High-precision miniaturized rotating PCB coil for small magnet aperture

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Presentation
PACMAN
WORKSHOP

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ELTOS circuiti stampati professionali

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Instrumentation & Measurement for Particle Accelerator Lab
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Università degli Studi del Sannio

Fermilab

CLIC

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OUTLINE

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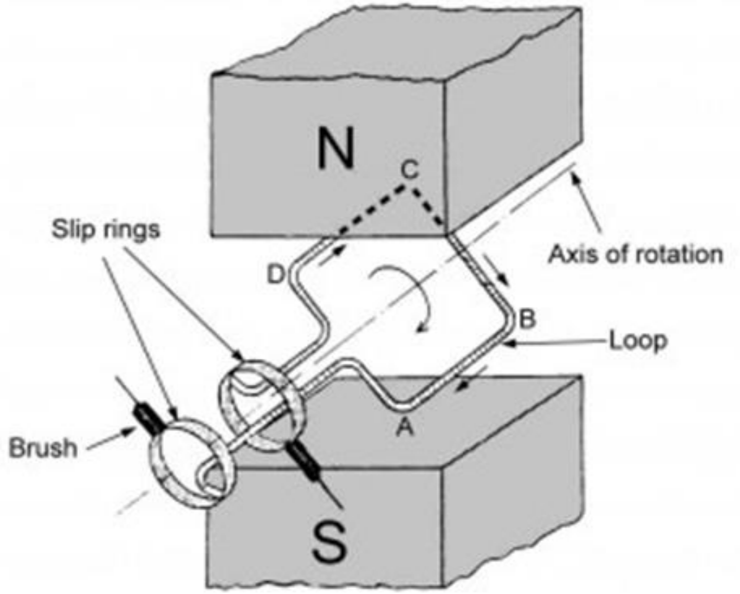
- **1. Understanding PCB probe design**
    - “Blind-eye” behavior of DQB PCB radial coil as function of layers thickness
    - How to move the BE of the DQB signal
    - DB and QB bucking dependence from coil thickness
- **2. PCB Manufacturing:**
    - Types of production
    - Methods used for CERN PCB miniaturized coil
- **3. PCB rotating coil calibration**
    - Classical calibration
    - CERN in-situ
    - FERMILAB in-situ
    - Fermilab individual rotation calibration (IRcal)
        - LabVIEW program for IRcal
        - Measurements with Fermilab setup
- **4. Small PCB CLIC coil:**
    - Short coil
    - Long miniaturized coil
    - Test-Bench
- **5. Alternative to standard PCB coil:**
    - Ribbon Cable probe (RC probe): new project at FERMILAB

Magnet alignment challenge…

Introduction

- The rotating coil method can be used for the magnet alignment. It can measure the magnet magnetic axis position by harmonic feed-down:
  - **Relative:** The magnet magnetic axis is referred to the geometrical center
  - **Referenced:** The magnet axis position is referred to external fiducials
- From the measured harmonic content other important magnet characteristics can be determined:
  - **Integral field gradient**
  - **Magnet field harmonics**
  - **Main field direction**
- Results can be cross-checked with vibrating-wire method

THE FARADAY LAW



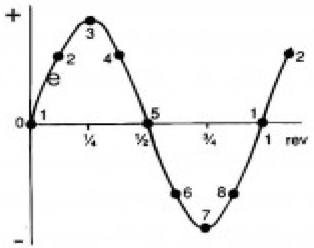
If a coil made of conductive material is rotated inside a magnet, the flux variation in time will induce an EMF. Then, the magnetic field harmonics can be determined and any magnet characterized.

Faraday's Law

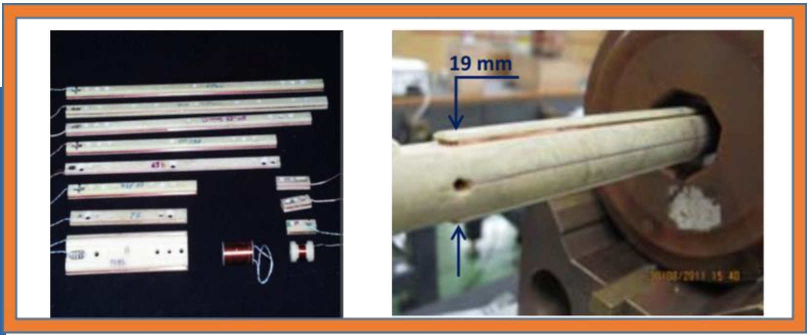
$$\varepsilon = -\frac{\Delta\Phi_m}{\Delta t}$$

ε = induced emf

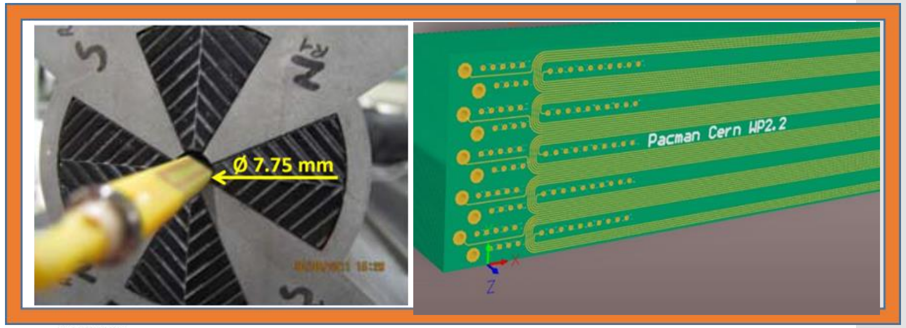
$\frac{\Delta\Phi_m}{\Delta t}$ = rate of change of magnetic flux through the circuit

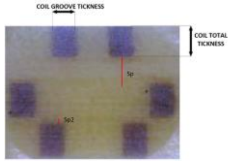


Hand-wound coils

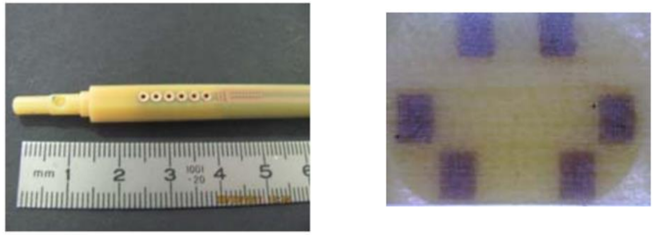


PCB coils





Rotating coils can be designed with different configurations



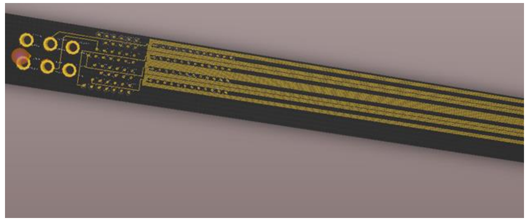
Tangential coils design

Independent coils outputs for
digital bucking
or
External analogue bucking

DB: Dipole Bucking
DQB: Dipole Quadrupole Bucking
DQSB: Dipole Quadrupole Sextupole Bucking

Radial coils design

On-board bucking



Independent output for digital bucking and on-board bucking

- Generally designed to have on-board **DB DQB DQSB**
    - Rotating coils with on-board bucking able to buck-out any harmonic order can be designed according to magnet apertures

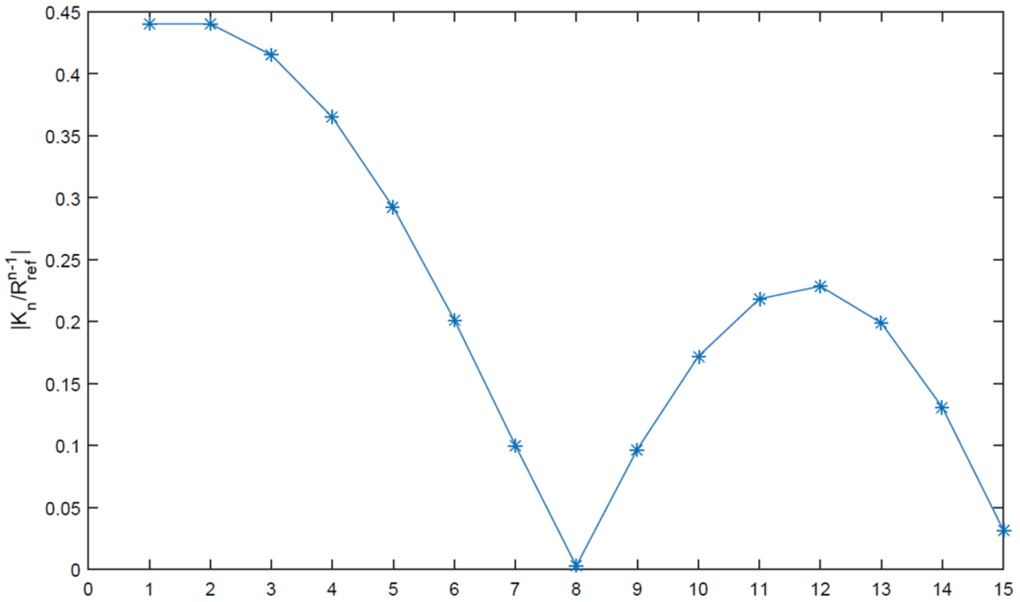
1. Understanding PCB probe design with on-board bucking

Studies for an optimized miniaturized PCB rotating coils design

“Blind eye” (BE)

<u>Example:</u> sensitivity behavior of a tangential coil

- Typical behavior of tangential coils.
- Determined from the opening angle ΔΘ of the tangential coil
- Radial coils have no BE behavior. Bigger ΔΘ determines a higher sensitivity for the first harmonics, smaller ΔΘ leads to a higher sensitivity to the higher harmonics



Length fixed to 1 m since the coil is longer than the magnet

<u>Sensitivity can be:</u>

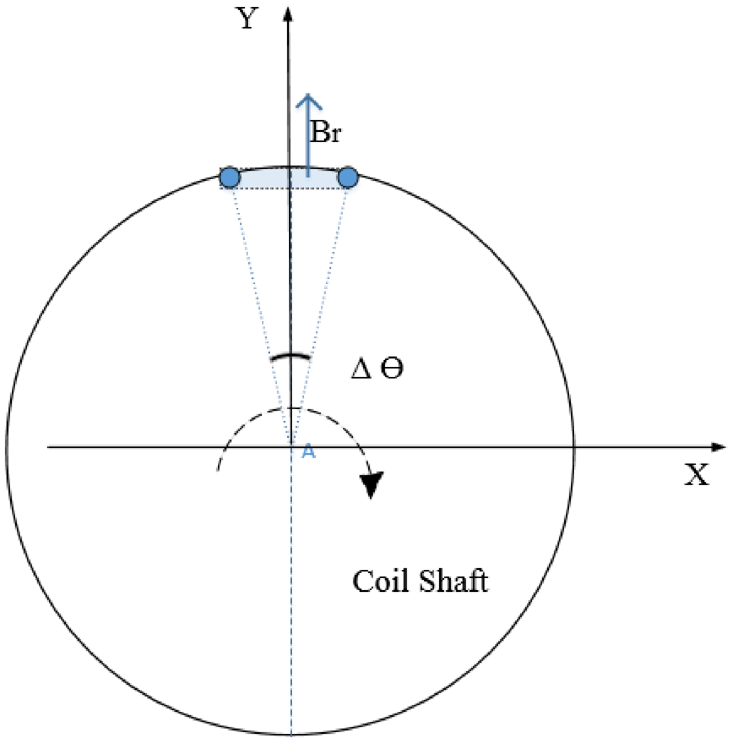
<u>-poor :</u>

_if the BE falls between two harmonics

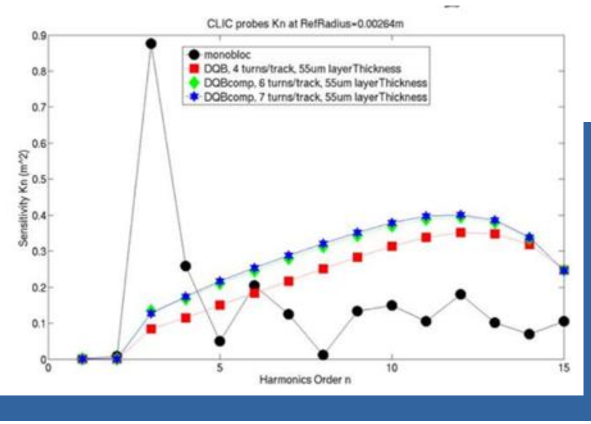
<u>-absent :</u>

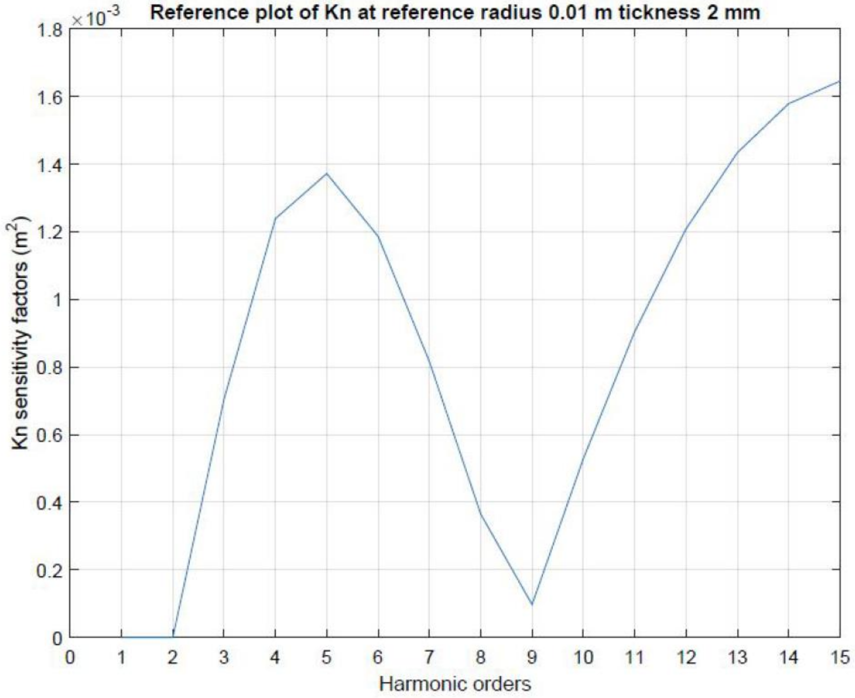
if the BE falls in correspondence of one harmonic (Example). <u>No sensitivity means that we are measuring only noise!</u>

What is the sensitivity behavior of a set of radial coils ?



