Update on the 3D model of FOOT dipoles for magnetic field mapping extraction

XVI FOOT Collaboration Meeting
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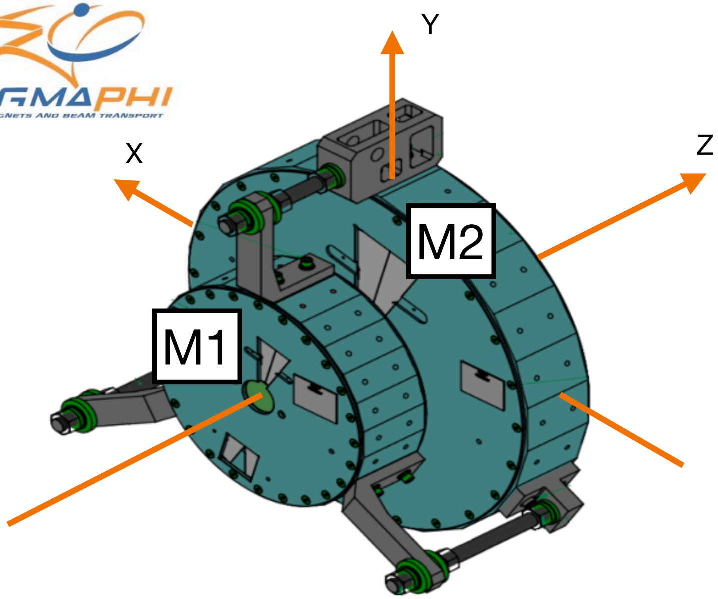
Outline

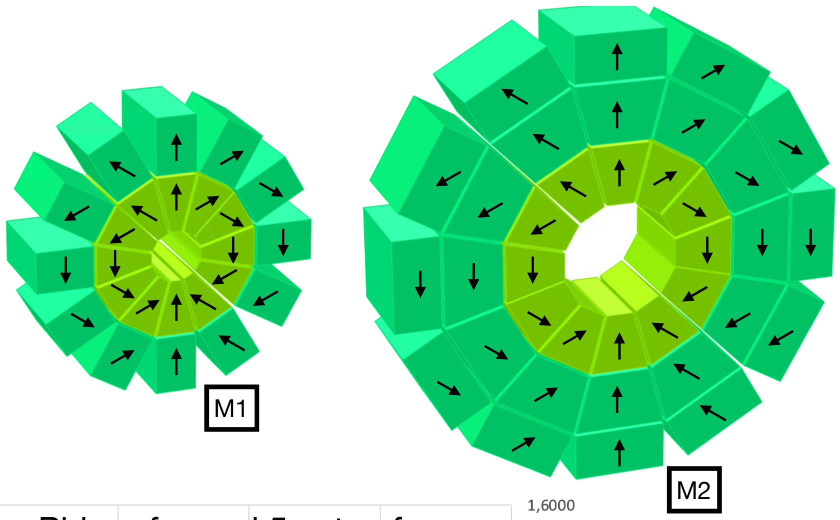
- Present a recap of the available measurements of the magnetic field spatial distribution over the dipole system.
- Introduce the 3D model developed from the mechanical design of SigmaPhi and validated using OPERA FEM analysis for the solution of the field equations.
- Show the comparison between the model and the set of measurements, highlighting possible sources of discrepancies.
- Next steps and conclusions.

Measurements @ SigmaPhi

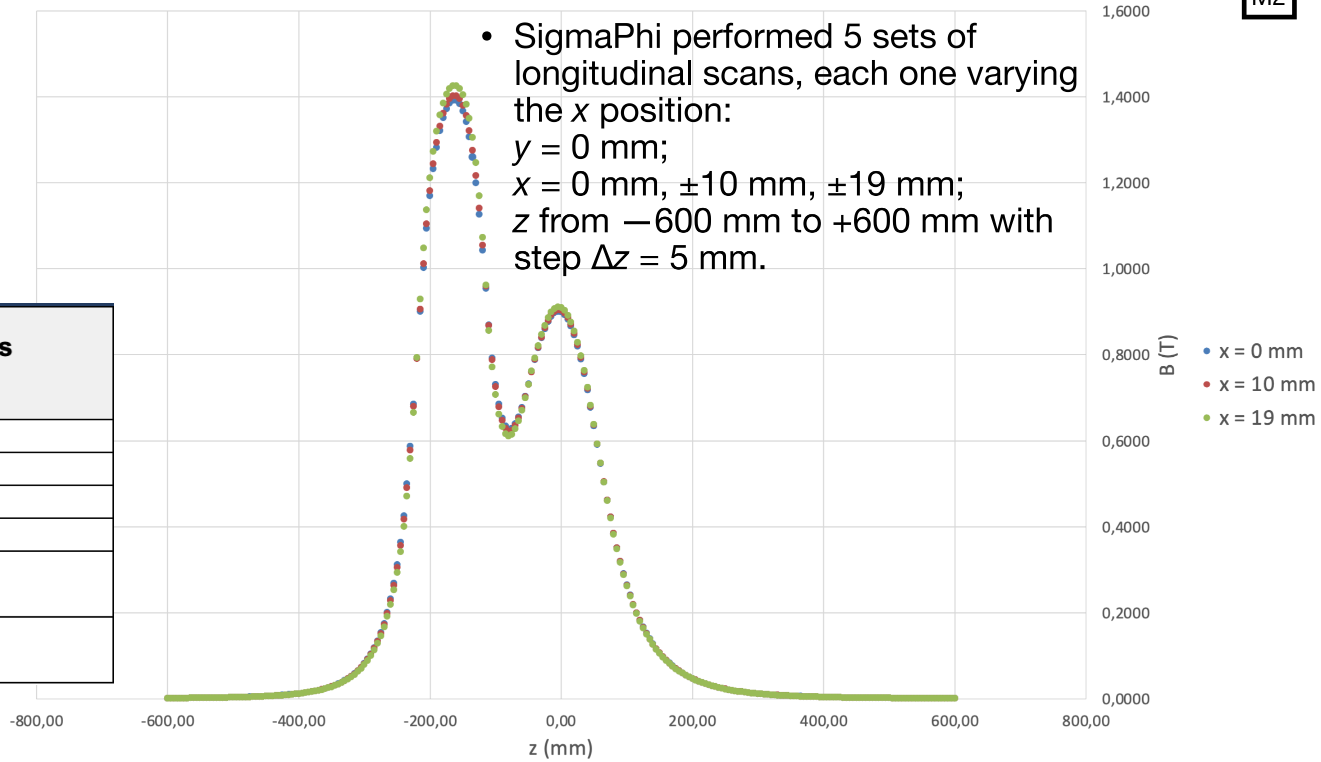


- 2 Halbach dipoles (**12** sectors) with Neodymium-Iron-Boron permanent magnets (**N38UH** and **N48H**) housed in cells.

- Also single magnets were measured.



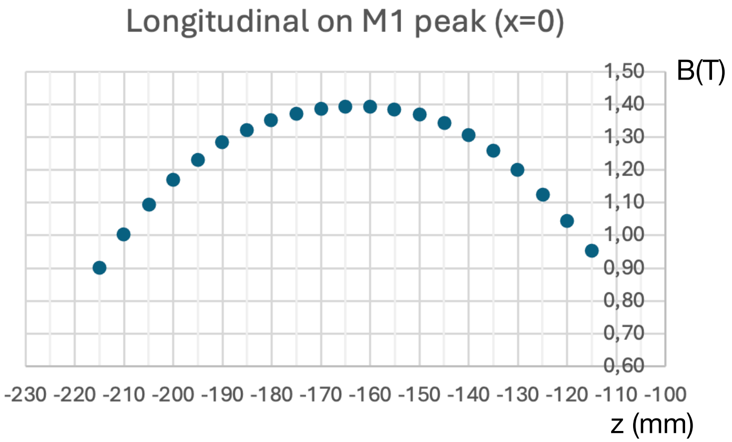
- SigmaPhi performed 5 sets of longitudinal scans, each one varying the x position:
  y = 0 mm;
  x = 0 mm, ±10 mm, ±19 mm;
  z from −600 mm to +600 mm with step Δz = 5 mm.

