Innovate for Sustainable Accelerating Systems (iSAS)

M. Baylac (CNRS-LPSC)

On behalf of the iSAS coordination panel :
J. D'Hondt (Brussels U.) scientific coordinator, Achille Stocchi (CNRS-IJCLab) project coordinator
Giovanni Bisoffi (INFN), Jens Knobloch (HZB)

EU HORIZON-INFRA-2023-TECH-01-01

Context

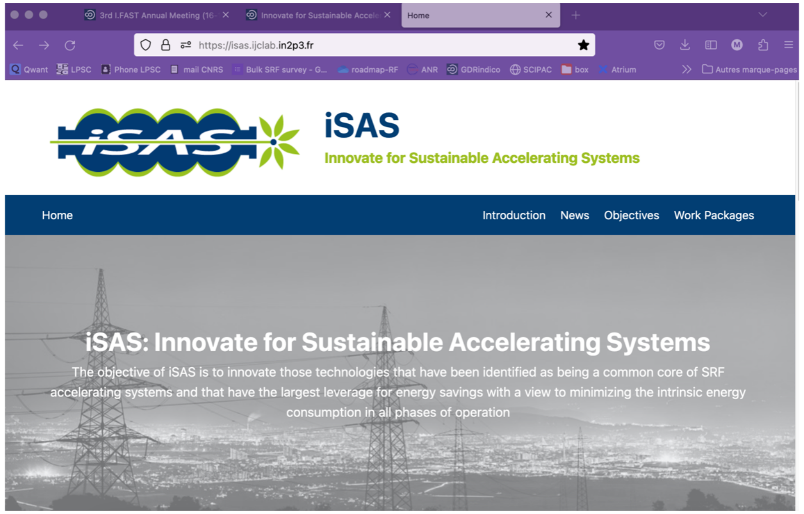
- Particle accelerators are exceptional instruments for research and multiple applications, but require important electrical consumption, especially for high beam power (high energy/intensity)

- In a global context of energy savings and sustainability
  - **minimizing the energy consumption of future accelerators is an unavoidable challenge**

> 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 update, 2020 (CERN-ESU-011)*

- Within the EU funding programs, HORIZON-INFRA-2023-TECH-01 call dedicated to "***New technologies and solutions for reducing the environmental and climate footprint of Research Infrastuctures*** »

- ***Project « Innovate for Sustainable Accelerating Systems (iSAS)»*** **approved, launched**
  - **Kick-off meeting 15-16 April, at IJCLab-Orsay**
  - https://isas.ijclab.in2p3.fr/

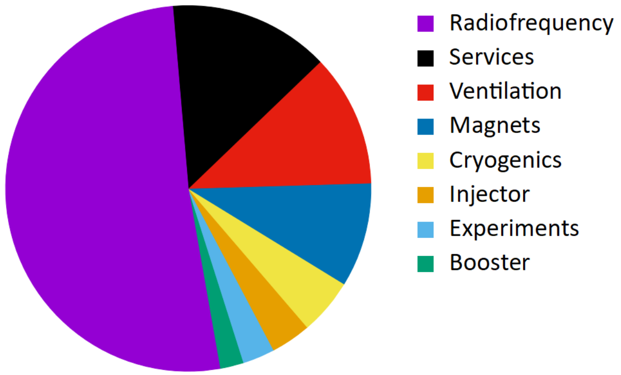


R&D within the scope of iSAS

- **How to tackle the difficult question of energy savings for accelerators ? What R&D to conduct ?**
  - Breakdown of power consumption of accelerators for different subsystems
    - Depends upon the type of machine (circular, linear, ..)
    - Example of electron-positron Higgs factory

E_{cm} = 240 GeV (ZH)
P_{grid} = 282 MW
E_{grid}/y = 1.33 TWh

→ dominated by RF
(compensating SR losses)



From M. Seidel, iSAS kick-off meeeting

For FCC-ee

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

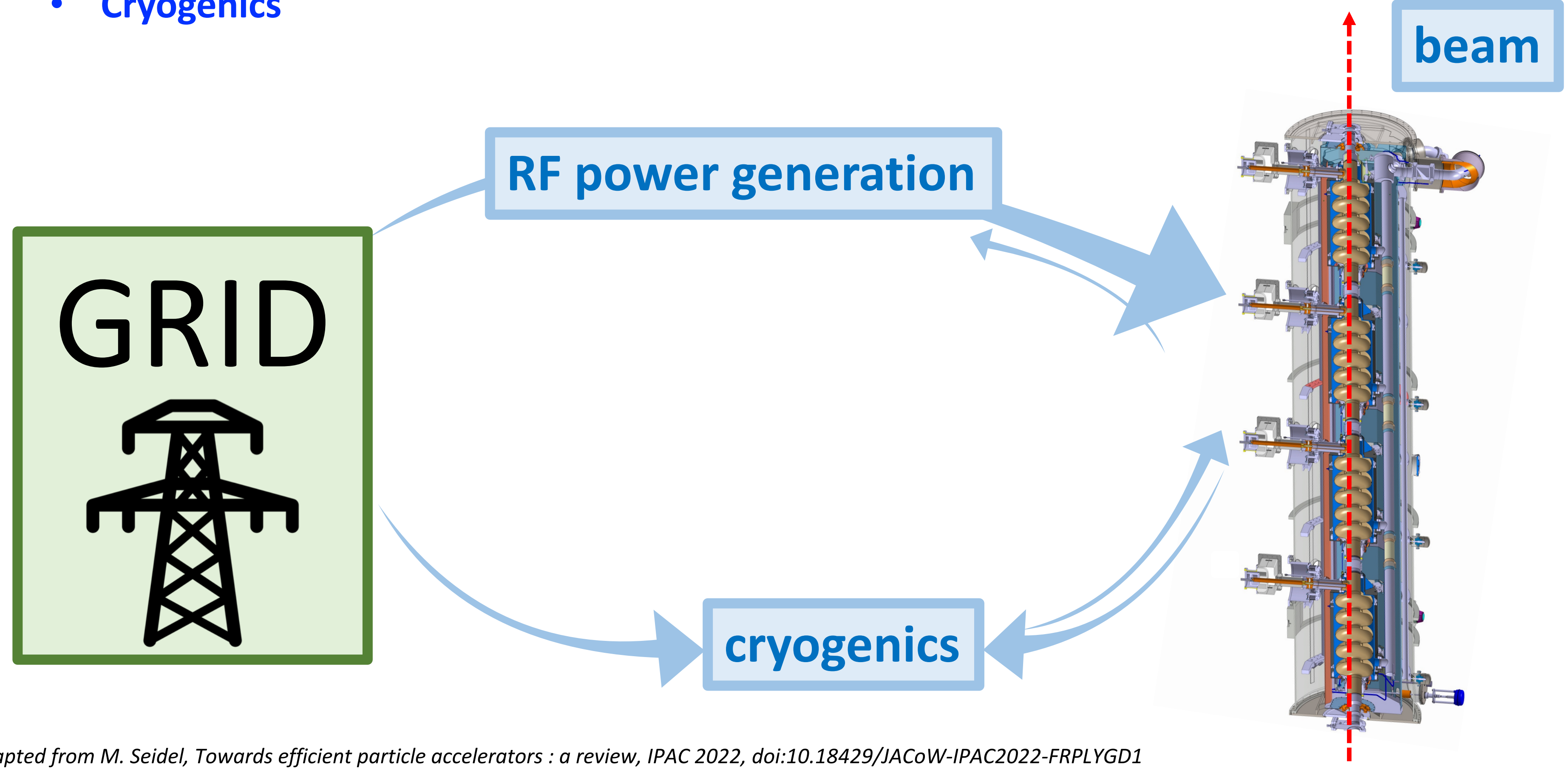
- **iSAS will mainly concentrate on the energy savings from the RF**
  - Complementary to meaningful programs for energy savings on high efficiency magnets, high efficiency RF sources, reuse of RF heat …

