Innovate for Sustainable Accelerating Systems (iSAS)

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Horizon Europe iSAS proposal, March 2023

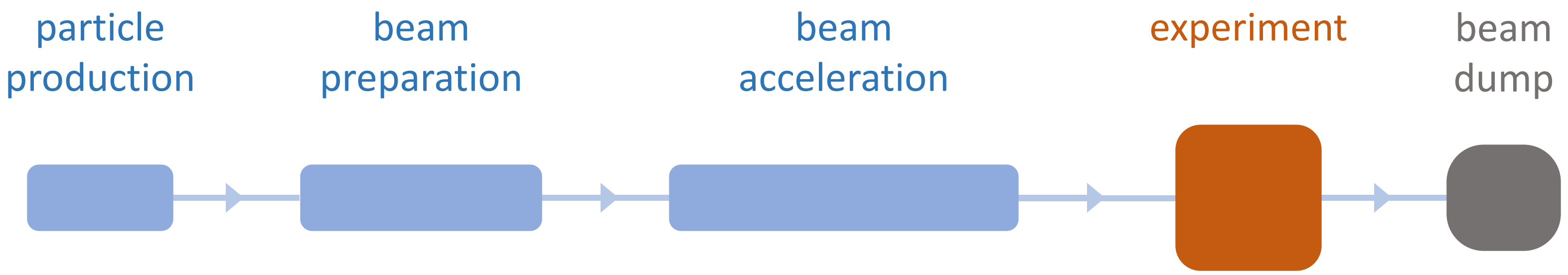
The energy efficiency of present and future accelerators […] is and should remain an area requiring constant attention.

A detailed plan for the […] saving and re-use of energy should be part of the approval process for any major project.

European Strategy for Particle Physics 2020

Where do accelerators use power ?

Basic structures of a particle accelerator



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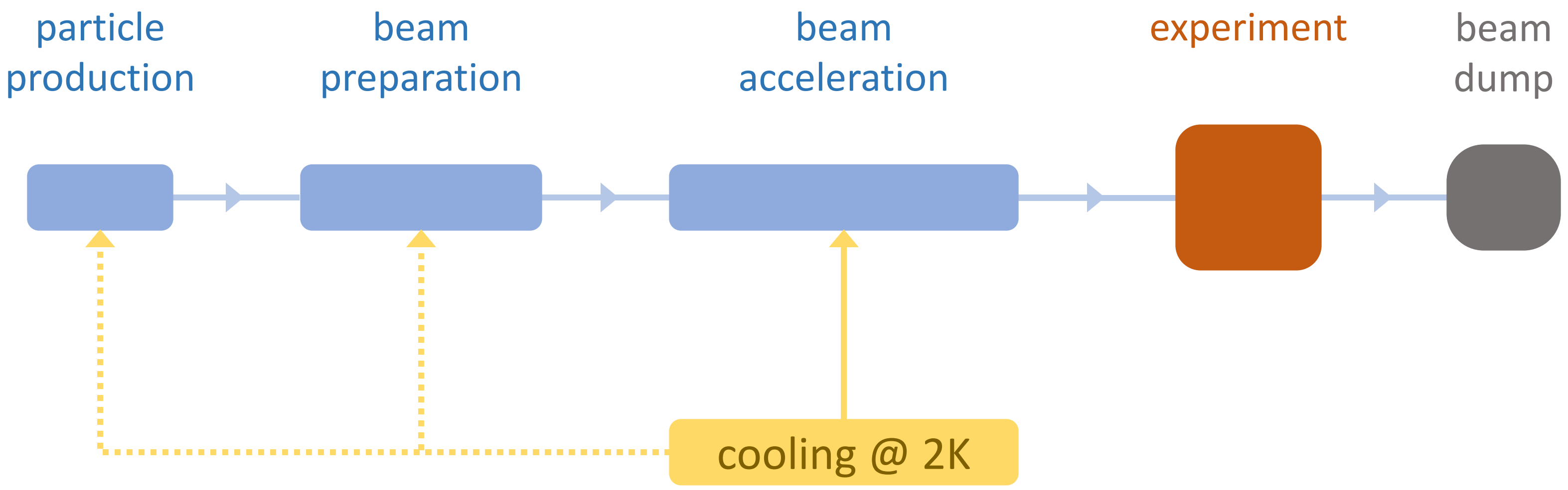

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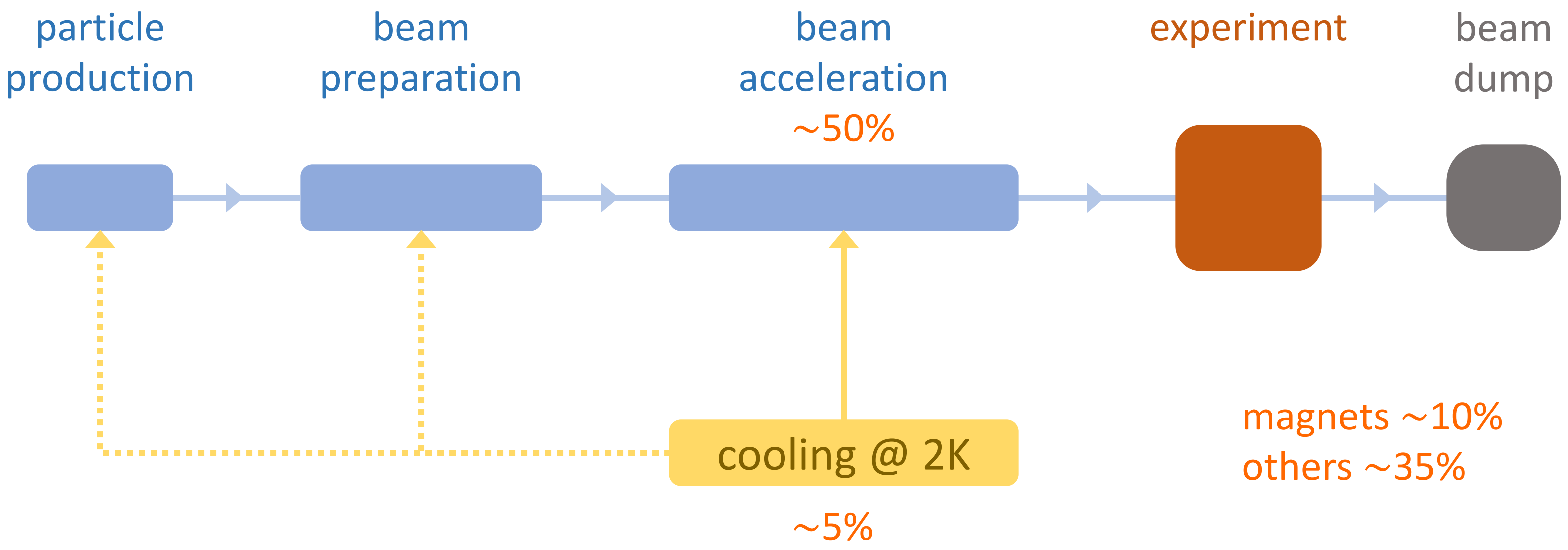
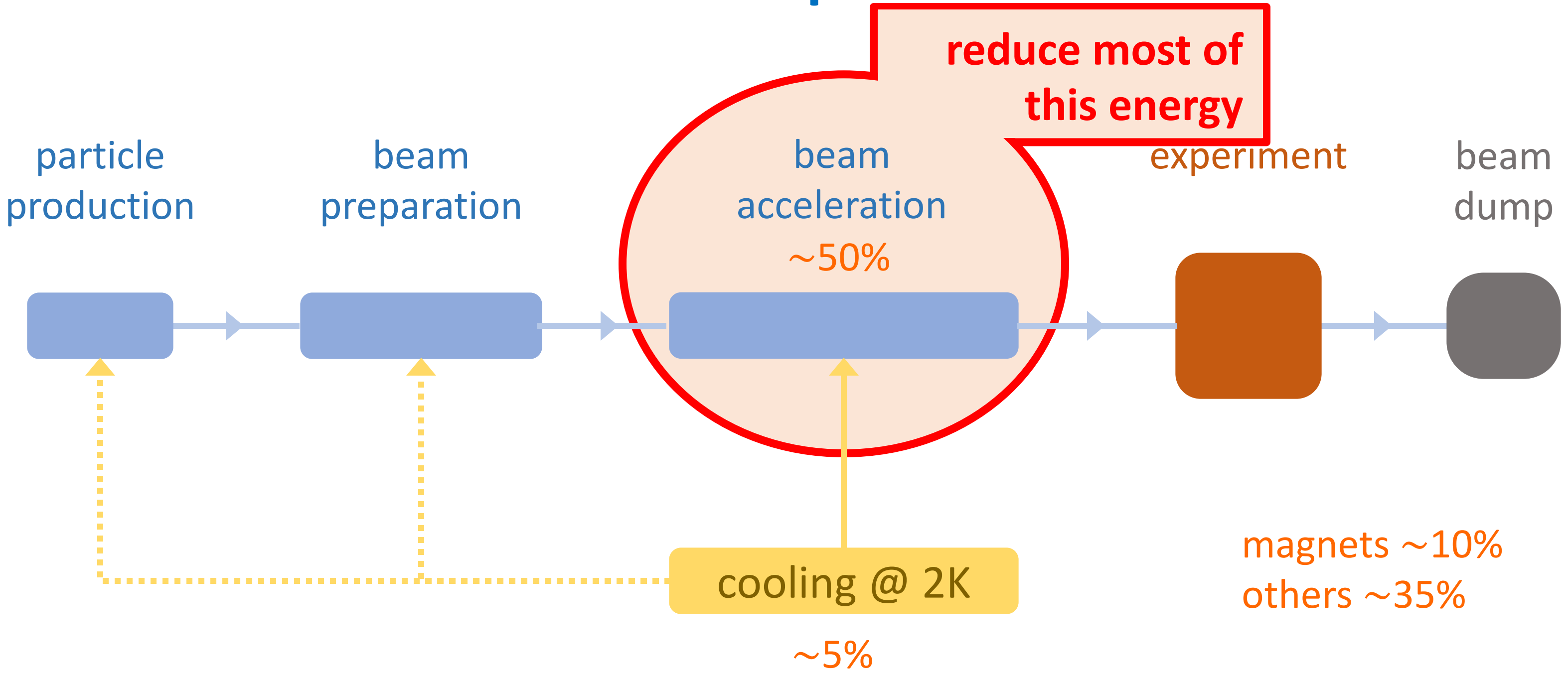


