Innovate for sustainable accelerators systems: main progress on the iSAS project

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On behalf of the iSAS project*

Funded by the European Union

* *https://isas.ijclab.in2p3.fr/contributors/*

Introduction

- Particle accelerators are exceptional instruments (research, applications), but in a context of energy savings and sustainability
  - **Minimizing the energy consumption of future accelerators is a challenge to be faced**
  - Highlighted in the European Strategy for Particle Physics (ESPP 2020) and further strengthened in the ESPP 2026

- EU call **dedicated to "*New technologies and solutions for reducing the environmental and climate footprint of Research Infrastructures* »** (HORIZON-INFRA-2023-TECH-01)
  - **Project « *Innovate for Sustainable Accelerating Systems* (iSAS)» launched (2024)**
  - Scientific coordinator: J. D'Hondt (Nikhef), project coordinator: A. Stocchi (CNRS-IJCLab)



https://isas.ijclab.in2p3.fr/

- **Resources and partners**
  - Total project budget of ~13 M€ with ~5 M€ funded from Horizon Europe
  - Partners : 12 research institutes and 6 industrial companies
  - HR ~1000 person-months spread over 4 years

- **Goal of the talk: panorama of the large R&D program performed by all iSAS collaborators of the different labs**
  - **Overview and some highlights of the accelerator R&D of iSAS**
    - **Which devices to study for efficient energy savings? ➔ scope**
    - **What are the main progress to date ? ➔ status**

Funded by the European Union

Work supported by funding from European Union's program EU HORIZON-INFRA-2023-TECH-01-01 under GA n°101131435

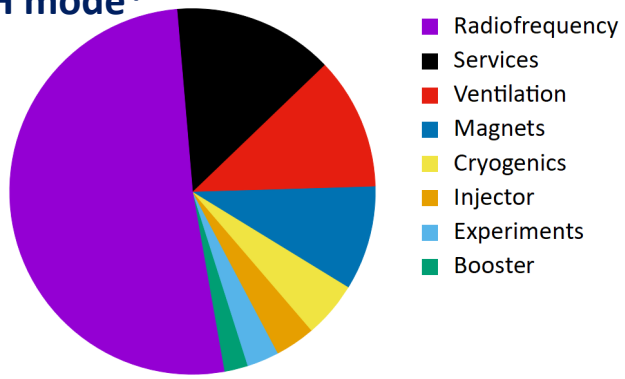
R&D within iSAS

- **Breakdown of power consumption of accelerators for different subsystems**
  - Depends upon the type of machine (circular, linear, ..) and mode of operation
  - Example of electron-positron Higgs factory

FCC-ee, ZH mode*

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

- **iSAS focuses on energy savings mainly on some RF systems, complementary to other meaningful R&D on, for example**
  - High efficiency RF power sources
  - High efficiency magnets

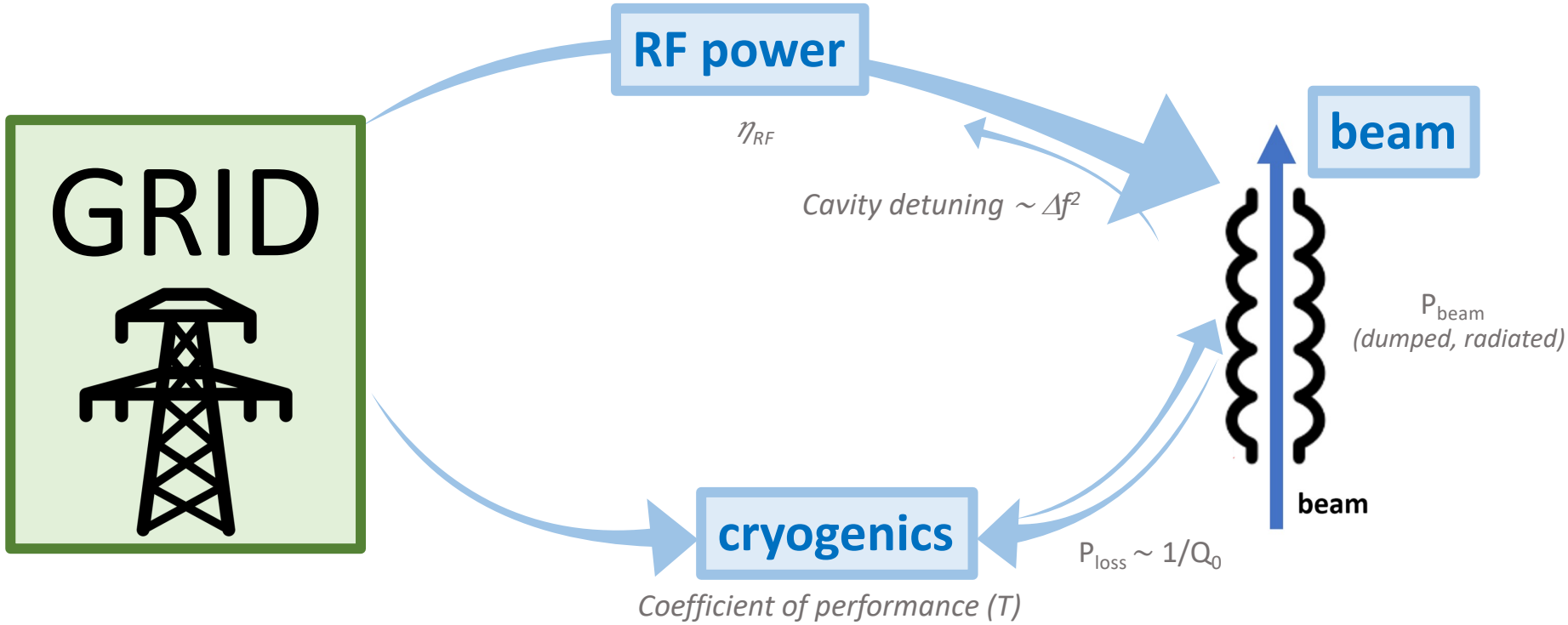
- **Two axes of iSAS**
  - Development of the energy savings technologies for accelerators
  - Implementation of the technologies at different levels

- **Main focus on the 3 ESFRI Research Infrastructures, HL-LHC, ESS and EuXFEL, to benefit from iSAS developments**

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

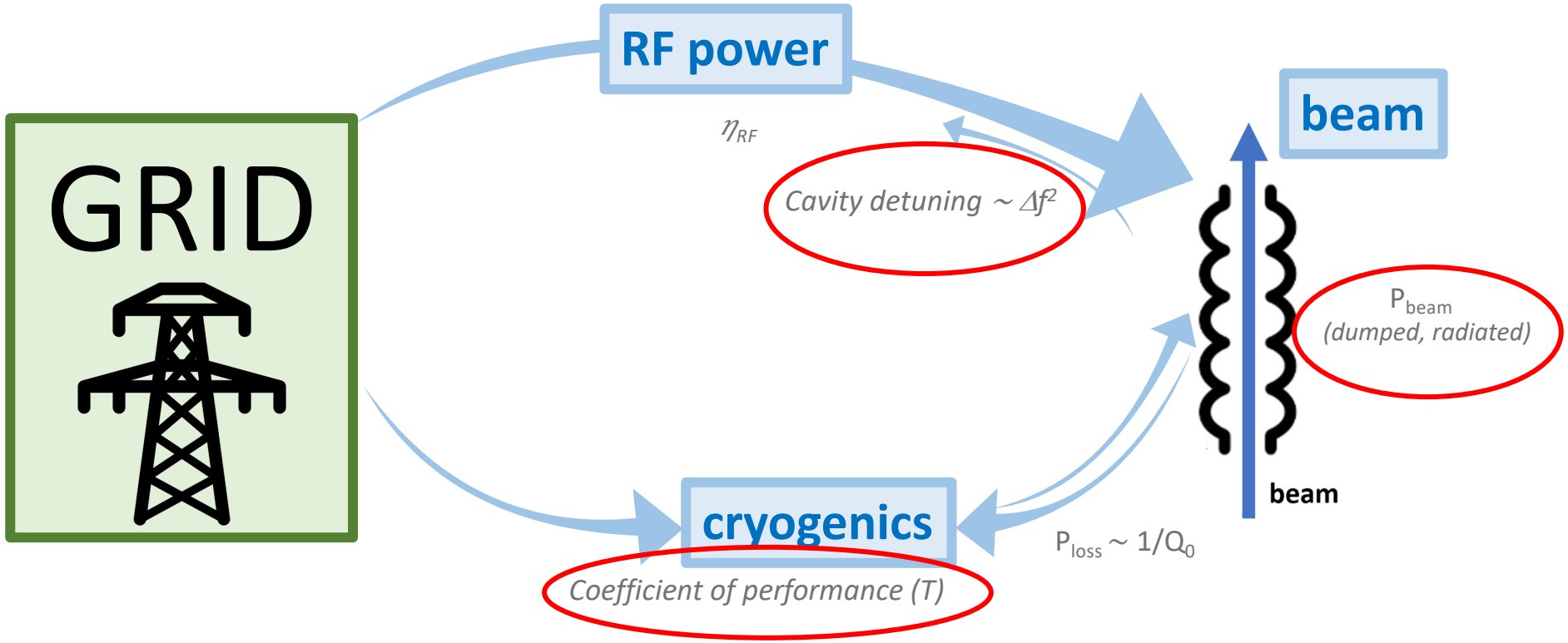
Sources of power inefficiencies from superconducting radiofrequency (SRF)

- **Multiple sources impacting the grid-to-beam power efficiency, including**
  - RF power source efficiency : η_{RF}
  - RF load by cavity detuning : Δf
  - Cavity cryogenic loss : $P_{loss} \propto 1/Q_0$
  - Generation of cryogenics (coefficient of performance) : COP
  - Loss of the beam power : P_{beam}



Mitigations of power inefficiencies for SRF

- **Multiple sources of power in-efficiency can be adressed by mitigation technologies**
  - RF power source efficiency : η_{RF} ➔ enhance efficiency of the RF sources
  - **RF load by cavity detuning : Δf** ➔ **deal with microphonics to reduce Δf** ➔ **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 (*Energy Recovery Linac*)** ➔ **iSAS Technology Area (TA#3)**



Scope of iSAS

- **Development of 4 technologies**
  - WP1 : Ferro-Electric Fast Reactive Tuner (FE-FRT)
  - WP2 : Optimized Low Level RF control (LLRF)
  - WP3 : Nb_3Sn films on Cu for 4.2 K cavity operation
  - WP4 : Couplers, Fundamental and Higher Order Modes

➔ ***Technology Areas (TA)***

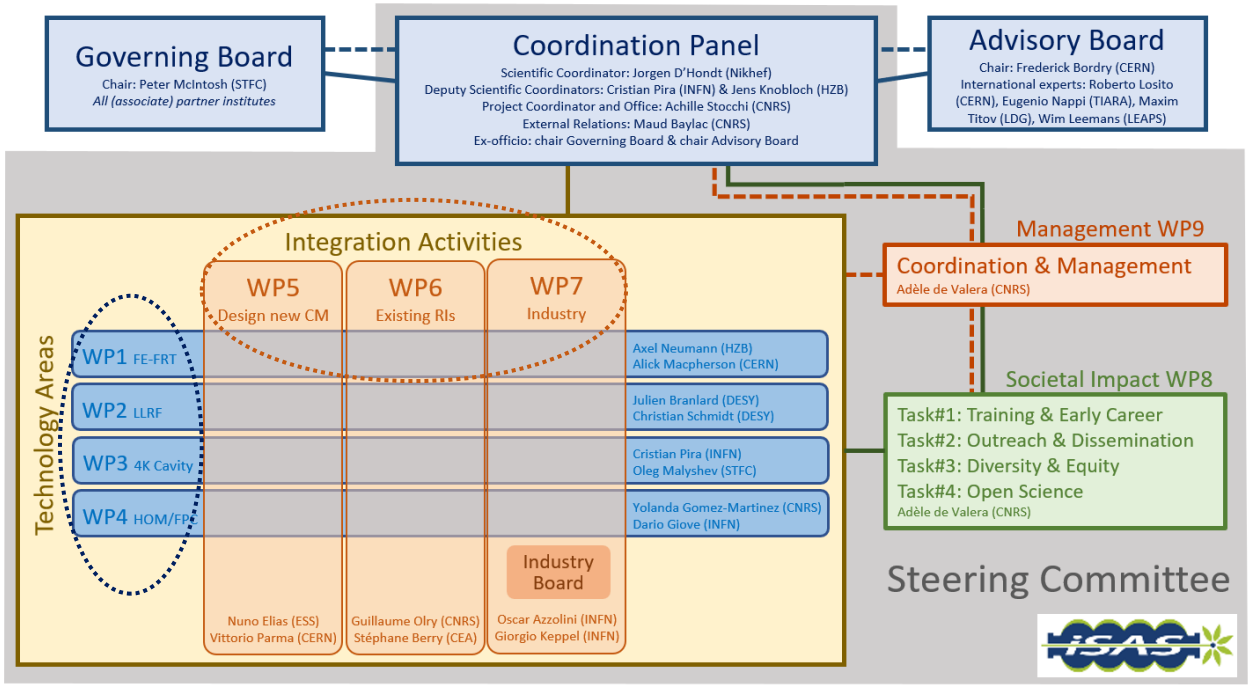
(TA#1) } Energy saving from the RF power
(TA#1) }
(TA#2) ➔ Energy saving from cryogenics
(TA#3) ➔ Energy saving from the beam

