Queensland University of Technology, Brisbane – 10/09/2025

FIELD MEASUREMENTS, WEB PROCEDURES, AND ONLINE TOOLS FOR ASSESSING OCCUPATIONAL EXPOSURE TO NON-IONIZING RADIATION

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CNR-IFAC

The Institute of Applied Physics "Nello Carrara" (IFAC) was established in March 2002 in Florence (previously IROE, Research Institute on Electromagnetic Waves).

IFAC has expertise in physical investigation methods for the development of devices and instruments, mathematical and computer methods for modeling and processing of data and images, with applications in:

- space, aerospace, and earth observation
- health, nanomedicine, and safety
- environmental monitoring and food quality
- cultural heritage

BRIC 2017-2025

- Collaborative Research Calls funded by INAIL (National Institute for Insurance against Accidents at Work)
- Involving several Italian institutions:
  - CNR-IFAC ("Nello Carrara" Institute for Applied Physics of the Italian National Research Council, Florence)
  - CNR-IFC Pisa
  - ISS (Italian National Institute of Health)
  - USL Siena
  - Policlinico San Matteo
  - University of Modena and Reggio Emilia

BRIC 2017-2025

- Activities focused on professional exposure related to AIMD (Active Implantable and Wearable Medical Devices) wearers
- Current project: Risk assessment and management deriving from exposure to new sources of electromagnetic fields for the protection of workers with active implantable medical devices

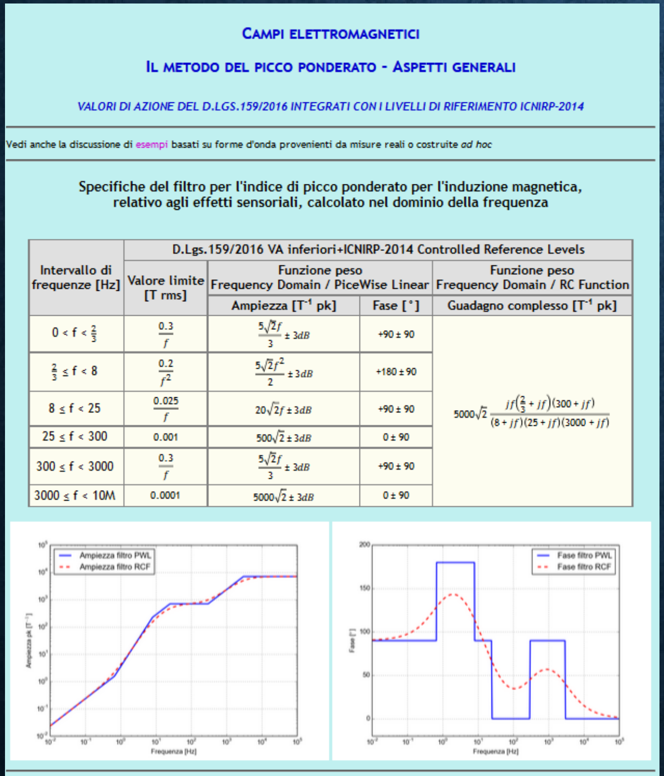
WEBNIR

- Web tools for the assessment of occupational exposure to Non Ionizing Radiation
- Web portal: https://webnir.eu
- 3 sections:
  - EMF (ElectroMagnetic Fields)
  - AIMD (Active Implantable and Wearable Medical Devices)
  - AOR (Artificial Optical Radiation)
- Updated with new technologies and implementation of new technical features (responsive site, multilingual, keyword search): https://webnir2.ifac.cnr.it (switching off soon)

WEBNIR

It makes available:

- Technical documents (web pages or PDFs)



CAMPI ELETTROMAGNETICI

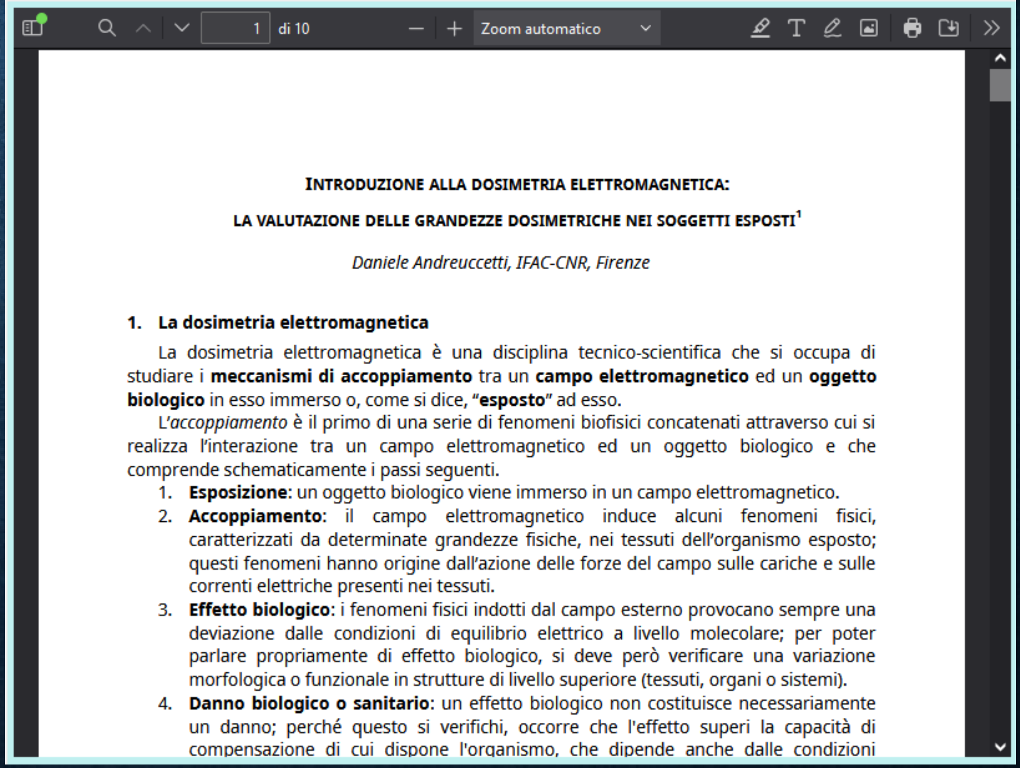
IL METODO DEL PICCO PONDERATO - ASPETTI GENERALI

VALORI DI AZIONE DEL D.LGS.159/2016 INTEGRATI CON I LIVELLI DI RIFERIMENTO ICNIRP-2014

Vedi anche la discussione di esempi basati su forme d'onda provenienti da misure reali o costruite *ad hoc*

Specifiche del filtro per l'indice di picco ponderato per l'induzione magnetica, relativo agli effetti sensoriali, calcolato nel dominio della frequenza

Intervallo di frequenze [Hz]	D.Lgs.159/2016 VA inferiori+ICNIRP-2014 Controlled Reference Levels			
	Valore limite [T rms]	Funzione peso Frequency Domain / PiceWise Linear		Funzione peso Frequency Domain / RC Function
		Ampiezza [T^{-1} pk]	Fase [°]	Guadagno complesso [T^{-1} pk]
$0 < f < \frac{2}{3}$	$\frac{0.3}{f}$	$\frac{5\sqrt{2}f}{3} \pm 3dB$	$+90 \pm 90$	$5000\sqrt{2}\,\frac{jf\left(\frac{2}{3}+jf\right)(300+jf)}{(8+jf)(25+jf)(3000+jf)}$
$\frac{2}{3} \le f < 8$	$\frac{0.2}{f^2}$	$\frac{5\sqrt{2}f^2}{2} \pm 3dB$	$+180 \pm 90$	
$8 \le f < 25$	$\frac{0.025}{f}$	$20\sqrt{2}f \pm 3dB$	$+90 \pm 90$	
$25 \le f < 300$	0.001	$500\sqrt{2} \pm 3dB$	0 ± 90	
$300 \le f < 3000$	$\frac{0.3}{f}$	$\frac{5\sqrt{2}f}{3} \pm 3dB$	$+90 \pm 90$	
$3000 \le f < 10M$	0.0001	$5000\sqrt{2} \pm 3dB$	0 ± 90	



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Zoom automatico

INTRODUZIONE ALLA DOSIMETRIA ELETTROMAGNETICA:

LA VALUTAZIONE DELLE GRANDEZZE DOSIMETRICHE NEI SOGGETTI ESPOSTI[1]

Daniele Andreuccetti, IFAC-CNR, Firenze

1. La dosimetria elettromagnetica

La dosimetria elettromagnetica è una disciplina tecnico-scientifica che si occupa di studiare i **meccanismi di accoppiamento** tra un **campo elettromagnetico** ed un **oggetto biologico** in esso immerso o, come si dice, "**esposto**" ad esso.

L'*accoppiamento* è il primo di una serie di fenomeni biofisici concatenati attraverso cui si realizza l'interazione tra un campo elettromagnetico ed un oggetto biologico e che comprende schematicamente i passi seguenti.

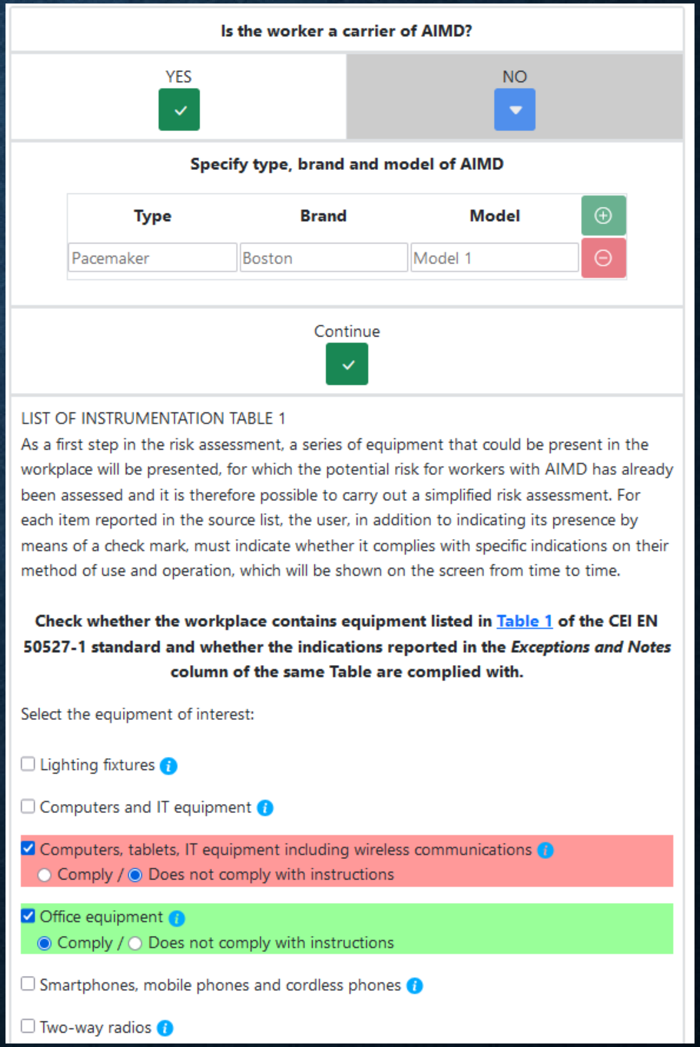
1. **Esposizione**: un oggetto biologico viene immerso in un campo elettromagnetico.
2. **Accoppiamento**: il campo elettromagnetico induce alcuni fenomeni fisici, caratterizzati da determinate grandezze fisiche, nei tessuti dell'organismo esposto; questi fenomeni hanno origine dall'azione delle forze del campo sulle cariche e sulle correnti elettriche presenti nei tessuti.
3. **Effetto biologico**: i fenomeni fisici indotti dal campo esterno provocano sempre una deviazione dalle condizioni di equilibrio elettrico a livello molecolare; per poter parlare propriamente di effetto biologico, si deve però verificare una variazione morfologica o funzionale in strutture di livello superiore (tessuti, organi o sistemi).
4. **Danno biologico o sanitario**: un effetto biologico non costituisce necessariamente un danno; perché questo si verifichi, occorre che l'effetto superi la capacità di compensazione di cui dispone l'organismo, che dipende anche dalle condizioni

WEBNIR

It makes available:

- Technical documents (web pages or PDFs)
- Interactive procedures

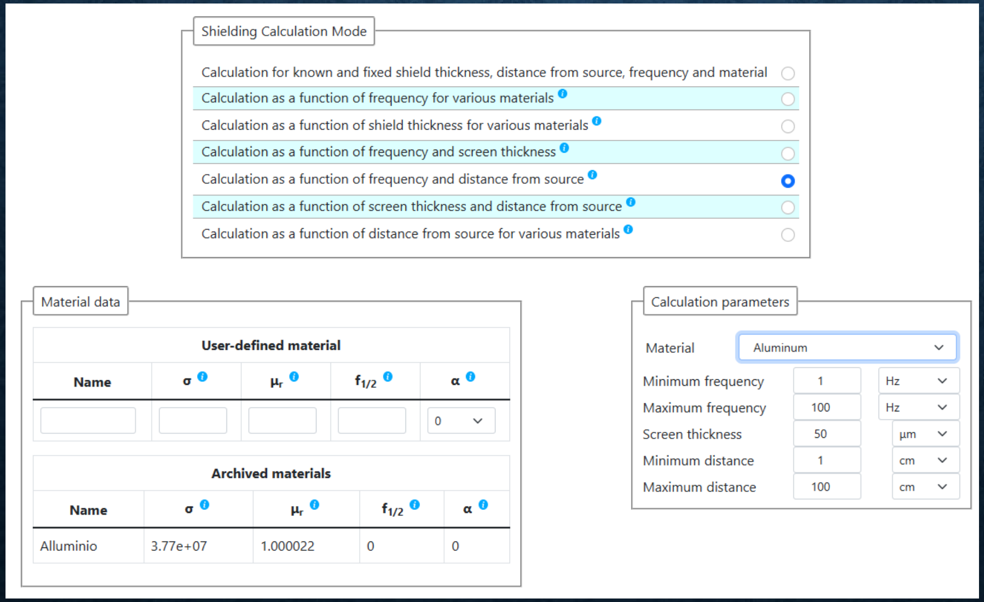
A backend interface allows the admin to insert data, automatically making available a frontend where the user can answer questions following a path according to the procedure.

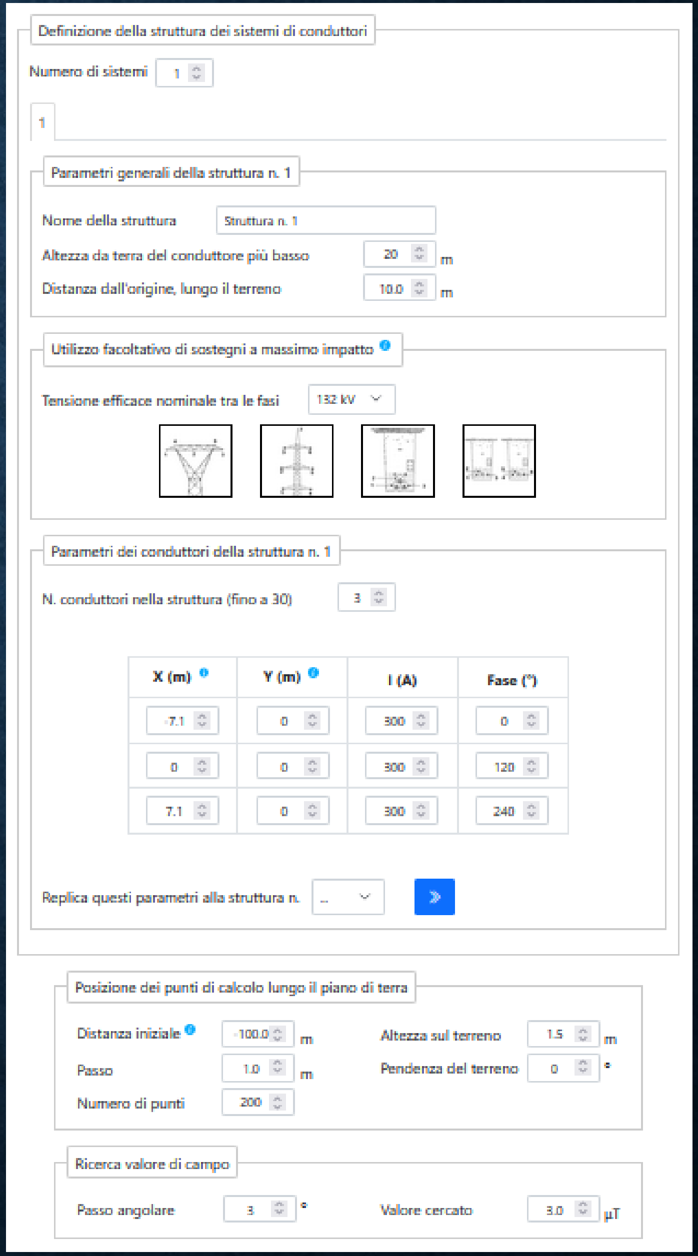


WEBNIR

It makes available:

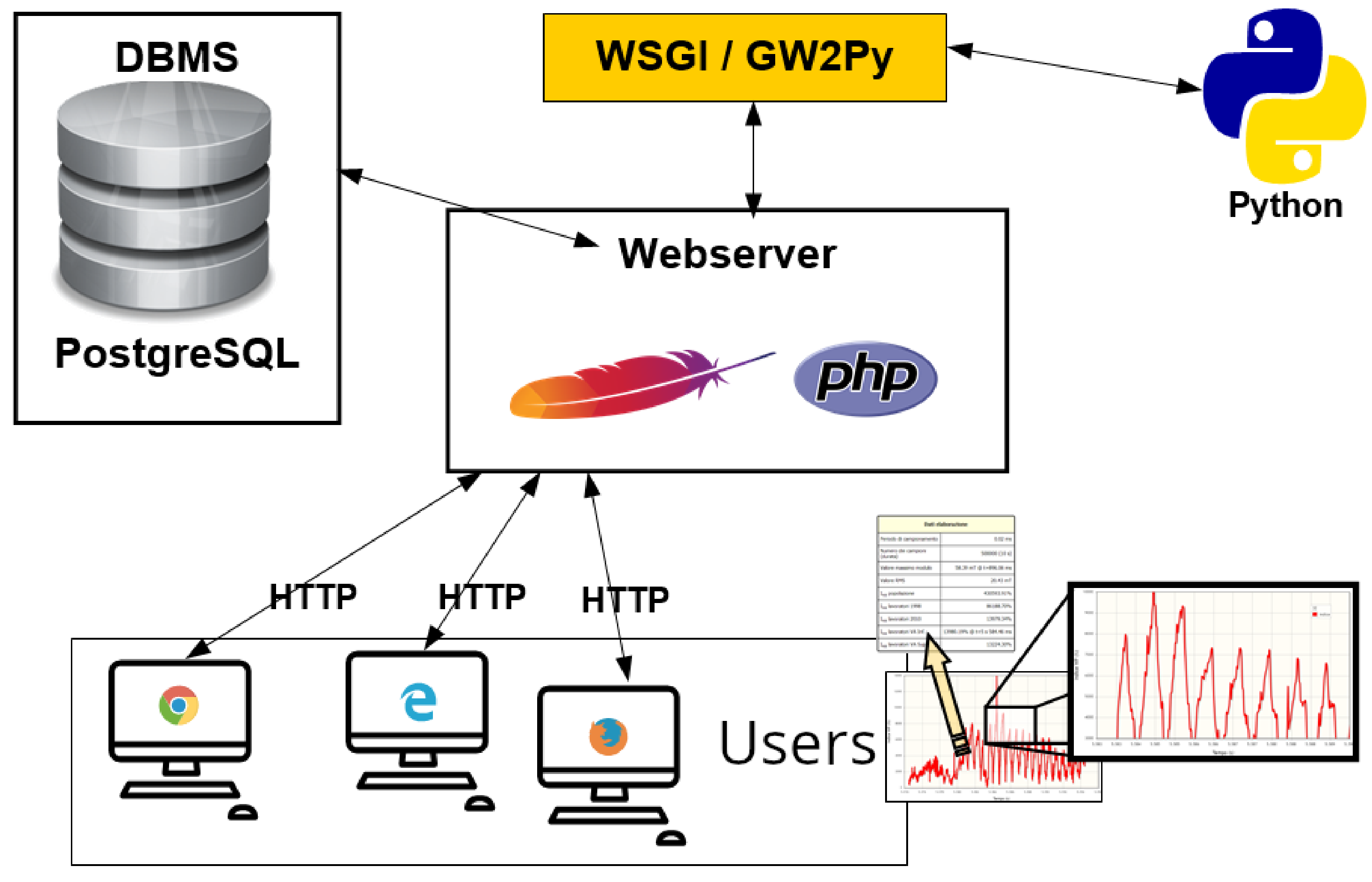
- Technical documents (web pages or PDFs)
- Interactive procedures
- Calculation applications





THE COMMUNICATION PROTOCOL

- The tools have a user interface created via a web page
- The computational load is split between the user's computer and the server platform
- Gw2Py: POST data to server, get data from server
- JSON as a standard format for data exchange



EMF TOOLS

- General aspects
  - Consultation and comparison of regulatory limits
  - Interpolation of index measurements and calculation of the compliance distance with determination of the uncertainty
- Characterization of sources in the external environment
  - Calculation of the electric field generated by systems of indefinite rectilinear conductors
- Processing of data files from exposure measurements
  - Calculation of weighted peak indices for low and intermediate frequency magnetic field sources
  - Motion in a Static Magnetic Field - Processing of Perceived Magnetic Field Measurements
  - Loading, recognition, and processing of measurement data files in the time or frequency domain
- Applications to support the reduction to compliance
  - Comparison of the electric field generated by systems of indefinite rectilinear conductors
  - Calculating the shielding effectiveness of an ideal screen

EMF TOOLS: CONSULTATION AND COMPARISON OF REGULATORY LIMITS

Regulations list | Regulations comparison | Regulations filter | Instructions

- ICNIRP Guidelines 1994 (Static magnetic fields)
- ICNIRP Guidelines 1998 (EMF up to 300 GHz)
- ICNIRP Guidelines 2009 (Static magnetic fields)
- ICNIRP Guidelines 2010 (LF)
- ICNIRP Guidelines 2014 (Movement in a static magnetic field)
- Raccomandazione 1999/519/CE
- Direttiva 2013/35/UE
- ICNIRP Guidelines 2014 + Direttiva 2013/35/UE
- ICNIRP Guidelines 2020 (100 kHz to 300 GHz)

- Tab system
- Regulations grouped by document (ICNIRP guidelines…)

EMF TOOLS: CONSULTATION AND COMPARISON OF REGULATORY LIMITS

ICNIRP Guidelines 2009 (Static magnetic fields)

ICNIRP. Guidelines on limits of exposure to static magnetic fields. Health Physics, Vol.96, N.4, April 2009, pp.504-514.

Download PDF: [INT] [EXT]

Code	Full name	
ICNIRP2009BSTAT	ICNIRP Guidelines 2009 - Exposure limits for static magnetic fields	Details

Short name	ICNIRP-2009 B-Stat
Type	Exposure limits
Quantity	Magnetic flux density
Metric	Static field or DC value
Subject	Population and workers
Effect	Undifferentiated
Level	Undifferentiated
Localization	Whole body exposure
Minimum frequency	0 Hz
Maximum frequency	0 Hz
Function	bstatico.icnirp2009
Reference document	ICNIRP Guidelines 2009 (Static magnetic fields)

Restriction	Value
Occupational exposure, spatial peak in the head or trunk	2 T
Occupational exposure, specific applications in a controlled environment where appropriate work practices are implemented to control the effects induced by movement, spatial peak	8 T
Occupational exposure, spatial peak for exposure of limbs only	8 T
Population exposure, spatial peak in any part of the body	400 mT
Prevention of potential indirect side effects resulting from exposure of persons with implanted electronic medical devices and implants containing ferromagnetic materials, and hazards from flying metal objects: much lower maximum levels may be appropriate, up to	500 µT

- Limits not dependent on frequency are displayed in a table

EMF TOOLS: CONSULTATION AND COMPARISON OF REGULATORY LIMITS

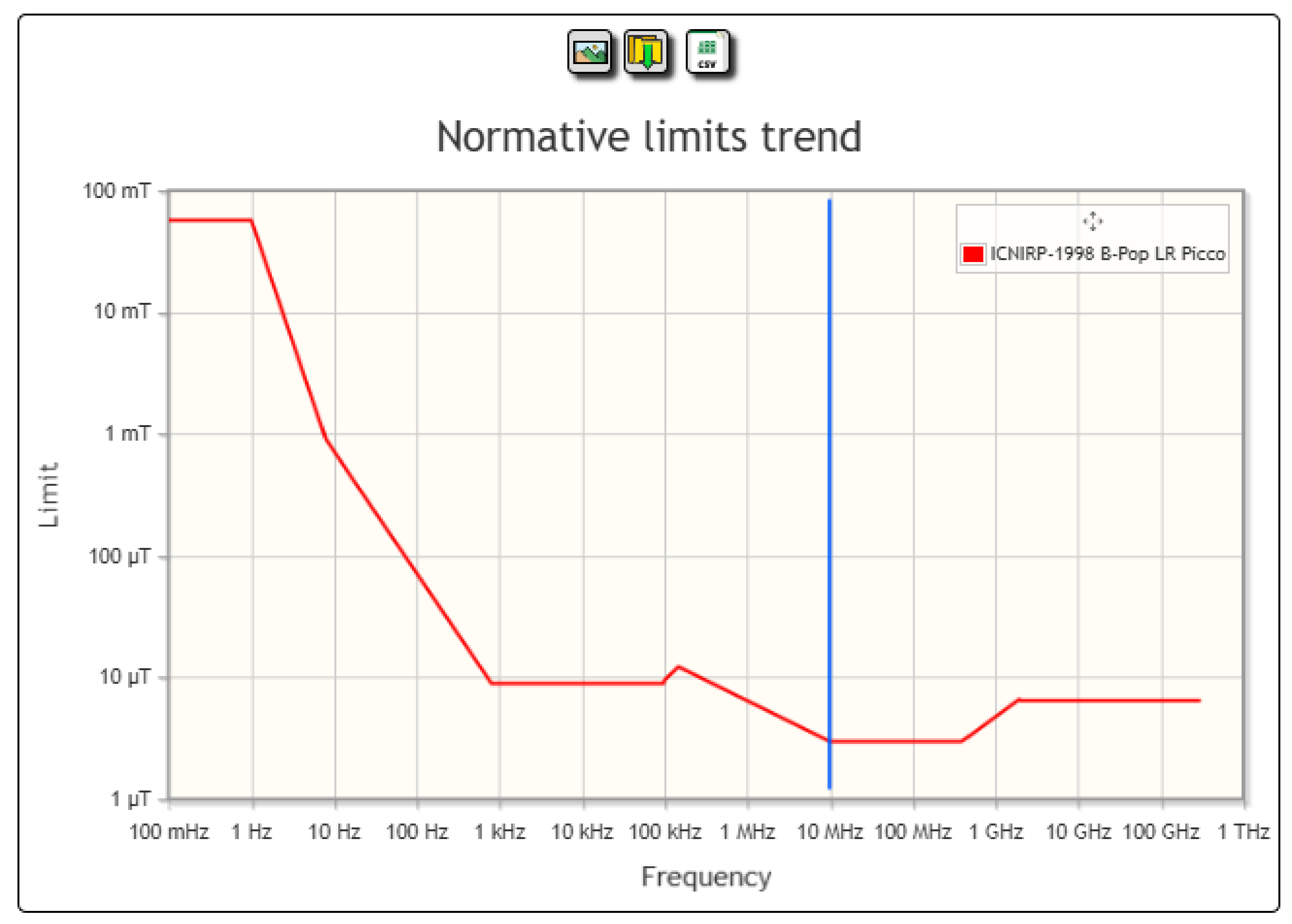
ICNIRP Guidelines 1998 - Magnetic induction - Limits for the general public - Peak reference levels

Details

Short name	ICNIRP-1998 B-Pop LR Picco
Type	Reference levels, action values (AV), action levels (AL)
Quantity	Magnetic flux density
Metric	Peak value
Subject	Population exposures
Effect	Undifferentiated
Level	Undifferentiated
Localization	Whole body exposure
Minimum frequency	0 Hz
Maximum frequency	300 GHz
Reference document	ICNIRP Guidelines 1998 (EMF up to 300 GHz)
Calculate limit at specific values	**Frequency** 300 GHz Calculate **Limit**