Example: typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC@250GeV

Basic structures of a particle accelerator



Example: typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

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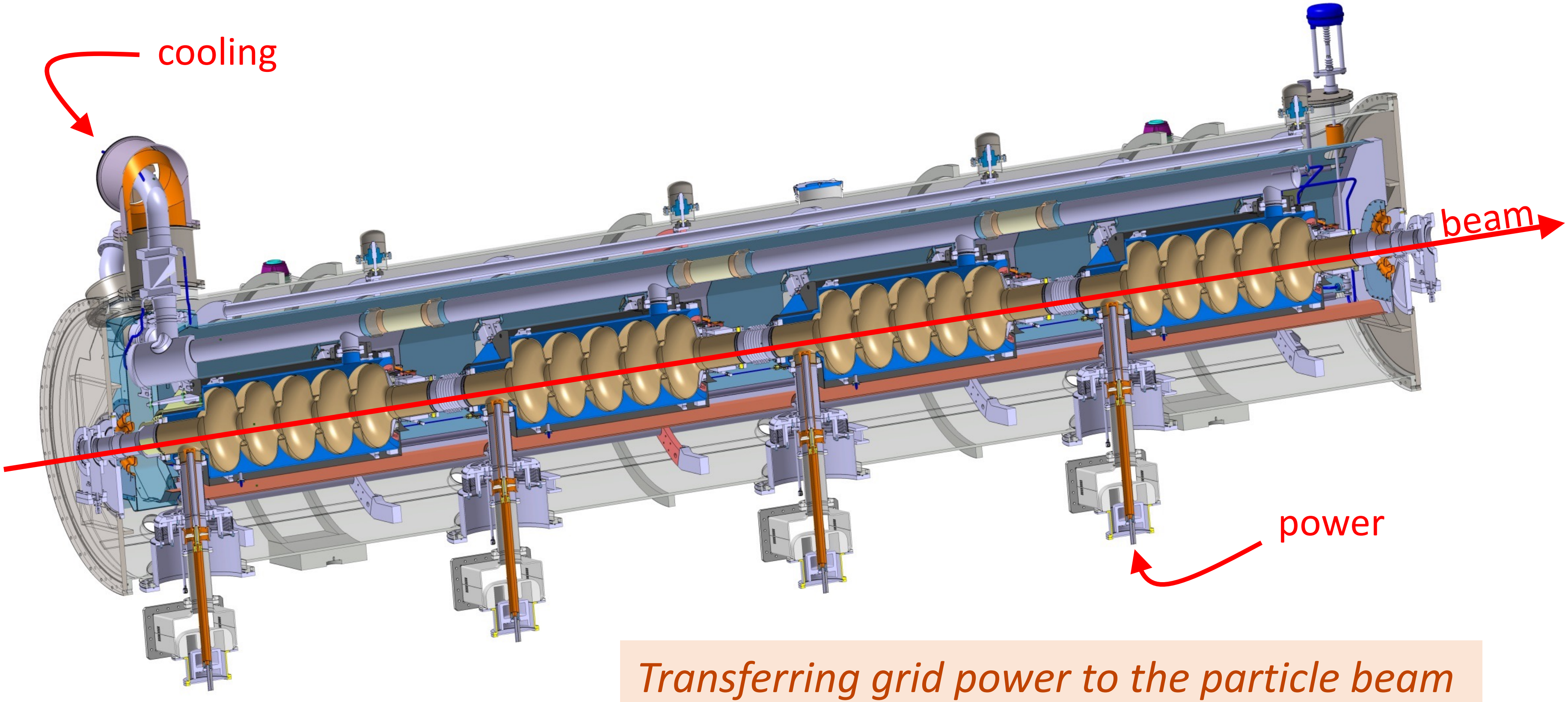
Key building block for beam acceleration: the SRF cryomodule



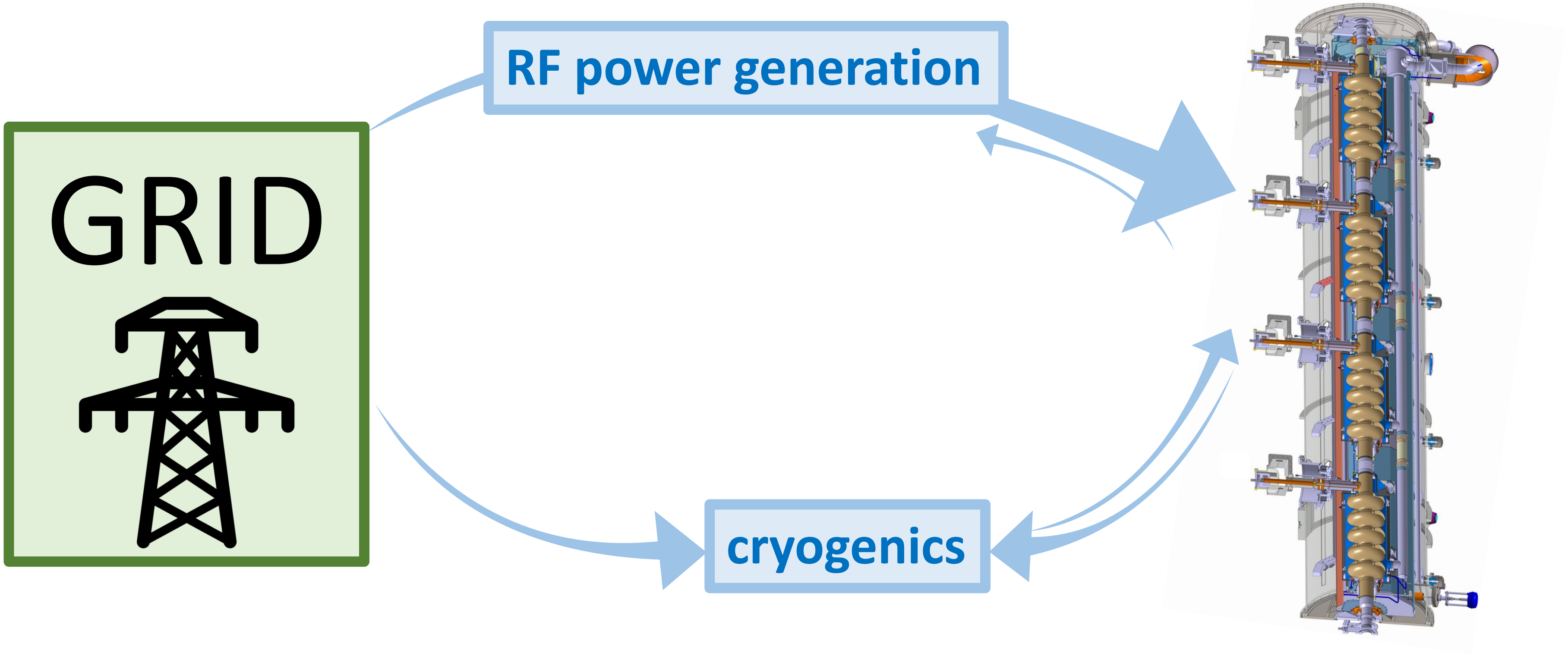
Transferring grid power to the particle beam

Superconducting Radio Frequency (SRF) is the enabling technology for modern accelerators

The main energy-saving technologies are universally applicable across SRF cryomodules and accelerators

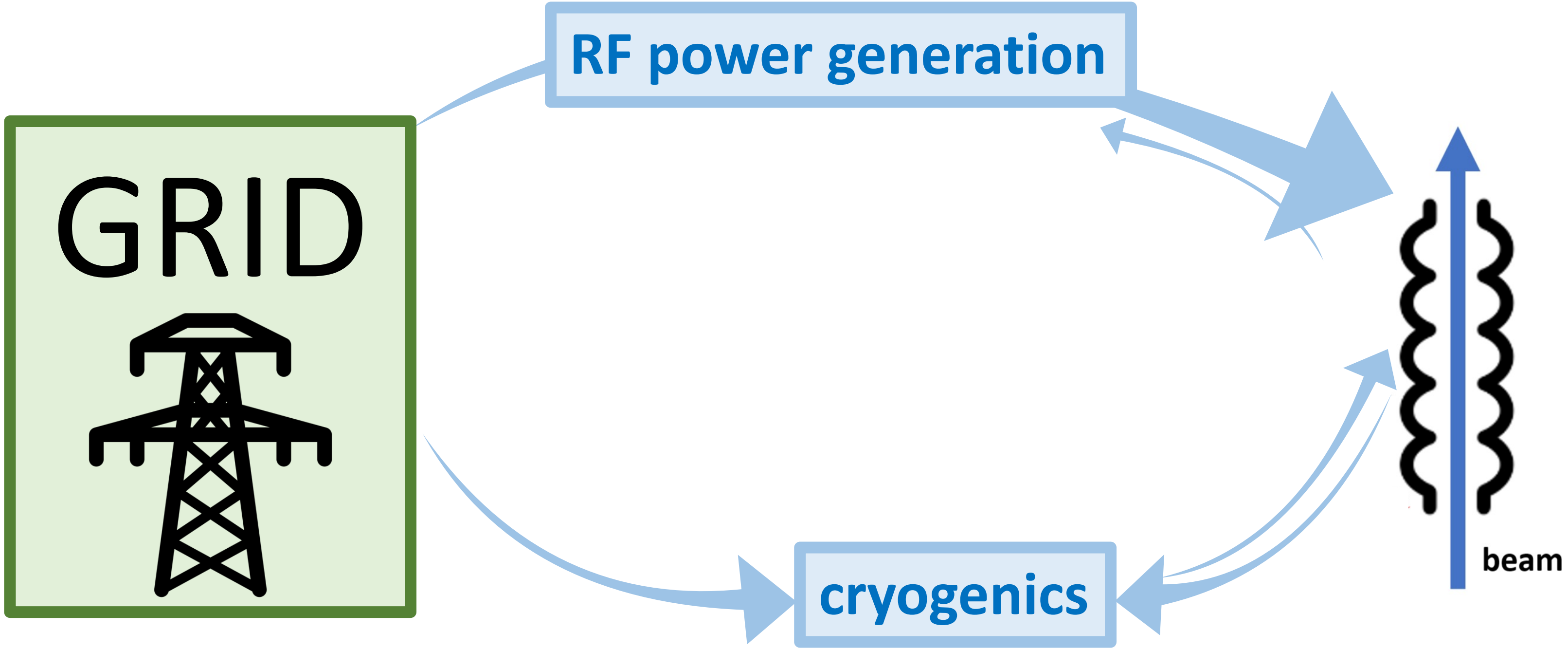
(e.g., ESS, EuXFEL, HL-LHC, …)