- **Implementation of these 4 technologies**
  - WP5 : In the design of a new energy-saving cryomodule
  - WP6 : In existing research infrastructures
  - WP7 : Into industrial solutions

➔ ***Integration Activities (INT)***

(INT#1)
(INT#2)
(INT#3)

iSAS organization chart

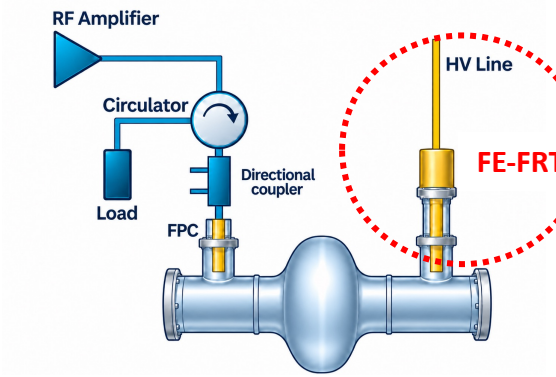


FE-FRT (TA#1) : scope

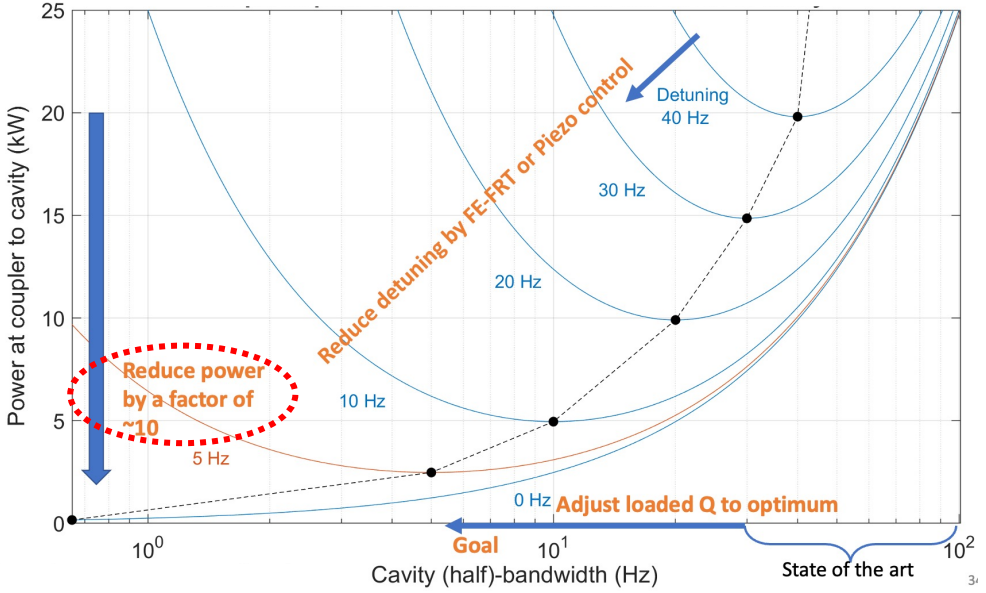
WP1 leaders: A. Neumann (HZB), A. Macpherson (CERN)

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

- **WP1 develops a novel fast tuning system, Ferro-Electric Fast Reactive Tuner (FE-FRT)**
  - **FE-FRT tuner : alternative to classical mechanical tuner for the cavity**
  - **Couples a tunable device to the cavity to change the frequency of the coupled system**
    - **HV applied to FE material with tunable dielectric constant** (BST: Ba, Sr, Ti) **to change its permittivity**
    - **Impedance change controls the resonance frequency of the coupled system**
    - **Very fast tuning response ~100 ns, tuning range ~ tens of kHz**
  - Based on previous work by CERN, univ. Lancaster, BNL and Euclid techlabs
  - Partners: HZB, CERN, CNRS, Univ. Lancaster
  - **Significant power saving expected**



FE-FRT coupled to a cavity



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 (from iSAS proposal)

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

I. Ben-Zvi, A. Macpherson and S. Smith, "Detailed design and optimization of ferroelectric tuners", Physical Review Accelerators and Beams 28.9 (2025): 093502, doi:10.1103/9sf7-wwyb

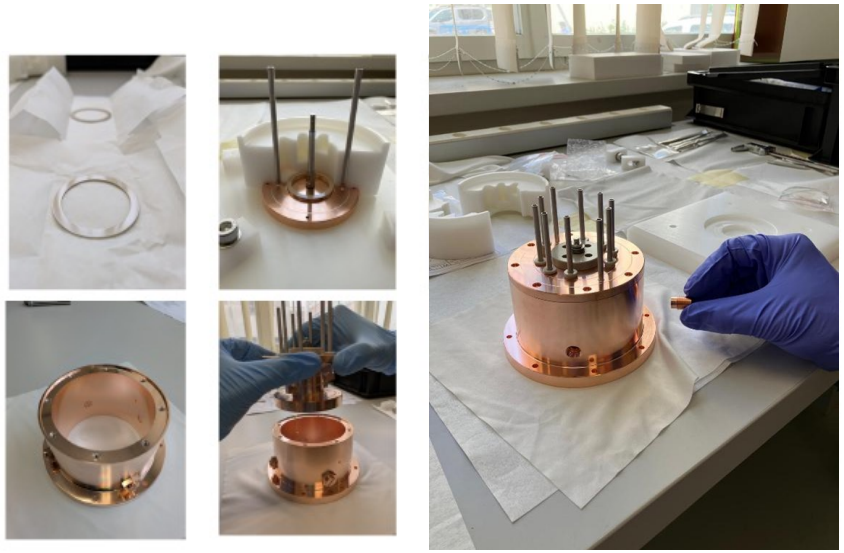
FE-FRT (TA#1) : status

WP1 leaders: A. Neumann (HZB), A. Macpherson (CERN)

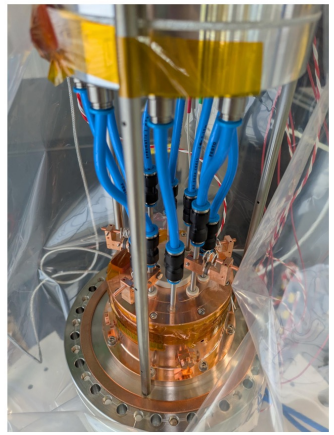
FE-FRT for transient beam loading : Develop and test a FE-FRT design for 400 MHz LHC cavities

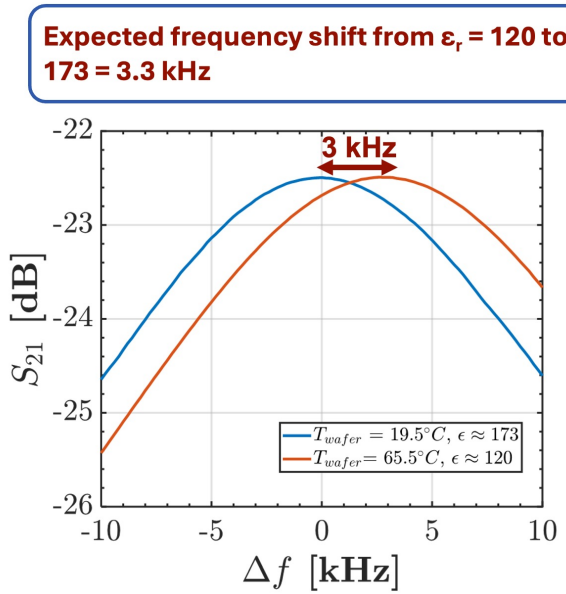
- **Specifications: 8 kHz tuning range, 7.2 kV bias voltage, 100 ns switching time at 150 kHz switching rate***
- **RF design and choice of material validated**
- **After manufacturing at CERN, the first warm tests have shown the expected tuning functionality**
- **Cold tests under preparation (Q3 2026)**

Courtesy of A. MacPherson (CERN)



Initial assembly of the ferroelectric section of the FE-FRT at CERN





Warm test: frequency adjustment by temperature change of FE material

*S. Smith *et al.,* "Towards high power tests of an FE-FRT for transient detuning", in Proc. SRF2025, Tokyo, Sep. 2025, pp. 516-521, doi:10.18429/JACoW-SRF2025-WEA03

FE-FRT (TA#1) : status

WP1 leaders: A. Neumann (HZB), A. Macpherson (CERN)

Technologies

FE-FRT for microphonics detuning compensation (HZB, Euclid Techlabs)

- ***Goal : Develop and test an FE-FRT at 1.3 GHz***
- **FE-FRT for the two-cell SRF cavity was designed and manufactured**
  - **Bench tests performed**
  - **Cold test in a cavity horizontal test stand (HoBiCat) to be done in December**
- **Design will be improved for a nine-cell TESLA/XFEL cavity**



- **To investigate materials permittivity in this frequency range, test stand developed to characterize the ferroelectric material at 1.3 GHz**
  - **measurements underway (permittivity versus voltage)**
  - **sample preparation (grinding, polishing, planarity of faces) is of utmost importance for optimal performance of the tuner**

FE-FRT for energy recovery linac (CERN, U. Lancaster, HZB, CNRS/IJCLab):

- ***Goal : Develop an FE-FRT at 802 MHz, to be tested in the energy recovery linac PERLE (also an use case for FCC-ee)***
- Considering limited available space in the end groups on most SRF cavities, retrofitting existing designs with a FE-FRT may require to combine the FE-FRT with an HOM or FPC port

J.S. Romero Jiménez *et al.,* "SRF cavity detuning characterization by continuous wavelet transform: a time-frequency analysis", IPAC'26 proc., doi: 10.18429/JACoW-IPAC2026-MOP7036

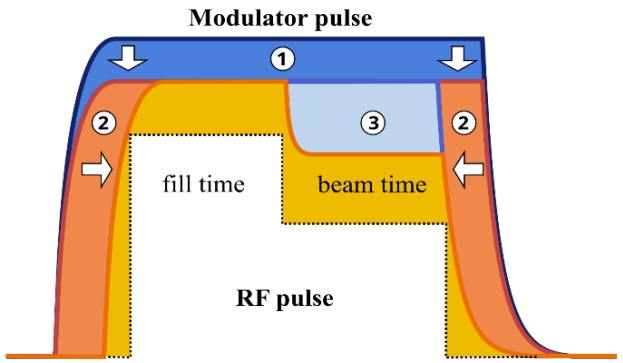
Optimized LLRF (TA#1) : scope

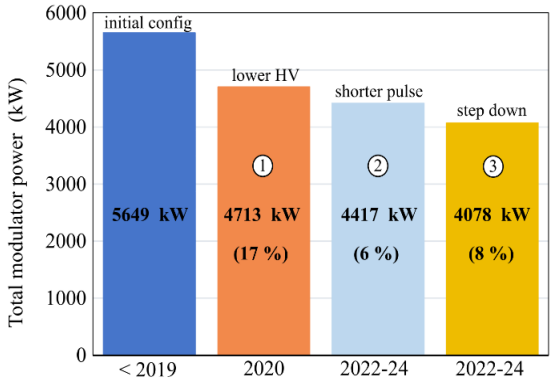
WP2 leaders : J. Branlard, C. Schmidt (DESY)

Technologies

- **Goal: reduce the required RF power by efficient field control and detuning control with Low Level RF system (LLRF)**
  - **Several factors of the LLRF tuning system impact the energy consumption** (coupling, shape of modulator pulse, amplifier …)
  - **Operation at higher Q_{ext} (narrower bandwidth Δf)**
    - Reduces the power needs ONLY IF resonance control can be guaranteed
    - But makes resonance control extremely challenging
  - **Challenge : find the highest Q_{ext} while meeting resonance control goals and without compromising operability or reliability**
  - **Significant power saving possible, for example:**

EU-XFEL: How shaping the modulator pulse can save power
➔ LLRF development to compensate introduced non-linearities





Successive adjustments
➔ power savings ~ 28%

J. Branlard *et al.*, "RF-based energy savings at the FLASH and European XFEL LINACs", in proc. of LINAC 2024, doi:10.18429/JACoW-LINAC2024-THZA003

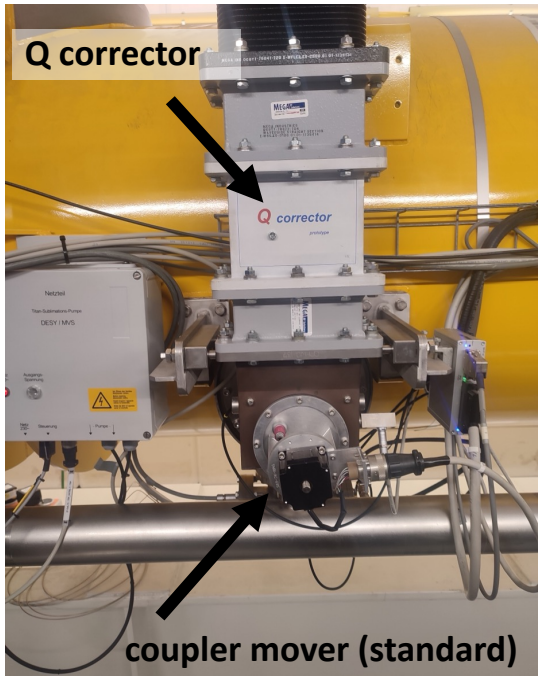
- **WP2 : demonstrate the operation of a digital LLRF system, integrating AI, for optimum control of field and detuning**
  - **Partners: DESY, CNRS, HZB**