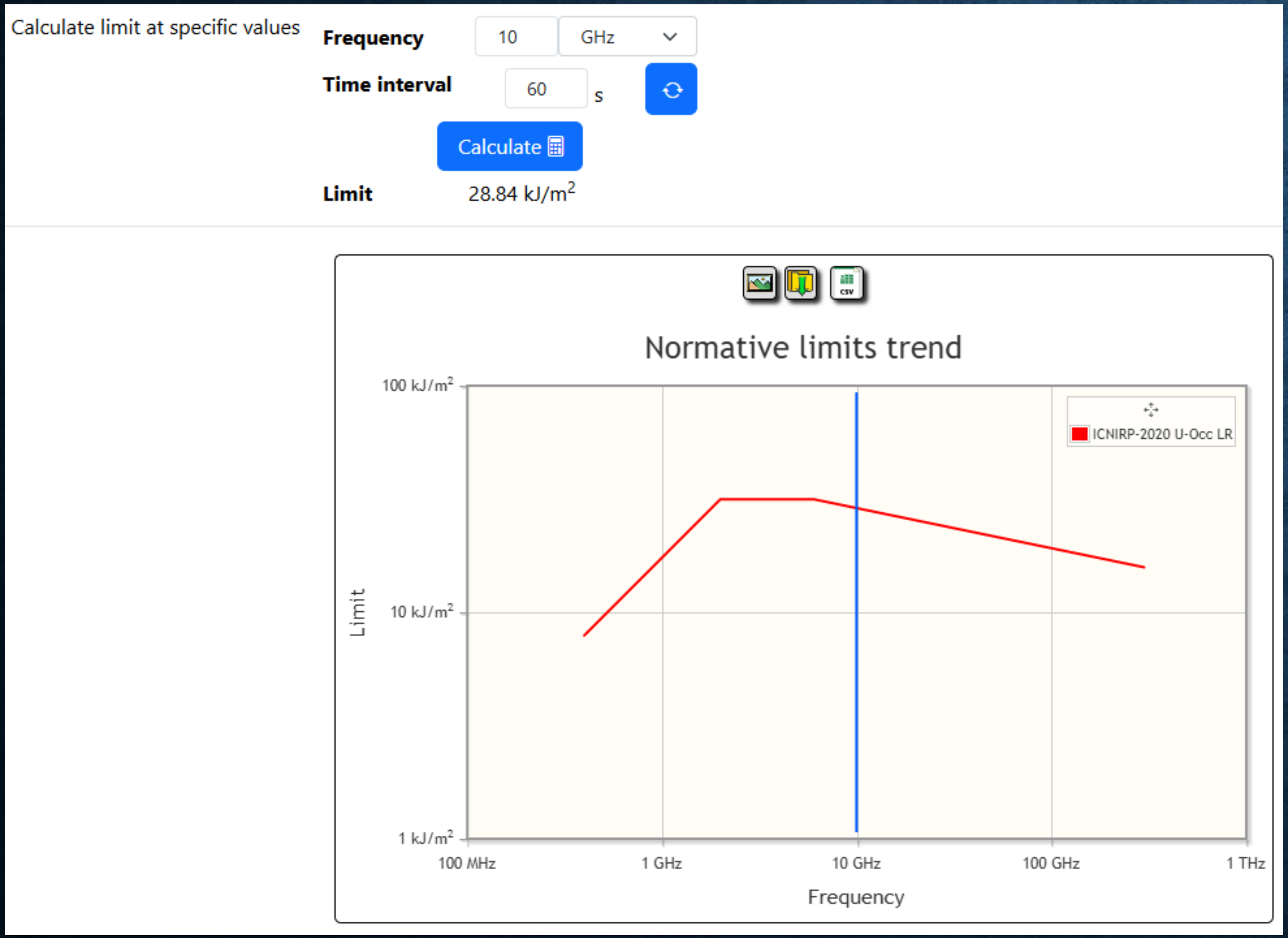
- Generic case: regulatory limit depends on the frequency
- User can calculate the limit at a specific frequency
- …

EMF TOOLS: CONSULTATION AND COMPARISON OF REGULATORY LIMITS



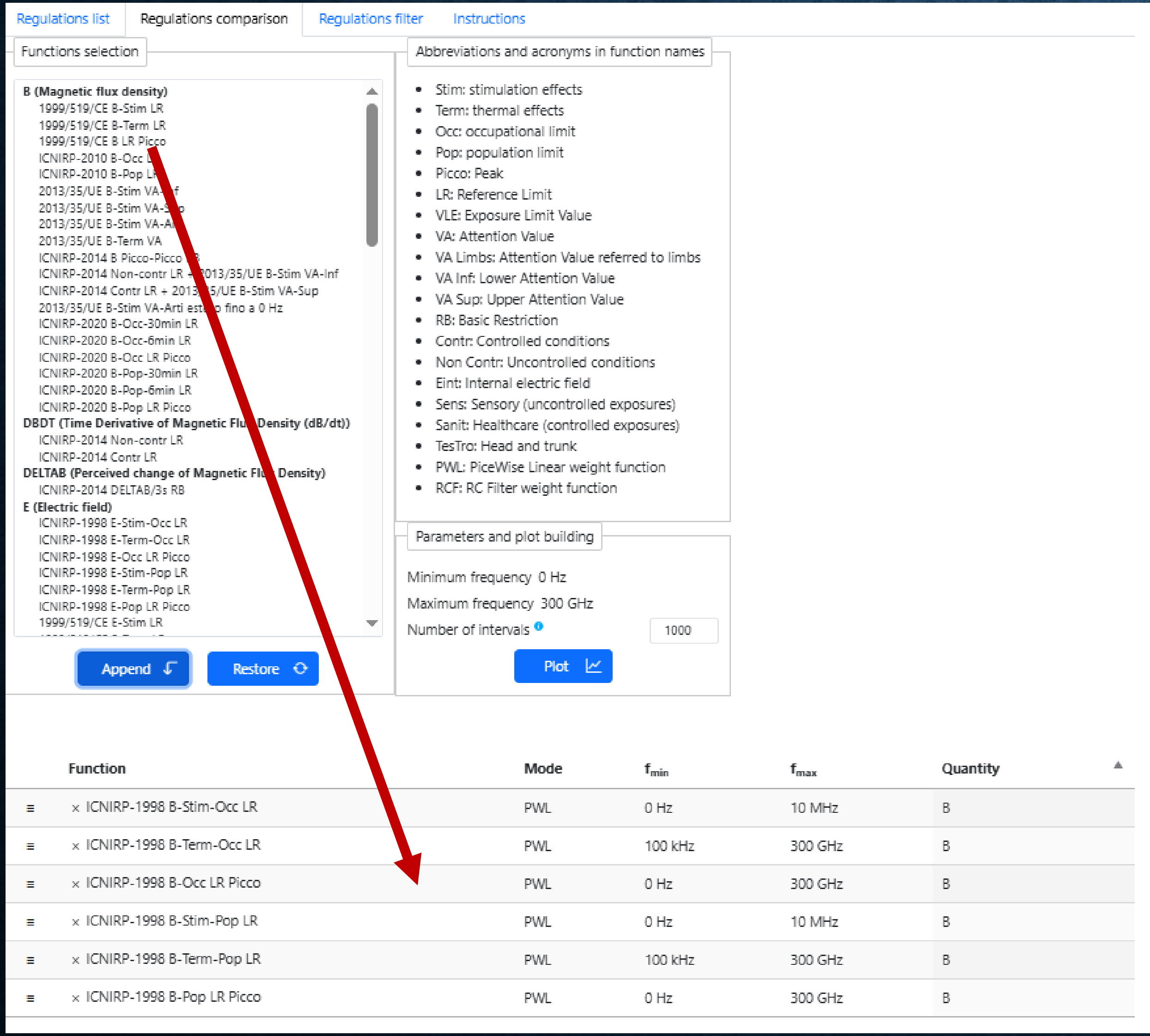
- Generic case: regulatory limit depends on the frequency
- User can calculate the limit at a specific frequency
- and plot limit trend vs. frequency

EMF TOOLS: CONSULTATION AND COMPARISON OF REGULATORY LIMITS



- In the 2020 ICNIRP guidelines, limits can depend:
  - on time
  - on frequency
  - on time AND frequency
- Calculation is performed at a specific time interval and frequency value
- Limit trend vs. frequency is displayed at the chosen time interval

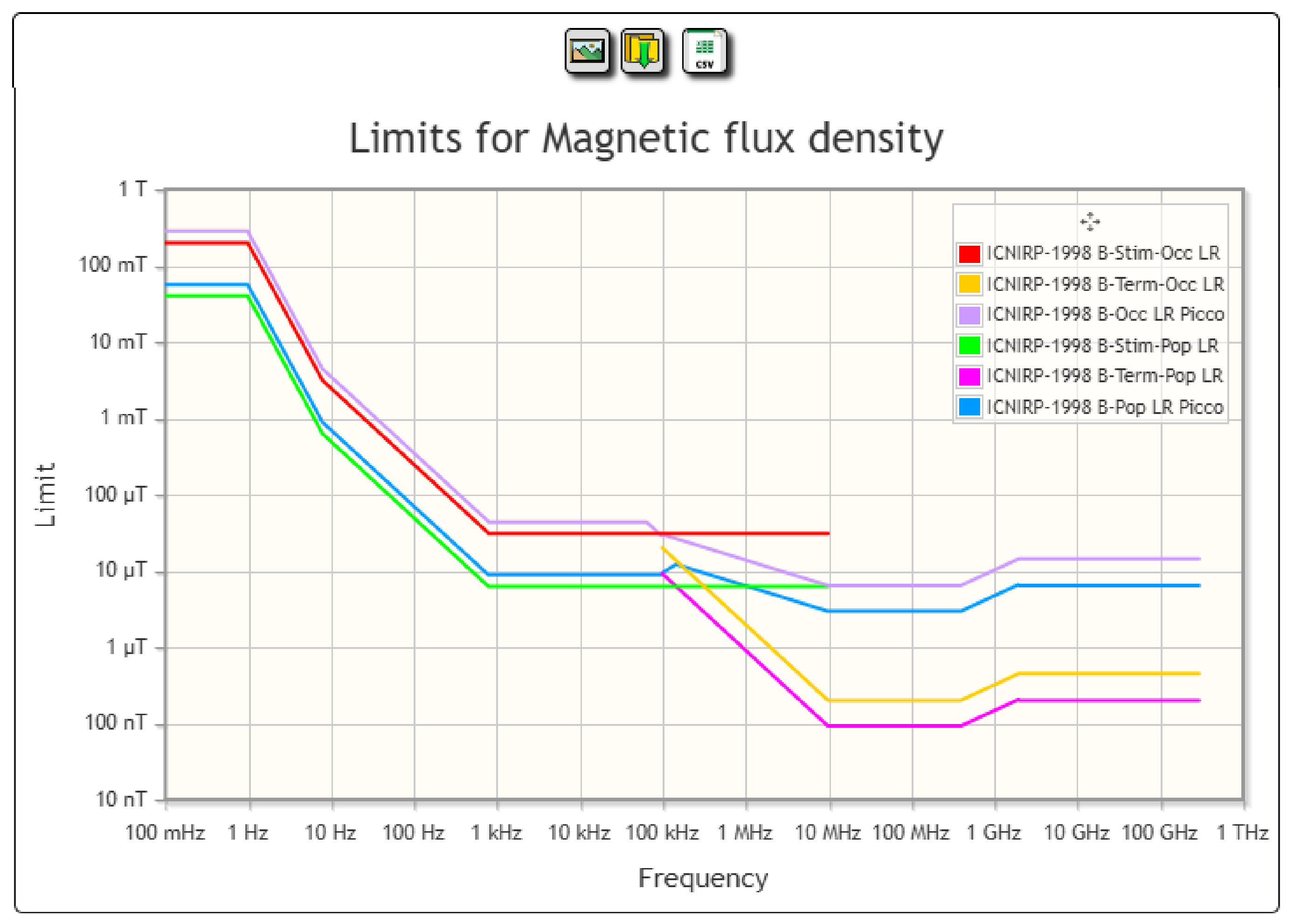
EMF TOOLS: CONSULTATION AND COMPARISON OF REGULATORY LIMITS



Comparison of limits:

- The user can select a set of limits to compare
- They are first displayed in a table, where user can set their order (as they will appear in plot)

EMF TOOLS: CONSULTATION AND COMPARISON OF REGULATORY LIMITS



Comparison of limits:

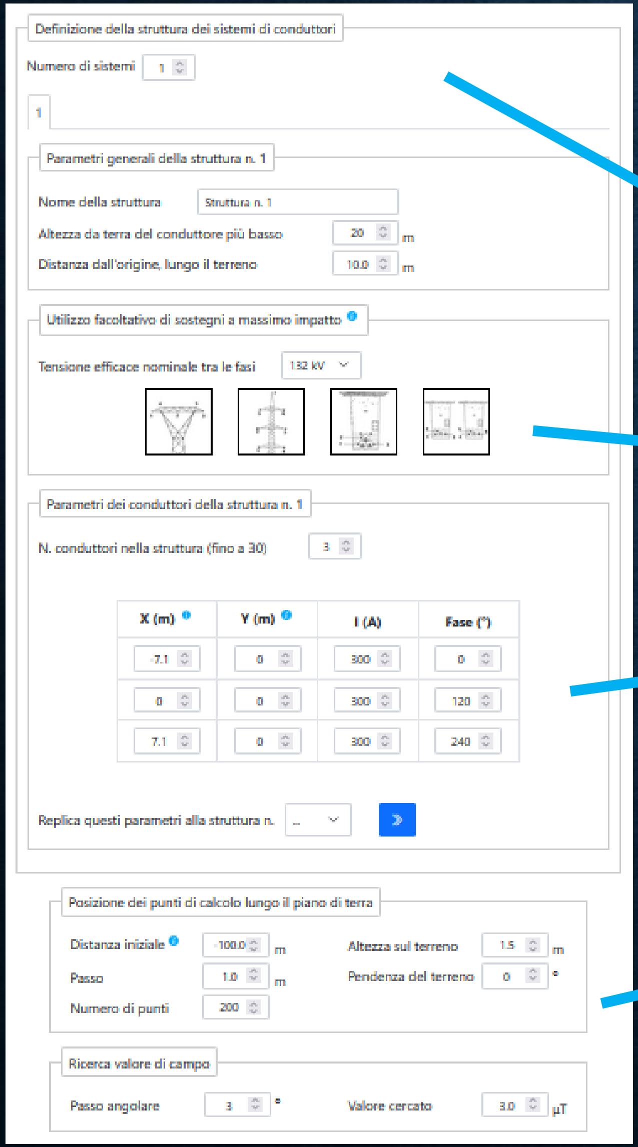
- The user can select a set of limits to compare
- They are first displayed in a table, where user can set their order (as they will appear in plot)
- and plot all of them (one physical quantity per graph)

EMF TOOLS: CHARACTERIZATION OF SOURCES IN THE EXTERNAL ENVIRONMENT

2 sets of tools share a similar interface:

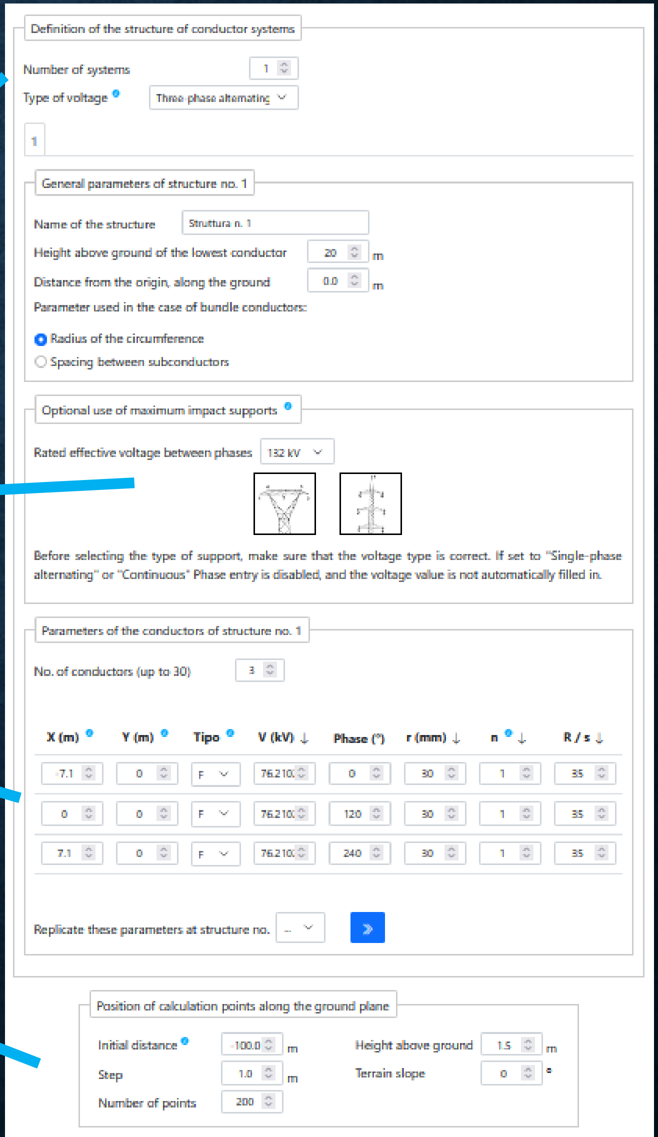
- Characterization of sources in the external environment
  - Calculation of the electric field / magnetic flux density generated by systems of indefinite rectilinear conductors
- Applications to support the reduction to compliance
  - Comparison of the electric field / magnetic flux density generated by systems of indefinite rectilinear conductors

EMF TOOLS: CHARACTERIZATION OF SOURCES IN THE EXTERNAL ENVIRONMENT

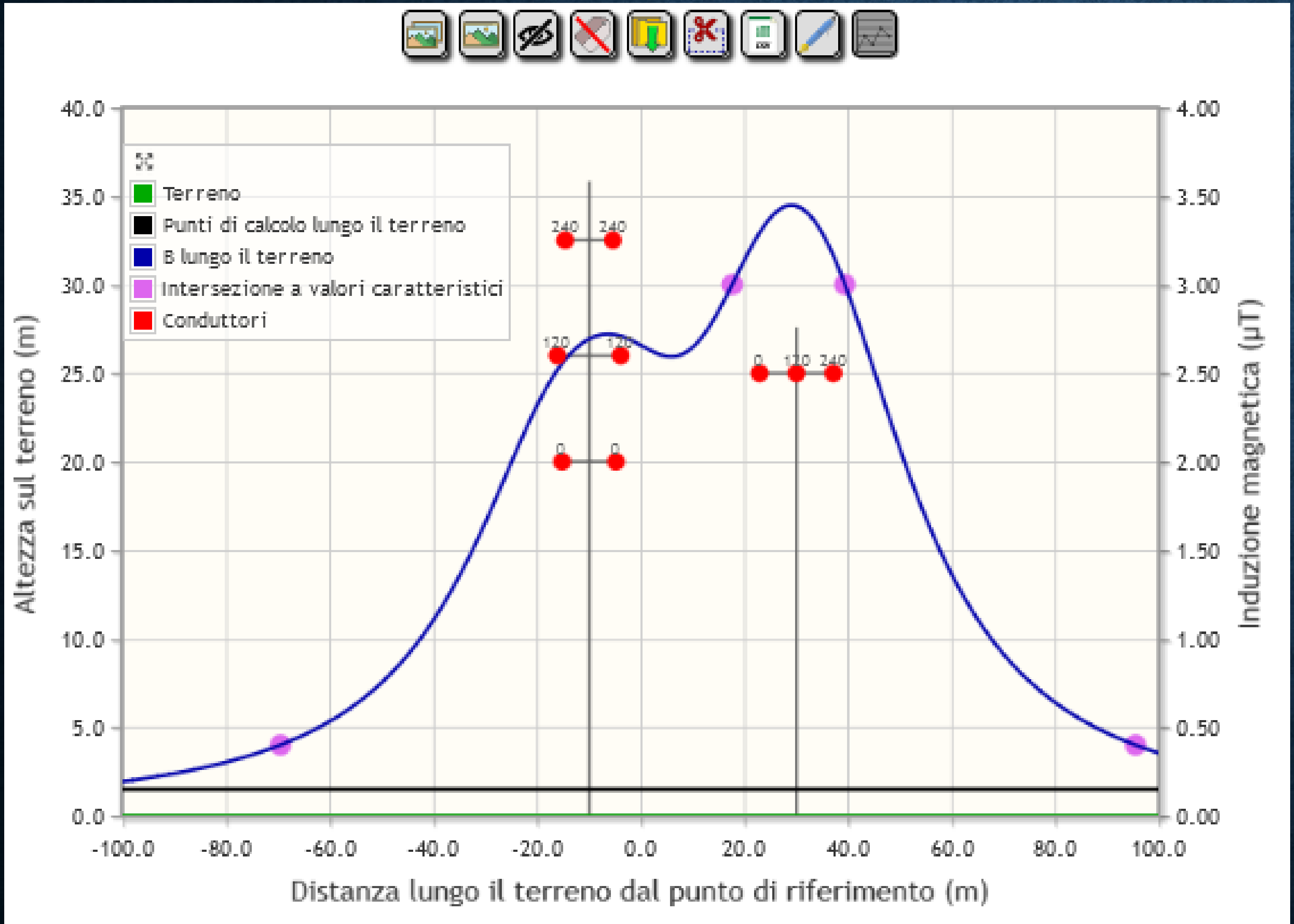


Calculating E or B

- User can define up to 10 power lines
- Eventually chose one from a database
- Insert power lines electric and geometric data
- Geometric calculation parameters



EMF TOOLS: CHARACTERIZATION OF SOURCES IN THE EXTERNAL ENVIRONMENT

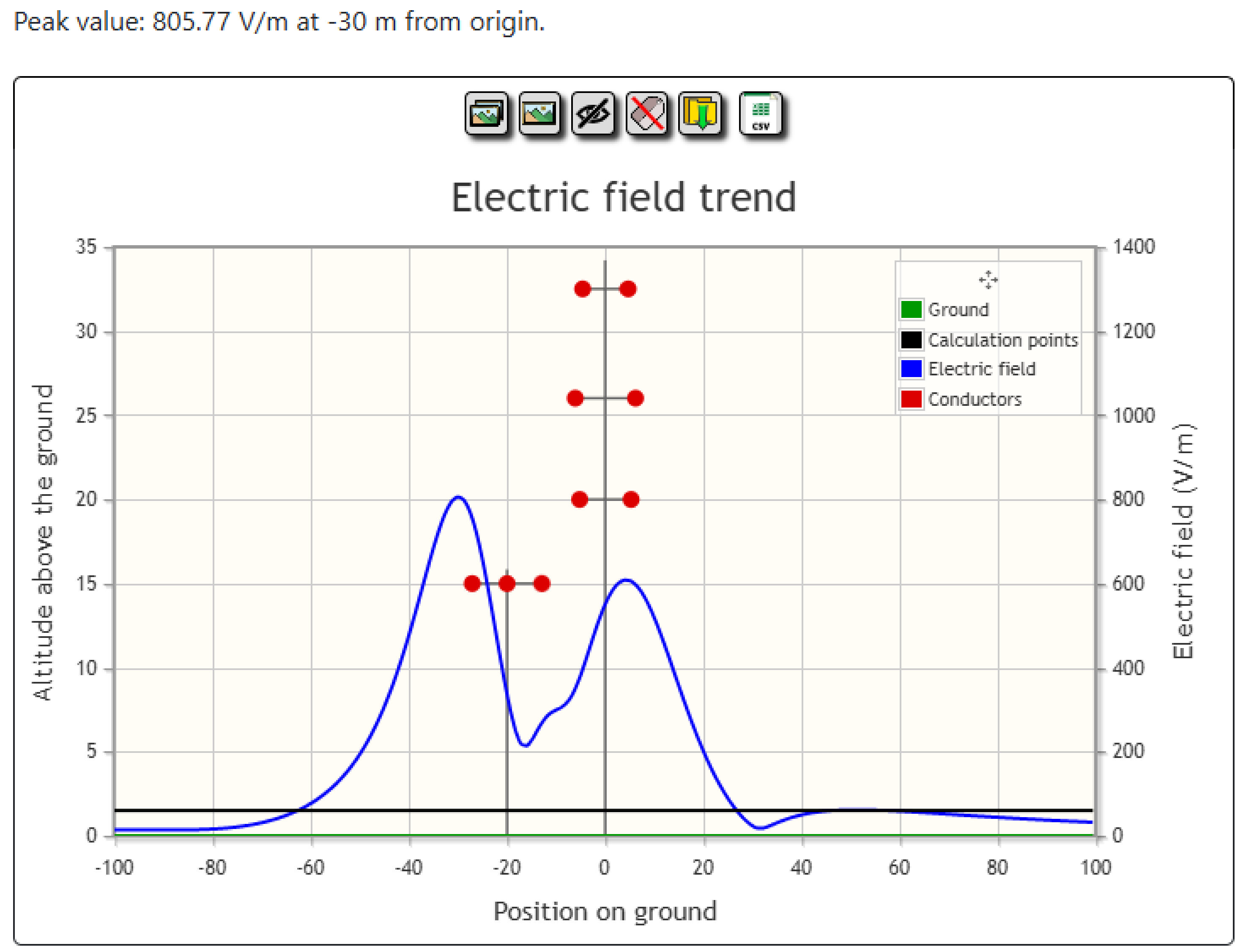


Magnetic flux density generated by systems of indefinite rectilinear conductors along a path parallel to the ground

EMF TOOLS: CHARACTERIZATION OF SOURCES IN THE EXTERNAL ENVIRONMENT

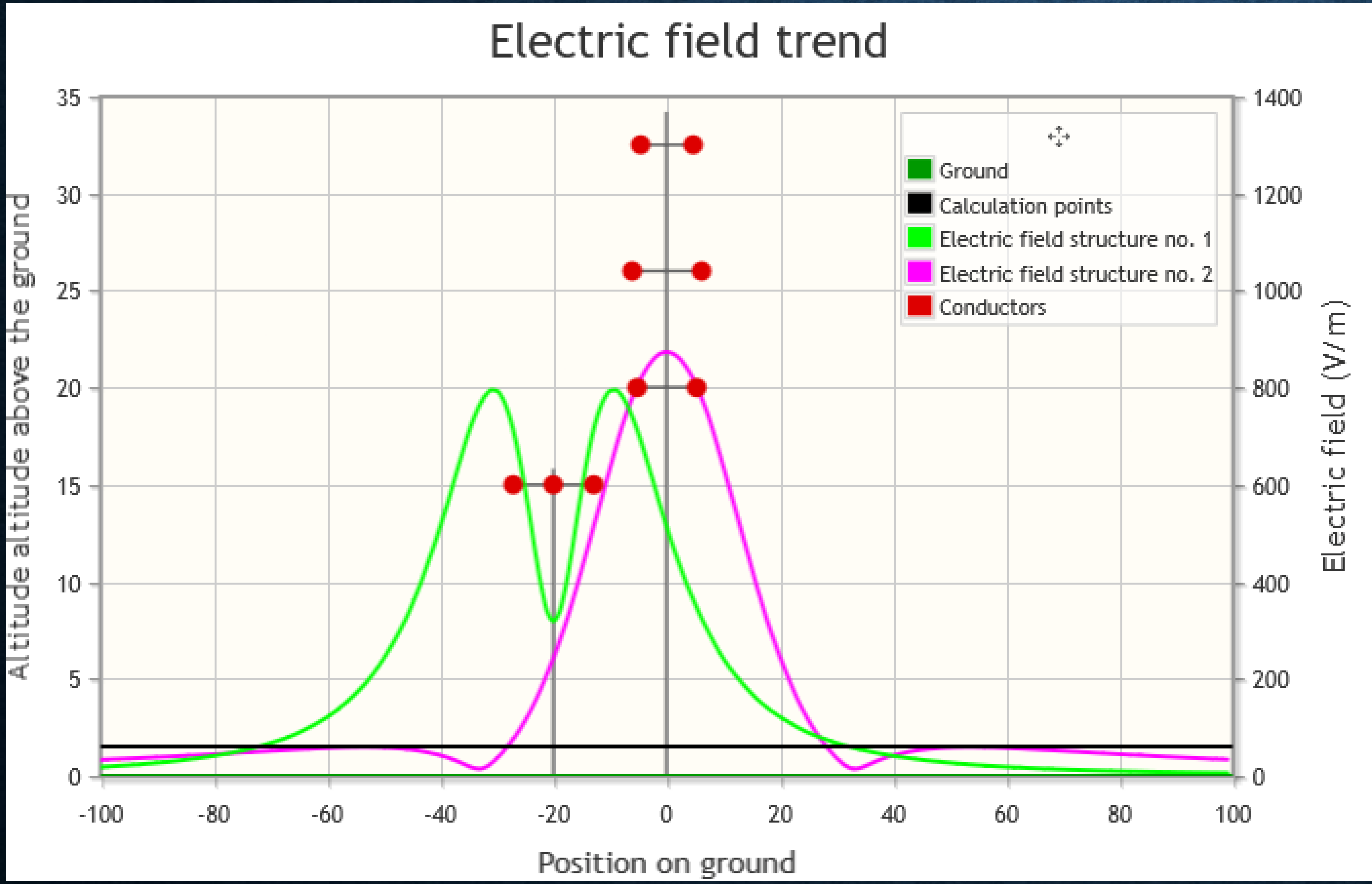
Position of points at a user-defined field value, around the wires

