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TOWARDS A MORE ENERGY-EFFICIENT
AND SUSTAINABLE PATH



SOLID STATE AMPLIFIERS DEVELOPMENTS IN THE EU PROJECT RF 2.0

FRANCIS PEREZ, ALBA



Funded by
the European Union



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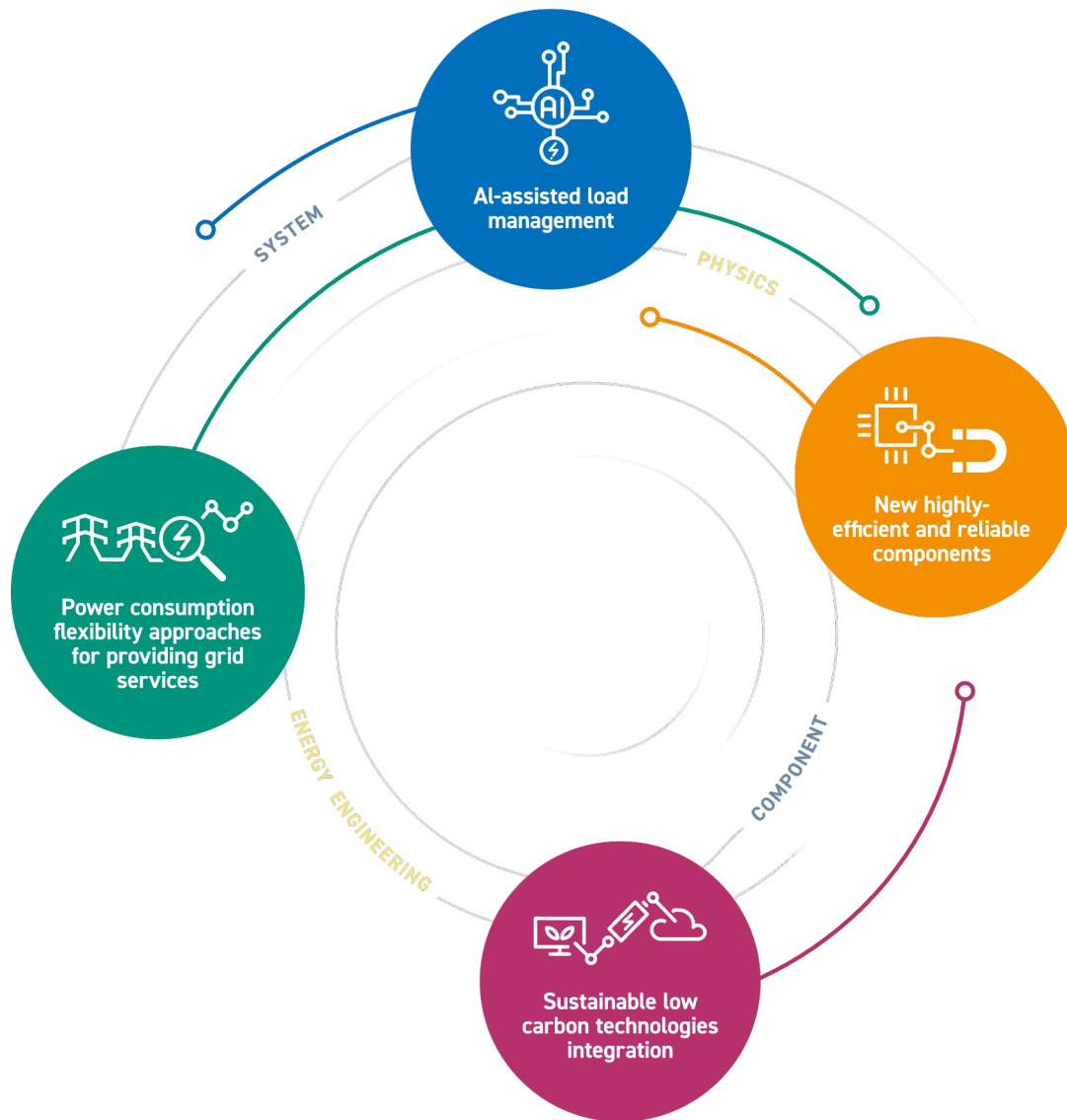
PROJECT OVERVIEW

CONSORTIUM & VISION



TOWARDS A MORE ENERGY-EFFICIENT AND SUSTAINABLE PATH

- The RF2.0 partners envision a future where accelerators are designed, operated, and supplied with 100% renewable energy, ensuring secure and stable performance at any time.
- This approach aims to make operations nearly independent of the public power grid while significantly reducing environmental impact.



RF2.0 APPROACH

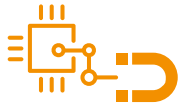
The RF2.0 partners have identified several bottlenecks towards this goal at component and system level, involving both the physics and the energy technology topics in an interdisciplinary and unique approach.

CONTRIBUTION OF RF2.0



AI-assisted load management

- New energy management approaches using AI
- Digital twins of accelerator components and systems



New highly-efficient and reliable components

- Permanent magnets
- Semiconductor technologies
- Solid-State Amplifier



Power consumption flexibility approaches for providing grid services

- Power electronics and DC grids
- Fast measurement systems (Phasor Measurement Units)
- Energy costs and resources analysis



Sustainable low carbon technologies integration

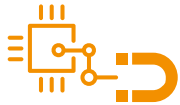
- Energy storage systems and technologies (batteries, supercaps, hydrogen)
- Flexible power consumption as for HPC centres / Renewable power-driven scientific computing

CONTRIBUTION OF RF2.0



AI-assisted load management

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New highly-efficient and reliable components

- Permanent magnets
- Semiconductor technologies
- **Solid-State Amplifier**



Power consumption flexibility approaches for providing grid services

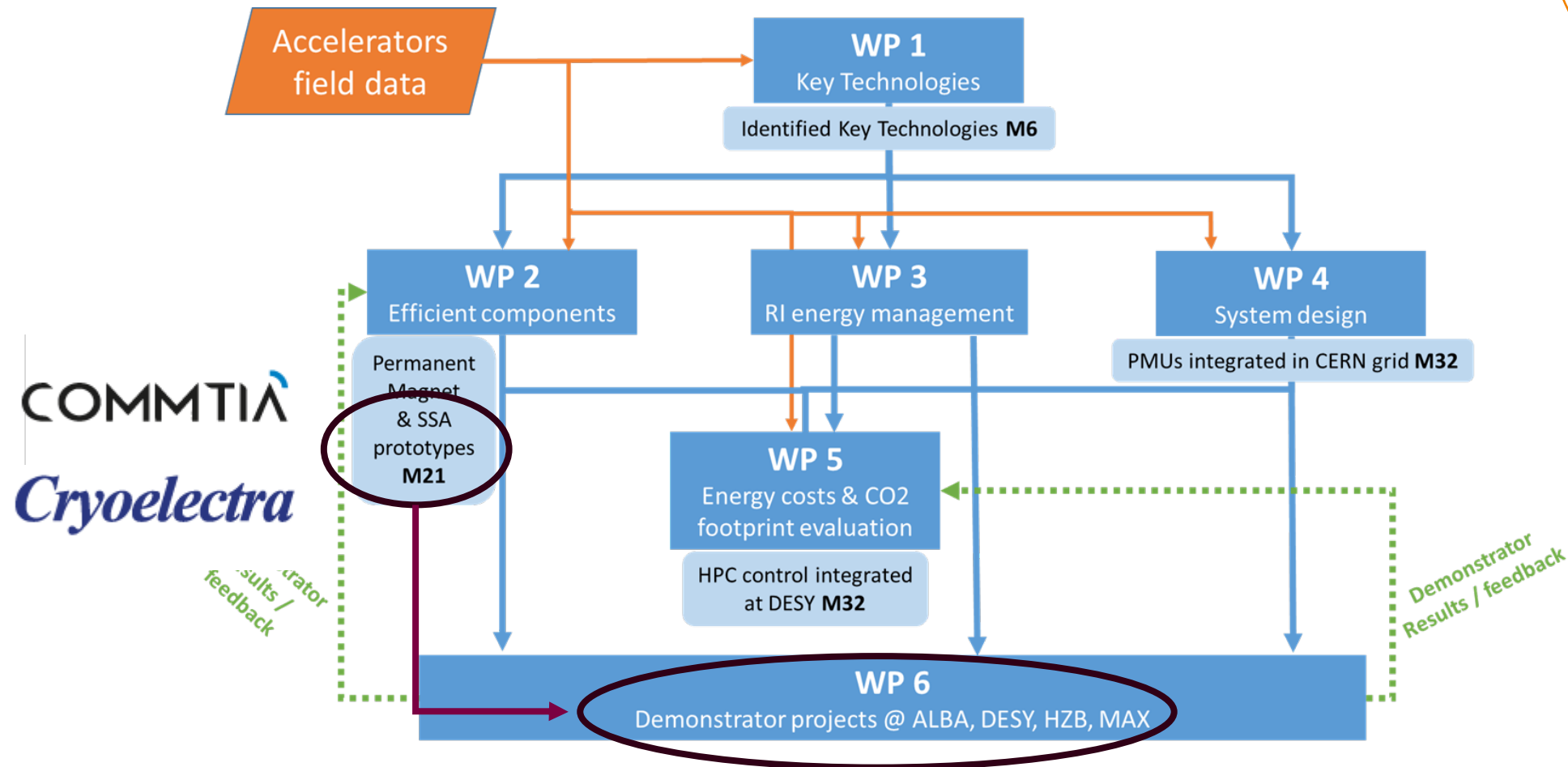
- Power electronics and DC grids
- Fast measurement systems (Phasor Measurement Units)
- Energy costs and resources analysis



