




ADVANCES IN PLASMA SCIENCE AND TECHNOLOGY IN BRAZIL: FROM ORIGINS TO PRESENT

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ABSTRACT

This review analyzes the evolution of plasma science and technology in Brazil, tracing its development from mid-20th-century origins to a consolidated, multi-institutional ecosystem. Organized around four core pillars – controlled fusion, technological plasmas under vacuum and at high temperature, basic plasma phenomena, and space and astrophysical plasmas – the review situates Brazilian progress within international advances in fusion, ionospheric physics, materials engineering, and plasma medicine. It synthesizes the legacy of vacuum-based efforts, including tokamak programs, electric propulsion, thin-film and surface-engineering technologies, and decades of ionospheric and space-weather research enabled by Brazil's equatorial location. The article examines the emergence of a distributed network of laboratories and companies linking the University of São Paulo (USP), National Institute for Space Research (INPE), Aeronautics Institute of Technology (ITA), State University of Campinas (UNICAMP), São Paulo State University (UNESP), and partner institutions to applications in aerospace, energy, manufacturing, agribusiness, and health. Particular emphasis is placed on the recent expansion of atmospheric-pressure plasma research, including cold atmospheric plasmas and plasma-activated liquids, which now support translational advances in medicine, dentistry, agriculture, environmental remediation, and catalysis, with the Brazilian Health Regulatory Agency (ANVISA)-approved devices and pilot-scale demonstrations. The review also discusses governance, community organization, and the effects of persistent funding constraints, noting the vulnerability of long-horizon research such as fusion and fundamental plasma physics. It concludes by identifying opportunities for mission-oriented programs in fusion and space, plasma-enabled decarbonization and green chemistry, industrial scale-up, and coordinated use of shared facilities to strengthen national competitiveness and support sustainable development.

KEYWORDS: Plasma technology, Fusion energy, Space plasma, Atmospheric plasma, Plasma medicine and agriculture.

AVANÇOS EM CIÊNCIA E TECNOLOGIA DE PLASMAS NO BRASIL: DAS ORIGENS AO PRESENTE

RESUMO

Esta revisão analisa a evolução da ciência e da tecnologia de plasmas no Brasil, traçando seu desenvolvimento desde as origens em meados do século XX até a consolidação de um ecossistema multi-institucional. Organizado em torno de quatro pilares centrais – fusão controlada, plasmas tecnológicos em vácuo e em altas temperaturas, fenômenos fundamentais de plasma e plasmas espaciais e astrofísicos – o texto situa o avanço brasileiro no contexto internacional das pesquisas em fusão, física da ionosfera, engenharia de materiais e medicina plasmática. Sintetiza o legado das iniciativas baseadas em vácuo, incluindo programas de tokamak, propulsão elétrica, tecnologias de filmes finos

e engenharia de superfícies, e décadas de estudos ionosféricos e de clima espacial viabilizados pela localização equatorial do país. O artigo examina o surgimento de uma rede distribuída de laboratórios e empresas que conecta a Universidade de São Paulo (USP), o Instituto Nacional de Pesquisas Espaciais (INPE), o Instituto Tecnológico de Aeronáutica (ITA), a Universidade Estadual de Campinas (UNICAMP), a Universidade Estadual Paulista (UNESP) e instituições parceiras a aplicações nos setores aeroespacial, energético, manufatureiro, agroindustrial e de saúde. Dá-se ênfase especial à recente expansão das pesquisas em plasmas em pressão atmosférica, incluindo plasmas frios atmosféricos e líquidos ativados por plasma, que atualmente impulsionam avanços translacionais em medicina, odontologia, agricultura, remediação ambiental e catálise, já contando com dispositivos aprovados pela Agência Nacional de Vigilância Sanitária (ANVISA) e demonstrações em escala piloto. A revisão também discute aspectos de governança, organização comunitária e os efeitos de restrições persistentes de financiamento, destacando a vulnerabilidade de pesquisas de longo horizonte, como fusão e física fundamental de plasmas. Conclui-se identificando oportunidades para programas orientados por missão nas áreas de fusão e espaço, descarbonização e química verde habilitadas por plasma, escalonamento industrial e uso coordenado de infraestruturas compartilhadas para fortalecer a competitividade nacional e apoiar o desenvolvimento sustentável.

PALAVRAS-CHAVE: Tecnologia de plasma, Energia de fusão, Plasma espacial, Plasma atmosférico, Plasma na medicina e agricultura.

INTRODUCTION

Plasma is often described in popular terms as the “fourth state of matter”, but more precisely, it is a partially or fully ionized gas in which electrons, ions, and neutrals interact through long-range electromagnetic forces. Unlike transitions among solid, liquid, and gas, the emergence of plasma is not a conventional thermodynamic phase change. Ionization imparts high electrical conductivity, strong coupling to fields, and collective behavior that supports waves, instabilities, and self-organization. Plasmas are ubiquitous in nature, from stellar interiors and the solar wind to lightning, and they are central to many technologies, including lighting, microelectronics, surface engineering, propulsion, environmental control, and biomedical tools.¹

The modern study of plasmas took shape in the early twentieth century with progress in ionized-gas physics, diagnostics, and the formulation of magnetohydrodynamics (MHD) as a framework for collective dynamics. Over subsequent decades, plasma science matured at the junction of electromagnetism, kinetics, and fluid mechanics.^{1,2} This maturation was propelled by three broad drivers: (i) the pursuit of controlled thermonuclear fusion in magnetic and inertial confinement schemes, (ii) the need to understand and forecast natural plasmas in space and astrophysical settings, and (iii) the rapid growth of low-temperature plasmas for industrial processing, particularly in semiconductor fabrication and thin-film technologies.³ The field that emerged is both fundamental and applied, uniting theory, computation, experiment, and engineering practice.^{3,4}

BIBLIOMETRIC CONTEXT OF BRAZILIAN PLASMA RESEARCH

A quantitative view of Brazilian scientific production underscores the consolidation and diversification of this field. As shown in Fig. 1a, the number of plasma-related documents with Brazilian affiliations remained very low until the early 1970s, reflecting the formative stage of the community. Beginning in the mid-1970s, coinciding with the establishment of the first coordinated research programs in fusion, technological plasmas, and space plasmas, publication output began a slow but steady increase. A marked acceleration occurs during the mid-1990s, aligned with the expansion of national facilities, such as tokamak upgrades, vacuum-processing laboratories, and ionospheric monitoring programs, and with the strengthening of graduate programs in physics and engineering. Over the last decade, production has stabilized at a mature level of several hundred documents annually, indicating a consolidated and continuously active research ecosystem.

composition of this output further illustrates the community's scientific profile. As shown in Fig. 1b, regular research articles account for most publications (approximately 82%), followed by conference papers (about 15%), with reviews, book chapters, and other formats representing only small fractions. This distribution reflects a community focused on generating original experimental and theoretical contributions, supported by active participation in national and international conferences. The recent appearance of review papers and book chapters, though still modest in number, suggests an increasing effort to synthesize knowledge and consolidate emerging subfields.

The disciplinary distribution of these documents, presented in Fig. 1c, mirrors the historical evolution of plasma research in Brazil. Physics and astronomy constitute the largest share ($\approx 40\%$), reinforcing the centrality of fundamental plasma physics, fusion studies, and space-plasma research. Materials science ($\approx 23\%$) and engineering ($\approx 12\%$) represent the second and third largest groups, highlighting the relevance of plasma-assisted materials synthesis, thin-film technologies, and process engineering. Chemistry Earth and planetary sciences, chemical engineering, energy, and areas in the life sciences collectively contribute a significant portion, reflecting the growing interdisciplinarity of plasma science, particularly in plasma-surface interactions, catalysis, atmospheric-pressure plasmas, and plasma-liquid-biosystem interfaces. Together, these indicators portray a community that is both scientifically consolidated and increasingly diversified.

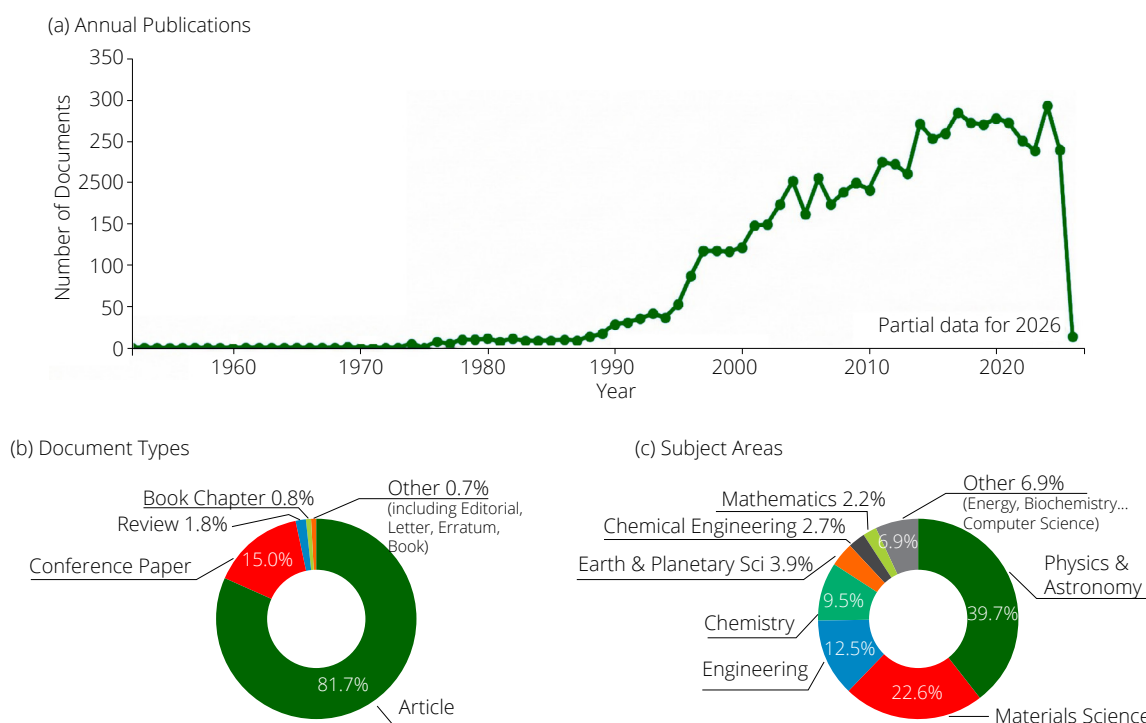


Figure 1: Bibliometric survey of plasma-related publications in Brazil. Data were obtained from the Scopus database (accessed on 6 November 2025) using the search query “Plasma” AND “Technology” AND “Science”, restricted to documents with at least one Brazilian institutional affiliation, resulting in 6,615 indexed publications. (a) Annual number of publications. (b) Distribution of document types. (c) Distribution by subject area.

Source: Elaborated by the authors.

HISTORICAL TRAJECTORY IN BRAZIL

Within Brazil, the development of plasma science followed a trajectory consistent with international trends but adapted to national priorities in space, energy, advanced manufacturing, and, more recently, health and environmental applications. By the 1970s, research had coalesced into four complementary pillars: controlled fusion, technological plasmas under vacuum and at high temperature, basic plasma phenomena, and space and astrophysical plasmas.^{5,6} Organizing work along these axes allowed the community to balance long-horizon scientific

goals with nearer-term industrial and technological needs. As facilities expanded and training programs matured, domestic expertise advanced in device operation, diagnostics, modeling, and technology transfer.

Magnetic-confinement fusion provided a durable foundation for plasma physics education and instrumentation. Medium-scale tokamaks and their successive upgrades enabled studies of stability, transport, edge physics, auxiliary heating, and control strategies relevant to next-generation fusion devices.^{6,7} These efforts strengthened Brazil's participation in international collaborations and created opportunities for students and early-career researchers to engage in fusion-oriented topics with well-defined methodological targets.

Space and astrophysical plasmas formed a second pillar with direct national relevance. Brazil's location near the geomagnetic equator, together with the operational demands of a growing space program, motivated sustained efforts in ionospheric monitoring, modeling, and forecasting.^{8,9} Studies of equatorial plasma irregularities, plasma bubbles, scintillation phenomena, and space-weather events directly supported satellite operations, communication, and navigation. The parallel development of plasma-based electric propulsion (EP) reinforced links between fundamental science and mission-oriented technologies.

Technological plasmas under vacuum and at high temperature established a third pillar with broad industrial implications. Plasma-assisted processes for thin films, coatings, and surface modification support multiple sectors requiring precise control of microstructure, composition, and mechanical performance. Techniques such as physical vapor deposition, plasma-enhanced chemical vapor deposition, ion nitriding, and thermal spraying are now routine in laboratories and pilot facilities, linking academic research to applications in aerospace, energy, electronics, and manufacturing. Advances in diagnostics, surface characterization, and multiphysics modeling have improved process understanding and accelerated industrial adoption.⁶

A fourth and increasingly prominent movement involves atmospheric-pressure plasmas and their interfaces with liquids, soft matter, and biological systems. Operation at ambient conditions enables treatment of heat-sensitive materials and direct contact with tissues or aqueous environments, expanding applications in medicine, dentistry, agriculture, and environmental engineering.¹⁰⁻¹² These include plasma-assisted disinfection, wound modulation, biofilm control, plasma-activated water (PAW) for agriculture, and plasma-driven remediation processes. The shift from exclusively vacuum-based reactors to atmospheric and hybrid configurations reflects a broader trend toward portability, adaptability, and integration with real-world environments.