EMF TOOLS: CHARACTERIZATION OF SOURCES IN THE EXTERNAL ENVIRONMENT



Electric field generated by systems of indefinite rectilinear conductors

EMF TOOLS: CHARACTERIZATION OF SOURCES IN THE EXTERNAL ENVIRONMENT



Comparison of the electric field generated by systems of indefinite rectilinear conductors

ANALYSIS OF COMPLEX SIGNALS

- General aspects
  - Interpolation of index measurements and calculation of the compliance distance with determination of the uncertainty
- Processing of data files from exposure measurements
  - Calculation of weighted peak indices for low and intermediate frequency magnetic field sources
  - Motion in a Static Magnetic Field - Processing of Perceived Magnetic Field Measurements
  - Loading, recognition, and processing of measurement data files in the time or frequency domain

ANALYSIS OF COMPLEX SIGNALS

STANDARD METHOD

1. Compliance with the limit is given by this formula, in which an evaluation is made for each frequency component in relation to the limit referred to that frequency.
2. It is a very conservative approach, as it is not said that all the components have a maximum at the same instant (extremely improbable situation)

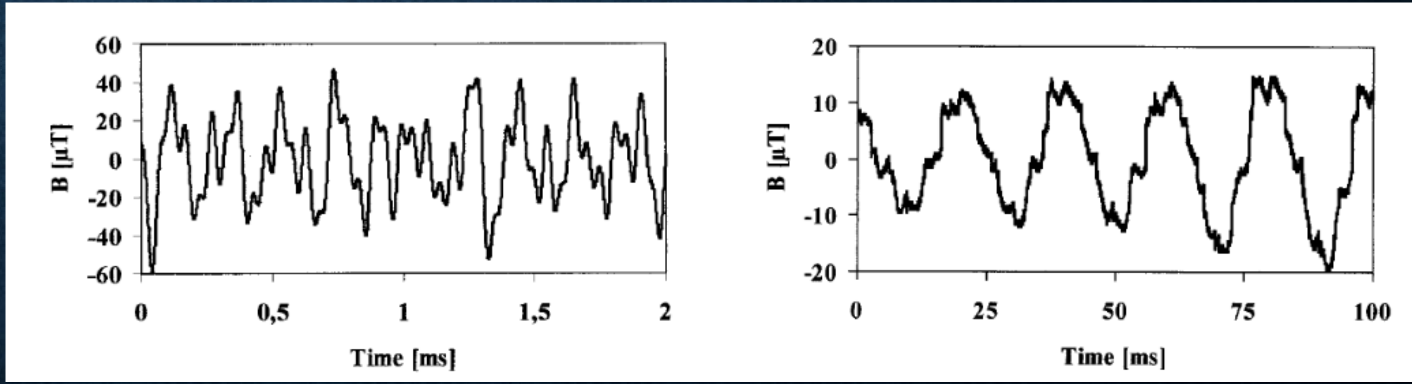
$$I_{MS} = \sum_{i=1}^{N} \frac{A_i}{L(f_i)} \leq 1$$

ANALYSIS OF COMPLEX SIGNALS

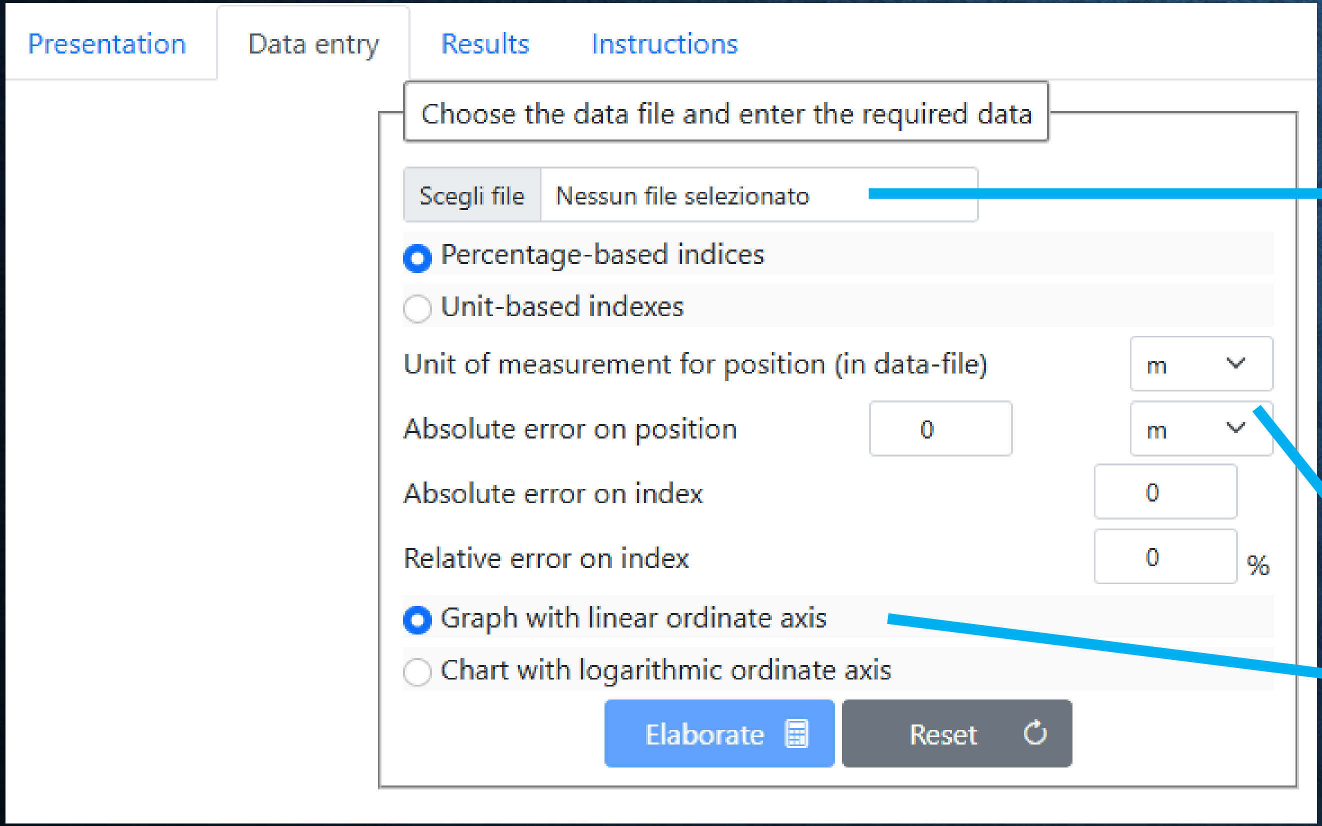
WEIGHTED PEAK METHOD (ICNIRP 2003-2010)

1. Differences in phases between different components are considered
2. Avoid overestimating the effect of the signal in an overly conservative manner
3. The approach can be shown to be valid for complex coherent and incoherent signals (complex non-sinusoidal waveforms, with or without phase coherence)

$$I_{WP} = Max\left|\sum_{i=1}^{N} \frac{A_i}{L(f_i)} \cos\left[2\pi f_i t + \vartheta_i + \varphi(f_i)\right]\right| \leq 1$$



INTERPOLATION OF INDEX MEASUREMENTS AND CALCULATION OF THE DISTANCE OF RESPECT



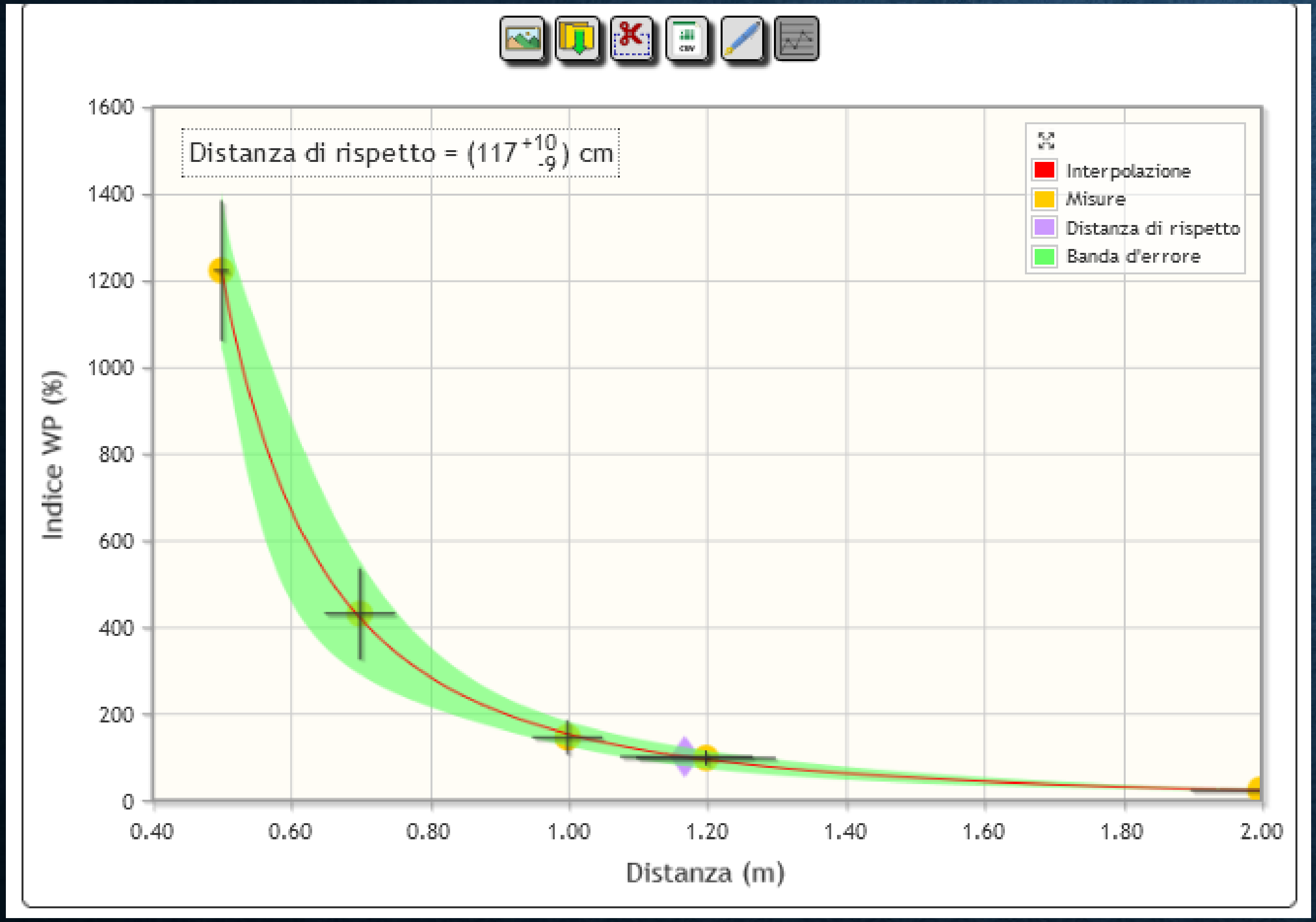
1) Select a text file (2 to 5 columns):

```
0.20,99.99
0.40,17.06
1.16,1.04
1.20,1.00
1.80,0.24
```

2) Insert distance unit and errors

3) Choose a kind of graph (lin/log)

INTERPOLATION OF INDEX MEASUREMENTS AND CALCULATION OF THE DISTANCE OF RESPECT



Interpolation with error bars and bands in a plot

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

3 applications:

- Motion in a static magnetic field: processing of perceived magnetic field measurements
- Calculation of weighted peak indices for low- and intermediate-frequency magnetic field sources
- Loading, recognition, and general processing of data files

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Motion in a Static Magnetic Field and

Calculation of Weighted Peak Indices:

- First procedures developed
- They are structured on the characteristics of specific measuring instruments, implementing specific scanning algorithms for the known output file format.

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Motion in a Static Magnetic Field - Processing of Perceived Magnetic Field Measurements

- Assessment of occupational exposure due to an operator's movement in any non-homogeneous magnetic field
- Narda-Metrolab THM-1176 probe, attached to a specific point on the operator's body
- The probe is connected via USB cable to a PC running the probe management software

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Motion in a Static Magnetic Field - Processing of Perceived Magnetic Field Measurements

Narda-Metrolab THM-1176 probe

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Motion in a Static Magnetic Field - Processing of Perceived Magnetic Field Measurements

- The subject is asked to perform movements typical of the various activities performed in relation to the task being studied, in areas where an intense static magnetic field is present
- During these movements, the instantaneous values of the magnetic induction vector detected by the probe are stored in a file on the personal computer
- The web tool allows processing of the data files

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Motion in a Static Magnetic Field - Processing of Perceived Magnetic Field Measurements

This instrument allows processing of magnetic field measurements that vary very slowly over time to derive the radiation protection parameters required by the ICNIRP-2014 “Guidelines for limiting exposure to electric fields induced by movement of the human body in a static magnetic field and by time-varying magnetic fields below 1 Hz”:

- the maximum ΔB variation in any 3-second interval
- the weighted peak index for stimulation effects.

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Calculation of weighted peak indices for low and intermediate frequency magnetic field sources

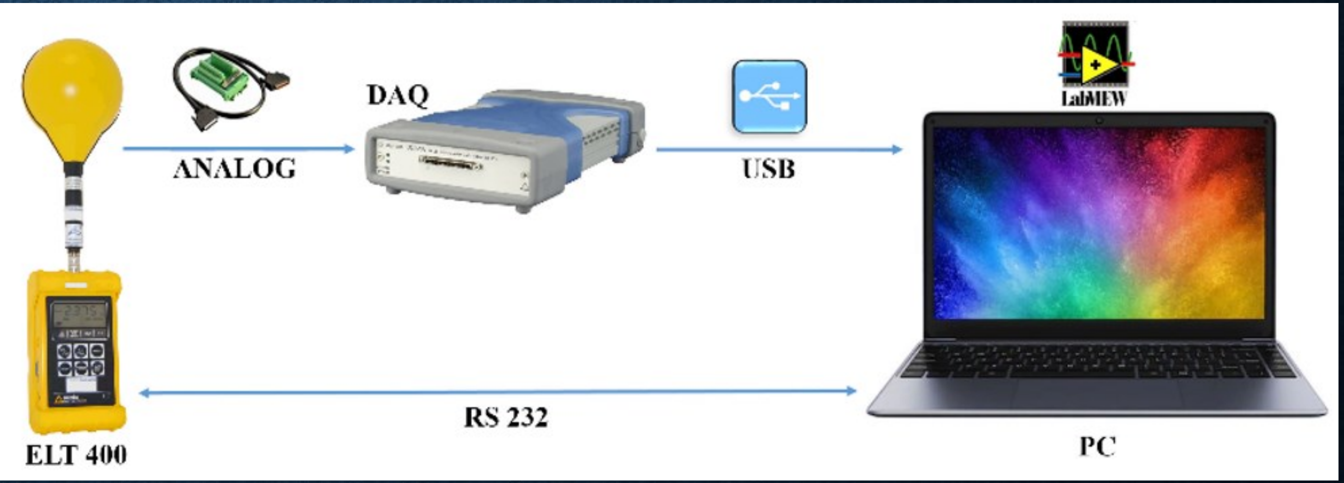
- A methodology for acquiring gradient magnetic field waveforms in the time domain has been developed.
- These waveforms are also essential for determining the weighted peak indices.

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Calculation of weighted peak indices for low and intermediate frequency magnetic field sources

Measurement chain:

- Narda ELT-400 meter with 100 cm^2 probe
- Agilent U2351A data acquisition system (connected to the meter's analog output)
- PC connected to both the data acquisition system via a USB connection and the meter via a standard RS232 connection
- On the PC: data acquisition and chain management program, developed by ENEA in a LabVIEW environment.



PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Calculation of weighted peak indices for low and intermediate frequency magnetic field sources

- This web tool allows you to process the data files produced by that instrument chain, which therefore relate to low-frequency magnetic flux density measurements (not limited to gradient fields in MRI).
- The radiation protection parameters required by law are derived, including the weighted peak indices for stimulation effects referred to any regulatory limit (not just those for which the index is provided directly from the meter display).

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

This approach used in the 2 tools has been expanded in order to accept files of the most generic type possible, potentially produced by <u>any</u> measurement chain, as long as they are in an open format (text file or spreadsheet). 2 possibilities:

- Measurement chain already known to the system (stored in the database)
- Measurement chain not present in the database. The user provides the description of the data format.

PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

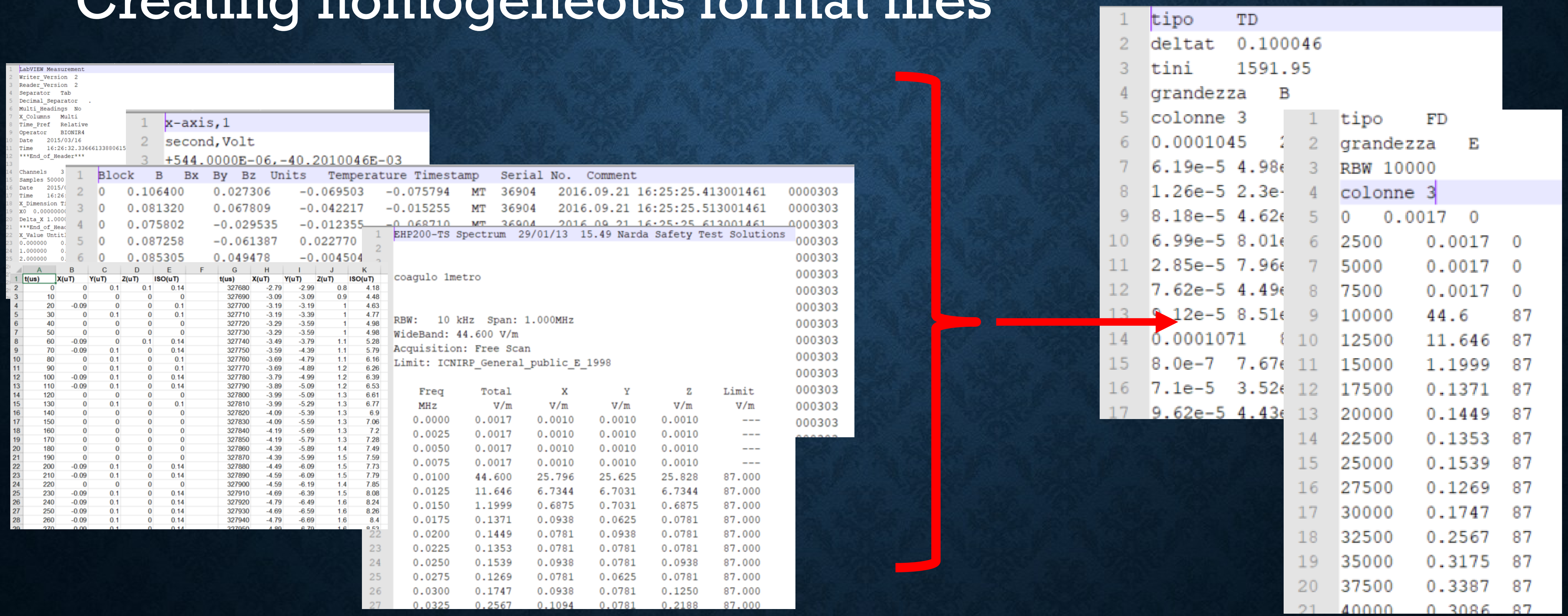
Loading, recognition, and processing of measurement data files in the time or frequency domain

Application structured in 3 sections (time domain, frequency domain, generic data), providing:

- Procedures developed for specific chains (divided into time and frequency domains)
- Generalized acquisition system for data files obtained from chains stored in DB
- Generalized acquisition for data files obtained from chains not stored in DB: the user must provide information about the structure of the data file

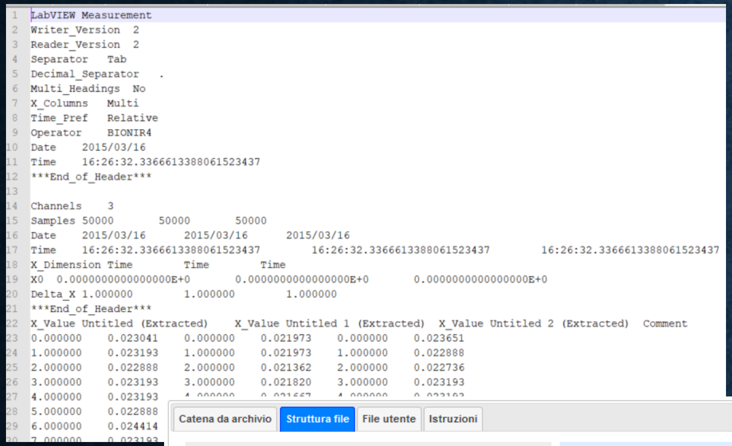
PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Creating homogeneous format files



PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Data file



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Reader_Version  2
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***End_of_Header***
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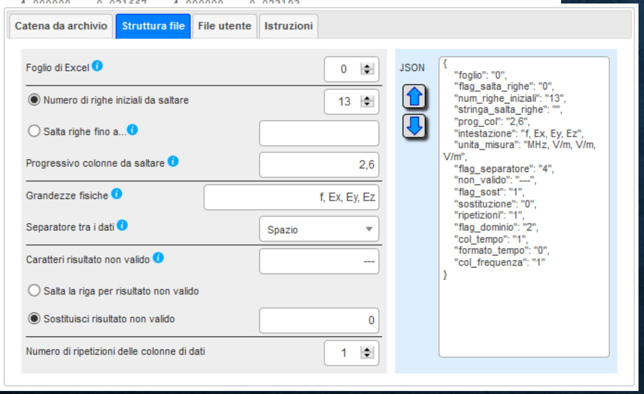

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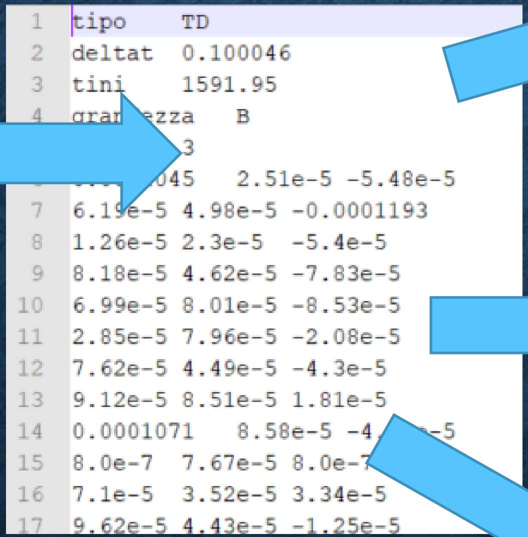
Information on file structure

