A Rotating Coil Array in “Mono-Bloc” Printed Circuit Technology for Small Scale Harmonic Measurements

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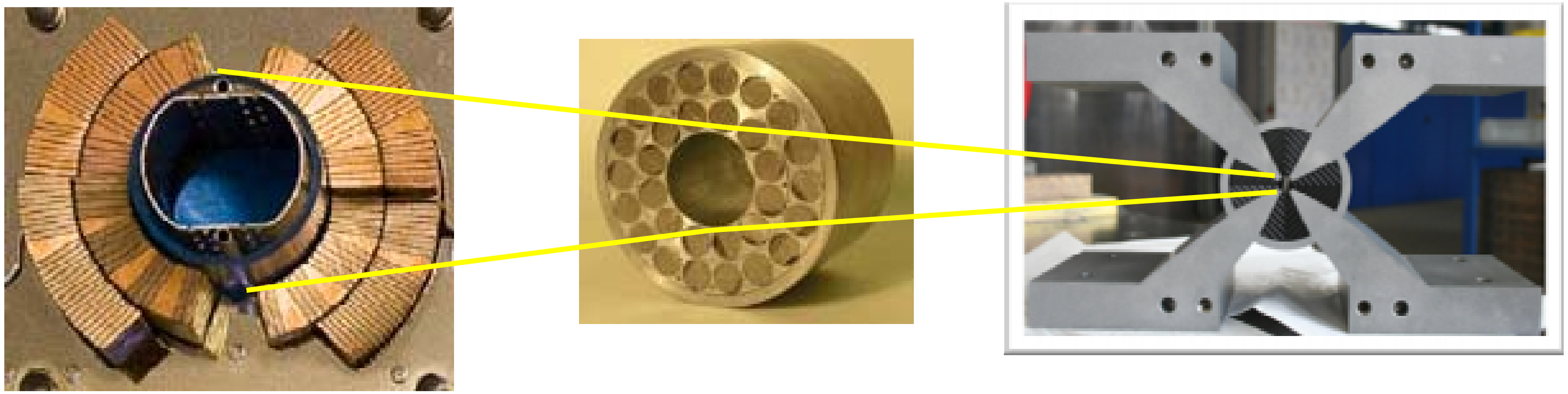
The Challenge:

New accelerator projects require field measurements in smaller and smaller apertures.
We need rotating coil arrays for reliable harmonic measurements.

LHC — Linac 4 — CLIC



Ø 50 mm —2.5 x→ Ø 20 mm —2.5 x→ Ø 8 mm

→ **How to build a harmonic coil array for such small apertures?**

Experience so far (Linac 4):

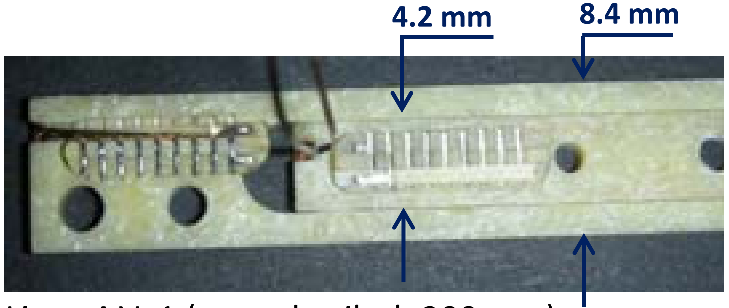
(ref. O. Dunkel, IMMW 16, PSI-Villingen, CH, 2009)

Two small “add-on” coils on a Ø 19 mm sandwich structure.

-Limit of mechanical feasibility.

-Unsatisfactory metrological performance.

→ Main problem: geometrical stability of nested coils (very thin and weak).



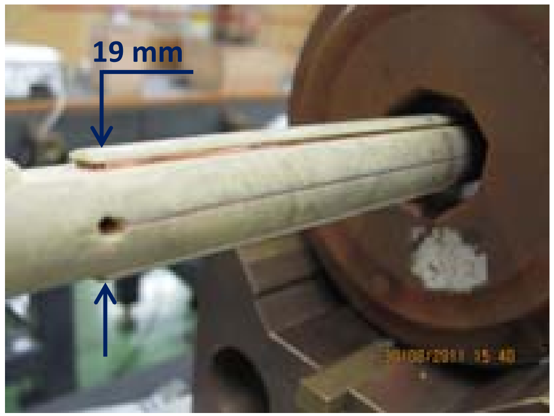
Linac 4 V. 1 (nested coils, l=200 mm)

Three coils “on-body” hand wound on a Ø 19 mm machined G10 rod.

-Good accuracy.

-But difficult to wind.

→ No more downsizing possible.



Linac 4 V. 2 (“on-body” winding)

Let's try PCB-coils :

- Conductor density with traditional winding techniques is ~6x higher.
  (ex.: 0.032mm wire: >900 /mm^2, PCB with min. sized tracks: ~ 150 /mm^2)

- BUT: peripheral infrastructure needs more space.
  (El. connections, cabling, coil positioning and fixation, rotating support, etc.)

- Coils in PCB techniques are not new (Animesh, Joe, etc.), but are generally used as "add-on" coils mounted on a rotating structure.

→ Difficult to build "assembled" coil arrays for apertures < ~10mm

→ Try to produce a multilayer circuit board integrating at least 3 coils in one stack

Some boundary conditions from the CLIC (Compact Linear Collider) project:

-Magnet aperture: 10 mm down to 8.25 mm

-Expected gradient ~200 T/m up to 530 T/m (hybrids)

-Measuring coils longer than 100 mm

-b1 and b2 bucking (so min. 3 coils array)

-Max. eff. coil area for a suitable acquisition

-Max. sensitivity to higher harmonics, in particular good sensitivity to b3

-Compatible to Cern's FAME (FAst MEasurement) system

Calculation of coil geometry and sensitivity:

Rref(mm)	2.640075756		
DTheta0(deg)	-90		
Data:	Coil1	Coil2	Coil3
L(mm)	150	150	150
Nt turns	200	200	200
Dx(mm)	0.4750	0.4750	0.4750
Dy(mm)	0.7500	0.7500	0.7500
Xf1(mm)	-1.1000	-1.6000	-2.7000
Yf1(mm)	2.4000	-1.6160	0.0000
Xf2(mm)	1.1000	1.6000	2.7000
Yf2(mm)	2.4000	-1.6160	0.0000
phi(deg)	-49.25	89.43	-180.00
Theta0(deg)	90.00	-90.00	90.00

All coils l = 150 mm, 200 trns.