BE behavior of DBQ PCB radial coil as function of layers thickness



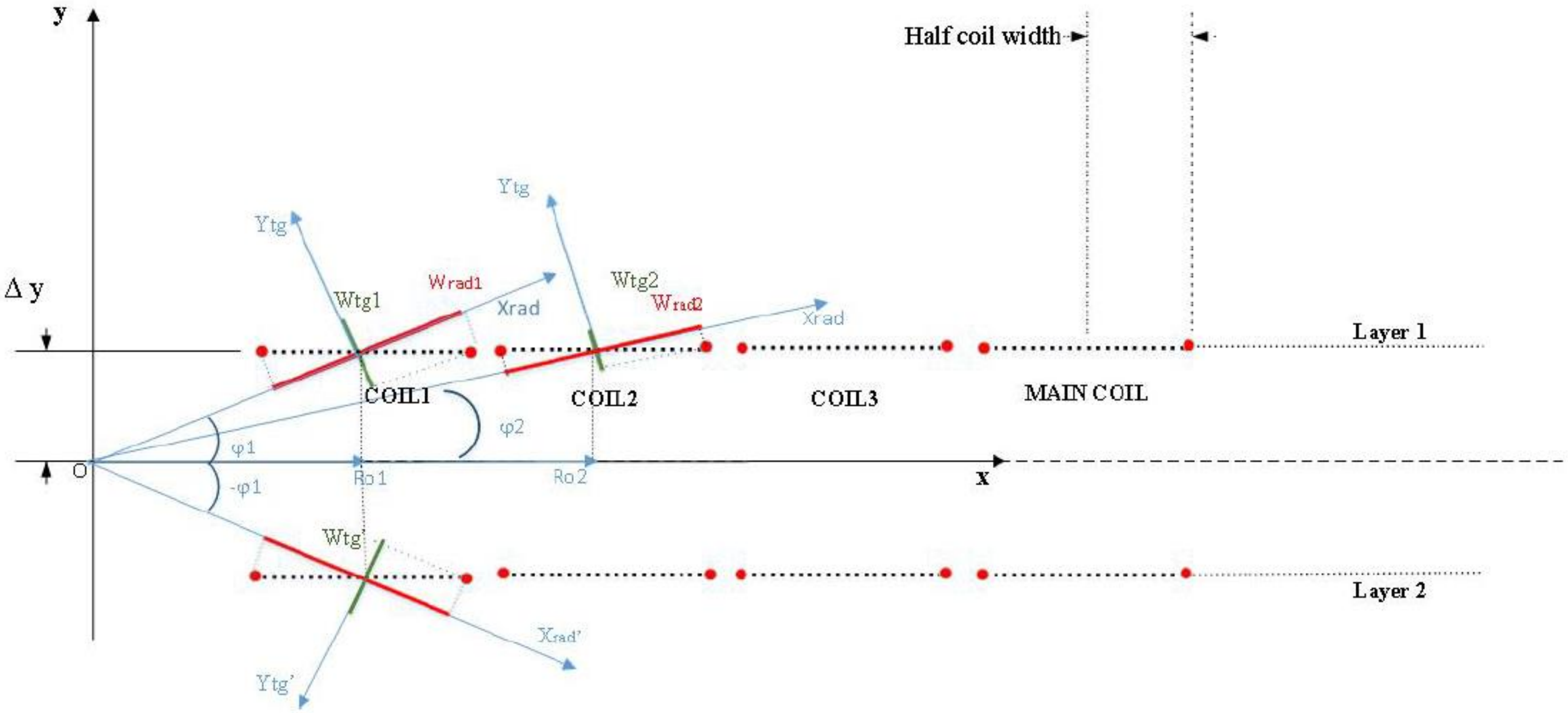


- Radial PCB coil with on-board bucking shows for some values of layers thickness a tangential behavior, not typical of radial coils.
- Coil assembly (sum of coils with different chirality) has a relative minimum similar to the tangential coil BE.
- Tangential coils DQB show a non homogeneous sensitivity
- Radial coils DQB show a homogenous sensitivity for small board thickness compared to the most external track radius.

To determine the BE cause and behavior:

- Simple case study focusing on a radial coil with on-board bucking with only two layers, 1 turn and length of 1 m and outermost trace of 10 mm.
- Evaluation of the undesired tangential component, present because thick coils are not purely radial

“Blind eye” behavior of DBQ PCB radial coil as function of layers thickness



- Superposition of effects → Coil’s radial and tangential components study, sum of the components’ effect → Kn factors calculation.

<u>At this aim, we approximate the system as linear, this will bring an error to higher-order harmonics</u>

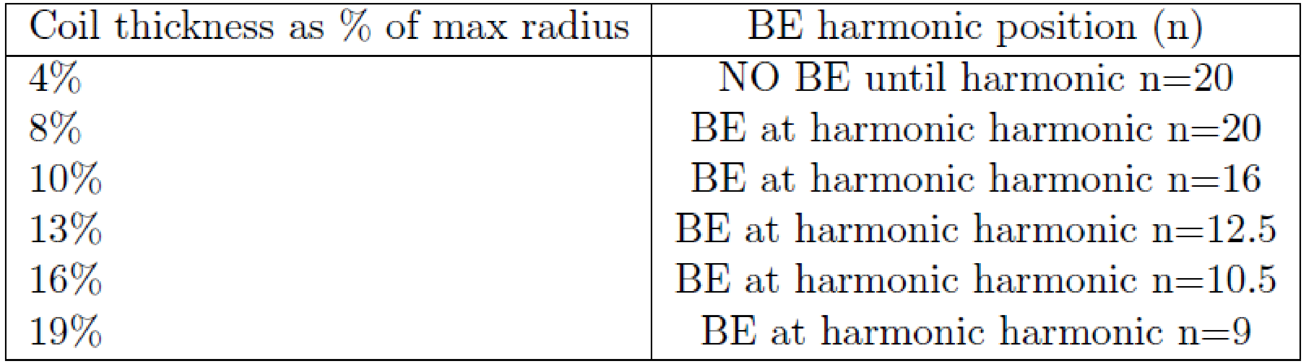
This error is extremely small and the radial/tangential separation gives the possibility to see the **effects due to the undesired tangential component resulting from the layer thickness**

“Blind eye” behavior of DBQ PCB radial coil as function of layers thickness

COIL THICKNESS OPTIMIZATION

→ it is clear that the BE behavior, usually associated with tangential coils, is due to the radial component instead.

The sum of the four coils shows BE behavior for big values of layer thickness.



Coil thickness as % of max radius	BE harmonic position (n)
4%	NO BE until harmonic n=20
8%	BE at harmonic harmonic n=20
10%	BE at harmonic harmonic n=16
13%	BE at harmonic harmonic n=12.5
16%	BE at harmonic harmonic n=10.5
19%	BE at harmonic harmonic n=9

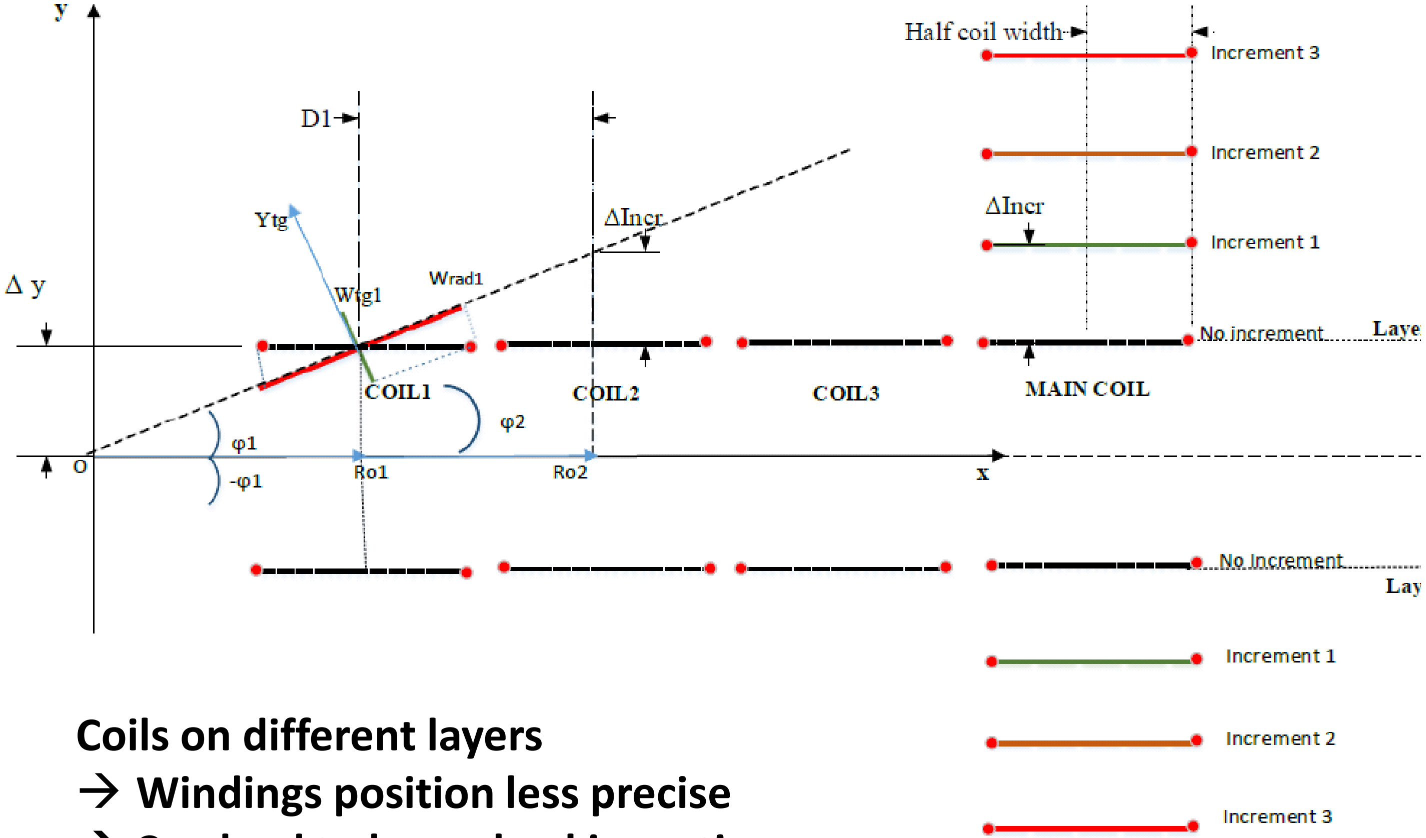
The study must be extended to the case of multiple layers :
In this case, the BE effect can be less strong due to the combination of BE effect of each layer with slightly shifted position

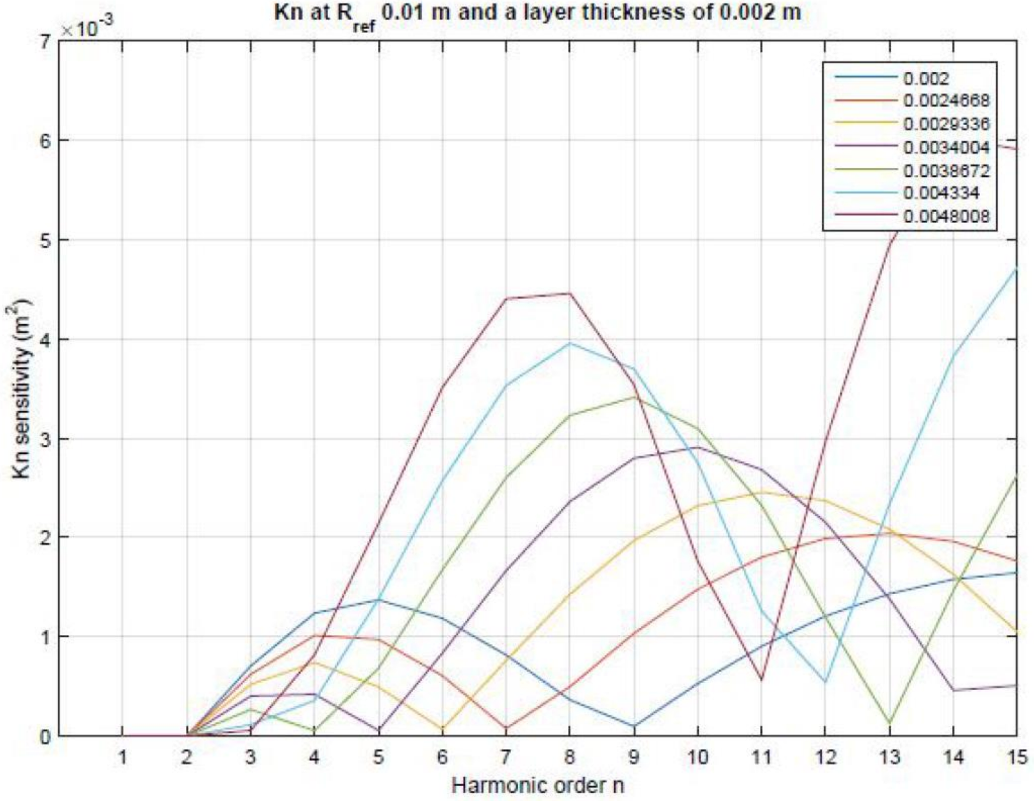
How to move the BE of the DQB signal Study

Customize the coil performances according to the magnet under test

The study was done for a two layers DQB coil

By only varying the thickness of the main coil it is possible to move the blind-eye and do a selective bucking of one single desired harmonic





Coils on different layers

→ Windings position less precise

→ Can lead to lower bucking ratio

2. PCB Manufacturing

Possible manufacturing methods for rotating coils

Printed circuit boards

- “ **Subtractive” manufacturing**

Rigid boards
- Planar geometries

->*50 -40 um tracks*

Flex boards
-Can be bent (< 4 layers)

->*30 um tracks*

-Necessity of tooling to avoid flex variations during manufacturing

Tracks material: Copper

-**IMPORTANT** :
to choose the good manufacturing process to fit the required tolerances

High-Density circuits require a special production

Thick film printed circuit boards

-”**Additive” manufacturing** (Serigraphic)

- On ceramic material (Glass, synthetic sapphire…)

3D shape can be done but width special tooling and is something of custom

- One mask for each layer with a different pattern technique suitable for high number of copies

Not suitable for tracks: below 100 um

Tracks material :

Gold: expensive
Silver : Problem of Ag migration in dielectric (multilayers) also with Pd

3D printed boards

- “**Additive” manufacturing**

Aerosol Printing:
-High density micro-droplets
-Tightly Focused

Inkjet:
Low density inks

Tracks material :
Ag nanoparticles
(Migration can be avoided)

- **3D shape can be done easily on one layer**
- **Multilayer**

Possible: *50 um tracks*

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PCB Production

Copper micro-incision to clean surface or to reach the desired thickness

Better to avoid to use micro-incision to reduce the copper height

Dry-film deposition with rollers

Exposition with LDI or photochemical process

The LDI was used for the PCB coils production

Dry-film Development

The speed must be opportunely chosen

Etching

- Spray (nozzles)
- Dipping

With horizontal or vertical machine: Vertical machine are more expensive but guarantee uniformity on two PCB double layer faces

Stripping

AOI Automated optical inspection

Troubles with 50 um/50 um tracks and spaces.