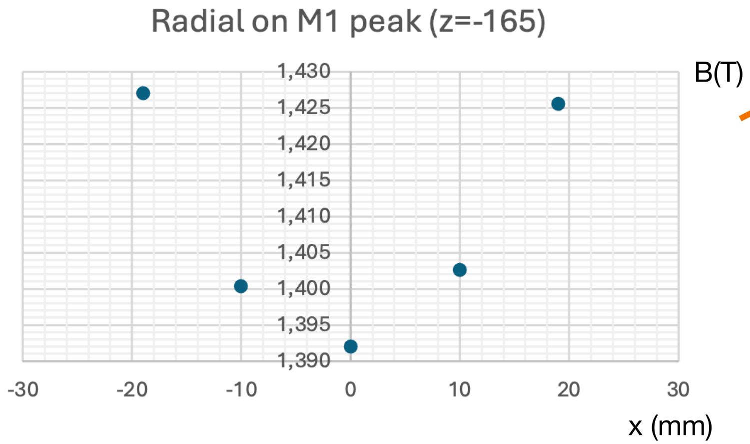


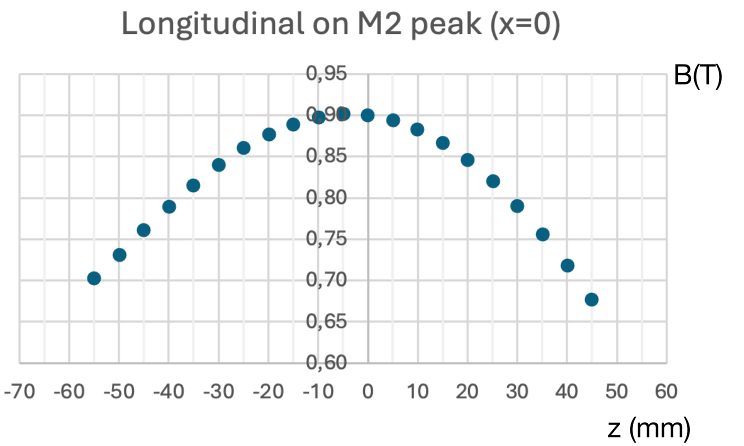
Parameters	Measured values
Nominal field (T) @Z=0mm (M2)	0,9009
Nominal field (T) @Z=-160mm (M1)	1,3920
Integrated field (T.mm)	322,3664
Good Field Region	Radius 19 mm
Transvers field homogeneity dB/B0 @Z=0mm (M2)	2,51E-02
Transvers field homogeneity dB/B0 @Z=-160mm (M1)	1,22E-02

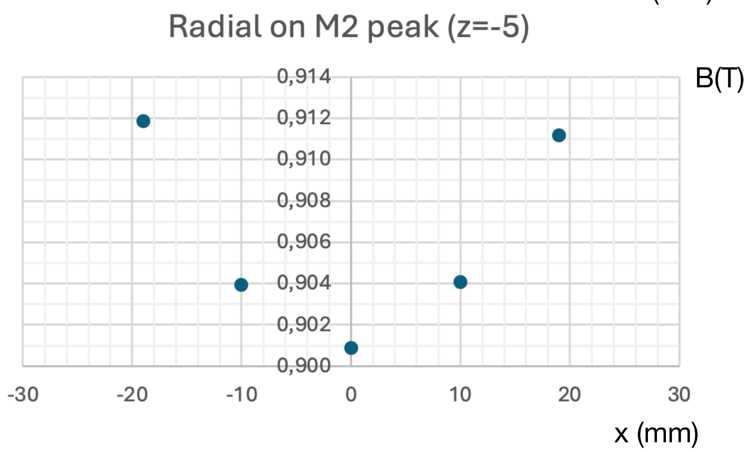
Measurements @ SigmaPhi

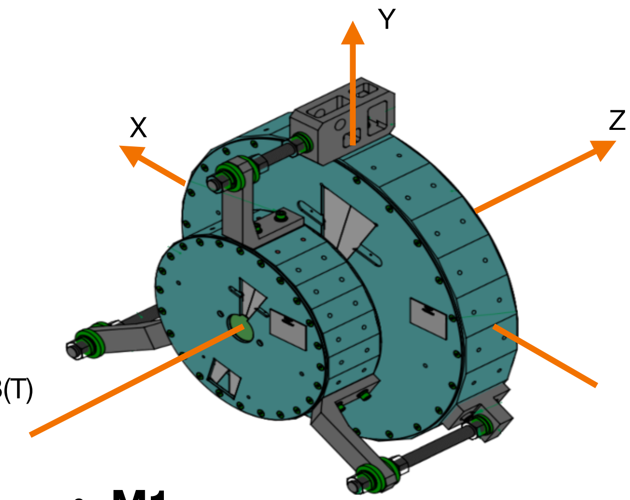
- No radial (along *x*) scans, but we can evaluate the alignment plotting the positions of the peaks measured during longitudinal scans at different *x*.











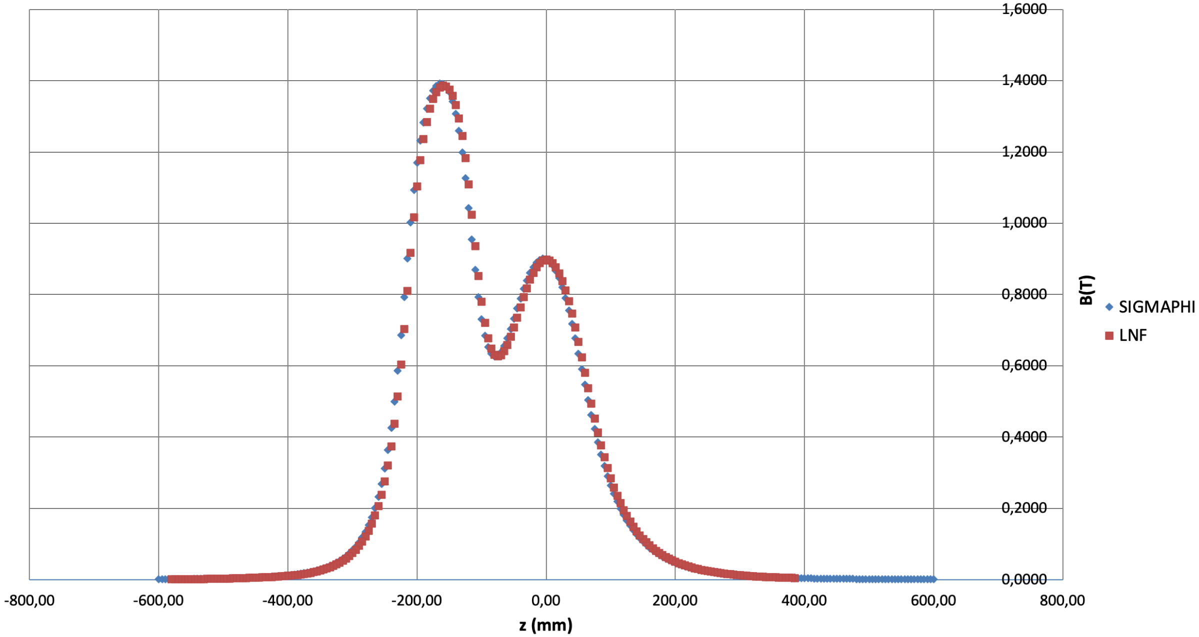
- **M1**
  B_y max: 1.3920 T
  @ *z*: −165 mm
  (parabolic fit: 1.4008 T @ −163.7 mm)

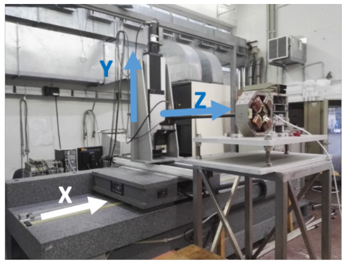
- **M2**
  B_y max: 0.9009 T
  @ *z*: −5 mm
  (parabolic fit: 0.8998 T @ −4.76 mm)

- Step quite large, not ideal to compare with the 3D model. Fitting not very accurate.

