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Constructing Electron Microscope Labs: Challenges and Solutions

Limei Cha[1*], Markus Walkling-Ribeiro[2], Zhenxi Guo[3], Yaron Kauffman[4], Constance Van Horne[5*]

[1]Department of Materials Science and Engineering, Guangdong-Technion Israel Institute of Technology, Shantou, China
[2]Department of Food Science, University of Copenhagen, Copenhagen, Denmark
[3]School of Life Science and Cryo EM core facility, Beijing University, Beijing, China
[4]Department of Materials Science and Engineering, Technion Israel Institute of Technology, Haifa, Israel
[5]Abu Dhabi School of Management, Abu Dhabi, United Arab Emirates
Email: *cha.limei@gtiit.edu.cn, researchmwr@outlook.com, guozhenxi@pku.edu.cn, mtyaron@tx.technion.ac.il, *c.horne@adsm.ac.ae

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Abstract

The construction of advanced laboratories for precision instruments, such as electron microscopes, involves unique challenges that are influenced by the specific environmental conditions required for optimal functionality. These include mitigating interference from magnetic fields and vibrations, which are critical for maintaining the precision and accuracy of the instruments used. This study aims to offer enhanced project management strategies and detailed construction solutions that address the environmental and technical needs specific to electron microscopy labs, thereby facilitating effective lab operations and extending the lifecycle of high-end precision instruments. Case studies of existing laboratory constructions, onsite investigations, and comprehensive reviews of the technical and environmental requirements provide the basis for a best practice for constructing sophisticated electron microscopy labs. The approach integrates both pre-construction planning and post-construction adjustments to create optimal operational environments. The findings suggest that successful lab constructions are those that incorporate thorough onsite assessments, strategic location choices, and the use of advanced construction materials and techniques specifically designed to counteract environmental challenges like magnetic and vibration interferences. Actionable guidelines for both planning and executing the construction of electron microscope labs highlighted in this tutorial are intended as an important resource to troubleshoot or upgrade existing lab facilities and to consult in preparation of future lab construction projects.

Keywords

Laboratory Construction, Development Strategies, Management, Case Study, Electron Microscope, Magnetic Shielding, Vibration

1. Introduction

With rapid technological progress in science and technology, large scientific instruments and/or united instruments play an increasingly important role for advanced experiments that are used to explore new areas of research and to discover previously unknown scientific phenomena. For example, aside from conventional electron microscopes (EMs) [1], cryo-EMs have led to the visualization of various bimolecular structures [2], and atto-second pulses of light have assisted in the study of electron dynamics in matter [3]. However, using these instruments effectively depends not only on their configuration and quality, but also on the physical workplace environment, both within the lab and the surrounding labs, building (s) and grounds.

In comparison to more common and smaller instruments, which require much less exacting conditions to function properly, the physical environment of larger sized, precision and advanced instruments is a critical factor. For instance, it has been reported that some high-end electron microscope (EM) labs have had to be moved and relocated due to the vibration caused by newly built, nearby subways [4] [5]. Particularly, in the design and construction phases of advanced laboratories for high-level instruments, developing and implementing a well-considered strategy before and during construction can conserve energy, materials, and human resources. Preparing for unforeseen issues is also crucial. Additionally, preplanning and learning from past projects can prevent redundancy in efforts. This approach is vital for universities committed to sustainable development.

In research that looks into architecture, construction, and environmental, health, and safety (EHS) standards, many scholars have concentrated on optimizing the layout of standard laboratories. Their focus areas include efficiently arranging tables and desks to maximize space, designing the routing systems for electricity, water, gas, and data networks from their sources to the points where they are needed, and creating ventilation systems that effectively circulate air [6]-[9]. These studies also examine the configuration of corridors that delineate work areas and provide access to emergency exits [9]. Construction experience and research from standard laboratories can be informative for advanced laboratories in many cases and valuable handbooks have been published [6]. However, less research has focused on the specific technical requirements for designing state-of-the-art laboratories, such as those equipped with precision EMs [10]-[14] and synchrotrons [15]. In a similar way with standard lab construction, core considerations, such as lab layout, the routing of energy and water cables and pipes, ventilation systems, EHS supplies etc., need to be considered in the lab construction for precision instruments. However, there are additional considerations that must be planned for successful and sustainable set-up and use of these advanced labs such as vibration and magnetic fields, which must be controlled for many EMs.

From the perspective of investors and supervisors of these projects, literature has predominantly concentrated on the progress of the project, and the efficiency of resources employed in the project – including both human resources and funding. In fact, there is a comprehensive body of literature and reports on "normal" laboratory construction. These documents detail the appropriate methods for dividing required work into distinct processes and stages, setting up cross-unit working groups and committees, and leading projects efficiently. Another crucial aspect to consider is the soft skills necessary for managing such projects, including project management, teamwork, communication, collaboration, and creative problem-solving [16]-[22].