INSTITUTIONAL ECOSYSTEM

The community that sustains these activities spans universities, research institutes, and technological centers distributed across the country. It integrates experimental facilities (from discharge chambers to tokamak halls), advanced diagnostics (optical emission spectroscopy, laser-based probes, mass spectrometry, and surface analysis tools), and modeling capabilities ranging from global 0D kinetics to fluid and particle-in-cell simulations. The ecosystem is strengthened by collaborations with industry, government agencies, and international partners. This mix has enabled both scientific advances and the training of a workforce capable of operating complex systems, developing instrumentation, and translating research into services and technologies. To illustrate this distribution, Fig. 2 presents a schematic map highlighting the principal plasma research groups active across Brazil.

This institutional distribution also aligns with the bibliometric patterns shown in Fig. 1. The Scopus dataset reveals that several of the highest-productivity researchers in plasma science are affiliated with Southeast institutions such as the University of São Paulo (USP), the São Paulo State University (UNESP), the State University of Campinas (UNICAMP), the National Institute for Space Research (INPE), the Aeronautics Institute of Technology (ITA), and the University of Paraíba Valley (UNIVAP). Their presence in Fig. 2 reinforces that these long-standing centers form the core of Brazil's plasma research output. The strong overlap between institutional geography and publication volume indicates a mature scientific infrastructure concentrated in this region, complemented by emerging groups in the South, Northeast, and Federal District.

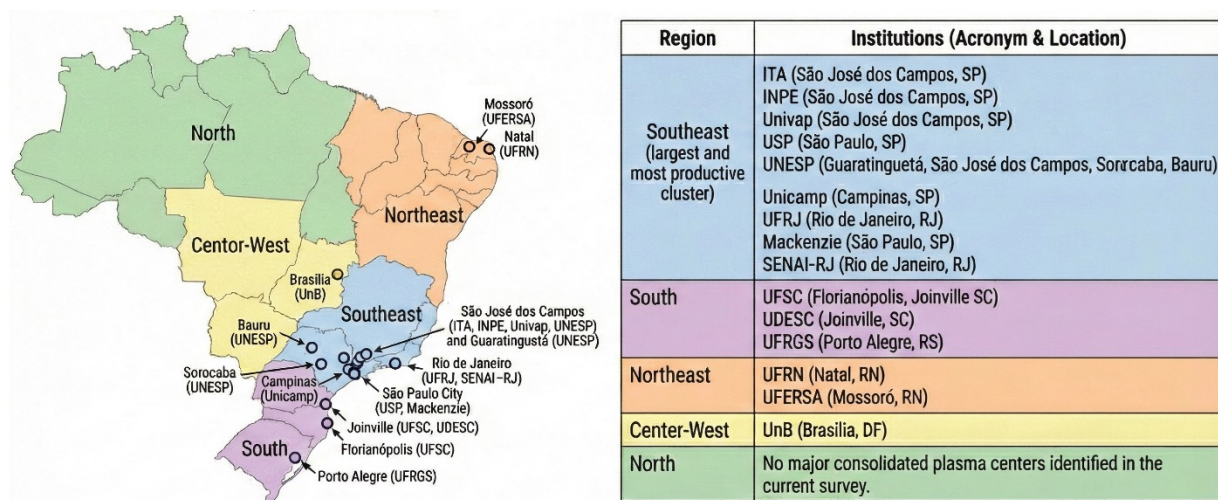


Figure 2: Geographical distribution of major plasma research groups in Brazil. A schematic representation of principal academic and research institutions engaged in plasma science and technology across the country. The figure highlights the strong concentration of groups in the Southeast region (ITA, INPE, USP, UNESP, UNICAMP, Mackenzie, UNIVAP, and UFRJ), which correspond to the institutions associated with many of the most prolific authors in the bibliometric survey of Fig. 1.

This alignment illustrates how the national research output in plasma science is driven largely by long-established centers in the Southeast, complemented by growing activity in the South, Northeast, and Federal District.

Source: Elaborated by the authors.

This review brings these threads together in a structured manner. First, it situates plasma science within a global framework and describes the historical consolidation of its four pillars in Brazil. Second, it examines representative facilities and programs, highlighting technical milestones and methodological advances. Third, it surveys applications in materials processing, space technologies, atmospheric-pressure plasmas, and plasma-liquid-biosystem interfaces. Finally, it discusses the cross-cutting issues that will shape future progress, including continuity of funding, modernization of equipment, regulatory frameworks for clinical and industrial deployment, and strengthened coordination between academic groups and end users. The objective is to provide an evidence-based account of how plasma science evolved into a mature and diversified field in Brazil, and to identify opportunities where strategic investment and collaboration can deliver high impact.

FOUNDATIONAL PILLARS: THE GENESIS OF PLASMA PHYSICS IN BRAZIL (1950-1970)

The international context and early Brazilian forays

The formal recognition of plasma as the fourth state of matter and the subsequent development of plasma physics as a distinct scientific discipline were products of early 20th-century investigations into disparate phenomena. The term “plasma” was first coined in 1929 by American chemist and physicist Irving Langmuir during his research on electrical conduction in vacuum tubes.^{1,2,13} Concurrently, the systematic investigation of plasma properties began in the 1930s through studies of electromagnetic wave propagation in the Earth’s ionosphere, a naturally occurring plasma layer.¹⁴ By the 1940s, astrophysical research into the constitution and evolution of stars, which are massive spheres of gravitationally confined plasma, further propelled the field’s development.^{15,16} The pioneering work of Hannes Alfvén on cosmic plasmas and MHDs, for which he received the Nobel Prize in Physics in 1970, solidified the field’s fundamental importance.^{16,17}

Following the Second World War, the global scientific landscape was reshaped by the pursuit of nuclear energy. The successful development of fission-based atomic weapons spurred a parallel, intense investigation into thermonuclear fusion, both for military applications and for the ambitious goal of generating clean, limitless energy.¹⁸ This global quest for controlled thermonuclear fusion,¹⁹ which requires creating and confining plasmas at

extreme temperatures, became the primary driver for plasma physics research worldwide and set the stage for its eventual emergence in Brazil.^{5,6}

Within this international context, plasma physics in Brazil began to take root. As a relatively new branch of physics, its pioneering contributions appeared in the 1950s and 1960s, concentrated within the burgeoning higher education and research institutions of the state of São Paulo.⁵

The São Paulo pioneers: seminal contributions of Bohm, Schützer, and Freire

The genesis of plasma physics in Brazil was not an isolated event but was significantly catalyzed by the arrival of world-class scientists and the dedicated efforts of local researchers who established the field's theoretical and educational foundations (Fig. 3).

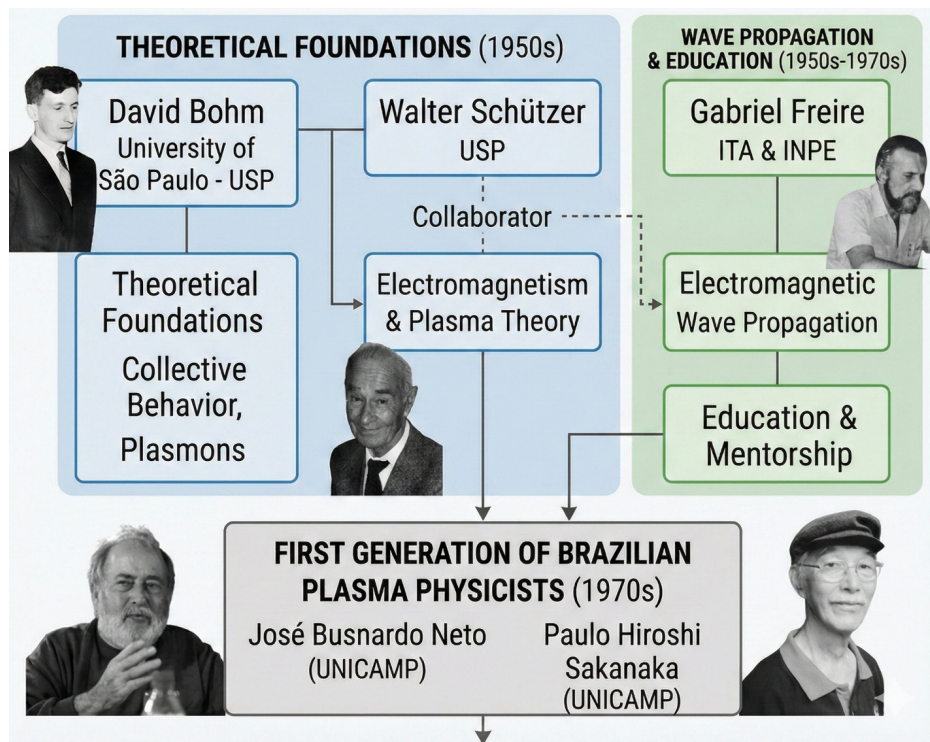


Figure 3: Foundations of plasma physics in Brazil and the São Paulo pioneers (1950s-1970s). Schematic representation of the key contributors who established the theoretical, experimental, and educational bases of plasma research in Brazil. David Bohm, at USP, advanced the theoretical understanding of collective behavior and plasmons. Walter Schützer, also at USP, developed foundational work on electromagnetism and plasma theory and collaborated with Bohm on early theoretical studies. Gabriel Freire, at ITA and INPE, extended the field into electromagnetic wave propagation and was instrumental in education and mentorship, training the first generation of Brazilian plasma physicists, including José Busnardo Neto (UNICAMP) and Paulo Hiroshi Sakanaka (UNICAMP).

Source: Elaborated by the authors.

The arrival of David Bohm at the USP in 1951 was a pivotal moment for Brazilian physics. An eminent American theoretical physicist, Bohm was a casualty of the McCarthy-era political persecution in the United States. Due to his past political affiliations, he was called before the House Un-American Activities Committee, and his refusal to testify against colleagues led to his suspension from Princeton University and ultimately his departure from the country.⁵ Brazil offered him a professional haven, and in turn, his presence provided the nascent Brazilian physics community with an intellectual powerhouse.⁹

During his tenure at USP from 1951 to 1955, Bohm made profound and lasting contributions to the theory of plasmas.^{5,20} His research, particularly his work on the collective behavior of electrons in metals and plasmas, laid the theoretical foundations for the modern understanding of these systems.^{21,22} This work introduced the fundamental concept of collective excitations, or “plasmons,” which describes how electrons in a plasma can exhibit coordinated,

wave-like behavior.²² This development was not merely a technical advance; it was part of Bohm's broader intellectual framework, which sought to understand how systems could exhibit both individual freedom and collective action, a concept he explored in his physical theories as well as his philosophical and political thought.²³ The fact that a political purge in one nation led directly to a scientific "brain gain" another underscores how geopolitical forces can unexpectedly shape and accelerate national scientific trajectories. Bohm's presence seeded a level of theoretical rigor in Brazil that might have otherwise taken decades to develop organically.

A key Brazilian collaborator during this period was Walter Schützer, a physicist at USP who worked alongside Bohm.^{5,20} Schützer was an integral part of the vibrant physics community in São Paulo, which included other luminaries such as César Lattes and Giuseppe Occhialini.^{5,20} His research focused on the fundamental principles of electromagnetism and their application to plasma phenomena, providing essential theoretical support for the burgeoning field.^{5,20}

While Bohm and Schützer laid the theoretical groundwork at USP, Gabriel Freire became a central figure in building the human infrastructure of Brazilian plasma physics. With a doctorate from Stanford University, Freire conducted research at two of Brazil's most important technological institutions: the ITA and the INPE.⁵ His work focused on the critical area of electromagnetic wave propagation in plasmas, a topic with direct applications in communications and diagnostics.^{24,25}

However, Freire's most enduring legacy lies in his role as an educator and mentor. He supervised a substantial number of master's and doctoral students who would constitute the first generation of dedicated plasma physicists in Brazil.⁵ Among them were future leaders such as José Busnardo Neto and Paulo Hiroshi Sakanaka, who later consolidated the field at the UNICAMP, thereby ensuring that the knowledge base and research traditions established by the pioneers were both preserved and significantly expanded.^{5,24}

Institutionalization of research and the four foundational sub-areas

By the 1970s, early initiatives coalesced into an organized community with four complementary fronts, namely controlled fusion, technological plasmas (vacuum/high-temperature), basic plasma phenomena, and space/astrophysical plasmas, anchored at USP, UNICAMP, ITA, and INPE (Table 1). This structuring balanced a long-horizon fusion agenda with nearer-term industrial and mission-driven goals, creating multiple pathways for training, instrumentation, and technology transfer.

Table 1: Key milestones in the history of plasma science in Brazil.

