INNOVATE FOR SUSTAINABLE ACCELERATOR SYSTEMS: MAIN PROGRESS OF THE iSAS PROJECT*

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On behalf of the iSAS project**

Abstract

Particle accelerators are essential instruments not only for fundamental research but also for advancing healthcare, high-tech developments and safety. They must now meet the challenge of energy sustainability. The European project named *Innovate for Sustainable Accelerating Systems* is dedicated to energy-saving of superconducting radiofrequency accelerating systems. iSAS will develop, prototype and validate new impactful energy-saving technologies so that SRF accelerators can operate with the same or improved performance with significantly less power consumption. Main progress of the project is highlighted.

INTRODUCTION

Particle accelerators have largely proven their value to science and society. Since their invention, their development has been significant, gaining, in a century, more than seven orders of magnitude in energy. Since accelerating particles to high energies require a large amount of power, accelerator community now faces the challenge of energy sustainability for the future machines. In the energy bill of accelerators, the breakdown per sub-systems identifies the areas with the highest consumption (magnets, radiofrequency, cryogenics …), strongly dependent on the type of accelerator (linear, circular). In the FCC-ee estimations, the largely dominant contribution comes from the radiofrequency (RF) systems which account for up to 50% of the total power consumption at the ZH production threshold [1]. The project *Innovate for Sustainable Accelerator Systems* (iSAS) [2] tackles core superconducting radiofrequency (SRF) technologies, with a large impact for energy savings. It is complementary to programs devoted to energy-saving magnets or high efficiency RF power sources.

iSAS aims to develop, prototype and validate SRF technologies so that accelerators can operate with the same or improved performance while using significantly less energy.

Focusing on SRF areas with high leverage for energy-saving, it aims to reduce the accelerator power bill from:

- **RF power**, through integration of the RF power source with smart digital control systems and novel tuners to rapidly compensate cavity detuning,
- **Cryogenics**, via R&D on SRF cavities with high performance at 4.2 K instead of 2 K to improve the Carnot and technical efficiency of the cryogenic system,
- **Beam power**, to enable efficient energy recovery of recirculating beams in SRF cavities with couplers to damp the Higher-Order Modes (HOMs) excited by high-current beams in the RF cavities.

This European-funded project gathers 12 research institutions (CEA, CERN, CNRS, DESY, EPFL, ESS, HZB, INFN, NIKHEF, UKRI, VUB, Lancaster University) and 6 industrial companies (ACS, Cryolectra, Euclid Tech labs, Research Instruments GmbH, Thin Film Equipment, Zanon) over 4 years. ESS, EuXFEL and HL-LHC are the main accelerator-driven ESFRI research infrastructures targeted for large benefit from iSAS developments. The energy-saving technologies, or devices, are developed within work packages (WP1-WP4) and integrated into:

- **a sustainable cryomodule** design, by addressing common engineering challenges of devices integration and proposing a parametric design (WP5),
- **existing research infrastructures**, by retrofitting existing accelerating systems: the ESS prototype cryomodule will be adapted, to demonstrate energy recovery of high-power beams in PERLE (WP6),
- **industrial solutions**, with co-developments with industry to raise Technological Readiness Level (TRL) for large-scale deployment at current, future infrastructures and towards industrial applications (WP6).

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SCOPE AND METRIC

iSAS focuses on SRF accelerating systems to save power from RF power, cryogenics and beam power:

- WP1: Ferro-Electric Fast Reactive Tuners (FE-FTRs),
- WP2: Low-Level Radio Frequency (LLRF) system,
- WP3: Coatings of Nb_3Sn on Cu cavities,
- WP4: Fundamental Power Couplers (FPCs) and Higher-Order Modes (HOM) dampers: HOM couplers and Beam Line Absorbers (BLAs).

A metric for energy saving performances across the different technologies was defined; it will be filled at the end of the project with equipment available and operational at that time. This metric focusses on the power required for operation: it will evaluate and compare the electrical power consumption with and without the iSAS technology or devices (FE-FRT, HOM ...) under similar conditions [3,4]. The comparison will be done across different use cases (specific to each technology), but always under similar conditions for each technology to ensure a fair comparison.

