Summary of Professional Accomplishments

1. Name

Bruno Cury Camargo

2. Diplomas, degrees conferred in specific areas of science or arts, including the name of the institution which conferred the degree, year of degree conferment, title of the PhD dissertation

2014 – PhD in Natural Sciences. Instituto de Fisica Gleb Wataghin, Universidade Estadual de Campinas – IFGW/UNICAMP (Gleb Wataghin Physics Institute, State University of Campinas). Especialization: Semiconducting physics. Title of dissertation: “Efeitos quanticos em semimetais de Dirac e heterostruturas relacionadas” (quantum phenomena in Dirac semimetals and their heterostructures). Supervisor. Prof. Dr. Yakov Kopelevich.

3. Information on employment in research institutes or faculties/departments or school of arts

2014-2015: Postdoctoral fellow, Faculty of Physics, University of Leipzig (now “Felix-Bloch institute for Solid State Physics”). Leipzig, Germany

2015-2016: Postdoctoral fellow, Laboratoire National des Champs Magnetiques Intenses (National high magnetic field laboratory) – LNCMI Toulouse. Toulouse, France.

2016-2020: Adjunkt (teaching/research post-doc), Institute of Physics Polish Academy of Science – IFPAN. Warsaw, Poland.

From 2021: Adjunkt (teaching/research position), Faculty of Physics, University of Warsaw (FUW). Warsaw, Poland

4. Description of the achievements, set out in art. 219 para 1 point 2 of the Act

The achievements described in this document correspond to a series of publications on **the study of doping and structural disorder effects on the electronic properties of graphite.**

4.1 Series of publications and role played in the work.

[1*] M. Muszynski, I. Antoniazzi, **B. Camargo**, *Ion-beam-milled graphite nanoribbons as mesoscopic carbon-based polarizers*, Appl. Phys Lett (2023)
Role: Designed and planned the work, coordinated the team, prepared the samples, collated the data, wrote the manuscript.

[2*] **B. Camargo**, B. Kerdi, A. Alaferdov, S. Zhuri, M. Birowska, W. Escoffier, *Self-doped graphite nanobelts*, Carbon **207**, 240 (2023).
Role: Designed and planned the work, coordinated the team, prepared the samples, performed electric transport measurements, analyzed the data, wrote the manuscript.

[3*] **B. Camargo**, P. Gierłowski, M. Kuzmiak, R. Jesus, O. Onufriienko, P. Szabó, Y. Kopelevich, *Macroscopic-ranged proximity effect in graphite*, J. Phys: Cond Mat **33**, 495602 (2021).
Role: Planned the work, prepared the samples, coordinated the team, performed electrical transport measurements, interpreted and analyzed the data, wrote the manuscript, procured funding.

[4*] **B. Camargo** and W. Escoffier, *Taming the magnetoresistance anomaly in graphite*, Carbon **139**, 210 (2018).
Role: Planned the work, prepared the samples, performed all measurements, interpreted and analyzed data, wrote the manuscript.

[5] R. Jesus, A. Turatti, **B. Camargo**, R. Silva, Y. Kopelevich, M. Behar, M. Gusmao, P. Pureur, *Electronic Transport and Raman Spectroscopy Characterization in Ion-Implanted Highly Oriented Pyrolytic Graphite*, J. Low Temp. Phys **190**, 141 (2018).
Role: Assisted in the interpretation of quantum oscillation data, in sample preparation, performed electric transport measurements, revised the manuscript.

[6*] **B. Camargo**, R. Jesus, B. Semenenko and C. Precker, *Electrical properties of in-plane implanted graphite nanoribbons*, J. Appl. Phys 122, 244302 (2017).
Role: Planned and executed the work, prepared the samples, performed transport and optical measurements, analyzed the data, modelled the system, wrote the manuscript.

[7] R. Jesus, **B. Camargo**, R. Silva, Y. Kopelevich, M. Behar, M. Gusmao, P. Pureur, *Magneto-transport properties of As-implanted highly oriented pyrolytic graphite*. Phys B: Cond Mat. **118**, 500 (2016).
Role: Assisted in the interpretation of quantum oscillation data, in sample preparation, performed electric transport measurements, revised the manuscript.

[8*] **B. Camargo**, Y. Kopelevich, A. Usher and S. Hubbard, *Effect of structural disorder on quantum oscillations in graphite*, Appl. Phys. Lett. **108**, 031604 (2016).
Role: Planned and executed the work, prepared the samples, performed transport, magnetic, and microscopy measurements, analyzed the data, modelled the system, wrote the manuscript.

