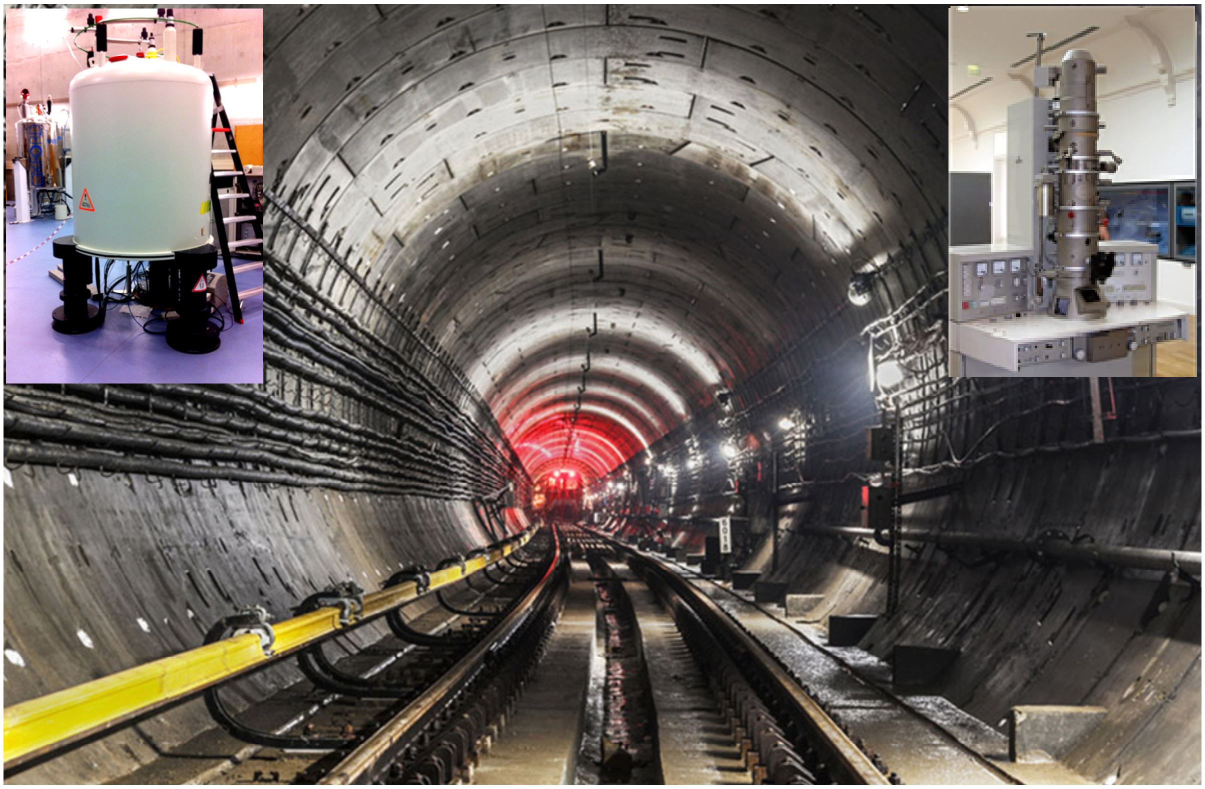
Bar-Ilan University
Tel-Aviv metro M2 line Ramat-Gan

EMC between University Instruments and the metro M2 Line



doc.ref.: BIU-Ramat-Gan-Metro-M2-EMC-v06.doc
version: 0.6
date: 05-09-2020
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0. Assessment Statement

Environmental impact of metro systems

The planning stage for a metro system in the Tel-Aviv metropolis is in full swing. The routes for three lines have been established and published to the general public. Line M2 will pass the community of Ramat-Gan. The plan has two alternative routes when passing the Bar-Ilan University, of which one will be choosen and be built.

The construction of a new metro system will have environmental impact such as (but not limited to) dust, vibration, noise and so-called electromagnetic emission both during construction and during operation. New electrical systems cause new electromagnetic phenomena in their environment and electromagnetic compatibility (EMC) with equipment already present in that environment must be managed.

The M2 is planned to pass the University at close range (northern route) or even beneath the University buildings (southern route). The University uses all types of scientific instruments in education and research. A new metro system is very well capable of causing electromagnetic fields that disturb the proper operation of the instruments, which would cause certain research to become very difficult or even impossible.

Assignment

The Bar-Ilan University instructed Microsim to perform an assessment on the risks of electromagnetic effects of metro operation, based on presently available information. Microsim has knowledge of and experience with investigating similar situations and has engineered solutions both in the Netherlands and abroad.

Scope

The technical scope of the assessment is: electromagnetic interference by M2 with scientific instruments of the University in the low and extremely low frequency bands. Interference in those frequency bands is presently not addressed in any EMC standard or guideline, so it has to be assessed on a situation specific basis.

Assessment

The outcome of this assessment for the Southern route is, that all listed instruments will suffer from electromagnetic interference caused by M2, most of them very severely. It is estimated that only very drastic mitigating measures will be adequate, like relocation to other existing buildings or even buildings that must be built entirely new. Construction of M2 along the southern route is not acceptable to Bar-Ilan University.

The outcome of this assessment for the Northern route is, that the expected emission of M2 will not rise above the immunity levels of the presently installed instruments, given certain assumptions on the design and construction of M2. However, after construction of the northern M2 route, Bar-Ilan University will face substantial location limitations when purchasing and installing new instruments.

Leusden, The Netherlands,
September 5th, 2020
(authorized signature)

Ir. D. van Bekkum,
(managing director)

1. Introduction

1.1 Location of University and planned alignment of M2

NTA Metropolitan Mass Transit System Ltd is presently planning a metro system for the Tel-Aviv metropolis. Plans are in the early development stage and routes have been planned for three lines: M1, M2 and M3.

M2 is an east-west line that is planned to pass nearby or even under the University district. For the exact routing, two options are being considered: the northern route and the southern route. The northern route passes the University buildings at close range. The southern route even passes directly under the University buildings. The local situation has been mapped in figure 1.1.

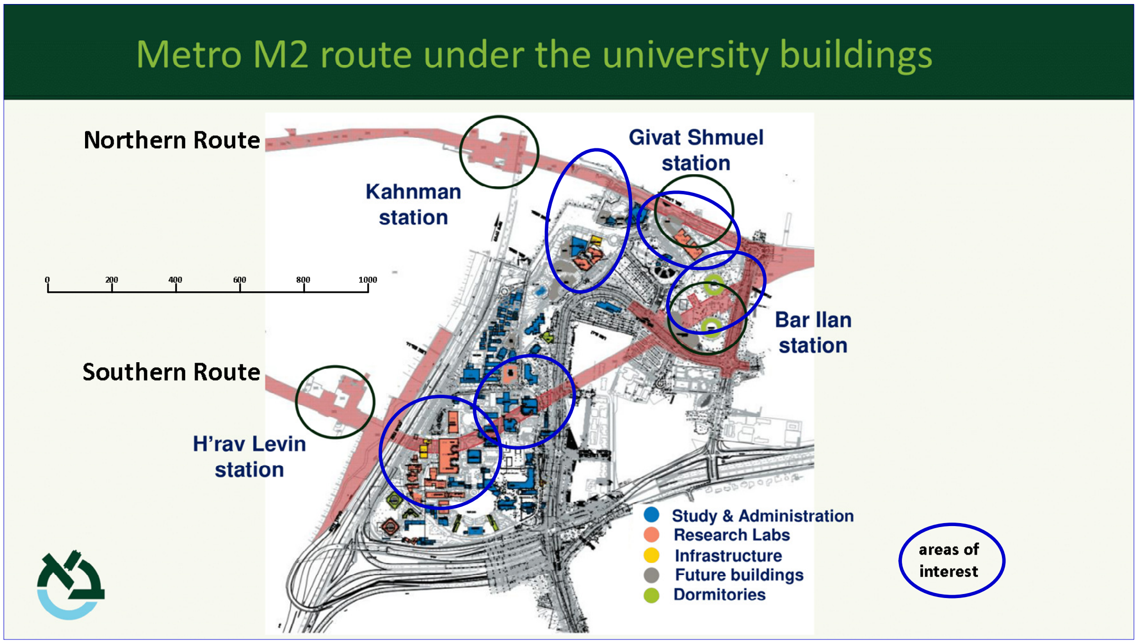

figure 1.1 – Bar-Ilan University buildings and routes of M2

The map also indicates some "areas of interest", buildings with scientific research laboratories which are very close to one of both routes. At first sight, the southern route seems to be causing higher risks of interference. But distance is not the only factor that determines that risk. The nature of M2's emission and the locations and properties of the instruments also play an important role. So both routes will be assessed.

The physical mechanisms and associated risks will be explained in the following chapters, but the fact that many buildings are situated within 300 m distance of the metro's alignment is sufficient reason for the University to do an in depth investigation.

1.2 Interference: scope

Rail systems like the planned M2 always have impact on their environments. Scientific institutions like the University use many instruments that are sensitive to noise, vibrations, humidity, dust and external electromagnetic sources. Prior to installation, the instruments locations are prepared to rule out interference, otherwise they will not perform adequately. Those measures are taken before actual installation. What happens in the outside world unforeseen and later on, can be a serious threat.

This document will assess one of those threats: electromagnetic (EM) interference, and especially from low and extremely low frequency electromagnetic fields.

1.3 EM interference: causes

Experience from other projects taught that (as a general rule of thumb) instruments closer than 300 m to an electrified rail line run a certain risk of interference. That sounds odd, but it must be taken into account , that scientific instruments, unlike common household appliances, can be extremely sensitive to external (ambient) magnetic fields.

EM interference from electrified rail systems has three main components that determine the magnitude of risk:

- high currents within the metro system (some thousends of Amps);
- relatively short distance of instruments to the alignment (some tens of metres);
- high degree of sensitivity of instruments (maximum of some tens of nano Tesla).

And all of those three components will be there, once the metro is in operation.

Magnetic fields can have unexpected properties, so it is necessary *not to assume that there won't be a problem*, based on feelings or implicit experience in other situations. It makes absolute sense to assume that there is a problem, *unless proven otherwise*.
An assessment in an early stage is very important, because it is very difficult and mostly extremely expensive, to take measures, once the metro is in operation. When interference turns out to ruin the operation of instruments, there is hardly any other possibility than either move the instruments to another location, or put severe restrictions on the operational service of the metro. That is a situation no one wants to face.

1.4 EM interference: risk assessment

The risk assessment will based on the presently available data and assumptions on the metro system that are in line with metro systems in general. Detailed data of the future Tel-Aviv metro system are not available yet, because the project is still in it's planning stage. But metro systems are in operation around the world, and data that are relevant for this assessment can and will be used.

This document has the following structure:

- chapter 2: "risks of electromagnetic interference describes the basic physics, the specific problems between electrified rail systems and scientific instruments and why these kind of problems are "new";
- chapter 3: "the metro system" describes the elements of electrified rail, that are root causes of this type of interference and why;
- chapter 4: "the university instruments" summarizes why certain instruments are sensitive to EM interference;
- chapter 5: "risk assessment" compares the results of an instrument by instrument technical investigation and estimates the risks;
- chapter 6: "mitigating measures" shortlists measures that can be taken to mitigate risks, explains why they reduce the risk and qualifies their feasibility;

2. Risks of Electromagnetic Interference

2.1 Electromagnetic fields in space

The generation of electromagnetic fields is (for the purpose of this document) also called "emission", though nothing physical is being emitted by a source. The term is used in radio telecommunications because mankind has the feeling that something is "emitted" by a radio source.