Optical stacking (Or by hand with precision tooling)and pressing

3. PCB rotating coil calibration

	CLASSIC CALIBRATION	CERN Displacement calibration	FERMILAB IN-SITU calibration	INDIVIDUAL ROTATION CALIBRATION
Board bucking type	No on-board bucking	No on-board bucking	on-board bucking	on-board bucking
Calibration frequency	Repeated as needed due to coil ageing effect and undesired displacement	Repeated as needed due to coil ageing effect and undesired displacement	Use as needed due to coil ageing effect and undesired displacement	Automatic update: Performed with every measurement
Magnets	Needs dipole and quadrupole reference magnets	Needs a quadrupole reference magnet	Reference magnet not needed, calibration done in situ	Reference magnet not needed, calibration performed with every measurement
Tooling	Dedicated custom tools	Needs precision linear stage	No linear stages needed	No linear stages needed
Calibration results metrology crosscheck	Not implemented	Not implemented	Implemented	Implemented
Use with short magnet	Can induce error	Can induce error	Can induce error	No induced error

CERN in situ calibration

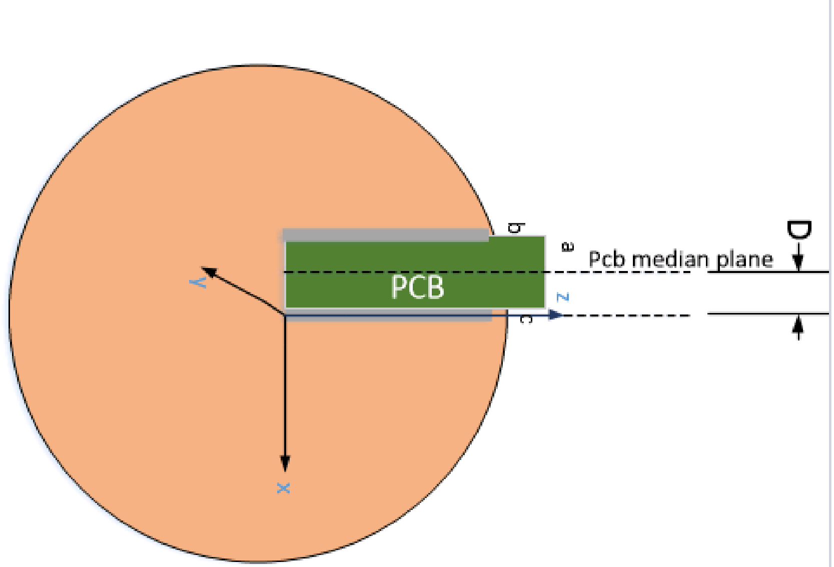
Coil area calibration:
Needs a SSW measurement of the magnet integral field. The magnet strength, corresponding to the integrated quadrupole gradient, is used to calibrate the coil effective width and area.

Rotation radius calibrated by measuring feed down dipole variation due to a coil and magnet relative displacement.

Fermilab in situ calibration

Error in PCB shaft assembly are calibrated:
Vertical displacement error D
Radial error

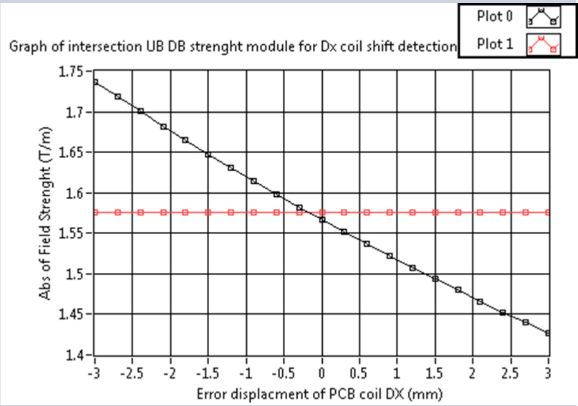
Results from UB ***strength*** to DB comparison



Individual rotation calibration (IRcal)

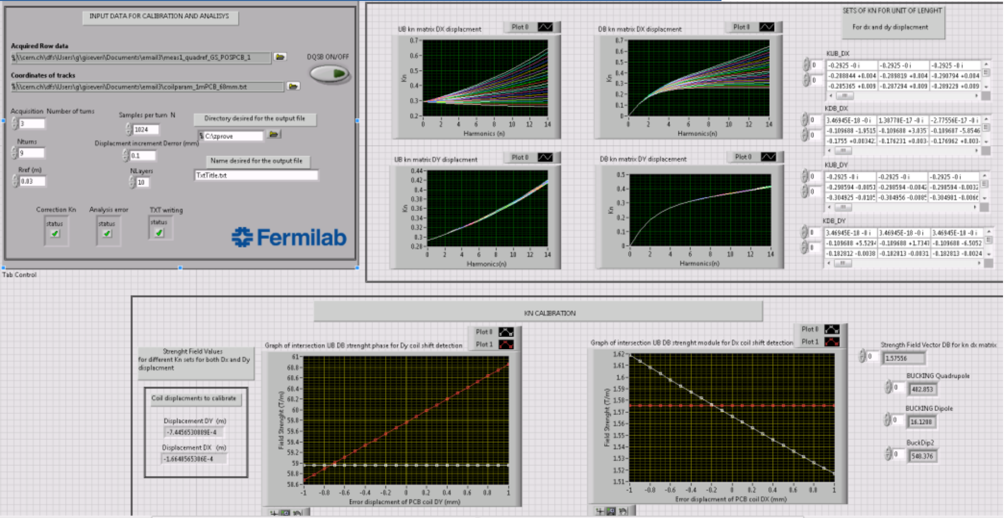
Error in PCB shaft assembly are calibrated:
Vertical displacement error D
Radial error

Results from UB ***strength*** to DB comparison



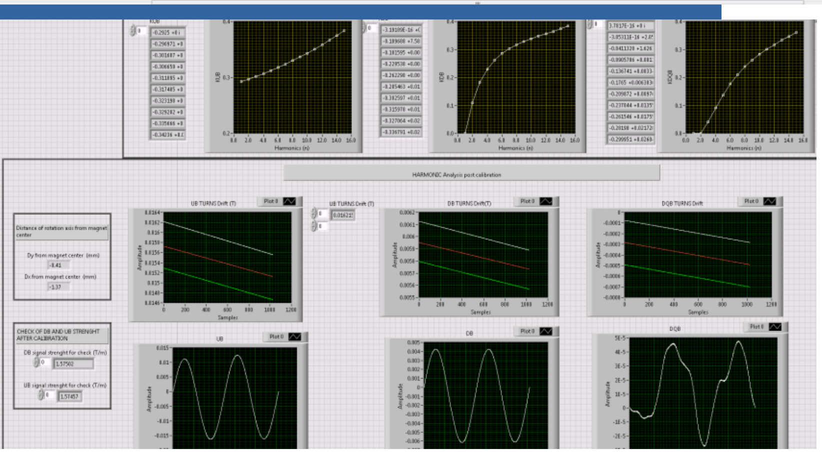
-> Uses a matrix of kn for both radial displacement Dx and Dy
Effective width can be measured from control tracks on both extremities

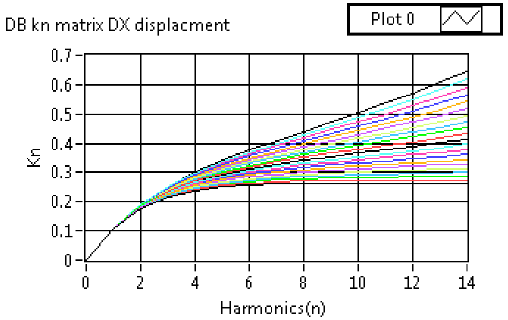
LabVIEW program for individual rotation calibration (IRcal) Implemented during the secondment activity

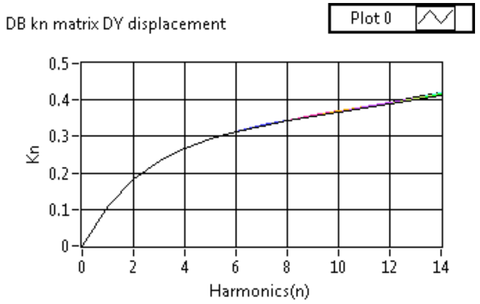


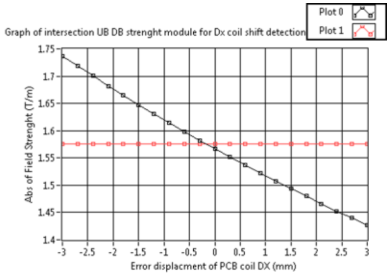
A matrix of sensitivity factors is created, representing successive board displacements for both UB and DB signals for both Dx and Dy displacements.

Kn matrix are applied to each coil turn to find the final board displacement values.









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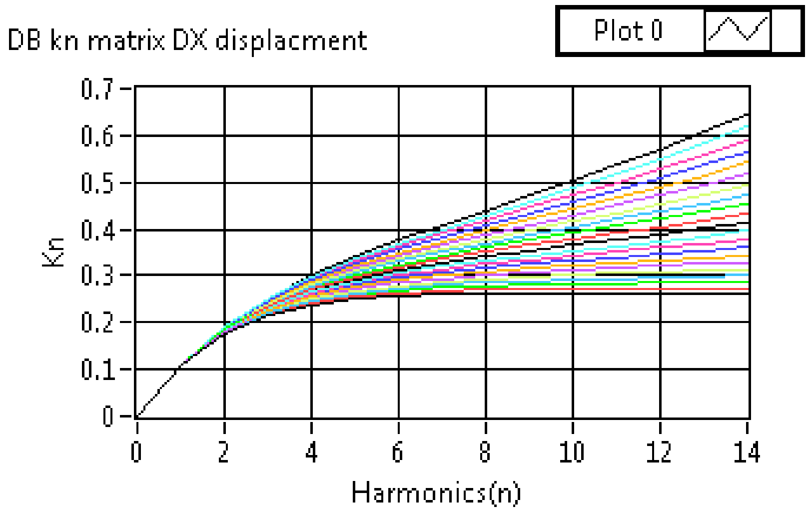
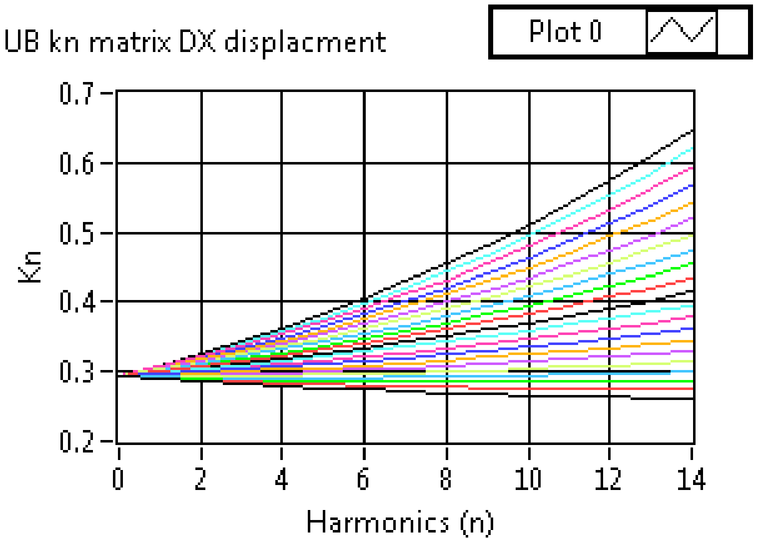
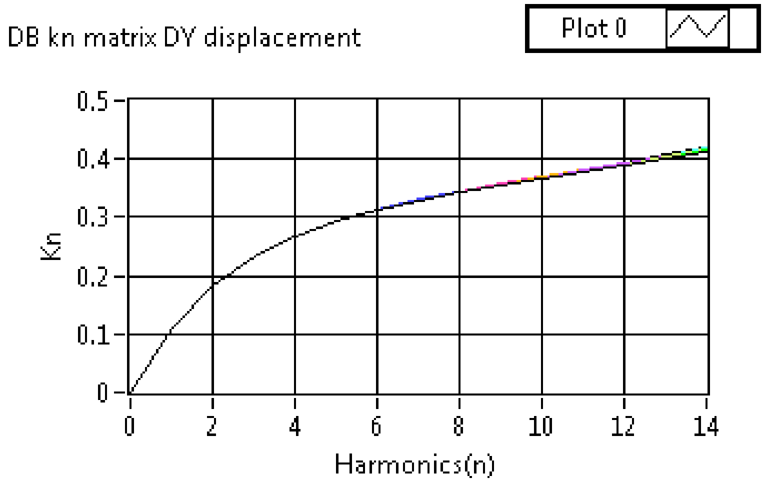
Individual Rotation calibration (IRcal)

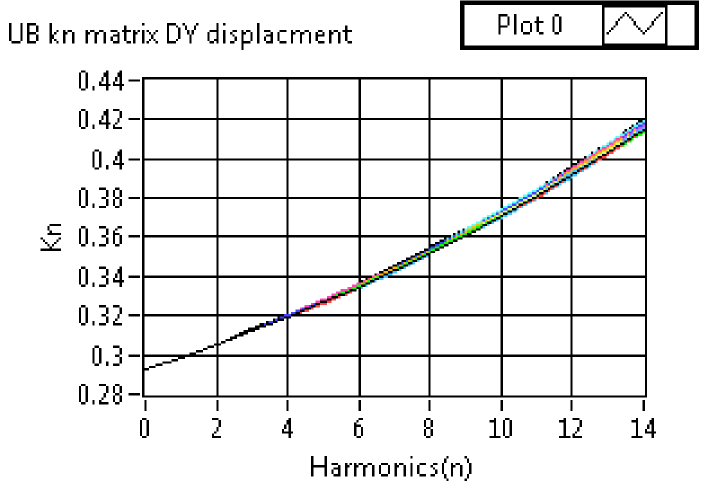
Matrix of Kn to calibrate the shift of the PCB COIL both for DB and UB

The shift along the dy direction determines a smaller variation compared to the dx shift