* - Applicant is the corresponding author

4.2 – Description of Scientific achievements:

Graphite is an allotrope form of carbon, composed by a large number of stacked graphene layers in a Bernal (ABABAB) structure. Band structure calculations define this material as a highly anisotropic quasi-compensated semimetal, with a Fermi surface composed of cigar-shaped electrons and hole pockets localized along the H-K-H edge of the Brillouin zone [A1].

Despite being a material with a broad technological interest, applications are hindered by the fact that graphite is not a single crystal. This generates a series of inconsistencies in the determination of its physical properties, with outcomes being strongly sample-dependent [8, A2]. For example, reports in the literature over the last 30 years identify different locations for the electron and hole pockets [A4], as well as native charge carrier concentrations spanning over 2 orders of magnitude [A2]. This difficulty partially arises from the absence of a consistent metric to determine what is a good or a bad sample – as subsequent results obtained on the same physical sample are generally reproducible. The problem is similar as the one faced by graphene at its inception: smallest variations in sample manufacturing processes (or the sample itself) have the potential to cause strong variations in the material's electric properties. This is perhaps best exemplified by the breakdown of the graphene into electron- and hole-rich puddles near the charge neutrality point [A3].

In this context, my work aims to understand how to properly assess the electric and magnetic properties of graphite, and how to successfully modulate them *in spite of* disorder. This is a difficult task, which can only be achieved by investigating the behavior of different types of graphite under different conditions, in an attempt to untangle intrinsic responses of the material from those associated with sample quality, disorder, and dopants. The work covers four overlapping topics. They are listed below:

- How to assess sample quality in graphite [2, 5-8],
- How to dope graphite [5-7],
- Controlling electronic phase transitions at high magnetic fields in graphite [2, 4],
- Exploring graphite quirks for the realization of novel devices [1, 3, 6].

In what follows, the section headers are loose indicators of the main contribution of the works being described within. However, section headings are not exclusive (i.e., works in refs [1-8] might be described within a single section, although they pertain to several).

4.2.1 - How to assess sample quality

Quality of graphite is a contentious topic. In general, the ratio of out-of-plane to in-plane resistivity (ρ_c/ρ_a), also thermed the electrical anisotropy, is an accepted parameter to estimate the ordering between graphene layers within a sample [A5, A6]. This parameter varies between 10 to values above 10000, and strongly depends on the kind of graphite considered [A1]. The largest values are observed in synthetic highly oriented pyrolytic graphite (**HOPG**) [A1, A6]. Another method to determine the quality of a graphite crystal is through the determination of its mosaicity, extracted from XRD measurements [A6]. The parameter conventionally used is the width of the rocking curves around the main diffractometry peaks, also termed the "full width at half maximum" (**FWHM**). This parameter directly measures the mosaic spread of a specimen. Synthetic HOPG present the smallest FWHM, which varies between 0.3° for the most anisotropic samples to values above 2° for the least anisotropic ones [8].

Natural and **Kish** graphite are also highly oriented. They are obtained from mining and as a byproduct of steel manufacturing, respectively. These types of graphite can present FWHMs above several degrees, with electrical anisotropy ratios of the order of 10-30 [A7]. Such metrics would rank them as of inferior quality next to their synthetic counterparts. Yet, the study of the physical properties of graphite (and graphene) most frequently favor natural and Kish graphite, which are sometimes mislabeled as "single crystalline". This is more prevalent in studies assessing the *out-of-plane* properties of the material. The justification behind this choice is that sparse "stacking faults" are more common among synthetic HOPG, which would mask the real behavior of its c-axis electrical transport [A7, A8]. However, this argument disregards the fact that HOPG also exhibits a better average stacking order in comparison with Kish and Natural graphite, as denoted from overall smaller mosaicities in XRD measurements.

During my work, I attempt to address this inconsistency by determining which parameter could be best utilized to link electronic and structural properties of graphite, and ultimately be used as a probe for material quality. This topic is addressed in different ways on the works [2, 5, 6, 7, 8].