Sustainable low carbon technologies integration

- Energy storage systems and technologies (batteries, supercaps, hydrogen)
- Flexible power consumption as for HPC centres / Renewable power-driven scientific computing

WORKFLOW



COMMITIA
Cryoelectra



HZB Helmholtz
Zentrum Berlin



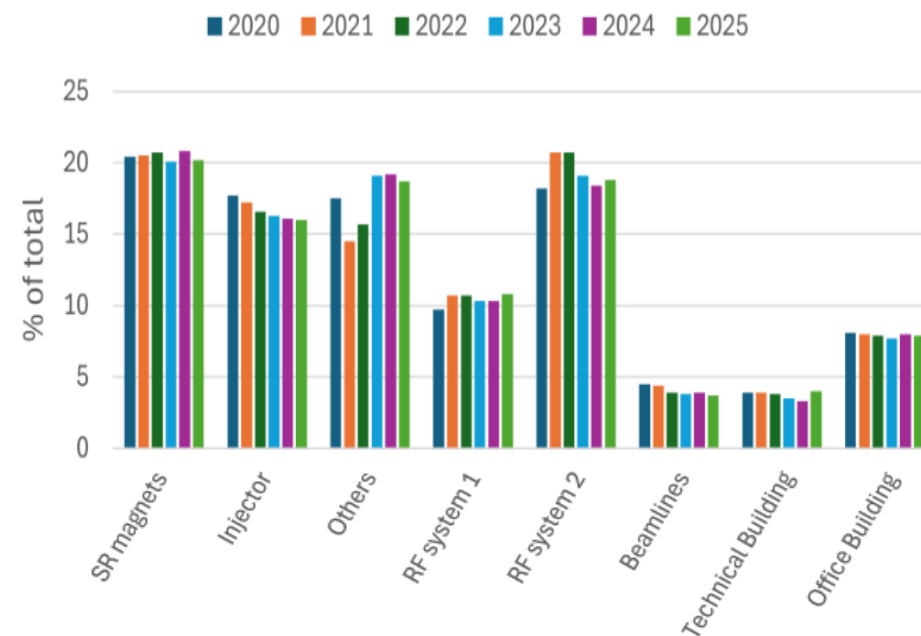
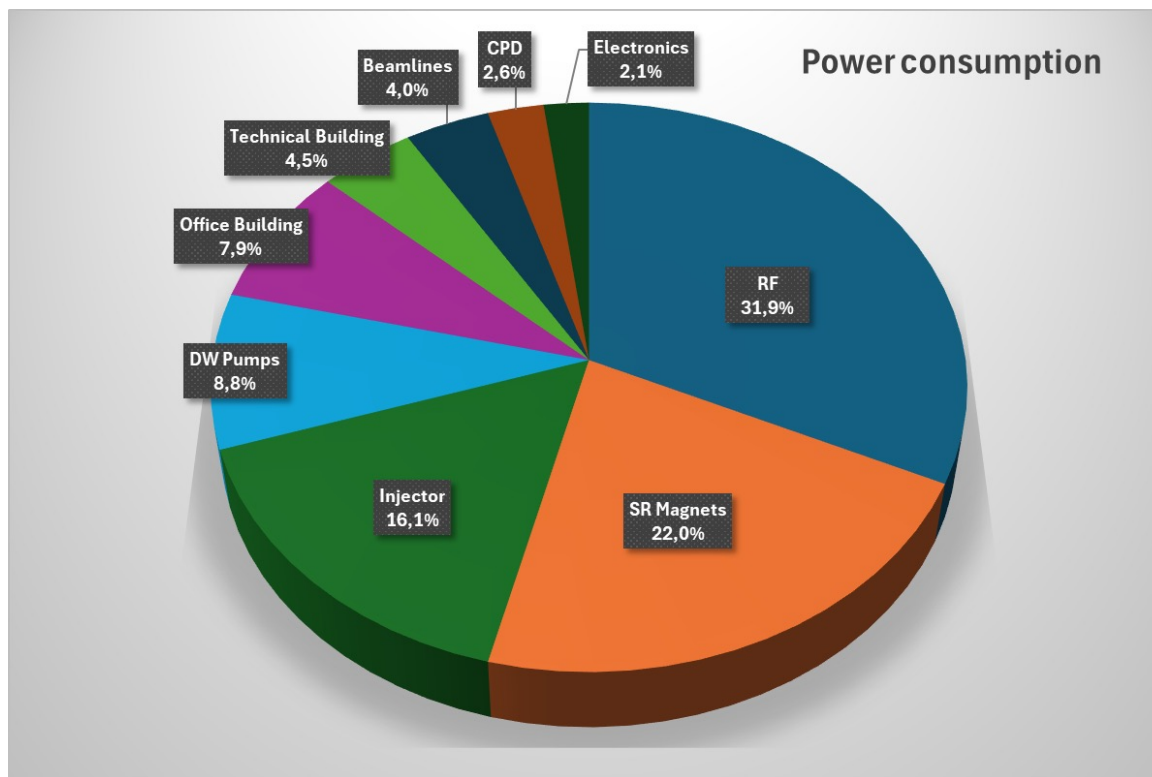
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MOTIVATION

