Guidelines for Working with Magnets

1. Purpose

The purpose of this document is to provide guidance to laboratory users, the Laboratory Safety Representative (LSR), and the Principal Investigators (PIs) or Center Director in the safety precautions required when using devices and equipment designed to generate magnetic fields (both static and time varying).

2. Scope

This document applies to all laboratories on the KAUST campus, including the KAUST Research and Technology Park and the Innovation Cluster.

3. Responsibilities

3.1. Health, Safety and Environment

- Review and provide advice on safety precautions.
- Provide training.

3.2. Principal Investigator

- Ensure personnel are trained to safely perform the task assigned.
- Determine the specific hazards and identify the hazardous areas.
- Ensure all protective control measures are maintained.

3.3. Laboratory Safety Representative (LSR)

- Ensure that all users work in a safe manner and follow all the safety precautions.
- Ensure that non-laboratory users are accompanied.
- **Immediately** notify the PI or Center Director and Research Safety Team of unsafe conditions, and all known or suspected incidents.

3.4. Laboratory Staff

- Have completed all required training.
- Follows all precautionary measures.
- **Immediately** notify the LSR, PI or Center Director and Research Safety Team of unsafe conditions, and all known or suspected incidents.

4. Introduction

The use of magnets, generating intense magnetic fields, are becoming the standard in research laboratories. Some of the new techniques, using superconductors, allow to reach static magnetic fields that can exceeds 20 Tesla (20 T). The issue is that shielding such large magnetic fields is very complex and residual fields outside the magnet can pose risks to the users and equipment located nearby.

4.1. Definitions

H Field is the magnetic field strength, measured in amps per meter (A/m) or amp-turn per meter for electromagnet.

B field is the magnetic flux density or magnetic induction. This quantity is the total numbers of flux line passing through a given area. It is considered the better measure of health hazards than the H field. The units are Tesla (T) or Gauss (G).
1 T = 10,000 G

4.2. Permanent versus Electromagnet

A permanent magnet is made up of ferromagnetic material that is magnetized and has its own magnetic field. This means that it will always displays a magnetic behavior, i.e. the magnetic field cannot be switched off. The strength of the magnetic field of a permanent magnet depends on the material used for its creation. Some permanent magnets are made from alloys of rare-earth elements and others are made of ferrite or alnico.

An electromagnet is made from a coil of wire which acts as a magnet when an electric current pass through it but stops being a magnet when the current stops. The strength of the magnetic field produced by the solenoid depends on the strength of current, the number of turns of the coil and the nature of the material.

4.3. Static Magnetic Fields

A magnetic field is a force field created by a magnet or charges that move in a steady flow as in direct current (DC). Static magnetic fields exert an attracting force on metallic objects containing for example, iron, nickel or cobalt. The quantity of ferrite (a form of iron) or martensitic steel (specific type of stainless steel alloy) in an object will affect its magnetic ability: the greater the quantity of these components, the greater the ferromagnetism.
Common sources of static magnetic fields include permanent magnets (which are found in appliances, toys, and medical devices), battery-powered appliances, MRI scanners, some electrified railway systems, and certain industrial processes.

4.4. Time-Varying Magnetic fields

Time-varying magnetic fields are magnetic fields that reverse their direction at a regular frequency. They can induce an electric current in a conductor present in this field as well as in a human body. Time-varying magnetic fields are produced by devices using Alternating Current (AC) such as antennas, microwaves, etc.

4.5. Superconducting Magnet

A superconducting magnet is an electromagnet made from coils of superconducting wire. They must be cooled to cryogenic temperatures during operation. In its superconducting state, the wire can conduct much larger electric currents than ordinary wire, creating intense magnetic fields. Superconducting magnets are used in Magnetic Resonance Imaging (MRI) scanners in hospitals and in scientific equipment such as nuclear magnetic resonance (NMR) spectrometers, mass spectrometers, and particle accelerators.

5. Hazards and Safety Precautions

5.1. Force Hazard

This is the highest hazard associated with the use of magnets. Indeed, magnets attract ferromagnetic objects which can become airborne in the presence of a strong magnetic field. Tools and compressed-gas cylinders can become uncontrollable and fly like missiles toward magnets in areas where strong static fields and strong field gradients (changes in field strength over distance) exist. Force hazard depends on the field strength and the field gradient, but also on how rapidly the magnetic field strength changes with distance. A field strength of 3 mT (30 G) is required to attract ferromagnetic objects.

Safety Precautions:

- Only use non-ferromagnetic tools when working with magnets such as authentic steel or aluminum.
- Prevent any magnetic material from entering areas where there is strong magnetic field (above 3 mT or 30 G).
- Never place any part of your body between the magnet and loose metal objects.

If a large object is attracted to the magnet and hits the magnet, leave the room since it may cause a superconducting magnet to quench. Notify your supervisor. If an injury has occurred, call 911 immediately.