- Two axis of iSAS: **Develop** and **implement** energy savings technologies for particle accelerators
  - R&D on technologies
  - Implementation, eased by raising the TRL levels of the technologies

- Main focus on the 3 ESFRI Research Infrastructures (RI): HL-LHC, ESS and EuXFEL
  - Yet, developed technologies are independent, potentially to be used on various SRF applications

Power transfer from the grid to the beam

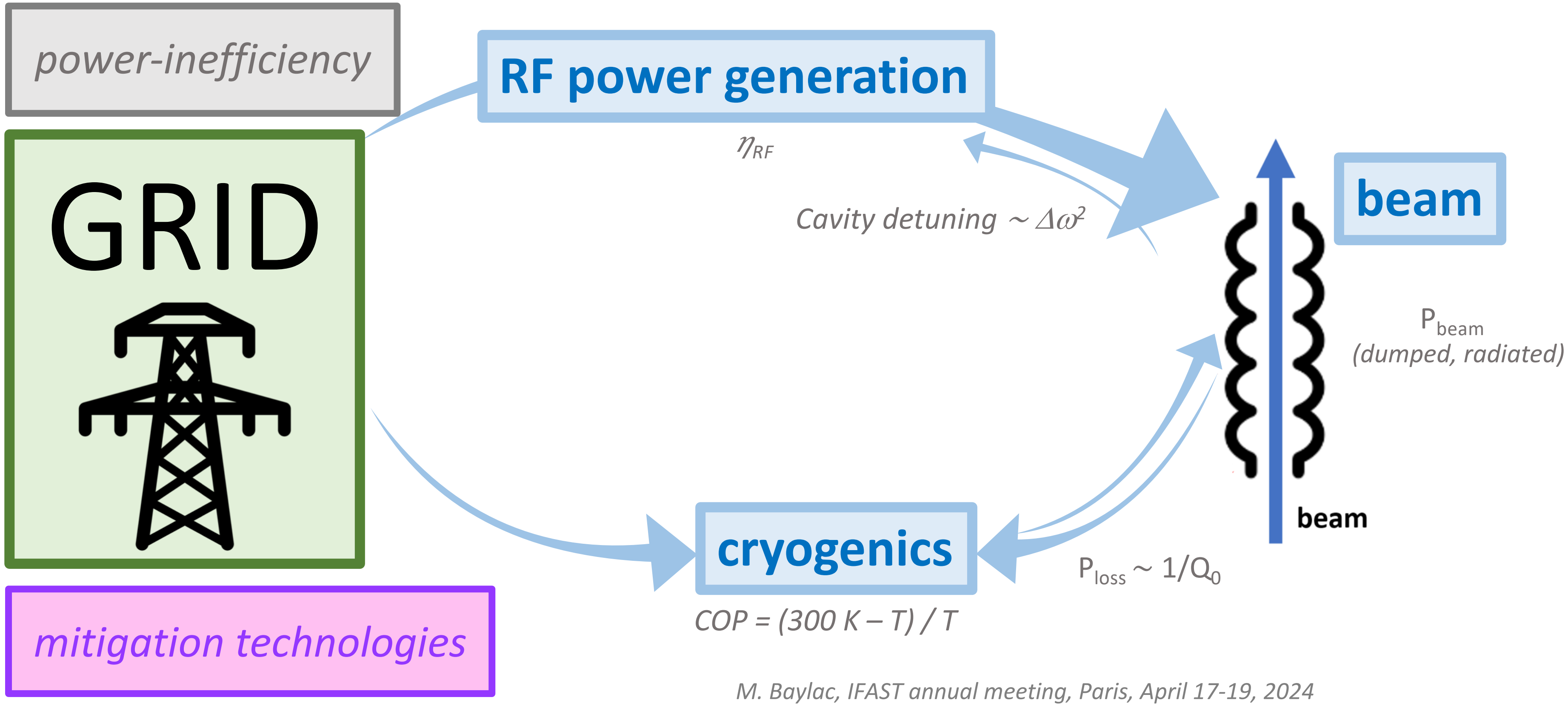
- iSAS aims to improve the efficiency of SRF linac ➔ cryomodule is the key element
- Essential powerflow to accelerate a beam in a cryomodule
  - RF power generation
  - Cryogenics



Adapted from M. Seidel, Towards efficient particle accelerators : a review, IPAC 2022, doi:10.18429/JACoW-IPAC2022-FRPLYGD1

