iSAS :
status and energy saving metric

M. Baylac (CNRS-LPSC)

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

Context

- Particle accelerators are exceptional instruments (research, applications), but in a context of energy savings and sustainability
  - **minimizing the energy consumption of future accelerators is an unavoidable challenge,** underlined by the ESPP (2020)

- **Project « Innovate for Sustainable Accelerating Systems (iSAS)» approved and launched in 2024**
  - EU programs HORIZON-INFRA-2023-TECH-01 call dedicated to “*New technologies and solutions for reducing the environmental and climate footprint of Research Infrastructures* »
  - Scientific coordinator Jorgen D’Hondt (Nikhef), project coordinator Achille Stocchi (CNRS-IJCLab)

- **Ressources and partners**
  - ~5 M€ funded from Horizon Europe for a total budget of ~13 M€
  - HR ~1000 person-months spread over 4 years
  - Partners : 12 laboratories/institutes and 6 industrial companies

iSAS

Innovate for Sustainable Accelerating Systems

iSAS: Innovate for Sustainable Accelerating Systems

The objective of iSAS is to innovate those technologies 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

Lode Vanhecke joins iSAS at the EPFL

Andrei Maalberg joins iSAS as a PostDoc

Related topic: ERL4ALL to extend the reach

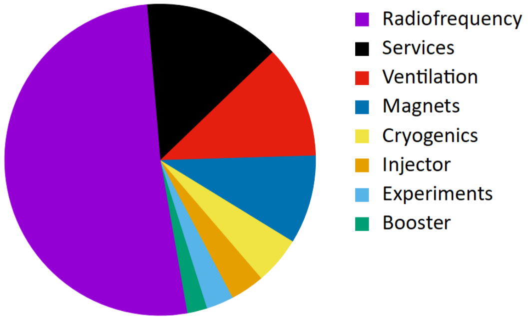
https://isas.ijclab.in2p3.fr/

R&D within the scope of iSAS

- **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)

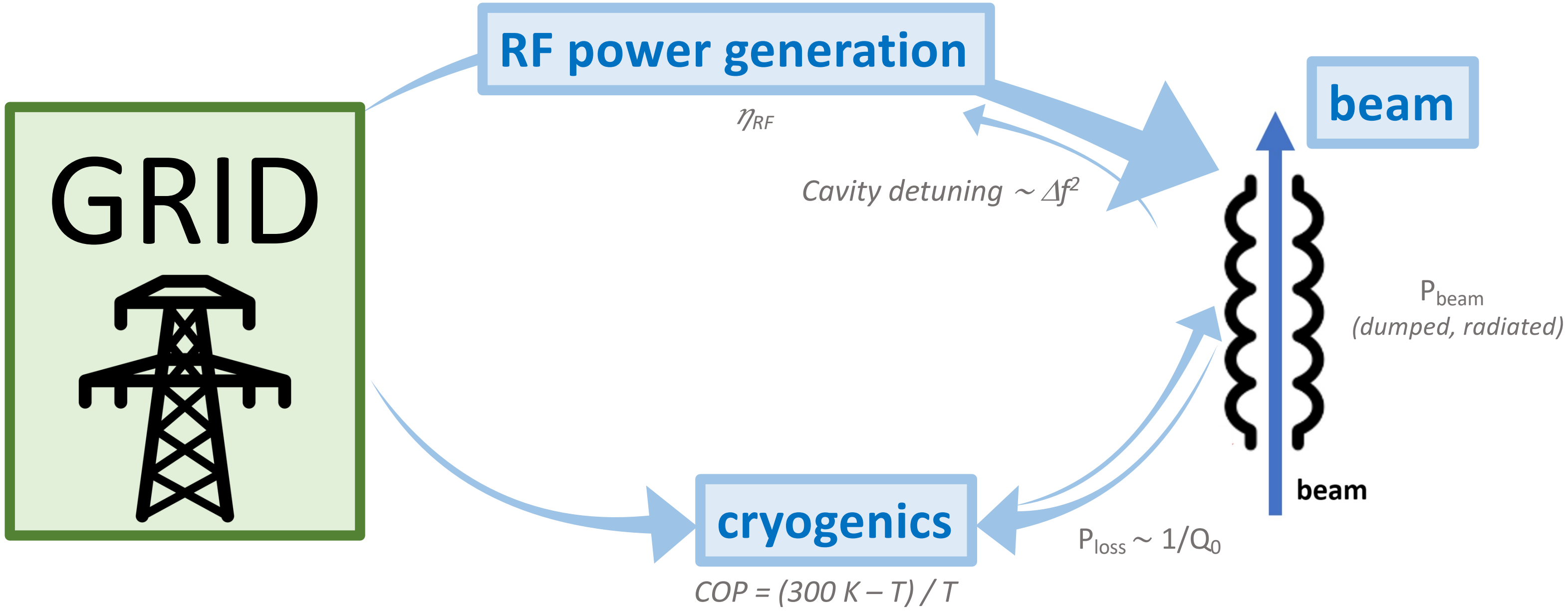
- **iSAS will mainly concentrate on the energy savings from the RF**
  - Complementary to meaningful programs for energy savings on high efficiency magnets, high efficiency RF sources, reuse of RF heat …

- **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

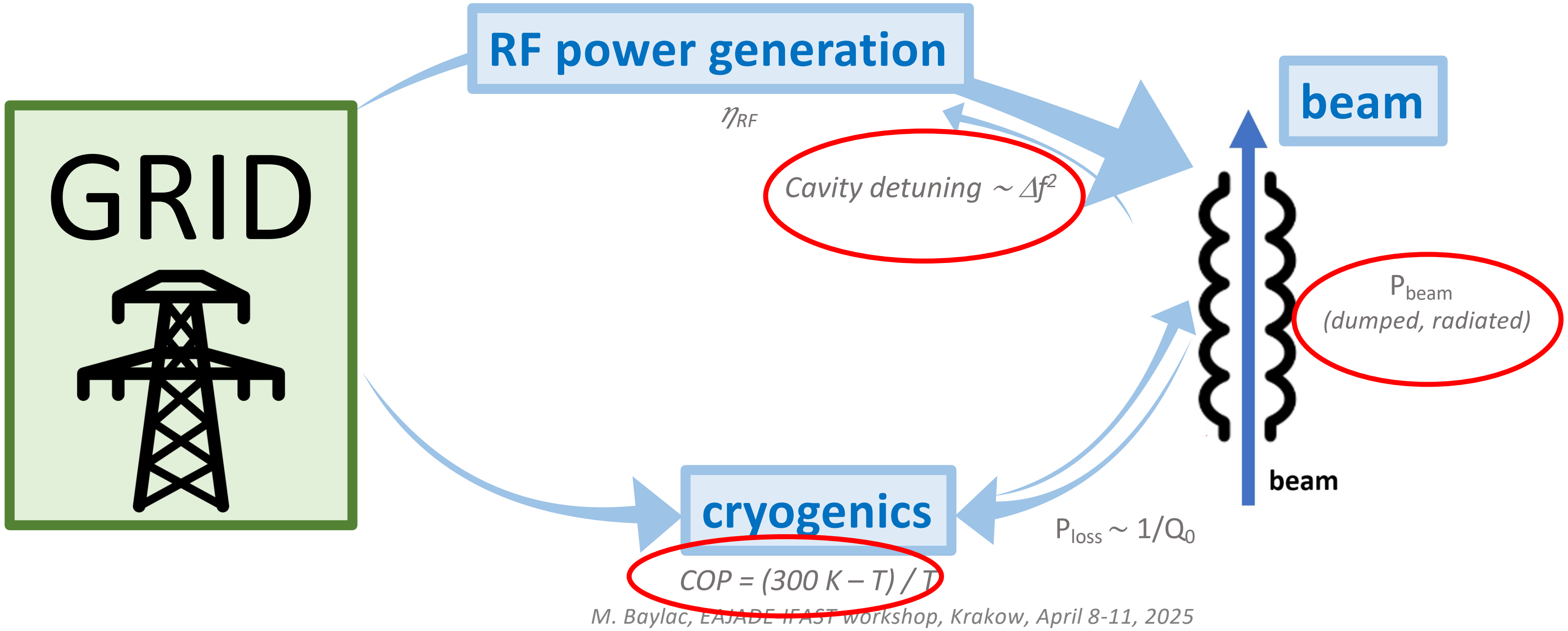
Sources of power inefficiencies

- **Multiple sources impacting the grid-to-beam power efficiency :**
  - RF power source efficiency : η_{RF}
  - RF load by detuned cavities
  - Cavity cryogenic loss : $P_{loss} \propto 1/Q_0$
  - Generation of cryogenics : COP
  - Loss of the beam power : P_{beam}



