Sustainable HEP 2026 — 5th Edition

Developing a Roadmap for Sustainable Cryomodule Design

PRESENTED BY NUNO ELIAS

2026-07-10

Work supported by funding from European Union’s program EU HORIZON-INFRA-2023-TECH-01-01 under GA n°101131435

Introduction

Context

- Particle accelerators are exceptional instruments (research, applications), but in a context of energy savings and sustainability
  - **Minimizing the energy consumption of future accelerators is a challenge to be faced**
  - Highlighted in the European Strategy for Particle Physics (ESPP 2020) and further strengthened in the ESPP 2026
- **EU call dedicated to "*New technologies and solutions for reducing the environmental and climate footprint of Research Infrastructures* »** (HORIZON-INFRA-2023-TECH-01)
  - **Project « *Innovate for Sustainable Accelerating Systems* (iSAS)» launched (2024)**
  - Scientific coordinator: J. D'Hondt (Nikhef), project coordinator: A. Stocchi (CNRS-IJCLab)
- **Resources and partners**
  - Total project budget of ~13 M€ with ~5 M€ funded from Horizon Europe
  - Partners : 12 research institutes and 6 industrial companies
  - HR ~1000 person-months spread over 4 years

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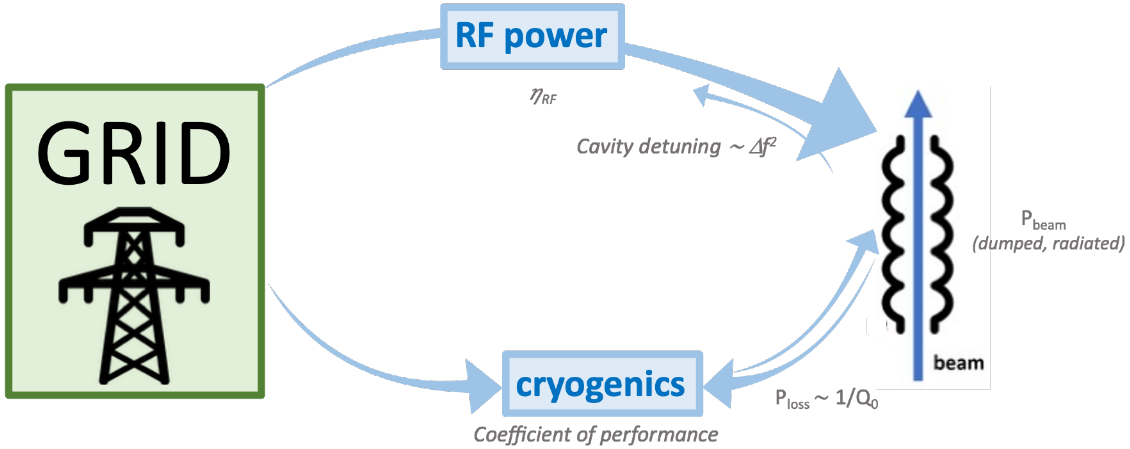
Background of the iSAS project

Sources of Power inefficiencies from SRF

- **Multiple sources impacting the grid-to-beam power efficiency, including**
  - RF power source efficiency : η_{RF}
  - RF load by detuned cavities
  - Cavity cryogenic loss : $P_{loss} \propto 1/Q_0$
  - Generation of cryogenics (coefficient of performance) : COP
  - Loss of the beam power : P_{beam}



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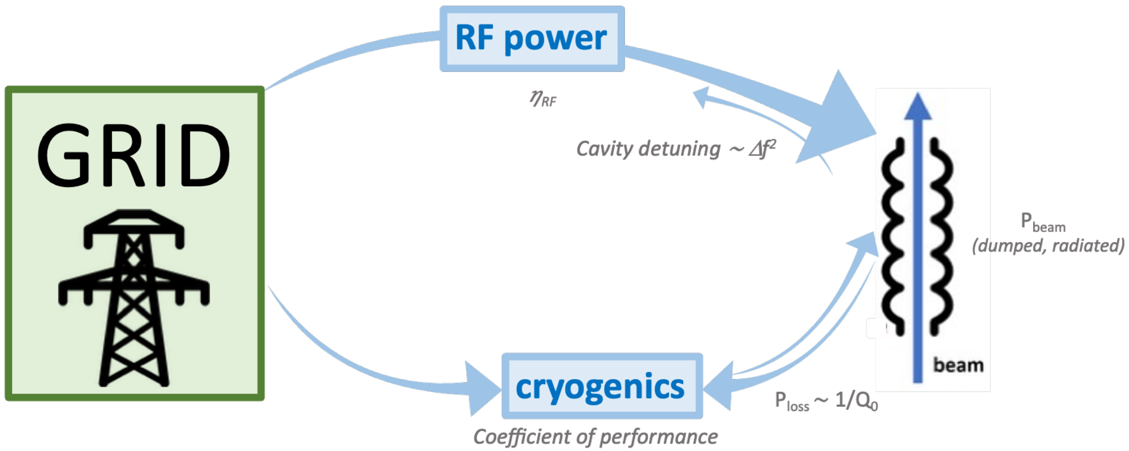
Sources of Power inefficiencies from SRF

- **Multiple sources impacting the grid-to-beam power efficiency, including**
  - RF power source efficiency : η_{RF} → enhance efficiency of the RF sources
  - RF load by detuned cavities → deal with microphonics to reduce Δf
  - Cavity cryogenic loss : $P_{loss} \propto 1/Q_0$ → improve quality factor of the cavity Q_0
  - Generation of cryogenics COP. → increase the operating temperature of the cavity (T)
  - Loss of the beam power : P_{beam} → recover the energy of the beam (*Energy Recovery Linac*)



