08.05 Electromagnetic fields (Edition 1999)

Overview

Since its discovery, electricity has radically transformed people's lives and has become an indispensable part of our civilisation. Electricity can be converted into any other kind of energy, such as mechanical work, heat or light, which means that its applications are universal. The use of electric energy inevitably entails the occurrence of **electric and magnetic fields**. These are almost always oscillating fields, as most technical devices are powered by alternating current or generate it themselves. Because the polarity of flux in an alternating current changes, field direction changes constantly, too. The number of cycles per second is known as the frequency, which is measured in Hertz (Hz). Fig. 1 summarises the spectrum of electromagnetic fields.

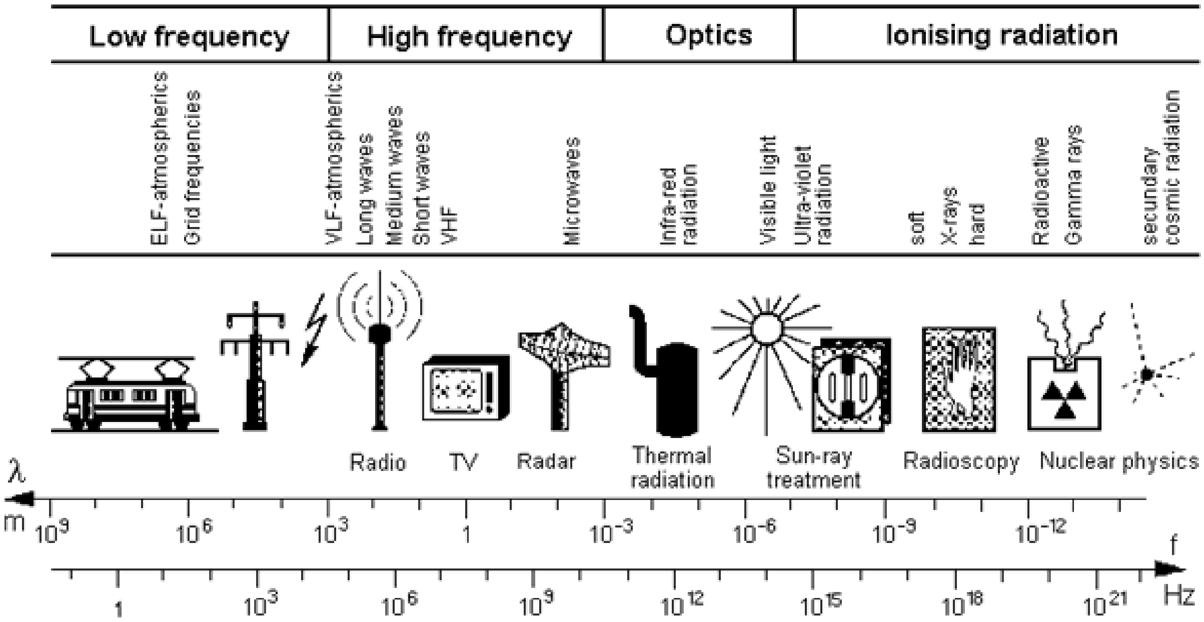

Fig. 1: Electromagnetic Spectrum: Applications and Manifestations of Electromagnetic Energy in Relation to Frequency f (or Wavelength λ) (VEÖ 91)

Strictly speaking, the term "electromagnetic field" only applies to high frequencies, where electric and magnetic fields are inextricably linked and can propagate freely in space as electromagnetic waves. At low frequencies, on the other hand, there are two independent fields, magnetic and electric. **Electric field strength** is described as **E** and measured in units of V/m or kV/m. The electric field is represented visually as field lines standing at right angles to the surface of the conducting object. Every geometry creates its own characteristic electric field. By way of example, Fig. 2 shows the field lines around a double-wire cable.

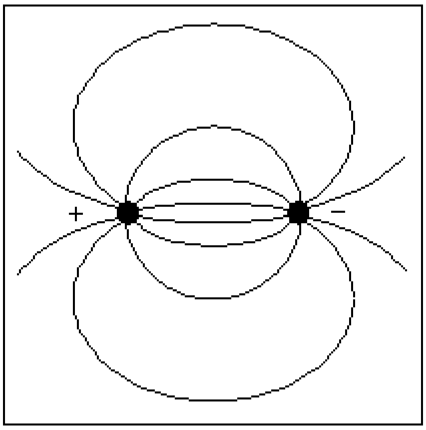

Fig. 2: Electric Field Lines around a Double-wire Cable

Magnetic field strength H is measured in amperes per metre (A/m), and **magnetic flux density B** in units of T (tesla). As magnetic flux densities are often very small, we usually refer below to a millionth of a tesla, or µT. Magnetic field lines run in circles around the conductor (cf. Fig. 3).

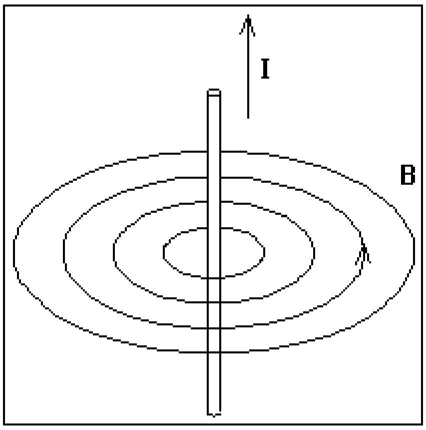

Fig. 3: Circular Magnetic Field B around a Conductor Carrying Current I

Electric and magnetic fields always spread out in space from a source. The electric field is a source field which occurs between separate charges (battery, mains socket). The magnetic field is a vortical field which only occurs when charges move, i.e. when a current flows. Any charged conductor has an electric field, whereas the magnetic field is only created when a flux begins, e.g. a lamp is switched on.

Field strengths decrease very rapidly as their distance from source increases.

Natural Fields

Static electric and magnetic fields (constant fields) of a significant field strength have always existed on this planet.