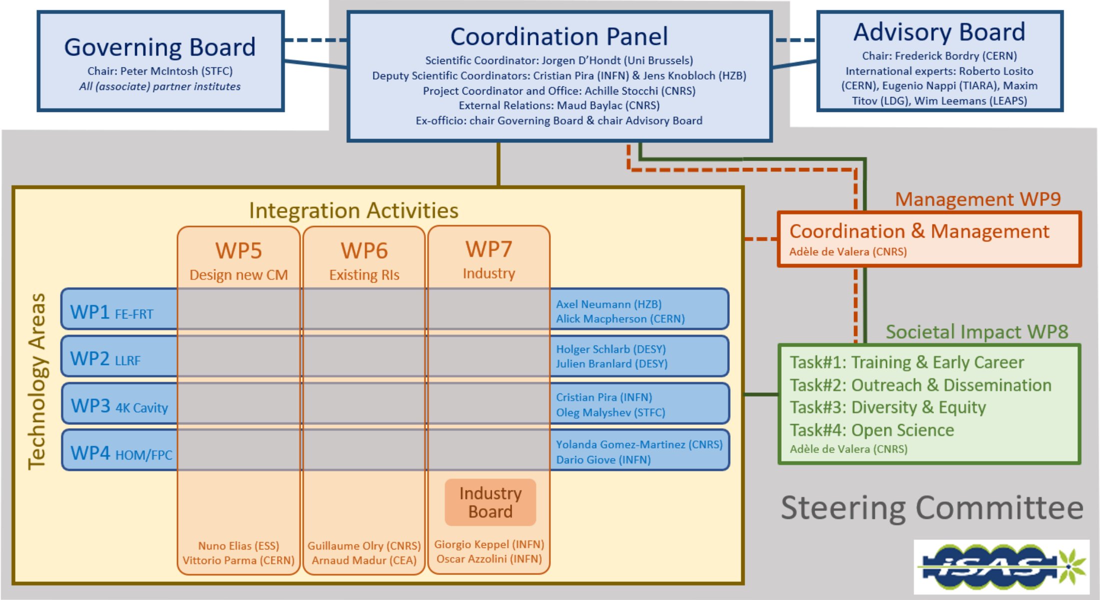
Sources of power inefficiencies and mitigations

- **Multiple sources of power in-efficiency can be adressed by mitigation technologies**
  - 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 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 (ERL)** → **iSAS technology area (TA#3)**



Scope of iSAS

- **Development of 4 technologies** ➔ ***Technology Areas (TA)***
  - WP1 : Ferro-Electric Fast Reactive Tuners (FE-FRT) (TA#1)
  - WP2 : Low Level RF controls (LLRF) (TA#1)
  - WP3 : Nb_3Sn on Cu films for 4.2 K cavity operation (TA#2)
  - WP4 : Couplers, HOM and FPC (TA#3)
- **Implementation of these 4 Technology Areas** ➔ ***Integration Activities (INT)***
  - WP5 : In the design of a new energy-saving cryomodule (INT#1)
  - WP6 : In current and future research infrastructures accelerator (INT#2)
  - WP7 : Into industrial solutions (INT#3)



Governing Board
Chair: Peter McIntosh (STFC)
All (associate) partner institutes

Coordination Panel
Scientific Coordinator: Jorgen D'Hondt (Uni Brussels)
Deputy Scientific Coordinators: Cristian Pira (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: Roberto Losito (CERN), Eugenio Nappi (TIARA), Maxim Titov (LDG), Wim Leemans (LEAPS)

Integration Activities
WP5 Design new CM – Nuno Elias (ESS), Vittorio Parma (CERN)
WP6 Existing RIs – Guillaume Olry (CNRS), Arnaud Madur (CEA)
WP7 Industry – Industry Board – Giorgio Keppel (INFN), Oscar Azzolini (INFN)

Technology Areas
WP1 FE-FRT – Axel Neumann (HZB), Alick Macpherson (CERN)
WP2 LLRF – Holger Schlarb (DESY), Julien Branlard (DESY)
WP3 4K Cavity – Cristian Pira (INFN), Oleg Malyshev (STFC)
WP4 HOM/FPC – Yolanda Gomez-Martinez (CNRS), Dario Giove (INFN)

Management WP9
Coordination & Management
Adèle de Valera (CNRS)

Societal Impact WP8
Task#1: Training & Early Career
Task#2: Outreach & Dissemination
Task#3: Diversity & Equity
Task#4: Open Science
Adèle de Valera (CNRS)

Steering Committee

Energy saving metric definition

- For the technologies developed within iSAS : **how to quantify the energy savings of these technologies**
  - **Simple, limited to cost of operation**

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

- Project requirements
  - Definition of the metric in early state of the project (deliverable May 2025)
  - Energy saving performances of the technologies to be measured at the end of the project

- Definition of the metric
  - Proposed by the WP leaders
  - Suported by the advisory board (March 2025)

FE-FRT (TA#1) : scope

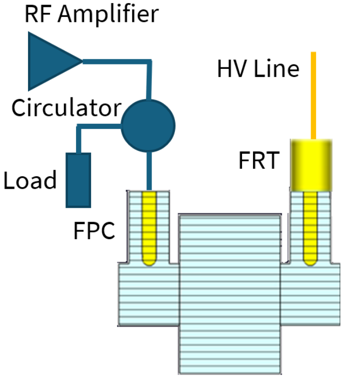
WP1 leader : A. Neuman (HZB)

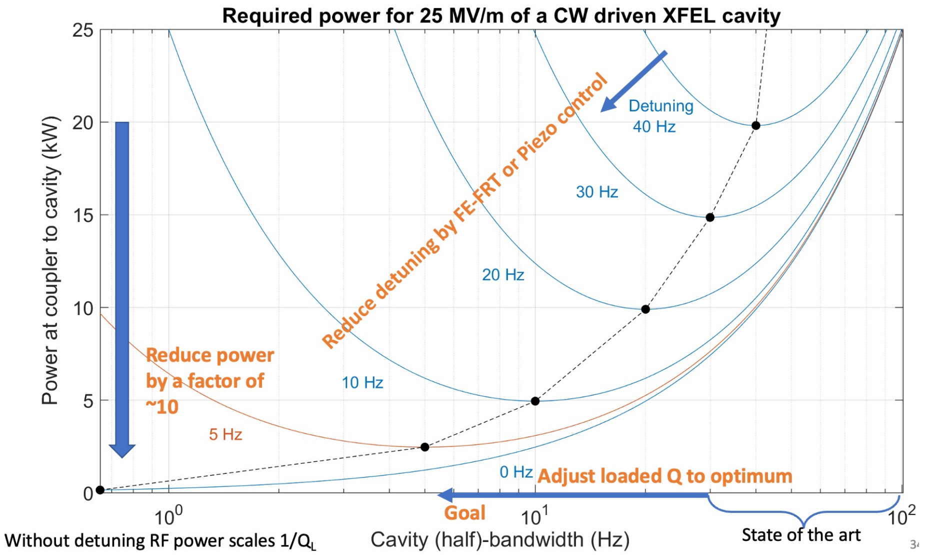
- **Goals : reduce the large RF power overhead required to**
  - **Compensate the detuning induced by mechanical vibrations**
  - **Control the transient beam loading**

- **WP1 : Develop novel fast tuning system, Ferro-Electric Fast Reactive Tuners (FE-FRTs)**
  - FE-FRT tuners : alternative to classic mechanical cavity tuner, avoid the complexity of control algorithms to damp the highly resonant mechanical-RF cavity-tuner system
  - FE-FRT tuners form a coupled system of cavity and a (usually) coaxial line with FE material, which changes its permittivity with HV
  - This change of impedance can control the resonance frequency of the coupled system
  - Based on previous work by CERN, Lancaster, BNL and Euclid techlabs
  - Partners: HZB, CERN, CNRS, Univ. Lancaster

Frequency changed by applying HV to FE material with tunable dielectric constant

Fast tuning response ~100 ns





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

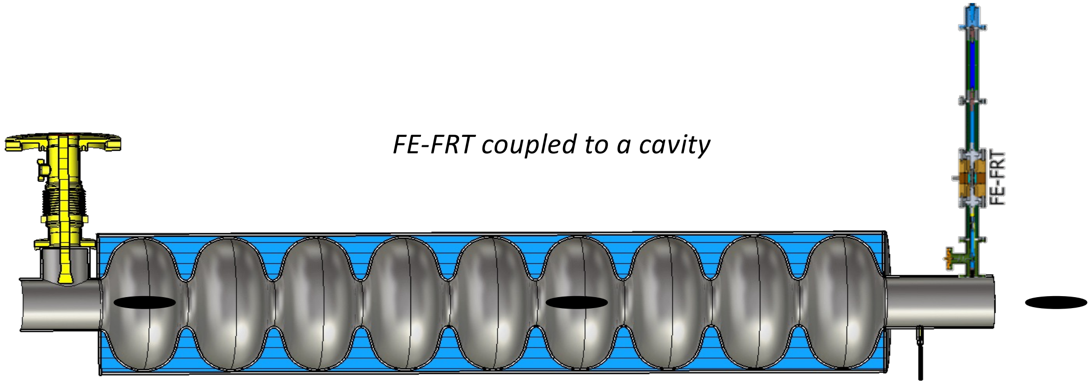
Conceptual design of a high reactive-power ferroelectric fast reactive tuner Phys. Rev. Accel. Beams, I. Ben-Zvi, G. Burt, A. Castilla, A. Macpherson, and N. Shipman, accepted 12 April 2024

FE-FRT (TA#1) : status

WP1 leader : A. Neuman (HZB)