In fact, both technical skills and management/soft skills are needed to successfully plan, design, lead, and finish a lab construction project. However, few articles on lab construction combine the key points from both engineering and management perspectives together.

Each advanced precision instrument has its own unique settings established by the manufacturer and consequently, each instrument has its own special requirements for laboratory design and location. The iterative design and construction process of the lab between key actors requires care and diligence. However, there is a gap in the literature to guide scientists in these important processes.

Using a case study of a recent lab construction, and the existing literature three main lessons were extracted in this tutorial. One, the fundamental points in lab construction for precision instruments, which can be adapted and applied on varied cases; two, a summary of problems-solution for advanced electron microscope lab construction, which may be used as a checklist for all roles in precision instrument lab construction; and three, an overall project management schedule, which guides from the instruments purchase strategy to soft skills in lab construction for the purchased instruments.

2. Materials and Methods

2.1. Objective and Process

Each type of EM has its own specific requirements for its operation in a lab setting, which requires a unique and complex project for each lab construction. For example, a transmission electron microscope (TEM) with a high accelerating voltage of 300 KeV, has totally different requirements than a bench-top scanning electron microscope. Therefore, lab construction can only be designed and conducted after the configuration of the EM to be purchased is known. Thus, the configuration of the instrument needs to be determined in the first phase, and lab construction can only be planned and begun in the second phase. In both phases many actors with different goals and motivations in the larger organization, be it a university or large research center, will be involved and also contribute their advice and expertise to the final advanced instrument purchase and lab construction.

The workflow of the two phases is illustrated in Figure 1 and further details are provided in sections 2.2 and 2.3. The application of this two-phase method will be illustrated in the case study in section 3.