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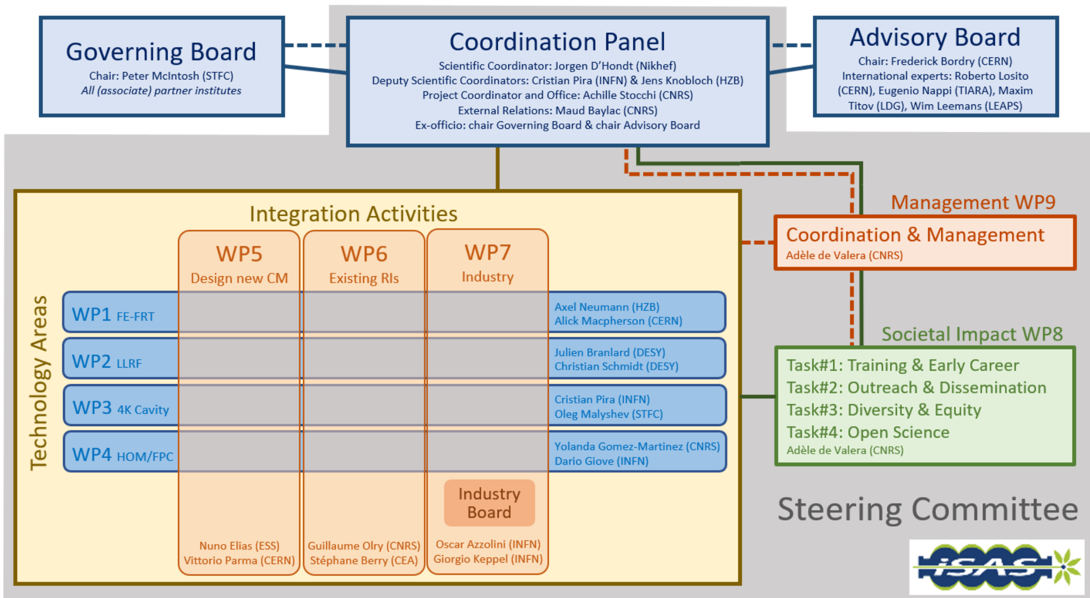
Scope of the iSAS project

Develop technologies and Integration

- **Development of 4 technologies**
  - WP1 : Ferro-Electric Fast Reactive Tuner (FE-FRT)
  - WP2 : Optimized Low Level RF control (LLRF)
  - WP3 : Nb_3Sn films on Cu for 4.2 K cavity operation
  - WP4 : Couplers, Fundamental and Higher Order Modes

- **Integration activities**
  - WP5 : In the design of a new energy-saving cryomodule
  - WP6 : In current and future research infrastructures accelerators
  - WP7 : Into industrial solutions

May 2026



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iSAS WP5

Integration into a linac Cryomodule

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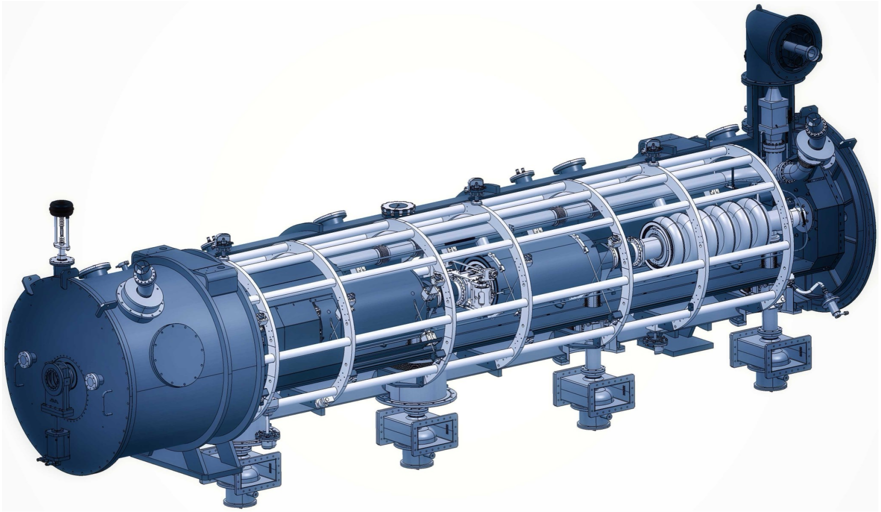
WP5 Main goal

The design of **any** LINAC cryomodule is optimised to meet the specific research objectives of the accelerator facility, while addressing **common challenges** such as high-power electric fields, ultra-low temperatures, ultra-high vacuum, precise alignment, etc.

WP5's main goal is to tackle the common engineering challenges of integrating iSAS technologies ***into a parametric design of a new cryomodule***, building on developments made with ESS cryomodules whilst benchmarking against other facilities.

In addition, to unlock the full energy-saving capability of this cryomodule, the objective of WP5 is to also address the challenging **beam dynamics requirements** when operating the new cryomodule in **Energy Recovery Linacs** with recirculating beams.