- **Status**
  - ferro-electric material characterisation is ongoing
    - Material characterisation
    - High voltage breakdown tests
  - potential use cases being explored, e.g. for FCC (connected to PERLE at 800 MHz)
  - design efforts ongoing : RF power requirements from kW's to 100's W
  - **FE-FRT workshop, Nov 13-14, 2025, at Berlin (HZB) : https://events.hifis.net/event/2275/**

➔ iSAS is a catalyser bringing the FRT community together and enhance developments for a broader set of applications



FE-FRT coupled to a cavity

FE-FRT (TA#1) : metric

WP1 leader : A. Neuman (HZB)

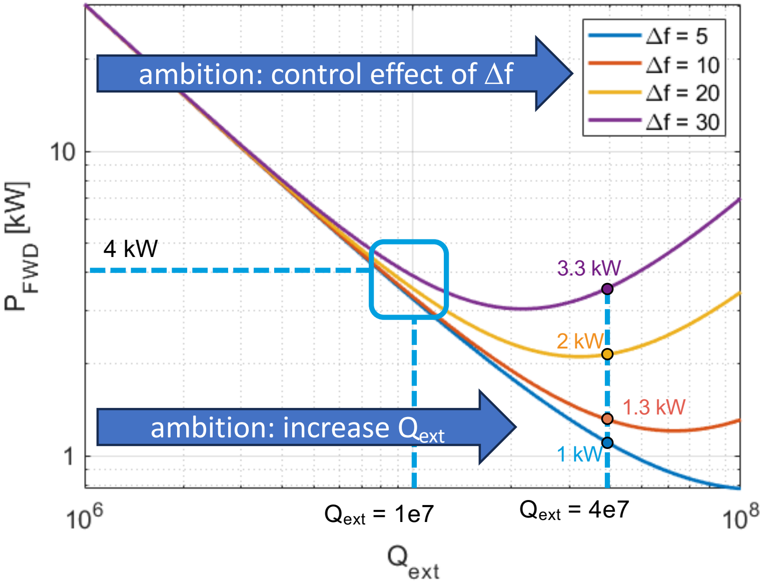
- **The metric to estimate the savings is the**
  - **invested RF power to drive the cavity at a given field (peak and average power) for microphonics compensation,** which will have to be converted to wall-plug power

- **The study case : TESLA cavity in CW mode at 16-20 MV/m**
  - **Reference test 1**: Operation at a typical, conservative loaded quality factor of e.g. **$1 \cdot 10^7$**. Measure microphonics detuning with piezo control, level of microphonics detuning, field stability with LLRF system and **power invest**.
  - **Reference test 2**: Repeat the first test by tuning the coupler to higher loaded Q of **$5 \cdot 10^7$** with piezo control. Validate the beforehand measured parameters → Operation possible at all?
  - **FE-FRT demonstration**: Operate the cavity **with FE-FRT and demonstrate micro-phonics detuning compensation and reachable, field stable, highest loaded Q.** Measure the **RF power level** and dissipated power in FRT (temperature sensors)

Smart LLRF (TA#1) : scope

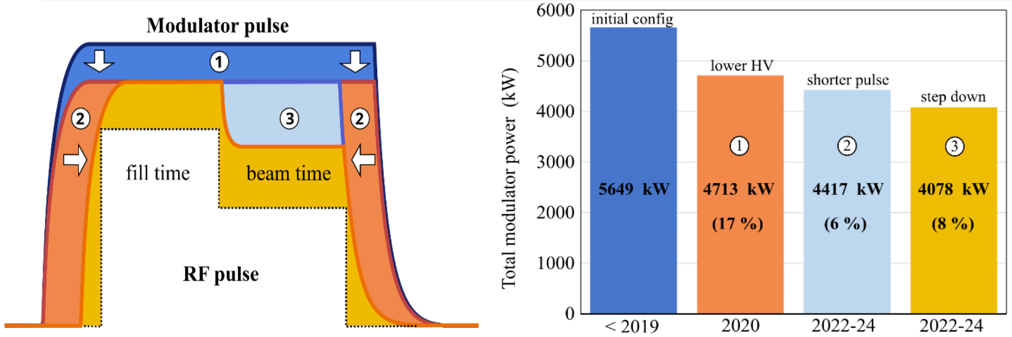
WP2 leader : J. Branlard (DESY)

- **Goals : reduce the required RF power by efficient field control and detuning control with Low Level Radio Frequency (LLRF)**
  - Operation at higher Qext (narrower bandwidth Δf)
    - Reduces the power needs IF resonance control can be guaranteed
    - But makes resonance control extremely challenging
  - **Challenge : find the highest Qext while meeting resonance control goals and without compromising operability or reliability**



Example: How shaping the modulator pulse can save power

→ LLRF development to compensate introduced non-linearities



Power savings > 1 MW (i.e. Mio €)

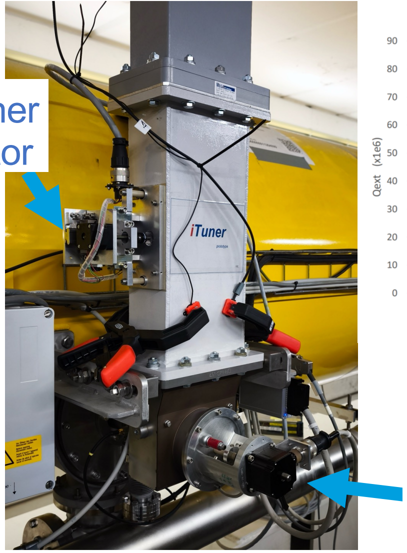
“RF-based energy savings at the FLASH and European XFEL LINACs”, J.Branlard *et al.* in proc. of LINAC 2024

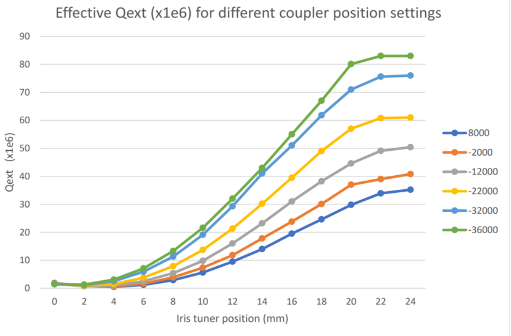
- **WP2 : demonstrate the operation of a digital LLRF system, integrating AI, for optimum control of field and detuning**
  - Partners: DESY, CNRS, HZB

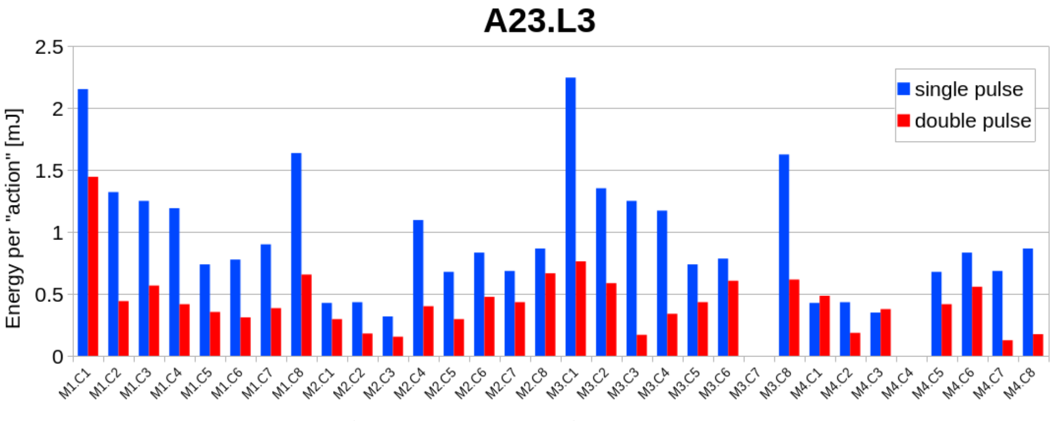
Smart LLRF (TA#1) : status
WP2 leader : J. Branlard (DESY)

- **Status**
  - **Extending the Qext range**
    - Development of 2 prototypes (DESY)
  - **Vibration analysis**
    - deep learning of cavity detuning under study at HZB
  - **Roadmap to integrate FE-FRT in the LLRF (link with WP1)**
  - **Optimizing the Lorentz force detuning at EuXFEL**
    - **double sine excitation of the piezo ➔ net energy saving factor of 2**

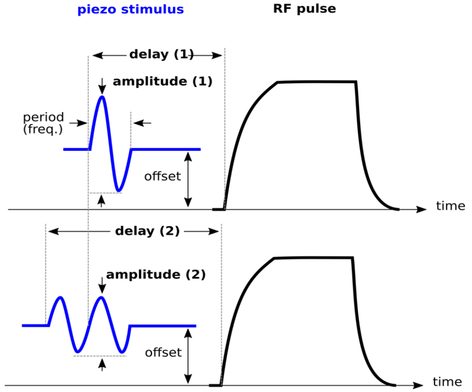
Iris-tuner (variable)







Courtesy Mariusz Grecki



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

Metric	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 working point optimization 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 cavities, etc.…)
- DESY, CNRS, HZB

