Innovate for Sustainable Accelerating Systems (iSAS)

reducing the energy footprint of SRF accelerators

Jorgen D’Hondt
Vrije Universiteit Brussel

fwo

iihe BRUXELLES BRUSSEL

VUB HIGH-ENERGY PHYSICS RESEARCH CENTRE

iSAS

Sustainable HEP 2024, 10-12 June 2024, ZOOM
https://indico.cern.ch/event/1355767/overview

particle physics ambition

high-energy & high-current beams

(energy x current = power)

particle physics ambition

high-energy & high-current beams

(energy x current = power)

caveat

power requirements of future colliders

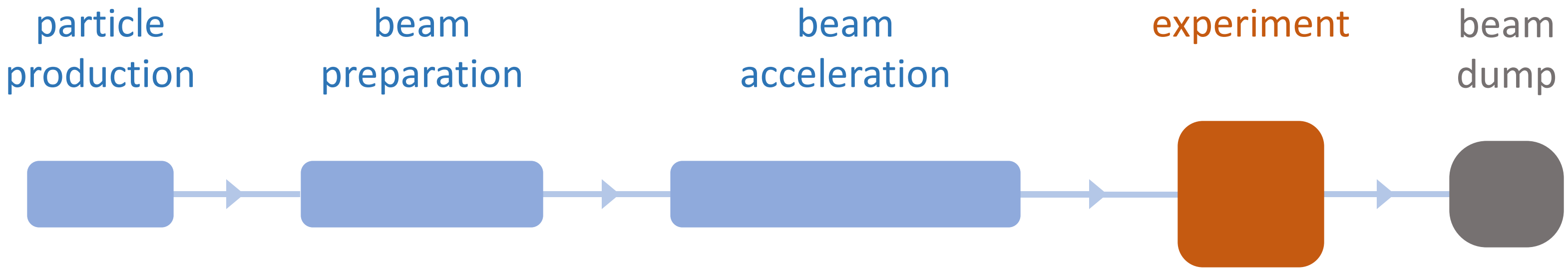
focus here on electron/positron accelerators

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

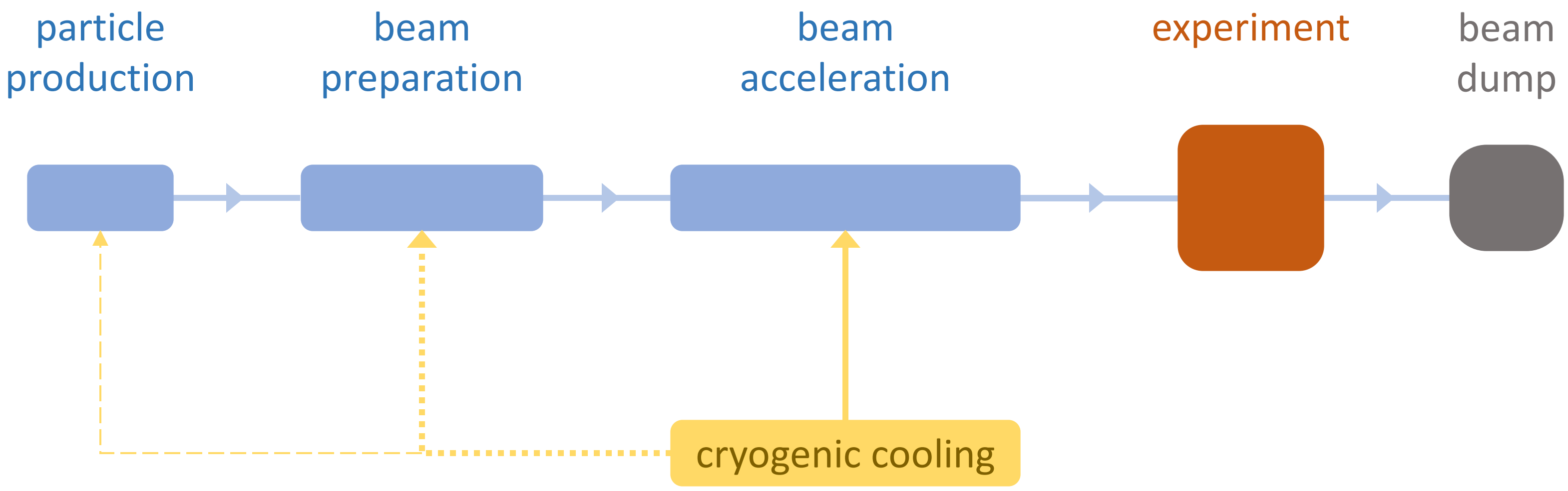
A detailed plan for the […] <u>saving and re-use of energy</u> should be part of the approval process for any major project.

European Strategy for Particle Physics 2020

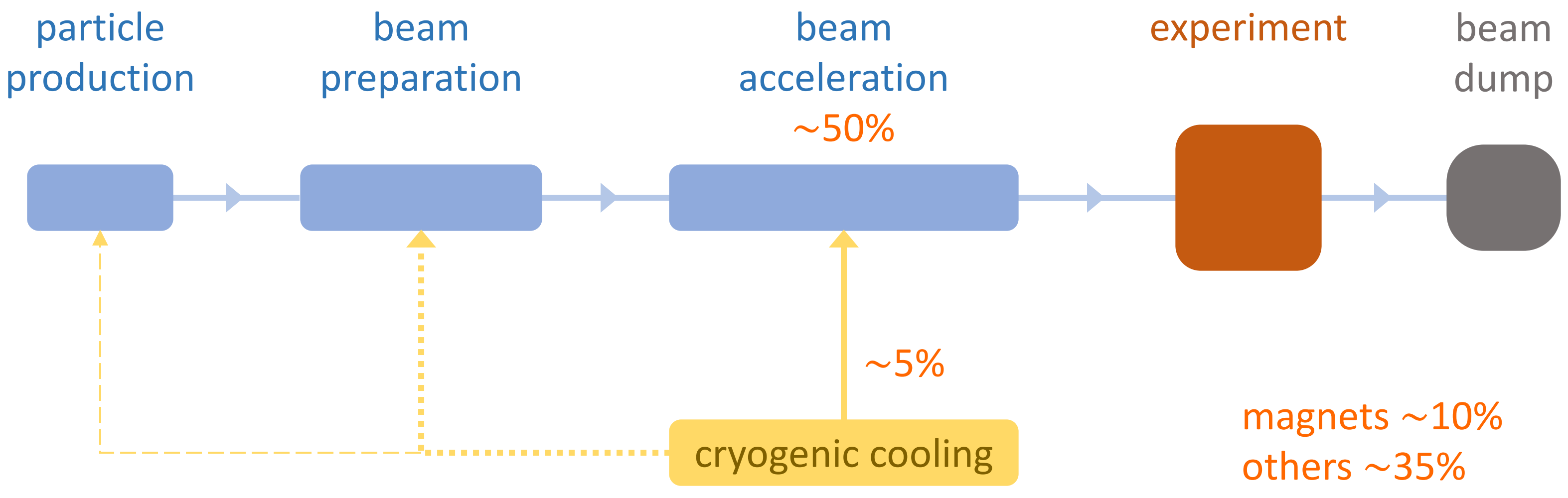
Basic structures of a particle accelerator



Basic structures of a particle accelerator



Basic structures of a particle accelerator



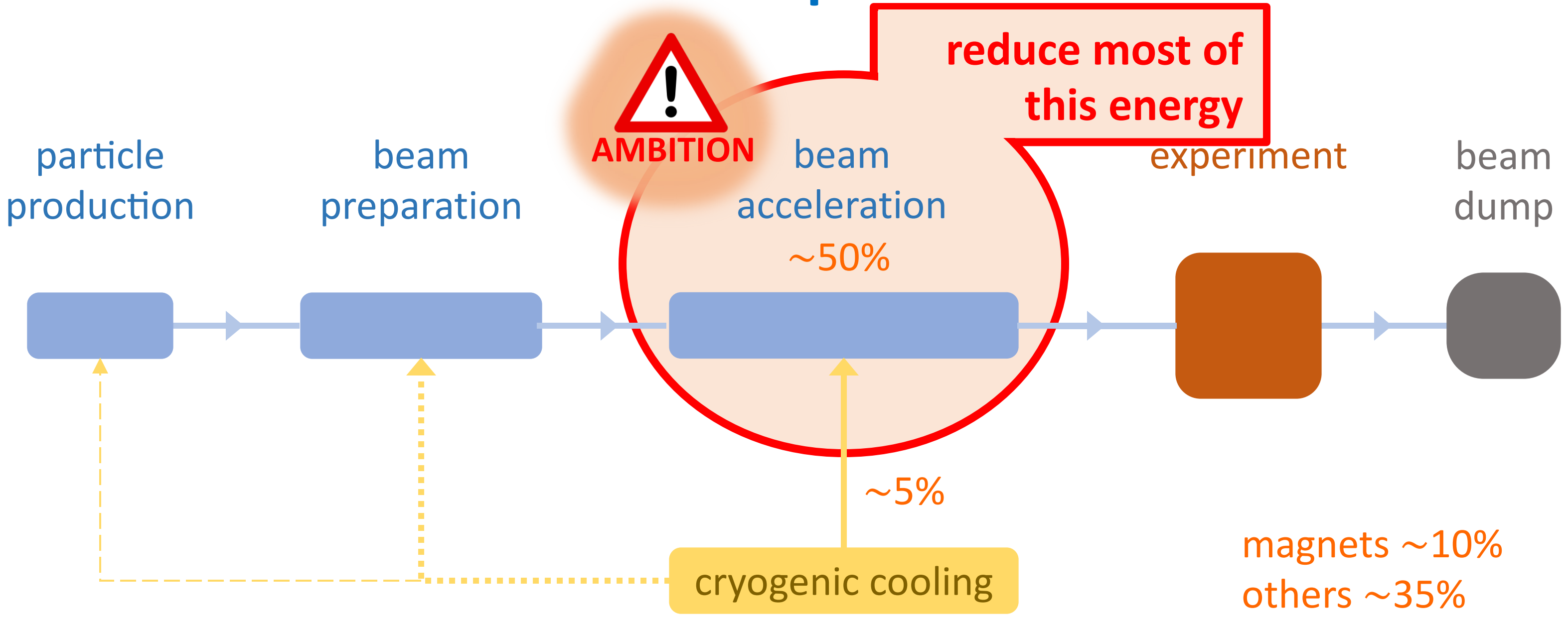
Typical power consumption for an electron-positron Higgs Factory

the highest priority next collider for particle physics

example FCC-ee@250GeV

FCC CDR, Eur. Phys. J. Special Topics 228, 261–623 (2019)