5.2. Electronic and Metal Implants

Individuals wearing passive (e.g. screws, pins, etc. as well ferromagnetic foreign bodies such as shrapnel, etc.) or active implants (e.g. pacemakers, defibrillators, neurological stimulators, etc.) should never enter an area where the magnetic field exceeds 0.5 mT (or 5 G). Static magnetic fields can cause passive implants to move in the body causing irreversible damage; they can also damage the electronics in active implants causing them to become electrically/electronically dysfunctional. In addition, when exposed to such magnetic fields, electronic components (e.g. chips, magnetic cards, hard disc, etc.) can be damaged or erased.

Safety Precautions:

- Control access to the area where magnetic field can exceed 0.5 mT (5 G).
- Demarcate the area where the magnetic field can exceed 0.5 mT (5 G). A demarcation on the floor (e.g. tape on the floor) is often used.
- Display warning sign at the entrance to the area where magnetic field can exceed 0.5 mT (5 G).

5.3. Cryogenic Gas Safety (superconducting magnets only)

5.3.1 Handling Cryogens

Superconducting magnets use liquid helium and/or nitrogen for cooling purposes which present an additional safety concern with the handling of cryogenic liquids. Direct contact with the skin or eye tissues can cause severe damage through frostbite (tissue damage from freezing). If the frostbite is severe, the damaged tissues may need to be amputated. In addition, inhalation of concentrated cryogen gases may cause loss of consciousness and (eventually) death through oxygen deprivation (asphyxiation).

Safety Precautions:

- Ensure that laboratory staff handling cryogens have taken the training Liquid Nitrogen and Cryogenic Safety via the online system.
- Laboratory staff must always wear the required personal protective equipment when handling cryogens such as insulated gloves, face shields or other splash eye/face protection, closed-toe shoes, and laboratory coats.
- Proper procedures for filling and transporting cryogens should be followed. At least 2 staff members should be present during filling.
- Always place cryogen in approved containers. The containers used for transporting cryogens should be made of metal. Glass dewars can easily implode, causing serious injury. All dewars should have appropriate pressure vents. Unvented containers can rupture as the liquid warms and expands. All transfers of cryogens should be continuously attended to prevent spills or frozen valves.
- Please review the Guidelines for Working with Cryogenic Liquids.

5.3.2 Quench

Quench is the unexpected loss of superconductivity in a magnet (e.g. NMR magnet), resulting in rapid heating through increased resistance to the high current. The superconducting magnet contains both liquid helium and liquid nitrogen. When a magnet quenches, the stored energy is released as heat, which boils off the liquid helium (i.e. convert the liquid helium into gas). The helium gas is vented out of the magnet dewar and can fill the room from the top down (helium is lighter than air), and forms a cloud near the ceiling. A quench is obvious: a big cloud of helium vapor will form above the magnet, accompanied by a loud whooshing sound that can create an oxygen deficient atmosphere. In addition, the quench can violently damage the magnet, and ferrous objects are drawn into the magnet bore.

Safety Precautions:

- Ensure that Toxic Gas Monitoring systems (oxygen level sensors) are in place to trigger an alarm in case of a magnet quench.
- A SOP to detail what should be done in case of a magnet quench should also be available.
- Ensure laboratory staff are trained and know what to do in case of a magnet quench.

5.4. Electrical Safety (electromagnets only)

5.4.1 Power Supplies

Power supplies used for NMR magnets and some other type of electromagnets operate at relatively low voltages (approx. 10 V); however, the current used may be very high (about 100 A in a superconducting magnet). High amperage is extremely dangerous if allowed to come in contact with human tissue.

Safety Precautions:

- NMR power supplies must only be checked, serviced or maintained by the magnet manufacturer (e.g. charge/discharge of the magnet must be done by the manufacturer, etc.).

5.4.2 Cables, wires, and connectors

All cables, wires, and connectors should be properly insulated to prevent contact with the operating current.

Safety Precautions:

- Inspect the cable and wires on a regular basis to ensure the integrity of the insulation.
- To prevent arcing, never break connections without first turning off the power to the circuit being handled.

6. Exposure Limits

There are no regulatory limits and the biological data is unclear. As a result, the limits proposed by the American Conference of Governmental Industrial Hygienists (ACGIH) are often used. The ACGIH has developed threshold limit values (TLVs) guidelines for static magnetic field flux densities to which it is believed that nearly all workers may be exposed on daily basis repeatedly without experiencing adverse health effects. The TLVs for a routine (8-hour) occupational exposure from static magnetic fields are listed in Table 1. **Workers with implanted ferromagnetic or electronic medical devices should not be exposed to static magnetic fields exceeding 0.5 mT (or 5 G).**

Table 1. Threshold Limit Values for Static Magnetic Fields.