Decade	Milestone	Key figures/institutions
1950s	Arrival of David Bohm at USP and pioneering work on collective phenomena and plasmons, establishing the first theoretical base for plasma physics in Brazil.	D. Bohm, W. Schützer (USP)
1960s	Gabriel Freire's work on electromagnetic wave propagation in plasmas and mentorship of the first domestic cohort of plasma physicists.	G. Freire (ITA/INPE); early students, including J. Busnardo Neto and P. H. Sakanaka
1970s	Institutionalization of plasma research into four foundational sub-areas – controlled fusion, technological plasmas, basic plasma phenomena, and space/astrophysical plasmas – anchored at USP, UNICAMP, ITA, and INPE; creation of UNICAMP's fusion group and the first steps toward indigenous confinement devices and geospace-plasma programs.	P. H. Sakanaka (UNICAMP fusion group); R. M. O. Galvão, I. C. Nascimento, I. L. Caldas, A. G. Elfimov (USP fusion/basic plasmas); G. O. Ludwig, M. A. Abdu (INPE tokamak and ionospheric/space-weather programs); early technological-plasma activities at ITA leading to the future LPP (H. S. Maciel, M. Roberto)

Source: Elaborated by the authors.

Controlled fusion (USP, UNICAMP, INPE)

At USP's Plasma Physics Laboratory, a cohort that would become nationally influential – Ricardo Magnus Osório Galvão, Ivan de Carvalho Nascimento, Iberê Luiz Caldas, and Alfredo G. Elfimov – advanced magnetized-plasma physics, stability, and wave phenomena, building the technical and human capital later leveraged for tokamak

operation, upgrades, and diagnostics.^{7,26} At UNICAMP, Paulo H. Sakanaka founded the Plasma Physics and Thermonuclear Fusion Group in 1974, establishing curricula, experimental infrastructure, and theoretical programs that matured into a durable fusion effort.²⁷ At INPE, early initiatives led by Gerson Otto Ludwig planted the seeds for an indigenous confinement-device program that, in the following decades, culminated in the development of the spherical tokamak experiment (ETE) and an integrated strategy linking device design, control, and diagnostics.²⁸ Together, these hubs created a critical mass for magnetic-confinement research in Brazil and enabled effective participation in International Thermonuclear Experimental Reactor (ITER)-relevant problem solving.

Technological plasmas – Vacuum and high-temperature (ITA, UNICAMP, USP)

At ITA, research on technological plasmas took shape in the 1980s when Prof. Homero Santiago Maciel, after returning from Oxford, established the Electrical Discharges Laboratory, which later evolved into the Plasmas and Processes Laboratory (LPP). Working with his students, Jayr Amorim, Gilberto Petraconi Filho, and Marcos Massi, he developed inductively coupled plasmas, hollow-cathode discharges, and magnetron sputtering systems, laying the experimental foundation for thin-film deposition, surface engineering, and modern plasma diagnostics at the institute. At UNICAMP (Gleb Wataghin Institute of Physics, [IFGW]), Prof. Aruy Marotta consolidated thermal-plasma torches and transfer to industry, coupling source design with metrology and pilot-scale trials.²⁹ At USP's Polytechnic School, cleanroom infrastructure built around the Microelectronics Laboratory (created in 1968 in the Department of Electrical Engineering and led in its early years by Carlos Alberto Morato de Andrade) and the Integrated Systems Laboratory (LSI) (founded in 1975 by João Antonio Zuffo) embedded plasma-enhanced chemical vapor deposition (PECVD) and sputtering into microfabrication flows, with in-house development of tools and processes.³⁰ Together, ITA-UNICAMP-USP now spans the full Research and Development (R&D) cycle, from reactor physics and process control to materials characterization and scale-up, supporting aerospace, energy, packaging, and mechanical components.

Basic plasma phenomena (USP/ITA)

USP consolidated a strong theoretical and experimental tradition in waves, instabilities, transport, and nonlinear dynamics, areas championed by I. L. Caldas and collaborators, establishing a pipeline that supported both fusion and low-temperature plasma research with modeling, diagnostics, and data-analysis capabilities.³¹ Within this tradition, Homero S. Maciel contributed essential work on low-temperature discharges, electron kinetics, and plasma-wall interactions, providing a basis for later developments in technological plasmas and diagnostics. In parallel, Marisa Roberto, working across ITA and USP, contributed to fusion-oriented studies, particularly in magnetic confinement and tokamak plasma behavior, helping to consolidate the theoretical foundations of the Brazilian fusion program.

Space and astrophysical plasmas (INPE, USP/Institute of Astronomy, Geophysics and Atmospheric Sciences [IAG])

At INPE, a core group led by Mangalathayil Ali Abdu, together with Inez S. Batista, João H. A. Sobral, Eurico R. de Paula, and collaborators, formalized equatorial-ionosphere monitoring and modeling programs, building long-term networks and models for plasma bubbles, spread-F, and scintillation in Brazil's equatorial sector.^{32,33} At USP's IAG, Elisabete M. de Gouveia Dal Pino, Gustavo A. Medina Tanco, and colleagues consolidated high-energy and plasma astrophysics through MHD-based simulations and observations of cosmic plasmas.^{34,35} This pairing of INPE's geospace-plasma program with IAG's astrophysical-plasma community connected fundamental plasma physics to national missions in communications, navigation, and space weather, while also training specialists who later bridged to electric-propulsion and other space-technology concepts.

The four-pillar arrangement diversified risk and relevance: fusion provided a unifying scientific challenge; technological plasmas delivered industrial impact; basic research ensured intellectual depth and methodological rigor; and space/astrophysical programs aligned with strategic national priorities. The outcome was resilience

across funding cycles, steady workforce formation (MSc/PhD pipelines), and a culture of instrumentation and facility building that enabled Brazil's later advances in tokamaks, space plasma, and materials processing.

THE ERA OF MAGNETIC CONFINEMENT: THE QUEST FOR FUSION ENERGY

The international program in controlled thermonuclear fusion has shaped plasma physics for decades, and Brazil has integrated into this effort through the construction, operation, and progressive upgrading of magnetic-confinement devices (tokamaks). National activities have been concentrated at three institutions that form the core of the Brazilian fusion community – USP, INPE, and UNICAMP – which operate the tokamaks illustrated in Fig. 4.

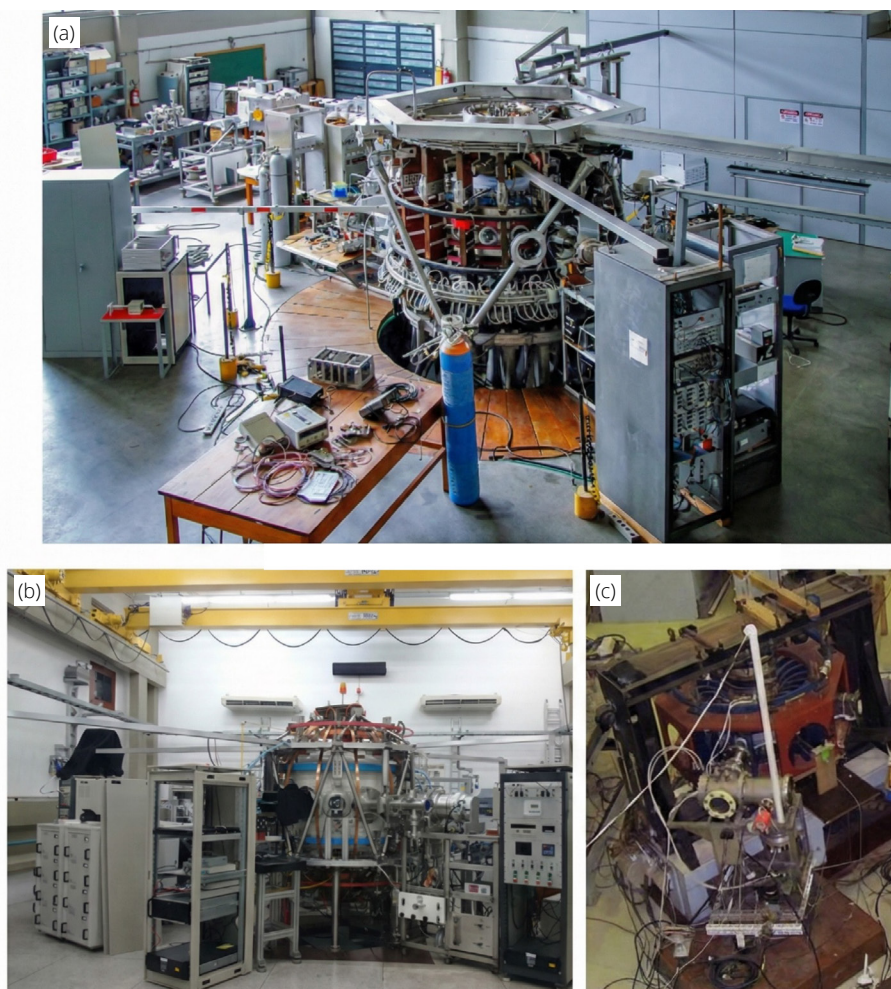


Figure 4: Photographs of the major Brazilian tokamak devices. (a) TCABR (IF-USP) – Medium-size conventional tokamak used for studies of MHD stability and plasma control.^{1,2} (b) ETE (INPE) – Spherical tokamak dedicated to low-aspect-ratio confinement studies.^{3,4} (c) NOVA-UNICAMP – Small tokamak used for training and foundational fusion research in Campinas.^{5,6}

Source: Elaborated by the authors.

USP and the Tokamak Chauffage Alfvén Brésilien (TCABR) tokamak

The Plasma Physics Laboratory (LFP) at USP hosts the TCABR, the largest and most significant fusion research device in the Southern Hemisphere.⁷ TCABR's trajectory illustrates how international collaboration can be leveraged to build domestic capability. Originally designed and operated as the Tokamak Chauffage Alfvén (TCA) at the École Polytechnique Fédérale de Lausanne (EPFL) from 1980 to 1992, the device was transferred to USP in 1994 and

extensively refurbished. It was recommissioned in 1999, now renamed TCABR to reflect its new home and role in the Brazilian program.^{36,37}

TCABR is a medium-sized tokamak with a circular plasma cross-section. Its main parameters are a major radius $R_0 = 0.615\text{m}$, minor radius $a = 0.18\text{m}$, toroidal magnetic field $B_0 \approx 1.1\text{T}$, and plasma current I_p up to 100 kA.^{36,37} It is designed to confine hydrogen plasma heated ohmically to central electron temperatures $T_e \approx 650\text{eV}$ (about $7.5 \times 10^6\text{K}$).³⁸ Although modest by the standards of large international devices, this parameter range is sufficient to access a broad spectrum of MHD phenomena that are directly relevant to reactor-grade plasmas.

The TCABR research program has combined fundamental studies with mission-oriented topics that anticipate the needs of next-generation reactors.³⁶⁻³⁸ Historically, core activities have included the excitation and diagnosis of Alfvén waves, characterization of MHD instabilities, investigations of edge plasma turbulence, and measurements of plasma rotation and transport.⁷ The LFP maintains a close connection with the associated Group for Oscillation Control, which provides theoretical and computational support on instabilities, turbulence, and chaos in magnetized plasmas, reinforcing the pipeline between basic plasma theory and tokamak experiments.³⁹

In recent years, TCABR has entered a major upgrade phase that signals a strategic repositioning of its scientific agenda. Coordinated by researchers such as Gustavo Paganini Canal and involving physicists including Wanderley Pires de Sá, the upgrade is designed to transform the machine into a platform for tackling ITER-relevant challenges.⁴⁰ The main elements of this upgrade include^{40,41}:

- Resonant magnetic perturbation (RMP) coils: installation of 108 RMP coils to study and control edge localized modes (ELMs), violent oscillations at the plasma edge that can erode plasma-facing components. ELM mitigation and control are high-priority issues for ITER and other burning-plasma devices.
- New shaping coils: additional poloidal field coils will enable advanced plasma shaping and divertor configurations (single-null, double-null, snowflake), essential for controlling heat and particle exhaust in high-performance scenarios.
- Graphite inner wall: lining the vacuum vessel with graphite tiles reduces impurity influx, thereby helping to maintain high plasma temperatures and stability.

This transition, from a primarily broad-based physics platform to a targeted, problem-driven facility, illustrates the Brazilian fusion community's ambition to move beyond generic contributions to the knowledge base and to engage directly with the key physics and technology questions posed by devices such as ITER.

INPE and ETE spherical tokamak

Complementing the work on the conventional tokamak at USP, the Associated Plasma Laboratory (LAP) at the INPE pursued a more exploratory route with the development of the ETE.²⁸ Building on conceptual and engineering studies carried out throughout the 1990s, including the completion of a minimal spherical-tokamak design around 1993, the ETE project was led by Gerson Otto Ludwig and a core LAP team comprising Edison Del Bosco, José G. Ferreira, Luis Filipe W. Barbosa, Luiz A. Berni, and collaborators, with important contributions from researchers such as Maria C. R. Andrade, Carlos S. Shibata, Ricardo M. Oliveira, and Mario Ueda. The device began operation at the end of 2000 as a compact spherical tokamak – i.e., a very low-aspect-ratio variant of the traditional tokamak concept, characterized by a tight, cored-apple geometry rather than a conventional torus.