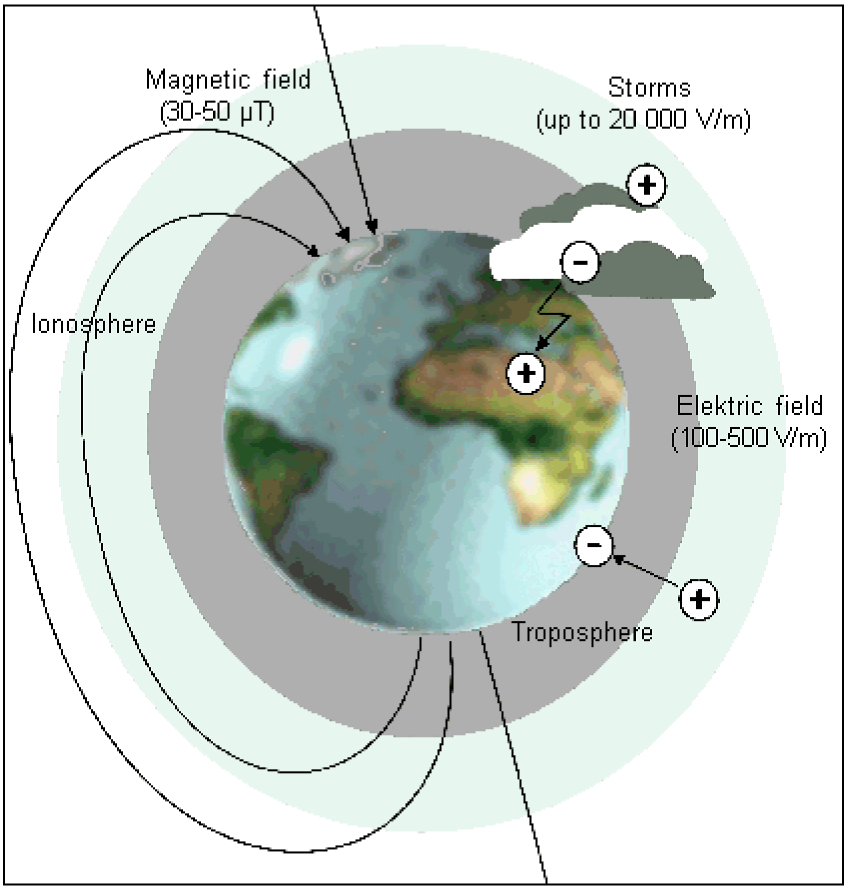

Fig. 4: Natural Electric (Direct) and Magnetic (Constant) Fields

The movement of air in the atmosphere and the ionising effect of cosmic radiation in the higher regions, the ionosphere, create a **field of direct electric current** between the surface of the Earth and the ionosphere. Under normal weather conditions, the field strength near the ground is around 100-500 V/m, whereas it can rise to 20,000 V/m (20 kV/m) during storms. Alternating currents at frequencies used in energy supply are practically non-existent. The natural background field strength at 50 Hz is only 0.1 mV/m.

The static **magnetic field** is familiar because of the way it affects a compass needle. It is almost constant over time and measures about 42 µT in Germany. This constant field is created by circular action in the Earth's core. Extremely high field strengths can occur in the vicinity of lightning (up to 1 T, which can cause heart failure in humans). Small variations in flux density are induced by the solar wind, which distorts the earth's magnetic field due to its streams of charged particles. Furthermore, global storm activity also results in high-frequency components within the magnetic field. However, these are so small that at 50 Hz the alternating field component is merely 10^{-6} µT (WHO 1984).

Technical Fields

At low frequencies technical field sources tend to be much stronger than naturally occurring fields. Most of these are either power supply installations, which generate and distribute electricity, or the technical entities which consume that energy. This includes industrial plants, private installations and consumer devices (e.g. household gadgets) and public transport systems (e.g. underground and railroad).

In addition to field emissions from large-scale technical plants, people are surrounded today, both at home and at work, by a multitude of sources of electric and magnetic fields which, if taken together, may be generating cumulated field strengths greater than those of the aforementioned technical plants. Field strength will depend primarily on the distance from the device in question and on its technical make-up, which accounts for a strong scattering of values for individual types of apparatus. The legend to the map lists the field strengths of electrical devices at normal usage distance ("Typical values for the magnetic flux densities of household devices at varying distances"). Comparison with the field strengths of high overhead voltage lines, also included in the map, shows that the field strengths of ordinary household gadgets are, indeed, often higher.

Biological Effects

"Electrosmog" is the buzzword which has directed public awareness towards technical field emissions in recent years. All over the world, numerous studies have been carried out on the possible effects of electromagnetic fields on humans, animals, plants and cell or tissue cultures, and a series of large-scale epidemiological surveys has also been conducted. The effects of electromagnetic fields generally depend on the frequency and intensity, but also on individual characteristics such as body size or angle towards the field.

Findings have been largely substantiated with regard to the effects of induced eddy currents at higher and medium-range field strengths (cf. Fig. 5), and these have formed the basis for the limit values in protective legislation.

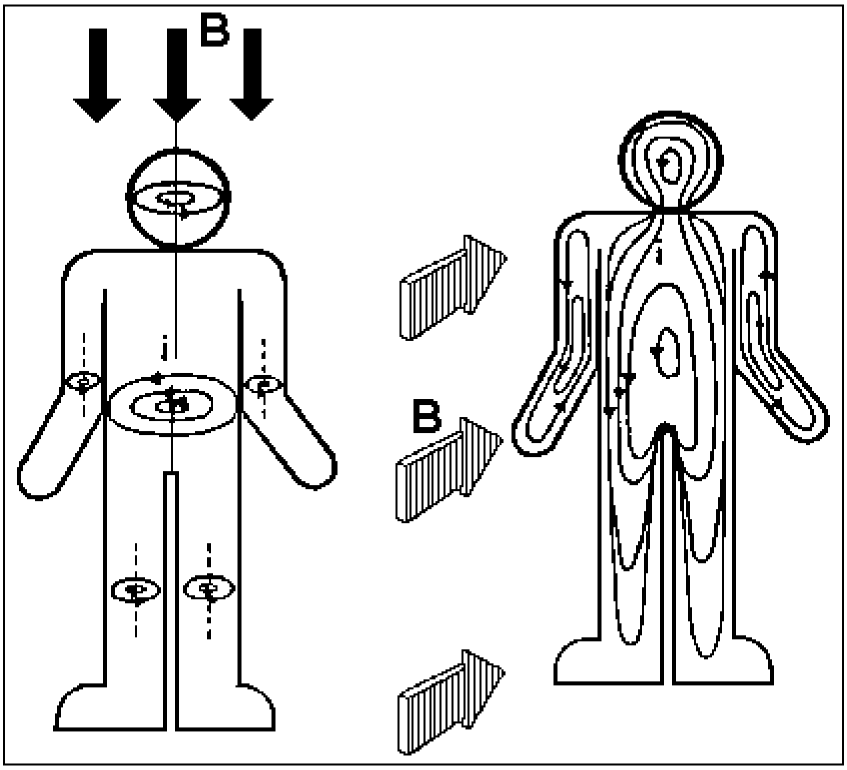

Fig. 5: Schematic Distribution of Eddy Currents Induced by Magnetic Fields of Longitudinal and Transversal Orientation Towards the Body (SSK 1990)

An external magnetic field induces eddy currents in the human body on a circular plane perpendicular to the direction of the field. Similarly, an electric field creates a flow in the body which follows the same direction as the field: under high overhead voltage lines, for example, the flow would be from head to foot - and vice-versa (alternating field!). These field-induced flows are recognised as the predominant cause of biological effects at low-frequency fields. Above certain trigger values, the induction flows, just like direct body current, cause effects which can damage the organism.

Tab. 1: Biological Effects of Different Current Densities at 50 Hz (cf. Bernhardt 1990)		
flux density [mA/m²]	**effect**	**required magnetic induction at 50 Hz [µT]**
> 1,000	extrasystoly; ventricular fibrillation; acute damage to health	> 500,000
100-1,000	values where irritation of sensitive tissue can be observed; health dangers possible	50,000 - 500,000
10-100	well-documented effects; clear visual and nervous effects; reports of accelerated healing of bone fractures	5,000 - 50,000
1-10	reports of subtile biological effects	500 - 5,000
< 1	lack of well-documented effects	< 500

Tab. 1: Biological Effects of Different Current Densities at 50 Hz (cf. Bernhardt 1990)

Although sensitive people can already detect electrical fields at 1kV/m, be it from the vibrations of body hair or due to discharge from conducting objects near the human body, there is no known danger to health, even when exposed for long periods of time. Indirect effects on electronic implants, e.g. rarely used types of single-pole artificial pacemaker, can occur from a field strength of around 2.5 kV/m or 20 µT, but life-threatening results are very unlikely. However, uncomfortable stutter rhythms can occur, which is why those affected people should stay away from strong fields (BfS 1994).

The scientific literature yields numerous epidemiological studies which address possible links between exposure to fields and the risk of cancer among certain sections of the population. So far, despite sometimes considerable effort, the results have been contradictory. Direct comparisons are rendered more difficult by varying circumstances. There is a shared emphasis, however, on the need for more research into both the epidemiology and the mechanisms at play.

Limit and Recommended Values

The observed effects have been used by various national and international bodies to establish limit or recommended values for different frequencies and areas of exposure. In addition to limits on direct field impact (V/m, A/m) at the workplace and among the general population, there are also maximum limits for indirect field impacts, pacemakers, small transmitters, partial body exposure, exposure of short duration, pulsed radiation, etc.