Electro magnetic emission has two components: electrical emission and magnetic emission. Generally speaking, electrical emission is not very much of an issue in rail systems. Most of the time, electric fields are relatively weak and addressed with proper insulation and insulation materials. We assume that that will also be the case for the M2 project. So the focus will be set to magnetic interference, though we will keep using the term EM interference.

Magnetic fields can be caused by different mechanisms, but in general, we concentrate on those caused by electric currents within an electrified metro system. Simply said, where currents flow, magnetic fields are present. They are basically four dimensional: in 3D space and time.

For the purpose of this document, we will refer to a spatial Cartesian or rectangular coordinate system, with rectangular axes x, y and z. Any vector can be decomposed into three spatial components or can be represented two sets of three numbers, representing the x, y and z of the point of engagement and representing the x, y and z of the end (point) of the vector. All arithmetic rules for addition, subtraction, etc. apply in each of the three directions.

In this document, we choose the following orientation:

- x: horizontally parallel to the metro track;
- y: horizontally perpendicular to the metro track;
- z: vertically perpendicular to the plain of x and y.

Also currents (represented by the capital I) have a vector value. But different from B, those will not appear everywhere in a 3D space, at least not for metro systems. Currents are confined to the space, occupied by electrical equipment and the associated conductors (cables and alike). That will be the basis for modelling when performing calculations.

2.2 Properties

For the purpose of this document, the following properties of magnetic fields, caused by currents, are important:

A. the direction (in space) of any magnetic field vector depends on the direction (in space) of its causing current. For example: a current in the x-direction causes magnetic field vectors in the y- and/or z-directions;
B. the magnitude of magnetic field vectors is directly proportional to the magnitude of the causing current. If a current magnitude rises (for example) to three times its original magnitude, so do all resulting magnetic field vectors;
C. magnitude and direction of a magnetic field vector depend on the distance of its point of engagement and its spatial position to the flow of its causing current. For a single current, the decrease of its magnetic vectors is proportional to the inverse of the distance;
D. if more currents flow in a 3D space (different magnitudes, different directions) then in every point in space, the total magnetic vector is the vectorsum of all individual vectors, caused by all individual currents.

This may look a little complicated at first sight, but it provides important clues for the management of electromagnetic fields.

Magnetic field can be manipulated by:

- changing the magnitude of currents;
- changing the distance to currents;
- changing the spatial paths of currents

These are the basic physical clues to reduce magnetic interference from a certain source. And they are basic for the analysis of interference risks, because instruments als have properties that obey the laws of Maxwell.

2.3 Environmental effects: time

And then there is the fourth dimension: time. When all currents remain *constant in space and time*, then all B-vectors remain constant in space and time. Those static situations are hardly interesting when investigating the effects of magnetic fields. Both humans, animals and instruments adapt to or can be tuned to such a situation. Though the earth's magnetic field is not the perfect example, it shows that (quasi) static magnetic fields are not a sources of much trouble.
But once currents start to change (either in space, or in time or both) then most (if not all) of the B-vectors will change as a function of time.

2.4 Sensitive instruments

The presence of special instruments also present special problems, which are normally overlooked when planning electrified rail systems. An example of the University's sensitive research and the use of special instruments is described by Prof. Lev Khaykovich (see annex A)

Figures 2.3.1 and 2.3.2 show two examples of sensitive equipment: (i) an electron microscope and (ii) nuclear resonance spectroscope. In short, the way these instruments can be disturbed by ambient low frequency fileds is summarized.

fig. 2.3.1 – electron microscope

fig. 2.3.2 – NMR spectrograph

Electron microscopes generate high energy electron beams from a high voltage source. The electrons pass through or scatter at samples (objects of research) inserted into the microscope. The electron beams must be focussed and diverted very precisely to cover the entire sample. Both actions are performed by highly accurate magnetic coils that operate the same way optical lenses operate on light. If an external magnetic field changes those fields, the process is ruined and the microscope no longer makes sharp images.

A nuclear magnetic resonance spectrograph generates a very strong constant magnetic field by means of a superconducting coil. Samples are placed in the bore of the coil and are perturbed by a weak VHF or UHF oscillating magnetic field. The nuclei of the sample respond by producing a signal of which the frequency is near to the resonance frequency of the nuclei, which on its turn depends on the strength of the strong static field and the properties of the sample's isotopes. An external magnetic field can disrupt that process, because the stability of the constant magnetic field is extremely important . Those coils are normally positioned with the bore upright, so this instrument is very sensitive to changes of the vertical component Bz of the flux density.

The conclusion is, that instruments that operate on the basis of very accurate static or slowly changing magnetic fields, may be very sensitive to interference by slowly changing ambiant fields produced by something like M2.

2.5 Induced voltages

Changing magnetic fields (also slowly changing ones) can induce voltages in nearby instruments. When a magnetic flux is being encompassed by a conducting (wire or circuit) loop or surface, then the changes of that flux will generate a voltage within that loop. And since the loop is conducting, a current will flow within the loop. The magnitude of those voltages is proportional to the speed of change of the encompassed magnetic flux. The transformer is the best known example where this effect is used for a specific purpose. Special instruments with any kind of conducting loops in their circuitry can thus be affected negatively. Though the change of the flux over time will not be big, it must be borne in mind that problems can arise.

2.6 Primary and secondary emission: stray currents

Currents within the metro system, both infrastructue and vehicles, will cause a magnetic field. When it concerns currents within the system, one could say that that is the primary emission of the system.

But there is a phenomenon that can cause currents outside the system, known as stray currents. Running rails of DC powered systems are not connected to earth for a number of reasons. But the electrical insulation between rails and earth is mostly such, that a small portion of the return currents leaves the running rails and flows back to the substation via mother earth. Figure 2.4.1 shows a typical picture, that explains the mechanism.

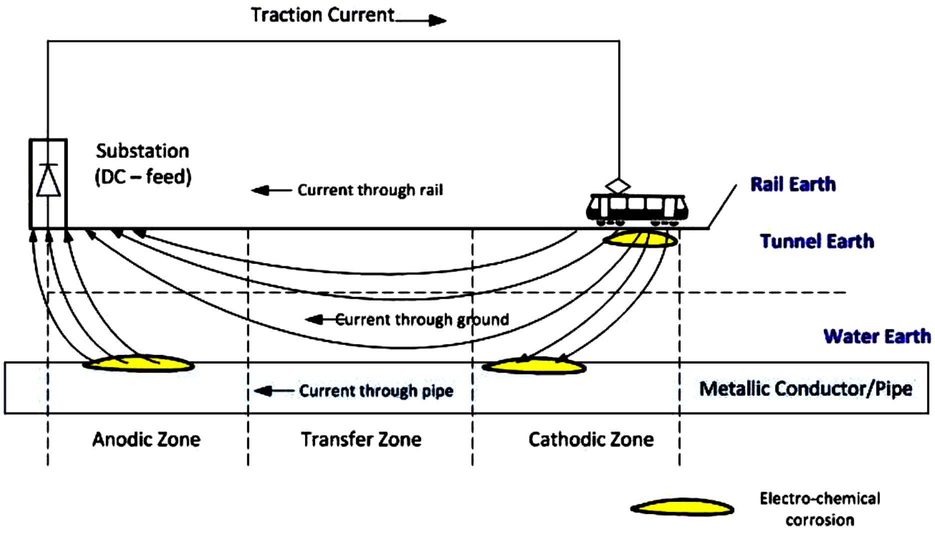

figure 2.4.1 – the stray current mechanism

Stray currents are a well known phenomenon in railway engineering and measures are taken to limit them. But the reason for this attention is the prevention is electrolytic corrosion of rails and adjacent metallic structures. Relevant railway standards are geared towards measures that limit stray current corrosion to acceptable levels.

Stray currents not only cause corrosion, they also cause electromagnetic emission, faithful to the appropriate law of nature. That is what we call the secondary emission of the metro system. The magnitude of those currents are generally much lower than the currents within the metro system (in the order of a few percentages). Stray currents from a metro system are mostly even lower than from a light rail system or a mainline railway.
But it is not so much the magnitude of stray currents that can have a negative impact. They flow across paths that can be unpredictable. When flowing too close to buildings or even through the buildings' earthing system with sensitive equipment, stray currents can have a very disturbing effect, due to their proximity.

2.7 Railway standards: the blind spot

Metro lines are constructed, very much based on the mandatory application of numerous technical recommendations, guidelines and standards, also relative to EMC. So the question is: is that not enough to avoid environmental impact of electromagnetic emission.

Electric rail systems causing electromagnetic emission is well known and adequately addressed by proper design and construction measures. National and international technical standards recognise the problem, define requirements and provide recommendations to avoid risks and assure proper mitigating measures. That works fine for higher frequency phenomena and well known "ordinary" mass produced electronic equipment. But sometimes that is not enough, because the standards have a blind spot.

An unknown niche that escapes the attention of railway planners, engineers and constructors is: *the emission of low to extremely low frequency emission of rail systems and its effects on special medical and/or scientific instruments*. Our experience is, that the application of standard railway engineering practises and railway standards (such as EN-50122-2 for instance) does not solve that kind of EMC problems. And if not addressed, then those problems will not be solved properly or even not at all.

3. The Metro System

3.1 Power and power supply

Electrified metro systems use electrical power, provided by so-called substations. Substations convert electrical power from a high voltage AC public grid to electrical power that is used by the metro vehicles, usually 750 Vdc. The use of d(irect) c(urrent) source is a legacy of more than a century ago. The fact that the voltage is constant does not mean that the current is constant. And when currents change over time, so do their resulting magnetic fields.

The flow of currents toward a moving vehicle requires long conductors in the infra and contacting elements on the vehicles. That is the reason for overhead wires and pantographs, or third rails and current collector shoes. Running rails are most of the time used as return current conductors, but some metro systems use a fourth (return current) rail.

Transport of electric power causes losses in the form of heat. Losses are proportional to the resistance of a conductor and proportional to the square of the current. Though the electrical resistance of rails is quite low, thousands of Ampères of current will cause significant losses and voltage drop. That is why electrified rail systems need more power substations than just one. For a metro system the distance between adjacent substations is in the order of 2 to 3 kilometres.

From a magnetic point of view, a metro system is a complicated set of currents, with sometimes different magnitudes, different directions in space and (within the vehicles) different and changing locations. And all those currents contribute in their own right to the total magnetic field they cause in the environment.

3.2 System behaviour

Currents within a metro system are not at all constant in space and time. The two main reasons are (i) the need for electrical power is not constant and, (ii) currents within the vehicles also move in space. Both effects cause the magnetic emission to change as a function of time, both in magnitude and direction. Though metro systems are simply called DC, they have a non-negligable AC nature.
So an observer or instrument along the line will experience a magnetic field that is frequently changing. And for an instrument along the line, two things are important: (i) the magnitude of the changes, (ii) the rate of the changes over time (simply said: frequency).

