H_2 absorbers is not included**. A separate estimate by the Muon Collider study based on XFEL and ILC cavities @ 2 K has been carried out for superconducting RF.
- The magnets for the **insertion regions and matching sections are not included** in this estimate due to lack of input from the study.
- This estimate **does not consider cooling scheme-specific additional power consumption**, as the one linked to distribution; it is solely based on the heat load to be extracted from the magnets' cold masses and thermal shields at their respective temperature levels **with no cryogenic margin (usually, between 30 to 50% on top).**
- Electrical power consumption for the 4.5 K_{eq} He option was calculated based on a He cryoplant providing **14 kW at 4.5 K_{eq}, with a COP^{-1} of 230 W_{el}/W** (typical HL-LHC helium cryogenic plant, incl. 3.6 kW @ 1.8 K).
- Electrical power consumption for the turbo-Brayton option was calculated based on a turbo-Brayton machine providing **200 kW at 80 K_{eq}, with a COP^{-1} of 7.5 W_{el}/W (35% Carnot)**; such equipment not existing at CERN today.
- The **heat loads considered for the collider were estimated as published in [2]**; the same assumptions were adopted for the accelerator magnet, disregarding the potential contribution from multiple cold-to-warm transitions.
- The heat loads for the target and cooling parts of the complex are input given by the magnet designers and are **preliminary**.
- The heat loads to be extracted in the tungsten absorbers is not considered a cryogenic load and therefore **has not been included.**

[2] Patricia Borges de Sousa *et al.* "*Cryogenic options for future accelerators: case study for the Muon Collider ring*". In: Proceedings of the 29th International Cryogenic Engineering Conference and International Cryogenic Materials Conference 2024. Submitted for publication on 10/12/2024