	Coil1	Coil2	Coil3
Coil Width:	2.2 mm	3.2 mm	5.4 mm
Rot.-Radius:	2.4 mm	1.6 mm	central

n	omp_Kn(1)
1	0.00000
2	0.00000
3	2.74577
4	0.91184
5	-0.88779
6	1.66758
7	4.20284
8	2.46763
9	29.27246
10	1.95408

Perfect bucking of dipole and main field.
Correct sensitivity to higher harmonics with
good sensitivity to sextupole and octupole.

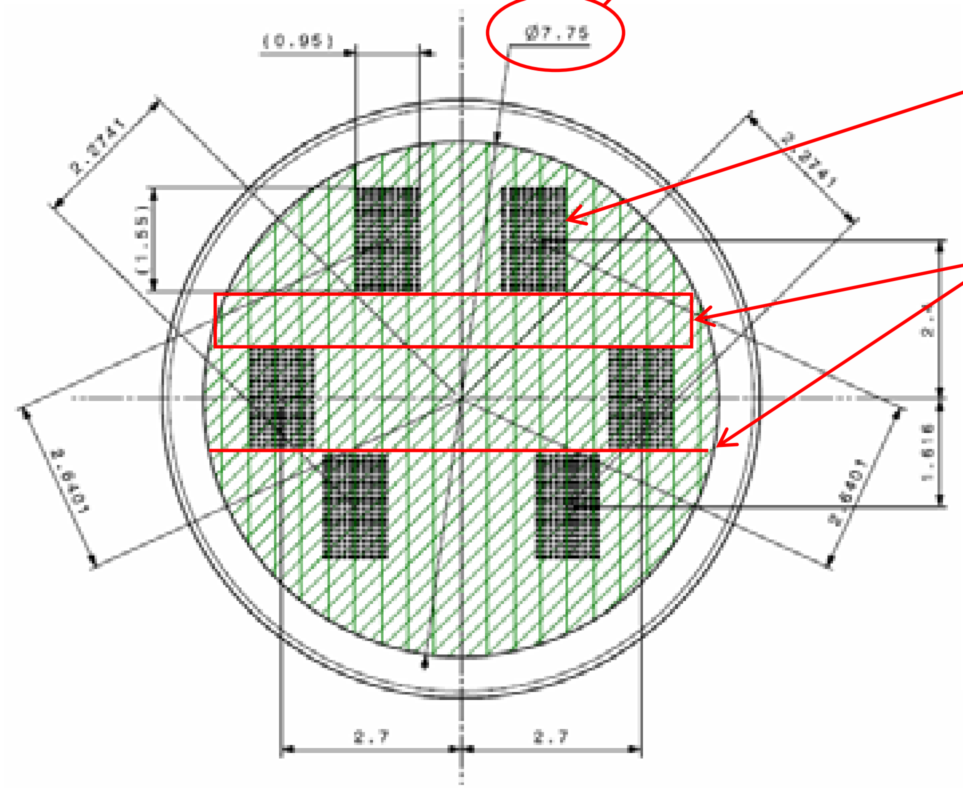
Design:

That is like it should be :

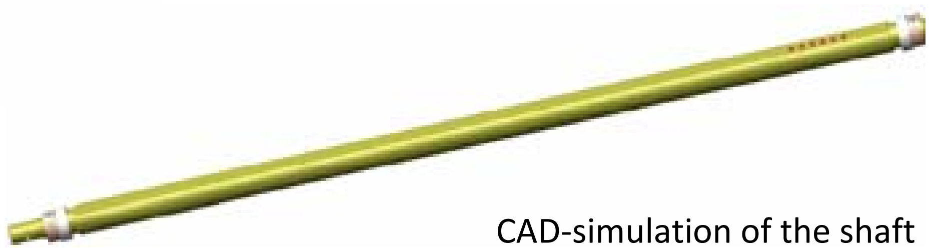
Overall Ø of the shaft: 7.75 mm

Cross section of the PCB stack with copper tracks

Space to be filled with Epoxy shims to get the right radius.



Shaft cross section presented to the PCB service



CAD-simulation of the shaft

Scale on the paper: 20:1!

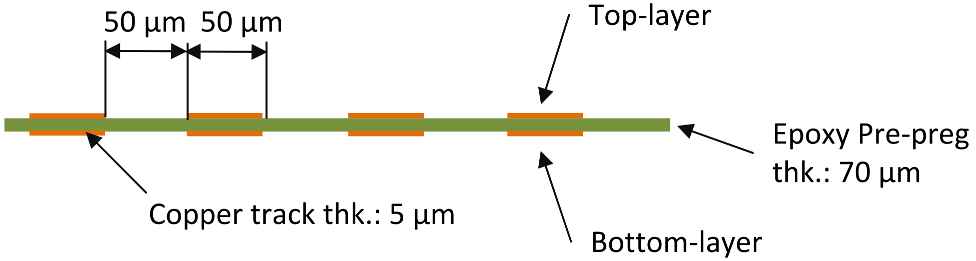
But now we need to realize it scale 1:1…!

