Non-Linear Kickers design and characterization

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ESRF | The European Synchrotron

SUMMARY

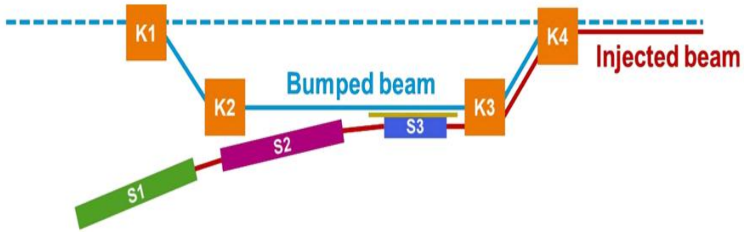
1. **Introduction**
    1. Current injection scheme
    2. NLK injection scheme

2. **Pulsed magnets measurement bench**
    1. Measurement principle
    2. Dipole kicker
    3. SOLEIL NLK
    4. Calibration

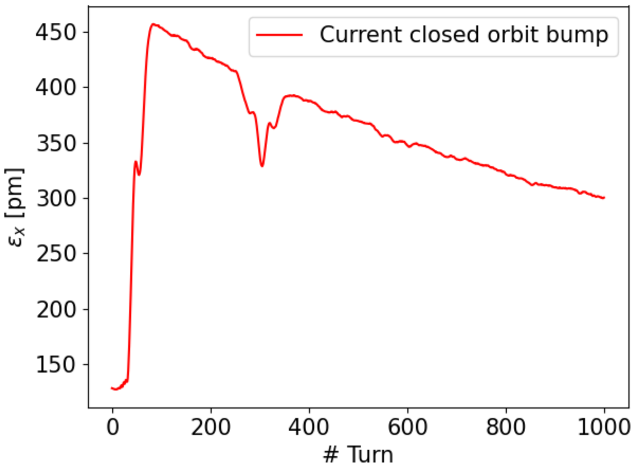
3. **Conclusion**

Introduction - Current injection scheme

- Standard injection scheme with 4 dipole kickers and 3 septum blades
- Closed orbit locally and temporarily displaced
- Generate huge perturbations for the beamlines



Current injection scheme.
EBS storage ring technical report, Sept. 2018

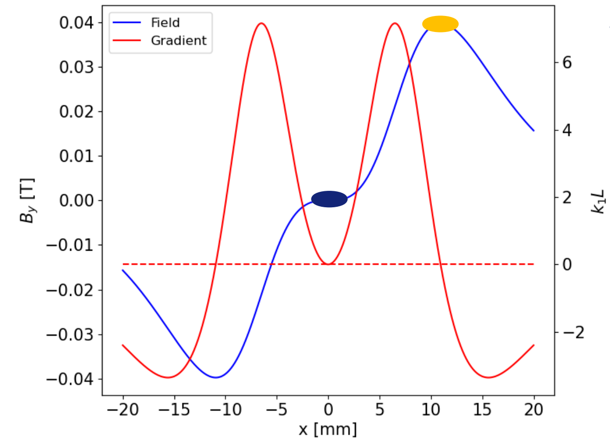


Simulation of the evolution of horizontal emittance in the first 1000 turns after injection.

1.2 Introduction - NLK injection scheme

PROPOSITION

- New injection system based on Non-Linear Kicker magnets (NLK)
- Octupolar-shaped magnetic field (varies in r^3 for $r \in [-5 ; 5]$ mm)
- Transparency for the beamlines
- Method invented at KEK, improved at BESSY and used in operation at MAX IV and SIRIUS



Stored (blue) and injected (yellow) beams representations.

Field (blue) and gradient (red) simulated with python (SOLEIL design).

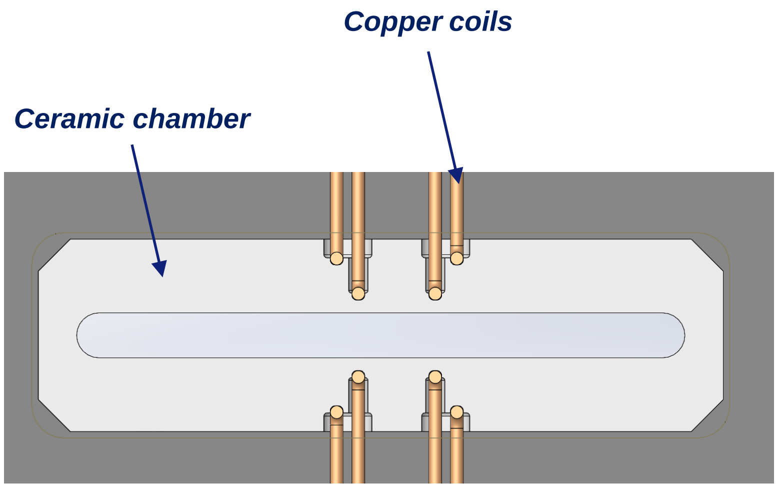
Magnetic Field	
B at stored beam	0 T
B at injected beam	0.17 T
B at 0.3 mm	$7 \,.\, 10^{-5}$ T
Total kick	12.2 mrad distributed over 3 NLK

Summary table of specifications

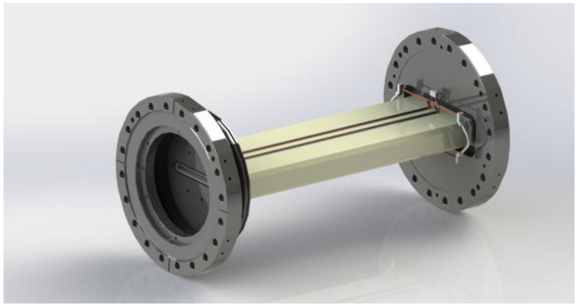
1.2 Introduction - NLK injection scheme

CURRENTLY

- Position of the inner conductors on a square of 6 mm
- Position of the outer conductors on a square of 12 mm
- Current flowing in the coils : 6.9 kA
- Ceramic vacuum chamber
- Design based on SOLEIL developments, thanks to the help of P. Alexandre, R. Ben El Fekih and A. Letrésor