FERRO-ELECTRIC FAST REACTIVE TUNER (WP1)

In WP1, led by HZB, fast-tuning systems are developed to compensate detuning due to mechanical vibrations or beam induced transient. Detuning is usually compensated at the expense of adding a significant power overhead to the RF system. As an alternative to classic mechanical cavity tuners (piezo), fast reactive tuners based on ferro-electric ceramic are RF devices coupled to an RF cavity via an antenna. By tuning the high voltage applied on the ceramics, the permittivity of the ferroelectric material within the tuner is varied, generating a change of impedance of the coupled cavity-tuner system and thus adjusting the resonance of the coupled system. With Ferro-Electric Fast Reactive Tuners (FE-FRTs), the change of permittivity allows to control the resonance frequency of the coupled system on a very fast time scale (~100 ns) with a tuning range in the tens of kHz [5,6]. Importantly, being non-mechanical, it does not excite any natural mechanical eigenmodes of the cavity. FE-FRTs require an additional RF port to install on the cavity, but avoid complex control algorithms required for the highly resonant mechanical, RF cavity and tuner system. FE-FRTs must maintain stability and reliability of operation and are most effectively applied on CW driven SRF cavities, especially for low beam-loading FELs or ERLs. As the power to operate a cavity at voltage scales with the square of the cavity bandwidth in low beam loading machines (microphonics case), savings in RF power are expected to be significant: factors up to 10 can be saved if the bandwidth of a cavity can be reduced to the low Hz range, depending on the level of beam loading. The metric to estimate the savings is the invested RF power to drive the cavity at a given field (peak and average power) for microphonics compensation, which will be converted to wall-plug power. It will be determined by comparing the RF power invest with the FE-FRT and without the FE-FRT (with the piezo control) at identical values of loaded quality factor Q and aiming for the highest Q_{ext} possible with FE-FRT. Several use cases will be tested.

For transient beam loading, CERN developed an RF design of a FE-FRT to compensate transient beam-loading by detuning for 400 MHz cavities, with a tuning range of 8 kHz for 7.2 kV bias voltage and 100 ns switching time, at up to 150 kHz switching rate, to be used for LHC or for a future use case with FCC. After the FE tuner has been manufactured, the first warm tests have shown the expected tuning functionality [7] and cold tests will follow.

HZB develops an FE-FRT to compensate microphonics detuning at 1.3 GHz: following planned tests on a 2-cell cavity, the design will be improved for a nine-cell TESLA/XFEL cavity. In this unexplored frequency range, the materials permittivity must be understood. HZB developed, together with Euclid Techlabs, a test stand to characterize the ferroelectric material at 1.3 GHz: measurements are underway and show that the preparation of the samples (grinding, polishing and planarity of faces) is of utmost importance for optimal performance of the tuner. In parallel, the FE-FRT for the two-cell SRF cavity was designed and manufactured, it will be tested in a cavity horizontal test stand (HoBiCat).

In order to integrate a FE-FRT in the PERLE energy recovery linac, a design at 802 MHz is underway, also a use case frequency for FCC (CERN, U. Lancaster, HZB, CNRS/IJCLab). Considering the limited available space in the end groups on most SRF cavities, including PERLE's, retrofitting existing designs with a FE-FRT may require to combine coupling with an HOM or FPC port.

OPTIMIZED LLRF (WP2)

The main goal of WP2, led by DESY, is to develop and demonstrate techniques for an efficient control of field and resonance of narrow-bandwidth RF cavities. An optimized Low-Level Radio Frequency (LLRF) system will improve the efficiency of controlling accelerating fields inside RF cavities while keeping them on resonance through advanced rejection of microphonics and detuning. To minimize RF power, cavities must operate at a quality factor Q_{ext} as high as possible, at a narrow bandwidth (i.e. below 10s of Hz). These conditions are extremely challenging for the control system as RF cavities are extremely sensitive to microphonics and easily subject to detuning. So, the challenge is to find the highest Q_{ext} (~Q_L) while maintaining resonance control, without compromising operability or reliability. FE-FRT can be used to provide fast frequency tuning. The use of AI (or machine learning-based algorithms) will be integrated in this optimized LLRF.