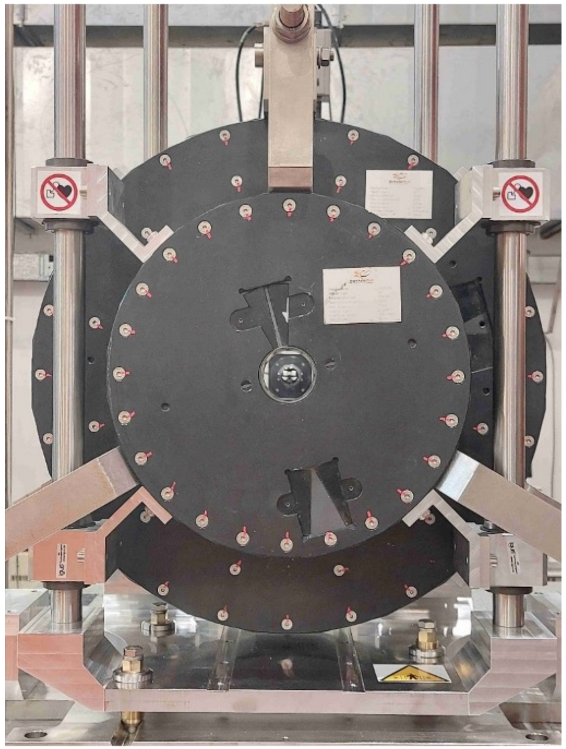
Measurements @ LNF

- Our measurements were performed with a 1D Hall probe on a 5 axis movement system on a granite bench.
- In order to have more flexibility, our measurements start on the magnet with the larger bore, i.e. M2, hence we have a different sign in the *x* and *z* axis w.r.t. SigmaPhi data.
- We are also centered on the point between the two dipoles, while SigmaPhi is at the center of M2.
- During alignment, a displacement of 1 mm has been detected between the mechanical axes of the two magnets.
- After inverting the *z* axis and reconstructing the origin of the reference frame, we compare the two data sets and find a good agreement, compatible with probes precision.



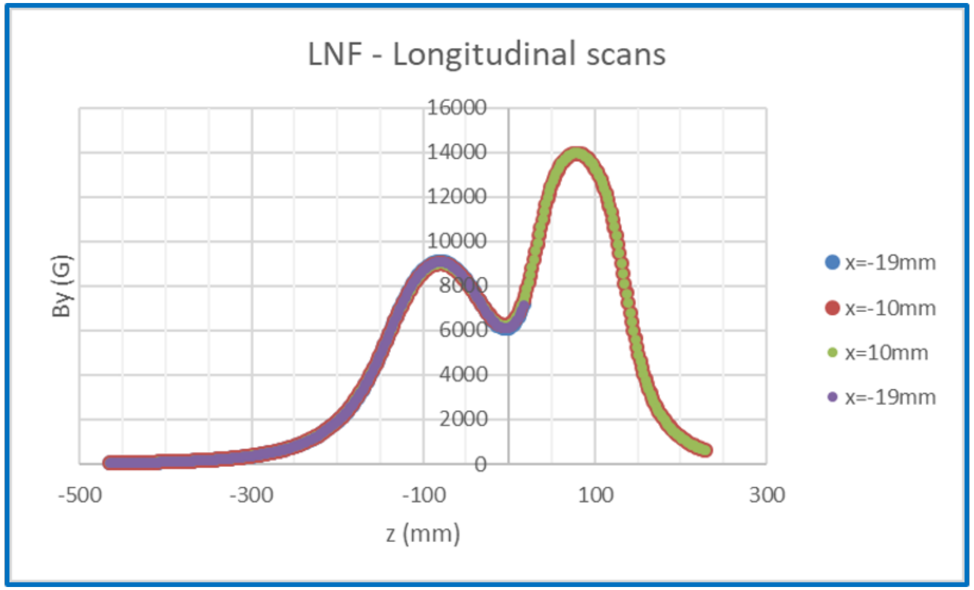


Current 5 axis Movement System



Measurements @ LNF

- After that, we performed further measurements (longitudinal all with step Δz = 2mm).
  - 2 radial scans around M1 and M2 peaks with Δx = 1 mm
  - 5 longitudinal scans with ***z* range = (—465; +499) mm**, ***x* = 0**, **±4 mm**, **±8 mm**
  - 2 longitudinal scans on **reduced *z* range = (—465; +299) mm**, ***x* = ±10 mm**
  - 2 longitudinal scans on **reduced *z* range = (—465; +17) mm**, ***x* = ±19 mm**
- All these measurements were used for comparison with SigmaPhi measurements (see presentation by L. Sabbatini @ previous meeting, 11/12/23, for details).

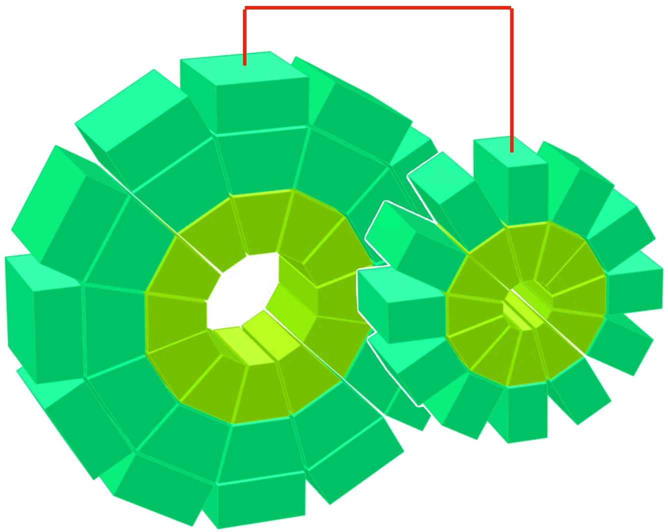


- A 3D model was built in order to run a simulation with OPERA, making a map of the magnetic field in the 3-dimensional space. Because the model was compared with the LNF data (more comprehensive than SigmaPhi), the *z* axis is again inverted (M2 comes before than M1).
- For following graphs, *z*=0 mm means the position between M1 and M2.
- (A new model with the right reference frame has already been developed for implementation in the original geometry).

3D model

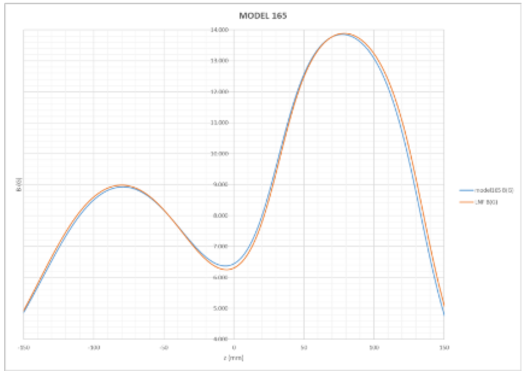
- The «as built» file provided by SigmaPhi is not updated to the latest version: the distance between the two magnets has not been modified according to the actual one (request for a distance between flanges increased to 55±1mm).
- Unfortunately, there are no measurements post-displacement, so we do not know for sure the distance between M1 and M2. The file has been adapted by modifying the position of the 2 magnets and varying the distance to identify the one that best reproduces data.
- Permanent magnets BH curves: N48H-Arnold-60, N38UH-Arnold-60.

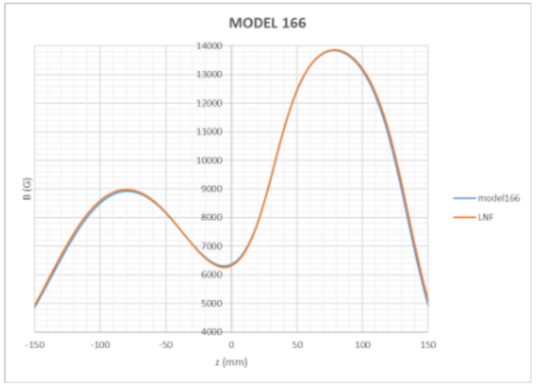
Distance between M1 and M2 centers:
165, 166, 167, 168 mm