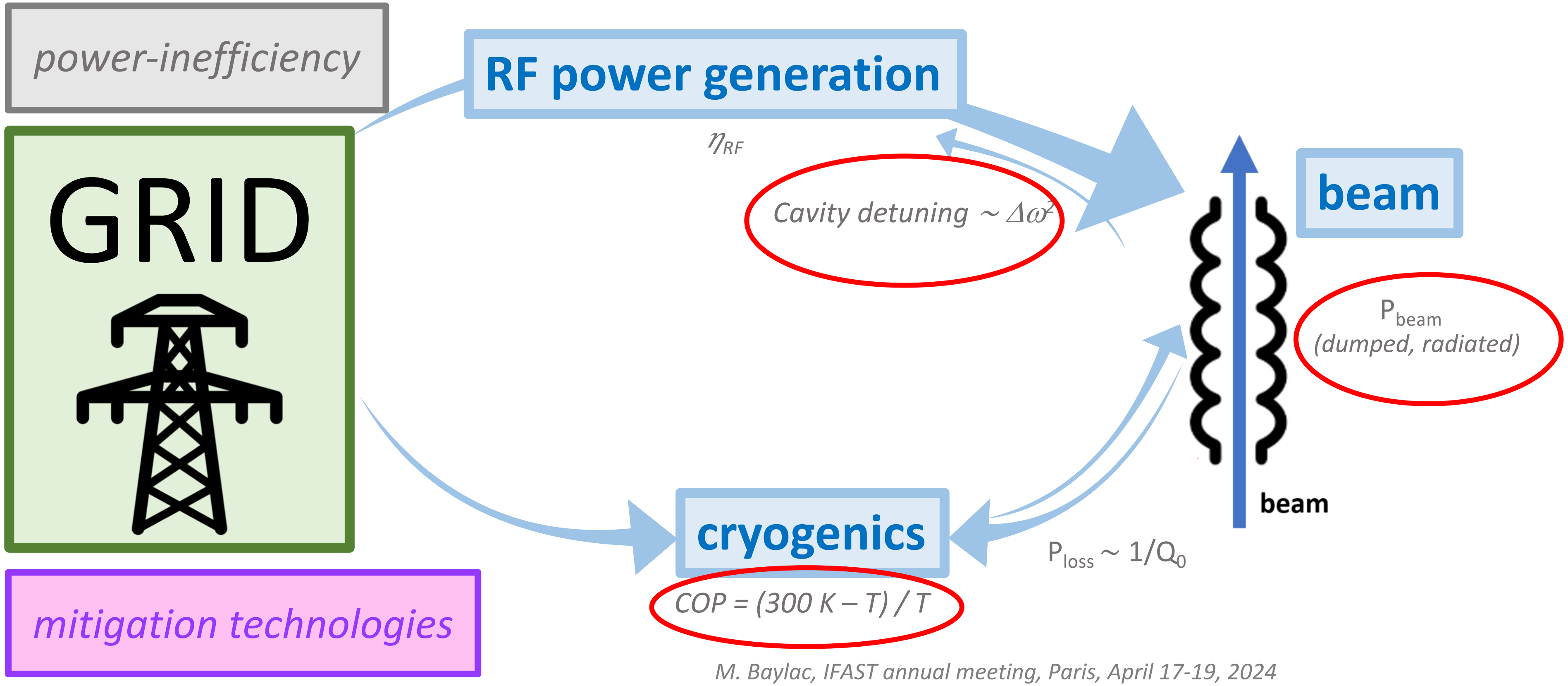
Power inefficiencies and mitigations

- **Multiple factors impact the grid-to-beam power efficiency and technologies for mitigation**
  - RF power source efficiency : η_{RF} ➔ amplifier with enhanced efficiency (e.g. solid state technology)
  - RF load by detuned cavities ➔ dealing with microphonics to reduce $\Delta\omega$
  - Cavity cryogenic loss : $P_{loss} \propto 1/Q_0$ ➔ improve quality factor of the cavity Q_0
  - Generation of cryogenics : COP ➔ increase the operating temperature of the cavity (T)
  - Loss of the beam power : P_{beam} ➔ recover the energy of the beam (ERL)



Key innovations of iSAS

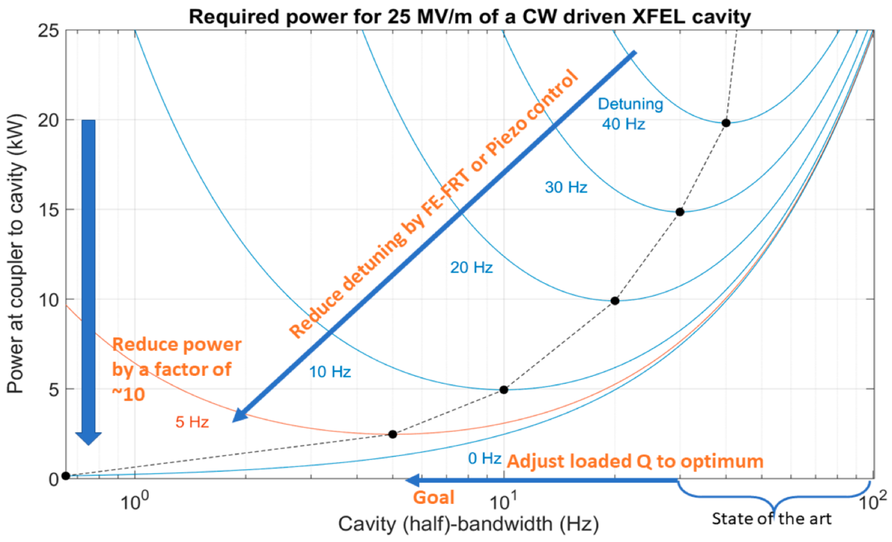
- **Technologies to mitigate power inefficiencies**
  - RF power source efficiency : η_{RF} → amplifier with enhanced efficiency (e.g. solid state technology)
  - RF load by detuned cavities → **dealing with microphonics to reduce ($\Delta\omega$)** → **iSAS technology area (TA#1)**
  - Cavity cryogenic loss : $P_{loss} \propto 1/Q_0$ → improve quality factor of the cavity Q_0
  - Generation of cryogenics : COP → **increase the operating temperature of the cavity (T)** → **iSAS technology area (TA#2)**
  - Loss of the beam power : P_{beam} → **recover the energy of the beam (ERL)** → **iSAS technology area (TA#3)**



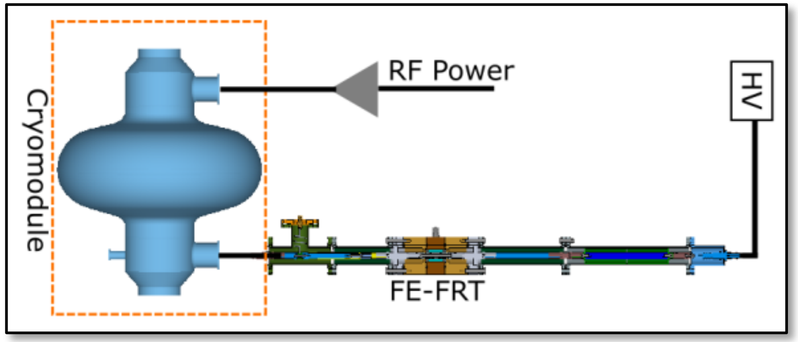
Energy saving from RF power (TA#1): objectives

- **Goals : reduce the large RF power overhead required to**
  - **Compensate the detuning induced by mechanical vibrations**
  - **Control the transient beam loading**

➔ **Develop novel fast tuning system, Ferro-Electric Fast Reactive Tuners (FE-FRTs)**
  - **Couple a tunable device to the resonator to change the frequency of the coupled system**
  - **Frequency changed by applying HV to a FE material with tuneable dielectric constant** (BST: Ba, Sr, Ti)
  - Based on previous work by CERN, Lancaster, BNL and Euclid techlabs



Required power for a number of detuning scenarios as a function of the cavity (half-)bandwidth for an EuXFEL cavity operated at 25 MV/m



FE-FRT coupled to a cavity

Fast tuning response ~100 ns
Tuning range ~ tens of kHz

N.C. Shipman *et al.*, "A Ferroelectric Fast Reactive Tuner for Superconducting Cavities", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 781-788. doi:10.18429

Conceptual design of a high reactive-power ferroelectric fast reactive tuner
Phys. Rev. Accel. Beams, I. Ben-Zvi, G. Burt, A. Castilla, A. Macpherson, and N. Shipman, accepted 12 April 2024

From Axel Neuman, iSAS kickoff meeting

Energy saving from RF power (TA#1): objectives

- **Goals : reduce the required RF power by**
  - **efficient field control and detuning control with Low Level Radio Frequency (LLRF)**

