NATIONAL ACCELERATOR LABORATORY

ENVIRONMENT, SAFETY & HEALTH DIVISION

Chapter 50: Non-ionizing Radiation

Selected Radio Frequency Exposure Limits

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1 Purpose

This document presents a subset of data most applicable to potential *radio frequency (RF)* hazards at SLAC, reproduced from the Institute of Electrical and Electronics Engineers (IEEE) Standard C95.1, "IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 kHz to 300 GHz" (IEEE Std C95.1). (That standard defines radio frequency as "a frequency that is useful for radio transmission, generally considered frequencies between approximately 3 kHz and 300 GHz" but covers frequencies starting at 0 kHz. The scope of this SLAC program is limited to the RF band.) The data are to be used by equipment owners and the non-ionizing radiation program manager when preparing preliminary hazard analyses and *radio frequency safety programs (RFSPs).*

2 Requirements

RF installations at SLAC must comply with the exposure levels given in IEEE Std C95.1. These levels are grouped in two tiers: upper tier for *restricted environments* and lower tier for the general public in uncontrolled environments.

The upper limit of the lower tier levels are *safety program initiation levels*: potential exposures at or above these levels require preparation of an RFSP (see Section 2.4). Once the RFSP is approved, a restricted environment is established in which exposures must not exceed the upper tier levels (see Section 2.3).

Note *The standard uses the term* exposure reference level (ERL) *to refer to exposure levels generally and* safety program initiation level *to refer to the upper limit of the lower tier. These terms replace the deprecated terms* maximum permissible exposure (MPE) *and* action level*, respectively.*

Note *Equipment owners are encouraged to consult the standards to verify that the equipment in question satisfies these limits. Contact the non-ionizing radiation program manager for any specific questions regarding the data presented here or in the standards.*

2.1 Symbols, Units, and Acronyms

A ampere

BR basic restriction

E electric field strength vector, measured in V/m

E	electric field strength amplitude, measured in V/m
f	frequency, measured in Hz
EM	electromagnetic
ERL	exposure reference level
GHz	gigahertz
H	magnetic field strength vector, measured in A/m
H	magnetic field strength amplitude, measured in A/m
Hz	hertz, cycles per second
kg	kilogram
kHz	kilohertz
J	joule
m	meter
MHz	megahertz
MPE	maximum permissible exposure
NIR	non-ionizing radiation
RF	radio frequency
RFSP	RF safety program
RMS	root mean square
S	equivalent power density vector in mW/cm^2
SAR	specific absorption rate
T	tesla
V	volt
W	watt
WBA	whole body average

2.2 Definitions

Note *The definitions below for far and near fields apply to simple sources of RF and microwave radiation (such as antennas or radar dishes) and are provided as a general guideline. These definitions may not be accurate for complex or irregularly shaped sources such as arbitrary radiation from broken or improperly connected waveguide flanges. Separate measurements of both the electric and magnetic fields should be made until it is certain that one is well outside the near field before relying on a single probe. A single probe is used only when the electric and magnetic fields are proportional, that is, the ratio of the two remains constant through space.*

action level. See *safety program initiation level*

averaging time.[1] The appropriate time period over which exposure is averaged for purposes of determining compliance with a maximum permissible exposure (MPE) limit or reference level

basic restriction (BR).[2] Exposure restriction based on established adverse health effects that incorporates appropriate safety factors and is expressed in terms of the in situ electric field (3 kHz to 5 MHz), specific absorption rate (100 kHz to 3 GHz), or incident power density (3 GHz to 300 GHz)

controlled environment. See *restricted area*

duty factor. The fraction of time a transmitter or source is emitting radiofrequency or microwave energy, usually expressed as the ratio of the time on to the sum of the time on and off during the averaging time. For continuous emitters, the duty factor is equal to 1. The duty factor is multiplied by the field measurement to obtain a time-averaged exposure.

electric field strength. The electric field strength, **E**, is a vector quantity that represents the force, **F**, on a positive test charge, q, at a point divided by the charge (**E** = **F**/q). Electric field strength is expressed in terms of a voltage gradient with units of volts per meter (V/m).

