Magnetic measurements of ITER TF Coils: status & perspective

Marco Buzio (CERN), Philippe Lerch (PSI)

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Perspective

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Introduction

- Project started Feb 2011 (first exploratory meeting at CERN)

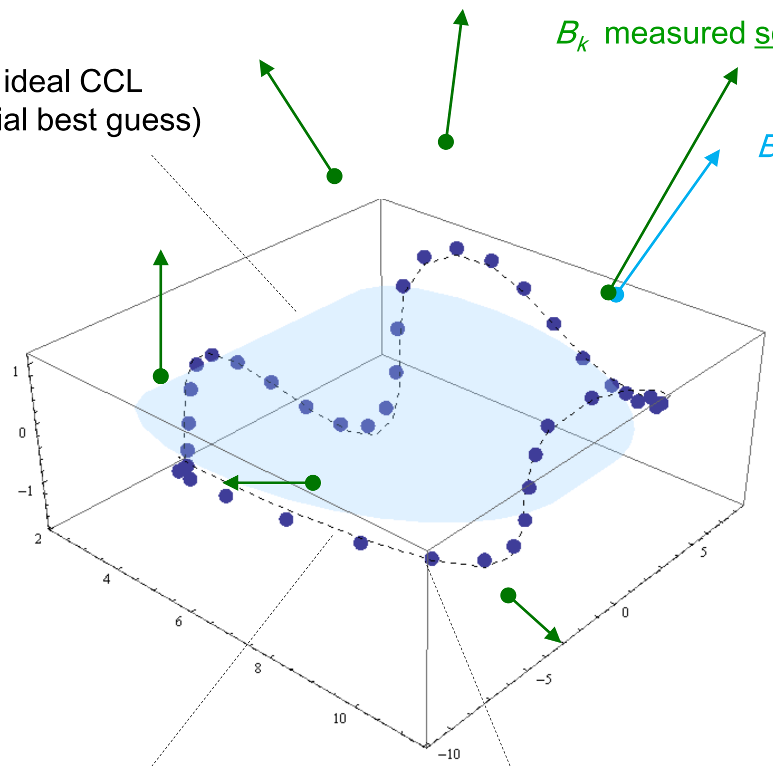
- **PSI**: project holder
  Contract ITER D 4HBLS3

  Contractual responsibilities: design and production of the instrument hardware & software, characterization, testing (mock-ups and full-scale)
  Actors: Philippe Lerch, Alexander Gabard, Stephane Sanfilippo

- **CERN**: consultancy
  CERN – ITER Agreement 13, 15, 19 and 21 (Task 3)

  Responsibilities: definition of test methods, calibration of components using CERN facilities, CCL shape reconstruction
  Actors: Laurent Deniau (2011), Marco Buzio, Naim Bruti (mechanics)

- Field measurement method: **AC TF coil excitation + fixed-coil fluxmeter**
- Strong points: synchronous AC detection, linear sensor of size commensurate to target
- Concern: impact of eddy currents
- CCL reconstruction method: modal representation of the deformation + iterative weighted least-squares minimization to match measurements and Biot-Savart computation



$$\boldsymbol{B}^{comp}(\boldsymbol{P}_k, \boldsymbol{\delta}) = \frac{\mu_0}{4\pi} \iiint_{\mathcal{V}} \frac{\boldsymbol{J}(\boldsymbol{r}') \times (\boldsymbol{P}_k - \boldsymbol{r}')}{|\boldsymbol{P}_k - \boldsymbol{r}'|^3} d\mathcal{V}'$$

objective function

$$\chi^2(\boldsymbol{\delta}) = \sum_{k=1}^{M} \frac{\left(B_k^{comp}(\boldsymbol{\delta}) - B_k\right)^2}{{\sigma_{B,k}}^2}$$

$$\sqrt{\frac{\chi^2(\boldsymbol{\delta}_{min})}{M - N}}$$

normalized objective function
(expected value ~1 at the minimum)

Summary of DPP results

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Initial configuration

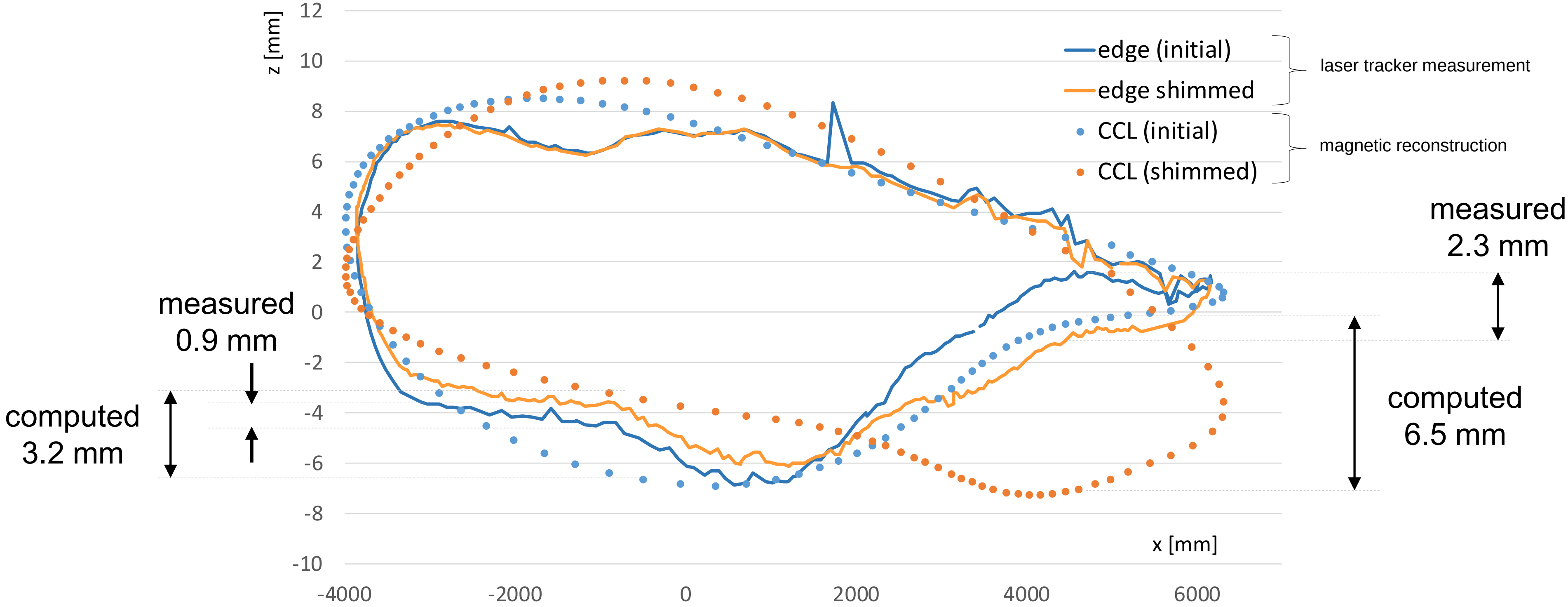
- First full-scale test with early prototype system at ASG La Spezia, Apr 2015
- AC excitation 55 A at 0.3, 0.5, 0.8 and 1.2 Hz
- Low max. levels: **0.7 mT** field and **5 mV** output coil voltage
- 780 measurement points at 15 azimuthal stations

Shimmed configuration

- Test repeated with wooden added shims to all 15 support blocks
- 11 × 19 mm + 2 × 17 mm + 2 × 15 mm shims to induce (gently) sag in the straight leg
- Shape of the top inner edge measured with laser tracker in both configurations

DPP results

- First results presented Nov. 2015 showed ~2 mm agreement (in the vertical coordinate *z*) between edge measurement and CCL reconstruction (initial configuration at 0.3 Hz)
- Analysis of the shimmed configuration was put on hold due to other priorities
- Latest results: **rough agreement between the shimmed and initial CCL, extrapolated at DC, and the respective edge surveys** (vertical mismatch 2~4 mm, radial comparison pending)
- Promising result despite unfavorable conditions: <u>both magnetic and geometric measurements see the same deformation</u>



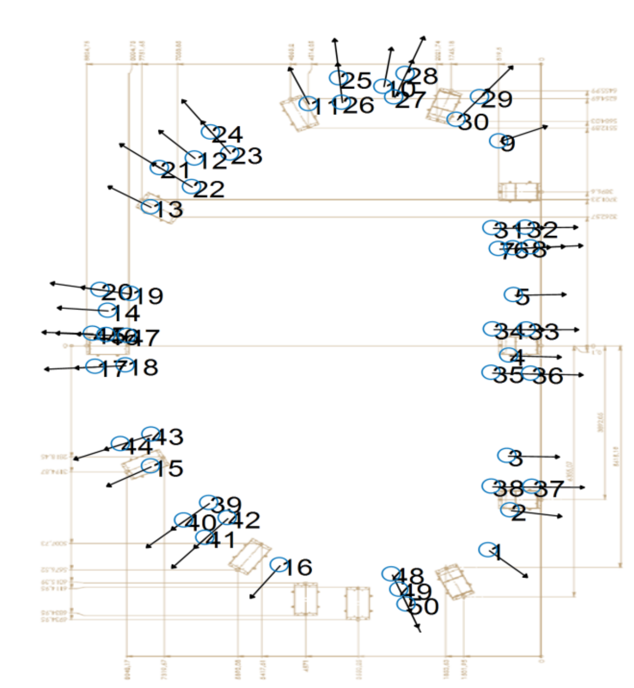
23 mm vertical offset subtracted from the figure (= 19 mm shims + pad thickness + uncertainty)

Summary of WP11 results

WP11 test summary

Acknowledgement: **thanks to ASG and F4E personnel for collaboration and support**

- Test duration: 7 days, about **140 h** total man-hours
- AC excitation 35-38 A at 0.10, 0.15 and 0.30 Hz (140 W dissipation max)
- Effective magnetic measurement duration: **50 × 5 min** ≈ 17% duty cycle → there's room for more data !
- 50 azimuthal stations (30 clusters), 48 simultaneous × 5 consecutive repetitions
- Reference fiducial network: 21 targets on WP + 14 on the floor/walls