Exposure	Maximum Magnetic Flux Density
Whole body (general workplace)	2 T (20,000 G)
Whole body (workers who have received training and work in a controlled environment)	8 T (80,000 G)
Limbs	20 T (200,000 G)
Individual wearing medical devices (ferromagnetic implants or electronic medical devices)	0.5 mT (5 G)

The ACGIH has also established TLVs that refer to the amplitude of the magnetic flux density (B) of sub-radiofrequency (sub-RF) magnetic fields in the frequency range up to 30 kilohertz (kHz); these values are set so that nearly all workers repeatedly exposed to time-varying magnetic field will not experience adverse health effects. Occupational exposures in the extremely low frequency range of 1 Hz – 30 kHz should not exceed the values listed in Table 2. Please note that in the case of NMR, only the sample is exposed to RF pulses so no worker should expect to exceed these limits.

Table 2. Threshold Limit Values for Sub-Radiofrequency (up to 30 kHz) Magnetic Fields.

Exposure	Frequency Range	Maximum Threshold Limit Value
Whole body exposure	1 – 300 Hz	60/f* mT
Hands and feet	1 – 300 Hz	600/f* mT
Arms and legs	1 – 300 Hz	300/f* mT
Whole and partial body	300 Hz – 30 kHz	0.2 mT
Point of contact[1]	1 Hz – 2.5 kHz	1.0 mA
Point of Contact[1]	2.5 kHz – 30 kHz	0.4×f mA

f*: Frequency in Hz. f: frequency in kHz, T: tesla

Note that for workers wearing medical devices, the TVLs in Table 2 may not protect against electromagnetic interferences with the device function. As a result, it is recommended that the exposure of persons wearing medical devices is maintained at or below 0.1 mT at power frequencies.

7. Control Measures

7.1. Engineering Controls

- **Shielding –** Magnetic fields are controlled by using permeable alloy that confines the magnetic flux lines and diverts them. Magnetic shielding can be made using high nickel alloys called “mu metal” or soft iron. Forming “mu metal” into a complex shield is expensive and “mu metal” is easily damaged. Such shielding is best applied near the field source, whenever practical. Another approach is to use non-permeable metals such as copper or aluminum to produce eddy currents that cancel out the original magnetic field. If it is determined that shielding is required, an experienced consulting firm should be hired to design the magnetic field shielding. Nowadays, most device equipped with powerful magnets such as NMR or EPR are actively shielded.
- **Quench protection –** To avoid a quench situation, use a cryogen level sensor system to detect the quench and trigger a lowering of the current and stored magnetic energy to prevent burnout of the conductor. Always refill or de-energize the magnet if low cryogen levels are indicated on the sensors.
  Examples of engineering controls for superconducting magnets are as follows:
  - Installation of a quench sensor; the sensor monitors the exhaust pressure of the NMR magnet. If the pressure exceeds a threshold level an alarm is raised.
  - Installation of liquid helium purge vent to allow excess helium gas to escape through an exhaust vent extending out through the roof
  - Internal sensors to indicate low levels of liquid helium
  - Visual and audible alarms
  - Positive access control such as locked doors and restricted access to authorized personnel only

[1] Currents induced from touching ungrounded objects (these object have acquired an induced electrical charge in a strong sub-RF magnetic field). These can lead to startle responses or severe electrical shocks.

- **Electrical grounding –** Metallic structures producing contact shocks should be electrically grounded or insulated.
- **Emergency exhaust –** In areas where superconducting magnets are used, it is recommended that an emergency exhaust is installed with a trigger button located near the exit door. If needed, the laboratory user can activate the trigger (i.e. press the button) to increase the removal of helium gas from the room. This is particularly useful if the magnet quenches.
- **Interlocks –** Areas where whole-body exposures to 60 Hz fields exceed 25 kV/m or 1 mT (10 G) must be restricted by positive means such as locked enclosures, interlocks, etc. Note that most powerful magnets used for research are shielded so that outside the equipment the magnetic field does not exceeds 0.5 mT (5 G).