2.2. Phase I: From Varied Needs to a Common Decision on Instrument Purchase

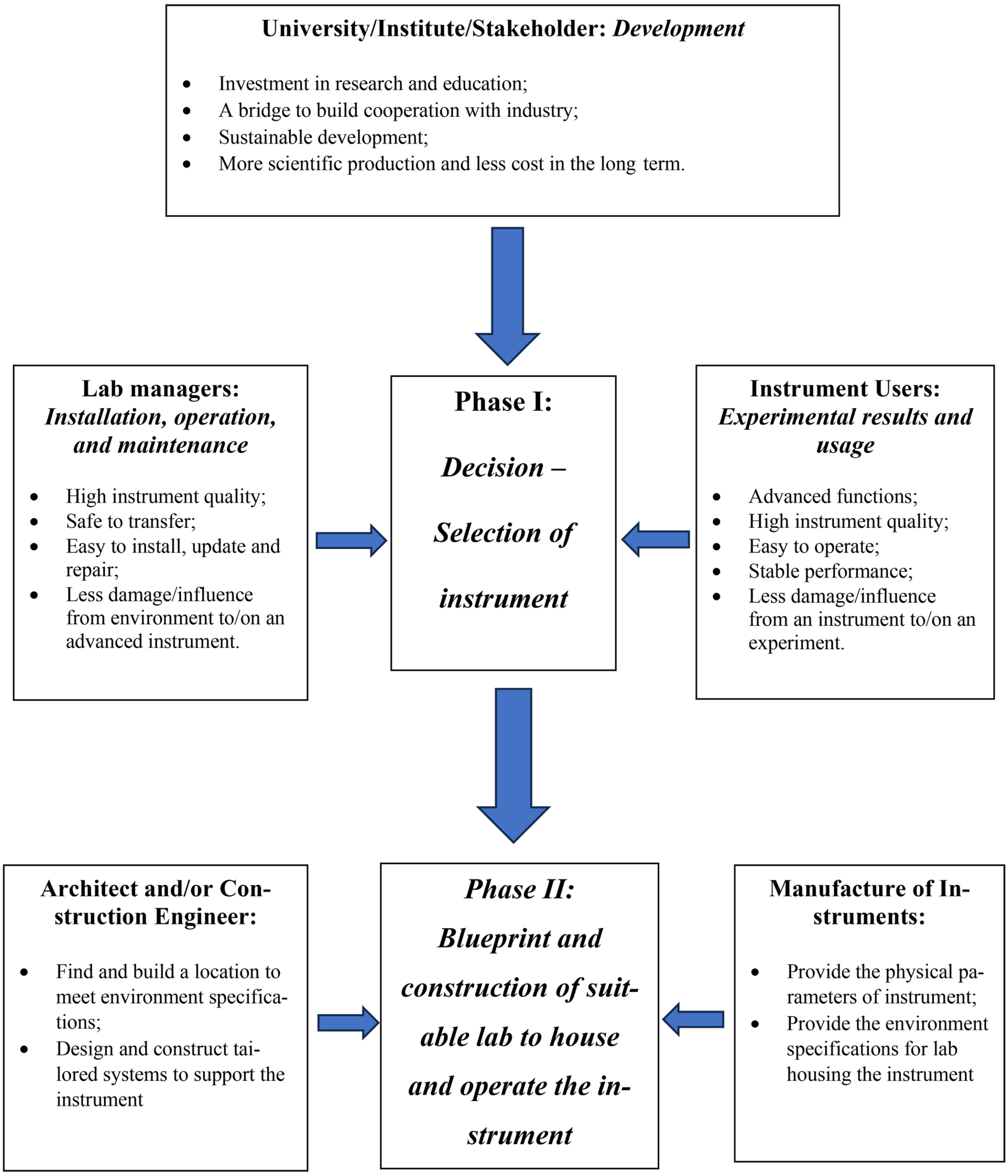


Figure 1. Factors and responsibilities affecting lab construction for advanced instruments in a workflow schematic.

The strategy of building up an EM advanced lab is usually the task of senior administration in a university setting or top management of a large research institution, who focus on long-term and sustainable development of the organization. In this way, the top management team focuses on balancing the needs of researchers and stakeholders from the community, who include local industry actors. These needs include financial aspects, research goals and often include competing interests. Within the organization purchasing the advanced equipment, there are many actors in the organization eager to take advantage of its capabilities, although not all will have the skills needed to properly gain full value. For example, research scientists will be eager to use the high-end advanced functions of the instrument, but they might need extensive training to use the delicate and costly instruments in a sustainable way. Another important user group and often acting as gatekeepers are lab engineers, who prefer to maintain a stable and robust instrument, that is convenient and inexpensive to update and repair, covering a variety of requests from both faculty and students. These researchers will need to be trained to use the instrument independently. Since all actors in an organization may have varied requirements of the same instrument, deep communications and collaboration are critical to find common ground, i.e. what type of EM should be purchased.

In **Figure 1**, the requirements and needs of the three major actors of an EM lab construction are listed in phase I, and the lab construction criteria for the instrument are provided in phase II.

However, some factors must be considered in both phases, for example, the short- and long-term maintenance of instruments. Additionally, the long-term financial aspects of the project can be impacted by costs associated with maintenance, usage, the special requirements of the chosen location and how the instrument is operated. Meetings and agreements need to be established by all three groups of actors in phase I, who must all ensure that information is exchanged fully and communication channels are open to arrive at common decisions, thus ensuring the sustainable construction and use of the lab.

2.3. Phase II: Building up a Proper Lab for the Instruments

After the key actors make the decision on the type of instrument to be purchased and installed, then the architects and civil engineers will enter the team. They will help design and build a lab for the EM, working to ensure a safe and stable working environment for both the EM and its operators. Due to the critical requirements for advanced instruments, the engineers need precise information from the instrument manufacturer, who knows what conditions are needed to run the EM smoothly and which environmental factors need to be avoided. Sometimes the construction group and the manufacturer may focus on different aspects of the same task, or even have contradictory solutions to a potential risk. At this moment, the lab manager needs to act as a bridge to connect and organize communications between the two important actors of EM lab construction projects.

Construction projects are classified into two types, one for lab construction in an open area or in a new/empty building, and the other for lab construction in a building under current use. When construction is done in an "undeveloped" area, lab design is more straightforward and aims at satisfying the specific requirements of the specific instrument or instruments chosen for the lab. The requirements of the lab and the character of the "undeveloped" building will also be taken into consideration. In some special cases, partially modifying the route of electricity cables and water supply pipes, ventilation system and parking lots will also be needed. Additionally, it is strongly suggested that extra space be allocated for future research development, keeping in mind potential interference with neighboring labs and specialized equipment as yet to be purchased.

For lab construction in a building in current use, onsite inspections to ascertain complete details of the future working environment of the EM, especially, taking into consideration the equipment in neighboring labs is extremely vital. Viewing the most up-to-date version of the blueprint of the entire building will also help to avoid problems. In section 3, our case study of an actual EM lab construction will further illustrate these necessities, and where potential challenges and remedies in advanced equipment lab construction are also discussed.