WHY RF EFFICIENCY MATTER

RF AMPLIFIERS CAN REPRESENT UP TO 1/3 OF THE OVERALL ENERGY CONSUMPTION OF AN ACCELERATOR



RF SYSTEMS

THE SOURCE OF RF POWER FOR MODERN ACCELERATORS

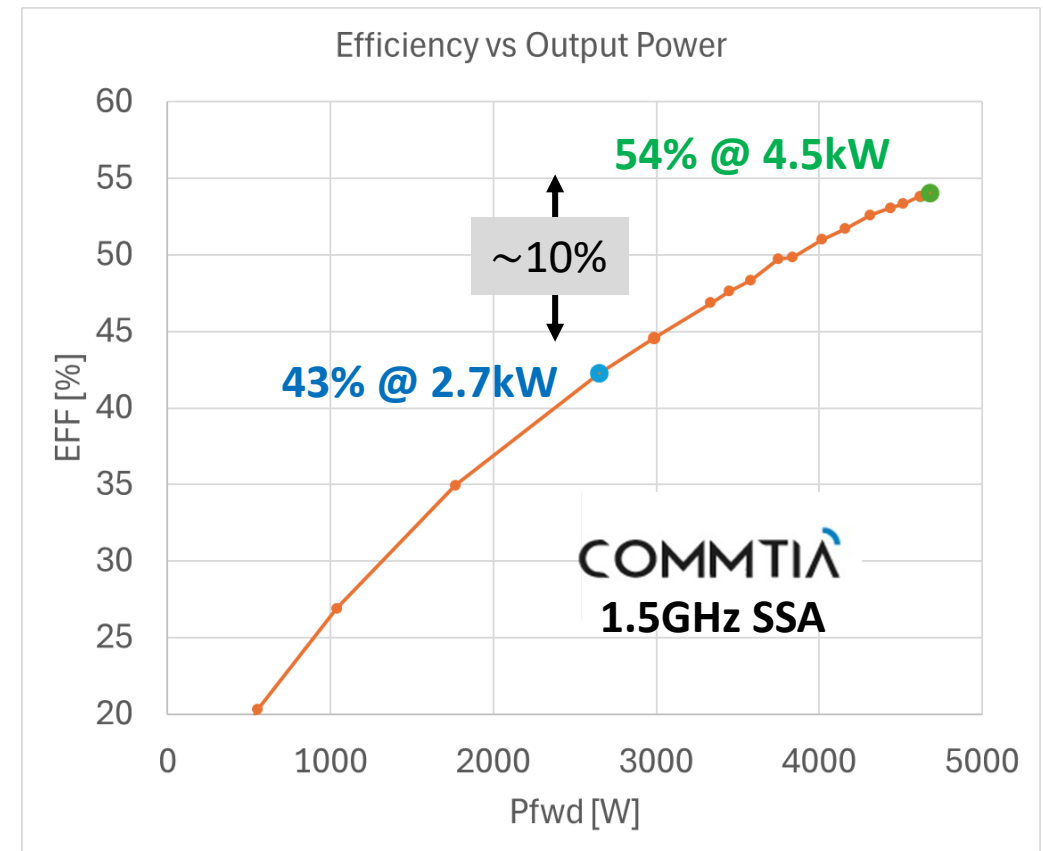
ARE SOLID STATE AMPLIFIERS (SSA)

At a given drain voltage, the efficiency of the SSA depends on the output power.

SSA are dimensioned to have enough operative margin, to cope with peak power requirements.



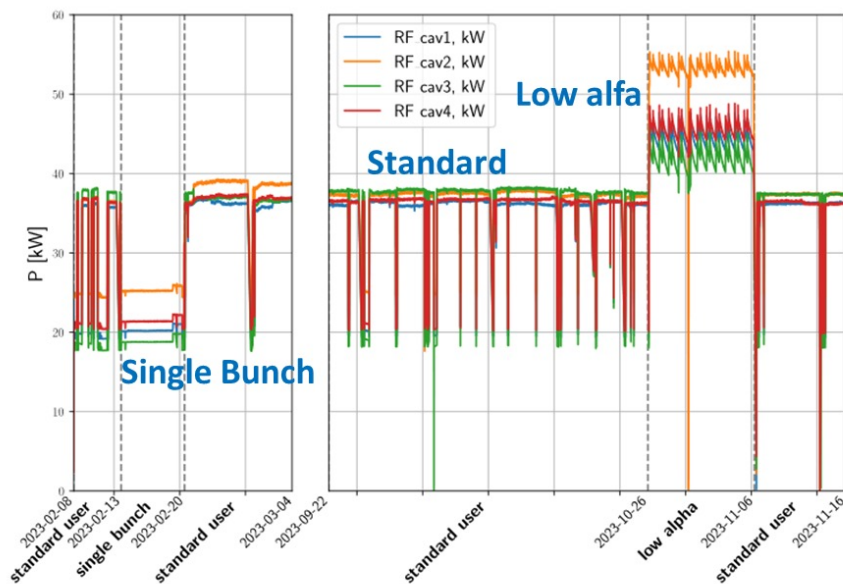
SSA operates usually and most of the time, out of the maximum efficiency



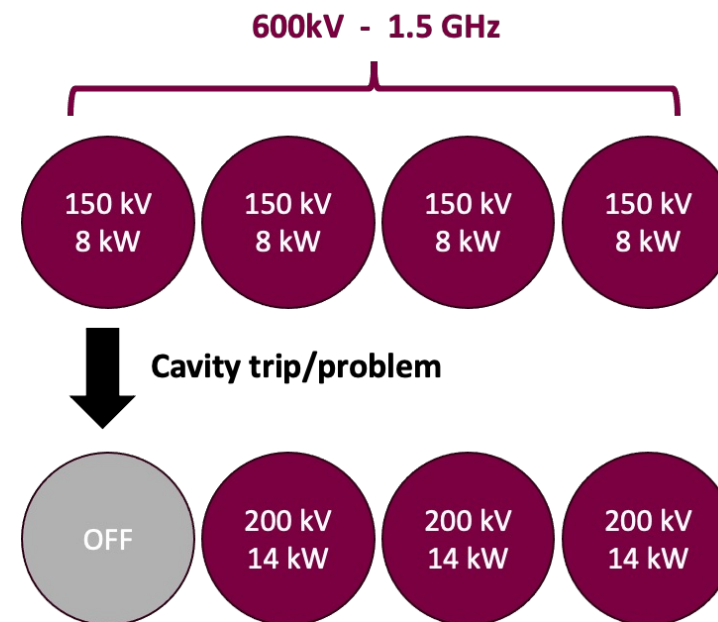
RF ACCELERATOR OPERATION

TWO CASES CONSIDERED: BESSY II & ALBA

BESSY II with different beam operation conditions



ALBA with different cavity configuration





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SSA DEVELOPMENTS

SSA DEVELOPMENT GOAL

THE GOAL IS TO IMPROVE OPERATIONAL EFFICIENCY,
IN DIFFERENT ACCELERATOR OPERATIONS CONDITIONS

Accelerators rely on high-power radio frequency (RF) systems to accelerate, condition, and store particle beams. At the heart of these RF systems are solid-state amplifiers (SSA), which convert electrical power into RF signal. But **SSAs are generally optimized for peak-rated power output, even though accelerators rarely operate under such conditions.**

In practice, **accelerators run at a wide range of power levels depending on the operations conditions**, and for most of the time, **they operate well below the maximum rated power**. Under these conditions, the **efficiency of SSAs drops significantly**, leading to excessive energy consumption and higher operational costs.

The goal of the project is to use sophisticated control systems that allow **for fine tuning of the RF characteristics of the amplifier by modifying the bias points of the integrated RF transistor amplifiers**. This allows optimizing the RF characteristics for **maximum efficiency at different output power levels**.