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WP5 Main Tasks

Task 5.1: Coordination on cryomodule design activities– M1-M48
- *General coordination by ESS as described above.*

Task 5.2: ESS cryomodules experience and benchmarking with other recent facilities– M1-M36
- *Compile the lesson learned from the ESS CM testing activities, technical commissioning, and initial operation.*
- *Benchmarking with projects in the implementation phase (worldwide).*
- *Develop a roadmap to develop a new, sustainable CM design.*

Task 5.3: Sustainable criteria for LINAC cryomodule design– M24-M48
- *Integrate findings from the other iSAS WPs into a generic CM design.*
- *Explore the sustainability criteria for the design.*

Task 5.4: Beam Dynamics for ERL-based accelerators with energy-efficient cryomodules – M1-M48
- *Simulate the beam dynamics of ERL-based accelerators when the energy efficient CM is included.*
- *Study the lattice design to optimize the beam and energy saving performances.*

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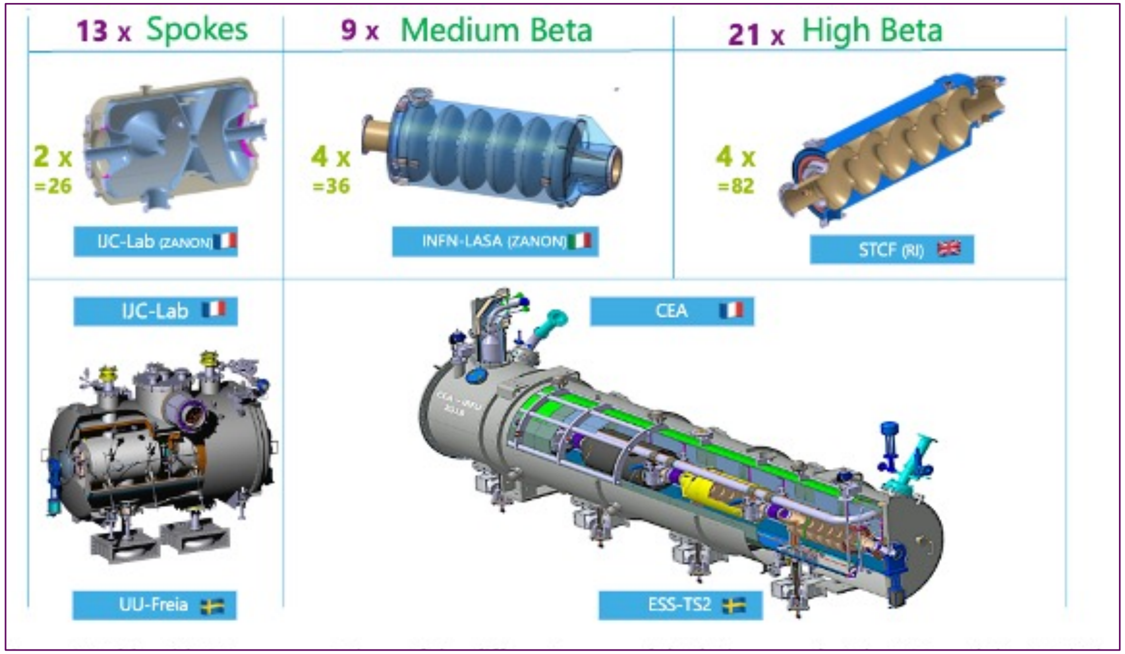
- **Scope**
- **System Overview**
- **CM Design Phase Lessons**
- **Manufacturing and Assembly phase Lessons**
- **Testing and Commissioning**
- **Sustainability aspects**
- **Conclusions**



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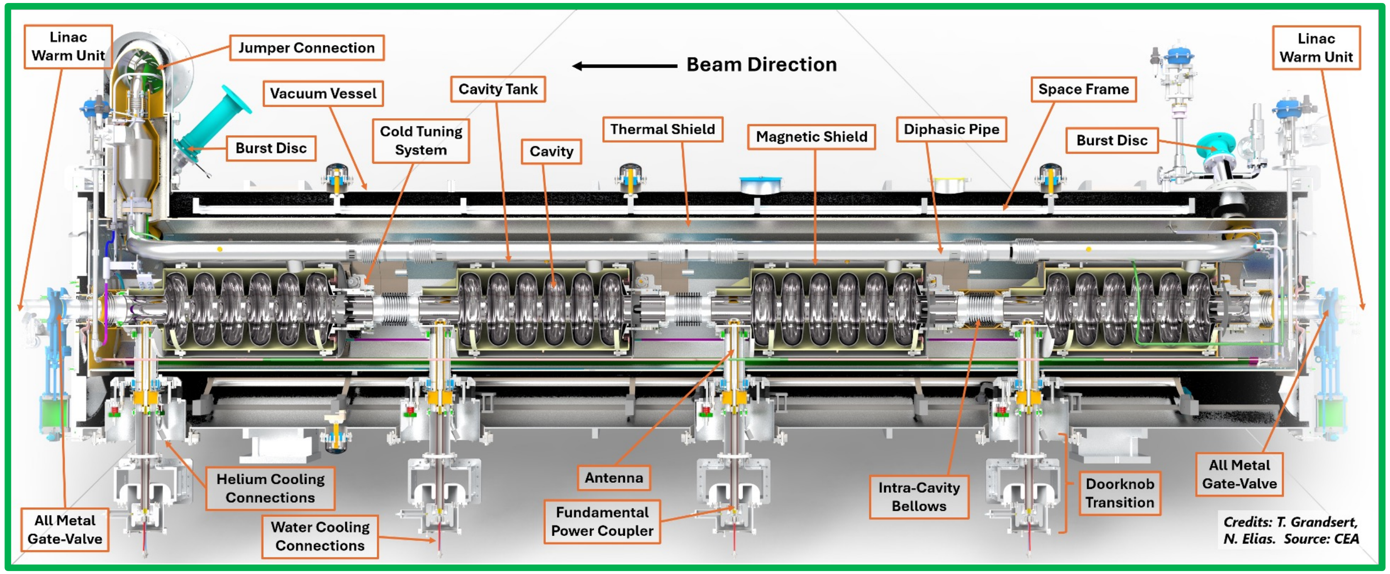