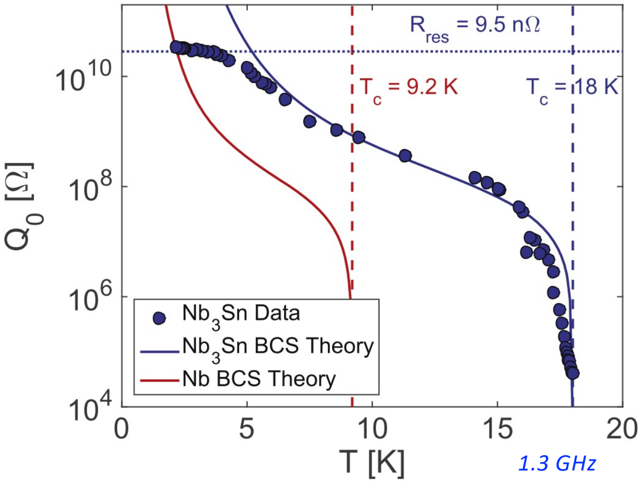
4 K cavities (TA#2) : scope
WP3 leader : C. Pira (INFN)

- **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}
    - **Expected reduction of cost of operation : factor of 3**

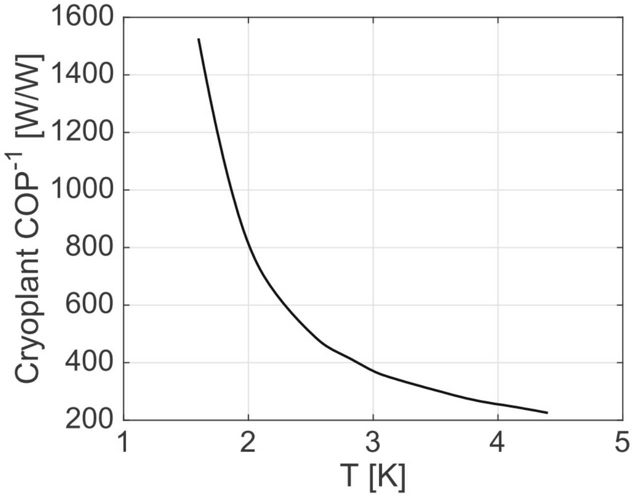
- **WP3 : Explore coatings of Nb_3Sn on Cu in order to**
  - **minimize flux trapping**
  - **Increase mechanical strength of the coating to allow better cavity tunability**
  - Partners: INFN, CEA, HZB, UKRI

➔ ***Complementary to I.FAST WP9, aim to go beyond the achievements of IFAST WP9***

Higher T_c of Nb_3Sn ➔ high Q_0 at ~4 K



COP 3 times better at 4.2 K than 2 K

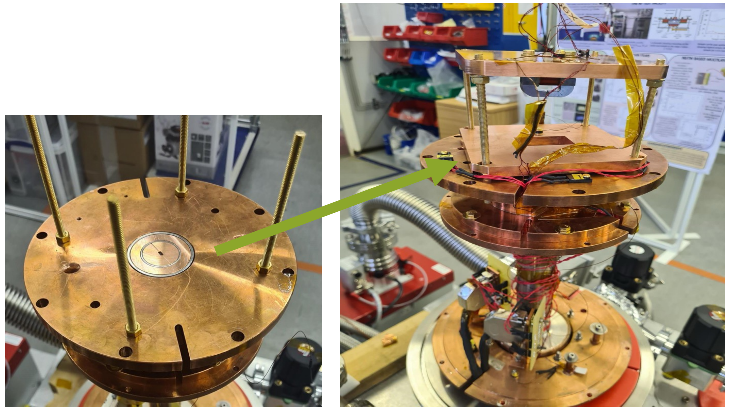


➔ Significant energy saving at 4.2 K

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

4 K cavities (TA#2) : status
WP3 leader : C. Pira (INFN)

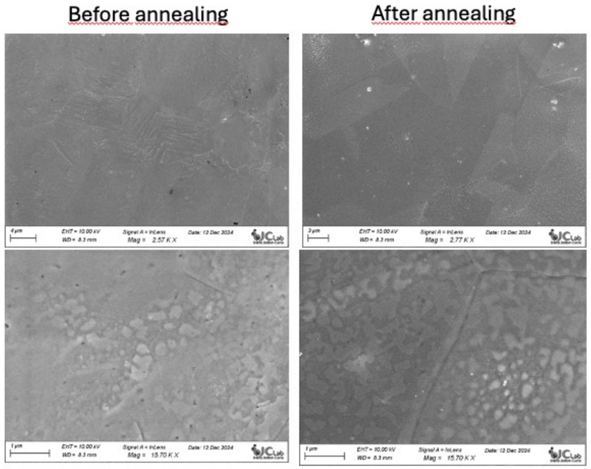
- **Status**
  - **Several facilities upgraded**
    - For material characterization
    - For sample and cavity tests
  - **First tests ongoing for flux trapping**
  - **Nb_3Sn coating systems ready to go**
  - **Several adaptive layers being tested (samples)**
  - ➔ **on track for a first coated cavity by summer**
    - first @STFC and later @INFN

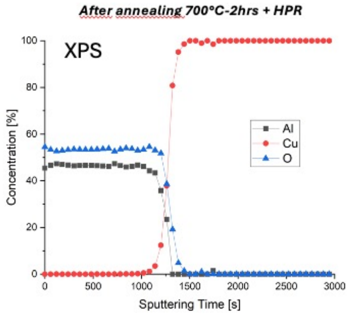


The Field Penetration Facility (UKRI)

The Choke cavity facility (UKRI)

Al_2O_3 (15 nm) /Cu EP (CEA)





- No cracks, no holes
- Al_2O_3 layer stable after annealing up 700°C in high vacuum and HPR.
- No Cu diffusion through the Al_2O_3
- Amorphous before or after annealing. No structure observed by SEM.

Courtesy of T. Proslier

4 K cavities (TA#2) : metric
WP3 leader : C. Pira (INFN)

- **Proposed metric : power dissipation of cavity cells**
  - P_{acc} per cell @ 1 MV/m (and cavity Q_0 vs E_{acc} curve)

- **Methodology**
  - **Measurement of Q_0 *vs* E_{acc} via an RF test**

    ➔ deduce surface resistance R_s

  ($R_s = R_{BCS}(T) + R_{res}$ determines the efficiency of the cavity : $Q_0 \propto 1/R_s$)

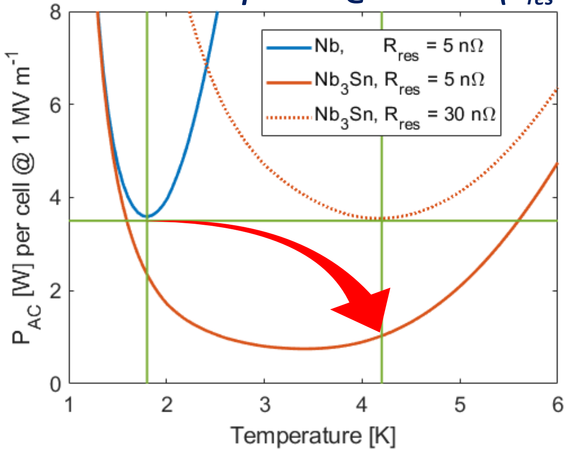
  - From this surface resistance evaluation of Nb_3Sn

    ➔ **estimate the operational cost at 4K**

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

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

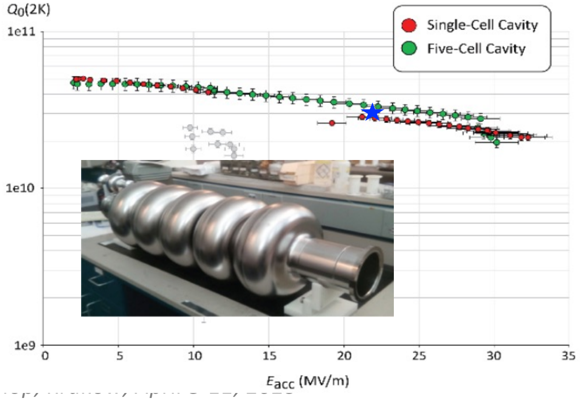
Expected: 0.7 – 3.5 W per cell @ 1 MVm^{-1} (R_{res} = 5-30 nΩ)



Courtesy of Sebastian Keckert (HZB)

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

A Nb_3Sn cavity at 4.2 K outperforms a Nb cavity at 1.8 K - even when at elevated residual resistance values



Example of Q_0 vs E_{acc} curve (bulk Nb, 800 MHz)

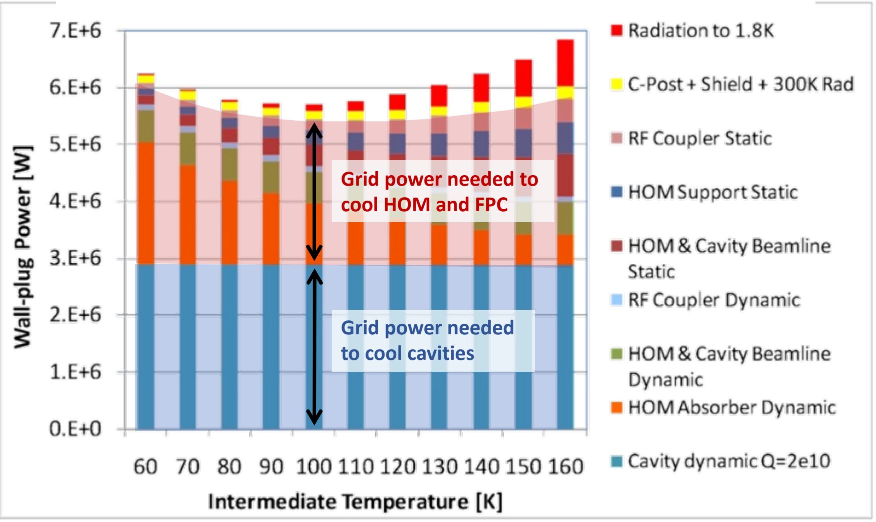
Couplers (TA#3) : scope
WP4 leader : Y. Gomez Martinez (CNRS-LPSC)