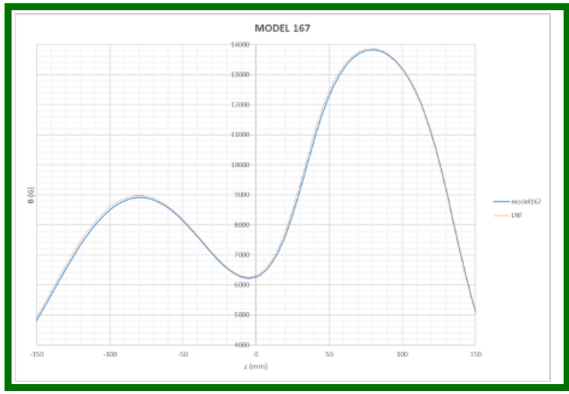


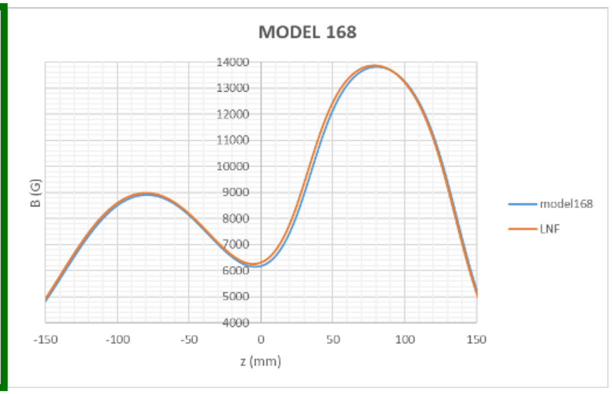
- First results show the comparison for longitudinal scans at *x* (and *y*) equal 0.
- **Disclaimer.** We have lots of sources of micro-uncertainties (radial misplacement, alignment of magnets, pitch angle, roll angle) which, at large distances, may contribute to large relative errors.
- We focus on the validation of the field in the area at the centers of the magnets and in the space between them.

3D model: Varying M1-M2 distance (*x*=0)

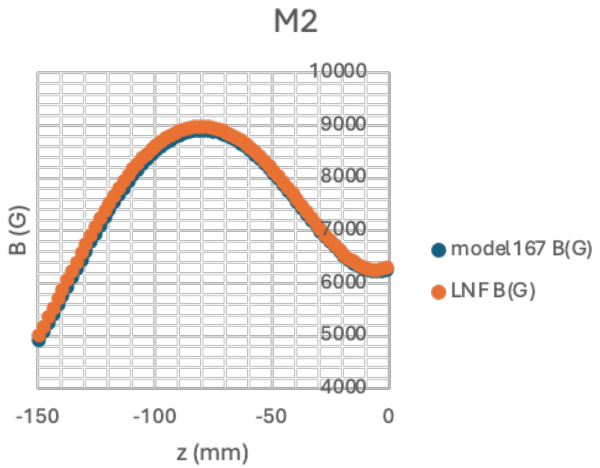


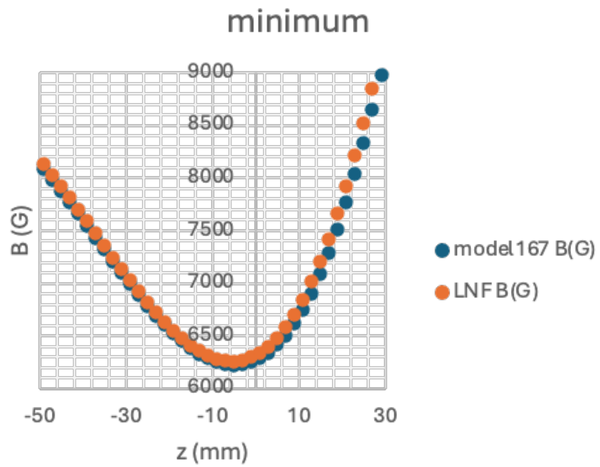


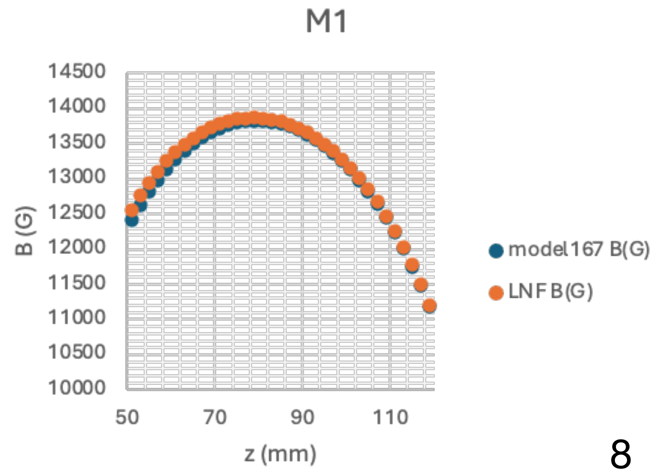




Analysis of the features of key points: the two maximum and the center of the system