DB kn matrix DX displacment

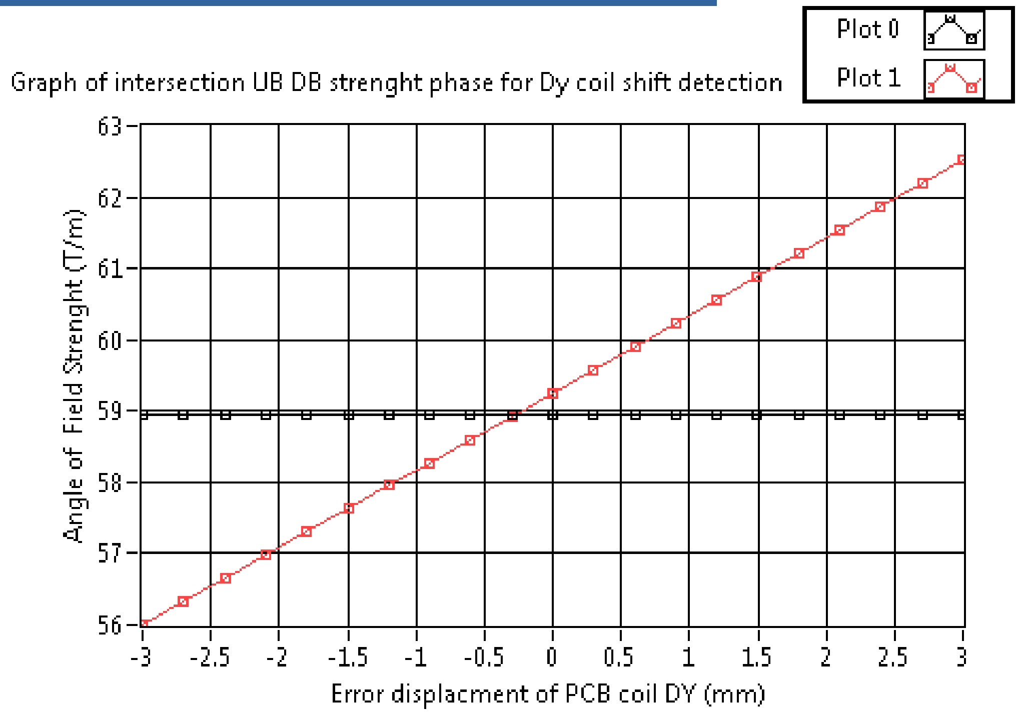

UB kn matrix DX displacment

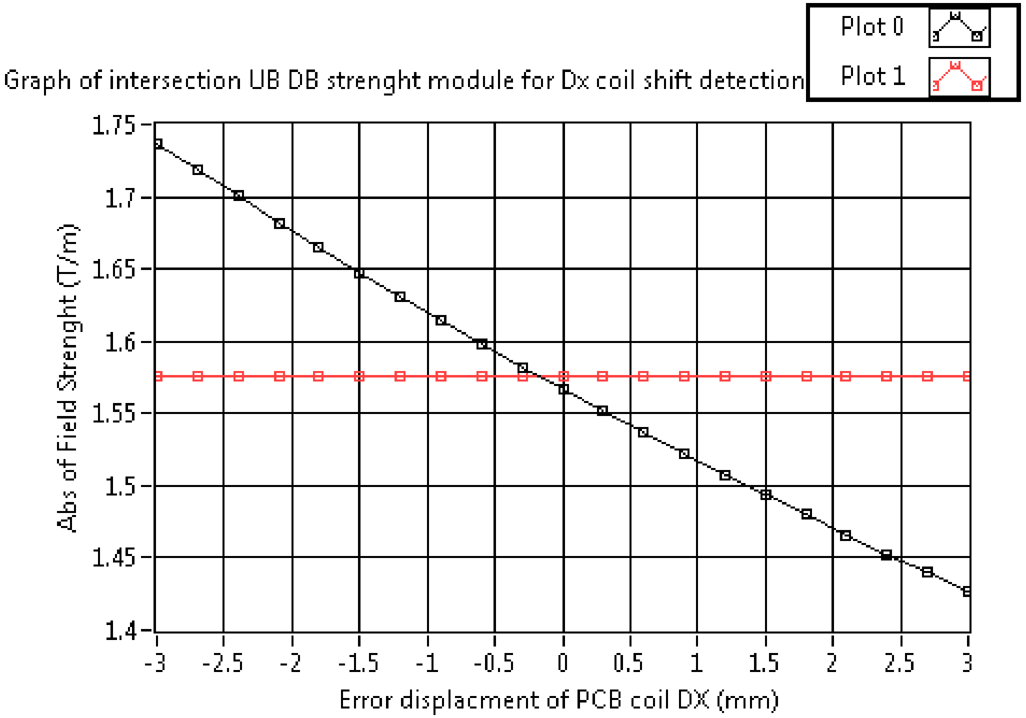

DB kn matrix DY displacement


UB kn matrix DY displacment

Program test with Fermilab Rotating coil Probe

The Program was tested with the Fermilab PCB coil with DB DQB and DQSB

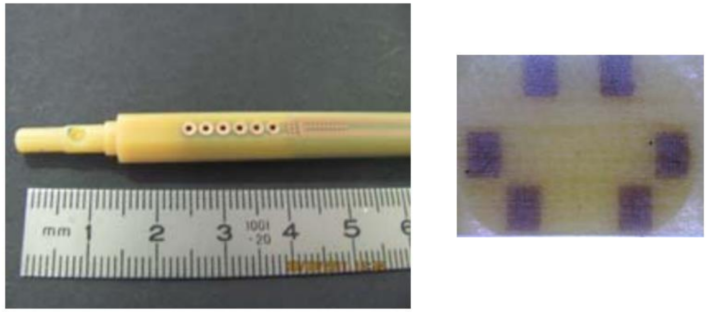




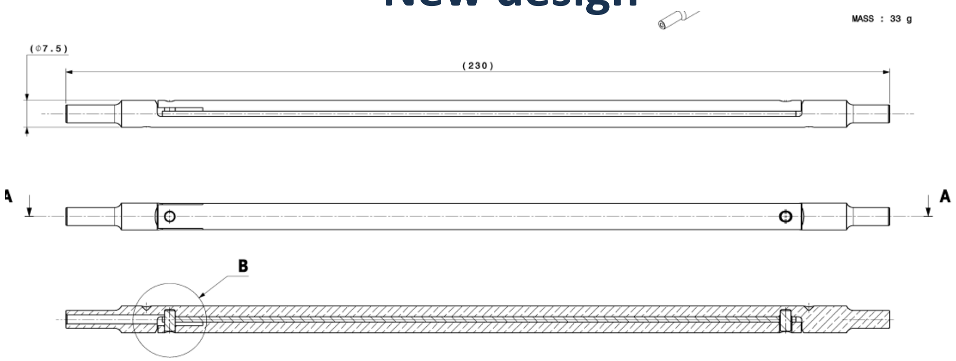
4. Small PCB CLIC coil

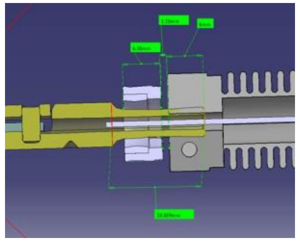
Double research Gap

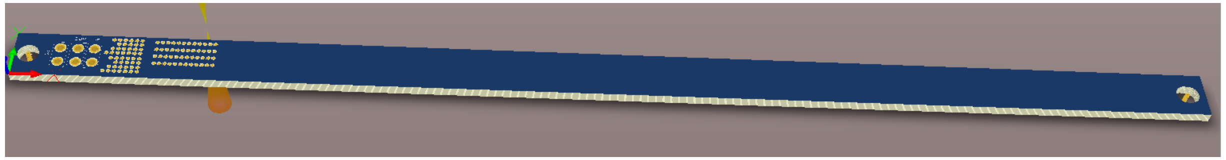
Old design

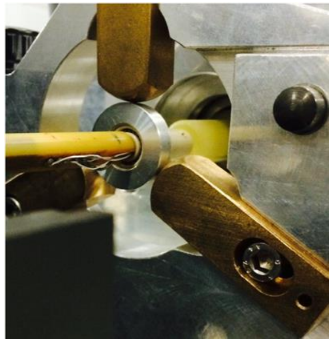


New design



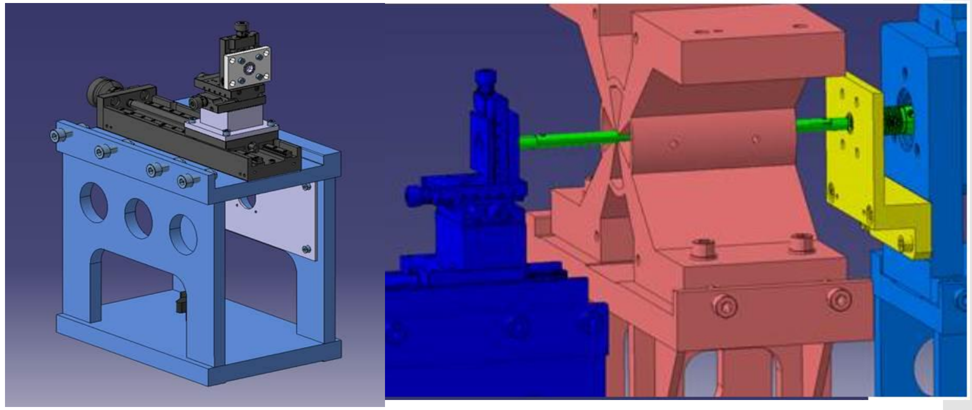






Old design

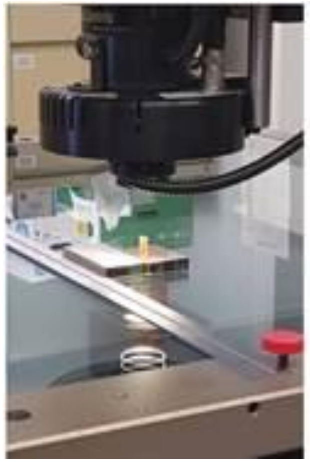
New design

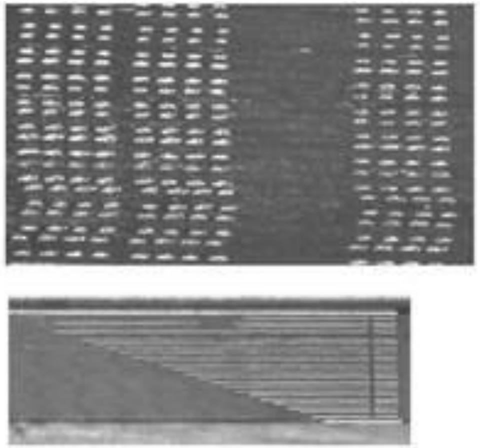


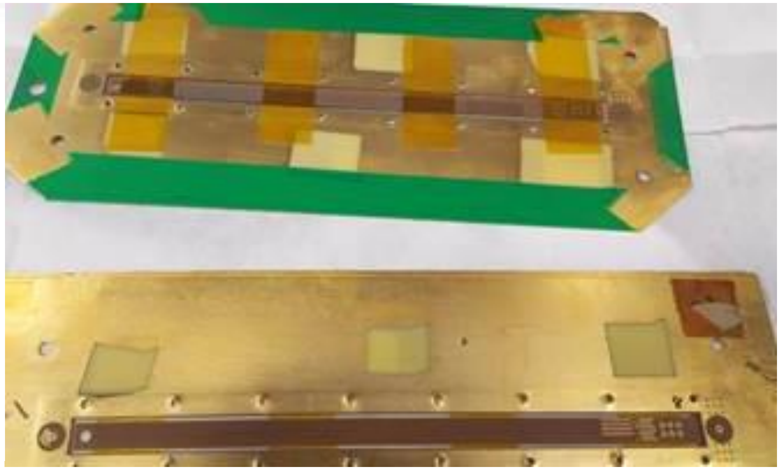
First PCB CLIC prototype

CLIC First Pacman Prototype

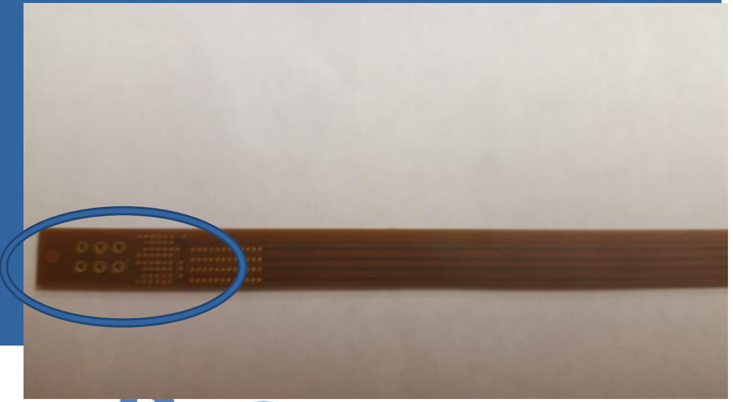
- PCB done at CERN PCB service
- Shaft for test done at Fermilab during the secondment







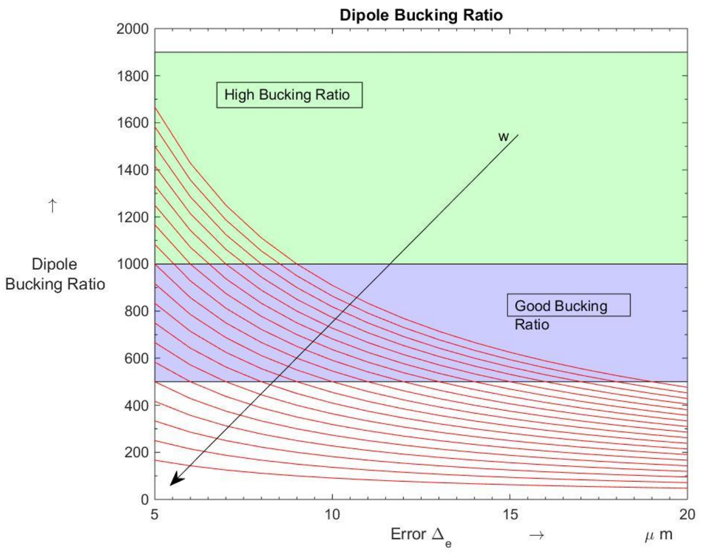
- High Precision Alignment Both Horizontal than longitudinal (26 layers coil)
- First version of Shaft implemented at FERMILAB is done with G10



Sagitta only due to external sapphire shaft (high young modulus), not to PCB.

