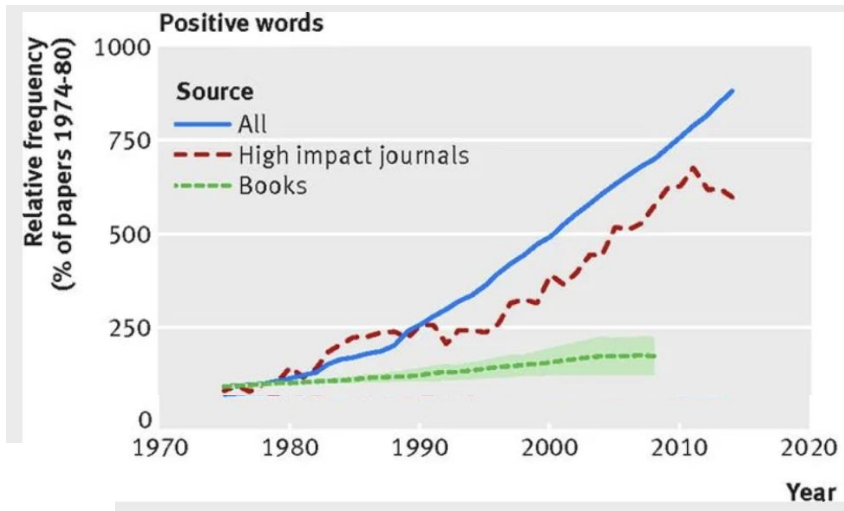


# AI Opportunities in TE-MSD

Stephan Russenschuck with contributions from M. Bonora, M. Buzio, A. Lu,  
M. Liebsch, S. Sorentino, V. DiCapua, M. Pentella,

# Is the AI-Boom a Science Hype?



Use of robust, novel, innovative, unprecedented in science writing

John Horgan, Scientific American Blog

Pareto-front  
Genetic algorithms  
Simulated annealing  
Fuzzy set optimization  
Particle swarms  
ANN-based optimization (FNN)  
Digital twins

Survivorship bias? Mistaking a successful subset as the entire set

# GPT and BERT

Generative pre-trained transformers (2017)

Bidirectional Encoder Representations from Transformers (2018)

Attention is all you need

Large Language Models LLM (translation, speech recognition, spell-checking, search engines, chatbots)

Computer vision (face-detection autofocus, noise reduction, generated bokeh)

Image generators

Robotics

Finance

Workflow automation

Fraud detection

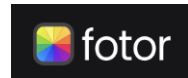
Medical diagnostics

Coding assistance

Driving assistants (autonomous systems)



Three cats sitting on chairs, yawning and wearing party hats. Created with



# Ask ChatGPT

## How can I measure the integrated magnetic field in accelerator magnets?

In particle accelerators, precise measurement of the integrated magnetic field generated by various electromagnets (such as bending dipoles, quadrupoles, sextupoles, and other higher-order lenses) is essential to ensure accurate beam steering, focusing, and stability. There are several methods and techniques for measuring the integrated magnetic fields in these electromagnets:

### 1. Rotating Coil Magnetometers (Rotating Coils)

- Principle:** A coil is rotated within the magnetic field, and the voltage induced by the changing magnetic flux through the coil is measured. The integrated field is proportional to the time integral of the voltage signal.
- Usage:** This is one of the [most common methods](#) used for field measurements in both dipole and higher-order magnets (quadrupoles, sextupoles, etc.).
- Advantages:**
  - Provides precise field measurements and allows [detection of higher-order field components](#).
  - Measures the integral of the field directly along the length of the magnet.
- Challenges:** Requires careful alignment and [calibration](#). The precision of the coil manufacturing and the rotation mechanism is critical.

### 2. Hall Probes

- Principle:** A Hall sensor, which is sensitive to magnetic fields, is moved through the magnetic field along the length of the magnet. The Hall voltage produced is proportional to the local magnetic field.
- Usage:** Used for measuring the magnetic field at discrete points along the length of the magnet. It can be used to create a field map.
- Advantages:**
  - Good for direct, [localized measurements](#) of the magnetic field strength.
  - Provides information on field uniformity and variations.
- Challenges:** The Hall probe must be accurately positioned. It measures the local field, so integrating over the length of the magnet requires scanning or moving the probe.

Omissions

### 3. NMR Probes (Nuclear Magnetic Resonance)

- Principle:** NMR probes measure the resonance frequency of a sample material (typically a proton in a hydrogen nucleus) placed in a magnetic field, which is proportional to the strength of the magnetic field.
- Usage:** Commonly used for extremely precise measurements of very uniform magnetic fields, particularly in dipoles and regions where high field accuracy is required.
- Advantages:** Highly accurate, with a precision on the order of parts per million (ppm).
- Challenges:** Limited to measuring very homogeneous magnetic fields and is typically not used for higher-order multipoles like quadrupoles or sextupoles.

