XFEL Accelerator R&D Status / Final Report
CW LLRF Development

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12.09.2025

Scope of the R&D activity (extension 2024 – 2027)

Summary

- Perform the **R&D necessary to adapt the LLRF system to continuous wave operation** in preparation of a possible upgrade of the European XFEL

Interface

- **High power RF solutions** (type of sources, waveguide Q_L tuner, operation efficiency, power budget, ...)
- **SRF cryomodules** and **cryogenics** (couplers, microphonics control, heat load, …)
- **Operations** and **beam-based feedbacks** (timing, controls, cavity bandwidth and tuning, beam manipulation…)
- **Other XFEL R&D proposals**
  - Improved diagnostics using machine learning
  - TS4i : LLRF development for SRF gun

Milestones

- LLRF **CDR** for the XFEL continuous / high-duty cycle upgrade
- LLRF **system prototype** for an SRF injector / TS4i

Scope of the R&D activity (extension 2024 – 2027)

- **Hire that directly benefited from this R&D project**
  - 1 PhD — Bozo Richter (contract ends Sept. 2026)
  - 1 Postdoc (1 year) — Yue Sun (now left)
  - 1 Scientist — Josh Einstein-Curtis (contract till end 2027)

- **Purchase enabled by this R&D project**
  - Procurement of test LLRF systems (i.e. to support CW operations at AMTF, CMTB)
  - Prototyping of new electronics (next generation ADC)

Achievements in the past year

- **(1) High-Qext** operation
  - extending Qext for legacy cyromodules
  - RF field and resonance control of high Qext cavities single cavities
  - Pulsed operation in vector sum control of high Qext cavities

- **(2)** HDC tests with **high-power CW sources**
  - IOT tests at CMTB
  - SSPA 4kW tests in AMTF (1.3 and 3.9 GHz)
  - Investigation of SSPA efficiency

- **(3) Heat load** tests
  - At XFEL (several tests on several CS)
  - At CMTB (XM46.1, XM50.1, next XM8)

Achievements in the past year

- **(1) High-Qext** operation
  - Extending Qext for legacy cryomodules
  - RF field and resonance control of high Qext cavities single cavities
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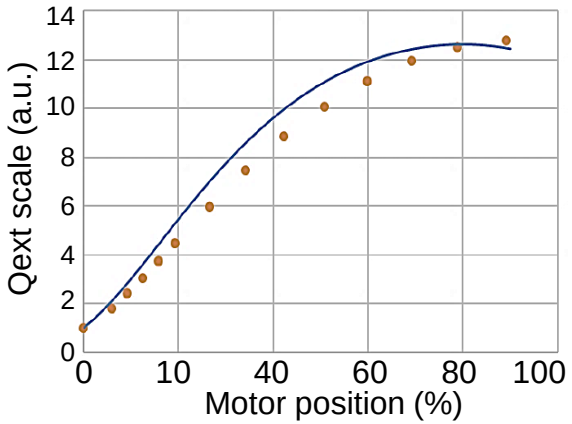
1. *Looking for a solution to push Qext of the existing cryomodules to higher values without having to modify the input coupler*
2. *Investigating the impact of new device on coupler temperature*
3. *Investigating the impact of new device on regulation*