Standard file



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gran ezza   B
3
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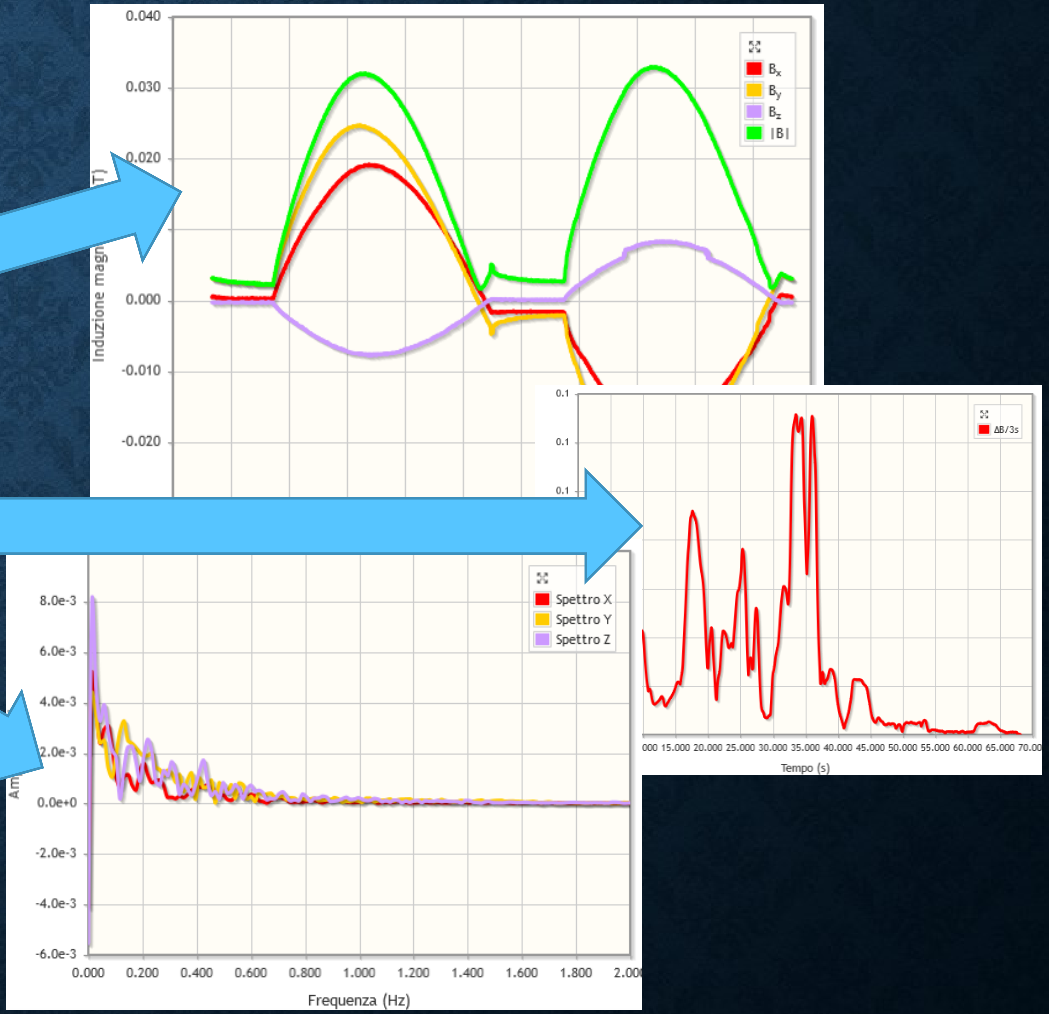
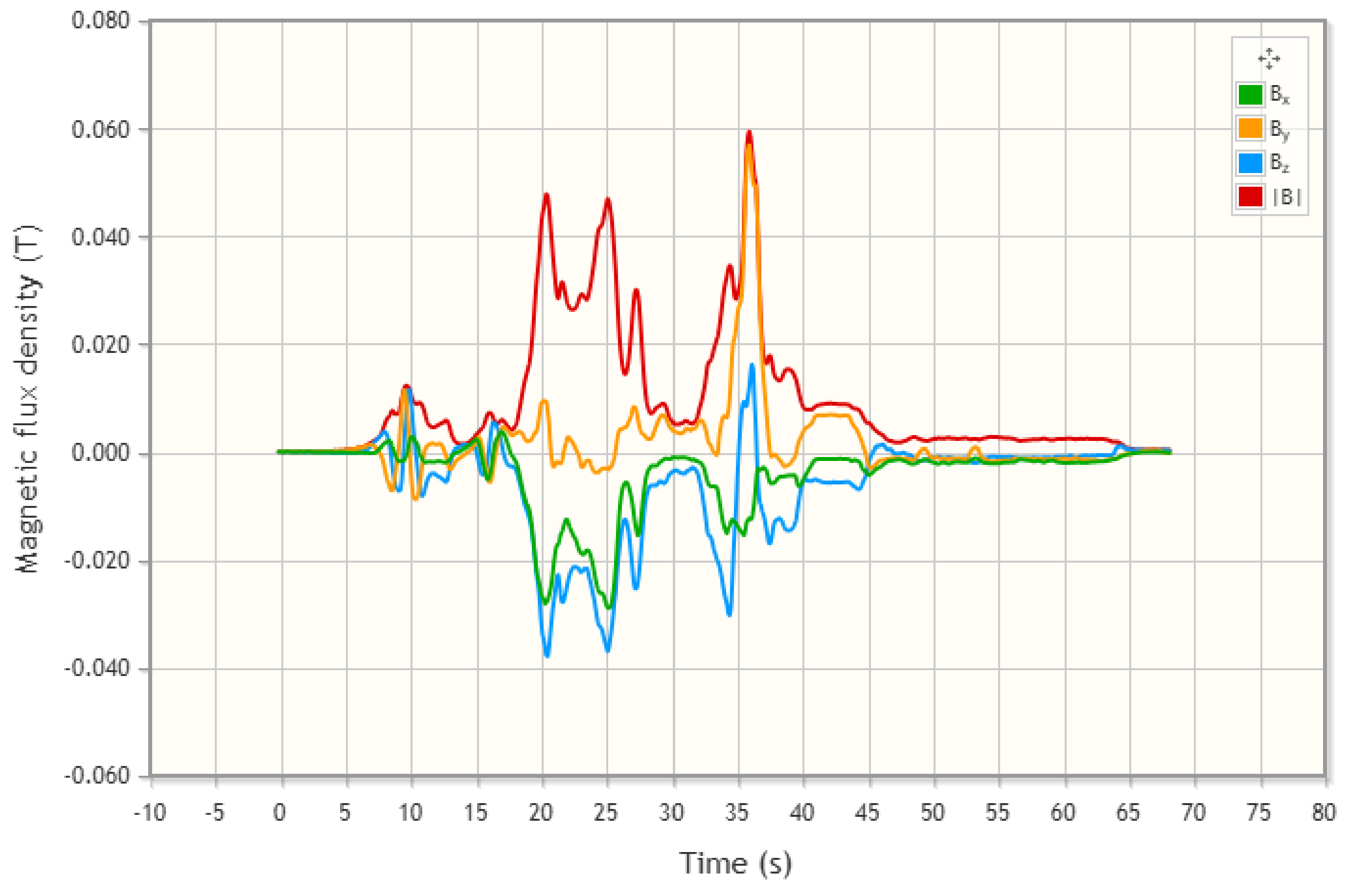
6.1 e-5 4.98e-5 -0.0001193
1.26e-5 2.3e-5  -5.4e-5
8.18e-5 4.62e-5 -7.83e-5
6.99e-5 8.01e-5 -8.53e-5
2.85e-5 7.96e-5 -2.08e-5
7.62e-5 4.49e-5 -4.3e-5
9.12e-5 8.51e-5 1.81e-5
0.0001071   8.58e-5 -4
8.0e-7  7.67e-5 8.0e-7
7.1e-5  3.52e-5 3.34e-5
9.62e-5 4.43e-5 -1.25e-5
```



PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Data output: components and module of H/B/E fields (condensed or all-data modes)

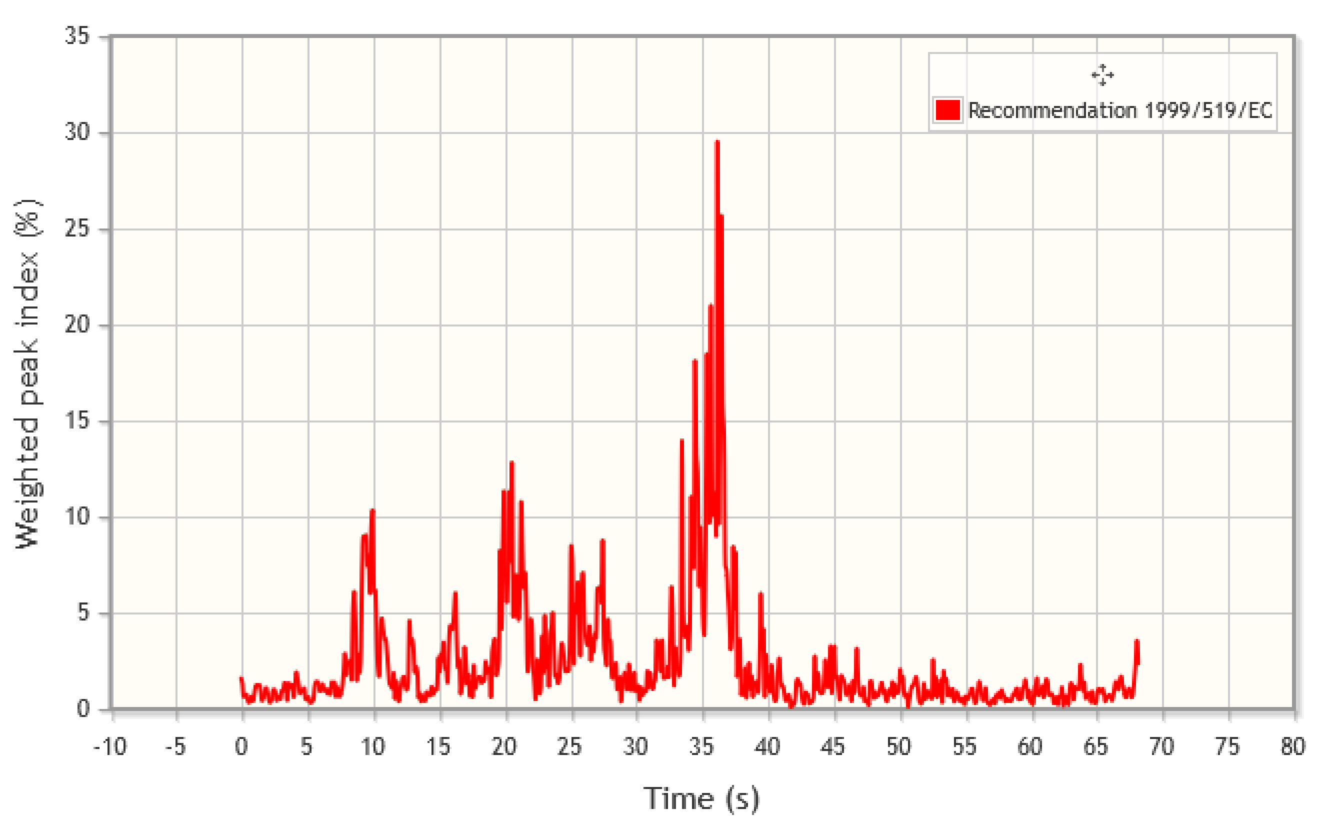
Data summary	
User file	magnet_2010.txt
Quantity	B (T)
Number of samples	683
Sampling period	100.1 ms
Overall duration	68.34 s
Maximum modulus value	59.40 mT @ 36.02 s
RMS value	15.67 mT



PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

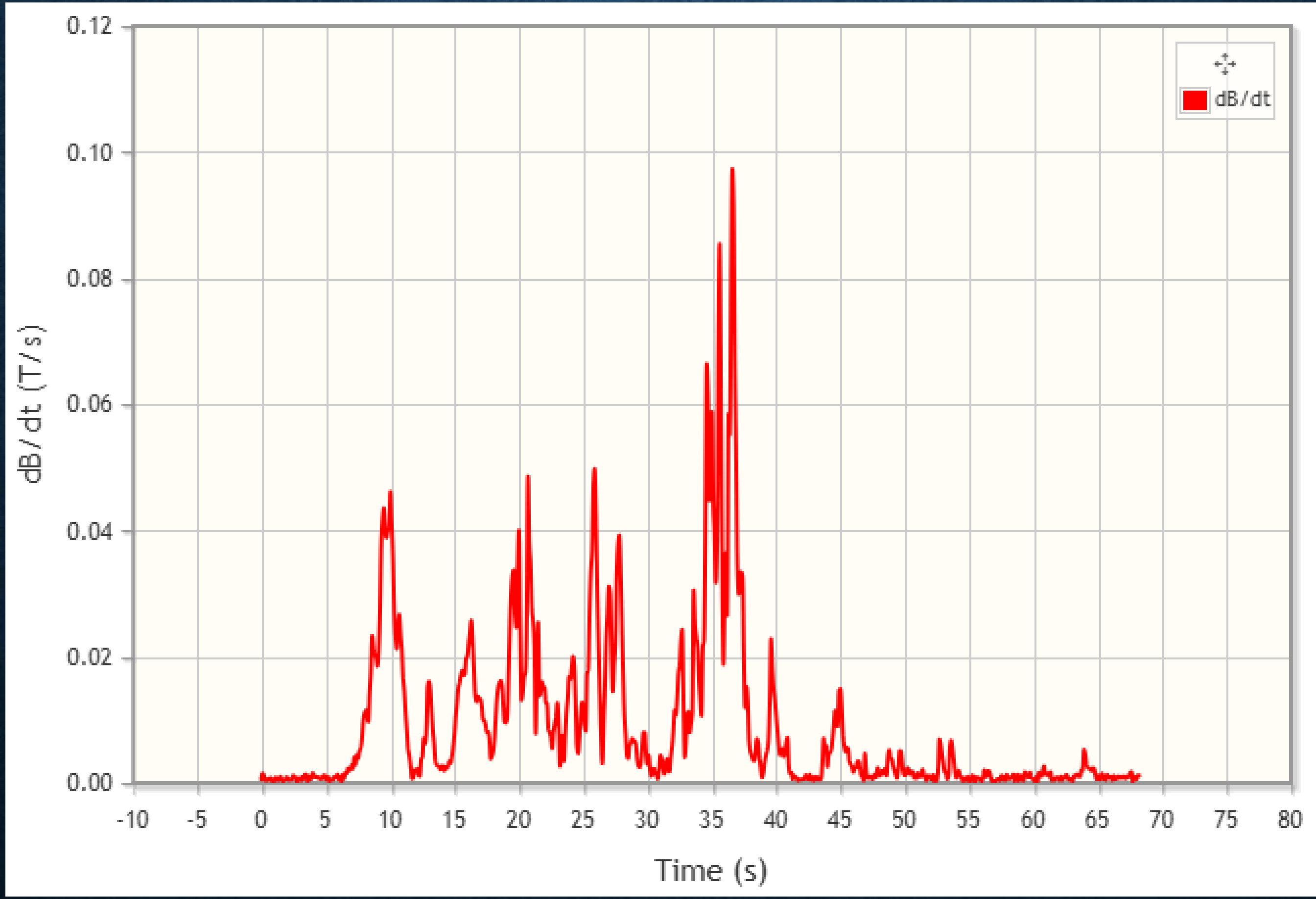
Data output: wheighted peak indices, according to different regulations

Weighted peak indices	
Standard file format:wp20250905133538175707213838.txt	
Recommendation 1999/519/EC	29.5%
ICNIRP 1998 Workers	5.9%
ICNIRP 2010 Workers	7.7%
D.Lgs. 81/2008 Lower AV	7.7%
D.Lgs. 81/2008 Upper AV	3.7%
Legislative Decree 81/2008 AV in limbs	1.2%



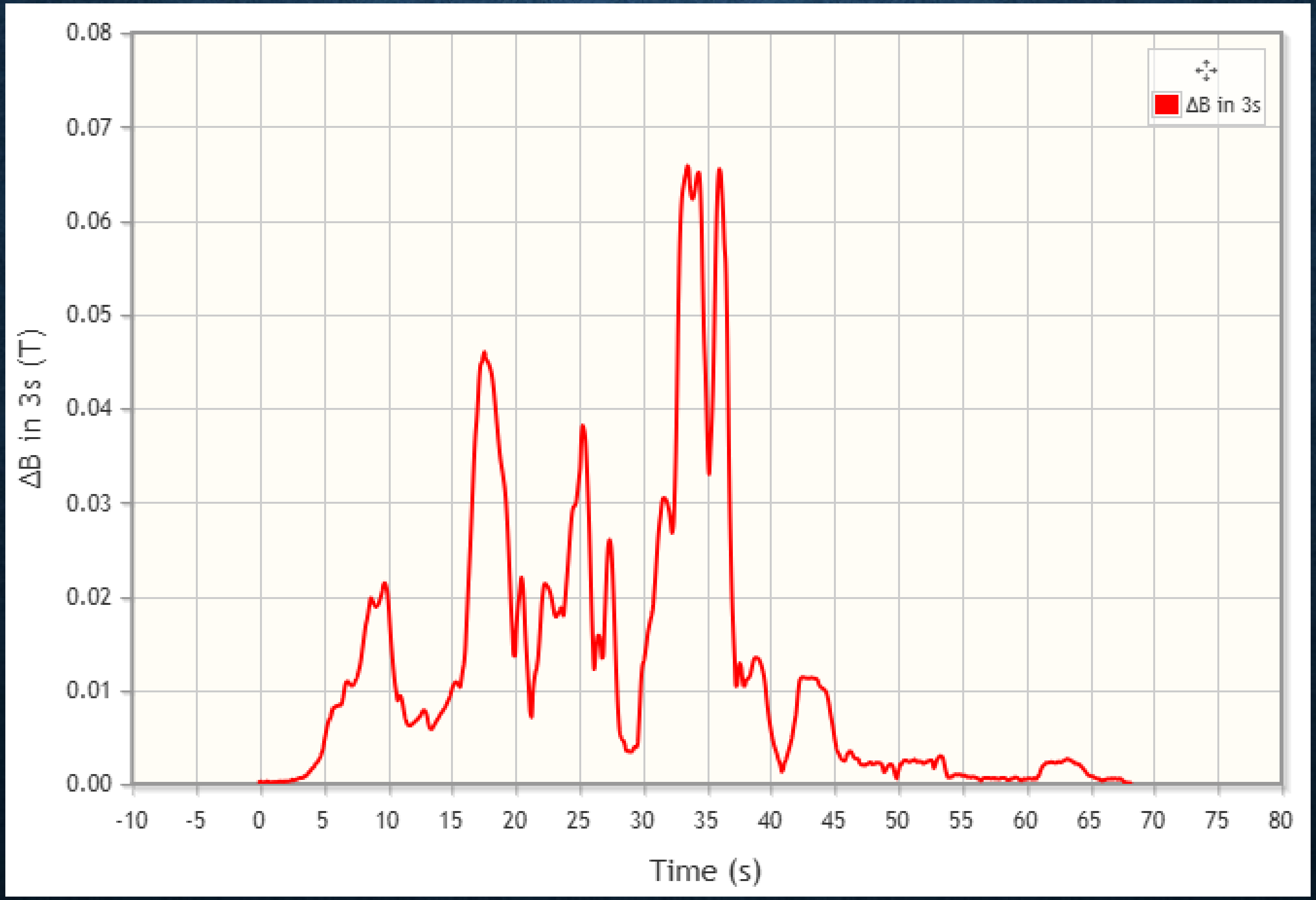
PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Data output: trend of dB/dt



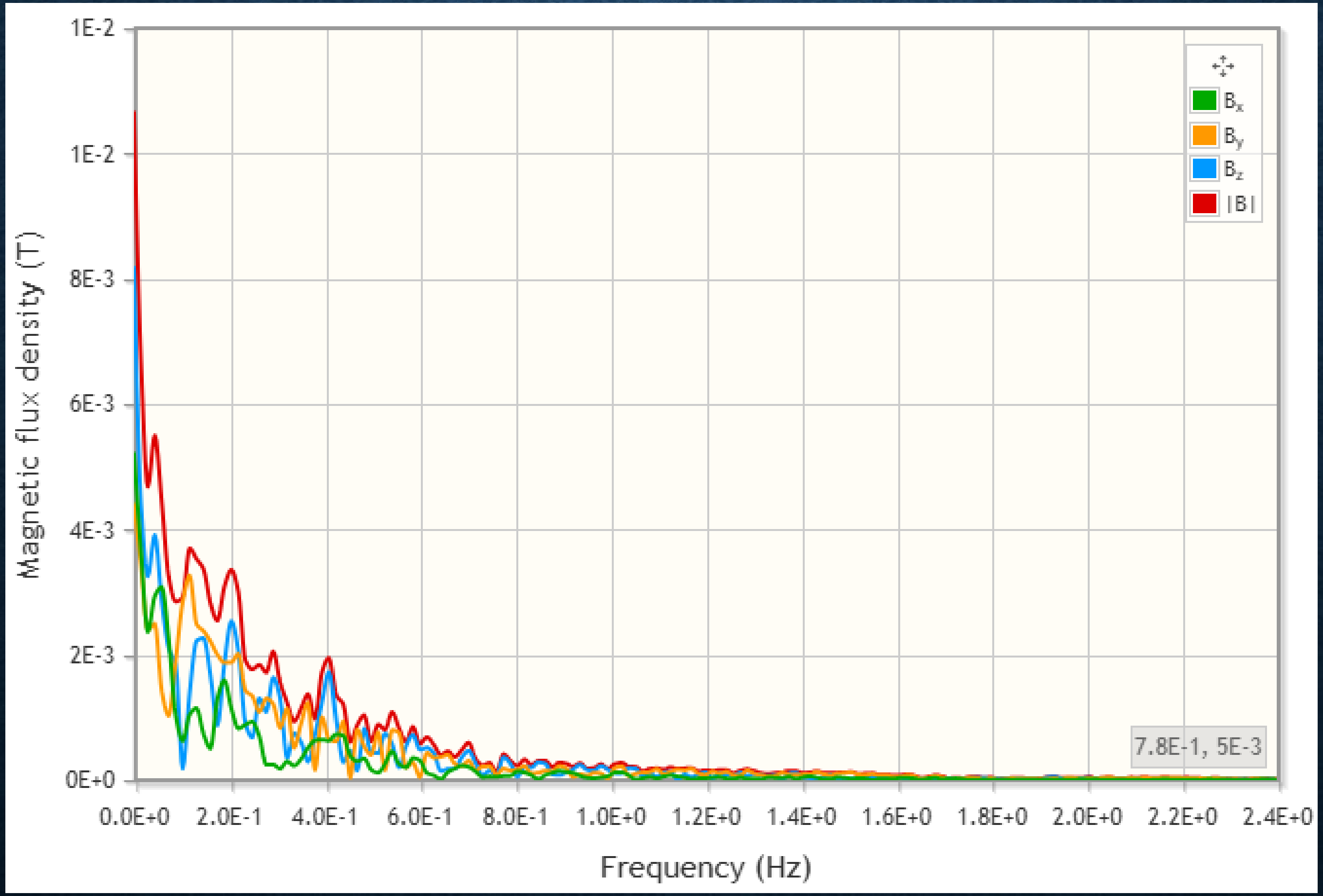
PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Data output: Max ΔB/3s and its trend over time



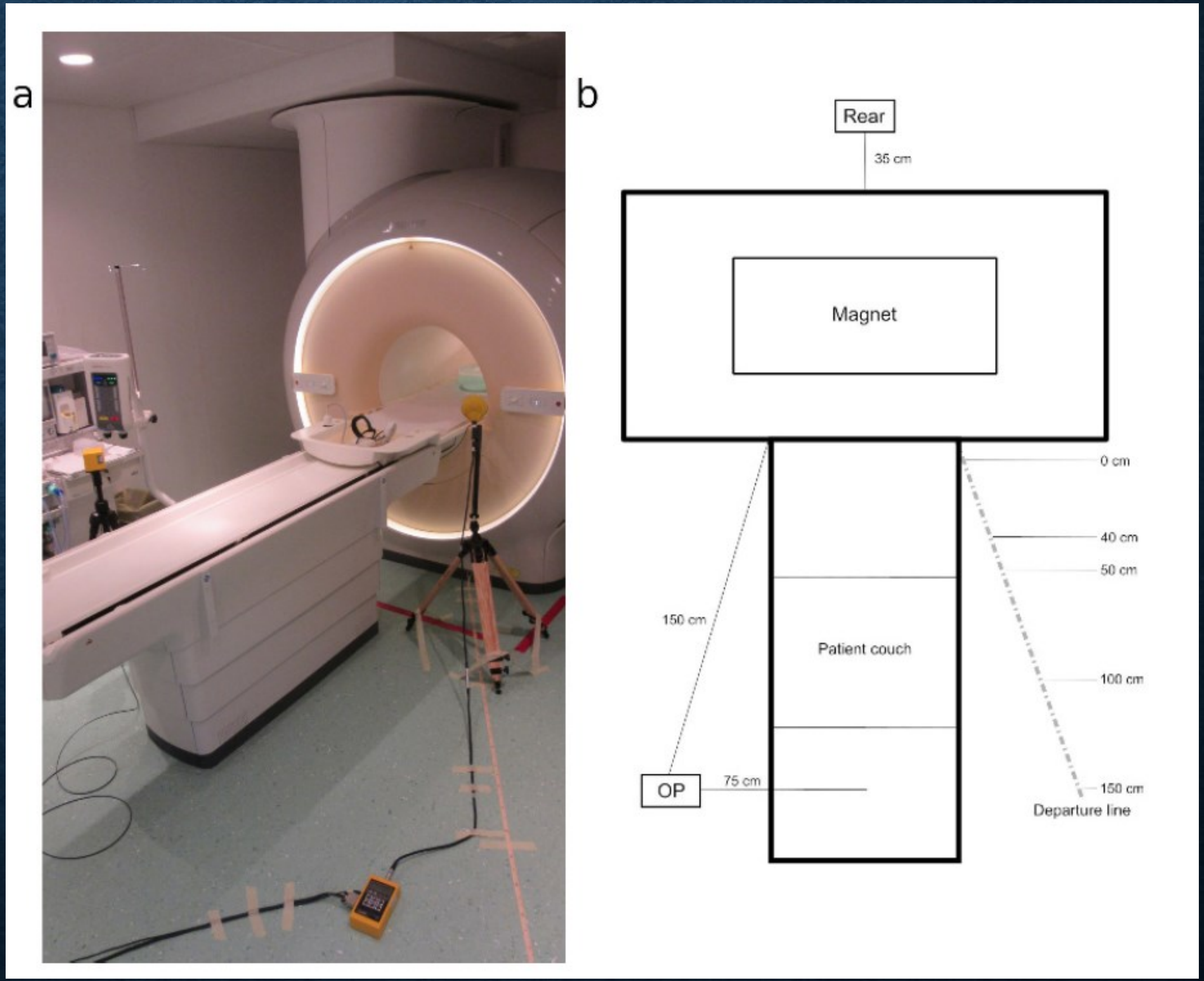
PROCESSING DATA FILES FROM EXPOSURE MEASUREMENTS

Data output: spectrum in continuous/discrete format



A CASE STUDY: ASSESSMENT OF THE EXPOSURE TO GRADIENT MAGNETIC FIELDS GENERATED BY MRI TOMOGRAPHS

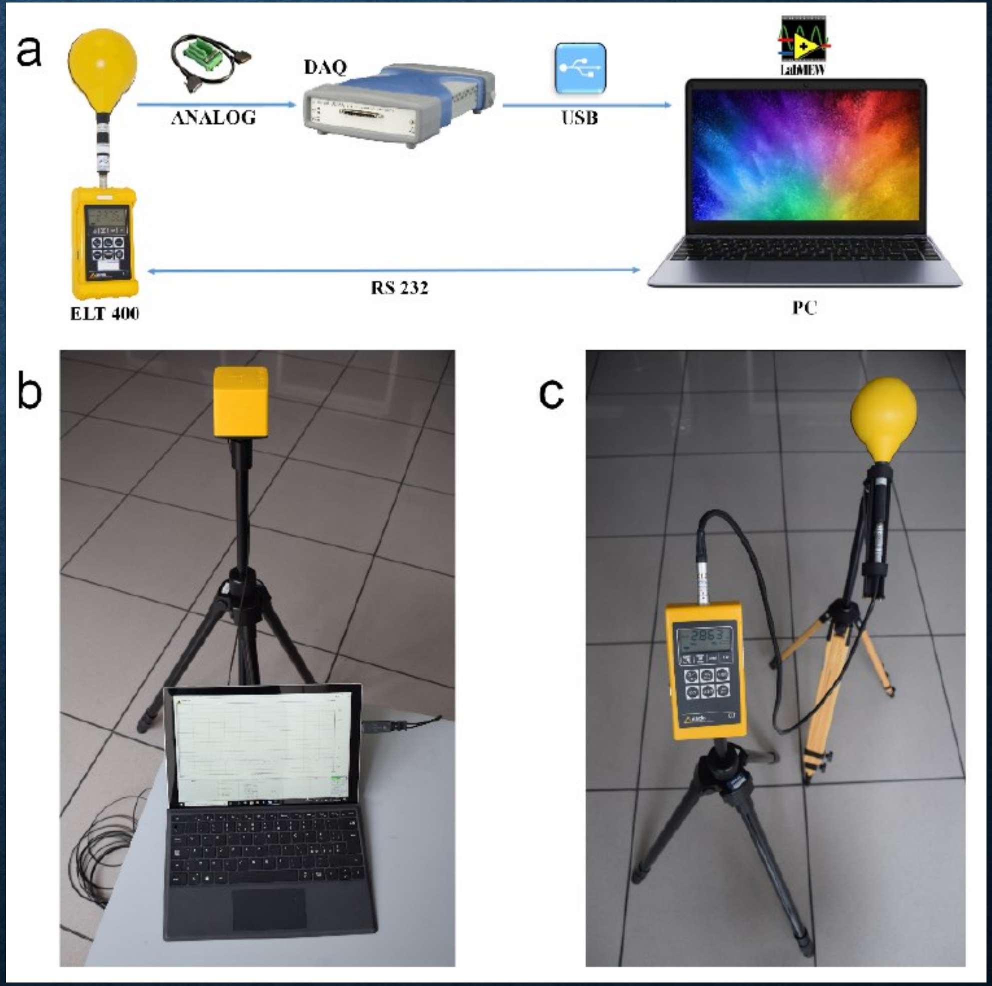
Tests carried out on different tomographs (1 and 1.5 T)



A CASE STUDY: ASSESSMENT OF THE EXPOSURE TO GRADIENT MAGNETIC FIELDS GENERATED BY MRI TOMOGRAPHS

Different instrumental chains:

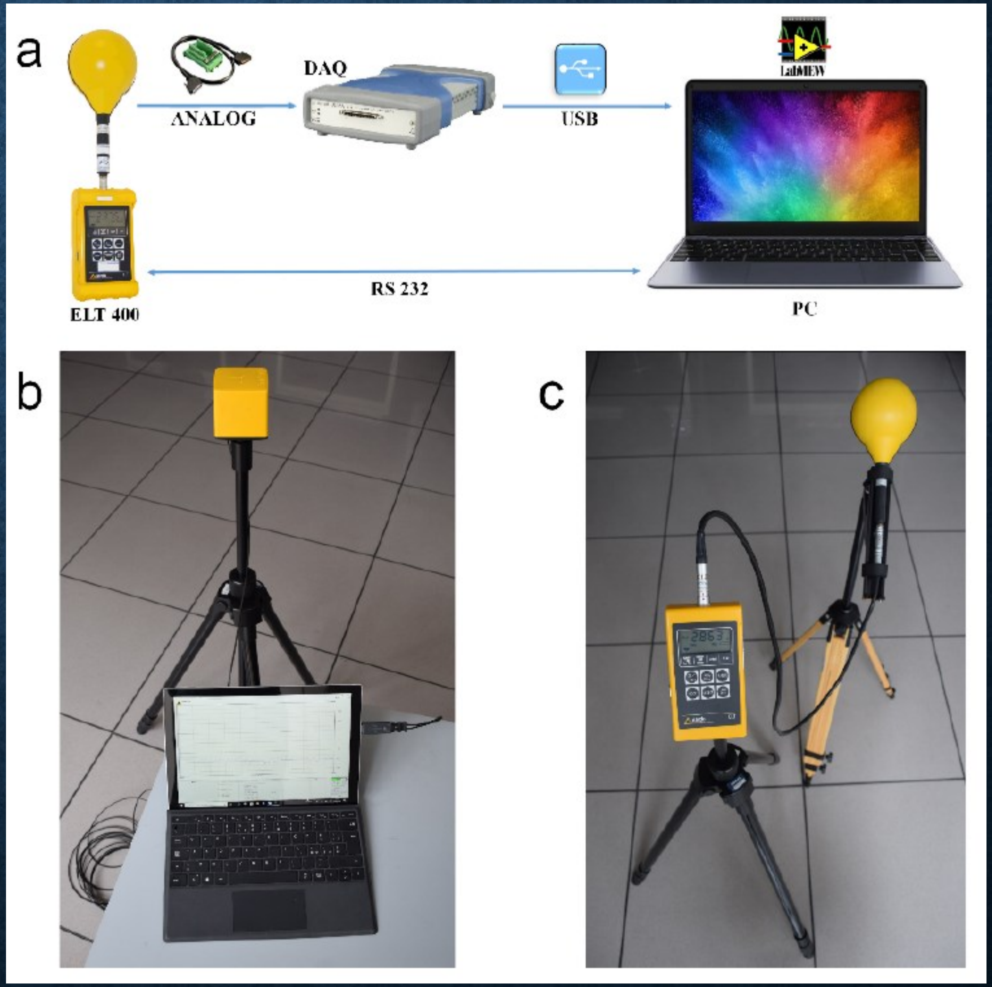
- Narda ELT-400 probe, data acquired via Agilent ADC
- Narda ELT-400, stand alone setup
- Narda EHP-50F



A CASE STUDY: ASSESSMENT OF THE EXPOSURE TO GRADIENT MAGNETIC FIELDS GENERATED BY MRI TOMOGRAPHS

Different instrumental chains:

- Narda ELT-400 probe, data acquired via Agilent ADC: provides raw data (analog output), skilled personnel required for data analysis
- Narda EHP-50F: Provides indexes, but no further analysis is possible



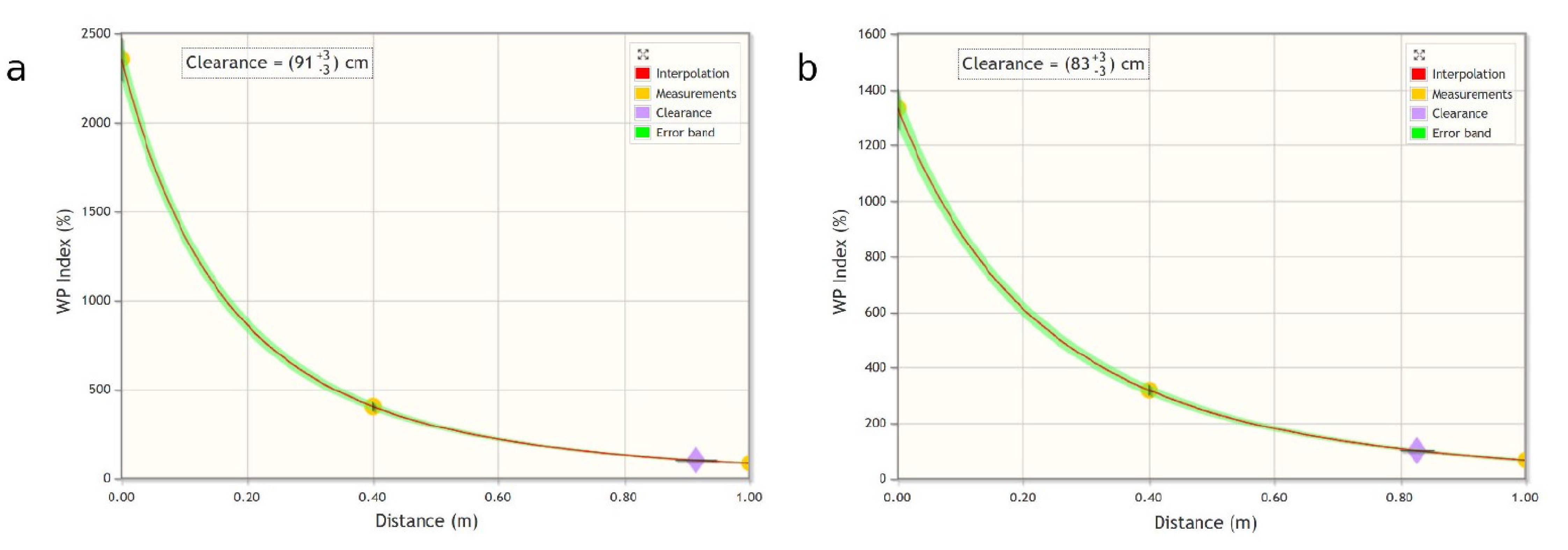
A CASE STUDY: ASSESSMENT OF THE EXPOSURE TO GRADIENT MAGNETIC FIELDS GENERATED BY MRI TOMOGRAPHS

I_{WP} are calculated at different distances from the gantry

Sequence	Distance (cm)	Height (cm)	RLs 1999/519/EC	Low ALs 2013/35/EU	High ALs 2013/35/EU
B1	0	100	1389%	45.0%	45.6%
	OP		22.5%	0.70%	0.60%
B2	0	100	2356%	76.0%	72.5%
	40		401%	13.0%	12.0%
	100		83%	2.50%	2.10%
	OP		51%	1.57%	1.25%
	0	160	1332%	40.1%	40.8%
	40		317%	9.70%	9.17%
	100		66%	2.00%	1.65%

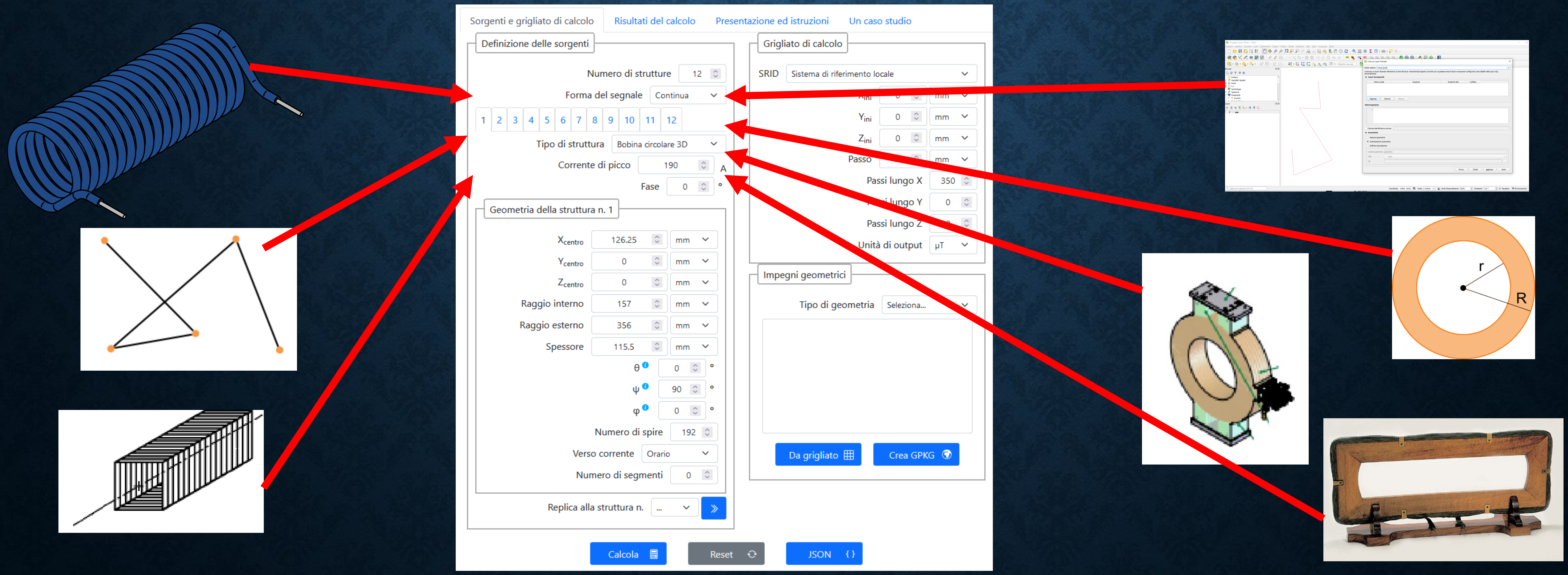
A CASE STUDY: ASSESSMENT OF THE EXPOSURE TO GRADIENT MAGNETIC FIELDS GENERATED BY MRI TOMOGRAPHS

Interpolation of indices is performed to get a compliance area



MAGNETIC FLUX DENSITY CALCULATION

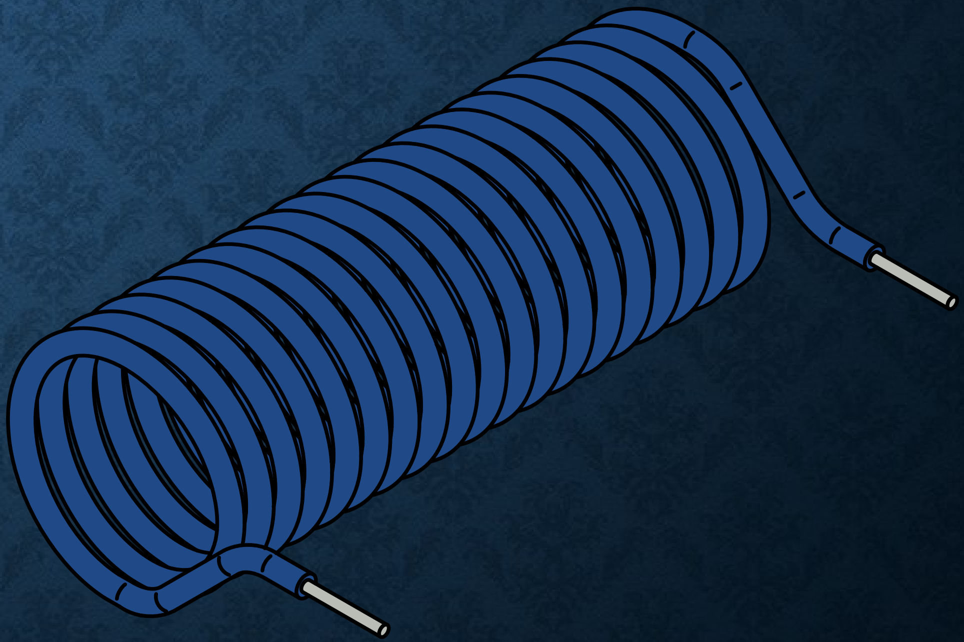
An application calculates the magnetic flux density generated by a system of various kinds of conductors, whose geometries can be defined as combination of several basic models.



MAGNETIC FLUX DENSITY CALCULATION

An application calculates the magnetic induction generated by a set of conductors of type:

- Circular section solenoid
- Rectangular section solenoid
- Corona coil
- 3D circular coil
- 3D rectangular coil
- Broken line
- Catenary
- Geometry imported from GIS files



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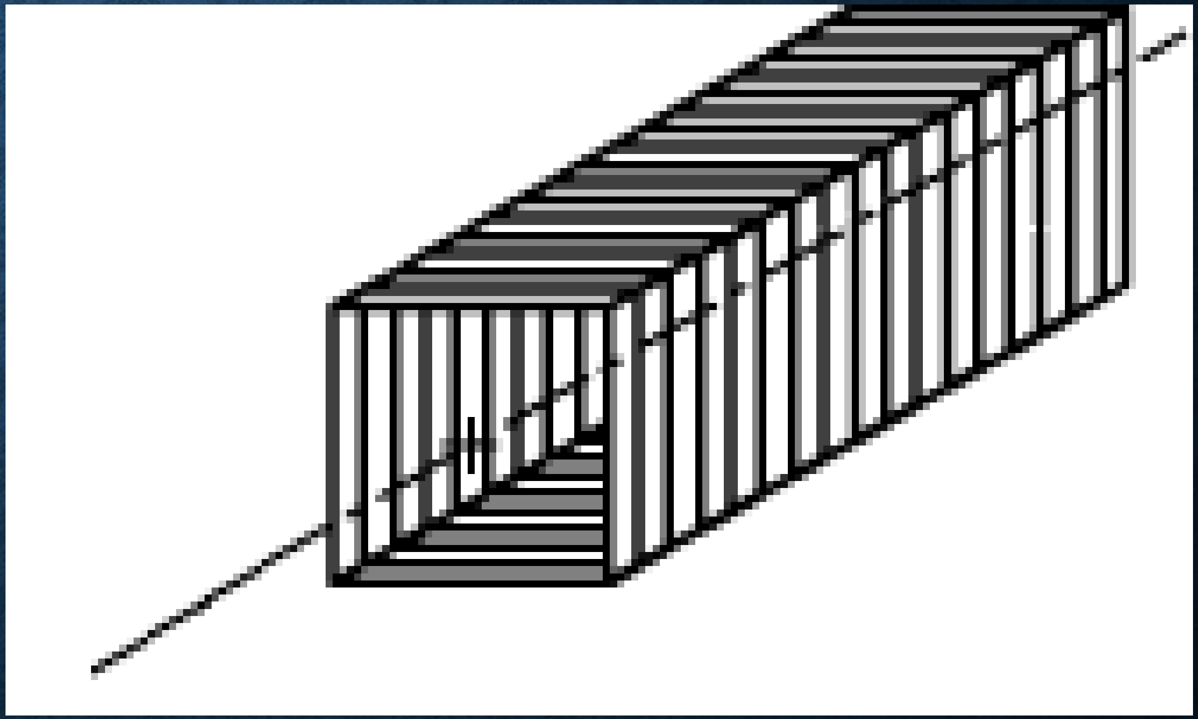

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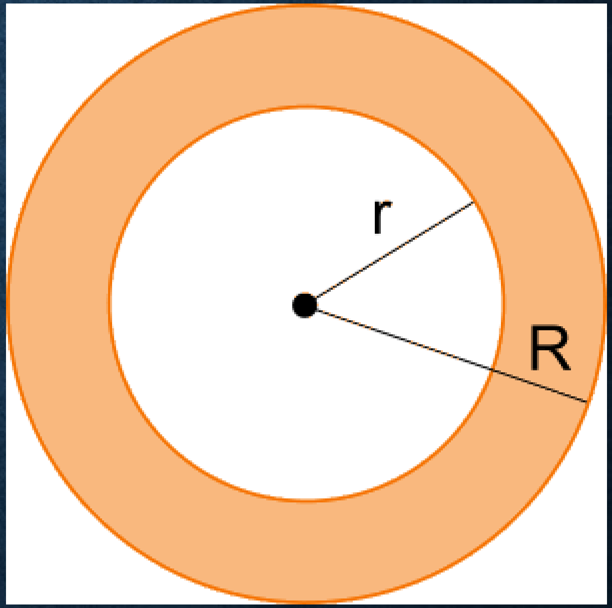

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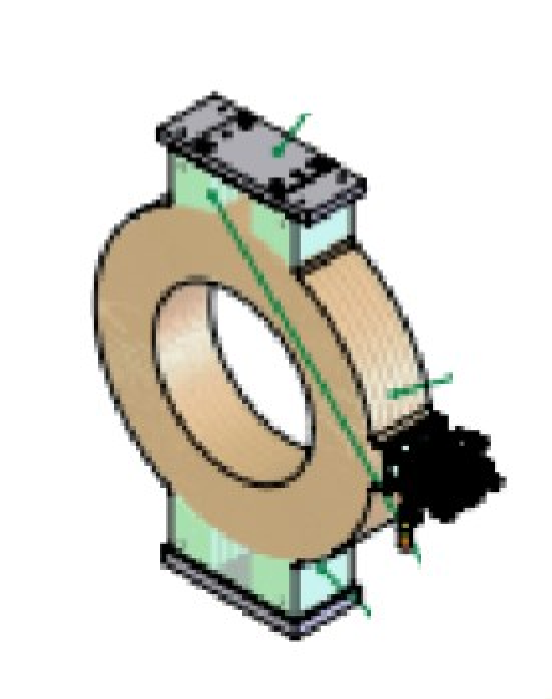

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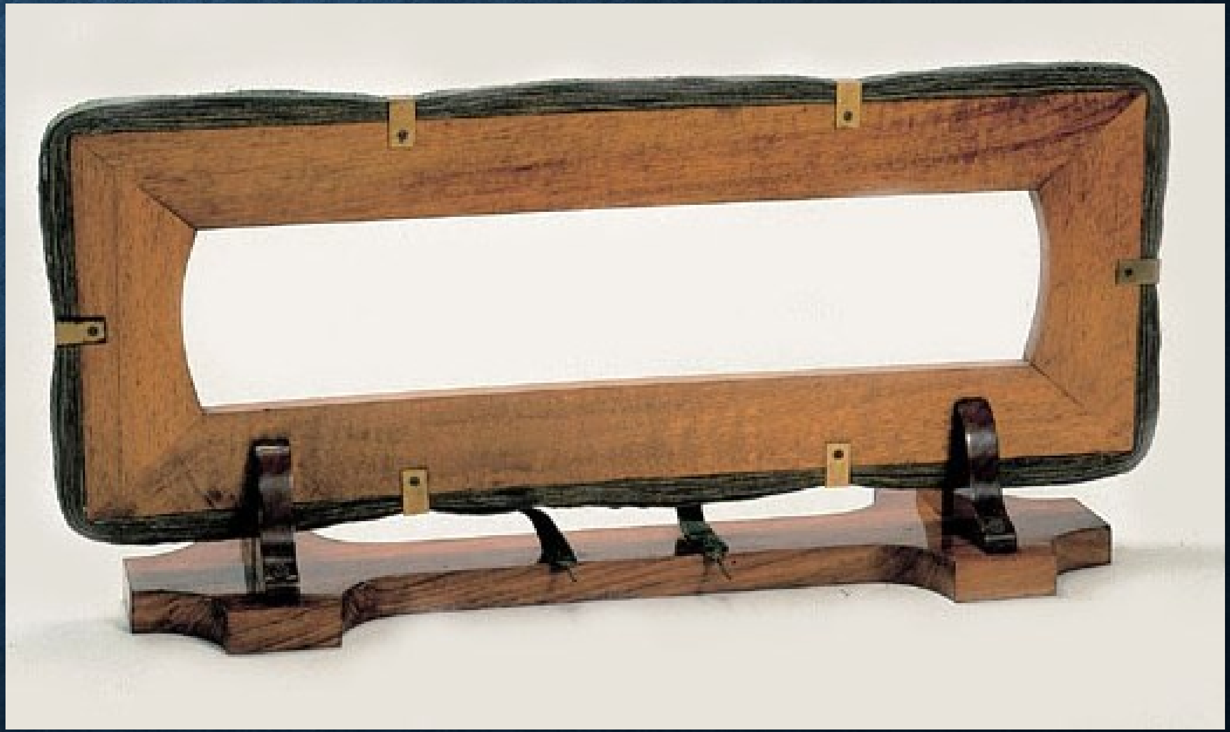

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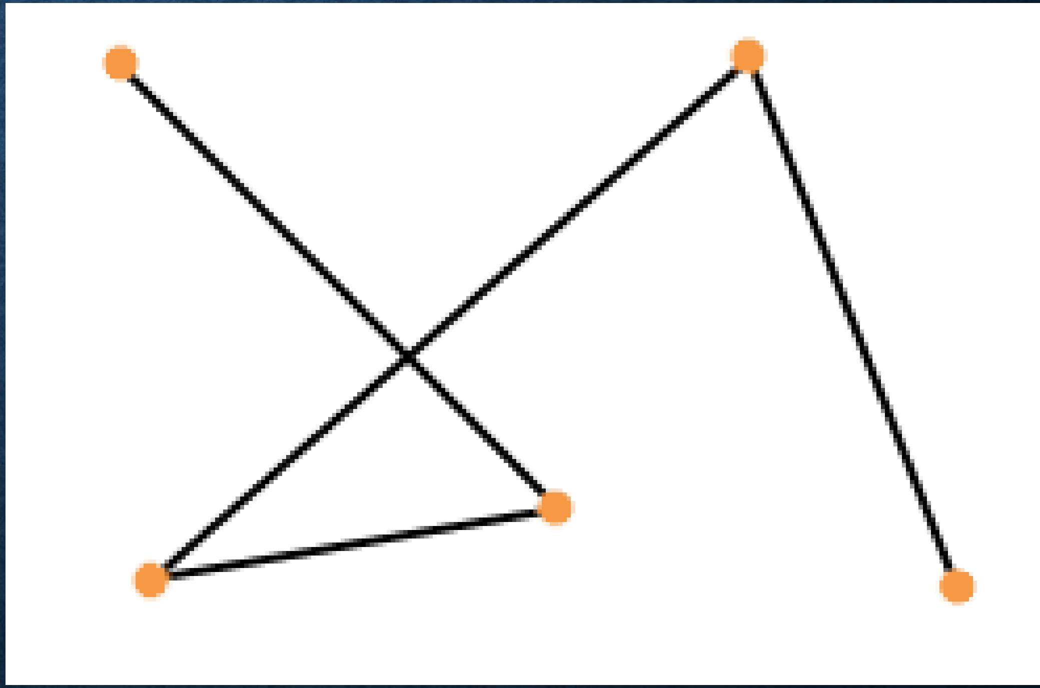

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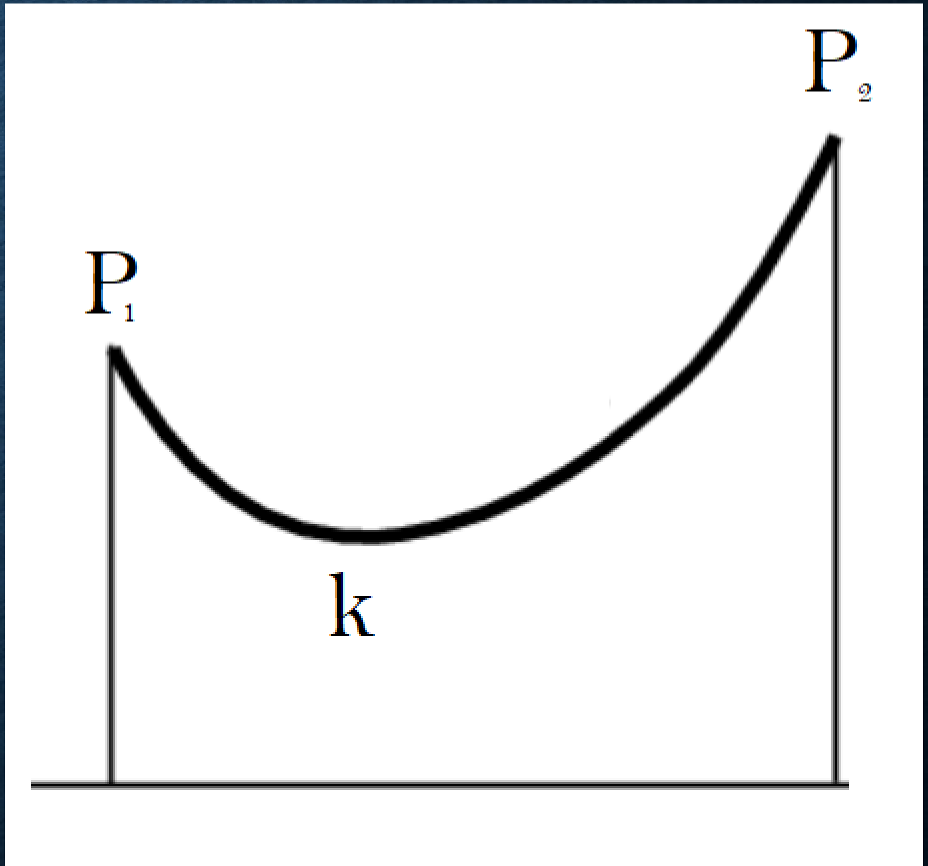

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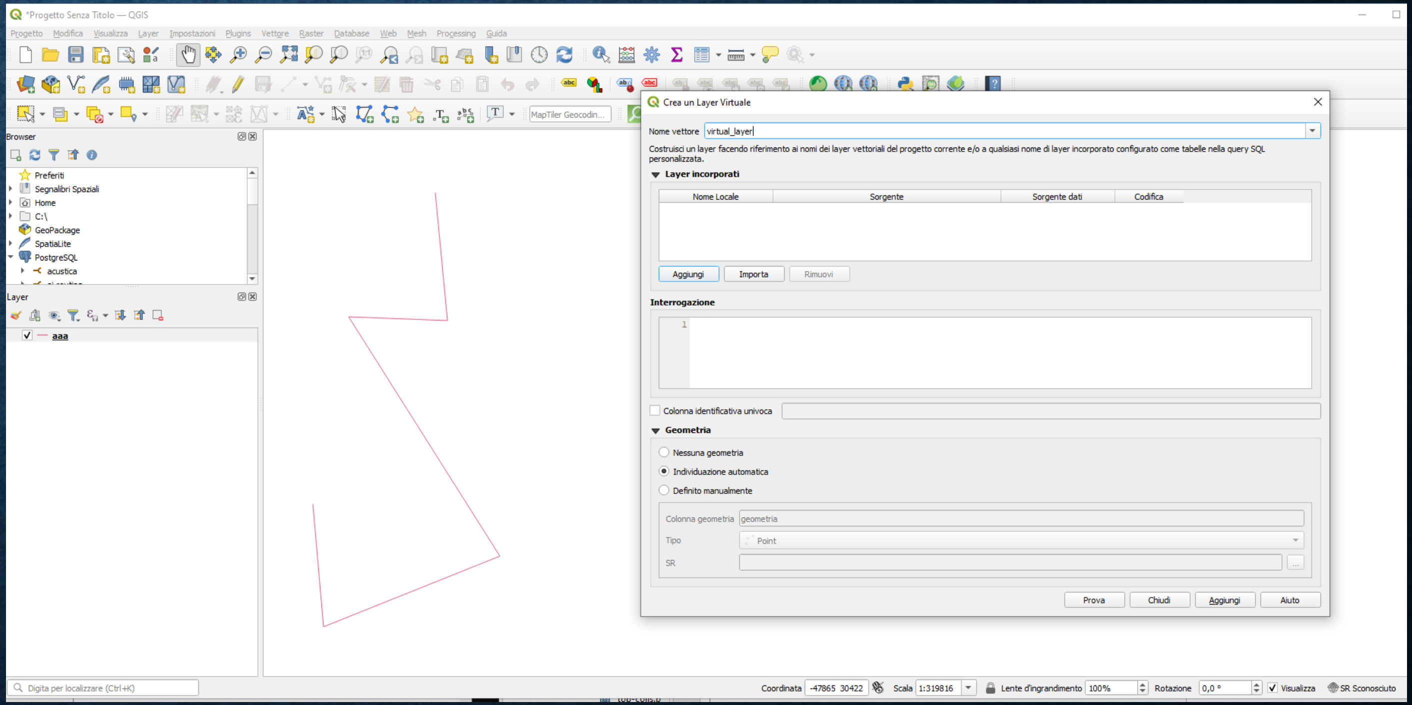


MAGNETIC FLUX DENSITY CALCULATION

In the various types of sources, the simplest constituent element can be:

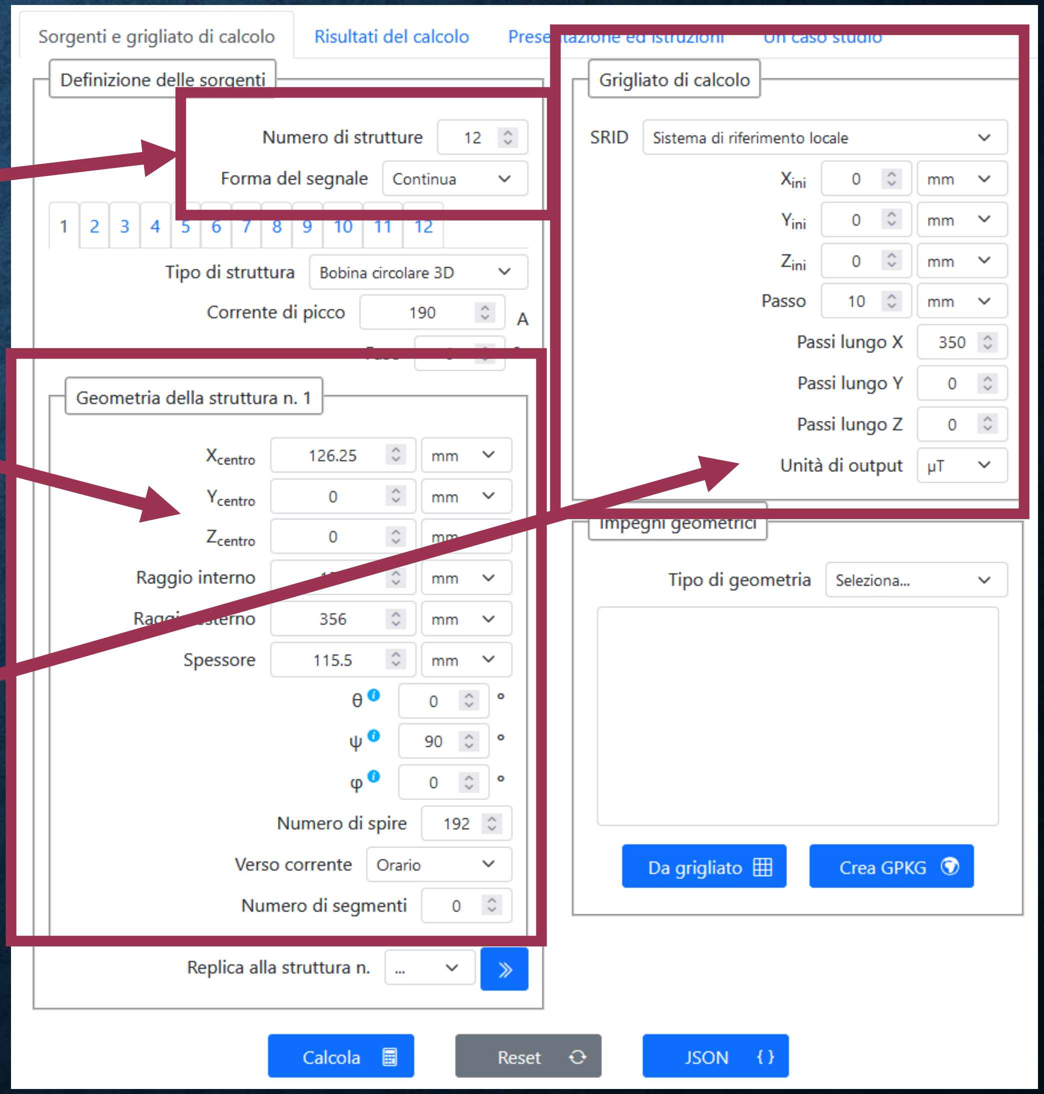
- a segment (as in the case of the catenary, which is approximated by a broken line)
- a circular loop

The contribution of the field at each point of the calculation grid is determined for each elementary source (segment or circular loop) and the results are then added.