Reference [8] contains my most substantive contribution to the discussion (the other works are presented below for their other points). In it, a comprehensive study of the Landau quantization regime in graphite with different qualities was carried out. Surprisingly, it was observed that the crystallographic sample quality, estimated from graphite's FWHM, does not correlate with the sample electronic mobility, nor with the material's quantum oscillations (**QO**) amplitude. A particularly striking result was that two synthetic graphite with very similar mosaicities presented markedly different QO amplitudes (ZYB and SPI-I). This showcases that the phenomenon reported was not a mere consequence of a "natural vs. synthetic graphite" dilemma, but rather a more fundamental issue about the characterization of this material.

Assuming a conventional Lifszitz-Kosevich picture for the description of the quantum oscillatory behavior reported, the sample-dependency of the QO amplitudes at a fixed temperature can be traced to variations of the system's Dingle temperature [A9]. This parameter is a measurement of the quantum scattering rate, and represents an "effective temperature" associated with the disorder-broadening of the Landau levels in the sample being probed. What was reported is that the material's roughness seems to better correlate with such a disorder, in lieu of the other conventionally-employed structural parameters. Roughness, however, is not readily obtainable from conventional XRD measurements, even in the (supposedly) highest-quality HOPG available.

The corrugation reported in the samples had characteristic lengths in the scale of hundredths or thousands of nanometers, happening over many unit cells (typical size ~2.5 A). Such a result implies that the broadening of Landau levels in graphite is influenced by features happening at ranges similar or above the material's cyclotronic radius (of approx. 300 nm/T).

Such a result showcases a graphite-graphene correspondence, which becomes increasingly relevant as the community pivots away from graphene, back towards its three-dimensional counterpart – motivated by the study of graphite blocks [A10] and twisted multilayered structures [A11]. Corrugations were already known to play an important role in single-layer graphene, acting as long-range scattering centers [A12]. The determination of the same behavior in **<u>bulk graphite</u>** is key in order to assess sample quality in larger flakes and in the new breed of devices with bulk-boundary features [A10]. The latter are not expected to be affected by interactions with substrate as harshly as their single-layered cousins due to **<u>screening effects</u>**. Yet, results in ref. [8] show that this is only partially true, with substrate morphology still remaining of uttermost importance. This observation is paramount for the application of the material in any technological applications associated with the quantum mechanical nature of charge carriers (e.g. spintronics or valleytronics).

Besides the obvious implication that conventional structural parameters are not necessarily useful in categorizing graphite, the main message from ref. [8] is **<u>that the lack of consistent and simple methods for assessing sample quality does not permit – at present – a proper comparison between two different graphite crystals, even if they share, technically, the same gradation</u>**. This is extremely important when comparing different types (or samples) of the material for their, e.g., in- and out-of-plane properties. To avoid any possible pitfalls, a proper investigation must address properties on <u>the same sample</u>, either by an ingenious experimental setup (e.g. unusual contact geometry), or through a modulation of the sample properties by an external factor.

4.2.2 - Control of the charge carrier concentration in bulk graphite

Although being a decisive factor in the determination of the quantum scattering rate, surface corrugation is not the only parameter to be wary of when characterizing disorder in graphite. I demonstrate this in refs. [5, 6, 7], through an attempt to modulate the electronic properties of bulk graphite with ionic doping. The thesis that was tested in these works was: If graphite is a monoatomic semimetal, it should be subjected to the same doping mechanisms routinely employed in the semiconducting industry.

Indeed, the implantation of neutrons in graphite is expected to introduce vacancies in the lattice, which trap electrons and dope the material with holes [A13]. However, from a quantum oscillatory behavioral standpoint, such a property is less well-established. A doubling of the charge carrier concentration in the material, for example, would require a doubling of the QO frequency, as well as its survival to magnetic fields twice as high. This is not observed in the original work of neutron implantation in graphite, neither assessed in subsequent investigations (see [A13] and references therein). In this aspect, a different route was employed during my research: to introduce doping in the material with ionic implantation, and track its effects by probing the evolution in the Landau quantization regime in Rxx an Rxy measurements. My activities, documented in [5, 7], demonstrate clearly that the introduction of ions in graphite along its c-axis does not modify the QO frequency, regardless of the type and fluence of the implanted elements. However, modifications in Hall and magnetoresistance curves are clearly observed. Because the frequencies of the quantum oscillatory behavior provide a direct measurement of the charge carrier concentration in the material, the changes reported in Rxx an Rxy can be attributed to a modulation of the relative mobility between electrons and holes. In this case, the main role of the implantation carried in graphite is to introduce disorder in the material, with a negligible effect on moving its Fermi level or altering graphite’s Fermi surface.