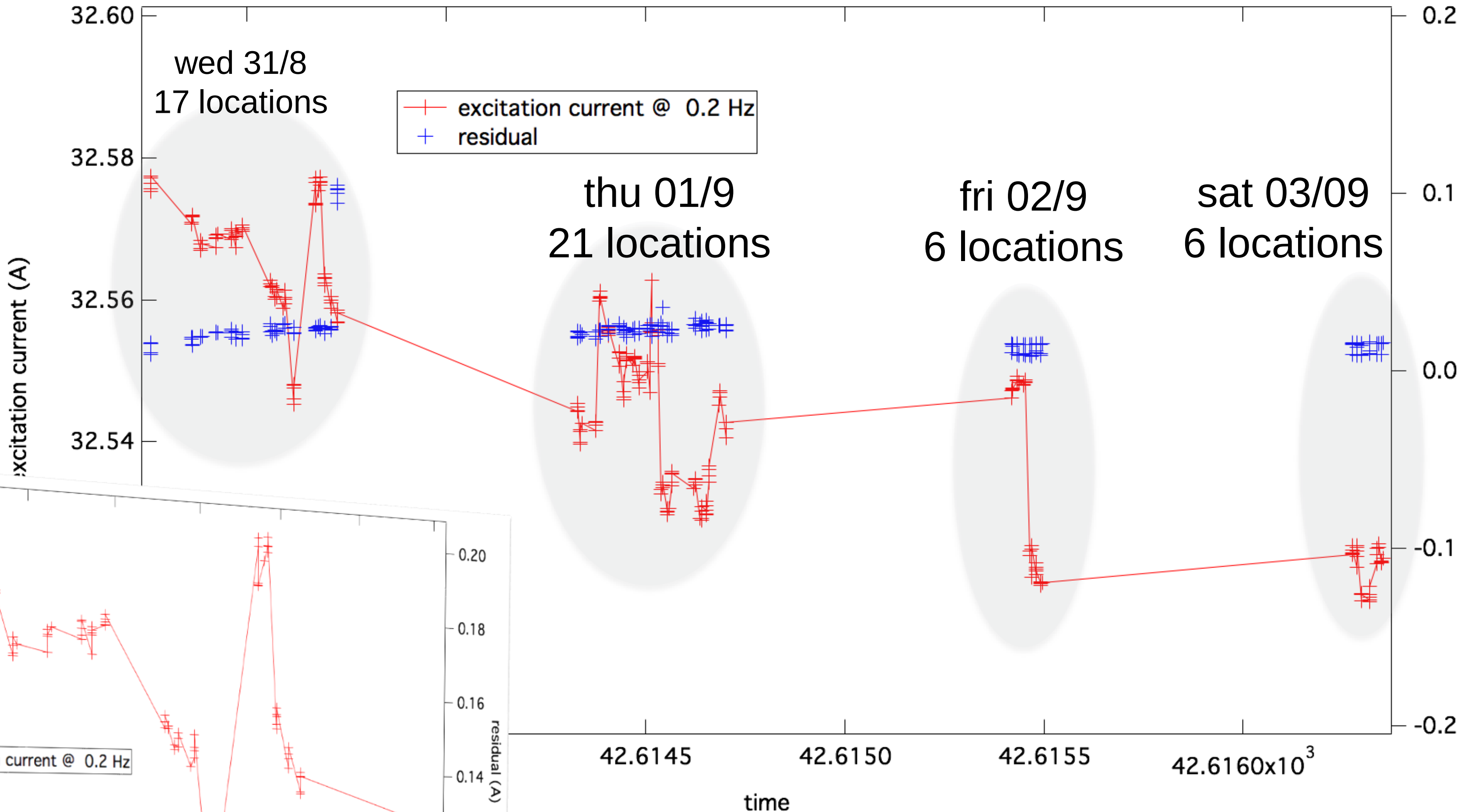


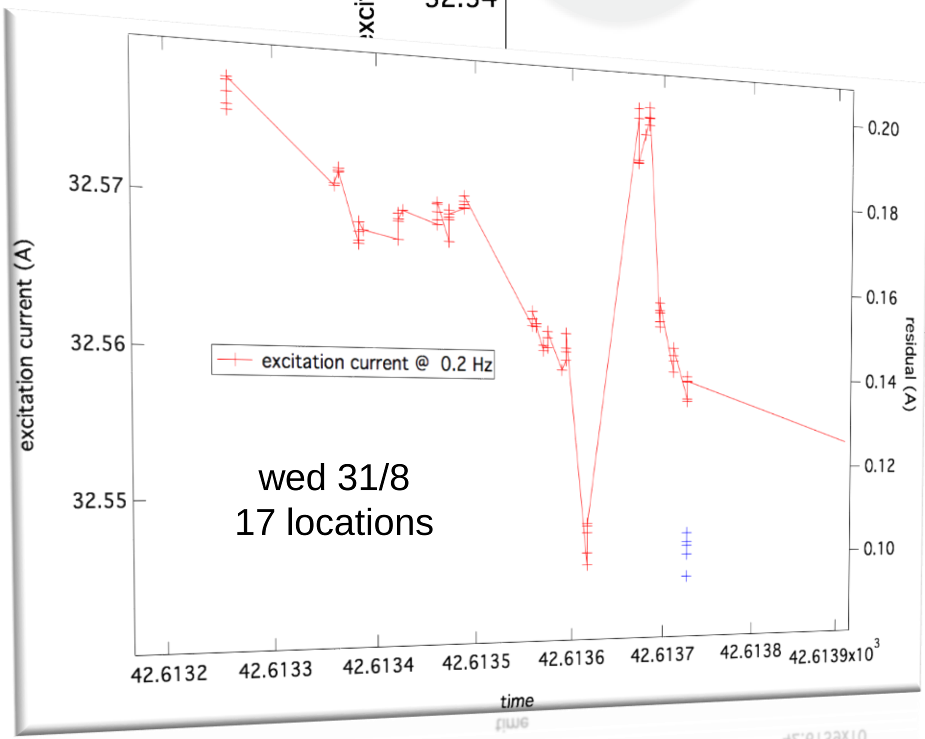
Azimuthal measurement stations grouped
in clusters of 1, 2 or 3 radially shifted positions
(not ideal w.r.t. Fourier analysis of the deformed shape)

Schedule breakdown

Day	Activity	Man-hours	Notes
Mon 29/8	Measurement system unloading and assembling Reference network setup, geometric survey Organization of the test schedule	2 × 12	
Tue 30/8	Hardware setup and verification DAQ calibration vs. frequency	2 × 12	Power supply instability
Wed 31/8	Test run – 17 × stations (1~17) DAQ calibration	2 × 12	some ASG co-activity (brazing at interconnectic
Thu 01/9	Test run – 21 × stations (18~38)	2 × 12	some ASG co-activity
Fri 02/9	Test run – 6 × stations (39~44) Geometric PCB calibration	2 × 12	some ASG co-activity
Sat 03/9	Test run – 6 × stations (45 ~ 50) Geometric PCB calibration System packing and loading	2 × 8	
Sun 04/9	Data file preparation and verification	2 × 4	
Mon 05/9	Discussion of measurement technique with A. Barutti at ASG Genova		

WP11 test timeline





- Average of 1h30 per station
- Includes: moving the system, laser tracker survey of instrument and reference network, saving and copying data files, calibration checks

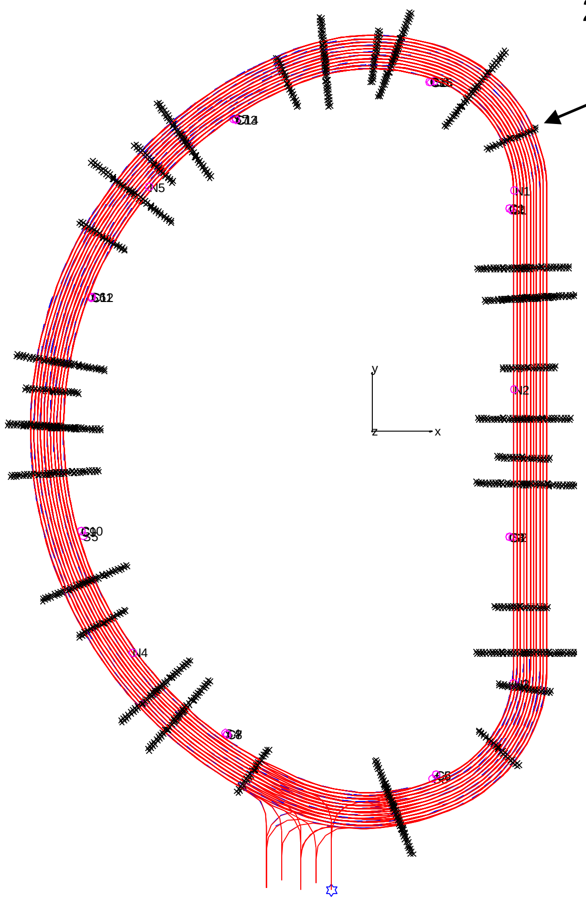
Measurement point locations

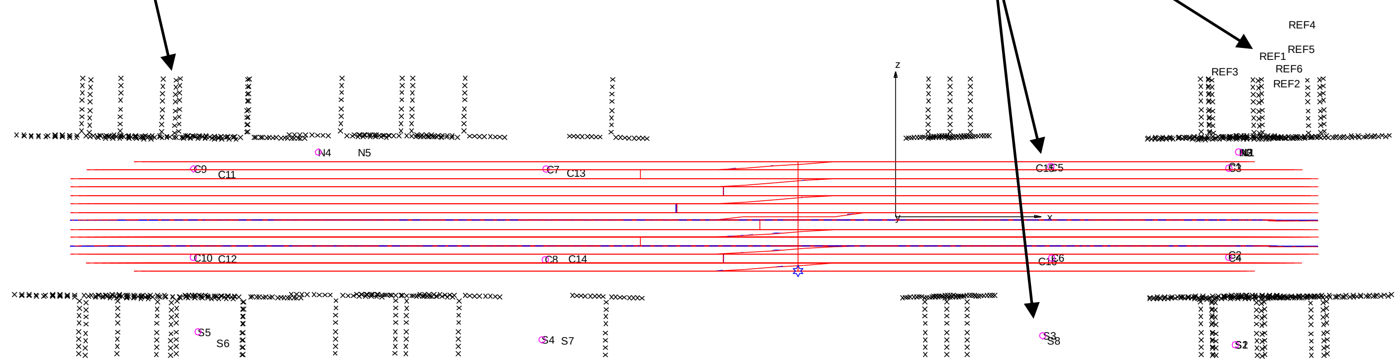
top view

side view

2400 measurement points

reference network fiducials

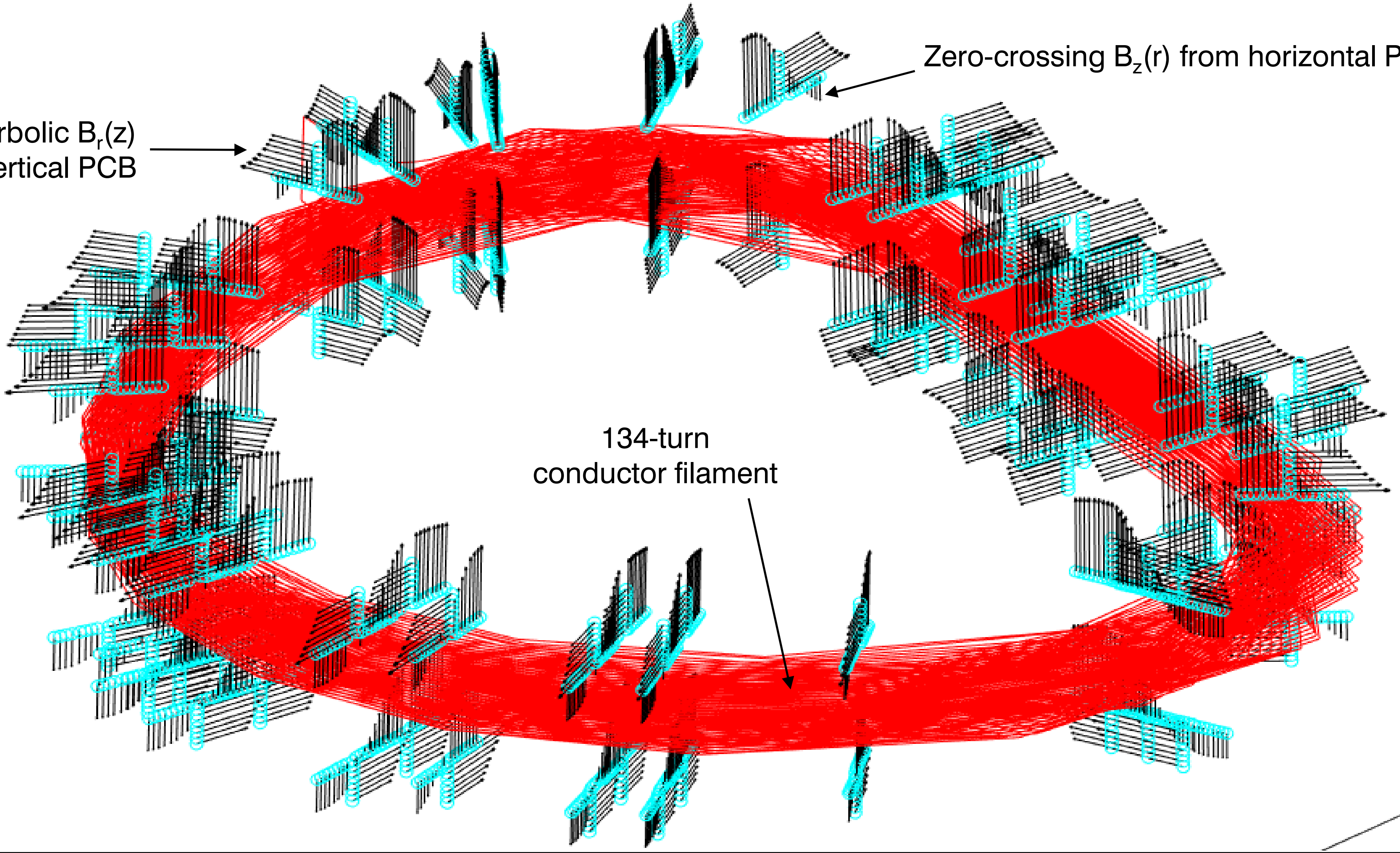




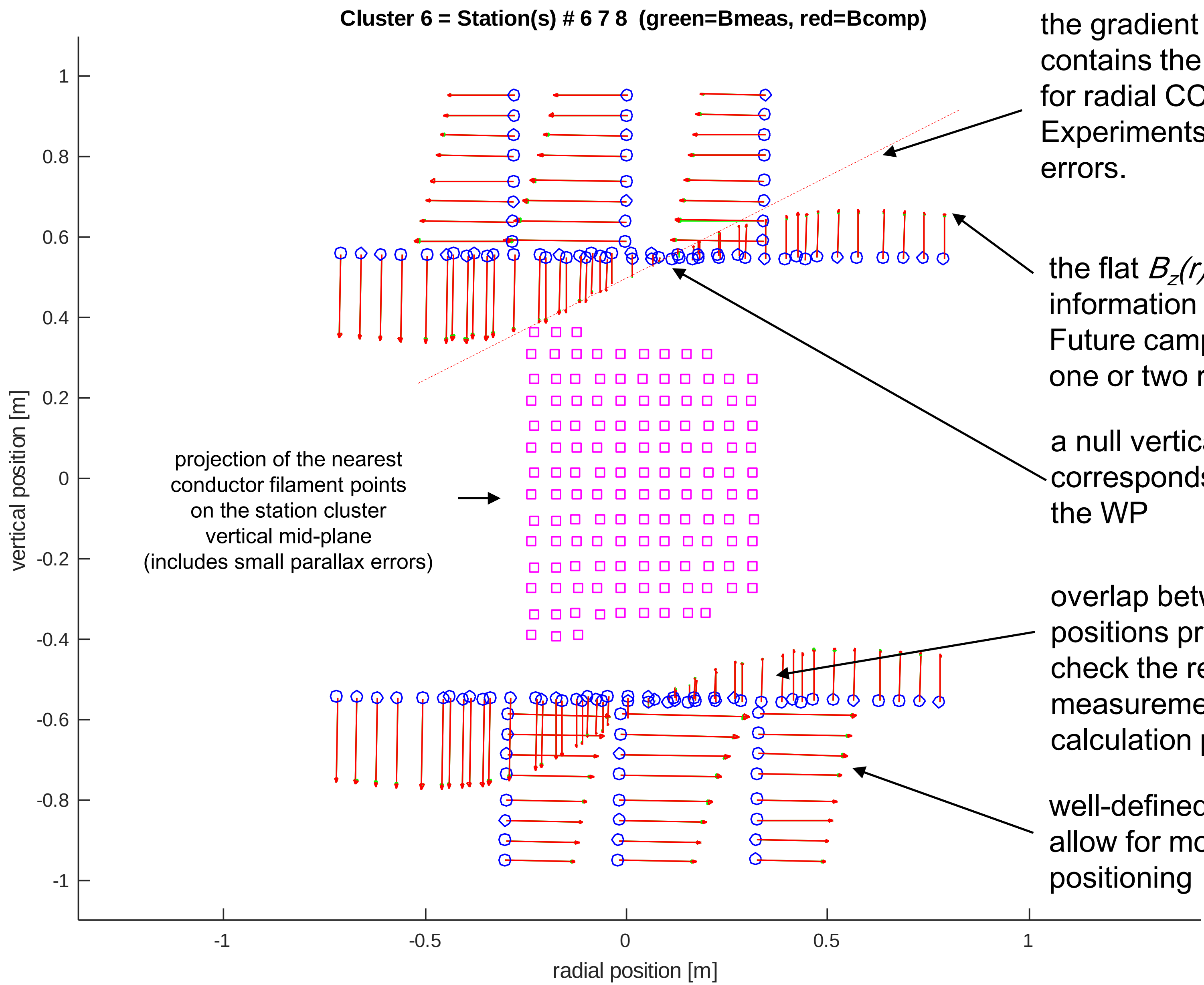
first point of the conductor filament
(origin of the azimuth θ)