Due to the different safety strategies which have been conceived for different sections of the population, it is difficult to compare the various limit and recommended values.

The International Committee on Non-Ionising Radiation Protection (ICNIRP, formerly INIRC) of the International Radiation Protection Association (IRPA) has defined a maximum admissible body current density of 10 mA/m² (INIRC/IRPA 1990) which takes its lead from the body's own physiological current densities. Acute danger to health from the disruption of nervous, muscular and cardiac functions only occurs at 10 - 100 times this amount (see Tab.1).

To protect the population at large, ICNIRP/IRPA recommends a further reduction by a factor of five, resulting in a body current density of 2 mA/m².

26th BImSchV

To protect the general population and local neighbourhoods from harmful environmental impacts, this basic precautionary value has been used in German legislation to derive maximum limits for electric and magnetic field strengths at a frequency of 50 Hz. These values are legally binding under the provisions of the 26th Ordinance (26. BImSchV 1996), in force since 1 January 1997, regulating the Federal Pollution Control Law. The limits for low-frequency installations - defined for the purposes of the Ordinance as "stationary plant for the transformation and transmission of electricity at a voltage of 1000 V or more" - are:

Tab. 2: Limit Values Established for Fixed Low Frequency Installations by the 26. BImSchV		
frequency in Hz	**effective values of electric field strength and magnetic flux density**	
	electric field strength in kV/m	**magnetic flux dendity in µT**
50 Hz fields	5	100
16 2/3 Hz fields	10	300

Tab. 2: Limit Values Established for Fixed Low-frequency Installations by the 26th BImSchV

To protect against harmful environmental impact, overhead and underground cables, overhead traction supply lines and electricity transformer stations must be constructed and operated in a manner to ensure that, within their zone of influence, at full capacity and taking account of exposure to other low-frequency installations, the limit values for electric field strength and magnetic flux density are not exceeded in buildings or on sites that are intended to be used by people on more than a purely intermittent basis.

Under certain circumstances, the limits for magnetic flux density may by exceeded by 100 % for a short duration, and electric field strength may be exceeded by 100 % within a small area. "For precautionary purposes, the construction of, or substantial modifications to, low-frequency installations close to dwellings, hospitals, schools, kindergartens, after-school care facilities, playgrounds or similar installations in these buildings or on these sites" must be carried out so that the maximum effective values reflect these limits. In addition, the State of Berlin recommends remaining well within these limits and, especially during planning, exploiting any potential there is for reducing the values in these specific areas to 10 %. These recommendations are based on the effects of electromagnetic fields on electric and electronic implants, which are not considered in the 26th BImSchV, and on publications by the Federal Agency for Radiation Protection (BfS 1994).

The limit values only apply to construction or substantially modification of installations. Installations which were built before the 26th BImSchV entered force must meet these requirements within three years of that date. It should also be noted that the limits need only be observed in areas where people are intended to be present on a more than intermittent basis. This does not cover, for example, agricultural land or railway station platforms. Although platforms may be in constant use, individual passengers do not essentially stay very long.

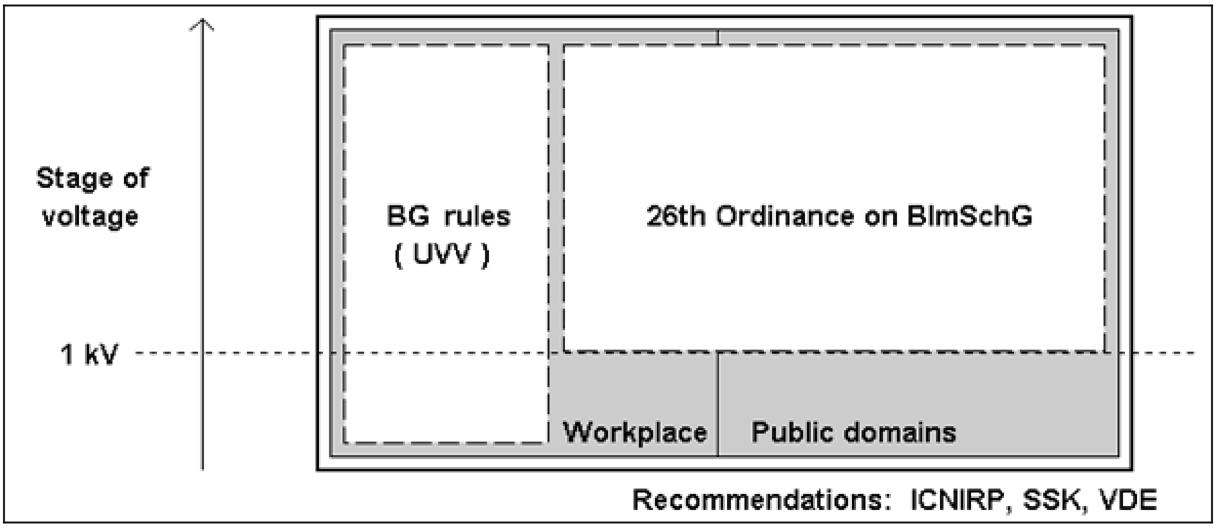

Fig. 6: Legal Scope of Different Limit and Recommended Values

BG = sectoral employers' liability associations (Berufsgenossenschaften)
UVV = Accident Prevention Regulations (Unfallverhütungsmaßnahmen)

As the limit values in the 26th BImSchV only concern certain installations - notably those with an operating voltage of 1000 V or more - it is often necessary in practice to consider the recommended values of the IRPA/ICNIRP (Tab. 3), which cover a far more comprehensive spectrum than those in the 26th BImSchV (see Fig. 6).

The IRPA/ICNIRP guidelines (ICNIRP/IRPA 1990, 1994, 1998) include both areas of public use and places of work. There are no limitations with regard to voltage levels or date of construction. The

IRPA/ICNIRP also addresses d.c. fields, which are an important feature in medicine and industry. However, the IRPA/ICNIRP values are not legally binding, having only the status of a recommendation. Yet they are important enough for the legislator to state explicitly that the limits in the 26th BImSchV are oriented to IRPA/ICNIRP guidelines.

At workplaces not covered by the 26th BImSchV - workplaces where the occurrence of electromagnetic fields can be expected - Accident Prevention Regulations apply which have been formulated by the *Berufsgenossenschaften* (sector-based employers' liability associations). These are currently being revised and will replace the previous recommendations of the *Berufsgenossenschaften* (the "Rules on Safety and Health Protection at Workplaces Exposed to Electric, Magnetic or Electromagnetic Fields", drawn up by the association responsible for the sector of precision mechanics and electrical engineering) (BGF 1995).

Tab. 3 summarises once more the limit and recommended values for public areas and workplaces. The scope of application is explicitly limited to 50 Hz. For historical reasons, recommended limits for occupational exposure were published in the early years by both the VDE (VDE 0848 1995) and the IRPA, founded on the generally recognised effects of strong electric and magnetic fields. The different field strength limits proposed by the two organisations are simply due to the different models they used for translating the same primary base values into secondary values for external fields. The IRPA also defined limit values for the general population which are still in place today, whereas the VDE did not attempt to remedy this lack until it introduced Amendments 1-3 to its Standard 0848, Part 4. Given that the VDE, which represents the interests of the electrical industry, is surely not free of a certain vested interest, the limits proposed by the VDE were never an unequivocal match for those of the IRPA and never progressed beyond the stage of a proto-standard. As a result, the legislator in Germany did not choose to be guided by the VDE, accepting instead the internationally undisputed values of the IRPA as the basis for the maximum limits in the 26th BImSchV. As part of the EU harmonisation effort, the European Committee for Electrotechnical Standardisation (CENELEC) has also proposed limit values. However, these are not likely to be adopted by the EC, and will probably be replaced by a recommendation from the Council of Ministers within the framework of guidelines on physical standards for workplaces.