First PCB CLIC prototype

CLIC First Pacman Prototype



FIRST NEW Prototype:

DQB ≈ 142

Measurements done at Fermilab. Several possible improvement action will be applied already to the long version of CLIC coil 500 mm

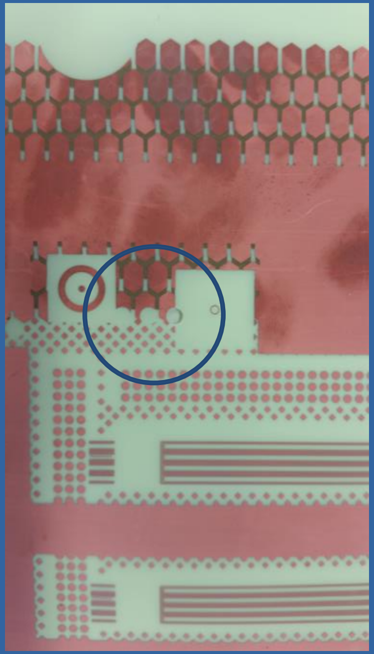
Old Prototype Design*:

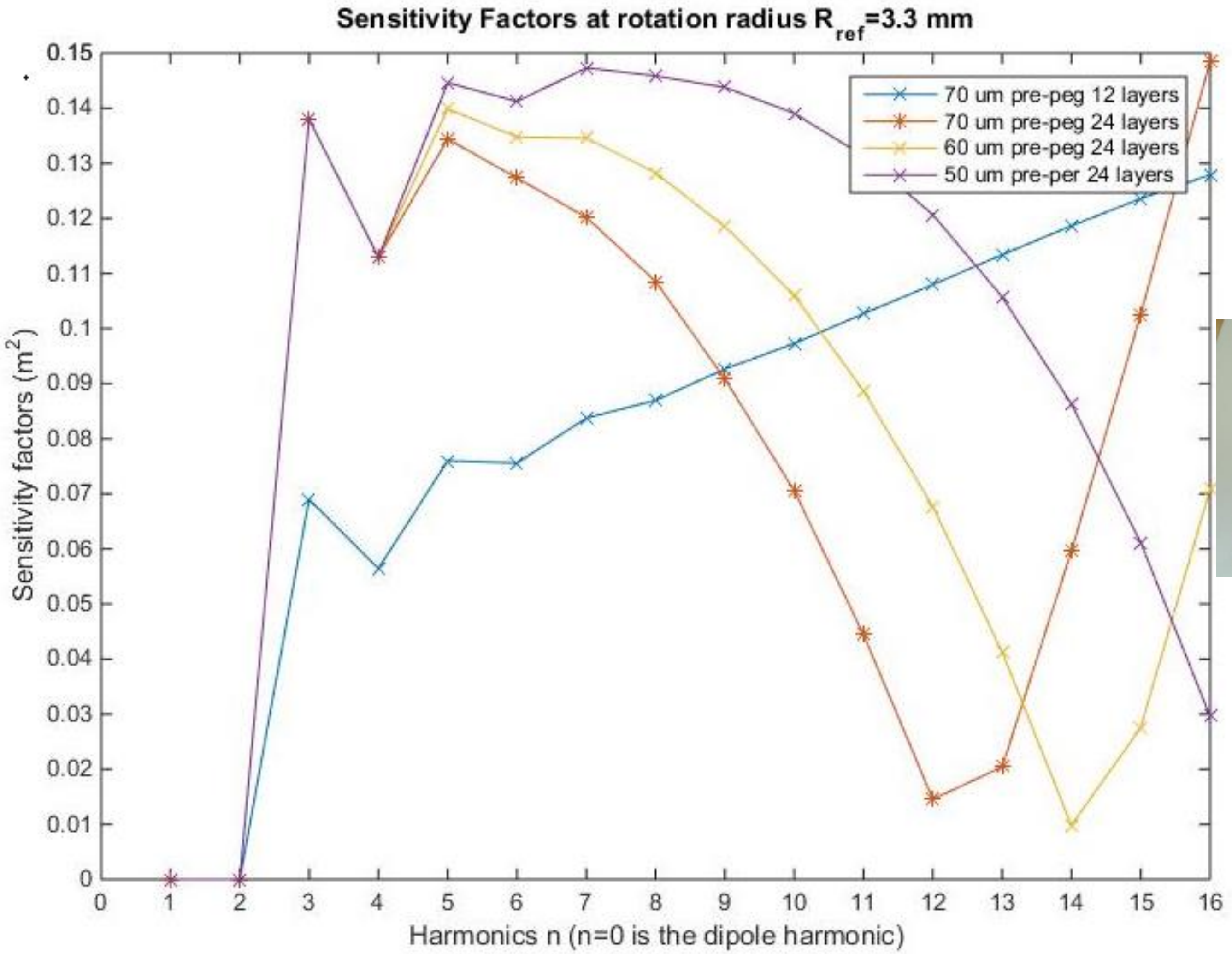
DQB ≈ 30

*IMMW 17 - INTERNATIONAL MAGNETIC MEASUREMENT WORKSHOP La Mola, Terrassa-Barcelona, Catalonia (Spain) 18-23 September 2011

Sensitivity point of view

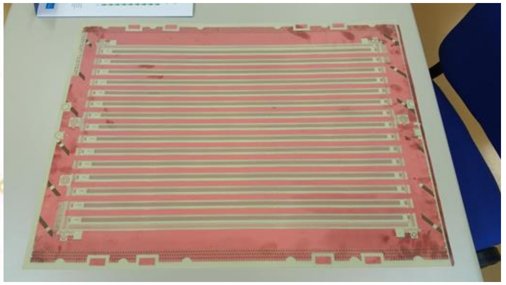
Design parameter are important





Trade off between:

Price, sensitivity and tolerances



5. Alternative to standard PCB coil

Activity during the Fermilab secondment

3d printed shaft for the ribbon COIL

RIBBON COIL HOLDER

RIBBON COIL FEATURES:

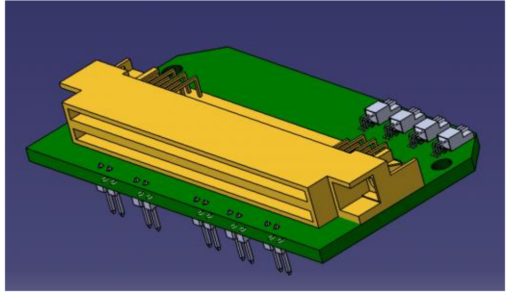
-Length 3 m

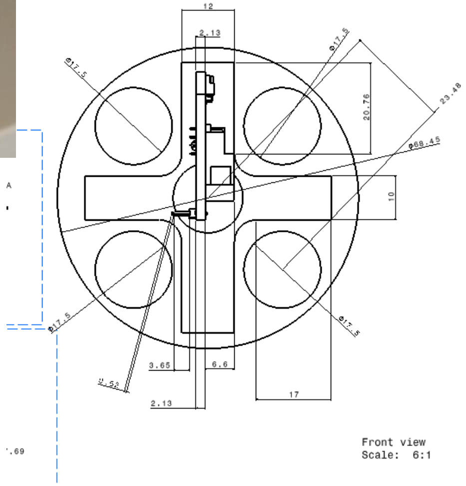
-connector will be hidden in the shaft

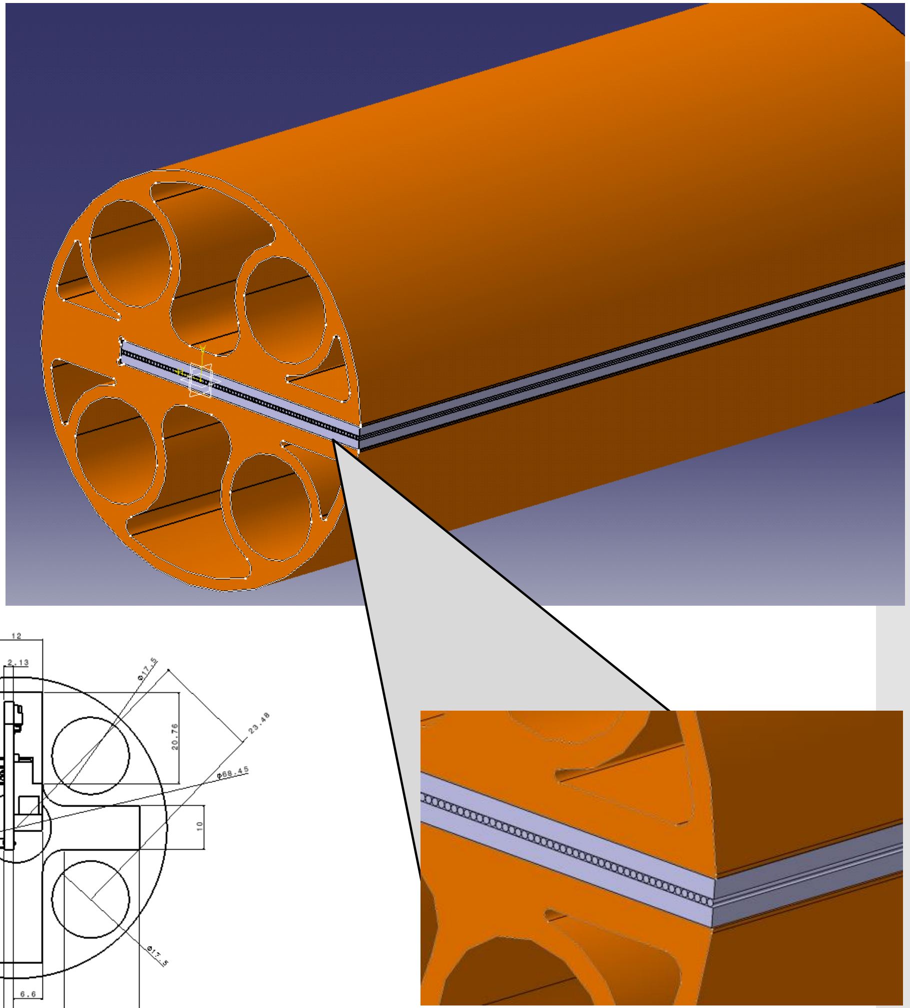
-3d printed shaft

- Shaft for test and design done at Fermilab during the secondment

Designed with CATIA







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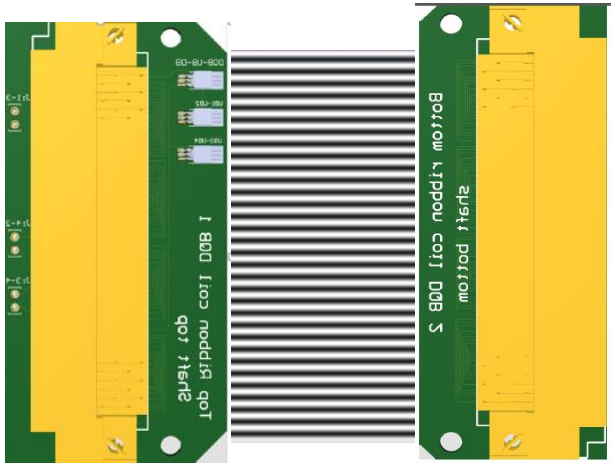
RIBBON COIL CONNECTORS DESIGN

ADVANTAGES OF RIBBON COIL:

- **ANY LENGTH**
- **EASY TO COSTUMIZE**
  - ADJUSTABLE LENGTH (ALSO MORE THAN 3 m)
- **SHAFT PIECES CAN BE REUSED FOR DIFFERENT LENGTH**
- **EASY TO REPAIR**
  - PIECES CAN BE CHANGED INDIPENDENTLY
- **THERE ARE NO DELAYS DUE TO PRODUCTION TIME:**
  - THE CONNECTOR USED ARE A STANDARD PRODUCTION AND CHEAP COMPARED TO A STANDARD PCB COIL



4 Signal Layers
Output signals:

-UB1 UB2 UB3 UB4
-DQB DB

4 Signal Layers
Output signals:

-UB1/A UB2/A UB3/A
-DQB/A DB
-DQB/B UB1/B UB2/B UB3/B
-DQSB

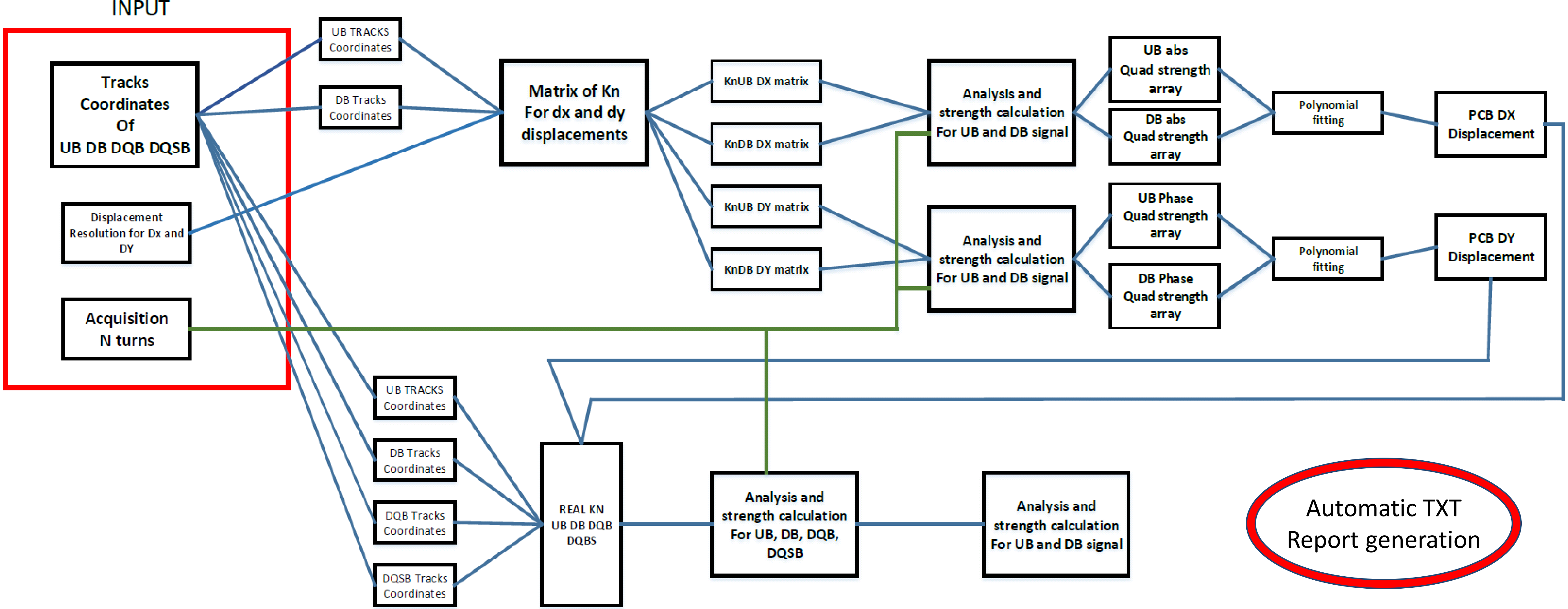
Conclusion

- Research on miniaturized rotating coils lead to building a set of design rules for high performance PCB transducers
- Using these design rules, coils’ properties can be tuned to obtain an optimized design for the type of magnet under test
- Alternative designs exist for long coils
- The new long prototype for CLIC is under construction, first results will be presented in the next 2 months

