A 750 MHz COMPACT AND VERSATILE $^{12}C^{6+}$ ACCELERATOR FOR ADVANCED RADIOBIOLOGY AND THERAPY RESEARCH

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Abstract

Irradiation of tumours with heavy ions, such as $^{12}C^{6+}$, represents one of the most advanced techniques currently available for cancer treatment. Its widespread deployment remains limited, requiring parallel advances in accelerator technologies that provide compact, efficient solutions and precise control over the irradiation parameters. Simultaneously, progress in radiobiology research is essential to optimise these parameters and strengthen the clinical evidence supporting this approach. In this context, Spain contributes to the field through the design and development of ALMA (Acelerador Lineal Multi-hAdrones), a compact, efficient, and versatile low-energy 10 MeV/u ion linear accelerator based on high-frequency accelerating structures. The facility is envisioned both as a prototype for the development of advanced accelerator technologies and as an infrastructure supporting an extensive radiobiology programme. The project managed by CDTI, co-funded by the European Regional Development Fund (ERDF) and led by AVS, in collaboration with CIEMAT and IFIC, the latter being the final recipient of the machine, which will be installed at its facilities. This work presents an overview of the accelerator, detailing its layout, main components, and design features that enable both technology testing and radiobiology applications.

INTRODUCTION

Hadron therapy has emerged in recent years as an advanced modality in radiation oncology, driving significant global investment in medical infrastructure based on particle accelerators [1, 2]. Compared to conventional photon-based radiation therapy, hadron beams—such as protons and heavy ions—exhibit a highly localized energy deposition profile, characterized by the Bragg peak. This allows the dose to be concentrated within the tumor volume while minimizing irradiation of surrounding healthy tissues, thereby reducing side effects and improving the quality of life for patients. Although proton therapy has experienced rapid clinical expansion due to its greater technological maturity, ion beam therapy has garnered growing interest thanks to its greater radiobiological effectiveness. In particular, carbon ions have a higher linear energy transfer (LET), which increases their efficacy against radioresistant and hypoxic tumors [3].

The choice of acceleration technology is determined by the clinical requirements of hadron therapy. The most widely used systems are cyclotrons and synchrotrons, although linear accelerators (LINACs) are emerging as a competitive alternative [4, 5] due to their intrinsic ability to adjust beam energy, their high repetition rates, and their modular design. These characteristics enable more precise active scanning, reduce beam losses, and minimize activation issues, making linacs a promising option for future facilities.

Regardless of the main beamline configuration, the injection section (0–10 MeV energy range) plays a critical role in determining the final beam quality. The injector is responsible for generating the beam, efficiently capturing it, and tuning its transverse and longitudinal phase spaces for subsequent acceleration. It must provide sufficient current, stability, and emittance control to meet the requirements of the main accelerator, whether it is a synchrotron, a cyclotron, or a linac. In conventional hadron therapy facilities, average currents are relatively low, on the order of nA [6]. However, new therapeutic modalities such as FLASH radiotherapy impose much more demanding requirements, as they require ultra-high dose rates in very short pulses [7]. This implies the need for significantly higher instantaneous intensities from the injector, while maintaining high beam quality.

As part of this technological development initiative, CIEMAT and IFIC, in collaboration with its industrial partner Added Value Solutions (AVS), is designing the compact accelerator ALMA, a high-frequency linac that will enable the acceleration of different ion beams, demonstrating that the technology and infrastructure required for this type of accelerator are feasible and sustainable. In the current stage of the project, the injector is being developed to support radiobiology studies on the efficacy of ions in cancer treatment at the LIRA (Laboratorio de Investigación en Radiobiología y Aceleradores) facility in Valencia. This article aims to provide a general overview of the main components of the injector and the current status of the project, offering technical details on the conceptual development and R&D.

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INJECTOR DESIGN

The primary function of the injector is to generate, extract, transport, bunch, and pre-accelerate ion beams to energies of a few MeV/u before injection into subsequent accelerating structures. The ALMA injector is designed to be compact, exhibit low emittance growth, and meet clinical requirements such as reliability and operational stability. Its main parameters are presented in the Table 1. The main subsystems are shown in Table 2 and described in detail in the following sections.