Optimized LLRF (TA#1) : status

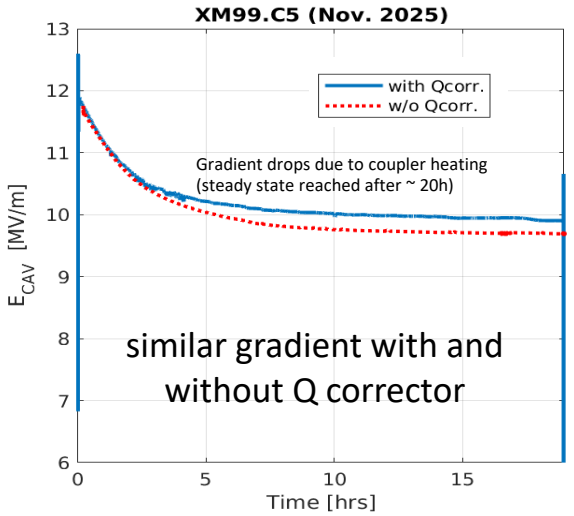
WP2 leaders : J. Branlard, C. Schmidt (DESY)

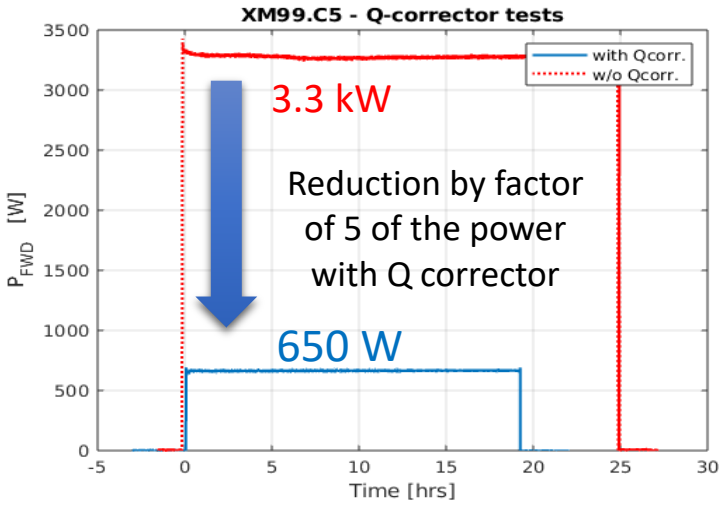
Technologies

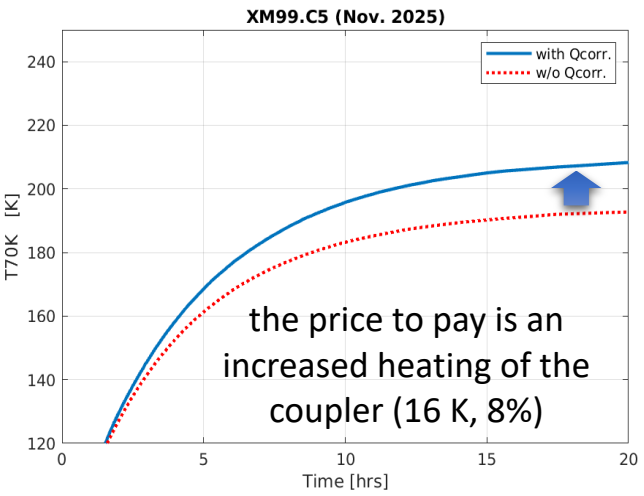
- **Efficient field control for high loaded-quality factor cavities**
  - **Developed prototypes (waveguide stub-tuners) to shift Q_{ext} to higher values (i.e. narrower cavity bandwidths)**
    - **Operating at higher Q_{ext} can bring significant RF power savings : factor of 5 measured on test stand**
    - **Currently investigating if coupler heating is safe for coupler**



Test stand AMTF on 2 cavities







Courtesy V. Katalev and J. Branlard (DESY)

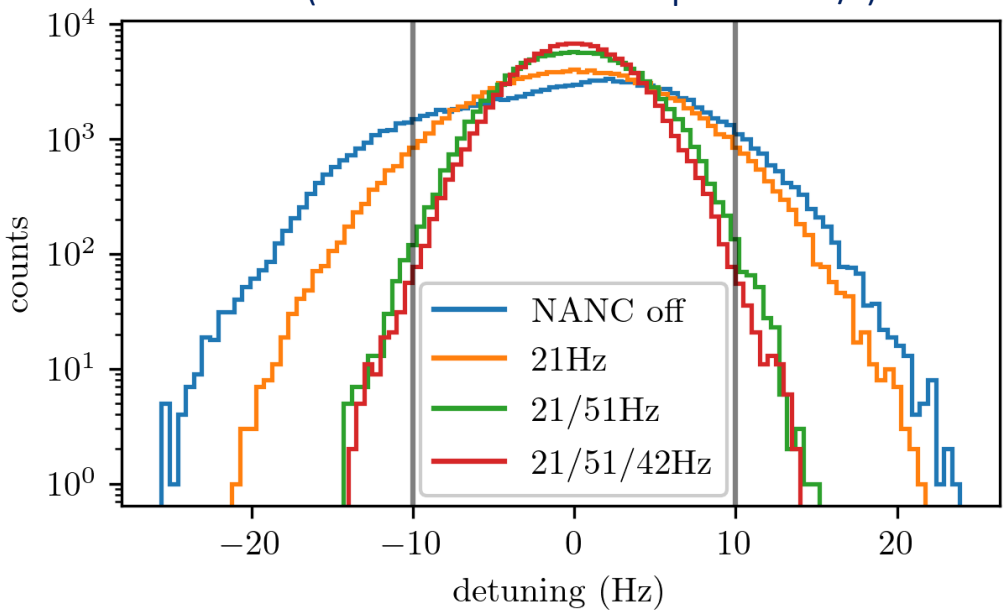
Optimized LLRF (TA#1) : status

WP2 leaders : J. Branlard, C. Schmidt (DESY)

Technologies

- **Microphonics suppression to allow higher gradient operation**
  - **Developed a *Narrow Bandwidth Active Noise Cancellation* (NANC) algorithm and demonstrated at SLAC (LCLS-II)**
    - **Reduction of vibrations by a factor of 2**
    - Without NANC, the cavity could operate at max 9 MV/m
    - **With NANC, the cavity can be operated at 15 MV/m**

Detuning of LCLS-II cavity (cryomodule 19, cavity 2) operated at 9MV/m,
(56 seconds of data sampled at 2kS/s)



Successive suppressing of dominating microphonic components at 21 Hz, 51 Hz and 42 Hz

➔ **reduction of peak-to-peak detuning by a factor of 2**

➔ reduction of peak / average power of 55% / 11% w/o beam loading

B. Richter et al., « Narrowband Active Noise Control for TESLA Cavities in cw », IPAC'26 proc., doi: 10.18429/JACoW-IPAC2026-WEP6149

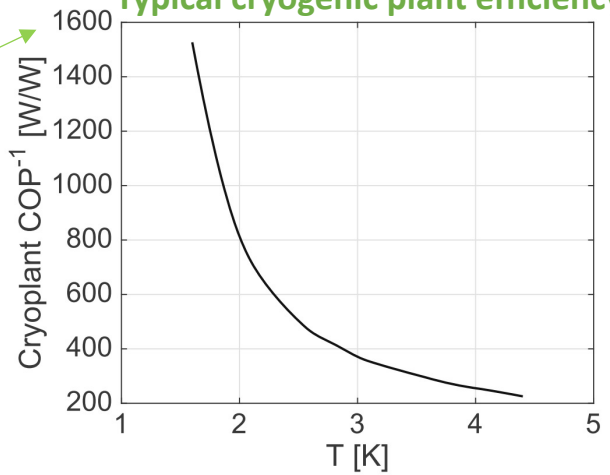
4 K cavities (TA#2) : scope

WP3 leaders : C. Pira (INFN), O. Malyshev (STFC)

- **Goal : reduce the necessary cryogenics power for cavity operation**
  - **Higher critical temperature Tc material allows operation at 4.2 K instead of 2 K while maintaining high Q_0 and E_{acc}**
  - **Power saving at higher T**

How many watts of wall power needed to remove one watt of heat ?

Typical cryogenic plant efficiency



Cryogenic plant efficiency:
3 times better at 4.2 K than 2 K

➔ significant energy saving at 4.2 K

S. Posen, D.L. Hall, « Nb_3Sn superconducting radiofrequency cavities: fabrication, results, properties, and prospects », Supercond. Sci. Technol. 30 (2017) 033004

- **WP3 : Explore coatings of Nb_3Sn on Cu in order to**
  - **Minimize magnetic flux trapping**
  - **Increase mechanical strength of the coating to allow better tunability of the cavity**
  - Investigation on
    - Planar samples
    - Quadrupole resonator (QPR)
    - **1.3 GHz cavity**
  - Partners: INFN, CEA, HZB, UKRI

➔ ***Complementary to the EU project I.FAST, aim to go beyond the achievements of I.FAST WP9 and will be continued within EPITA***

4 K cavities (TA#2) : status

WP3 leaders : C. Pira (INFN), O. Malyshev (STFC)

Technologies

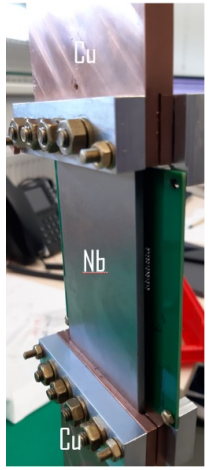
Advanced characterization facilities to investigate:

Flux trapping



Upgrade performed on Choke cavity facility for residual field penetration

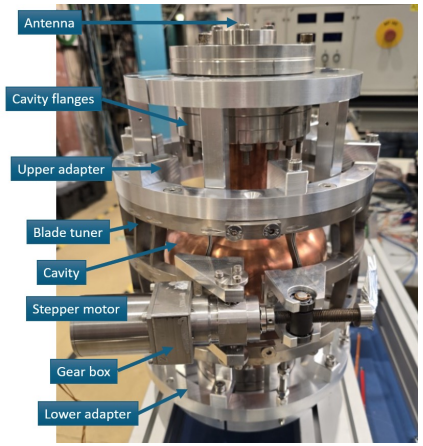
Science and Technology Facilities Council



CRAFT facility built and tested (simulation conditions of cavity cooldown for planar samples)

HZB Helmholtz Zentrum Berlin

Tunability



Blade Tuner built and tested (evaluate impact on Nb_3Sn coatings of realistic mechanical tuning conditions)

HZB Helmholtz Zentrum Berlin

To enhance film mechanical stability and tunability, interlayer between Nb_3Sn coating and Cu substrate : adaptive layers by atomic layer deposition (ALD)

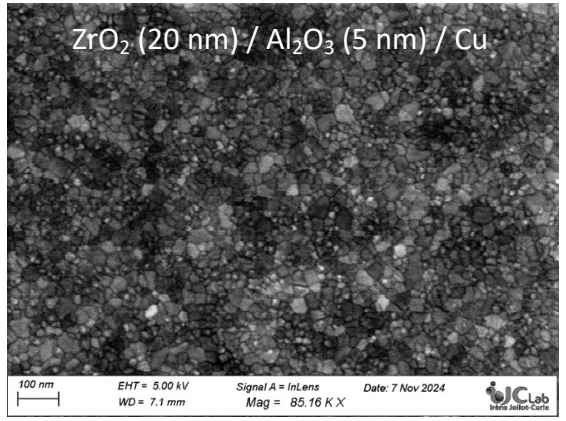
Al_2O_3, ZrO_2 and AlZrOx oxides successfully coated by ALD and stable up to 750 °C

Mitigation of thermo-electric currents proven on a 1.3 GHz Cu cavity from CERN : ALD layer between Cu and thick Nb film

From T. Proslier and I. Curvi (CEA)

cea





D. Seal *et al.*, "A high throughput facility for the RF characterisation of planar superconducting thin films", Supercond. Sci. and Technol. 37 (11), 115012 (2024), doi.org/10.1088/1361-6668/ad7643