Note: the Q-tuner is developed by V. Katalev

Extending external coupler (Qext) range

Current max Qext = 1e7
Possible HDC Qext = 6e7



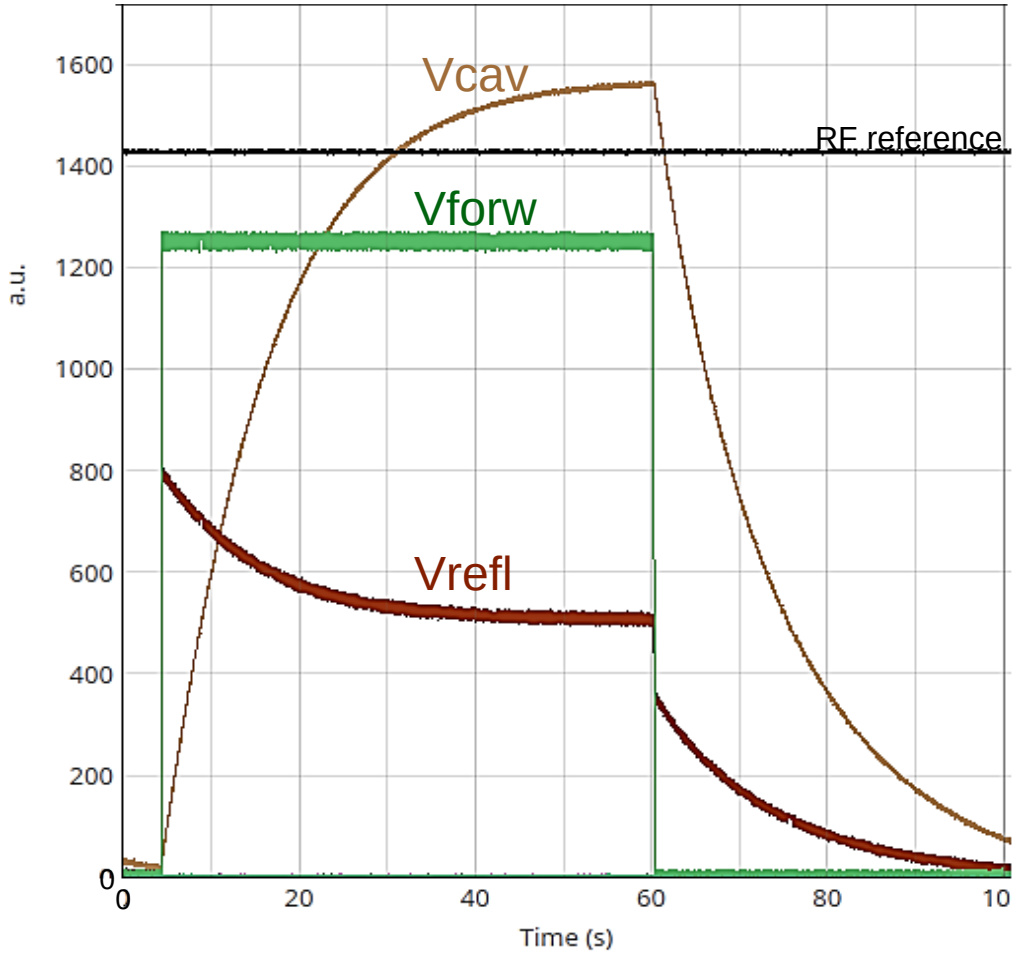
Waveguide Q-tuner offers
a factor 10 increase in Qext

Achievements in the past year

- **(1) High-Qext** operation
  - Extending Qext for legacy cryomodules
  - RF field and resonance control of high Qext cavities single cavities
  - Pulsed operation in vector sum control of high Qext cavities

1. *Driving a cavity with extremely narrow bandwidth requires a LLRF system capable of locking to the cavity resonance frequency as it is increasing in gradient (SEL)*

2. *This LLRF development is also driven by the need to upgrade our VTS at AMTF*



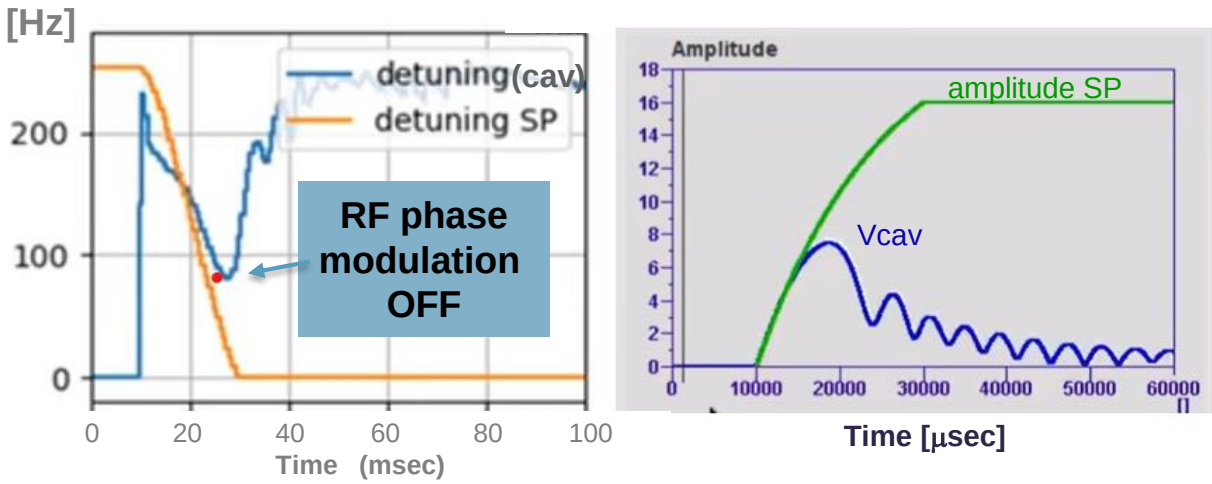
SEL test of a 1.3 GHz SRF cavity with a coupling of Q_L = 5e10