2.4. Internal and External Communication

Detailed and refined plans require direct and open communications among all actors during the two phases. This approach, combined with onsite visits and tours, will result in robust decision making and improved solutions to both foreseen and unforeseen problems. Aside from the required communications between the actors shown in Figure 1, continuous and open communication with local government is also fundamental. When planning the lab, it is necessary to know the development plan of the local area for the following decades. For instance, long-term plans for new routes for roadways, high-speed rail, subways, water mains and drainage, the construction layout of the free spaces around the campus/research center, and any reconstruction plans for the surrounding area should be known to the extent possible and kept up-to-date. With this information, the optimal location for the lab can be determined and thereby, costly reconstruction or relocation projects avoided.

3. Case Study and Analysis: Challenges and Solutions in Electron Microscope Lab at GTIIT

3.1. Background

An advanced laboratory was recently constructed at a newly established Sino-foreign engineering university in southern Guangdong Province, China. The Electron Microscopy Center (EMC) of the Guangdong Technion Israel Institute of Technology (GTIIT) is composed of three EM labs, i.e. a scanning electron microscope (SEM) lab, a TEM lab and a focused ion beam electron microscope (FIB) lab. The EMC is a public platform and offers service and cooperation to two sets of actors, research groups on campus and external users. As the first public platform of the new university, the EMC was located in the basement of a newly constructed and empty building, which is a research center that will be filled with many different kinds of labs.

3.2. Phase I to Phase II

Table 1. Overview of potential challenges and solutions for electron microscope (EM) lab construction.

Challenges	Sources of problems	Actions before/during the lab construction	Possible solutions
High Stray Magnetic field	• Nearby high voltage/low voltage converter power stations nearby; • Elevators nearby; • Electric wire /cables around; • Subway near the campus; • Neighbouring big instruments, which may induce an electromagnetic field.	Find the locations of these sources through professional onsite investigations (this step is essential to deal with all challenges); Use rooms which are distant from the main sources. Still problems? Look to possible solutions column.	Install a magnetic shielding structure, which includes two modes, i.e. active and passive. See section 3.3.1
Strong Vibration	• Vehicle movement nearby; • Ventilation system in the building; • Water supply tubes and drainage system in the building; • Large, impactful events in nearby facilities/stadiums; • Interfering activity from nearby labs and/or workshops.	Set the lab on the lowest floor of the entire building; Keep the lab a distance from parking lots, stadiums, workshops, and waste water wells on campus; Keep the lab as far as possible from the highways and/or subways which are around the facility. Still problems? Look to possible solutions column.	Install the EM on an active vibration isolation stage, or isolate the base of the EM lab from the surrounding area. See section 3.3.2
Loud Acoustic Noise	• Ventilation system; • Water supply and drainage system; • Instruments nearby; • Experiments performed nearby.	Combining onsite investigation with the latest blueprint of the routes of piping (for water, gas and air) to find out the main sources, then keep the lab far from the main sources of noise; Make a "keep quiet " request to actual and potential neighbors.	Install sound proofing materials on the walls of EM labs; Cover the tubes/pipes which produce noise by sound absorbing material; Change the route of noisy piping; Communication with neighboring labs whose instruments/experiments are noisy.
Transportation path for big instruments	• Corridor size; • Corridor angle; • Gradient of stairs; • Elevator size; • Bearing capacity of elevator; • Size of doors.	Chose the right room for the EM lab to which all transportation paths are wide enough, flat, and safe. It is better to double check requirements with the EM manufacturer.	Modify/enlarge the public transport paths (remove door frames, open walls…), and possibly set up a temporary gantry crane to transfer instruments horizontally.

Continued

Temperature	• Local climate	Install adequate air conditioners/heating.	Isolate EM labs from surrounding area by means of doors
Humidity	• Local natural environment	Employ proper dehumidifiers.	Isolate EM labs from surrounding area with doors sealed against water vapor
Water leakages	• Cracks on ceiling and wall; • Cracks on floor; • Cracks on water supply tubes; • Condensation from air conditioner (AC); • Condensation from fresh air exchange system.	Waterproofing the lab is the key standard and its implementation should be approved before installing EMs, and should be regularly inspected. Remove and reroute any water/ fresh air supply tubes which are above the ceiling of EM labs. Avoid heavy construction which might cause cracks on the walls, floors and ceilings.	Use waterproof glue to fill tiny cracks or holes. Adjusting the rate of air flow in the AC. Cover thermal insulation materials on the fresh air tube and/or air exchange tube. For extensive repairs, communicate with specific professional companies to find proper solutions.
Grounding	/	Set individual grounding rod for each EM.	Use public grounding rods, when no individual rod can be installed.