From Grid to Beam



Picture adopted from M. Seidel (IPAC 2022)

From Grid to Beam



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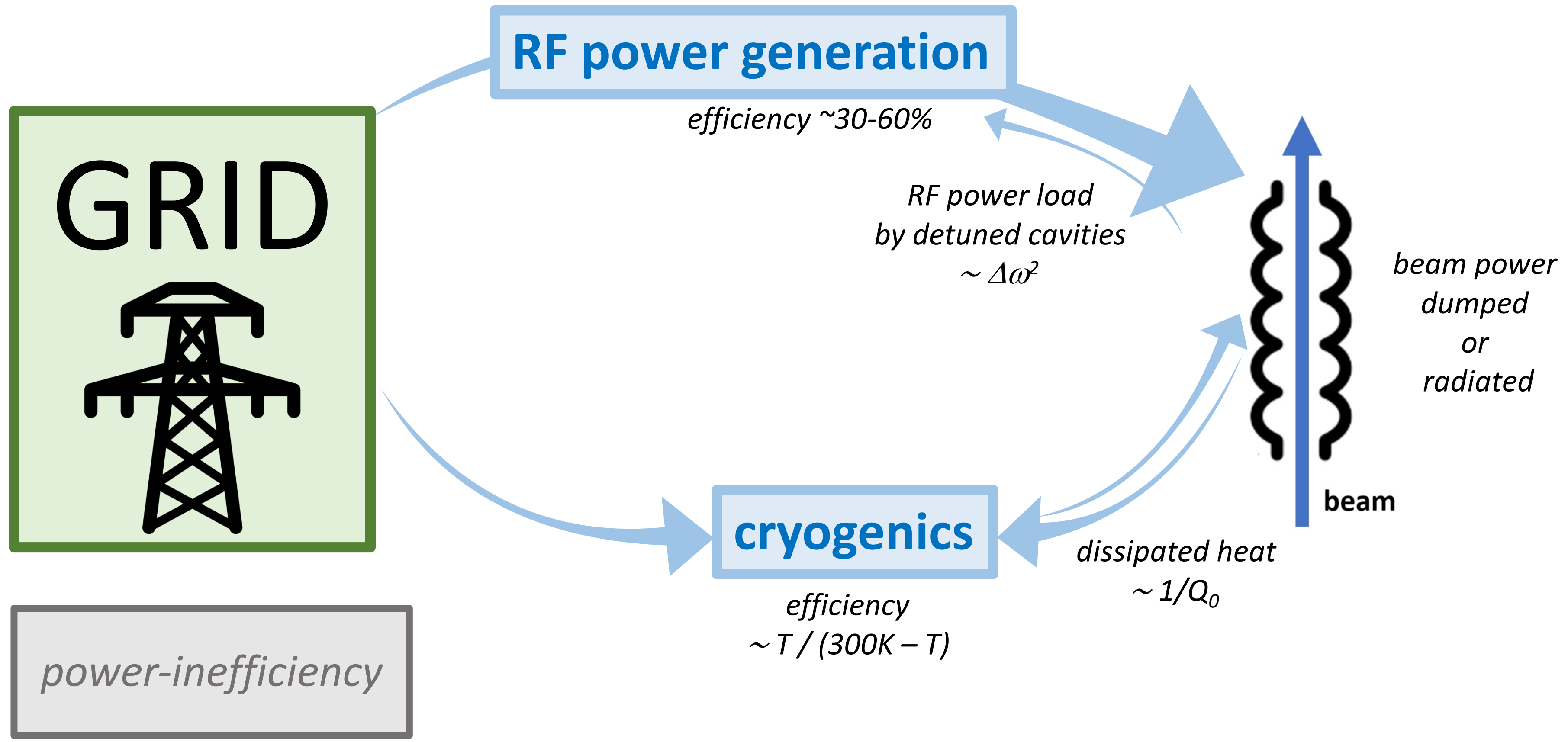
From Grid to Beam



From Grid to Beam

improve amplifier efficiency

e.g. solid state amplifiers for oscillating power demands

GRID

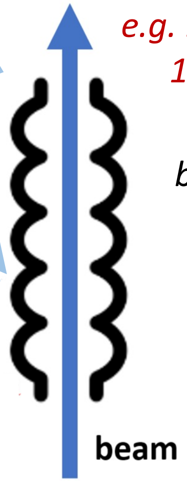
RF power generation

efficiency ~30-60%

recover the energy from the beam

e.g. ERL reaching 100% recovery

RF power load by detuned cavities
$\sim \Delta\omega^2$



beam power dumped or radiated

dealing with microphonics

e.g. Fast Reactive Tuners

cryogenics

efficiency
$\sim T\,/\,(300K - T)$

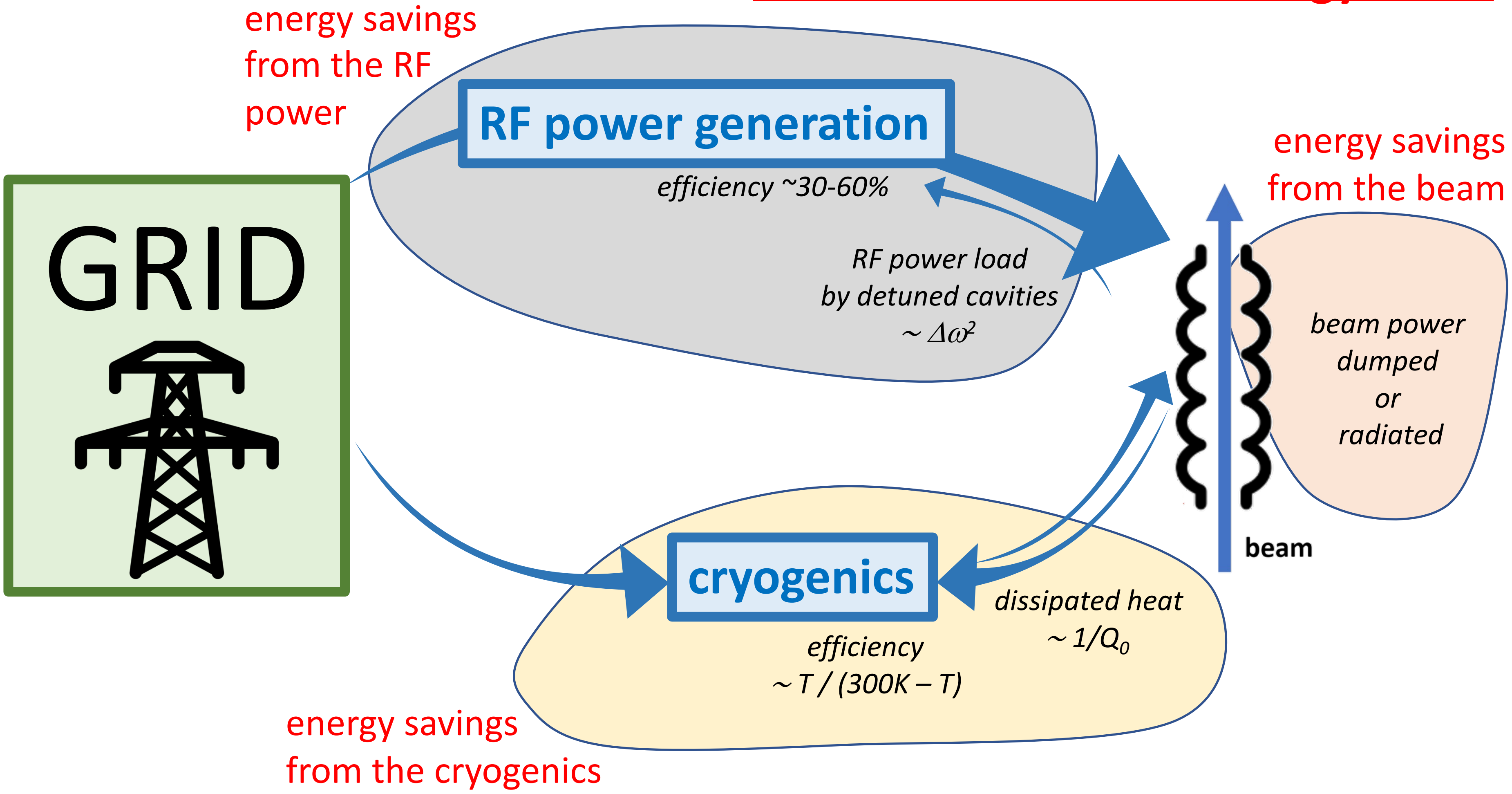
dissipated heat
$\sim 1/Q_0$

mitigation with novel technologies

operate cavities at higher T & improve Q_0 of cavities

e.g. Nb_3Sn from 2K to 4.2K ➔ 3x less cooling power needed

Three main iSAS Technology Areas



from the overall Accelerator R&D Roadmap
and responding to a Horizon Europe call, we

Innovate for Sustainable Accelerating Systems (iSAS)

with focus on these three main iSAS Technology Areas (TAs)
to develop energy-saving solutions
for cryomodules of modern SRF accelerators

with support from
Enterprise Europe Network (EEN), EuXFEL GmbH, I.FAST, LEAPS, LDG and TIARA

HORIZON-INFRA-2023-TECH-01-01
New technologies and solutions for reducing the environmental and climate footprint of RIs

REGULATIONS

- **Specific conditions**
  - *Expected EU contribution per project: around 5M EUR.*
  - *Consortia must include at least 3 different research infrastructures, each of them being an ESFRI infrastructure, and/or a European Research Infrastructures Consortium (ERIC) or another research infrastructure of European interest (i.e. a research infrastructure which is able to attract users from EU or associated countries other than the country where the infrastructure is located). Consortia should be built around a leading core of at least 3 world-class research infrastructures and can include a wider set of RIs.*
  - *Other technological partners, including industry and SMEs, should also be involved, thus promoting innovation and knowledge sharing through co-development of new technical solutions for research infrastructures.*
  - *Proposals should built on and explain any synergies and complementarities with previous or current EU grants, including those under other parts of the Framework Programmes.*
- **Expected Outcome**
  - *Reduction of environmental impacts (including climate-related)*
  - *Optimisation of resource and energy consumption integrated through the full life cycle of research infrastructures*
  - *Increased long-term sustainability of European research infrastructures*
- **Scope**
  - *The aim of this topic is to deliver innovative technologies and solutions which reduce the environmental and climate footprint of RIs through the full life cycle of research infrastructures. Proposals should identify common methodologies, among the concerned RIs, to assess environmental impact and strategies to reduce it, as well as efficiency gains in the broader ecosystem.*
  - *Proposals should address the following aspects, as relevant:*
    - *new technologies and solutions for research infrastructures enabling transformative resource efficiency (e.g. energy consumption) and reduction of environmental (including climate-related) impacts, including, when relevant, more sustainable and efficient ways of collecting, processing and providing access to data;*
    - *validation and prototyping;*
    - *training of RI staff for the operation and use of the new solutions;*
    - *action plans to deploy the new developments at wider scale and ensure their sustainability;*
    - *measures to ensure an environmentally effective integration of the solutions in the local contexts;*
    - *societal engagement to foster acceptance of the solutions in the local and regional communities.*

HORIZON-INFRA-2023-TECH-01-01

New technologies and solutions for reducing the en...