Basic structures of a particle accelerator



Typical power consumption for an electron-positron Higgs Factory

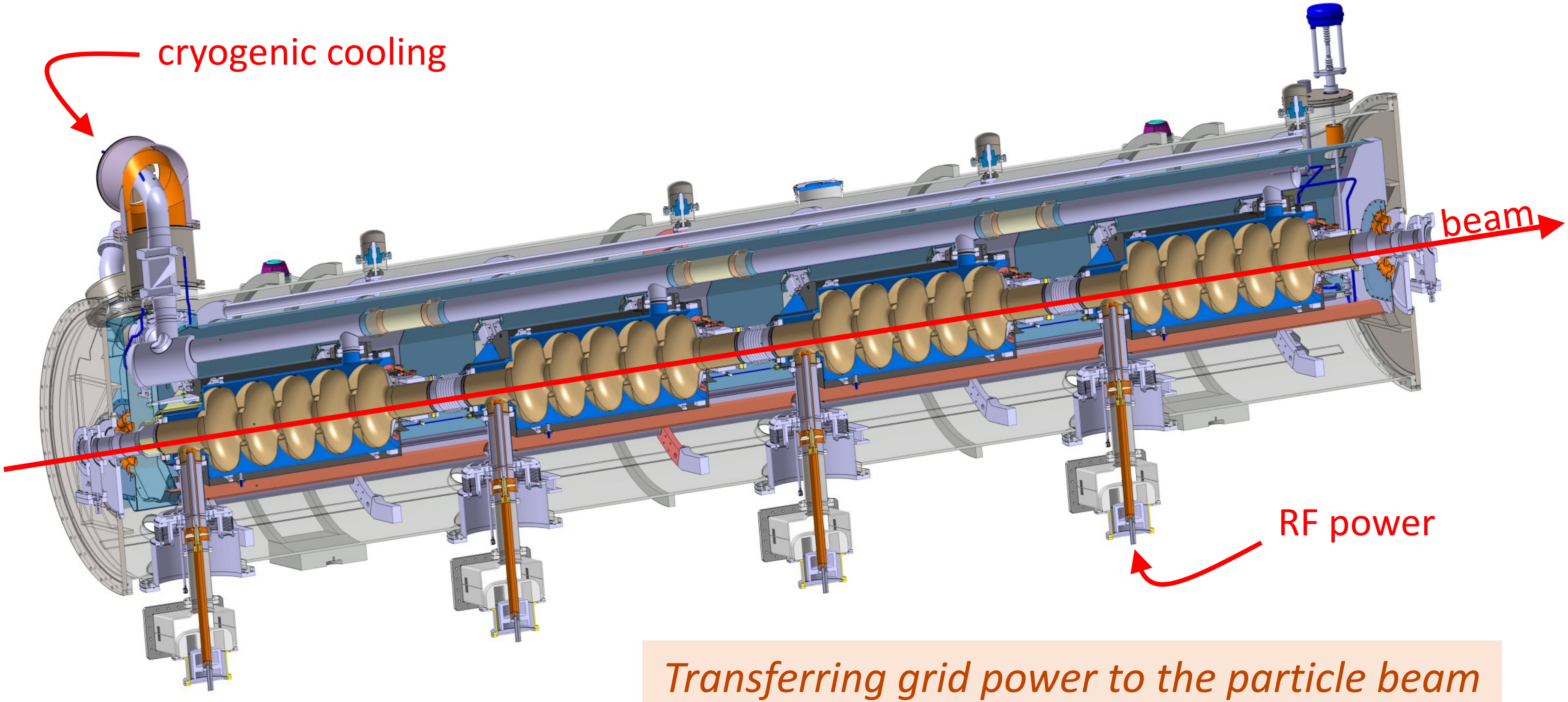
the highest priority next collider for particle physics

example FCC-ee@250GeV

FCC CDR, Eur. Phys. J. Special Topics 228, 261–623 (2019)

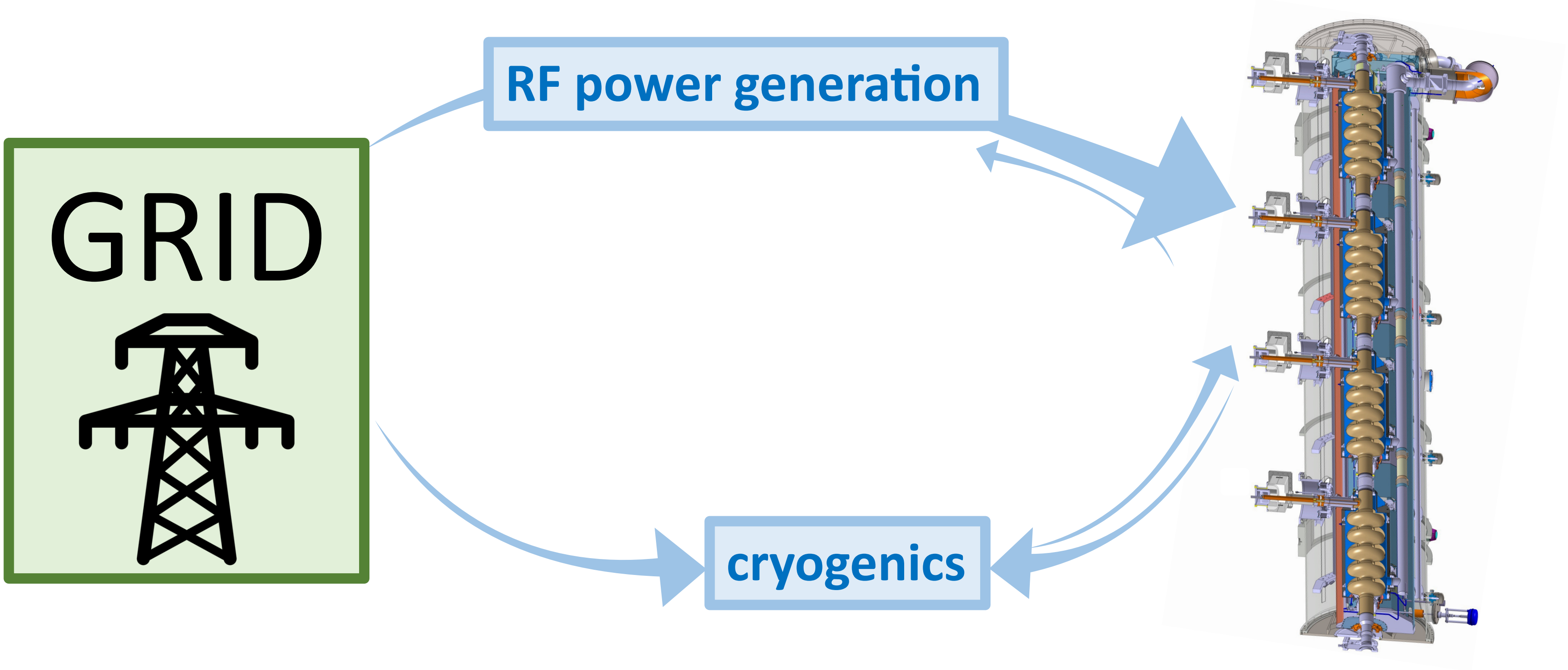
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