Since a LLRF system is constantly required for cavity field control, the system cannot be switched off for comparison purposes but options of the optimized LLRF can be switched ON/OFF to evaluate their impact on power consumption. Several factors of the LLRF tuning system impact the consumption of the accelerator so several metrics will be used and measurements will be performed at different facilities to cover multiple operational cases [4]. Optimization using the LLRF system can lead to significant savings in the electrical power of an accelerator. For example, the step-wise optimization of the modulator pulse shape implemented at the EU-XFEL led to a reduction in accelerator power consumption >1 MW [8].

Several waveguide stub-tuner prototypes were developed to externally increase Q_{ext} and tested at DESY: a factor of 10 increase in Q_{ext} was demonstrated. This reduces the required RF power by a factor of 5, at the expense of small temperature increase of the coupler (8%). Analysis is on-going to fully understand the heating process.

During field ramp up, cavities with narrow bandwidth experience a very large detuning induced by Lorentz forces, equivalent to tens of bandwidths. When operating multiple cavities with a single amplifier, using the standard self-excited loop ramp up technique is not an option. The frequency of the RF must be modulated to always drive the cavity on resonance during the fill time (in pulsed mode), the resonance filling. A new model-based technique of adaptative resonance filling has been demonstrated at DESY's cryomodule test stand: it uses iterative learning to ramp-up the field in narrow bandwidth SRF cavities.

A new technique to compensate Lorentz force detuning (LFD) was fully deployed at EuXFEL: with an improved efficiency of the piezo control, a factor of 2 savings in the energy deposited in the piezo elements was proven without hardware modification [9], benefitting piezo lifetime.

A method was developed and tested at DESY to supress microphonics using narrow-bandwidth active noise cancellation (NANC). It was also implemented and tested on the LCLS-II LLRF architecture at SLAC (USA). Results demonstrate an improvement of a factor > 2 in narrow bandwidth microphonics rejection, as illustrated in Fig.1. This allowed the controlled cavity to operate at 15 MV/m with NANC on, compared to 9 MV/m without [10].

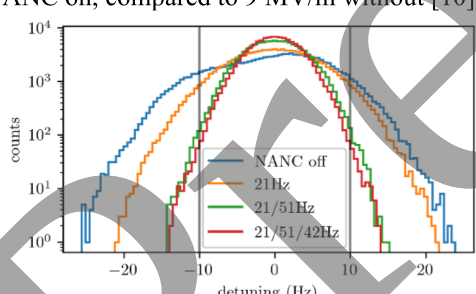

Figure 1: LCLS-II detuning histogram as a function of detuning frequency (cryomodule 19, cavity 2, 9 MV/m). Successive suppressing of 21, 51 and 42 Hz dominating microphonic components reduces peak-to-peak detuning [10].

A new technique was developed to estimate the detuning and bandwidth of a cavity based on Luenberger Observer [11]. One of the main benefits is its robustness for pulsed and continuous operation. It is currently in its evaluation period at the cryomodule test stands at DESY.

Exploring AI-based method for RF detuning compensation, a hybrid model that learns detuning dynamics from data was designed [12]. The hybrid nature of this data-driven model enabled the derivation of a stability theorem. These results will be used to design a control law for detuning compensation.

THIN FILMS ON COPPER (WP3)

Led by INFN LNL, WP3 explores coatings of Nb3Sn thin films on copper substrate aiming to operate RF cavities at a temperature higher than 2 K: replacing bulk Nb cavities, operated at 2 K, by Nb_3Sn cavities at 4.2 K would reduce the cryogenic power by a factor of 3 [13]. The goals of iSAS are to optimize Nb_3Sn on Cu technology, focusing on its RF properties, mechanical strength to allow cavity tunability despite the brittleness of the film and minimization of trapped flux and thermocurrents. For the energy saving metric detailed in [4], we consider the power dissipation of the cavity cell at a given accelerating field, accounting for the performance of the material (via its surface resistance, R_s) and the coefficient of performance (COP) of the cryogenic system. Flux trapping will be measured on planar samples before testing the full cavity. Characterization facilities are updated within iSAS: Choke cavity residual field trapping (R_s measurements with 7.8 GHz cavity) [14] and magnetic field penetration [15,16] at UKRI, measurement of flux trapping and flux dynamics (CRAFT at HZB) and quadrupole resonant (QPR) at HZB.