- **Goals : reduce the heat loads of the cryogenics by**
  - **reducing the power deposited by the Fundamental Power Coupler (FPC) and Higher-Order Mode coupler (HOM)**

  ➔ new designs for high current operation while minimizing static and dynamic heat loads in the cryogenic system
    - FPC : coupler to introduce the power to excite the fundamental mode of the cavity (antenna)
    - HOM : coupler used to damp the HOM trapped in the cavity
    - BLA (Beam Line Absorber): used to damp HOM propagating through the beam pipes by absorbing directly their power

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

Example : Grid power for cooling the Cornell ERL LINAC



Grid power needed to cool HOM and FPC

Grid power needed to cool cavities

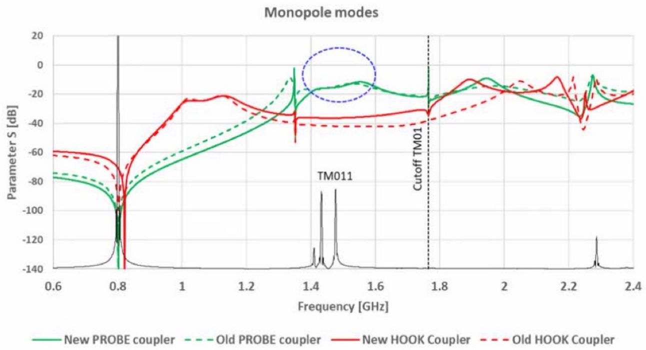
Figure adapted from "Cornell Energy Recovery LINAC Project Definition Design Report", G Hoffstatter, S. Gruner, M. Tigner, eds. (2013)

➔ HOM and FPC : half of the full cryogenic load

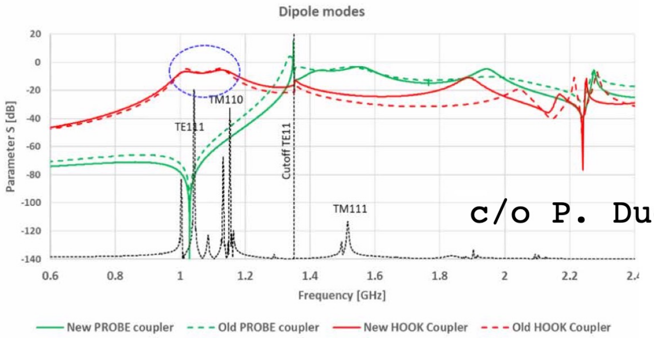
Couplers (TA#3) : status
WP4 leader : Y. Gomez Martinez (CNRS-LPSC)

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

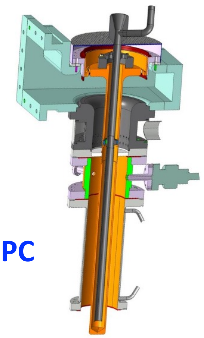
Hook coupler



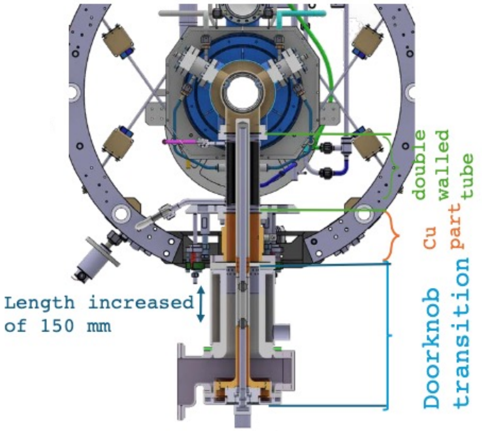
- **Status Fundamental Power Coupler (FPC)**
  - SPL coupler design
  - Adaptation underway for the mechanical integration in the PERLE cryomodule
  - HV conditioning protocole under discussion



c/o P. Duchesne



SPL FPC

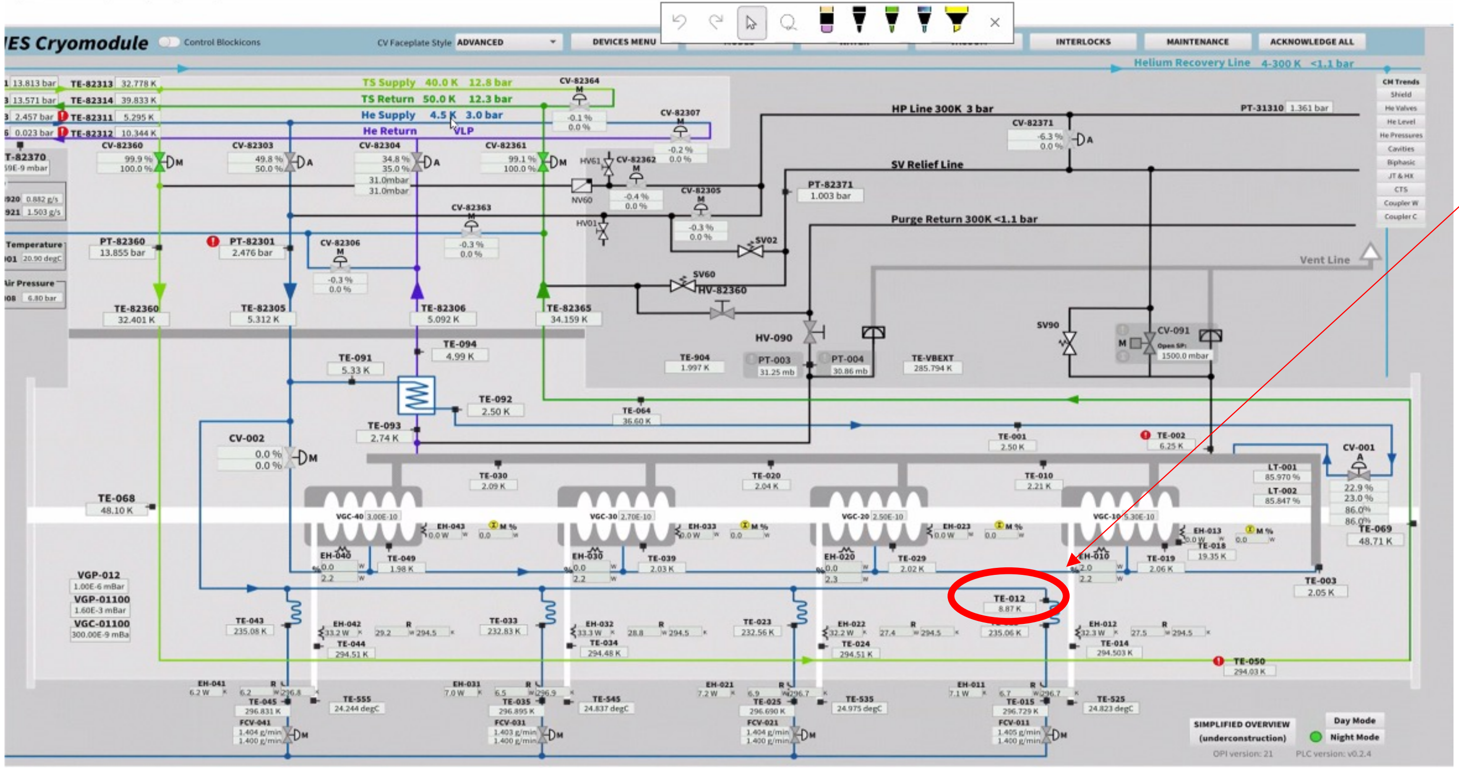


FPC proposed in the WP6 cryomodule

c/o S.Blivet & G. Olivier

Data from ESS cryomodule WP4/WP5

- **Thermal calculations, with the existing design**
  - Cooling power consumption performed from the ESS data by CERN
  - **ESS cryomodule data indicate ~9K inlet temperature to FPC, whereas design value is 5K (5.8K was measured on prototype)**
    - **the major consumption comes from the inlet line to the couplers**



