

TECHNOLOGICAL INNOVATION FOR NEXT-GENERATION PARTICLE ACCELERATORS: KEY OUTCOMES OF THE I.FAST PROJECT*

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Abstract

Next-generation particle accelerators demand innovative technologies able to meet the performance and sustainability requirements of particle physics and applied science, while ensuring high efficiency and reduced costs for industrial and societal applications. The I.FAST (Innovation Fostering in Accelerator Science and Technology) Project, supported by the European Commission under the Horizon 2020 program, has fostered progress in the accelerator community by developing a portfolio of breakthrough technologies and strategic roadmaps for future research infrastructures, such as energy-frontier hadron and lepton colliders, and for medical and environmental applications. The project contributed to the development of novel accelerator designs – including multi-TeV muon colliders, plasma-based accelerators, and high-brightness synchrotron light sources – as well as advanced materials, high-performance components, and cutting-edge manufacturing and diagnostic tools. These efforts collectively aim to improve the energy efficiency, sustainability, affordability, and compactness of future facilities. Key outcomes include novel radiation-resistant beam window and absorber materials, stabilization tools for laser accelerators, C- and X-band RF devices for free electron lasers, low-loss LTS and high-temperature superconducting CCT magnets, innovative SRF cavity fabrication and coating methods, additively manufactured linac structures, and high-efficiency klystrons and permanent magnets.

INTRODUCTION

Next-generation particle accelerator facilities face increasingly stringent requirements in terms of performance, energy efficiency, and cost to serve both fundamental research and a wide range of applied sciences and societal applications. Meeting these expectations demands new

technologies, materials, and design approaches that enable more compact, energy-efficient, and cost-effective infrastructures. In parallel, the growing market demand for accelerator-based solutions, including medical, industrial, and environmental applications, highlights the need for an innovation ecosystem capable of rapidly translating R&D advances into practical, deployable systems.

The I.FAST project was implemented in continuation with previous EU projects on accelerator technologies [1-3] to address these strategic needs within the accelerator domain. Through extensive networking initiatives involving a broad community of academic, research, and industrial partners – which included four Challenge-Based Innovation events [4], the Accelerator Industry Permanent Forum [5], and a dedicated industry exchange program [6] – the project has expanded and structured the accelerator innovation ecosystem and reinforced long-term collaboration between research and industry, promoting the rapid transfer of emerging technologies to applied science and societal applications. Partly through its Innovation Fund [7], the project has also supported the development of a diverse portfolio of high-level prototypes, demonstrating novel solutions for magnet technologies, RF systems, and compact components suitable for a wide range of accelerator platforms and applications [8].

This paper provides an overview of the main achievements of the I.FAST project and their impact on accelerator technology. Detailed technical methodologies and results are documented in the project’s technological delivery reports, available in [8].

FUTURE CONCEPTUAL DESIGNS AND TECHNICAL SOLUTIONS

I.FAST contributed to new design concepts and key technologies for future high-energy facilities. The project participated in the design of the multi-TeV muon collider based on a proton driver source, and to its structured technological R&D plan [9]. In laser-plasma acceleration, both ultrashort targets for high repetition-rate operation and long targets for high-energy electron beams at low

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repetition rates were developed and tested [10]. An axiparabola optic was designed and tested at laboratory scale, maintaining laser focus over a 15 mm gas jet and increasing the energy gain from 0.3 to 1.1 GeV. These results were complemented with the development of active feedback loops to improve beam pointing and shape stability in compact laser-plasma accelerators [11].

To mitigate ripple of slow-extracted beams in particle therapy synchrotrons, an ultra-sensitive AC current measurement system based on a dual-transformer configuration was developed, with the goal of stabilizing power-supply currents minimizing beam micro-structure fluctuations, and was complemented by a dedicated knock-out extraction device with optimized excitation signal, achieving a record resolution [12].

For synchrotron light sources, improvements included the prototype of a Hybrid Electromagnet-Permanent magnet with Tuneable Optics (HEPTO), a combined dipole-quadrupole permanent magnet device to reduce operating costs and carbon footprint of synchrotron light accelerators. The target integrated dipole and quadrupole fields have been achieved within 0.01%, as well as the target integrated field homogeneity of 5×10^{-4} [13]. Other developments included construction of a prototype permanent magnet combined-function dipole with longitudinally varying field, specifically developed for its integration into the Elettra Synchrotron Light Source in Trieste, Italy [14]. For Free-Electron Laser based light sources, developments included two successful prototypes of C-band RF photocathode guns [15], and a full prototype module of the “CompactLight” X-band accelerating structure [16].

