1.6 MW, 144 MHz SOLID STATE POWER AMPLIFIER FOR ELSA ELECTRON LINAC

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Abstract

The 19 MeV electron linear accelerator ELSA at CEA DAM has been in operation for 30 years. A renovation of the RF system was necessary to improve the reliability of the system. The second part of the renovation addresses the 144 MHz RF amplifier that supplies power to the photo-injector. The former tetrode-based amplifier has been replaced by a 1.6 MW Solid State Power Amplifier delivered by Ampegon company. One of the challenges was to design a compact amplifier to keep the same footprint. This paper presents the amplifier, the tests and the commissioning.

INTRODUCTION

The ELSA facility was commissioned in the early 90's as a high efficiency IR FEL [1]. For this purpose, the electron linac was designed to meet FEL requirements such as low emittance beam and high repetition rate. Thus, the photo-injector was designed at 144 MHz in order to have a large homogeneous accelerating field on the photo-cathode and to minimize energy dispersion at emission. The second accelerator stage consists of 3 cavities at 433 MHz, powered by a 6 MW klystron. The original RF system was designed to deliver high repetition rate RF pulses up to 150 Hz.

Since the beginning of the 2000's, ELSA facility has been used as a high-brightness electron source or as a picosecond X-ray source either by bremsstrahlung radiation in high-Z materials or by inverse Compton scattering. Several upgrades of the facility have been made during the two last decades such as adding a third accelerating stage at 1300 MHz, adding a new beam line, improving the inverse Compton source. But the original RF sources were still in operation until recently. The main failures occurring during beam delivery were actually due to RF amplifier faults and resulted in a decrease of the mean time between failures (MTBF) because of component obsolescence. This was not acceptable for users. In 2022, the 433 MHz klystron modulator has been replaced by a new one delivered by JEMA company. In 2024, the original 2.5 MW tetrode-based amplifier was replaced by a Solid State Power Amplifier (SSPA) (Fig. 1).

SPECIFICATIONS & DESIGN

Main specifications of the RF amplifier are given in Table 1. With a maximum of 4 kW mean power, either pulse duration or repetition rate must be decreased to maximize the other parameter.

Figure 1: Picture of the new SSPA on ELSA Facility.

Whereas the pulse droop can be balanced by the low-level RF (LLRF) signal at the input, the pulse-to-pulse reproducibility specification is a parameter of uttermost importance to guarantee the stability of the electron beam, since this fluctuation is purely random.

Table 1: RF Amplifier Specifications

Parameter	Value
Frequency	144.44 MHz
Maximum power	1.6 MWp
Pulse duration	500 µs max.
Repetition rate	1-10 Hz
Mean power	4 kW max.
Pulse droop	< 2%
Pulse to pulse reproducibility	< ± 0.1%

Another important specification in this kind of equipment was the footprint available for the amplifier. It had to be fitted in a 8300 mm × 1200 mm footprint.

To meet those requirements, Ampegon Company proposed a design based on the combination of 80 × 22 kWp RF power modules with splitters and combining structures. Each module is composed of a splitter, 16 amplifier pallets fixed on a water-cooled plate, a control board and an

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unisolated quarterwave combiner. Each pallet integrates the MRFX1k80N LDMOS transistor from NXP Company [2]. One specificity of the pallet design is that there is no circulator to protect the transistors. Pallets are designed in order to be protected against power reflection in case of a faulty pallet. The modules are combined ten by ten with an isolating planar combiner. This combiner was developed specifically for this amplifier in order to be plugged directly at the back of the modules (Figure 2). The combination is done in two stages. The first one is a 5-way combination: two of them combine the 10 modules, and the second stage is a 2-way combination. Both combinations are isolated. The 2 × 5 50 Ω resistors of the two first stages of the combination are shown in Figure 2.

