Master thesis proposal

[NT-Race]

Keywords : carbon nanotubes, growth kinetics, videos, AI analysis, AI recognition, AI tracking

SCIENTIFIC DESCRIPTION :

Carbon nanotubes (CNTs) are quasi-one-dimensional tubular crystals composed of sp^2-hybridized carbon. Their exceptional electronic, optical, and mechanical properties make them prime candidates for next-generation devices. Nevertheless, their scalable deployment is currently hindered by limited understanding of their growth kinetics and structural dependencies. Addressing these challenges requires **high-throughput experimental approaches**, **advanced imaging**, and **automated data processing**.

This project proposes to accelerate the kinetics study of single-walled CNT (SWCNT) growth via a tandem of **high-throughput characterization**, **computer vision**, and **AI-driven data analysis**.

It brings together two complementary teams: the **Physics of Nanomaterials and Field Emission group (PNEC)** from Institute Lumiere Matiere (ILM) of Université Claude Bernard Lyon 1, and the **Charles Coulomb Laboratory (L2C)** from Université de Montpellier. Both are engaged in high-throughput studies of SWCNT growth using advanced microscopy. This new collaboration promises to enhance **automation**, reduce manual processing, expand dataset volume, boost **reproducibility**, and compress analysis cycles via **AI-augmented extraction of kinetic data**.

The PNEC team investigates **field-directed SWCNT growth via Environmental Transmission Electron Microscopy (ETEM)**. Custom TEM-compatible silicon chips with dual cantilevers—one heated via Joule effect, the other acting as a biasing electrode—facilitate CNT alignment and growth monitoring through **high-throughput microscopic imaging** (Fig. 1a–b, c–d). The recorded videos are converted into **kymographs** (space–time plots), where growth rates emerge as slopes (Fig. 1e–g). Videos often contain tens to hundreds of CNTs, many exhibiting complex, overlapping, or nonlinear kinetics (Fig. 1h–i), making manual extraction slow and prone to errors.

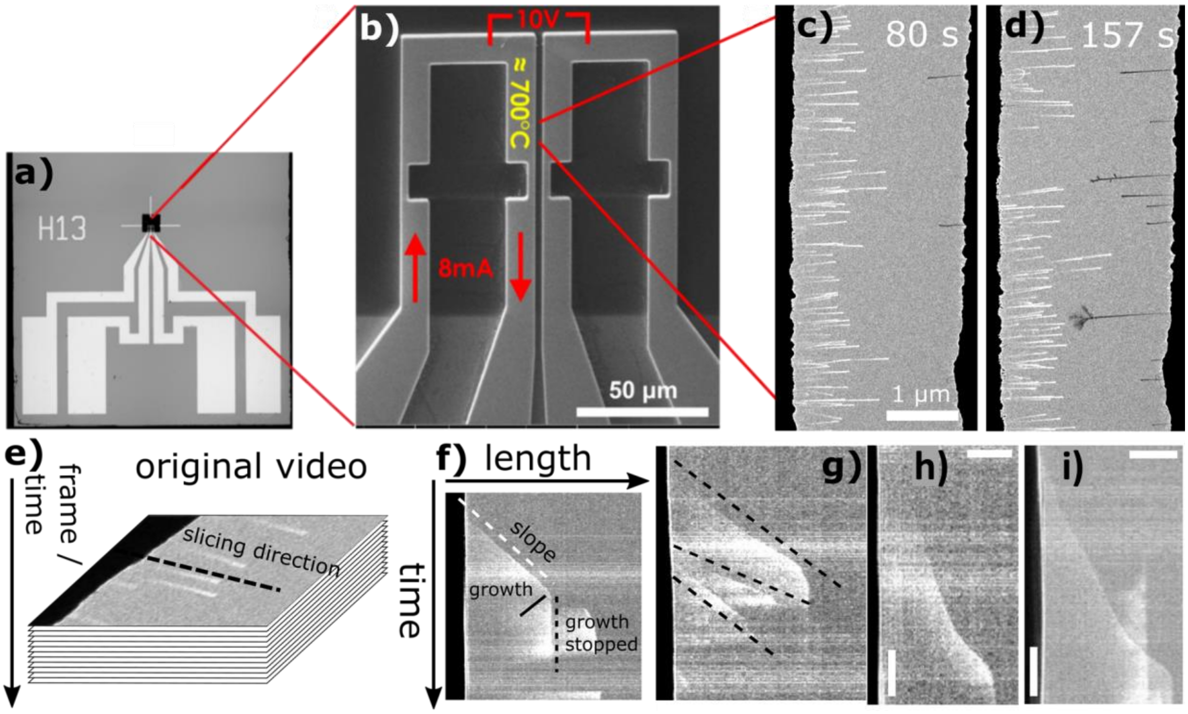

Figure 1. (a) SEM image of a TEM-compatible chip used for CNT synthesis. (b) Close-up of the cantilever region. (c, d) Frames from a typical CNT growth video. (e) Schematic illustration of video-to-kymograph conversion, transforming spatial (X, Y) and temporal (T) coordinates into nanotube length (L) vs. time (T). (f, g) Examples of simple linear CNT growth kymographs. (h, i) Examples of complex kymographs showing overlapping signals and nonlinear CNT growth. In (f - i), slopes correspond to growth, while vertical segments indicate termination.