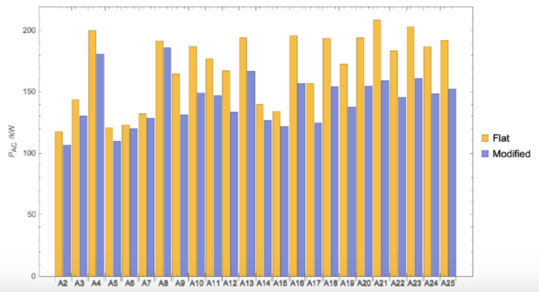
➔ ***demonstrate the operation of a digital LLRF system, integrating AI, for optimum control of field and detuning***

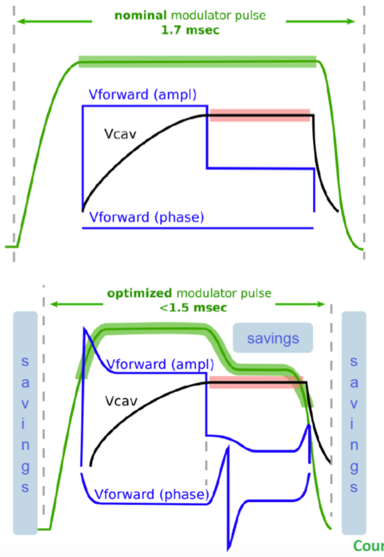
WP2: Low Level RF controls

Reduce energy consumption @ EuXFEL

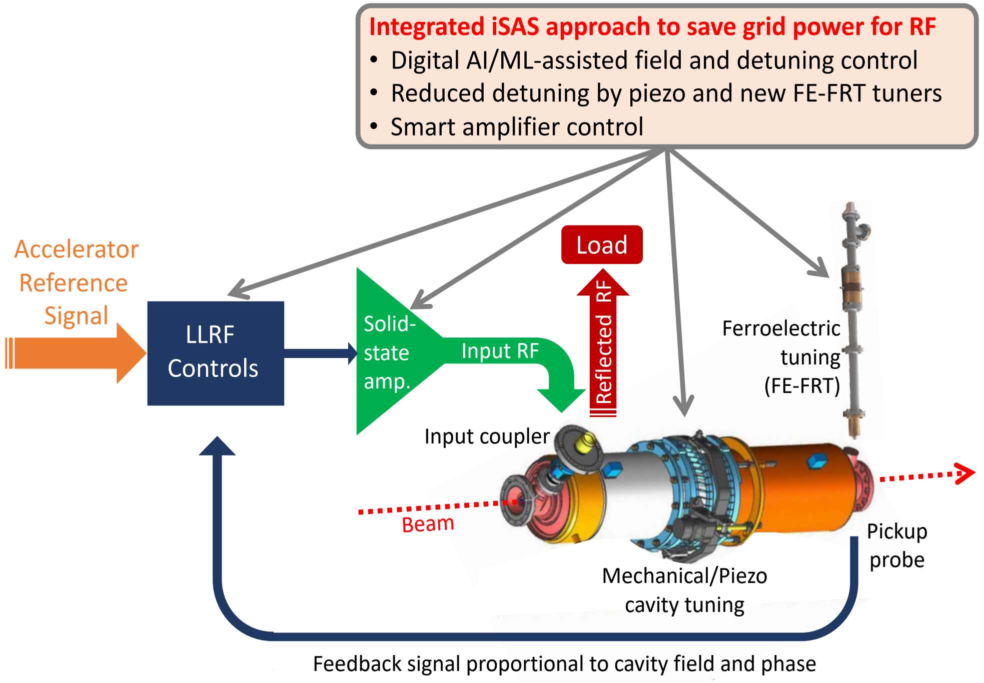
Successive iterations, implemented over the last 2+ years

- **Shorten** modulator pulse : 1700 msec → 1500 msec
- **Step down** 15-20% over 100 usec
- Implemented on **17/20** stations in L3
- Estimated additional power savings ~ **650 kW** (out of 5 MW total power)





Courtesy: J. Branlard



➔**At EU-XFEL: savings of 650 kW out of 5 MW by optimizing modulators**

From Holger Schlarb, iSAS kickoff meeting

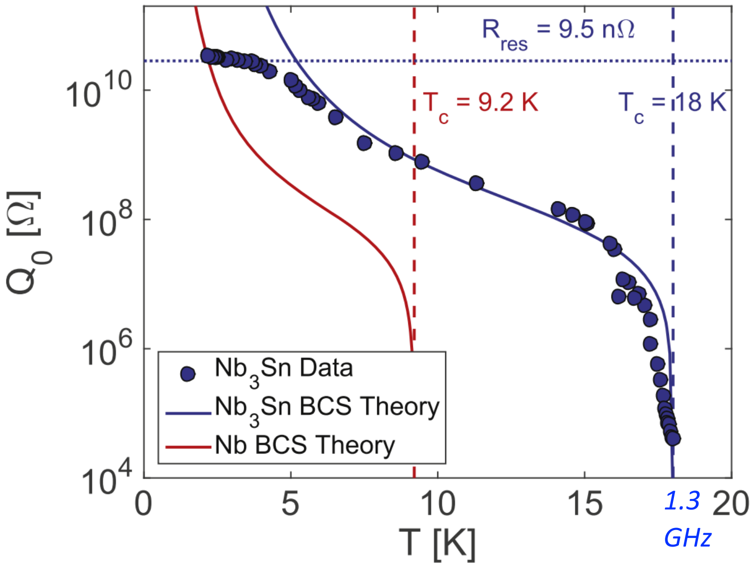
Energy saving from cryogenics (TA#2) : objectives

- **Goals : reduce the necessary cryogenics power with**
  - **Higher Tc material allows operation at 4.2 K instead of 2 K while maintaining high Q_0 and E_{acc} thus reducing both**
    - operation cost : estimated to a factor of 3
    - investment cost : tens of M€ for ESS, XFEL

➔ ***Explore coatings of Nb_3Sn on Cu to minimize flux trapping and test the tunability of thin-film cavities with a prototype***

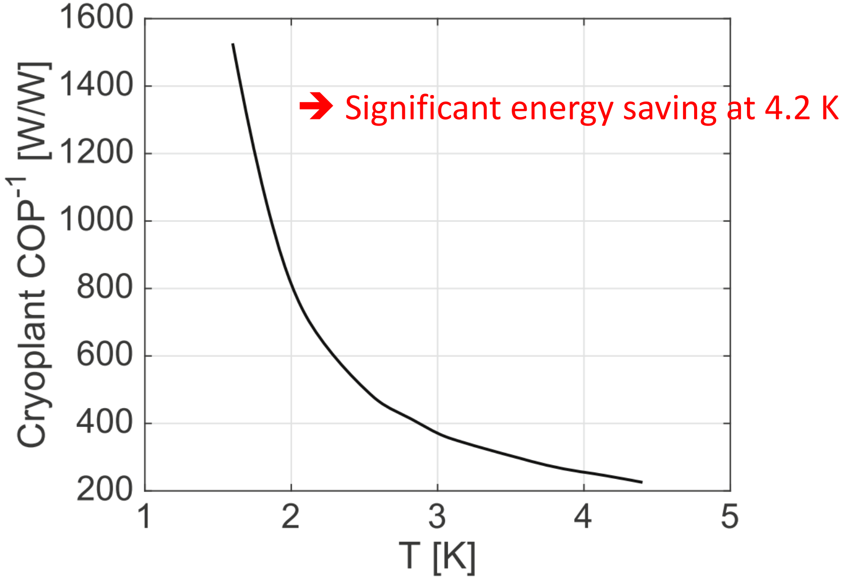
➔ ***Strong synergy with I.FAST, aim to go beyond the achievements of IFAST WP9***

Higher T_c of Nb_3Sn ➔ high Q_0 at ~4 K



S. Posen et al, Nb3Sn superconducting radiofrequency cavities: fabrication, results, properties, and prospects, Supercond. Sci. Technol. 30 (2017) 033004

COP 3 times better at 4.2 K than 2 K



Extra construction cost between 2K and 4 K operation

Table 1: Cost estimation of the 2 K part for two examples of recent projects.