A strong and broad impact with a 5M EUR EU-project

develop an impactful and well-motivated project that is also a catalyser for the implementation of the Accelerator R&D Roadmap

***Goal**: develop, prototype and validate the essential energy-saving and energy-recovery SRF technologies to potentially retrofit existing Research Infrastructures and integrate in the design of a novel sustainable LINAC cryomodule with a broad portfolio of future applications in industry and at accelerator Research Infrastructures (RIs)*

Sustain the impactful 20th-century accelerator applications into an energy-low 21st century!

- S...
  - *(ERIC) or ... where the ... echnical ... ammes.*
-
- S...
  - *... full life cycle of research ... impact and strategies to reduce it, as well as efficiency*
  - *... research infrastructures enabling transformative resource efficiency (e.g. energy consumption) and reduction of environmental (... climate-related) impacts, including, when relevant, more sustainable and efficient ways of collecting, processing and providing access to data;*
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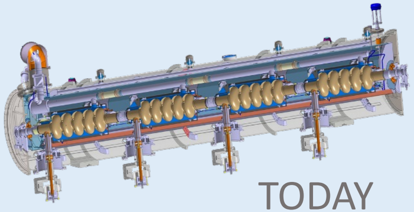
“Innovate for Sustainable Accelerating Systems” – *brief abstract*

AMBITION – With the ambition to maintain the attractiveness and competitiveness of European research infrastructures and to enable Europe’s Green Deal, we propose to Innovate for Sustainable Accelerating Systems (iSAS) by establishing enhanced collaboration in the field to broaden, expedite and amplify the development and impact of novel energy-saving technologies to accelerate particles. The objective of iSAS is to innovate those technologies related to the cryomodule that have been identified as being a common core of SRF accelerating systems and that have the largest leverage for energy savings with a view to minimizing the intrinsic energy consumption in all phases of operation.

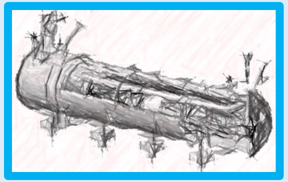
METHODOLOGY – Based on a recently established European R&D Roadmap for accelerator technology and based on a collaboration between leading European research institutions and industry, several interconnected technologies will be developed, prototyped, and tested, each enabling significant energy savings on their own in accelerating particles. The collection of energy-saving technologies will be developed with a portfolio of forthcoming applications in mind and to explore energy-saving improvements of existing research infrastructures on the ESFRI Roadmap, for example the ESFRI Landmarks HL-LHC, ESS and EuXFEL. Considering the developments realised, the new energy-saving technologies will be coherently integrated into the parametric design of a new accelerating system, a LINAC SRF cryomodule, optimised to achieve high beam-power in accelerators with an as low as reasonably possible energy consumption.

IMPACT – Through inter- and multidisciplinary research that delivers and combines various technologies, it is the long-term ambition of iSAS technologies to reduce the energy footprint of SRF accelerators in future research infrastructures by half, and even more when the systems are integrated in Energy-Recovery LINACs.