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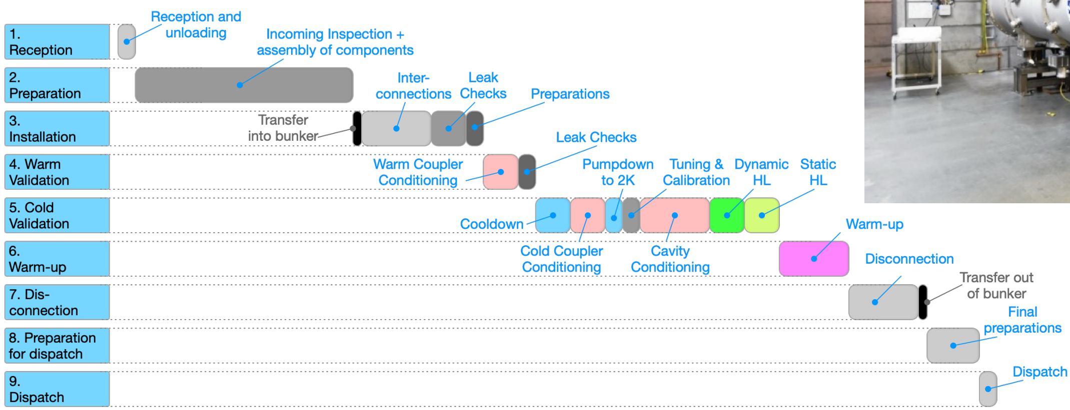

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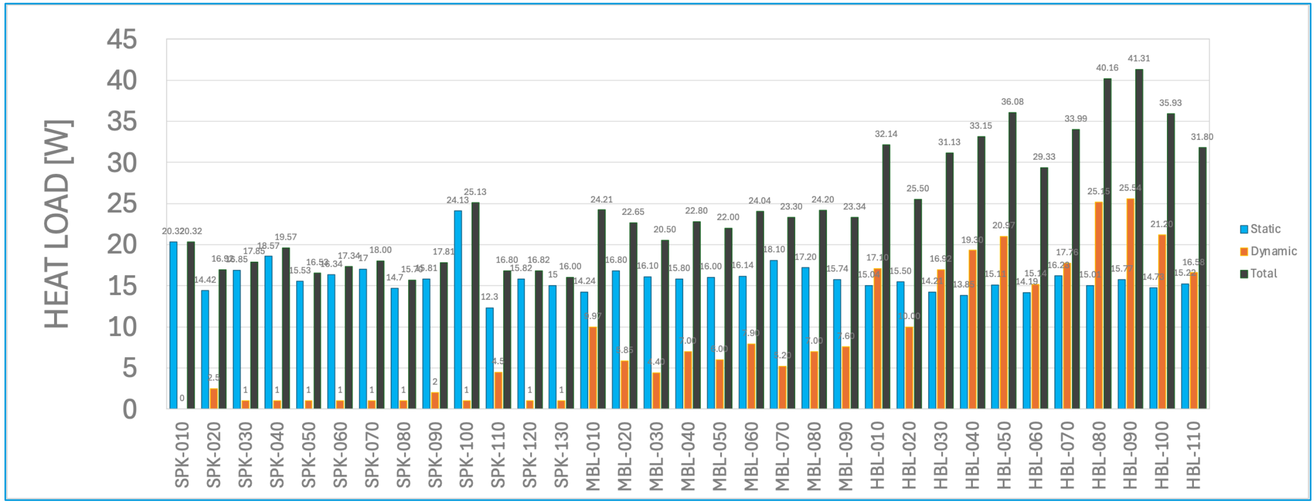

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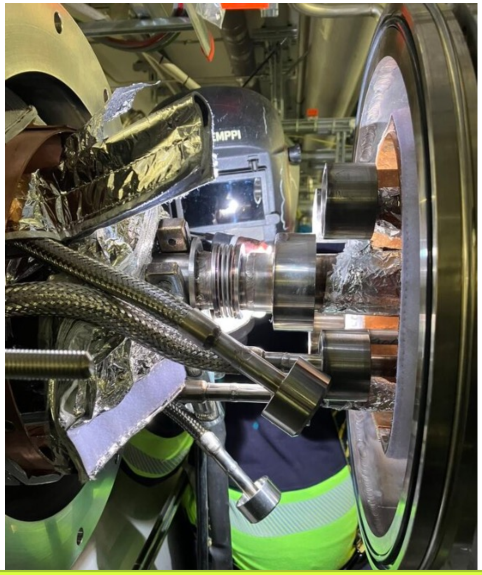

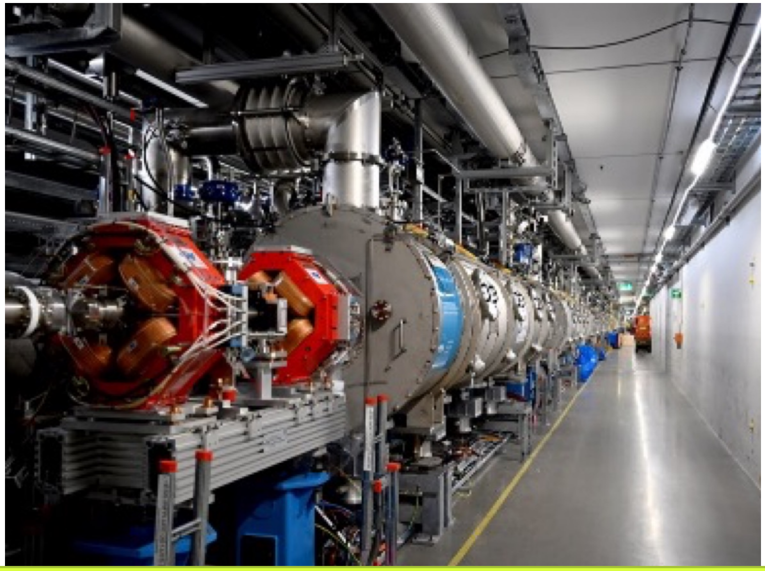

Paper at ICEC30-ICMC2026, Daejeon, South Korea ***"Lessons Learned from the ESS Elliptical Cryomodule Design and Operation : Paving the way for Sustainable Accelerating Systems (iSAS)"***