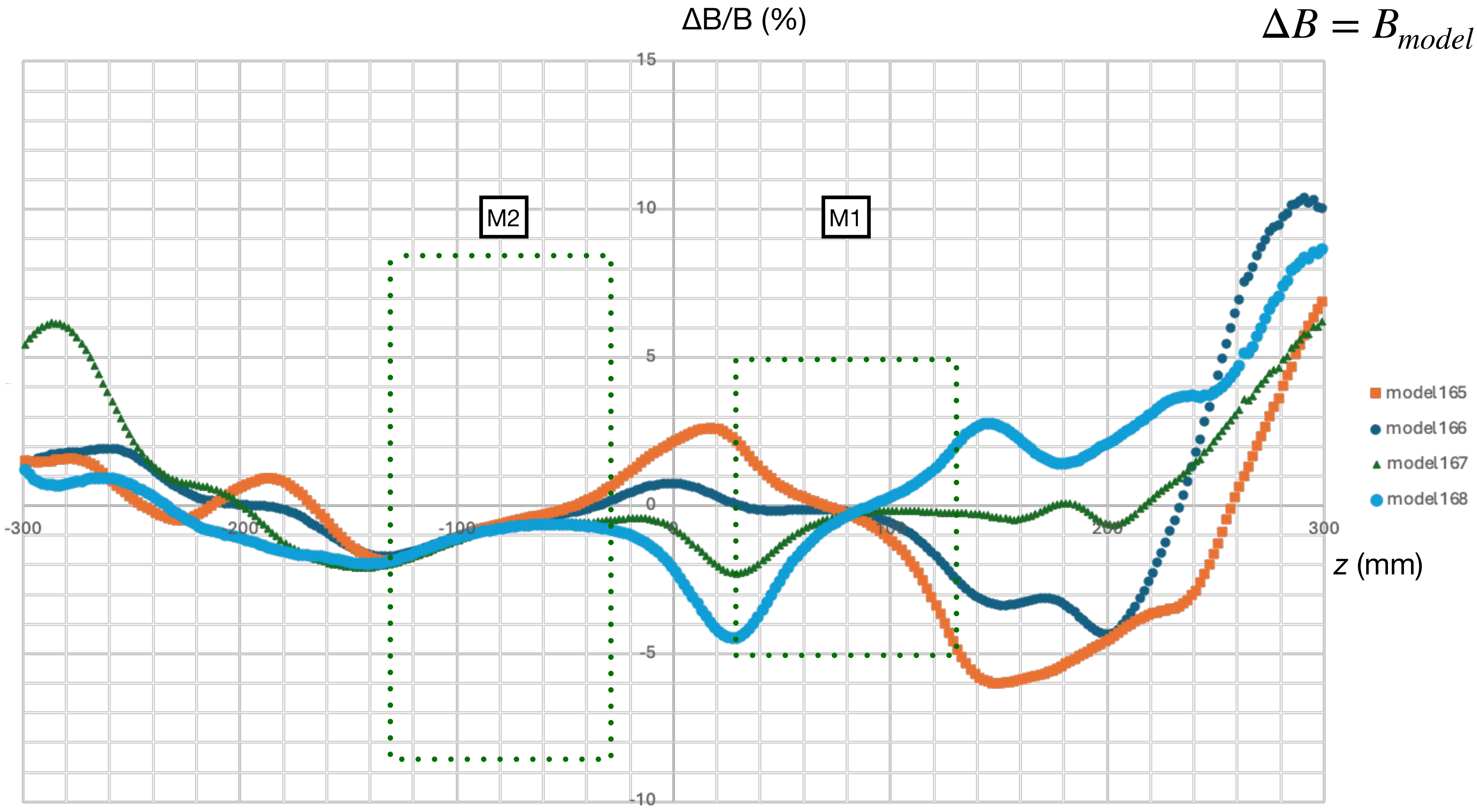






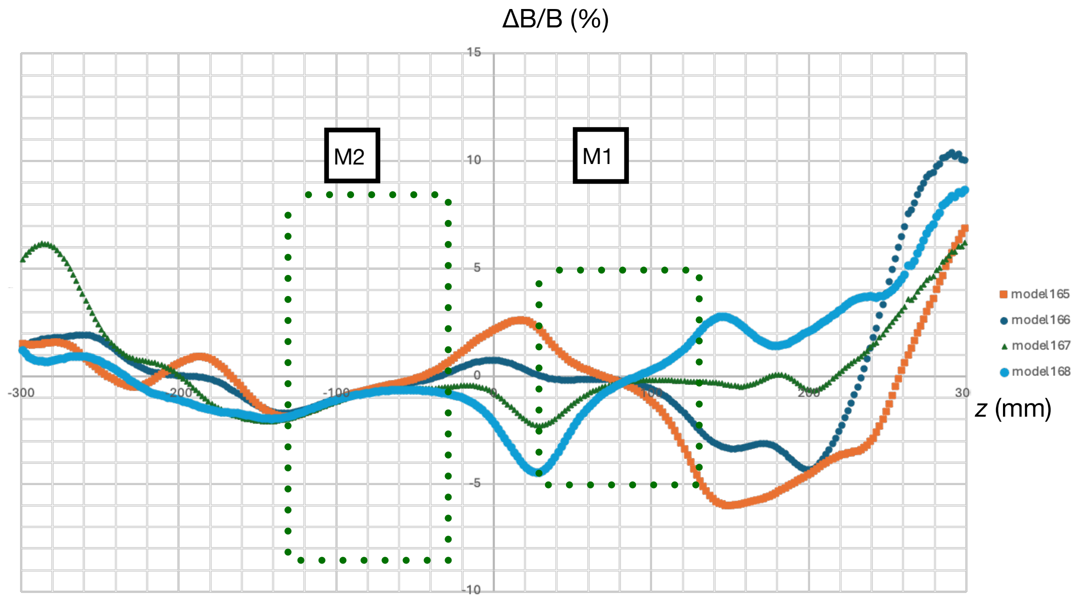
3D model: Varying M1-M2 distance (*x*=0)

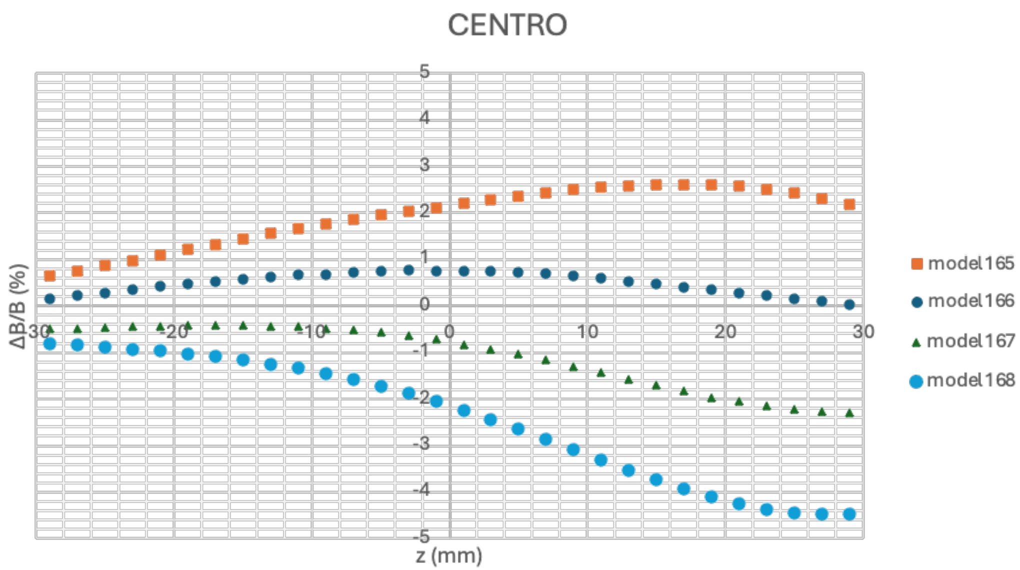
$$\Delta B = B_{model} - B$$



3D model: Varying M1-M2 distance (x=0)

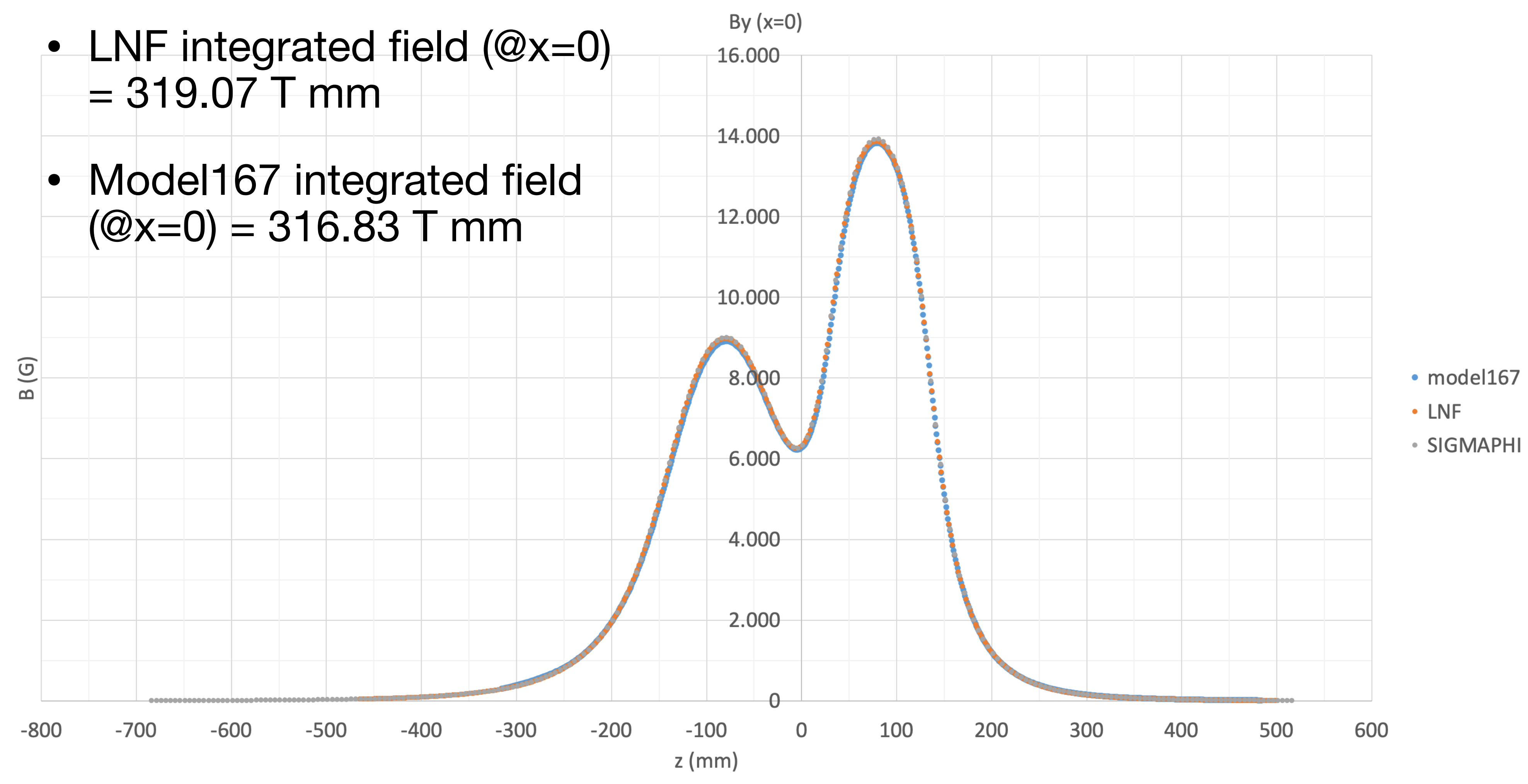
- From a first analysis, the model at 166 mm and 167 mm distance give the best results at the center of the two magnets (<1% or relative error).
- The 167 mm model shows also lower relative error at larger distances, so we keep this model for comparison with longitudinal scans at different *x* positions.