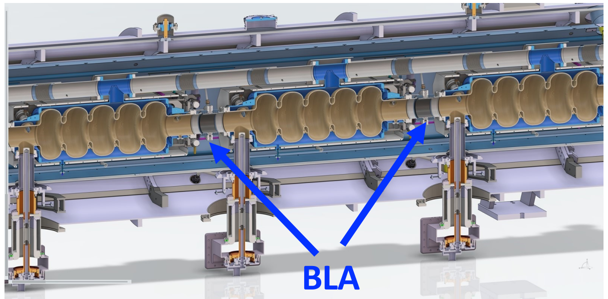
Should be 5K

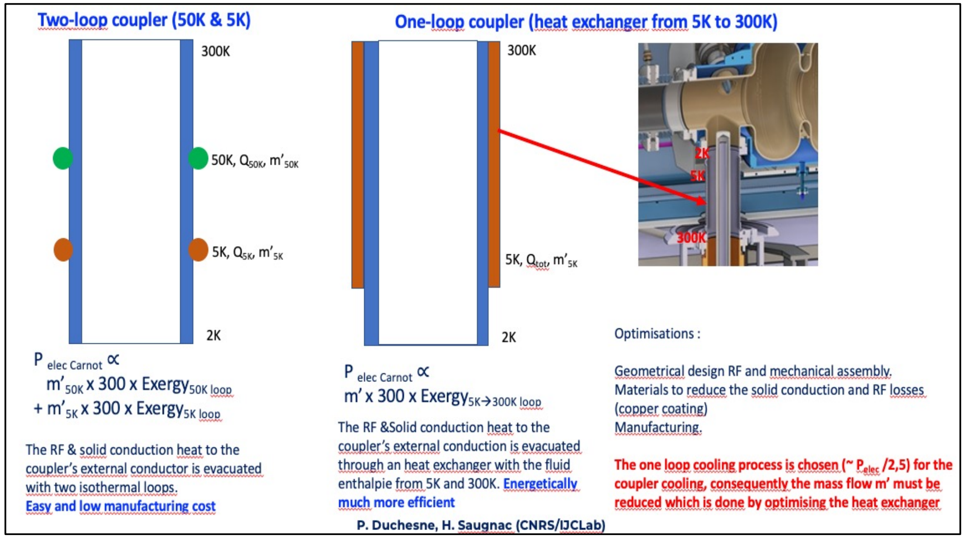
➔ **reducing conduction to the bath (from ~9K to 2K) by improving the thermal insulation on the cryoline to the FPC**

Feedback from ESS cryomodule: N. Elias (ESS)

Couplers (TA#3) : metric
WP4 leader : Y. Gomez Martinez (CNRS-LPSC)

- **WP4/WP5 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 (50K & 5K) and the existing one-loop design (IJCLab)
- **WP4 HOM : calculation of the electrical power consumption**
  - Comparison between 2 options : HOM@2K and HOM@5K
- **WP4 BLA : calculation of the electrical power consumption**
  - Comparison between 3 options : no cold BLA (BLA@300K), BLA@50K and BLA@50K with thermalization @5K





Two-loop coupler (50K & 5K)

$P_{\text{elec Carnot}} \propto$
$m'_{50K} \times 300 \times \text{Exergy}_{50K\ \text{loop}}$
$+\, m'_{5K} \times 300 \times \text{Exergy}_{5K\ \text{loop}}$

The RF & solid conduction heat to the coupler's external conductor is evacuated with two isothermal loops.
Easy and low manufacturing cost

One-loop coupler (heat exchanger from 5K to 300K)

$P_{\text{elec Carnot}} \propto$
$m' \times 300 \times \text{Exergy}_{5K \rightarrow 300K\ \text{loop}}$

The RF &Solid conduction heat to the coupler's external conduction is evacuated through an heat exchanger with the fluid enthalpie from 5K and 300K. **Energetically much more efficient**

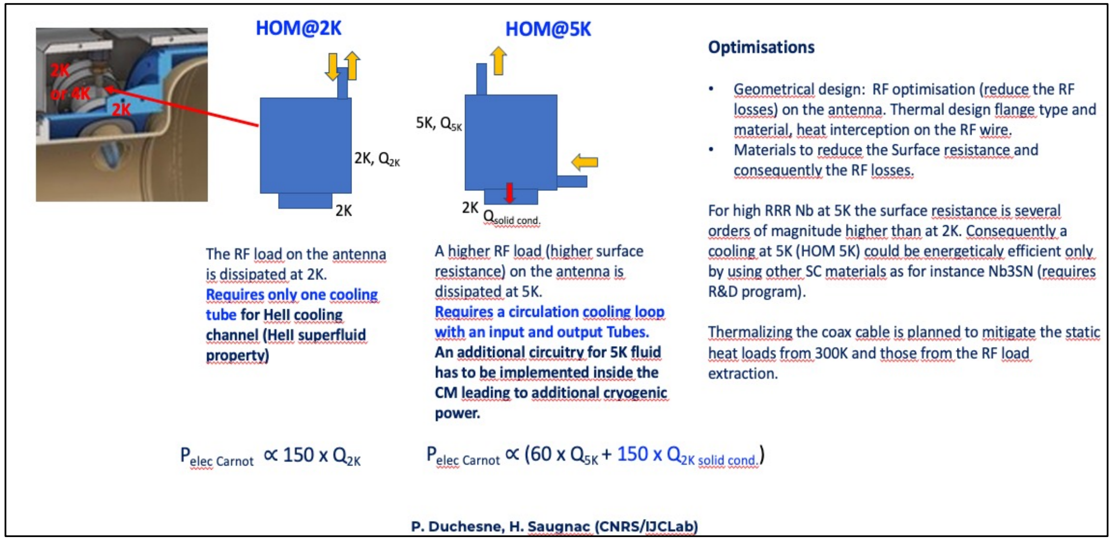
Optimisations :

Geometrical design RF and mechanical assembly.
Materials to reduce the solid conduction and RF losses (copper coating)
Manufacturing.

The one loop cooling process is chosen (~ P_{elec} /2,5) for the coupler cooling, consequently the mass flow m' must be reduced which is done by optimising the heat exchanger

P. Duchesne, H. Saugnac (CNRS/IJCLab)

FPC



HOM@2K

The RF load on the antenna is dissipated at 2K.
Requires only one cooling tube for HeII cooling channel (HeII superfluid property)

$P_{\text{elec Carnot}} \propto 150 \times Q_{2K}$

HOM@5K

A higher RF load (higher surface resistance) on the antenna is dissipated at 5K.
Requires a circulation cooling loop with an input and output Tubes.
An additional circuitry for 5K fluid has to be implemented inside the CM leading to additional cryogenic power.

$P_{\text{elec Carnot}} \propto (60 \times Q_{5K} + 150 \times Q_{2K\ \text{solid cond.}})$

Optimisations

- Geometrical design: RF optimisation (reduce the RF losses) on the antenna. Thermal design flange type and material, heat interception on the RF wire.
- Materials to reduce the Surface resistance and consequently the RF losses.

For high RRR Nb at 5K the surface resistance is several orders of magnitude higher than at 2K. Consequently a cooling at 5K (HOM 5K) could be energeticaly efficient only by using other SC materials as for instance Nb3SN (requires R&D program).

Thermalizing the coax cable is planned to mitigate the static heat loads from 300K and those from the RF load extraction.

P. Duchesne, H. Saugnac (CNRS/IJCLab)

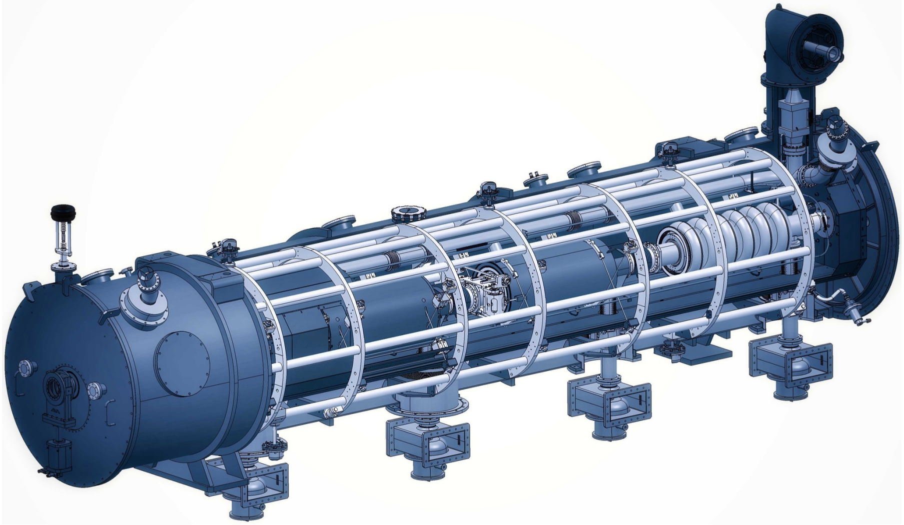
HOM

Cryomodule design
WP5 leader : N. Elias (ESS)

- **Goal : Implementation of technologies in the design of a new energy-saving cryomodule**
- **WP5 : Develop a parametric design of a new cryomodule tackling integrating the iSAS technologies**

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

- **Status**
  - **Lessons learned from ESS are being compiled**
  - **Survey launched to benchmark the performance across facilities**



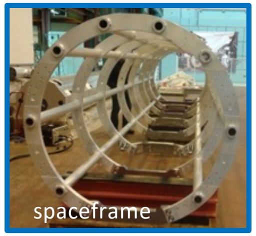
GOAL:
minimize the operational energy cost

Retrofit into existing cryomodule
WP6 leader : G. Olry (CNRS-IJCLab)