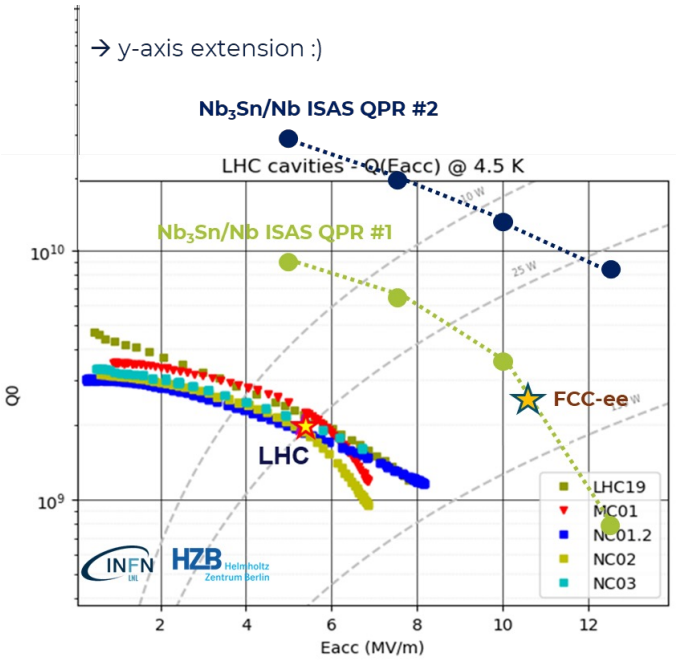
4 K cavities (TA#2) : status

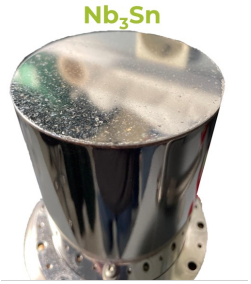
WP3 leaders : C. Pira (INFN), O. Malyshev (STFC)

Technologies

Coating recipe optimized and validated on small planar resonator (QPR)

Q_0 value on QPR 10 times > Q_0 LHC





9 nΩ at 4.5 K
(20 mT, 417 MHz)

D. Fonnesu *et al.*, "Recipe optimization and SRF test of Cu-compatible Nb_3Sn films by DC magnetron sputtering from a stoichiometric target", Sci Rep 16, 3539 (2026)

C. Pira et al., "Nb_3Sn on Cu SRF cavities R&D at INFN LNL», IPAC'26 proc., doi: 10.18429/JACoW-IPAC2026-MOP7030

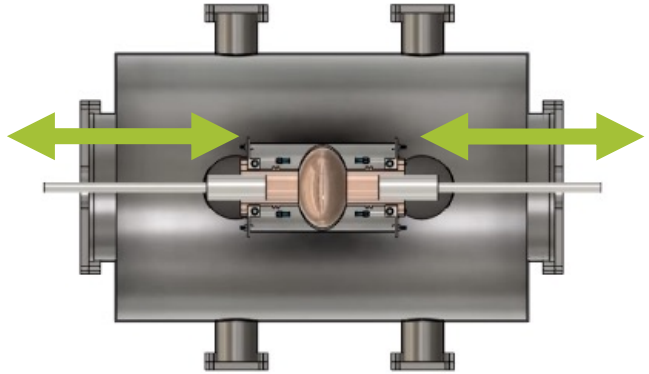
2 coating systems for 1.3 GHz cavities ready, in the testing phase

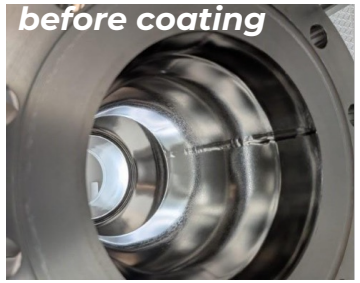
Rectangular magnetron
Rotating Cavity



M. Lazzari *et al.*, "Development of a new system for Nb_3Sn thin film deposition on 1.3 GHz cavities", in Proc. SRF2025, Tokyo, doi:10.18429/JACoW-SRF2025-TUP31

Double movable magnetrons
Fixed cavity







R. Valizadeh *et al.*, "First 1.3 GHz Nb cavity coated with Nb_3Sn thin film deposition by PVD magnetron sputtering", in Proc; SRF2025, Tokyo, doi:10.18429/JACoW-SRF2025-TUP33

Couplers (TA#3) : scope

WP4 leaders: Y. Gómez-Martínez (CNRS-LPSC), D. Giove (INFN)

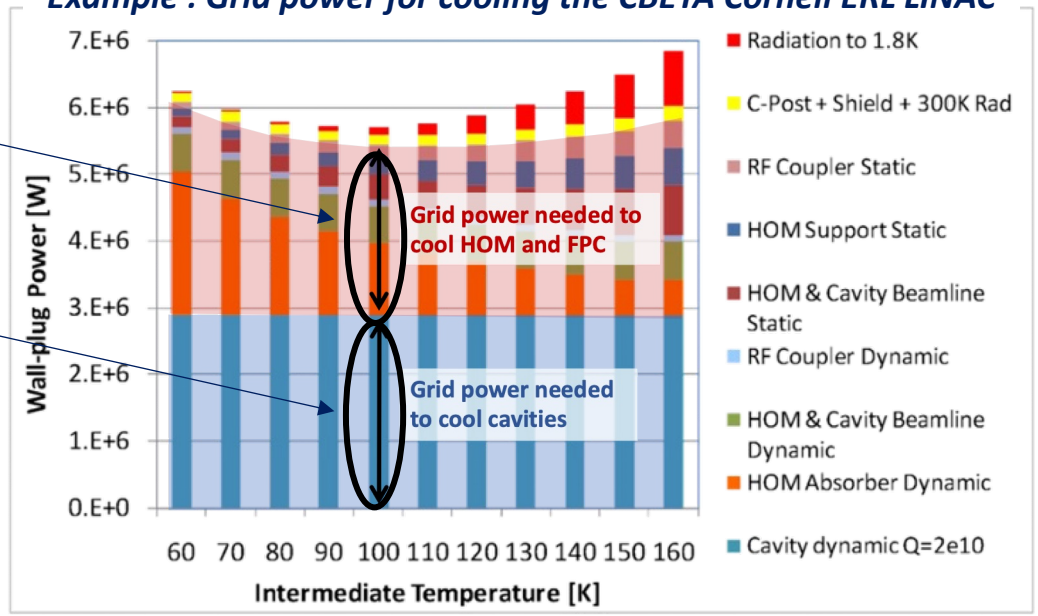
Technologies

- **Goal : reduce the heat loads of the cryogenics by lowering the power deposited by**
  - **Fundamental Power Coupler (FPC) : coupler to introduce the power to excite the fundamental mode of the cavity (antenna)**
  - **Higher-Order Mode (HOM) coupler : coupler used to damp the higher order modes trapped in the cavity**
  - **Beam Line Absorber (BLA) : used to damp HOM propagating through the beam pipes by directly absorbing their power**

Example : Grid power for cooling the CBETA Cornell ERL LINAC

Grid power needed to cool HOM and FPC

Grid power needed to cool cavities



HOM and FPC : half of the full cryogenic load
➔ optimization is important to minimize energy

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

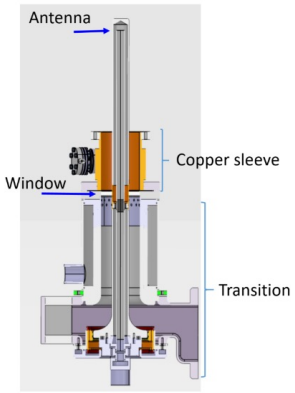
- **WP4 : Design & build prototypes for integration and test in accelerator-like conditions in a cryomodule** (energy-recovery PERLE)
  - Partners: CNRS/LPSC, INFN, CERN

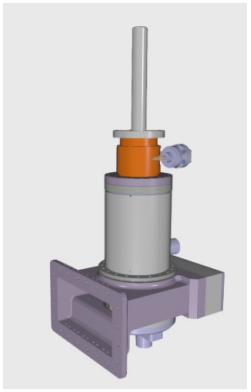
Couplers (TA#3) : status

WP4 leaders: Y. Gómez-Martínez (CNRS-LPSC), D. Giove (INFN)

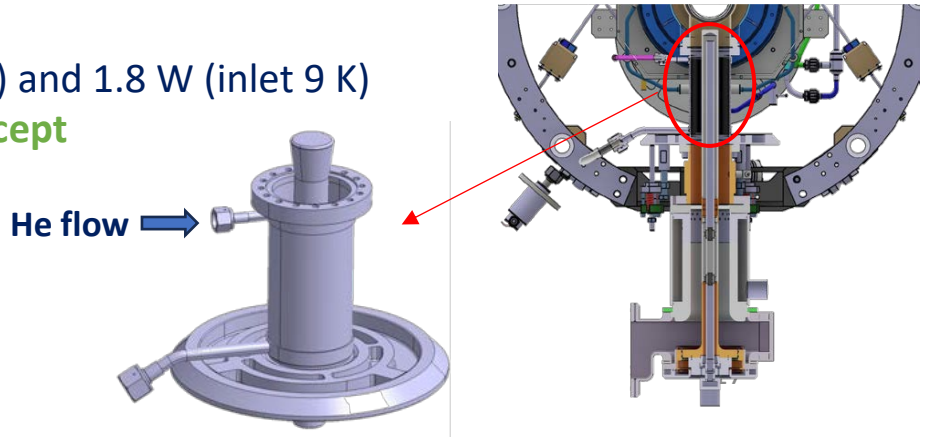
Technologies

- **Fundamental Power Couplers (FPC)**
  - **Design (CNRS/IJCLab)**
    - Based on the design of the 704 MHz SPL coupler by CERN
    - RF and mechanical simulations done, adapted to the ERL cryomodule (PERLE)
      - **Operating frequency: 801.58 MHz**
      - **Maximum power: 50 kW continuous wave**





  - **Thermal simulations performed by CERN**
    - **Thermomechanical studies were carried out to define the antenna and the window air cooling (C. Sharp)**
      - **Strongly turbulent air flow rate > 400 l/min to cool antenna circuit and window**
      - Electrical heaters on the window to mitigate the risk of condensation
    - **Reuse ESS outer conductor cooling: cylindrical double-walled tube (DWT) cooled with supercritical helium flow (K. Canderan)**
      - Estimation of heat loads in outer conductor, cost of cryogenic plant and He mass flowrate to minimize heat loads to the cavity helium bath at 2 K
      - **Strong impact of the He inlet temperature on cryogenic costs**
        - Heat released to the He bath at 2 K from DWT is 0.5 W (inlet 5.1 K) and 1.8 W (inlet 9 K)
      - **Cooling with Helium flow more energy efficient than with a heat intercept**
        - With He flow ~ 65% saving on total equivalent cryogenic cost

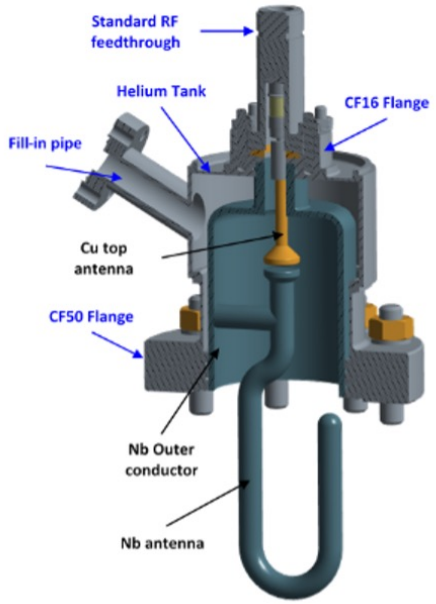


  - **Manufacturing drawings underway**

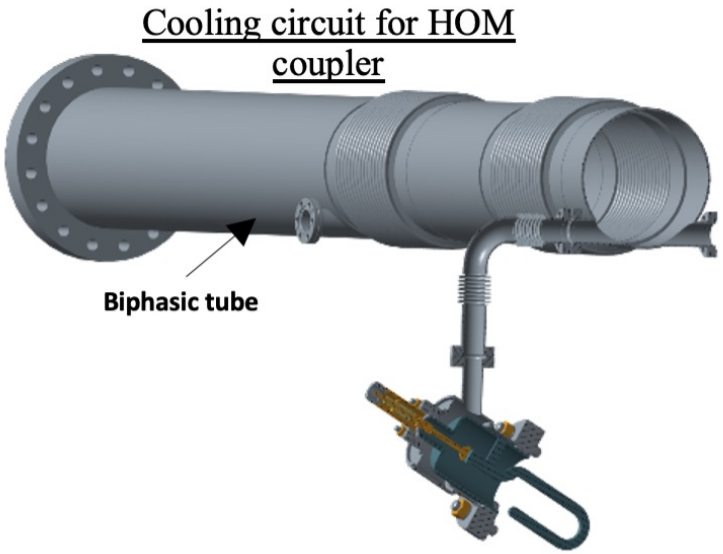
Couplers (TA#3) : status

WP4 leaders: Y. Gómez-Martínez (CNRS-LPSC), D. Giove (INFN)

- **Higher Order Mode (HOM) coupler**
  - Several configurations of HOM couplers were studied as HOM power produced in a high current multi-turn ERL can be high*
  - Based on the RF design of the 802 MHz hook coupler for HL-LHC developed by CERN, optimized by CNRS/IJCLab for PERLE
    - optimum transmission of unwanted modes (TE111&TM110) with efficient rejection of the fundamental mode
    - **2 hook per cavity is selected**
  - RF simulations, thermal calculation and mechanical integration done
  - **Fabrication is underway**



HOM couplers : hook design



c/o P. Duchesne (IJCLab)