The **L2C** studies CNT growth at atmospheric pressure on quartz substrates using **in-situ Homodyne Polarization Microscopy (HPM)**. This technique exploits the strong optical anisotropy of CNTs to separate their weak scattering signal from the much stronger substrate reflection (Fig. 2a). Combined with advanced image processing, this method captures both CNT growth and structural transformations (Fig. 2b–d) in **large-volume datasets**. These videos can also be represented as kymographs (Fig. 2e–f). The high CNT density in the videos, coupled with complex contrast variations, makes manual analysis even more challenging than in ETEM data.

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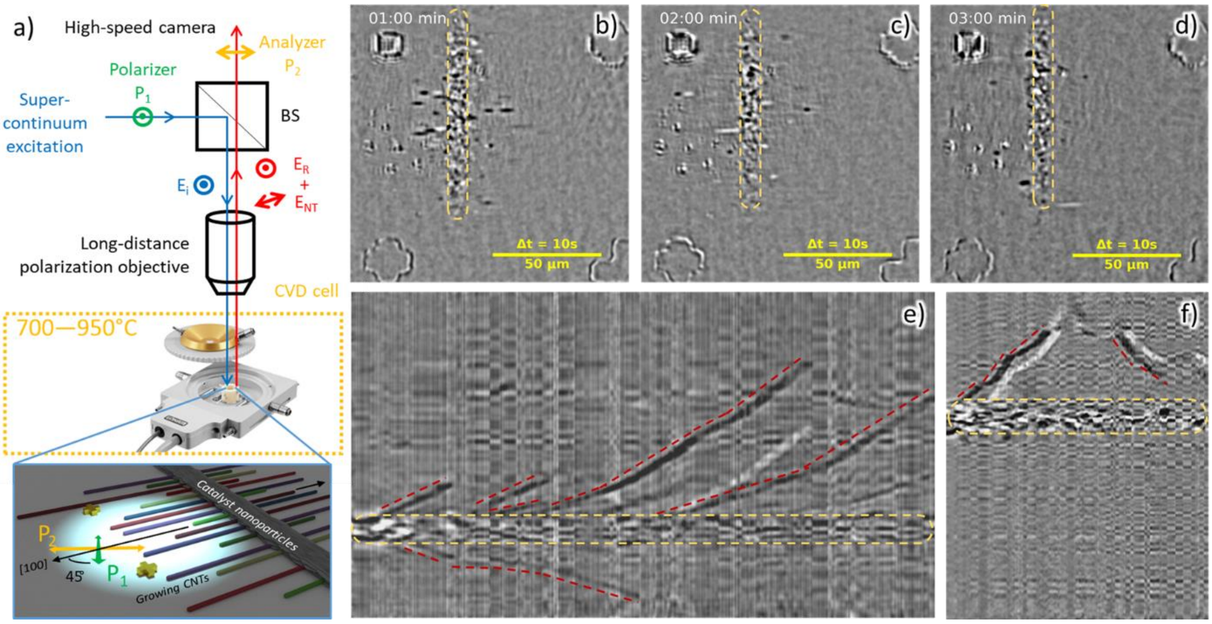

Figure 2. (a) Schematic of the Homodyne Polarization Microscopy setup. A supercontinuum light source excites CNTs across the visible spectrum, while crossed polarizers isolate CNT signals at 45° to the substrate reflection. (b–d) Snapshots from in-situ videos after differential processing. The thick yellow vertical line marks the catalyst region; horizontal dark segments correspond to CNT growth, while bright features indicate structural transformations. (e, f) Kymographs illustrating complex kinetics: (e) multiple growth regime transitions; (f) alternating growth and etching. Red dashed lines highlight extracted kinetic curves.

Overall, this project focuses on developing an AI-assisted recognition and kinetic extraction framework to transition from manual analysis to high-throughput, reproducible, and efficient statistical processing. Beyond simply accelerating workflows, the goal is to design a universal system capable of handling data from two complementary in-situ approaches: ETEM, providing atomic-scale resolution under controlled environments, and HPM, enabling high-throughput optical observation at ambient conditions. Developing a tool that can robustly process kymographs from both techniques requires combining expertise from the two research teams. The collaboration between PNEC and L2C is thus essential: it ensures access to diverse data types, broadens the statistical significance of results, and guarantees that the resulting framework will not be tailored to a single experiment, but rather generalized across multiple imaging modalities. This integrative approach will create a versatile, scalable tool, strengthening reproducibility and accelerating the extraction of quantitative insights into carbon nanotube growth.