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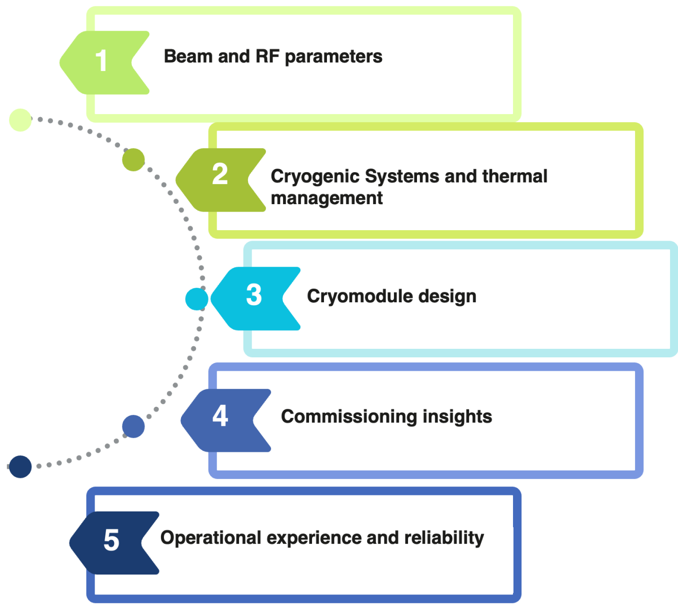
Main steps of the benchmarking methodology:

- Definition of **key technical areas** of interest to be included in the benchmarking study
- Proposal of **cryomodule design concepts, facilities and experts**
- Definition of specific points of interest for each area and **drafting of the questionnaire**
- **Literature research and pre-filling of the answers**
- Initial contact and **questionnaire distribution**
- Follow-up **face-to-face interviews**
- **Compilation** of answers and **final report**.



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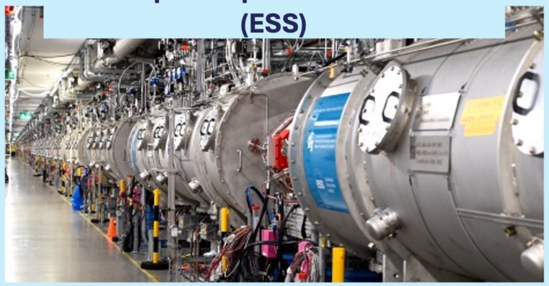
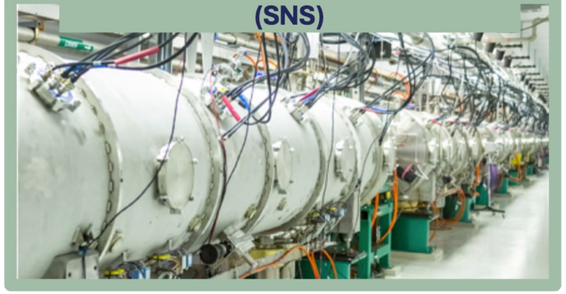


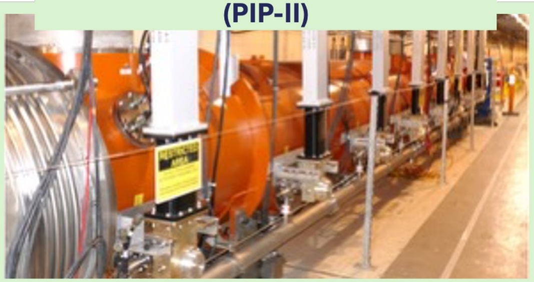
Spallation Neutron Source (SNS)



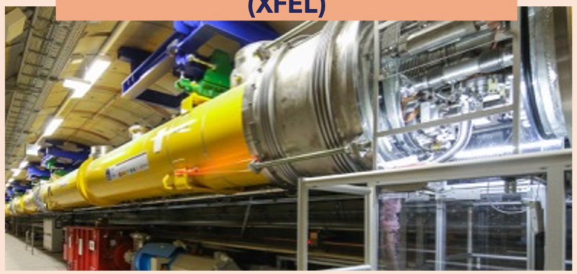
Large Hadron Collider (LHC)

Linac Coherent Light Source II (LCLS-II)

Proton Improvement Plan II (PIP-II)



European X-ray Free-Electron Laser (XFEL)



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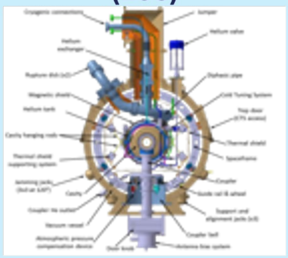

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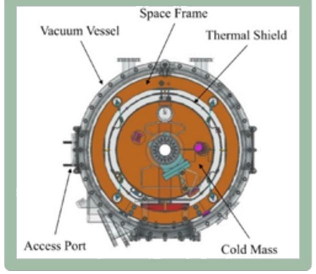

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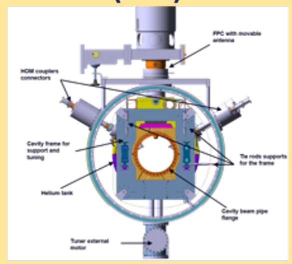

