OPERATIONAL EXPERIENCE ON A COMMERCIAL SOLID STATE POWER AMPLIFIER WITH INTEGRATED LLRF UNIT

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Abstract

In this contribution we report on the operational experience gained with a commercial off-the-shelf solid-state RF power amplifier equipped with an embedded low-level RF (LLRF) control system, in use for the sub-harmonic buncher cavity of the HB^{2}TF project at INFN LASA. We summarize the motivations behind adopting a turnkey solution, highlighting expected benefits in terms of reliability, maintainability, and integration effort. The paper presents the main results of our testing campaign, including performance stability, response under varying operating conditions, and preliminary assessments of control accuracy. Finally, we provide notes on the synchronization strategy implemented to interface the RF control system with the laser-driven photo-cathode used as beam source.

INTRODUCTION

The electron bunches generated by the DC Gun of the HB2TF Test Facility currently being installed at INFN LASA [1] have a long longitudinal profile to avoid emittance dilution. After the gun, to minimize nonlinear energy spreading due to RF waveform in the foreseen SC booster, bunches need to be compressed to shorter length. As the beam is still non-relativistic, the simplest method of bunch compression is the velocity bunching. To this purpose a sub-harmonic bunching stage has been designed making use of two 650 MHz, spherical re-entrant shape, copper cavities. The first of these two buncher cavities (Buncher #1) has been machined and will be installed and tested in June 2026 on the first version of the beam line. The cavity will operate using a power amplifier internally specified and commissioned to the Italian Company SyES srl [2]. In this paper we will describe the main features of the amplifier and the first experience gained during its development.

THE BUNCHER CAVITIES

The two bunchers designed for the HB^{2}TF test-stand took inspiration from the structure used in cERL and scaled down in frequency. The E.M. studies have been carried out using as a first tool the Superfish code and the detailed behavior has been optimized using Ansys HFSS commercial simulator.

The cavities have been machined from bulk copper pieces using a high-precision lathe and the resulting two main halves have been brazed. The cooling channels have been inserted in the outer shell of the cavities, and they are able to remove all the thermal power dissipated in the wall. The cooling circuit comprises an external thermos-chiller (model HRS 150-WF-40 from SMC) for each cavity.

A compact coaxial power coupler, able to withstand the full incident RF power, has been designed and is now in the machining phase. Further details about the buncher cavities, the coaxial power coupler and their current status are in the paper THP2107 [3] also at this conference.

The beam loading of the buncher cavities is minor, as the RF power is almost all dissipated in the cavity walls. The power budget to feed both buncher cavities is reported in Table 1.

Table 1: Nominal Requirements for the RF Power Chain of the Two Bunchers

	$E_{z\ max}$ = 2.7 [MV/m] Buncher #1	$E_{z\ max}$ = 2.7 [MV/m] Buncher #2
Beam power [kW]	2	2
Cavity power [kW]	11	14
Total power [kW]	13	16
+15% margin	15	18
Target forward power – [kW]	16-18	18-20

POWER AMPLIFIER REQUIREMENTS

The use of RF power amplifier with resonating cavities introduces specific operational aspects that in turn result in few uncommon requirements for the amplification unit. These may be summarized as in the following:

- Fast response time for RF shutdown: the electric fields excited in the resonant cavity can occasionally generate discharges. Since a discharge causes a large mismatch in the load, the reflected power will increase significantly. The implemented protection system will shut down the RF power (zeroing the small signal) in a time interval suitable to prevent damage to the amplifier.
- Robustness to multipacting: multipacting is a resonant permanent discharge phenomenon that may occur when operating a resonator under vacuum. It causes a mismatch in the load, which results in an increase in the VSWR (Voltage Standing Wave Ratio).
- Compliancy to pulsed operation at least for cavity conditioning: cavity conditioning requires rapid pulsing of the RF signal while steadily increasing both amplitude and duration until target operating conditions are achieved. Typical pulses in use could be:
  - Forward power rise time: < 1 µs
  - Pulse duration: 20 – 100 µs

  - Repetition rate: < 1 kHz
- Compliancy to full reflection transient: due to the characteristic of the resonant cavity load (Ql ~ 30000, time constant ~ 15 µs) the amplifier is able to withstand total reflection at full power for an initial time of the pulse comparable to the first few cavity time constants: request is full reflection up to 100 µs. The system is designed to operate in such a way as to withstand a maximum reflected power value in continuous wave mode not less than 30% of the maximum output power from the amplifier.
- Designed for seamless integration with an LLRF control system: to operate a resonant RF cavity to the level of stability required by beam dynamics an additional control stage is mandatory and known as Low-Level RF control or LLRF.