An alternative to avoid such a disorder could be to implant ions parallel to the planes of graphene composing graphite. In this orientation, the vast channels generated by graphite’s layered structure would act as pathways for the ions, easing their penetration in the material and reducing the amount of disorder introduced - a phenomenon termed “ionic channeling”. This was the approach chosen in my work on ref. [6]. There, it was demonstrated, for the first time, the effect of in-plane ionic implantation over the electric properties of graphite microstructures. For this, mesoscopic graphite nanoribbons were fabricated with an ion-beam-milling technique. Samples had an unusual geometry, seldom found in the literature. Namely, ribbons possessed heights (their dimension along the stacking direction) larger than their width (measured along the in-plane direction). This permitted an easy bombardment of ions perpendicular to the ribbon’s c-axis, with devices having their electric properties probed after subsequential implantations performed **in the same sample.** Such an approach bypassed problems associated to sample-dependency, as it forfeited the comparison between different objects (in-line with the conclusions previously drafted in ref. [8]).

Interestingly, the ionic implantation along planes caused a dramatic, yet consistent, decrease on graphite’s resistivity - over an order of magnitude, depending on the dose. This result is in strong contrast to my other attempts reported in refs. [5, 7], which were done parallel the sample’s c-axis and yielded a negligible variation of the zero-field sample resistivity on subsequent implantations. Results for the nanoribbons [6] are reasonably well-explained by the Drude model, under the assumption that implantation both includes interstitial ions in the region between the layers, as well as generates a progressive amorphization of the sample due to stray ions breaking in-plane bonds [6]. Unfortunately, the sample geometry (which would be later used in ref. [1] for graphite-based polarizers) did not allow for a proper assessment of other material parameters, such as the Hall effect or quantum oscillations. The sample placement atop a flat substrate, with the c-axis pointing along the surface of the latter, prevented quantizing magnetic fields to be applied, or the electric connection of the device in a Hall bar configuration.

Despite the demonstration that ionic implantation can be employed as a tool to control the magnetoresistance or resistivity of graphite, either through the modulation of disorder [5, 7], or through doping [6], this technique is limited in the fact that, once prepared, a device cannot be easily tuned. An alternative is to control the charge carrier concentration in the material in-situ through the electrostatic doping of thin flakes. Such a method has the added benefit to avoid sample variability due to disorder, and is routinely employed – to great success - in graphene and multilayer graphene samples. In graphite, said approach has been already shown to influence the material's quantum oscillatory regime [A14], although less effectively than in graphene due to a strong interlayer screening caused by graphite's semimetallic nature.

4.2.3 - Controlling electronic phase transitions at high magnetic fields

With this knowledge, my experiments in ref. [4] constitute the first employment of an electrostatic-doped graphite sample to study the electronic phase transitions induced in the material by magnetic fields deep in the quantum limit. Such transitions are a fingerprint of bulk graphite, first reported in the 1980's, and manifest as a high resistance state (HRS) in RxB measurements for B > 35 T. Although the phenomenon's true nature remains a point of debate, all theoretical modelling on the topic describes the microscopic origin of the HRS as a Fermi surface instability along graphite's c-axis, triggered by a 3D-to-1D dimensional crossover when only the lowest Landau level is occupied and the Zeeman degeneracy is lifted [A15 – A17]. However, the experimental determination of its exclusive out-of-plane character remains elusive. Because the HRS is observed both in graphite's in-plane and out-of-plane resistivity, most experiments dedicated to its exploration attempt to correlate measurements performed in different geometries on **different specimens.** As demonstrated in ref. [8], however, this comparison is debatable – at best – due to graphite not being a single crystal. With the sole exception of soundwave propagation measurements [A16], no demonstration of the 3D (or the in+off-plane) character of the HRS had been performed to date.

My work in ref. [4] contributed to this discussion by demonstrating two characteristics of the HRS which had been, surprisingly, hitherto unaccounted for:

(i) I have demonstrated that the phenomenon is suppressed in samples between 4 nm and 10 nm thick. This consolidates the field-induced HRS in graphite as a bulk effect (rather than purely 2D), and experimentally establishes 4 nm as the lower-bound thickness limit for its observation in multilayer graphene devices (samples must be at least 4nm thick).

(ii) I demonstrated that the HRS can certainly be modulated through the application of gate voltages in thin graphite flakes.