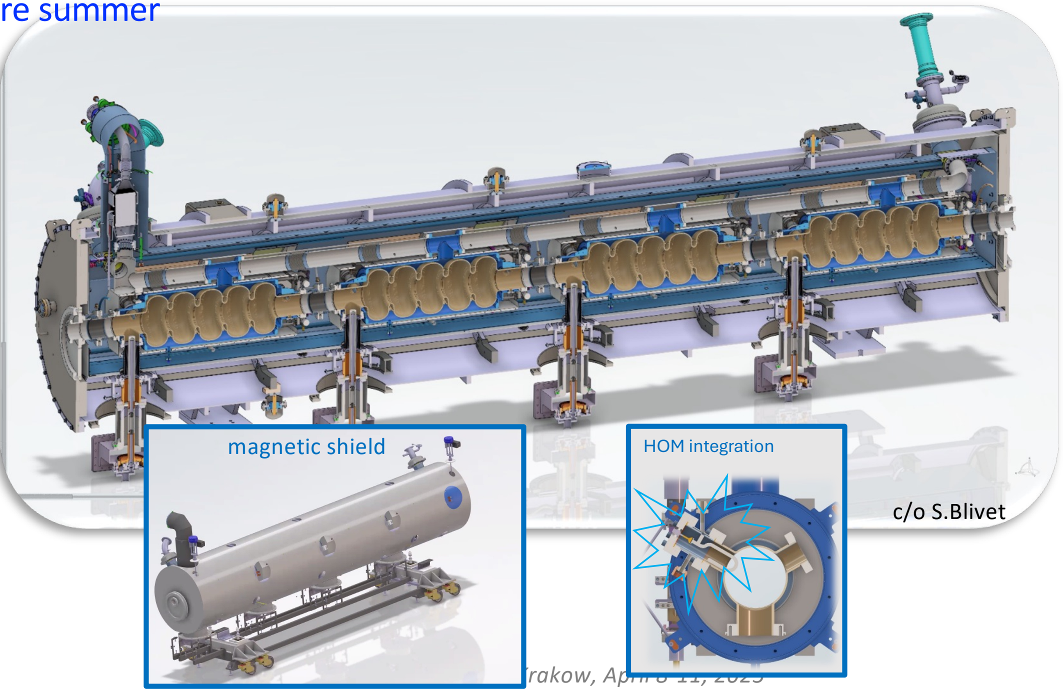
- **Goal : implementation of technologies in current and future research infrastructures accelerator**
  - iSAS will expedite the integration of technologies by **retrofitting existing accelerating systems**
- **WP6 : retrofit of iSAS technologies into the PERLE cryomodule** (high current, multi-turn energy recovery linac)
- **Partners : CNRS/IJCLAB, CEA, ESS, INFN, Lancaster University**
- **Status**
  - Design in progress of the iSAS-PERLE cryomodule (WP1 and WP4 feed into WP6)
  - technical review of design before summer


vacuum vessel

exiting ESS cryomodule parts

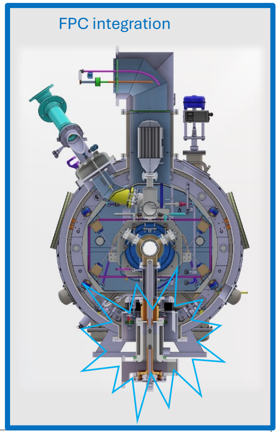

spaceframe

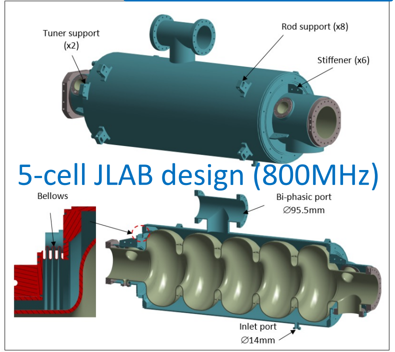

thermal Shield


magnetic shield

HOM integration

c/o S.Blivet


FPC integration



5-cell JLAB design (800MHz)

Overview of the jacketed cavity.

Implementation into industrial solutions :
WP7 leader: G. Keppel (INFN)

- **Goal : Establish and foster the relations with industry towards co-development**

- **WP7 :**
  - engage with industry in the early phases of the R&D
  - increase the Technology Readiness Level (TRL) of iSAS technologies
  - opportunities for dissemination of iSAS technologies

- **Partners : INFN, CNRS**

Conclusions

- With iSAS, impactful new energy-saving technologies will be developed, validated and integrated with a direct impact on current research infrastructures and their upgrades
- Energy saving metric defined, will be measured/determined at project's end
- On the long term, these technologies aim to reduce the energy footprint of future SRF accelerators towards a sustainable operation

iSAS kick-off, April 2024, Orsay

iSAS 1st annual meeting, March 2025, Padova

Thanks for your attention

BACK UP

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

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 metric summary proposal – 1/2

- **WP1 FE-FRT : measurements of RF power on the TESLA cavity in CW mode at 16-20 MV/m compared between reference cases (to be converted to wall plug power)**
  - Reference test 1: conservative $Q_L = 1 \cdot 10^7$ with piezo system
  - Reference test 2: high $Q_L = 5 \cdot 10^7$ with piezo system
  - FE-FRT case test 3: high Q_L with FE-FRT

- **WP2 LLRF : several measurements and calculations**
  - Measure the accelerator AC consumption with and w/o the applied LLRF optimization (instantaneous AC consumption)
  - Measure the peak and the integrated forward RF power with and w/o the LLRF optimization (RF power usage)
  - Compute the AC-to-RF efficiency of the high-power source (i.e. SSA) with and w/o 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..)

- **WP3 Nb_3Sn on Cu : evaluation of P_{acc}**
  - 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 (and construction) 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

Energy saving metric summary initial proposal – 2/2

- **WP4/WP5 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 (50K & 5K) and the existing one-loop design (IJCLab)

- **WP4 HOM : calculation of the electrical power consumption**
  - Comparison between 2 options : HOM@2K and HOM@5K

- **WP4 BLA : calculation of the electrical power consumption**
  - Comparison between 3 options : no cold BLA (BLA@300K), BLA@50K and BLA@50K with thermalization @5K

Nb_3Sn on Cu: Multiple challenges (C. Pira)

In I.FAST

- the effect of substrate and PVD deposition parameters on the superconducting properties (Tc and Rs) of Nb3Sn coatings was mainly studied
- An optimal sputtering recipe/protocol was defined, and the first 1.3 GHz prototype cavity will be deposited and measured in the coming months.

In ISAS

- we will study and optimize two aspects/properties not studied in I.FAST: **tunability and trapped flux**.
- At the end of ISAS an optimized cavity will be produced and measured : tunability and trapped flux need to be optimized before moving to the next step, proposed in I.FAST-2

In I.FAST-2

- moving from a vertical test (I-FAST and ISAS) to a cryocooled cryomodule (I.FAST-2)

From I.FAST to ISAS to I.FAST-2

- continuous increase in TRL

A15 are Brittle materials

Complicate Phase Diagram

Low melting point substrate

Substrate preparation

Interface diffusion

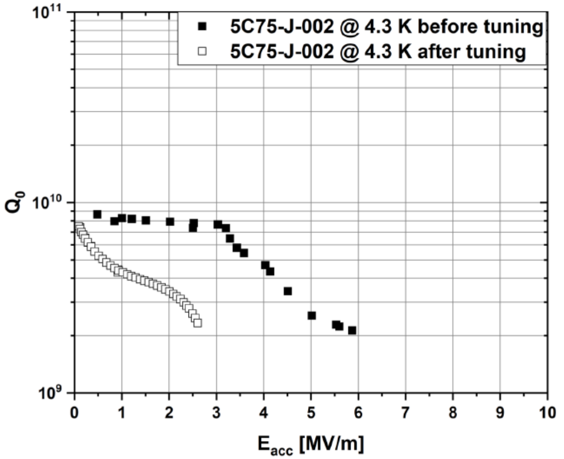
Target Production

Coating Parameters

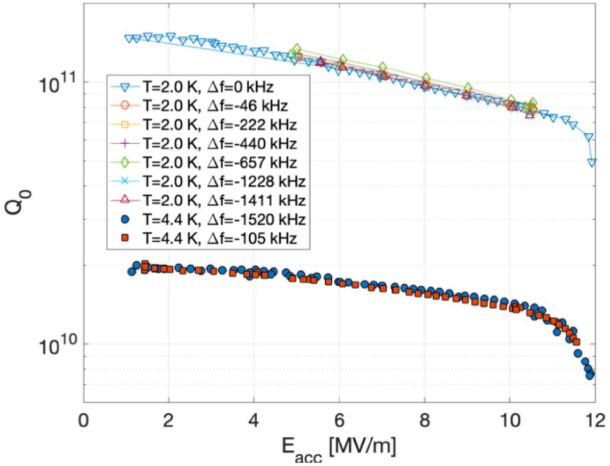
Trapped Flux

Tuning

Cavity Tunability



Strong performance degradation after **room temperature** tuning for 200 kHz



Little change in the coated cavity performance after tuning up to 1400 kHz at **cryogenic temperatures**

Nb_3Sn is extremally brittle

Eremeev, G. (2023). Tunability/robustness of Nb3Sn (No. FERMILAB-SLIDES-23-402-TD). Fermi National Accelerator Laboratory (FNAL), Batavia, IL (United States).