Required performances and parameters of the RF power amplifier required for the first cavity buncher at beta 0.74 of the HB^{2}TF project are summarized in the following Table 2.

Table 2: Specifications for the RF Power Amplifier for the First Buncher Cavity

Parameter	Value
Center frequency	650 MHz
3 dB bandwidth	≥ 0.5 MHz
Output power – Max	18 kW @ 1 dB comp
Amplifier technology	Solid State, class AB
Amplifier design	Modular, ≥ 4 modules
Module design	Composite, ≥ 6 RF pallets, with planar BALUN
Operating mode	CW, pulsed
Input power interval	0 - 8 dBm for max. power
Dynamic range	≥ 15 dB
Phase stability	+/- 1 deg
Amplitude stability	+/- 0.1 dB
Plug power efficiency	> 50%
Output reflected power	30 % of max. power
Output reflected power	Foldback or shutdown
VSWR protection	Complete
Full refl. protection	Pulses shorter than 100 µs
Harmonics	< -30 dBc
Spurious oscillations	< -60 dBc
Main cooling system	Liquid cooled

AS BUILT CHARACTERISTICS

The Italian company SyES srl (Lissone – Monza e Brianza area) has been awarded for the design and manufacturing of the above-mentioned amplifier.

Their proposed design is based on a liquid-cooled RF amplifier built via solid-state power amplifier (SSPA) assembly specifically engineered for the 650 MHz frequency, delivering a total output of 18 kW split into nr.5 independent hot pluggable amplifier modules capable of a dual output of 2kW power each. The overall appearance of the finished amplifier is reported in Fig. 1.

Figure 1: Solid State amplifier for the first buncher cavity, as built.

The RF section consists of the division, amplification, and combining stages, featuring six Ampleon BLF978P [4] 50V LDMOS transistors that provide high power and efficiency with a rugged modular design. To ensure maximum reliability with respect to reflected power, each of the six pallets is equipped with an integrated RF circulator; because these circulators provide absolute isolation at the pallet level, the final 3-way combiners are non-isolated, a strategic choice that reduces cost and complexity, also minimizing insertion loss.

Transistors are biased in class AB, working in push-pull mode thanks to input and output planar baluns; this coplanar structure ensures much higher repeatability and reduced cost than the coaxial baluns which are traditionally used at VHF/UHF frequencies. To handle thermal management, a specialized Thermal Gap Pad is positioned beneath the output balun of each pallet. This material (Softtherm-86/525 from Kerafol [5]) provides an ideal compromise between thermal conductivity and the dielectric constant required for optimal RF performance.

The RF pallets are manufactured on a TC350 substrate [6], chosen for its superior thermal conductivity, essential for dissipating the heat concentrated at the pallet level, while the output combiner utilizes RO4350B laminates [6], chosen for its ease of manufacturing (compatible with standard FR-4 material processing) and low-loss characteristics.

The RF Section is fed by a single-input, 6-way power divider (Fig. 2), while the driver stage is housed in a separate location within the amplifier to ensure electromagnetic isolation and optimize the overall thermal footprint.

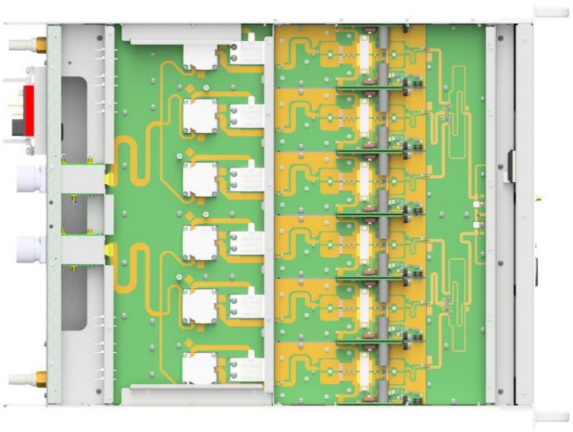

Figure 2: single amplifier unit layout.