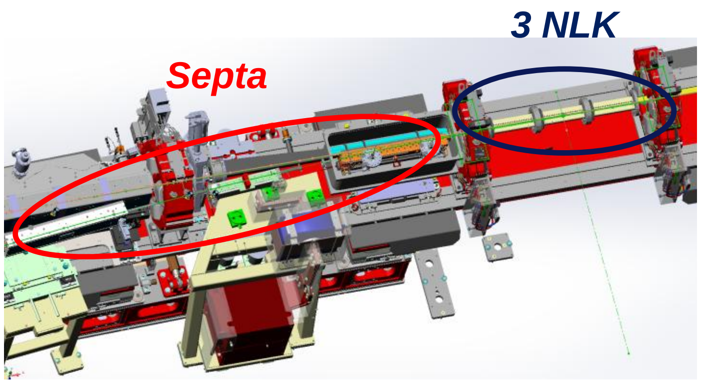
Cross-section of the proposed non-linear kicker.



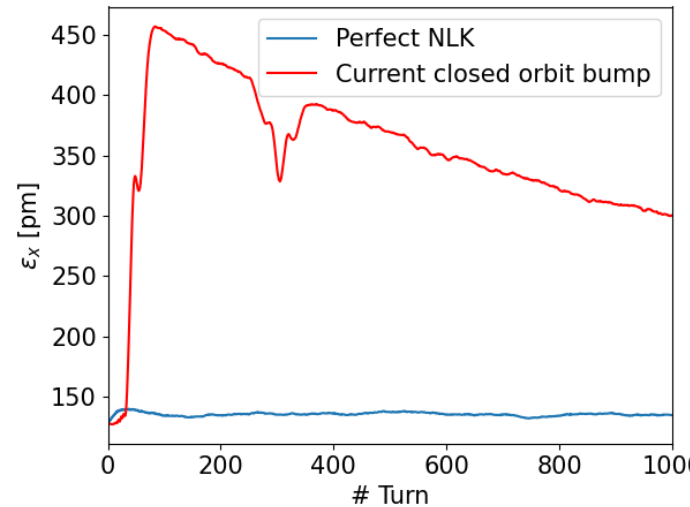
Assembly of the NLK (30cm long).

1.2 Introduction - NLK injection scheme

- No more dipole kickers
- Closed orbit is no more displaced
- No perturbation for the beamlines

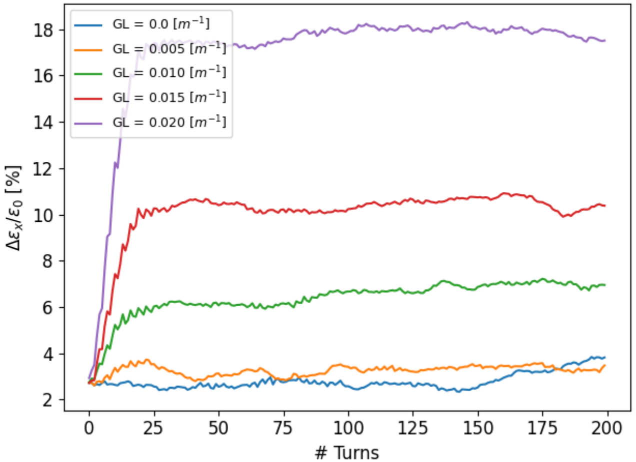


NLK injection scheme.

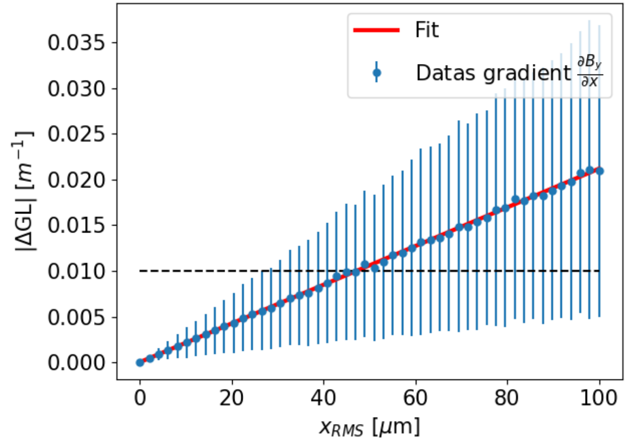


Simulation of the evolution of horizontal emittance in the first 1000 turns after injection.

- No emittance growth beyond 5-6%
- Determine the gradient value at which the acceptable limit is reached
- Match this gradient value to an RMS position error of the coils



Emittance growth as a function of the NLK gradient.

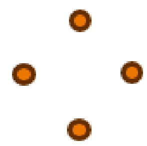


Statistical study on the relative error of the gradient.

Conclusion : An RMS positioning error of 50 µm for the 8 coils is acceptable.