Vapor Tin Diffusion Nb_3Sn on Nb cavities can be tuned only at cryogenic T

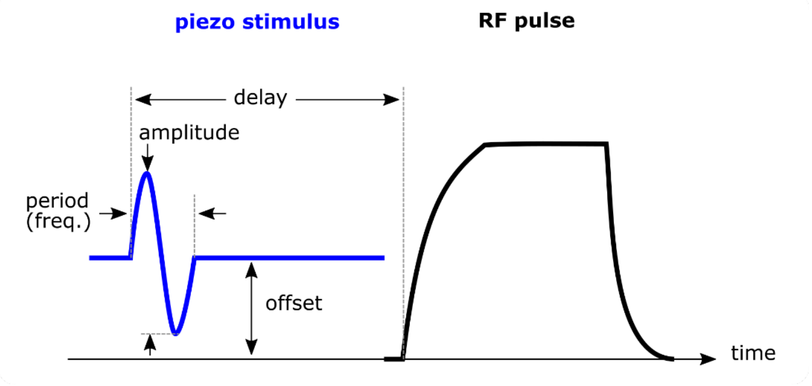
An interlayer in Nb_3Sn on Cu coatings can be added to enhance film mechanical stability and tunability

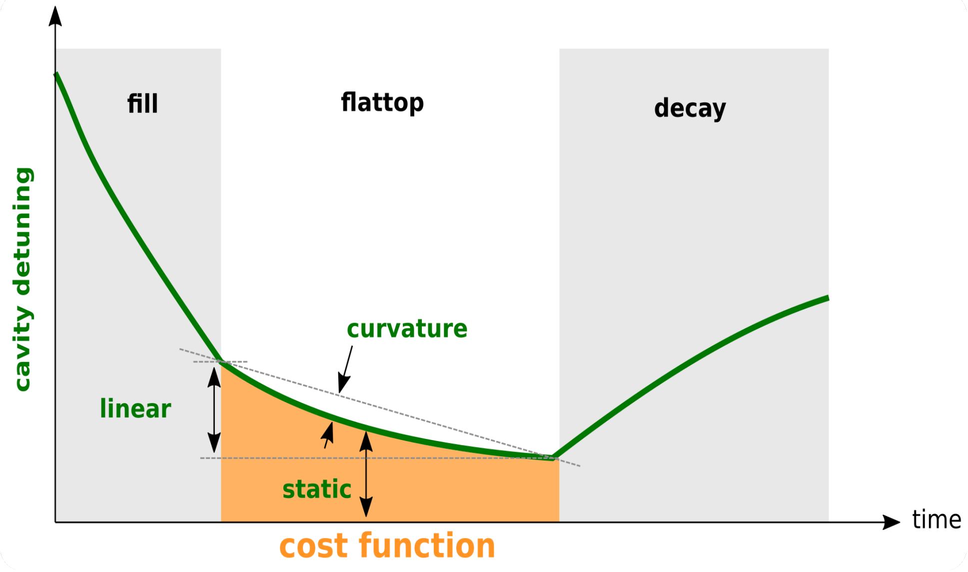
Optimizing Lorentz force detuning at EuXFEL

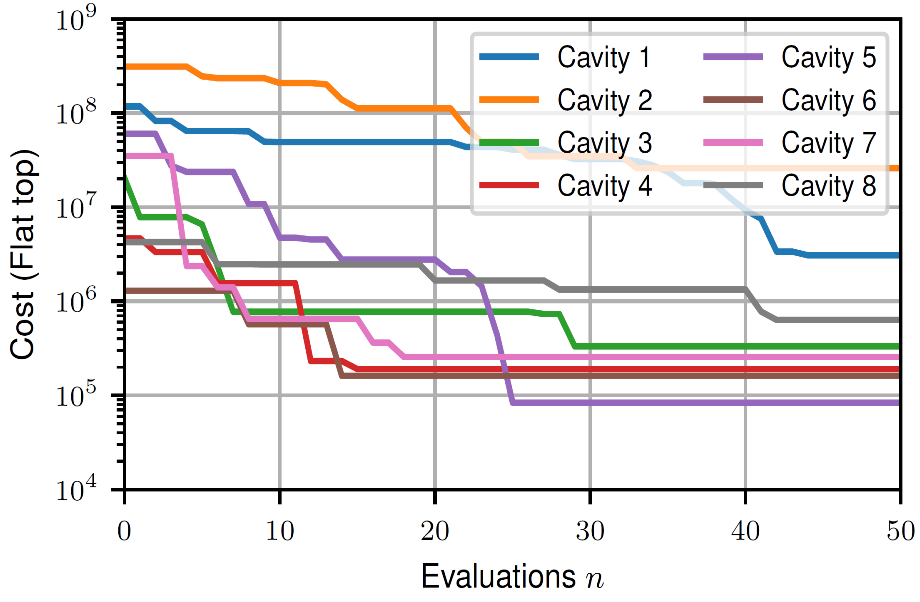
Parameter optimizer

1. Bayesian optimization of piezo stimulus parameters:

- delay
- amplitude
- offset



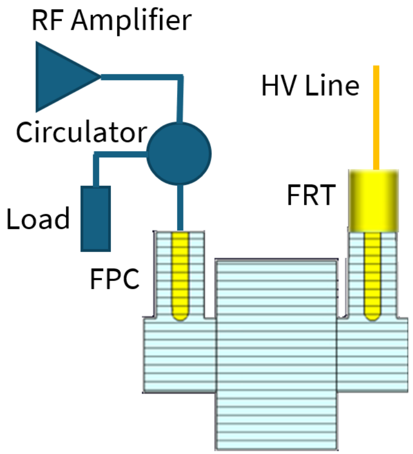




Courtesy Jannis Luebsen

FE-FRT

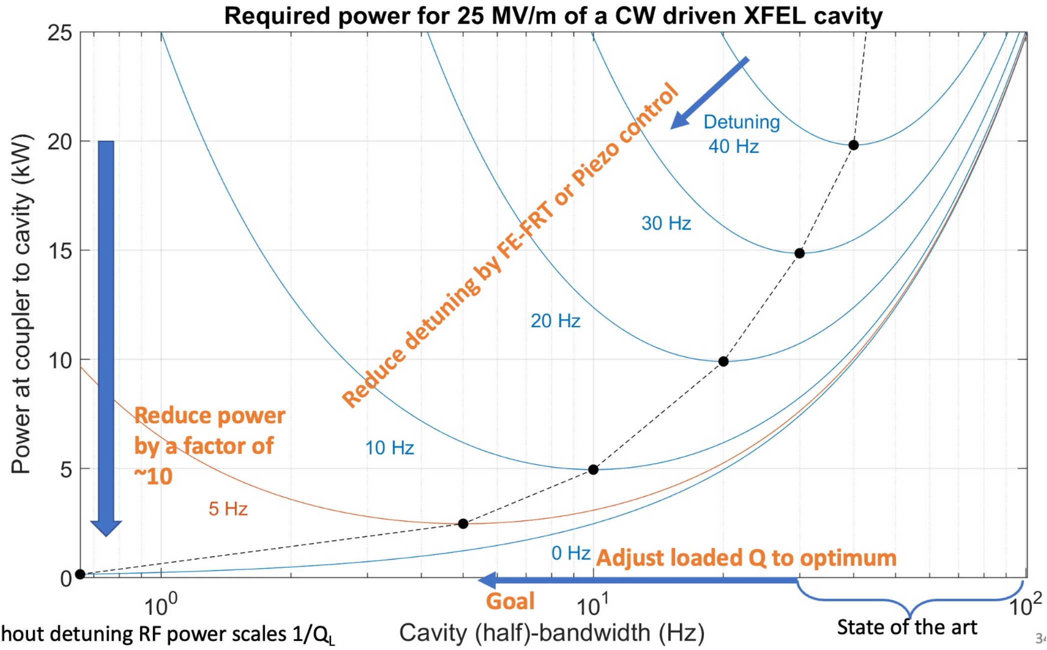
- FE-FRT tuners are an alternative to classic mechanical cavity tuner, however, require an additional RF port, but circumvent the complexity of control algorithms needed for damping the highly resonant mechanical-RF cavity-tuner system
- They form a coupled system of cavity and a usually coaxial line with ferro-electric material, which changes its permittivity with HV
- This change of impedance can control the resonance frequency of the coupled system



Scheme by N. Shipman

$$P_{\mathrm{f}} \approx \frac{\boxed{V_{\mathrm{cav}}^2}}{\frac{R}{Q} Q_{\mathrm{L}}} \frac{1}{4} \left\{ \underbrace{\left(1 + \frac{\frac{R}{Q} Q_{\mathrm{L}} I_{\mathrm{b0}}}{V_{\mathrm{cav}}} \cos \phi_{\mathrm{acc}}\right)^2}_{\text{resistive}} + \underbrace{\left(\boxed{\frac{\Delta f}{f_{1/2}}} + \boxed{\frac{\frac{R}{Q} Q_{\mathrm{L}} I_{\mathrm{b0}}}{V_{\mathrm{cav}}} \sin \phi_{\mathrm{acc}}}\right)^2}_{\text{reactive}} \right\}$$

Variations of microphonics or bunched beam pattern in time domain dictates switching of HV in time & amplitude



From Axel Neumann