At UKRI STFC Daresbury Laboratory, the low-power SRF test facility for fast turn-out testing of planar superconducting sample has been upgraded and put into operation (7.8 GHz). At HZB, the CRAFT apparatus, simulating conditions of the cavity cooldown, for planar sample testing has been successfully commissioned and used to investigate flux expulsion in dynamic temperature gradients with samples of Nb bulk, Nb thin film and Nb_3Sn.

HZB developed a platform to reproduce realistic mechanical tuning conditions and evaluate their impact on Nb_3Sn coatings. Mechanical tuning to adjust the resonance frequency of a 1.3 GHz cavity by 1 MHz, corresponds to millimeter-scale actuator motion and induces strains in the 10^{-4}–10^{-3} range within the cavity structure. Such strain levels are critical, as they may lead to cracking, delamination, or changes in superconducting properties. For this test, a TESLA-shaped prototype copper cavity was equipped with a blade tuner. Measurements show a linear relationship between cavity deformation and frequency shift over the tuning range. The tuning system demonstrates stable and reproducible operation across the required frequency range, reaching a sensitivity of 0.025 Hz per motor step. This operational tuning tool in realistic mechanical conditions (elongation, contraction) is ready for integration into cryogenic environments.

An interlayer between the Nb_3Sn coating and the Cu substrate is studied to enhance film mechanical stability and tunability. CEA develops insulating atomic layer deposition (ALD) oxide thin film layers acting as a diffusion and thermo-current barriers for Nb_3Sn and Nb deposition on Cu samples. The oxide layers have to be resistant to the high temperature conditions (650°C) occurring in Nb_3Sn deposition. It is also important to study the thickness dependence of the layer structural and chemical stability and diffusion properties. Several oxide alloys were tested with different thicknesses on electropolished Cu coupons. Oxides of Al_2O_3, ZrO_2 and $AlZrO_x$ were successfully coated by ALD, stable up to 750 °C and able to mitigate thermo-current generation. The thermo current mitigation proof of concept was successfully achieved on a electropolished 1.3 GHz Cu cavity from CERN. The insertion of a 18 nm thick insulating Al_2O_3 ALD layer between the Cu cavity and a 6 microns thick Nb film deposited by HIPIMS showed a 10 fold reduction in thermo current amplitude. The major next step will be to coat and test a 1.3 GHz Cu cavity with ALD layer and Nb_3Sn film. CEA also carried out surface characterization studies by tunneling spectroscopy and x-ray diffraction for Nb_3Sn films deposited at UKRI, INFN-LNL and CERN on Cu and Nb substrates.

Coating recipe on a small planar resonator (QPR) was optimized and validated [17,18]: the best samples exhibit a state-of-the-art surface resistance of 9 nΩ at 4.5 K (20 mT, 417 MHz), corresponding to a quality factor 10 times higher than the baseline specifications for LHC Nb/Cu cavities and already meeting the requirements for FCC-ee. Two new coating systems for 1.3 GHz cavity are in the testing phase before cavity deposition: a rectangular magnetron with a rotating cavity at INFN [19] and a double movable magnetron system within a fixed cavity at UKRI [20].

COUPLERS AND HOM DAMPERS (WP4)

Led by CNRS, WP4 is devoted to Fundamental Power Couplers (FPCs) and HOM dampers. It is strongly linked to WP6, focusing on integration of iSAS technologies in accelerators. The energy saving mostly relies on cooling to limit heat loads to the cryogenic bath, while preserving the functional RF requirements. Design optimization is of utmost importance as FPCs and HOM dampers can account for half of the cryogenic load on a linac [21].