Achievements in the past year

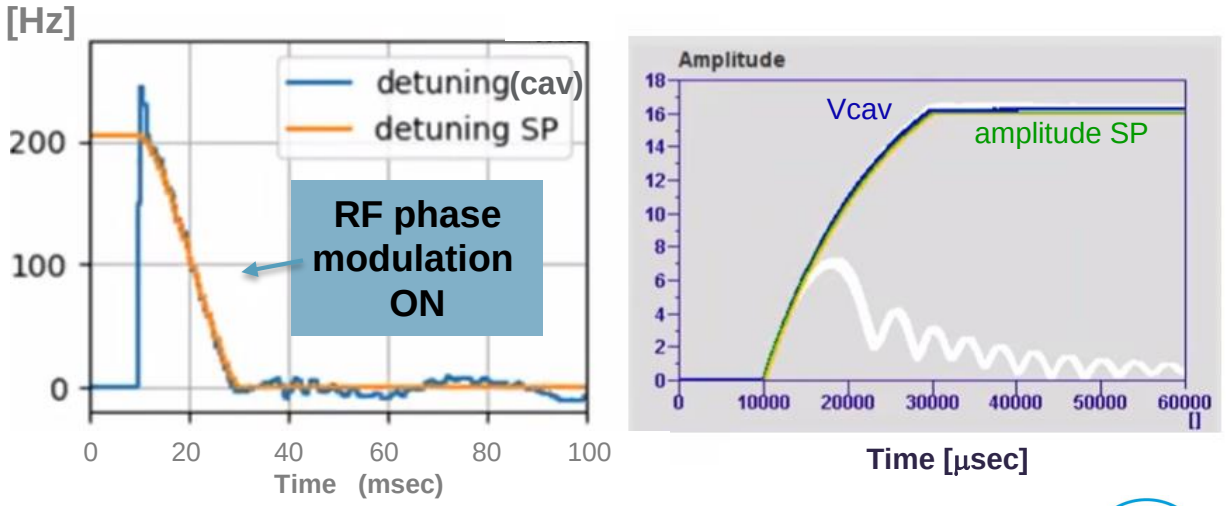
- **(1) High-Qext** operation
  - Extending Qext for legacy cryomodules
  - RF field and resonance control of high Qext cavities single cavities
  - Pulsed operation in vector sum control of high Qext cavities

1. *Due to the repetitiveness of Lorentz Force Detuning experienced during pulsed operation, the RF phase of the drive can be modulated to compensate for the detuning experienced during ramp up*

2. *This phase modulation can be done with RF or with piezo allowing for vector sum control even at very high Qext*



cavity filling in open loop (Qext = 6e7, Ecav = 16 MV/m)



Achievements in the past year

- **(2)** HDC tests with **high-power CW sources**
  - IOT tests at CMTB
  - SSPA 4kW tests in AMTF (1.3 and 3.9 GHz)
  - Investigation of SSPA efficiency

1. *Two different **LLRF systems** have been developed to perform either **single cavity regulation** (SCC) or **vector sum control** (VSC)*

2. *The goal is to answer a question critical to the HDC upgrade: "what stability and gradient can be reliably achieved in SCC and VCS for high Qext cavities?"*

