RF SYSTEM UPGRADE OF ELSA ELECTRON LINAC AT CEA

M. Collet[†, ‡], A.-S. Chauchat[‡], V. Le Flanchec[‡]
CEA DAM Île-de-France, Bruyères-le-Châtel, France
G. Devanz, T. Hamelin, O. Piquet, CEA Paris-Saclay, Gif-sur-Yvette, France

Abstract

The 19 MeV ELSA electron linear accelerator, operated by CEA DAM for 30 years, is currently undergoing a major upgrade of its RF accelerating structures to boost operational reliability, availability, and performance. The first phase (2022) targeted the second accelerating stage and replaced the 433 MHz klystron modulator. The new modulator, developed by Jema Energy, is based on a high-voltage Marx architecture to enhance pulse stability and overall system maintainability. The second phase (2024) focused on the first accelerating stage, which feeds the 144 MHz photo-injector. The original tetrode-based RF amplifier has been replaced by a high-power solid-state amplifier developed by AMPEGON, capable of delivering up to 1.6 MW peak power. A key challenge of this upgrade was achieving an architecture with a comparable footprint and thermal management constraints to the former tube-based system while preserving RF performance specifications. The upcoming third phase, currently in the design stage, will involve a redesign of the 1.3 GHz RF system, including new accelerating cavities and power sources, to extend beam energy and pulse duration. This contribution provides an overview of the upgrade program, detailing the design considerations, testing, commissioning, and integration activities. It also highlights technological choices, and shares operational lessons learned.

INTRODUCTION

Commissioned in the early 1990s as a high-efficiency IR Free Electron Laser (FEL) [1], the ELSA electron linac at CEA DAM was later repurposed as a user facility, delivering electron and X-ray beams to the scientific community. Its 144 MHz photo-injector, driven by a 72 or 144 MHz Nd:YAG laser interacting with an alkali photocathode, generates low-emittance, high-charge bunches with tunable lengths of 20–100 ps, enabling high-current pulse trains for users [2]. The main accelerator line then includes three 433 MHz cavities. The second stage is constrained by RF source and power supply limitations, restricting operations to 250 µs pulse trains at 10 Hz and capping the maximum linac exit energy at 17 MeV for low beam currents. In 2015, a 1.3 GHz third accelerating stage was added to the X-ray beamline, pushing the beam energy to 30 MeV and enabling higher beam currents, thereby overcoming the second stage's power limitations. The facility features three beamlines: a Bremsstrahlung X-ray line, an Inverse Compton Scattering (ICS) X-ray line and a straight-through electron line. A double-alpha magnet [3] splits and directs the beam into these lines.

However, after more than 30 years of operation, ELSA's original RF systems have reached their limits. Frequent amplifier faults, driven by component obsolescence, have reduced the mean time between failures (MTBF), compromising reliability and increasing downtime. To address these critical issues and meet evolving user demands, we launched a major RF upgrade program. The first phase (2022) replaced the 433 MHz klystron modulator with a high-voltage Marx modulator, improving pulse stability and maintainability. The second phase (2024) substituted the 144 MHz tetrode-based amplifier with a 1.6 MW solid-state power amplifier (SSPA), overcoming footprint and thermal constraints while matching RF specifications [4]. Looking ahead, the third phase will redesign the 1.3 GHz RF system, including new cavities and power sources, to extend beam energy to ~40 MeV and pulse duration to 200 µs. To better understand the motivations behind these upgrades, the following section details the current RF system and its limitations.

RF SYSTEM OVERVIEW

ELSA linac RF system is organized into three distinct accelerating stages, each powered by dedicated RF sources (Fig. 1). This section provides an overview of the original architecture, its operational constraints, and the key limitations that motivated the current upgrade program.

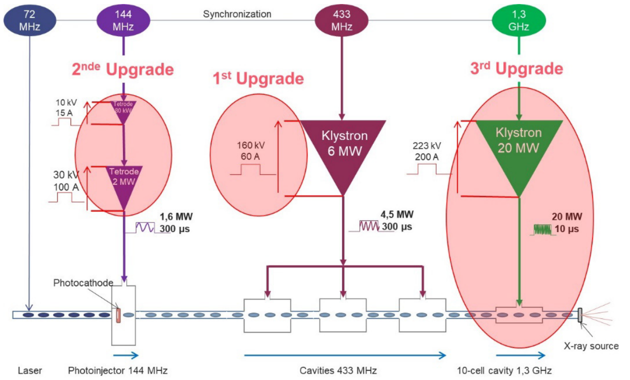

Figure 1: Overview of original ELSA RF system with the three upgrades.