Tab. 3: Limit and Recommended Values for Electric and Magnetic Fields

committee	recommended values at 50 Hz		date of introduction
	occupational:	general:	
IRPA recommendations	10 kV/m; 500 µT	5 kV/m; 100 µT	published 1990 confirmed 1998
DIN VDE 0848 Part 4	20 kV/m; 5,000 µT	-	October 1989
26th Ordinance to BImSchG	-	5 kV/m; 100 µT	1st January 1997
Accidential Prevention Regulations, Precision Mechanics and Electrical	21 kV/m; 1,400 µT	6.7 kV/m; 400 µT	pobably end of 1998
CENELEC - Human exposure to electromagnetic fields (low frequency)	30 kV/m; 1,600 µT	10 kV/m; 640 µT	will probably not be adopted by EC

Tab. 3: Limit and Recommended Values for Electric and Magnetic Fields

CENELEC - European Committee for Electrotechnical Standardisation

IRPA/INIRC - International Non-Ionising Radiation Committee/International Radiation Protection Association; its work is continued by the ICNIRP

DIN VDE - Deutsches Institut für Normung e.V. (German Standardisation Institute), Verband Deutscher Elektrotechniker e.V. (Association of German Electrical Engineers)

BImSchG - Federal Pollution Control Law

Statistical Base

The electromagnetic field strengths shown here are derived from measurements and calculations relating to selected field sources with frequencies from 0 to 500 Hz, collected during the project to create an "Emission Register for Low-Frequency Electric and Magnetic Field Exposure in Berlin" (Koffke et al. 1995, Stenzel et al. 1996, Frohn et al. 1995, Skurk et al. 1996, Frohn et al. 1996).

The project was supported by: Berliner Kraft- und Licht-Aktiengesellschaft (BEWAG), Senatsverwaltung für Gesundheit, Senatsverwaltung für Stadtentwicklung, Umweltschutz und Technologie, VEAG - Vereinigte Energiewerke Aktiengesellschaft.

The following districts of Berlin were observed:

- Berlin-Buch/Karow — new residential blocks near high-voltage overhead lines and railroad
- Berlin-Charlottenburg — S-Bahn (rapid transit railtrack) and railroad in the city area
- Berlin-Hellersdorf / Marzahn / Hohenschönhausen — residential and mixed areas with a high proportion of high-voltage overhead lines

The following field sources were taken into account:

- 110 kV, 220 kV, 380 kV high-voltage overhead lines
- 110 kV underground transmission cables
- transformer station at Karow
- 10 kV medium voltage stage
- 1 kV system
- substations
- railroad
- S-Bahn

A complete description of all tests can be found in the References (FGEU 1994, FGEU 1995, FGEU 1996, Frohn et al. 1996, Koffke et al. 1995, Stenzel et al. 1996).

The maps were based on plane table drawings (scale 1 : 10 000) from the Berlin Department of Construction and Housing. For the high-voltage overhead lines, underground cables and substations, grid maps were additionally provided by the power utilities (Bewag and VEAG), and these were used to correct deviations.

All maps were completely digitized and converted to vector format. The operating data for installations run at 50 Hz were also provided by the power utilities, and their projection files supplied the information on pylon design, pylon heights and minimum ground clearance at the centre of pylon fields.

The data for railtrack calculations (railroad and S-Bahn) were drawn from literature and plane table drawings, as there was no information from the operators. Feeder points and other special features have, therefore, not been considered. The precise course of the railtrack is traced with a horizontal deviation of ± 10 m.

Methodologies

Electric and magnetic fields are characterised by strong spatial variations and rapid fluctuations over time. Time-variation predominantly affects the magnetic field, which responds in proportion to current flow and can pass unchanged through any substance, with the exception of ferromagnetic or conducting materials. The electric field, on the other hand, is heavily distorted by buildings or vegetation, where these objects provide a shielding effect.

In procuring the displayed values, various methods were used. These partly rely on pure measurements or calculations, and partly on a combination of both.

Measurements

Measurements generally only served for categorising objects (e.g. substations, 1 kV cables etc.) and for standardising calculation data (e.g. railway traction currents), because although measurements describe a precise field condition, they only represent a very brief moment of time. When establishing information about large areas, measurements are not necessarily the best approach, in that they incur a substantial workload. Measurements are preferable in complex scenarios, which is often the case at workplaces.

Calculations

Calculation techniques (Utmischi 1976, Haubrich 1974, FGEU 1997) should not be regarded merely as a substitute for complicated measurements. They can be irreplaceable, such as in planning new installations or simulating different operating conditions.

Fields, in contrast to conventional environmental factors, can be fully described by the properties of the field source. We do not have to compensate for phenomena such as the drift of gaseous emissions due to air movements, followed by off-site inputs after precipitation.

However, this advantage only comes into play if the field can spread undisturbed. This is practically always the case for low-frequency magnetic fields, as ferromagnetic materials do not occur in the environment in sufficient quantities. Electric fields, meanwhile, are often distorted by buildings or vegetation. Nevertheless, the assumption of undisturbed field strengths generally represents the worst-case scenario.

The undisturbed field strengths along high-voltage overhead lines were calculated for the entire area under study. Measurements only served to verify the calculations. The field distribution around rail installations was determined locally and extrapolated for whole sections of track.

Calculations were carried out with the program package WinField® (FGEU 1997).

High-voltage Overhead Lines

In the area under study in Buch, there are three high-voltage overhead lines, around which the magnetic flux density was calculated by assuming average currents. The 110 kV supply line is partly underground. We must assume that the electric load changes throughout the day.

The calculations of electric field strength were based on the actual operating voltages at the time of measurement. These were 400 kV for the 380 kV line, 229 kV for the 220 kV line and 110 kV for the 110 kV line (operating voltage can change as a function of load). We must also remember that the sag of the overhead conductors exerts a major influence on field strength at ground level. This is ultimately dependent on the temperature of the cables, which among other things rises with an increase in transmitted wattage or air temperature. To simulate the field, an average sag at an outdoor temperature of +10 °C was assumed (in line with DIN VDE 0210). To demonstrate the influence of cable sag on the magnetic and electrical fields below the power lines, field strengths were calculated for the transverse profiles of three different cable sags (see Tab. 4).

Tab. 4: Calculated Peak Electric and Magnetic Field Strengths with Sag Variations of ± 1 m (Pylon Field 447-448; Minimum Sag 10.70 m) in the 380 kV/m Overhead Line

	sag deviation from mean value		
	- 1 m	0 m	+ 1 m
B_{max} [µT]	1.78 (87 %)	2.05	2.38 (116 %)
E_{max} [kV/m]	6.05 (88 %)	6.91	7.94 (115 %)

Tab. 4: Calculated Peak Electric and Magnetic Field Strengths with Sag Variations of ± 1 m (Pylon Field 447-448; Minimum Sag 10.70 m) in the 380 kV/m Overhead Line

It is apparent that cable sag has a decisive influence on the field strengths at ground level. The smaller the distance to the ground, i.e. the greater the sag on the cable, the greater this effect will be.

To verify the calculations, cross profiles were measured 1 meter above the ground at precisely defined points with known sag while simultaneously recording the conduction current. These measurements show a 95 % agreement with the calculated field strengths (cf. Fig. 7).