The result (ii) is an extremely surprising outcome, if the conventional characteristics of graphite are considered. Graphite exhibits an interlayer screening length of ~1 nm [A14]. Therefore, the modulation of its HRS by gate voltages (point (ii)) is inconsistent with a 3D bulk phenomenon occurring over lengths above 4 nm in the c-axis direction (point (i)). Results (i) and (ii), can be conciliated either if (a) the interlayer screening length in graphite is larger than expected, or if (b) there is a large in-plane contribution to the HRS. In both scenarios, the co-existence of the HRS and Shubnikov-de-Haas QO with frequencies above 40 T require the HRS to be triggered outside the quantum limit, thus being at odds with the current understanding of the phenomenon [A8, A14 - A17].

In ref. [4], I concluded that (b) was the most likely scenario at play. This hypothesis is now supported by more recent results obtained by colleagues in the field, such as speed of sound and specific heat measurements performed by D. LeBoeuf [A16] and C. Macenat [A17]. In this context, a new (2023) work by C. Mullan [A18] et al. might hold the key to clarifying my observations from 2018 [4]: In their work, it was theorized that finite-size-effects in thin graphite flakes in the Landau quantization regime can lead to electronic standing waves along graphite's c-axis, which are not pinned in the x-y direction. In light of this information, the modulation of the HRS observed in my work [4] can be re-interpreted as a change of the in-plane dynamics of such stationary waves by a surface potential landscape introduced by the application of gate voltages, thus providing a microscopic justification for the HRS 's in-plane character reported by me [4].

Although exciting, the mechanism outlined above is of difficult verification with the experimental techniques available to date. To that extent, one way to bypass discussions or interpretations surrounding the role of a surface potential landscape [A18] or screening [A14] in my graphite flakes of ref. [4] would be to achieve homogeneously-doped samples which, contrary to those obtained in refs. [5, 6, 7], remain in the Landau quantization regime at magnetic fields in excess of 7 T. This is the approach recently taken by me in ref. [2]. In it, a partnership with A. Alaferdov, from UNICAMP, yielded novel graphite samples, obtained from a vigorous mechanical treatment of bulk flakes followed by a flash annealing at 3000 ^{o}C for few seconds.

Upon investigating the magnetoresistive behavior of this material at high magnetic fields, I reported the occurrence of quantum oscillations with frequencies around 85 T [2]. This value is much larger than those conventionally found in graphite, which reside in the range of 4 T -7 T [A4]. On closer inspection, such a novel oscillatory behavior could be attributed to a new group of charge carriers in graphite, with native concentration about 10 times that of the pristine material. The characterization of the sample structural parameters allowed a tentative attribution of such carriers to self-doping caused by defects introduced during the mechanical treatment [2].

Surprisingly, samples containing such a carrier group still exhibited the HRS, at the same field and temperature range as the one reported for pristine graphite [2, 4]. This demonstrates the possibility of triggering of the HRS in bulk graphite outside the quantum limit. Such a demonstration is paramount, as it reinforces that the electronic instability is not exclusive to the lowest Landau bands, corroborating the earlier results reported by me in ref. [4]. Besides a relevant addition to the literature surrounding the HRS, my contribution is also of fundamental importance for applications: The demonstration of a disorder-induced group of charge carriers in graphite microstructures provides a simple, yet effective, method to tune the properties of graphite ribbons for use as sensors or interconnecting elements in real devices.

4.2.4 - Exploring graphite properties through the realization of devices

Over the course of studying the electronic properties of graphite, I have employed unusual geometries and sample configurations. These constitute devices that could, in principle, be used in the semiconducting industry, or as probes to further the knowledge about graphite.

One of such unusual geometries, presented in refs. [1] and [6], has been labelled "graphite nanoribbons". These are blocks of graphite with submicrometric lateral size and several micrometers of thickness. They are deposited atop substrates, with the material's c-axis along the substrate surface (perpendicular to the normal direction). In ref. [6], I investigated them for their potential as graphite interconnecting agents with hard-tuned charge carrier concentrations - sec. 4.2.2. However, I later realized that this geometry could allow for studies, as well as applications, aiming at the natural anisotropy of graphite.