Field map

- **7200** data points @ 35~38 A = 48 pick-up coils × 50 stations × (0.1, 0.15 and 0.2 Hz)
- Max. measured field: **1640 μT** (radial), 1360 μT (vertical)
- Max. measured gradient: 2.7 μT/mm (radial), **3.4 μT/mm** (vertical)



Local field map example



the gradient at the zero-crossing contains the information necessary for radial CCL positioning. Experiments show there large relative errors.

the flat $B_z(r)$ profile contains no useful information for the radial positioning. Future campaigns should be limited to one or two radially shifted stations

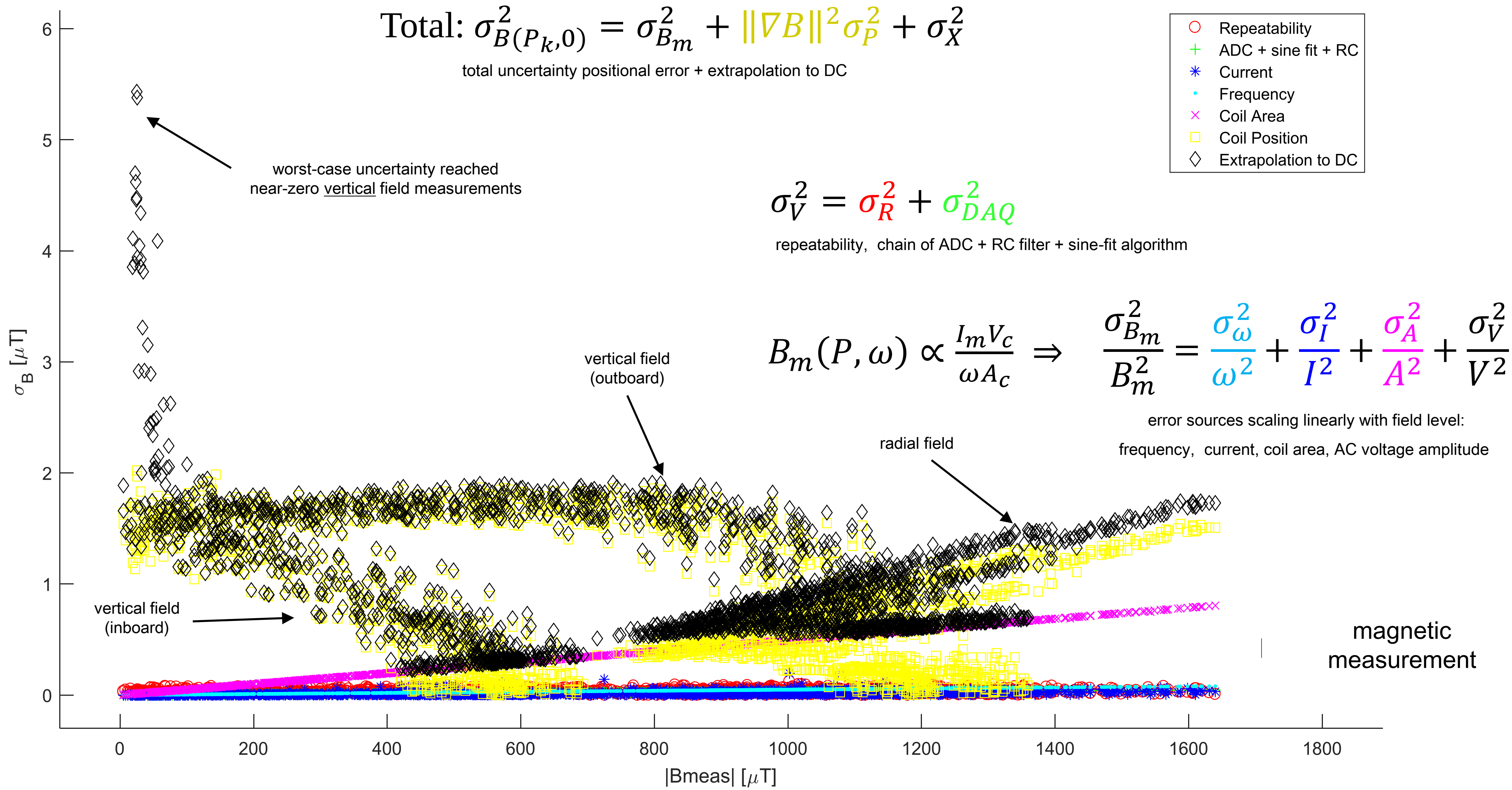
a null vertical field component corresponds roughly to the center of the WP

overlap between radially shifted positions provides the opportunity to check the repeatability of the measurement (interpolation needed, calculation pending)

well-defined hyperbolic *Br(z)* profiles allow for more precise vertical CCL positioning

Measurement uncertainty

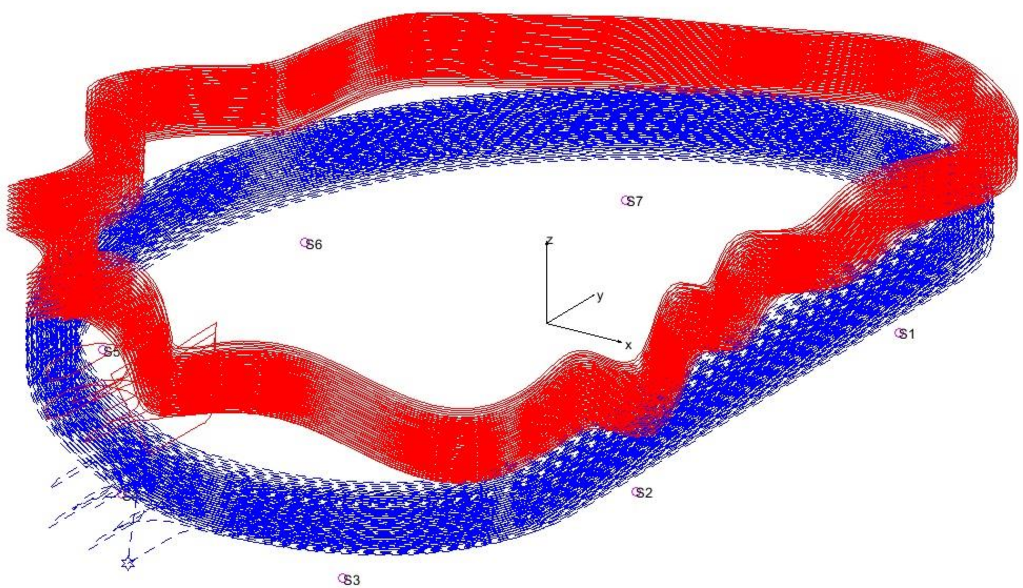
- Uncertainty of the magnetic measurement alone **< 0.5 μT** (~3·10^{-4} of full range, all frequencies)
- Estimated total measurement uncertainty generally ≤ 2 μT (~10^{-3} of full scale)
- Dominant terms: coil position error (0.8 mm RMS), coil area (5.5·10^{-4})



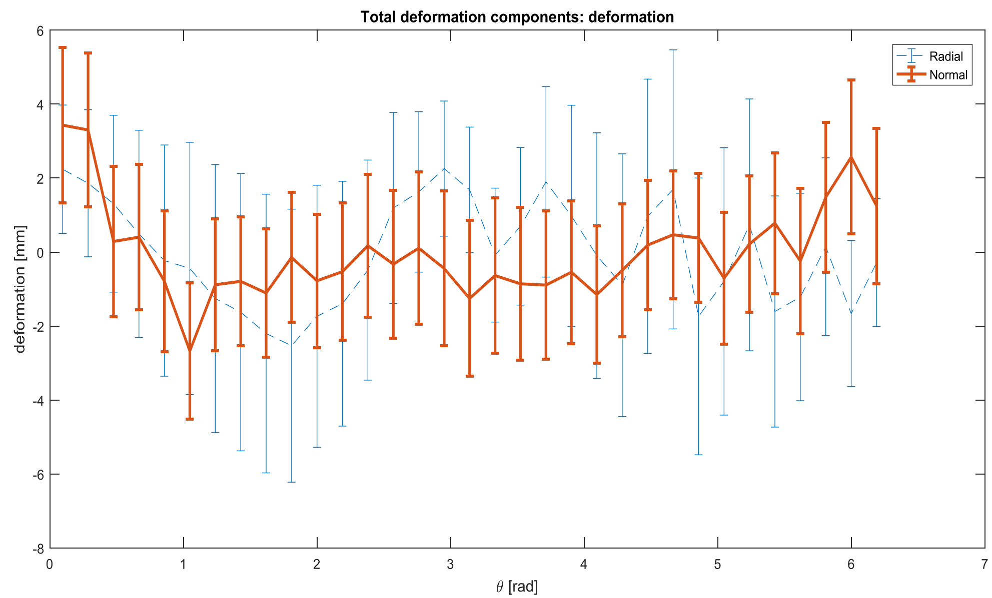
Reconstructed CCL

- First stable result of WP11 CCL reconstruction
- Conductor discretized with 21300 points (220 mm step, 160 segments/turn)
- Biot-Savart computation on a 5 $\times$ 3 grid on each measuring coil
- Shape defined by **55 d.o.f.**: 6 rigid-body + homothety + harmonics up to ***n*=12** (λ = 2.8 m)
- Excitation current included as a variable to compensate for systematic coil area error

- Max CCL deformation (excl. rigid-body modes) **4.1 mm**
- RMS deformation uncertainty: **±2 mm normal**, **±3 mm radial**