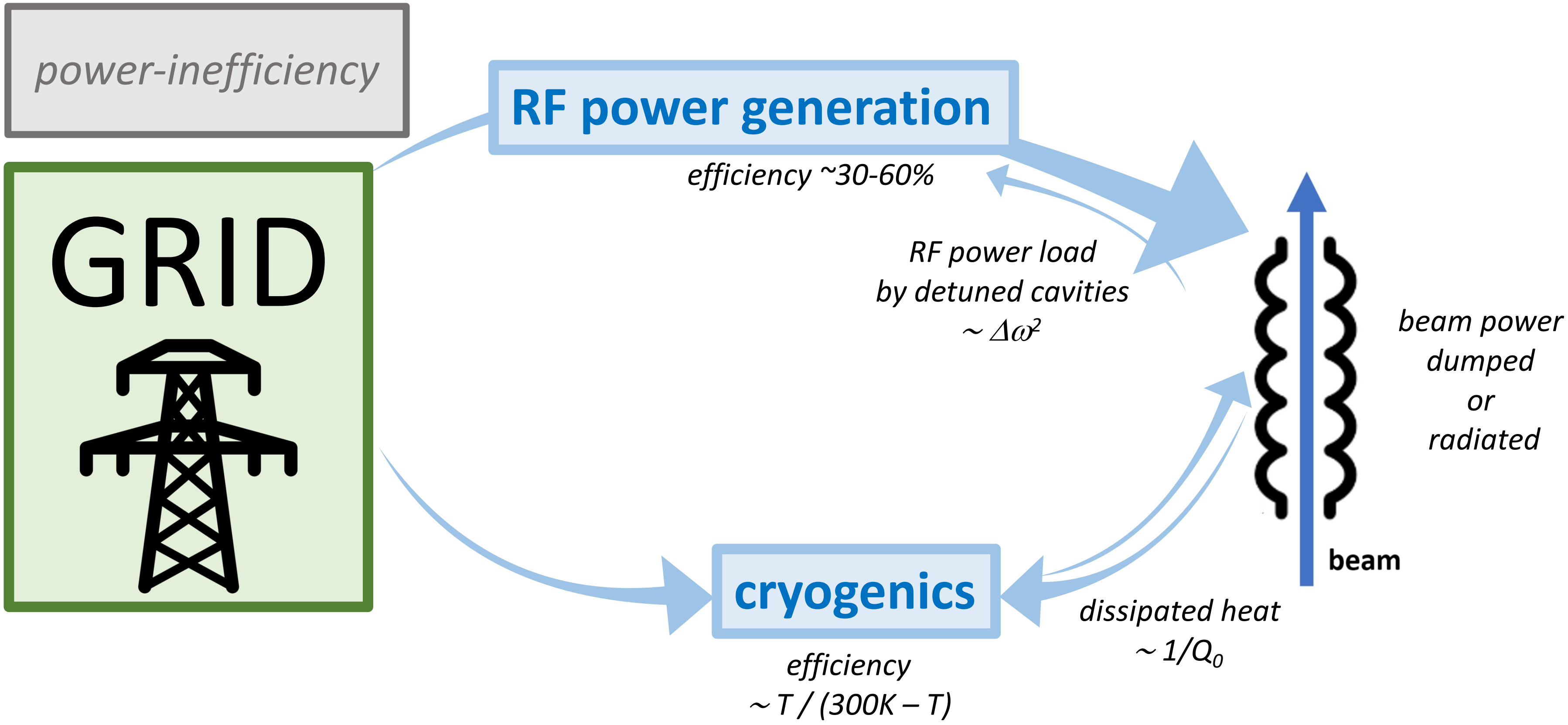


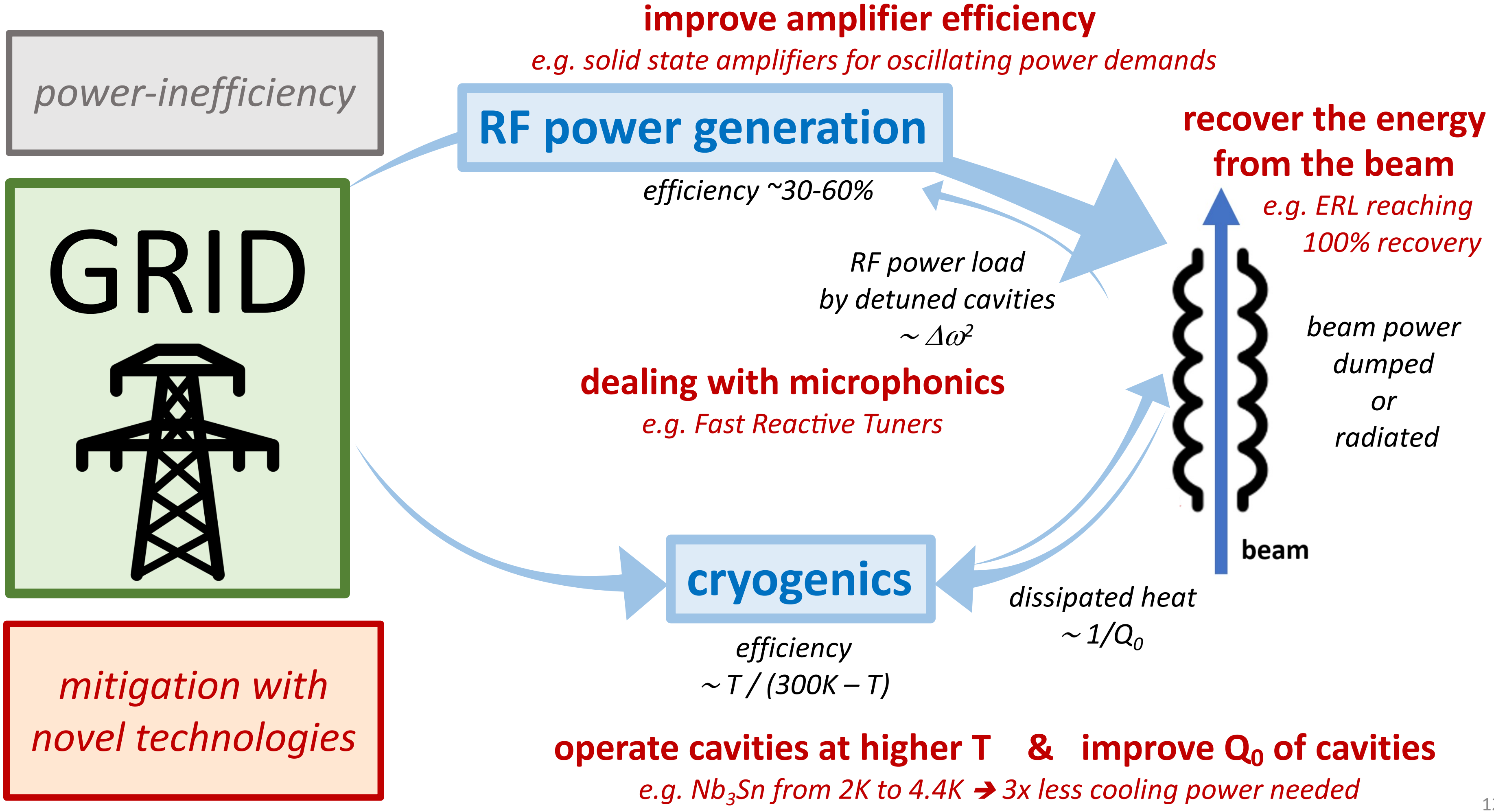
Transferring grid power to the particle beam

Sustainable Accelerating Systems – from Grid to Beam

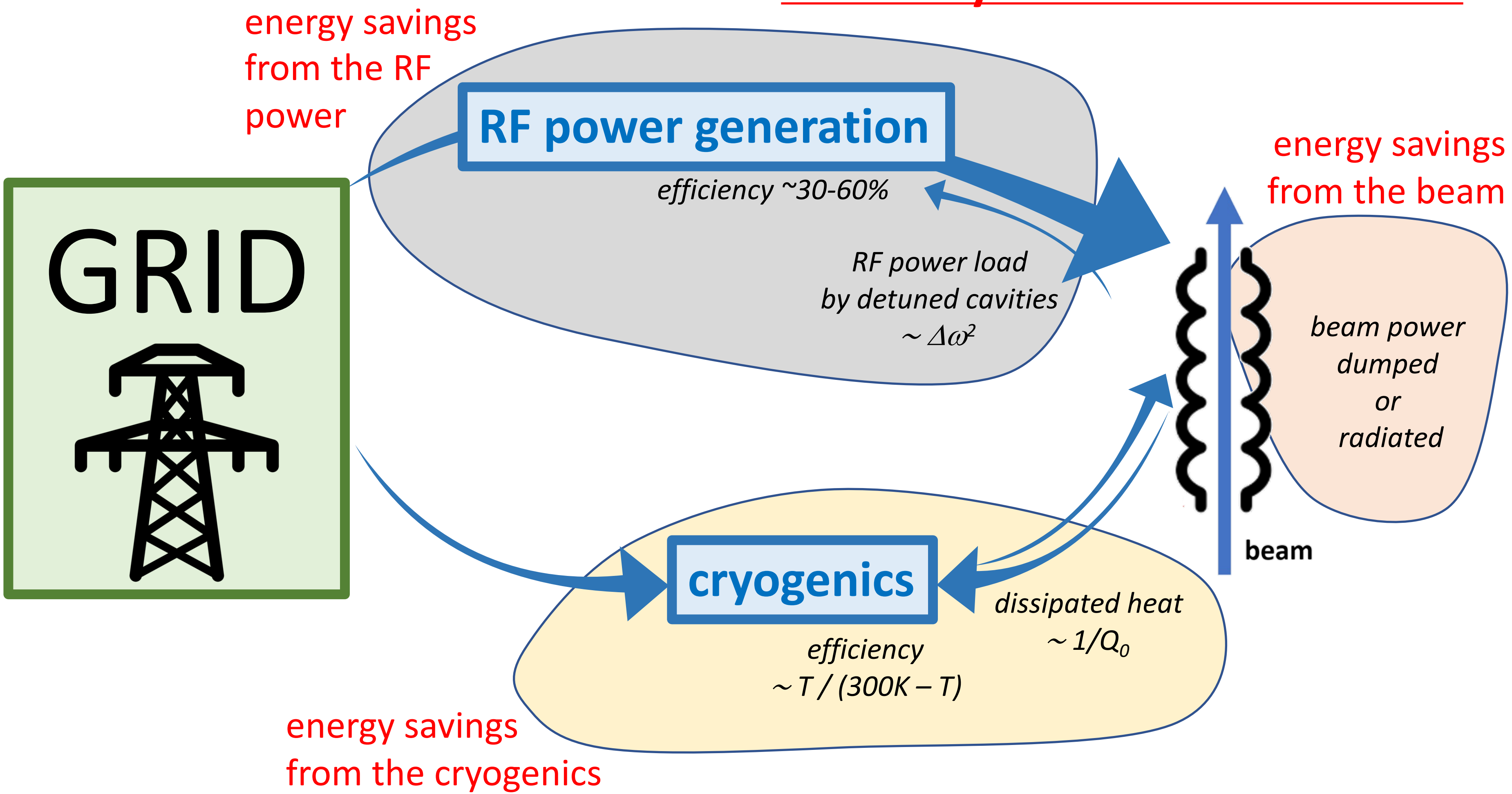


Picture adopted from M. Seidel (IPAC 2022)