electromagnetic (EM) energy. The total energy stored in the electric and magnetic fields in a given volume. If this electromagnetic energy is absorbed by a body, the energy will raise the body temperature, whether or not the energy is confined in space or radiated. For radiated fields, electromagnetic energy consists of an electric field and a magnetic field oscillating in unison.

exposure reference level (ERL).[3] The maximum exposure level relative to ambient electric and/or magnetic field strength or power density, induced and/or contact current, or contact voltage. ERLs provide an adequate margin of safety against established adverse health effects. Also referred to as *maximum permissible exposure (MPE)*. See also *safety program initiation level*

induced body current. Currents induced in an individual during exposure to radio frequency electromagnetic fields

magnetic field strength. The force with which a magnetic field acts on an element of current situated at a particular point. Magnetic fields can be referred to in terms of two vector quantities: magnetic flux density,

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1 Definition per IEEE Std C95.1

2 Definition per IEEE Std C95.1

3 Per IEEE Std C95.1

B, or the magnetic field strength, **H**. The literature pertaining to extremely-low-frequency (ELF) radiation typically uses magnetic flux density, and the RF community uses magnetic field strength. The International System of Units (SI) unit for flux density is the tesla (T). Another commonly used unit for flux density is milligauss (mG), where 1 µT = 10 mG. In contrast, the RF community expresses field strength in terms of amperes per meter (A/m). Field strength and flux density in vacuum are related by the following equation: 1 A/m = 12.57 mG.

maximum permissible exposure (MPE). See *exposure reference level (ERL)*

power density. Power per unit area normal to the direction of propagation, usually expressed in terms of watts per square meter (W/m^2) or milliwatts per square centimeter (mW/cm^2). (The conversion between the two units is 10 W/m^2 = 1 mW/cm^2.)

power density, plane wave. Although most RF exposure standards are written in terms of **E** and **H** fields, it is sometimes convenient to express field strength in terms of the equivalent plane wave power density, **S**, in watts per square meter (W/m^2)

pulse-modulated field. An electromagnetic field produced by the amplitude modulation of a continuous-wave radio frequency or microwave carrier signal at a known repetition rate with a controlled duty factor

radiation, electromagnetic (EM). The transmission of energy through space in wave form, which can be characterized in terms of a wavelength and a frequency

radiation, non-ionizing (NIR).[4] Includes all radiations and fields of the electromagnetic spectrum that do not normally have sufficient energy to produce ionization in matter; characterized by energy per photon less than about 12 eV, wavelengths greater than 100 nm, and frequencies lower than 3×10^{15} Hz

radio frequency (RF).[5] A frequency that is useful for radio transmission, generally considered frequencies between approximately 3 kHz and 300 GHz

safety program initiation level.[6] The lower tier *exposure reference level (ERL)* above which a safety program must be implemented. Also referred to as *action level.*

2.3 Exposure Reference Levels

Note *The following tables and graphs are reproduced from and numbered the same as in Section 4.3.2 of IEEE Std C95.1. Note although the standard and tables and graphs below cover the range from 0 kHz to 300 GHz, the scope of this SLAC program is limited to the RF band, approximately 3 kHz and 300 GHz.*

4 Definition per “Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (up to 300 GHz), International Commission on Non-Ionizing Radiation Protection.” *Health Physics* 74 (4): 494-522; 1998

5 Definition per IEEE Std C95.1

6 Definition per IEEE Std C95.1

Table 8 ERLs for Whole-body Exposure of Persons Permitted in Restricted Environments (100 kHz to 300 GHz)

Frequency range (MHz)	Electric field strength (E)[a,b,c] (V/m)	Magnetic field strength (H)[a,b,c] (A/m)	Power density (S)[a,b,c] (W/m^2)		Averaging time (min)
			S_E	S_H	
0.1 to 1.0	1842	16.3 / f_M	9000	100 000 / f_M^2	30
1.0 to 30	1842 / f_M	16.3 / f_M	9000 / f_M^2	100 000 / f_M^2	30
30 to 100	61.4	16.3 / f_M	10	100 000 / f_M^2	30
100 to 400	61.4	0.163	10		30
400 to 2000	—	—	f_M / 40		30
2000 to 300 000	—	—	50		30

NOTE—S_E and S_H are plane-wave-equivalent power density values, based on electric or magnetic field strength respectively, and are commonly used as a convenient comparison with ERLs at higher frequencies and are sometimes displayed on commonly used instruments.