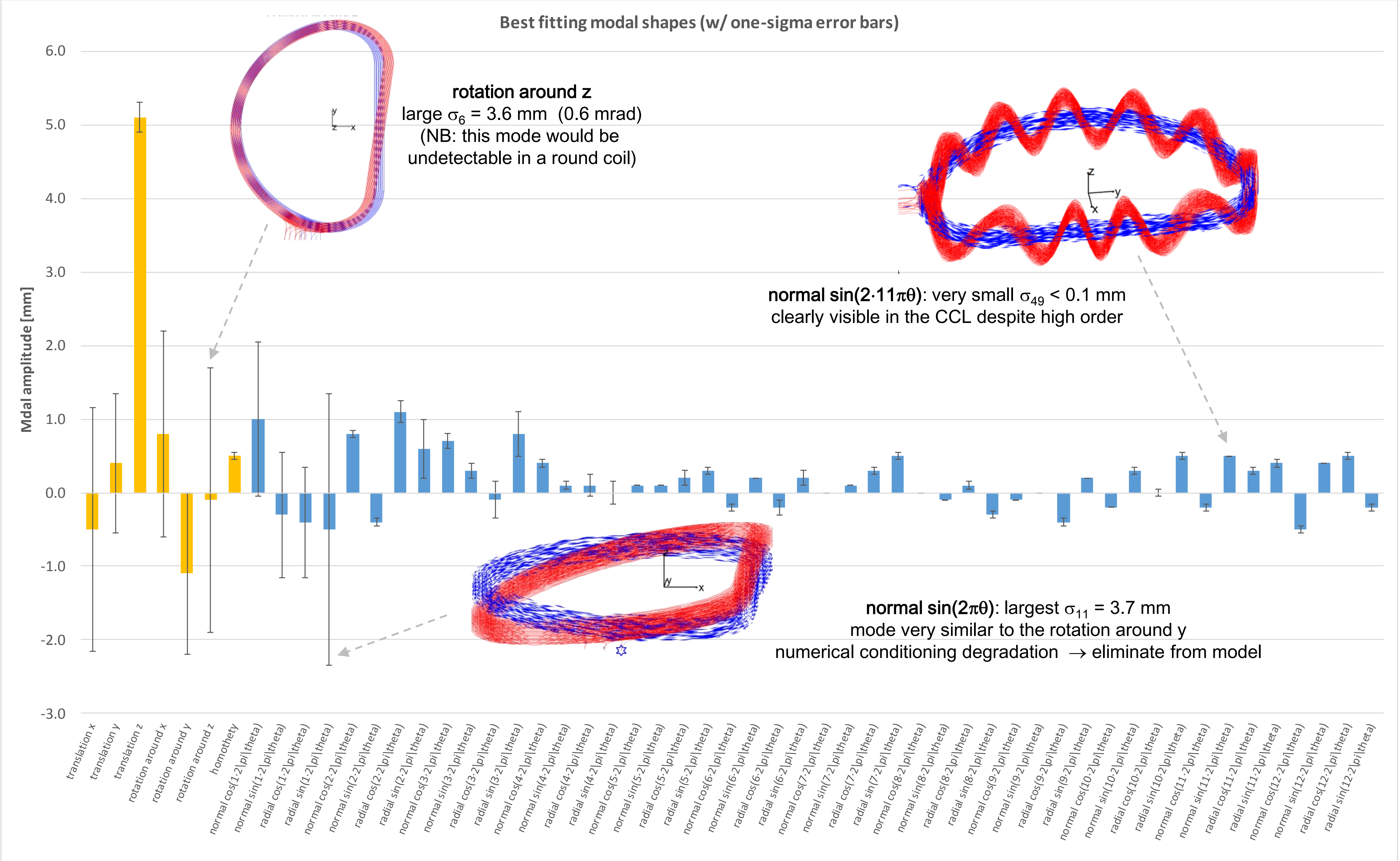


deformation exaggerated for visualization
(harmonic components only)



radial (horizontal) and normal (vertical) deformation at discrete CCL points
azimuth θ counterclockwise starting from connection region
no clear difference between straight and curved regions

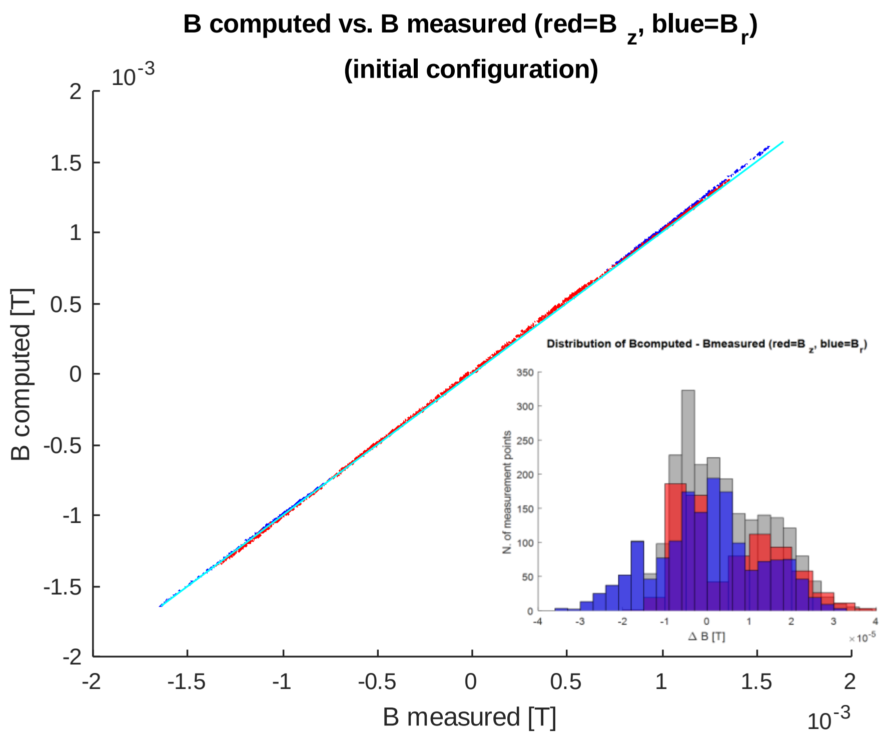
Best-fit results

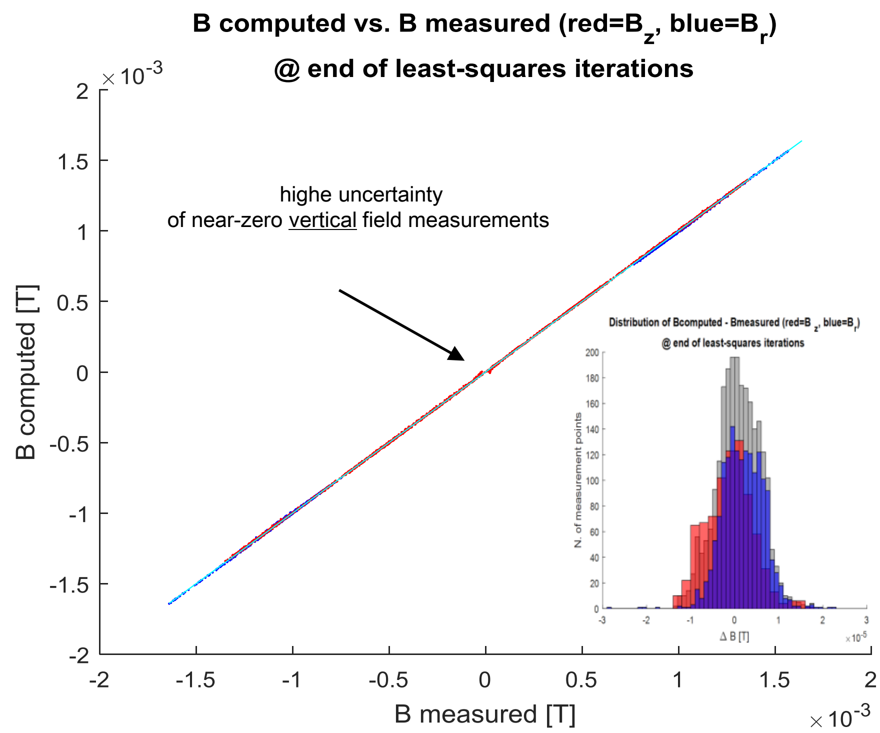


Best-fit quality

Agreement between calculation and measurements improved 3× by the minimization:

	(initial best guess)		(end of least-squares iterations)	
• RMS field difference	**14 μT**	→	**5 μT**	
	0.8 %	→	**0.3 %**	(w.r.t. full scale 1.6 mT)
• Normalized χ^2	**13.6**	→	**4.6**	
• Correlation slope	**1.009**	→	**0.99998**	

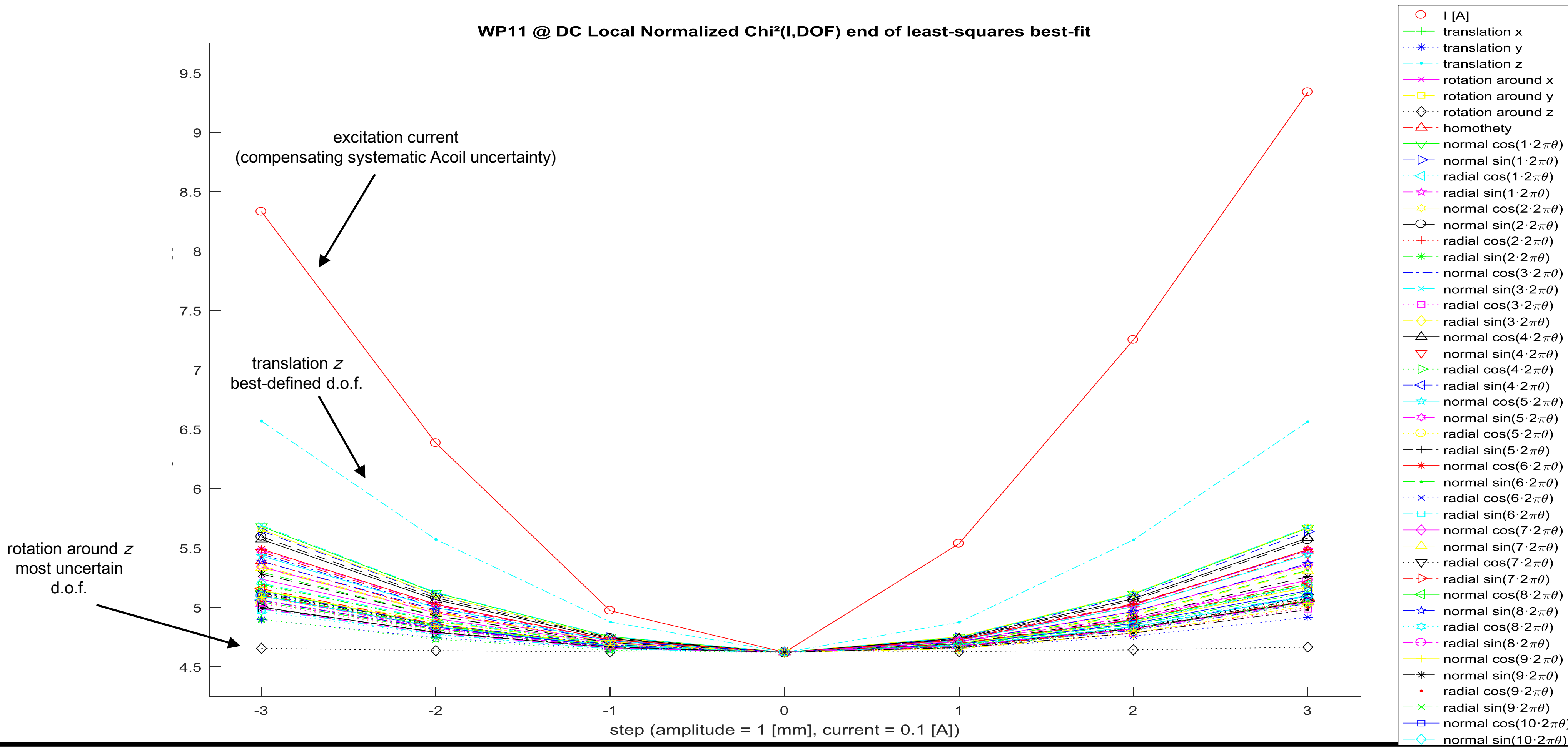




Have we really found a minimum ?

- Hessian matrix positive definite ⇒ guaranteed local minimum
- **Normalized χ^2 = 4.6** reasonably close to expected unit value
- RMS field difference = **5 μT** is best result so far in *numerous* trial-and error attempts

⇒ we are probably close to the global minimum (for this particular dataset)



Conclusions
Part I

Conclusions – Part I

- The delivered instrument provides a magnetic measurement uncertainty ≈ $3 \cdot 10^{-4}$ very good metrological performance even in … at a level as few mT !
- Early concerns such as eddy current effects proven to be manageable
- System + reconstruction method are capable to reconstruct the position of the CCL within an **uncertainty of 4 mm** (radial direction) and **6 mm** (vertical direction) (at one sigma)
- Uncertainty analysis → clear indications towards feasible improvements
- *A posteriori* refinement of the accuracy of the WP11 CCL is still possible (PCB calibration, upgrade of the reconstruction algorithm)

Improving the measurement accuracy

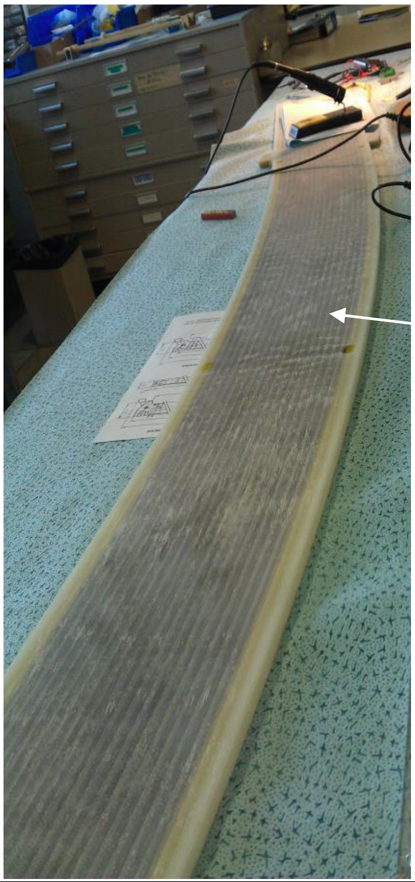
Ways to improve accuracy

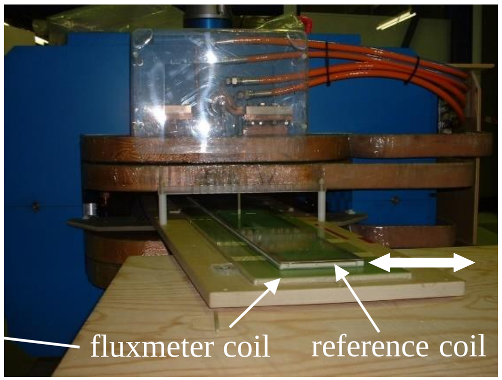
Hands-on experience + error analysis + numerical exploration of post-processing options ⇒
clear roadmap towards the specified accuracy of 1~2 mm
(inboard leg and elsewhere except connection region, according to the minutes of the kick-off meeting and several discussions)