power-inefficiency
GRID
RF power generation
efficiency ~30-60%
RF power load
by detuned cavities
~ Δω²
beam power
dumped
or
radiated
beam
cryogenics
efficiency
~ T / (300K – T)
dissipated heat
~ 1/Q0


power-inefficiency
GRID
mitigation with novel technologies
improve amplifier efficiency
e.g. solid state amplifiers for oscillating power demands
RF power generation
efficiency ~30-60%
recover the energy from the beam
e.g. ERL reaching 100% recovery
RF power load by detuned cavities
~ $\Delta\omega^2$
beam power dumped or radiated
dealing with microphonics
e.g. Fast Reactive Tuners
beam
cryogenics
dissipated heat
~ $1/Q_0$
efficiency
~ T / (300K – T)
operate cavities at higher T & improve Q_0 of cavities
e.g. Nb_3Sn from 2K to 4.4K ➔ 3x less cooling power needed

Three key innovation directions

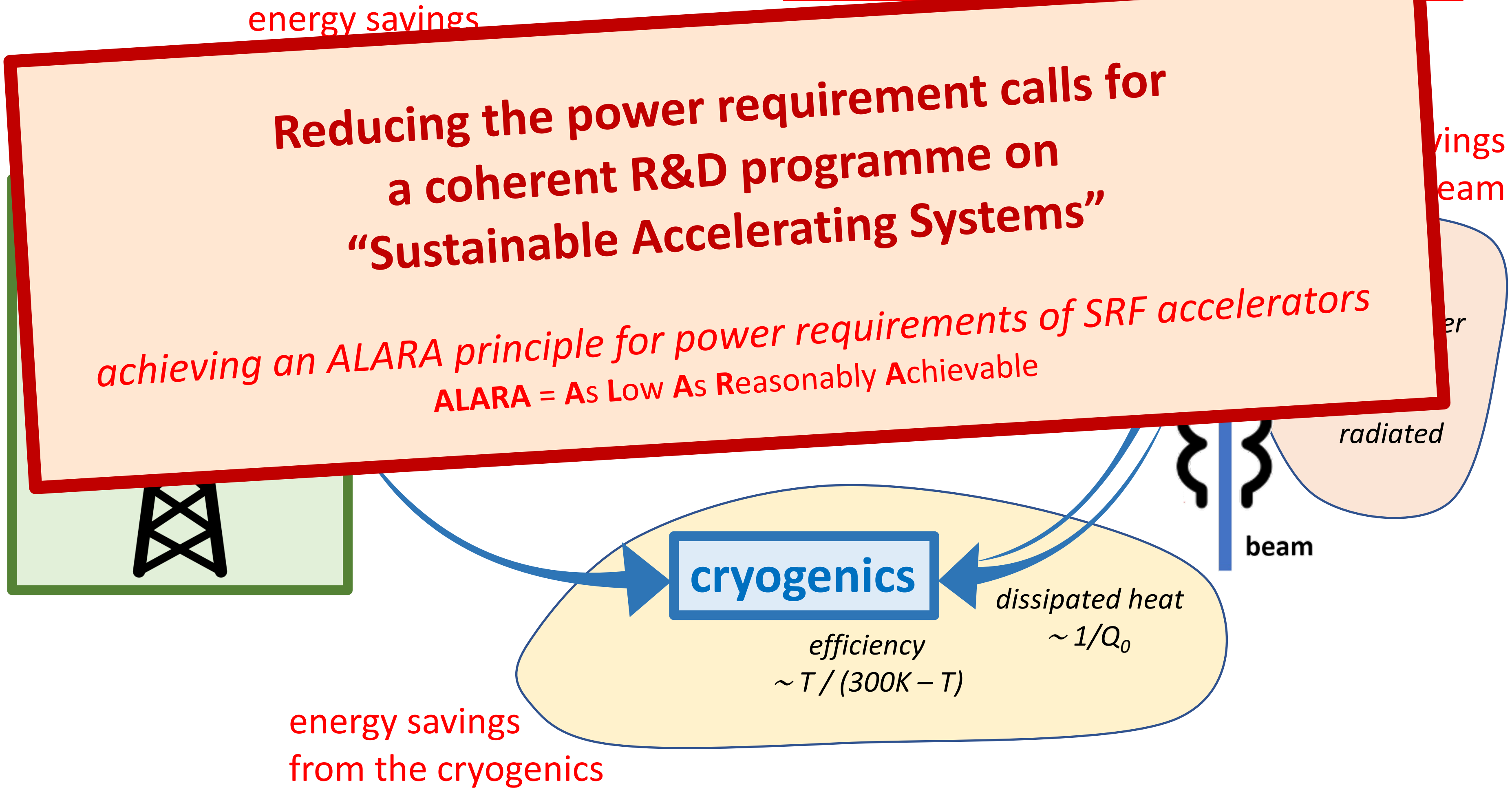


Three key innovation directions

Reducing the power requirement calls for a coherent R&D programme on "Sustainable Accelerating Systems"

achieving an ALARA principle for power requirements of SRF accelerators

ALARA = **A**s **L**ow **A**s **R**easonably **A**chievable



Three key innovation directions

energy savings

Reducing the power requirement calls for a coherent R&D programme on "Sustainable Accelerating Systems"

achieving an ALARA principle for power requirements of SRF accelerators

ALARA = **A**s **L**ow **A**s **R**easonably **A**chievable

Innovate for Sustainable Accelerating Systems (iSAS)

develop a new design of an SRF cryomodule

integrating the most impactful energy-saving technologies (incl. RF & ERL aspects)

Kick-off meeting 15-16 April 2024 @ IJCLab: https://indico.ijclab.in2p3.fr/event/10302/

https://isas.ijclab.in2p3.fr

Horizon Europe

from the cryogenics

iSAS is now an approved and ongoing Horizon Europe project

Spread over 4 years (2024-2028): ~1000 person-months of researchers and ~12.6M EUR

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

DESY. INFN UKRI UK Research and Innovation HZB Helmholtz Zentrum Berlin

ess EUROPEAN SPALLATION SOURCE Lancaster University EPFL 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)

ACS ACCELERATORS AND CRYOGENIC SYSTEMS Cryoelectra RF Technology for Particle Accelerators euclid TECHLABS research instruments TFE THIN FILM EQUIPMENT Zanon RESEARCH & INNOVATION SRL

“Innovate for Sustainable Accelerating Systems”

AMBITION – 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 – Several interconnected technologies will be developed, prototyped, and tested, each enabling significant energy savings. 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 – The long-term ambition is 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.

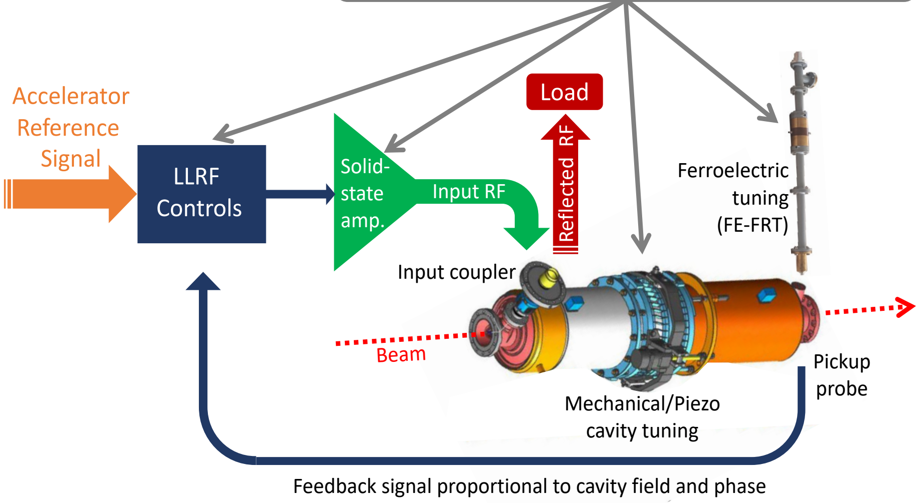
iSAS *develops, prototypes & validates SRF energy-saving technologies*

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

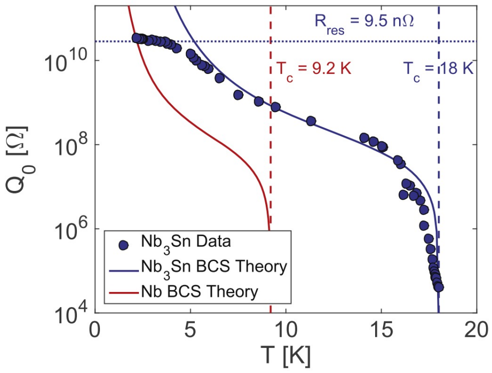
iSAS *develops, prototypes & validates SRF energy-saving technologies*

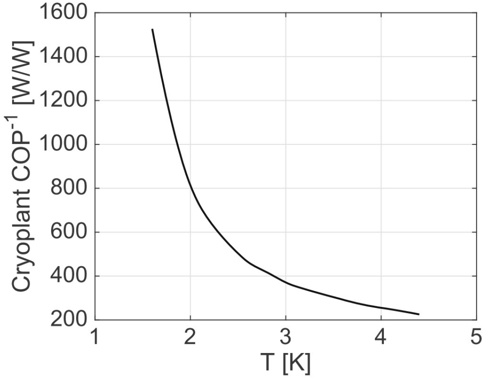
TA#2: energy-savings from cryogenics

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, and the various US-based achievements (e.g., GARD).