Thank you for your attention

LabVIEW program for IRcal

MAIN SCHEME



INPUT

Tracks Coordinates Of UB DB DQB DQSB

Displacement Resolution for Dx and DY

Acquisition N turns

UB TRACKS Coordinates

DB Tracks Coordinates

Matrix of Kn For dx and dy displacements

KnUB DX matrix

KnDB DX matrix

KnUB DY matrix

KnDB DY matrix

Analysis and strength calculation For UB and DB signal

UB abs Quad strength array

DB abs Quad strength array

Polynomial fitting

PCB DX Displacement

Analysis and strength calculation For UB and DB signal

UB Phase Quad strength array

DB Phase Quad strength array

Polynomial fitting

PCB DY Displacement

UB TRACKS Coordinates

DB Tracks Coordinates

DQB Tracks Coordinates

DQSB Tracks Coordinates

REAL KN UB DB DQB DQBS

Analysis and strength calculation For UB, DB, DQB, DQSB

Analysis and strength calculation For UB and DB signal

Automatic TXT Report generation

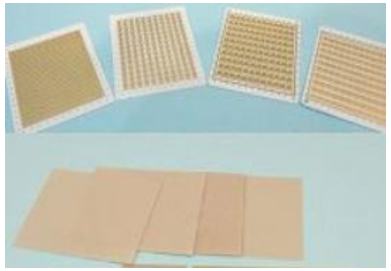
PACMAN Eltos circuiti stampati professionali SIGMAPHI Instrumentation & Measurement for Particle Accelerator Lab IMPALA Fermilab Università degli Studi del Sannio clic CERN

Other Options

Flex PCB

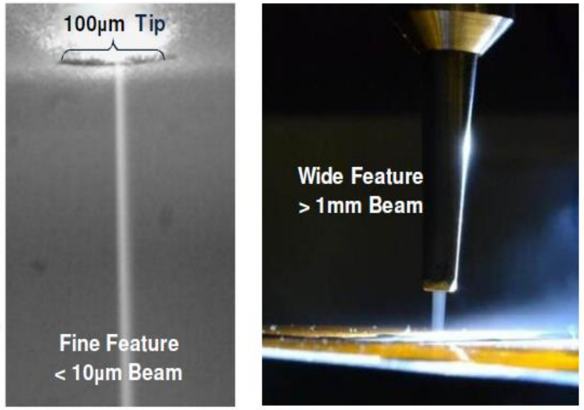
Rigid PCB

Thick-film

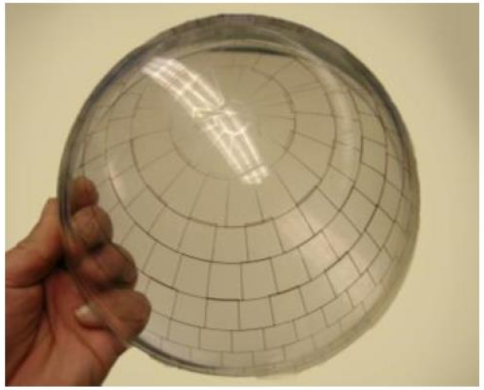


All THESE ARE EXPENSIVE!!!
THERE ARE A LOT OF MANUFACTURING PROBLEMS FOR BIG SIZE COIL

Aerosol-printing
Photos from Optomec site



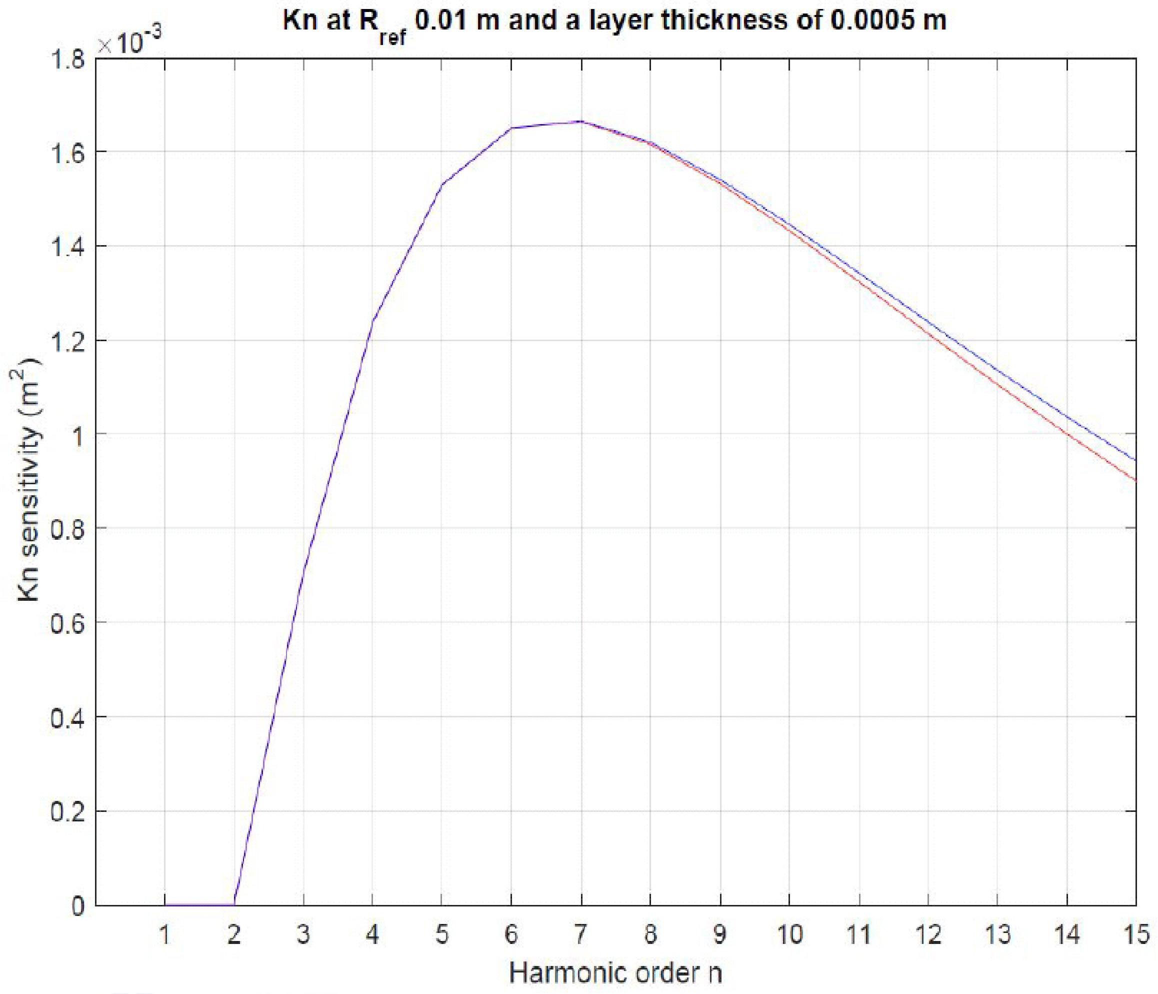
EMI Shielding Printed onto a Dome

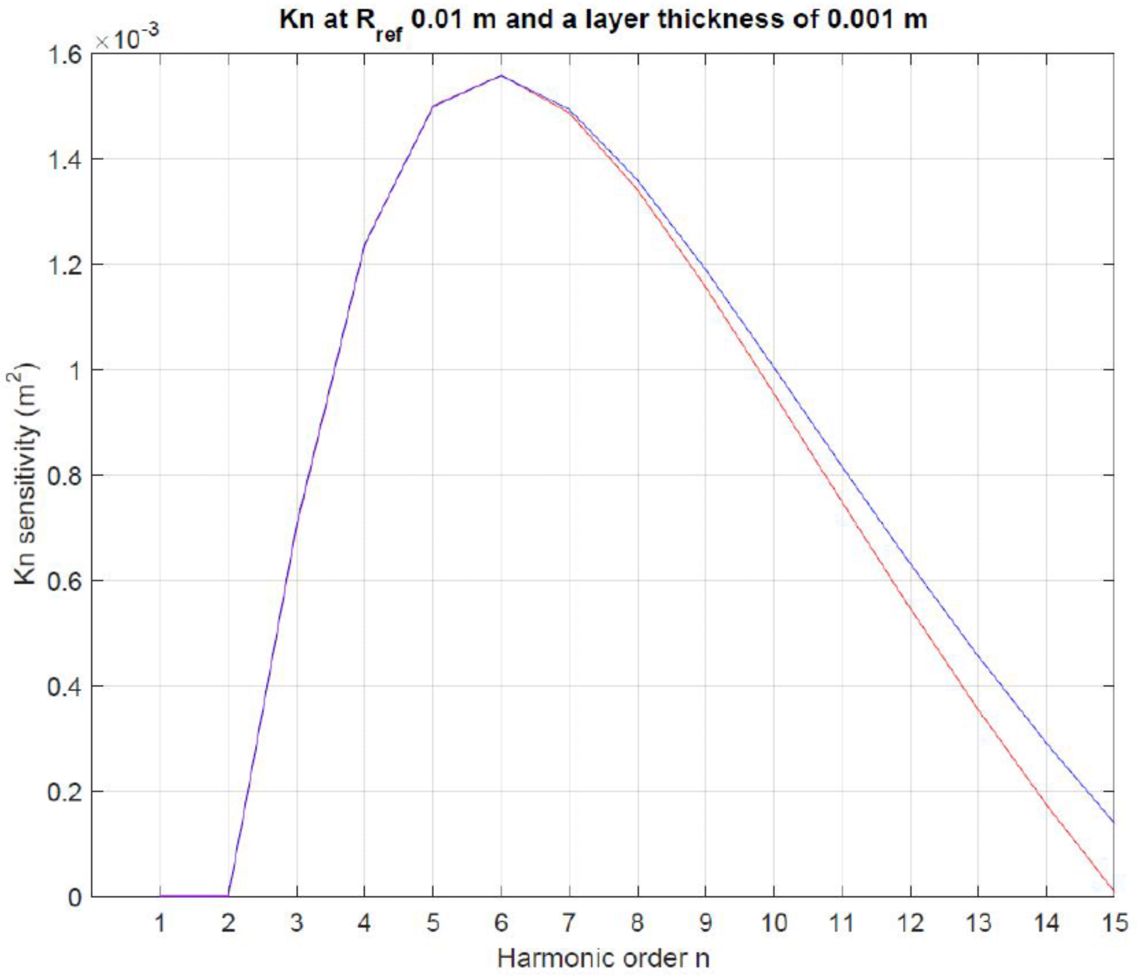


“Blind eye” behavior of DBQ PCB radial coil as function of layers thickness

DQB kn sensitivity factors calculated with:

- Approximated formula (red)
- Tracks coordinates, not approximated (blue)

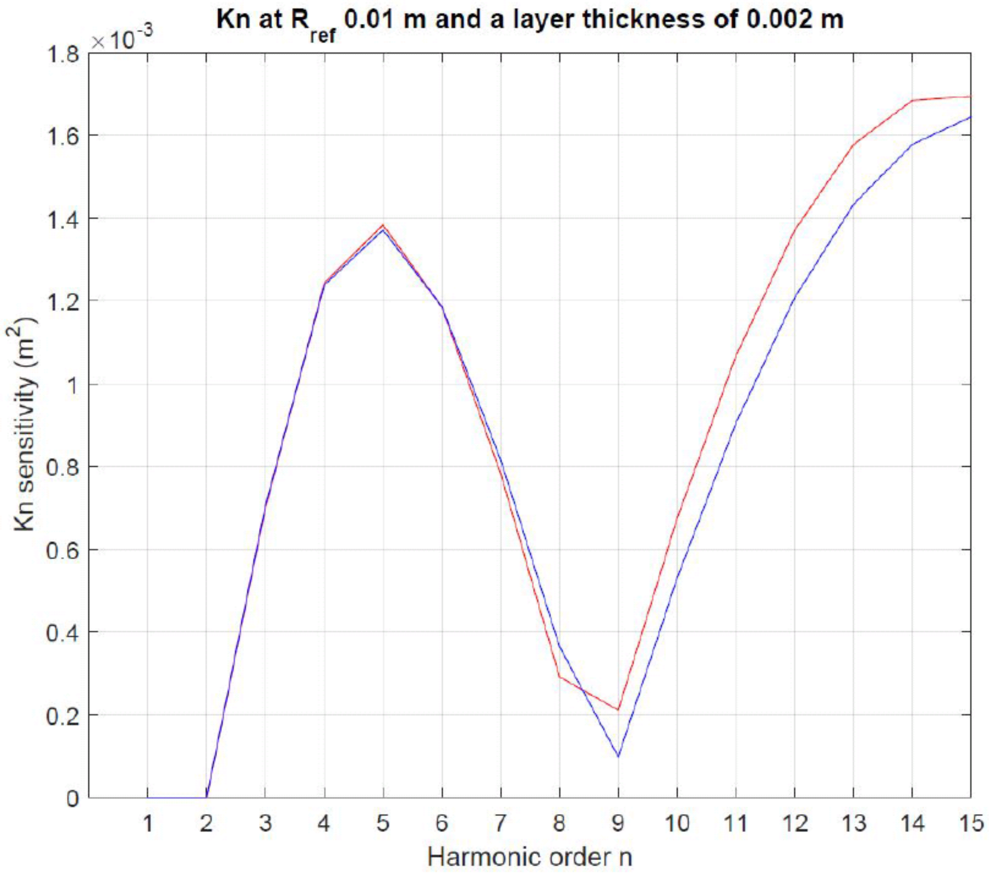




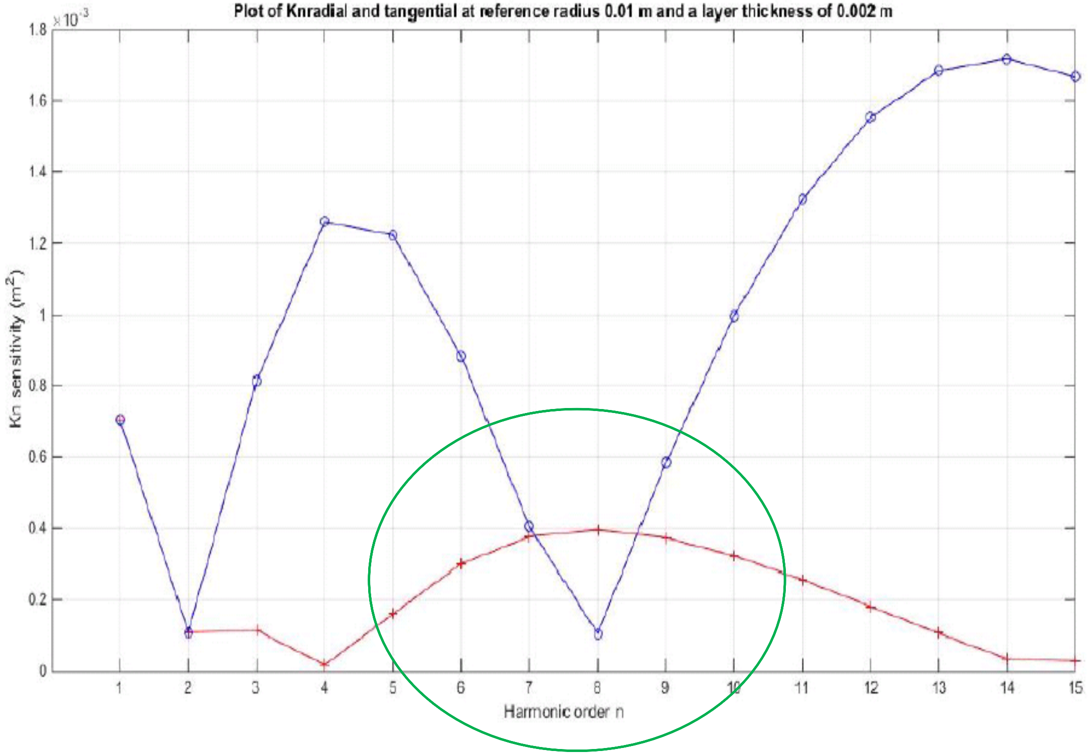
“Blind eye” behavior of DBQ PCB radial coil as function of layers thickness