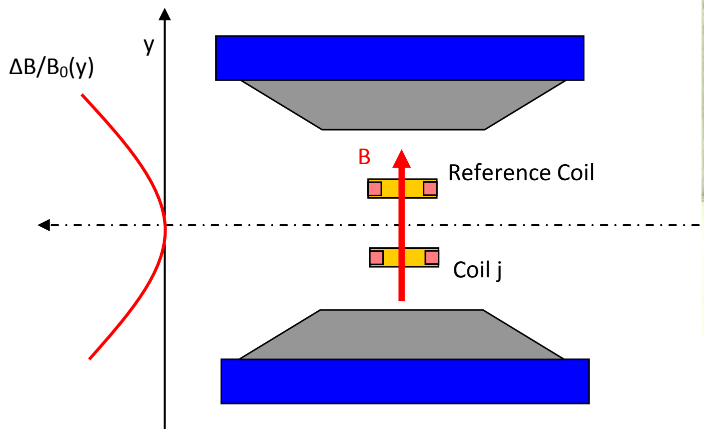
- tackle magnetic and geometric uncertainty sources
  - frequency, excitation current and AC coil voltage are well under control
  - largest magnetic contribution comes from measuring coil area
  - large indirect magnetic contribution from geometric survey
  - obvious help: higher current source (also indispensable for reliability)
- improve calibration procedures
  - coil area calibration can be calibrated *a posteriori*
  - rigorous coil area and geometry calibration checks must be enforced during the test campaign
- optimize field sampling strategy
  - number and location of measurement points
  - constraints: time required, development of new coil supports
- upgrade instrumentation hardware and software
  - electronic data acquisition components to be upgraded, in the framework of a possible future contract

Coil area calibration - 1

- CERN experience with large- and small-scale PCB → typical deviations from nominal ~10^{-4}
- Recent test campaigns at CERN and PSI on a subset of units → scatter **$5.5\cdot10^{-4}$**
  (value used conservatively in the present analysis).
- Recommendation: "classic" pulsed-mode relative calibration w.r.t. a movable reference coil
- Minimal impact on hardware (dismounting the PCB and shipping to CERN), ~2 man-months necessary
- Expected improvement of one order or magnitude







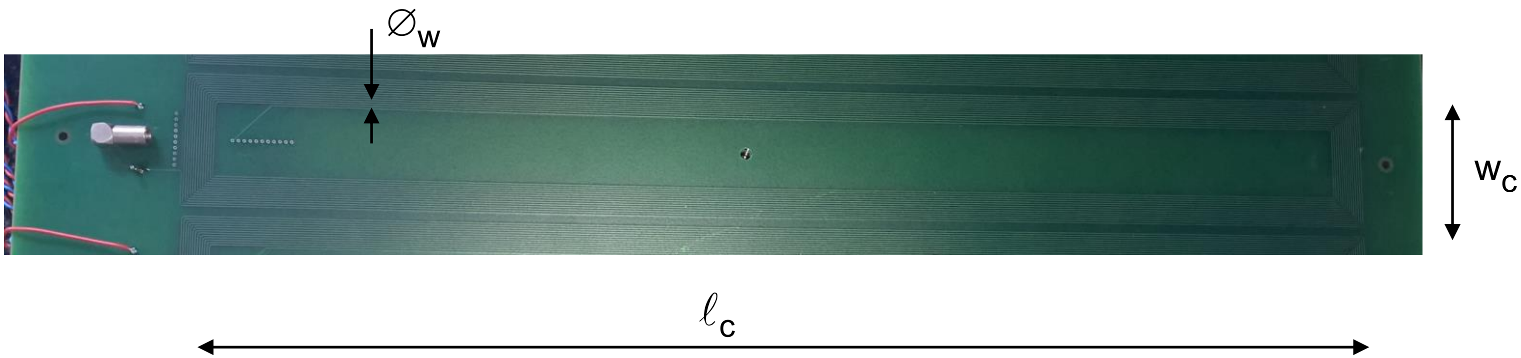
symmetric positioning in a dipole guarantees that both coils see the same field

« new » NMR-mapped , large aperture dipole
recently added to our team's magnet test hall in Prevessin

Coil area calibration - 2

- Purely electronic calibration check should be envisaged to complement the magnetic calibration
- Electrical parameters R,L,C strongly dependent upon coil geometry
- Correlation with surface area very good for long and narrow windings
- Resistance measurements alone not precise enough, but (self- or mutual-) inductance is
- Tests on PCB fluxmeters for other projects are ongoing both at CERN and PSI to find the method with the best correlation to surface (RLC meter, Network Analyzer, AC frequency sweep)

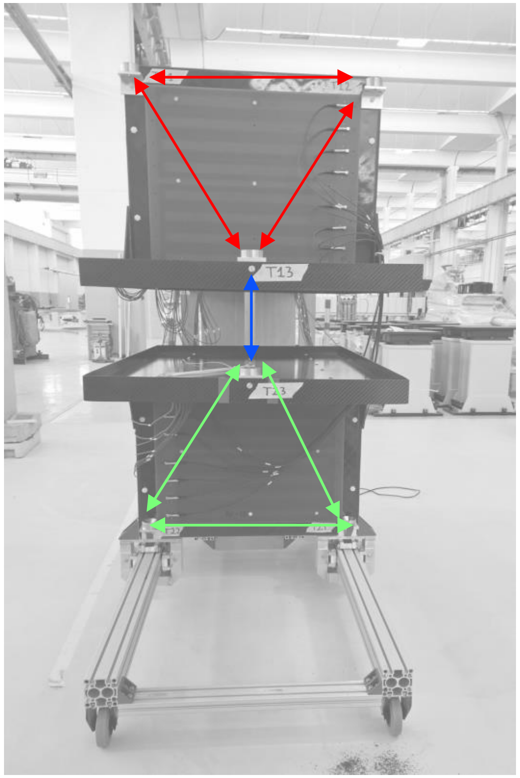
- Main advantage: this measurement can be carried out automatically at little extra cost on the mounted PCB → **automated check during a test campaign**

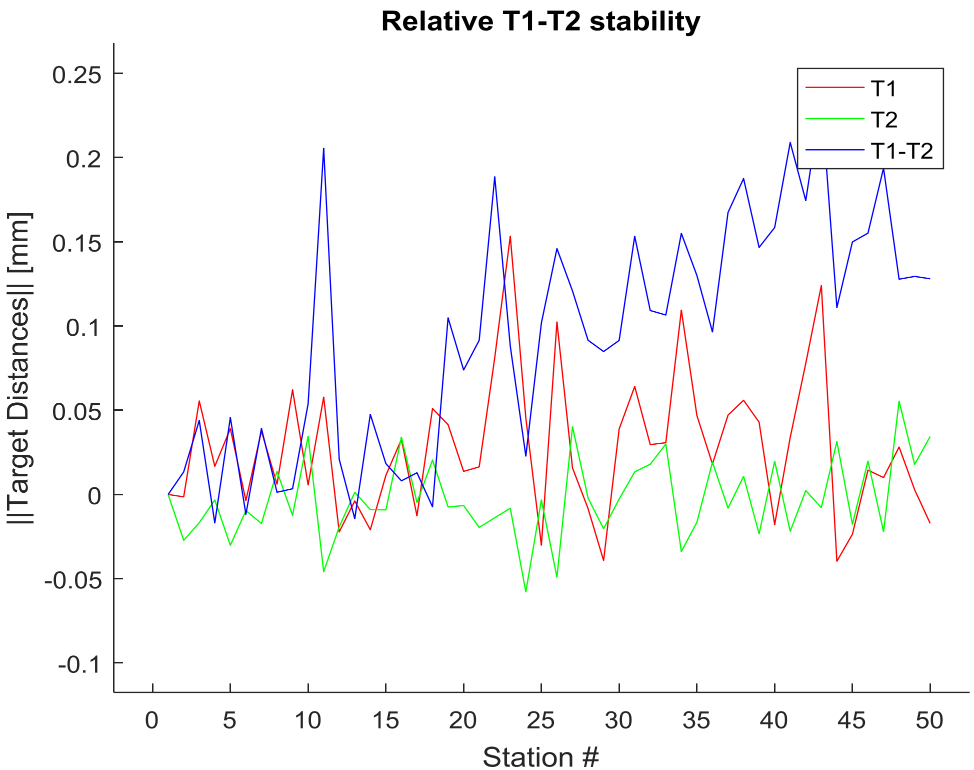


$$\begin{cases} A_c = N_T \ell_c w_c \\ R_c = \dfrac{8}{\pi} N_T \rho \dfrac{\ell_c + w_c}{\varnothing_w^2} \\ L_c = \dfrac{\mu_0}{\pi} N_T^2 \left(\ell_c \ln \dfrac{\ell_c}{\varnothing_w} + w_c \ln \dfrac{w_c}{\varnothing_w} + 2\sqrt{\ell_c^2 + w_c^2} - \ell_c \sinh^{-1} \dfrac{\ell_c}{w_c} - w_c \sinh^{-1} \dfrac{w_c}{\ell_c} - \dfrac{7}{4}(\ell_c + w_c) \right) \end{cases}$$

Positional uncertainty

- Geometrical calibration of the PCB coil positions is the weakest link in the chain
- RMS bundle error **~0.6 mm** (DPP) **~0.8 mm** (WP11)
- Errors may be linked to beam obstruction (not always reported by SA), manual handling of the targets, having to work on a scaffold or with upside-down or vertical target holders, data file and point name mismatch (1~2 k measurements taken) …
- Stability over one week: reference network 80 μm
  T1-T2 fiducials 200 μm ⇒ ×4 improvement appears possible !





stability assessed via all pairwise fiducial distances

Hardware:

a) Measurement redundancy: increase from 3 → 5 the fiducials on each «T» holder visible from all angles during the test campaign

b) Glue retroreflector prisms (much cheaper than spheres) in place, as many as needed to allow measuring from all required angles. The tracker can identify and measure automatically the fiducials without the need to touch them during the magnetic measurement → large speed and reliability improvement

c) Monitor continuously the instrument's stability during measurements (add an accelerometer)

Procedure:

d) Repeat calibration daily, rather than weekly, during the campaign

e) Post-processing consistency checks (stability of reference and instrument fiducials) in real-time at every station

Software:

f) Control LEICA Spatial Analyzer from the LabView acquisition software. This would allow automated measurement triggering and data archiving at each station, merging magnetic and geometric data and eliminating the risk of accidental mismatches

Improving the CCL reconstruction

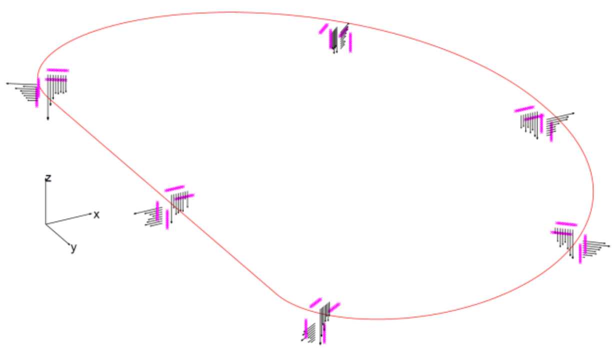
Get more data points

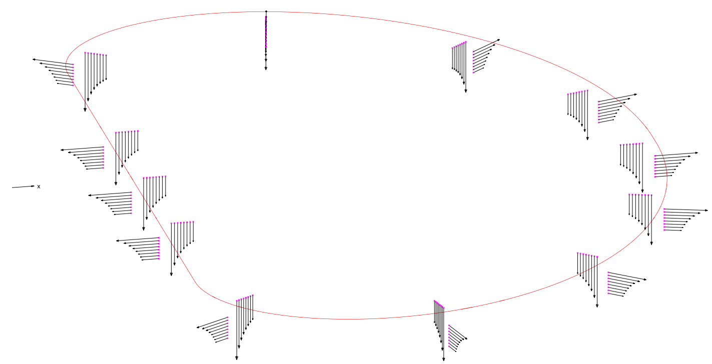
Increasing the number of data points n_p is the easiest (albeit time consuming) way to improve accuracy:

- (trivially) random noise effects average out, uncertainty of the average scales with $n_p^{-½}$
- More azimuthal stations → improvement of the Fourier representation of the deformation
  (universal but well-known to be slowly converging)
  - reduce aliasing error (f > $f_{Nyquist}$ become low-order errors; filtering, commonly done in the time domain, is <u>not</u> possible in the angular domain)
  - reduce Gibbs phenomenon (ringing at steep jumps)

  Theoretical limit from coil length = 68 stations excluding overlap (oversampling)
- Increased n. of points → decrease the condition number of the linear system
  (roughly speaking, the amplification factor of measurement errors)

For each measured point: at least one more frequency to reduce uncertainty of the extrapolation to DC