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.

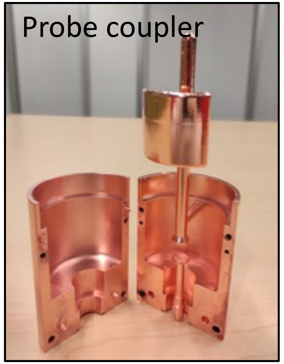
iSAS *develops, prototypes & validates SRF energy-saving technologies*

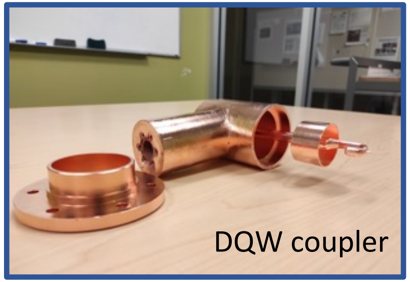
pictures from W. Kaabi

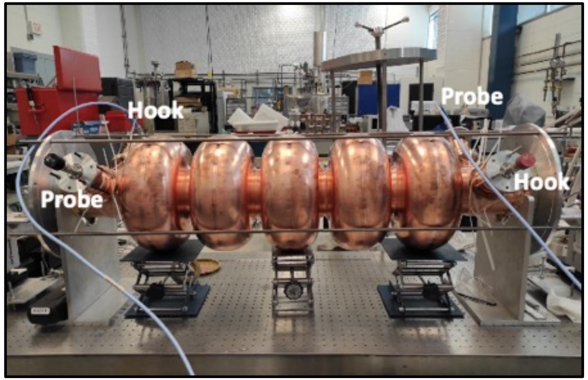
TA#3: energy-savings from the beam

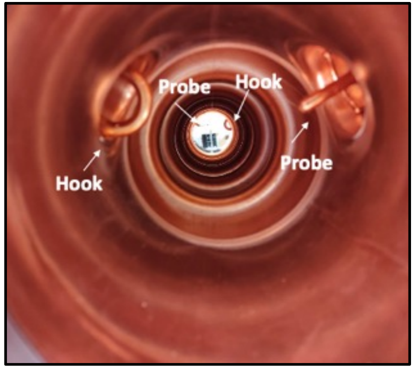
The objective is to reduce the total power deposited into the cryogenics circuits of the cryomodule of the Higher-Order Mode (HOM) couplers and fundamental power couplers (FPCs) leading to a significant reduction of the heat loads and the overall power consumption.

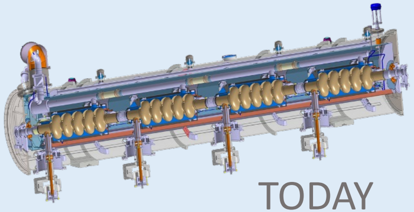
iSAS will improve the energy efficiency of the FPCs and HOM couplers by designing and building prototypes that will be integrated into a LINAC cryomodule capable of energy-recovery operations and to be tested in accelerator-like conditions.