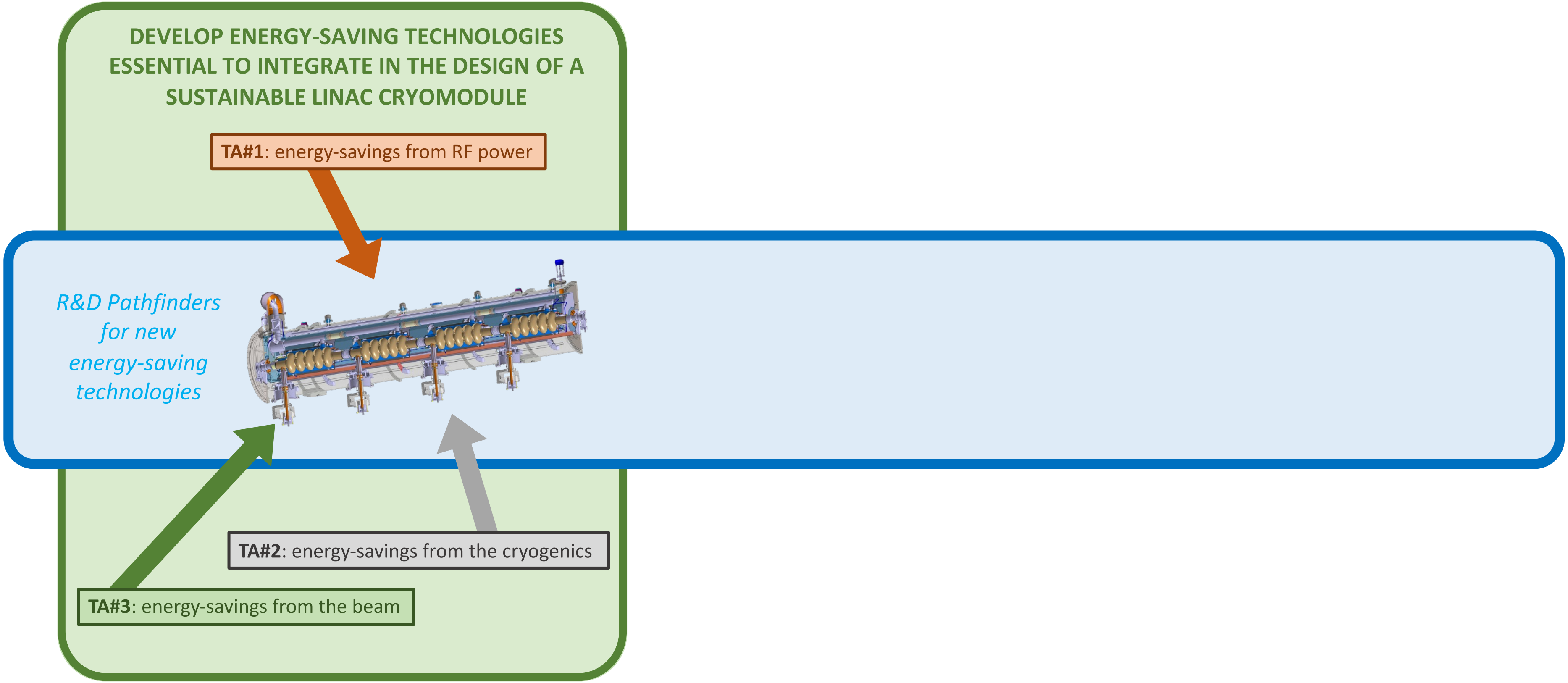
INNOVATE TECHNOLOGIES TOWARDS A SUSTAINABLE ACCELERATING SYSTEM



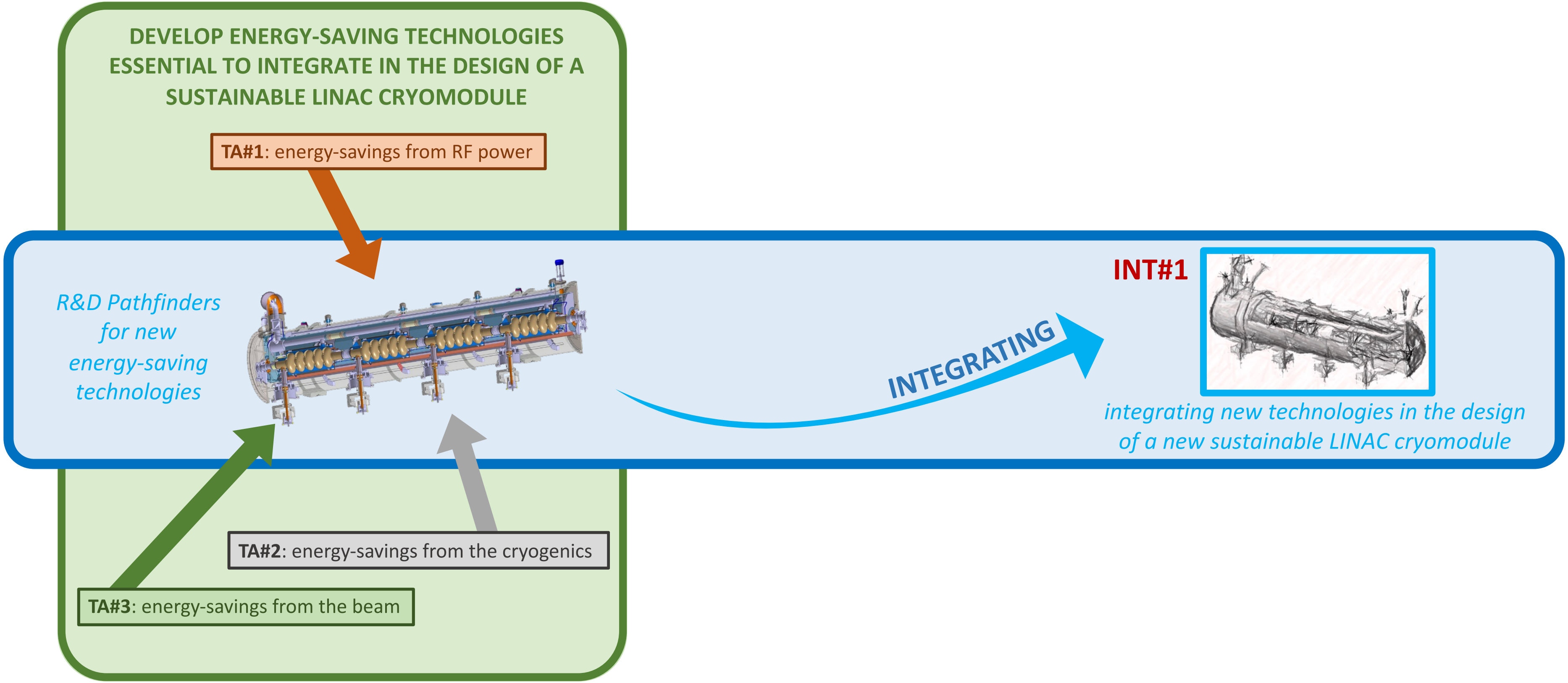
TODAY



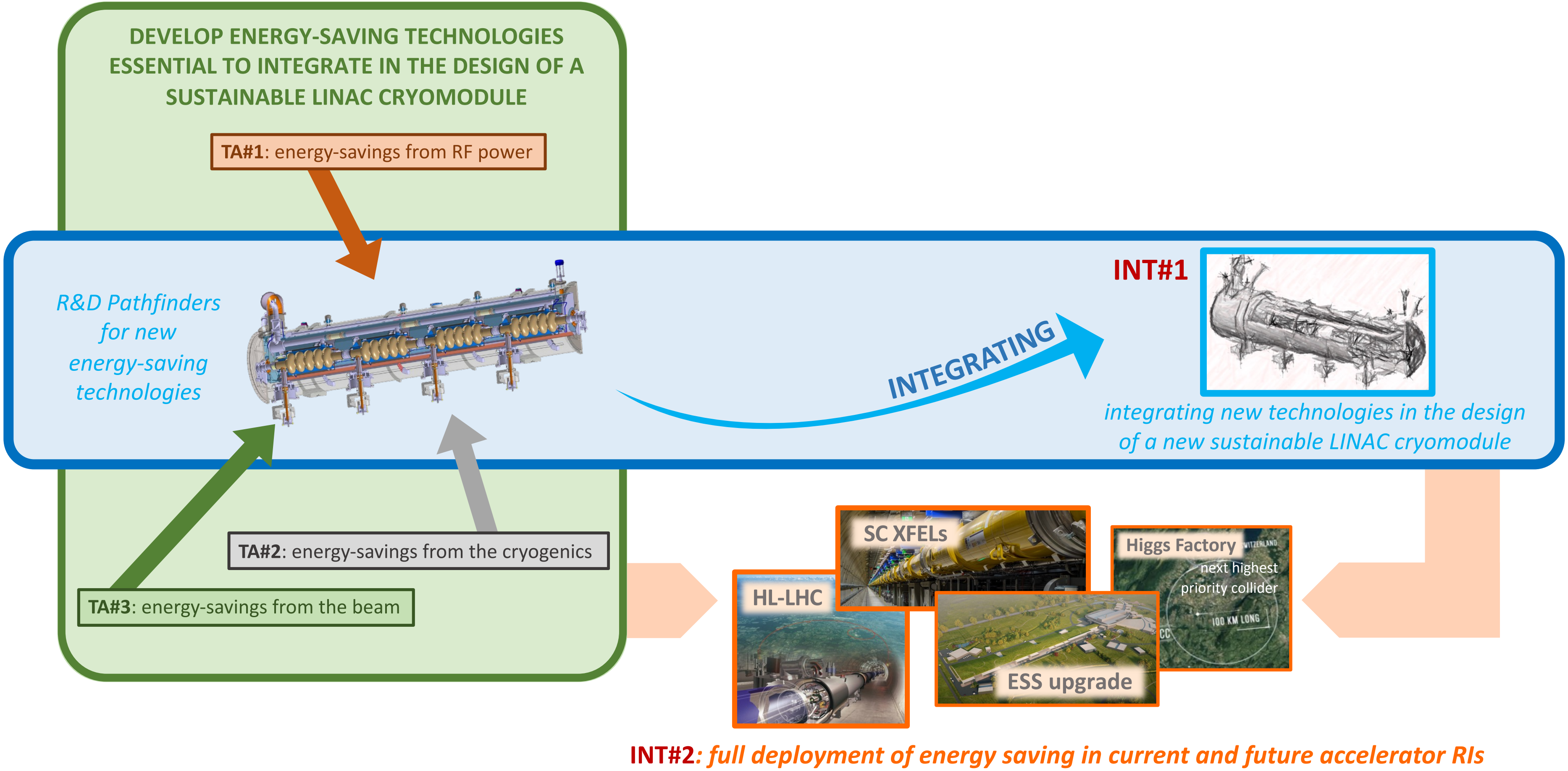
NEW DESIGN



TA: Technology Area

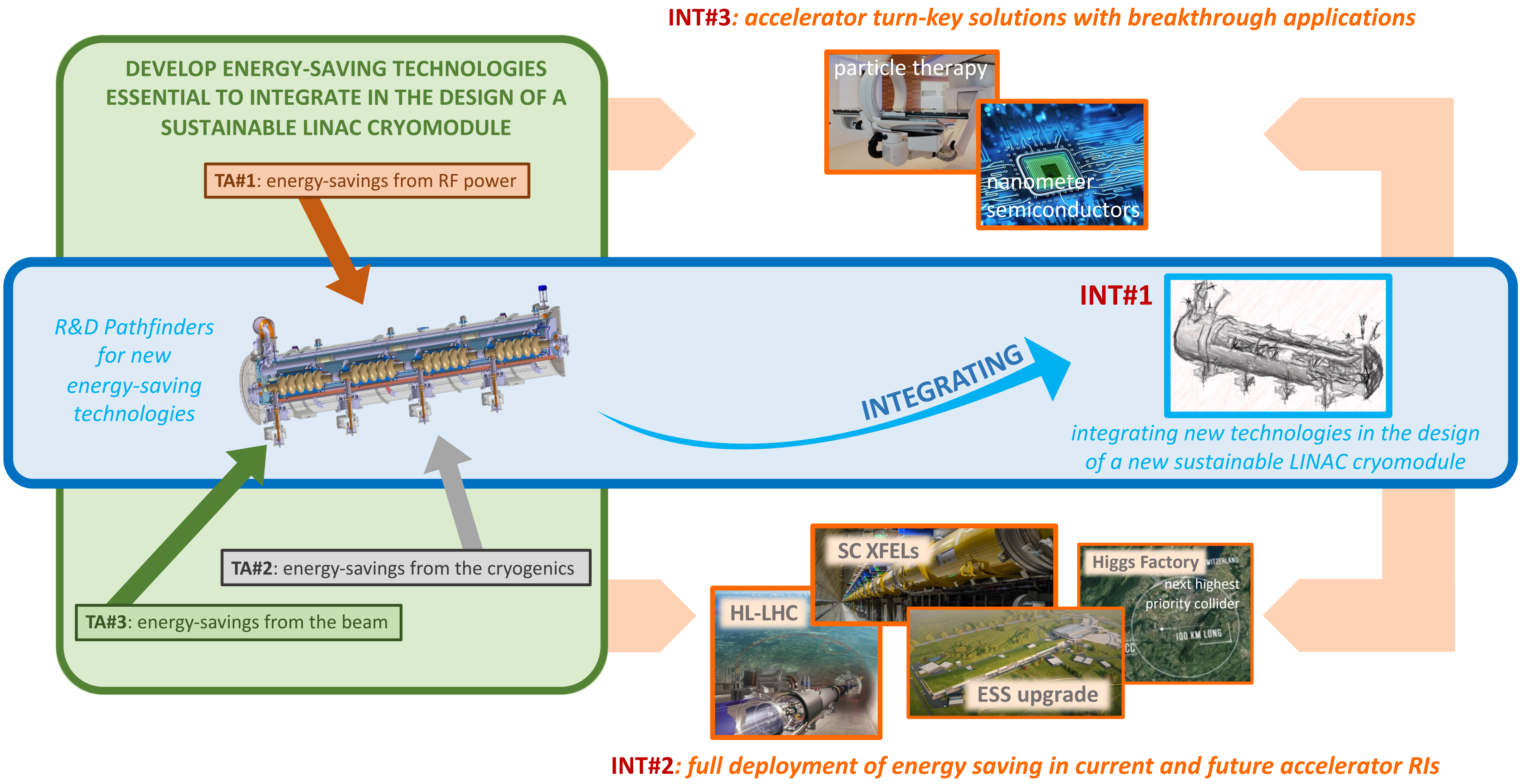


TA: Technology Area, INT: Integration Activities



TA: Technology Area, INT: Integration Activities

RIs: Research Infrastructures



INT#3: accelerator turn-key solutions with breakthrough applications
DEVELOP ENERGY-SAVING TECHNOLOGIES ESSENTIAL TO INTEGRATE IN THE DESIGN OF A SUSTAINABLE LINAC CRYOMODULE
TA#1: energy-savings from RF power
particle therapy
nanometer semiconductors
R&D Pathfinders for new energy-saving technologies
INTEGRATING
INT#1
integrating new technologies in the design of a new sustainable LINAC cryomodule
TA#2: energy-savings from the cryogenics
TA#3: energy-savings from the beam
SC XFELs
HL-LHC
ESS upgrade
Higgs Factory
next highest priority collider
100 KM LONG
INT#2: full deployment of energy saving in current and future accelerator RIs

iSAS Objectives – *Technology Areas*

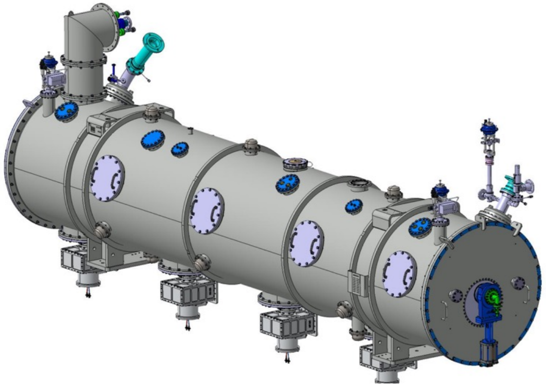
- **TA#1: energy-savings from RF power** – *While great strides are being made in the energy efficiency of various RF power generators, the objective of iSAS is to ensure additional impactful energy savings through coherent integration of the RF power source with smart digital control systems and with novel tuners that compensate rapidly cavity detuning from mechanical vibrations, resulting in a <u>further reduction of power demands by up to a factor of 3</u>.*