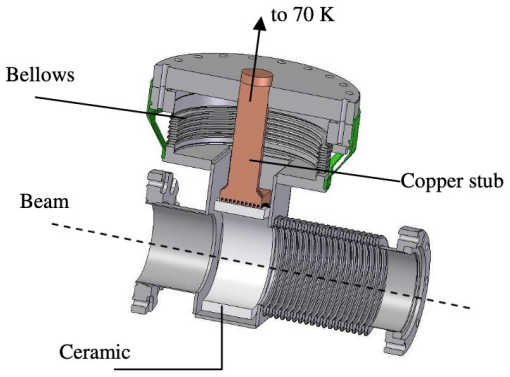
*C. Barbagalo, "Design and optimization of higher order mode couplers for the superconducting cavities of the PERLE energy recovery linac", PhD thesis, Université Paris-Saclay (2024), 2024UPASP092, tel-04805279

Couplers (TA#3) : status

WP4 leaders: Y. Gómez-Martínez (CNRS-LPSC), D. Giove (INFN)

Technologies

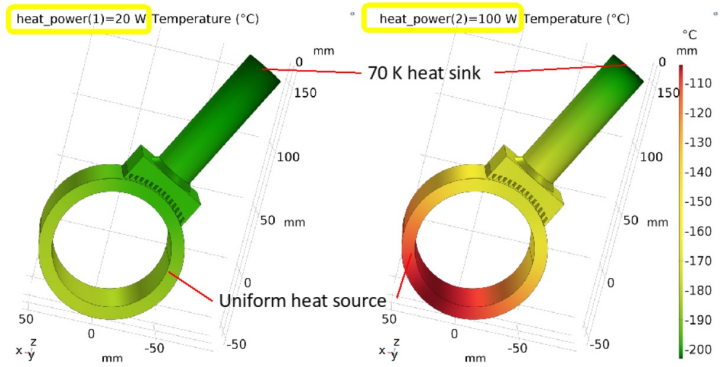
- **Beam Line Absorbers (BLAs)**
  - **BLAs at 1.3 GHz are developed for the BriXSino ERL by INFN (D. Giove)**
    - Cooling by conduction through copper stubs directly at the cryogenic temperature
    - Specifications defined and design of XFEL/LCLS-II selected
    - Thermal simulations confirmed that power levels up to 100 W are acceptable
  - **BLAs at 802 MHz are developed for the PERLE ERL by CNRS**
    - Simulations of thermal power deposition, up to 150 W, are in progress for a design similar to the one by INFN
  - **For both frequencies, RF simulations to assess BLA absorption performance**
    - Including ceramic Sienna Technologies STL-150D14 (cryogenic compatible) and Kyocera SC1000



Beam Line Absorber of EU-XFEL

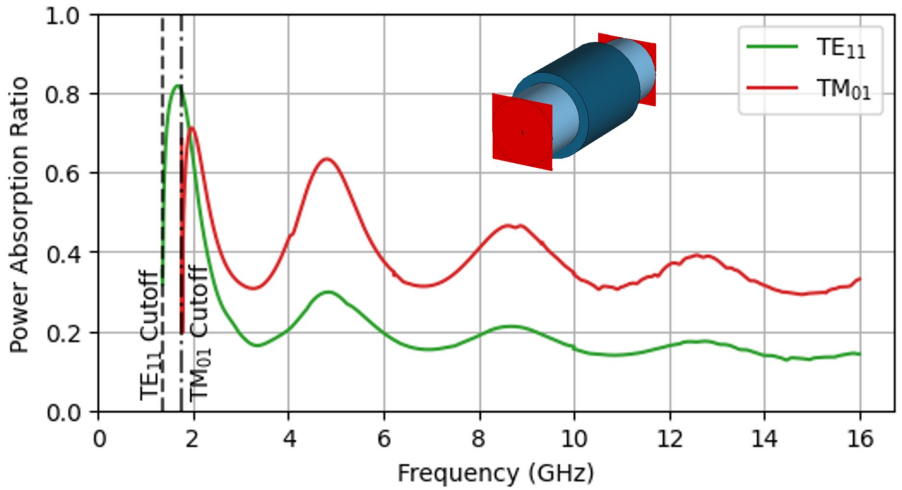
From N. Mildner *et al.,* Proc. SRF2005, Ithaca, NY, USA

Courtesy of D. Giove (INFN)



Thermal model BLA for BriXSino (COMSOL)

Simulation of BLA absorption ratio in a beam pipe section for STL150D for TE11 and TM01 modes (c/o A. Perez Ruiz et al)



A. Perez Ruiz *et al.,* Dielectric Characterization of BLA Samples for Next-Generation High Intensity Electron Beam SRF Accelerators, IPAC'26 proc., doi: 10.18429/JACoW-IPAC2026-MOP7022

Cryomodule design: scope & status

WP5 leaders : N. Elias (ESS), V. Parma (CERN)

Integration

- **Goal : Implementation of technologies in the design of a new energy-saving cryomodule**
  - **Address common engineering issues to integrate the iSAS technologies in a parametric cryomodule design**

- **Compilation of lessons learned from the ESS cryomodule performed*, including**
  - design, manufacturing, assembly, testing and sustainability aspects

- **Benchmark of performance of 6 facilities (SNS, LHC, PIP-II, XFEL, LCLS-II and ESS) for high-beta elliptical cryomodules (400 MHz - 1.3 GHz)****
  - comparison of cryogenic system and thermal management, cryomodule design, commissioning, operation and reliability

- **Collected data will translate into practical engineering strategies to build a parametric tool for cryomodule design with sustainability criteria (energy saving, life-cycle, availability, maintainability, repairability …)**

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



ESS cryomodule design

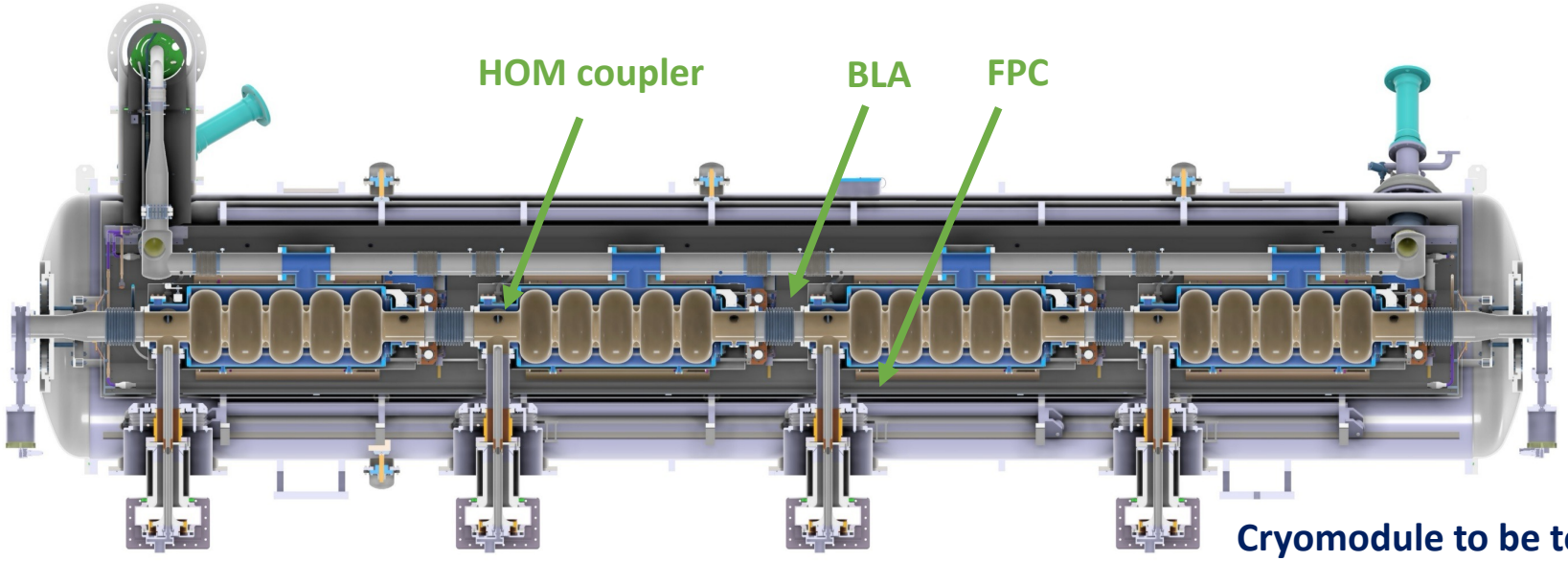
*N. Elias *et al.,* "Lessons Learned from the ESS Elliptical Cryomodule Design and Operation: Paving the way for Sustainable Accelerating Systems (iSAS)", ICEC30-ICMC2026, Daejeon, South Korea, 2026
**N. Elias *et al.,* "Compilation of ESS CM lessons learned and benchmarks from facilities in implementation phase", iSAS deliverable D16 (2026), doi:10.48550/arXiv.2606.24590

Retrofit into existing cryomodule : scope

WP6 leaders : G. Olry (CNRS-IJCLab), S. Berry (CEA)

Integration

- **Goal : implementation of technologies in current and future research accelerators to speed up their deployment**
  - **Retrofit of iSAS technologies into the PERLE cryomodule to demonstrate high current, multi-turn energy recovery**
    - Power coupler, HOM coupler and beam loss absorber developed in WP4
  - 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 …
- **Partners : CNRS/IJCLab CEA, ESS, INFN, Lancaster University**



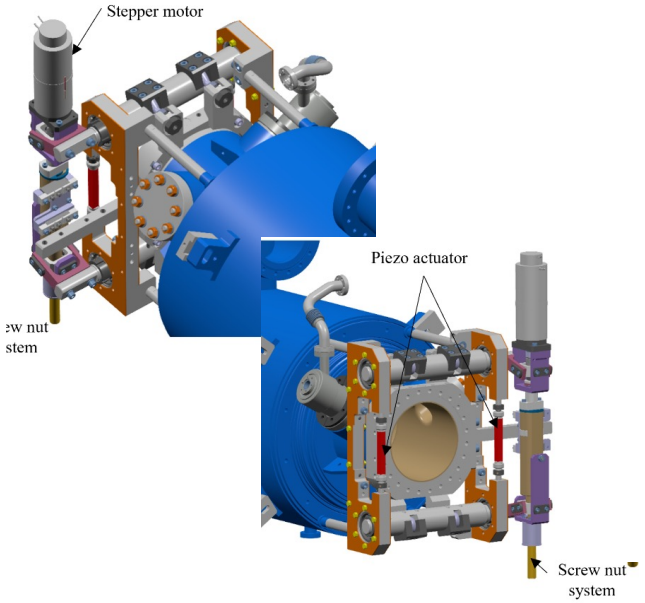
Cryomodule to be tested at PERLE

Retrofit into existing cryomodule : status

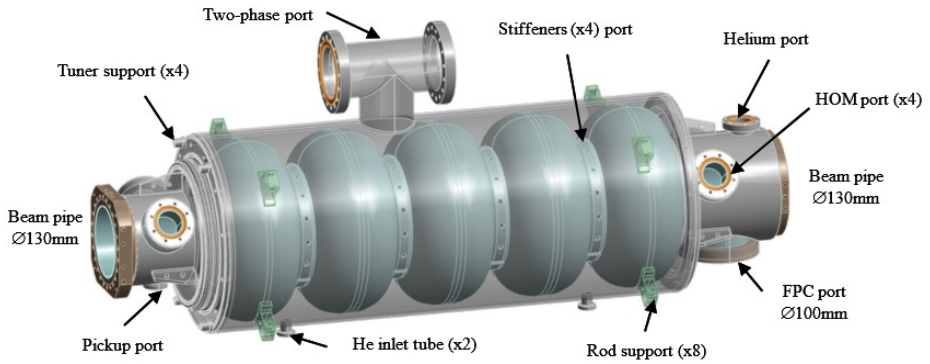
WP6 leaders : G. Olry (CNRS-IJCLab), S. Berry (CEA)

Integration

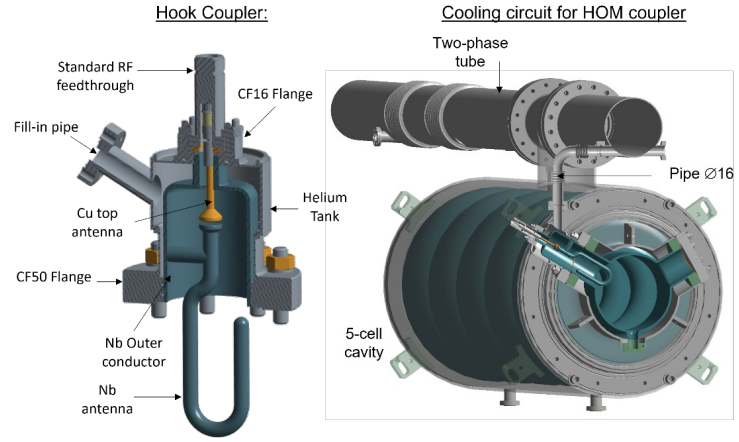
- **Based on the JLab design, the cavity cells were finalized by CNRS/IJCLab**
  - **manufacturing has started**
- **The helium tank was optimized to cool the HOM ports**
- **Preparation of bare cavities will include**
  - heat treatments, field flatness and clean room preparation at IJCLab
  - electro-polishing at CEA/Saclay
- **A first cold test of the bare cavity in a cryostat at INFN and final cold test 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**