Table 1: Main Injector Parameters

Parameter	Value
Ion species	$^{1}H^{+}$, $^{4}He^{2+}$, $^{12}C^{6+}$
Input energy	15 keV/u
Output energy	10 MeV/u
Operating frequency	749.48 MHz
Repetition rate	200 Hz
Pulse width	10 µs
Beam current	~10 µA

Ion Source

The injector begins with the ion source, which determines the fundamental properties of the beam. ALMA bases its ion source on an electron cyclotron resonance ion source (ECRIS) supplied by Pantechnik. ECRIS are particularly well-suited for medical accelerators due to their ability to produce highly charged ions with relatively high current and excellent stability. These sources operate by confining electrons in a magnetic field configuration that satisfies the cyclotron resonance condition, enabling efficient ionization of the injected gaseous species. The extraction system shapes the beam and initiates its transport to the downstream section. The quality of the extraction optics is crucial, as it directly influences the beam emittance and the adaptation to the low-energy beam transport (LEBT) section.

Low-energy Beam Transport

The low-energy beam transport line (LEBT) connects the ion source to the first acceleration stage—in this case, a radiofrequency quadrupole (RFQ)—and shapes the beam in both the transverse and longitudinal planes in accordance with the criteria for acceptance by the RFQ.

Table 2: Injector Layout

Subsystem	Function and design focus
Ion source	Beam generation with high charge state
LEBT	q/m selection, chopping and transverse matching with basic diagnostics
RFQ	Beam bunching and initial acceleration
MEBT	Beam matching with loss control and diagnostics
IH-DTL	Efficient main acceleration at low-β with high shunt impedance and compactness

Immediately downstream of the ion source, a dipole magnet is used for charge-to-mass selection. The resolution capability of the magnet, together with the beam optics at its entrance and exit, directly influences the beam purity and transmission efficiency that can be achieved.

A beam chopper, consisting of electrostatic deflectors combined with an absorber, imposes the required temporal structure on the beam. Since the ion source generates a continuous beam, it defines the macro-pulse that will be maintained throughout the entire accelerator chain, which is essential for synchronization with downstream RF structures.

In order to improve operational reliability, a variable-aperture collimator is incorporated to eliminate halo particles, limit the transverse size, and serve as a protective device against anomalous beam conditions. A triplet of quadrupoles provides flexible focusing of the beam envelope, allowing for precise adjustment of the Twiss parameters. To complement the focusing system, a solenoid is included to provide axisymmetric focusing and greater flexibility in adjustment just before the RFQ entrance. A diagnostic chamber located between the quadrupole triplet and the solenoid provides information about the beam ahead of its acceleration. It includes a vacuum tank specially designed to mount a Faraday cup and an X-Y beam profiler. These diagnostic systems are essential for validating beam transport, optimizing RFQ adaptation, and detecting deviations from nominal conditions.

Radiofrequency Quadrupoles

A set of two 750 MHz radiofrequency quadrupoles provides the first accelerating cavity in the ALMA injector. It captures the 15 keV/u beam, bunches it longitudinally and focuses it transversely while raising the energy to 5 MeV/u, which is suitable for injection into subsequent structures. A compact design was chosen, at the cost of intentional losses at low energy [8]. The RFQ electrodes are realized as four vanes with trapezoidal longitudinal modulation, which increases the transit-time factor and acceleration efficiency compared with conventional two-term-potential vanes, allowing a shorter cavity and reduced RF power consumption. Detailed finite-element simulations determine the maximum surface electric field, which is kept around twice the Kilpatrick limit by appropriate choice of aperture, intervane voltage and vane tip geometry; short, high-modulation cells in the bunching section are the critical locations. Thermal-structural simulations [9], using the low duty cycle typical of medical operation, define cooling layouts and water temperatures that stabilize the resonance frequency; modest temperature adjustments of the coolant compensate for RF heating and keep the injector cavity on tune.

The first RFQ has been subjected to an exhaustive characterization and tuning campaign of the radiofrequency field to validate its performance. Bead-pull measurements were used to reconstruct the field profile, and through an iterative process using mobile tuners, the field was adapted and the cavity was tuned to meet the acceleration requirements [10]. RF conditioning and characterization using a proton beam [11] will confirm the suitability of high-frequency RFQs for compact linear accelerators used in hadron therapy.

