STAR CONDITIONING AND INITIAL BEAM COMMISSIONING

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1 Introduction

The commissioning phase of the STAR infrastructure (Southern Europe Thomson Back-scattering Source for Applied Research), hosted at the University of Calabria, has recently commenced. STAR is a compact light source facility, which exploits the inverse-Compton scattering (ICS) effect, by delivering monochromatic, tunable, polarized X-ray beams with picosecond duration in the 40–350 keV energy range. These compact machines are attracting strong interest from the international scientific community as innovative X-ray sources capable of complementing or surpassing conventional synchrotron light sources, while offering micrometric source sizes, ideal for phase-contrast imaging, and more other distinctive advantages.

The STAR project, including its high-energy upgrade (STAR HE-Linac), has been developed in collaboration with INFN and coordinated by INFN-LNF (Frascati National Laboratories), the INFN Milan division, and the LASA laboratory. In 2025, a first major milestone has been achieved with the acceleration of the electron beam and the successful transport of both the electron bunch and the high-energy IR laser pulse (500 mJ, 5 ps) to the interaction point (IP). Electron bunches are generated in a UV laser-driven high-brightness RF photoinjector at energies of a few MeV, with a charge of 250 pC and a temporal duration of 5 ps (FWHM). During early commissioning, the beam has been accelerated up to 95 MeV, with a design capability of at least 150 MeV.

In this Report, we discuss the layout of the STAR HE-Linac, the installation process, the conditioning of all services, the first beam characterization and transport from the photocathode to the IP, together with the characterization of the UV drive laser and the IR collision laser. These activities represent the step toward the generation and characterization of the first X-ray Compton photon beams.

2 Star High-Energy Linac Layout Upgrade

The STAR [1, 5] high-energy linac layout upgrade is based on two beamlines. The original beamline, referred to as the low-energy line (LE-line), consists of an S-band RF Gun followed by a single S-band accelerating cavity. It operates at a maximum beam energy of 65 MeV, enabling the operation of an ICS source with photon energies up to 70 keV.

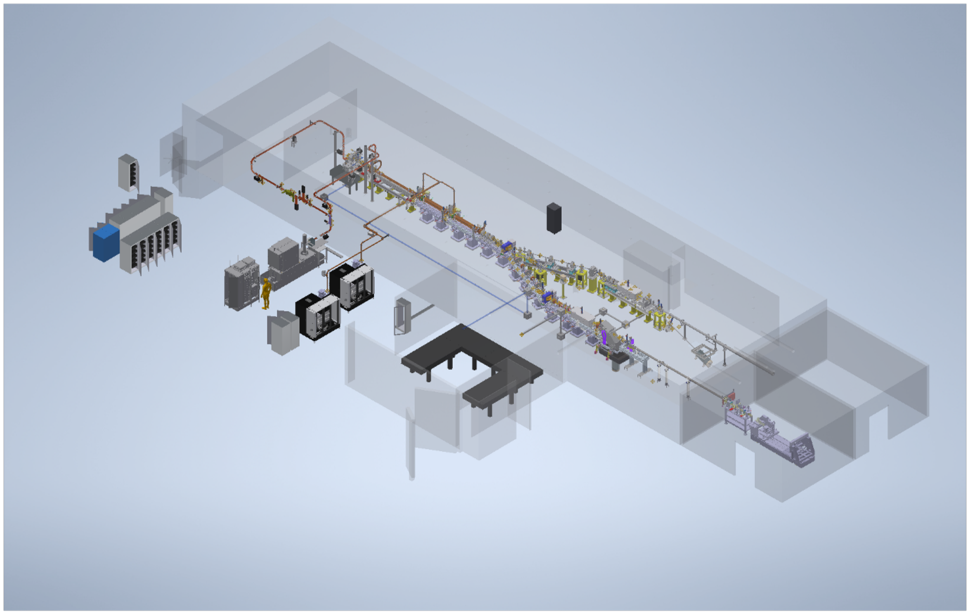

Figure 1: *Rendering of STAR facility including the accelerator bunker, the modulator hangar area and the two experimental hutches.*

The new high-energy line (HE-line) represents an upgrade of the existing configuration, extending the linac acceleration capability from 65 MeV to 150 MeV. This enhancement is achieved through the installation of two additional C-band accelerating cavities. The upgraded HE-line will drive an ICS source capable of producing photons with energies up to 350 keV. The rendering of STAR facility including the accelerator bunker, the modulator hangar area and the two experimental hutches are shown in fig. 1. The nominal operational parameters of the STAR project are listed in 1.