Electric vehicles have electric drive systems. Especially during acceleration and braking, those are by far the biggest electrical consumers. The way those function technically also determines their current consumption as a function of time. A very common technique is the so-called asynchonous drive system. The drive converts the DC voltage to a three phase switched puls pattern of variable frequency and delivers it to motor. The rotor of it has no copper wired windings and does not need brushes to bring current to the rotating rotor. It has copper bars which have been shorted at both ends. The variable frequency is delivered to three stator windings that causes a magnetic rotating flux, which forces the rotor to rotate. The rotor consists of some sort of metal cage with copper bars, electrically shorted at both ends. In those bars large currents flow because of induction by the flux of the stator. Since the rotor tries to counteract, it will rotate. The mechanical rotation of the rotor and the flux rotation in the stator however are not synchronous and it is essential that it remains asynchronous. For a vehicle, the rotational speeds of stator field and rotor must increase from zero to line speed. That is done by changing the pulse pattern and that causes a gradual increase of the DC current. When the flux in the motor reaches its point of saturation, then the absorbed current reaches its maximum and then remains constant, until the vehicle reaches line speed. The point of maximum current depends on the design of the drive system, but typically will be reached at vehicle speeds between 25 and 35 km/h.

The associated pattern of current absorbtion will cause a one-on-one magnetic field, which is typically for the drive systems. And since all drives of a vehicle must operate synchronous (which is something else than synchronity between rotor and stator field), this pattern is typically for a vehicle.

Figures 3.2.1 and 3.2.2 shows the typical "signature" of an accelerating vehicle.

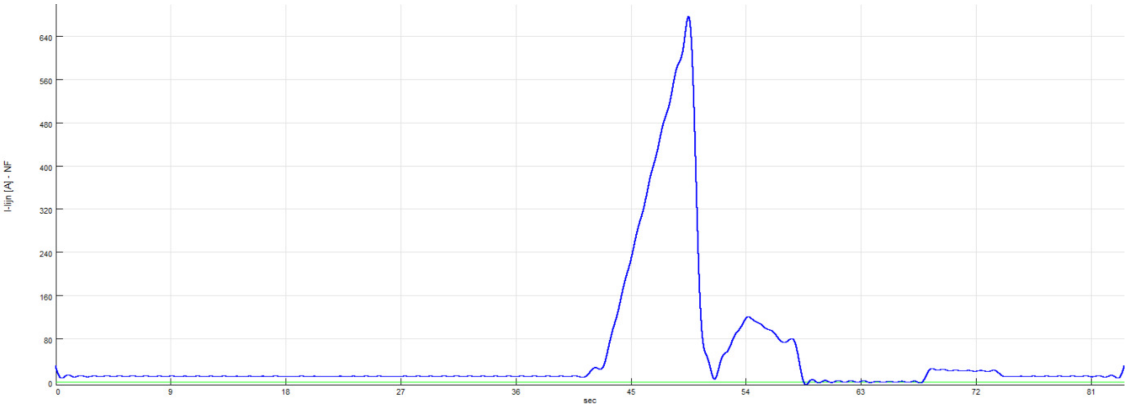

figure 3.2.1 – measured current absorbed by vehicle – LD filtered with fc=1 Hz

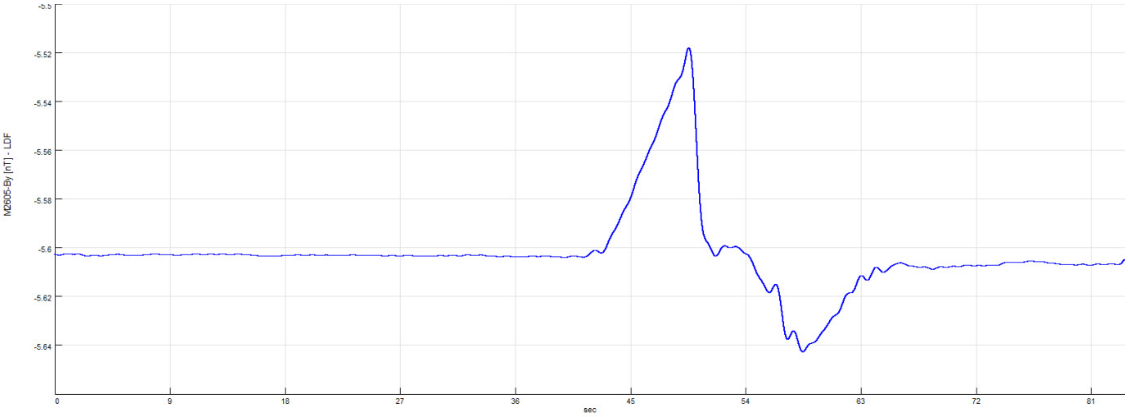

figure 3.2.2 – measured fluxdensity at 29 m distance from the vehicle – LD filtered with fc=1 Hz

The top figure shows the time plot of the current as absorbed by a vehicle. This is the typical signature of a vehicle that starts to accelerate and keeps accelerating. The absorbed current rises linearly up to either the point of maximum current or the maximum allowed line speed. Then it suddenly drops, in this case, because the vehicle reached the maximum locally allowed speed. The driver then reduced power demand. The bottom figure shows the (horizontal portion of the) magnetic fluxdensity at the same time.

Other types or designs of drive systems can have a different pattern, but it will always be (i) relatively low frequency, (ii) high current. And if more vehicles are powered by one substation, individual patterns will add up to a total magnetic field in the environment. The key question is: can different types of instruments cope with this kind of environmental changes? The answer at this point is: that depends on the instrument's sensitivity.

3.3 A generic metro system

The metro system of Tel-Aviv has not yet entered it's design stage, so many parameters that have impact on the system's EM emission cannot be quantified exactly. In order to be able to perform emission calculations, a number of properties must be quantified. Some provisional data were made available and those have been included as much as reasonably possible. Other data have been used, based on accumulated knowledge of and experience with rail systems around the world. The list below summarizes the data, used for calculations. Of course when more accurate data will become available, both modelling and calculations' results will become more accurate.

The model uses the following input in order to calculate the emission of M2:
- line with two tracks. Track separation at the station: 13.5 m;
- station length: 193 m;
- platform length at least 140 m;
- vehicle length: 126 m
- power supply: 750 Vdc third rail;
- maximum acceleration: 1.0 m/sec^2
- maximum current per vehicle: 3500 A (500 A per carriage);
- number of drive units: 14 (2 per carriage);
- carriage length: 18 m;
- track gauge: 1435 mm;
- track depth: 30 m below street level;
- position of substations: some distance from the station, say 1 km to both sides;
- maximum line speed: 90 km/h = 25 m/sec;
- platform: centered between two tracks, distance between center lines of tracks: 13.5 m;
- third rail: along outer sides of tracks, 0.70 m from outer rail, 0.50 m high.

The question of course is: what if the above figures deviate from the (final) design and construction of M2? The answer is simply: the assumptions of today may not be a full hundred percent equal to the reality of tomorrow, but the differences (with respect to the essentials of EM interference) will not be that big. A metro remains a high capacity transportation system, which requires a lot of electrical power, resulting in substantial currents, some tens of meters below street level.

4. Emission of M2

4.1 Modelling

In order to calculate the emission of M2, the system was modelled in 3D[1]. The model has three components: (i) infrastructure, (ii) vehicles, (iii) traffic situation. The infratructure was modelled according to the data in paragraph 3.3. Vehicles were (for the moment) a little bit simplified as just current absorbing and returning units with 14 drive units each. It is assumed that they have modern asynchronous traction drive systems, of which the the current consumption behaviour is as described in the previous chapter. For the traffic situation, three distinctive states were choosen: (i) two vehicles accelerating after a stop and powered by two substations, (ii) two vehicles accelerating after a stop and powered by one substation, (iii) two vehicles driving at a distance of 100 m from the platform and powered by one substation.
For first order calculations, the secundary emission is not taken into consideration, because a reasonable prediction of the amount of stray currents and their paths through the ground is not possible at the moment. And because it is not known whether the ground has specific magnetic properties, the relative magnetic permeability is assumed to be one (1).

4.2 Power supply

For various different reasons, a train driving between two substations receives more power from one than from the other. The most obvious reason is distance. Trains draw the highest currents from the most nearby power substations (power supply unbalance). However not only the two nearest substations contribute to the power demand of a vehicle, but also the more distant substations do, though substially less. For the calculations below, it is assumed that power to the vehicles will be delivered by the power substation either directly in front of the vehicle or directly behind the vehicle or by both. Power from one substation only can also happen at (temporary) outages of a substation or one of its transformer-rectifier groups can cause this type of unbalance. That will have impact on the flow of currents and thus on the associated magnetic field.

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[1] 40-Rehovot\4020-Berekeningen\402010-Model-01\40201035-Parmset-06\

4.3 4D Magnetic Fiels, 3D Models and 2D Graphs

Magnetic fields have properties in four dimensions, three in space and one in time. For low and extremely low frequencies, the exact behaviour in time is less important, as long the changes are a matter of seconds. When magnitudes change within in a period of seconds or some tens of seconds, magnitudes are the dimension to consider. We will first look at the magnitudes of each of the three components (identified by Bx, By and Bz) and their resultant Bt. Bt is the root of the sum of squares or Bt= SQRT(Bx*Bx + By*By + Bz*Bz).

Calculation of 3D models is nice, but representation of results in mostly done in 2D, especially when accurate data must be assessed. Scatterplots are sometimes used to give an overall impression and color pixels are used as the third dimension on a 2D sheet of paper. We will use 2D graphs in order to have a good impression of the numerical results.
The magnetic field (or more precisely: the magnetic flux density) components will be represented in 2D graphs for the purpose of clarity. Calculated magnitudes will be graphed as a function of x, y or z respectively, because spatial position is an essential parameter. So for instance, Bt(y) means a graph representing the magnitude of component Bt (the total) as a function of distance y to the metro's alignment. Such a function is also dependent of x and z, so a 2D graph should be written as "Bt(x=0; y; z=1.5)" or "Bt(y) for x=0.0 and z=1.5" when the longitudinal position would be x=0 and the height would be z=1.5 m.

As indicated before, we will use a Cartesian coordinate system, so we must choose the position of its origin. That will be: x=0 is the centerpoint of a stop, y=0 is the center line of the alignment and z=0 is ground level. The +x-direction is to the west, the +y-direction is to the south and the +z-direction is upward, making it a right-handed system.

4.4 Calculations and Graphs

The results of calculations show the emission of M2 for that situation and that point in time. Values do not include those of a static background field. The amount of emission must be interpreted as *"the amount of change of the environmental background field (like the earth's magnetic field) by M2"*. And that is were sensitive instruments may have a problem. So whenever the M2 emission is zero, then the background field of an instrument will not change and the graphs show zero values.

The first type of graphs shows the field's components as function of the longitudinal position x at a fixed distance y from the alignment, indicated by Oy. The second type of graphs shows the field's components as a function of distanc y to the alignment at a fixed longitudinal position x indicated by Ox. All values have been calculated for observers at a height of 0 m. Or Oz=0 though not further mentioned in the header of the graphs.

Each of the field components has its own colour: black for Bt, green for Bx, red for By and blue for Bz. MAx and MBx indicate the positions of the vehicles on the track. MAx=-40 means that the vehicle on the southern track is 40 m west of the center point. MBx=+40 means that the vehicle on the northern track is 40 east of the center point. Mz indicates the depth of the tracks, 30 m below ground level. Both draw maximum current (7 carriages at 500 A each). Power is supplied either from each of both power substations in equal portions of 1750 A from the east and 1750 A from the west (indicated by P11), or from one power station for the total of 3500 A from the east (indicated by P01).