Design:

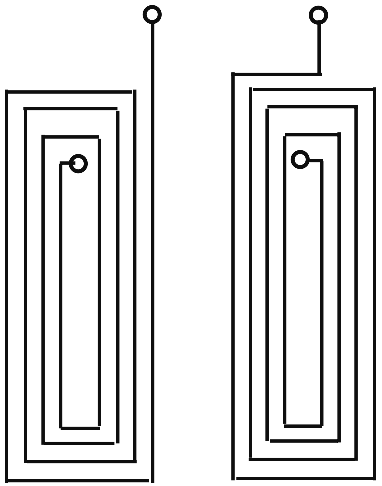
The PCB:

-Copper track width: 50 µm
-Copper track thickness: 5 µm
-Distance between tracks: 50 µm
-No. of turns turns on a layer: 10
-Thickness of the epoxy pre-preg (layer support) without copper tracks : 70 µm
-Thickness of insulation pre-preg between two double layers 70 µm
-Thickness of a stack for 1 coil with 200 turns: 1.430 mm
(10 double layers + 9 insulation pre-pregs)

→ Use of double-layers limits the number of pre-pregs and allows 20 turns/layer
(each epoxy pre-preg has a top and a bottom copper track)



Scheme of a double layer



Scheme of copper tracks

PCB-production:

1
- 30 double-layers, 10 for each coil.
- 8 designs on 1 support, 16 circuits/sheet
- Control tracks to check cross section

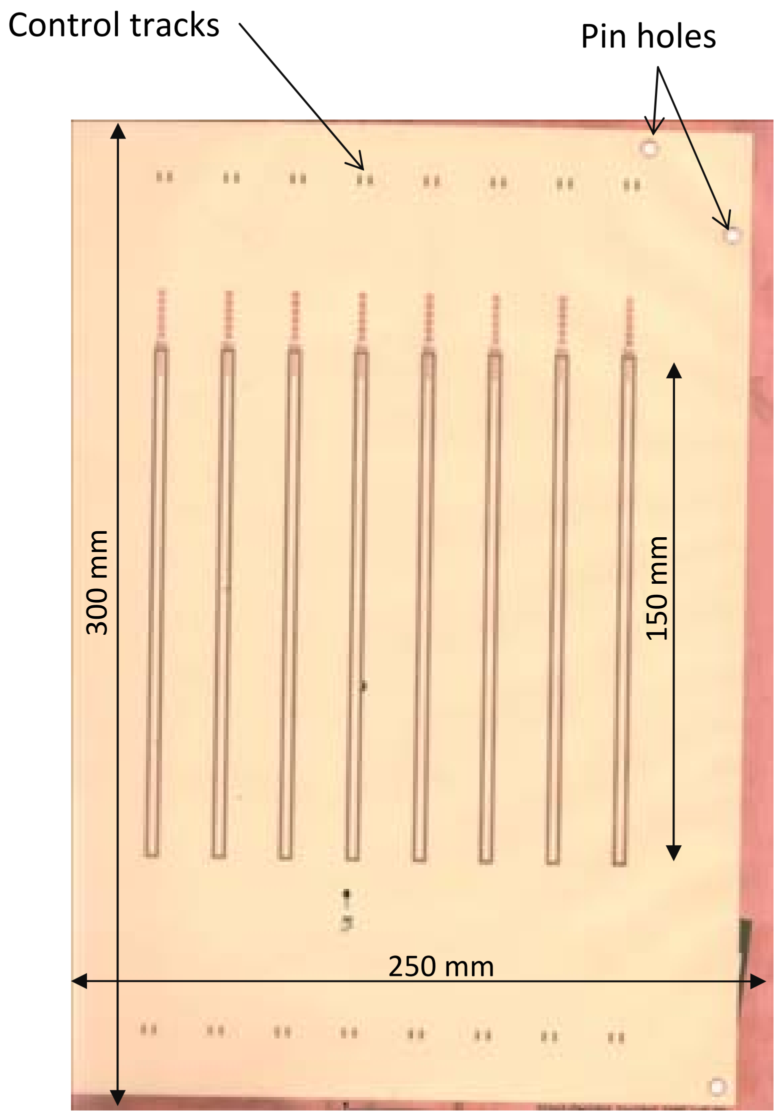
2
- Pile up and polymerize separately 1 stack per coil

→ 3 plates of ~1.5 mm thickness/each

3
- Connect all 20 tracks/plate in series (metalized [copper] holes)

4
- Pile up the three stacks (Epoxy shims to determine vertical distance of the coils to each other)
- Press and polymerize

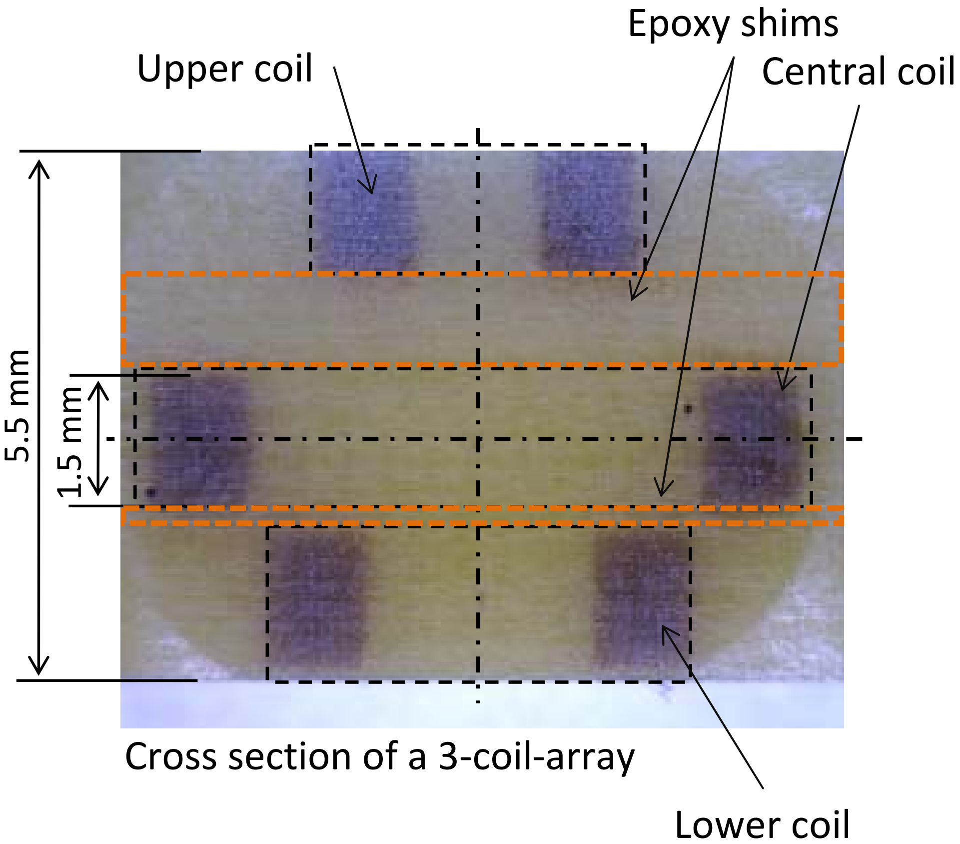
5
- Metalize holes for signal cable connection