EMs are instruments that are sensitive to the environment in which they operate. Their performance, such as imaging, is heavily impacted by conditions such as ground stability, magnetic fields, temperature, humidity, etc. [23]-[25]. To avoid negative impacts of the external environment and to make use of these advanced equipment in the long term, proper design and implementation of lab construction are essential. Therefore, the onsite investigation with architects, civil engineers, and a lab manager - who has gathered complete information concerning the specificities of the EMs from manufacturers - should be completed before the design of the construction project gets under way. Moreover, regular visits should be arranged by these actors throughout the construction process.

Using the case study of the construction of the EM labs at GTIIT and other construction cases in China, the most common challenges and corresponding solutions have been summarized in **Table 1**. In the latter the factors that can cause these challenges have been listed as "Sources of problems". This table can be used as a checklist for onsite visits before lab construction to ensure that foreseen and unforeseen issues are accounted for. For challenges occurring after lab construction, or showing up due to a change in the external environment, either due to natural factors or external actors, additional solutions are provided. Due to the varied nature of lab set-ups, there may be more than one solution provided for each challenge.

3.3. From Suggested Solutions to Onsite Actions

If (1) the sources of major problems can be detected and the lab can be located far from the sources of problems [14], and if (2) solutions to problems can be managed, then most challenges in **Table 1** can be solved by local civil construction companies and contractors. However, the majority of local civil contractors oftentimes have little, if any, experience with the magnetic shielding and vibration reduction needed for EM labs. Therefore, this tutorial would like to focus on these special challenges in EM lab construction in detail. From the case study of GTIIT (part 3.3.1 and 3.3.2), it is clear that all parameters/conditions need to be measured/considered and different solutions should be evaluated to achieve successful lab installation.

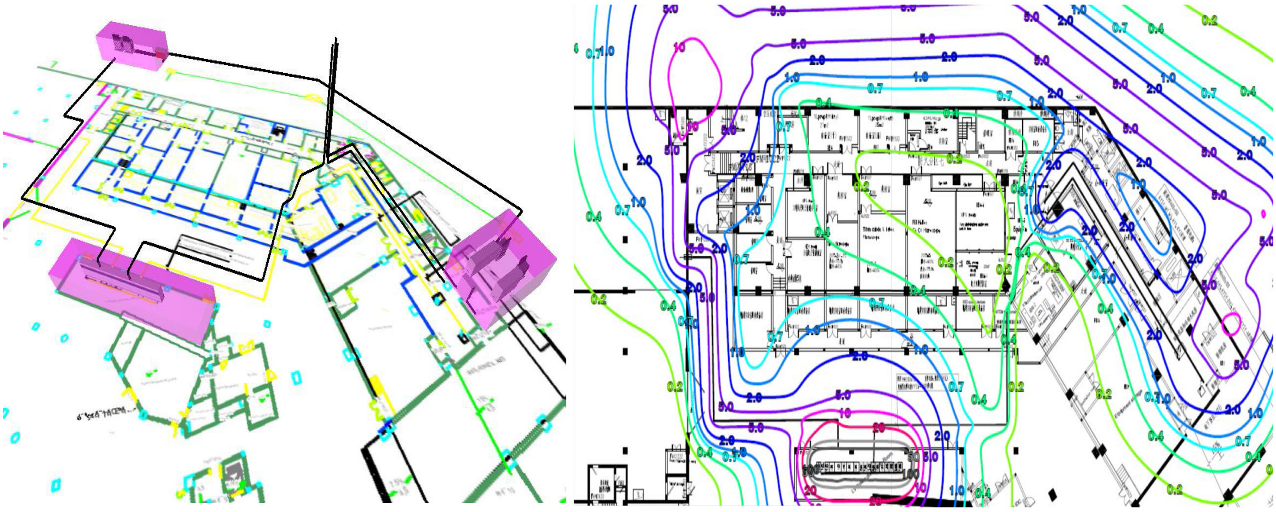
3.3.1. Decreasing the Magnetic Field in the EM Lab

The initial step involves assessing the actual magnetic field at the proposed site for the EM lab. By comparing this data with the standards provided by the EM manufacturer, we can determine whether the magnetic field is sufficiently low to safely operate the EM. If the field is within safe limits, the chosen location is suitable for the EM. If not, it will be necessary to either implement a system to reduce the magnetic field strength or select an alternative location that meets the required standards. It should be noted that, if the EM lab is to be built in an existing and operational building, the magnetic field strength in the lab should be measured when the electricity is under maximal load in all neighboring labs. Proper communication and coordination with all neighbors will take time and a concentrated effort, but knowing the real maximal magnetic field strength will allow for the construction of the best system for magnetic shielding.