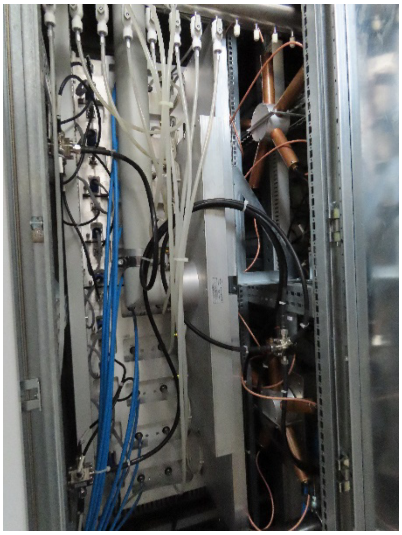

Figure 2: Picture of the 10-way combiner with the 2 × 5 resistors in a star topology.

The 80 modules are distributed in 8 cabinets with a 10 ways combiner, then 2 cabinets are combined with a 2-way isolating combiner. The last combiner, a 4-way to 1 port is not isolated. Figure 3 gives an overview of the combination network.

TESTS OF THE AMPLIFIER

The amplifier has been tested at different stages of production. Around 20 parameters have been measured on the modules. Measurements confirm that the power gain for all modules is greater than 20 dB. The phase scattering is ±4° around the average phase.

After assembly of the modules and the coaxial network, the amplifier has been tested first on a dummy load at Ampegon facility, and then after delivery on site at CEA on a dummy load. Characteristic curves depending on transistor bias voltage are given in Figure 4.

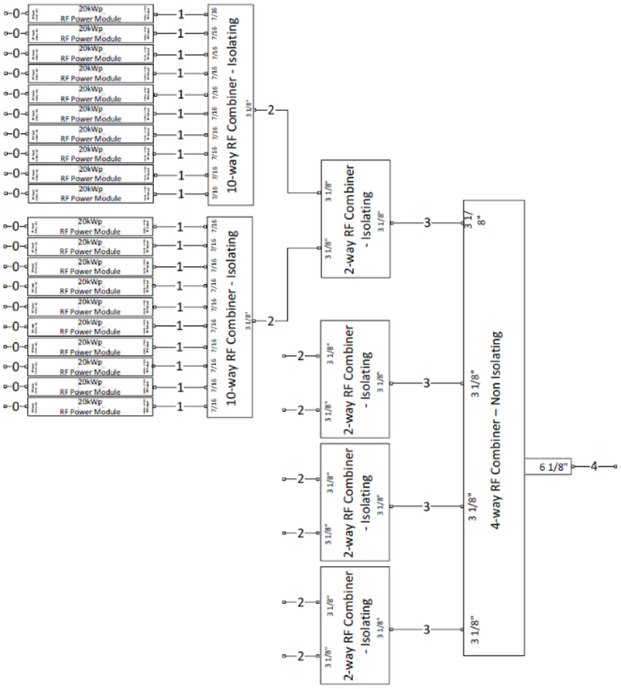

Figure 3: Overview of the combination.

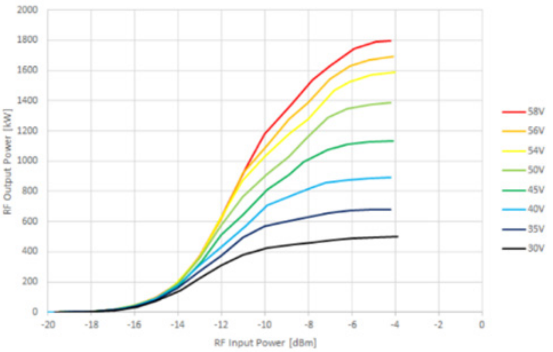

Figure 4: Characteristic curves of the amplifier as a function of transistor bias voltage.

Temporal parameters of the pulse meet the specification, with a pulse droop of 0.23 % and a pulse-to-pulse reproducibility of 0.012%.