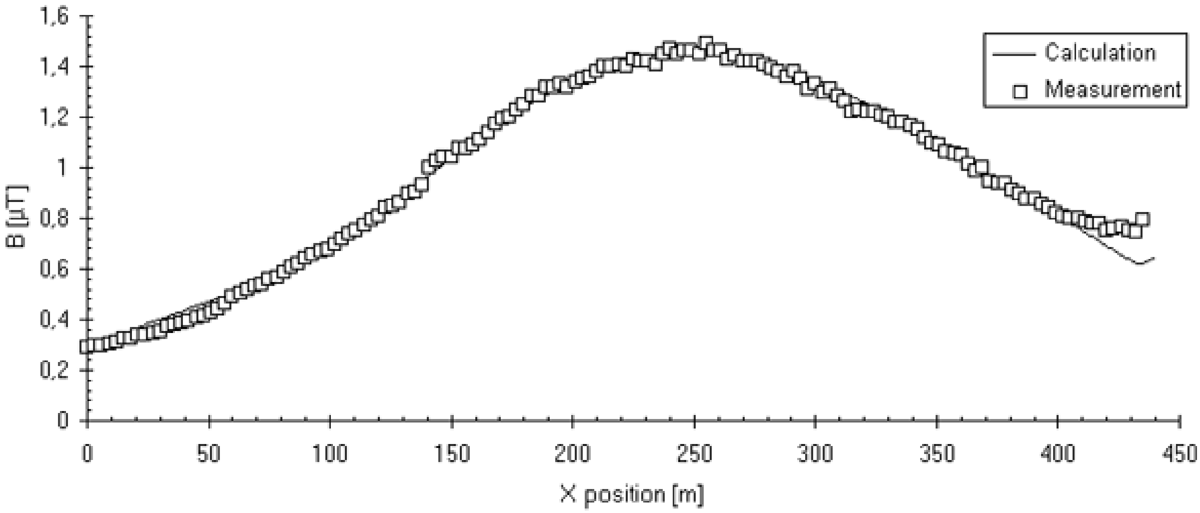

Fig. 7: Measured and Calculated Longitudinal Profile of Magnetic Flux Density 1 m above Ground beneath an 380 kV Overhead Line. The Pylons are Situated at Positions 0 m and 440 m.

These constant changes in cable sag (due to atmospheric temperature and load), and therefore in the distance between the lines of conduction and the ground, are the main reason, together with current flow, why measurements along overhead power lines can only yield momentary field strengths. This means that only measurements taken under specified conditions are of value and can be used as a base for calculations - ideally one cross profile per pylon field. Only if the measurement and calculation tally sufficiently the parameters for calculation can be applied to the whole line.

Underground Cables

The underground section of the 110 kV line was treated by analogy to the overhead line in measuring and calculating field strengths.

In practice it emerged that the field strengths on footpaths and roads created by the underground cable were very low and confined to a narrow space above the trench.

An electric field component does not occur over underground cables, as they are surrounded by an earthed metallic outer casing and lie in soil, which conducts.

Substations

Magnetic flux density was measured within a radius of very few meters around substations. This is sufficient, because at distances above 2-3 m the fields of low-voltage cables are stronger. Standardising time variance was unnecessary, as short-term fluctuations are low. Similarly to overhead lines, the load patterns of substations show slight variation in the course of a day or year. An electric field strength does not occur in the vicinity of substations, as the installation's electric field is shielded by the walls.

Railroad

The overhead traction current and the reverse current in the tracks can be determined by simultaneous long-term measurements of magnetic flux density at varying distances (e.g. 5, 10 and 20 m) from the track. For this purpose, the currents - as input parameters in a calculated simulation - are varied until the field strength profile of the magnetic field matches the measurements taken. It is essential to have exact knowledge of the route configuration. The results of the simulation will then have local validity. However, they cannot simply be extrapolated for longer segments of the route, as the magnetic fields caused by railway tracks are dependent on a multitude of parameters. The proportion of reverse current, and thereby compensation of the magnetic field, decreases, for example, as the distance to the next substation increases. To study a length of railway, therefore, we need several profiles composed from long-term measurements. The greater the density of profiles, the more we can deduce from the simulated traction currents.

This technique was used at Savignyplatz in the Berlin borough of Charlottenburg with a total of 15 longitudinal measurements. A typical long-term measurement of magnetic flux density at a frequency of 16 2/3 Hz is shown in Fig. 8.

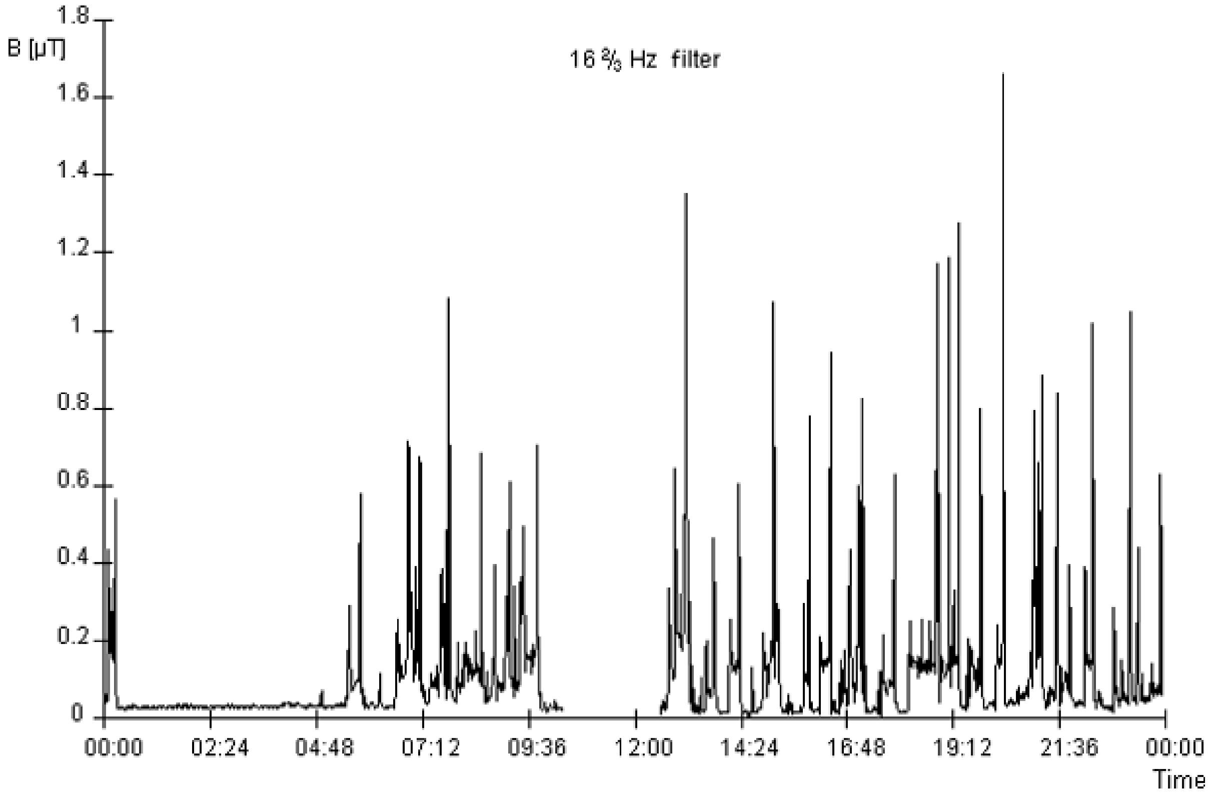

Fig. 8: Magnetic Flux Density at 11.2 m Distance from the Railtrack in Schlüterstrasse, Berlin-Charlottenburg

Due to the limited storage capacity of the measuring equipment, the duration was restricted to 21 hours, accounting for the gap between 10:11 a.m. and 12:52 p.m.