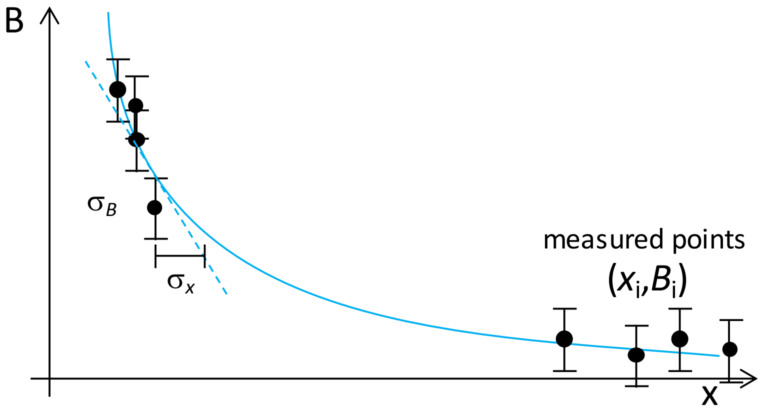
Synthetic example: 1.4 mT field , 17 d.o.f, 96 → 192 data points, condition number 8600 → 126
NB: CN improvement levels off quickly, and correct data point placement becomes more important

Measure B_z on the coil midplane

- Results indicate that the accuracy of the match between measured and computed field (hence the accuracy of the reconstructed CCL) is better in the vertical direction

- The position of existing horizontal PCBs is mechanically convenient but not so efficient
  - lost information due to <u>large field component lying in the plane of the measuring coil</u>
  - field profile crosses zero (high uncertainty) and then flattens out

- Positional information derives directly from the gradient:



$$\|\nabla B\| \approx 3\ \mu\mathrm{T/mm}$$

$$\sigma_x = \frac{\sigma_B}{\|\nabla B\|} \approx$$ **0.3 mm/□□**

- The additional effort to measure on the mid-plane could be offset by relaxing the number of radial shifts at each azimuthal station

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Data analysis improvements

Matlab post-processing code developments (if possible within the scope of CERN – ITER Agreement)

- Include measured phase in the eddy current model → **improved extrapolation to DC**
- Impact of positional uncertainty on magnetic field uncertainty on a component basis, rather than using only the gradient vector norm as implemented now *or*
  total least squares formulation
- Deformation representation:
  - **stepwise** constant modal shapes (should be better for highly localized deformations)
  - non-rigid TFC cross-section, e.g. **dual pancakes represented individually as rigid objects**
- chain the implemented minimization algorithms (grid search, monte carlo, hessian method, levenberg-marquardt) so that **global minimum** may be sought automatically, rather than manually
- inclusion of measurement data from other sources (namely, ASG's Hall probes !) in order to compare field maps and **carry out the best-fit with the augmented dataset**

Series WP tests

Upgrade to series tests

Existing prototype system and test procedures need to be upgraded in view of a series test run.

- 1 week test campaign → three/four man job:

  - operation of the magnetic instrumentation
  - operation of the laser tracker
  - data validation and consistency check in real-time
  - hands-on tasks

- Increase the flexibility of the PCB coil assembly:

  - approach the coil mid-plane as much as possible with the horizontal PCBs
  - parallel channels acquisition: very useful for speed and stability
  - measure preferentially inboard (higher field, closer to where it will be used !)
  - keep one LEICA station near the center of the coil
  - design hard to optimize in view of frequent shipping (size, weight, fragility)
  - if needed: additional PCB coils could be procured quickly at CERN

- Other practical improvements:

  - more robust cabling routing and/or electronic switches
  - streamlined, simplified front-end LabView interface
  - automated and cross-referenced test data archiving of merged magnetic and geometric
  - systematic raw data archiving
  - coil temperature monitoring
  - UPS to facilitate moving the equipment around the coil

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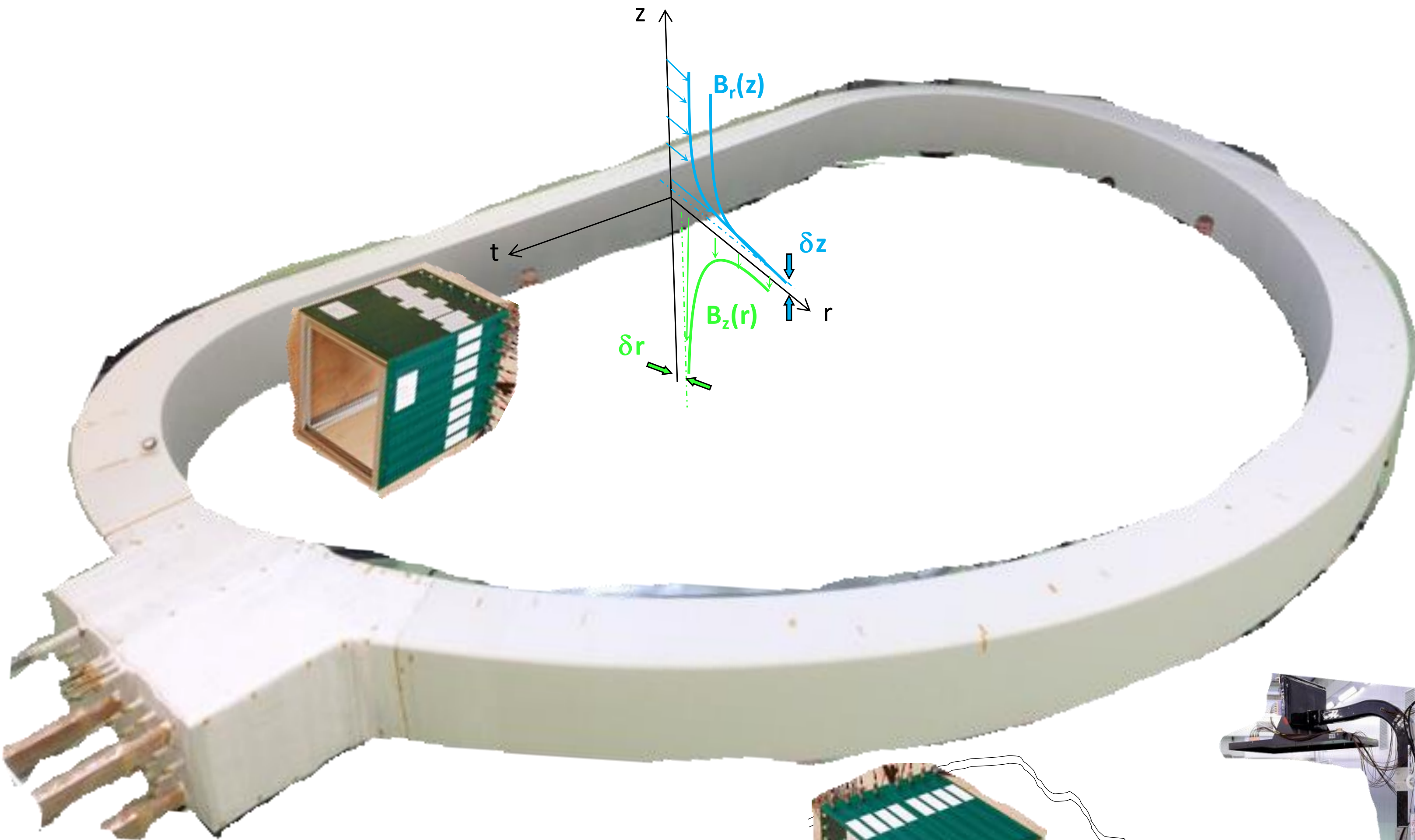
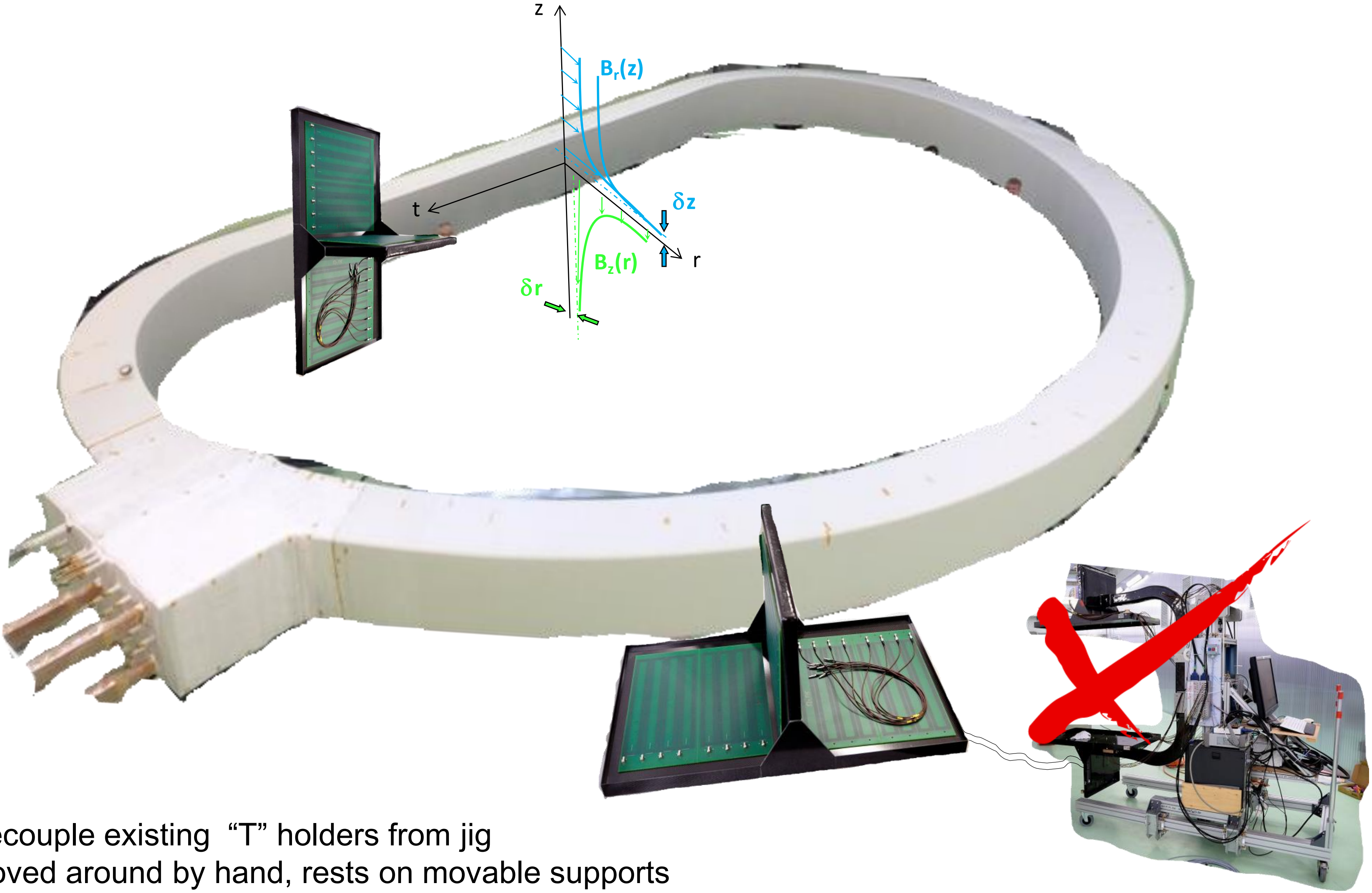
PCB coil upgrade 1/3



- PCB cube jig(s) (one exists, more can be easily done)
- In addition to the existing T1/T2 holders
- Moved around by hand, rests on movable supports (rolling tables, hooks)

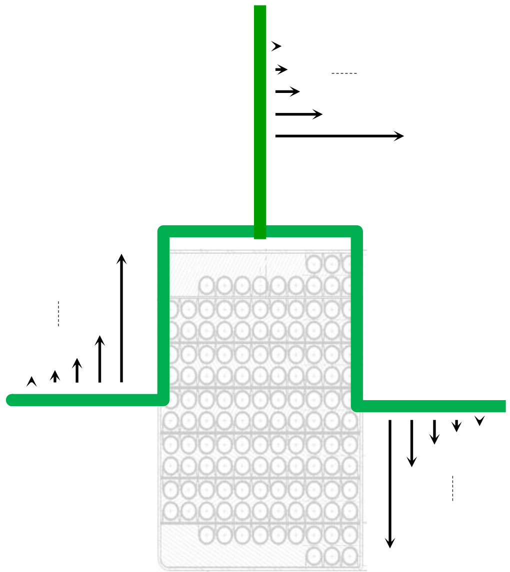
PCB coil upgrade 2/3



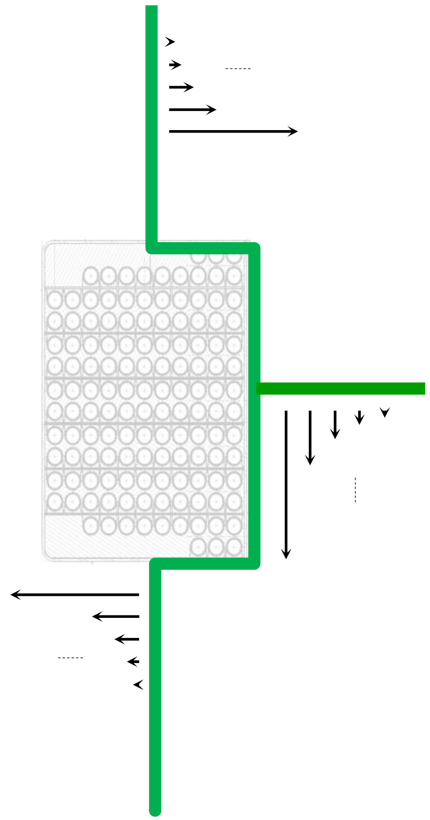
- Decouple existing "T" holders from jig
- Moved around by hand, rests on movable supports
- Enables doubling up cheaply the whole system