4 kW SSA in AMTF

40 kW IOT in CMTB

Achievements in the past year

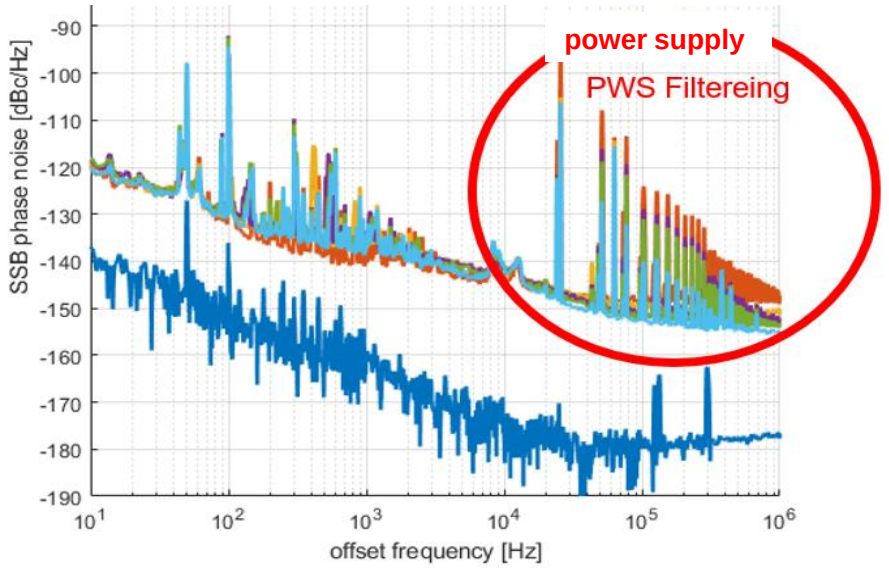
- **(2)** HDC tests with **high-power CW sources**
  - IOT tests at CMTB
  - SSPA 4kW tests in AMTF (1.3 and 3.9 GHz)
  - Investigation of SSPA efficiency

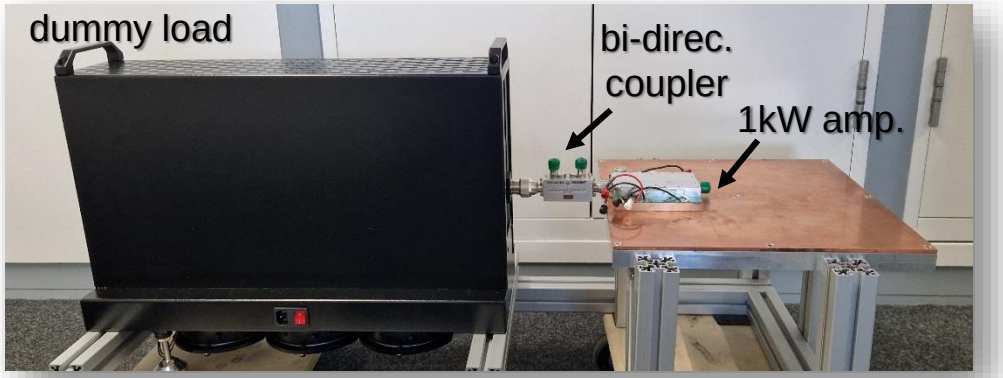
1. *The **phase noise performance** of the power amplifier plays a crucial role in the overall RF stability. We've characterized our existing sources, and will continue with the new ones*

2. *The **power efficiency** of the power source is a key factor for the overall AC budget in HDC mode. We've developed a test stand to better understand the challenges associated with efficiency*

3. *We've started dialog with some vendors to bring these topics up. A solution for HDC might require a **custom design.***

additive phase noise characterization of our current Cryoelectra 4kW SSPA





HELMHOLTZ

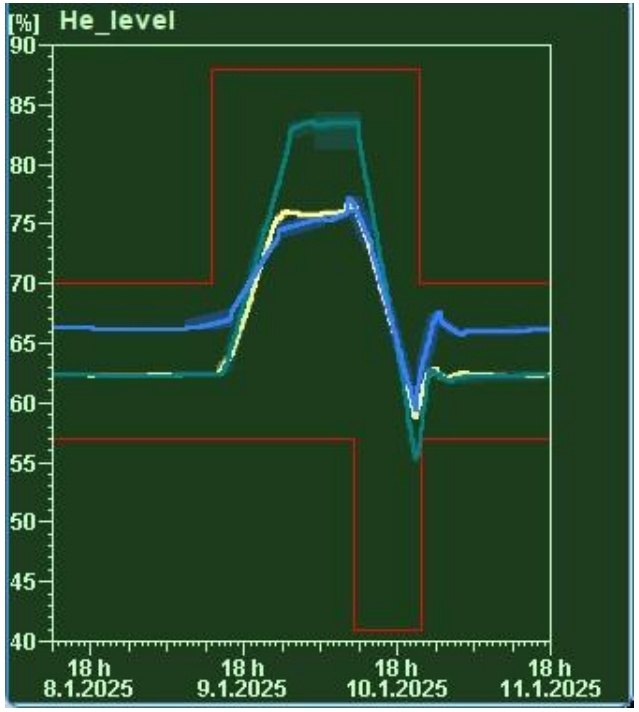
DESY.