Typically for railway installations, the mean value for the full measurement period is several magnitudes smaller than the peak values. Each of these peak values was caused by one or more movements of trains between the stations Zoologischer Garten and Savignyplatz, in most cases by trains leaving Zoologischer Garten. The magnetic field is not emitted from the train, but is generated in a circle around the system of catenary and track. As the overhead lines were being fed from Wannsee at the time of measurement, the field only persisted at this site while a train was drawing energy between the point of measurement and Zoologischer Garten. This never lasted longer than five minutes (Plotzke et al. 1995). As the train passed, the field strength dropped suddenly to almost zero. The residual field (base level in Fig. 8) was caused by trains standing at Zoologischer Garten which were drawing energy from the overhead supply for control technology, air conditioning etc.

The individual long-term measurements were used to draw up a profile of maximum field exposure for an ICE train travelling from Zoologischer Garten to Charlottenburg (see Fig. 9, the maximum value of 1.99 µT was measured in a restaurant directly under the viaduct). The fall in magnetic flux density with distance is clearly recognisable. In addition, a numerical calculation of magnetic flux density has been included; its maximum value is based on a simulated overhead current of 226.2 A and a reverse current component through the track of 68 %.

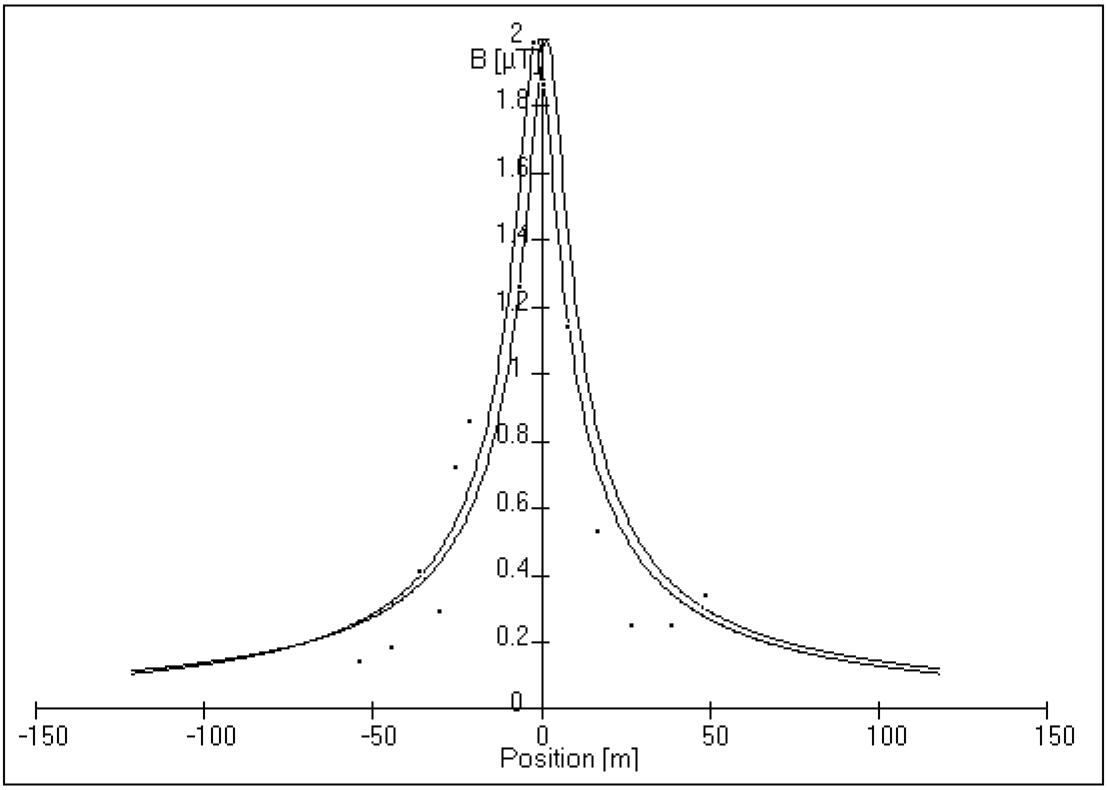

Fig. 9: Peak Magnetic Flux Densities by the Railroad Track - Determined by Simulation

The measured values are marked as dots. The curve on the left represents the magnetic flux density when a train passes on the southern track, the curve on the right corresponds to magnetic flux density on the northern track.

In order to calculate the magnetic flux density on the total track in Charlottenburg, each track was simulated by a three-conductor system (2 tracks, 1 catenary; transversal overhead conductor). Operating current was assumed to be 226 A, the figure yielded for the overhead lines by simulation. A method based on a uniform traction and reverse current along the entire segment is obviously generalising in a manner which is not necessarily realistic.

In Charlottenburg the railroad and the S-Bahn tracks run along a viaduct about 4 m high. As reference points for the observation of magnetic flux density, heights of 1 m and 6 m above the ground were chosen. The height of 1 m is relevant for persons in the vicinity of the railway. The second height of 6 m (or 2 m above the track itself) was chosen to assess the exposure of passengers on the platform or in the trains. For the latter group, the measurements are only of limited value as they ignore the influence of the train on magnetic flux density (possibly a significant reduction, e.g. in the case of the ICE (FGEU 1996)).

It must also be remembered that these are maximum values which only occur during short peaks. Generally the average magnetic flux densities are at least one magnitude lower. The peak values are of relevant interest however, as they are used to determine EMT, or electromagnetic tolerance (e.g. for evaluating screen disturbances).

The overhead conductors for the railroad service (operating voltage 15 kV) also generates an electric field. This was calculated for a height of 2 m above the track. The maximum value of 1.2 kV/m is found in the centre above the track, were passengers are completely shielded by the train's metal body. A person standing directly on the edge of the platform at Savignyplatz is exposed to a maximum field strength of 0.4 kV/m.

Berlin S-Bahn (Rapid Transit Railtrack)

The procedure for the S-Bahn track was the same as the one described above. Unlike the main line, however, the field was a direct one, as the Berlin S-Bahn is powered by direct current (operating voltage 700 V).

Measurements of the magnetic flux density along S-Bahn routes indicate a time variance different from that of the railroad service (see Fig. 10) due to the greater frequency of trains. It is easy to recognise how fluctuations in the direct magnetic field fade with the reduction in service once normal operations close for the night around 1 a.m.

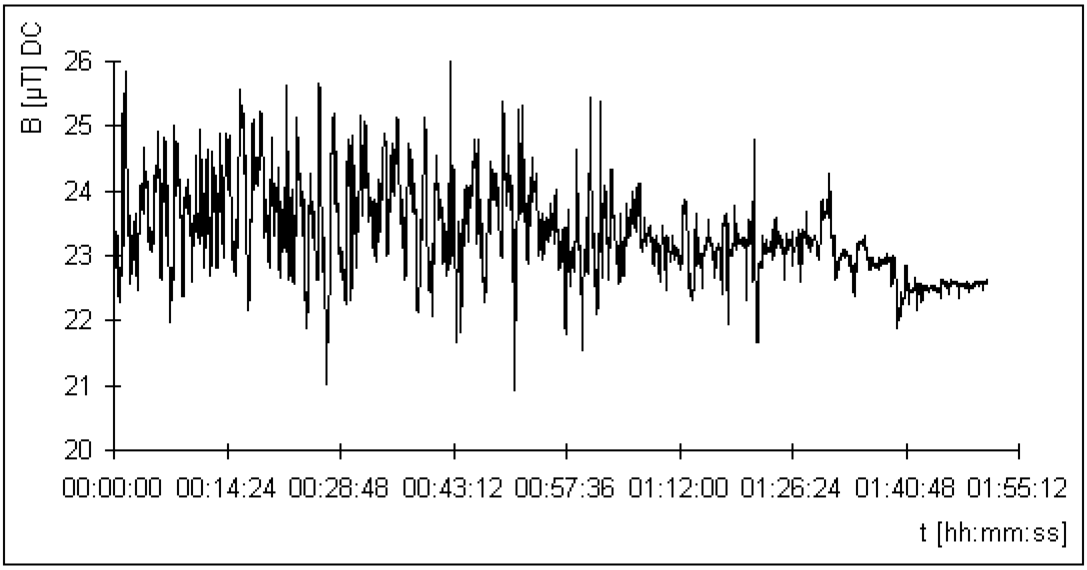

Fig. 10: Constant Magnetic Field beneath the S-Bahn Bridge over Knesebeckstrasse by Savignyplatz during Night-time Measurement which Shows Rail Traffic Waning

The level at the end of the measurement is accounted for by the Earth's magnetic field, but with the measuring probe positioned vertically and not towards the Earth's magnetic field of 42 µT.