4.5 Case 1: acceleration from stop – double power supply

The line will have two tracks with a centered platform, third rails on the outer sides of the tracks and a vehicle on each track between the two substations. Two vehicles can have different positions on the line, but high levels of emission will occur when two vehicles accelerate from the same station towards the next station at the same time, but are still not too far away.
When starting to accelerate, it will take about 10 seconds for the vehicles to reach their point of maximum current absorbtion. That point will be reached when both vehicles have moved forward about 50 m, less than half of the vehicle's length[2]. From that moment on they will maintain constant maximum current. The torque will drop hyperbolically and the rate of acceleration will drop, until the vehicle reaches maximum line speed or has to decelerate for whatever reason.

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[2] 352020-Model-02\35202010-Parmset-01\Tel-Aviv-Metro-Ramat-Gan-Model-02-Parmset-01-C315-MA-050-MB+050-v01-Bn(x).txt

The emission was calculated for vehicle's positions at the moment of reaching maximum current in a situation of balanced power supply. Figures 4.5.1 tot 4.5.5 show what the magnitudes of the field components are at that moment. The graphs show the fluxdensity as a function of longitudinal distance x. Each graph shows the fluxdensity at a certain horizontal distance y to the centerline of M2.

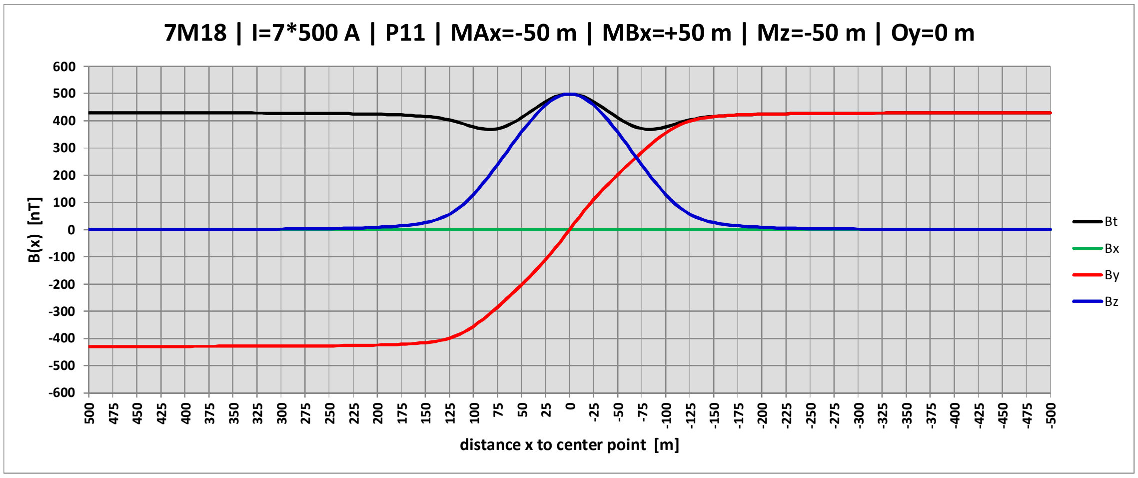

figure 4.5.1

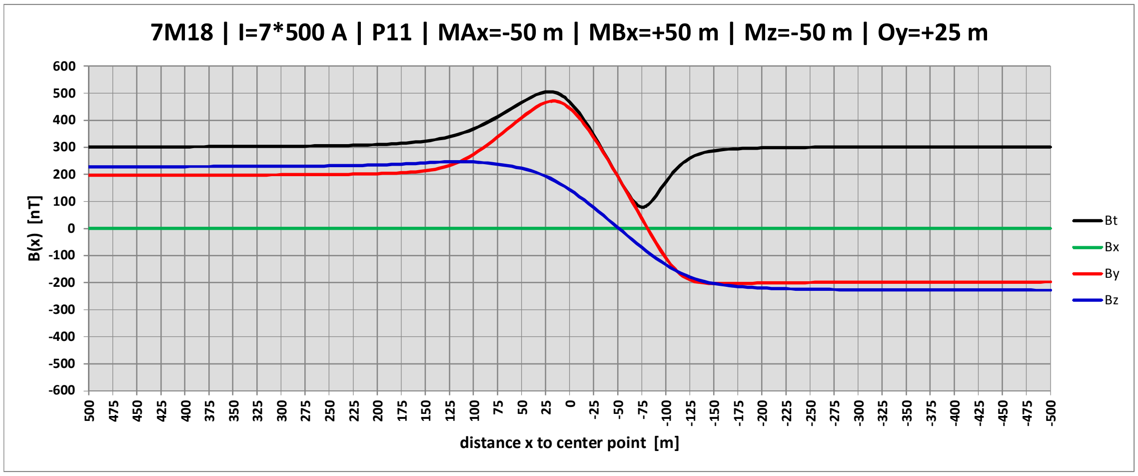

figure 4.5.2

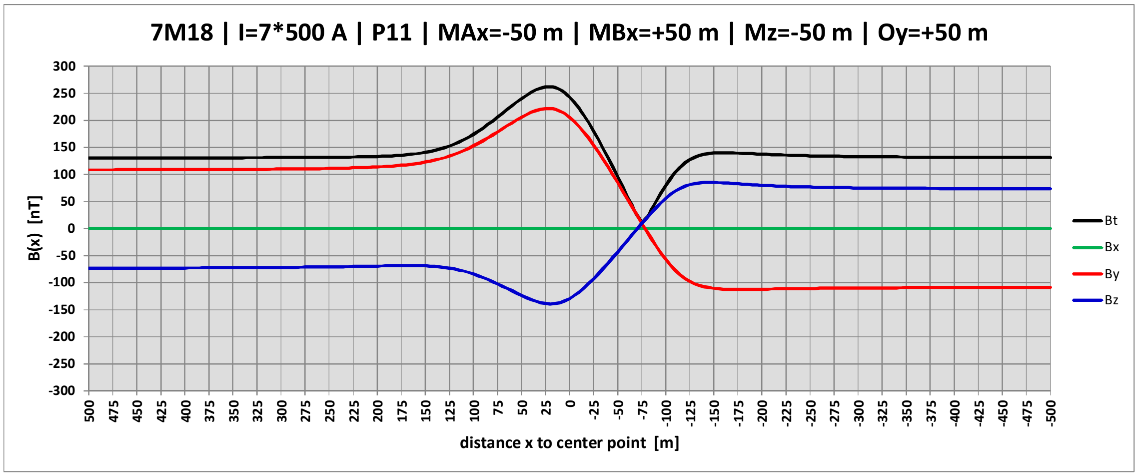

figure 4.5.3

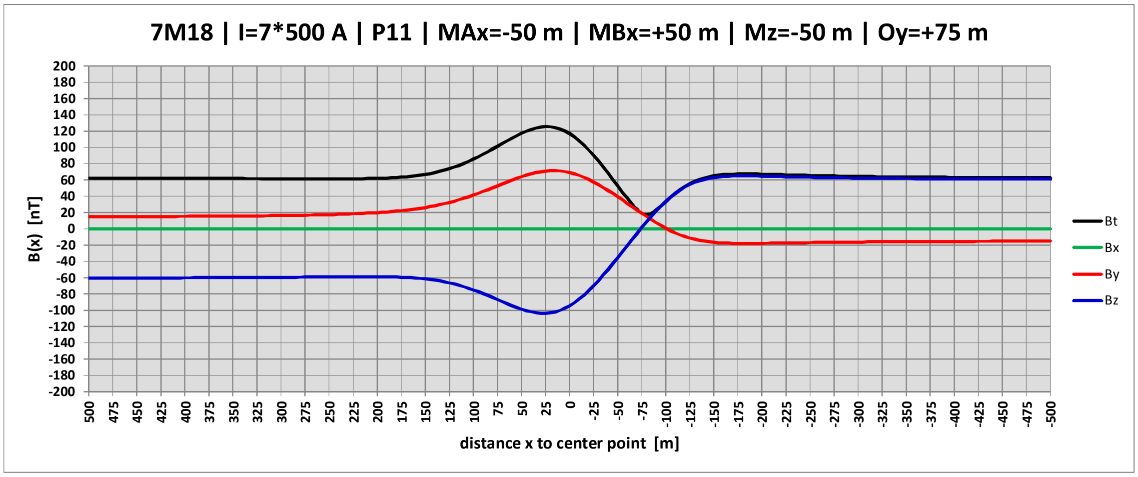

figure 4.5.4

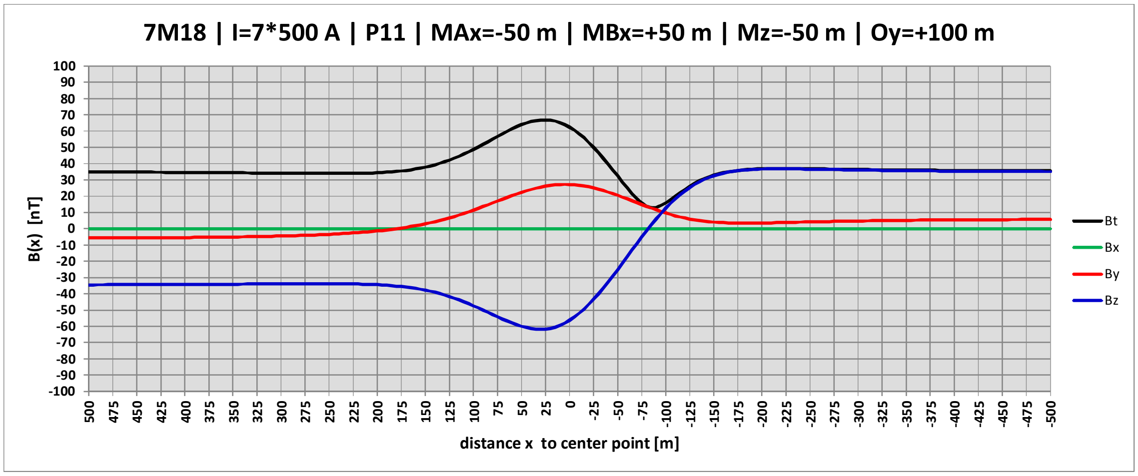

figure 4.5.5

Magnetic fields decrease by increasing distance to the "source". Because distance of instruments to M2 matter, the question is: what is the rate of decrease. That can be illustrated with graphs that show the fluxdensity's components as a function of y (see figures 4.5.6 to 4.5.8). The graphs have a logarithmic y-axis and show the absolute value of the flux density components. Bx has not been shown, because its value is very close to zero. The graphs were drawn for a constant value of x=0.

The graphs show some remarkable things, especially closer to the alignment (less than 50 m). In that area, for example:

- Bx is very low, if not zero, because high currents flow mainly in the x-direction;
- By will change polarity at y=0 m. Within a very short range around y=0 m By will be very low, but that changes rapidly;
- Bz will change polarity at y=43 m. Within a couple of meters around y=43 m the Bz will be very low, but that also changes very rapidly;
- between y=0 and y=50 m distance, the component with the highest value changes from the z-direction to the y-direction. That is important when considering an instrument's directional sensitivity, because many instruments do not have equal sensitivity in all three directions.