Spherical tokamaks are of particular interest because their low aspect ratio ($A \approx 1.5$ in the case of ETE) allows operation at high normalized pressure (β) while pointing to potentially more economical and efficient reactor configurations.⁴² In this context, ETE represented a major milestone: an indigenous Brazilian effort that covered the full chain from conceptual design and numerical modeling of the poloidal-field system to the construction of the vacuum vessel (Inconel 625), toroidal and poloidal coils, power supplies, control and data acquisition, and a suite of diagnostics. The machine was designed as a small-to-medium spherical tokamak with major radius $R_0 \approx 0.30\text{ m}$, minor radius $a \approx 0.20\text{ m}$, aspect ratio $A \approx 1.5$, toroidal field $B_0 \approx 0.4\text{ T}$, and a nominal plasma current $I_p \approx 0.2\text{ MA}$,

with design provisions to reach currents of the order of 0.4 MA in upgraded scenarios.²⁸ These parameters are consistent with both design papers and early operation reports, which document first plasmas at the end of 2000 and subsequent discharges with $I_p \approx 45$ kA in the commissioning phase, later progressing to $I_p \approx 0.2$ – 0.22 MA with central electron temperatures up to ~ 160 eV and densities around 2 – 3×10^{19} m⁻³.⁴³

The ETE research program was structured to exploit the unique physics of low-aspect-ratio plasmas and to prepare the ground for an advanced torus experiment concept. Core topics included equilibrium and stability in highly shaped configurations, confinement and transport at low aspect ratio, and the exploration of non-inductive and bootstrap current-drive schemes, all of them essential ingredients for steady-state operation in future fusion reactors.²⁸ In parallel, the LAP team used ETE as a platform to develop and validate diagnostic techniques (e.g., magnetic diagnostics, Thomson scattering, stray-field measurements, and Alfvén-wave antenna studies), thereby strengthening the domestic capability to couple advanced theoretical work on instabilities, turbulence, and transport with high-quality experimental data in a fully home-built fusion device.⁴⁴

Contributions from UNICAMP and the consolidation of fusion science

UNICAMP constituted the third pillar of the Brazilian magnetic-confinement fusion program. At its IFGW, research in plasma physics and controlled fusion began in 1974, when Sérgio Porto invited Paulo Hiroshi Sakanaka, then at the Courant Institute of Mathematical Sciences of New York University, to join the Department of Quantum Electronics. Shortly thereafter, Sakanaka and colleagues José Busnardo Neto, Ricardo Galvão, Shuko Aihara, Massanobu Niimura, Helmut K. Bockelmann, and Aruy Marotta founded the plasma research group and the Plasma Laboratory at UNICAMP, establishing one of the first university-based groups in Brazil devoted explicitly to plasma physics and thermonuclear fusion.⁶ By 1978, the UNICAMP group was already recognized as one of only four Brazilian teams working on controlled nuclear fusion, and in 1979 a dedicated plasma-laboratory building was completed, enabling the construction of a series of linear, high- β devices. Among these, the Tupã-1 linear magnetic-confinement machine, commissioned in 1982, played a key role in combining theoretical and experimental studies of plasma behavior and confinement, and in training students who would later contribute to national tokamak efforts.⁴⁵

A decisive step in consolidating UNICAMP's role in fusion research came in 1996, when the laboratory received, as a donation from Kyoto University, the NOVA-II tokamak. Reinstalled and recommissioned at IFGW as the NOVA-UNICAMP tokamak, this small conventional machine – with iron core, conducting shell stabilization, and typical parameters of major radius $R_0 \approx 0.30$ m and minor radius $a \approx 0.06$ m – became the experimental centerpiece of the fusion laboratory.^{46,47} Designed and operated primarily to investigate plasma-wall interaction, edge and impurity transport, and to support the development of optical diagnostics, NOVA-UNICAMP provided excellent access for spectroscopy and other measurements in hydrogen and helium plasmas. Extensive visible and vacuum-ultraviolet spectroscopy campaigns, together with Thomson scattering, interferometry, and Langmuir probes, turned the device into a versatile platform for diagnostic development and benchmarking.^{47,48} Its compact size and relatively low operating cost allowed a high discharge repetition rate, which was particularly valuable both for iterative comparison between theory and experiment and for hands-on graduate and undergraduate training.

Together, the programs at USP (TCABR), INPE (ETE), and UNICAMP (NOVA-UNICAMP) created a critical mass of expertise and infrastructure, forming a robust national community dedicated to magnetic-confinement fusion (Table 2). This institutional arrangement embodied a two-tiered development strategy: by acquiring and upgrading an established international device such as TCABR, the community secured a reliable “workhorse” for mainstream tokamak physics, including Alfvén-wave heating, MHD activity, and edge-plasma studies, as well as advanced diagnostics. In parallel, the indigenous design and construction of the ETE spherical tokamak pushed Brazilian groups toward innovative low-aspect-ratio concepts, informing questions of equilibrium, confinement, and current drive in compact geometries. NOVA-UNICAMP complemented these efforts by offering a flexible, lower-cost platform focused on plasma-wall interaction and diagnostic development, with a strong emphasis on student training. Taken together, this triad maximized Brazil's contribution to the global fusion effort and fostered unique domestic capabilities in advanced plasma science and engineering.

Table 2: Comparison of major Brazilian tokamak experiments (TCABR, ETE and NOVA-UNICAMP).

Parameter	TCABR	ETE	NOVA-UNICAMP
Institution	USP	INPE	UNICAMP -IFGW
Type	Conventional tokamak	Spherical tokamak	Conventional tokamak (iron core, conducting shell)
Aspect ratio (R/a)	High (≈ 3.4)	Low (≈ 1.5)	Moderate (compact conventional device, ≈ 5.0)
Plasma shape	Circular (upgradable to shaped plasmas)	Elongated, low-aspect-ratio configuration	Circular
Origin	Transferred from EPFL (Switzerland)	Indigenous Brazilian design (LAP/INPE)	Donated NOVA-II tokamak from Kyoto University (Japan), reinstalled at UNICAMP
Key research areas	Alfvén waves, MHD instabilities, edge physics, advanced diagnostics	Low-aspect-ratio physics, confinement, equilibrium, current drive, diagnostic development	Plasma-wall interaction, edge/impurity transport, visible and VUV spectroscopy, diagnostic development, student training

Source: Elaborated by the authors.

PLASMAS IN SPACE RESEARCH AND TECHNOLOGY: IONOSPHERIC STUDIES, ASTROPHYSICS, AND PROPULSION

Brazil's extensive territory and strategic interests have long required a robust national space program, in which plasma science plays a central role. At INPE and partner institutions, research spans both the natural plasma environment of near-Earth space and plasma-based technologies relevant to space operations and space weather services.

Ionospheric research: leveraging Brazil's equatorial advantage

The terrestrial ionosphere, an ionized region extending roughly from 60 to over 1000 km in altitude, is strongly structured by the geomagnetic field. The Brazilian sector is particularly distinctive because it simultaneously hosts the geomagnetic equator and the South Atlantic Magnetic Anomaly (SAMA), where the intensity of the geomagnetic field reaches a global minimum. This configuration enhances energetic particle precipitation and ionization and produces a highly dynamic low-latitude ionosphere, turning Brazil into a natural laboratory for plasma irregularities and space-weather phenomena.⁴⁹

Since at least the 1970s, INPE scientists have led international efforts in the observation and modeling of equatorial plasma bubbles and equatorial spread-F (ESF) irregularities over Brazil.⁵⁰ Plasma bubbles are large-scale depletions of F-region electron density that typically develop after sunset and can extend thousands of kilometers along geomagnetic field lines. Their occurrence and morphology in the Brazilian sector have been documented through ionosondes, airglow imagers, satellites, and, more recently, dense Global Navigation Satellite Systems (GNSS) receiver networks, with detailed climatological studies quantifying their seasonal and longitudinal patterns and impact on radio propagation.^{51,52}

These irregularities severely affect trans-ionospheric radio signals, producing scintillation and loss of lock in GNSS receivers, as well as amplitude and phase fluctuations in HF and VHF communications. Early work on "equatorial anomaly effects on GPS scintillations in Brazil" demonstrated how plasma bubbles and ESF irregularities compromise positioning and navigation services across the country.⁵⁰ More recent reviews of GNSS-based monitoring networks in Brazil show how the national infrastructure has evolved into a sophisticated system capable of tracking ionospheric irregularities in near real time and feeding both scientific research and operational services.^{50,53}

To organize and operationalize these efforts, INPE established in 2007 the Brazilian Studies and Monitoring of Space Weather Program (EMBRACE).^{50,54} EMBRACE has progressively developed ground-based and space-based monitoring capabilities – magnetometer chains, ionosondes, GNSS-based total electron content (TEC) and scintillation maps,

and other instruments – forming the backbone of Brazil's national space-weather service.⁵⁴ In particular, TECMaps and derived indices produced by EMBRACE are now widely used to detect and characterize plasma bubbles and associated scintillation over South America, supporting both research and operational forecasting.⁵⁵

In this way, ionospheric plasma research at INPE has evolved from pioneering basic studies to an integrated scientific-operational framework. The same physical understanding of equatorial electrodynamics, plasma instabilities, and SAMA-driven ionization that guides academic work now underpins real-time products that help protect Brazilian communication, navigation, and surveillance systems against space-weather disturbances. The Brazilian case thus illustrates how a geographically “challenging” plasma environment can be converted into a strategic advantage, anchoring both cutting-edge plasma physics and critical national services.

Development of EP systems for space applications

In parallel with its work in ionospheric and space-weather research, Brazil has developed a sustained program in EP aimed at providing national capability in thruster technologies for satellites and space missions. EP uses electric and magnetic fields to accelerate an ionized propellant, achieving higher specific impulse than chemical rockets and thereby reducing propellant mass for station-keeping, orbit transfer, and small-satellite maneuvers.

At INPE, activities in EP date back to the mid-1980s, when the LAP began systematic studies of Kaufman-type ion engines and hollow cathodes within the framework of the Brazilian Complete Space Mission. This work, coordinated by Gilberto M. Sandonato, led to the formation of the Ion Propulsion Group and the development of the PION series of gridded ion thrusters, together with the corresponding vacuum test infrastructure. During the 1990s and 2000s, the group implemented thrust-balance diagnostics, obtained performance curves for a 5-cm ion thruster, and contributed to the creation of the Brazilian Electric Propulsion Network in 2011 to coordinate EP activities among different institutions.

From the early 2000s onward, INPE's research expanded toward pulsed plasma concepts. In collaboration with international partners, Brazilian teams investigated high-energy ablative pulsed plasma thrusters (APPTs) and two-stage PPTs (TS-PPT), producing experimental data and scaling relations for these devices.⁵⁶ More recently, this line of work has converged on the development of the variable specific impulse PPT (VSI-PPT), coordinated by Rodrigo Intini Marques at INPE. The VSI-PPT is a solid-propellant PPT whose geometry and discharge parameters are designed to permit some adjustment of specific impulse and thrust-to-power ratio in orbit, with a view to use on small-satellite platforms.⁵⁶ In March 2024, INPE reported the first successful high-exhaust-velocity test of the VSI-PPT in a dedicated vacuum facility, demonstrating the operational feasibility of this thruster concept under laboratory conditions.⁵⁷

In parallel, the University of Brasília (UnB) has become a second important center for EP in Brazil. Under the leadership of José L. Ferreira and, later, Paolo Gessini, the LFP at UnB has investigated a broad set of EP devices, including permanent-magnet Hall thrusters (PHALL-I and PHALL-II), helicon-based ambipolar thrusters, APPTs, arcjets, resistojets and hollow cathodes. The PHALL program, initiated around 2003, demonstrated Hall-effect thrusters that employ permanent magnets instead of electromagnets, with typical thrust levels in the 100-600 mN range at 400=00 W, and ion exhaust velocities of approximately 38-52 km/s, supported by Langmuir-probe measurements, optical spectroscopy, and numerical modeling.⁵⁸ At lower power levels, UnB and INPE have jointly reported results on APPTs, including performance-scaling studies relevant to micro- and small-satellite applications.⁵⁷

A third contributor is the Federal University of ABC (UFABC), where Hall-effect thruster development has been pursued within the framework of the Brazilian Space Agency's “Uniespaço” university program. A notable outcome is the PHALL-derived Hall thruster project described by J. L. Silva and collaborators, which covers 2003-2013 efforts on design, construction, and experimental characterization of permanent-magnet Hall thrusters, as well as orbit-transfer simulations in cooperation with INPE and UNESP. More recently, numerical modeling groups at the Federal University of Santa Catarina (UFSC) have joined this ecosystem by exploring the discrete unified gas kinetic scheme as an alternative to particle-in-cell methods for plasma plume and channel modeling, further strengthening Brazil's capability in EP simulation.⁵⁸

These efforts have led to a multi-institutional EP program featuring ion engines, APPTs, Hall thrusters, resistojets, and advanced simulations. International reports now recognize Brazil's contributions, highlighting INPE's TS-PPT and VSI-PPT advancements, UnB's Hall and plasma thrusters, and UFSC's work in plasma simulation as significant global achievements.