Again, in the longitudinal values measured for the S-Bahn, maximum values tallied with those calculated by numerical simulation on the basis of a traction current of 1,300 A and a reverse current component of 100 % (see Fig. 11). Due to the relatively short distances between the feeder points a very high reverse current component can be assumed.

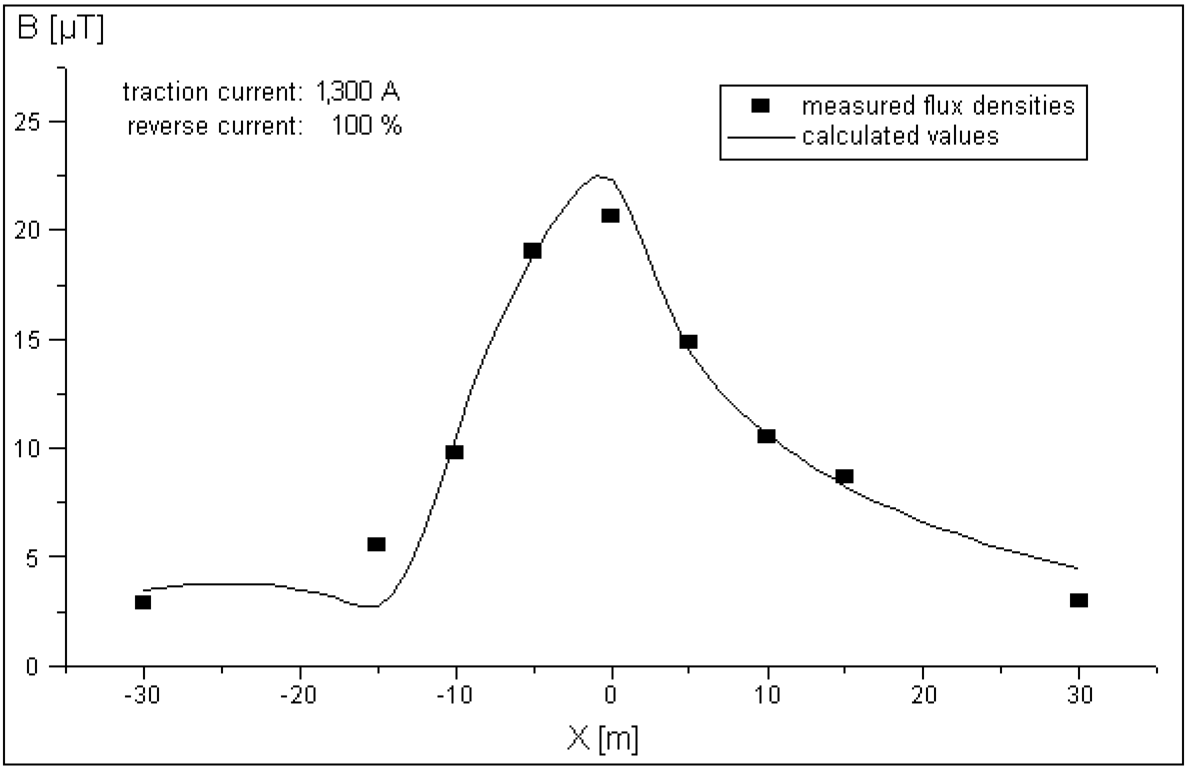

Fig. 11: Measured and Calculated Development of the Magnetic Field under the Bridge over Knesebeckstrasse in Berlin-Charlottenburg

The Earth's magnetic field of up to 42 µT has already been subtracted. Position 0 is half-way between two S-Bahn tracks.

It should be borne in mind that the natural (constant) electromagnetic field is 42 µT and both EMT thresholds and human health recommendations are several magnitudes larger.

Map Description

Map 08.05.1: Power Stations, Electricity Grid and Lines of Distribution

The map shows the high and highest voltage grids operated by Bewag at stages 380 kV, 220 kV and 110 kV. The Bewag grid is linked into Germany's interregional power grid via the 380 kV and 220 kV lines and the transformer stations (TS) at Teufelsbruch in the west, Malchow in the north and Wuhlheide in the south-east of the city.

Currently a 380 kV diagonal link is being constructed underground from TS Teufelsbruch via TS Mitte to TS Friedrichshain, and by the year 2000 this will be extended onwards to the transformer station in the eastern Borough of Marzahn. From TS Marzahn to TS Neuenhagen (to the east of Berlin) a new 380 kV overhead line is being built. Once the 380 kV diagonal link is completed, the 110 kV and 220 kV lines which still bring power from Neuenhagen into the city can be decommissioned.

The 110 kV system links Bewag's inner-city power stations to Berlin's electricity grid. Simultaneously, this stage of voltage is used to supply approx. 80 110/10(6) kV transformer stations which distribute electricity across town. In the western part of the city, the 110 kV lines are predominantly underground, in the east a 110 kV overhead network is the backbone of power provision.

Map 08.05.2: Magnetic Flux Density beneath High-voltage Overhead Lines (50 Hz)

The illustration shows the magnetic flux density generated 1 m above ground by the high overhead voltage line in Buch/Karow. We can see that areas of equal flux density merge beneath the lines. It is not possible to distinguish which field is caused by which line. At the bottom, the course of the 110 kV line which is partly constructed under ground is clearly discernible. Even though the field strengths above the course are consistent, they do not spread as far in the vicinity of the underground cable. The reason for this is the compact way the 110 kV cable was laid, leaving only a weak residual field. Directly above the cable, however, this advantage is cancelled out by the proximity of the cable to the surface of the ground compared to the overhead cables. At higher voltages the field strengths above underground supply lines are actually higher than those beneath equivalent overhead lines, because due to the increased transmission wattage the cables need additional cooling, which prevents a compact laying.

In line with DIN VDE 0848 T1 (VDE 0848 1995), the maximum magnetic flux densities calculated for the high overhead voltage lines for a height of 1 m above ground show the following values for the assumed parameters (medium load):

overhead line	increase at peak load	magnetic flux density B
110 kV	2.0 µT	+ 53 %
220 kV	4.2 µT	+ 14 %
380 kV	2.6 µT	+ 42 %

The validity of the calculation was substantiated by selected measurements. In the case of a greater load the magnetic flux density increases in proportion to wattage. The calculated maximum fields strengths at 1 m above ground for the 110 kV underground line at average transmission loads are:

laying technique of the 110 kV line	magnetic flux density B
cable in a pipe*	0.35 µT
free cable	0.24 µT

This technique is only used beneath roads.

To place this in context, we should indicate the magnetic flux density at 1 m above ground for 1 or 10 kV underground lines in Buch/Karow. The maximum was 0.67 µT, which is higher than the values for the 110 kV line.