Achievements in the past year

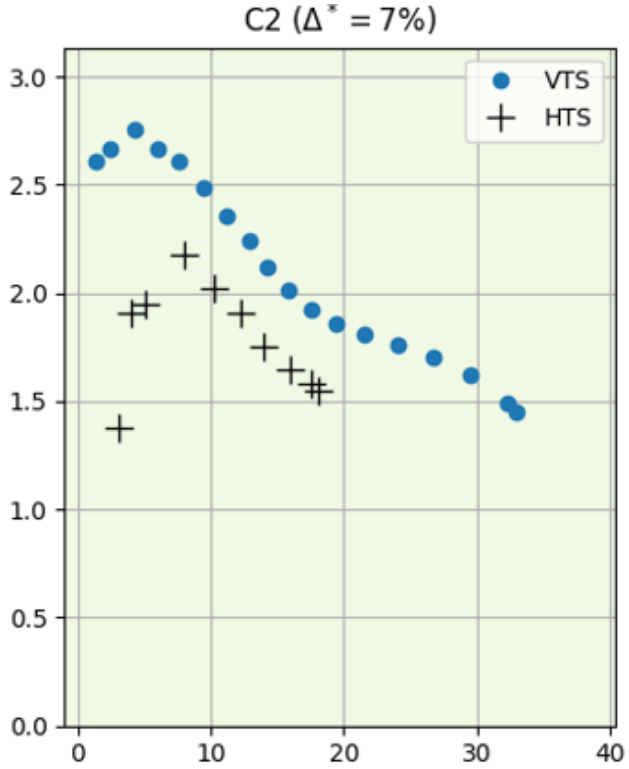
- **(3) Heat load** tests
  - At XFEL (several tests on several Cryostrings)
  - At CMTB (XM46.1, XM50.1, next XM8)

1. *MKS developed a new technique to estimate the cryomodule **dynamic cryoload**.*
2. *A measurement campaign has started to measure as precisely as possible the cryoload of our **series cryomodules.***

Dynamic Heat Load
(Helium evaporation method)
XFEL Cryo-string 8 and 9



Dynamic Heat Load
(Helium evaporation method)
XM46.1 at CMTB



Deviations from plan

- Which of your originally planned achievements for the past year could not be reached?
  - **Development of the next generation ADC (factor 10 better resolution)**
    - Prototyping work has been on-going for several years
    - Demo boards have been produced,
    - The original deadline for first batch production was Q3.2025 –> 1 year delay
    - Delay due to
      - Higher priority work (related to accelerator operation)
      - Production schedule was too optimistic
      - The complexity of some design choices was not expected
    - No show stopper, just more time required than planned and still within the time frame of the R&D project

Timeline of this R&D activity

- *Outline the **major development steps** within the timeframe of the proposal*
  - *CW control of the cavity field and resonant frequency in narrow bandwidth (high Q_L)*
  - *Third harmonic CW operations*
  - *Modernization of LLRF system and performance improvement*
  - *LLRF system for CW injector (TS4i)*
  - *Documentation and CDR*

Proposed Date	Milestone Description	Updated Date
Q4.2024	Algorithms developed for cavity parameter estimation (bandwidth, tuning)	Done + published
Q1.2025	Cavity resonance control tested at CMTB	On-going, paper Oct'25
Q3.2025	Next generation digitizer prototypes produced	**Q4.2026**
Q4.2026	LLRF CDR first draft completed	Start with FOS
Q4.2026	LLRF system for TS4i installed	LLRF ready, except piezo?