Fundamental Power Coupler

FPCs introduce power in the cavities to excite the fundamental mode. Based on the RF design of the 704 MHz SPL (Superconducting Proton Linac) coupler developed by CERN [22], RF and mechanical simulations were done by CNRS to adapt it to the PERLE energy recovery linac (ERL) cryomodule. A simple and robust design is sought. The RF design was optimized, main specifications are:

- Operating frequency: 801.58 MHz
- S11 at operating frequency: <-30 dB
- Required bandwidth at -20 dB: 10 MHz
- Maximum power: 50 kW continuous wave
- External quality factor: $7\times10^6 < Q_{ext} < 1\times10^7$

Antenna, window and outer conductor thermal studies have been performed by CERN, aiming to maintain temperatures everywhere in an acceptable range, minimize antenna deformation, prevent condensation on the window, avoid induced stresses in the window and reduce radiation heat loads to the cavity. Studies concluded that a strongly turbulent air flowrate of at least 400 l/min is required for the antenna and window air cooling system. The outer conductor, made of a cylindrical double walled tube (DWT) cooled with supercritical helium flowing between the two walls, is reused from the ESS prototype cryomodule. Some studies estimated the heat loads in the outer conductor, the equivalent cost to the cryogenic plant in operation and the helium mass flowrate to minimize the heat loads to the cavity helium bath at 2 K. Simulations showed that the He inlet temperature significantly impacts cryogenic costs. Heat released to the He bath @2K from DWT is 0.5 W (inlet 5.1K) and 1.8 W (inlet 9 K). Electrical heaters must maintain temperatures of the warm flange and the outlet He pipe above the dew point. Manufacturing drawings are underway.

Higher Order Modes Couplers

Higher order modes can be excited in cavities by high-power beams and ERLs are particularly subject to HOM excitations due to recirculation of high-current beams. Improper extraction of HOMs can strongly limit the beam intensity due to beam breakup instabilities (BBU). HOM couplers damp the HOMs trapped in the cavity and deposit them into loads at higher temperatures. Several configurations of HOM couplers were studied [23] and the option with 2 hook per cavity is selected (Fig. 2). CNRS performed RF simulations, thermal calculation and mechanical integration. Based on the RF design of the 800 MHz hook coupler for HL-LHC developed by CERN, the coupler was optimized by CNRS for PERLE for optimum transmission of the unwanted modes (TE111&TM110) while ensuring efficient rejection of the fundamental mode. Made of high RRR Nb antenna, the couplers are confined in a He tank for active cooling at 2 K without recirculation thanks to the superfluid helium properties. Fabrication is underway.

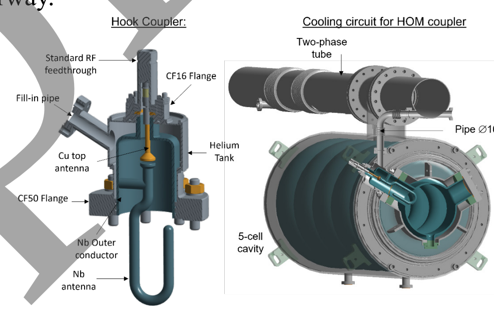

Figure 2: HOM couplers hook configuration and cooling circuit. Courtesy of P. Duschene (CNRS/IJCLab).

Beam Line Absorbers

With a large beam pipe, HOM frequencies propagate along the beam pipe and broadband lossy materials can absorb the propagating modes (Beam Line Absorbers). Meanwhile, the fundamental mode remains confined in the cavity. BLAs allow HOM power to be extracted away from ultra-cold cryogenic regions, thus reducing cryogenic heat loads. Modern BLAs typically employ ferrite tiles, silicon carbide ceramics, lossy dielectric composites.

BLAs with a ceramic material at 1.3 GHz are developed by INFN, for the BriXSino ERL. The selected cooling technology is conduction through copper stubs directly at the cryogenic temperature. The specifications have been defined and the design of XFEL/LCLS-II has been selected.The basic design was adapted from the experience gained with DESY and applied to LCLS-II as well. A thermal simulation conducted on this model confirmed that power levels up to 100 W are compatible.

For BLAs at 802 MHz for the PERLE configuration, simulations of thermal power deposition, up to 150 W, are in progress for a design similar to the one discussed above.