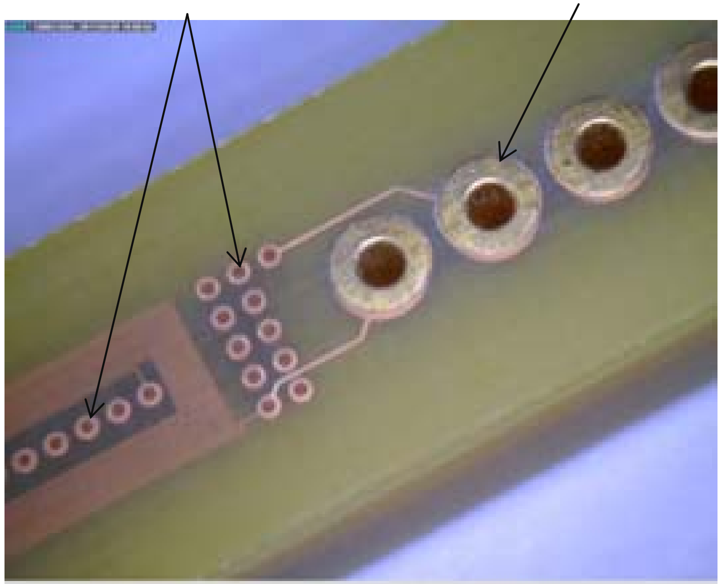
PCB layer for upper coil, upper layer (1 preg)

PCB-production:

→ We get a ~5.5 mm thick epoxy plate with 8 x 3-coil-arrays



Cross section of a 3-coil-array



View of the coil interconnection and the connectors for the signal cables

PCB-production:

Possible ⚡ …and ✦ :

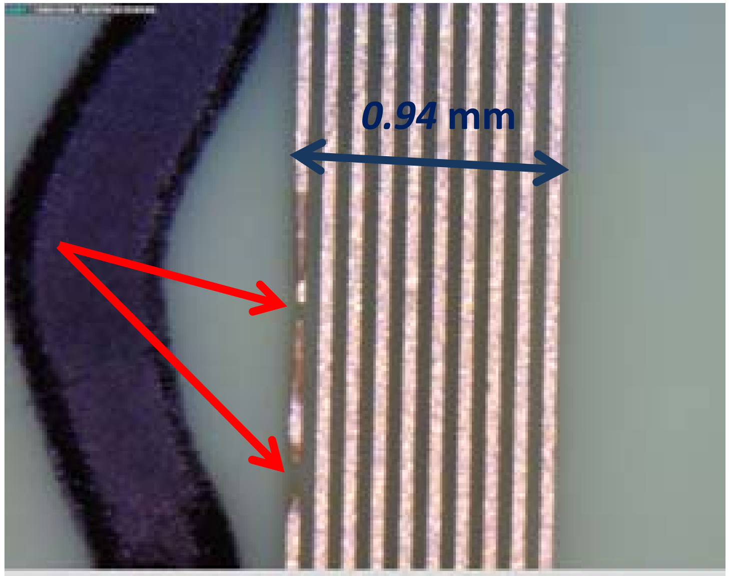
- ⚡ We need 480 (!) circuits without any failure in order to succeed the 8 arrays
- ✦ Fastidious, individual control of each circuit, re-printing of faulty layers

- ⚡ Accurate pile-up to avoid "sloped" coils
- ✦ Well adjusted pins (press sole) and pinholes (layers)

- ⚡ A layer inversion can only be discovered magnetically (resistance remains the same) and after production and assembly of the complete batch
- ✦ You need a careful operator…

- ⚡ A stack inversion shifts coils out of axis
- ✦ Fail safe pin/pinhole configuration

- ⚡ Inhomogeneous press causes unequal radii
- ✦ Control press forces with a dummy

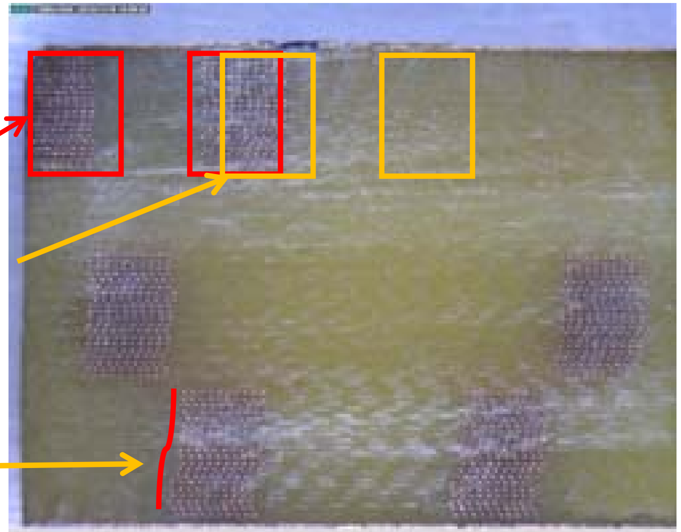


Faulty track on a layer

This…

…should be there !