Example	XFEL	ESS
Cryomodules #	~100	~40
Pumps	25 M€	10 M€
Heaters	1 M€	400 k€
Linac length	~1 km	400 m
Lines	1 M€	400 k€
2K total	~27 M€	~11 M€
Total cryogenic installation	80 M€ (?*)	50 M€

* For XFEL, an already existing facility was completed so the exact figures are not known

C. Antoine, R&D in superconducting RF: thin film capabilities as a game changer for future sustainability, in Proc. IPAC2023, Venice, Italy

From Cristian Pira, iSAS kickoff meeting

Energy saving from beam (TA#3) : objectives

- **Goals : reduce the heat loads of the cryogenics by**
  - **reducing the power deposited by the Fundamental Power Couplers (FPCs) and Higher-Order Mode (HOM)** by new designs for high current operation **while minimizing their static and dynamic heat loads in the cryogenic system**

➔ *Designing and building prototypes to be integrated and tested in accelerator-like conditions in a cryomodule capable of energy-recovery operation*

Grid power for cooling the Cornell ERL LINAC

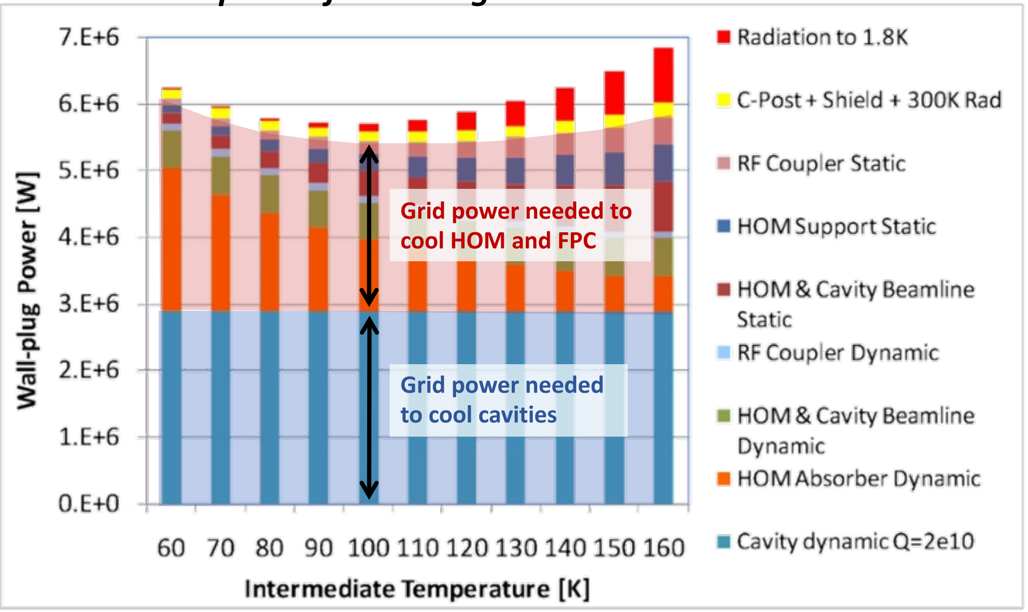


Figure adapted from "Cornell Energy Recovery LINAC Project Definition Design Report", G Hoffstatter, S. Gruner, M. Tigner, eds. (2013)

CERN HiLumi HOM Coupler

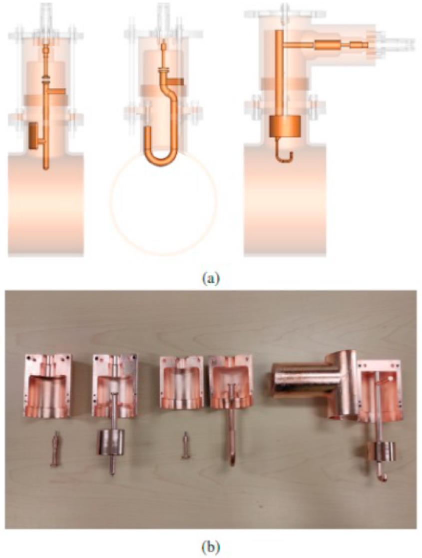


Figure 1: Mechanical design (a) and 3D-printed plastic and copper-coated prototypes (b) of the Probe, Hook, and DQW HOM couplers (from left to right).

C. Barbagallo et al, "First coaxial HOM coupler prototypes and RF measurements on a copper cavity for the PERLE project", in *Proc. IPAC'23*, Venice, Italy

➔ HOM and FPC : half of the full cryogenic load

From Yolanda Gomez Martinez, iSAS kickoff meeting

Energy saving from RF power (TA#1)
WP1 and WP2

- **WP1 : Ferro Electric Fast Reactive Tuners (FE-FRT) – Axel NEUMAN (HZB)**
  - 1.1 : coordination
  - 1.2: **FE-FRT for Transient Beam Loading**: design & performance tests for an LHC 400 MHz cavity in an existing cryomodule
  - 1.3: **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)
  - 1.4: **FE-FRT for Microphonics compensation in Energy-Recovery LINAC** (ERL) mode: for 800 MHz cavities and study the requirements for integration in a cryomodule
  - **Participants : HZB, CERN, CNRS, Univ. Lancaster**

- **WP2 : Low Level RF controls (LLRF) – Holger SCHLARB (DESY)**
  - 2.1 : coordination
  - 2.2 : **Efficient field control for high loaded-quality factor** (Q_L>5E7) cavities in CW and long pulse operation (incl. a ML-based feedback controller)
  - 2.3 : **Vibration analysis and detuning control** of cavities (including ML-based control)
  - 2.4 : **Integrate LLRF control using FE-FRT**
  - 2.5 : **Energy efficient supervisory control and fault diagnosis** (including ML-based diagnosis)
  - **Participants : DESY, CNRS, HZB**