2.1 Test bench for pulsed magnets - Principle of measurement

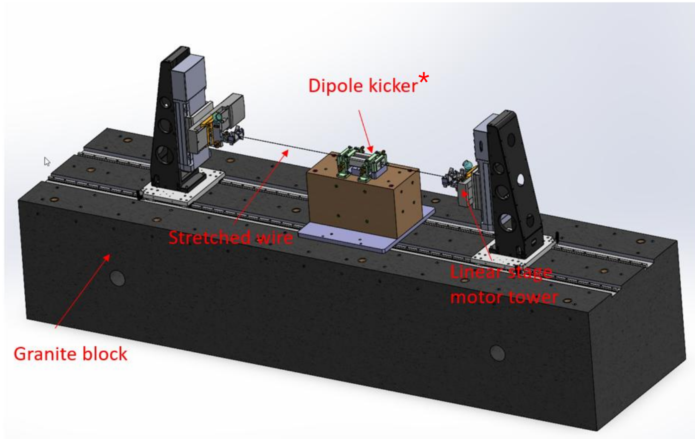
- Adaptation of stretched-wire measurement
- 2 loops for simultaneous measurement of horizontal and vertical planes
- Voltage (V) measured across loops and converted to magnetic flux value



Wires arrangement

- **Theoretically :**
  - Faraday's law **:** $$V = -\frac{d\varphi}{dt}$$
  - Magnetic flux **:** $$\varphi = \int \mathbf{B} \cdot d\mathbf{S}$$

- **Practically :**

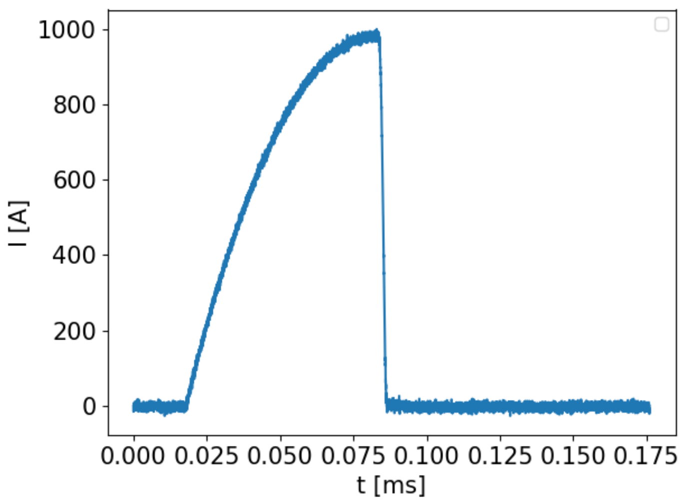


* Soon with ESRF NLK

3D scheme of the magnetic test bench.

2.3 Test bench for pulsed magnets – Principle of measurement

- Spare injection dipole kicker installed on the bench
- Experimental set-up for the commissioning

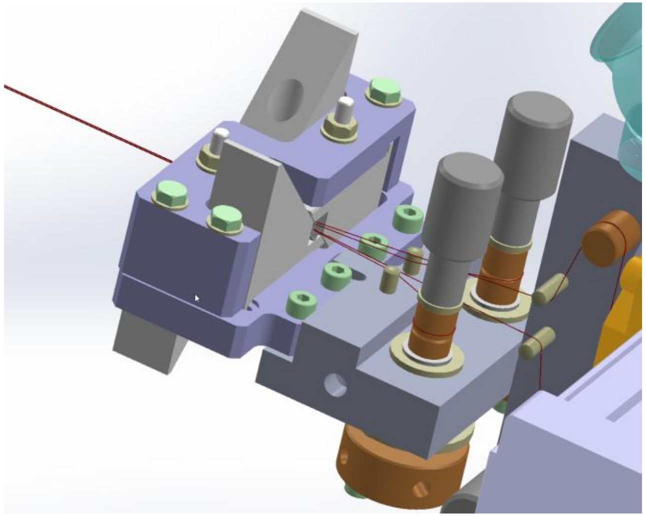


Current profile delivered by the power supply.

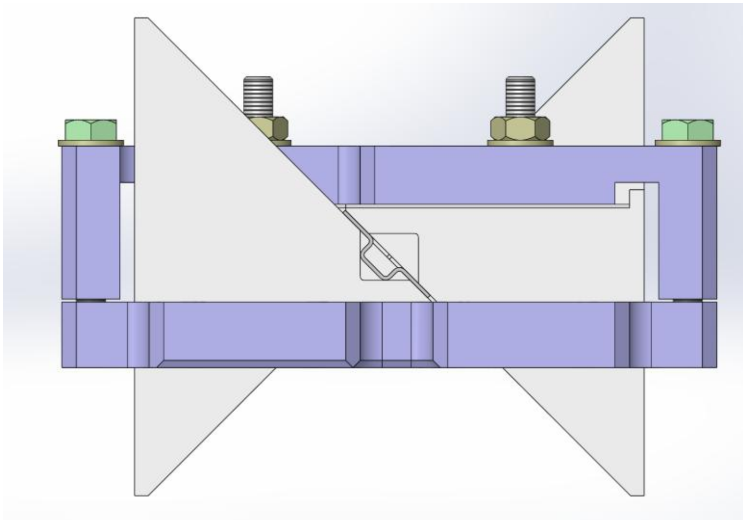
Test bench with a dipole kicker.

2.3 Test bench for pulsed magnets – Principle of measurement

- Adjustable spacing between the wires
- Wires are stretched one by one
- Easy to adjust the stretching of the wire

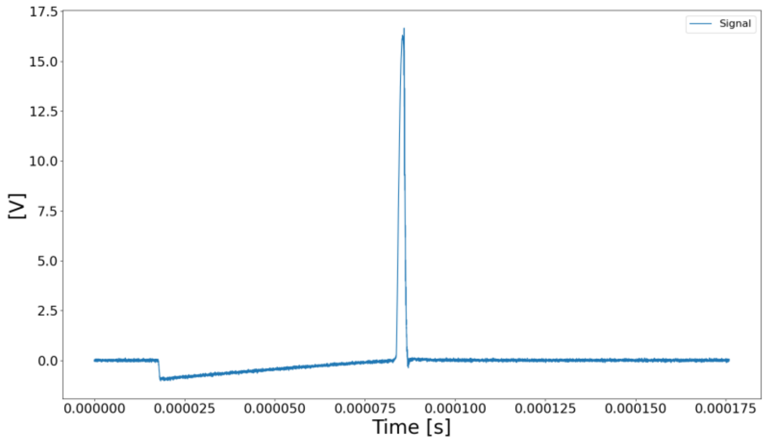


3D mechanical layout of the wires stretching system.