SSA DEVELOPMENT PROJECTS

THE GOAL IS TO IMPROVE OPERATIONAL EFFICIENCY,
IN DIFFERENT ACCELERATOR OPERATIONS CONDITIONS

Two projects:

- fundamental RF frequency (**500 MHz**)
developed by **HZB & Cryoelectra**
- 3rd harmonic frequency (**1.5 GHz**)
developed by **ALBA & COMMTIA**



Cryoelectra



COMMTIA

SSA DEVELOPMENT CONCEPTS

GOAL IS TO IMPROVE OPERATIONAL EFFICIENCY,
IN DIFFERENT ACCELERATOR OPERATIONS CONDITIONS

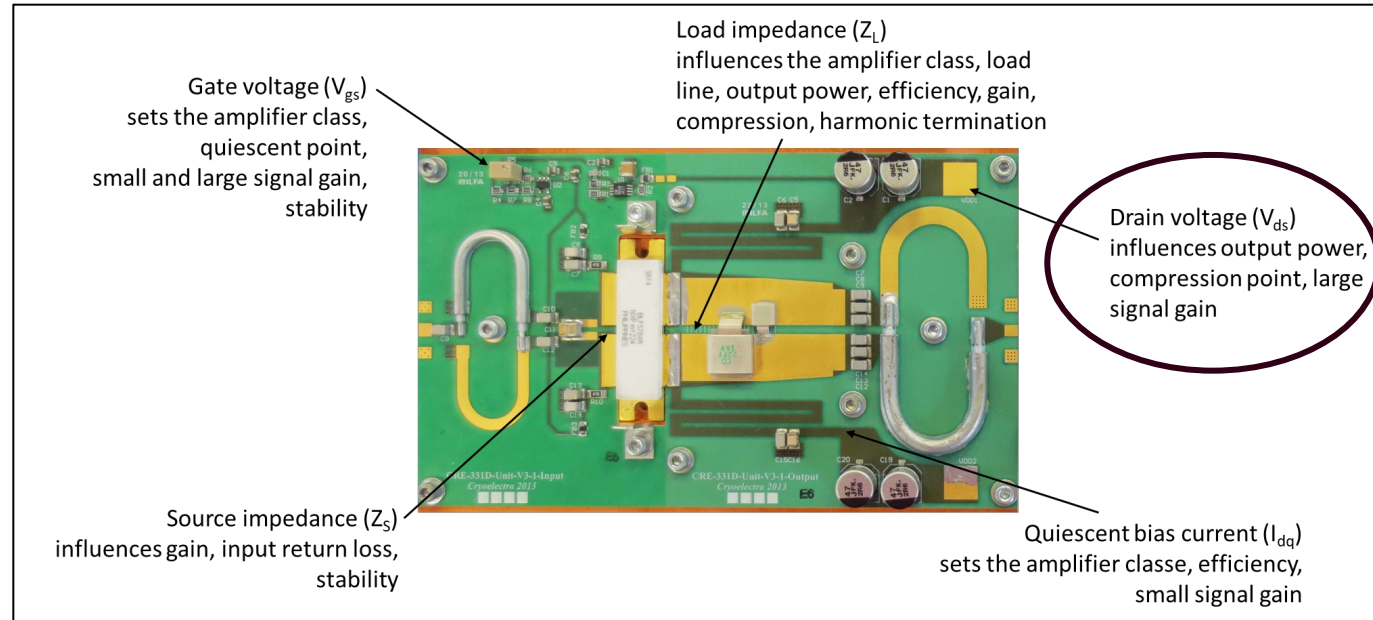
Two concepts:

- The HZB & Cryoelectra team has developed an **Adaptive Compression Point Control algorithm (ACPC)** which adjust the amplifier's compression point accordantly to the operation mode of the accelerator.
 - **Different settings for different operation mode: SB, MB, Hybrid (static).**
- the ALBA & COMMTIA team has developed an **Active Parametrization Digital Control (APDC)** which in communication with the accelerator's low-level RF (LLRF) system is able to optimize the operating efficiency of the SSPA depending on the required RF power.
 - **Settings change when the operation conditions change, i.e. when a cavity is switched off due to a trip (dynamic).**

SSA DEVELOPMENT CONCEPTS

GOAL IS TO IMPROVE OPERATIONAL EFFICIENCY,
IN DIFFERENT ACCELERATOR OPERATIONS CONDITIONS

Both systems are similar at the fundamental level, since they **both act over the drain bias voltage applied to the solid-state transistors of the amplifier**, but they have been optimized for two different accelerator's needs during operation.

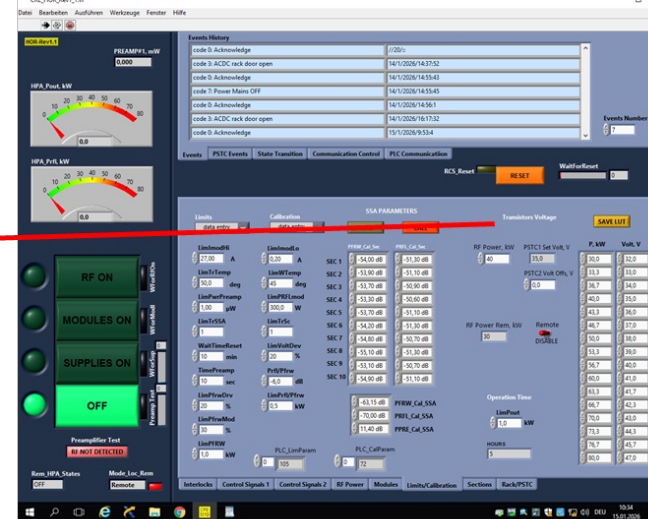
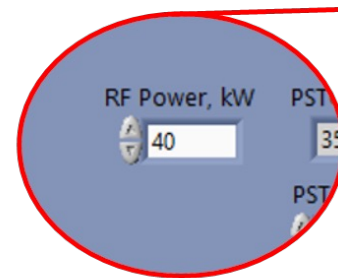


Cryoelectra
Birger Nordmann

SSA DEVELOPMENT CONCEPTS

GOAL IS TO IMPROVE OPERATIONAL EFFICIENCY,
IN DIFFERENT ACCELERATOR OPERATIONS CONDITIONS

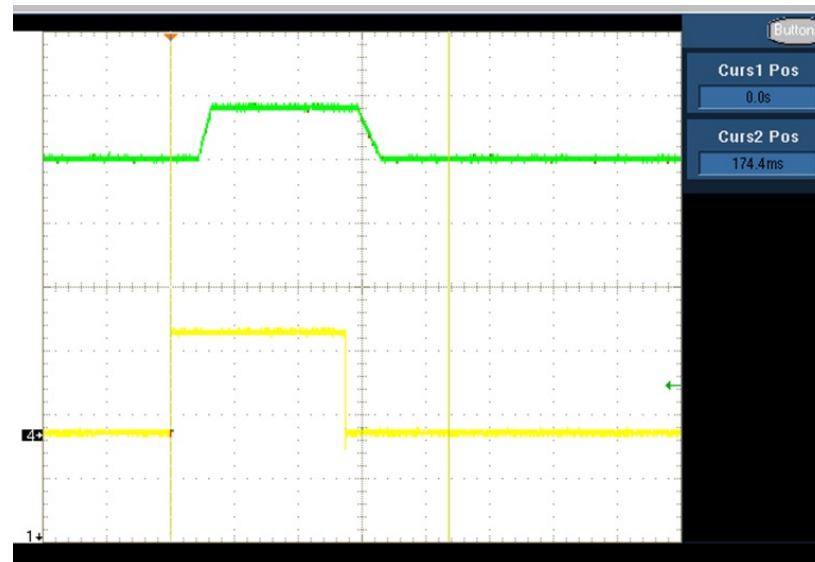
- The **Cryoelectra/HZB project** will cope mainly with the **different modes of current and power** that the BESSY II storage ring operates along the year, so it is **self-sufficient**, and the settings are given prior to the new mode of operation.