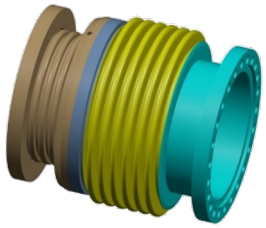
Cold tuning system (c/o S. Blivet, IJCLab)



5-cell jacketed cavity (c/o P. Duschene, IJCLab)



HOM and cooling circuit (c/o P. Duschene, IJCLab)

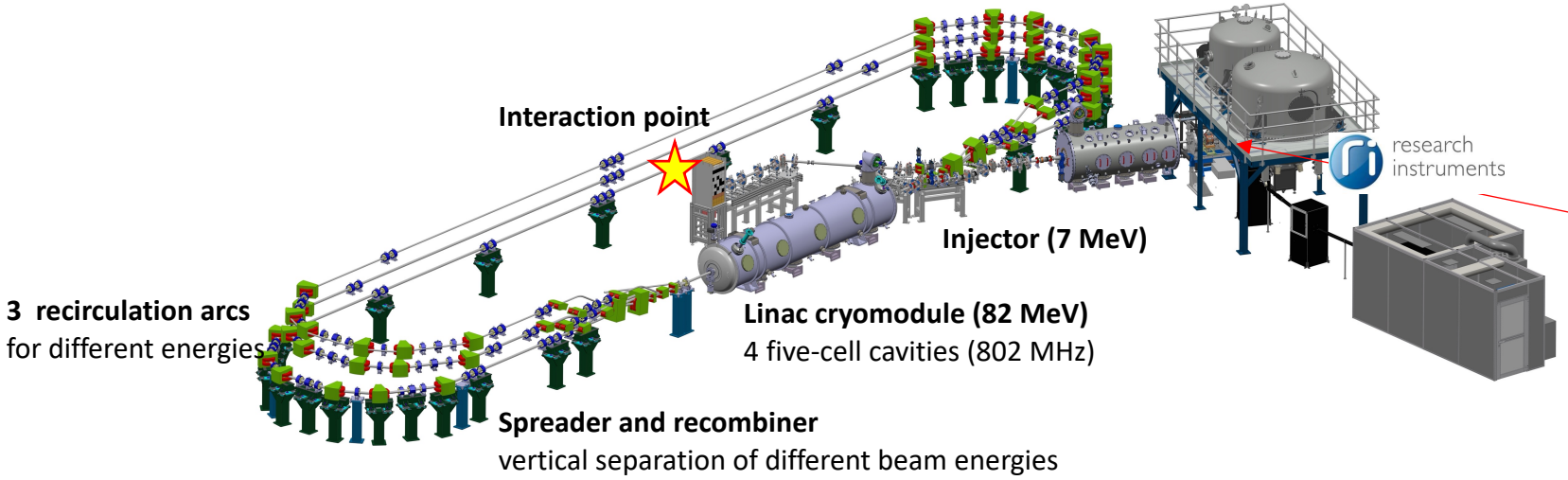


BLA (c/o G. Olivier, IJCLab)

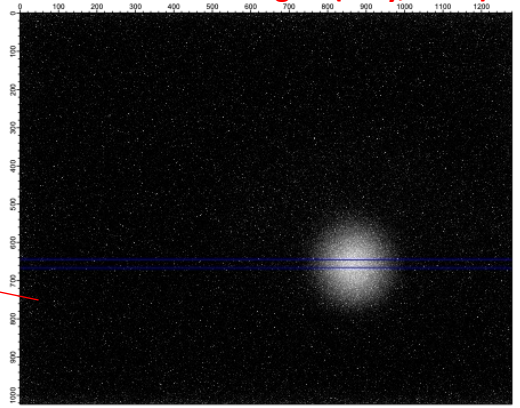
Energy recovery linac, PERLE,
integration facility of iSAS technologies

Integration

- **Powerful Energy Recovery linac for Experiments (PERLE) at IJCLab (Orsay, France)**
  - **Aims to demonstrate energy recovery in multi-MW regime : electrons, 20 mA, 250 MeV over 3 loops (P_{beam} = 5 MW)**
- **Phase 1 - ERL 1 tour : 20 mA, 89 MeV (P_{beam} = 1,8 MW) under construction : iSAS cryomodule to be tested at PERLE**
  - **First beam out the photogun : 5 mA**
    - **DC gun operated with pure N_2 as insulating gas, no use of SF_6 (most potent greenhouse gas) or fluorinated gas**
- Beam dynamics to evaluate and optimize the energy recovery process while mitigating instabilities by EPFL (WP5)
- Consumption model of PERLE underway, to be compared to classical solutions (LPSC)



First beam out of gun (May, 2026)



5 mA measured out the gun (August)

J. Michaud *et al.,* "Status of the Beam Dynamics studies for the PERLE ERL", IPAC'25 proc., doi: 10.18429/JACoW-IPAC2025-MOPS041
F. Bouly *et al.,* "Preliminary power balance assessement of the PERLE energy recovery linac", IPAC'26 proc., doi: 10.18429/JACoW-IPAC2026-MOP7179
F Bouly *et al.,* "RF coupling choices, power requirements and impact on transients for PERLE", IPAC'26 proc., doi: 10.18429/JACoW-IPAC2026-WEP6126
T. Pieloni *et al.,* "Recirculation modelling for ERL", IPAC'26 proc., doi: 10.18429/JACoW-IPAC2026-WEP5145
M. Baylac *et al.,* "High current photogun for the energy recovery linac PERLE », IPAC'26 proc., doi:10.18429/JACoW-IPAC2026-THP2104

Implementation into industrial solutions

WP7 leaders: O. Azzolini, G. Keppel (INFN)

Industry

- **Goal : Establish and foster the relations with industry towards co-development**
  - Engage with industry in the early phases of the R&D
  - Increase the Technology Readiness Level (TRL) of iSAS developments
  - Opportunities for dissemination

- A website lists competencies for both industrial and academic partners*
- 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
- Industry board is set up

- **Partners : INFN, CNRS**



*Industry: https://web.infn.it/isas/industrial-section/
** https://indico.ijclab.in2p3.fr/event/11291/timetable/#20250314

Conclusions

- iSAS is a large consortium* of 12 research institutes and 6 industrial companies
- Within iSAS, impactful technologies for SRF are and will be developed, validated and integrated
- Energy saving metrics for the technologies will be measured (or determined) by the end of the project
- Very large R&D program ongoing** by all the participants of the consortium
- Direct impact on current research infrastructures and their upgrades
- On the long term, these technologies aim to reduce significantly the energy footprint of future SRF accelerators

Thanks to all the iSAS collaborators and thank you for your attention



Work supported by funding from European Union's program EU HORIZON-INFRA-2023-TECH-01-01 under GA n°101131435

Funded by the European Union

* https://isas.ijclab.in2p3.fr/contributors/

** M. Baylac *et al.,* "Innovate for sustainable accelerator systems: main progress on the iSAS project », IPAC'26 proc., doi:10.18429/JACoW-IPAC2026-TUI7T01

BACK UP

Energy saving metrics

Metric

- **Energy saving metrics for the technologies developed within iSAS (WP1-WP4)**
  - **Keep it simple: metrics limited to operational power (cost)**

- **We compare the power consumption with and without the « iSAS technology » (WP1-WP4) in similar conditions***
  - Measured (or expected) wall plug power consumption (kW)
  - Comparison of the consumption with and without the device, or the option or optimization of the device
  - Conditions : the use case to be specified for each technology

- **FE-FRT : measure RF power (TESLA cavity, CW, 16-20 MV/m), compare reference cases** (converted to wall plug power)
  - **Comparison FE-FRT and piezo system**, aim for highest Q_L with FE-FRT

- **LLRF cannot be switched OFF, but different options of the LLRF system can be turned ON/OFF, or adjusted**
  - **Measurements will be done with and without the LLRF optimization**

- **Nb_3Sn on Cu: evaluation of dissipated power per cell : P_{acc} per cell @ 1 MV/m by**
  - **With the surface resistance of Nb_3Sn (measurement of Q_0 vs E_{acc}), estimate the operational cost at 4 K and compare it to bulk Nb 2 K (same gradient)**

- **Couplers : calculation of the electrical power consumption**
  - **Comparison existing design and couplers with different cooling regimes**

*M. Baylac *et al.*, "iSAS WP9 - task 9.5 - Milestone 32: verifiable metric for energy-saving performances", milestone 9.5 (2025), doi: 10.48550/arXiv.2605.29576

Energy saving metrics – 1/2

Metric

- **Energy saving metrics for the technologies developed within iSAS (WP1-WP4)**
  - **Keep it simple: metrics limited to operational power (cost)**

- **We compare the power consumption with and without the « iSAS technology » (WP1-WP4) in similar conditions***
  - Measured (or expected) wall plug power consumption (kW)
  - Comparison of the consumption with and without the device, or the option or optimization of the device
  - Conditions : the use case to be specified for each technology

- **FE-FRT : measure RF power (TESLA cavity, CW, 16-20 MV/m), compare reference cases** (converted to wall plug power)
  - **Reference tests: with piezo system**, at conservative $Q_L = 1.10^7$ and high QL = 5.10^7
  - **Comparison with FE-FRT** : high Q_L with FE-FRT and aim for highest Q_L

- **LLRF cannot be switched OFF, but different options of the LLRF system can be turned ON/OFF, or adjusted**
  - **Measure the accelerator AC consumption** with and without the applied LLRF optimization (instantaneous AC consumption)
  - **Measure the peak and the integrated forward RF power** with and without the LLRF optimization (RF power usage)
  - Compute the AC-to-RF efficiency of the high-power source (i.e. SSA) with and without working point optimization of LLRF
  - Provide examples of improved up-time or trip recovery time thanks to LLRF supervisory control and fault diagnostics
  - Measurements at different facilities (DESY, HZB, CNRS) with different test conditions (CW, pulsed, beam or not..)

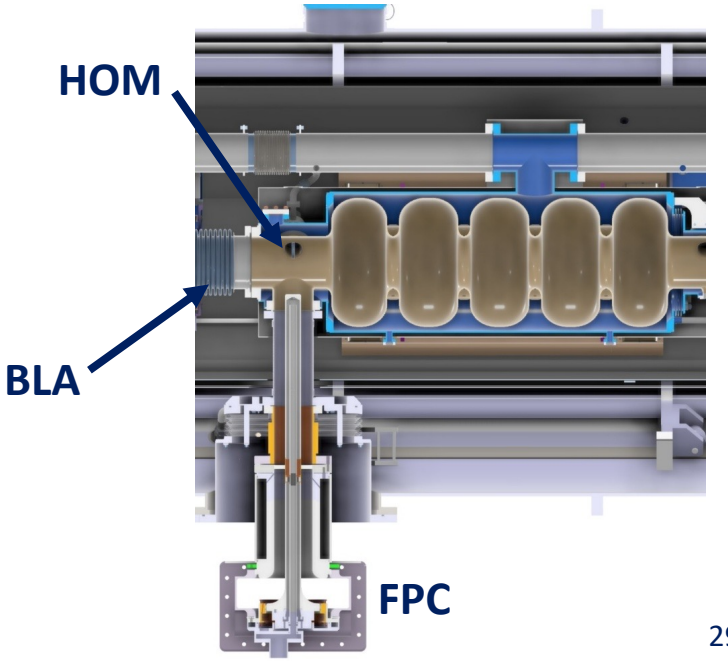
M. Baylac *et al.*, "iSAS WP9 - task 9.5 - Milestone 32: verifiable metric for energy-saving performances", milestone 9.5 (2025)
M. Baylac *et al.*, "Innovation for sustainable accelerating systems: iSAS project" in Proc. 16th Int. Conf. on Heavy Ion Accelerator Technology (HIAT'25), East Lansing, MI, USA, Jun. 2025, paper TUZ01, pp. 107-111

Energy saving metrics – 2/2

Metric

- **Nb_3Sn on Cu: evaluation of dissipated power per cell : P_{acc} per cell @ 1 MV/m by**
  - Measurement of Q_0 *vs* E_{acc} via an RF test ➔ deduce the surface resistance
  - From the surface resistance of Nb_3Sn, estimate the operational cost at 4K and compare to bulk Nb 2K same gradient
  - Study cases
    - 1.3 GHz cavity baseline by I.FAST
    - new cavity optimized at the end of ISAS
    - QPR data already available

- **Couplers : calculation of the electrical power consumption with existing design and compare with different cooling regimes**
  - **FPC**
    - Comparison between cooling regimes (turbulent/laminar) with existing design
    - Comparison between the current one-loop design and a two-loop design (50 K & 5 K)
  - **HOM**
    - HOM cooled at 2 K (current design) and HOM cooled at 5 K with an additional circuit
  - **BLA**
    - BLA at 300 K
    - BLA cooled at 70 K
    - BLA cooled at 70 K with thermalization at 5 K



FE-FRT (TA#1) : metric

WP1 leaders: A. Neumann (HZB), A. Macpherson (CERN)

- **The metric to estimate the savings is the**
  - **invested RF power to drive the cavity at a given field for microphonics compensation,** converted to wall-plug power

- **The study case : TESLA cavity (1.3 GHz) in CW mode at 16-20 MV/m operated with FE-FRT or piezo tuner**
  - **Reference test 1: Operation at a typical, conservative loaded quality factor of e.g. 1.10^7 with piezo control**
    - Measure microphonics detuning, field stability with LLRF system, RF power
  - **Reference test 2: Repeat the first test by tuning the coupler to higher loaded Q of 5.10^7 with piezo control**
    - Validate the beforehand measured parameters
  - **FE-FRT demonstration: Operate the cavity with FE-FRT, demonstrate microphonics detuning compensation and stable field and aim for the highest loaded Q**
    - Measure the RF power level and dissipated power in FRT (temperature sensors)

Optimized LLRF (TA#1) : metric

WP2 leaders : J. Branlard, C. Schmidt (DESY)

- **LLRF cannot be switched OFF for the sake of comparing power consumption**
  - **Yet different options of the LLRF system can be turned ON/OFF or adjusted ➔ several metrics**

Metrics	How to measure
Instantaneous AC consumption	**Measure the accelerator AC consumption with and without the applied LLRF optimization** for a direct comparison. This can be measured at the **modulators** for example.
RF power usage	**Compare the peak and the integrated forward RF power with and without the LLRF optimization**.
AC-to-RF efficiency	**Compute the AC-to-RF efficiency of the high-power source** (i.e. SSA) with and without optimized working point by the LLRF
Accelerator up-time, or trip recovery time	**Provide examples where the accelerator up-time or trip recovery time** has been improved following the implementation of the LLRF supervisory control and fault diagnostics.