The co-location of ionospheric/space-weather expertise and electric-propulsion development within INPE creates a particularly productive feedback loop. Long-term monitoring of equatorial plasma irregularities and space-weather hazards feeds directly into the design of robust EP and communication subsystems for satellites operating in the South American sector, while onboard EP systems provide new opportunities for controlled experiments in the near-Earth plasma environment. This integration – linking fundamental plasma physics, environmental characterization, and thruster technology – gives the Brazilian space program a distinctive comparative advantage in designing propulsion solutions tailored to operations in low-latitude, disturbed ionospheric conditions.

Astrophysical plasmas

Because more than 99% of the visible matter in the universe is in the plasma state, plasma physics and astrophysics are naturally interconnected. In Brazil, this interface has been developed in a systematic way since the 1990s, with a particularly prominent role played by groups at the USP.⁵⁹

At the IAG-USP, the Group of Plasma Astrophysics and High Energies (GAPAE), coordinated by Elisabete M. de Gouveia Dal Pino, has for more than 2 decades investigated fundamental plasma processes in cosmic environments.^{34,35,60} From the mid-1990s onward, the group has combined high-performance MHD simulations with multi-wavelength observations to study topics such as⁶⁰:

- Magnetic reconnection and particle acceleration in relativistic jets and accretion-disk systems;
- The role of turbulence and reconnection in the amplification and diffusion of magnetic fields in the interstellar medium and star-forming clouds;
- Shock-field interaction and magnetic-field amplification in relativistic outflows, with applications to gamma-ray bursts and active galactic nuclei;
- Cosmic-ray acceleration in regions of fast reconnection around compact objects and in large-scale structures.

These efforts involve a broad collaboration network that includes, among others, Damien Falceta-Gonçalves, Grzegorz Kowal, Rafael Santos-Lima, Gustavo Medina-Tanco, and international partners such as A. Lazarian and G. Kowal. Numerical work by these teams has provided three-dimensional MHD simulations of turbulent reconnection and particle acceleration, models of reconnection-driven flares in jet/disk systems, and studies of magnetic-field diffusion (“reconnection diffusion”) in molecular clouds and galactic disks.

On the observational side, GAPAE and associated groups use and interpret data from X-ray and gamma-ray observatories to constrain models of high-energy sources in which plasma processes are central, such as the Galactic Center (Sgr A*), microquasars, active galactic nuclei, and galaxy clusters. This expertise in high-energy and plasma astrophysics provided the scientific basis for Brazil's formal engagement, from the late 2000s onward, in the Cherenkov Telescope Array (CTA), the next-generation ground-based gamma-ray observatory.⁶¹

A recent São Paulo Research Foundation (FAPESP) thematic project (grant 21/02120-0), coordinated at IAG-USP, consolidates this line of work under the umbrella of “investigation of high-energy and plasma-astrophysics phenomena” and supports the installation of the *Astrofisica con Specchi a Tecnologia Replicante Italiana* (ASTRI) Mini-Array, a nine-telescope CTA precursor, in partnership with Italian and Brazilian institutions.^{62,63} Within this framework, Brazilian researchers contribute both to the development of data-analysis tools and to the theoretical interpretation of CTA and ASTRI observations, with particular emphasis on the role of plasma turbulence, reconnection, and shocks in the production of very-high-energy gamma rays.

These activities align Brazilian plasma-astrophysics research with advanced MHD and kinetic modeling for interpreting high-energy observatory data. This work deepens knowledge of turbulence, reconnection, and particle

acceleration in cosmic plasmas, enhances the country's role in international collaborations like CTA, and trains new researchers bridging plasma physics and astrophysics.

THE INDUSTRIAL TRANSITION: PLASMA TECHNOLOGY FOR MATERIALS SCIENCE

While fusion and space research represent the grand challenges of plasma science, the application of plasmas to modify and create new materials has generated more immediate and widespread industrial impact. In Brazil, this trajectory began with vacuum-based technologies strongly coupled to the aerospace and defense sectors and has progressively evolved into a diversified ecosystem of processes, laboratories, and companies serving microelectronics, aerospace, energy, packaging, and mechanical components.^{6,17}

From the 1980s onward, technological plasmas under vacuum and at high temperature became a central pillar of Brazilian plasma science, with institutions such as ITA, UNICAMP, and USP consolidating programs in thin-film deposition, surface engineering, ion nitriding, and thermal spraying.⁶ Within this context, the development of plasma-assisted materials processing at ITA and partner institutions laid the groundwork for the present industrial transition described below.

To illustrate the institutional concentration of plasma research in this region, Fig. 5 presents the main plasma research groups located in the Southeast of Brazil, which historically constitutes the country's most consolidated cluster for vacuum-based, thermal, and advanced materials plasma technologies.



Figure 5: Major plasma research groups in the Southeast of Brazil. A schematic overview of the principal institutions engaged in plasma science and technology in the Southeast region, including ITA/LPP, INPE/LAS, USP/LFP and LSI, UNICAMP/CCSNano, UNESP laboratories, Mackenzie, and COPPE/UFRJ. This region forms the historical and technological core of Brazilian plasma research, encompassing fusion, materials processing, diagnostics, and industrial partnerships.

Source: Elaborated by the authors.

VACUUM-BASED SURFACE ENGINEERING: THIN FILMS AND SURFACE MODIFICATION

The development of vacuum-based plasma processing at ITA builds on the program initiated in the 1980s by Prof. Homero Santiago Maciel, whose group established the first low-pressure plasma sources that later supported the institute's expansion into thin-film deposition, surface engineering, and plasma diagnostics. Over the subsequent decades, this activity matured into the LPP, which became a national reference in vacuum-based plasma technologies,

closely aligned with the aerospace and defense sector in São José dos Campos. Today, the laboratory operates as a strategic R&D center, supporting both fundamental investigations and applied developments in plasma-surface interactions, including tribology, corrosion protection, space-environment simulation, and nanostructured coatings. A concise chronology of the principal Brazilian surface-engineering groups discussed in this section is presented in Fig. 6. Key research lines at LPP-ITA include:

- Thin-film deposition: using PECVD and dc/rf magnetron sputtering (including HiPIMS), researchers develop advanced coatings such as diamond-like carbon (DLC), Ag-DLC, silicon carbide (SiC), gallium nitride (GaN), and titanium dioxide (TiO₂) for microelectronics, wear-resistant components, and sensors.
- Surface modification of polymers: a significant effort is devoted to the treatment of polymers and rubbers, many of them used in aerospace and high-performance engineering, to improve adhesion, durability, wettability, and barrier properties without compromising bulk performance.
- Nanotechnology: the LPP employs plasma-assisted techniques to synthesize and functionalize nanomaterials, such as carbon nanotubes and metal-containing DLC, for next-generation composites, sensors, and biointerfaces, integrating thin-film processes with nanoscale engineering.

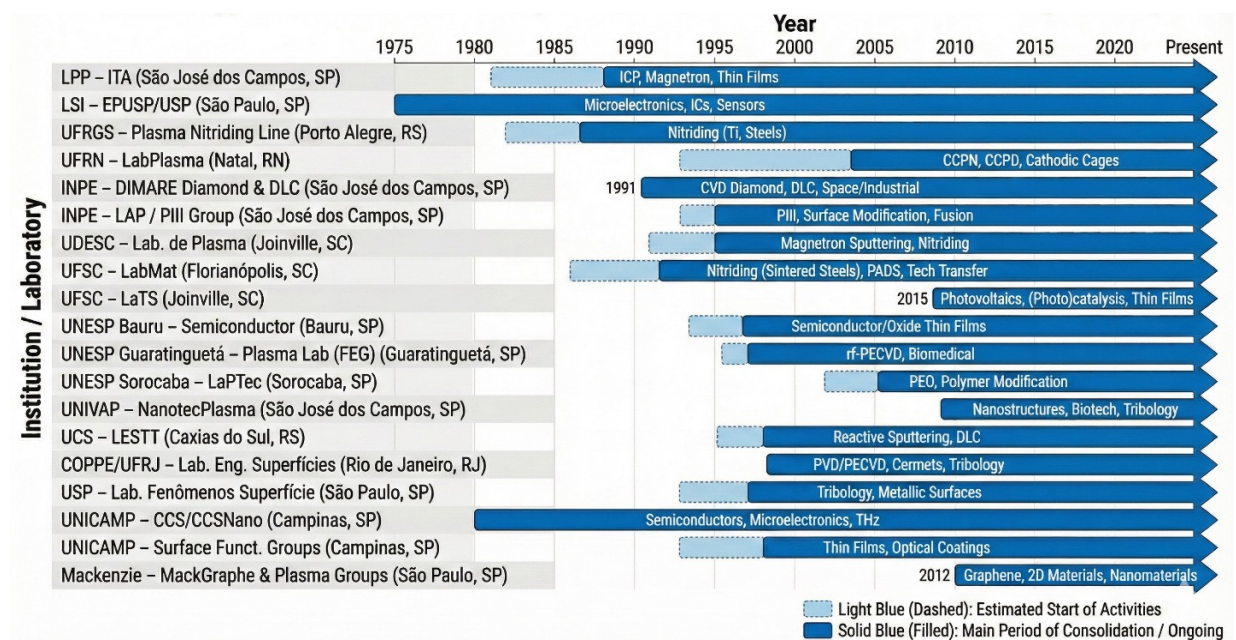


Figure 6: Chronological timeline of the main Brazilian research groups dedicated to vacuum-based plasma surface engineering. The horizontal bars represent the lifespan of each laboratory, distinguishing between the estimated start of activities (indicated by dashed light blue sections) and the main period of consolidation and ongoing activity (solid dark blue sections). Annotations within the bars highlight the primary research focus of each group.

Source: Elaborated by the authors.

Beyond ITA, other institutions have built complementary expertise in vacuum-plasma technologies for surface engineering. At the State University of Santa Catarina (UDESC) in Joinville, the Laboratory of Plasmas, Films and Surfaces has maintained, since the early 2000s, a strong program in magnetron sputtering, plasma nitriding, and plasma-assisted surface modification. The group is led by Luís César Fontana, Abel André Cândido Recco, and Jacimar Nahorny, with contributions from researchers such as Julio César Sagás; their work includes triode magnetron sputtering of TiN and TiAlN, carbonitriding of tool steels, and plasma treatment of polymers and wood surfaces for adhesion and tribological control.^{64,65}

A relevant contributor to plasma-based surface engineering in southern Brazil is the Materials Laboratory (LabMat) at UFSC, originally founded in 1962 and renamed in 1989. Since the late 1980s, LabMat has developed a solid program in plasma processing and powder metallurgy under the leadership of Aloísio N. Klein, Joel L. R. Muzart, and

collaborators. Early efforts, including the “Development of Plasma-Nitrided Sintered Steel” project (1991), established ion-nitriding capabilities for sintered alloys and initiated studies on plasma nitriding, nitrocarburizing, carburizing, and plasma-assisted sintering. The Plasma Assisted Debinding and Sintering process, created with Lupatech and patented internationally, became one of the group’s key innovations. A long-standing collaboration with Embraco/Whirlpool enabled the industrial adoption of plasma nitriding for compressor components. LabMat has since broadened its work to include plasma cleaning, thin hard coatings, tribology, ceramics, and polymers, and has trained specialists now active in other southern plasma groups, including UDESC, strengthening a regional ecosystem in plasma-assisted surface engineering. A second UFSC initiative in plasma-assisted surface engineering is the Laboratory of Surface Treatments (LaTS) at UFSC Joinville, created in 2015 and registered nationally as the Technology of Surfaces, Coatings and Nanostructures group. LaTS develops thin films and surface treatments via chemical, electrochemical, and plasma-assisted processes for applications in photovoltaics, (photo)catalysis, metal-mechanical components, and aerospace engineering. The group has recently expanded into biodiesel production using plasma-assisted biocatalysis.