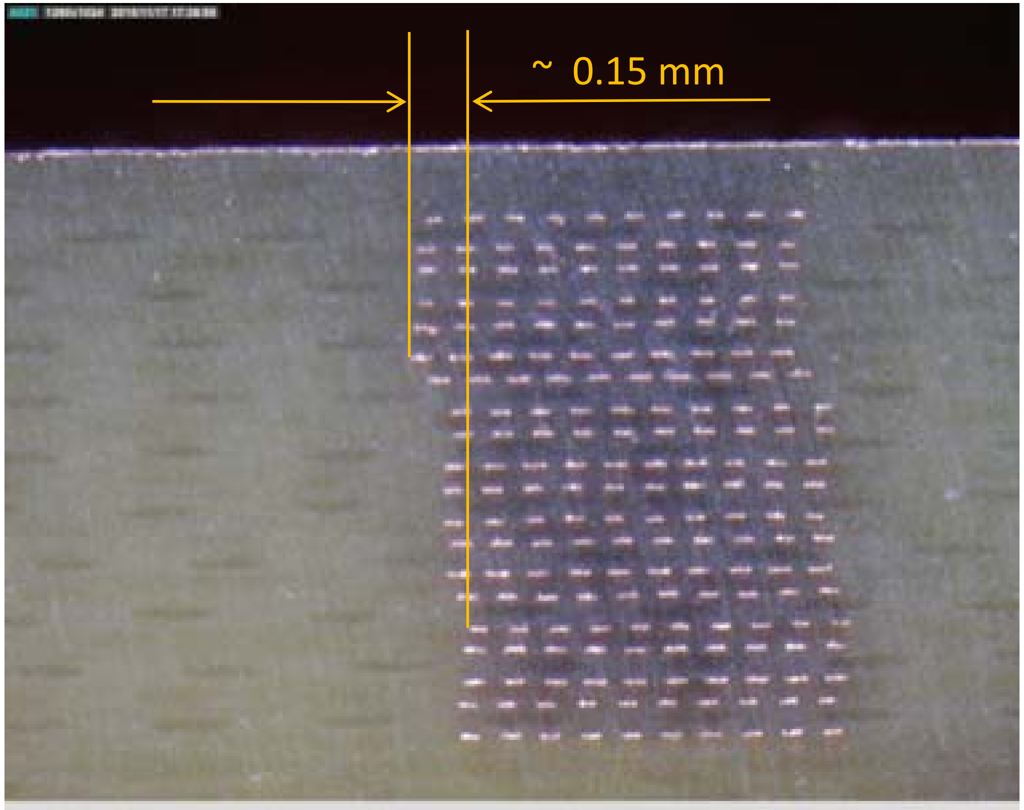
Coil slope



1st trial: stack-inversion and slope!

PCB-production:

Possible …and :



Coil with a slope due to badly adjusted pins and pinholes

Now make a rotating coil array from it:

1. **Electrical and magnetic check**
   - Coil resistance > 6 KΩ !
   - Layer inversion can only be checked magnetically, resistance remains the same !

2. **Cut the rough arrays precisely out of the plate**
   - Use pinholes as reference
   - We got 8 arrays from a plate of 25 x 30cm

3. **Machine the rough array to a rotating shaft**
   - The art is now to position the rotation axis perfectly centered w/r to the coils
   - A Swiss watchmakers company is the perfect partner for this operation

4. **Assembly of the shaft with ball bearings and cables, equipment with an extension and connection to a motor unit**

Rough array, coils well centered laterally

Machined coil array, central coil in the rotation axis

Coil and shaft assembly:

Cabling of the 3 coils

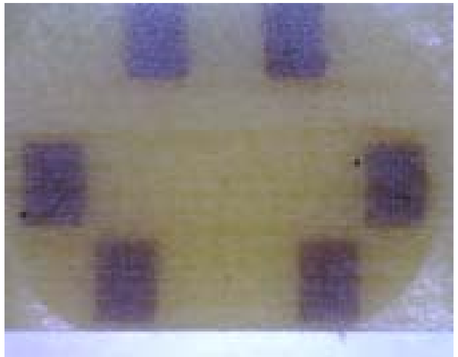
Watchmakers fine art

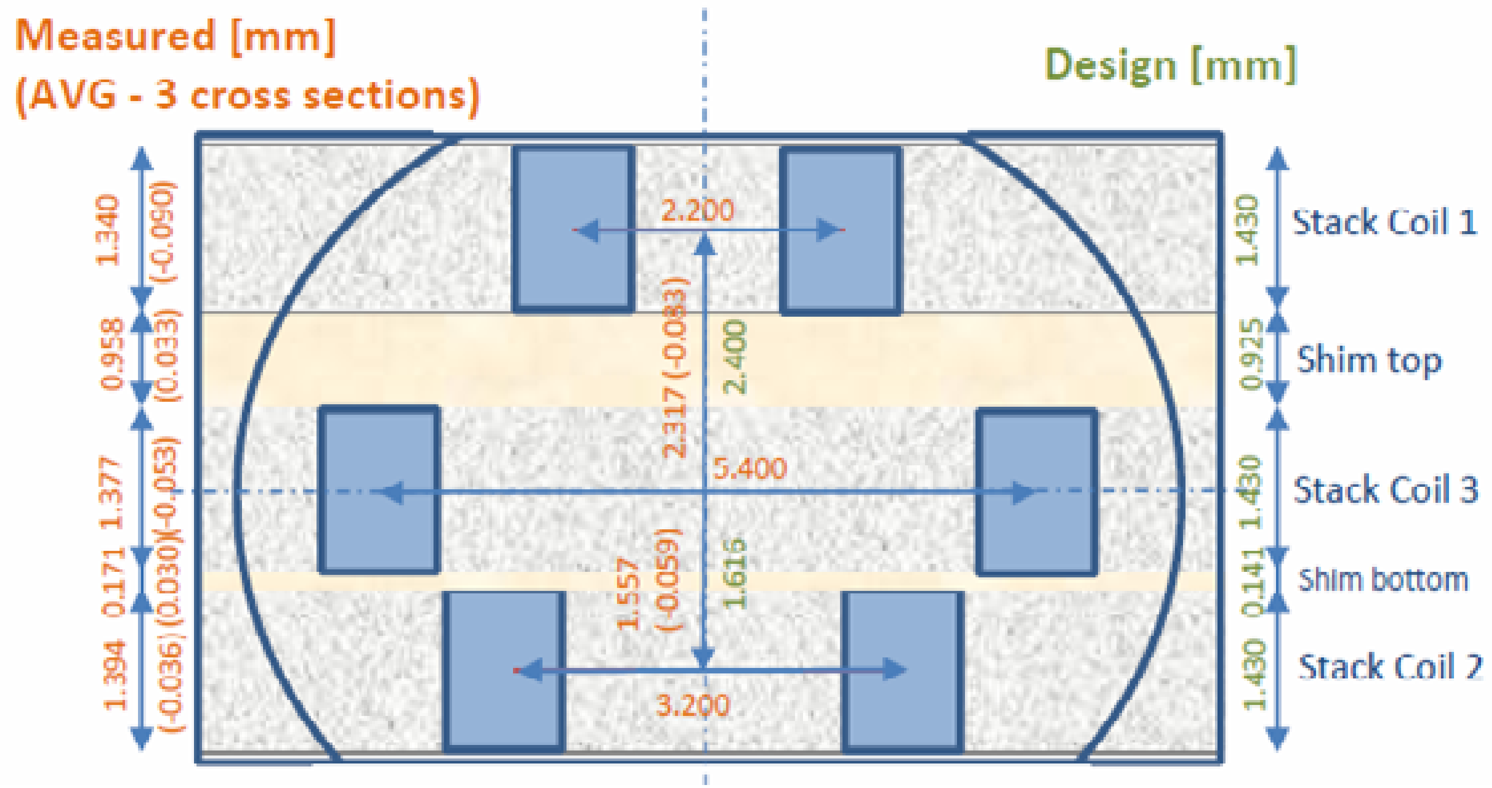
Delicate assembly

Assembly of a shaft

Dimensional Control and Magnetic Calibration

Measurements under a microscope
on a cut of a prototype:





Most of the dimensions within a few 0.01 mm accuracy

Dimensional Control and Magnetic Calibration

Magnetic calibration on a prototype:

	Central Radius			Measuring Radius		
No. turns:						
Coil:	Top	Central	Bottom	Top	Central	Bottom
Theory	2.4 mm	0 mm	1.616 mm	2.640 mm	2.7 mm	2.274 mm
Magn. Calibr.						
1st Prototype	2.335 mm	0.010 mm	1.580 mm	2.588 mm	2.698 mm	2.231 mm
Diff w/r theorie:	-0.065 mm	0.010 mm	-0.036 mm	-0.052 mm	mm	-0.043 mm
Diff Unitss	-278		-228	-201	-7	-193

Good mechanical precision (within a few 0.01 mm!)

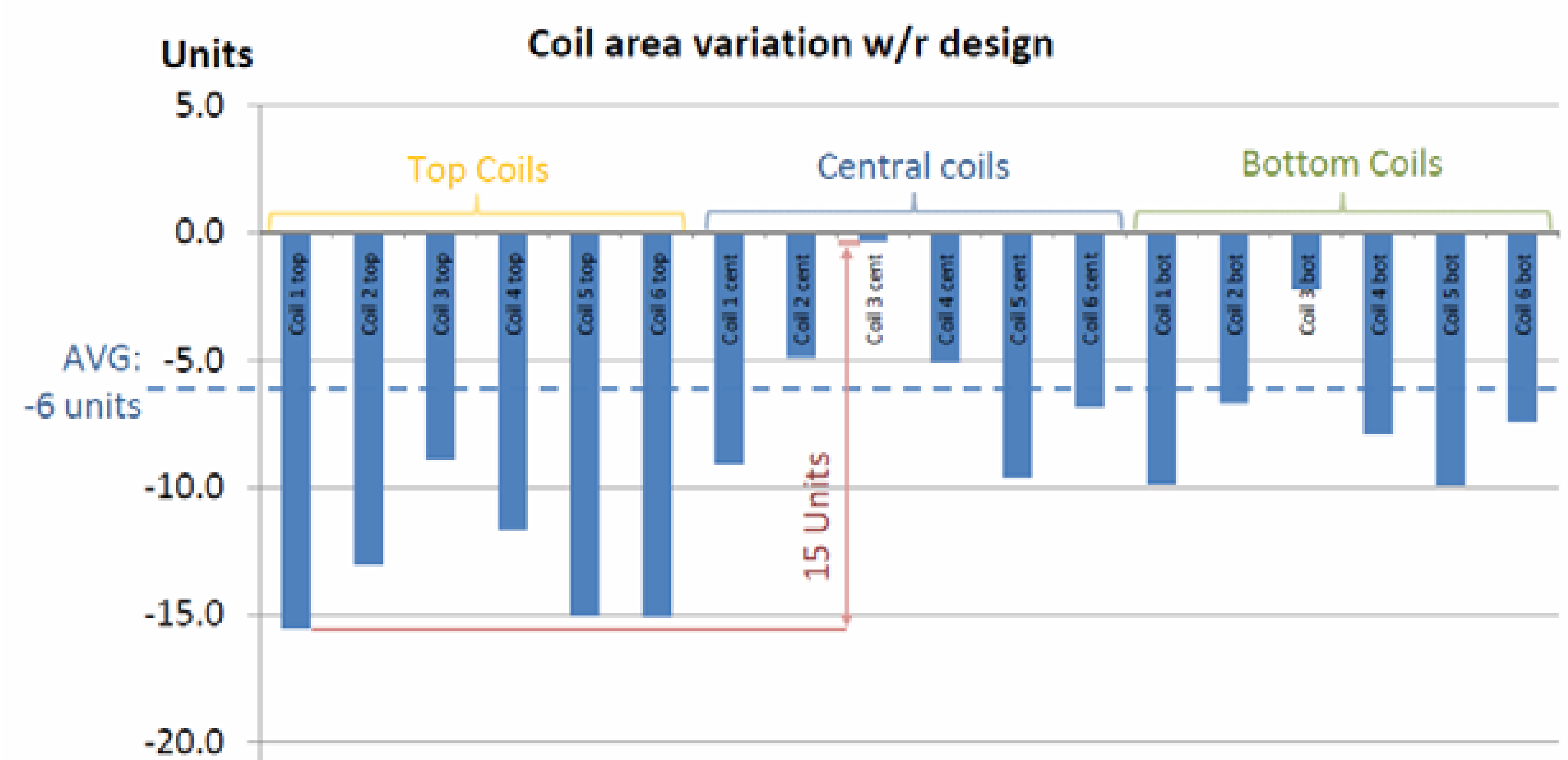
But high relative error due to small dimensions:

0.03mm on a radius of 1.6 mm = 2%!