Such is the case of my work in ref. [1]. In it, I explored the optical properties of graphite perpendicular to the c-axis direction. Historically, access to these have been achieved by mechanicallypolishing the edges of bulk samples [A20, A21]. However, this invariably causes graphene planes and graphite blocks to bend over, yielding off-plane measurements which are “poisoned” by large in-plane contributions. In ref. [1], I bypassed this problem by utilizing graphite blocks with sides polished through ion-beam milling: the same type of sample used previously in ref. [6]. This novel approach allowed me to demonstrate the possibility of harnessing the anisotropy of graphite for the construction of all-carbon-based optical polarizers, 100% compatible with current graphene-based technology. Simultaneously, my measurements allowed for a verification of previous Raman spectra obtained in graphite along the stacking direction [A20, A21] -but now unhindered by the limitations associated with the mechanical polishing.

Finally, in ref. [3], I explored the possibility of superconductivity in graphite-based devices. The discussion surrounding the topic is not new, dating back from the 1970’s [A22]. However, in all reports, the phenomenon is described as an elusive property of graphite, either hidden in the regions of small puddles, or in the form of a phase-decoherent superconducting gas [A23]. In ref. [3], I attempted to address this point by exploring the superconducting proximity effect. The thesis was: if graphite is indeed a phase-fluctuating superconductor, or a set of weakly-coupled superconducting islands, then the presence of an external superconductor in close proximity to the system might trigger a macroscopic response in the material. Results indeed did reveal that the use of superconducting electrodes for current injection affected the electric properties of bulk graphite, with signatures of induced superconductivity persisting over distances in excess of 1 mm from where the superconducting electrodes were placed.

My results in ref. [3] become more interesting and increasingly more relevant in the context of twistronics. It is now known that twisted multiplayer graphenes do exhibit superconductivity, generated by electronic instabilities caused by band flattening. The latter is a result of superlattices introduced by periodic mismatches between top and bottom layers [A25]. The same thing occurs in bulk layered materials, although the regions subjected to such potentials are spread, at random, throughout the bulk of the material. In this context, our results suggest that it is possible to harness the phenomenon seen in (quasi) 2D crystals in 3D systems as well, through a proper design of device geometry. The added advantage of this method is the lesser susceptibility of bulk systems to environmental conditions, caused by their smaller surface/volume ratio in comparison with purely 2D crystals.

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5. Presentation of significant scientific or artistic activity carried out at more than one university, scientific or cultural institution, especially at foreign institutions

<u>**Internship at Faculty of Physics, University of Leipzig (14 months)**</u>

After receiving my PhD in 2014, I was awarded a grant covering a 14-month internship at the Faculty of Physics, University of Leipzig (Germany). There, I joined the group of Superconductivity and Magnetism, headed by Prof. Dr. Pablo Esquinazi (PE). My personal objectives, at the time, were two-fold: To acquire experience with microfabrication techniques, and to explore the possibility of superconductivity in graphite nano-tapes. The latter was an active research field of PE.

To achieve my goals, I was tasked with obtaining mesoscopic graphite samples in unusual geometries, to explore the role of stacking disorder on their electrical and magnetic properties (through electrical transport and magnetic measurements), and to implement instrumentation for magnetometry.

Over the course of my stay, I did successfully designed and implement a vibrating reed and a torque magnetometer, which were used for experiments in tandem with SQUID magnetometry, conventional electric magnetotransport measurements, and atomic force microscopy. I was also successful in fabricating graphite samples in thin-film and thin-ribbon configurations, by employing my recently-learned electronic lithography and focused-ion-beam techniques.

The internship realized in the university of Leipzig was a fundamental experience, as it equipped me with the professional skillset necessary to fabricate the samples that I would use later in my career (e.g. in refs. [1, 2, 4, 5, 6, 7]). Unfortunately, one of my main goals - the verification of superconductivity on the fabricated structures – remained unachieved. However, results obtained over the internship were redeployed towards the study of the effect disorder and the of ionic implantation in graphite (sec. 4.2.1 and 4.2.2), both in the direction parallel, as well as perpendicular to graphite planes. This resulted (either directly or indirectly) in publications in the journals J. Appl. Phys, Appl. Phys Lett. and J. Low Temp. Phys.

<u>**Internship at National Laboratory of High Magnetic Fields in Toulouse, France (12 months)**</u>

After completing my research at the university of Leipzig, I joined the group NANO at the National Laboratory for High Magnetic Fields (LNCMI) in Toulouse (France). My work at the institution occurred in close collaboration with Dr. Walter Escoffier (WE), and revolved around the the fabrication and electronic characterization of soft-chemistry-grown nano-objects with high crystallinity. Namely, I studied the electric properties of single-crystalline platinum nanostars at magnetic fields up to 90 T. To achieve this objective, I had to implement the clean-room procedures necessary for their electrical contacting, in a newly-established facility for sample processing.