- **Study case**
  - **Different facilities offer different test options (CW, pulsed, presence of beam, narrow bandwidth…) : DESY, CNRS, HZB**

4 K cavities (TA#2) : metric

WP3 leaders : C. Pira (INFN), O. Malyshev (STFC)

- **Proposed metric : AC power dissipation of each cavity cell**
  - **P_{acc} per cell @ 1 MV/m**

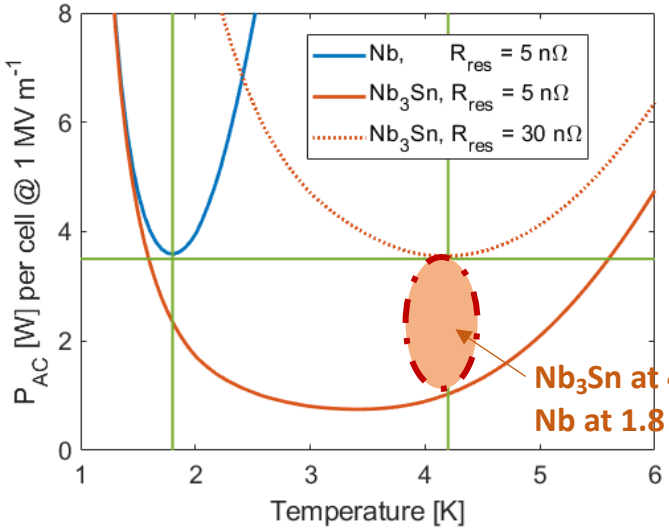
- **Methodology**
  - **Measurement of Q_0 *vs* E_{acc} via an RF test**
    - ➔ **deduce surface resistance R_s** via $Q_0 = G/R_s$

    ($R_s = R_{BCS}(T) + R_{res}$ determines the efficiency of the cavity)

  - Determine the residual resistance from this surface resistance
    - ➔ **estimate the grid power of Nb_3Sn at 4K**

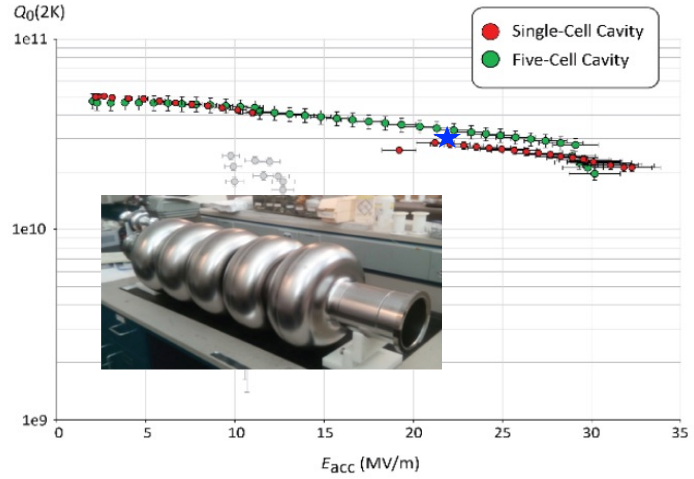
  - **Comparison with bulk Nb at 2 K at same gradient**

- **Study case**
  - QPR data
  - 1.3 GHz cavity baseline by I.FAST
  - **new cavity optimized at the end of ISAS**



Calculated AC power dissipation of Nb and Nb_3Sn cavity cells at 1.3 GHz

C. Antoine et al., "Thin-film SRF roadmap", I.FAST deliverable report D9.1, 2025. doi:10.5281/zenodo.14731411



Bulk Nb cavity performance at 802 MHz (Q_0 vs E_{acc} curve)

F. Marhauser *et al.*, "802 MHz ERL cavity design and development", in Proc. IPAC2018, Vancouver, doi :10.18429/JACoW-IPAC2018-THPAL146

Couplers (TA#3) : metric

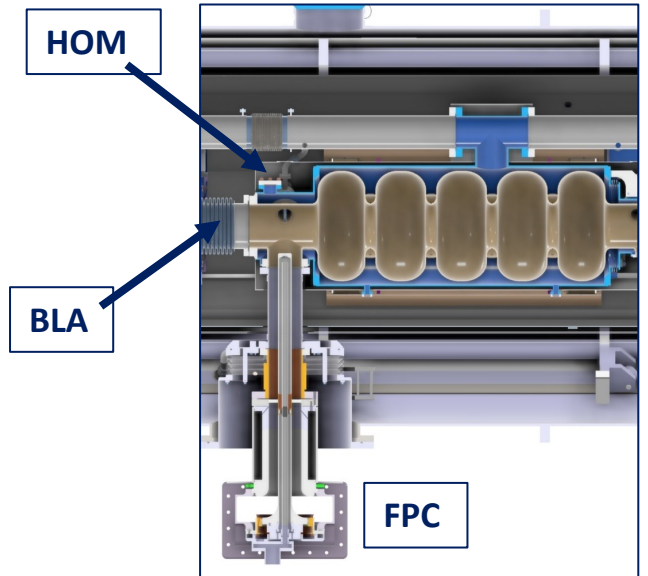
WP4 leaders: Y. Gómez-Martínez (CNRS-LPSC), D. Giove (INFN)

Energy saving will be evaluated by comparing different cooling regimes:

- **FPC : calculation of the electrical power consumption, with existing coupler design**
  - Comparison between cooling regime (turbulent/laminar) with existing design (CERN)
  - Electrical consumption considering the inlet line to the couplers with feedback from ESS (CERN)
  - Comparison between a two-loop design (50 K & 5 K) and the **current one-loop design** (IJCLab)

- **HOM : calculation of the electrical power consumption and comparison of 2 cooling options**
  - **HOM cooled at 2 K (current design)**
  - HOM cooled at 5 K with an additional circuit

- **BLA : calculation of the electrical power consumption and comparison of 3 cooling options (under study)**
  - BLA at 300 K
  - BLA cooled at 70 K
  - BLA cooled at 70 K with thermalization at 5 K



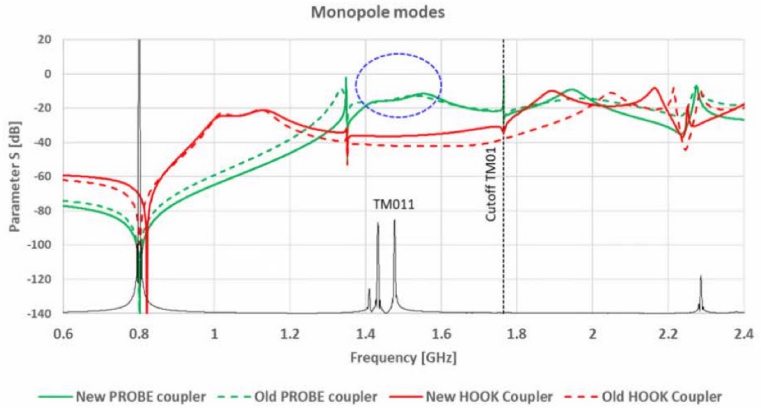
Couplers (TA#3) : status

WP4 leader : Y. Gomez Martinez (CNRS-LPSC)

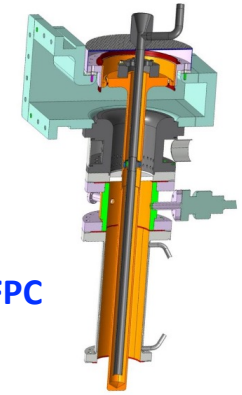
- **Status of HOM coupler**
  - optimal geometry selected and optimized (800 MHz)
  - ➔ reduced number of HOM couplers required per cavity (2)



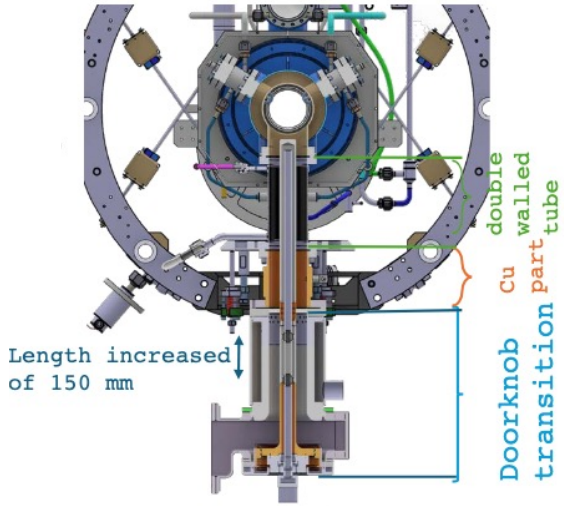
Hook coupler



- **Status of Fundamental Power Coupler (FPC)**
  - Design : from SPL project (CERN)
  - Adaptation underway for the mechanical integration in the PERLE cryomodule
  - HV conditioning protocole under discussion

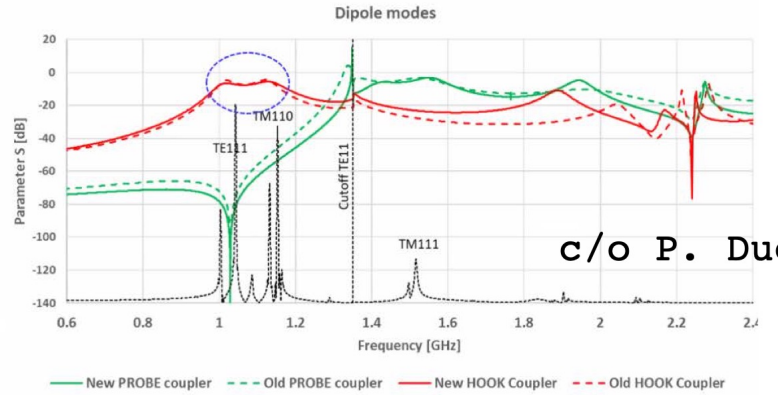


SPL FPC



FPC proposed in the WP6 cryomodule

c/o S.Blivet & G. Olivier



c/o P. Duchesne

Cryomodule design: status

WP5 leaders : N. Elias (ESS), V. Parma (CERN)

- **Compilation of lessons learned from the ESS cryomodule performed, including**
  - design, manufacturing, assembly, testing and sustainability aspects

- **Survey launched to benchmark the performance across 6 facilities (SNS, LHC, PIP-II, XFEL, LCLS-II and ESS) for high-beta elliptical cryomodules (400 MHz-1.3 GHz)**
  - Comparison of cryogenic system and thermal management, cryomodule design, commissioning, operation and reliability