- **TA#2: energy-savings from cryogenics** – *While major progress is being made in reusing the heat produced in cryogenics systems, the objective of iSAS is to develop superconducting cavities that operate with high performance at 4.2 K (i.e., up to 4.5 K depending on the cryogenic overpressure) instead of 2 K, thereby <u>reducing the grid-power to operate the cryogenic system by a factor of 3</u> and requiring less capital investment to build the cryogenic plant.*

- **TA#3: energy-savings from the beam** – *Significant progress has been achieved in maintaining the brightness of recirculating beams to provide high-intensity collisions to experiments, but most of the particles lose their power through radiation or in the beam dump system. The objective of iSAS is to develop dedicated power couplers for damping the so-called Higher-Order Modes (HOMs) excited by the passage of high-current beams in the superconducting cavities, <u>enabling efficient recovery of the energy of recirculating beams back into the cavities before it is dumped, resulting in energy reduction for operating, high-energy, high-intensity accelerators by a factor ten</u>.*

iSAS Objectives – *Integration Activities*

- **INT#1: integration into the design of a LINAC cryomodule**
  While LINAC cryomodules are designed for specific accelerators, the objective of iSAS is to address the common engineering challenges of integrating iSAS energy-saving technologies into a parametric design of a new sustainable accelerator system.



- **INT#2: integration into existing RIs** – *While various RIs envisage upgrades, the objective of iSAS is to expedite the technical integration of energy-saving technologies by retrofitting existing accelerating systems. An existing cryomodule will be adapted, ready to demonstrate energy recovery of high-power recirculating beams in the PERLE research facility, paving the way for high-energy, high-intensity electron beams with minimal energy consumption.*
- **INT#3: integration into industrial solutions** – *While iSAS technologies are emerging, the objective of iSAS is to plan for concrete co-developments with industry to expedite reaching a Technology Readiness Level (TRL) sufficiently advanced towards largescale deployment of the new energy-saving solutions at current and future RIs as well as to prepare the path for industrial applications. For many future RIs and industrial applications SRF is the enabling technology.*

iSAS concrete Work Packages

- **R&D Pathfinders for three Technology Areas (TA) for energy-saving**

  TA#1: energy savings from the RF power *(short-term and very wide applications)*

  WP.1: optimal integration of Ferro-Electric Fast Reactive Tuners (FE-FRT) to deal with microphonics (400, 800 and 1300 MHz)
  WP.2: low-level RF controls (LLRF controls incl. AI)

  TA#2: energy savings from the cryogenics *(medium-term and wide applications)*

  WP.3: high-temperature SRF cavities above 4.2 K (thin Nb_3Sn films on Cu)

  TA#3: energy savings from the beam *(long-term and specific applications)*

  WP.4: Higher-Order Mode damping and fundamental power couplers

- **INT#1: integrate these technologies into the design of a sustainable LINAC cryomodule**

  WP.5: based on the ESS cryomodules, develop a parametric design for an optimally sustainable LINAC cryomodule, ready to be adapted and built for various future applications in industry and in accelerator RIs

- **INT#2: integrate these technologies into existing LINAC cryomodules at RIs**

  WP.6: engineering aspects to integrate and test energy-saving iSAS technologies in a cryomodule, and verify the options to retrofit existing SRF systems at RIs, with a focus on ESS, HL-LHC, EuXFEL

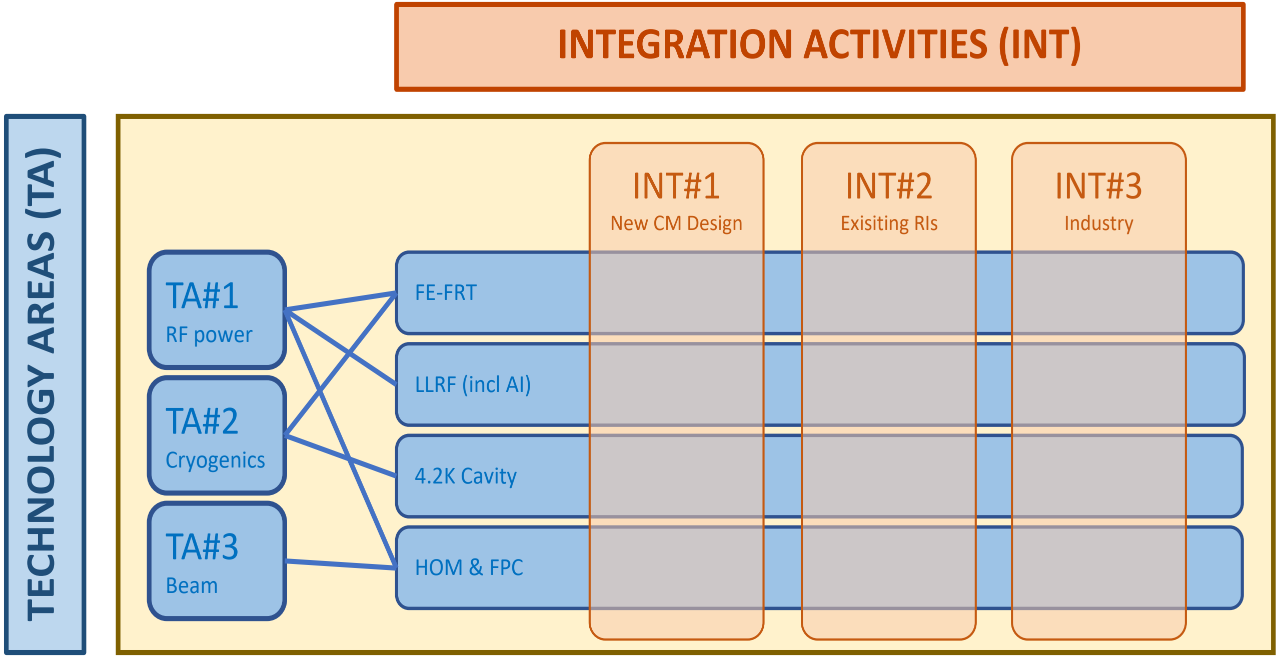
- **INT#3: integrate towards turn-key solutions and applications in industry**

  WP.7: prepare the co-developments with industrial partners such that when the new technologies and the new designed LINAC cryomodule are developed and validated, their Technology Readiness Level is sufficient such that industry can consider building them

iSAS cross coordination

The ambition of iSAS is to pave the way by developing common solutions for the engineering and industrial challenges to expedite the integration of energy-saving solutions.

The methodology to achieve the iSAS objectives is based on a profoundly cross-disciplinary fertilization between different disciplines, from RF engineering to material science, electronics, mechanical engineering, and cryogenics, with co-developments between leading research and industrial institutions.



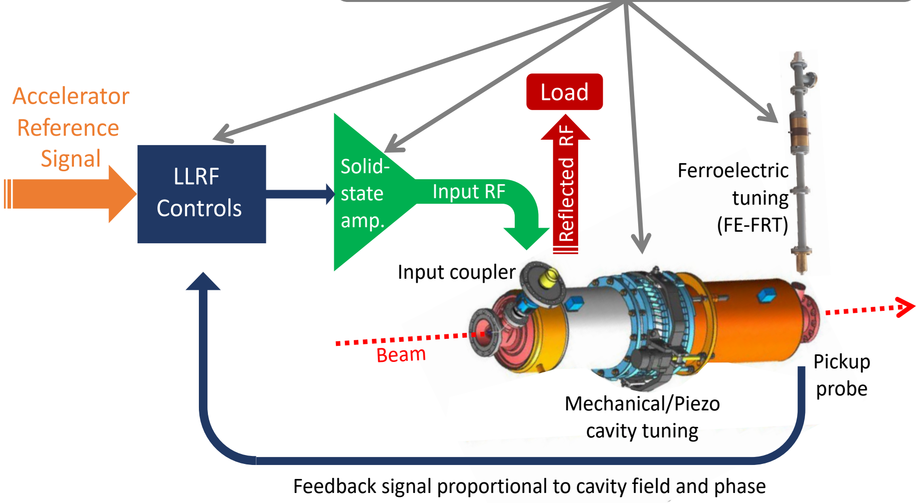
iSAS *develops, prototypes & validates SRF energy-saving technologies*

TA#1: energy-savings from RF power

The objective is to significantly reduce the RF power sources and wall plug power for all SRF accelerators with ferro-electric fast reactive tuners (FE-FRTs) for control of transient beam loading and detuning by microphonics, and with optimal low level radio frequency (LLRF) and detuning control with legacy piezo based systems. iSAS will demonstrate operation of a superconducting cavity with FE-FRTs coherently integrated with AI-smart digital control systems to achieve low RF-power requirements.

Integrated iSAS approach to save grid power for RF

- Digital AI/ML-assisted field and detuning control
- Reduced detuning by piezo and new FE-FRT tuners
- Smart amplifier control



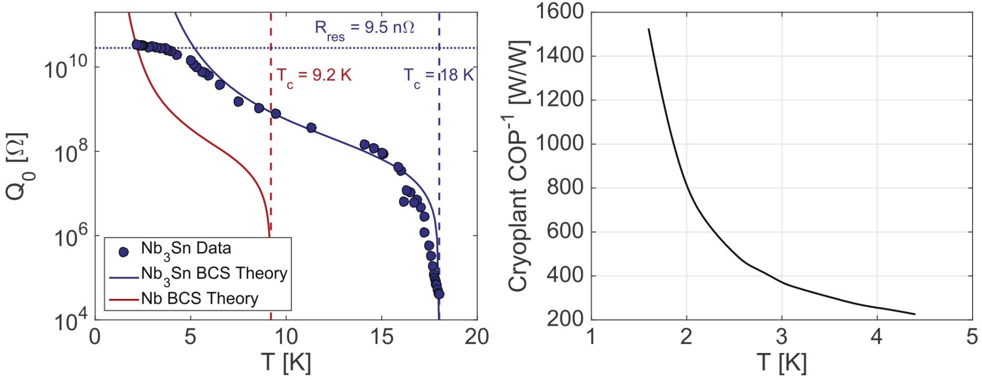
Schematic overview to compensate detuning with new FE-FRTs avoiding large power overhead and to compensate with AI-smart control loop countermeasures via the LLRF steering of the RF amplifier the disturbances in SRF cavities that impact field stability

iSAS *develops, prototypes & validates SRF energy-saving technologies*

TA#2: energy-savings from cryogenics

The objective is focused on the development of thin-film cavities and aims to transform conventional superconducting radio-frequency technology based on off-shelf bulk niobium operating at 2 K, into a technology operating at 4.2 K using a highly functionalized material, where individual functions are addressed by different layers. iSAS will optimize the coating recipe for Nb_3Sn on copper to optimize tunability and flux trapping of thin-film superconducting cavities and to validate a prototype beyond the achievements of the ongoing Horizon Europe I.FAST project.