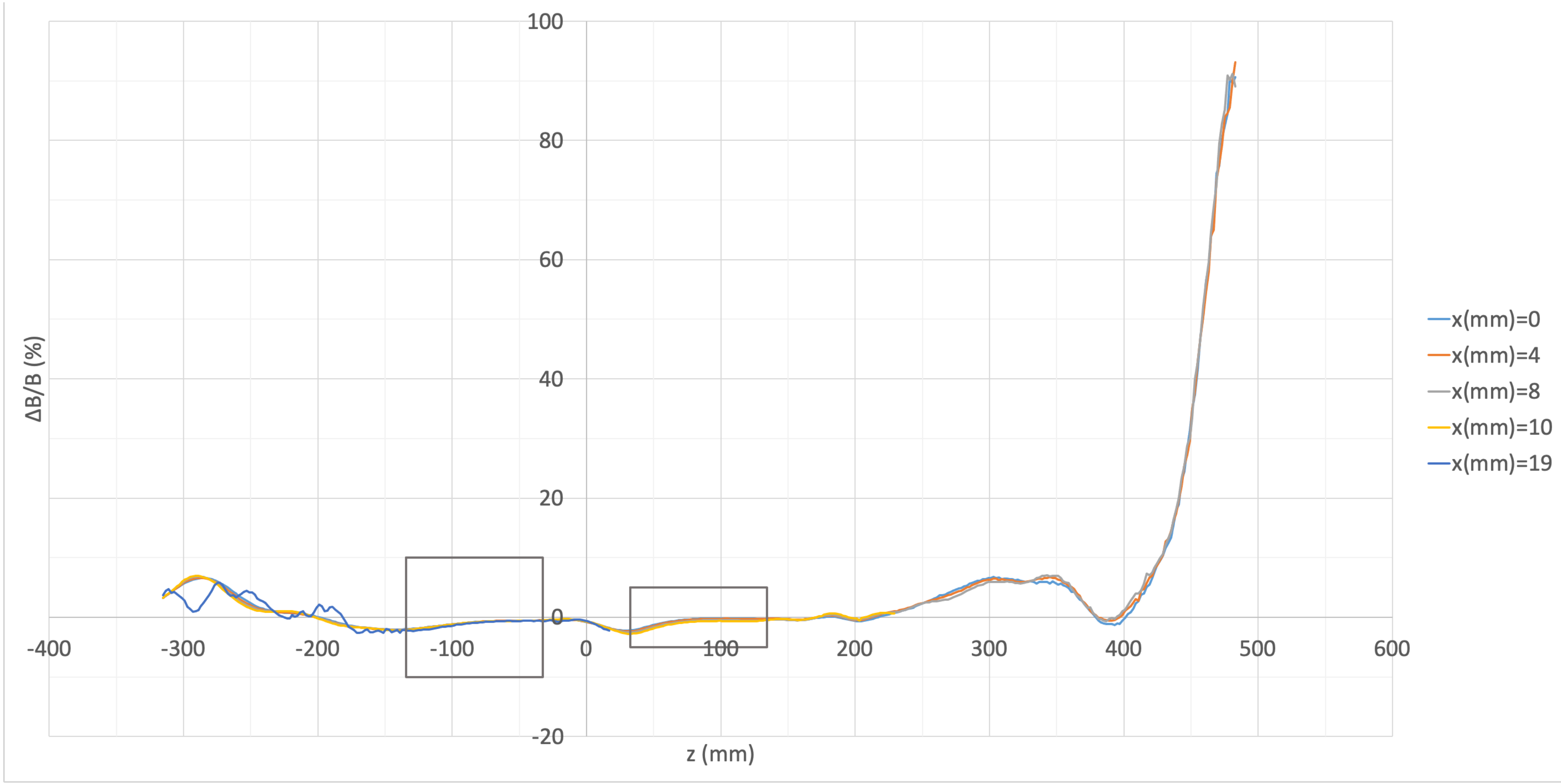


3D model: 167 mm distance

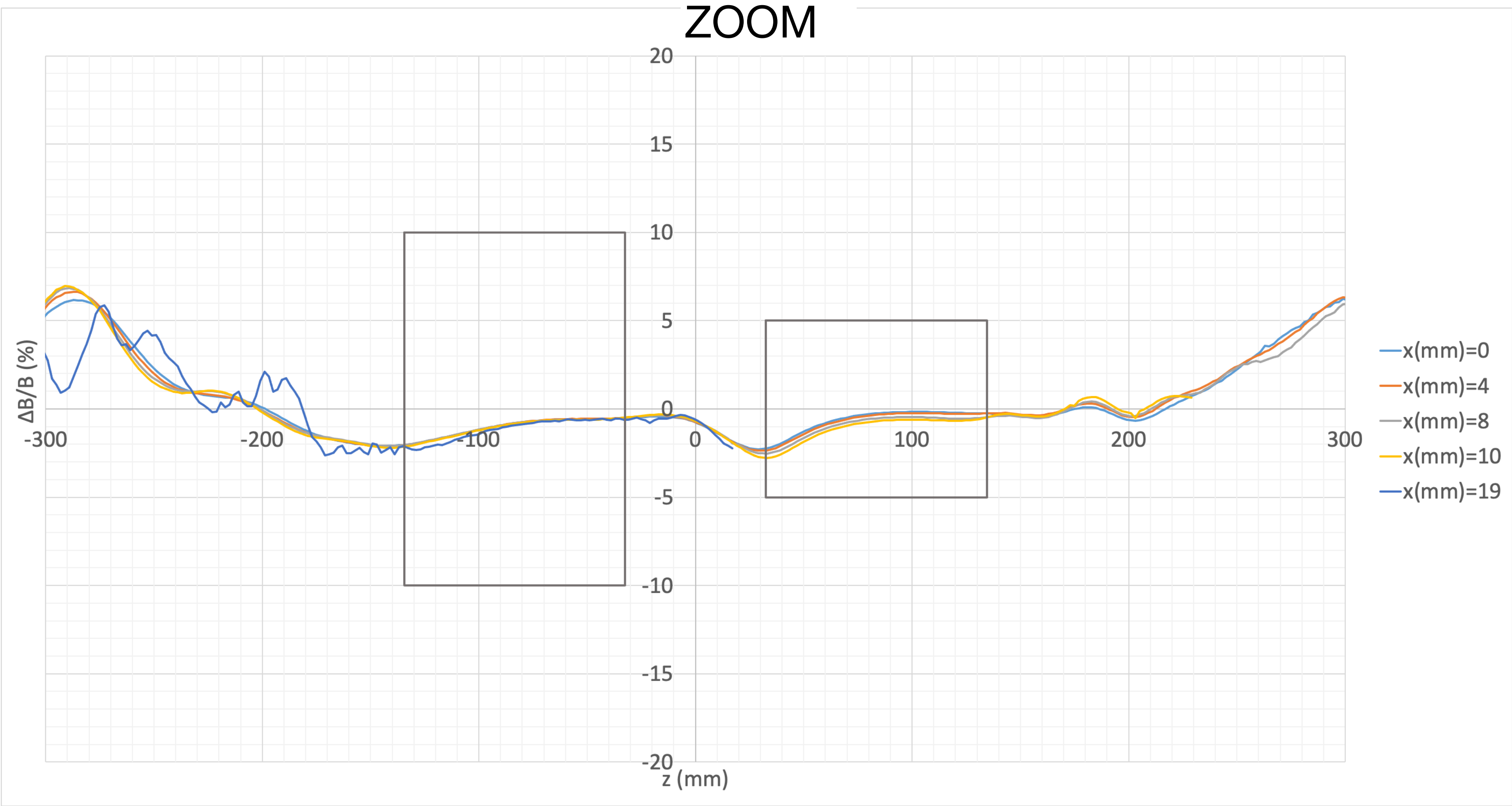
- LNF integrated field (@x=0) = 319.07 T mm
- Model167 integrated field (@x=0) = 316.83 T mm