For both frequencies, RF simulations to assess BLA absorption performance including Sienna Technologies STL-150D14 ceramic [24] and Kyocera SC1000 are performed by CNRS [25].

INTEGRATING THESE TECHNOLOGIES

WP5, led by ESS, is devoted to the integration of the iSAS technologies into a sustainable cryomodule design, by addressing common engineering challenges. A compilation of lessons learned from the ESS cryomodule has been performed including design, manufacturing, assembly, testing and sustainability aspects [26]. To benchmark this study with other recent facilities and establish a robust baseline for the definition of the sustainability criteria to be considered for a new cryomodule design, a study was conducted for high-beta elliptical cryomodules (400 MHz-1.3 GHz). This analysis compared data across six facilities SNS, LHC, PIP-II, XFEL, LCLS-II and ESS regarding cryogenic system and thermal management, cryomodule design, commissioning insights and operational experience and reliability [27]. Main conclusions are:

- Beam and RF parameters drive the design, 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 design of sustainable cryomodules and directly contribute to developing a parametric tool for cryomodule design. The sustainability criteria include energy saving, life-cycle, availability, maintainability, repairability and industrial solutions.

WP6, led by CNRS, aims to integrate the iSAS technologies into existing research infrastructures, namely at the high current ERL PERLE. In a sustainable spirit, many components from one ESS prototype medium beta cryomodule are reused. Spare ESS cryomodule components are re-used (vacuum vessel, spaceframe, thermal shield, coupler interfaces, several cooling circuits…). The adaptations for the high current ERL will integrate the optimized HOM, FPC and BLA components developed in WP4. Originally studied by JLab [28], the design of the cavity cells has been finalized by CNRS/IJCLab to adjust the frequency and stiffness sensitivities and integrate HOM couplers and FPC. The He tank was optimized to allow the cooling of HOM ports. The manufacturing has started. Preparation of bare cavities will be done at IJCLab for heat treatments, field flatness and clean room preparation and at CEA for electro-polishing. A first cold test of the bare cavity in a cryostat will be performed at INFN before being returned to the manufacturer for the finalization of the fabrication (He tank welding). A final cold test will be carried out of the fully jacketed cavity. The tuner is adapted from ESS and MYRRHA cold tuning system (CNRS/IJCLab). The cryomodule will be assembled at CEA/Saclay.

WP7, led by INFN, focusses on integration into industrial solutions. It aims to foster collaboration between the companies and the research institutions participating in iSAS, in order to raise the initial TRLs to levels more suitable for industry. In addition, WP7's primary objective is to disseminate the iSAS technologies and attract new companies. A website lists competencies for both industrial and academic partners [29]. An industrial workshop provided a structured forum to engage companies involved in iSAS to present their competencies and to identify specific technical areas of interest [30]. An industry board is set up.

ENERGY RECOVERY LINAC

Energy-recovery linacs are a promising technology for high current and high-quality beam with minimum power consumption and footprint [31]. For an ERL, the power of the accelerated beam after the interaction point is recovered, thus reducing the RF needs drastically. To estimate this power saving, a consumption model of the CW 20 mA PERLE ERL is under developement [32]. Beam dynamic studies are performed to evaluate and optimize the energy recovering process while mitigating instabilities (WP5).

OTHER ACTIONS

Work package 8, led by CNRS, focuses on the societal impact of the project. Actions will adress training and early carrier researchers, outreach and dissemination, open science, diversity and equity.

CONCLUSIONS

Launched in 2024, the EU funded project iSAS aims to develop and integrate accelerator technologies while minimizing their power consumption. Several energy saving technologies have already been developed and demonstrated at different facilities (FE-FRT, optimized LLRF, Nb_3Sn coated QPR resonators), with many more results expected in the coming years.

In parallel, integration of iSAS technologies is progressing well, particularly in the PERLE cryomodule where different devices will be being evaluated at 802 MHz. This work is nicely complemented by the engineering strategies, under development, aiming at defining a sustainable cryomodule design, thereby broadening the impact of iSAS.

A detailed metric to evaluate the energy-saving performances of all the developed technologies has been defined and will be evaluated at the end of the programme.

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