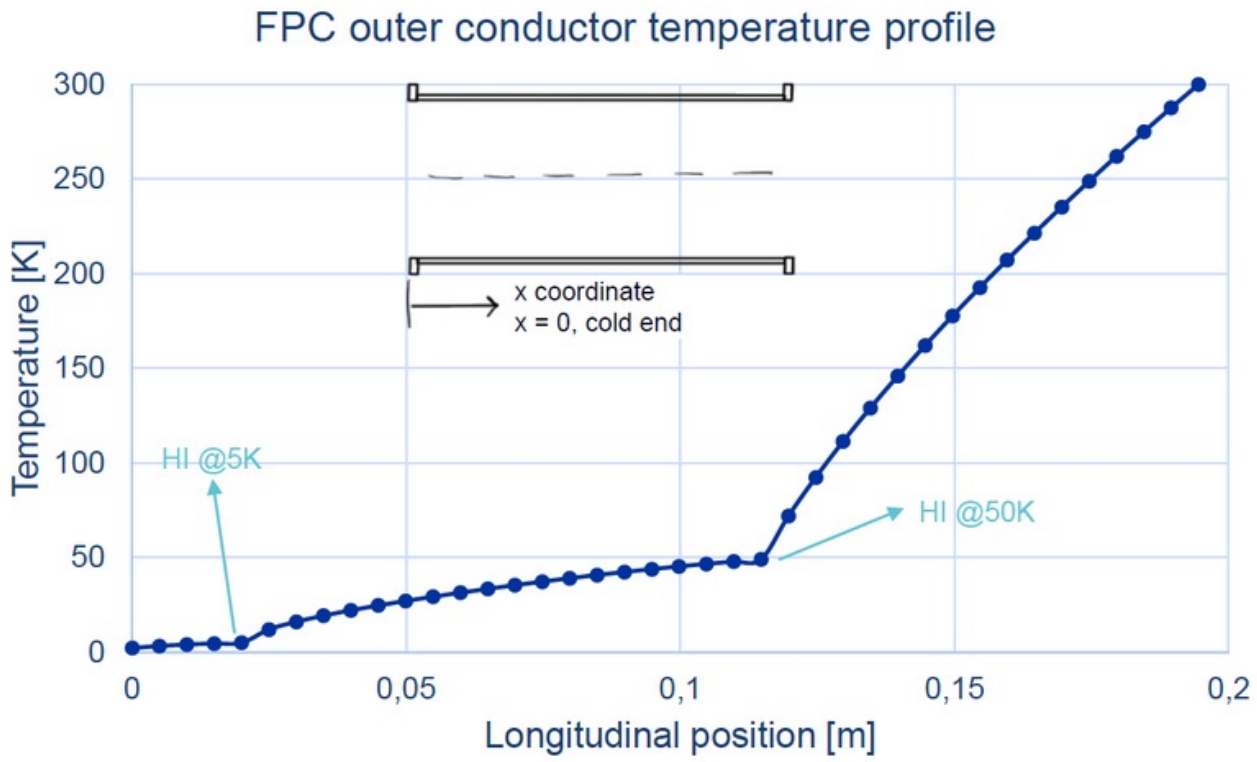
- **Main conclusions are:**
  - **Beam and RF parameters drive the design, while cryogenic efficiency impacts the overall sustainability,**
  - **High availability and long-term reliability are primary metrics for sustainability**
  - **Common trends (multi-level temperature architectures, modular cryogenic segmentation, accessibility) have emerged as industry standards**

- **A practical engineering strategies will be built, to build a parametric tool for cryomodule design with sustainability criteria**
  - **energy saving, life-cycle, availability, maintainability, repairability …**

Results : FPC cooling scheme
Comparison with heat intercepts

	RF on (full reflection) Inlet at 5K	RF on (full reflection) Heat intercepts
Heat released to the bath	0.5 W	0.5 W
Liquefaction capacity	23.1 mg/s	-
Equivalent refrigeration load at 4.5K	470 W	-
Heat released @5K	-	6.3 W
Heat released @50K	-	28.7 W
Total cryogenic cost [W_{el}] (*)	0.9 kW	2.21 kW
RF power dissipated	4.8 W	5.28 W

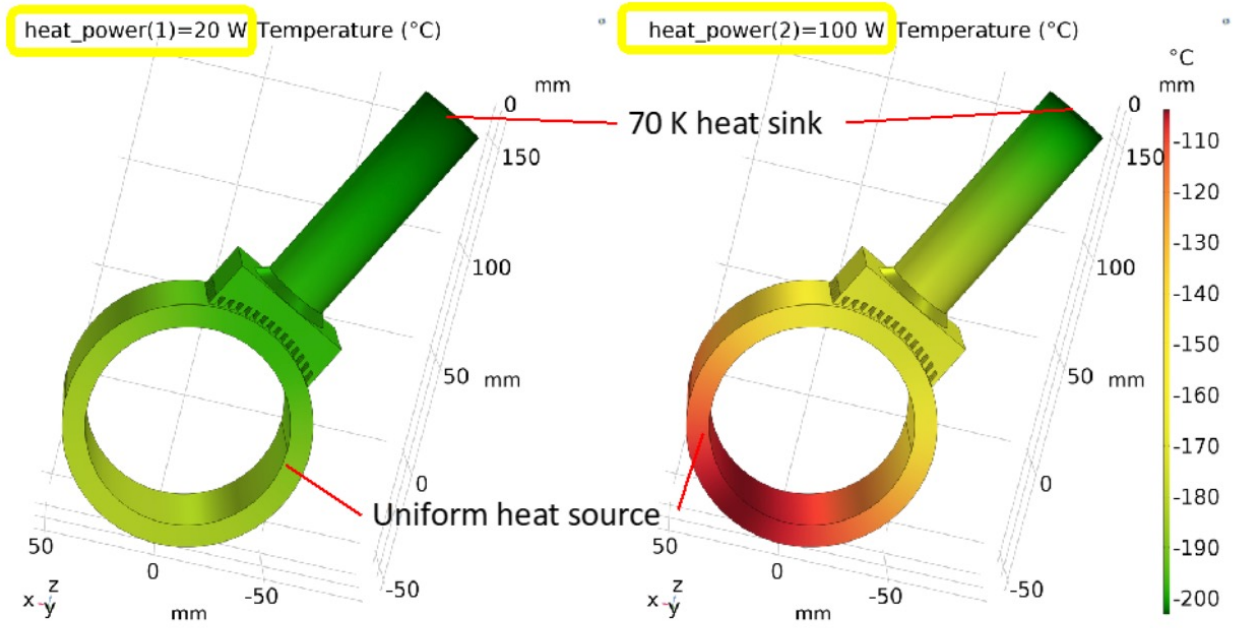
Values for a single coupler
(*) W_{el} calculated assuming 15% of the Carnot efficiency for heat released at 2K and 30% for heat release between 4K and 50K



The solution with active helium cooling (inlet at 5K) results in an energy saving of 65% compared to the heat intercepts. The higher the inlet temperature of the helium in the DWT the smaller the energy saving!

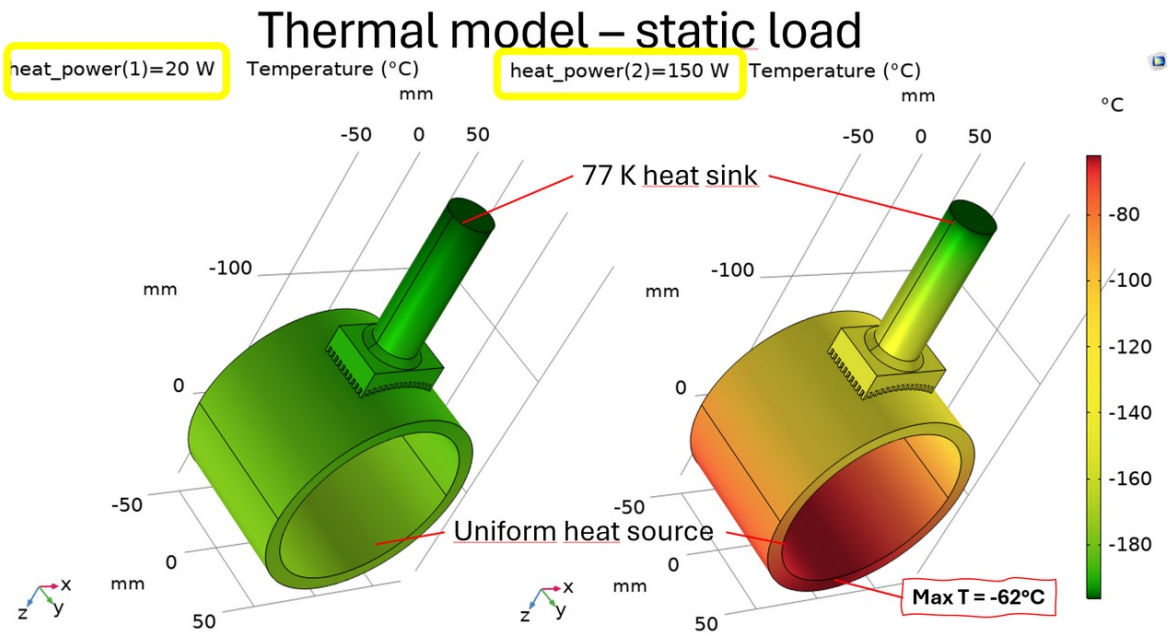
BLA thermalization

A : BriXSino



BLA for BriXSino at 70 K

B: PERLE



BLA for PERLE under study

HOM and BLA for PERLE

In a cavity (with HOM couplers) : power generated by the HOMs is about 110 W for 120 mA
Approximately 80% of this power goes out of the cavity and must be absorbed by BLA
20% must be absorbed by HOM couplers (few W per coupler)

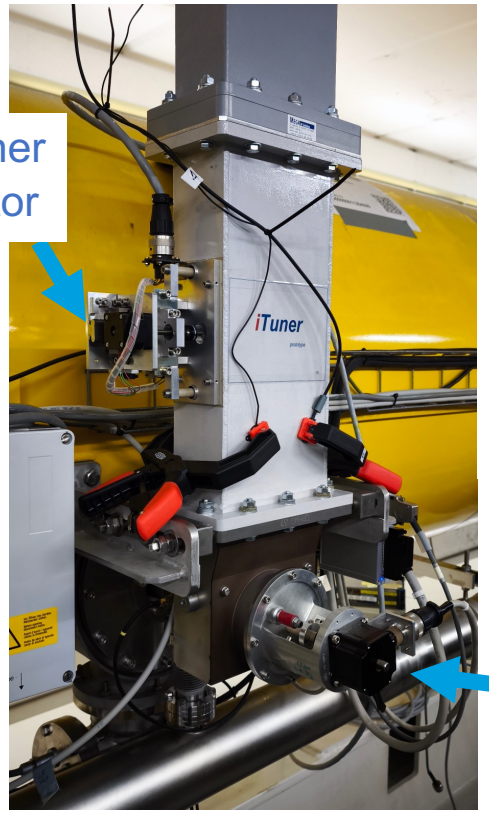
Five-cell cavity at 801.58 MHz - 2P2H damping scheme with BLAs										
	P_{tot}	$P_{P,(1)}$	$P_{H,(2)}$	$P_{P,(3)}$	$P_{H,(4)}$	$P_{FPC,(5)}$	$P_{bp,(6)}$	$P_{bp,(7)}$	$P_{BLA,(8)}$	$P_{BLA,(9)}$
[W]	141.09	1.47	0.93	1.58	0.31	18.83	23.74	46.65	16.05	31.53
[%]		1.04	0.66	1.12	0.22	13.35	16.83	33.06	11.37	22.35
Five-cell cavity at 801.58 MHz - 4DQW damping scheme with BLAs										
	P_{tot}	$P_{D,(1)}$	$P_{D,(2)}$	$P_{D,(3)}$	$P_{D,(4)}$	$P_{FPC,(5)}$	$P_{bp,(6)}$	$P_{bp,(7)}$	$P_{BLA,(8)}$	$P_{BLA,(9)}$
[W]	107.7	2.43	2.43	2.62	2.62	17.10	22.65	32.99	10.12	14.74
[%]		2.25	2.25	2.43	2.43	15.88	21.03	30.64	9.40	13.69

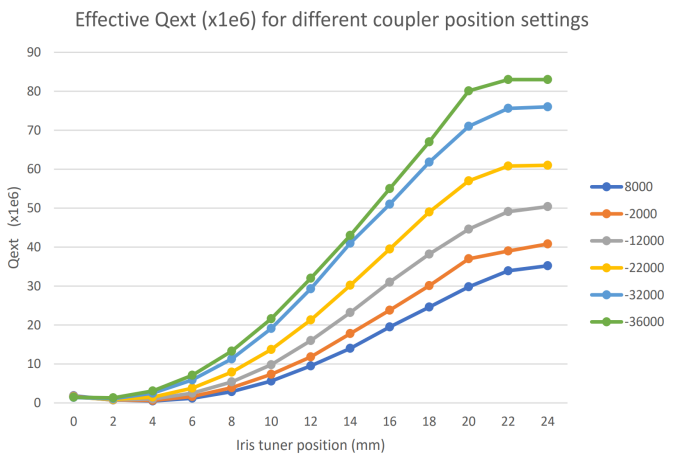
*C. Barbagalo, “Design and optimization of higher order mode couplers for the superconducting cavities of the PERLE energy recovery linac”, PhD thesis, Université Paris-Saclay (2024), 2024UPASP092, tel-04805279

Smart LLRF (TA#1) : status 2025
WP2 leader : J. Branlard (DESY)

- **Status**
  - **Development of 2 prototypes (DESY) with iris tuner**
    - Extending the Qext range
  - **Vibration analysis**
    - Deep learning of cavity detuning under study at HZB
  - **Optimizing the Lorentz force detuning compensation at EuXFEL**
  - **Roadmap to integrate FE-FRT in the LLRF**
    - link with WP1

Iris-tuner (variable)





Courtesy Mariusz Grecki