As the amplifier is connected to a photo-injector whose photocathode must be replaced twice a month, it must tolerate the significant reflected power generated during the conditioning of each newly prepared photocathode. Therefore, the amplifier should withstand a Voltage Standing Wave Ratio (VSWR) of up to 2 before being shut down by a fast interlock triggered by the reflected power signal from the RF coupler. Neither the Ampegon dummy load neither the CEA dummy load were able to create this level of reflected power. Thus, the test was done for a VSWR of 1.48, corresponding to 60 kW of reflected power over the 1600 kW.

CONNECTION TO THE PHOTO-INJECTOR

Achieving a stable, high-level accelerating voltage in an RF cavity necessitates two primary functions: resonant frequency tuning and precise control of the RF signal's amplitude and phase. In ELSA accelerator, the first function is done between the high-power pulses. A low-level CW RF signal is injected in the cavity between the high-power pulses. The CW transmitted signal is picked up from another antenna in the cavity to be compared in phase with the input signal. A cavity plunger is then moved inside the cavity to compensate for the measured phase difference to tune the cavity [3]. The second function is guaranteed by an adaptive feedforward control loop as described in [4] and [5].

During the commissioning of the amplifier of the photo-injector cavity, some pallets and modules control boards were damaged because of high level reflected power and poor conduction of the RF signal to the ground. Some adjustments had to be made to avoid further damages on the amplifier:

- A security interlock on the LLRF was added, to avoid emission when RF is off.
- The input level threshold was decreased.
- The RF grounding was improved
- The possibility to select the time range when the reflected power is measured and compared to a threshold to cut-off the amplifier if the reflected power is too high was added. Indeed, because of the short RF pulse (~200 µs) and the long cavity filling time (~60 µs), the reflected power is quite high during the rising and the falling edge of the pulse even with a trapezoidal shape of the input pulse [4]. The reflected power is then measured at the centre of the pulse when the reflected power is the lowest in normal operation allowing to decrease the RF cut-off threshold and better protect the amplifier.
- About the cavity frequency tuning, it appeared that when the bias voltage is activated to power the transistors, there is still some CW RF power in the cavity, moreover in phase with the CW low level signal used to tune the cavity. This last signal has been shifted out of phase in order to have a more stable cavity tuning and limit reflected power.
- The last adjustment was due to the fact that the former and the new amplifier do not have the same gain curve as shown in Figure 5. This is a problem because in ELSA facility, a new photocathode has to be conditioned twice a month. Consequently, RF voltage has to be increased slowly from 500 kV to nominal voltage 2 MV to limit electric arcs in the cavity. As the slope of the SSPA curve is steeper, the parameter of the feedforward control loop of the amplifier must be adjusted to limit the excessive variation in the LLRF input signal.

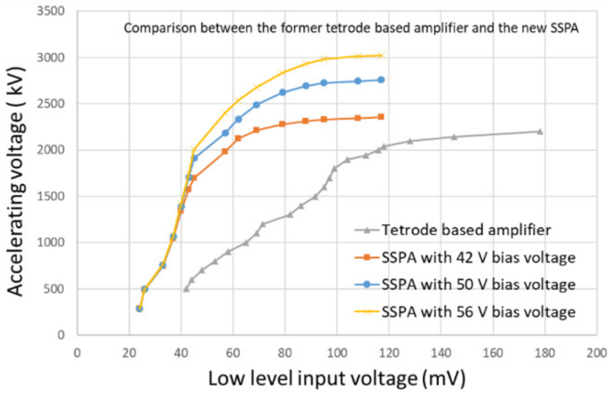

Figure 5: Gain curves of the former tetrode-based amplifier and the new SSPA.

CONCLUSION

A new 1.6 MW 144 MHz SSPA has been installed by Ampegon Company to replace the former tetrode-based amplifier at ELSA facility. Requirements have been met in a compact design and maximal power has been injected in the photo-injector to accelerate electrons. Following damages to the pallets and control boards caused by excessive reflected power, several adjustments were implemented. The adjustments on the LLRF consisted first on improving the cavity tuning by shifting the CW low level signal phase used to tune the cavity. The second adjustment consisted in studying the gain curve of the new SSPA to adapt the feedforward control loop in order to limit the strong variations of the LLRF input signal.

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