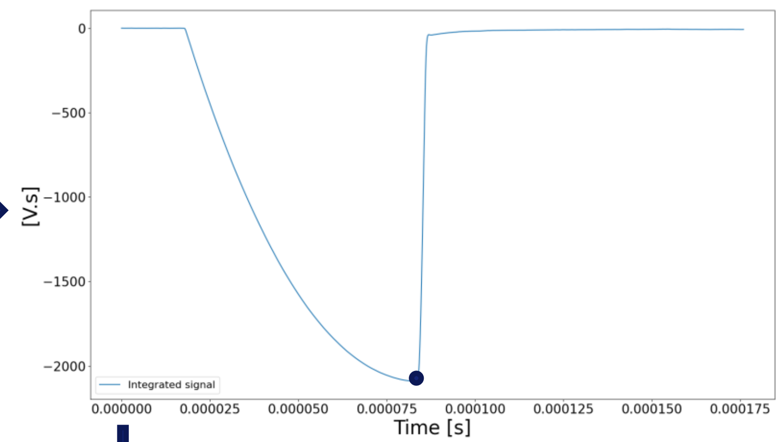


2D cut of the stretching system.

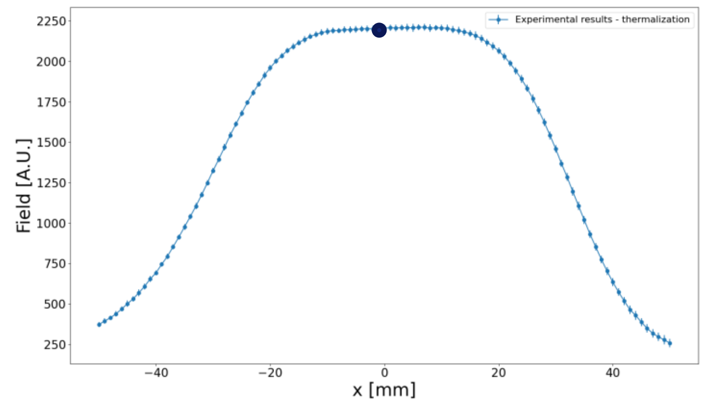
2.1 Test bench for pulsed magnets - Principle of measurement



Measured the induced voltage on the wire (1).



Cumulative integral of the signal (2).

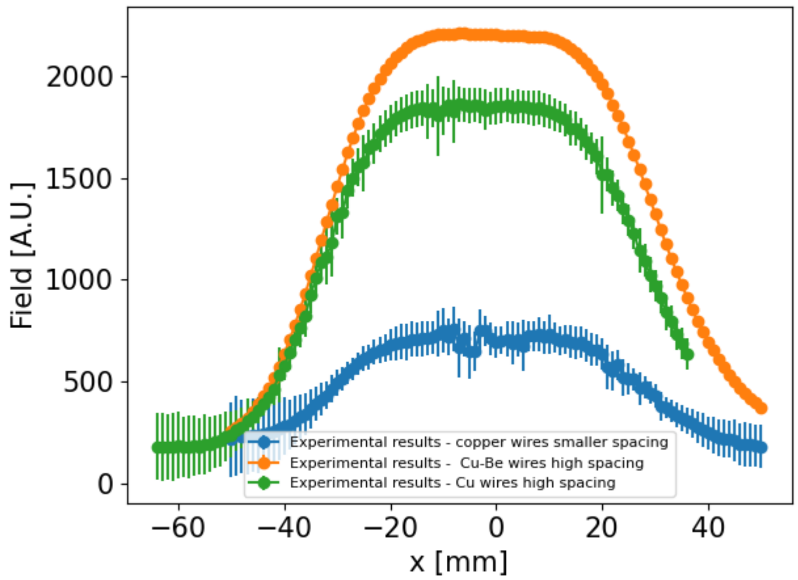


Magnetic field map (3).

- Step 1 : Measure the induced voltage on the wire
- Step 2 : Integral of (1) and find the peak value
- Step 3 : Building the magnetic field map

2.2 Test bench for pulsed magnets – Dipole kicker

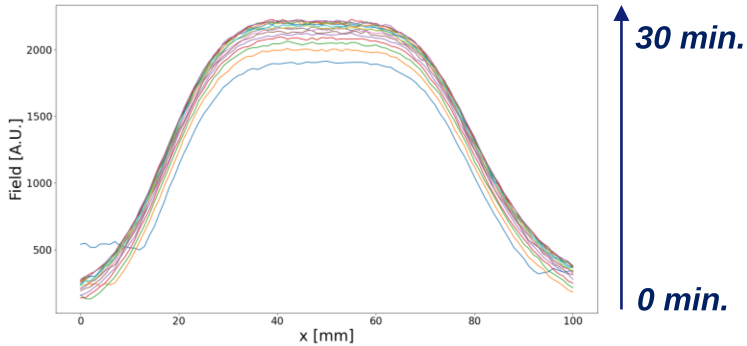
- Commissioning of the bench
- Measurements performed on a dipole kicker
- Many configurations tested



Magnetic field map as a function of bench configuration.

2.2 Test bench for pulsed magnets – Dipole kicker

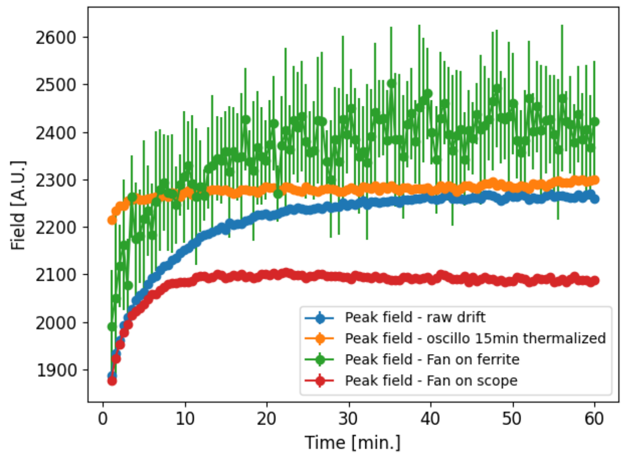
- Large error bars on measurement points
- Superimpose each measured field map to see the drift of the values
- Several sources of drift considered (high-voltage power supply, magnet ferrite, oscilloscope)
- Test with a fan to characterize the problem



Overlay of field maps in order of measurement.