[a] For exposures that are uniform over the dimensions of the body, such as certain far-field plane-wave exposures, the exposure field strengths and power densities are compared with the ERLs in Table 8. For more typical nonuniform exposures, the mean values of the exposure fields, as obtained by spatially averaging the plane-wave-equivalent power densities or the squares of the field strengths, are compared with the ERLs in Table 8. (See notes to Table 7 through Table 11 in 4.3.5.)

[b] f_M is the frequency in MHz.

[c] The E, H, and S values are those rms values unperturbed by the presence of the body.

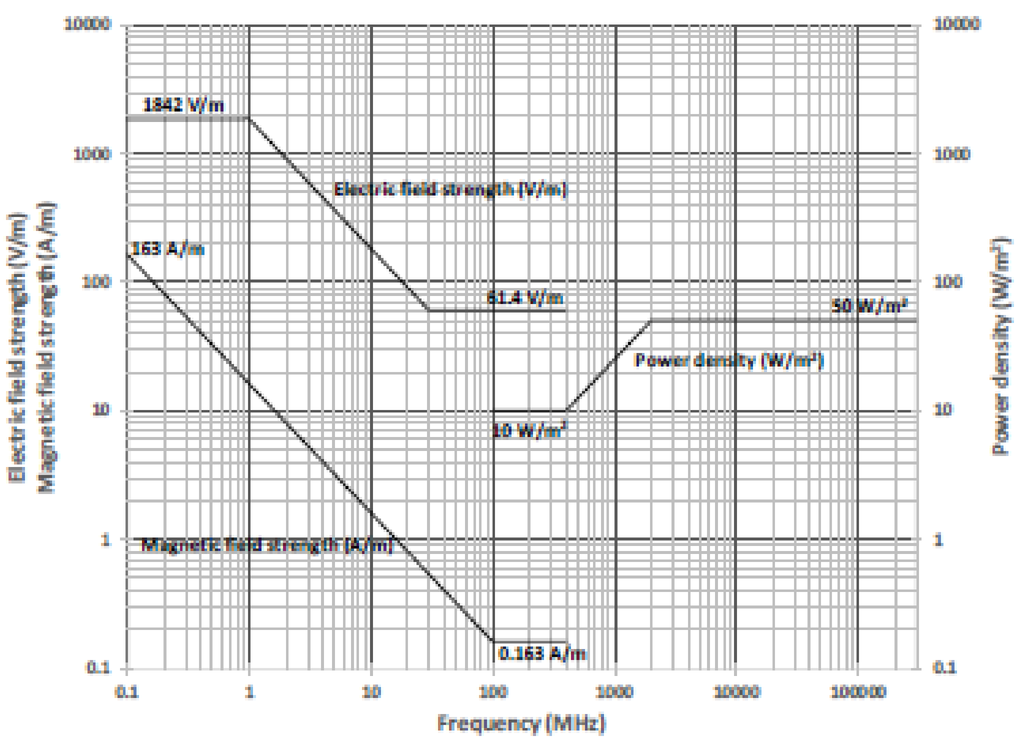

Figure 4 Graphical Representations of the ERLs in Table 8 for Electric and Magnetic Fields and Plane-wave-equivalent Power Density – Persons in Restricted Environments

2.4 Safety Program Initiation Levels

The *safety program initiation level* values in Table 7 indicate that an RF safety program (RFSP) plan must be initiated and submitted for review to the non-ionizing radiation program manager. Once the RFSP is approved, a *restricted environment* is established in which exposures must not exceed the limits shown in Table 8.