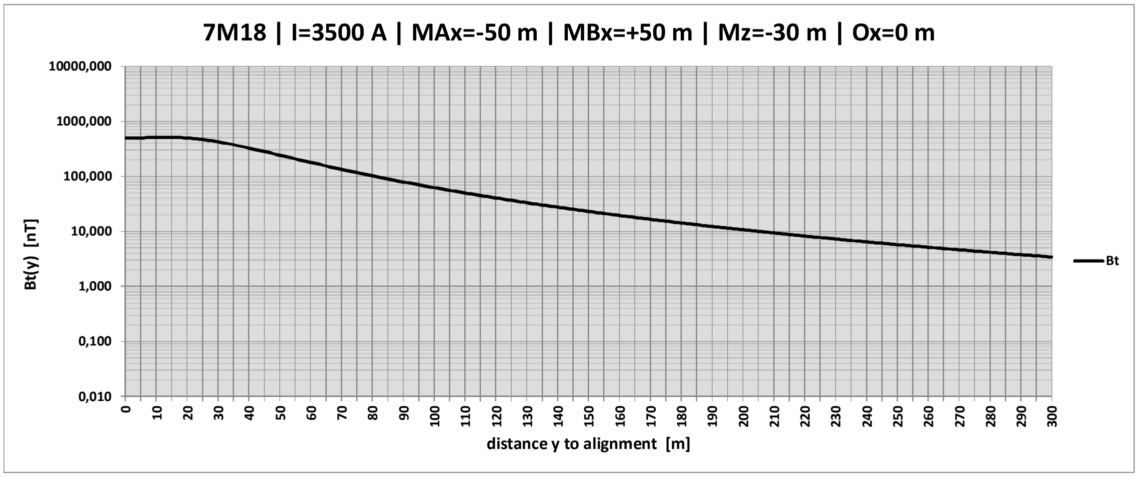

figure 4.5.6

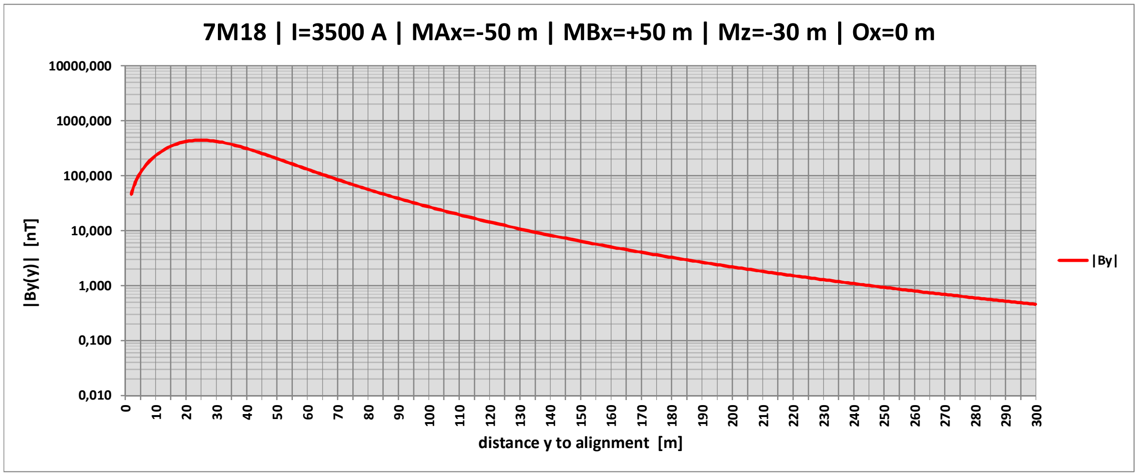

figure 4.5.7

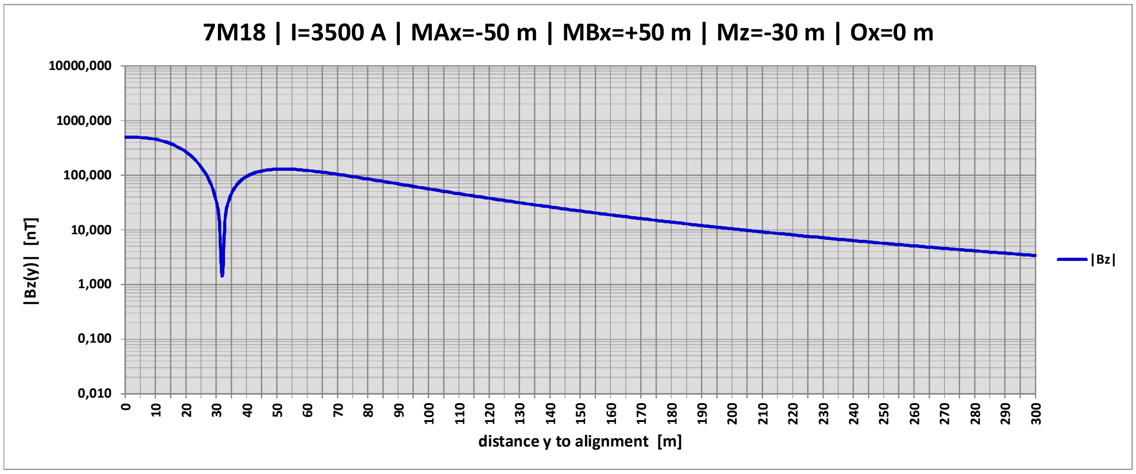

figure 4.5.8

4.6 Case 2: acceleration from stop – single power supply

This case has the same traffic situation as case 1, but with power supply from one substation only[3]. Figures 4.6.1 to 4.6.5 show that the fluxdensities on one side of the trains will increase substantially, while dropping at the same time on the other side of the vehicles.

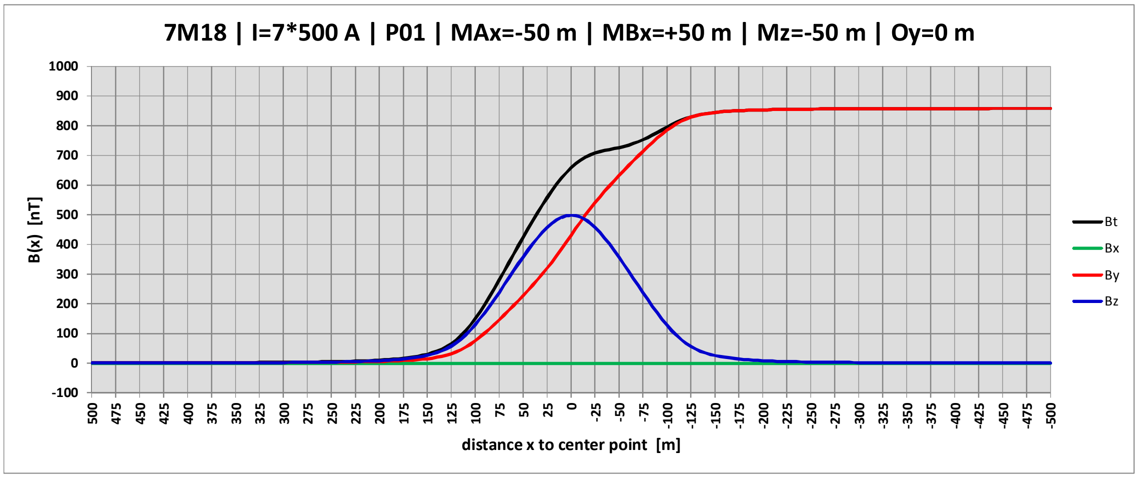

figure 4.6.1

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[3] 352020-Model-02\35202015-Parmset-02\Tel-Aviv-Metro-Ramat-Gan-Model-02-Parmset-02-C315-MA-050-MB+050-v01-Bn(x).txt

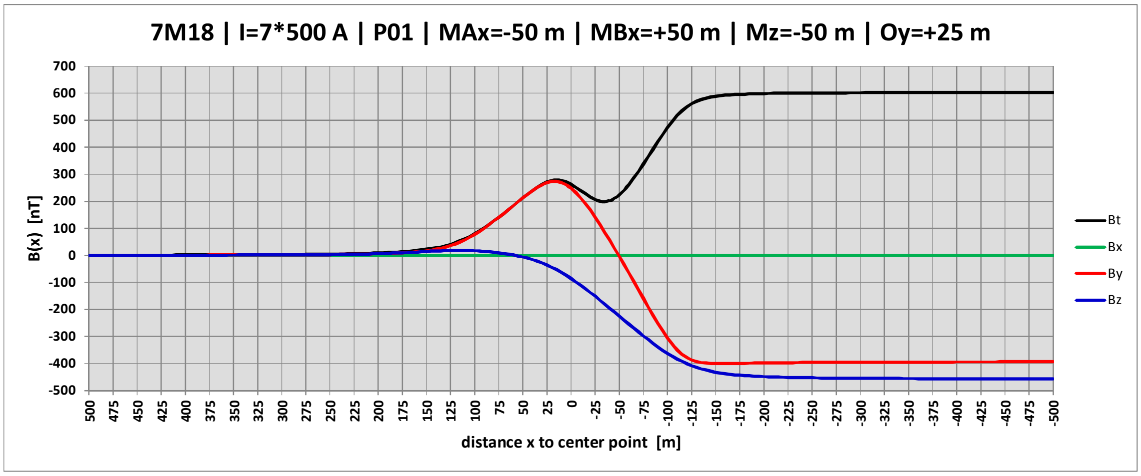

figure 4.6.2

Remarkable is, that the shapes of the curves change significantly within a distance of about 50 m (see figures 4.6.1, 4.6.2 and 4.6.3). At distance y=0 the Bz is only positive, but at y=25 m the Bz is mainly negative. For y-0 By is only positive and at y=25 m By drops from x=15 m and then turns negative at x=-50 m.