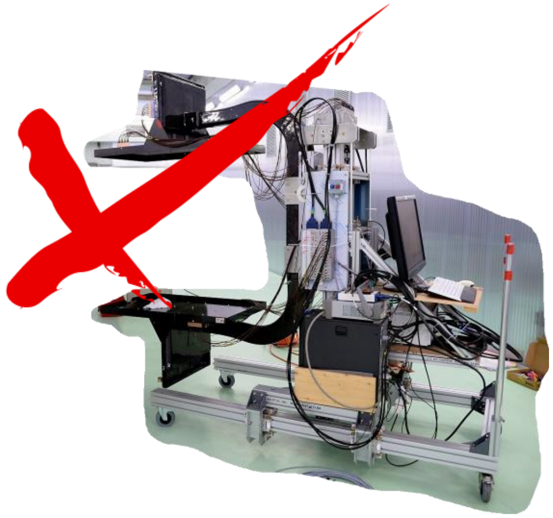
PCB coil upgrade 3/3

emphasis on radial CCL accuracy



emphasis on vertical CCL accuracy





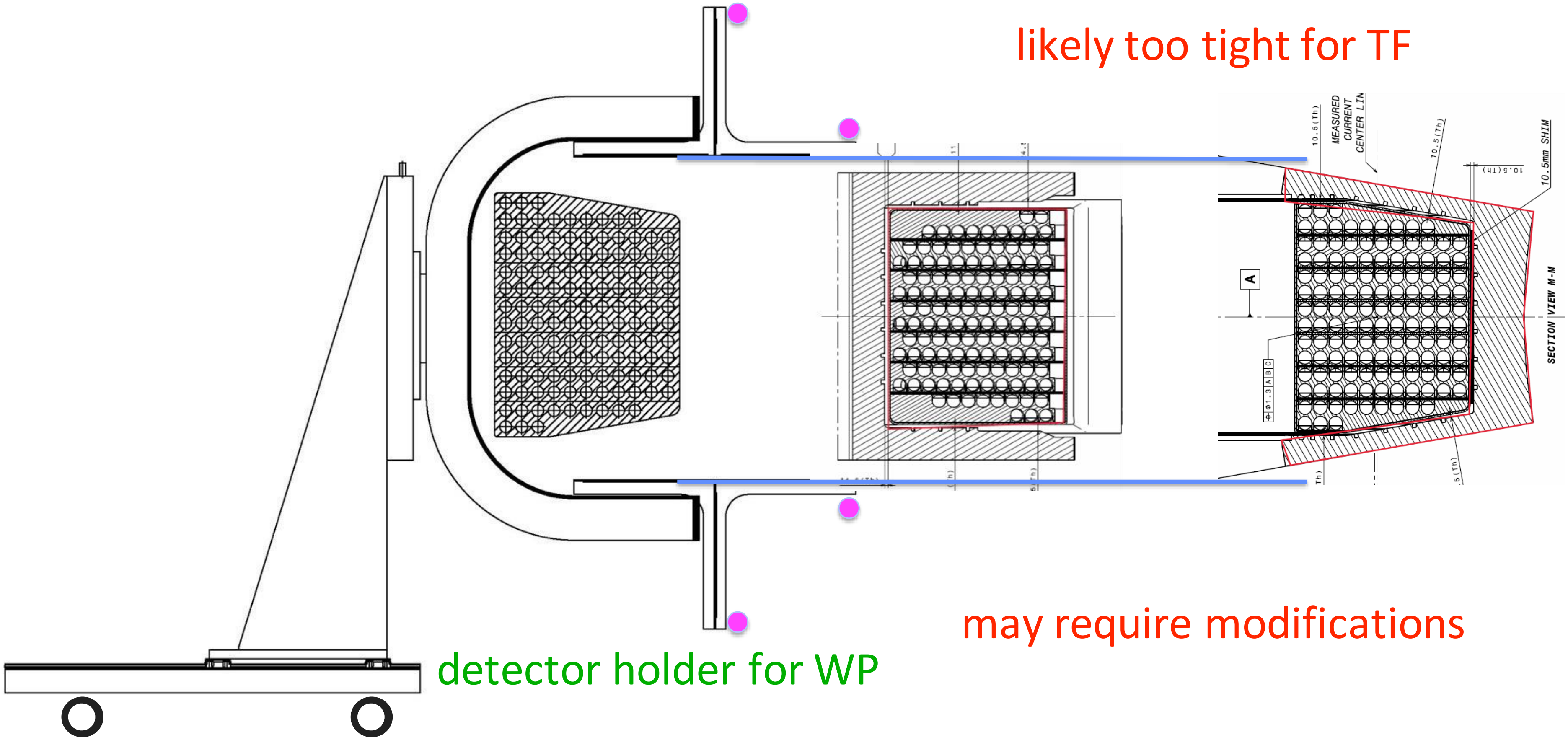
- Fully new coil supports to replace existing T1-T2 holders
- Simulations (+ input on geometrical constraints) needed to optimize the geometry
- Moved around on rolling supports, separately from DAQ chassis

PCB coil upgrade options

Configuration	☺	☹
additional free-standing PCB jig	• 2 additional coil PCBs available now, more could be procured in 2-3 months • minimal change to the acquisition system (15 channels still free, more can can be added easily) • easy to position arbitrarily (including pedestals, interconnections …) • concept readily implementable	• bulk of $B_z(r)$ measurements remain sub-optimal • more cables to drag around • probably incompatible with TFC
split up T1/T2 (replaces existing setup)	• no change to acquisition system, all parts already there • easy to position at will with the help of hooks or rolling tables (including pedestals, interconnections) • allows cheap duplication of the system (shipping to Japan ?)	• number of simultaneous measurements cut in half at each station
new multi-PCB jig (replaces existing setup)	• keep high parallel acquisition channel count • more stable mechanically	• bulkier, suitable mechanics must be design • positioning might be less flexible w.r.t. smaller size options

Series TFC tests

Compatibility of existing setup



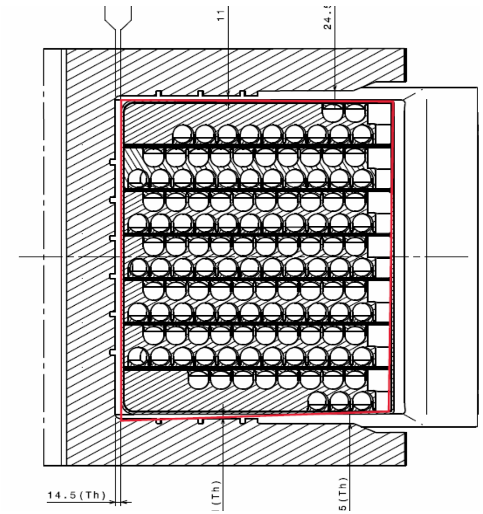
- Existing PCB support jig likely to require modifications (more so considering the need for mid-plane measurements)

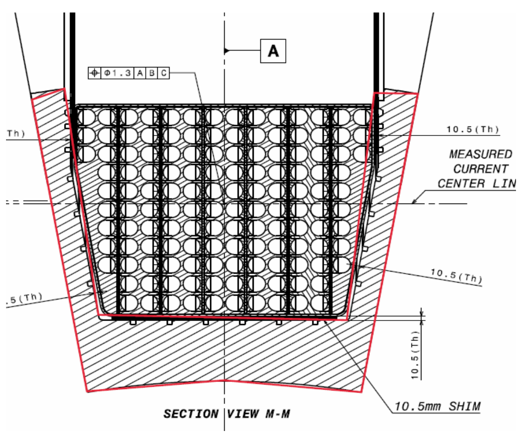
- Simple (pessimistic) filament model: eddy currents time constant proportional to conductor area

Winding Pack: A = 0.13 m² τ_e = 0.22 s, ε = 0.74

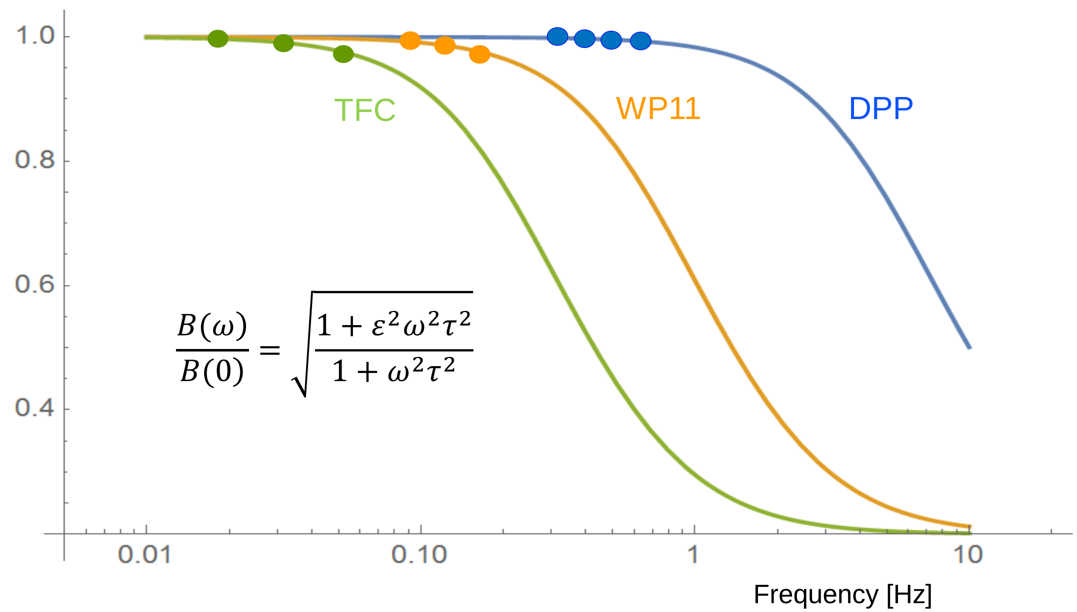
TFC: A = 0.41 m² τ_e = **0.67 s**

$$\tau_e = \frac{L_e}{R_e} = \frac{\lambda_e}{2\pi}\frac{\mu_0\mu_r}{\rho_e}A_e$$