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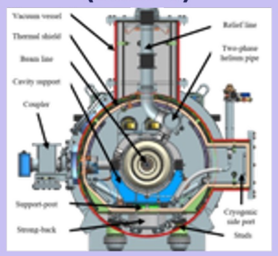
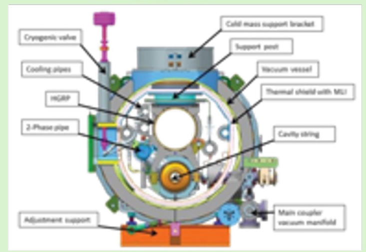
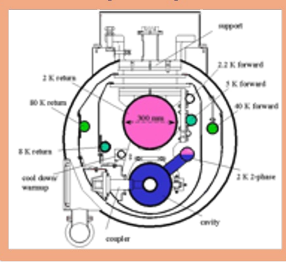


Proton Improvement Plan II (PIP-II)



European X-ray Free-Electron Laser (XFEL)



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1 **Beam and RF parameters**

- Focus: particles, accelerating gradients, operating frequencies, duty cycle.
- Goal: Understand how beam physics requirements drive the complexity and energy demands of the CM.

The beam structure requirements and RF parameters, including choice of frequency, fundamentally dictate the SRF and cryomodule architecture:

- **CW machines** prioritize **high Q_0** to minimize dynamic losses, while **pulsed machines** tend to push **higher peak gradients**
- The type of machine (circular multi-pass, linear single-pass) and particles to be accelerated also dictate different requirement (alignment, losses, beam stability thresholds, etc.)
- **Wide range in delivered FPC power**. Moreover, within the limit of the six facilities considered, **two main families** were identified, when it comes to orientation within the cryomodule, **either vertical or horizontal**.
- In **proton linear accelerators**, the beam exhibits **lower sensitivity to trapped HOM perturbations**

ESS	*SNS*	*LHC*	*XFEL*	*LCLS-II*	*PIP-II*

- LCLS-II and PIP-II use nitrogen-doped cavities to achieve a high Q_0: 2.7×10^{10} at 16 MV/m for LCLS-II and 3.3×10^{10} at 21 MV/m for PIP-II.
- Peak value gradient above 16MV/m for all the facilities operating in pulsed mode. ESS and XFEL cavities are equipped with fast-piezo tuners, while SNS cavities do not need fast compensation with piezo actuators.

- XFEL, LCLS-II, and PIP-II operates with average RF power of 2.15kW, 7kW and 35kW respectively, with FPCs designed for a peak power of 156 kW, 7 kW and 43kW respectively, at the nominal duty cycle. The FPCs have horizontal orientation and bellows in the transmission line ensure sufficient flexibility to compensate for the cold mass thermal contraction.
- ESS, SNS and LHC operates with average RF power of 43 kW, 44kW and 300 kW respectively, with FPCs designed for a peak power of 1.1 MW, 550kW and 350 kW respectively, at the nominal duty cycle. The FPCs have a vertical - bottom or top for the LHC- orientation, these designs do not have bellows in the transmission line.

- ESS and PIP-II cavities do not have HOM couplers. SNS originally included HOM couplers, however operational experience indicated they were not required to achieve goal performances, and given occasional leaks and failures, they have been progressively removed during cryomodule repairs.
- Circular colliders like the LHC, and electron machines like XFEL and LCLS-II require the integration of HOM couplers in the cavity design.

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2 **Cryogenic Systems and thermal management**
- Focus: Machine architecture, Cooling circuit layouts, temperature and pressure levels, static and dynamic heat loads, and cooling capacity cryogenic plant. Management of helium inventory and ODH risk
- Goal: Characterizing design choices for cryogenic systems.

Significant diversity exists in cooling circuit segmentation, temperature levels, and thermal shield configurations

- A **multi-level temperature architecture** (2K, 4.5/ 5-10K, 35–80 K) is standard across all facilities.
- For cavities operating at **low duty cycles, static heat loads** strongly impact the total cryogenic consumption. For cavities **operating in CW** instead, the cryogenic losses are driven by the **dynamic heat loads** (except for LHC).
- For the **FPC outer conductor**, it was observed a preference for the active cooling with helium, for operation with high average RF power (>40/50 kW). **Active cooling is considered more flexible / adjustable**, than fixed thermal intercepts.
- **Cryogenic distribution strategy** (continuous vs segmented) strongly affects maintainability and failure recovery capability.

Facilities (ESS, SNS, LHC, XFEL, LCLS-II, PIP-II)	
ESS, SNS, XFEL, LCLS-II, PIP-II	A three-level architecture (typically 2 K, 4.5–10 K, and 35–80 K) is the standard for optimizing thermal efficiency across all facilities.
LHC	Due to assembly compromises, the LHC uses a single temperature level (4.5 K) and a floating thermal shield made of MLI blankets.
ESS, SNS, LHC, XFEL	The percentage of static heat load, compared to the total heat load to the cavity bath, is indicated per facility: ESS 44.1%, SNS 73.7%, LHC 83.7%, XFEL 45.8%
LCLS-II, PIP-II	The percentage of static heat load, compared to the total heat load to the cavity bath, is small for facilities operating in CW, LCLS-II 10%, PIP-II 12.5%.
ESS, SNS, LHC	Active helium cooling is considered more flexible for high average RF power operations or for designs qualified for higher values of peak power, ESS, SNS and LHC use ~5 K helium to cool the FPC outer conductors.
XFEL, LCLS-II, PIP-II	Facilities with lower average power, such as XFEL, LCLS-II, and PIP-II, the outer conductor is cooled with fixed temperature thermal intercepts (copper braids) connected to the cryogenic lines.
XFEL, LCLS-II	Accelerating modules are integrated into a single vacuum vessel string. In case of maintenance the entire linac must be warmed up.
SNS, PIP-II	Cryomodules are stand-alone units, with access hatches, connected to the external distribution line via bayonets. The maintenance work may be performed through the access hatches, otherwise the cryomodule can be removed with the rest of the machine cold.
ESS, LHC	Cryomodules are stand-alone units, with access hatches, connected to the external distribution line via jumper with welded connections. The maintenance work may be performed through the access hatches, otherwise the cryomodule can be removed, warming up the linac