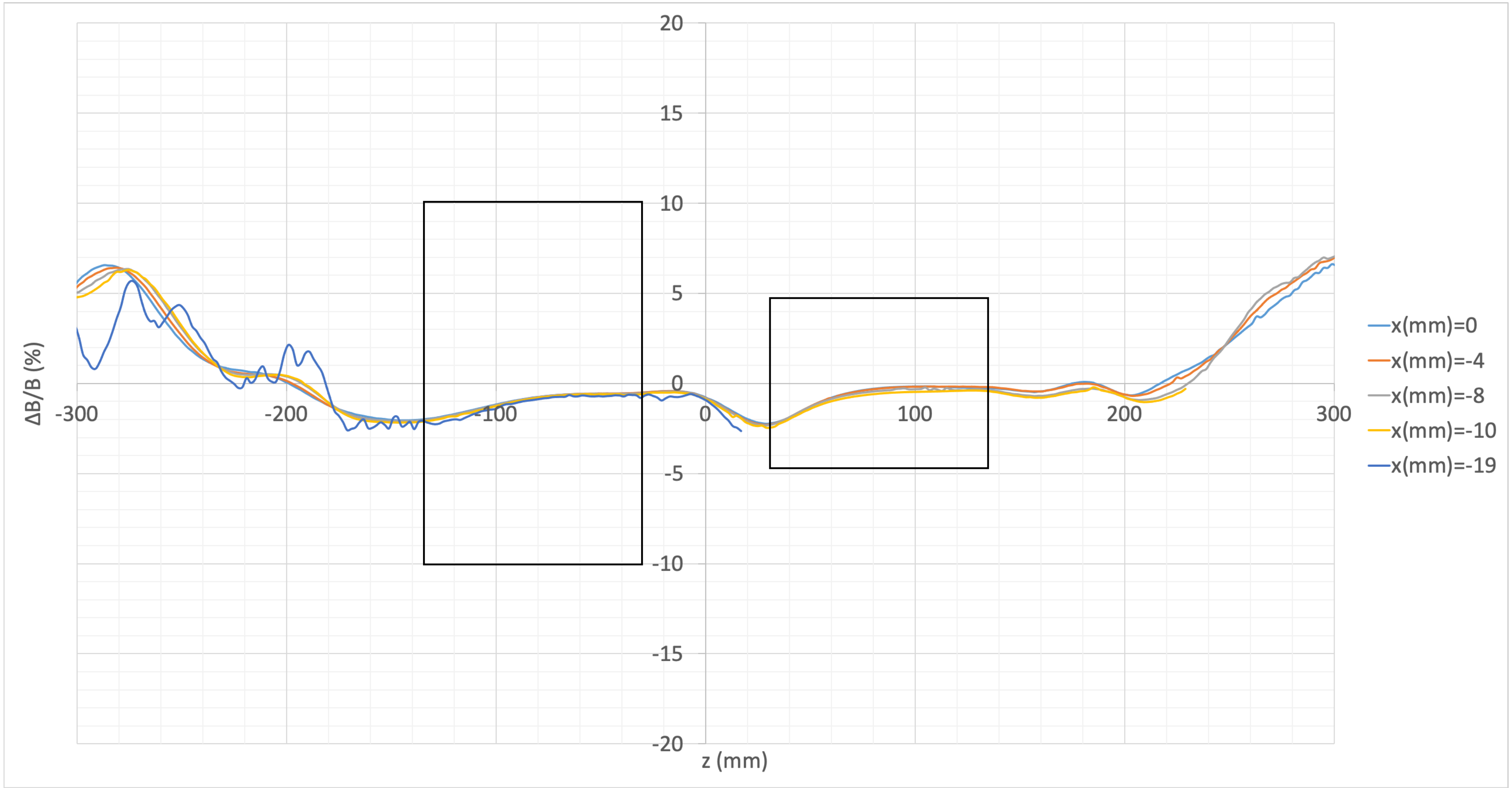
Comparison of «167» with long. scans at different *x*



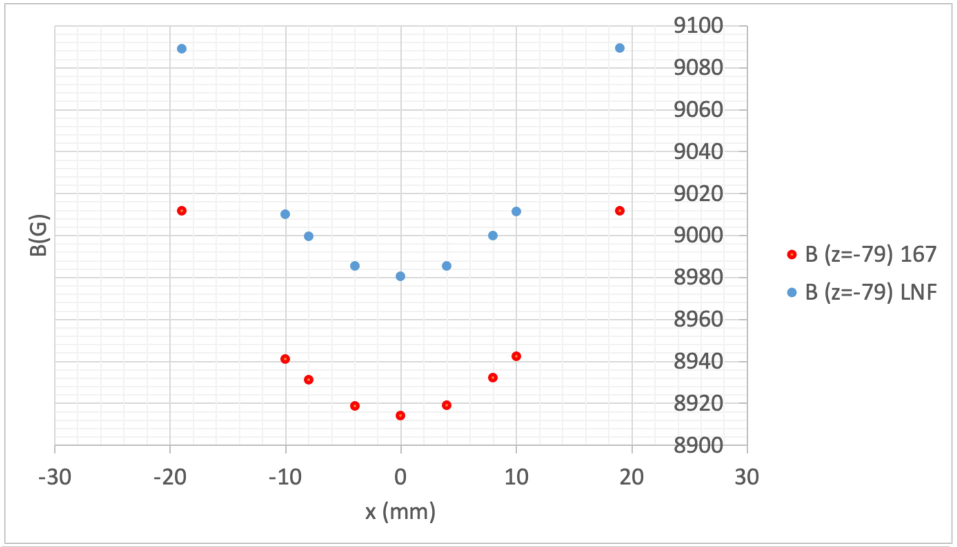
Comparison of «167» with long. scans at different *x*