ADVANCED MATERIALS

Regarding the development of advanced materials for accelerator applications, chromium-graphite composites were optimized for use as absorbers in beam-intercepting devices, such as collimators [17]. Radiation-hard high-power beam windows were also devised and tested under ion and proton beams [18]. Despite the appearance of microscopic defects, the thermophysical properties of the materials remained unchanged after irradiation, confirming their suitability for demanding high-power beam environments. Ongoing and future work for these two technologies focuses on the optimization of the chromium-graphite sintering process to reduce production costs, and, for beam windows, on their full integration of these beam windows into operational systems.

SUPERCONDUCTING MAGNETS

In the field of magnet technologies, I.FAST explored the design and produced two demonstrators of Canted Cosine Theta (CCT) superconducting magnets, to be used in low-energy synchrotrons as those used for carbon ion therapy of cancer [19, 20]. A combined-function CCT magnet using low-temperature superconductor NbTi was successfully constructed through precision machining of aluminum-bronze mandrels, manual winding of multi-strand Nb-Ti cables, and implementation of low-resistance splices and wax impregnation techniques, culminating in a fully

assembled system ready for cryogenic qualification (Fig. 1a) [21]. The second demonstrator was a High Temperature Superconducting (HTS)-based 4T CCT demonstrator, successfully constructed through the automated winding of two-tape REBCO cables, precise in-situ soldering and low-resistance splicing, and vacuum-assisted wax impregnation, resulting in a fully assembled 4 T-class dipole magnet ready for cryogenic qualification (Fig. 1b) [22]. To further explore HTS technology for fast-ramped applications, a set of parameters for an HTS nucletron-type cable was explored, identifying AC losses in commercially available tapes as the main technological challenge [23].

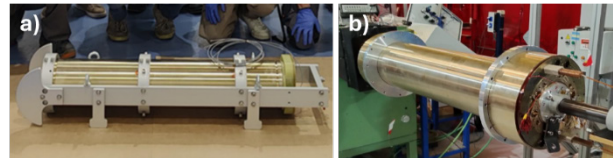


Figure 1: Combined LTS CCT (a) and HTS CCT (b) magnet demonstrators [21, 22].

HIGH-PERFORMANCE RF COMPONENTS

I.FAST advanced RF power generation technologies for high-performance accelerator components. A high-efficiency klystron prototype was developed for the High-Luminosity LHC upgrade, to increase the delivered RF power from 300 to 350 kW while maintaining the same electrical power consumption [24]. This performance gain was achieved through targeted design modifications, including a new six-cavity interaction structure incorporating second and third harmonic cavities, improved tuning systems for selected cavities, and a redesigned collector providing greater margin for power dissipation. Ongoing work addresses second-order multipacting effects and harmonic cavity detuning, alongside the implementation of enhanced cooling solutions to avoid excessive heating of the harmonic cavities. A 1 kW GaN RF solid-state power amplifier operating at 750 MHz was also designed and implemented, achieving a maximum gain of 19.14 dB and a power efficiency of 82.45% for an output power of 1148 W [25].

ADVANCED MANUFACTURING TECHNOLOGIES

A major objective of I.FAST was to broaden the technological portfolio available for accelerator component fabrication by advancing innovative manufacturing and surface engineering techniques. Additive manufacturing (AM) was successfully applied to the production of seamless copper and niobium RF cavities operating at 6 GHz, meeting surface quality requirements after post-processing (Fig. 2a) [26]. The AM design flexibility was also leveraged to fabricate high-frequency Radio Frequency Quadrupole (RFQ) modules with optimized cooling channels (Fig. 2b), eliminating the need for complex brazing steps typical of conventional fabrication [27]. A full RFQ demonstrator was subjected to vacuum tightness and electromagnetic

characterization, with ongoing work focused on post-processing to meet surface roughness requirements.

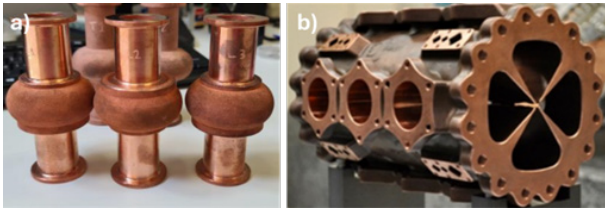


Figure 2: View of additively manufactured RF cavities (a) and quadrupole (b) [26, 27].