MEBT and IH-DTL Cavities

A matching section or medium-energy beam transport line (MEBT), has been placed between the RFQ and the subsequent acceleration stages. This section adapts the beam parameters using magnets for transverse adaptation. It includes a diagnostic box and beam position monitors [12] for beam characterization. Precise alignment is essential to minimize beam losses before the subsequent cavities.

The beam is further accelerated using compact Interdigital H-mode (IH-DTL) RF cavities. Its adoption is primarily driven by its high shunt impedance, compact footprint, and excellent efficiency for low-β ion beams, which are essential requirements in hospital-based accelerator systems. The injector incorporates three independent IH-cavities, which maximizes the acceleration gradient and the required power supply while maintaining optimal beam conditions. A triplet of magnets is located between each of the cavities to optimally match the beam between each acceleration section.

IH cavities operate in a TE_{11}-like mode, where the accelerating electric field is concentrated along the beam axis between drift tubes, supported by alternating stems connected to opposite sides of the cavity. The RF design [13–15] is optimized by adjusting the drift-tube lengths, the gaps between them, and the tank radius. The goal is to maximize the shunt impedance and the achievable voltage, while keeping surface fields within acceptable breakdown limits. Special attention is paid to the shape of the end cell, which is used not only as a termination but also as an RF tool to flatten the field and correct dipole components that would otherwise deflect the beam. The cell geometry has been optimized in both the inductive region and the capacitive of the cavity to achieve maximum RF efficiency. In the latter, the drift tubes feature angled-face profiles designed to maximize the accelerating field and suppress unwanted field components that could degrade beam quality, resulting in improved transverse beam dynamics [16].

From the perspective of beam dynamics, IH-DTLs are based on a KONUS-type structure [17], in which longitudinal bunching and acceleration are partially decoupled. This results in efficient acceleration with lower longitudinal emittance growth and high transmission, preserving beam quality to $\beta \approx 0.15$. Regarding the transverse focus, a set of quadrupoles is located between each of the IH cavities, enabling matching between the cavities and preventing potential misalignments.

Higher frequencies improve the compactness and gradient of the cavities, although they impose stricter mechanical tolerances and greater sensitivity to manufacturing errors. Therefore, thermal and mechanical stability are therefore central design considerations [18]. Thermal expansion could cause geometric geometry deformation, leading to frequency shifts and disturbances in the acceleration field. To mitigate these effects, water-cooling circuits with controlled flow conditions are integrated directly into the structures. Another key aspect of the design is the quantification of frequency mismatch, which can directly affect beam dynamics by altering the acceleration field [19]. Therefore, the coupling between thermal, mechanical, and electromagnetic domains has required iterative optimization, in which RF design and manufacturing tolerances are addressed simultaneously.

CONCLUSION

The ALMA injector represents a significant step forward in the development of compact linear accelerators for hadron therapy and radiobiology applications. Its design demonstrates that high-frequency linac technology can be successfully adapted to a reduced footprint while maintaining performance in terms of beam quality and stability. This is particularly relevant in the context of emerging clinical and research demands, where compactness, reliability, and cost-effectiveness are key enabling factors for wider deployment.

One of the most relevant aspects of the project is the integration of a complete injector optimized for multi-ion operation. The combination of an ECR ion source, a versatile LEBT, and a high-frequency RFQs provides a robust front-end capable of delivering well-controlled beams under demanding conditions. The ability to impose a well-defined temporal structure at low energy and preserve it throughout the accelerator is particularly important for advanced irradiation schemes. The use of 750 MHz accelerating structures constitutes a key innovation in the design, enabling a high accelerating gradient and a substantial reduction in the overall length of the injector, while introducing new challenges in terms of RF design and mechanical tolerances. The implementation of KONUS beam dynamics in IH cavities, combined with optimized cell geometries and dedicated matching sections, ensures efficient acceleration with limited emittance growth.

Overall, ALMA will be a versatile facility that bridges the gap between accelerator technology development and research in radiobiology. Its modular and scalable design makes it a promising candidate for future clinical applications and new radiation modalities. In this regard, the project not only contributes to the advancement of accelerator physics but also to the broader goal of improving cancer treatment through more precise and effective beam therapies.

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