The original RF power sources of ELSA linac relied exclusively on tube-based technologies which, after over 30 years of operation, reached significant performance and maintenance limits (Fig. 2). Specifically, the 144 MHz stage was based on a tetrode-based amplifier paired with high-voltage power supplies, while the 433 MHz and 1.3 GHz stages employed klystrons driven by traditional

---

[†] martin.collet@cea.fr

[‡] Also at Université Paris-Saclay, CEA, Laboratoire Matière en Conditions Extrêmes, Bruyères-le-Châtel, France

pulse-forming network (PFN) modulators. Despite their initial robustness, these systems exhibited critical operational issues over time:

- Frequent failures: Recurring issues in electronics and high-voltage components led to significant unplanned downtime.
- Reduced reliability: A decline in the Mean Time Between Failures (MTBF) had a direct impact on the facility's overall availability and efficiency.
- Maintenance complexity: Aging hardware made diagnostics and repairs increasingly challenging.
- Component obsolescence: Many critical parts, including vacuum tubes and high-voltage capacitors, are no longer commercially available.

Figure 2: Original tube-based RF components.

To address these challenges, a strategic three-phase upgrade program was deployed: a solid-state Marx modulator for the 433 MHz stage (2022), the installation of a 1.6 MW SSPA for the 144 MHz stage (2024), and a redesign of the 1.3 GHz system currently in development.

433 MHZ MARX MODULATOR

The 433 MHz accelerating stage of ELSA, originally powered by a klystron and pulse-forming network (PFN) modulator, was the first to undergo a major upgrade in 2022. The PFN-based system, while functional, suffered from frequent high-voltage failures, reduced pulse stability, and increasing maintenance complexity due to aging components. To address these issues, it was replaced by a solid-state Marx modulator developed by JEMA Energy (Irizor Group), as shown in Fig. 3.

Figure 3: Modulator during operation at CEA DAM.

This system was specifically designed to replace the PFN modulator while reusing the existing infrastructure. In particular, the original pulse transformer specifications were maintained, allowing the reuse of the oil tank and its klystron interface. However, all internal components within the oil tank were replaced and the installation and commissioning were achieved within only three weeks.

The Marx generator consists of 8 modules connected in series, producing a 27 kV, 500 A pulse that feeds the pulse transformer. This architecture enables the use of low-voltage components while achieving the required high-voltage output. Due to the relatively long pulse duration (up to 300 µs), a bouncer circuit is implemented to limit the voltage droop to below 2%. The modulator was tested at full power both at Jema's facility and on-site at CEA with results summarized in Table 1.

Table 1: Measured Performance of the Marx Modulator

Parameter	**Value**
Peak voltage	176 kV typ. / 190 kV max.
Peak current	65 A typ. / 80 A max.
Pulse duration	220 µs typ. / 300 µs max.
Repetition rate	1 Hz typ. / 10 Hz max.
Rise and fall time	30 µs typ.
Voltage droop	1%
Pulse to pulse reproducibility	± 0.02 %

Key advantages of this upgrade include a modular architecture enabling simplified maintenance, improved reliability via of solid-state switches and fast protection ensured by an integrated braking circuit.

The system was successfully commissioned in 2022 and has since demonstrated stable and reliable operation, significantly reducing facility downtime.

144 MHZ SOLID-STATE POWER AMPLIFIER

The second upgrade phase focused on replacing the tetrode-based amplifier of the 144 MHz photo-injector with a high-power Solid-State Power Amplifier (SSPA). This new system, developed by Ampegon, is designed to deliver a peak RF power of 1.6 MW with a pulse duration of up to 500 µs.

Figure 4: SSPA during operation at CEA DAM.

To meet footprint constraints, the amplifier features a compact modular architecture based on 80 RF modules, each delivering 22 kW peak. Each module incorporates a splitter, an internal combiner and 16 amplifier pallets mounted on a water-cooled plate. These pallets integrate NXP MRFX1K80N LDMOS transistors [5]. The system is distributed over 8 standard 19" racks and relies on a multi-stage RF combining architecture (Fig. 4). This configuration relies on a 10-way combining stage within each rack, followed by a 2-way combining stage between racks, and a final 4-way combination to the output. This modular design ensures high fault tolerance and operational continuity, as the system is designed to maintain operation even in the event of individual module failures. Extensive testing was carried out at the manufacturer's facility and at CEA. The results summarized in Table 2, confirm that the system meets or exceeds all technical specifications.

Table 2: Measured Performance of the 144 MHz SSPA

Parameter	**Value**
Frequency	144.44 MHz
Peak power	1.6 MW typ. / 1.8 MW max.
Pulse duration	220 µs typ. / 500 µs max.
Repetition rate	1 Hz typ. / 10 Hz max.
Rise and fall time	1 µs typ.
Pulse droop	0.23 %
Pulse to pulse reproducibility	± 0.012 %

During commissioning on the photo-injector, several adjustments were implemented to improve robustness, including reinforced RF grounding, adaptation of LLRF interlocks and optimization of feedforward control to match the SSPA gain characteristics. Successfully commissioned in 2024, the system has since demonstrated stable performance, fully compliant with operational requirements.