MAGNETIC FLUX DENSITY CALCULATION

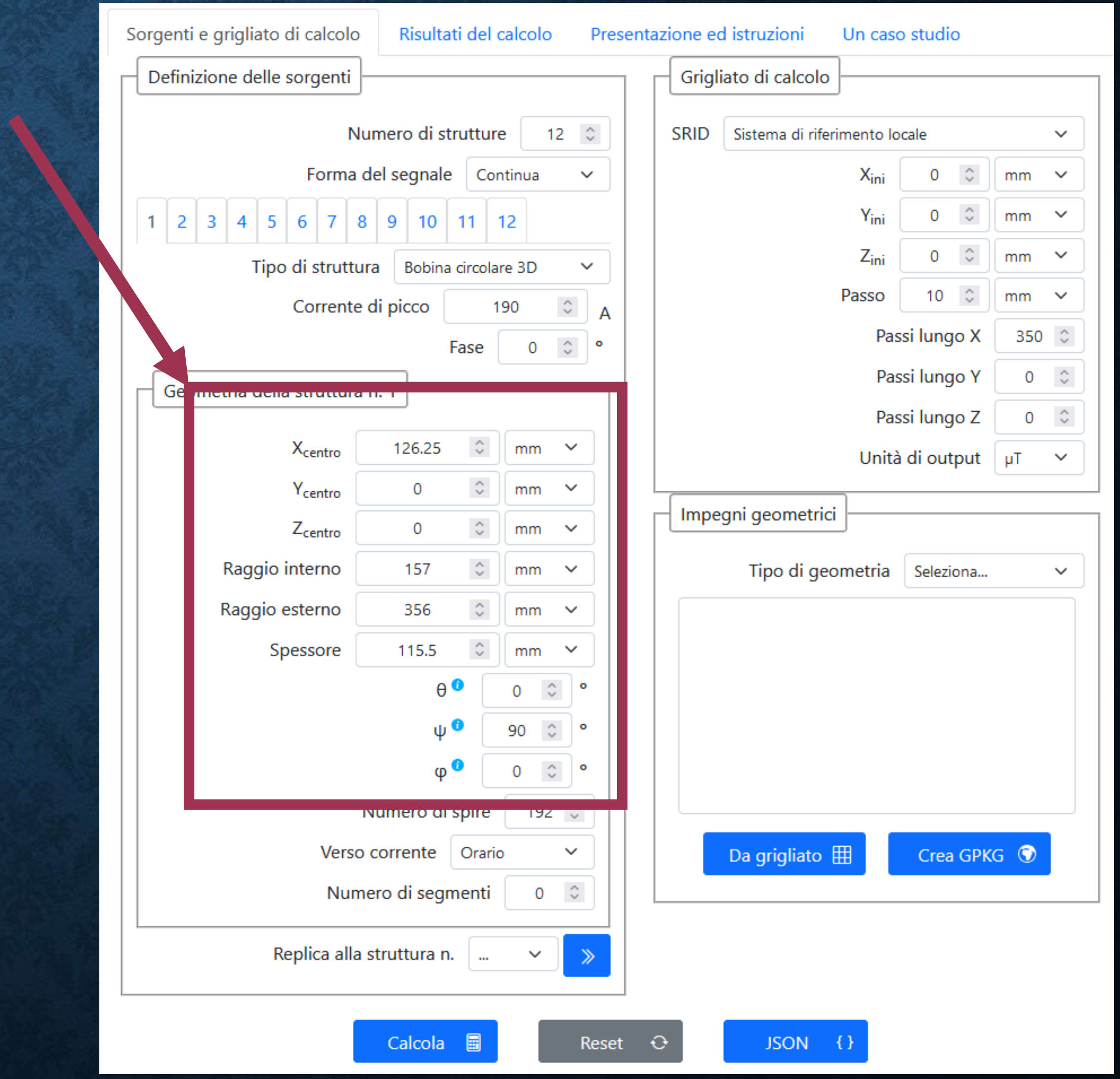
The user can:

- specify up to 12 configurations of conductors of these types
- define their geometric and electrical characteristics
- calculate the value of magnetic induction in a regular grid



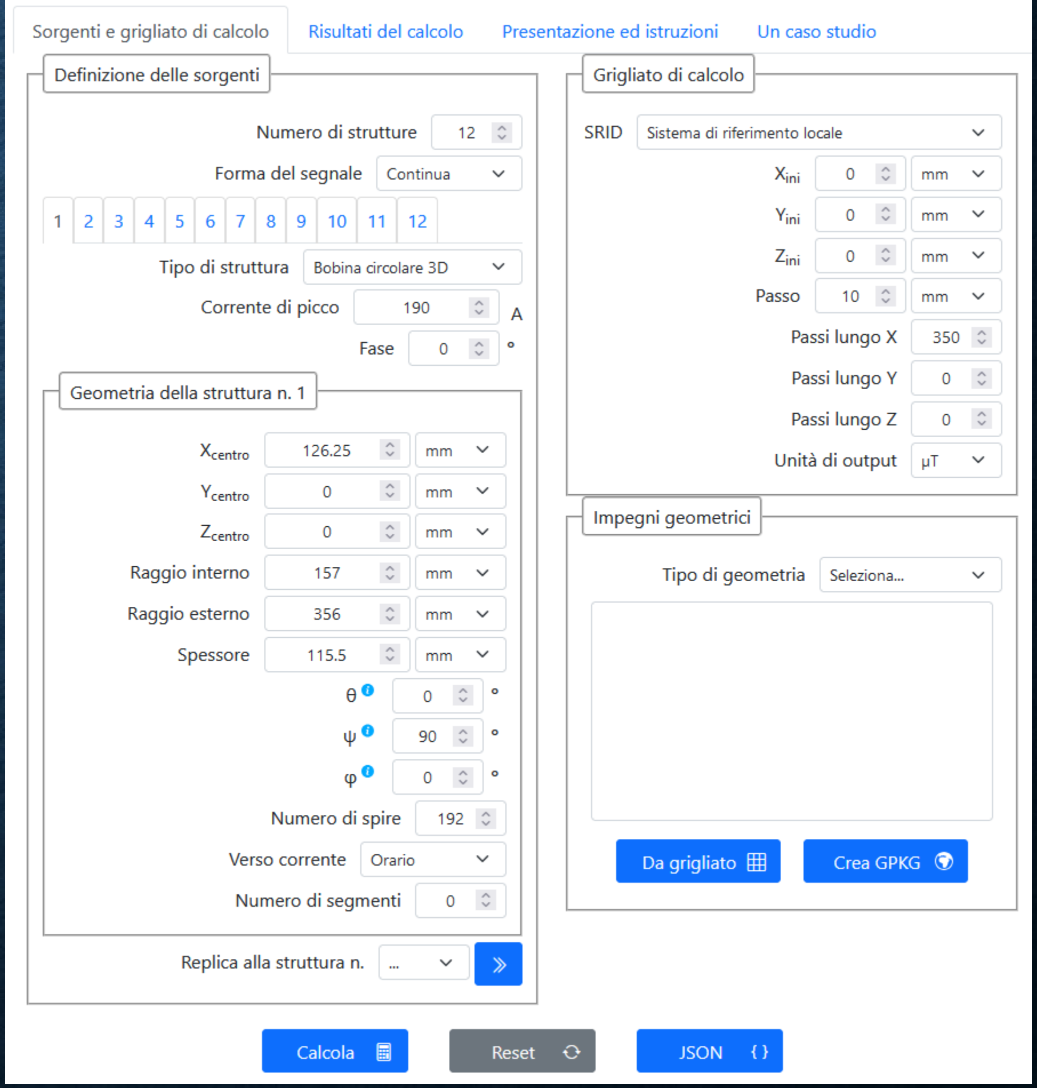
MAGNETIC FLUX DENSITY CALCULATION

- Geometries can be positioned and oriented appropriately in space
- Any set of conductors that can be represented as a combination of simple configurations can be described.



MAGNETIC FLUX DENSITY CALCULATION

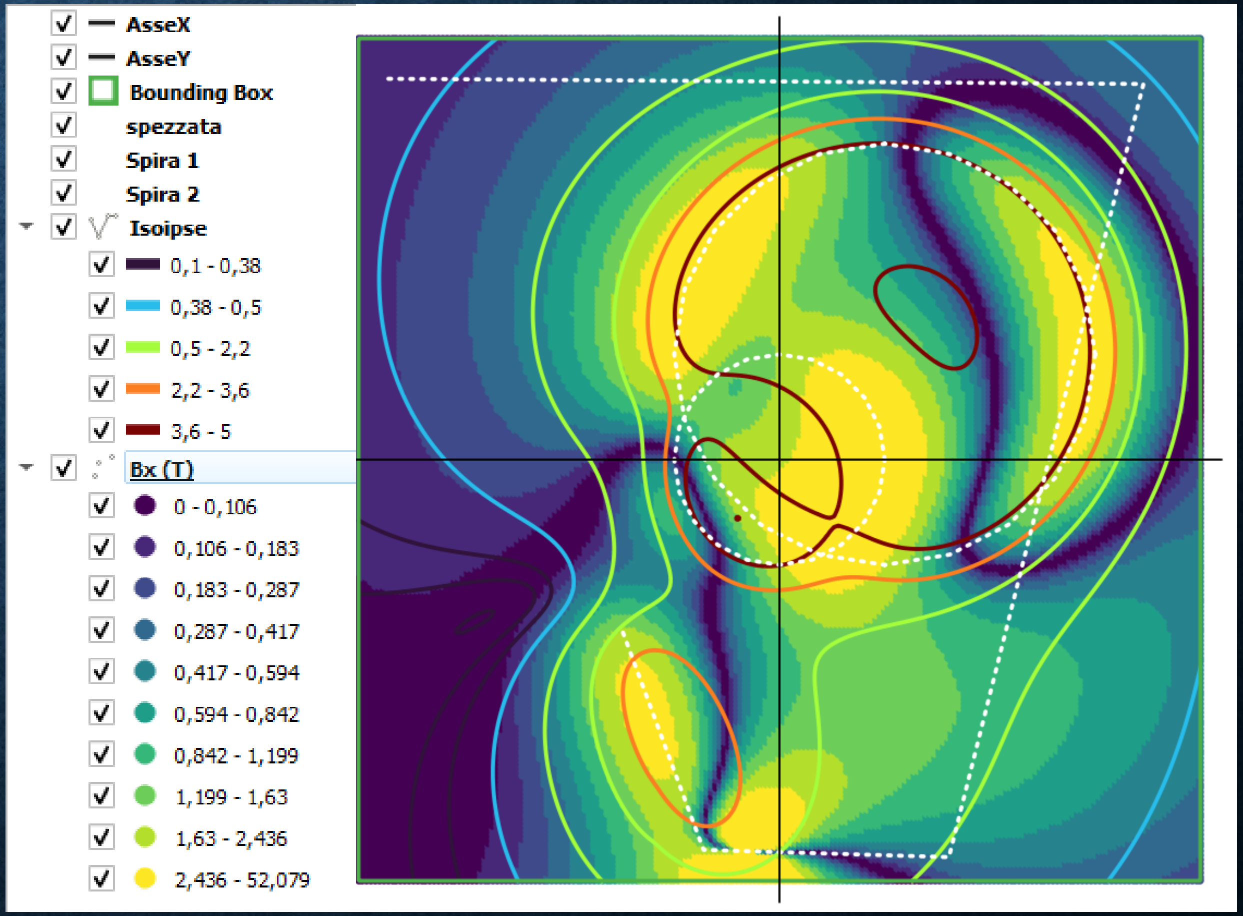
- The calculation is performed in free space
- The presence of ferromagnetic elements inside the coils is not considered
- Nor other objects in the surrounding space



MAGNETIC FLUX DENSITY CALCULATION

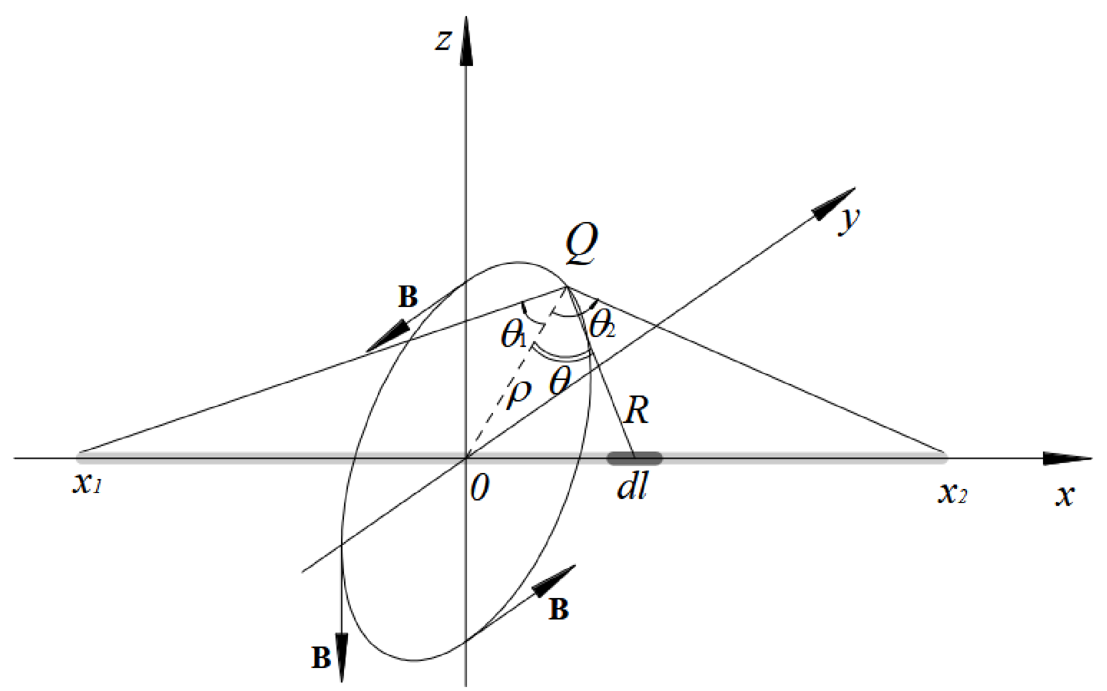
Example of expected output:

- 3 simple sources (one broken line, 2 circular loops)
- Field map in QGIS
- Isohypses
- Overlap with sources and bounding boxes (of the calculation grid)



MAGNETIC FLUX DENSITY CALCULATION

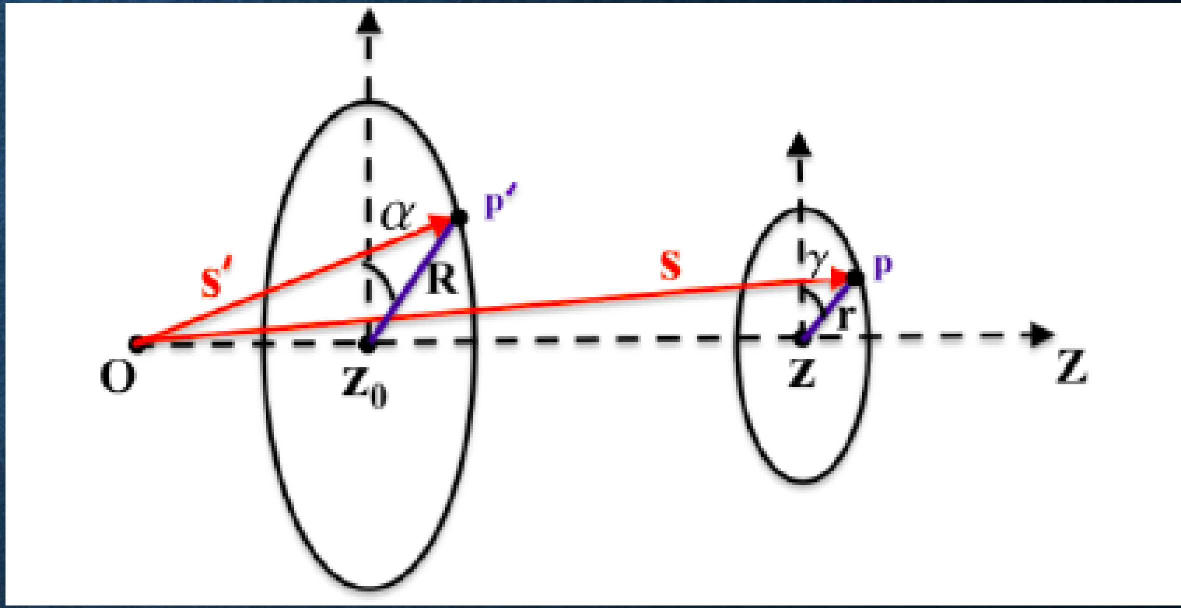
The solution to the field calculation of a segment carrying current is quite simple.



$$\mathbf{B} = \frac{\mu_0 I}{4\pi\rho}\left(\sin\theta_2 - \sin\theta_1\right)\hat{\varepsilon}$$

MAGNETIC FLUX DENSITY CALCULATION

- The solution **<u>in all space</u>** in the case of a circular loop requires more complex mathematical considerations
- It starts from the determination of the vector potential.



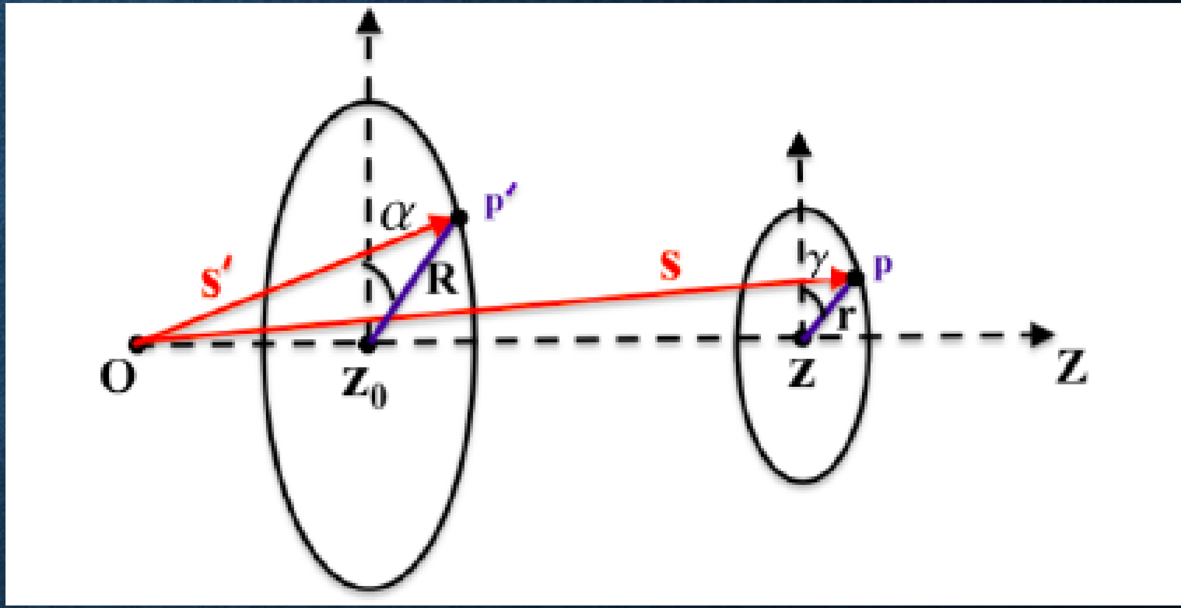
MAGNETIC FLUX DENSITY CALCULATION

Magnetic flux is a zero-divergence field, it can be expressed as a curl of a potential field:

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

and by choosing the Coulomb gauge we get the solution :

$$\vec{A} = \frac{\mu_0 I}{4\pi} \oint_C \frac{\overrightarrow{dl}}{s}$$



MAGNETIC FLUX DENSITY CALCULATION

The longitudinal and radial components for the magnetic flux density are obtained :

$$B_z = \frac{\mu_0 I}{2\pi\sqrt{z^2 + (R+r)^2}}\left(\frac{R^2 - z^2 - r^2}{z^2 + (r-R)^2}E(k) + K(k)\right)$$

$$B_r = \frac{\mu_0 z I}{2\pi r\sqrt{z^2 + (R+r)^2}}\left(\frac{R^2 + z^2 + r^2}{z^2 + (R-r)^2}E(k) - K(k)\right)$$

$$k = 2\sqrt{\frac{rR}{z^2 + (R+r)^2}}$$

$$E_1(k) = \int_0^{2\pi} \frac{d\theta}{\sqrt{1 - k^2(\sin\theta)^2}}$$

$$E_2(k) = \int_0^{2\pi} \sqrt{1 - k^2(\sin\theta)^2}\,d\theta$$

E, K: complete elliptic integrals of I and II species

MAGNETIC FLUX DENSITY CALCULATION

An alternative procedure, proposed by INFN, leads to :

$$B_r = \frac{\mu_0 I M_z}{2R}\left[\frac{\xi}{2\eta(1+\xi)}\right]^{\frac{3}{2}}\left[{}_2F_1\left(\frac{3}{2},\frac{3}{2};2;\frac{2\xi}{1+\xi}\right) - {}_2F_1\left(\frac{1}{2},\frac{3}{2};1;\frac{2\xi}{1+\xi}\right)\right]$$

$$B_z = \frac{\mu_0 I}{2R}\left[\frac{\xi}{2\eta(1+\xi)}\right]^{\frac{3}{2}}\left[(\eta+1)\,{}_2F_1\left(\frac{1}{2},\frac{3}{2};1;\frac{2\xi}{1+\xi}\right) - \eta\,{}_2F_1\left(\frac{3}{2},\frac{3}{2};2;\frac{2\xi}{1+\xi}\right)\right]$$

$$\xi = \frac{2rR}{r^2 + R^2 + (z - z_0)^2}$$

$$\eta = \frac{r}{R}$$

$$M_z = \frac{z}{R}$$

${}_2F_1$: hypergeometric function

MAGNETIC FLUX DENSITY CALCULATION

The mathematical equivalence of the two methods is demonstrated using the relations:

$$E\left(\frac{2\xi}{\xi+1}\right)=\frac{\pi}{2}\frac{1-\xi}{1+\xi}\,{}_2F_1\left(\frac{1}{2},\frac{3}{2};1;\frac{2\xi}{1+\xi}\right)$$

$${}_2F_1\left(\frac{3}{2},\frac{3}{2};2;\frac{2\xi}{1+\xi}\right)=\frac{4E\left(\frac{2\xi}{\xi+1}\right)+\left(\frac{\xi-1}{\xi+1}\right)K\left(\frac{2\xi}{\xi+1}\right)}{\frac{2\pi\xi(1-\xi)}{(\xi+1)^2}}$$

VALIDATION OF THE PROCEDURE

An internal validation of the software results was performed by comparing:

- the exact formulation that uses elliptic integrals
- the exact formulation that uses the hypergeometric function
- the approximate calculation in which the loop is approximated with a broken line, progressively increasing the number of segments constituting the single loop (tests were performed by approximating the loop with 20, 200, and 2000 segments)

VALIDATION OF THE PROCEDURE

Validation result:

- The result obtained in the first 2 cases is coincident up to the 13th digit, the 2 formulations are equivalent, and the discrepancies are due to the implicit approximations in the libraries used. In particular, the language used to perform the calculations is Python 3.9 and the SciPy.special library is used to calculate elliptic integrals and hypergeometric functions.
- The comparison of these results with those obtained from the approximation with a broken line showed a progressive convergence in the number of identical digits as the number of segments with which the loop is approximated increases.