However, if the EM lab is set up in a new or empty building with few neighbors, it is difficult to estimate the real magnetic field in the future, as it could increase substantially with the arrival of neighboring labs. In this situation, we suggest calculating the magnetic field distribution of the whole building, and then find the best location for the EM lab. There are six key steps involved in this process:

- Mark the locations of power stations supplying electricity to the potential EM lab location and the entire building on the blueprint(s) of the whole campus.
- Check the capacity of each power station, and calculate its maximal load, i.e., the maximal input/output current through the main cables.
- Map the routes of electricity cables which connect stations and the building, as well as the routes of main cables in the entire building.
- Simulate the magnetic fields on each floor according to the information from the first three steps.
- Analyze the strength of magnetic fields and find rooms, where the magnetic field is low enough to be used as EM labs.
- Combine this information with the other requirements of the environment, find the best locations for the EM lab.

Using the case study of the lab construction of the EM lab at GTIIT as an example, **Figure 2(a)** exhibits a model displaying the power supply system around the research building, where the EM lab is located. There are three alternating current (AC) power stations in pink and the routes of main cables connecting stations indicated by thick black lines. The top-left pink box and the right pink box are high voltage power stations, and the bottom-left pink box is a low voltage power station. **Figure 2(b)** shows the simulated magnetic field distribution in the basement of the research building. The magnetic field strengths are noted on each of the color-coded loops. Simulating the magnetic field map is a powerful tool to predict the proper location for an EM lab [25].

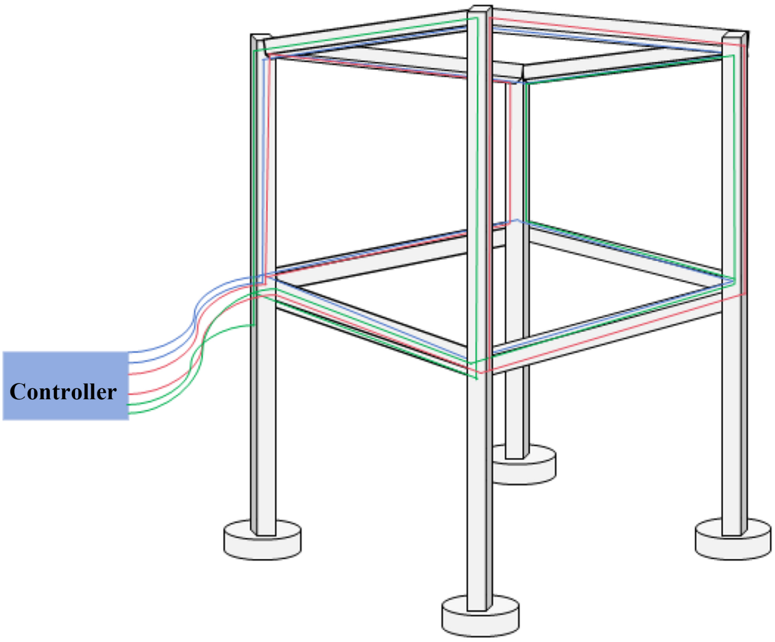


(a) (b)

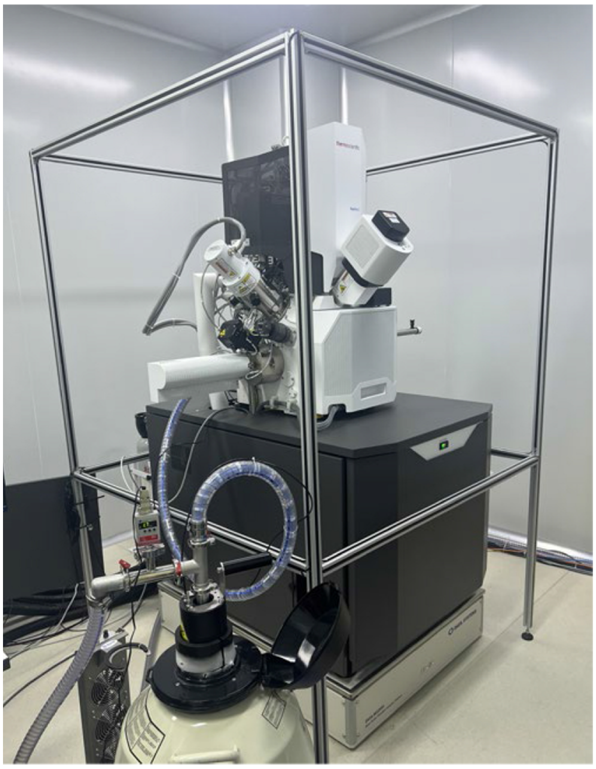
Figure 2. (a) A layout of the electrical power supply system. The main cables (black line) connect the three power stations (boxes in pink) in the diagram; (b) The calculated electromagnetic field distribution induced by these power stations and cables [26].