Conclusion: the electronics inside the oscilloscope heat up and cause the drift

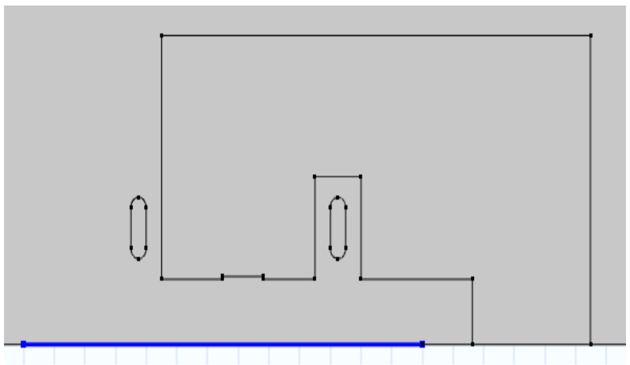
Solution : Pre heating of the oscilloscope before starting a measurement sequence



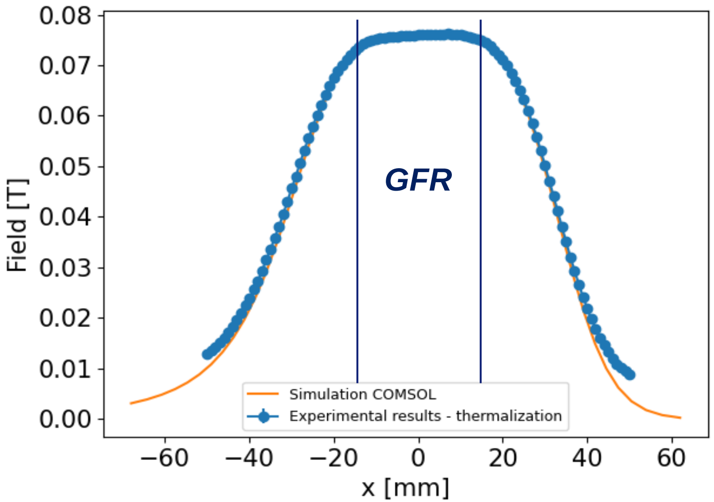
Thermal drift of the peak field.

2.2 Test bench for pulsed magnets – Dipole kicker

- COMSOL 2D model of the dipole kicker
- Comparison of experimental and simulation results to validate bench data



COMSOL 2D model of the dipole kicker.



Agreement of experimental data with the simulated field.

- Differences between simulation and measurement at the edges of the field, but overall satisfactory fit
- Due to the way the simulation is parameterized and the differences between the models and the real kicker (assembly errors, coil positioning, etc.)

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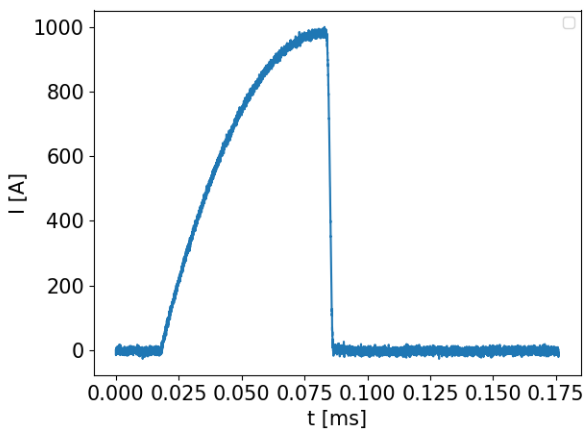
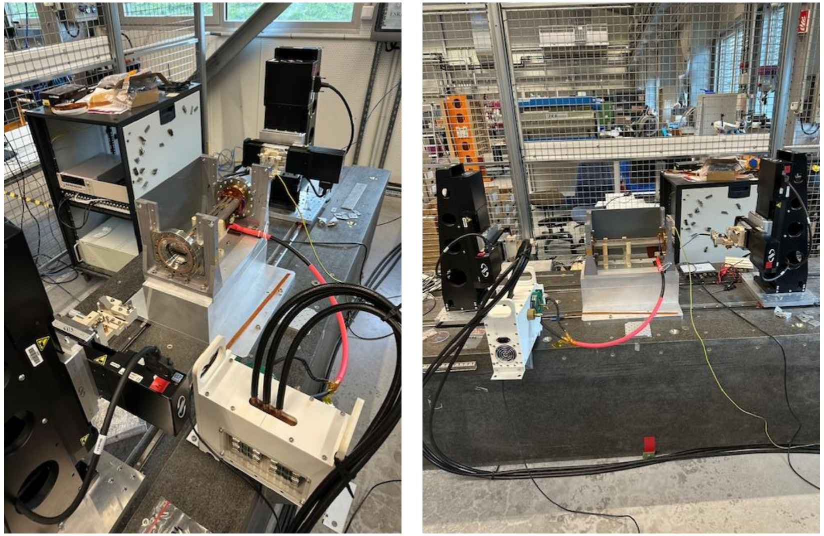
2.3 Test bench for pulsed magnets – SOLEIL NLK

- SOLEIL NLK (MIK) has been installed on the bench
- Test the bench performance in real condition with a non-linear magnet
- Start with a horizontal scan and then elliptical profile measurement has been developed