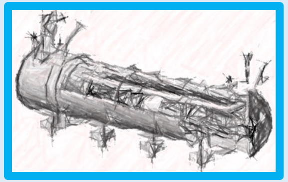




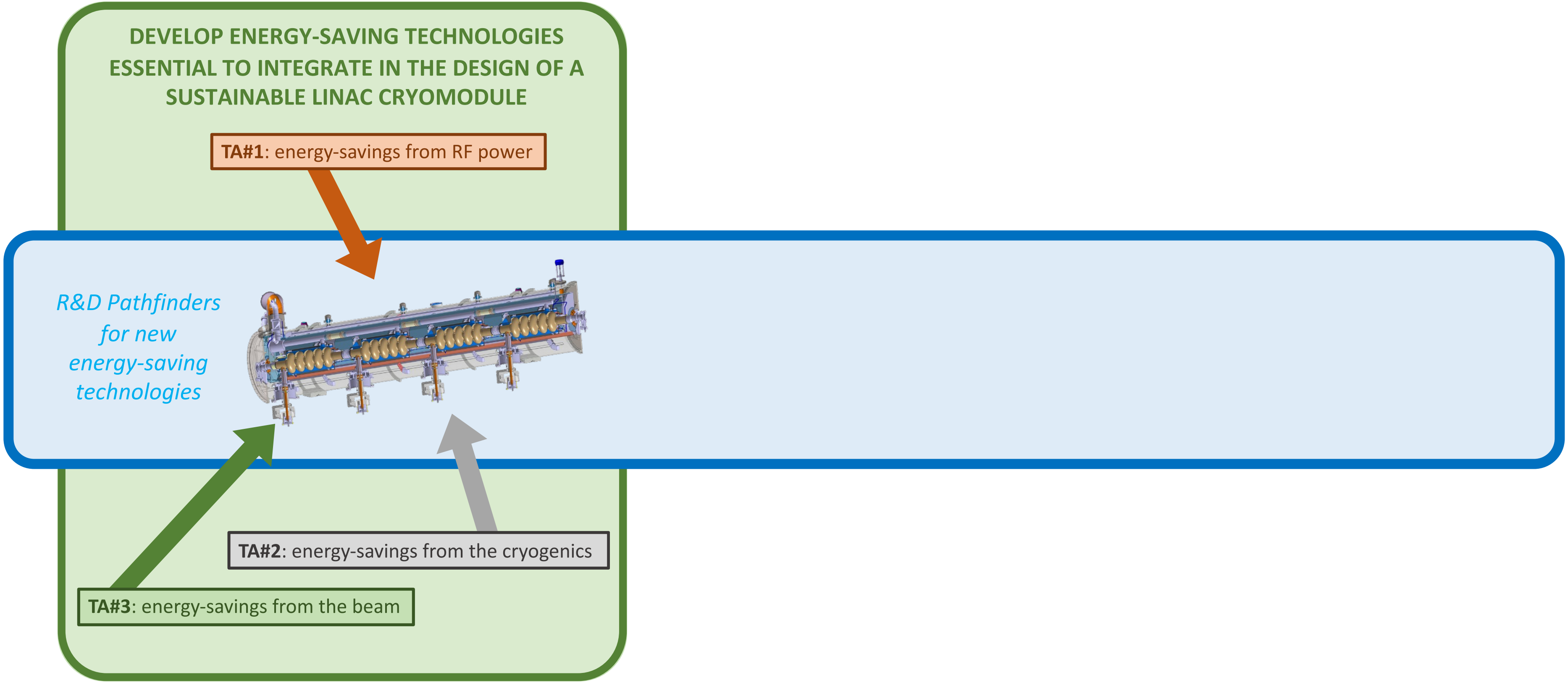


TODAY

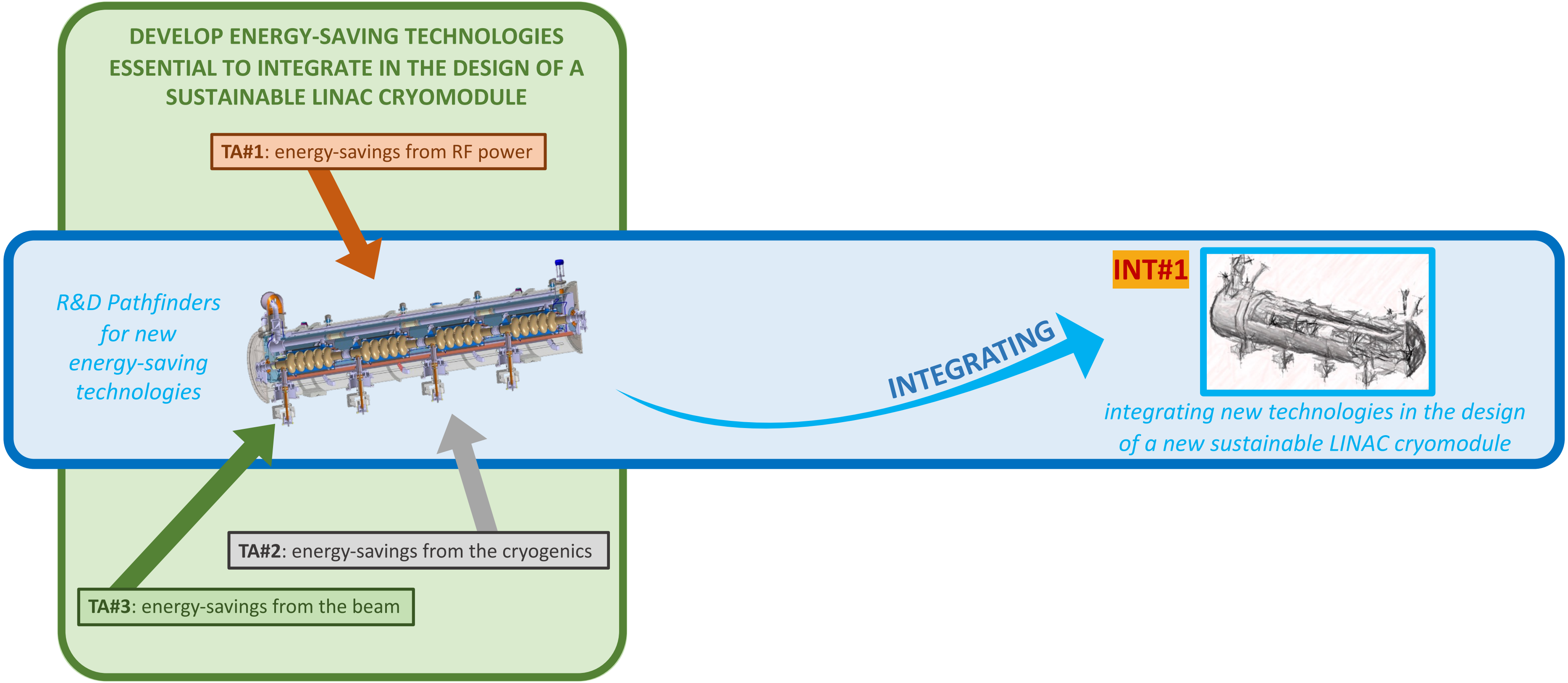
INNOVATE TECHNOLOGIES TOWARDS
A SUSTAINABLE ACCELERATING SYSTEM



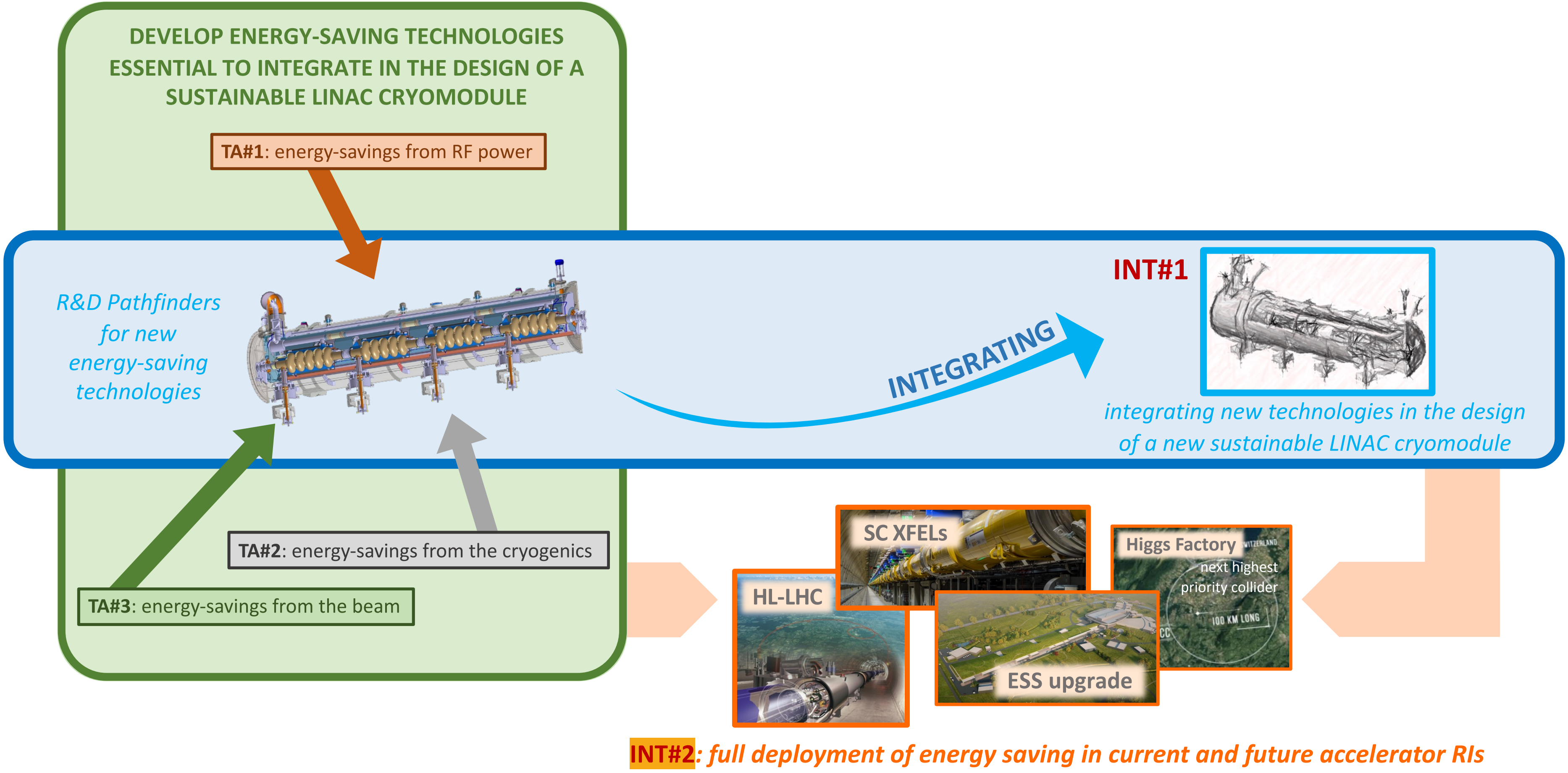
NEW DESIGN



TA: Technology Area

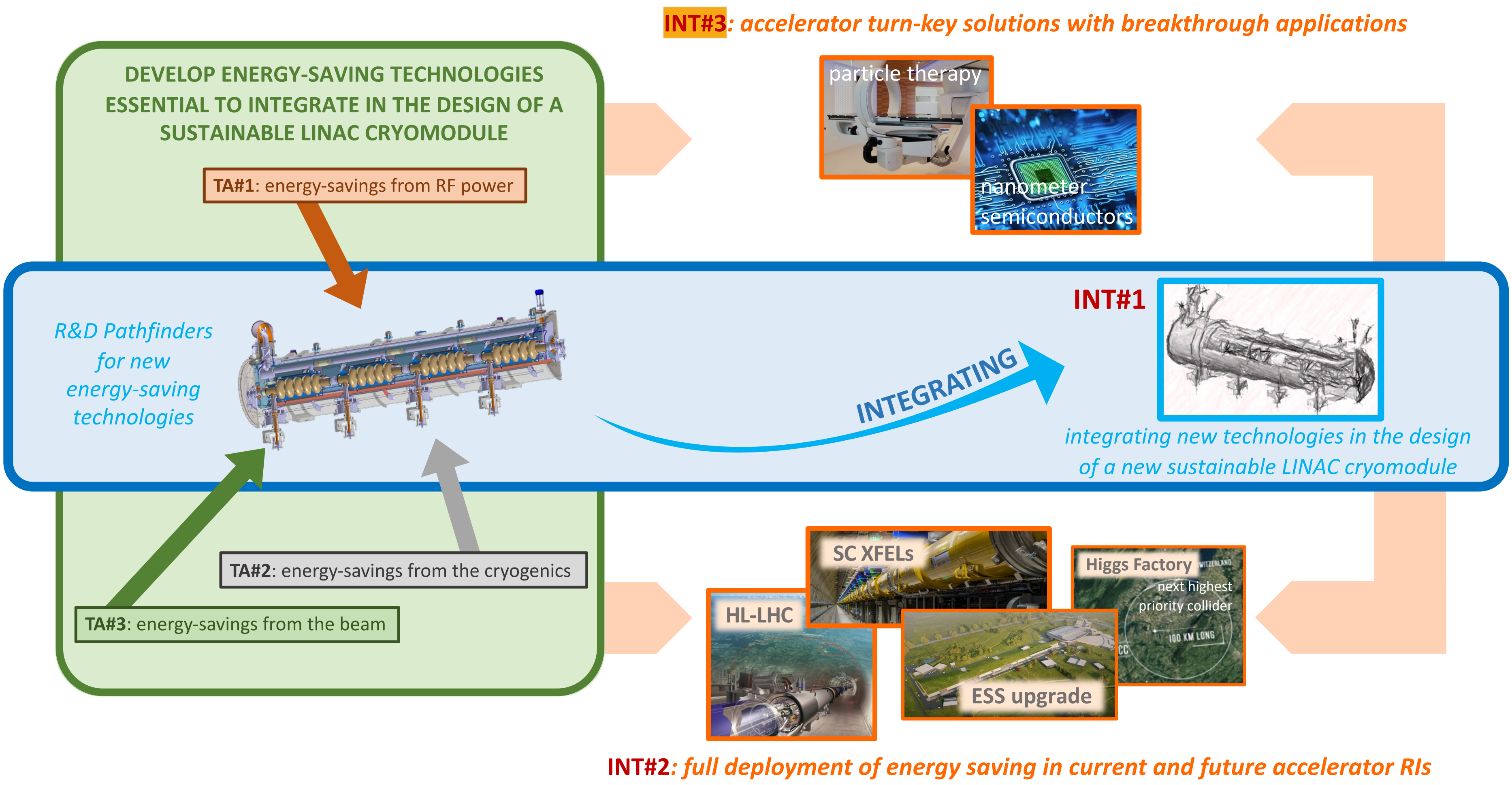


TA: Technology Area, INT: Integration Activities



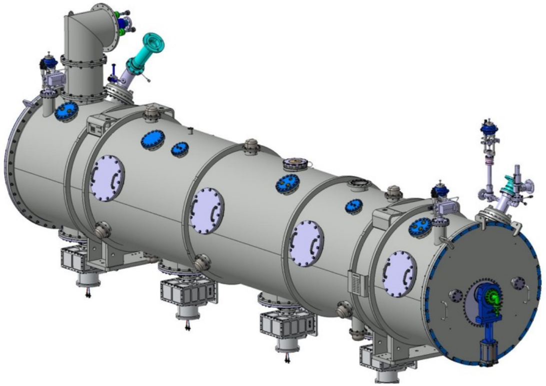
TA: Technology Area, INT: Integration Activities