Moving up to the system level, the complete SSPA features five of these amplifier units, resulting in a total of ten 2 kW outputs (see Fig. 3). Each of these outputs is equipped with a 7/8" EIA connector, selected to ensure the necessary power handling capability and mechanical robustness. These are merged using two progressive hybrid combiners. Unlike traditional 3-dB hybrid combiners, a progressive hybrid combiner is highly advantageous for high-power systems as it handles higher power with smaller dimensions and requires smaller loads. This dramatically simplifies the mechanical and cooling layout.

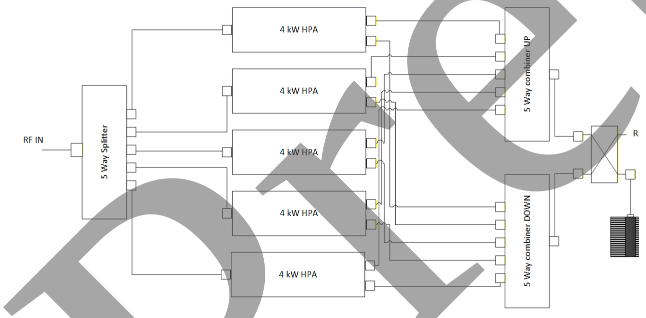

Figure 3: high-level system overview of the SSPA.

The design choice to split each individual amplifier into two separate 2 kW outputs is specifically optimized to match the requirements of the progressive combining topology. Finally, the outputs from the two progressive combiners are merged through a standard 3dB hybrid, which serves as the final combining stage to deliver the total combined power to the main load.

EMBEDDED LLRF CONTROLS

The amplifier must guarantee a seamless integration, both hardware and firmware, with a Low-Level RF or LLRF controller operating in closed loop to drive and stabilize amplitude and phase of E.M. field inside the cavity. For the amplifier unit being developed by SyES for the buncher cavities of the HB^{2}TF project, the LLRF controller is directly embedded in the amplifier architecture.

Its main features are:

- Amplitude/Phase feedback loop for beam operations: automatic correction of feedback out signal Amplitude and Phase in order to achieve target Amplitude/Phase of input signal feedback; the phase loop speed can be chosen in a large interval (roughly from 4°/µs to 0.2°/ms).
- Automatic Frequency Correction (AFC) for operations w/o beam: the reference out signal frequency can be automatically adjusted in order to match the cavity resonance frequency variations caused by temperature, minimizing the amount of reflected power.
- Internal signal generator: both CW or Pulsed drive signal, within 60-900MHz band with about 0.1Hz resolution for CW, max Pulse Period of 170 s with 40ns resolution for pulsed mode (both Internal Reference or External Reference Mode).
- Signal and Pulse Generation are based on internal 10MHz OCXO that can be locked to External 10 MHz
- Power detection and modulation functions.
  - Forward and Reflected Power Detection.
  - The amplitude target can switch between two different levels with switching instants defined by pulse rising/falling edges.
  - Foldback: the Forward Out Power can be automatically reduced if Reflected Power overcomes a user-defined threshold.
  - Output Power Limiter: the Feedback Out power can be limited in order to avoid accidental over-power.

Further details about the embedded LLRF control developed for the HB^{2}TF bunchers are in the paper MOP7052 [7] also at this conference

CONCLUSION

A 650 MHz 18 kW Solid-State RF amplifier and its embedded LLRF control system have been developed to operate at the buncher cavities of the HB^{2}TF project at LASA. The first complete setup for buncher #1 (beta 0.74) is targeted for experimental qualification this summer.

REFERENCES

[1] INFN LASA: www.homelasa.mi.infn.it

[2] SyES srl.: https://syes.eu/scientific/

[3] D. Giove et al., "Installation and First Tests of a High Brightness Beam Test Facility for ERL Applications at INFN-LASA", presented at IPAC26, Deauville, France, paper THP2107, this conference.

[4] Ampleon: https://www.ampleon.com/

[5] Kerafol: https://www.kerafol.com/en/

[6] Rogers Corporation: https://www.rogerscorp.com/

[7] M. Corvino et al., "A New Generation of Digital Low Level RF Control Systems", presented at IPAC26, Deauville, France, paper WEP6151, this conference.