- **Warning**: very different calculation times (10x with a loop approximated by 20 segments)

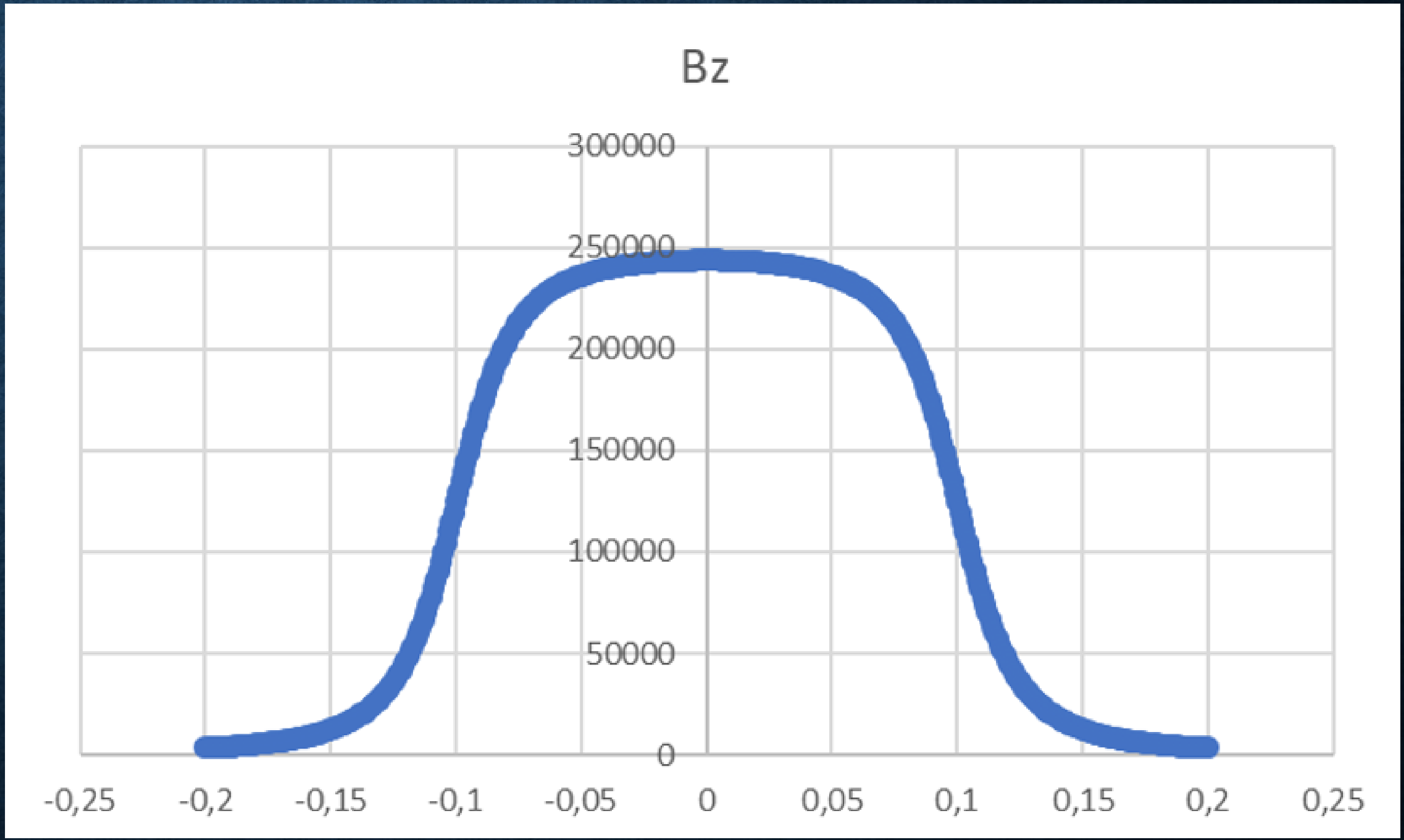
VALIDATION OF THE PROCEDURE

Finally, the expected result at the center of a solenoid:

- 200 coils
- radius: 25 mm
- distance between coils: 1 mm
- current intensity: 200 A

coincides with that expected from the theory for the infinite solenoid:

$$B = \frac{\mu_0 N I}{l}$$



THE RESULTS OF THE CALCULATION

At the end of the calculation:

- some summary values of interest are displayed (calculation time, minimum and maximum values of the induction module)
- it is possible to download the text file containing the results:

X	Y	Z	B	Bx	By	Bz
0.0	0.0	0.0	628.3185307179	0.0	0.0	628.3185307179
0.0	1.0	0.0	0.317730752302	0.0	0.0	0.317730752302
0.0	2.0	0.0	0.039380643144	0.0	0.0	0.039380643144
0.0	3.0	0.0	0.011650089610	0.0	0.0	0.011650089610
0.0	4.0	0.0	0.004912192226	0.0	0.0	0.004912192226
0.0	5.0	0.0	0.002514405568	0.0	0.0	0.002514405568
0.0	6.0	0.0	0.001454895688	0.0	0.0	0.001454895688
0.0	7.0	0.0	0.000916126557	0.0	0.0	0.000916126557
0.0	8.0	0.0	0.000613700191	0.0	0.0	0.000613700191
0.0	9.0	0.0	0.000431005356	0.0	0.0	0.000431005356
...						
100.0	98.0	0.0	0.000000114455	0.0	0.0	0.000000114455
100.0	99.0	0.0	0.000000112751	0.0	0.0	0.000000112751
100.0	100.0	0.0	0.000000111072	0.0	0.0	0.000000111072

Ready to be imported in Excel, QGIS…

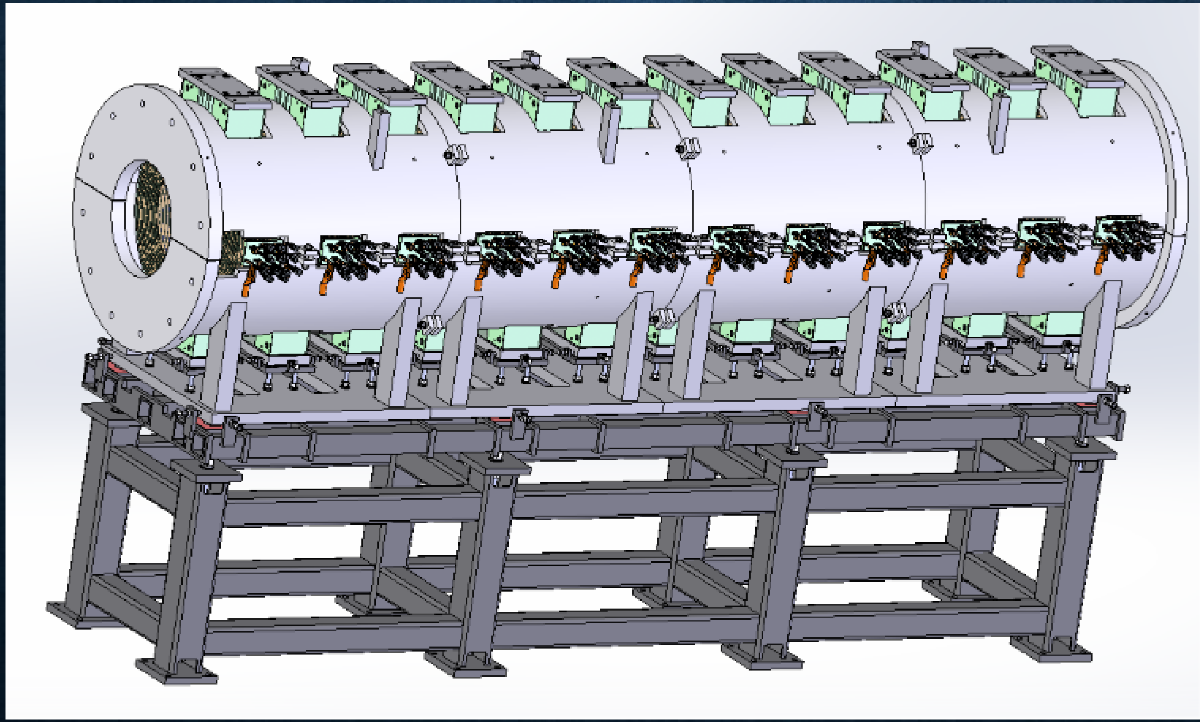
THE RESULTS OF THE CALCULATION

At the end of the calculation :

- …
- it is possible to download a zip file containing the source geometries in GeoPackage format
- it is possible to set 2 values (for 2 Cartesian axes) among those for which the calculation was performed in the grid and display the trend of the field (modulus and components) along the third coordinate in the graph.

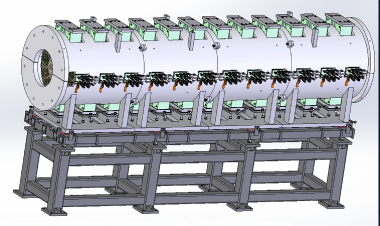
PRACTICAL APPLICATIONS

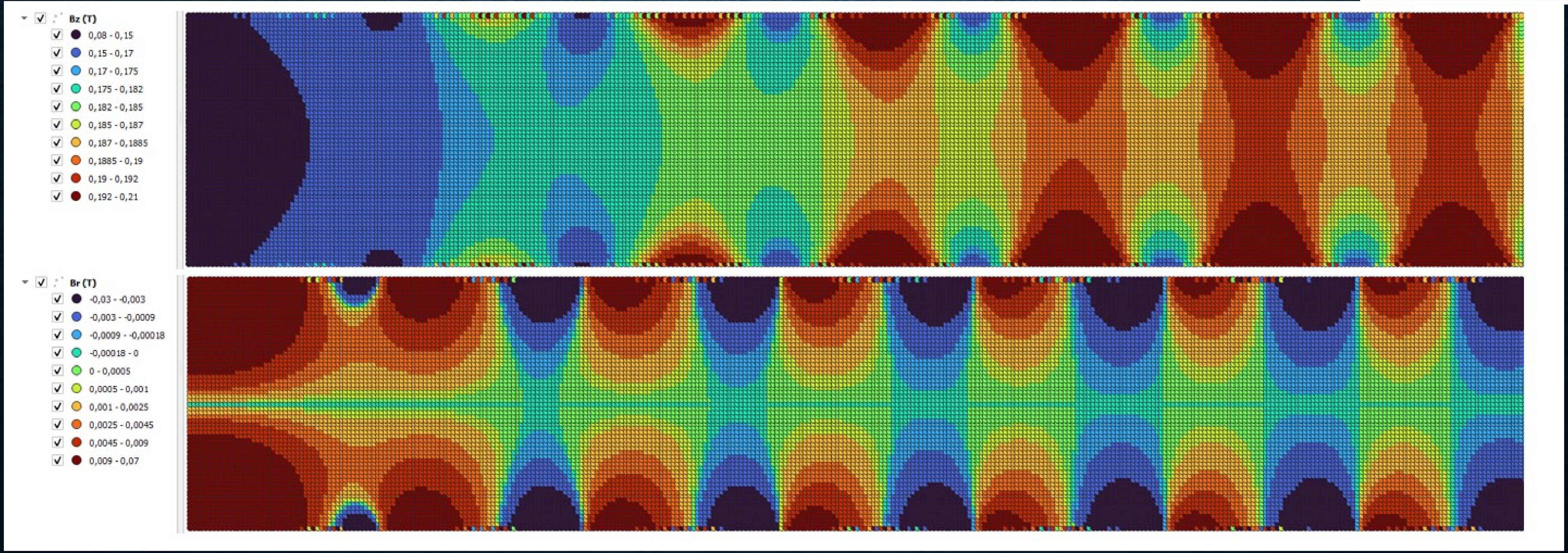
In the accelerator field, there are several relevant applications of focusing systems for charged particle beams using magnetic lenses.



PRACTICAL APPLICATIONS

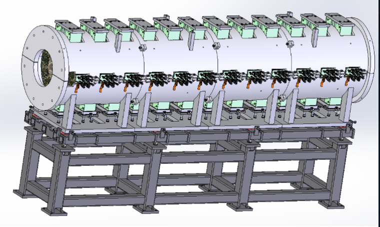
Maps with the axial (above) and radial (below) field components.

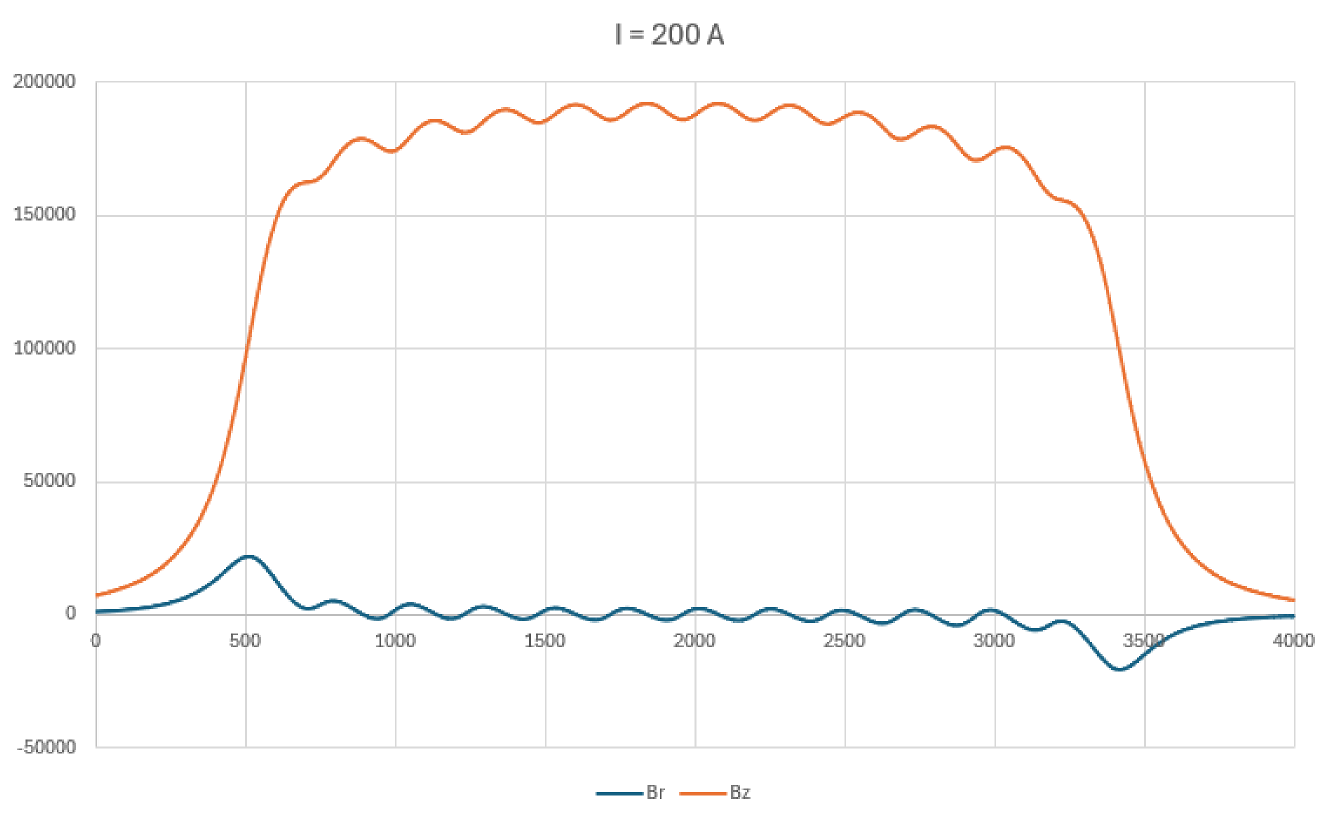




PRACTICAL APPLICATIONS

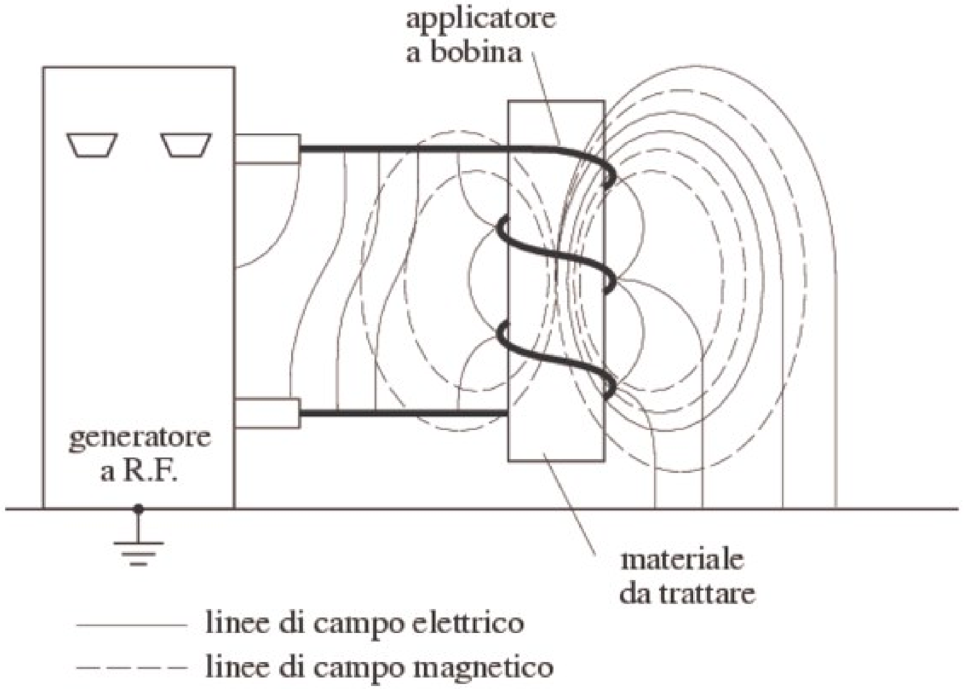
Trend of the radial (in blue) and axial (in orange) components of the induction along a trajectory parallel to the central axis of the structure.





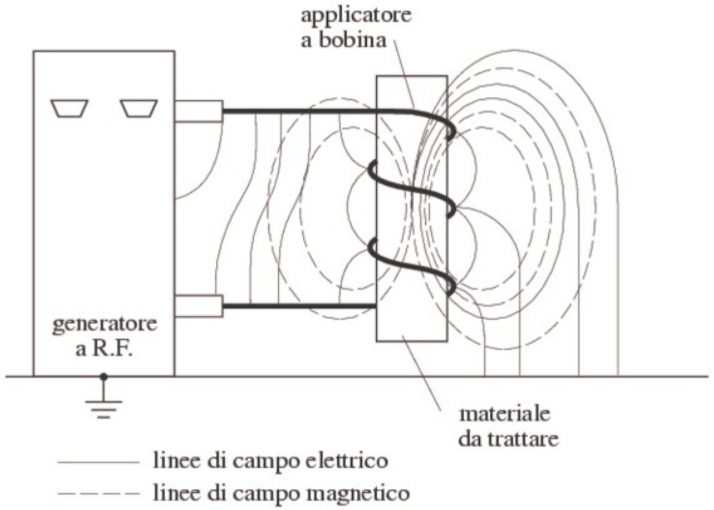
PRACTICAL APPLICATIONS

In the field of radiation protection, a case study is that of exposure to the magnetic field generated by an induction furnace used in the goldsmith industry.



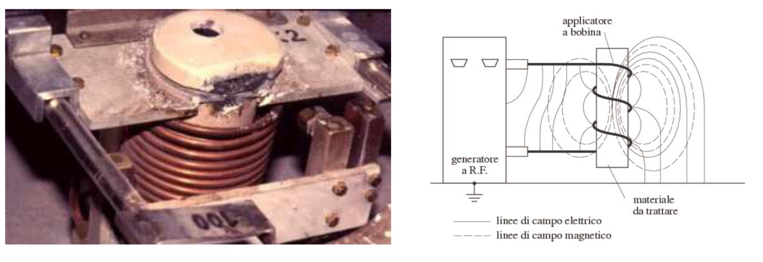
PRACTICAL APPLICATIONS

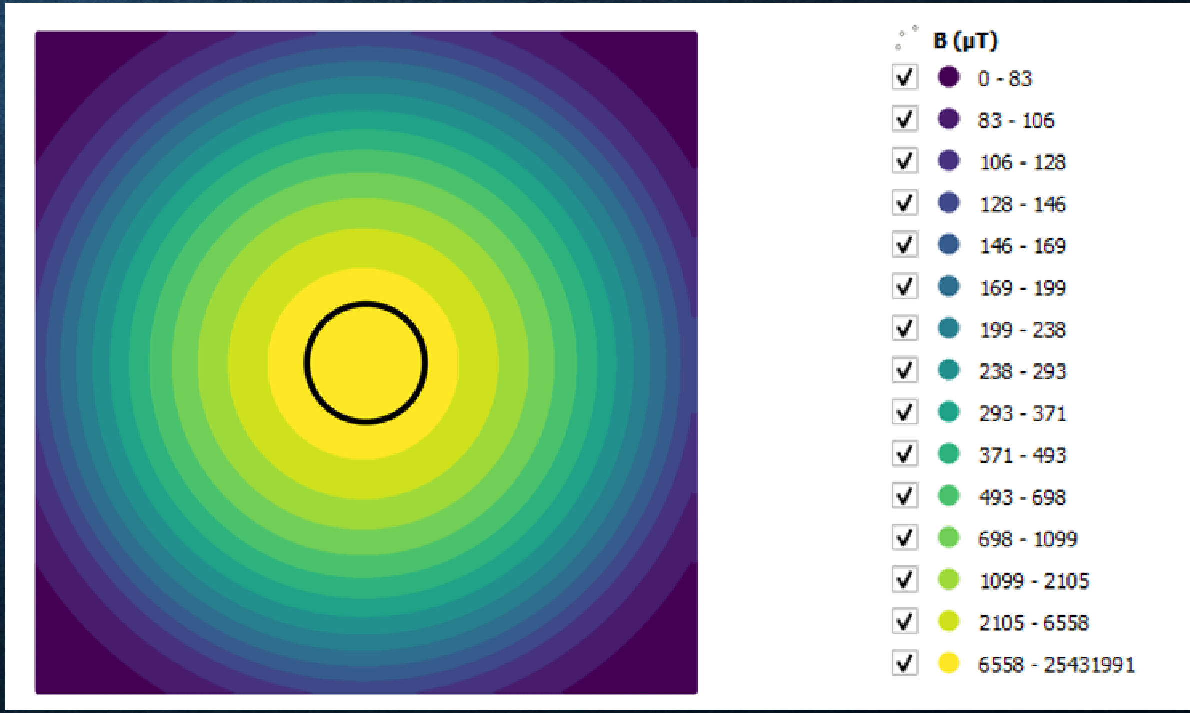
- It is a solenoid wrapped around a cylindrical crucible, connected to a radio frequency generator.
- It uses strong magnetic fields to induce eddy currents in the metals to be worked, heating them until they melt.
- Typical working frequencies range from a few kHz to a few tens of kHz.



PRACTICAL APPLICATIONS

- The results of the calculation are reported, displayed in QGIS, and superimposed on the source geometry (in the horizontal plane), automatically exported by the calculation program in geoPackage format.
- The results are consistent with the simulations performed when the device was analyzed.





AIMD

2 specific tools dedicated to AIMD available on WebNIR platform:

- Estimation of the voltage induced at the input of a pacemaker
- Operational indications for risk assessment in workers with AIMD

Documents about *Source recognition and characterization*:

- RFID
- UMTS and LTE
- Wi-Fi and Bluetooth

ESTIMATION OF THE VOLTAGE INDUCED AT THE INPUT OF A PACEMAKER

The tool allows to calculate the voltage induced at the input terminals of a pacemaker, according to its exposure conditions (the values of electric field intensity and/or magnetic field), through the implementation of the formulas reported in the appendix of the standard CEI EN 50527-2-1 ed. 2 (2016).

ESTIMATION OF THE VOLTAGE INDUCED AT THE INPUT OF A PACEMAKER

Estimation of the induced voltage (green symbol in the graph) across a pacemaker as a function of the electric and magnetic field – worst case conditions on a loop of area = 225 cm^2.

$\mathbf{V}_{pp}^{\ ind,max}$: maximum induced voltage in open circuit, expressed as a peak-to-peak value (V)

$\mathbf{E}(t)$: instantaneous value of the measured electric field (V/m)

$\mathbf{B}(t)$: instantaneous value of the measured magnetic field (A/m)

Frequency range		$\mathbf{V}_{pp}^{\ ind,max}$	Paragraph Standard 50527-2-1
[16.6 Hz; 60 Hz]	Unipolar	$\max\left(3,6\cdot10^{-7}\cdot\lvert\mathbf{H}(t)\rvert+4,4\cdot10^{-9}\cdot\lvert\mathbf{E}(t)\rvert\right)\cdot f$	E.3.5.1