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3

Cryomodule design
- Focus: characterize internal components, cavity string assemblies, power couplers, tuners, and magnetic shielding.
- Goal: Map the constraints, design choices and integration aspects regarding the cryomodule design and its assembly sequence

While cavity technology is broadly similar (elliptical SRF cavities), integration philosophies differ:

- **Variations in cavity supporting schemes**, vacuum forces compensation, longitudinal references and alignment strategies have been identified.
- Helium tank design influences mechanical stiffness and microphonics sensitivity.
- **Variations in Magnetic shielding implementation** (cold vs warm, single vs multi-layer) with impact on achievable Q_0
- Some facilities reported **design compromises** made to facilitate assembly, reduce cost, or drivers related to schedule
- The **integration of a second thermal shield**, when in presence of the 8-10K heat intercept, was evaluated but not always considered convenient
- It appears now a **standard to include access hatches** in the cryomodule design.

ESS	*SNS*	*LHC*	*XFEL*	*LCLS-II*	*PIP-II*

Cavities are supported by the Helium Gas Return Pipe (GRP), which acts as the main structural backbone and an Ivar rod that provides longitudinal anchoring.
Cavities are supported and aligned with spaceframe at ambient temperature connected to the vacuum vessel. For the SNS cryomodule, a Nitronic rod is added for longitudinal anchoring.
Cavities are supported by a frame anchored to the vacuum vessel through six tie rods.
Cavities are supported by two support posts (one fixed, one sliding) mounted on a strongback support at ambient temperature.

The introduction of a cold magnetic shield outside the helium tank is a common practice for all the facilities using Niobium cavities. LCLS-II cavities have two layers of cold magnetic shielding.
SNS and PIP-II cryomodules have also a warm global magnetic shield.
LCLS-II and PIP-II cavities rely as well on fast cooldown across the Nb transition temperature to sweep out the trapped magnetic flux and reach the required Q_0.
LHC cavities in copper with Nb coating are not sensitive to magnetic field.

For LCLS-II and PIP-II, given the availability of a low temperature heat intercept, it was evaluated the possibility of having a second thermal shield. Although, the effective reduction of the heat load to the 2K was not considered sufficient to justify the cost, complexity and space occupation of a second shield.
In the XFEL cryomodule instead, there are two thermal shields, resulting in very minimal heat loads to the cavity bath.

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4

Commissioning insights

•Focus: Knowledge gained during the assembly, testing, and initial installation phases.

•Goal: Document technical difficulties in the commissioning phase, providing useful feedback for future sustainable designs.

Several key elements emerged during the discussion on commissioning experience and lessons learned:

- A primary goal across facilities is to minimize **discrepancies between "as-designed" and "as-tested/operated"** performance, specifically addressing issues like cryoplant limitations and unexpected heat load differences
- Success depends on maximizing preparation before tunnel installation, maintaining strong in-house expertise, accurate planning that allows smooth sequence and sufficient flexibility
- It is strongly recommended to **develop the design of cryomodules and their associated services together**, to ensure system compatibility and avoid late-stage conflicts
- Focusing on continuous **quality controls** and accurate interface matching is essential to reduce rework

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iSAS WP5

Integration into a linac Cryomodule

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Task 5.2: ESS cryomodules experience and benchmarking with other recent facilities – M1-M36
- ***Compile lesson learned from the ESS CM*** *testing activities, technical commissioning, initial operation.*
- ***Benchmarking with projects in the implementation phase (worldwide).***
- *Develop a roadmap to develop a new, sustainable CM design.*

5 **Operational experience and reliability**
•Focus: Factors limiting cryomodule performance, mitigation strategies, machine availability, capability for maintenance, repair and replacement.
•Goal: Use real -world operational data to ensure that energy -saving innovations do not compromise the facility's scientific output.

Long-term availability emerged as a critical sustainability metric.
Facilities emphasized:

- **Redundancy of internal equipment** is critical in operation (ex: facilities now design for extra RF capacity, when possible, to compensate for individual cavity failures without beam degradation).
- Different experiences have been described regarding **cavity performance degradation and strategies for compensation** with the remaining cavities.
- **Modular cryogenic systems and replacement strategies**. The ability or not to isolate a single cryomodule for maintenance without affecting adjacent units strongly impacts overall machine uptime.
- Importance of **accessibility** was emphasized, more specifically for couplers and tuners.
- Failure modes reported include FPC degradation, tuner actuator failure, and vacuum-related incidents.
- **Cryoplant trips** remain a major bottleneck for availability.
- The cryoplant design includes **safety margins** to compensate for **uncertainty** in the estimation of cryomodule static and dynamic heat loads.