Table 1: *Main parameters of HE-linac and LE-linac.*

	HE-linac	LE-linac
Energy range	40 - 150 MeV	23 - 65 MeV
Rep. rate	100 Hz	
Bunch charge range	100 - 500 pC	
Normalized Emittance (x,y)	2.0 μm	
Bunch energy spread	0.5%	
Bunch length – rms [ps]	$\leq$ 5 ps	
Bunch spot dimensions (x,y) at IP	40 μm	

The electron beam is generated by an S-band photo-injector RF Gun, working at 100 Hz repetition rate and accelerated by a single 3 m long S-band traveling-wave structure. The S-band linac operates at 2856 MHz frequency, with a maximum peak input power of 50 MW (details can be found in [2]). The RF Gun is followed by a solenoid in the typical scheme of emittance compensation [6].

The key technical specifications for the C-band structure include: 102 total cells, 1.8 m length,

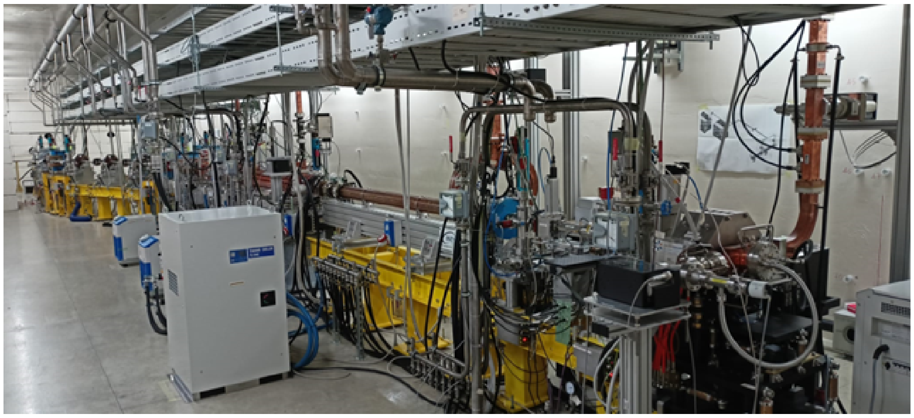

Figure 2: *Current picture of STAR Linac at UNICAL.*

and a nominal RF input power of 40 MW (details can be found in [2])

3 Installation and Conditioning Phases

The installation of the STAR-HEL upgrade is completed, and the acceptance tests were carried out in December 2023. This phase included the testing of the electrical, hydraulic and related automation and auxiliary systems as well as the high-power commissioning of the two C-band RF power stations, the testing of the low-level C-band RF system and control system configuration based on EPICS. The vacuum system (equipped with multiple ion pumps of varying speeds to achieve a vacuum level of approximately 10^{-8} mbar and several vacuum valves), the characterization and commissioning of the magnets with related power supplies and the assessment of the installed diagnostics devices were also successfully carried out. In 2025, we officially started the conditioning phase of the accelerator. The S-band RF system reached stable operation during the initial conditioning phase, delivering approximately 32 MW peak power with well-defined flat-top pulse profiles and no significant pulse distortion. Subsequently, conditioning of the C-band accelerating structures was performed. The first cavity was successfully processed up to 30 MW peak power, while the second cavity is operated at approximately 20 MW, after fixing initial amplitude instabilities. A current picture of STAR Linac at UNICAL with all subsystems installed is shown in fig. 2.

4 Electron and Laser Beams Commissioning in 2025

In 2025, commissioning activities began with electron beam generation and transport through the three RF accelerating structures and associated magnetic elements, with the objective of delivering the beam to the HE-Line interaction point (IP). Initial photoemission measurements, validated by Faraday cup diagnostics (see fig. 3), confirmed electron extraction, capture and acceleration from the photocathode (up to 3 MeV). The temporal correlation between the Faraday cup signal and the RF/laser reference demonstrated correct synchronization between laser injection and RF phase. The beam generation was further verified by observing a well-centered, 1 mm diameter spot on the YAG:Ce screen downstream of the RF photoinjector (see fig. 4 left), consistent with matched beam extracting conditions. Steering magnets and solenoids were optimized to correct trajectory and focusing during transport. The H-shaped dipole at the end of the linac was set to deflect the beam into the HE-Line. Diagnostics after the first dogleg dipole showed a stretched, energy-dispersed