Approx. Kn: red
Standard formula: blue

Since the formula well approximate the Kn can be used to study the BE behavior for values of layer thickness higher than 1mm



The undesired tangential component does not determine the blind eye



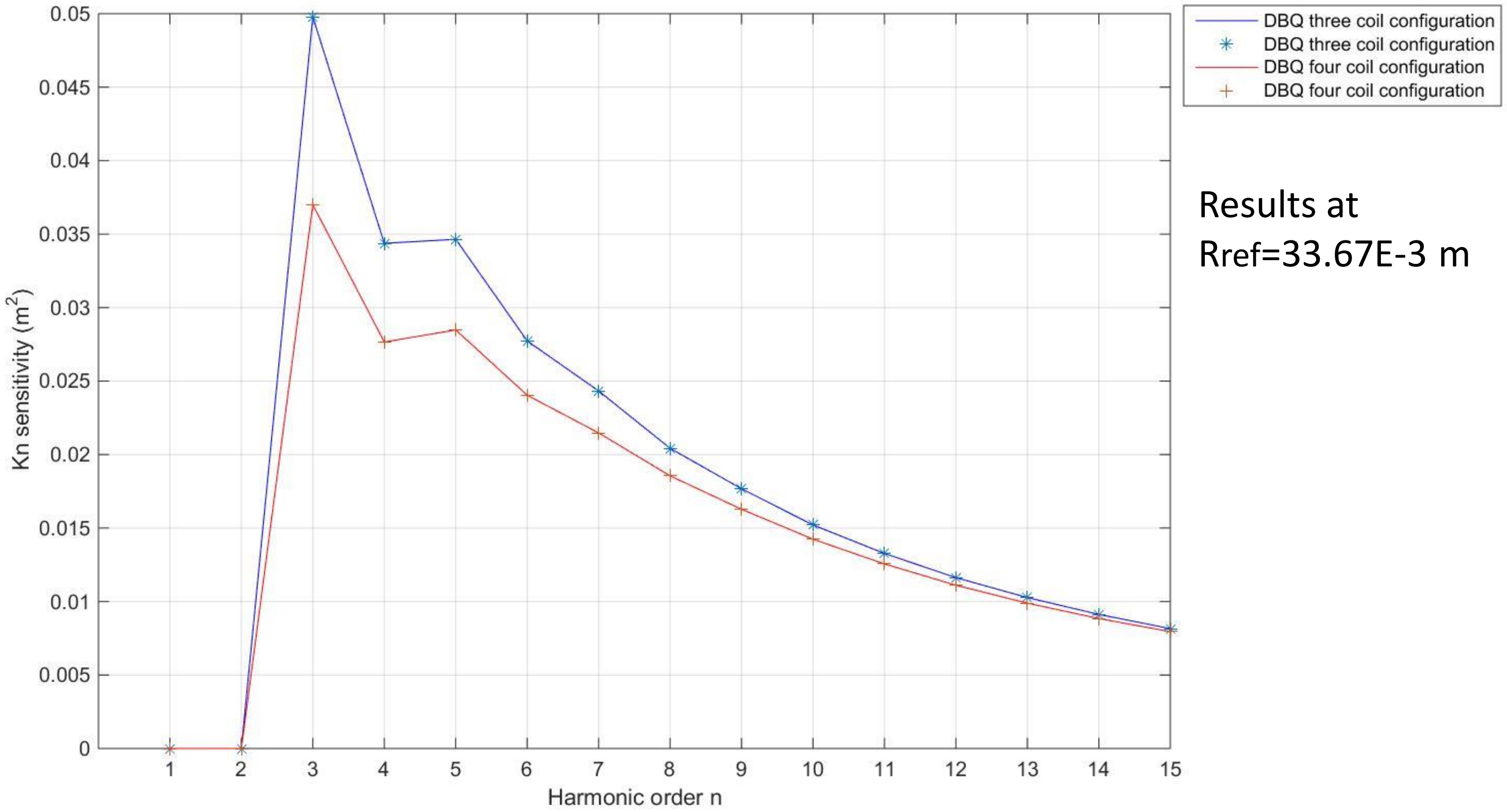
Rad component: Blue

Tang component: Red

RIBBON COIL CONNECTORS DQB DESIGN

Ribbon Coil Sensitivity

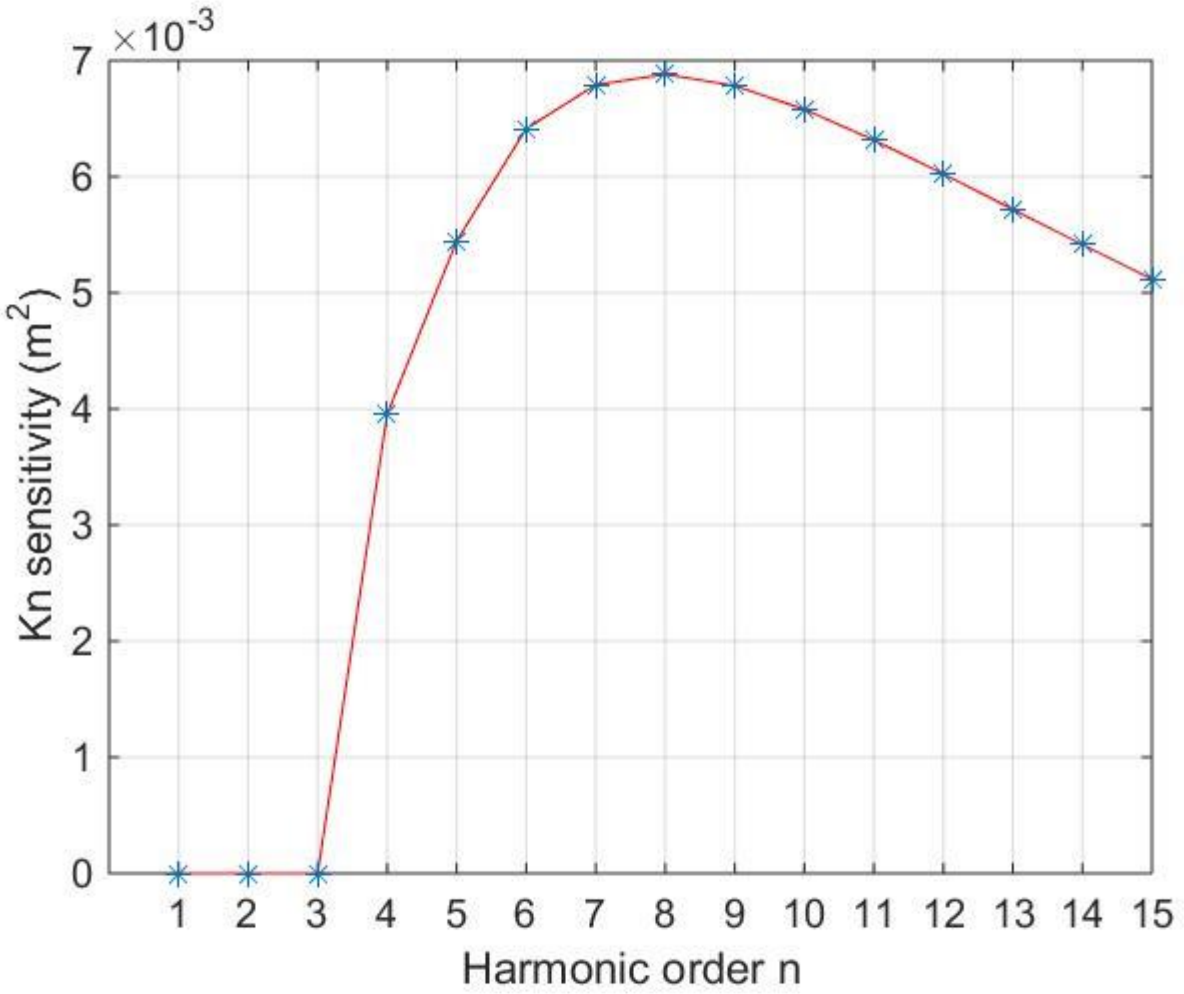
Different configurations have been studied for the DQB design. 4 coils configurations were chosen.



Results at
Rref=33.67E-3 m

RIBBON COIL CONNECTORS DQSB DESIGN

Ribbon Coil Sensitivity

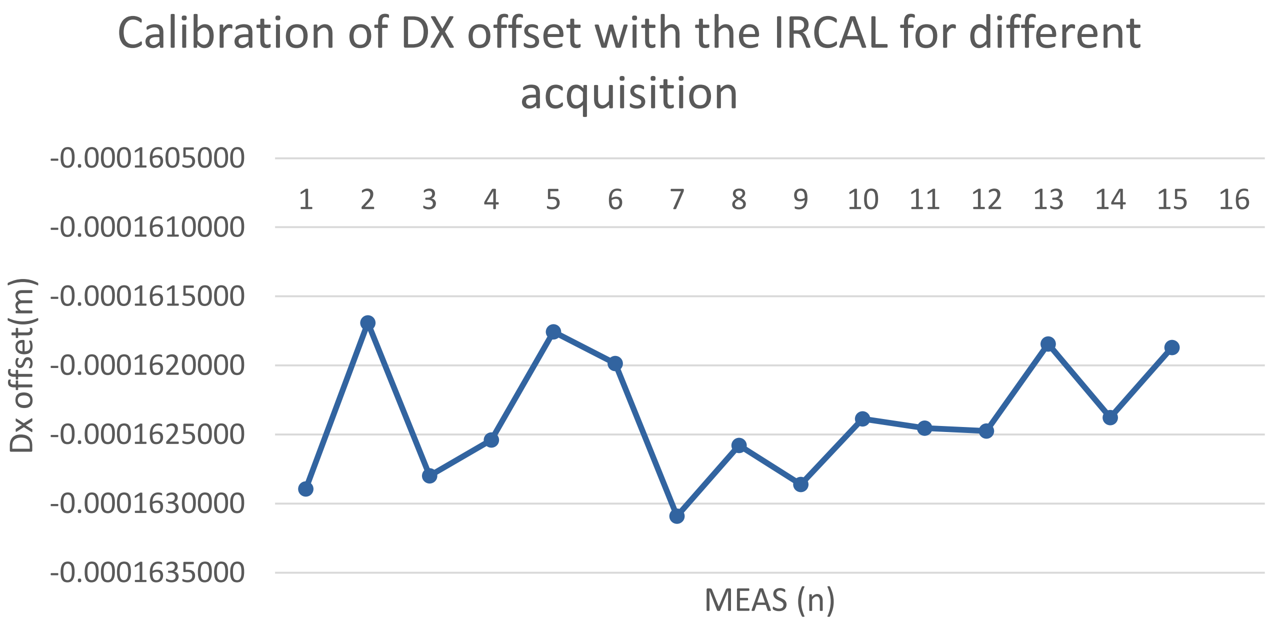


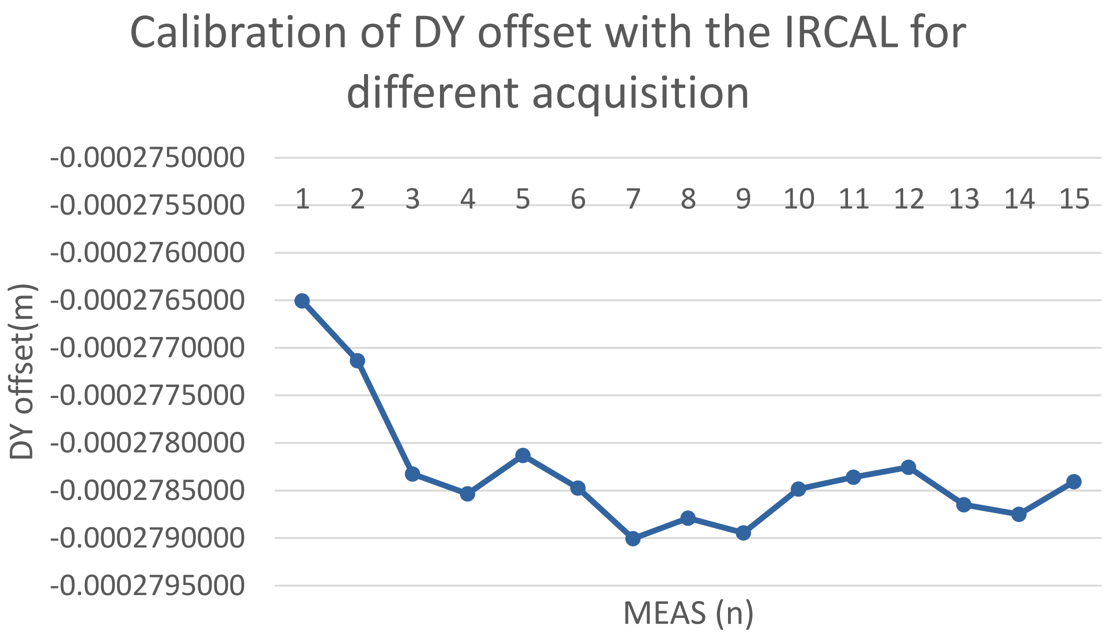
Results at
Rref=33.67E-3 m

Program test with Fermilab Rotating coil Probe

STD Dx (m)	STD DY (m)
4.48952E-07	6.66354E-07

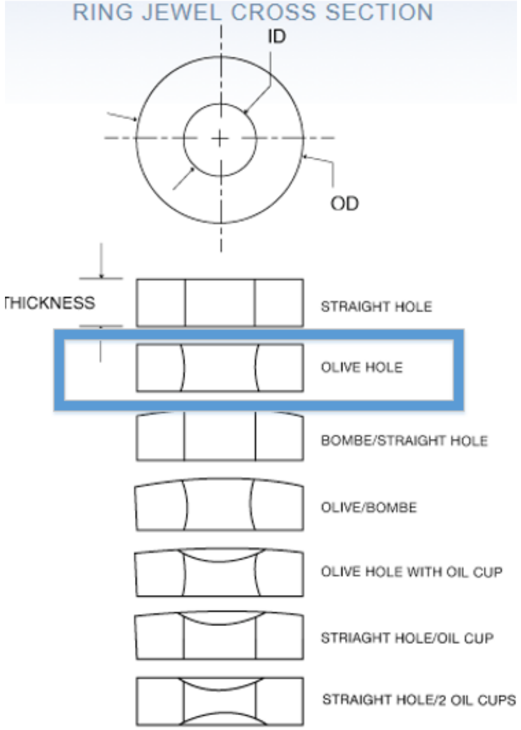
The Program was tested with the Fermilab PCB coil with DB DQB and DQSB


Calibration of DX offset with the IRCAL for different acquisition


Calibration of DY offset with the IRCAL for different acquisition

Material used for shaft and bearings

Sapphire Shaft
and
Bearings



- It is not possible to use synthetic sapphire shaft with synthetic sapphire bearings.