# Ask ChatGPT

## How can I measure the integrated magnetic field in accelerator magnets?

### 4. Fluxmeters

- Principle:** Fluxmeters are used to measure the magnetic flux through a coil, which is related to the integrated magnetic field strength across the area enclosed by the coil.
- Usage:** Used in conjunction with stationary or moving coils to measure the total magnetic flux, particularly in dipole magnets.
- Advantages:** Directly measures the integrated magnetic field (also known as the magnetic flux).
- Challenges:** Accuracy depends on the coil's size, geometry, and alignment. It is less practical for higher-order fields due to their complex spatial distributions

### 5. Vibrating Wire Technique

- Principle:** A current-carrying wire is placed inside the magnet, and when it vibrates in response to the Lorentz force, the frequency of vibration depends on the magnetic field strength. By measuring the wire's vibrations, the field strength can be inferred.
- Usage:** Can be used for precise field mapping and measuring higher-order magnetic fields.
- Advantages:** Provides detailed field measurements and can resolve complex field distributions.
- Challenges:** The setup can be complex and sensitive to vibrations and mechanical alignment.

Hallucination

### 6. Search Coils

- Principle:** A search coil is moved through the magnetic field, and the induced voltage is measured. The voltage is integrated to obtain the total flux.
- Usage:** Used to measure the integrated magnetic field strength over the length of the magnet.
- Advantages:** Simple and effective for measuring the integrated magnetic field in dipoles and quadrupoles.
- Challenges:** For higher-order lenses, more complex coil geometries and careful positioning are required to capture the specific field components.

Repetitions

### 7. Harmonic Coil Systems (Multiple Coil Configurations)

- Principle:** A system of coils arranged in a specific pattern is used to measure different multipole components of the magnetic field. As the coil array rotates or moves through the field, the induced voltages are analyzed to separate out the different harmonics (dipole, quadrupole, sextupole, etc.).
- Usage:** Especially useful for characterizing higher-order magnetic lenses such as quadrupoles, sextupoles, and beyond.
- Advantages:** Capable of measuring the entire field distribution and resolving individual multipole components.
- Challenges:** Complex setup and analysis. Requires accurate coil geometries and sophisticated data processing techniques.



# Ask ChatGPT

## How can I measure the integrated magnetic field in accelerator magnets?

### 8. Stretched Wire Method

- **Principle:** A wire is stretched across the length of the magnet, and a current is passed through it. The wire experiences a force due to the magnetic field (Lorentz force). By moving the wire and measuring the force at different positions, the magnetic field can be reconstructed.
- **Usage:** Often used for measuring the integrated field gradient in quadrupoles and higher-order lenses.
- **Advantages:** Simple to implement for integrated field measurements and sensitive to field gradients.
- **Challenges:** Sensitive to alignment errors and mechanical precision of the setup.

Hallucination

### 9. Laser-based Interferometric Techniques

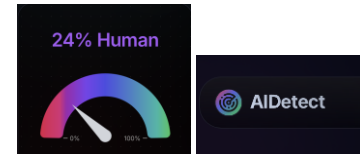
- **Principle:** Laser interferometry can be used to measure small displacements or oscillations caused by the magnetic forces acting on current-carrying wires or magnets. These displacements can be correlated with the magnetic field strength.
- **Usage:** Used in high-precision applications, especially for mapping fields in higher-order magnets where extreme precision is needed.
- **Advantages:** Very high precision and non-invasive.
- **Challenges:** Requires sophisticated optical setups and is sensitive to environmental vibrations.

### Summary of Methods:

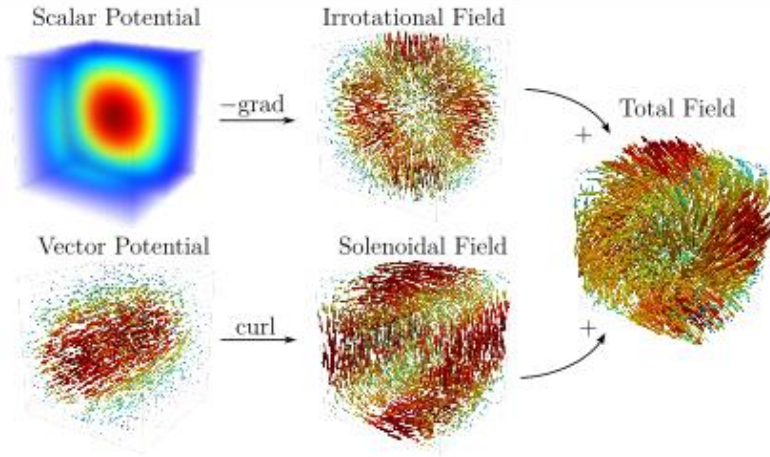
- **For Dipole Magnets:** Rotating coil magnetometers, fluxmeters, NMR probes, and Hall probes are commonly used to measure the integrated magnetic field.
- **For Quadrupoles and Higher-Order Lenses:** Harmonic coil systems, rotating coils, vibrating wire techniques, and stretched wire methods are often used for characterizing field gradients and higher-order field components.