→ Needs improvements

Dimensional Control and Magnetic Calibration

Accuracy of the coil areas is a lot better:

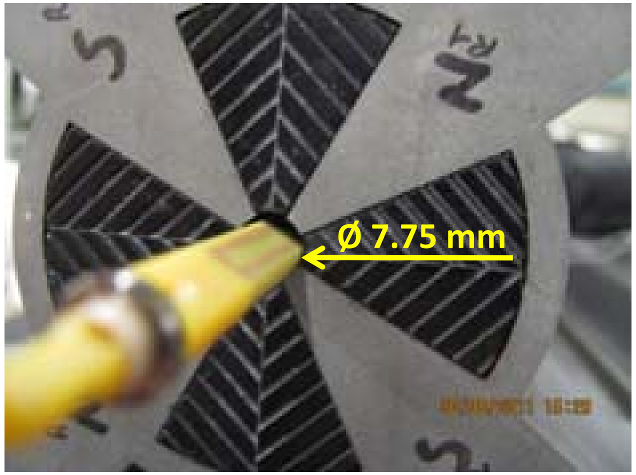


- AVG variation of 18 coils w/r design: **-6 units**
- Abs. variation of all 18 coils: **15 units**
- Abs. variation of diff coil shapes (top-, central- or bottom) : max. **8 units**

→ Very regular coil areas

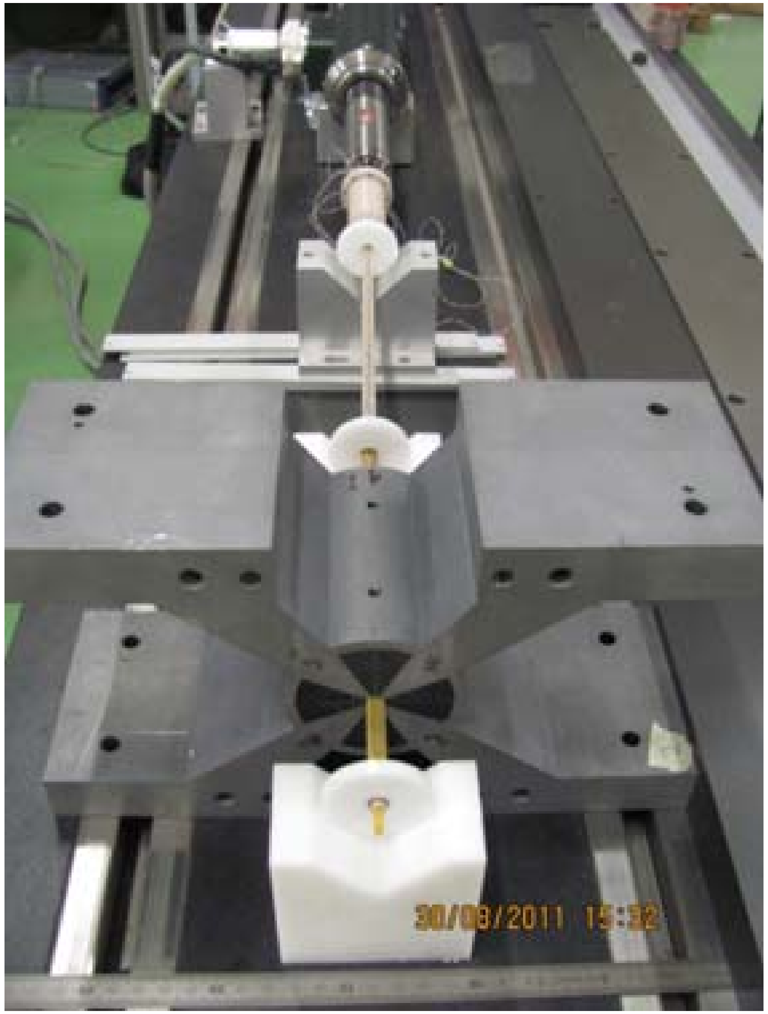
First Measurements

Installation in the CLIC "QD0 Short Prototype", l = 100 mm, aperture Ø 8.25 mm



Coils in the aperture

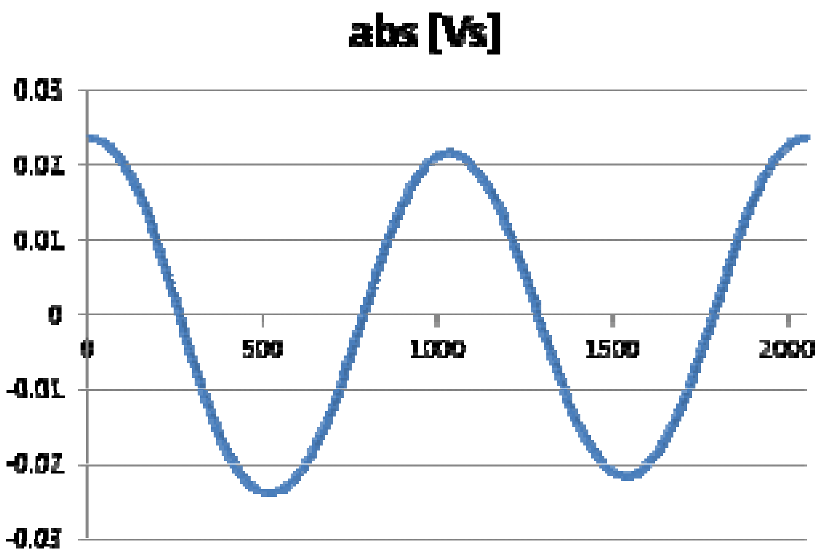
Connection of the shaft to the MRU motor unit