It is obvious that the intensity of magnetic fields decreases with the distance from the power stations and main cables. The highest intensity of the magnetic field ranging from 20 mG (red circle around the low voltage power station) to 1 mG (pink circles around the two high power stations), and the lowest magnetic field is circled by the light green loops (0.2 mG). Therefore, the EM labs at GTIIT were placed within the area circled by light green loops. In addition to the impact from the AC, the direct current (DC) electromagnetic field can also influence the operation of the EM. Since elevators are the main source of DC electromagnetic fields in the building, EM labs should also be situated away from all elevators.

The second stage is to compare the measured or/and simulated magnetic field intensity in the lab candidate location with the requirements of the EM. Magnetic fields should be reduced if the onsite measured value and/or simulated data is higher than the prescribed limit. By analyzing the difference between these two values and identifying the source of the external magnetic field, we can select the appropriate solution. Typically, there are two types of solutions: active and passive. Active magnetic field cancelation uses a cube-shaped frame [14] [27] [28] (as shown in **Figure 3**), in which electrical cables, detectors and sensors are installed, to enclose the EM. By adjusting the current in the cables embedded in the frame via a set of sensor-devices outside, an electromagnetic field will be produced to counteract the external stray magnetic field impacting the lab. In this way, the magnetic field strength around the EM column will be reduced. Active magnetic cancellation is usually employed when the stray magnetic field is induced by an external DC electric field (like elevators, trains, or subways).



(a)



(b)

Figure 3. Active magnetic field cancellation (a) is a cube-shaped shielding frame [27], and (b) is an active magnetic field cancellation which supports an electron microscope in Beijing University.

If the stray magnetic field is primarily induced by an AC electric field, the EM labs should be enclosed by a hexahedral box which is composed of metal plates. This is called passive magnetic field shielding. The metal plates are embedded into the walls, floor and ceiling of the lab, like an inner shell. **Figure 4** provides a schematic drawing of a passive magnetic field shielding. Usually, high magnetic permeability materials are used to deal with electromagnetic fields at low frequency, and high electricity conductivity materials are employed to shield from electromagnetic fields at high frequency. The types of metal, the thickness of the metal plate, and welding quality of the metal plates/bars will influence the shielding effects [29].

Regardless of the shielding methods used, onsite measurements should be taken again after shielding, to make sure the EMs are operating in an environment, where the stray magnetic field is low enough.

The advanced EM labs at GTIIT were built in an "empty" building, so that the distribution of the magnetic field induced by the main cables could only be estimated. Thus, a passive magnetic shielding system was chosen. It protected the EM, eliminated the side effects on experiments, and avoided the potential problems that could occur during (possible) reconstruction.

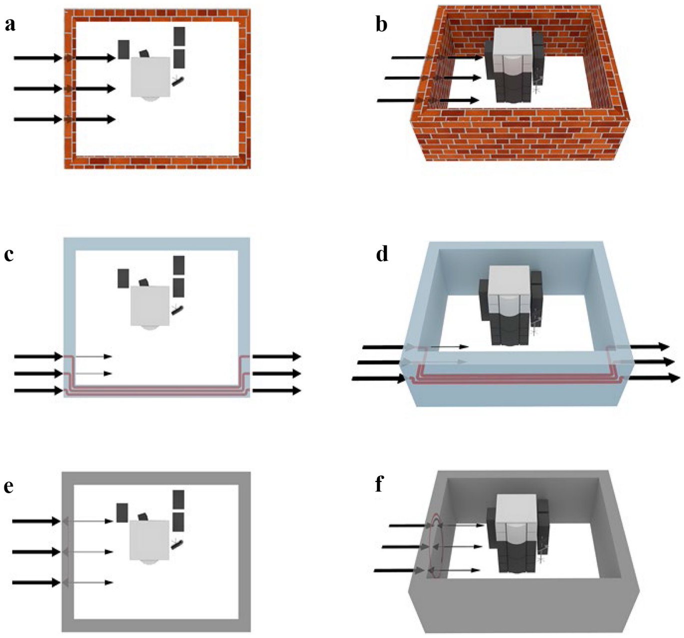


Figure 4. Schematic drawing of passive magnetic field shielding, including both top (left images a, c, and e) and side (right images b, d, and f) views. The arrows indicate the magnetic field. Images a and b illustrate a lab without a shielding shell, where the magnetic field strength changes before and after penetrating the wall of the lab. Images c and d represent a lab shielded by high magnetic permeability materials, where the magnetic field inside the lab is lower than outside the lab. Images e and f show a lab shielded by high electricity conductivity materials, where the magnetic field in the lab is decreased [29]. Ceilings and floors are removed in all images.