During my stay in France, I also kept previous collaborations and used the available facilities to advance my research about graphite. At the time, I performed my first magnetotransport measurements on thin graphite layers at high magnetic fields. These samples are of utmost importance to the understanding of magnetic-field-induced electronic phase transitions in graphite, as they are thin films that behave as bulk graphite, but can have their charge carrier concentration modulated through back- and top-gating (as well as implantation).

The research developed in LNCMI was very successful, resulting in the establishment of the clean-room processes necessary for any future preparation of few-layered systems and submicrometric objects. Results in Pt nanostars yielded devices acting as nanometric frequency multipliers, as reported in in the journal *Nanoscale* [Nanoscale 9, 14635 (2017)]. Meanwhile, the study of the electrical properties of graphite created the foundations for a longstanding collaboration that so far has led to two works published in the journal *Carbon* (sec. 4.2.3).

Internship at Institute of Physics, Polish Academy of Sciences (48 months)

My stay in France ended in October 2017, after which I relocated to Warsaw, Poland. There, I joined the group of Prof. Dr. Marta Z. Cieplak (MC) at the Institute of Physics, Polish Academy of Sciences (IFPAN). My task, as a post-doc, was to implement a microwave impedance spectroscopy setup in direct collaboration with Dr. Piotr Gierlowski (from the same group). The end-goal was to measure the London penetration depth in iron-based superconductors as a function of disorder induced via electron bombardment.

During the course of my work, I also used the installations of IFPAN to continue my research on the electric and magnetic properties of graphite and other high-mobile quasi-compensated semimetals, such as bismuth. For that, I employed the electric transport instrumentation existent at the group of MC to perform measurements of superconductor-graphite and superconductor-Bi heterostructures, and to characterize samples that would be later used for measurements with WE, with whom I kept contact after the end of my internship at LNCMI.

My work at IFPAN was rather successful. The results on microwave impedance spectroscopy were particularly challenging, and lead to interesting results demonstrating the thermally-induced healing of superconducting properties of $Ba_{0.5}K_{0.4}Fe_2As_2$, as recently reported on [Physica C, DOI 10.1016/j.physc.2023.1354347]. Works in graphite and bismuth have led to publications in J. Appl. Phys, J. Phys. Cond. Mat. and in J. of Magnetism and Magnetic Materials (partially described in sec. 4.2.3).

6. Presentation of teaching and organizational achievements as well as achievements in popularization of science or art

Teaching

Before Phd:

- Laboratory of electromagnetism (Laboratory classes)
- Laboratory of mechanics (Laboratory classes)
- Introduction to general physics (Exercise classes)
- Electromagnetism (Exercise classes)

After PhD:

- Physics of Carbon (Lecturer)
- Dirac equation in condensed matter (Lecturer)

- Fundamental of Physics II (Electricity and Magnetism) (Assistant)
- Physics laboratory for Nanoengineering (Laboratory classes)
- Electrodynamics (Exercise classes)
- Laboratory of electronics (Laboratory classes)
- Quantum Mechanics (Exercise classes)
- Solid state laboratory classes – Optics (Laboratory classes)
- Vacuum and Cryogenics (Lecturer)

Popularization of Science

- Participation on the European researcher's night (Nuit Europeene des Chercheurs) on 2016 (Toulouse, France)
- Participation on the Warsaw Picnic of Science (Piknik Naukowe), years 2018 and 2019 (Warsaw Poland).
- Faculty of Physics, University of Warsaw, Summer school of Physics (Szkola Letnia Fizyka), years 2022 and 2023 (Warsaw, Poland).

Organization contribution

- Organizing committee of XIX Polish National conference of superconductivity (Poland, 2019).

7. Apart from information set out in 1-6 above, the applicant may include other information about his/her professional career, which he/she deems important.

Awarded grants as PI

- 2014-2015 *The secrets of Dirac semimetals* (Agency: Brazilian National Scientific Council - CNPq),
- 2015-2016 *Unveiling the fundamental electronic properties of nano-objects in strong magnetic fields*. (Agency: Campus France)
- 2018-2021: *Unveiling the nature of electronic phase transitions in Dirac systems* (Polish National Science Foundation – NCN/POLONEZ).

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(Applicant's signature)