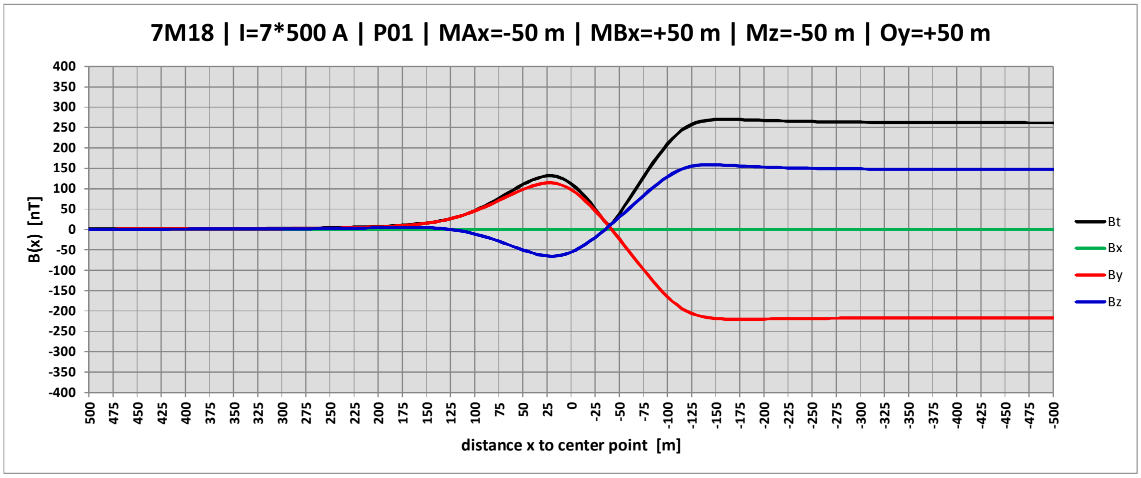

figure 4.6.3

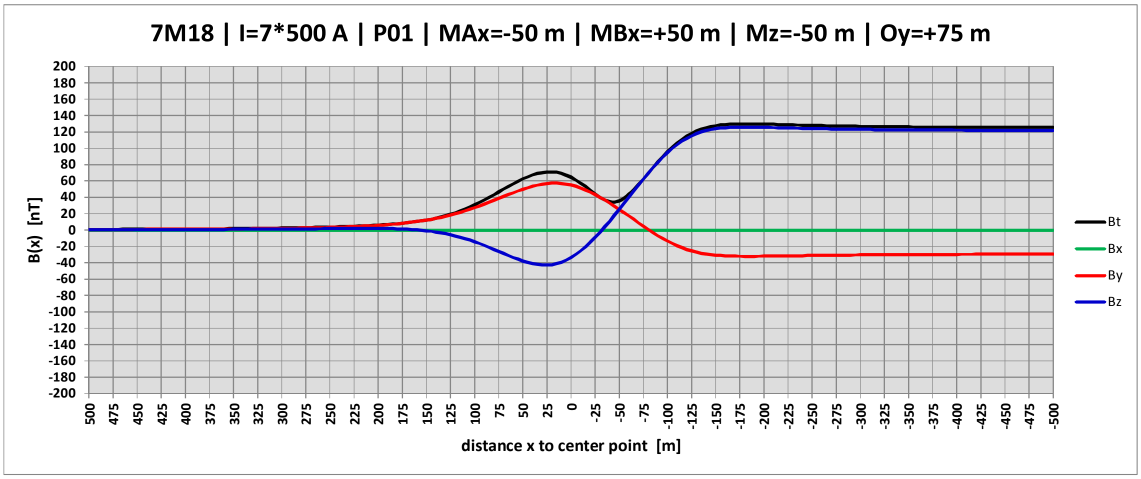

figure 4.6.4

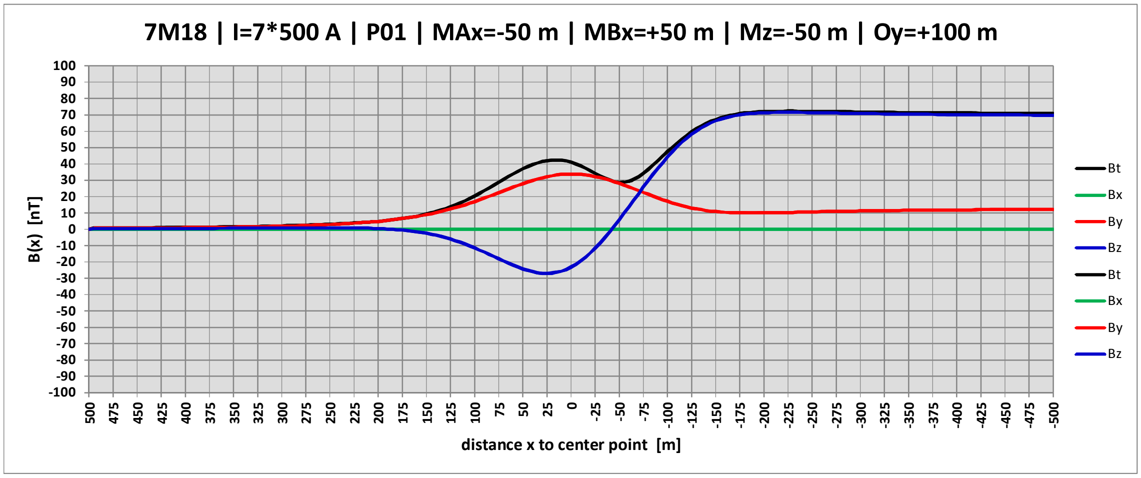

figure 4.6.5

Figures 4.6.6 to 4.6.8 show the fluxdensity components as a function of distance. But different from the graphs in the previous paragraph, the logitudinal position is not x=0 m but x=-50 m.

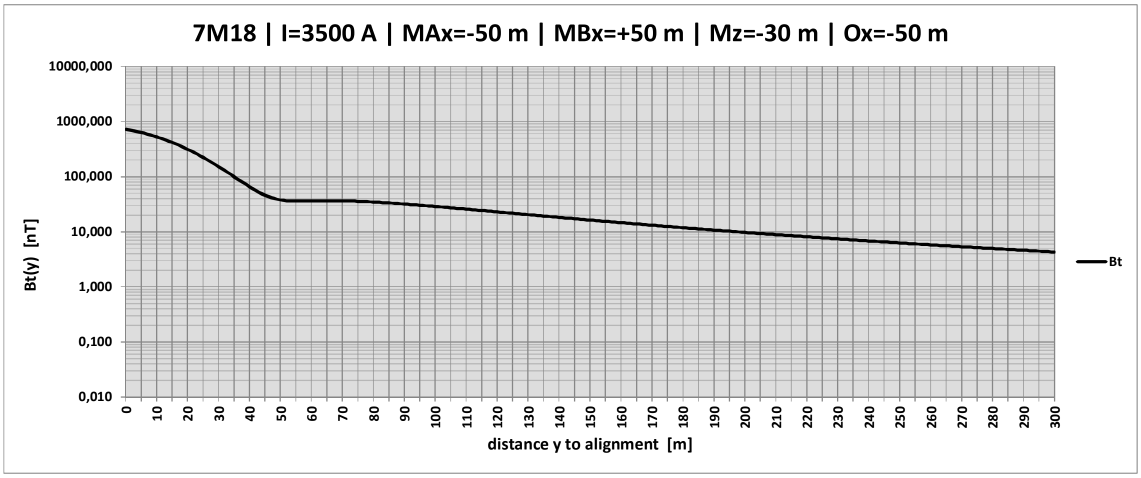

figure 4.6.6

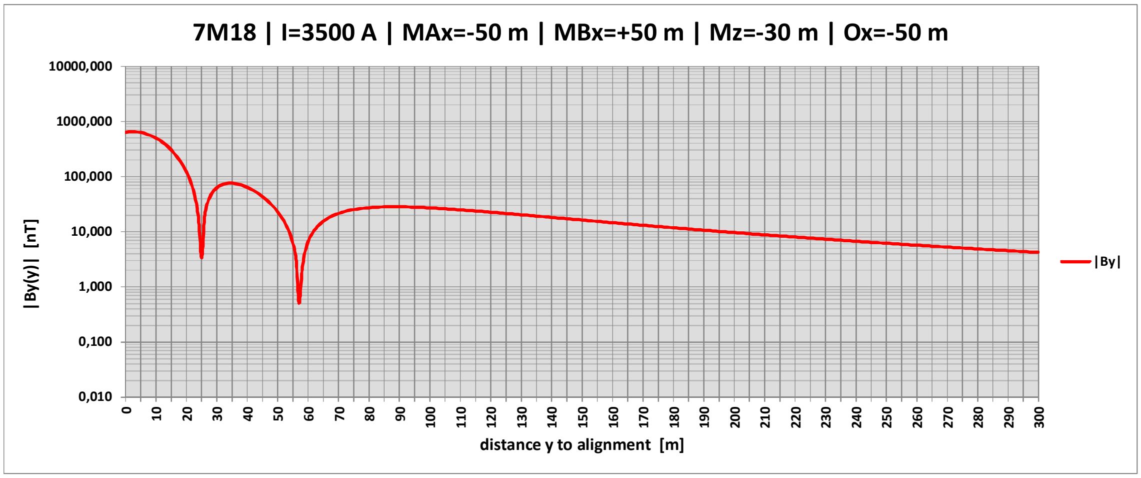

figure 4.6.7

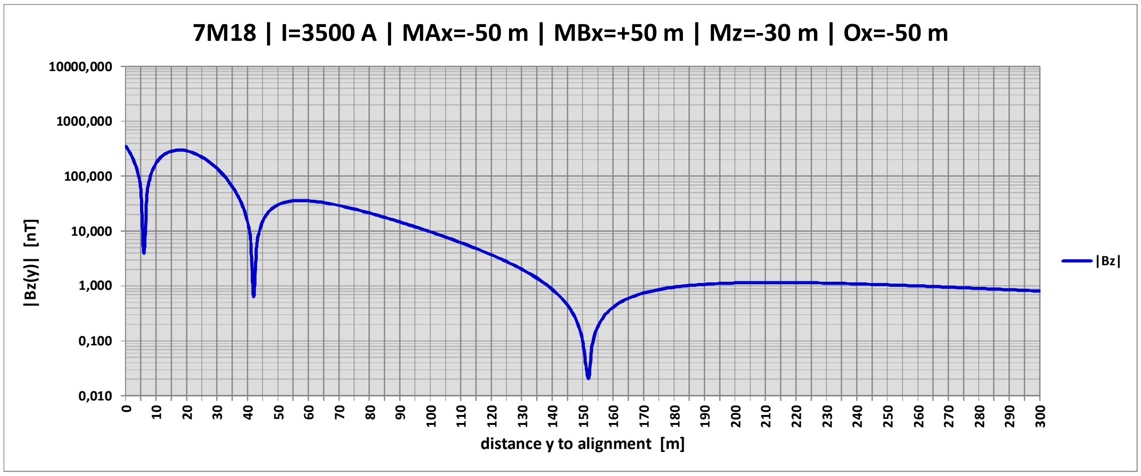

figure 4.6.8

The By changes polarity two times, one time for y=25 m and a second time at y=57 m. The Bz changes polarity three times, first at y=6 m, then at y=42 m and then at y=152 m.

The figures show, that one must be very careful with estmation of fluxdensity magnitudes. It cannot be simply assumed that magnitudes will uniformly decrease as a function of increasing distance. And therefor it is important to bring the exact locations of instruments into the picture.

4.7 Case 3: drive at some distance from stop

This case has two vehicles (one on each track at 300 m distance from the centerpoint of the station[4]. Also in this case, power comes from one substation.

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[4] 352020-Model-02\35202025-Parmset-04\Tel-Aviv-Metro-Ramat-Gan-Model-02-Parmset-04-C315-MA+100-MB+100-v01-Bn(x).txt