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
Higgs Factory
next highest priority collider
100 KM LONG
ESS upgrade
INT#2: full deployment of energy saving in current and future accelerator RIs

iSAS Objectives – *Integration Activities*

- **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.*

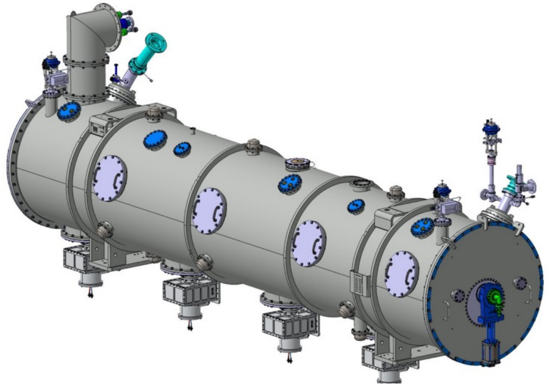


- **integration into existing RIs** – *While various RIs envisage upgrades, the objective of iSAS is to expedite the technical integration of energy-saving technologies by retrofitting existing accelerating systems. An existing cryomodule will be adapted, ready to demonstrate energy recovery of high-power recirculating beams in the PERLE research facility, paving the way for high-energy, high-intensity electron beams with minimal energy consumption.*

- **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.*

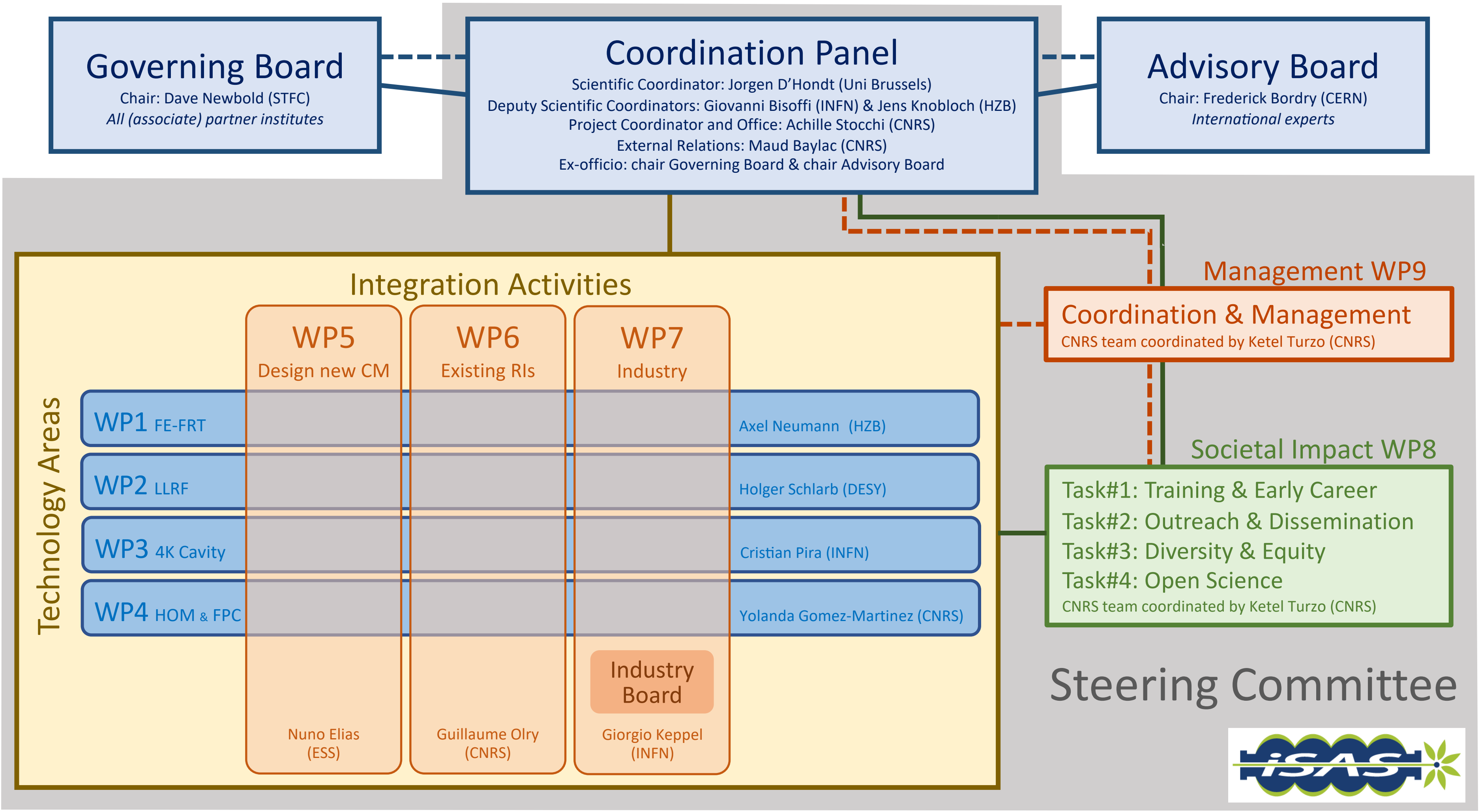
iSAS Objectives – *Integration Activities*

- **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.*



- **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.*

- **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.*


Governing Board
Chair: Dave Newbold (STFC)
All (associate) partner institutes
Coordination Panel
Scientific Coordinator: Jorgen D'Hondt (Uni Brussels)
Deputy Scientific Coordinators: Giovanni Bisoffi (INFN) & Jens Knobloch (HZB)
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
Design new CM
WP6
Existing RIs
WP7
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
iSAS

Innovate for Sustainable Accelerating Systems

Kick-Off Meeting / 15-16 april 2024

IJCLab Orsay

iSAS

Innovate for Sustainable Accelerating Systems

Kick-Off Meeting / 15-16 april 2024

IJCLab Orsay

cnrs université PARIS-SACLAY Université Paris Cité

Innovate for Sustainable Accelerating Systems (iSAS)

https://isas.ijclab.in2p3.fr

- Enabling technologies for our most prominent future particle collider programs delivering breakthrough performances, i.e. best physics for least power
- Connects leading European institutions and industry to expedite the development of sustainable technologies that are essential to realize the ambition expressed in the European Strategy for Particle Physics
- iSAS will have a catalyzing effect to realize the Accelerator R&D Roadmap
- The energy saving technologies further developed in iSAS will enable industrial applications with SRF accelerators

Innovate for Sustainable Accelerating Systems (iSAS)

https://isas.ijclab.in2p3.fr

- Enabling technologies for our most prominent future particle collider programs delivering breakthrough performances, i.e. best physics for least power
- Connects leading European institutions and industry to expedite the development of sustainable technologies that are essential to realize the ambition expressed in the European Strategy for Particle Physics
- iSAS will have a catalyzing effect to realize the Accelerator R&D Roadmap
- The energy saving technologies further developed in iSAS will enable industrial applications with SRF accelerators

HIGH-ENERGY PHYSICS RESEARCH CENTRE

Thank you for your attention!

Jorgen.DHondt@vub.be

EXTRA INFORMATION on iSAS

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 further reduction of power demands by up to a factor of 3.*

- **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 reducing the grid-power to operate the cryogenic system by a factor of 3 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, 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.*

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

very concrete

energy-savings from RF power (HZB, CERN, CNRS, Uni.Lancaster, DESY)

FE-FRT

- *FE-FRT for Transient Beam Loading: design & performance tests for an LHC 400 MHz cavity in an existing cryomodule.*
- *FE-FRT for Microphonics: design, fabricate and validate in a cryomodule like setup for 1.3 GHz cavities, single-cell and multi-cell (TESLA/XFEL).*
- *FE-FRT for Microphonics compensation in Energy-Recovery LINAC (ERL) mode: for 800 MHz cavities and study the requirements for integration in a cryomodule.*

LLRF

- *Efficient field control for high loaded-quality factor (Q_L>5e7) cavities in CW and long pulse operation (incl. a ML-based feedback controller).*
- *Vibration analysis and detuning control of cavities (incl. ML-based control).*
- *Integrate a FE-FRT with a digital LLRF system & demonstrate operation in a horizontal test stand.*
- *Energy efficient supervisory control and fault diagnosis (incl. ML-based diagnosis).*

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

very concrete

energy-savings from cryogenics (INFN, CEA, HZB, UKRI)

- *Flux trapping: study how trapped magnetic flux may affect the superconducting properties of the thin film and its RF surface resistance.*
- *RF tunability: study and improve mechanical properties of superconducting thin films to assess the impact of future cavity tuning during normal 4.2 K operation.*
- *Adaptive layers: developing suitable adaptative layers on Cu for subsequent Nb_3Sn deposition to reduce the detrimental effect of mechanical deformation on the superconducting properties of Nb_3Sn.*
- *Working cavity @ 4.2K: optimize the superconducting coating procedure of 1.3 GHz cavities including an adaptive layer and demonstrate suitability for 4.2 K operation (using Cu cavities originally produced for I.FAST).*

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

very concrete

energy-savings from the beam **(CNRS, INFN, CERN)**

HOM

- *HOM coupler design: with simulations for various models and mechanical integration issues in a cryomodule*
- *Fabrication of HOM couplers: R&D on fabrication strategy for prototypes at 800 MHz and 1.3 GHz*
- *Test of the HOM couplers: performance validation of the design with RF measurements on mock-up cavities*

FPC

- *RF coupler design: optimize cost, cooling, heat loads, fabrication time, and mechanical integration issues in a cryomodule*
- *Fabrication of RF couplers: build 4 prototypes*
- *Test of the RF couplers: performance validation of the design with RF conditioning in CW mode (50kW)*

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.