Within the UNESP system, three additional hubs have become important actors in plasma-based surface engineering. At the Faculty of Engineering of Guaratinguetá (FEG/UNESP), a plasma laboratory dedicated to thin films and surface treatment has been developed around rf-PECVD and plasma immersion ion implantation and deposition (PIII&D). Under the coordination of Rogério Pinto Motta, and with contributions from researchers such as Milton Eiji Kayama and collaborators, the group has produced a broad series of works on plasma-polymerized thin films (from precursors such as acetylene and HMDSN), DLC-type coatings, and plasma treatment of metallic and polymeric substrates for tribological and biomedical applications.⁶⁶⁻⁶⁹ These activities include the synthesis and characterization of polymeric films deposited by low-pressure rf plasmas, studies on friction reduction in orthodontic NiTi wires treated by PECVD, and the development of atmospheric-pressure plasma devices for polymer deposition and surface modification.⁶⁶⁻⁶⁹

At the UNESP campus in Sorocaba, the Technological Plasma Laboratory (LaPTec) – part of the Institute of Science and Technology – has established a multidisciplinary platform combining vacuum and non-thermal plasmas (NTPs). Coordinated by Nilson C. Cruz and Elidiane C. Rangel, LaPTec works on plasma-assisted surface engineering of metals and polymers, focusing on plasma electrolytic oxidation (PEO) of light alloys, oxidation and barrier coatings (e.g., $\text{SiO}_x/\text{SiO}_x\text{C}_y$), and plasma treatment of commercial polymers and packaging materials.^{70,71} The group has reported thin oxide films (e.g., ZnO and alumina) on polymer substrates, plasma-modified polymer surfaces for improved barrier and adhesion properties, and collaborative studies with dentistry groups on the use of NTPs to tailor the surface chemistry and wettability of dental resins and acrylic materials.⁷⁰⁻⁷³

Complementing these activities, the UNESP campus in Bauru (Faculty of Sciences, FC/UNESP) hosts the Semiconductor Film Laboratory, a long-standing program on plasma-assisted semiconductor and oxide thin films. Coordinated by José Humberto Dias da Silva, the group has investigated amorphous and polycrystalline III-V semiconductors (such as GaAs and GaSb), nitride alloys (GaN, GaMnN), and TiO_2 -based coatings deposited mainly by rf magnetron sputtering and related plasma techniques, with emphasis on optical and electronic properties, microstructure, and stability.^{74,75}

A second major axis of development is articulated by the National Institute of Surface Engineering (INCT-INES), which federates several Brazilian laboratories dedicated to plasma-assisted and ion-beam surface modification. Within this network, one finds: the Surface Engineering and Heat Treatment Laboratory (LESTT) at the Caxias do Sul University (UCS), with researchers such as Israel J. R. Baumvol, Carlos Alejandro Figueroa, Cláudio Perottoni, and collaborators, working on reactive magnetron sputtering of nitrides and carbides (e.g., TiN, VC), DLC coatings, and plasma-assisted thermochemical treatments; the surface-engineering and tribology groups at the Federal University of Rio Grande do Sul (UFRGS) (e.g., Gabriel Vieira Soares, Pedro Grande), focusing on plasma nitriding, Ti(N,C,O,H) systems and advanced tribology; the Surface Phenomena Laboratory at the Polytechnic School/USP, coordinated by Amilton Sinatora and collaborators, applying plasma-assisted treatments and thin-film coatings to mechanical components; and plasma-based surface functionalization activities at UNICAMP (e.g., Francisco C. Marques, Edison F. Motta, Paulo Mei).⁷⁶

In the Northeast, the Plasma Materials Processing Laboratory (LabPlasma) at the Federal University of Rio Grande do Norte (UFRN), coordinated by Clodomiro Alves Jr., has played a pivotal role in the development of cathodic cage

plasma nitriding (CCPN).⁷⁷ This technique, conceived at LabPlasma, uses a cage as an active cathode to achieve highly uniform nitrided layers on steels and other alloys, and has been widely applied to austenitic stainless steels and tool steels. Building on this expertise, Alves and co-workers further introduced cathodic cage plasma deposition, a low-cost and versatile thin-film technique that reconfigures the cathode into a cage geometry to improve plasma uniformity around complex substrates, enabling the deposition of TiN, TiO₂, and other hard coatings for tribological and corrosion-resistant applications.^{78,79}

An additional strategic node is the diamond and DLC coatings program at INPE, led by Vladimir Jesus Trava-Airoldi and collaborators. Since the 1990s, INPE has developed CVD diamond and DLC coatings for space and industrial applications, with emphasis on deposition mechanisms, stress control, and adhesion on metallic substrates such as molybdenum, steel, and titanium.^{80,81} These coatings have been applied as solid lubricants in satellite moving parts, optical and thermal protection layers, and wear-resistant, bactericidal surfaces, and have given rise to successful technology-transfer initiatives through the spin-off company Clorovale/CVDVale (1997).^{80,82} At INPE's LAP, a dedicated program on plasma immersion ion implantation and plasma-assisted surface modification, coordinated by Mario Ueda, has been active since the mid-1990s, building on LAP's earlier fusion and basic-plasma activities and extending them toward advanced surface engineering and technology transfer.

The NanotecPlasma Group at UNIVAP was established in the early 2010s, following Homero S. Maciel's retirement from ITA, through the joint effort of Rodrigo S. Pessoa and Lúcia Vieira. The group consolidated laboratory infrastructure for plasma-processed thin films, cold-plasma applications in biotechnology, nanostructured materials, and tribology. It is currently led by Lúcia Vieira.

Other important contributions come from surface-engineering laboratories in the South and Southeast regions, many of them also integrated into INCT-INES or related networks. The Surface Engineering Laboratory at the Metallurgical and Materials Engineering Program (PEMM)/Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering (COPPE)/Federal University of Rio de Janeiro (UFRJ) employs PVD (including magnetron sputtering) and PECVD to produce ceramic-metallic thin films with tailored optical and mechanical properties. At UFRGS, groups at the Institute of Physics and School of Engineering have long experience in plasma nitriding of titanium and steels for biomedical and mechanical applications (e.g., works by M. P. Kapczinski, R. L. Dalcin, E. S. Lima, and collaborators).⁸³ In addition, the National Cooperation Network in Plasma Engineering (Reconplasma) connects laboratories at Fundação Centro Tecnológico de Minas Gerais (CETEC-MG), UFRN, UDESC, ITA, and other institutions, promoting coordinated advancements in plasma-based surface treatments and thin-film deposition.

In addition to laboratories explicitly dedicated to surface engineering, several microelectronics and nanotechnology centers in the Southeast make intensive use of vacuum-based thin-film and plasma processes. The LSI at the Polytechnic School/USP, founded in 1975, operates cleanroom infrastructure for integrated-circuit and sensor fabrication in which vacuum deposition and plasma-based patterning are routine steps. At UNICAMP, the Center for Semiconductor Components and Nanotechnologies (CCSNano, formerly CCS) maintains a complete semiconductor process line that integrates thin-film deposition, lithography, and plasma etching, supporting both device prototyping and national collaborations in microelectronics and THz instrumentation. At Mackenzie Presbyterian University, the MackGraphe Institute and associated engineering groups combine the synthesis and characterization of graphene and other two-dimensional nanomaterials with plasma-based thin-film deposition and thermal-plasma treatments for coatings and biomaterials. Together with the surface-engineering lines at COPPE/UFRJ, these centers extend vacuum-plasma capabilities toward semiconductor technology, photonics, and multifunctional nanostructured coatings, reinforcing the bridge between basic plasma science and high-tech applications in electronics and optics.

Collectively, these developments demonstrate how a program that started in the 1980s at ITA with a small, low-pressure discharge lab has grown over 40 years into a national network of vacuum-based plasma facilities and processes. This network now includes LPP-ITA, UDESC's Laboratório de Plasma, Filmes e Superfícies, the plasma groups at UNESP-Guaratinguetá, UNESP-Sorocaba (LaPTec), and UNESP-Bauru, UFRN's LabPlasma, UCS/LESTT, UFRGS/USP/UNICAMP surface-engineering groups, and the INPE diamond/DLC program, among others, and underpins a significant fraction of Brazil's advanced surface-engineering capabilities, providing a robust bridge between academic plasma science and industrial materials technology, as summarized in Fig. 6.

Thermal plasmas for industrial processes

Thermal plasmas, characterized by temperatures of several thousand kelvin and near-equilibrium conditions, are indispensable tools for high-enthalpy materials processing, metallurgical transformation, and waste destruction. Their ability to melt, dissociate, or reform virtually any material has positioned them as a core technology for aerospace, environmental engineering, and heavy industry.

The structured development of thermal-plasma research in Brazil began at UNICAMP in the early 1980s, when Aruy Marotta founded one of the first national groups dedicated to arc-plasma reactors. From 1980 to the mid-1990s, Marotta's laboratory pioneered transferred and non-transferred arc torches, plasma-chemical reactors for hazardous-waste destruction, and heat- and mass-transfer models for industrial plasma systems, offering an applied technological axis parallel to the university's basic research in plasma physics and fusion.²⁹

Almost simultaneously, an industrial-oriented effort in thermal plasmas was established at the Technological Research Institute (IPT), in São Paulo. Since the late 1980s, IPT has investigated thermal-plasma metallurgy and high-temperature processing, as documented by an internal strategic assessment on plasma technologies published in 1991 and by outreach reports highlighting *metalurgia a plasma térmico* as a promising route for refining metals and treating refractory materials. In the early 2000s, this line evolved into a dedicated Plasma Laboratory within the Division of Mechanics and Electricity, where Antônio Carlos da Cruz and collaborators developed a plasma furnace for aluminum recycling in partnership with the Brazilian Aluminum Association (ABAL) and FAPESP.⁸⁴ The pilot "IPT plasma furnace" uses an argon thermal-plasma torch to melt aluminum scrap while minimizing oxidation and eliminating the need for salt fluxes, thereby reducing the generation of hazardous "black sludge" and improving metal yield. By the mid-2000s, this plasma-furnace program had become a national reference for the application of thermal plasmas to recycling and waste treatment, complementing academic developments at UNICAMP and ITA and illustrating IPT's role as a bridge between plasma science and industrial process innovation.⁸⁴

A third axis of sustained development was consolidated at the LPP-ITA. From the mid-2000s onward, following Gilberto Petraconi Filho's postdoctoral training at UNICAMP in Prof. Aruy Marotta's thermal-plasmas laboratory, he expanded LPP's capabilities into the thermal-plasma domain by modernizing arc-torch architectures, implementing high-temperature optical diagnostics, and establishing high-heat-flux facilities dedicated to aerospace applications. Across the 2010s-2020s, LPP has become one of Brazil's leading centers for high-enthalpy plasma systems, with research focused on:

- Aerospace and hypersonics (2000s-present): high-enthalpy arc-jet systems for thermal protection system (TPS) testing, atmospheric re-entry simulation, and hypersonic material evaluation.⁸⁵
- Waste-to-energy and environmental plasma processing (2000s-present): plasma gasification of municipal solid waste, petroleum residues, and hazardous solids, with emphasis on syngas composition, reactor efficiency, and plasma-gas reaction modeling.⁸⁶
- Biomass conversion and renewable fuels (2010s-present): plasma-assisted gasification and reforming of agricultural residues and other organics, integrating chemical kinetics, plasma diagnostics, and energy conversion modeling.⁸⁷

A further strategic node in the national landscape is the Thermal Plasma Laboratory (LPT) at the Federal University of Espírito Santo (UFES), in Vitória, state of Espírito Santo, coordinated by Prof. Alfredo Gonçalves Cunha. Installed in 2003, the LPT occupies an area of about 250 m² and is closely linked to the Laboratory of Carbonaceous and Ceramic Materials (LMC). Its activities focus on the development of thermal plasma torches and their application to energy and materials processing, particularly the pyrolysis of natural gas and hydrocarbon residues to produce hydrogen and carbonaceous materials (carbon black and, more recently, graphene-like structures) in collaboration with industrial partners such as Petrobras. In parallel, UFES researchers have also investigated plasma-based surface engineering, including plasma nitriding and cathodic-cage configurations for steels, consolidating UFES as an important center in southeastern Brazil for thermal-plasma applications in energy and materials science.⁸⁸

The development of UNICAMP, IPT, ITA, and UFES from the 1980s onward shows how Brazil's thermal-plasma research has grown into a strong multi-institutional network supporting advanced materials, environmental, and aerospace technologies. This collaboration links academic plasma research to industrial innovation.

The corporate ecosystem: commercializing plasma technology in Brazil

The growth of plasma science in Brazil is also reflected in the gradual appearance of companies that apply these technologies in practical industrial contexts. Rather than being limited to academic laboratories, plasma processes are now employed in surface engineering, materials processing, recycling, polymer treatment, energy systems, and advanced manufacturing. This shift indicates that plasma technologies have reached a stage of technical maturity that enables their incorporation into different segments of the production chain.

Some representative examples include:

- TTI Thermtec (Paraná) – A long-standing provider of plasma nitriding services, applying glow-discharge thermochemical treatments to improve the hardness, wear resistance, and service life of steels used in tools, molds, and mechanical components. Its activity illustrates how plasma nitriding has become a consolidated industrial process in Brazil.⁸⁹
- Plasmar Tecnologia (Rio Grande do Sul) – Based in the metal-mechanical hub of Caxias do Sul, Plasmar offers plasma nitriding, carbonitriding, and thin-film deposition for precision components. These treatments demonstrate the integration of plasma surface engineering within regional manufacturing chains.⁹⁰
- Recaltech (São Paulo) – Recaltech develops and applies thermal-plasma systems for waste gasification, biomass processing, and the recovery of high-value materials. Its work with plasma torches reflects the growing national interest in high-temperature plasma technologies for energy and environmental applications.⁹¹
- Unipac/Grupo Jacto (São Paulo) – Unipac introduced plasma-assisted barrier coatings for plastic agrochemical containers, reducing permeation without the need for multilayer structures. This approach exemplifies how plasma processes can improve packaging performance while supporting recycling initiatives.⁹²
- Surface Plasma Engineering (São Paulo) – This technology-based company designs atmospheric-pressure plasma devices for surface activation before printing, painting, or bonding. Such systems provide an alternative to flame treatments and chemical primers, highlighting the practical advantages of atmospheric plasmas in industrial settings.⁹³
- CVDVale (São José dos Campos, São Paulo) – Originating from plasma-materials research at INPE in the 1990s, CVDVale produces diamond and DLC coatings by plasma-assisted CVD. These coatings are used in cutting tools, dental components, and wear-resistant parts, representing a successful example of long-term technology transfer from federal research institutions to industry.⁹⁴
- Turbomachine (São Paulo) – Active in gas-turbine and propulsion technologies, Turbomachine has participated in developments involving plasma-assisted combustion and high-enthalpy thermal environments. Its engagement illustrates how plasma processes can intersect with aerospace and energy-conversion technologies.⁹⁵
- NIIT Nitretação a Plasma (Araquari, Santa Catarina) – NIIT is one of the national references in the fabrication of plasma-nitriding reactors and related equipment. In addition to providing industrial nitriding treatments, the company designs and manufactures complete reactor systems, demonstrating how industrial capabilities in Brazil have evolved from merely applying plasma treatments to developing the underlying equipment and infrastructure.⁹⁶

Together, these examples demonstrate how plasma technology has gradually expanded into diverse segments of Brazilian industry. Each company occupies a specific niche, namely surface treatment, advanced coatings, thermal-plasma processing, atmospheric plasma activation, industrial plasma equipment, or high-performance materials, but all maintain a clear connection to the scientific foundation established within Brazilian universities and research laboratories. This ecosystem illustrates the progressive integration of plasma science into real-world technological applications across the country.