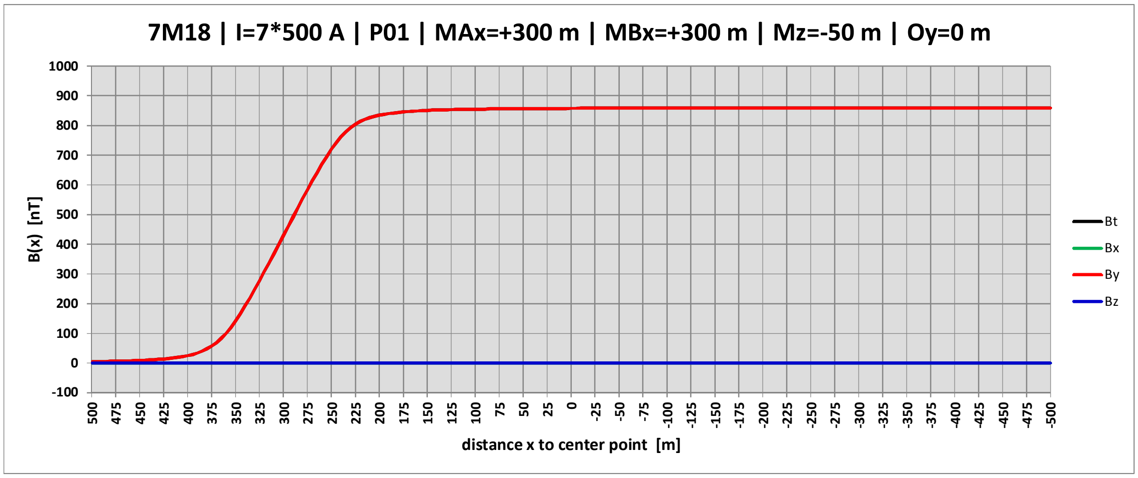

figure 4.7.1

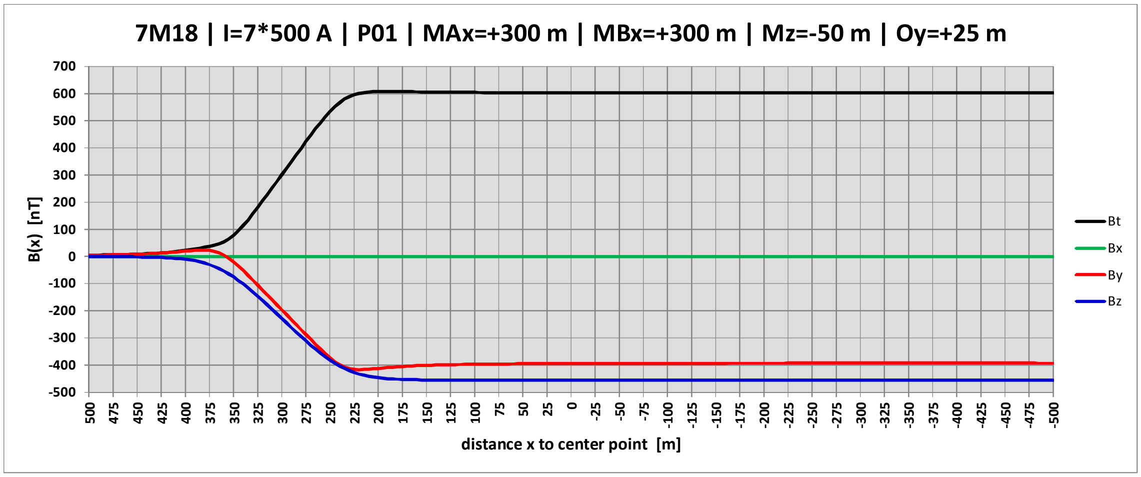

figure 4.7.2

These figures illustrate that the presence and position of the vehicles are a determining factor. When vehicles are further away from the station, the fluxdensity around the station has a quite straight forward shape.

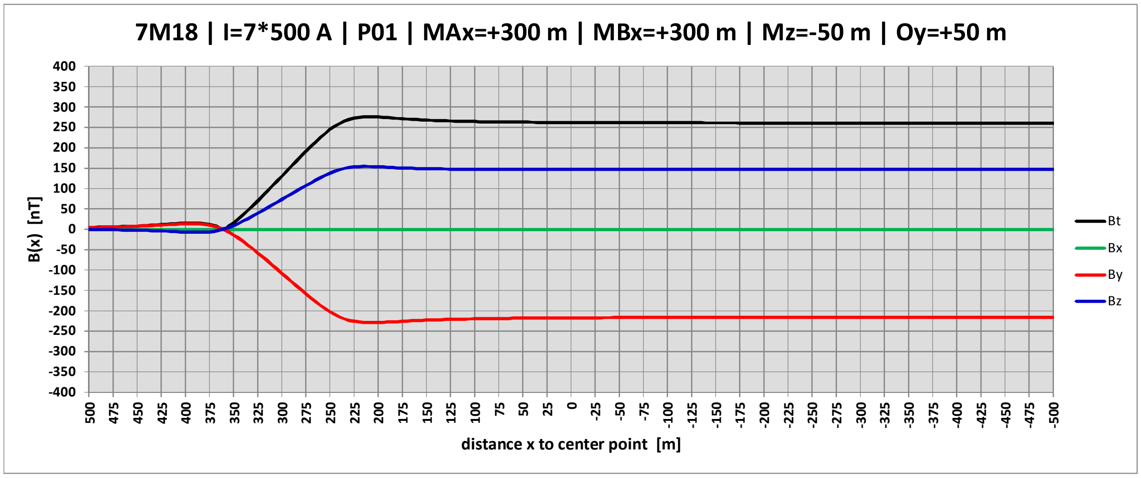

figure 4.7.3

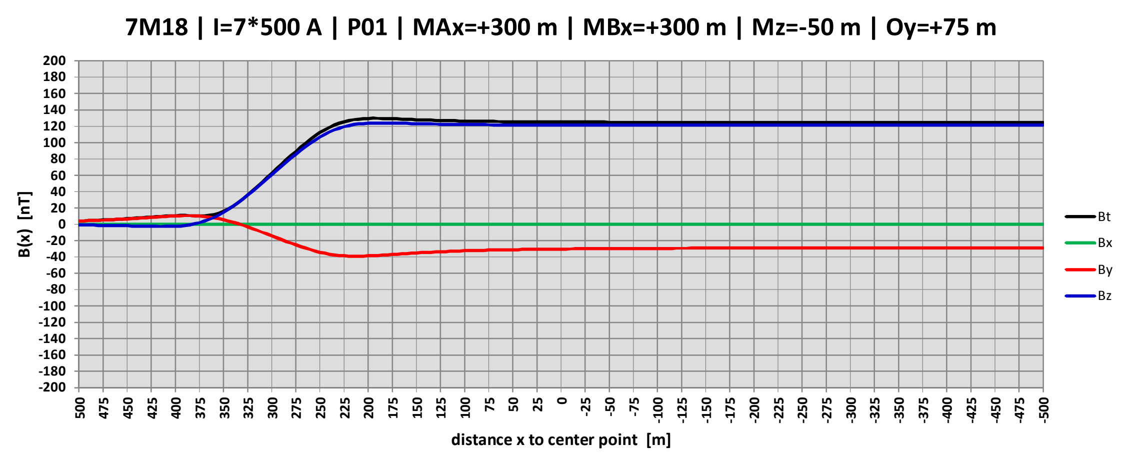

figure 4.7.4

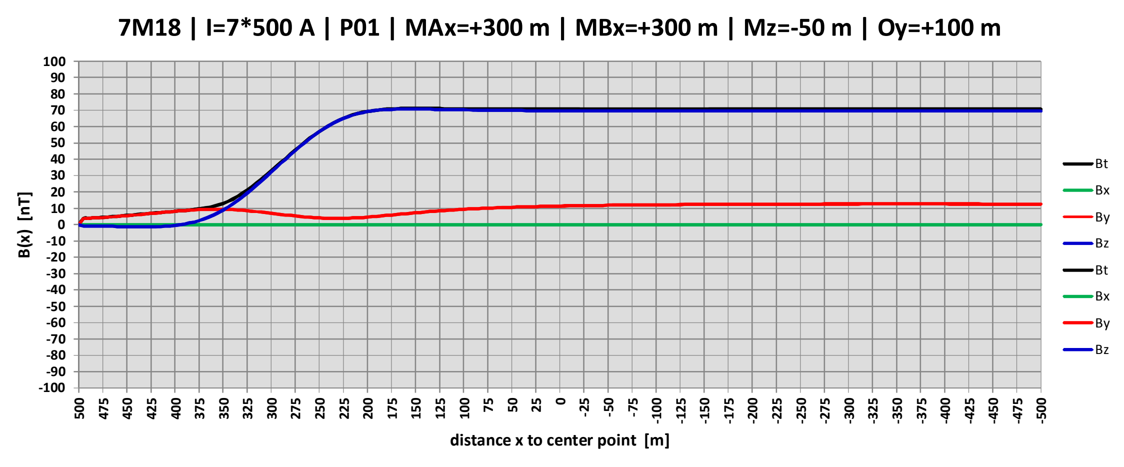

figure 4.7.5

4.8 EM Interference

The above calculated results tell something about the emission of M2. Though the outcome of this calculations makes sense, it shows that an emission pattern can dramatically change over a distance of some tens of meters. Not only the magnitude changes but also the direction of the field. Whether the above calculated kind of emission is harmful to the University's instruments, depends on the levels of immunity and spatial position and orientation of each instrument.

5. The University Instruments

The University listed their most sensitive instruments and provided figures of their respective immunity levels. The instruments (by type) have been put into the assessment tables 6.2.1 and 6.3.1 in column 2. Because distance is an important parameter, both horizontal and vertical distance were provided. and put into the tables in columns 5 and 6 respectively. Columns 7 show the immunity levels and columns 8 the calculated emission of M2.

6. Risk Assessment

6.1 Calculation of M2 emission for each instrument

The M2 emission been calculated for a single side power supply and two vehicles drawing their maximum currents. That situation is similar to the situation as described in paragraph 4.6, but now for vehicles along the line. The assessment was made for the vectorsum Bt of the three individual fluxdensity components Bx, By and Bz. So vectordirection has not (yet) been taken into account. For each single instrument, Bt was calculated for the instrument's position, both in terms of horizontal distance to the centerline of the alignment and to its vertical height above top-of-rail.

The emission calculations were made both for the northern and southern route. The differences are caused by different horizontal distances of each instrument and thus by different angles of emission. The Bar-Ilan buildings close to the alignment are situated in between two stations. For the northern route the stations are Kahnman in the west and Givat Shmuel in the east. For the southern route the stations are H'rav Levin in the west and Bar-Ilan in the east. It is assumed that both tracks at the projected point of shortest distance have a horizontal center line separation of approximately 7 m. All instruments are assumed to be at a height of 31.6 m above top-of-rail, except for a number of instruments in building 206. Those are located in the basement at a height of 25.6 m above top-of-rail.

6.2 Risk of interference by M2 on the southern route

If M2 would follow the southern route, then the emission would be as presented in table 6.2.1. The last but one column shows the immunity levels of the instruments. The last column shows the calculated emission of M2 at the locations of the instruments.

table 6.2.1

Bar-Ilan University
List of Instruments - sensitivity - emission of M2

nr	type	building	floor	h.dist-S [m]	v.dist [m]	Bt-max [nT]	Bt-M2S [nT]
1.01	SQUID magnetometers - Superconducting QUantum Interference Devices	202	0	118	31,6	10	52,1
1.02	MOKE – Magneto Optic Kerr Effect microscopes	202	0	118	31,6	10	52,1
1.03	AI – Atomic Interferometers	202	0	118	31,6	1	52,1
2.01	E-beam lithographer	206	-2	18	25,6	100	996,5
2.02	SEM – Scanning Electron Microscope	206	-2	18	25,6	100	996,5
2.03	JEOL 1400 TEM – Transmission Electron Microscope	206	-2	18	25,6	10	996,5
2.04	Cryo-TEM – Cryogenic Transmission Electron Microscope	206	-2	18	25,6	10	996,5
2.05	HRSEM – High Resolution Scanning Electron Microscope	206	-2	18	25,6	10	996,5
2.06	FIB – Focused Ion Beam microscopes	206	-2	18	25,6	100	996,5
2.07	ESEM – Environmental Scanning Electron Microscope	206	-2	18	25,6	100	996,5
2.08	JEOL 2100 HRTEM – High Resolution Transmission Electron Microscope	206	-2	18	25,6	10	996,5
2.08	AFM – Atomic Force Microscopes	206	-2	18	25,6	10	996,5
2.10	XRD – X-Ray powder Diffraction analyzers	206	-2	18	25,6	100	996,5
3.01	SQUID magnetometers - Superconducting QUantum Interference Devices	206	0	18	31,6	1	1439,7
3.02	AFM – Atomic Force Microscopes	206	0	18	31,6	10	1439,7
3.03	various sensitive electronics	206	0	18	31,6	10	1439,7
4.01	AFM – Atomic Force Microscopes	209	0	-39	31,6	10	439,9
4.02	Micro electronics sensitive to stray currents	209	0	-39	31,6	10 pA	
5.01	NMR - Nuclear Magnetic Resonance spectroscopes	211	0	-18	31,6	100	996,5
5.02	EPR - Electron Paramagnetic Resonance spectroscopes	211	0	-18	31,6	100	996,5
6.01	Measuring instruments sensitive to stray currents	901	0	118	31,6	1 pA	

Some of the instruments are mainly sensitive to stray currents, rather than electromagnetic emission. The maximum allowed values are shown, but the expected amount of stray currents has not been calculated.