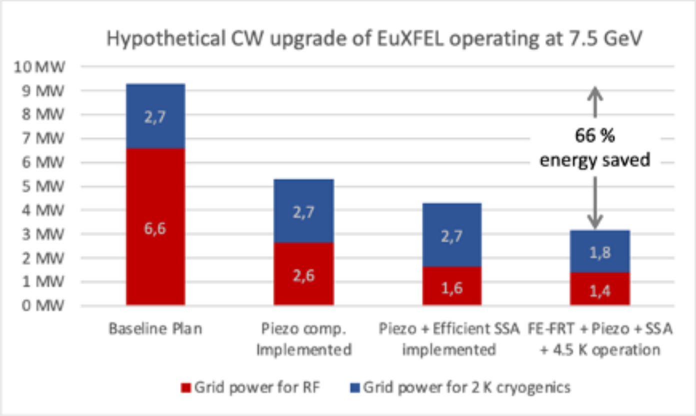
iSAS Technologies		initial TRL	target TRL
TA#1	FE-FRT for transient detuning @ 400 MHz	4	6
	FE-FRT for transient detuning @ 800 MHz	1-2	4
	FE-FRT for microphonics @ 400 MHz	3	5-6
	FE-FRT for microphonics @ 800-1300 MHz	1-2	5-6
	LLRF controls	3-4	7
	LLRF + FE-FRT controls	2-3	6
TA#2	Nb3Sn-on-Cu films 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

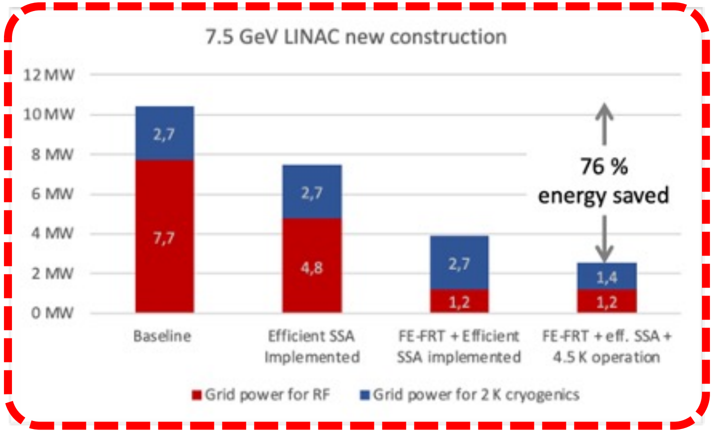
up to fully functional prototypes in relevant environment

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





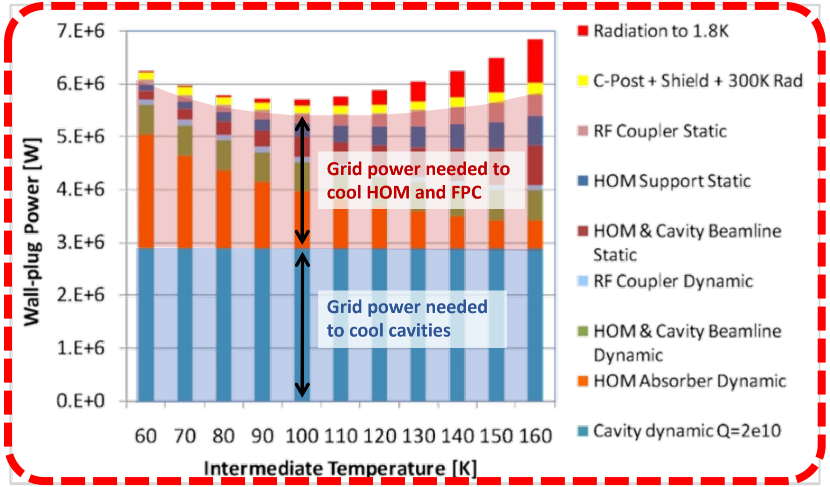
For an upgrade of EuXFEL to CW, a refurbishment of the injection LINAC cavities is being considered. This could provide the opportunity to retrofit some iSAS technology developments as well. The figure (left) depicts the expected energy savings if various iSAS developed technologies are implemented (assumption: 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.

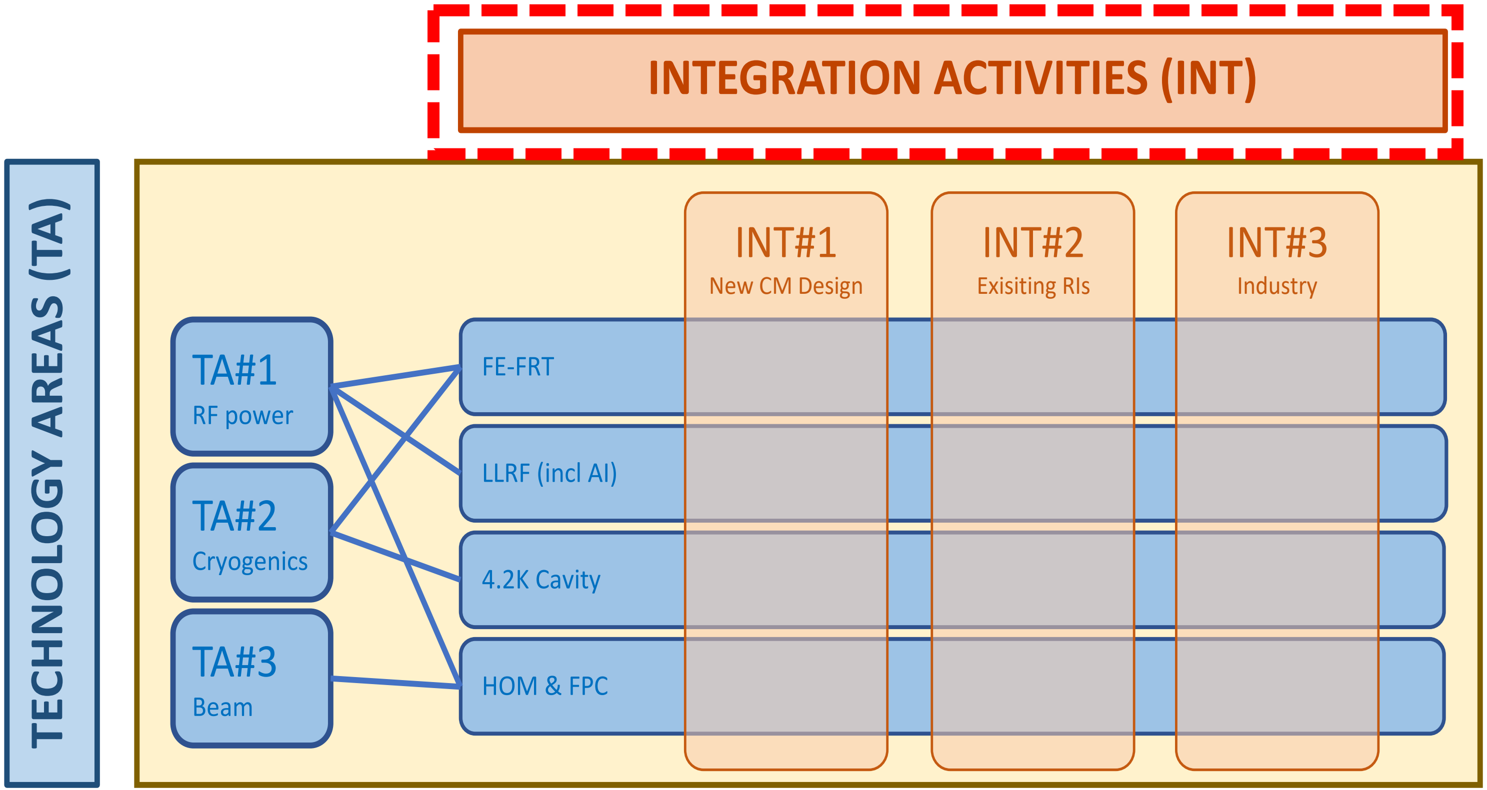
"Cornell Energy Recovery LINAC Project Definition Design Report"
G. Hoffstatter, S. Gruner, M. Tigner, eds. (2013)



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

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.



iSAS Objectives – *Integration Activities*

very concrete

- **integration into the design of a LINAC cryomodule** **(ESS, CNRS, CERN, INFN, CERN, EPFL)**
  - *Lessons learned with ESS cryomodules and benchmarking with other recent facilities will be compiled, and a roadmap will be developed towards a new sustainable CM design.*
  - *Sustainable criteria for LINAC cryomodule design will be developed.*
  - *Beam dynamics will be developed for ERL-based accelerators with the energy-efficient iSAS technologies.*

- **integration into existing RIs** **(CNRS, Uni.Lanc., CEA, ESS, INFN)**
  - *Retrofitting FE-FRT into existing cryomodules, HL-LHC oriented.*
  - *Adapt an existing ESS cryomodule to integrate new HOM couplers and FPC.*
  - *Fabrication and validation of cryomodule components (e.g., cavities).*
  - *Assembly and (cryogenic and RF) tests of adapted cryomodule.*

- **integration into industrial solutions** **(INFN, CNRS)**
  - *Relations with industries: engagement to expedite the evolution from low to higher TRL (involving an Industry Board involved in design reviews with a view on industrialization).*
  - *Business opportunities: develop an iSAS project repository and disseminate the innovative technologies.*