SSA DEVELOPMENT CONCEPTS

GOAL IS TO IMPROVE OPERATIONAL EFFICIENCY,
IN DIFFERENT ACCELERATOR OPERATIONS CONDITIONS

- The **Commtia/ALBA project**, for ALBA, operates mainly in one single mode of operation, so the system has been optimized to be able to react almost real-time when the requirement of power by the cavities changes, **adjusting the efficiency's parameters in communication with the LLRF system.**



COMMTIA



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**HARDWARE
IMPLEMENTATION**

500MHZ CRYOELECTRA

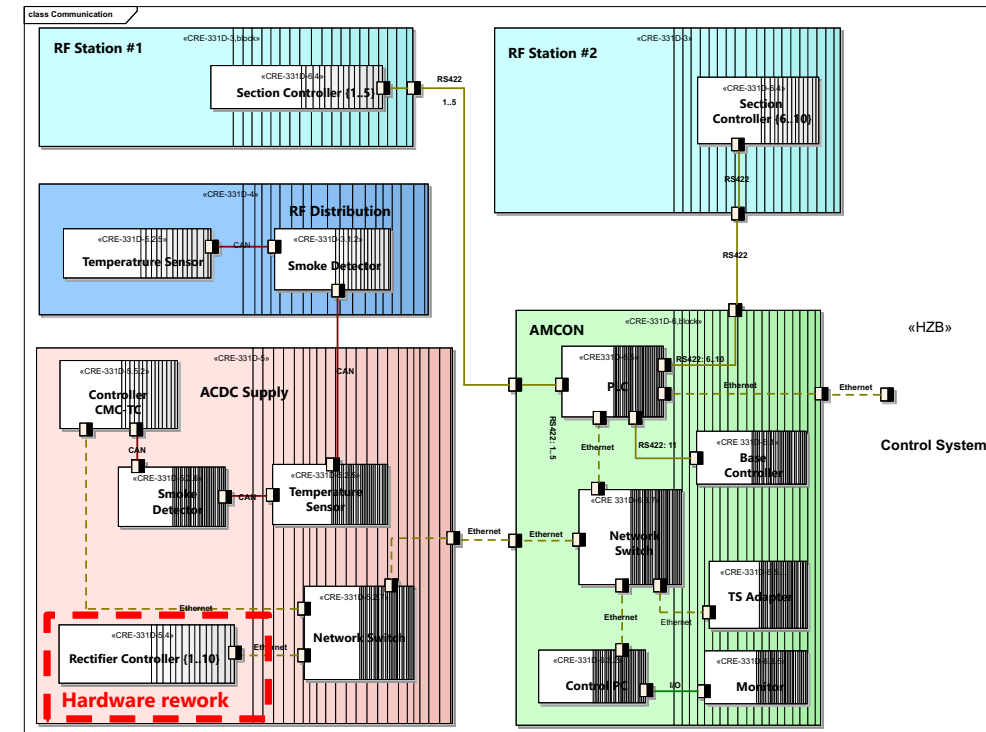
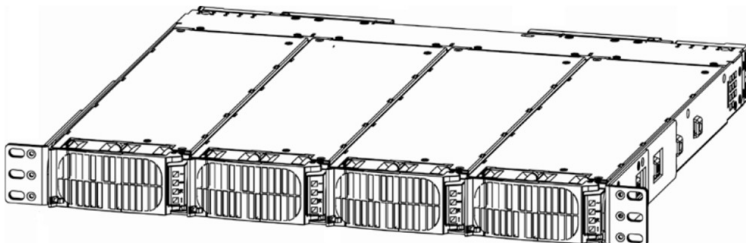
Cryoelectra



RETROFIT OF AN EXISTING CRYOELECTRA SSA AT HZB

To be able to implement the **Adaptive Compression Point Control algorithm (ACPC)** two modifications were required:

- **Replacement of the power supplies** that feeds the transistors to have enough precision on bias voltage control.
- **Modify the controller**, allowing fine adjustment control of the power supplies, with optimized communication.



1.5 GHZ COMMTIA

RETROFIT OF AN EXISTING COMMTIA SSA AT ALBA

COMMTIA



The implementation of the **Active Parametrization Digital Control (APDC)** was done for two amplifier operation modes:

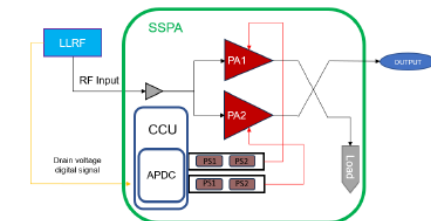
- **Slow dynamic mode:** This mode is controlled by software. The LLRF (Low Level RF) sends to the SSA a command (via Modbus) to set its operating point.
- **Fast dynamic mode:** The SSA has been retrofitted to include a TTL hardware interface, so that the LLRF can directly set the corresponding bias of the power amplifiers depending on the operating RF output power.

Involves firmware.

A Modbus command has been added to control the bias of the power amplifiers.

Involves firmware and hardware.

The hardware development consists in adding a 4-pole connector to fit the TTL signal.



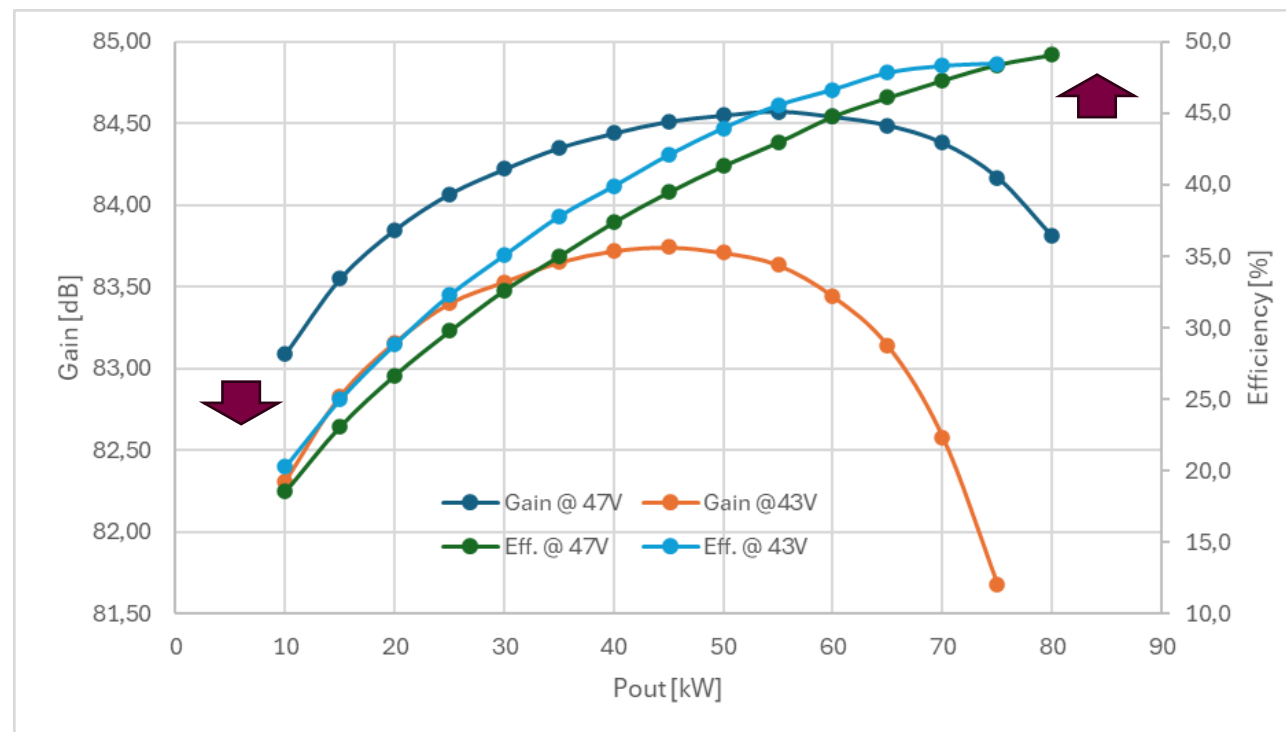


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**MEASUREMENTS AND
PERFORMANCE**