Table 7 ERLs for Whole-body Exposure of Persons in Unrestricted Environments (100 kHz to 300 GHz))

Frequency range (MHz)	Electric field strength (*E*)[a,b,c] (V/m)	Magnetic field strength (*H*)[a,b,c] (A/m)	Power density (*S*)[a,b,c] (W/m²)		Averaging time (min)
			S_E	S_H	
0.1 to 1.34	614	$16.3 / f_M$	1000	$100\,000 / f_M^2$	30
1.34 to 30	$823.8 / f_M$	$16.3 / f_M$	$1800 / f_M^2$	$100\,000 / f_M^2$	30
30 to 100	27.5	$158.3 / f_M^{1.668}$	2	$9\,400\,000 / f_M^{3.336}$	30
100 to 400	27.5	0.0729	2		30
400 to 2000	—	—	$f_M / 200$		30
2000 to 300 000	—	—	10		30

NOTE—S_E and S_H are plane-wave-equivalent power density values, based on electric or magnetic field strength respectively, and are commonly used as a convenient comparison with ERLs at higher frequencies and are sometimes displayed on commonly used instruments.

[a] For exposures that are uniform over the dimensions of the body, such as certain far-field plane-wave exposures, the exposure field strengths and power densities are compared with the ERLs in Table 7. For more typical nonuniform exposures, the mean values of the exposure fields, as obtained by spatially averaging the plane-wave-equivalent power densities or the squares of the field strengths, are compared with the ERLs in Table 7. (See notes to Table 7 through Table 11 in 4.3.5.)

[b] f_M is the frequency in MHz.

[c] The *E*, *H*, and *S* values are those rms values unperturbed by the presence of the body.

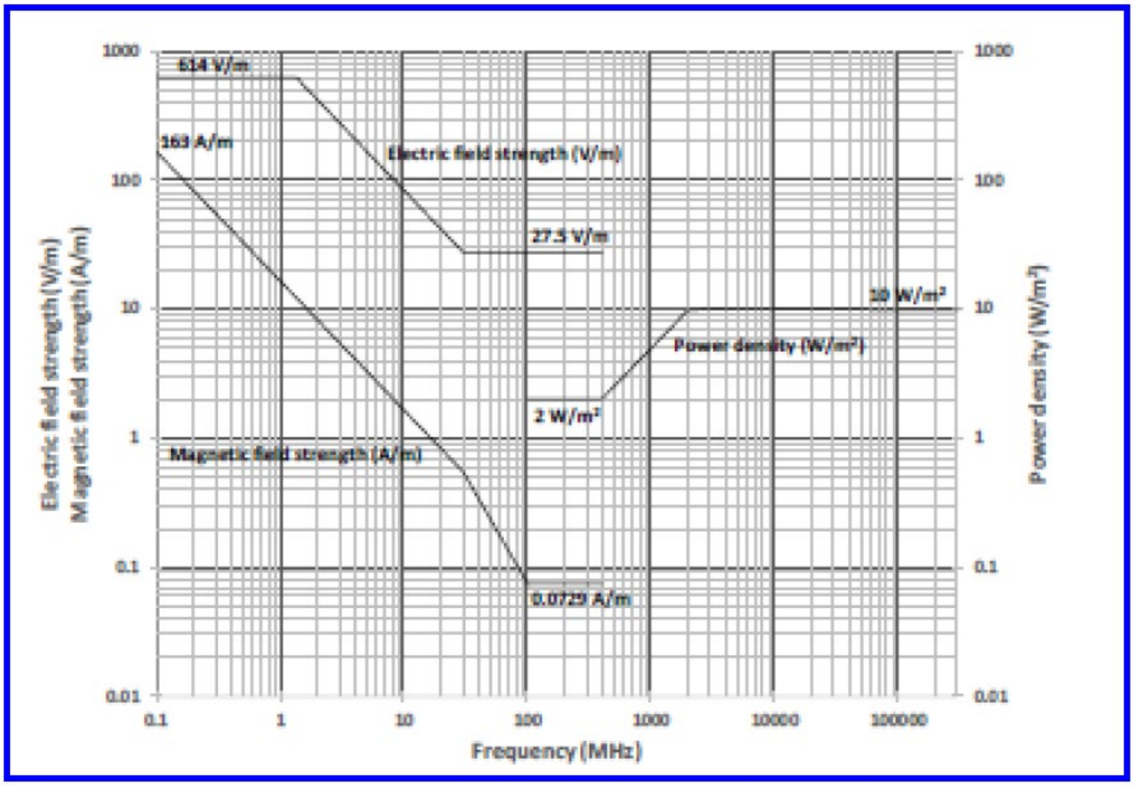

Figure 3 Graphical Representations of the ERLs in Table 7 for Electric and Magnetic Fields and Plane-wave equivalent Power Density—Persons in Unrestricted Environments

2.5 ERLs for Localized Exposures

The C95.1 standard also has allowances for localized (that is, non-whole body) exposures and other special cases that are addressed in its Tables 9, 10, and 11 that are incorporated into this SLAC ESH Manual chapter by reference.