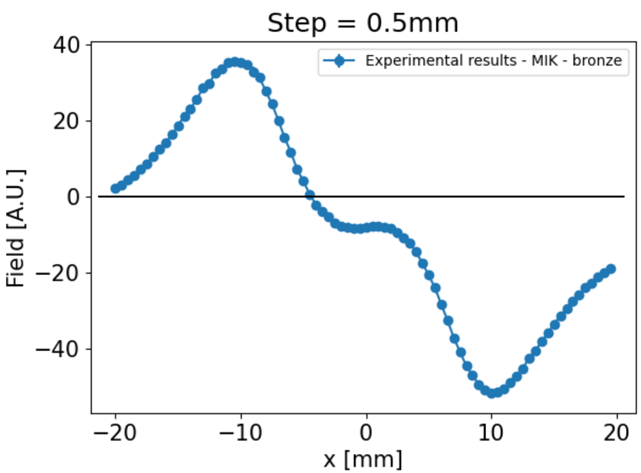
Current profile delivered by the power supply.



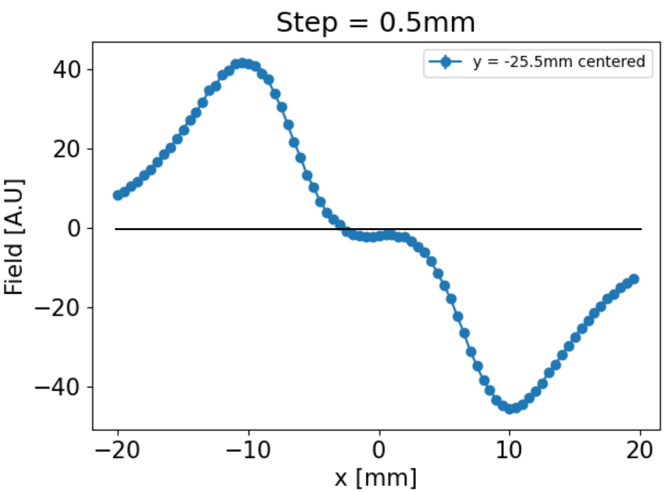
Test bench with SOLEIL NLK.

2.3 Test bench for pulsed magnets – SOLEIL NLK

- Oscilloscope is introducing an artificial dipole offset in the raw data acquired
- Post processing is needed to remove this offset induced by the scope that causes this dipole
- Acquire the noise causing this vertical dipole when there is no current flowing in the conductors and remove it point by point



Integrated scope noise removed from the raw data



Field map with the vertical dipole.

Field map without the artificial dipole offset.

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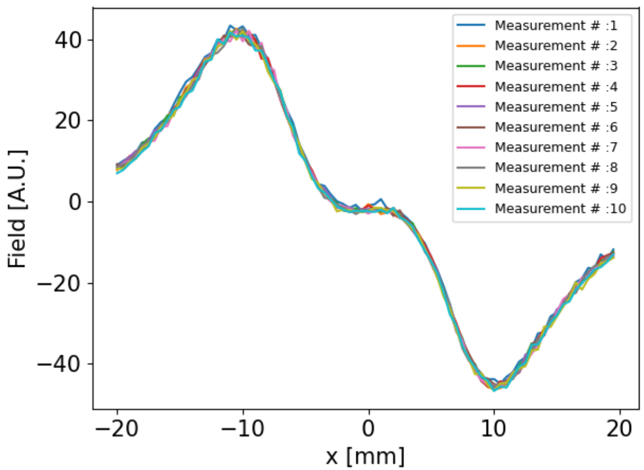
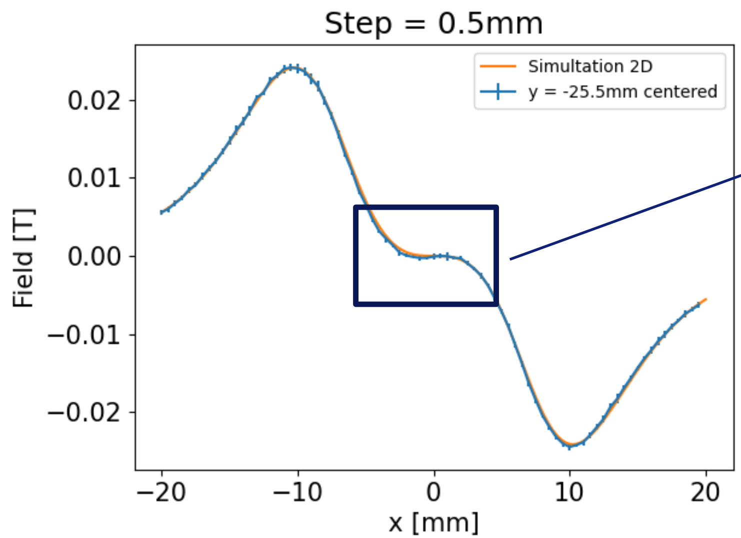
2.3 Test bench for pulsed magnets – SOLEIL NLK

- First results of linear scan show a good agreement between the simulation (COMSOL 2D) and the experimental data

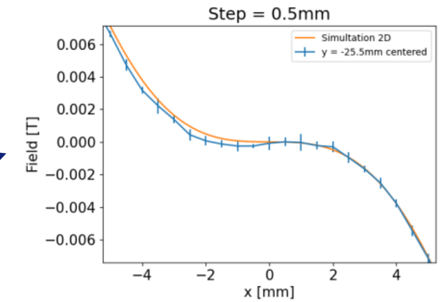
- Measurements are reproducible



Reproducibility of the measurements.