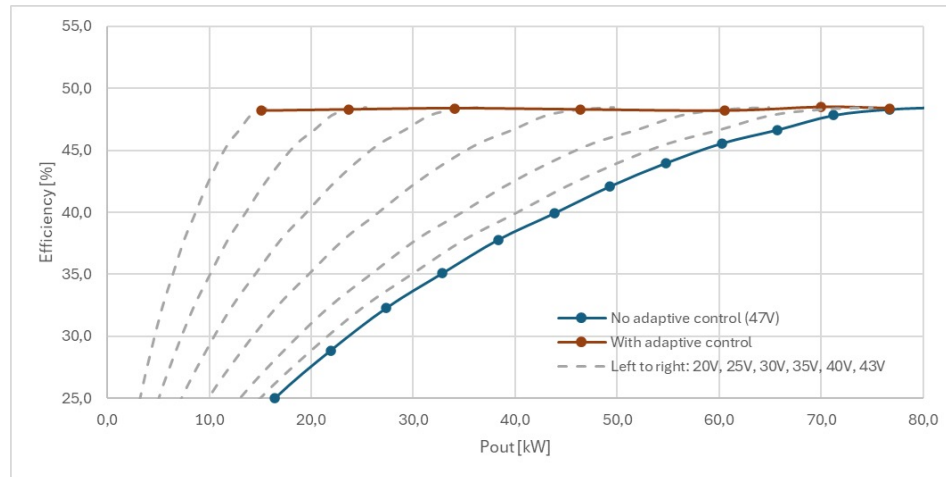
500MHZ CRYOELECTRA GAIN AND EFFICIENCY CHARACTERIZATION



Gain and efficiency characterisation at different **output power** for two different **bias voltaje (43 and 47V)** of the transistor

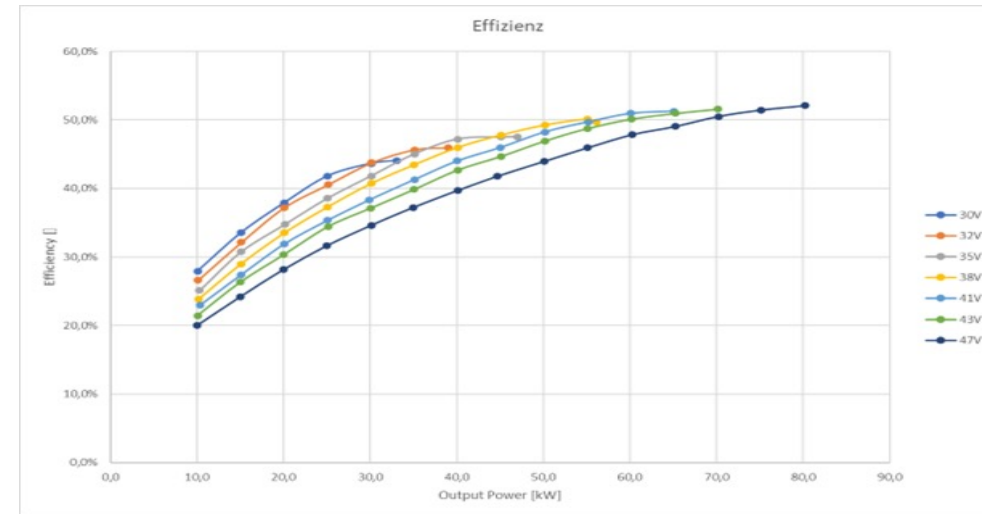
500MHZ CRYOELECTRA EFFICIENCY OPTIMIZATION WITH THE ACPC

Foressen / estimated performance



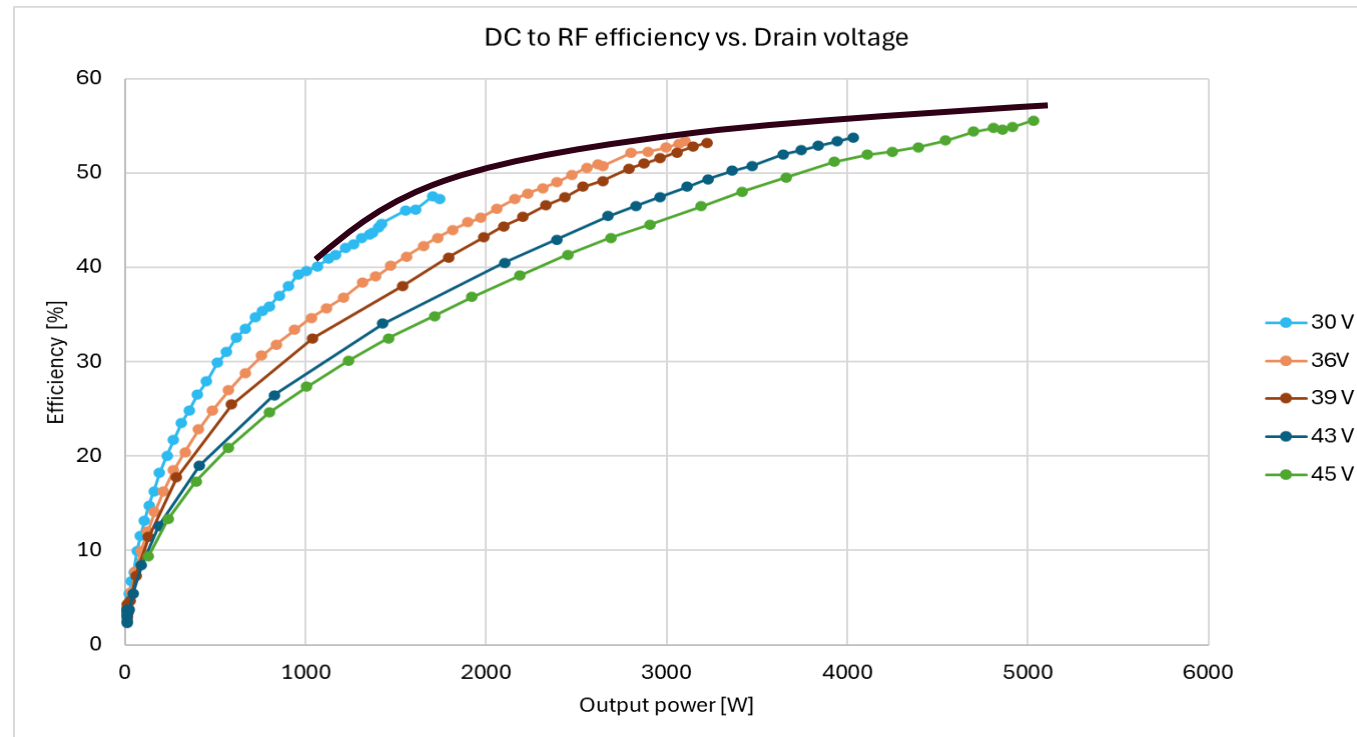
Efficiency vs RF output power
in factory default (**blue, measured**)
with adaptive control (**brown, estimated**)
for the CRE-331D 500MHz 75kW amplifier

Actual performance



Efficiency vs RF output power
characterization for **several bias voltages**
of the CRE-331D 500MHz 75kW amplifier

1.5 GHZ COMMTIA EFFICIENCY OPTIMIZATION WITH THE ACPC



Efficiency vs RF output power
 characterization for **several bias voltages**
 of the COMMTIA 1.5GHz 5kW amplifier