2.6 Notes to IEEE Std. C95.1 Tables 7 through 11

The following notes are excerpted from IEEE Std C95.1, Section 4.3.5.

The following provides explanatory notes for Table 7 through Table 11:

a) The ERLs refer to exposure values obtained by spatially averaging the plane-wave-equivalent power densities, depending on frequency as follows (see Annex D for details):

   1) **Frequencies between 100 kHz and 6 GHz:** The ERLs for fields between 100 kHz and 6 GHz limit the WBA SAR and, therefore, correspond to the spatial average of the incident plane-wave-equivalent power density (or spatial average of the squares of the rms electric field strengths or magnetic field strengths) averaged over the projected area of the body.

   2) **Frequencies between 6 GHz and 300 GHz:** The ERL is expressed in terms of the incident power density spatially averaged over any square area of 4 cm^2. For exposures from millimeter-wave pulses, the fluence limit is averaged over 1 cm^2 square area of the body surface. The ERLs in Table 11 (see 4.3.3.2) provide guidance on limiting local exposure to RF fields above 6 GHz where the region of interest is the body surface.

b) For near-field exposures at frequencies below 400 MHz, the applicable ERL is in terms of rms electric and magnetic field strength, as given in Table 7 and Table 8 (see 4.3.2), columns 2 and 3. For convenience, the ERL may be expressed as plane-wave-equivalent power density, given in Table 7 and Table 8, column 4. For frequencies below 30 MHz, both the rms electric and the magnetic field strength shall be determined; for frequencies between 30 MHz and 400 MHz, either field component is sufficient provided that the point in question is in the far-field of the source. In the near field of a source, both fields shall be determined and compliant with the ERLs. For determining compliance with the ERLs in Table 7 or Table 8 (see 4.3.2) at the higher frequencies (above 400 MHz), either field component may be used when expressed as plane-wave-equivalent power density.

c) Compliance with the WBA ERL is intended to help ensure that the WBA DRL is not exceeded. However, in spatially nonuniform fields, compliance with the WBA ERL might not ensure compliance with the local DRL. For this reason, Table 9 and Table 10 provide guidance on limiting the magnitude of local ERL, which is intended to help ensure that local DRL is not exceeded.

d) For uncorrelated (in time) fields, for instance, mixed or broadband fields at a number of frequencies for which there are different values of the ERL, the percentage of the ERL [in terms of E^2, H^2, or power density (S)] incurred within each frequency interval shall be determined and the sum of all such percentages shall not exceed 100 %. For frequencies between 100 kHz and 5 MHz the ERLs for electrostimulation and for heating apply independently. In this frequency band the fractional summation for each ERL shall be considered separately. See Annex D for examples of ERL summations for each type of ERL.

   In a similar manner, for mixed or broadband induced currents at a number of frequencies for which there are different values of the ERL, the fraction of the induced current limits (in units of A/m^2) incurred within each frequency interval shall be determined, and the sum of all such fractions shall not exceed unity.

3 Forms

The following are forms required by these requirements:

- None

4 Recordkeeping

The following recordkeeping requirements apply for these requirements:

- None

5 References

SLAC Environment, Safety, and Health Manual (SLAC-I-720-0A29Z-001)

- Chapter 50, "Non-ionizing Radiation"
  - Non-ionizing Radiation: Radio Frequency Source Review, Operation, and Maintenance Requirements (SLAC-I-730-0A05S-013)
  - Non-ionizing Radiation: Radio Frequency Source Review Procedure (SLAC-I-730-0A05C-002)

Other SLAC Documents

- None

Other Documents

- Institute of Electrical and Electronics Engineers (IEEE) Standard C95.1, "IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 kHz to 300 GHz" (IEEE Std C95.1)