Energy saving from cryogenics (TA#2,TA#3):
WP3 and WP4

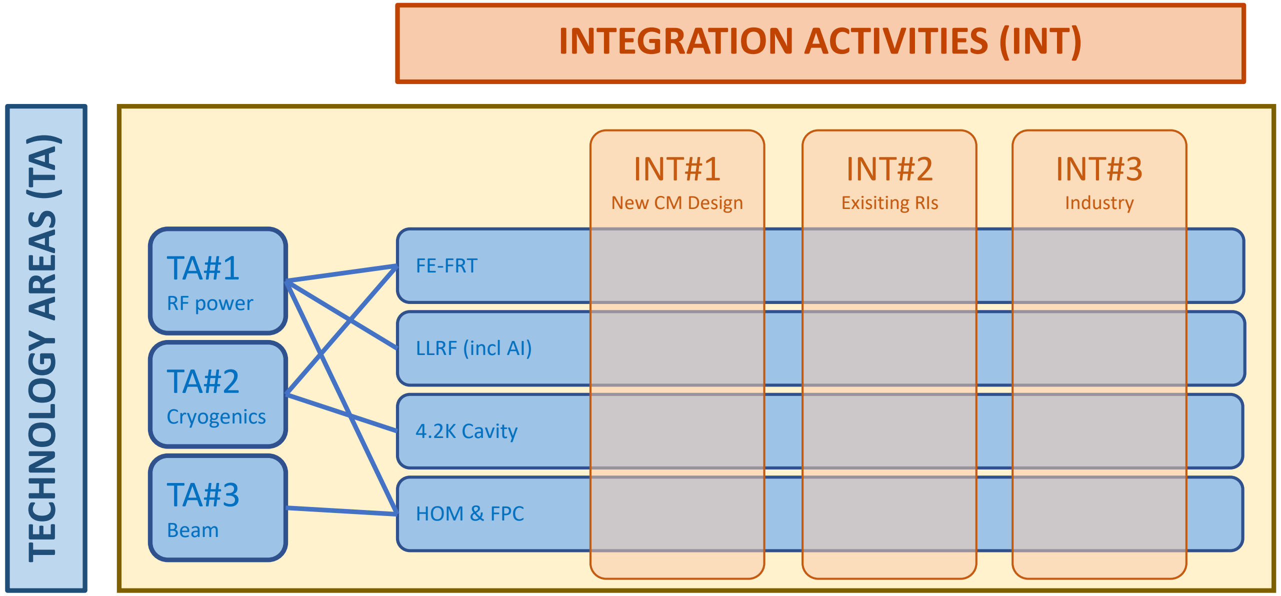
- **WP3 : Nb_3Sn on Cu films for 4.2 K cavity operation – Cristian PIRA (INFN)**
  - 3.1 : coordination
  - 3.2 : **Flux trapping**: study how trapped magnetic flux may affect the superconducting properties of the thin film and its RF surface resistance
  - 3.3 : **RF tunability**: study and improve mechanical properties of superconducting thin films to assess the impact of future cavity tuning during normal 4.2 K operation
  - 3.4 : **Adaptative 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
  - 3.5 : **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)
  - Participants : INFN, CEA, HZB, UKRI

- **WP4 : HOM and FPC – Yolanda GOMEZ MARTINEZ (CNRS/LPSC)**
  - 4.1 : coordination
  - 4.2 : **HOM coupler design**: with simulations for various models and mechanical integration issues in a cryomodule
  - 4.3 : **Fabrication of HOM couplers**: R&D on fabrication strategy for prototypes at 800 MHz and 1.3 GHz
  - 4.4 : **Test of the HOM couplers**: performance validation of the design with RF measurements on mock-up cavities
  - 4.5 : **RF coupler design**: optimize cost, cooling, heat loads, fabrication time, and mechanical integration issues in a cryomodule
  - 4.6 : **Fabrication of RF couplers**: build 4 prototypes
  - 4.7 : **Test of the RF couplers**: performance validation of the design with RF conditioning in CW mode (50 kW)
  - Participants : CNRS/LPSC, INFN, CERN

Implementation of iSAS technologies

- **Development of 4 technologies** ➔ ***Technology Areas (TA)***
  - WP1 : FE-FRT (TA#1)
  - WP2 : LLRF (TA#1)
  - WP3 : 4K cavity (TA#2)
  - WP4 : HOM couplers and FPC (TA#3)

- **Implementation of these 4 Technology Areas** ➔ ***Integration Activities (IA)***
  - **WP5 : In the design of a new energy-saving cryomodule** (IA#1)
  - **WP6 : In current and future research infrastructures accelerator** (IA#2)
  - **WP7 : Into industrial solutions** (IA#3)

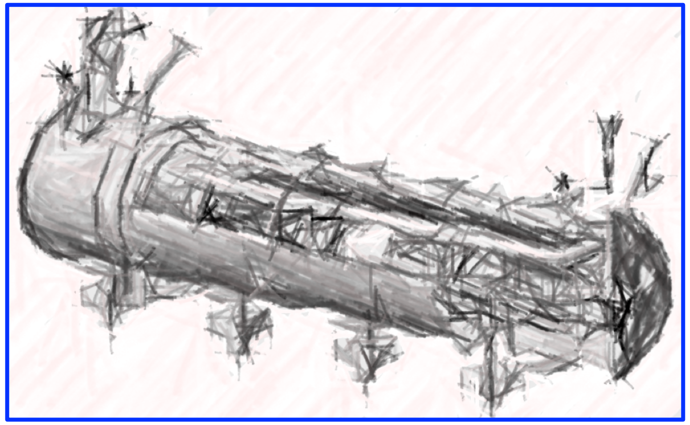


Implementation in a new linac cryomodule : WP5

- **Implementation of technologies in the design of a new energy-saving cryomodule**
  - While LINAC cryomodules are designed for specific accelerators, iSAS will address the common engineering challenges of **integrating the technologies into a parametric design** of a new energy-saving accelerator system

- **Structure – Nuno ELIAS (ESS)**
  - 5.1 : Coordination
  - 5.2 : **Lessons learned with ESS cryomodules and benchmarking with other recent facilities**
  - 5.3 : **Sustainable criteria** for LINAC cryomodule design
  - 5.4 : **Beam dynamics for ERL-based accelerators** with the energy-efficient cryomodules

- **Partners : ESS, CNRS, CERN, INFN, EPFL**

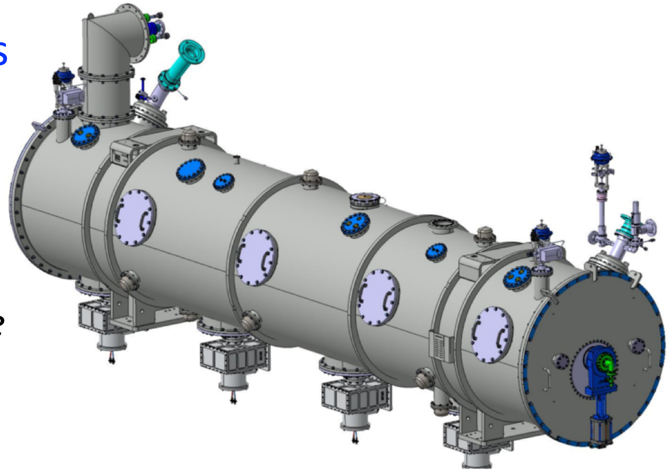


Integrating the technologies into a parametric cryomodule design

Implementation in existing and future RI : WP6

- **Implementation of technologies in current and future research infrastructures accelerator**
  - While various RIs envisage upgrades, iSAS will expedite the integration of technologies by **retrofitting existing accelerating systems**