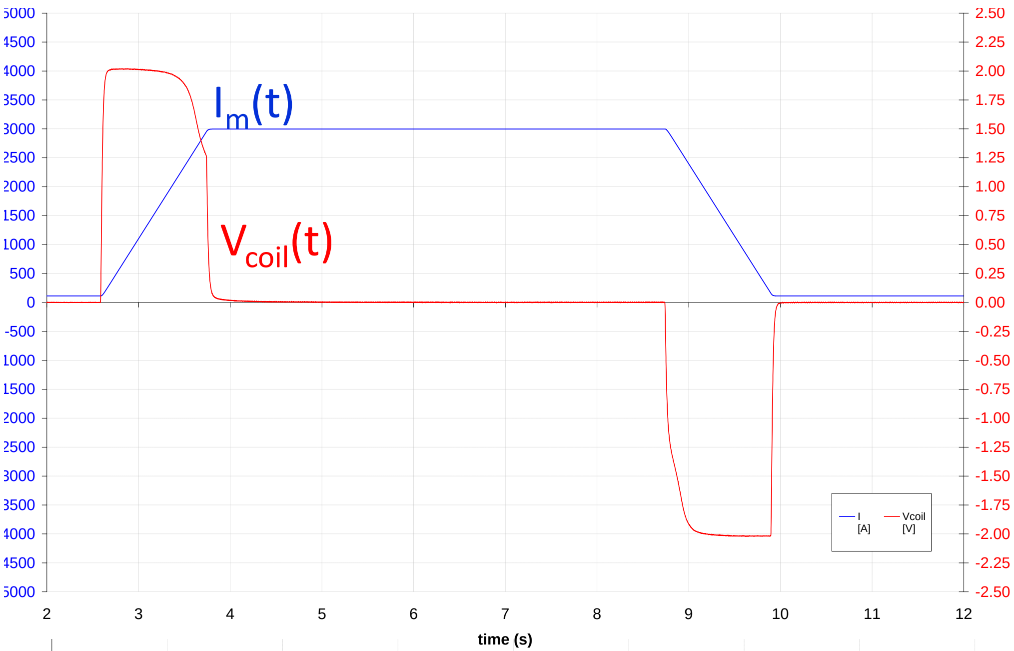




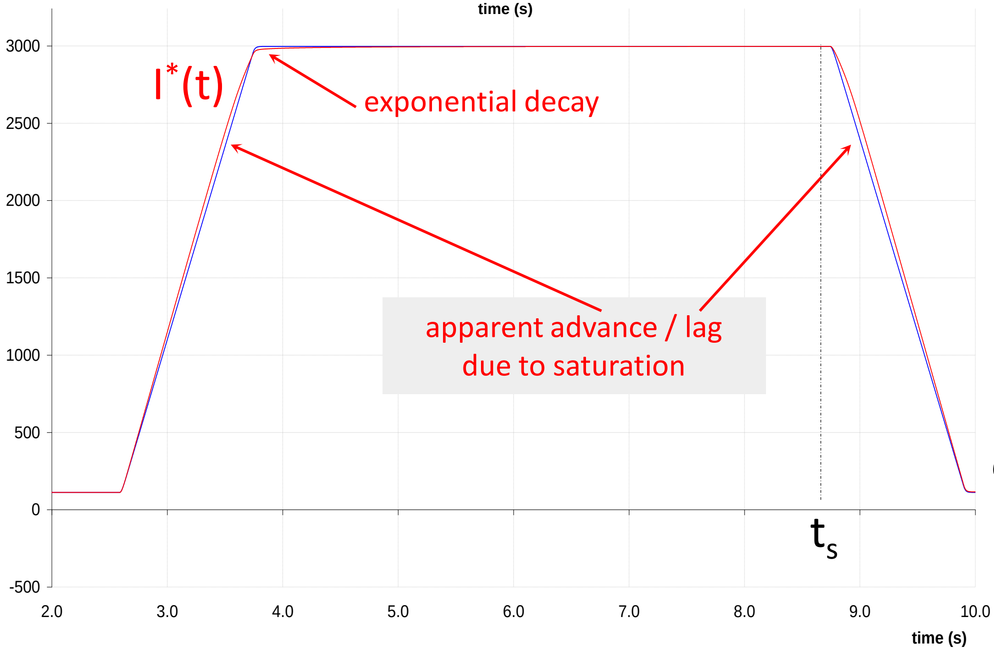
B_0	Field amplitude	$I_m k_m \sqrt{\frac{1+\varepsilon^2\omega^2{\tau_e}^2}{1+\omega^2{\tau_e}^2}}$
V_{c0}	Coil voltage amplitude	$A_c I_m k_m \omega \sqrt{\frac{1+\varepsilon^2\omega^2{\tau_e}^2}{1+\omega^2{\tau_e}^2}}$

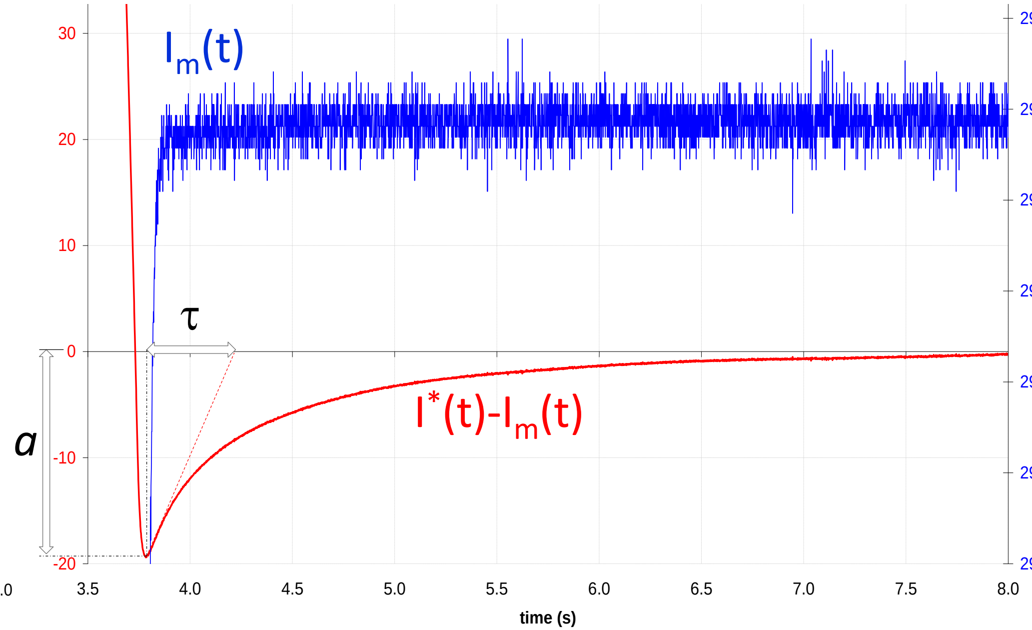


$$\frac{B(\omega)}{B(0)} = \sqrt{\frac{1+\varepsilon^2\omega^2\tau^2}{1+\omega^2\tau^2}}$$

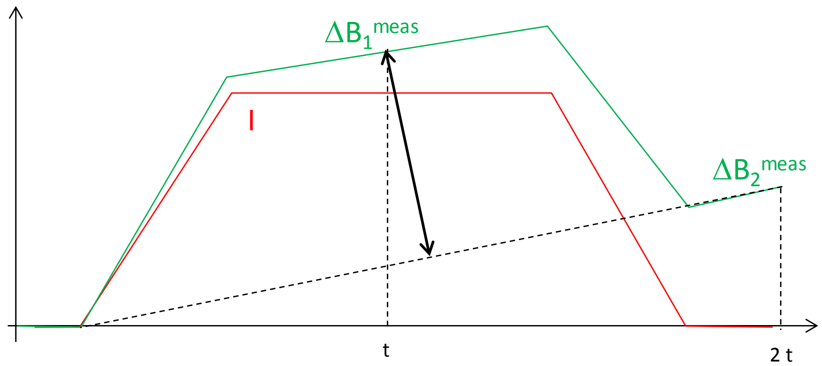


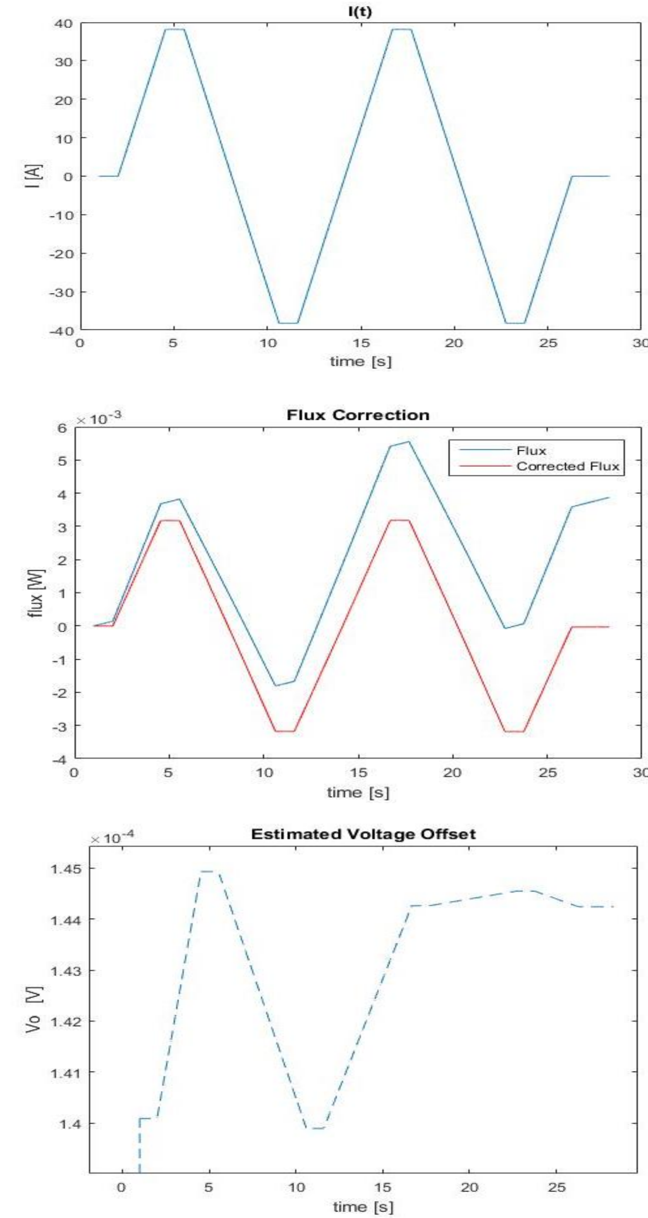
- Classic method: current plateaux of duration >> expected τ
- High-speed (needed to evaluate V_{offset}) acquisition of integral coil voltage $\rightarrow$ detailed profile of I^*-I_m
- The relative amplitude $a/I_m(t_s)$ and logarithmic decay ratio τ of the exponential starting at the end of the ramp eddy current effect





Pulsed mode – drift correction





$$\Delta B^{meas} = \frac{1}{A_c} \int (V_c + V_{offset}) dt \qquad \Delta B = \Delta B_1{}^{meas} - \frac{\Delta B_2{}^{meas}}{2}$$

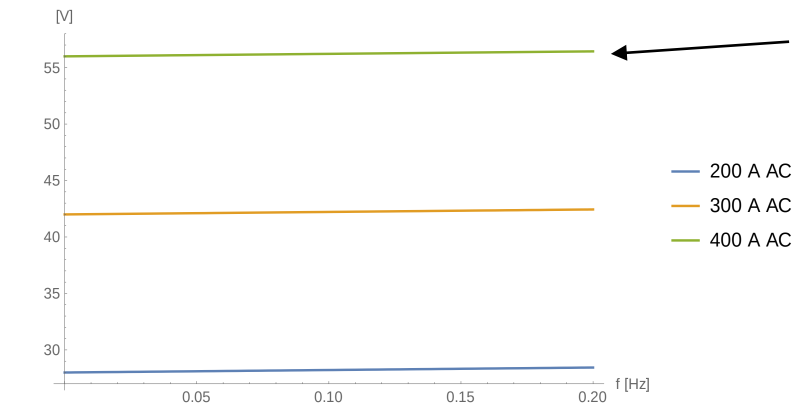
Integrator drift can be corrected to 1st order assuming that V_{offset} is constant

- Example of integrator drift correction (): voltage offset is estimated on the plateaux at constant current, when all dynamic effects have vanished, and is interpolated in between
- Advantage: **measurement done in equivalent DC conditions**, no change to the acquisition hardware, minor software upgrade
- Disadvantage: loss of the AC synchronous detection

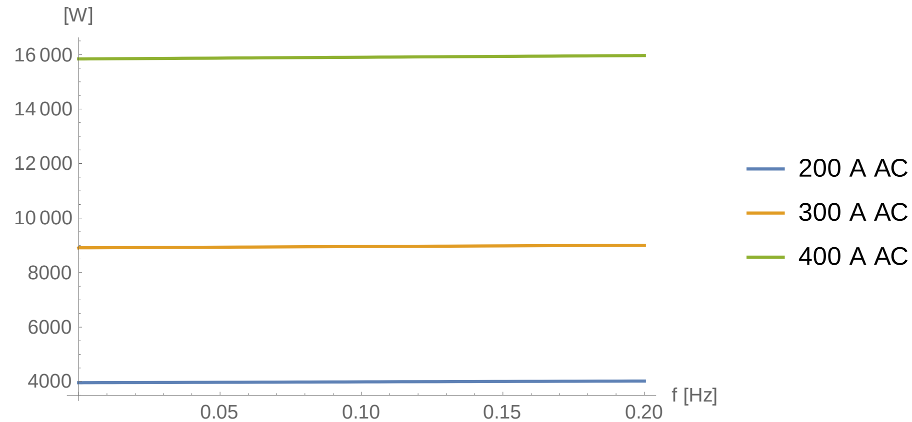
permeability measurement of ITER TFC co-wound tape

Dedicated power supply

- Kepco setup absolutely inadequate for TFC tests
- **~300 A / 60 V** dual mode AC/pulsed power supply available from different sources
  (Informal offer from DANA, IT: ~50 k€. Offer from PSI PS Group pending. Shared purchase with CERN ? Is a call for tender necessary ?)
- Max. power and duty cycle to be optimized as a function of acceptable ΔT limits ?



Small inductive voltages in the frequency range envisioned



High power ! 2×38U racks, ~400 kg, air cooled units
(difficult to transport)

WP11 test

Conclusions
Part II

Conclusions – Part II

- **Strategy to reach the target accuracy is clear**: focus on coil area calibration, laser tracker measurements, number and distribution of measurement points
- Work on the post-processing of DPP and WP11data still in progress
- We proposed a range of options to **upgrade hardware and software** of the measurement system in view of a **series test scenario**
- **Testing a fully assembled TF coil appears feasible**, provided a new power supply is used (also highly recommended to continue WP tests !)
- Even in the TFC scenario, we recommend testing at least two more WP to allow comparison before/after insertion
- Last occasion to finalize the design: must include now all possible future use cases

Last thought – what about direct field mapping ?

- Two distinct aims that could be decoupled: coil assembly quality / field modelling in operation
- Why use a CCL when a field map can be directly provided to derive field in the plasma region ?
- The existing measurement technique can be readily adapted to provide field measurements on the TFC mid-plane or (much better) on the boundary of a suitably defined, source-free domain **Ω**
- R&D to model efficiently the field inside such 3D domains being launched at CERN for various accelerator magnet applications (**spherical and toroidal harmonic expansions**)
- Possible synergy with HEP experimental magnets ?