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Deliverable Abstract

Risk analysis related to impact of iSAS technologies

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1. INTRODUCTION

This document presents the risk analysis of the technologies developed within the iSAS project (Deliverable D34). It focuses on the risks associated with achieving the expected energy-saving performance of the iSAS technologies (developed in WP1 to WP4), as well as on the impact of their deployment across European Research Infrastructures (RIs). It also considers the reverse perspective, namely the risks related to synergies across European RIs that may influence the energy-saving performance and implementation of the iSAS technologies.

The proposed approach consists of performing, for each technology, a risk analysis addressing the achievement of the expected energy savings, the targeted Technology Readiness Level (TRL), and the required operational performance, while considering the potential trade-offs between these objectives.

This deliverable builds upon the following reference documents:

- WP1 to WP4 impact risk analysis milestones (M38, M39, M40 and M41) [1–4];
- Verifiable metrics for energy-saving performance (M9.5) [5].

2. WP1: FE-FRT

Work package 1 aims to demonstrate savings in RF power by developing a **ferroelectric fast reactive tuner (FE-FRT)** to adjust the resonance frequency of the cavity with a bias voltage on the FE material. The design of each FE-FRT needs to be shaped and optimized for a given accelerator. The two main applications are to compensate microphonics detuning of SRF cavities in continuous wave mode and to counter-tune the beam induced transient due to non-uniform beam filling, as e.g. in LHC. Both effects will significantly reduce average and peak RF power overhead **(TA#1)**, required to stabilize the RF fields and therefore the beam. A risk analysis including mitigation measures was produced [4]. The impact of WP1 technology must be analysed for each of these two applications.

The microphonics demonstrator at HZB will be performed in the dedicated HoBiCaT horizontal test stand, providing a test environment close to an SRF cryomodule. A positive outcome will open up possible applications of such a device with the CW upgrade of EU XFEL, the operation of the LHeC demonstrator PERLE and other existing and future accelerators with a design adapted to each SRF cavity, including an additional RF port to install the FE-FRT. For transient beam-loading demonstration, the measurements at CERN can only be performed in a vertical cryostat to demonstrate the tuning range and thus, the required transient beam-loading compensation as required by HL-LHC for example. The device is not planned to be tested with beam at CERN. Therefore, this prevents from retrofitting the existing LHC cavities with FE-FRT on the timescale of iSAS. However, the demonstration of the tuning range allows for a variety of future applications, such as FCC.

If both iSAS WP1 devices fail to demonstrate the expected performance, there is a risk that the technology will not be considered sufficiently mature to advance to the next Technology Readiness Level (TRL) through integration into the cryomodule and cavity design of an existing or future accelerator. In such a case, depending on the nature of the shortcomings identified, additional research and development activities would be required before progressing to the next TRL.

For the outcome of iSAS and especially the demonstration of significant energy savings within the proposed metric [5], the measurements performed at CERN for the transient beam-loading demonstrator and the microphonics compensation at HZB, act as **prototypes of TRL level 6 to 7**, that is a realistic test in a relevant environment close to accelerator operation.

3. WP2: LLRF

Work package 2 aims to develop **low-level radio-frequency** (LLRF) systems to control the accelerating field in the SRF cavities. Optimized control of the RF field can lead to significant saving from the RF power **(TA#1)**. Within WP2, the following risks for the optimized LLRF system have been identified:

- Risk n° 1: staffing shortages stemming from recruitment challenges,
- Risk n° 2: availability of FE-FRT for LLRF integration,
- Risk n° 3: working with industry on efficient control of solid-state power amplifiers (SSPA),
- Risk n° 4: increased test costs and change in institute budget.

These risks could compromise the ability of WP2 to:

- Either, deliver the expected milestones in time or deliver them at all: for example, if no FE-FRT is available, we cannot demonstrate LLRF resonance control with an FE-FRT,
- Or, fail to reach the expected savings, based on the defined metrics [5]: for example, if our test time is shortened due to increased Helium costs, we might only be able to demonstrate 20% savings due to lack of experiment time.

For each of these risks, mitigation strategies were thought out to minimize the risks impact, as reported in [3]. The mitigation strategies explore synergies where possible and looking into shifting priorities to meet deadlines (Risk n°1 and Risk n°3). While simulation work is not a substitute for an actual experimental demonstration, it can still clarify interfaces and identify issues and solutions: this will be done for Risk n°2. Finally, being aware of potential risks early in the development stage allows adjusting the schedule to optimize test time (Risk n°4).
In most cases, the risk cannot be truly removed but its impact can be minimized through the mitigation strategy. While some deliverable might be compromised by these risks, the mitigation strategies propose alternative deliverables or subtasks that demonstrate that progress towards the final goal has been made, and represent key milestones, preparing the way for future work.

The target TRL level is 7, although some demonstrations have been performed on operating machines, for example the NANC algorithm was tested on LCLSII, leading to even higher TRLs [6].