THE ATMOSPHERIC REVOLUTION: COLD PLASMA APPLICATIONS

While vacuum-based systems defined the first wave of plasma technology, the most dynamic and rapidly expanding frontier today lies in cold atmospheric plasma (CAP). By generating partially ionized gases at or near room temperature and atmospheric pressure, CAP sources dispense with bulky and costly vacuum infrastructure, enabling compact, portable devices. This shift has dramatically lowered the barrier to entry for plasma technology and opened a broad spectrum of applications in heat-sensitive environments, particularly in medicine, dentistry, agriculture, food processing, and environmental remediation.⁹⁷⁻¹⁰¹

In CAP systems, electrons remain highly energetic while the gas temperature stays close to ambient, allowing direct or indirect treatment of living tissues, biological fluids, polymers, and complex surfaces without thermal damage. The resulting plasmas can be operated in continuous or pulsed mode, using jets, dielectric barrier discharges, or surface discharges tailored to specific applications. Beyond conventional “dry” treatments, CAP has also enabled the development of plasma-activated liquids (PALs), such as PAW and plasma-activated saline (PAS), which store reactive species for indirect treatment strategies.^{102,103}

Brazilian researchers have embraced this atmospheric revolution across multiple domains. In the last decade, groups at UNESP, ITA, UNICAMP, UFABC, UFRGS, the Federal Rural University of the Semi-Arid Region (UFERSA), and other institutions have developed a diverse portfolio of CAP sources, ranging from hand-held jets and dielectric barrier discharge devices to reactors for PALs. These efforts are increasingly articulated through large, multi-institutional programs that connect fundamental plasma physics, diagnostics, and modeling with translational research in biomedicine, dentistry, agriculture, and environmental technologies. The result is a second wave of plasma science in Brazil, strongly oriented toward interdisciplinary applications, regulatory compliance, and technological innovation.

Plasma medicine and dentistry: from laboratory to clinical practice

The ability of CAP to safely interact with living tissues has catalyzed the emergence of plasma medicine, with dentistry rapidly becoming one of its most active subfields. When operated under appropriate conditions, CAP produces a cocktail of reactive oxygen and nitrogen species (RONS), together with UV/VUV radiation, transient electric fields, and charged particles that act synergistically. This combination can inactivate a broad spectrum of pathogens—including antibiotic-resistant bacteria and fungi—disrupt biofilms, modulate inflammatory responses, stimulate angiogenesis and tissue regeneration, and, under specific regimes, trigger apoptotic pathways in cancer cells.^{104,105} Complementary strategies employ PALs, which allow the controlled delivery of reactive species to hard-to-reach sites such as root canals, periodontal pockets, or irregular wound beds.¹⁰²

In Brazil, this transformative potential has led to a coherent research agenda that spans fundamental mechanisms, device engineering, physicochemical characterization, and pre-clinical and clinical studies. A central driver of this agenda is the FAPESP Thematic Project *Use of low temperature atmospheric pressure plasma in dentistry: from laboratory bench to clinics* (2019/05856-7), coordinated by Cristiane Yumi Koga-Ito (UNESP-ICT) and involving key partners at UNESP-FEG, under the leadership of Konstantin G. Kostov, and at ITA, represented by Rodrigo Sávio Pessoa.¹⁰⁶ This multi-institutional program integrates:

- The design, electrical optimization, and dosimetric control of CAP jets and dielectric-barrier-discharge (DBD) devices for intraoral and extraoral applications;
- Comprehensive physicochemical and spectroscopic analyses of the discharges and the resulting PALs/PAW, including OES, UV-Vis, Raman, FTIR, electrochemical probes, and computational modeling;
- *In vitro* studies focused on biofilm inactivation, surface modification of dentin and enamel, endodontic disinfection, antimicrobial activity on oral pathogens, and enhancement of adhesive interfaces in restorative materials;
- *In vivo* and pre-clinical efforts dedicated to the translational pathway of CAP-based interventions in dentistry and oral medicine.

Within this framework, research groups led by Konstantin G. Kostov at UNESP-FEG have developed, optimized, and characterized a series of novel CAP jets and surface-DBD actuators for dental use. Their work encompasses sterilization of dental materials, modification of enamel and dentin surface chemistry and topography, enhancement of bond strength between adhesives and composites, and suppression of multispecies oral biofilms.⁹⁸ Parallel contributions from LPP-ITA have expanded the field toward plasma-liquid interactions, particularly through the systematic study of PAW and PAS generated by argon- and air-based CAP and DBD systems. Pessoa's group has elucidated mechanistic pathways for the formation of ROS/RNS in PAW/PAS, quantified the evolution of species such as H_2O_2 , NO_2^- , NO_3^- , $\text{O}_3(\text{aq})$, and peroxyxynitrite, and established correlations between discharge parameters (voltage, frequency, gas flow, electrode configuration) and the biological potency of the activated liquids. These investigations have been directly applied to antifungal and antibacterial activity (e.g., *Candida albicans*), biofilm disruption, cytocompatibility, effects on cancer cell lines, and the modulation of redox stress in cellular systems, thereby reinforcing the translational relevance of PAW/PAS in oral-health contexts.^{97,98,102-105,107-109}

Systematic and narrative reviews led by Brazilian teams now consolidate the state of the art in CAP for dentistry, highlighting promising results in caries management, endodontic disinfection, periodontal therapy, implant decontamination, whitening procedures, and biofilm control. These reviews also emphasize the current need for protocol standardization, quantitative dosimetry, interlaboratory reproducibility, and long-term safety and biocompatibility assessments.^{97,98,102}

At the UNICAMP, researchers at the Piracicaba Dental School and associated materials groups have explored non-thermal atmospheric-pressure plasma as an adjunct in dental bleaching and adhesive procedures, relating plasma-treatment parameters to changes in enamel and dentin properties, antibacterial performance, and biomaterial surface behavior.¹¹⁰ These studies complement the efforts at UNESP and ITA by extending cold plasma applications to clinically relevant protocols and by integrating plasma treatments with advanced analyses of dental tissues and implant surfaces.

Complementary work by Alves Júnior and collaborators at UFERSA and elsewhere has extended plasma medicine into animal-model oncology, biomaterial surface activation, endothelial-cell biocompatibility studies, and plasma-liquid oxidation systems.^{111,112}

A distinctive feature of the Brazilian trajectory in plasma medicine is the rapid progression from laboratory research to regulated clinical implementation. The Brazilian Health Regulatory Agency (ANVISA) has already approved both imported and nationally developed CAP devices, demonstrating that this technology has moved beyond the experimental stage and into routine medical use.¹¹³

On the international side, the German company Terraplasma Medical GmbH has introduced the plasma care® system into the Brazilian market through the Alyaplasma platform.¹¹⁴ The device is marketed nationally for painless treatment of acute and chronic wounds, leveraging bactericidal and healing-promoting cold plasma generated from ambient air. ANVISA has formally registered both the Sistema Plasma care and its dedicated sterile spacer, under notifications 82071039001 and 82071039002, respectively. This establishes plasma care® as one of the first CE-certified medical CAP devices with regulatory clearance for clinical use in Brazil, particularly in wound management and dermatological care.

On the domestic front, the Brazilian company Adoxy Medical has developed the Mjolnir Pro™, a DBD cold plasma platform designed for dermatological and aesthetic applications. The device holds ANVISA registration 82149139005 and has been evaluated in clinical and translational studies – for instance, in the treatment of melasma, where CAP produced by the Mjolnir Pro™ demonstrated modulation of melanogenesis, increased skin permeability to topical actives, and absence of post-inflammatory hyperpigmentation, confirming its safety profile.

Together, these developments illustrate how CAP technologies in Brazil have rapidly evolved from research prototypes to regulated medical products integrated into clinical and aesthetic practice.¹¹⁵

These developments reflect a mature innovation cycle in Brazil: advances in plasma physics support source improvement and biological research; large programs like the FAPESP Thematic guide movement toward clinical protocols; and a responsive regulatory and industrial sector enables approval and commercialization of CAP medical devices. Plasma medicine and dentistry are advancing as both scientific frontiers and opportunities for Brazil to demonstrate its ability to innovate and implement plasma technologies in real healthcare settings.

Plasma in agriculture: innovations for food security and sustainability

Given that agribusiness remains a pillar of the Brazilian economy, the application of plasma technologies in agriculture represents a strategic alignment between national scientific capacity and economic priorities. CAP and related plasma-activated processes offer chemical-free, sustainable solutions to several major agronomic challenges, such as seed dormancy, pathogen load, and low vigor in seed lots.

In Brazil, the Laboratório de Plasma (LabPlasma) at UFERSA has emerged as a leading center for agricultural-plasma research, under the direction of Clodomiro Alves Júnior.¹¹⁶ Studies conducted there and elsewhere in Brazil demonstrate that cold-plasma treatment of seeds can significantly increase germination rates, seedling vigor, and storage viability by modifying the seed-coat wettability, reducing surface microbial load, and altering imbibition kinetics.^{117,118} The group of LPP-ITA has also performed some research in the plasma-agriculture field in recent years using gliding arc discharge.¹¹⁹

Beyond seed priming, plasma technologies are increasingly being applied across the agricultural value chain – for example, in the development of recyclable, high-performance agrochemical packaging using plasma-activated surface coatings (e.g., by Unipac/Grupo Jacto) and in commercial adoption of plasma-nitriding or plasma-deposition treatments for agricultural equipment.¹²⁰ These examples illustrate that plasma technology in Brazil is not only progressing in foundational research but is also being translated into industrial supply-chain innovation.

Environmental remediation: plasma-based solutions for water and waste

Plasma technology offers powerful tools for addressing environmental pollution, and NTP has become an active research area in Brazil as a form of advanced oxidation process (AOP) for water and wastewater treatment. Using electrical discharges directly in or above aqueous solutions, plasma reactors can generate highly reactive ROS/RNS that degrade organic pollutants, disinfect pathogens such as *Escherichia coli*, and avoid chlorine-based by-products like trihalomethanes. Recent reviews highlight NTP's capacity; for example, a Brazilian-context review identified AOPs, including plasma methods, as viable routes for removing contaminants of emerging concern from aquatic matrices.¹²¹

Entrepreneurial translation of these technologies is underway in Brazil. The startup WIER, founded by chemical engineer Bruno Mena Cadorin, developed a commercial solution combining cold-plasma and ozone-generation for water purification and air sanitization; the firm's technology is positioned for industrial effluents, ambient air, and agricultural settings, signaling a move from pure research toward deployable systems.¹²²

Together, these developments show how Brazil is leveraging plasma science beyond the academic laboratory: from the seed of device physics to full-scale industrial and environmental applications. By aligning its scientific base with national-scale environmental and food-security imperatives, plasma technology emerges as a strategic enabler in Brazil's sustainable-development agenda.

THE BRAZILIAN PLASMA SCIENCE COMMUNITY: CHALLENGES AND FUTURE HORIZONS

A relatively small yet unified community has supported the progress of plasma science and technology in Brazil, guiding its evolution from initial theoretical and experimental work to today's broad range of applications, including fusion, space, technology, and biomedical fields. This community has been organized around professional societies, periodic national meetings, graduate programs, and multi-institutional research networks, while operating under the broader constraints of Brazilian science and technology policy. The advances documented in this review show that Brazilian groups have achieved international visibility and have delivered technologies of clear socioeconomic relevance. At the same time, the future of the field remains tightly coupled with the stability of funding, the renewal of infrastructure, and the capacity to retain and attract qualified human resources.

The role of the Brazilian Physical Society (SBF) and community organization

The SBF has been the main institutional anchor for the plasma community. Within SBF, the Plasma Physics Commission provides representation in the society's governance structure and helps define priorities across three major subareas: technological plasmas, fusion plasmas, and space/basic plasmas.¹²³ This subdivision mirrors the four pillars discussed in this review and has facilitated a coherent community identity even as research topics have diversified.