Techniques/methods in use: short description

Using the Python programming language, we will develop a computer vision model to accelerate recognition and kinetic extraction from both HPM and ETEM videos. The system will be based on a **Mask R-CNN architecture** with ResNet backbones, trained to track kinetic curves in kymographs with varying contrast, brightness, and noise levels.

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The training strategy includes two steps:

1. **Pre-training** ResNet classifiers (ResNet-18, ResNet-34, and ResNet-50) on artificial kymograph datasets generated from real video data.
2. **Fine-tuning** the Mask R-CNN with these backbones on manually annotated real kymographs.

This two-stage approach ensures robust recognition of diverse kymograph types. Artificial data reduces preparation time by minimizing manual annotation, the most time-consuming step. Furthermore, models of different complexity (ResNet-18 vs. ResNet-50) provide flexibility: lightweight models for laptops with gaming GPUs, and more powerful models for dedicated high-performance workstations.

Budget description and use: how will the grant be spent

5 kE – trainee salary (830 EUR per month for 6-month internship)

Applicant skills:

Proficiency in Python (numpy, matplotlib, PyTorch, PIL, pandas)

Interest in computer vision and artificial intelligence

Optional: knowledge of CNT growth processes and properties

Industrial partnership: No

Internship supervisors:

P.I. Vladimir PIMONOV, postdoctoral researcher, ILM, **vladimir.pimonov@univ-lyon1.fr**

Expert in **carbon nanotube growth kinetics**, **advanced microscopy (ETEM, HPM)**, and **AI-based image analysis**. Skilled in developing **computer vision and deep learning models (Mask R-CNN, ResNet)** for automated recognition and kinetic data extraction. Combines strong background in **nanomaterials science** with proficiency in **Python programming, data processing, and high-throughput analysis**, ensuring robust and reproducible results.

Ref.: - **Pimonov V.**, Tahir S., **Jourdain V.** (2025). Deep-learning recognition and tracking of individual nanotubes in low-contrast microscopy videos. BJNano. 2025, 16, https://www.beilstein-journals.org/bjnano/articles/16/96

Vincent JOURDAIN, Pr L2C, vincent.jourdain@umontpellier.fr

Expert in ***in situ* optical studies of carbon nanotube growth**. He led the ANR-funded DARWIN project on boosting the chiral selectivity of carbon nanotubes by directed evolution.

Ref.: - **Pimonov V.**, Tran H.-N., Monniello L., Tahir S., Michel T., Podor R., Odorico M., Bichara C., **Jourdain V**. (2021). Dynamic instability of individual carbon nanotube growth revealed by in situ homodyne polarization microscopy. Nano Letters. https://pubs.acs.org/doi/10.1021/acs.nanolett.1c03431

- Förster G. D., **Pimonov V.**, Tran H.-N., Tahir S., **Jourdain V.**, Bichara C. (2023). Swinging Crystal Edge of Growing Carbon Nanotubes. ACS Nano, 17(8):7135-7144. https://pubs.acs.org/doi/10.1021/acsnano.2c07388

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Expert in **field-directed growth of carbon nanotubes under ETEM**, **field emission analysis**, and **nanomechanical characterization**. He leads the ANR-funded SOLITUBE project on ETEM growth of carbon nanotubes. His notable contributions include pioneering **in situ imaging** and **kinetic studies** of CNT growth under electric fields, supported by a strong publication record in nanomaterials and electron emission mechanisms.

ref : - **P. Vincent** et al., « Observations of the synthesis of straight single wall carbon nanotubes directed by electric fields in an Environmental Transmission Electron Microscope", Carbon, 213, 118272, 2023 https://doi.org/10.1016/j.carbon.2023.118272

P. Vincent et al, "Field emission characterization of field aligned carbon nanotubes synthesized in an environmental transmission electron microscope", J. Vac. Sci.Technol. B, 42, 022802, 2024 https://doi.org/10.1116/6.0003413

V. Pimonov et al., "Electric fields, forces and modification of the tunnel barrier during field electron emission and field evaporation from single-wall carbon nanotubes", J. Vac. Sci.Technol. B, 43, 043202, 2025 https://doi.org/10.1116/6.0004707

Internship location : Institute and location

Institut Lumière Matière, Lyon

Possibility for a Doctoral thesis: Yes, depending on the profile of trainee, the project may lay the foundation to a PhD supported by the Doctoral School