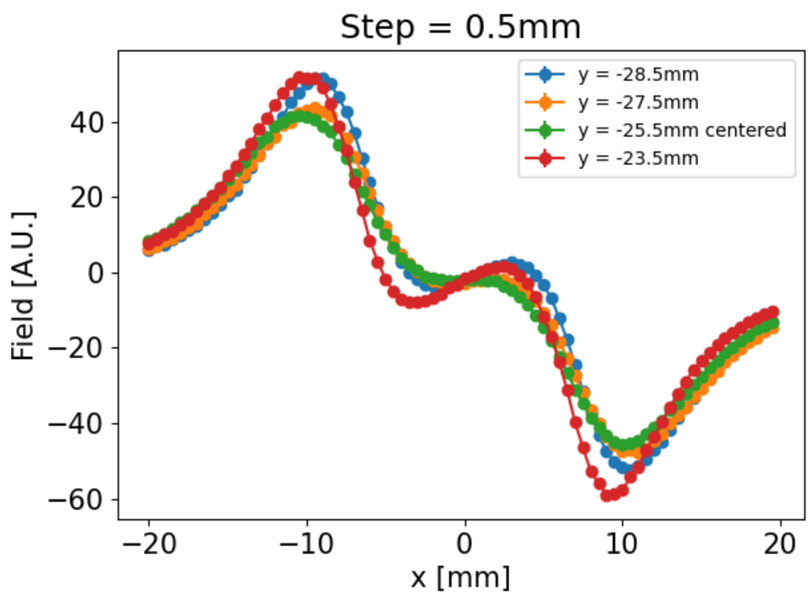
Agreement of experimental data with the simulated SOLEIL NLK field.



Zoom on the octupole part

2.3 Test bench for pulsed magnets – SOLEIL NLK

- Sensitivity to misalignment of the coil used to perform the measurement is important
- Fiducialization methods have to be defined for our prototype



Field map reconstructed with respect to different vertical positions of the wires.

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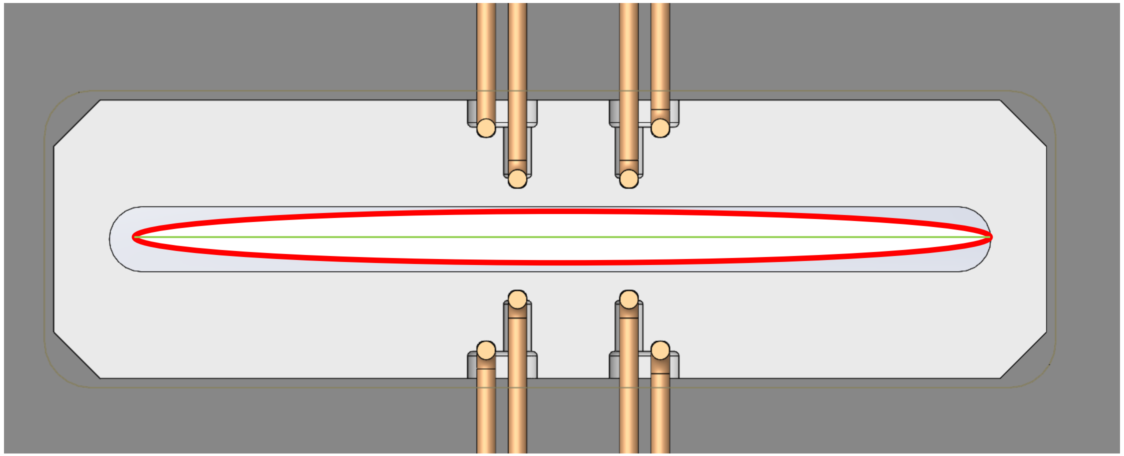
2.3 Test bench for pulsed magnets – SOLEIL NLK

- **Horizontal scan functional but non-optimal :**
  - Sensitivity to misalignment
  - Passage through a field free region (magnetic center) → reconstruction on measurement noise
- **Solution : Measurement on a closed contour following the opening of the chamber :**
  - No sensitivity to misalignment
  - Maximization of the measured signal



Horizontal scan (green) and measure on a closed contour (red).

2.3 Test bench for pulsed magnets – SOLEIL NLK

How do we reconstruct with such profile ?

- Circular multipole reconstruction

$$\begin{pmatrix} B_0 \\ \vdots \\ B_n \end{pmatrix} = \mathrm{M} \cdot \begin{pmatrix} a_0 \\ \vdots \\ a_n \\ b_0 \\ \vdots \\ b_n \end{pmatrix}$$

- M is a matrix depending on our measurement, we want to inverse it to be able to compute the multipole coefficients

$$\mathrm{M_{mn}} = \mathrm{f(x, y, m, n)} = \sum_{n=1}^{N} (b_n + i a_n) \left(\frac{x_m + i y_m}{r_0} \right)^{n-1}$$

- Finally we compute the multipole coefficients

$$\begin{pmatrix} a_0 \\ \vdots \\ a_n \\ b_0 \\ \vdots \\ b_n \end{pmatrix} = \mathrm{M}^{-1} \cdot \begin{pmatrix} B_0 \\ \vdots \\ B_n \end{pmatrix}$$

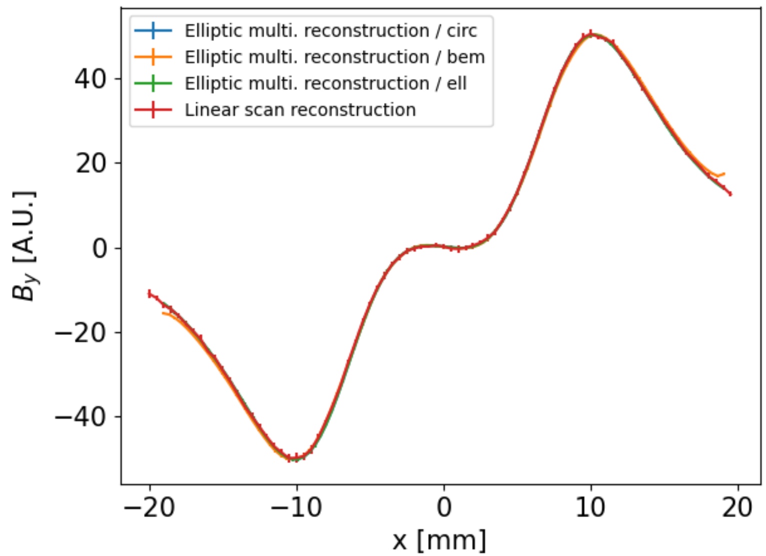
Equations from : G. Le Bec, J. Chavanne, and C. Penel, "Stretched wire measurement of multipole accelerator magnets", Phys. Rev. Spec. Top. Accel