Reference? Could be worth trying

Main concern: Intellectual property -> CERN copyright committee  
How best to integrate domain-specific knowledge



# Ask ChatGPT (Coding Assistance)



Lack of experience in the group:  
Perhaps much better results using tools such as GitHub Copilot

Given the three components of the magnetic flux density on a grid, can you create Python code for computing the scalar and vector potentials on the same grid using the Helmholtz decomposition?

Main concern: Intellectual property, data privacy, licensing

```
def helmholtz_decomposition(Fx, Fy, Fz, dx):
    # Get the dimensions of the grid
    nx, ny, nz = Fx.shape

    # Create the k-space grid
    kx = fftfreq(nx, d=dx) * 2 * np.pi
    ky = fftfreq(ny, d=dx) * 2 * np.pi
    kz = fftfreq(nz, d=dx) * 2 * np.pi
    KX, KY, KZ = np.meshgrid(kx, ky, kz, indexing='ij')

    # Compute the divergence of F in Fourier space
    F_div = fftn(Fx) * KX + fftn(Fy) * KY + fftn(Fz) * KZ

    # Avoid division by zero for k = 0
    K_squared = KX**2 + KY**2 + KZ**2
    K_squared[0, 0, 0] = 1.0 # To avoid division by zero at the origin

    # Compute the scalar potential phi in Fourier space
    phi_k = -F_div / K_squared

    # Transform phi back to real space
    phi = np.imag(fft(phi_k))

    # Compute the curl of F in Fourier space
    Fx_k, Fy_k, Fz_k = fftn(Fx), fftn(Fy), fftn(Fz)

    # Compute vector potential A in Fourier space
    Ax_k = (KY * Fz_k - KZ * Fy_k) / K_squared
    Ay_k = (KZ * Fx_k - KX * Fz_k) / K_squared
    Az_k = (KX * Fy_k - KY * Fx_k) / K_squared

    # Transform A back to real space
    Ax = -1.0 * np.imag(fft(Ax_k))
    Ay = -1.0 * np.imag(fft(Ay_k))
    Az = -1.0 * np.imag(fft(Az_k))

    return phi, Ax, Ay, Az

# Example of usage:
# Define a vector field (Fx, Fy, Fz) on a regular grid
nx, ny, nz = 64, 64, 64
x = np.linspace(-np.pi, np.pi, nx, endpoint=False)
y = np.linspace(-np.pi, np.pi, ny, endpoint=False)
z = np.linspace(-np.pi, np.pi, nz, endpoint=False)
X, Y, Z = np.meshgrid(x, y, z, indexing='ij')

# Example vector field (you can replace with your field data)
Fx = -2.0 * np.sin(X) * np.cos(Y) + 2.0 * np.sin(Z) * np.cos(Z) - np.sin(X) * np.sin(Y)
Fy = -2.0 * np.sin(Y) * np.cos(X) - np.cos(X) * np.cos(Y)
Fz = -2.0 * np.sin(Z) * np.cos(Y) - 2.0 * np.sin(X) * np.cos(X)

# the ground truth solution
Ax_gt = np.sin(Y)**2
Ay_gt = np.cos(Z)**2
Az_gt = np.sin(X) * np.cos(Y)
phi_gt = np.sin(X)**2 + np.sin(Y)**2 + np.sin(Z)**2

# gauging
phi_gt -= np.mean(phi_gt)
Ax_gt -= np.mean(Ax_gt)
Ay_gt -= np.mean(Ay_gt)
Az_gt -= np.mean(Az_gt)

dx = x[1] - x[0]

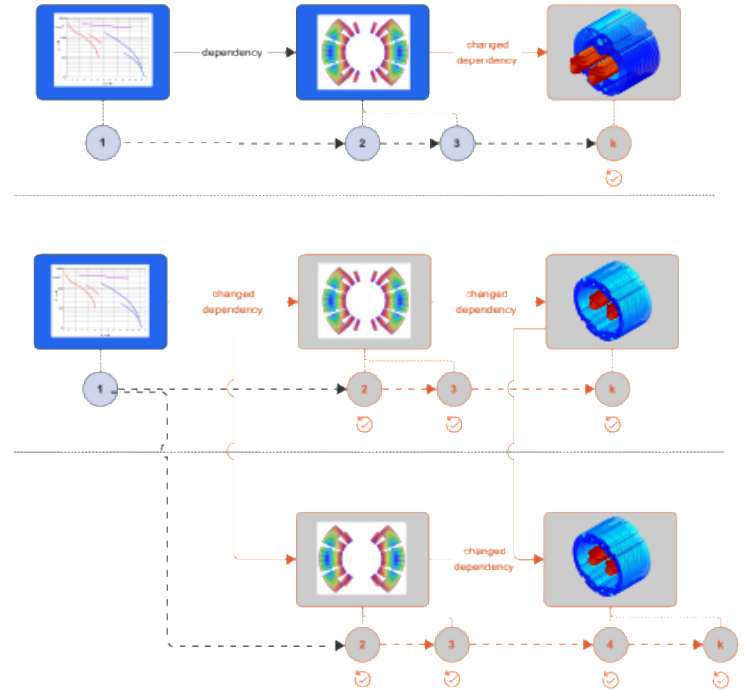
# Perform the Helmholtz decomposition
phi, Ax, Ay, Az = helmholtz_decomposition(Fx, Fy, Fz, dx)

print("Scalar potential (phi):", phi)
print("Vector potential (Ax, Ay, Az):", Ax, Ay, Az)
```