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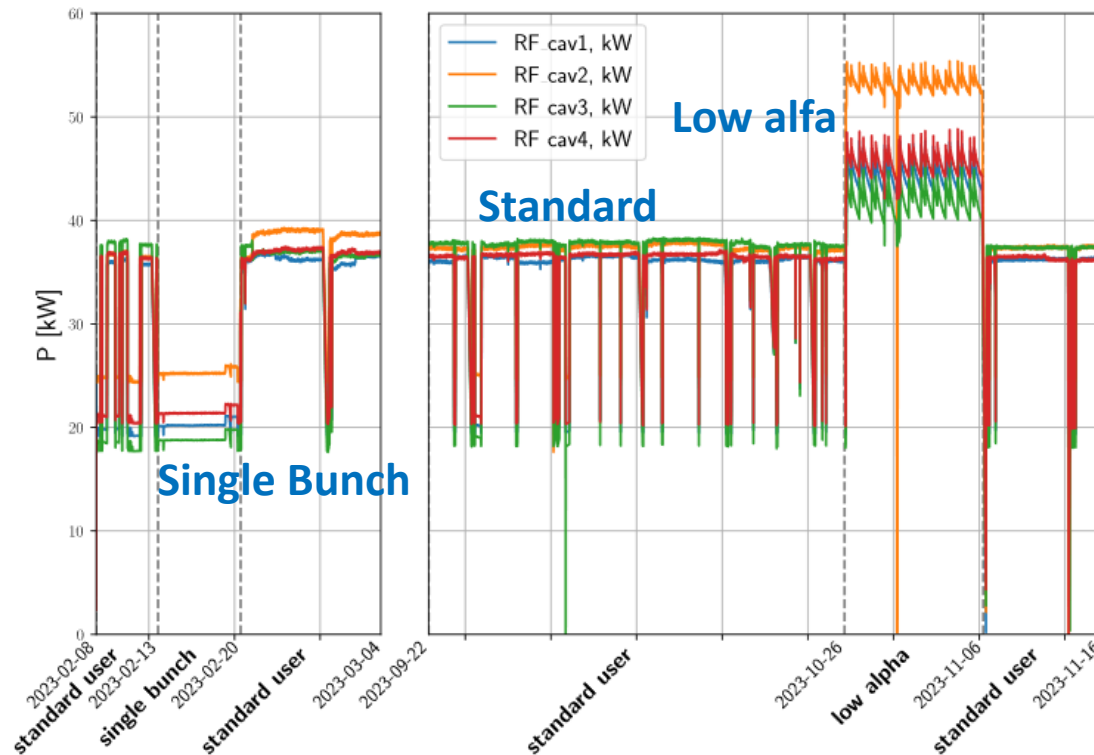
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**RESULTS FOR A
REAL ENVIROMENT**

500MHZ CRYOELECTRA ESTIMATION ON THE OPERATION AT BESSY II

Cryoelectra

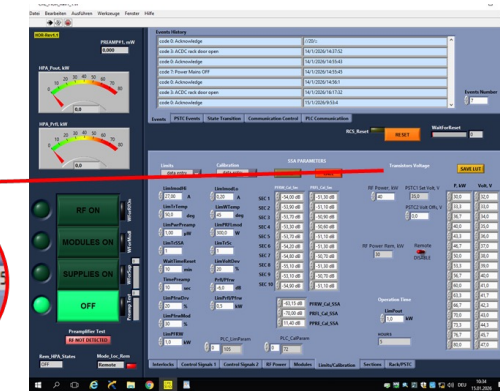
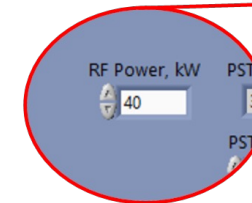
HZB Helmholtz
Zentrum Berlin



Measured RF power of the cavities in use at BESSY II during real operation of the accelerator.

Average power per cavity for each mode:

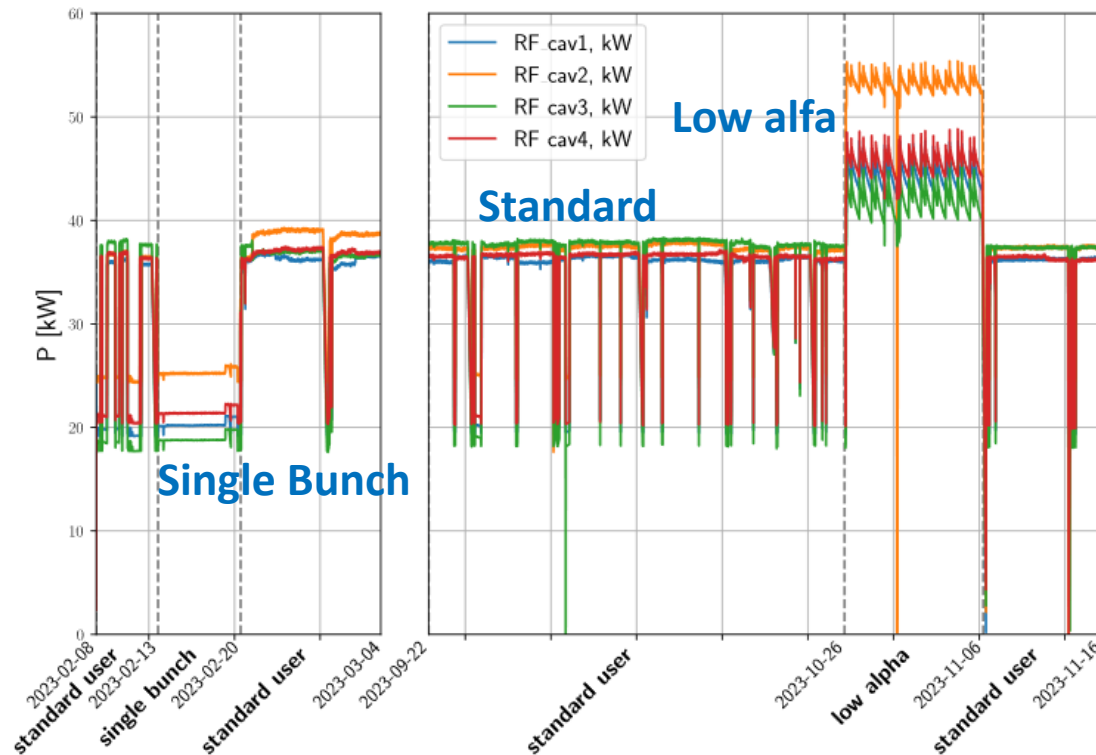
- **Standard User** 38kW
- **Single Bunch** 21kW
- **Low Alfa** 48kW



500MHZ CRYOELECTRA ESTIMATION ON THE OPERATION AT BESSY II

Cryoelectra

HZB Helmholtz
Zentrum Berlin



The increase efficiency can be estimated, per each operational mode, as:

- **Standard User** 8% (39% → 47%)
- **Single Bunch** 10% (29% → 39%)
- **Low Alfa** 5% (44% → 49%)