	Bipolar	$\max\left(1,8\cdot10^{-8}\cdot\lvert\mathbf{H}(t)\rvert+2,3\cdot10^{-10}\cdot\lvert\mathbf{E}(t)\rvert\right)\cdot f$	
[60 Hz; 150 kHz]	Unipolar	$3,6\cdot10^{-7}\cdot\mathbf{H}_p\cdot f$	E.3.3
	Bipolar	$1,8\cdot10^{-8}\cdot\mathbf{H}_p\cdot f$	
[150 kHz; 5 MHz]		$3,6\cdot10^{-10}\cdot\sqrt{10^6\cdot\mathbf{H}_p^{\ 2}+\mathbf{E}_p^{\ 2}}\cdot f$	E.3.6
[5 MHz; 30 MHz]		$\max\begin{Bmatrix}6 & 55\cdot10^{-10}\cdot\mathbf{H}_p\cdot f^{1,4}\\ 3 & 6\cdot10^{-10}\cdot\sqrt{10^6\cdot\mathbf{H}_p^{\ 2}+\mathbf{E}_p^{\ 2}}\cdot f\\ 3 & 17\cdot10^{-16}\cdot\mathbf{E}_p\cdot f^{1,9}\end{Bmatrix}$	E.3.7
[30 MHz; 200 MHz]		$5,1\cdot10^{-2}\cdot\max\begin{Bmatrix}377\cdot\mathbf{H}_p\\ \mathbf{E}_p\end{Bmatrix}$	E.3.8
[200 MHz; 400 MHz]		$4,1\cdot10^{23}\cdot\max\begin{Bmatrix}377\cdot\mathbf{H}_p\\ \mathbf{E}_p\end{Bmatrix}\cdot f^{-3}$	
[400 MHz; 450 MHz]		$6,37\cdot10^{-3}\cdot\max\begin{Bmatrix}377\cdot\mathbf{H}_p\\ \mathbf{E}_p\end{Bmatrix}$	

ESTIMATION OF THE VOLTAGE INDUCED AT THE INPUT OF A PACEMAKER

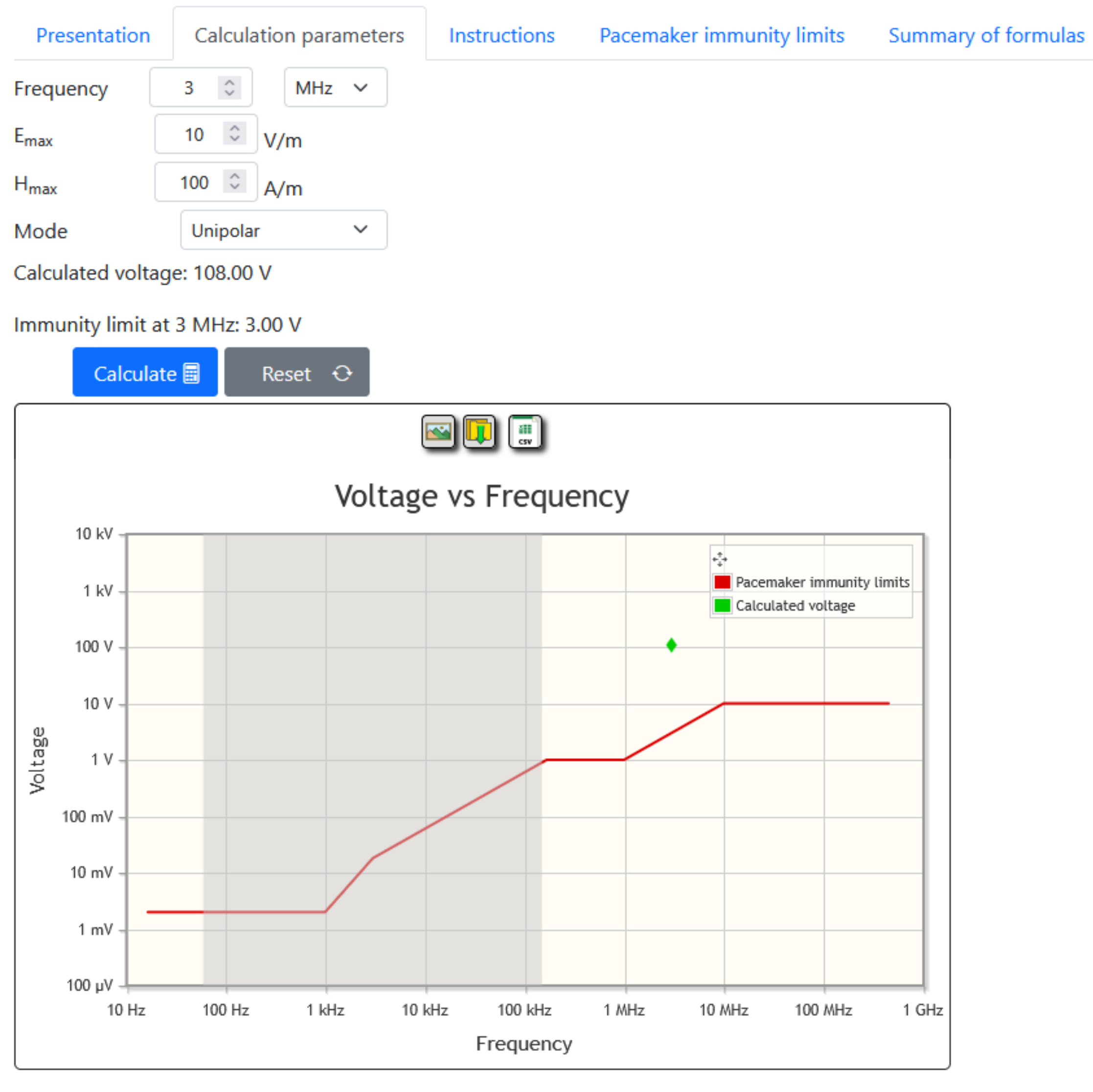
The induced voltage value obtained can be compared with the immunity levels that pacemakers must satisfy, at various frequencies (16.6 Hz - 60 Hz, and 150 kHz – 450 MHz), to verify their compatibility under actual exposure conditions.

In the range between 60 Hz and 150 kHz there are no validated studies that allow the electric field to be correlated with the induced voltage on the pacemaker, therefore the instrument does not support this frequency range. The calculation is performed for a purely magnetic field.

ESTIMATION OF THE VOLTAGE INDUCED AT THE INPUT OF A PACEMAKER

The calculation is performed by entering the frequency of interest and the maximum peak values of the electric and magnetic fields measured.

The induced voltage value obtained is compared with the immunity levels that pacemakers must satisfy, at the various frequencies, in the conducted immunity tests provided for in the technical standard EN 45502-2-1:2003 (table in next slide).



ESTIMATION OF THE VOLTAGE INDUCED AT THE INPUT OF A PACEMAKER

Immunity limits of pacemakers (red line in the graph) for conducted disturbances in the frequency range [16 Hz; 450 MHz] according to the tests indicated in *Standard 45502-2-1: Active implantable medical devices*.

Frequency range	Test signal amplitude (peak-to-peak)	Paragraph Standard 45502-2-1
[16.6 Hz; 1 kHz]	$2mV$	27.5.1
[1 kHz; 3 kHz]	$2mV \cdot \left(\frac{f}{1kHz}\right)^2$	
[3 kHz; 167 kHz]	$6mV \cdot \left(\frac{f}{1kHz}\right)$	
[167 kHz; 1 MHz]	$1V$	27.5.2
[1 MHz; 10 MHz]	$1V \cdot \left(\frac{f}{1MHz}\right)$	
[10 MHz; 450 MHz]	$10V$	27.5.3

In the case of bipolar measurements, the test signal amplitudes are reduced by a factor of 10.

RISK ASSESSMENT FOR WORKERS WITH AIMD

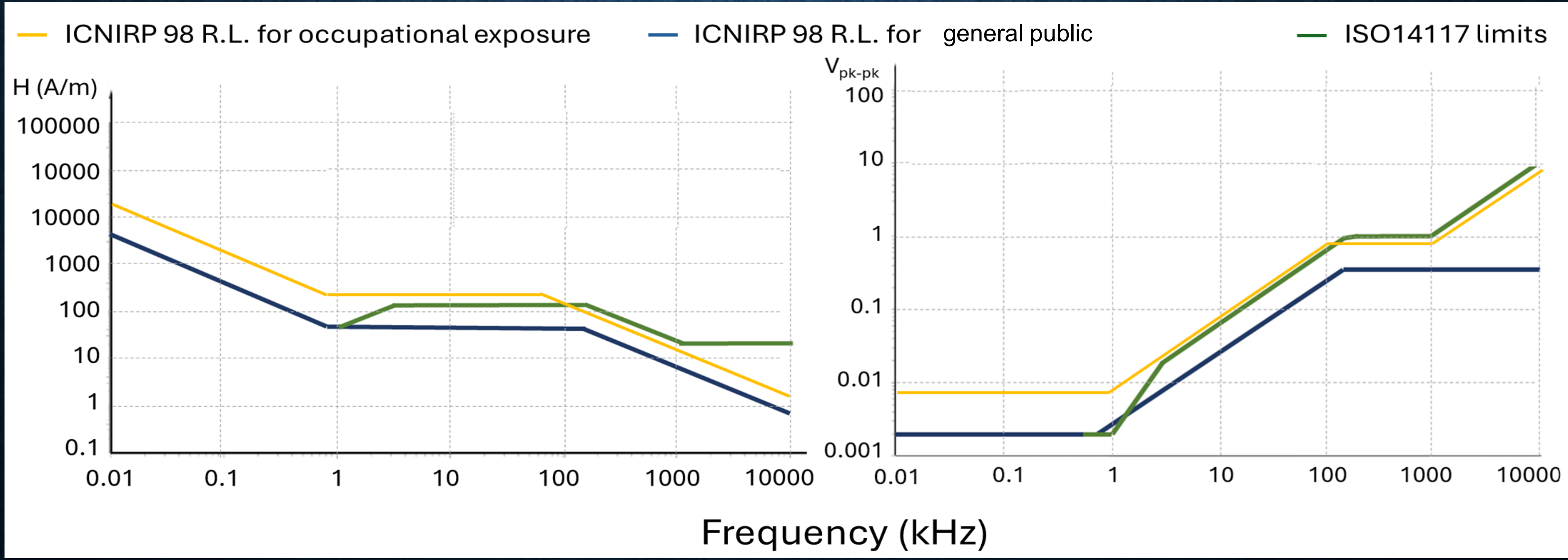
In the EU, the EMC requirements for AIMDs are provided in the standards of the family EN45502. As for pacemaker and implantable cardioverter defibrillators, EMC requirements are provided in the ISO 14117:2019 - Active implantable medical devices — Electromagnetic compatibility — EMC test protocols for implantable cardiac pacemakers, implantable cardioverter defibrillators, and cardiac resynchronization devices.

Standards' background: the immunity levels are determined to protect the AIMD from the foreseeable electromagnetic environment derived from the European Recommendation 1999/519/EC, which was based on the recommendations for the General Public of the ICNIRP Guidelines 1998.

RISK ASSESSMENT FOR WORKERS WITH AIMD

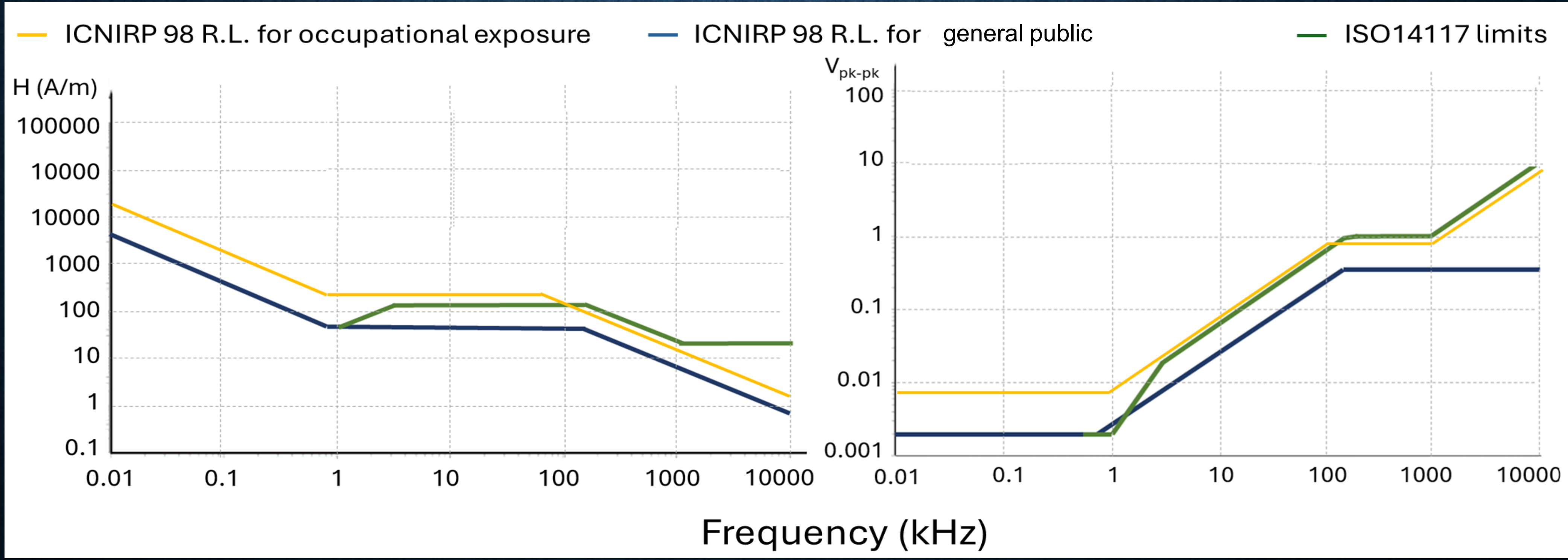
Comparison between the immunity test level adopted by ISO 14117 and ICNIRP 1998 reference level for the general public and occupational exposure (10 Hz to 10 MHz).

The risks for a worker who wears an AIMD could be considered acceptable if exposed to EMF levels below the ICNIRP reference levels for the General Public.



RISK ASSESSMENT FOR WORKERS WITH AIMD

In workplaces, powerful sources of EMF are likely to be encountered, and reference levels for the General Public can be exceeded. Thus, the safety of a worker who wears an AIMD is not guaranteed anymore. In addition, the aforementioned standards take into account only the EMF sources that can be encountered in common-life scenarios (e.g., LTE/4G cellular phones, Wi-Fi transmitters, etc.).



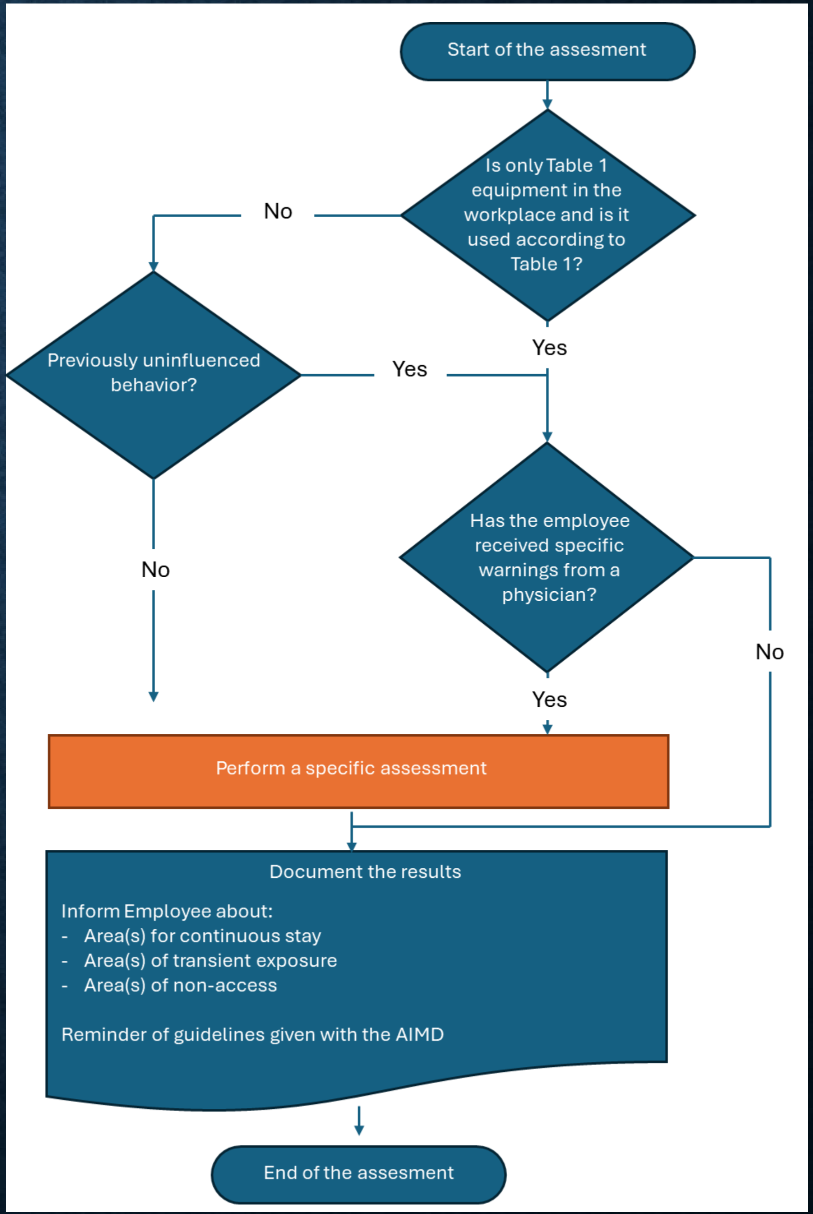
RISK ASSESSMENT FOR WORKERS WITH AIMD

The EMF sources in a work environment can be very specific in terms of modulation, pulse repetition time, etc., and can pose a risk even at levels below the ICNIRP reference levels for the General Public.