The results are dramatic. All instruments will be disturbed by M2. The emission is way higher than the immunity levels indicated. Even mitigating measures will not be sufficient, unless very drastic

measures are taken into account, such as moving instruments to buildings hundreds of meters away or replanning the alignment to a distance of hundreds of meters.
The conclusion is simply that, as far as Bar-Ilan University is concerned, the southern route is unacceptable.

6.3 Risk of interference by M2 on the northern route

If M2 would follow the northern route, then the emission would be as presented in table 6.3.1. The last but one column shows the immunity levels of the instruments. The last column shows the calculated emission of M2 at the locations of the instruments.

table 6.2.1

Bar-Ilan University
List of Instruments - sensitivity - emission of M2

nr	type	building	floor	h.dist-N [m]	v.dist [m]	Bt-max [nT]	Bt-M2N [nT]
1.01	SQUID magnetometers - Superconducting QUantum Interference Devices	202	0	993	31,6	10	0,4
1.02	MOKE – Magneto Optic Kerr Effect microscopes	202	0	993	31,6	10	0,4
1.03	AI – Atomic Interferometers	202	0	993	31,6	1	0,4
2.01	E-beam lithographer	206	-2	893	25,6	100	0,6
2.02	SEM – Scanning Electron Microscope	206	-2	893	25,6	100	0,6
2.03	JEOL 1400 TEM – Transmission Electron Microscope	206	-2	893	25,6	10	0,6
2.04	Cryo-TEM – Cryogenic Transmission Electron Microscope	206	-2	893	25,6	10	0,6
2.05	HRSEM – High Resolution Scanning Electron Microscope	206	-2	893	25,6	10	0,6
2.06	FIB – Focused Ion Beam microscopes	206	-2	893	25,6	100	0,6
2.07	ESEM – Environmental Scanning Electron Microscope	206	-2	893	25,6	100	0,6
2.08	JEOL 2100 HRTEM – High Resolution Transmission Electron Microscope	206	-2	893	25,6	10	0,6
2.08	AFM – Atomic Force Microscopes	206	-2	893	25,6	10	0,6
2.10	XRD – X-Ray powder Diffraction analyzers	206	-2	893	25,6	100	0,6
3.01	SQUID magnetometers - Superconducting QUantum Interference Devices	206	0	893	31,6	1	0,6
3.02	AFM – Atomic Force Microscopes	206	0	893	31,6	10	0,6
3.03	various sensitive electronics	206	0	893	31,6	10	0,6
4.01	AFM – Atomic Force Microscopes	209	0	913	31,6	10	0,5
4.02	Micro electronics sensitive to stray currents	209	0	913	31,6	10 pA	
5.01	NMR - Nuclear Magnetic Resonance spectroscopes	211	0	823	31,6	100	0,7
5.02	EPR - Electron Paramagnetic Resonance spectroscopes	211	0	823	31,6	100	0,7
6.01	Measuring instruments sensitive to stray currents	901	0	208	31,6	1 pA	

The results are such that the expected emission is small. The fact that (presently) all sensitive instruments are located at a very large distance from the northern route (approximately 900 m) causes the emission to be lower than the sensitivity levels of the instruments. The downside however is, that after construction of the northern M2 route, Bar-Ilan University will face substantial location limitations when purchasing and installing new instruments.

6.4 Assumptions on M2

The emission of M2 was calculated based on the afore mentioned assumptions on the metro system's design[5]. Emission values can change very much with that type of changes. The position of the third rail for instance (either next to one side of the track or next to the other side) makes differences of hundreds of nT. So recalculation will be necessary when the design of M2 changes.

7. Mitigating measures

When mitigating measures will be necessary, there are a couple of options. Not all of them are cheap or practical, but the full spectrum is listed, for reasons of completeness.

Increase distance

Distance between M2 and an instrument is a crucial factor. Increasing distance reduces the risk of interference. For M2 that could mean re-routing the alignment further north or much further south.

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[5] **35-Ramat-Gan\3520-Berekeningen\302020-Model-02\35202035-Parmset-06**

Laying the tracks of M2 at a substantial deeper level certainly helps. The present depth is about 30 m below street level, but lowering to (for example) minus 50 m will significantly decrease the EM emission. A third option is, to move certain instruments to a building which is further away from the alignment. And if not available, construction of a new building at a suitable location can be a solution.

Shielding

Shielding against (extremely) low frequencies is highly unpractical and mostly not sufficient. Passive shielding may require a lot of material with a high magnetic permeability and even special constructions of the rooms or buildings to be shielded. In general this is not very practical for situations like these. The alternative sometimes may be active shielding by Helmholtz or Maxwell cages. But the problem with those cages is that they shield the instrument inside but are a source of interference for the instruments outside. It is often not an option.

Raising the line voltage

Modern electric rail vehicles operate on electric power. Voltage and current are to some degree interchangeable. Raising the line voltage results in a decrease of currents and thus in a decrease of EM emission. Line voltage is a metro system wide (not local) parameter, but it is a serious option to consider.

Limiting the current

Another way to decrease emission is, to limit the current in areas with sensitive equipment. For modern rail vehicles, it is quite easy for their drive systems to do that. The process could be automated by using the vehicle's position information which is on board anyway. Another method is to limit the current from the supplying substation at certain stretches. The use of regulating power electronics makes that very feasible.

Changing the lay-out of power supply

Within the metro system, currents flow back and forth. Keeping those flows at short distances from one another (or aligning their flow's axes) will reduce the emission. A simple example is to use two third rails at either side of each track in sensitive areas. Also the use of a fourth (return current) rail should be considered. Whether that results in sufficient reduction, must be calculated.

Location of power supply substations

The location of substations can make a substantial difference to the amount of emission from M2 around the sensitive locations. Though also technical measurements can be taken, a balanced power supply to vehicles moving in a sensitive area, is one of the possible measures.

On-board power supply

On-board power supply by means of batteries or supercaps (or both) is becoming increasingly common in light rail systems. Fact is that this form of power supply has a very low EM emission signature. For a number of practical reasons, such an option could be limited to a part of the M2 line where low emission is of utmost importance.

The effects of these measures have not been modelled and calculated at this point in time. So it is not know yet which types of measures or combination of measures will be sufficient to bring the emission of M2 below the respective levels of immunity of the instruments.

Annex A – Bar-Ilan University – scientific opinion

Faculty of Exact Sciences **הפקולטה למדעים מדויקים**

Department of Physics המחלקה לפיסיקה

July 16, 2020

To whom it may concern,

Metro Ramat Gan project – scientific opinion

Dear Sir/Madam,

Th purpose of this document is to explain the difficulties related to the construction of a metro line right below the University research infrastructures. It can have a long-term impact on the ongoing and future scientific research projects due to creation of various types of environmental noises.

One of the most important fields in the modern scientific research is in the field of precision measurements and one of the most important developments in the last three decades in this field is the development of atom interferometric sensors. They are used now in fundamental studies of general relativity and cosmology and applied in the fields of metrology, geophysics, space, civil engineering, oil and minerals exploration and navigation [1]. Although we are going to concentrate here on these specific sensors, the requirements on the environmental noise level (seismic and electromagnetic) posed by other modern precision measurement devices will be similar.

Atom interferometric sensors are at the forefront of modern research in fundamental physics and they are functional at a large number of Universities and R&D facilities across the world. They are used in measurement of fundamental constants of nature such as h/M (where h is the Plank constant and M is the mass of an atom) and fine structure constant. These measurements require so high level of sensitivity ($< 10^{-10}$) that even a stormy weather in the winter and a costline proximity affect the results [2]. Another application of these sensors is for testing the equivalence principle (also known as the universality of free fall). Current state-of-the-art performance in this direction reaches 10^{-9} sensitivity with reported dominant systematic uncertainties from uncontrollable magnetic field environmental noise [3]. The most sensitive applications of the atom interferometric sensors are those involved in search for dark matter and dark energy candidates and gravitational wave detection. The required sensitivity of these devices (10^{-13} at 2 Hz) can only be achieved within a special underground scientific platform characterized by ultra-low seismic and electromagnetic noises resulted by distancing this platform from regions with heavy industrial and human activities [4]. The last example is made just to emphasize the level of requirements. This type of projects is beyond the reach of a single research group or even a single University.

The field of precision measurements has been growing fast in recent years and becoming one of the most important directions in modern fundamental physics research [5]. As a part of the strategic plan of Bar-Ilan University and its aim to pursuing the innovative and high quality competative research, it is seeking to hire one or more researchers in this field in the near future. The hiring of researchers in this field is just a matter of time and the construction of new facilities that produces unavoidable prominent noise such as

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www.biu.ac.il

the Metro line in close proximity to the University research facilities will most likely prevent from those researches to join Bar-Ilan University. This would have an immediate negative influence on the future of the University and on its ability to stay competitive.

Furthermore, considering the current needs of the ongoing University research, the development of a gravitation sensor is planned in the Ultracold Atoms Laboratory in the near future (in collaboration with researchers from Ben-Gurion University). This device is based on a novel principle [6] and is expected to improve sensitivity of similar devices by a significant factor. The uncontrollable environmental noises caused by the Metro line construction are not limited exclusively to the construction phase of the project but will continuously be present during the active operational phase. These noises will generate a source of systematic uncertainties in high precision measurements which are difficult to characterize and compensate for. Modern advanced research facilities require a quiet and controllable environment. The new Metro line will pose a great challenge for complying with this firm requirement.

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[1] K. Bongs et.al., “Taking atom interferometric quantum sensors from the laboratory to real-world applications”, Nature Reviews Physics 1, 731 (2019).
[2] C. Freier et. al., “Mobile quantum gravity sensor with unprecedented stability”, J. of Physics: Conf. Series 723, 012050 (2016).
[3] G. Rosi et. al. “Quantum test of the equivalence principle for atoms in coherent superposition of internal energy state”, Nat. Commun. 8, 15529 (2017).
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[6] I. Kuzmenko, T. Kuzmenko, Y. Avishay, and Y. Band, “Atoms trapped by a spin-dependent optical lattice potential: realization of a ground state quantum rotor”, Phys. Rev. A, 100 033415 (2019).

Sincerely yours,

Lev Khaykovich,
Head of the Ultracold Atoms Laboratory,
Physics Department, QUEST Center and Institute for Nanotechnology and Advanced Materials,
Bar-Ilan University

Annex B – Abbreviations and Definitions

EMC Electro magnetic compatibility: a situation where two or more functioning electric systems can properly function in each other's presence.

EME Electro magnetic emission: the generation of electric and magnetic fields by a functioning electric system

EMI Electro magnetic interference: a situation where one functioning electric system causes disturbance to the proper operation of another (adjacent) system.

LOI Level of immunity: the magnitude of external electric and/or magnetic fields in the presence of an electric system, that does not disturb its proper functioning.