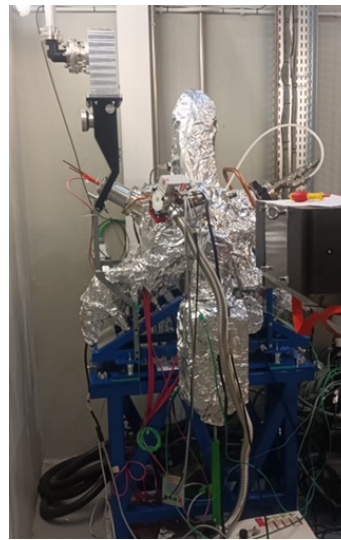
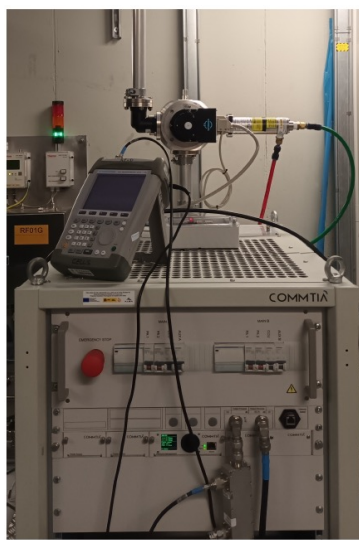
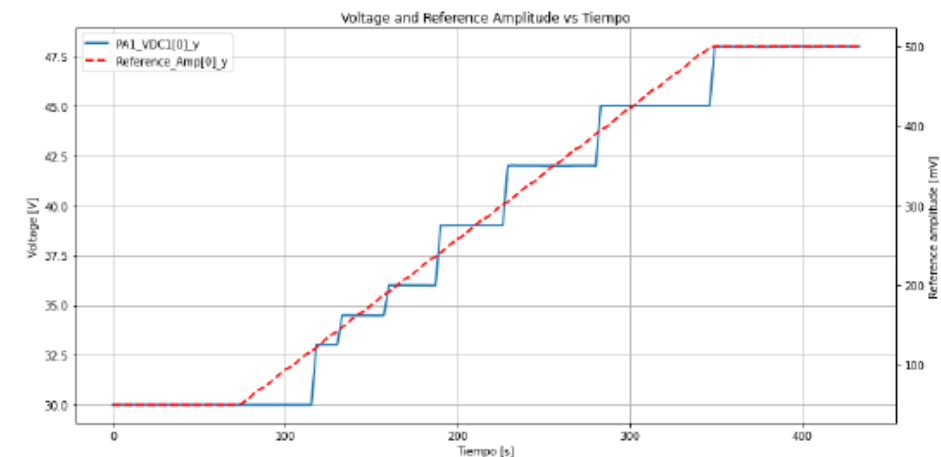
The estimated yearly energy savings for a standard operation year is estimated to be ~**400 MWh**.

1.5 GHZ COMMTIA TESTS AT ALBA

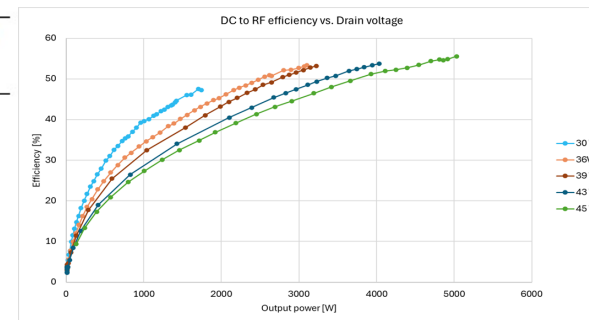


COMMTIA

- The retrofitted SSA was installed in the RF lab of ALBA.
- **The LLRF was modified to drive the APDC.** →
- A 1.5 GHz cavity was installed in the bunker.
- Real power test were done with the SSPA, LLRF and cavity.



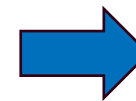
Drain Voltage V	LLRF [mV]	APDC [bit]	Max. output power [W]
30	111.2	000	1743.8
36	143.0	001	3001.9
39	183.2	010	3224.6
43	234.0	011	4138.7
45	300.0	100	4382.8
46	385.0	101	4681.2
48	493.0	111	5092.1



Ignacio Serrano, *et al.*, "SSPA efficiency improvement studies at ALBA in the framework of the RF2.0 project", Proceedings IPAC'26, 2026.

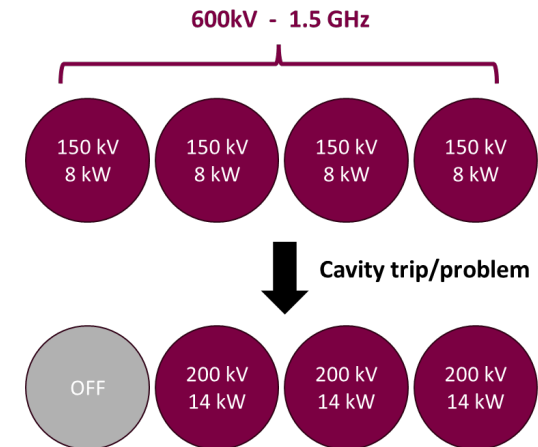
1.5 GHZ COMMTIA ESTIMATION ON THE OPERATION OF ALBA

- At ALBA we will run with 4 harmonic cavities, with an overvoltage, so that **when a cavity fails** the remaining 3 cavities provides still enough voltage for the beam to survive.
- In this situation, **the power requirement for each cavity increases.**
- So, **if not APDC is implemented**, the bias voltage of the SSA has to be the one for the higher power requirement, so most of the time **the SSA is running at a not optimized point.**
- With the APDC, the bias voltage **can be dynamically adjusted to operate the SSA always close to the maximum efficiency at the given power.**



Around ~25 MWh energy savings
(increase efficiency ~17%)
for a 6000 hours operation per
year with a trips rate of 0,4%

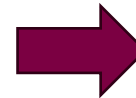
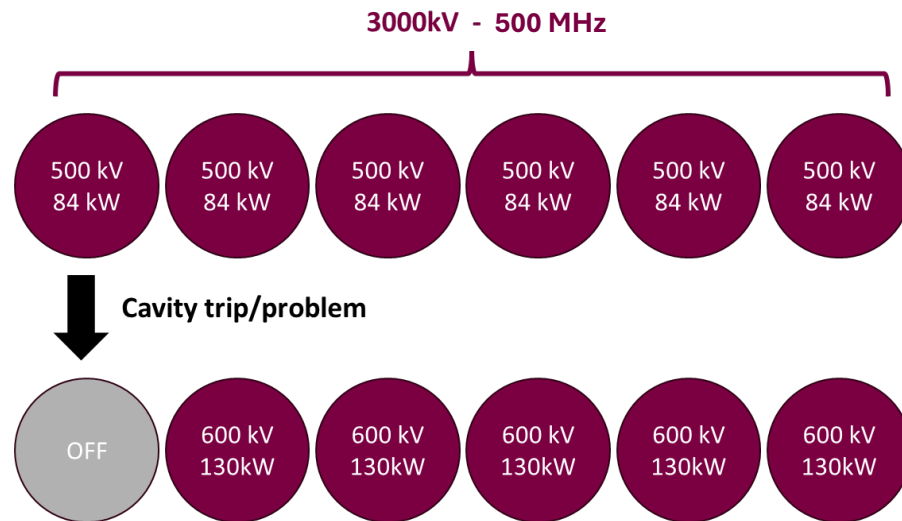
COMMTIA
ALBA



500 MHZ ESTIMATION ON THE OPERATION OF ALBA



- At ALBA we will run with 6 fundamental cavities, with an overvoltage, so that when a cavity fails the remaining 5 cavities provides still enough voltage for the beam to survive.
- **If we apply the same concept**, the expected energy saving are:



Around ~**800 MWh energy savings**
(13% increase efficiency)
for a 6000 hours operation per year
with a trips rate of 0,4%

ALBA annual consumption is ~20 GWh (electrical power)



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CONCLUSION

CONCLUSION

- The two developments by **Cryoelectra** and **Commtia** has been implemented and tested.
- The first one shall allow to operate at the **different modes of operation of BESSY II** with a considerable annual energy savings.
- The second one shall allow to **operate ALBA, with dynamic adjustments** of the efficiency of the SSA, with important annual energy savings.

Cryoelectra
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COMMTIA

ALBA

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THANK YOU FOR YOUR ATTENTION



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This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101131850 and from the Swiss State Secretariat for Education, Research and Innovation (SERI).



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