4. WP3: thin films

Work package 3 aims to perform R&D **thin films of Nb_3Sn on copper substrates** in order to operate SRF cavities at higher cryogenic temperatures, thus saving significant energy from the cryogenics **(TA#2).** Several prototypes will be produced and tested aiming for the final demonstration of a fully coated SRF cavity. A risk analysis including mitigation measures was produced [2].

Within WP3, the main challenges to achieve the project objectives are technological. In particular, scaling up from small planar samples to large three-dimensional surfaces amplifies two risks that are inherent to Nb_3Sn SRF technology. The first is the mechanical fragility of the Nb_3Sn coating, which may limit or even prevent cavity tuning. This issue will be addressed in Task 3.2 through a study on small samples to evaluate the effectiveness of ALD interlayers to improve mechanical properties of the Nb_3Sn/buffer layer/Cu structure.

However, the first experimental results are not expected until the second half of the project. The second risk, common to all SRF cavities regardless of the superconducting material, is the presence of localized defects that can severely degrade RF performance. This challenge is particularly difficult to mitigate during the R&D phase. Indeed, the most effective way to minimize such defects is to implement stringent cleanroom manufacturing protocols, which can only be fully established once the fabrication process has been optimized. During the project, localized defects will be identified through thermal mapping and their occurrence minimized by applying rigorous cleanroom procedures and good laboratory practices throughout the fabrication process and minimized as much as possible through good laboratory practices. In WP3, it was demonstrated on small planar resonators that the target figure-of-merit values for the accelerating field can be achieved using PVD technology, thereby proving in principle the feasibility of meeting the project objectives.

To produce fully coated cavities, the work has been split between two institutions with two different coating systems. From an organizational perspective, assigning two institutions to each task provides built-in redundancy and reduces the risk of significant impacts on project execution.

The target TRL level is 5 with fully coated cavities to be characterized.

5. WP4: couplers

Work package 4 aims to develop couplers and dampers, **Fundamental Power Coupler (FPC) and Higher Order Mode (HOM) coupler as well as Beam Line Absorber (BLA**). FPCs deliver RF power (kW to MW range) from the RF source to the cavities, generating the accelerating electromagnetic field. In addition to saving energy from the RF with efficient power transfer **(TA#1)**, significant energy saving from the cryogenics **(TA#2)** can be reached by optimizing the cooling schemes of the couplers to limit the heat loads to the cryogenic bath. Because of high-current recirculating beams, Energy Recovery Linacs (ERLs) are particularly subject to HOMs which induce RF losses in the superconducting cavity walls. Thus, HOM dampers contribute not only to efficient energy recovery from the beam **(TA#3)** but also to savings from the cryogenics (TA#2) by depositing the RF losses into loads at higher temperatures (ideally room temperature).

In WP4, the potential barriers towards achieving the optimal energy savings with the risk description and the mitigation measures are [1]:

Potential barriers	Risk description	Mitigation measures	Metrics
Q_{ext} performances not achieved	Poor transfer of energy to the beam (FPC) Poor damping of the HOMs (HOMC)	Extensive studies and controls at each stage (manufacturing, preparation, assembly) [11,12]	Calculate of the Q_{ext} [7,8] with simulations [9,10] (Q_{ext} vs antenna penetration) and dimensional controls [11,12]
BLA ceramic properties not adequate	Insufficient HOM damping by the BLAs	Experimental setup to measure ceramic properties at cryogenic temperature (ε', ε'', μ', μ'') [13]	Measurement of ε', ε'', μ', μ'' of the ceramic *vs* simulation power absorption ratio [14]
Not optimal cooling schemes of FPC, HOMC, BLA	Higher than optimal heat loads increasing cryogenics consumption	ESS data feedback Extensive studies carried out	For each component (FPC, HOMc and BLA) two cooling schemes will be studied to compare their cooling power consumption [5]

Since ERLs are particularly subject to HOM issues, WP4 technologies impact European ERL RIs such as PERLE and BriXSinO by:

- Conducting detailed studies on FPC and HOM couplers which can be used for other ERLs,
- Advancing the progress of BLAs by exploring various ceramic materials and testing them at cryogenic temperatures at the new and unique test stand developed at IJCLab within iSAS,
- Enabling large-scale optimization and analysis of power consumption in cryogenic systems across different cooling schemes for components,
- Integrating WP4 components into PERLE and BriXSinO ERLs to demonstrate energy recovery in linacs.

The primary risk associated with the deployment of iSAS technologies across European Research Infrastructures (RIs) is the potential lack of sufficient funding to implement all of the technologies under development. If budget constraints arise, the proposed mitigation strategy is to prioritize the implementation of the technologies offering the greatest impact in terms of energy savings, operational benefits, and readiness for deployment.

In WP4, the target **Technology Readiness Level is 6**, as prototypes will be tested on test benches for experimental demonstration.

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