2.3 Test bench for pulsed magnets – SOLEIL NLK

- Measuring on a closed contour allows the magnetic field to be reconstructed at any point within it using the Python library MagField [1]

[1] G. Le Bec, “Magnetic field tools, a C++/Python library for magnetic field processing”, in Proc. IPAC’23 ; https://gitlab.esrf.fr/IDM/magfield

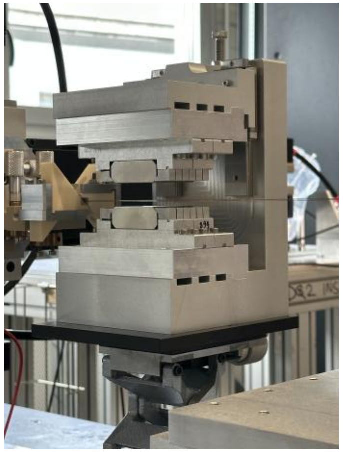
- Measurement routine script recently completed



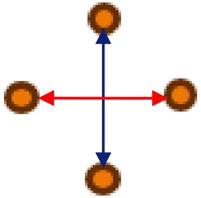
Reconstruction of the transverse magnetic field of the MIK using closed contour measurement.

2.4 Test bench for pulsed magnets – Calibration

- To achieve a clean measurement of the field, a calibration of the measurement coil (i.e. the wires) is needed
- To do that we use a permanent quadrupole designed in-house
- We want to know the distance between the vertical and horizontal wires composing the measurement coil
- We want to compute the total area of the measuring coil to get a calibration factor and other useful information



Permanent quadrupole used for calibration.

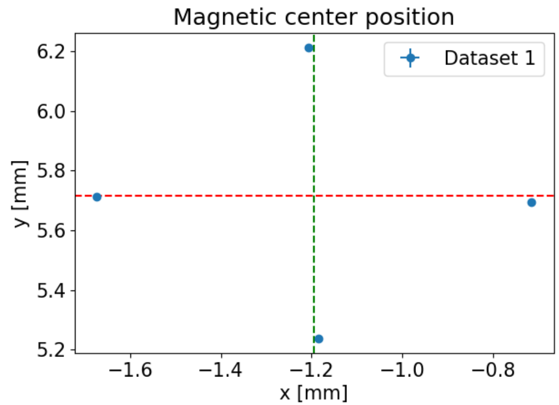


Wires arrangement and distance to measure (blue and red lines).

2.4 Test bench for pulsed magnets – Calibration

How do we proceed ?

- Using a nanovoltmeter from Keithley we measure the field integral of the permanent quadrupole wire by wire
- From this, we can compute the magnetic center associated to a wire
- We get four magnetic center positions each offset by the distance between the wires
- We can compute theses distances and determined what are the actual positions of our wires, the area of the whole coil and a calibration factor for our bench.
- Data analysis on going



Spatial disposition of the wires within the measurement coil.

Horizontal distance : 0.95864 mm $\pm$ 3.55e-5 mm

Vertical distance : 0.97439 mm $\pm$ 9.78e-5 mm

3 Conclusion

- Commissioning of test bench dedicated to pulsed magnets measurement
- Several field reconstruction methods implemented
- Correct for the angles within the wires positions
- Measure our prototypes beginning of next year
- Test in beam conditions, summer next year

Thank you for your attention

Acknowledgements :

S. WHITE, L. R. CARVER, N. CARMIGNANI, S. M. LIUZZO, T. PERRON, G. LE BEC, C. BENABDERRAHMANE, L. BORTOT, T. BROCHARD, D. BABOULIN, B. OGIER, F. BIDAULT, M. MORATI and M. DUBRULLE for their contributions to this presentation

Back-up

How do we reconstruct with such profile ?

- **Elliptic multipole reconstruction**

$$\begin{pmatrix} B_0 \\ \vdots \\ B_n \end{pmatrix} = \mathbf{M} \cdot \begin{pmatrix} a_0 \\ \vdots \\ a_n \\ b_0 \\ \vdots \\ b_n \end{pmatrix}$$

- **M is a matrix depending on our measurement, we want to inverse it to be able to compute the multipole coefficients**

$$\mathrm{M_{mn}} = \mathrm{f(x, y, m, n)} = \frac{B_0}{2} + \sum_{n=1}^{N} E_n \frac{\cosh(\eta + i\psi)}{\cosh \eta_0}$$

- **Finally we compute the multipole coefficients**

$$\begin{pmatrix} a_0 \\ \vdots \\ a_n \\ b_0 \\ \vdots \\ b_n \end{pmatrix} = \mathbf{M}^{-1} \cdot \begin{pmatrix} B_0 \\ \vdots \\ B_n \end{pmatrix}$$

Equations from : G. Le Bec, J. Chavanne, and C. Penel, “Stretched wire measurement of multipole accelerator magnets”, Phys. Rev. Spec. Top. Accel

Back-up

How do we reconstruct with such profile ?

- **Boundary Element Model (BEM) multipole reconstruction**

- The boundary is divided in short segments
- The contributions of sources on segments are added
- The source distribution is computed from the values of the potential on the boundary, via a matrix inversion