An existing cryomodule will be adapted, ready to demonstrate energy recovery of high-power recirculating beams in PERLE



Technologies integrated on the PERLE cryomodule

- **Structure – Guillaume OLRY (CNRS/IJCLab)**
  - 6.1 : Coordination
  - 6.2 : **Retrofitting Fast Reactive Tuners** into existing cryomodules
  - 6.3 : **Adapt the existing ESS cryomodule**
  - 6.4 : **Fabrication and validation of cryomodule components**
  - 6.5 : **Assembly and test of the adapted cryomodule**

- **Partners : CNRS/IJCLAB, CEA, ESS, INFN, Lancaster University**

Retrofitting of technologies in existing RIs

Implementation into industrial solutions :
WP7

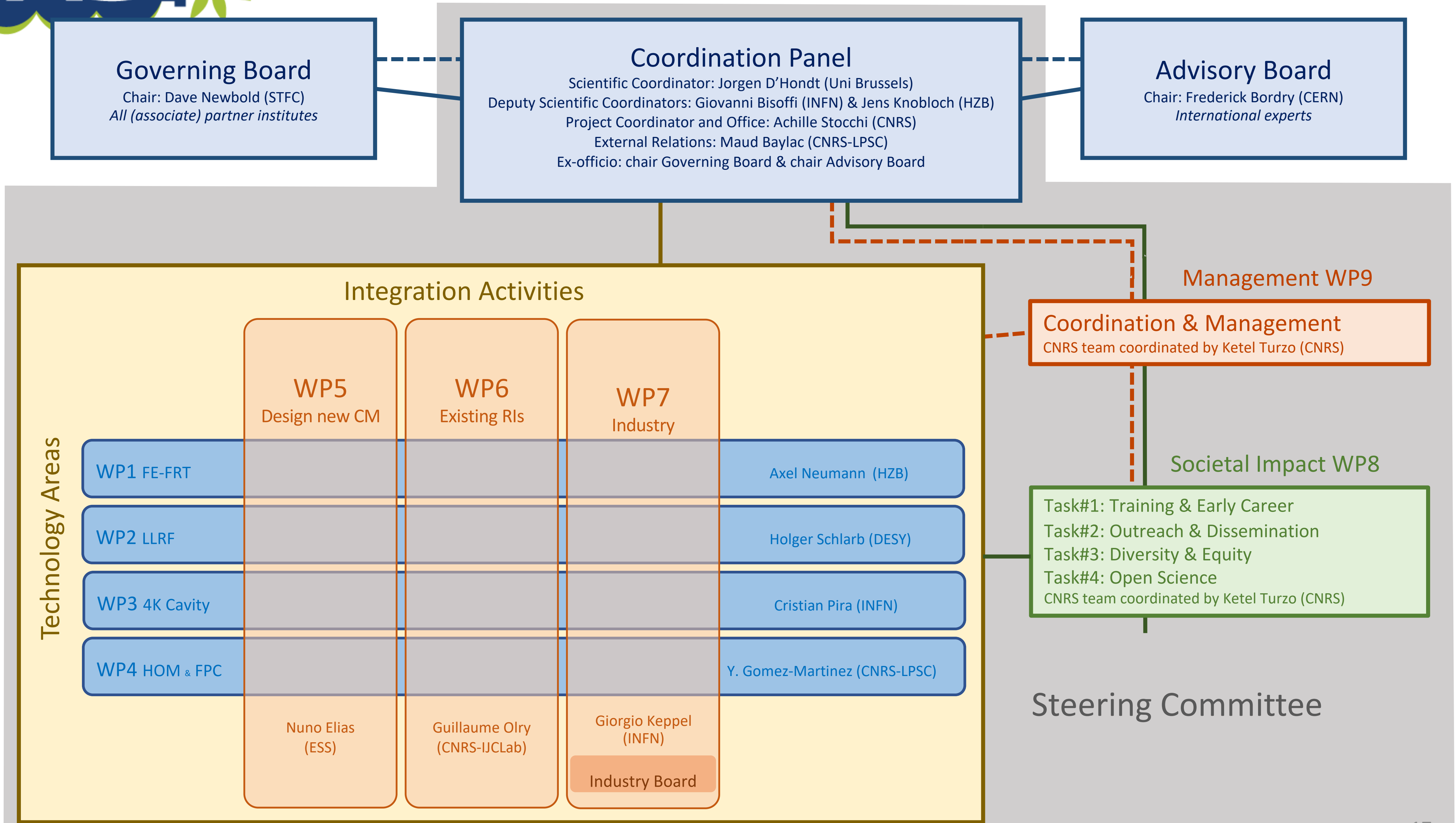
- **Implementation of technologies into industrial solutions**
  - While iSAS technologies are emerging, iSAS aims for concrete **co-developments with industry to increase the Technology Readiness Level** (TRL) sufficiently towards largescale deployment of the energy-saving solutions at current and future Ris, as well as industrial applications.

- **Structure – Giorgio KEPPEL (INFN)**
  - 7.1 : Coordination
  - 7.2 : **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)
  - 7.3 : **Business opportunities**: develop an iSAS project repository and disseminate the innovative technologies

- **Partners : INFN, CNRS**

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

Organization of iSAS



Ressources and partners

- **4.7 M€ funded from Horizon Europe for a total budget of ~13 M€**
- **HR ~1000 person-months spread over 4 years**
- **Partners :**