Map 08.05.3: Undisturbed electric field strength beneath High-voltage Overhead Lines (50 Hz)

This map shows the electric field without any kind of environmental influence (except pylon influence). The surface area is the same as in Map 08.05.2. The maximum values calculated, in line with DIN VDE 0848 Part 1 (VDE 0848 1995), for the electric field strengths of the high overhead voltage lines at 1 m above ground and for the assumed parameters are:

overhead line	**electric field strength E**
110 kV	2.0 kV/m
220 kV	4.8 kV/m
380 kV	7.6 kV/m

The validity of these calculations was again confirmed by selected measurements. As a rule, the electric field strength is independent of the current flow. In the case of low load, however, the electric field strength decreases slightly because the temperature of the conductor cable drops, so that the cable is tauter and rises further from the ground.

The electric field strength exceeds 5 kV/m over certain small areas, but all of these are on land, such as forest or meadow, where people are not usually intended to remain for long periods. To assess the maximum electric field strength of 7 kV/m under the 380 kV overhead transmission line, it is important to consider the special circumstances in which it was planned. The line was built in 1979 to the standard TGL 200-0614, which applied in the former GDR. The field strengths should not be considered critical as they occur exclusively outside built-up areas and in reality there is some reduction due to vegetation. In addition, we must regard the calculated electric field as idealised, especially at greater distances from the overhead lines, because once again vegetation and buildings significantly reduce the strength under authentic conditions.

Above the underground line, electric field strength is zero (see Methodology).

Maps 08.05.4 and 08.05.5: Magnetic Flux Density and Undisturbed Electric Field Strength by High-voltage Overhead Lines (50 Hz) in Vertical Profile

The position of the profiles is marked on maps 08.05.2 and 08.05.3. The illustrations reveal that field strengths vary vertically as well as horizontally. In this format it is clear that the sources of the field strengths are the conducting cables. Field strengths decrease with distance from the cables at a rate of 1/r (r = radial distance to the cable). The limit values for magnetic flux density imposed by the 26th BImSchV are exceeded only very close to the cables, an area deep inside the safety zone. Anybody approaching the cables would be hit by spark-over before reaching the area where values exceed the limit. With the undisturbed propagation displayed here, the electric fields only just touch these admissible limits around the deepest cable sag.

Map 08.05.6: Influence of Trees on the Spread of Electric Fields beneath Overhead Lines (50 Hz)

Houses, trees or hedges noticeably distort the electric field. The example of 3 trees of 5 m height beneath an overhead 220 kV line is shown here. The field strength between the trees' branches is higher than on the opposite, undistorted side (left). However, field strength directly beneath the trees is lower, as the electric field is deflected by the tree canopy. Without the trees, a completely symmetric field strength pattern would prevail (the field could be perfectly mirrored on an axis vertically traversing the centre of the pylon).

The reduction of electric field strength in the immediate vicinity of a tree is around 85 % beneath a 380 kV line, and 5 m further on it is still about 50 % (IZE 1994).

Map 08.05.7: Magnetic Flux Density at a Substation (50 Hz)

At the time of measurement at 1 m above ground, this station was operating at about 50 % of its nominal capacity (630 kVA).

No field strengths are marked for the interior of the station as this normally inaccessible area could not be entered for measurement. In the vicinity of the station there are two local peaks in magnetic flux density: the bottom right-hand corner, where the transformer and low-voltage distribution are located, and by the upper wall, where we find the high-voltage switchgear. At 9 different substations the magnetic flux densities measured for these peaks ranged from 0.85 to 3.54 µT. As the distance from the wall increased, flux density fell rapidly and at 1.75 m only measured 0.3 µT.

Depending on design, higher field strengths may occur at substations. This is always the case when parts of the electric installation, especially the low-voltage distribution, are fitted directly to an outer wall. Situations where the image quality of visual data displays may be disturbed by low-frequency magnetic fields in the immediate vicinity of the building (approx. 1-2 m) only occur when the station is integrated into a building ("fitted stations").

Map 08.05.8: Magnetic Flux Density by the Railroad Track at Savignyplatz (16 2/3 Hz)

Shown here is the oscillating magnetic field at 16 2/3 Hz in the vicinity of the railway section near Savignyplatz station which is generated by the railroad overhead traction supply and the tracks. This field is not constant, only occuring when trains are passing between Zoologischer Garten and Savignyplatz. Two heights were chosen for calculation. 1 m above ground is relevant for people on the pavements and streets or in the shops at Savignyplatz, while 1 m above the station platform at Savignyplatz applies to passengers and rail personnel.

At a traction current of 226 A, the maximum railroad induced field strengths calculated for people waiting on the platform at the S-Bahn station Savignyplatz is 4.8 µT or 0.4 kV/m (16 2/3 Hz).

The average magnetic flux densities are at least one magnitude lower. By the viaduct, at 1 m above ground level, the maximum flux density is 2 µT (16 2/3 Hz).

The peak values caused at rail installations by railroad trains are relatively high compared to those of 50 Hz power supply. However, they are only of short duration - and the limit values for 16 2/3 Hz fields are higher (10 kV/m and 300 µT). Station platforms are not designed for people to remain for long periods, and usually their "dwell-time" is brief. The 26th BImSchV does not, therefore, apply. Rail-based transport systems are also not covered by the 26th BImSchV, as these vehicles are not fixed installations.

Map 08.05.9: Magnetic Flux Density by the S-Bahn Track at Savignyplatz (0 Hz, Constant Field)

When considering the constant magnetic field at Savignyplatz station and in the vicinity of the S-Bahn track, we must remember that it is derived from peak traction currents. The peak field strengths calculated for people waiting on the platform were 79 µT (0 Hz, constant field)

The average magnetic flux densities are at least one magnitude lower. By the viaduct at 1 m above ground level, maximum flux density is 25.8 µT (0 Hz).

The magnetic flux densities measured in the trains are a magnitude higher than those below the viaduct, as fields at rail installations also decrease rapidly with distance. Even lower electromagnetic emissions can only be expected from highly sophisticated transport systems such as the maglev train Transrapid 07 planned to run between Berlin and Hamburg (Stenzel, Plotzke 1996).

A comparison of magnetic flux densities induced by high-voltage overhead lines and those in the vicinity of S-Bahn and railroad tracks present basic difficulties. The flux densities at S-Bahn installations may be greater than those of 50 Hz power supply, but they are a long way from exceeding the index values, as IRPA/ICNIRP recommend a maximum threshold of 40 mT (= 40,000 µT) for constant magnetic fields and the 26th BImSchV does not define any limits at 0 Hz. All the same, in the immediate vicinity there are often EMT disturbances that can only be eliminated by magnetic shielding (Naunheim 1991) for the affected devices.

Tab. 5 summarises the most important measurements and calculations. Field strengths are classified by frequencies (0, 16 2/3 and 50 Hz) and represent either average or peak values, depending on the case.

Tab. 5: Summary of Key Measurments and Calculations					
field source	elektric field strength (kV/m)		magnetic flux density (µT), medium load	peak value	peak value
	50 Hz	16 2/3 Hz	50 Hz	16 2/3 Hz	0 Hz
high voltage overhead line					
110-kV	2.0		2		
220-kV	4.8		4.2		
380-kV	7.6		2.6		
underground cable					
10/1-kV cable			0.35		
110-kV cable			0.24		
grid substation					
max. at the building wall			3.45		
at 1.75 m distance			0.3		
main-line railtrack					
on the platform		0.4		4.8	
beside the viaduct				2.0	
beside plane track line				20.0	
in the trains				36.0	
S-Bahn					
on the platform					79.0
beside the viaduct					25.8
beside plane track line					29.0
in the trains					241.0

Tab. 5: Summary of Key Measurements and Calculations

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