Supercond. Sci. Technol. 30 (2017) 033004

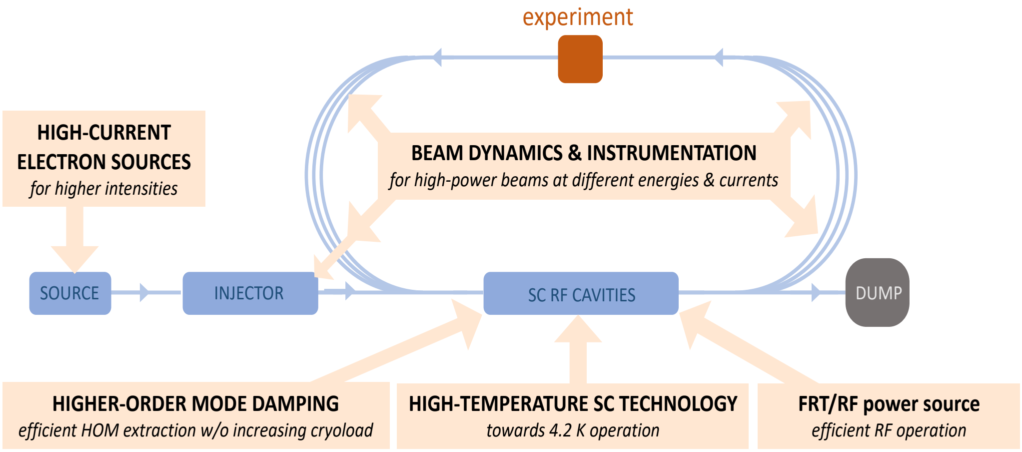


The higher critical temperature (T_c) of Nb_3Sn allows for the maximum value of quality factor Q_0 for 1.3 GHz cavities to be achieved at operating temperatures of about 4 K compared to 2 K for Nb (left figure). The graph on the right shows the efficiency of a cryogenic plant (COP) as a function of temperature achieving about 3 times higher COP efficiency when operating at a temperature of 4.2 K than at 2 K. This suggests that operating a cryogenic plant at 4.2 K with Nb_3Sn SRF cavities, can lead to significant better performances and energy savings.

iSAS develops, prototypes & validates SRF energy-saving technologies

TA#3: energy-savings from the beam

The objective is to reduce the total power deposited into the cryogenics circuits of the cryomodule of the Higher-Order Mode (HOM) couplers and fundamental power couplers (FPCs) leading to a significant reduction of the heat loads and the overall power consumption. iSAS will improve the energy efficiency of the FPCs and HOM couplers by designing and building prototypes that will be integrated into a LINAC cryomodule capable of energy-recovery operations and to be tested in accelerator-like conditions.



towards full high-power energy recovery

Technology Readiness Level (TRL)

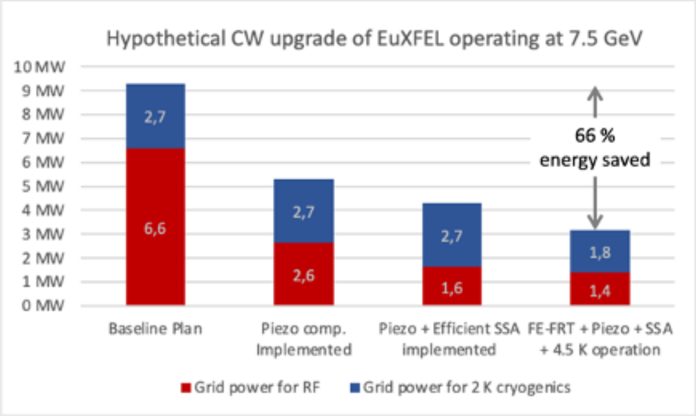
The readiness of the energy-saving iSAS technologies will be improved to prepare them towards industrialisation and cost-effective mass production for current and future RIs.

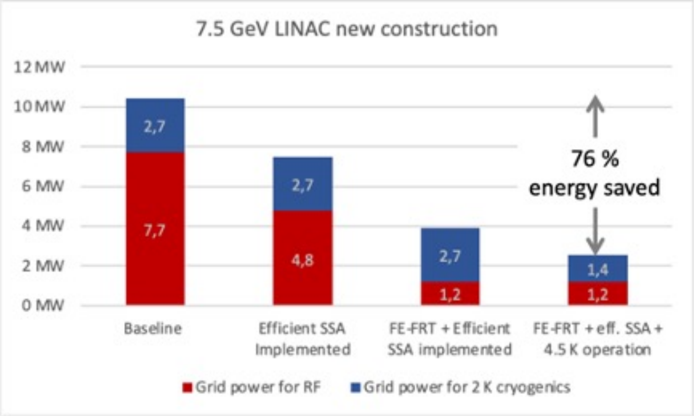
iSAS Technologies		initial TRL	target TRL
TA#1	FE-FRT for transient detuning @ 400 MHz	4	6
	FE-FRT for transient detuning @ 800 MHz	1-2	4
	FE-FRT for microphonics @ 400 MHz	3	5-6
	FE-FRT for microphonics @ 800-1300 MHz	1-2	5-6
	LLRF controls	3-4	7
	LLRF + FE-FRT controls	2-3	6
TA#2	Nb3Sn-on-Cu films for 4.2-K cavity operation	2-3	4-5
TA#3	Higher-Order Mode couplers	2-3	5
	Fundamental Power Couplers	2-3	5

The objective of iSAS is for RIs and European industry to co-develop industrial solutions for energy-savings technologies in accelerators, delivering applications that can be implemented across various accelerator-driven research and non-research infrastructures.

Impact of iSAS technologies on FELs

example EuXFEL





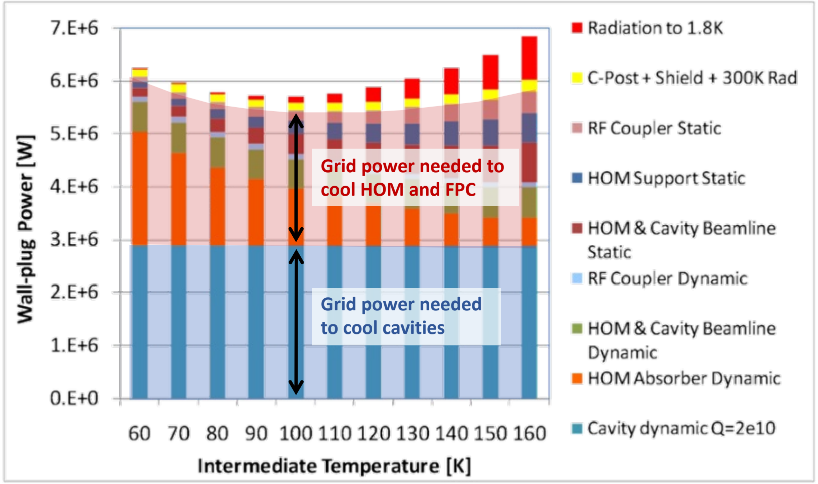
For an upgrade of EuXFEL to CW, a refurbishment of the injection LINAC cavities is being considered. This could provide the opportunity to retrofit some iSAS technology developments as well. The figure (left) depicts the expected energy savings if various iSAS developed technologies are implemented (assumption: 0.1 mA beam current), the degree of modifications, but also the benefits, are increasing from left to right. The achievable total energy savings amounts to 66%, more than 6 MW, avoiding 2.9 tons CO_2 per hour of operation for Germany's electrical energy mix (485 g CO_2/kWh). Future LINACs can be optimally designed to take full advantage of the iSAS technologies, as integrated in the cryomodule being designed in iSAS. The right figure shows that the full savings for a 7.5-GeV LINAC is of the order of 76% (RF + cryogenics cavity cooling). Not included here are the additional potential savings by optimizing the heat load from HOM and FPC couplers – for the Cornell system their load accounts for nearly 4 MW – or any scheme to recover the beam power (750 kW in these examples).

Impact of iSAS technologies on SRF accelerators

example Cornell ERL LINAC

iSAS develops new designs for both fundamental power couplers and HOM couplers dedicated to beam operation at very high currents while minimizing their static and dynamic heat loads in the cryogenic system. The reduction in the required cryogenic power will depend on the final design but the energy savings potential is expected to be large. As an example, the adjacent figure shows the grid power required to cool various parts of the cryomodules in the 5-GeV Cornell ERL LINAC design for different configurations of the cryogenics. The HOM and fundamental power couplers account for nearly half of the full cryogenic load. Even a moderate improvement can thus save powers in the MW range. The required cooling power scales linearly with the beam energy, so for the most ambitious future SRF accelerators, the savings in wall-plug power can be in the tens of MW and more range.