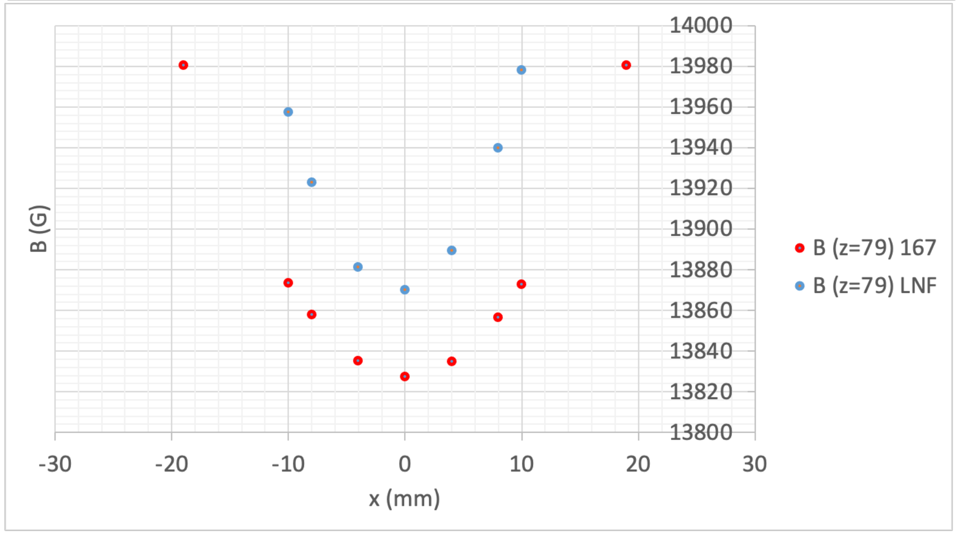


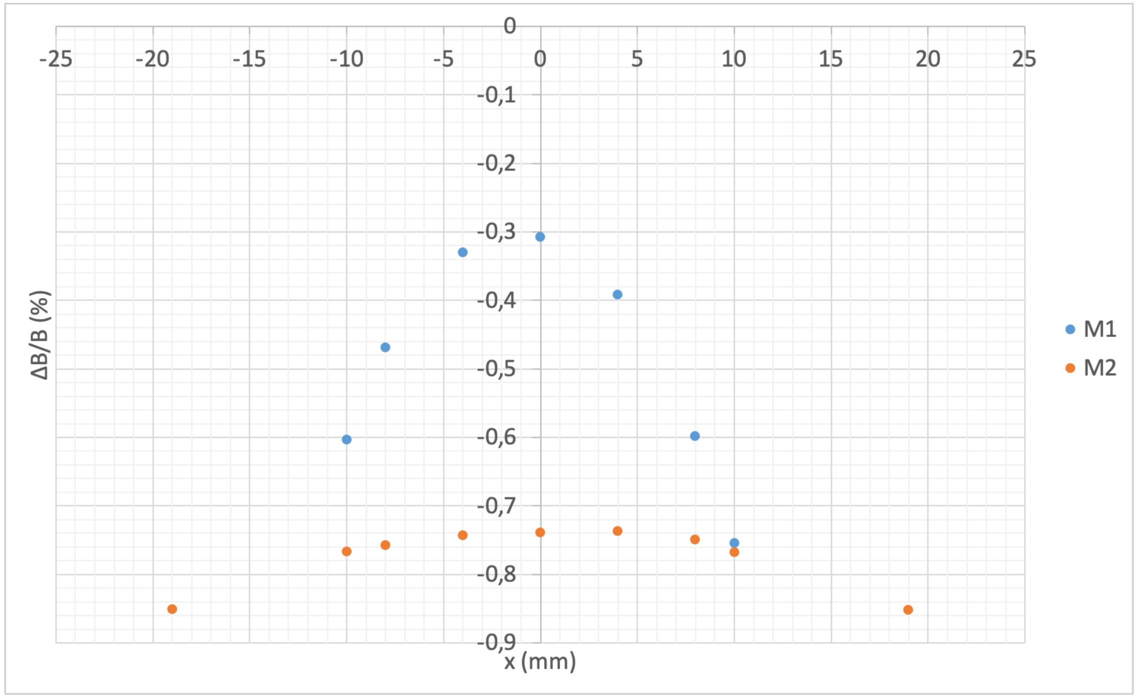
Comparison of «167» with long. scans at different *x*



Comparison of «167» with radial measurements

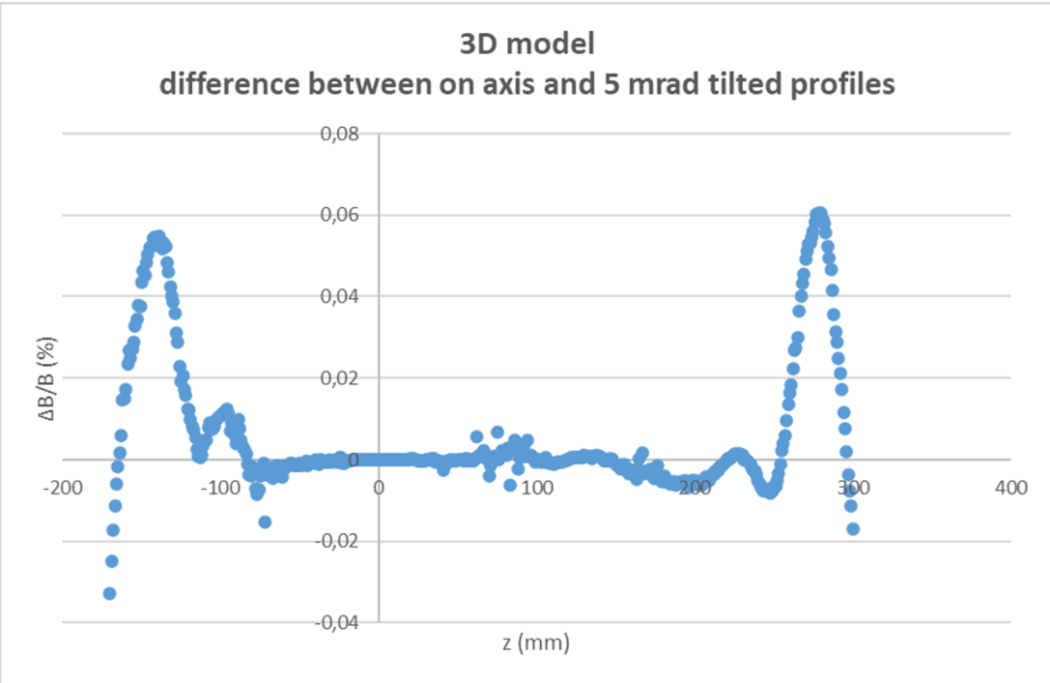


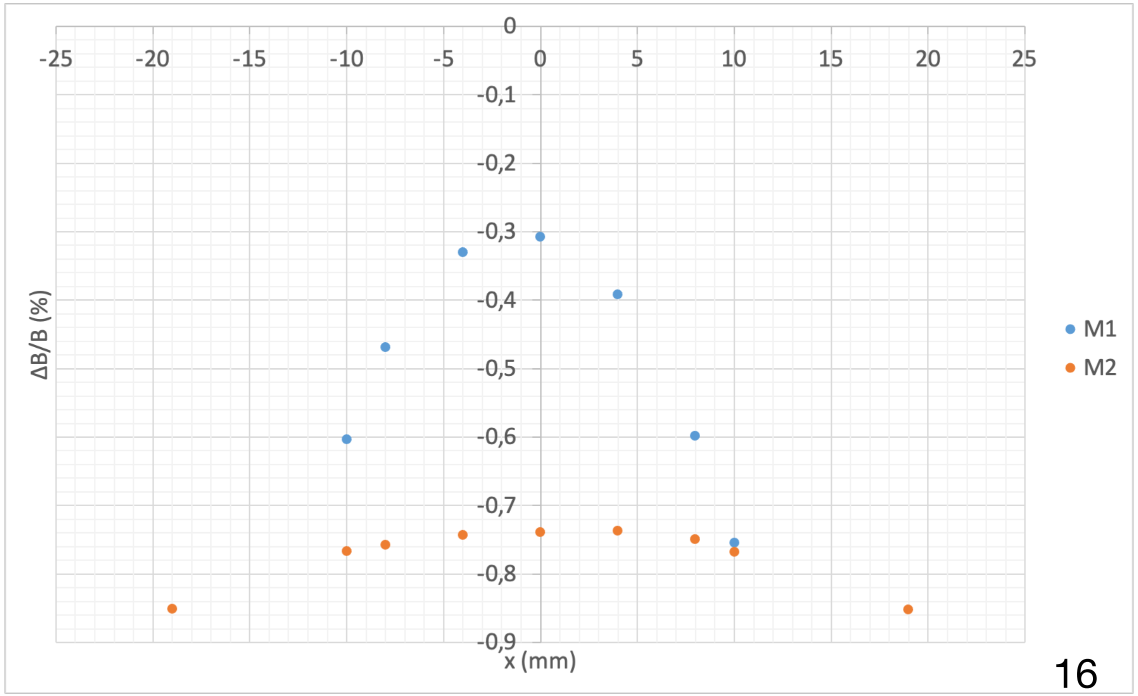




Possible sources of errors and geometry effects

- Tests have been performed introducing an initial angle between the axes of the magnets. Up to 5 mrad: neglectable.
- Comparison with radial measurements show no significant influence from an initial tilt in the alignment of the magnets.





Conclusions

- Comparison between 3D model and measurements at LNF gave encouraging results. The relative error in the region where the magnetic field is more intense is below 2%, with no significant variation between data sets taken at different transverse positions.
- The new geometry is ready. We will perform some routine validation and then produce a file with the complete mapping of the magnetic field.

		x=-19mm	x=-10mm	x=0mm	x=10mm	x=19mm
M1	B_{max} SigmaPhi (G)	14269	14004	13920	14026	14256
	B_{max} LNF (G)	---	13954	13867	13974	---
	Δ (%)	---	**0,36**	**0,38**	**0,37**	---
	Homogeneity SP (%)	2,51	0,60		0,76	2,41
	Homogeneity LNF (%)	---	**0,63**		**0,77**	---
M2	B_{max} SigmaPhi (G)	9119	9039	9009	9041	9112
	B_{max} LNF (G)	9089	9011	8981	9012	9090
	Δ (%)	**0,33**	**0,31**	**0,31**	**0,32**	**0,24**
	Homogeneity SP (%)	1,22	0,33		0,36	1,14
	Homogeneity LNF (%)	**1,21**	**0,34**		**0,35**	**1,22**
min	By SigmaPhi (G)	6106	6223	6265	6216	6102
	By LNF (G)	6112	6223	6262	6214	6096
	Δ (%)	**-0,10**	**0,01**	**0,05**	**0,03**	**0,11**
Int.	SigmaPhi (T mm)	324,83	322,94	322,37	323,20	324,69
	SigmaPhi (T mm)	*152,23*	319,39	321,99	319,67	*152,21*
	LNF (T mm)	*151,16*	318,33	320,95	318,52	*151,09*
	Δ (%)	*0,70*	**0,33**	**0,32**	**0,36**	*0,74*