Consequently, the existing standards reasonably protect the General Public wearing AIMDs but are not sufficient to protect workers wearing AIMDs. For these reasons, the EU has developed a series of technical standards to support the employers in the risk assessment of workers who wear AIMDs: the general standard EN50527-1 with the particular standards EN50527-2-X for the different AIMD classes.

RISK ASSESSMENT FOR WORKERS WITH AIMD

The EN EN50527 family standards provide a general procedure for the specific assessment required for workers with an AIMD: an initial simplified analysis is required, followed, when necessary, by a deeper specific risk assessment for the AIMD-employee.

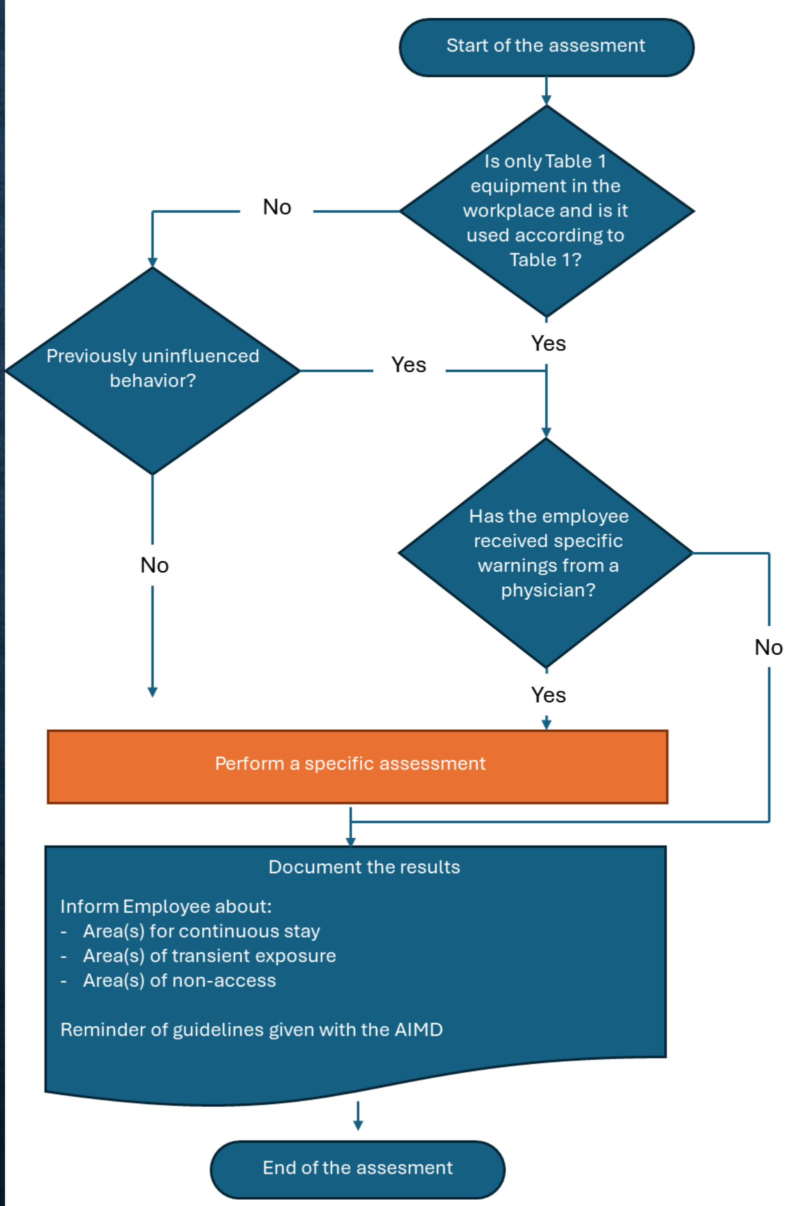


RISK ASSESSMENT FOR WORKERS WITH AIMD

The initial simplified analysis starts from the identification of all the EMF sources active in the workplace and their comparison with a list of equipment reported in a table, called whitelist.

The simplified analysis can be considered sufficient if:

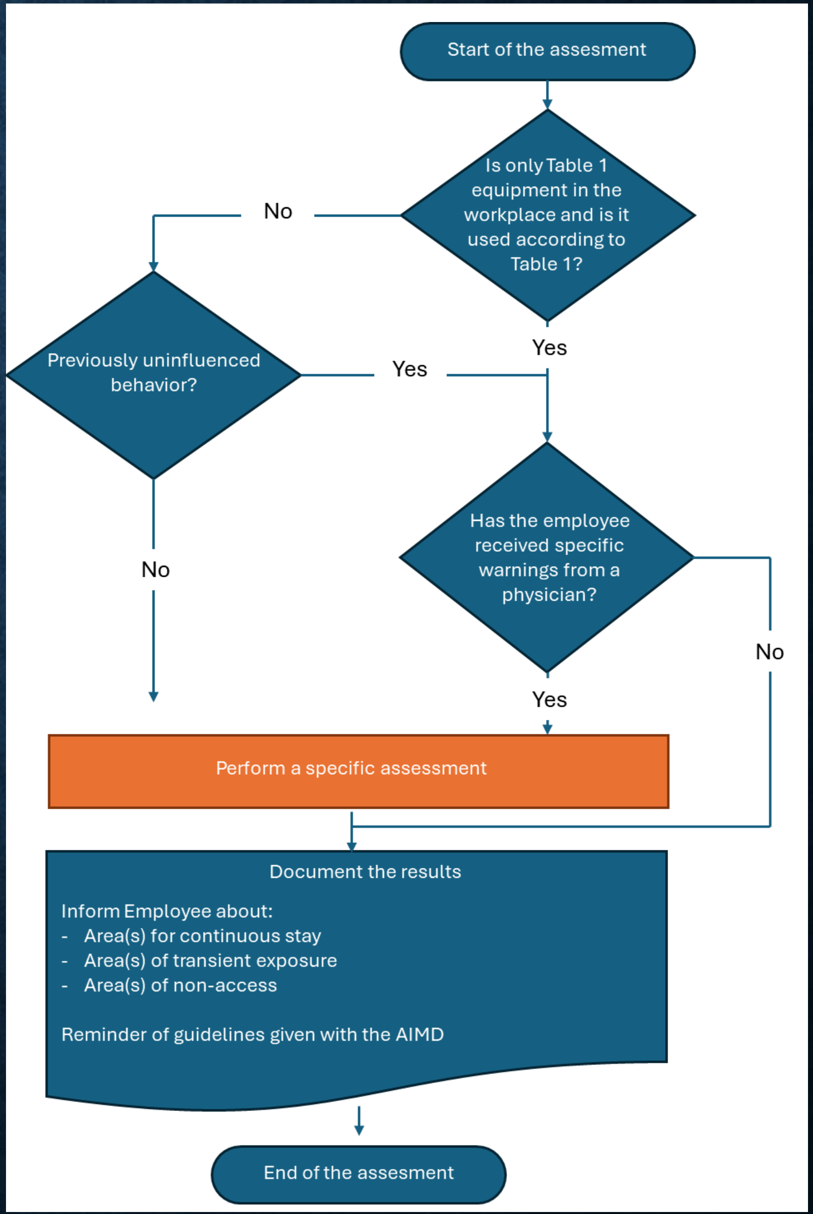
- all the EMF sources are listed in the table;
- all the EMF sources are used in accordance with the indication reported in the "exceptions and remarks" column;
- the AIMD employee has not received specific warnings from the responsible physician that the AIMD may be susceptible to EMI from one of the present equipment.



RISK ASSESSMENT FOR WORKERS WITH AIMD

If one of the previously mentioned conditions is not verified, a specific risk assessment shall be carried out, under the specifications provided in Annex A of the standards. The risk assessment should involve input from:

1. the employer and, if applicable, his/her occupational health and safety expert and/or occupational physician;
2. the AIMD employee and his/her responsible physician; and
3. experts (technical and medical), e.g., the manufacturer of the AIMD.

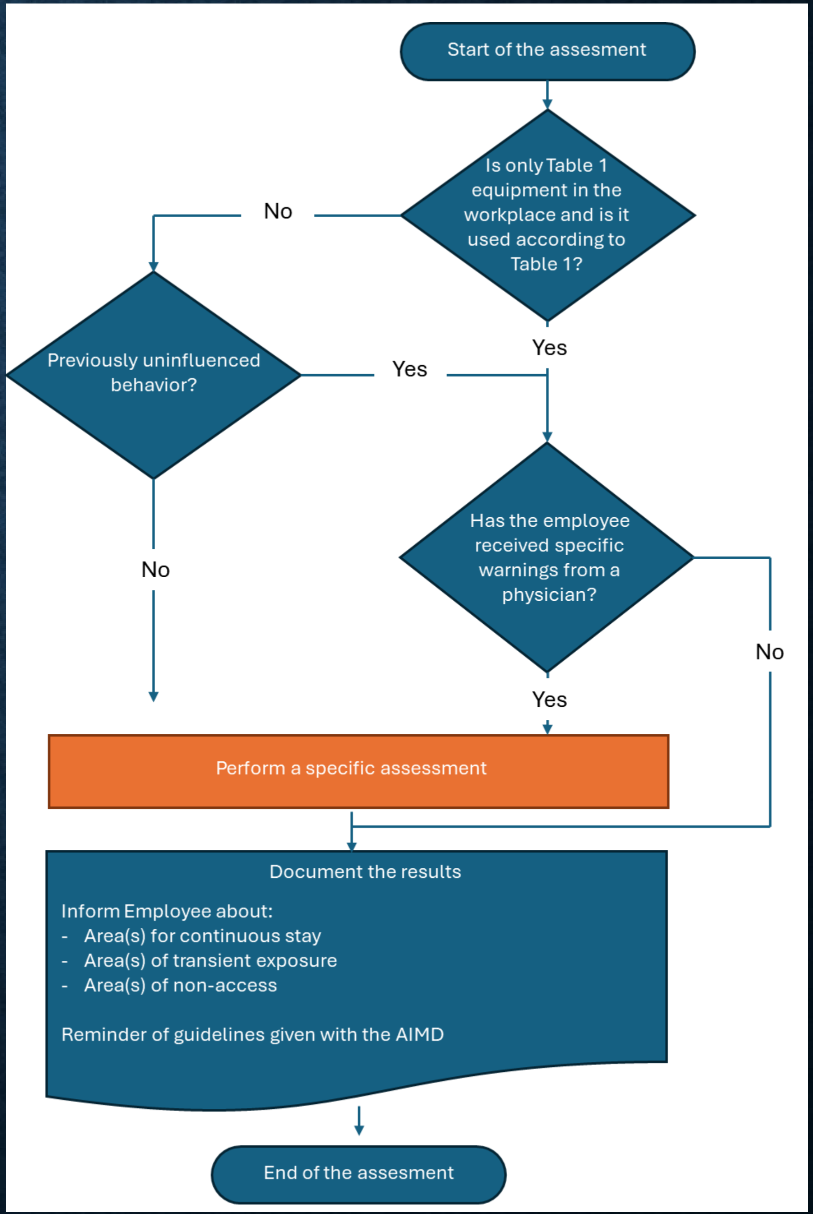


RISK ASSESSMENT FOR WORKERS WITH AIMD

Then, two alternative methods to perform the risk assessment are proposed: the "non-clinical approach" and the "clinical approach".

The former bases risk assessment on measurement, calculation, and/or information provided by the manufacturer of the AIMD and does not involve the worker directly.

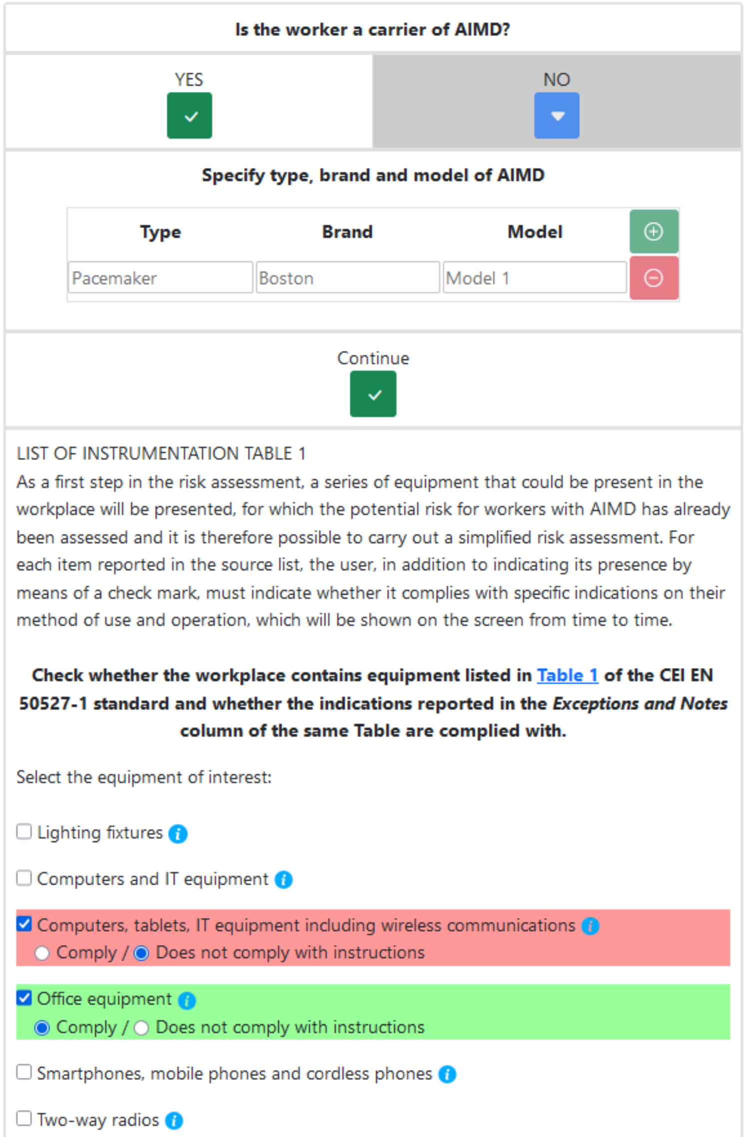
The latter needs the AIMD employee to be exposed under clinical supervision to the foreseeable exposure situations or in a laboratory simulating the workplace exposure situation.



THE AIMD SECTION OF WEBNIR

The guided procedure implemented on the WebNIR platform for risk assessment for workers with AIMDs follows the steps indicated in the technical standard 50527-1, as described previously.

As a first step, after having entered the details of the AIMDs present in the examined worker, the user must indicate whether, in the workplace, there are certain sources of electromagnetic fields, chosen from a pre-established list (the whitelist), indicating for each of these the compliance with the instructions provided in it.


Is the worker a carrier of AIMD?

YES / NO

Specify type, brand and model of AIMD

Type	Brand	Model
Pacemaker	Boston	Model 1

Continue

LIST OF INSTRUMENTATION TABLE 1

As a first step in the risk assessment, a series of equipment that could be present in the workplace will be presented, for which the potential risk for workers with AIMD has already been assessed and it is therefore possible to carry out a simplified risk assessment. For each item reported in the source list, the user, in addition to indicating its presence by means of a check mark, must indicate whether it complies with specific indications on their method of use and operation, which will be shown on the screen from time to time.

Check whether the workplace contains equipment listed in Table 1 of the CEI EN 50527-1 standard and whether the indications reported in the *Exceptions and Notes* column of the same Table are complied with.

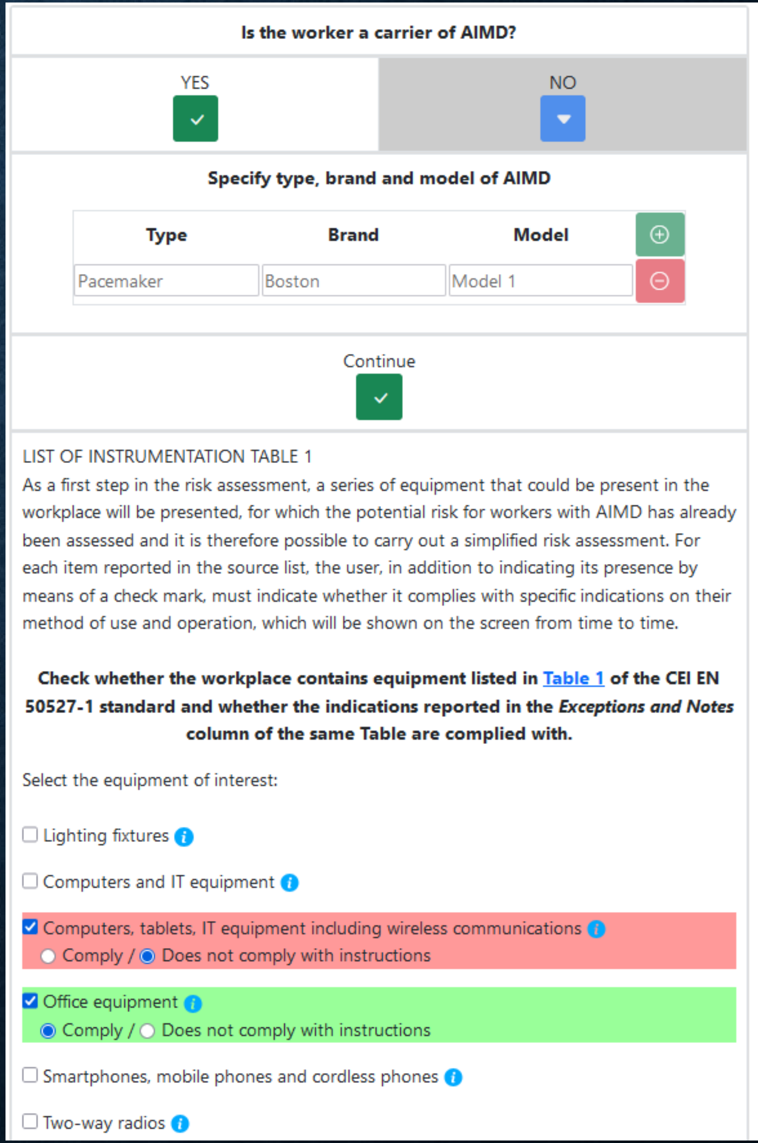
Select the equipment of interest:

- [ ] Lighting fixtures
- [ ] Computers and IT equipment
- [x] Computers, tablets, IT equipment including wireless communications
  - ( ) Comply / (•) Does not comply with instructions
- [x] Office equipment
  - (•) Comply / ( ) Does not comply with instructions
- [ ] Smartphones, mobile phones and cordless phones
- [ ] Two-way radios

THE AIMD SECTION OF WEBNIR

For such sources, the potential risk for workers with AIMDs has already been assessed, and it is therefore possible to carry out a simplified risk assessment.

The user will then be asked to indicate the presence of other sources not listed in the table, and he will finally be presented with a series of questions relating to the work environment and the clinical history of the worker for whom the risk assessment has to be performed. The procedure will conclude with creating a report summarizing the outcome of the risk assessment procedure.



THANKS