"Cornell Energy Recovery LINAC Project Definition Design Report"
G. Hoffstatter, S. Gruner, M. Tigner, eds. (2013)



Grid power for cooling the Cornell ERL LINAC.
(figure adapted from reference)

Impact of iSAS technologies on HEP e^+e^- colliders

example future e+e- Higgs Factories

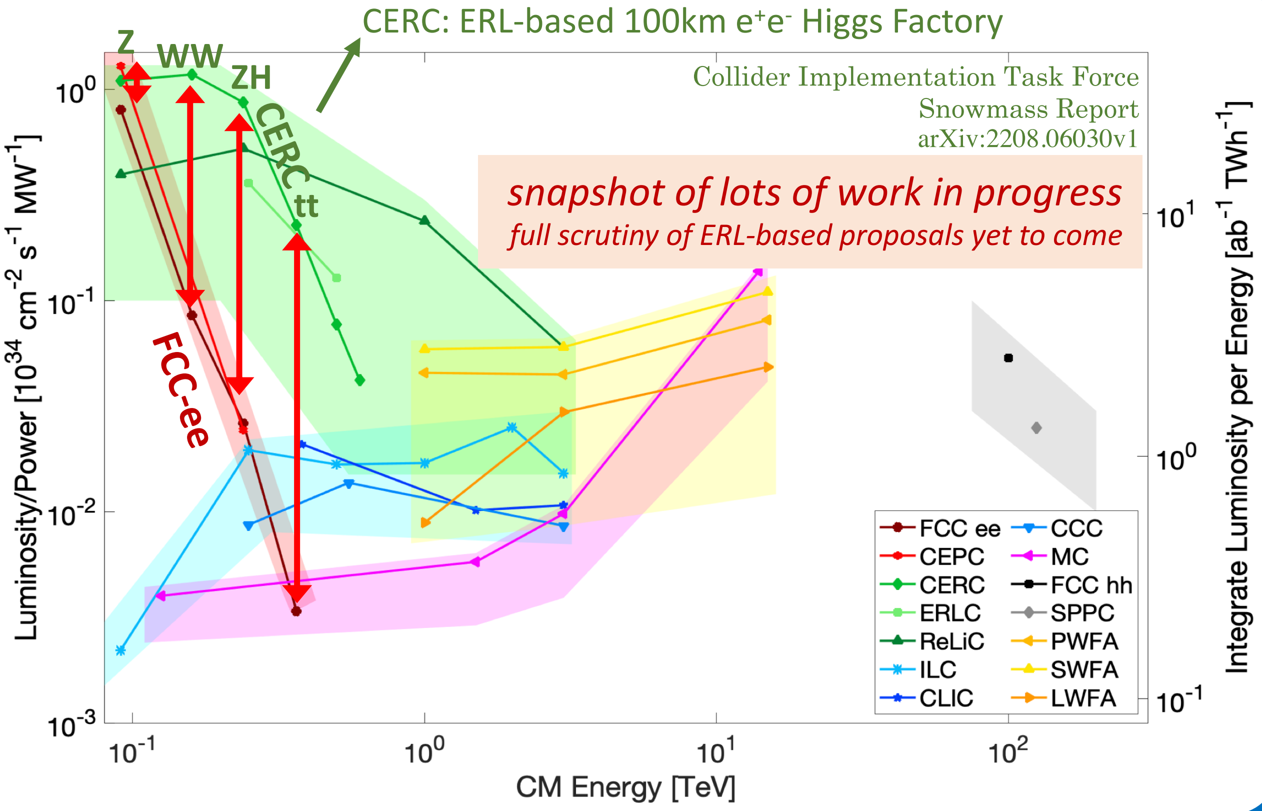
This plot <u>suggests</u> that with an ERL version of a Higgs Factory one might reach

x10 more Higgs bosons

or

x10 less electricity costs

NOTE: several additional challenges identified to realise these ERL-based Higgs Factories



References for CERC: PLB 804 (2020) 135394 and arXiv:2203.07358

iSAS organisation

Spread over 4 years: ~1000 person-months of researchers and ~12.6M EUR

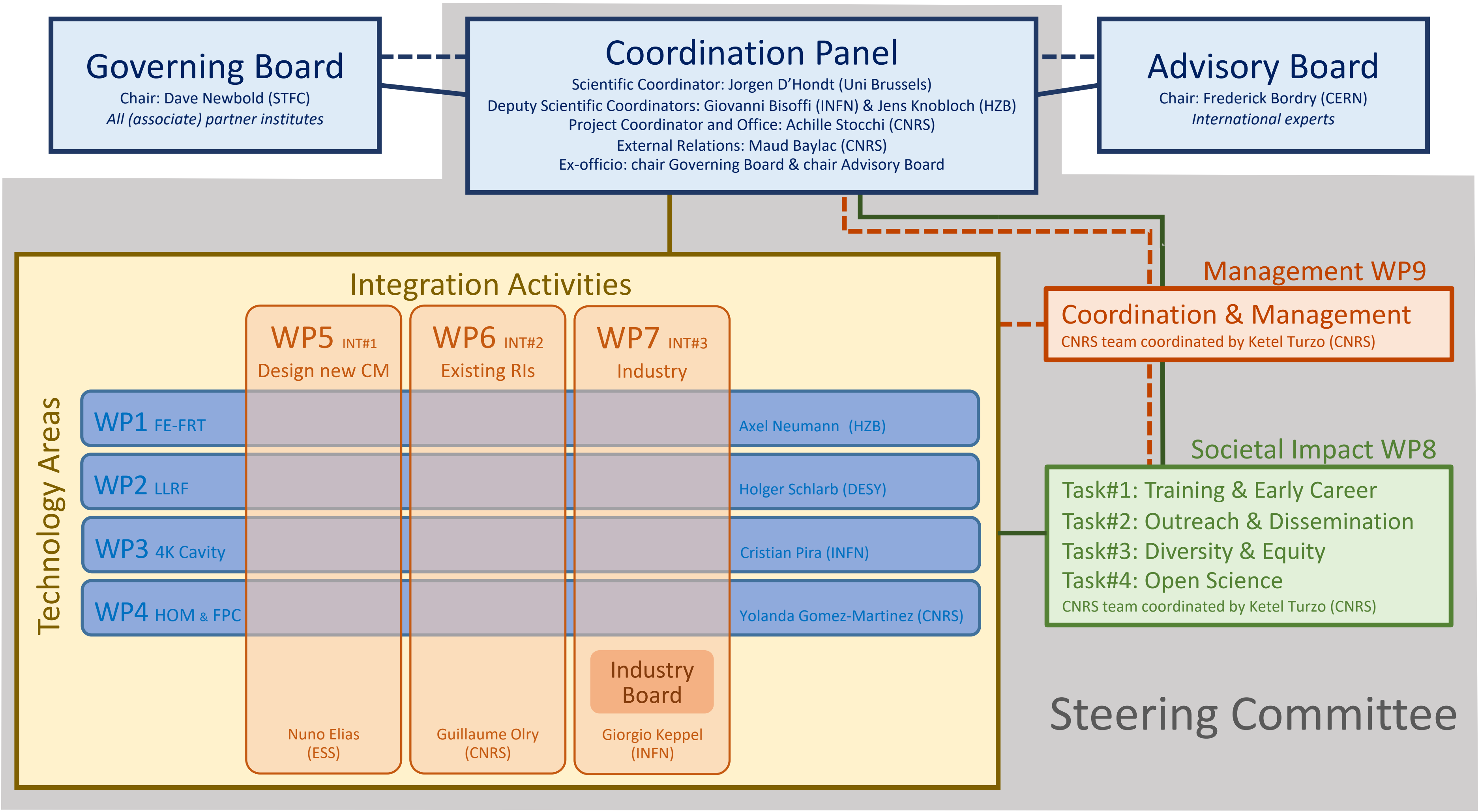
(of which 5M EUR is requested to Horizon Europe)

DESY. INFN UK Research and Innovation HZB Helmholtz Zentrum Berlin

European Spallation Source — Lancaster University — École Polytechnique Fédérale de Lausanne — cea

VUB Vrije Universiteit Brussel — cnrs — IJCLab Irène Joliot-Curie — CERN

+ industrial companies: *ACS Accelerators and Cryogenic Systems* (France), *RI Research Instruments GmbH* (Germany), *Cryoelectra GmbH* (Germany), *TFE Thin Film equipment srl* (Italy), *Zanon Research* (Italy), *EuclidTechLab* (USA)


Governing Board
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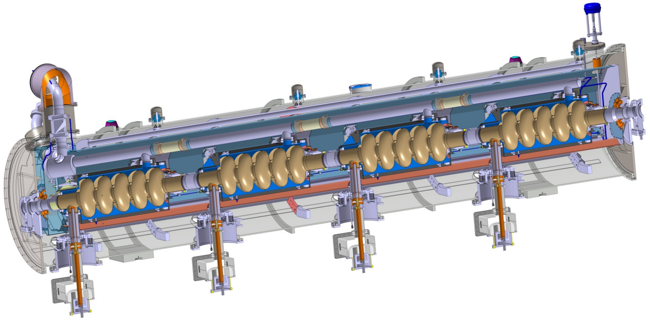
Project Coordinator and Office: Achille Stocchi (CNRS)
External Relations: Maud Baylac (CNRS)
Ex-officio: chair Governing Board & chair Advisory Board
Advisory Board
Chair: Frederick Bordry (CERN)
International experts
Integration Activities
WP5 INT#1
Design new CM
WP6 INT#2
Existing RIs
WP7 INT#3
Industry
Technology Areas
WP1 FE-FRT
Axel Neumann (HZB)
WP2 LLRF
Holger Schlarb (DESY)
WP3 4K Cavity
Cristian Pira (INFN)
WP4 HOM & FPC
Yolanda Gomez-Martinez (CNRS)
Industry Board
Nuno Elias (ESS)
Guillaume Olry (CNRS)
Giorgio Keppel (INFN)
Management WP9
Coordination & Management
CNRS team coordinated by Ketel Turzo (CNRS)
Societal Impact WP8
Task#1: Training & Early Career
Task#2: Outreach & Dissemination
Task#3: Diversity & Equity
Task#4: Open Science
CNRS team coordinated by Ketel Turzo (CNRS)
Steering Committee

Innovate for Sustainable Accelerating Systems (iSAS)

- As a leading pathfinder to enable sustainable SRF accelerators, with iSAS the most impactful new energy-saving technologies will be developed, validated, and integrated towards industrial solutions with a direct and verifiable impact on current research infrastructures and their upgrades.



- The outcomes of iSAS are expected to help reshape what is feasible in the future landscape of continuous-wave SRF accelerators.
- As a leading pathfinder to enable sustainable SRF accelerators, In the long term, the impact of iSAS is to reduce the energy footprint of future SRF accelerators in research infrastructures by at least half, and to unlock new facilities that maintain Europe's leading position to enable fundamental science breakthroughs in an energy sustainable manner.
- The new sustainable technologies will stimulate the European industry to take a leading role in building cost- and energy-efficient SRF systems for new accelerators with impact in, for example, the semiconductor and medical sectors.