7.2. Administrative Controls

- **Area designation -** As part of the design process, the static magnetic field in the facility must be identified by measurement or calculations where pacemaker hazards (> 0.5 mT or >5 G) and projectile hazards (> 3 mT or >30 G) will exist. Places where excessive whole-body exposures (>60 mT or >600 G) could occur must also be identified. The area designation can be achieved by adding a painted line or tape placed on the floor around the magnet where the various field strengths are. Other examples include the use of a chain, rope, or fence. Table 3 illustrates the main demarcation lines that are recommended.
  Provisions must be made to secure and restrict access by pacemaker users to places where whole-body magnetic fields exceed 0.5 mT (5 G). The 0.5 mT (5 G) line is a demarcation between uncontrolled and controlled areas and must be clearly identified. For fields with exposure less than 5 G, no controls or posting are required.
- **Warning sign posting –** Warning signs should be posted at the entrance to the laboratory where magnetic fields exceed the limits given in Table 3. Areas where potential mechanical/force hazards exist (>3 mT or > 30 G) must be conspicuously demarcated. Tools, compressed-gas cylinders, and other articles made of magnetically permeable materials must be kept out of such areas. The following warning positing is recommended:
  - Caution sign should be posted in areas where the magnetic field strengths exceed 0.5 mT (or 5G) to warn individuals with pacemakers or other active implants (i.e. medical electronic implants) to keep out.
  - A caution sign must be displayed in areas where magnetic fields exceed 3 mT (30 G) to inform of potential mechanical/force hazards. People with passive implants (including foreign ferromagnetic bodies) must be kept out of areas where field strengths exceed 3 mT (30 G). It is recommended that these areas are surveyed to determine where potential mechanical/force hazards exist.
- **Registration –** for users of the Nuclear Magnetic Resonance equipment, a questionnaire should be completed by the possible laboratory users prior to gaining access to the laboratory. The questionnaire should request the individual to inform if s/he has implants or medical devices that may be dangerous in presence of a magnetic field.
- **Standard Operating Procedures (SOP) –** a SOP should be read and understood by all authorized users. It should describe the safety precautions and include the procedures to follow to operate the magnet, in case of an emergency, etc.

- **Training –** All laboratory users authorized to use powerful magnets should have the Magnet Safety Training and read the SOP related to the equipment. If they are authorized to use superconducting magnets we also recommend that users take the Liquid Nitrogen and Cryogenic Safety training in via the online system.

Table3. Demarcation of magnetic field strength and for protection of people and equipment.

Magnetic Flux Density	Limit/Restriction Description	Entrance forbidden to
0.5 mT (5 G)	Maximum value allowed for members of the public, persons wearing passive or active implants	– Public – Passive or active implants wearer – Non-authorized personnel
3 mT (30 G)	Above this value the magnetic field can drag/attract ferromagnetic objects	Any ferromagnetic objects
60 mT (600 G)	Whole-body Threshold Limit Value (8-hour exposure)	Authorized users only

7.3. Personal Protective Equipment (PPE)

When handling cryogens, wear insulated gloves and face shields or other splash eye/face protection, closed-toed shoes, and lab coats.

Insulating garments and equipment should be used in areas where 60-Hz electric fields exceed 5 kV/m, as demonstrated by measurement or calculation. Insulating gloves or, preferably, engineered controls (e.g., enclosure or shielding of a field source) must be used to avoid contact with objects that could expose personnel to sparks associated with field strengths greater than or equal to 5 kV/m.

8. Emergency Procedure

8.1. Emergency Involving Personnel

In case of injury, the other users in the laboratory must:

- Stay with the injured person (if it is safe to do so);
- Call 911 (KAUST landline) or 012-808-0911 (mobile phones) and indicate the location of the incident and if an ambulance is needed. Do not hang–up until you are told to do so;
- Immediately contact the PI or LSR;
- If needed, the injured person must go to the KAUST Health Emergency Room as soon as possible;
- Log the incident in the reporting system;
- Collaborate with the RST to investigate the cause of the incident.

8.2. Non-Personnel Emergency

In case of **non-personnel emergency,** the laboratory user must:

- Isolate the system from the main power supply (if it is safe to do so);
- If there is a fire, activate the fire alarm by pulling the nearest fire alarm pull station;
- Evacuate the laboratory and inform others in the vicinity;

- Call 911 (KAUST landline) or 012-808-0911 (mobile phones) and indicate the location of the incident and if an ambulance is needed. Do not hang–up until you are told to do so;
- Close all doors when leaving;
- Report to the designated assembly point;
- Do not re-enter the laboratory until you have been told it is safe to do so;
- Log the incident in the reporting system;
- Collaborate with the RST to investigate the cause of the incident.

9. References

[1] 2020 Guide to Occupational Exposure Values, ACGIH (2020)
[2] ICNIRP Guidelines on Limits of Exposure to Static Magnetic Fields, Health Physics, 96 (4), 504 – 514 (2009)
[2] ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields, Health Physics, 99 (6), 818 – 836 (2010)
[3] Static Magnetic Field Hazards, EPFL, visited August 2020 https://www.epfl.ch/campus/security-safety/en/lab-safety/hazards/static-magnetic-fields-hazard/
[4] Electromagnetic Radiation and Fields, Lawrence Berkley National Laboratory, visited August 2020 https://ehs.lbl.gov/resource/documents/radiation-protection/non-ionizing-radiation/electromagnetic-radiation-and-fields/

Document History

REV	DATE	PREPARED BY	DESCRIPTION
01	2018		Initial Document
02	2020	D. Darios	Complete revision, change the structure