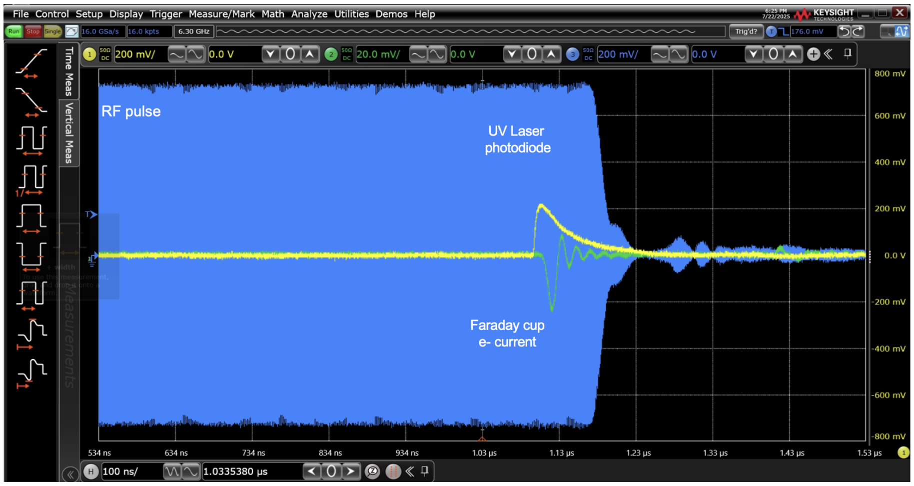

Figure 3: *Oscilloscope traces: the blue trace represents the RF pulse, the yellow signal is the UV laser photodiode, the green trace shows the electron current measured by the Faraday cup.*

profile with pronounced halos along the bend direction, consistent with operation in a region of non-closed dispersion and partial spectrometer behavior. At this stage, the quadrupole triplets in the dispersive section were not yet fully utilized. Despite the lack of full dispersion compensation and fine focusing, tuning of the second dogleg dipole enabled beam transport through the entire line to the interaction chamber. The beam profile at the chamber entrance appeared as a thin horizontal filament, indicative of non-optimized optics but successful transmission (fig. 4 right). This result was significant for an initial commissioning phase, particularly through the dogleg section. The beam energy was estimated at 95 MeV, corresponding to a potential X-ray energy of 150 keV. The high-power IR laser (500 mJ, 5 ps, 100 Hz) had already been aligned and focused at the IP in preparation for beam–laser collision, as shown in fig. 5.

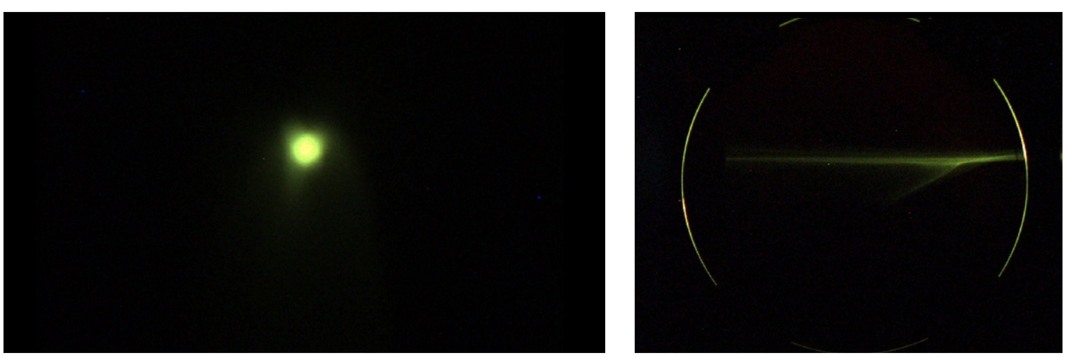

Figure 4: Beam spots on YAG:Ce of the electron beam: left) at the exit of the RF photoinjector; right) at the entrance of the interaction chamber.

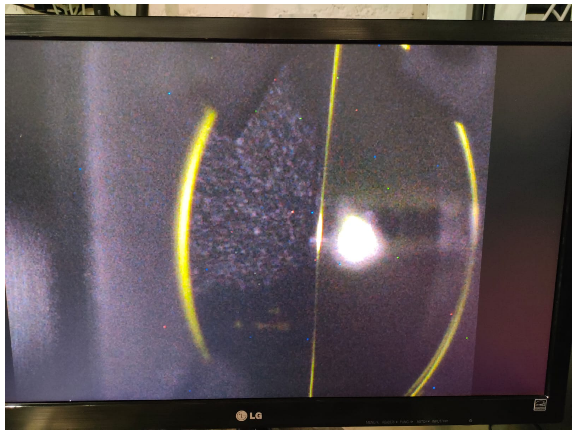

Figure 5: *YAG:Ce of the IR laser beam in the interaction chamber.*

5 Conclusions

The initial commissioning campaign, covering RF conditioning through full beam transport, was successfully completed by the end of September 2025 with the generation, acceleration, and delivery of the electron beam to the interaction chamber. The commissioning process highlighted the intrinsic complexity of manual tuning in a highly coupled, non-linear, multi-parameter system. Next milestone is to work on the collision of the electron and IR laser beams, both spatially and temporally, in order to start measuring Compton X-rays on a flat panel located just downstream the IP chamber. The commissioning milestone of 2025 was formally acknowledged by the technical-scientific representative of the Italian Ministry of University and Research, who expressed a positive evaluation of STAR's operational status.

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