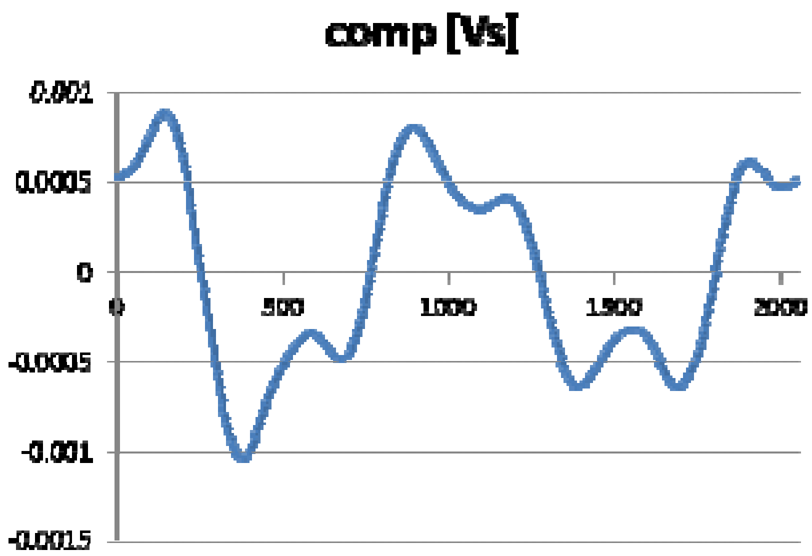
The measurement set-up

First Measurements

CLIC “QD0 Short Prototype”



Absolute signal [Vs]



Compensated signal [Vs]

→ **Bucking ratio: ~ 30**

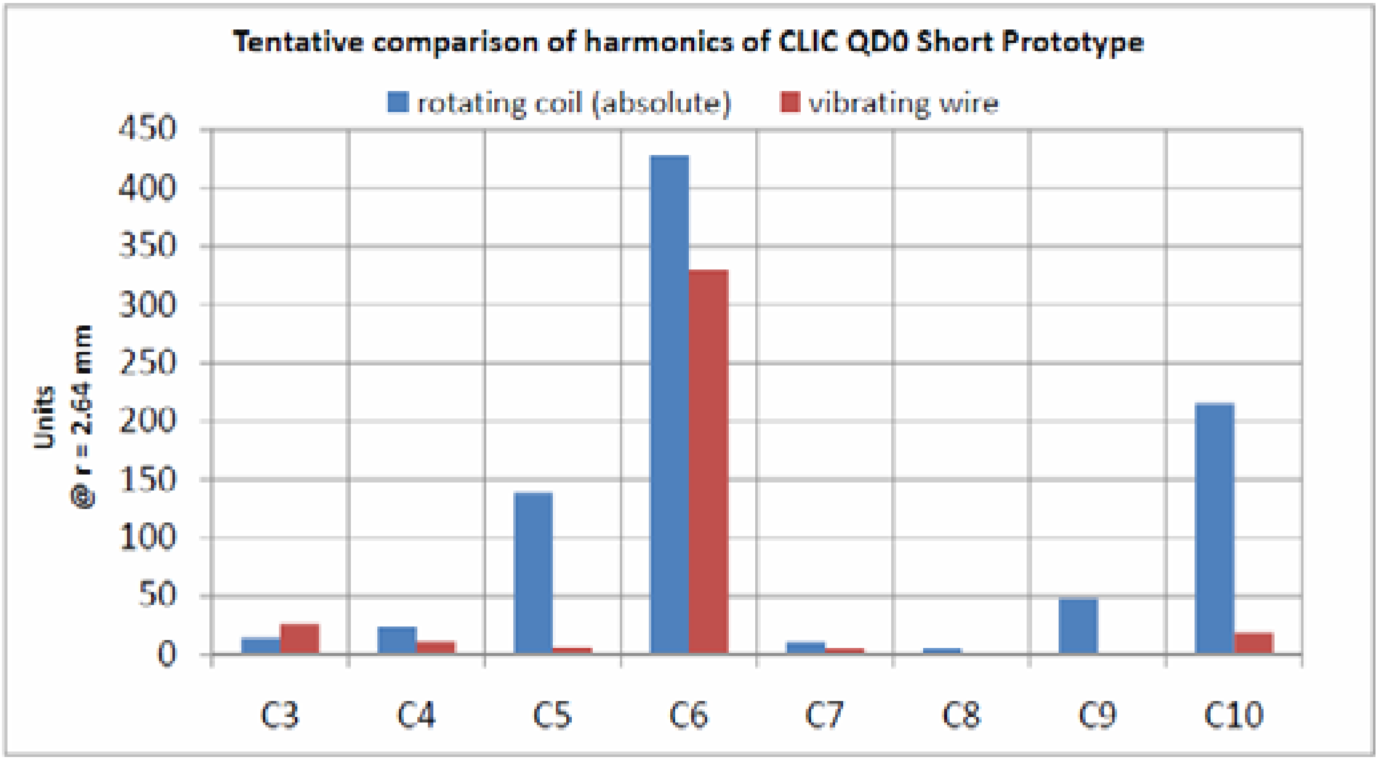
Preliminary Results:

CLIC "QD0 Short Prototype"

Gdl:

Rotating PCB coil:	20.64 Tm/m	→ **Diff. < 2 %**
SSW:	20.24 Tm/m	

Harmonics :



See also talks during this workshop:

**Carlo Petrone (CERN)
22-09-11, 10:00h**

**Juan Garcia-Perez (CERN)
22-09-11, 12:00h**

What we have experienced so far:

😊 and ☹

- Small sized coils relatively easy to design and to produce
- Precise coil geometry and excellent reproducibility of coil dimensions
- Compact electrical connection
- Coils with quite high resistance (close to integrator impedance)
- PCB-people don't think like MM-people: we need precisely piled up layers, a perfect control of the stack thickness, precise location of coils w/r to outside world; they do not…
- Control of the coils only possible after the manufacturing process
- No coil of the array can be changed in case of damage (or layer inversion!), the whole array is useless in this case.
- The shape of the rotating shaft happens after the coil-"winding", so the rotation axis must be positioned w/r to the existing coils
- Small shaft diameter makes the array weak and easily deformable
- Delicate assembly of a measurement set-up due to extremely small sized components.

→ Small PCB arrays are not "plug and play", but – until now - the only way to measure harmonics in small apertures

To do list:

- Improve magnetic calibration procedure

  (see also talk during this workshop: Lucio Fiscarelli (CERN), 20-09-11, 10:00h)

- Improve harmonic analysis w/r to particular coil geometry

- Improve manufacturing process for pcb-arrays, in particular the control of the vertical coil distance (measuring radius) and the straightness of the shaft

- Make cross checks with other measurement techniques (stretched wire, vibrating wire)

- Work on a solution for a long shaft (1.8m long magnet with 10 mm aperture)

- ….

Thank you for listening!

Any questions?