3.3.2. Reducing Vibration in EM Labs

The effect of vibration can be reduced in three ways: 1) place the EM on a vibration isolation stage as shown in **Figure 5(a)**, which is also called an active vibration isolator; 2) separate the foundation on which the EM is placed from the ground beneath [23] [24] [30] (**Figure 5(b)**), which is considered the passive method, and 3) combine both the active and passive methods together (**Figure 5(C)**). The most suitable anti-vibration method needs to be chosen according to the lab location and vibration characteristics detected by onsite investigation.

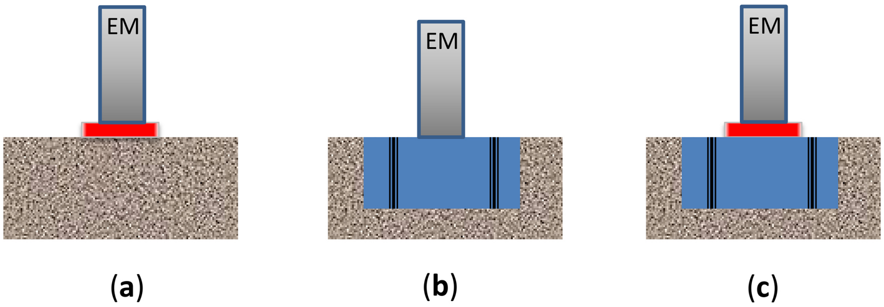


Figure 5. Schematic of three methods applied in anti-vibration projects in electron microscope (EM) labs. Figure (a) shows an active vibration isolation stage separating the surrounding ground from the EM; Figure (b) indicates an independent foundation (blue box) of an EM lab; and Figure (c) presents a combination of the isolation foundation and an active vibration isolation stage.

With active vibration isolation, there are sensors, circuits, and actuators assembled [31]. The vibration induced by the environment can be counteracted by the isolation platform which provides movements in the opposite directions precisely and with the appropriate speed. When the vibration frequency is low, the active vibration isolation stage would be a better solution, while in cases of high vibration frequency such as 20 Hz, an independent foundation (the passive option) may be a more suitable choice due to its lower cost.

It should be pointed out that installing an independent foundation (**Figure 5(b)**) is only appropriate when the lab is located on the lowest floor of the entire building. A waterproof layer should be applied in all dimensions to protect the independent foundation, and a soft buffer layer should separate the independent foundation and the ground matrix. Any resonance should be avoided, which might be generated by the passive foundation and the EM, as well as the active isolation stage and the EM. Thus, local geological characteristics and the physical parameters of the EM need to be considered, and precise measurements after construction need to be taken.

In the case of the GTIIT advanced EM labs there were special requirements due to the unique environment of the university. There is a truck highway running next to campus with busy traffic 24 hours per day, a parking lot in the basement, and neighboring labs. Thus, a combination of an active isolation stage and a passive independent foundation was installed, i.e. the method illustrated in **Figure 5(c)**.

Aside from vibrations originating from the ground, the walls of the lab might also transmit vibrations. For example, the pipes for the ventilation system, which are adjacent to or going through the walls, may cause vibrations and noise. Any pipes should be covered by sound absorption material. For the spaces in the wall, where the pipes enter, a buffer layer should be inserted to isolate the piping from the wall. Air conditioning units which are used in the lab, as well as the outlets for fresh air going into the lab, should be kept at a proper distance from the column of the EM. All these issues can be resolved before or even during lab construction, if regular and professional onsite investigations and good communication are used. Although many challenges and solutions have been discussed in this work, there may be still some other factors need to be considered [32], depending on the unique environment and conditions of the EM.

4. Conclusion

Using the results of a case study of an actual EM lab project, a strategy for the implementation of advanced lab design and construction was developed. This approach highlighted in this tutorial combines technological insights and management perspectives to propose a common workflow. Beyond technical skills and techniques, soft skills such as communication and critical problem-solving are essential. It is crucial to establish clear and open communication channels, hold regular meetings among all stakeholders with diverse needs, and develop a consensus on the design during both instrument procurement and lab construction phases. Moreover, this study also emphasizes that regular onsite visits and investigations are key to refining the plan. The lab manager acts as a vital link to coordinate all parties and ensure smooth progress in the construction process. Finally, a checklist of common issues and solutions, along with a detailed case report, serves as a valuable best practice resource for future lab managers embarking on the development of an EM lab or any similar facility involving advanced and sensitive equipment.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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