# AI as a support tool: Pilots

- Knowledge management using AI tools
  - Domain-specific assistants
    - → example: TRAPecista
    - 26+ registered projects at CERN (AccGPT)
- Support of design/production/test processes
  - Magnet design
  - Production follow up and QA
  - Measurement analysis
  - Reporting

Resources: 2 TECH/DOCT Backed up by their supervisors, IT expert (3 years), and centralized support

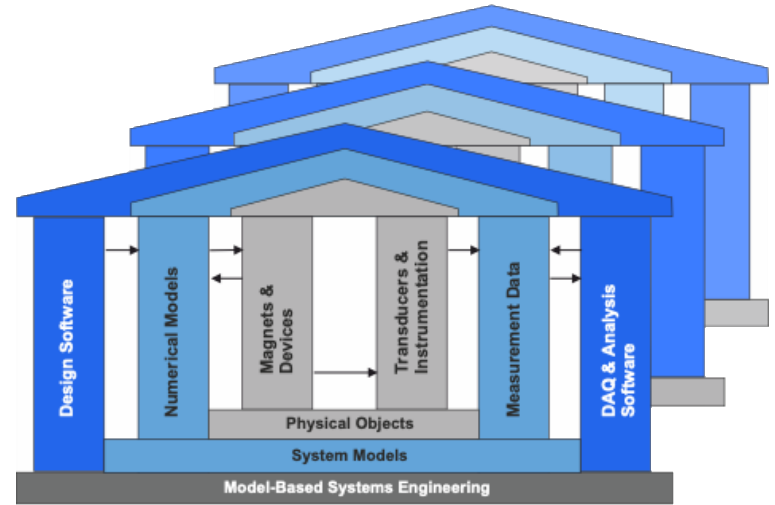


Product generation engineering –  
models and pipelines  
Magnet Model Management Layer 3ML



# AI for specific tasks: Pilots

- MBSE (Digital Twins, Hybrid Modelling)
- Time-series prediction
  - -> Example: Real-time prediction of magnetic fields in accelerator magnets for machine control
  - Hysteresis and eddy-current modeling
  - Quench-signal analysis
- Ignorance (unrecognized systematic effects) mitigation



Physics-informed neural networks (PINNs) versus deep learning (transformers)

What must/can be measured, what must/can be simulated, what can we predict

Resources: 2-3 TECH/DOCT (engineering, applied physics, **not** IT) on project budgets. Backed up by their supervisors, a group IT expert, and central support.

# Enabling Functionality

- AI lives from training data. Ensure that our data are structured and accessible
  - Databases and structured storage of measurements (magnetic, material), processes (production, control) → 3ML, eMIP, Test and Measurement databases
  - Programmatic access to data (Python, web services), well-defined data structures

Resources: 1.5 Staff FTE + 2 TECH/ADMIN students + 3 FSU independent of any AI application

- Physical resources such as GPUs and servers
- Frameworks, guidelines, and training to develop machine-learning solutions
  - Hyper-Parameters: Training sets, feature dimensionality, learning algorithms (supervised/unsupervised), validation sets.
- Benchmarking of AI libraries, LLM model builders, models (horses for courses), vector database architectures

Resources: Working groups (ATS) and competency pool (groups) backed up by central support (CERN IT?)

# Roles in software development/application for acc. magnets