FUTURE 1.3 GHZ RF SYSTEM

Following the successful modernization of the first two RF stages, a third upgrade phase is currently under preparation. This phase aims to address both the obsolescence of the existing 1.3 GHz RF system and the current limitations in beam performance. The existing equipment, installed around 20 years ago, has become increasingly difficult to maintain and diagnose. The primary objectives for this phase include the replacement of aging RF components to ensure long-term operational reliability, an increase in beam energy from the current 19 MeV to a target of approximately 40 MeV and the extension of the RF pulse duration from 1–2 µs up to 200 µs.

This upgrade will significantly enhance the performance of ELSA facility, enabling a broader range of experimental conditions. To meet those requirements, a comprehensive system upgrade is required, including a new long-pulse RF power source, new accelerating cavities, and updated beamlines. The project has recently been approved, and the kick-off phase has started.

Preliminary studies have already been launched, specifically regarding the cavity design. The current post-accelerating structure consists of two coupled 5-cell sub-cavities operating at 1.3 GHz. Although the cavity design theoretically supports accelerating gradients up to ~19 MV/m, operation is currently limited to approximately 13 MV/m due to RF breakdown phenomena. Consequently, the achievable beam energy remains below expectations. To investigate these limitations, a study was initiated in collaboration with CEA IRFU. Numerical simulations of the electromagnetic fields (Fig. 5) show no major design flaw, confirming that nominal performance should be theoretically achievable. Several hypotheses are currently under investigation, including coupling effects between the two sub-cavities leading to parasitic modes, insufficient vacuum conditions lowering the breakdown threshold and manufacturing tolerances inducing non-uniform surface electric fields.

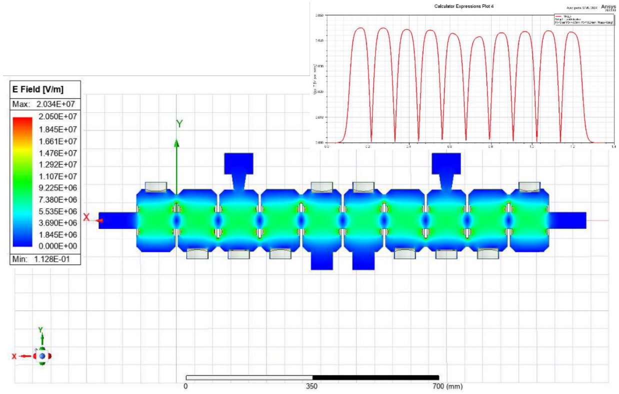

Figure 5: Electric field map and field flatness along the cavity axis (simulated by T. Hamelin from CEA IRFU).

These findings will lead to the upcoming design and fabrication of two new 5-cell accelerating cavities. This new design will improve field uniformity, reduce breakdown sensitivity, and facilitate stable operation at higher gradients to reach the targeted 40 MeV by 2030.

CONCLUSION

The major RF upgrade program of the ELSA electron linac is effectively addressing the challenges of equipment obsolescence while significantly enhancing the facility's performance. The successful integration and commissioning of the 433 MHz Marx modulator in 2022 and the 144 MHz 1.6 MW solid-state power amplifier in 2024 have already demonstrated a substantial improvement in operational reliability and pulse stability. These milestones validate the technological transition from aging tube-based systems to modern, modular solid-state architectures.

The upcoming third phase, focused on the 1.3 GHz system, represents a critical step to push the linac's capabilities to a beam energy of 40 MeV and a pulse duration of 200 µs. With the design of new 5-cell accelerating cavities and the acquisition of new power sources already underway, ELSA is well-positioned to ensure another decade of high-performance operation for X-ray and electron beam applications.

REFERENCES

[1] R. Dei-Cas *et al.,* “Status report on the low-frequency photo-injector and on the infrared FEL experiment (ELSA)”, *Nucl. Instr. and Meth. A,* vol. 296, issue 1-3, pp. 209-216, 1990. doi;10.1016/0168-9002(90)91211-S

[2] J.-G. Marmouget, A. Binet, Ph. Guimbal, and J.-L. Coacolo, “Present Performance of the Low-emittance, High-bunch Charge ELSA Photo-injected Linac”, in *Proc. EPAC'02*, Paris, France, Jun. 2002, paper TUPRI067, pp. 1795-1797.

[3] A. Pires *et al.*, “Comparison of the simulation of electron beam transport in the double alpha magnet compressor of a 17-MeV electron accelerator using CST PS, TraceWin and RF-Track”, *Nucl. Instrum. Methods Phys. Res. A,* vol. 1077, p. 170541, 2025. `doi.org/10.1016/j.nima.2025.170541`

[4] A.-S. Chauchat, M. Collet, B. Fritsche, and V. Le Flanchec, “1.6 MW, 144 MHz solid state power amplifier for ELSA electron linac”, presented at the IPAC'26, Deauville, France, May 2026, paper MOP7049, this conference.

[5] NXP Datasheet of MRFX1K80N, Rev.0, 04/2018 `https://www.nxp.com/docs/en/data-sheet/MRFX1K80N.pdf`