Risks to R&D Project

- What are the risks associated with your R&D project that may prevent or limit you
  - to achieve the planned goal of your activity
  - provide the deliverables
  - jeopardize the time line of your project

- **Availability of test stand and cryomodules (i.e. CMTB, AMTF)**
  - Parallel activities: FLASH shutdown, LIMP
  - Schedule of module assembly
  - TUEV, cryo maintenance, IOT or klystron failures, etc…

- **Challenge in finding (and keeping) personnel**
  - 3 times, we‘ve had people leave after ~1 year

Outlook / Summary

- Write the **Feasibility and Option Study** for the HDC upgrade (this year) and start working on CDR (next year)

- **Vector sum tests** at CMTB
  - Demonstrate VS (8 cavities) at high Qext (tentative Qext = 6e7)
    - 10 MV/m in CW
    - 18 MV/m in pulsed
    - Note: XM8 is not adequate for Qext > 1-2e7
  - Publication

- **Single cavity tests** at AMTF
  - Performance evaluation of Qtuner in single cavity control (20 MV/m, Qext = 6e7), CW, pulsed
  - Demonstrate automatic cavity ramp-up
  - Publication

- The PhD student (main driver) will finish in September next year, **how to proceed ?**

List of publications (since 2024)

- [1] B. Richter, et al., “Limitations of the EuXFEL 3rd harmonic cryomodule in high duty cycle operation”, in Proc. LINAC'24, Chicago, IL, USA, Aug. 2024, pp. 324-327. doi:10.18429/JACoW-LINAC2024-TUPB002
- [2] Y. Sun et al., “Influence of environmental parameters on calibration drift in superconducting RF cavities”, in Proc. LINAC'24, Chicago, IL, USA, Aug. 2024, pp. 331-334. doi:10.18429/JACoW-LINAC2024-TUPB005
- [3] A. Eichler et al., “Enhancing quench detection in SRF cavities at the EuXFEL: Towards machine learning approaches and practical challenges”, in Proc. IPAC'25, Taipei, Taiwan, Jun. 2025, doi: 10.18429/JACoW-IPAC25-THPS134
- [4] B. Richter et al., “Estimation of superconducting cavity bandwidth and detuning using a Luenberger observer”, arXiv:2506.21207v2 [physics.acc-ph] 10 Jul 2025
- [5] B. Richter et al. “Resonance filling of narrow-bandwidth cavities”, title t.b.c., to be presented at LLRF Workshop 2025, Newport News, VA, USA, Oct. 2025

BACKUP SLIDES

SLIDES FROM LAST R&D PROPOSAL

Scope of the R&D activity

Summary

- Improved microphonics detection and detuning control ➡ Very good results, promising solution for HDC pulsed
- Development of SRF Gun LLRF ➡ Mostly ready, components delivered. Piezo drive to clarify
- LLRF and CW tests of the 3rd harmonic cryomodule ➡ Done, results published
- Modernization of the LLRF system detection chain ➡ Prototype boards to help with design choices, first revision end 2026
- LLRF preparation for a CW injector towards a CDR ➡ Change scope ? CDR for injector → CDR for HDC

Interface

- Test stand schedule (AMTF, CMTB, Ts4i) ➡ Some deliverables are linked to external schedule

Deliverables

- Demonstration of detuning control in CW
- LLRF for SRF gun test stand (Ts4i)
- LLRF system for 3.9 GHz CW + recommendations for 3.9 GHz module in CW operation ➡ DONE
- Prototype of next generation ADCs ➡ Deliverable end 2026
- LLRF CDR (partial) for a CW injector

Summary

- *Emphasize the **collaborative aspect** of this proposal*
  - *Many tests planned in collaboration **with other M-groups at DESY***
    - *Collaboration with MHF (SSA, waveguide tuner, IOT, etc…)*
    - *Collaboration with MKS (heat load tests at XFEL / CMTB / AMTF etc…)*
    - *Collaboration with MXL (HDC Jork workshops)*
  - *Collaboration **with industrial partners***
    - *Cryoelectra : SSA efficiency control*
    - *Struck System : new ADC production*
    - *MTCA community → benefits for other MTCA users*
  - *Collaboration **with other Helmholtz institutes***
    - *Test of algorithms / software / firmware / hardware*
    - *ELBE (HZDR), HobiCat/BESSY (HZB)*
  - *Synergies with **R&D financed by third party grants***
    - *iSAS : initiative for sustainable accelerator systems*