Historically, a key instrument for community building was the Brazilian Meeting on Plasma Physics (EBFP), a topical SBF meeting launched in 1991 and held every 2 years as a dedicated forum for basic plasma phenomena, controlled fusion, space and astrophysical plasmas, and technological applications. In the 2010s, the plasma activities originally concentrated in EBFP were progressively merged into larger SBF events, particularly the Autumn Meeting (EOSBF), which is now the largest multi-area meeting of the society and regularly gathers hundreds to around a thousand participants from different subfields of physics. In this configuration, plasma-oriented symposia and contributed sessions are organized within EOSBF and other major SBF meetings, preserving a national forum for plasma research while enhancing interaction with neighboring communities such as condensed matter, optics, and materials science.^{124,125} Recent editions have also combined the EBFP label with regional or Latin American plasma workshops under the SBF umbrella, reinforcing the international dimension of these activities.

Complementing the role of SBF, the Brazilian Vacuum Society (SBV) constitutes a second, increasingly important hub for the plasma community, especially in technological plasmas and thin-film processing. Its flagship event, the Brazilian Congress of Vacuum Applications in Industry and Science (CBrAVIC), is held regularly and brings together researchers and engineers working on vacuum technology, surface engineering, sputtering, plasma-assisted deposition, and related diagnostics. A significant fraction of Brazilian plasma groups active in materials processing, nanostructured coatings, and plasma-surface interaction now present their work at CBrAVIC, which has become a natural meeting point between plasma physics and the broader vacuum and surface-science community.

These meetings are complemented by graduate schools, specialized workshops, and thematic programs supported by Brazilian agencies such as the Coordination for the Improvement of Higher Education Personnel (CAPES),

National Council for Scientific and Technological Development (CNPq), FAPESP, and other state foundations. Over the past 2 decades, this ecosystem – structured around SBF (including EOSBF and plasma-focused symposia), SBV (through CBrAVIC), and a network of graduate programs – has enabled the consolidation of roughly a dozen modern plasma laboratories across Brazil and a community of a few hundred active researchers and students. In strategic areas such as fusion, space weather, and plasma technology for materials and health, multi-institutional centers and thematic projects have emerged as important mechanisms for sharing large facilities, coordinating training, and maintaining continuity across political cycles.

Systemic challenges: funding, infrastructure, and human resources

Notwithstanding this organizational maturity, the Brazilian plasma community operates within a science and technology system that has experienced a prolonged period of fiscal stress. Since around 2015, successive federal budgets have imposed deep reductions on the Ministry of Science, Technology, and Innovation (MCTI) and on its main funding instruments. Analyses from Pesquisa FAPESP and other sources show that, by 2021, the discretionary budget of MCTI had fallen to roughly 16% of its 2013 level, with Universal CNPq calls for research projects suspended and most resources diverted to maintaining a minimal number of scholarships.¹²⁶ In parallel, the National Fund for Scientific and Technological Development (FNDCT), which finances infrastructure and innovation programs via the Financier of Studies and Projects (FINEP), saw more than 90% of its resources frozen in 2021 despite a law approved by Congress to prevent such contingencies.¹²⁷

The situation culminated in 2017-2021 with internationally reported cuts and contingencies: a 44% reduction in the federal science budget in 2017¹²⁶ and, later, a decree that effectively removed around 90% of the resources originally planned for federal science in 2021, triggering worldwide concern about the sustainability of Brazilian

research.^{128,129} The approval of Complementary Law 177/2021, which in principle forbids the contingency of FNDCT resources, was a major political victory for the scientific community, led by organizations such as the Brazilian Society for the Advancement of Science (SBPC) and

the Brazilian Academy of Sciences (ABC).¹³⁰ However, implementation has been gradual and, in some years, partial, with subsequent budget decrees still limiting the effective release of funds.¹³¹

For plasma laboratories, these dynamics have concrete consequences. The freeze of CT-Infra and related infrastructure programs has sharply reduced the capacity to modernize equipment, with national investments in research infrastructure falling by an order of magnitude between 2016 and 2020.¹²⁶ Many tokamak, space-plasma, and advanced materials facilities now rely on life-extension strategies, cannibalization of spare parts, and ad hoc international collaborations to remain operational. Recruitment and retention are equally affected: the contraction of federal university budgets, the instability of CAPES and CNPq scholarship programs, and the scarcity of postdoctoral fellowships have all contributed to both external “brain drain” and an internal diversion of talent away from academic careers.¹³²

The resulting picture is paradoxical. On the one hand, plasma technology, fusion, and nanotechnology have been repeatedly cited in strategic documents and calls for proposals as priority areas for Brazilian industrial innovation and energy transition. On the other hand, the broader erosion of the Science, Technology, and Innovation (STI) system undermines the very human and infrastructural base needed to deliver on these priorities.^{133,134} The resilience demonstrated by the plasma community, through international networking, multi-institutional projects, and partial buffering by some state agencies such as FAPESP, should not obscure the structural vulnerability of large, long-term programs. Without predictable funding and mechanisms for equipment renewal, even well-organized communities risk entering a mode of “maintenance research,” where the main effort is to keep existing facilities alive rather than to explore new frontiers.

Future trajectory: Opportunities in high-value sectors

Despite these constraints, the medium-term prospects for plasma applications are strongly aligned with global technological and market trends. International market analyses indicate that the global cold plasma market was valued at roughly US\$ 2-3 billion in the mid-2020s and is projected to grow at double-digit annual rates, driven by applications in wound care and dermatology, sterilization, food safety, packaging, and surface engineering.^{135,136} In Latin America specifically, the cold-plasma market is expected to grow at > 15% compound annual growth rate (CAGR) toward 2030, reaching on the order of tens of millions of dollars.^{135,136} In parallel, recent roadmaps and reviews highlight NTP and plasma catalysis as key tools for an “electrified” chemical industry, including decentralized ammonia and fertilizer production, CO₂ conversion, and hydrogen generation, all of which are highly relevant to Brazil’s energy and agribusiness sectors.^{137,138}

In this context, Brazilian plasma research is likely to evolve along two partially distinct tracks. The first comprises application-driven subfields with clear routes to value creation, such as CAPs and PALS for medicine, dentistry, food and environmental microbiology, and agriculture, as well as plasma-enhanced processes for advanced coatings, batteries, and semiconductor devices. These areas are well-positioned to attract private partners, participate in global value chains, and align with national strategies for health, food security, and a low-carbon industry. Emerging collaborations with agribusiness, medical-device manufacturers, and aerospace companies suggest that, under the current funding regime, these subfields may consolidate further and form the backbone of a Brazilian “plasma industry.”

The second track consists of long-horizon, capital-intensive domains such as magnetic-confinement fusion, large tokamak upgrades, dedicated space-plasma missions, and some aspects of basic plasma physics. These areas depend more heavily on sustained public investment, international consortia, and stable graduate-training pipelines. In an environment of chronic budget volatility, they are at greater risk of stagnation or of being reduced to small-scale, theory-and-simulation-only efforts. The risk is not merely the loss of specific projects but the erosion of the foundational expertise that underpins more applied innovations: diagnostics, modeling, control, and extreme-condition engineering.

A strategic response to this asymmetry will require mission-oriented programs that integrate both tracks. For example, national initiatives in space weather and space situational awareness, fusion-relevant materials and diagnostics, plasma-enabled green chemistry for fertilizers and fuels, or advanced manufacturing for aerospace and health could couple curiosity-driven research to clearly articulated societal goals. Within such frameworks, the plasma community's existing strengths, multi-institutional collaboration, experience with complex facilities, and a culture of cross-disciplinary work can be leveraged to negotiate more stable funding and to attract younger generations.

In sum, the Brazilian plasma science community stands at a critical juncture. Its historical achievements, organizational maturity, and strong alignment with global trends place it in a promising position. Yet realizing this potential will depend on the country's ability to translate recent legal advances around FNDCT and STI policy into predictable, long-term investment, while fostering mechanisms that connect foundational research to high-value applications. Under such conditions, the community will be able not only to maintain its current activities but also to lead mission-oriented efforts in energy, space, health, and sustainable industry that are of strategic importance for Brazil.

CONCLUSION

The history of plasma science and technology in Brazil exemplifies how a relatively small community, built around a few pioneering centers, can evolve into a mature and diversified ecosystem when it combines scientific ambition with strategic diversification and institutional resilience. From its mid-20th-century origins, catalyzed by figures such as David Bohm, Gabriel Freire, and their Brazilian collaborators, the field was progressively organized around four complementary pillars – controlled fusion, technological plasmas under vacuum and at high temperature, basic plasma phenomena, and space and astrophysical plasmas. Over time, this structure was reinforced by a broad institutional base and is now reflected in a consolidated bibliometric profile, with thousands of plasma-related publications distributed across physics, materials science, engineering, chemistry, space science, and emerging life-science applications.

Over the decades, this architecture has generated a coherent portfolio of achievements that spans the full spectrum from fundamental plasma physics to technology deployment. In vacuum-based systems, Brazil has established a visible role in magnetic-confinement fusion through devices such as TCABR, ETE, and NOVA-UNICAMP, and has used these platforms to address topics ranging from MHD stability and Alfvén-wave physics to edge transport and advanced diagnostics. In space and geospace plasmas, the country has leveraged its equatorial geography and the SAMA to build a globally recognized program in ionospheric irregularities, scintillation, and space weather, culminating in operational frameworks such as EMBRACE that directly support national communication and navigation services. Parallel efforts in technological plasmas have underpinned advances in thin-film deposition, surface engineering, thermal spraying, EP, and microelectronics, while also seeding an entrepreneurial ecosystem in which specialized companies now offer plasma nitriding, diamond and DLC coatings, atmospheric-pressure surface activation, plasma reactors, and plasma-assisted environmental solutions to various industrial sectors.

The most dynamic development of the last 3 decades has been the “atmospheric revolution” in low-temperature plasmas operated at or near ambient pressure, including their interfaces with liquids and biological systems. Brazilian groups have rapidly adopted CAPs and PALs (such as PAW and PAS) for applications in medicine and dentistry, food and environmental microbiology, agriculture, and environmental remediation. These activities range from the design and dosimetric control of CAP sources to the physicochemical and spectroscopic characterization of discharges and liquids, pre-clinical and clinical studies, and the emergence of ANVISA-approved devices for dental and medical use. Pilot-scale demonstrations of PAW in agribusiness and collaborations with industry indicate that these atmospheric-pressure technologies are now moving along credible translational pathways, aligning plasma science with national priorities in health, food security, environmental protection, and low-carbon industry.

At the same time, the community operates under structural constraints that have become particularly acute over the past decade. Chronic volatility in federal science and technology budgets, delayed infrastructure renewal, and the risk of brain drain pose significant challenges, especially for long-horizon, capital-intensive domains such as fusion, large

tokamak upgrades, dedicated space-plasma missions, and basic plasma physics. By contrast, application-driven areas with clearer routes to value creation, such as CAP and PALs for health and agriculture, or plasma-assisted processing for advanced materials and batteries, are relatively better positioned to attract private partners and to integrate into global value chains. This asymmetry underscores a central paradox: a field with demonstrable strategic value for energy, space, health, and sustainability remains vulnerable to short-term funding cycles and underinvestment in foundational research, even as it succeeds in generating near-term technological impact.

Looking ahead, the potential contribution of plasma science and technology to a more sustainable, healthy, and technologically competitive Brazil is substantial. Realizing this potential will require mission-oriented programs that explicitly couple curiosity-driven research to societal challenges in areas such as fusion energy and high-temperature plasmas, space weather and space situational awareness, plasma-enabled decarbonization and green chemistry (including fertilizers and fuels), advanced coatings and functional materials for aerospace and energy, and plasma-based medical and agri-food technologies. It will also depend on predictable, long-term public investment (including the effective implementation of FNDCT and state-level STI policies), coordinated national roadmaps that integrate universities, research institutes, companies, and regulatory bodies, and robust governance of shared facilities, graduate training, and multi-institutional networks under the leadership of organizations such as the SBF. Under such conditions, the Brazilian plasma community is well positioned not only to preserve its existing strengths but to transform its accumulated expertise into enduring scientific, technological, and socioeconomic impact in service of national development and global sustainability.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Pessoa RS, Petraconi Filho G, and Maciel HS; **Methodology:** Pessoa RS, Leite DM, Pereira ALJ, and Sobrinho ASS; **Research:** Pessoa RS, Leite DM, Pereira ALJ, and Sobrinho ASS; **Writing - First draft:** Pessoa RS, Leite DM, and Pereira ALJ; **Writing - Proofreading & Editing:** Pessoa RS, Pereira ALJ, Petraconi Filho G, and Maciel HS; **Funding Acquisition:** Pessoa RS and Petraconi Filho G; **Resources:** Pessoa RS, Petraconi Filho G, and Maciel HS; **Supervision:** Pessoa RS, Pereira ALJ, Leite DM, Sobrinho ASS, Petraconi Filho G, and Maciel HS; **Final approval:** Pessoa RS.

DECLARATION OF USE OF INTELLIGENCE ARTIFICIAL TOOLS

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AVAILABILITY OF DATA AND MATERIALS


The data will be made available upon request.




ETHICAL APPROVAL

Ethical approval was not required for this work, as it did not involve human participants, animals, identifiable personal data, or biological samples. The study relied solely on experimental procedures and analytical methods that do not fall under ethical oversight requirements.

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