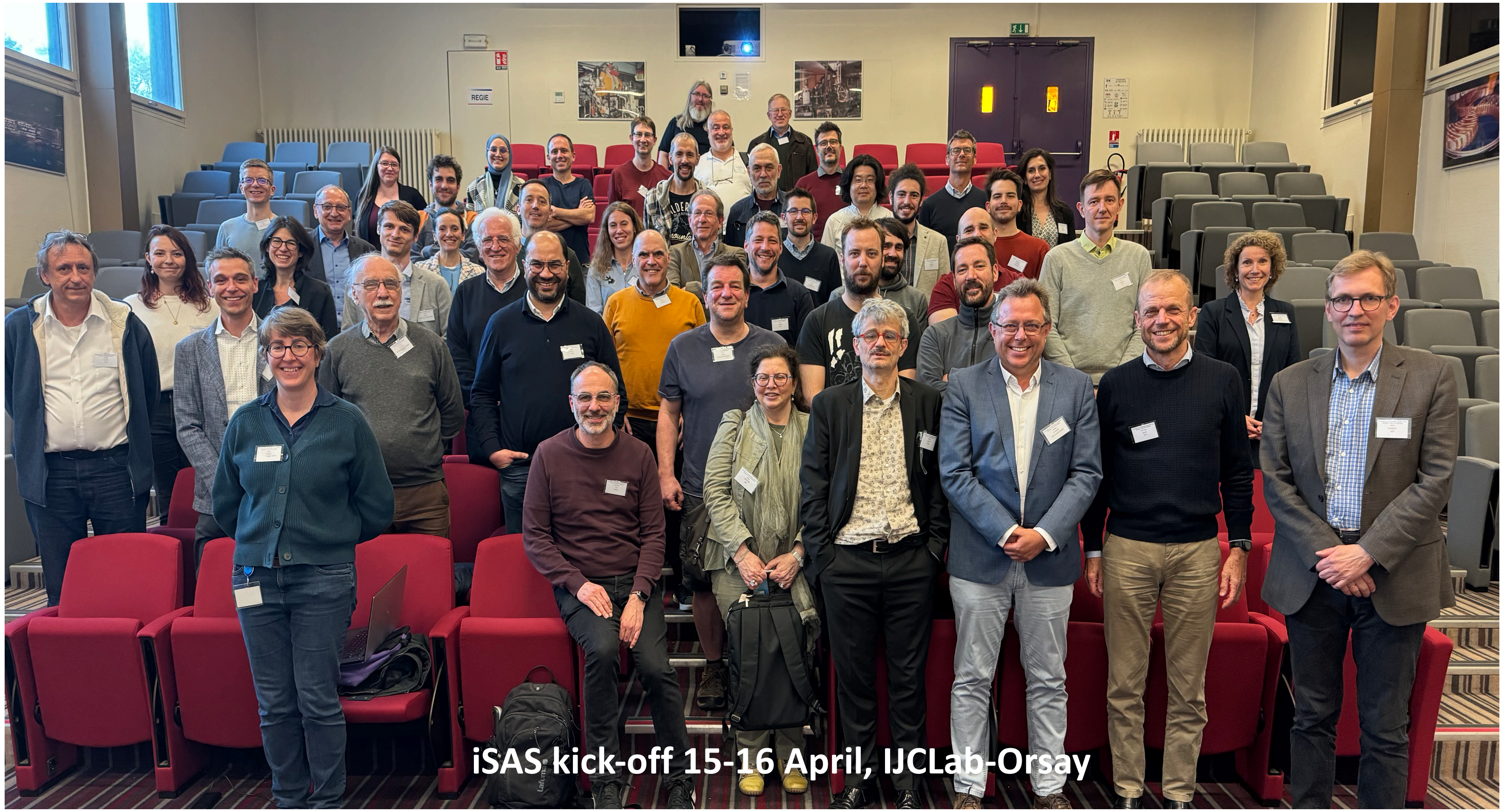
+ industrial companies: *ACS Accelerators and Cryogenic Systems* (Fr), *RI Research Instruments GmbH* (Germany), *Cryoelectra GmbH* (Germany), *TFE Thin Film equipment srl* (Italy), *Zanon Research* (Italy), *EuclidTechLab* (USA)

- **Support of EuXFEL GmbH, I.FAST, LEAPS, LDG, TIARA as well as Enterprise Europe Network (EEN)**

EU HORIZON-INFRA-2023-TECH-01-01

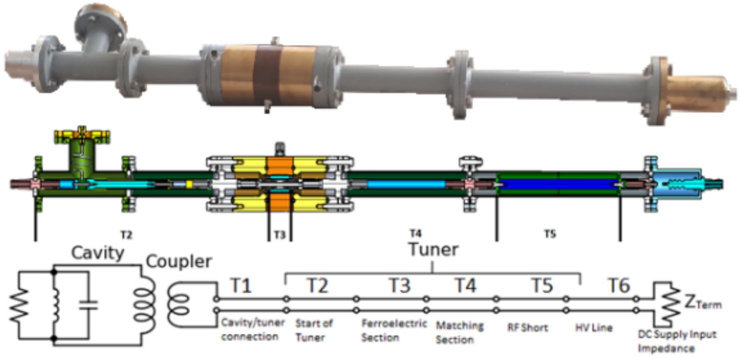
Conclusion

- **With iSAS, impactful new energy-saving technologies will be developed, validated and integrated with a direct impact on current research infrastructures and their upgrades**
- **These technologies will stimulate the European industry to take a leading role in building systems for new accelerators**
- **On the long term, these technologies aim to reduce the energy footprint of future SRF accelerators towards a sustainable operation**


iSAS kick-off 15-16 April, IJCLab-Orsay

BACK UP

From Axel Neuman, iSAS kickoff meeting



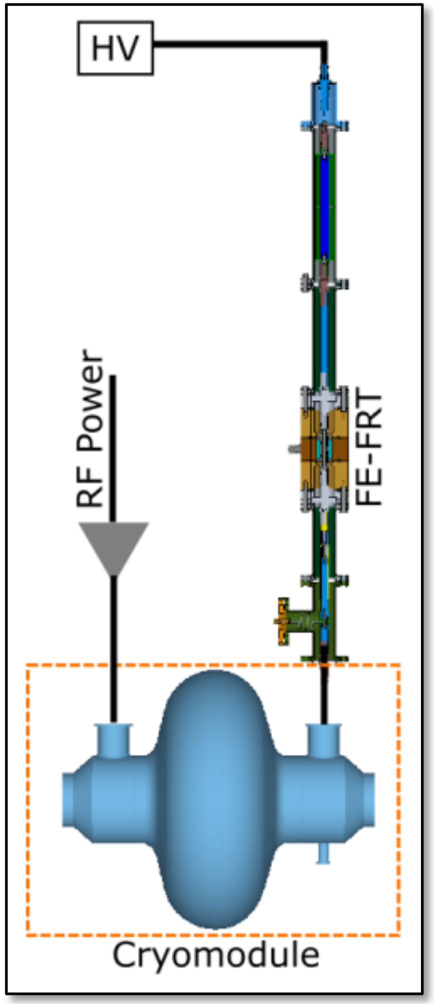
Prototype FE-FRT designed and built at Euclid and later sent to CERN

N.C. Shipman *et al.*, "A Ferroelectric Fast Reactive Tuner for Superconducting Cavities", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 781-788. doi:10.18429

- Instead of changing the boundary conditions via mechanical deformation for the fundamental mode
  → Couple a tunable device to the resonator changing the frequency of the coupled system
- This can be done, by applying HV to a FE material such as BST class: $BaTiO_3$-$SrTiO_3$
  → Tuneable dielectric constant

Conceptual design of a high reactive-power ferroelectric fast reactive tuner
Phys. Rev. Accel. Beams
Ilan Ben-Zvi, Graeme Burt, Alejandro Castilla, Alick Macpherson, and Nicholas Shipman
Accepted 12 April 2024

→ We don't start from zero. All the following is based on previous work by CERN, Lancaster, BNL and euclid



Pros and Cons:

- Non-mechanical, no complex transfer/ coupling behaviour as with e.g. piezos
- Fast tuning response on sub 100 ns timescale
- Tuning range on the order of tens to hundred (?) of kHz

But, physics is never for free

- A suitable coupler port is needed
- The material needs to operate at room temperature, windows, thermal transition required
- Low loss material for a high figure of merit required
- Fast switching HV source for transient detuning application
- HV breakdown of ceramics