Significant progress was made in superconducting thin-film technologies for RF cavities, with systematic optimization of deposition parameters for alternative superconducting materials to niobium [28]. Among these, Nb_3Sn emerged as the most promising candidate for operation at 4 K, exhibiting lower RF surface resistance than NbTi. Optimal Nb_3Sn deposition conditions were established, with DC power densities below 3 W/cm^2 and deposition temperatures of approximately $570 \text{ }^\circ\text{C}$ on copper substrates and $650 \text{ }^\circ\text{C}$ on niobium. Films deposited on copper and on $30 \mu\text{m}$ niobium buffer layers achieved critical temperatures above 17 K and RF surface resistances as low as $23 \text{ n}\Omega$ at 4.5 K, 20 mT, and 400 MHz. Specific cavity configurations, including choke cavities, open and closed 6 GHz cavities, and quadrupole resonators, proved essential for the optimization and validation of thin-film superconducting RF performance. Based on these results, two systems for Nb_3Sn coating in 1.3 GHz cavities with innovative solutions have been designed and built. The first 1.3 GHz bulk Nb cavity has been successfully coated with Nb_3Sn via PVD, then RF tested in a vertical cryostat [29].

Surface engineering techniques were also explored to enhance RF cavity performance. Atomic Layer Deposition (ALD) was used to deposit superconducting layers and multilayers on SRF cavities [30]. While niobium post-deposition on ALD-coated coupons was successful, preliminary tests revealed partial film delamination. In parallel, laser annealing was performed to improve the microstructure and adhesion of thin niobium films on copper, providing localized heating of the inner cavity surface without affecting the bulk material [31]. This approach improved coating quality, despite difficulties in depositing uniform coatings on complex cavity geometries. Non-evaporable getter (NEG) coatings were also employed in the fabrication of vacuum chamber prototypes and their Photon Stimulated Desorption (PSD) performance was assessed using a dedicated synchrotron radiation beamline [32].

DIAGNOSTIC TOOLS

In the area of beam diagnostics, machine learning (ML) techniques were explored to classify beam pulses based on subtle differences in measured current, phase, and position, to identify errant beam conditions in real time [33]. A low-latency architecture based on field-programmable gate arrays (FPGAs) was established, demonstrating beam shape discrimination capability. However, robust identification

of precursors to anomalous beam conditions will require larger datasets from stable machine operation.

In parallel, an ultra-fast electro-optic beam position monitor with sub-50 ps time resolution was fabricated and tested, demonstrating compliance with the requirements for intra-bunch diagnostics at the LHC and future hadron accelerators [34].

STRATEGIES AND ROADMAPS

In parallel with the technical development, I.FAST pursued the definition of strategic roadmaps for further advancement of its technology portfolio. These documents provide the foundation for identifying the next steps in the development process. Some have already been used in the preparation of the EPITA proposal [35], the project that succeeded I.FAST as the flagship EU-funded project for collaborative accelerator R&D activities. The I.FAST strategic roadmaps are:

1. Roadmap for future advanced accelerators [36].
2. Strategy for Lasers for plasma acceleration [37].
3. Enabling technologies for ULE rings [38].
4. HTS European Strategy [39].
5. Thin-film SRF Roadmap [40].
6. Sustainable accelerators report [41].
7. Strategy for Implementing Novel Societal applications [42].
8. Strategy for the development of European Technology Infrastructure [43].

SUMMARY AND CONCLUSIONS

By promoting technological progress and strengthening coordination across the accelerator community, the I.FAST project has reinforced the foundation for the development of next-generation accelerator infrastructures. Throughout its duration, the project contributed to the development of a broad portfolio of high-level prototypes in close collaboration with industry, establishing a robust model for the effective transfer of knowledge and technology from the R&D stage to applied science and societal applications.

Key technical outcomes include the development of advanced beam-resistant materials, high-performance RF systems, low-loss HTS magnet technologies, precision diagnostics, and advanced manufacturing methods, such as additive manufacturing and thin-film superconducting coating technologies. These advances were complemented by conceptual designs and technical solutions for novel accelerator systems – including multi-TeV muon colliders, laser-plasma accelerators, and high-brightness synchrotron light sources – that enable more compact, energy-efficient, and sustainable facilities serving fundamental research as well as medical and environmental applications.

Beyond its technical achievements, the project demonstrated that progress in accelerator science and technology requires strong community integration, large-scale co-creation with industry, and long-term strategic planning. By combining scientific innovation with active industry involvement, I.FAST has supported the European accelerator community in taking a leading role in the development of

the next generation of high-performance, sustainable, and socially impactful accelerator technologies.

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