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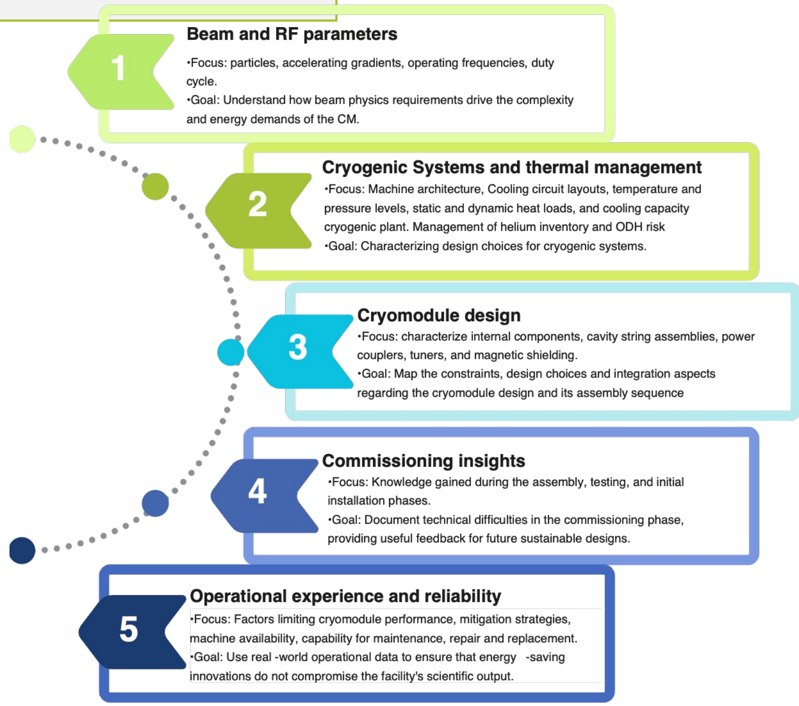
- Beam and RF parameters are the design drivers, while cryogenic efficiency impacts the overall sustainability.
- Common trends, (multi-level temperature architectures, modular cryogenic segmentation, accessibility) have emerged as industry standards.
- High availability and long-term reliability are primary metrics for sustainability.
- The collected data will be translated into practical engineering strategies, to build a **Roadmap for the development of sustainable cryomodules.**
- The resulting guidelines will directly contribute to the **development of a parametric tool for cryomodule design**.



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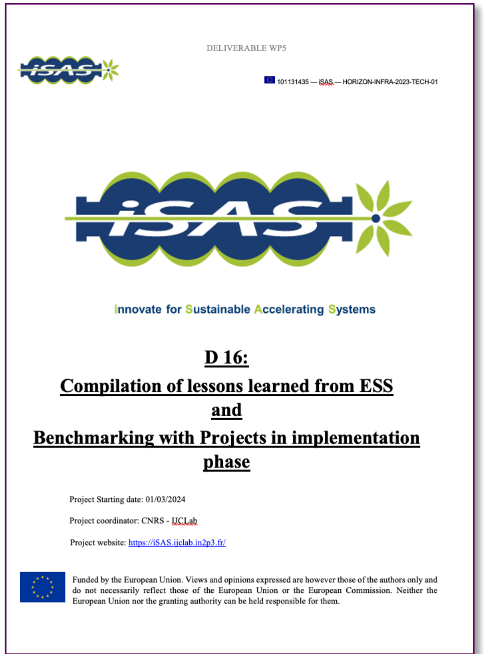

DELIVERABLE WP5

101131435 — iSAS — HORIZON-INFRA-2023-TECH-01

Innovate for Sustainable Accelerating Systems

D 16:

Compilation of lessons learned from ESS
and
Benchmarking with Projects in implementation phase

Project Starting date: 01/03/2024

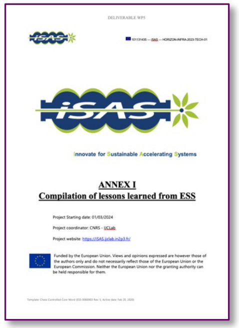
Project coordinator: CNRS - IJCLab

Project website: https://iSAS.ijclab.in2p3.fr/

Funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the granting authority can be held responsible for them.

Report :
"Compilation of ESS CM lessons learned
& Benchmarks from facilities in implementation phase"

https://arxiv.org/abs/2606.24590


ANNEX I
Compilation of lessons learned from ESS

Annex I : Detailed Report on "Compilation of Lessons Learned from ESS"


ANNEX II
Benchmarking Cryomodule Designs for iSAS WP5

Annex II: Detailed Report on "Benchmarking Cryomodule Designs for iSAS WP5"

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iSAS WP5

Parametric cryomodule design

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Task 5.3: Sustainable criteria for LINAC cryomodule design – M24-M48
• Integrate findings from the other iSAS WPs into a generic CM design.
• Explore the sustainability criteria for the design.

PARAMETRIC	DESIGN for a	SUSTAINABLE	CRYOMODULE with	ISAS TECHNOLOGIES
- Which Parameters are relevant?	*- Design Drivers? - Requirements? - Constraints ? - Uncertainty ?*	*- Energy Savings*	*- Main Functions*	*- State-of-the art*
- Desired / Achievable degree of complexity?	*- Best Practices*	*- Lifecycle*	*- Main Components*	*- Looking into the future at proposed acc. syst.*
	- Systems Engineering approach	*- Availability - Maintainability - Repairability*	*- Systems Integration*	*- Quantification of gains*
	- Design Dilemmas	*- Industrial Solutions?*		

Engineering Toolbox for CM design: Decision making tool

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Summary and Outlook:

- **Strategic Objective:**
  The iSAS initiative is establishing new technologies and the roadmap for next-generation, energy-efficient superconducting accelerator design.
- **Comprehensive Benchmarking:**
  Through a systematic analysis of six global facilities (ESS, LHC, XFEL, PIP-II, SNS, LCLS-II), we have identified the critical parameters driving thermal efficiency and operational reliability.
- **Key Drivers for Sustainability:** Our assessment confirms that success relies on four main pillars:
  - Standardisation & Modularisation
  - Industrial Readiness
  - Collaborative Governance
  - Optimised Design Trade-offs
- **Future Outlook:**
  The upcoming phase transitions into the development of a **parametric design framework** and an **engineering toolbox**, providing a practical blueprint for sustainable implementation across future research infrastructures.

Thank you

Sustainable HEP 2026

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