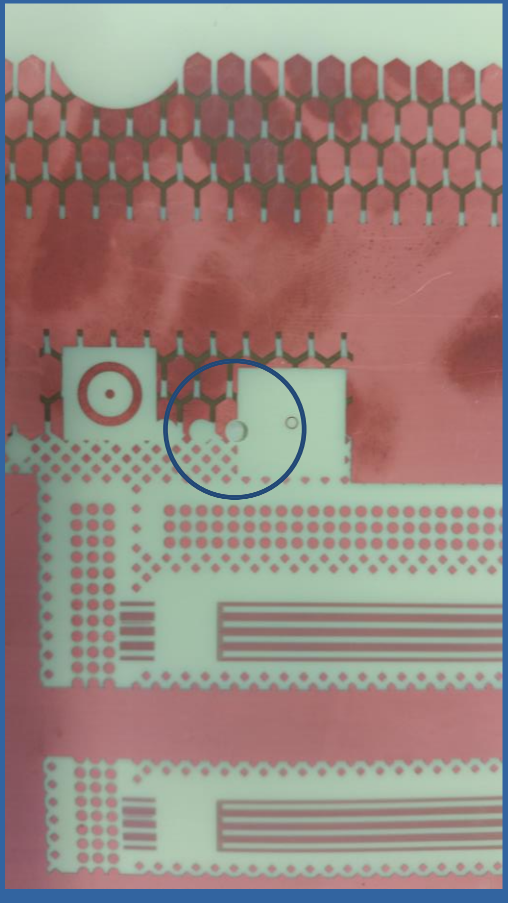
➢ Necessity of non magnetic material rings around the shaft to be in contact with olive sapphire bearings.

Young modulus = 431.492 GPA
(Higher than: alumina, carbon-fibre, Glass-fibre…)

Material	Young Modulus E (GPA)	ρ MASS DESITY (Kg dm^{-3})
FR-4	24	1,850
Synthetic Sapphire	431.492	3.99
Alumina	380	3.9
Glass-fibre	5.5	2.5
Carbon fibre	250	2

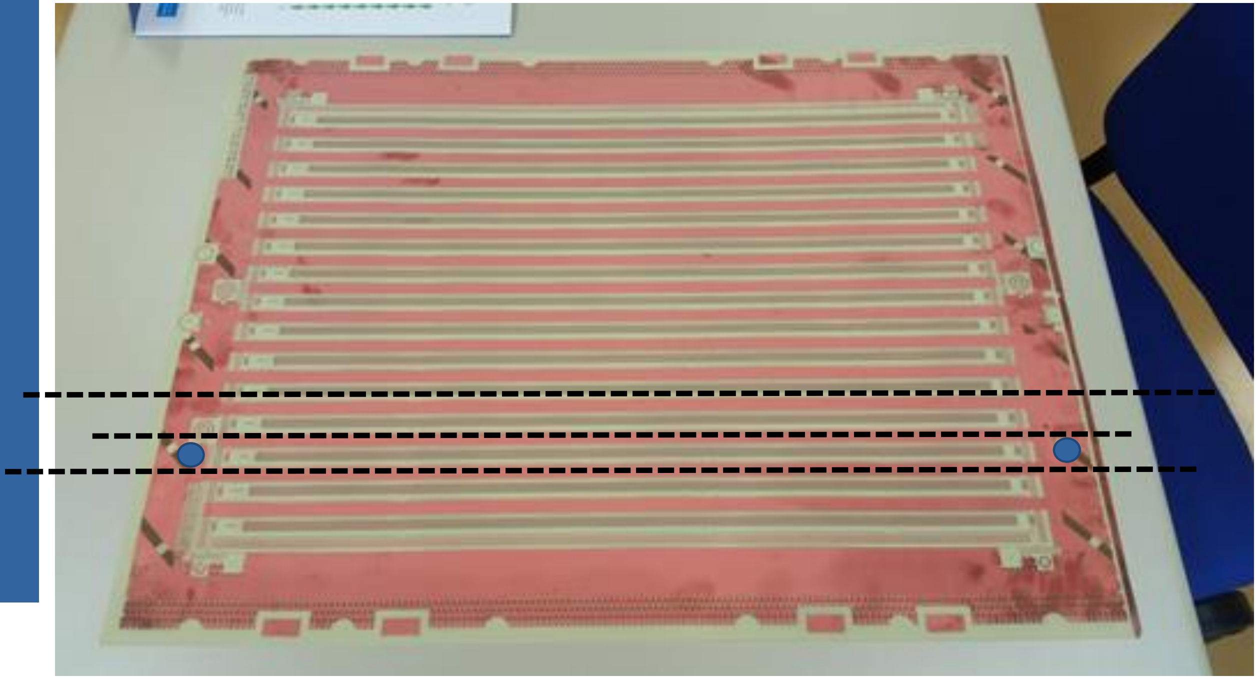
- The roughness is ~50-100 nm flat surface (~100 nm for rod)

Long CLIC PCB coil



Production of CLIC main beam type one PCB rotating coil:

-500 mm length
-50 um tracks with 50 um space between tracks
-10 um copper
-50 um pre-peg and FR-4
-14 layers

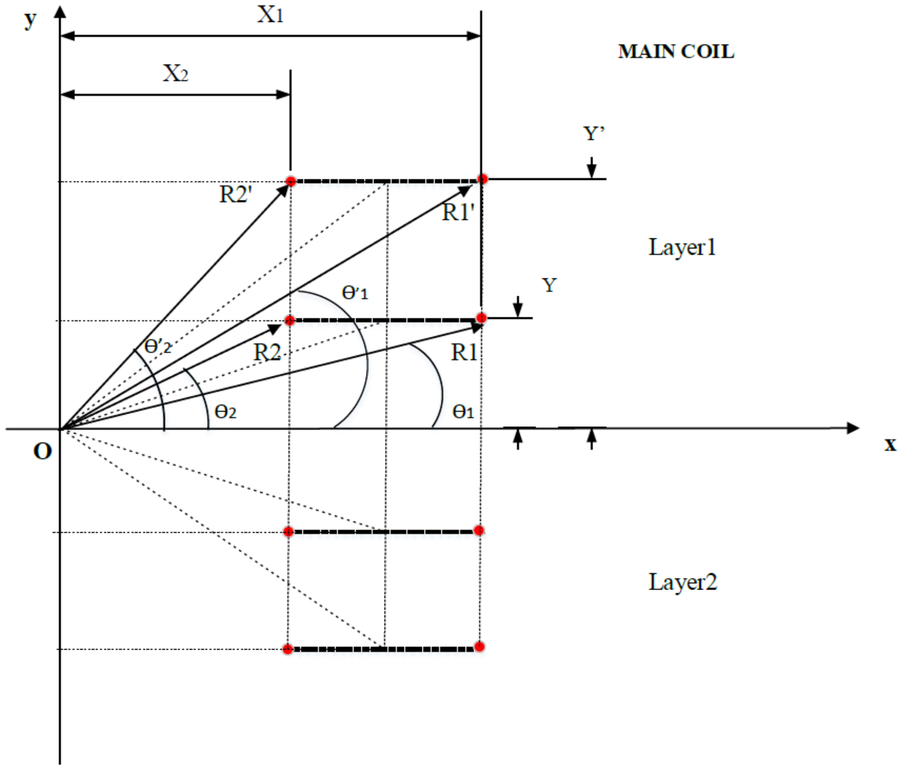


DB and QB bucking are independent from thickness

This theoretical study can be applied to an innovative PCB design for a selective bucking with a tunable BE

The study was done for a two layers DQB coil

Both dipole and quadrupole bucking are insensible to symmetric variations of layers thickness of singular coils



This is not true anymore for higher order harmonics, it is therefore possible to move the BE with different main coil thickness

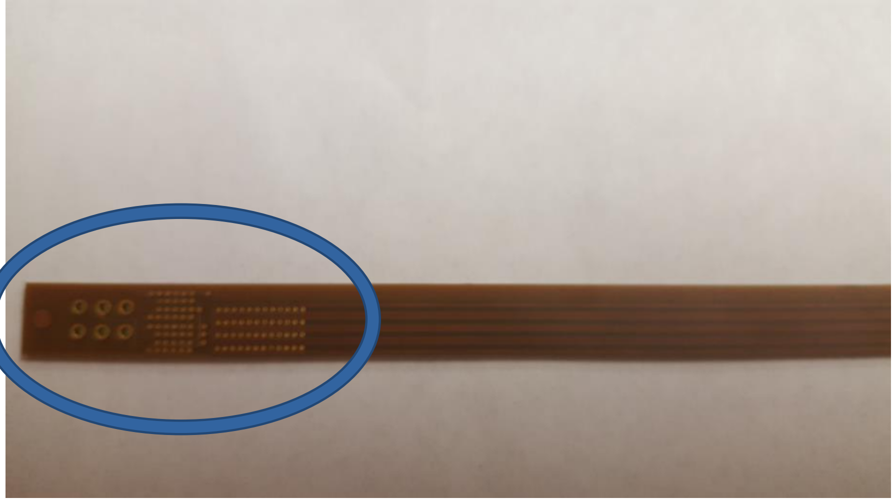
First PCB CLIC prototype

On board DB and DQB bucking

CLIC First Pacman Prototype

PCB manufactured at CERN PCB service

Shaft for test done at Fermilab during the secondment



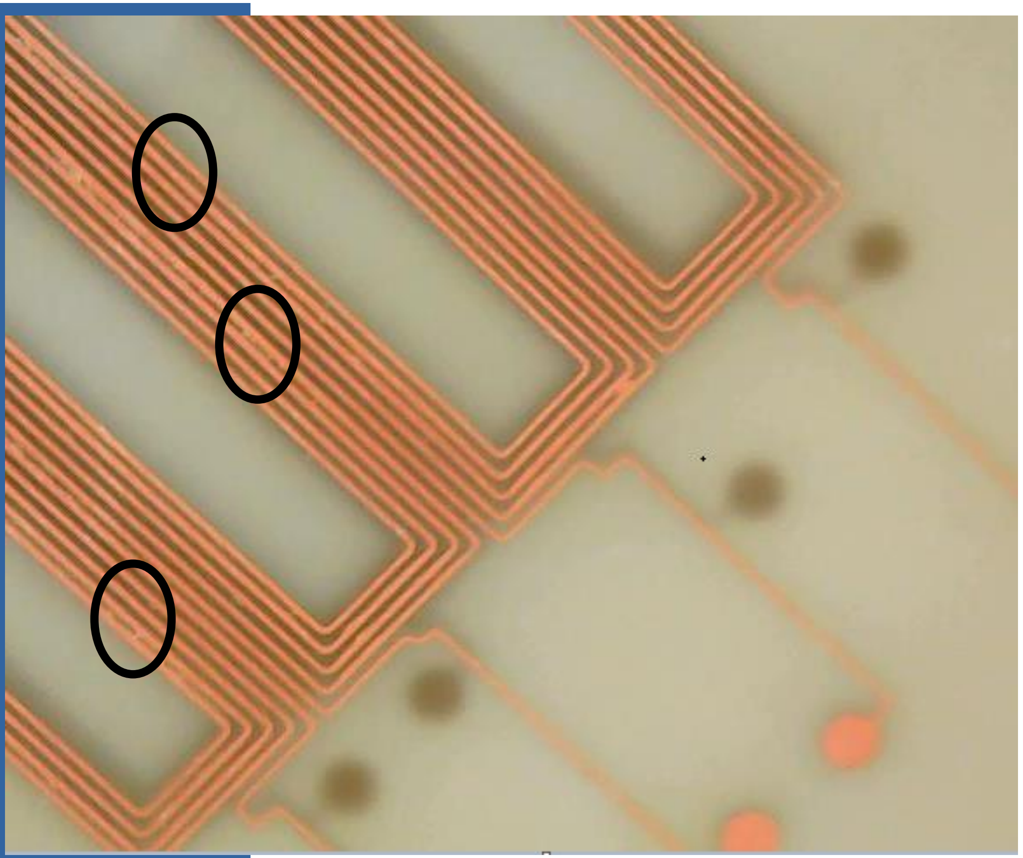
Output signals:

- UB
- DB
- DQB

Fiducials used for a precise alignment:

- Requires special tools
- Not compatible with mass production
- LDI high resolution model

PCB production: resolution problems



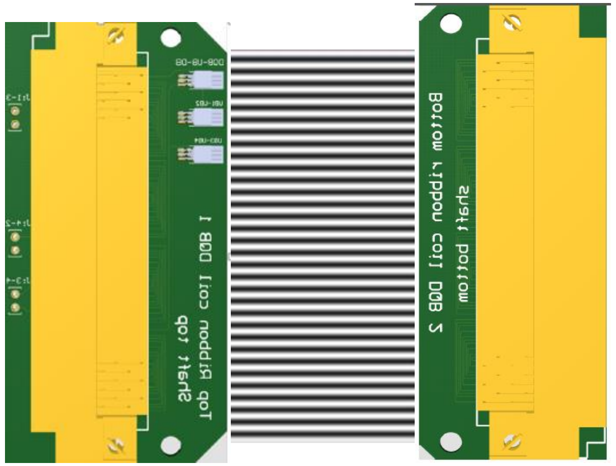
- When Gerber files (infinite resolution) are converted to machine format, special attention must be given to resolution settings.
- The photo illustrates the consequences of a resolution error.

RIBBON COIL CONNECTORS DESIGN

Ribbon Coil

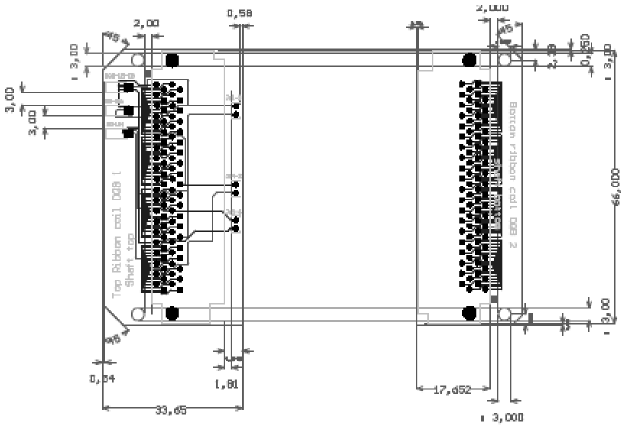
Design with ALTIUM DESIGNER

-Production of step to verify the assembly with CATIA



4 Signal Layers
Output signals:

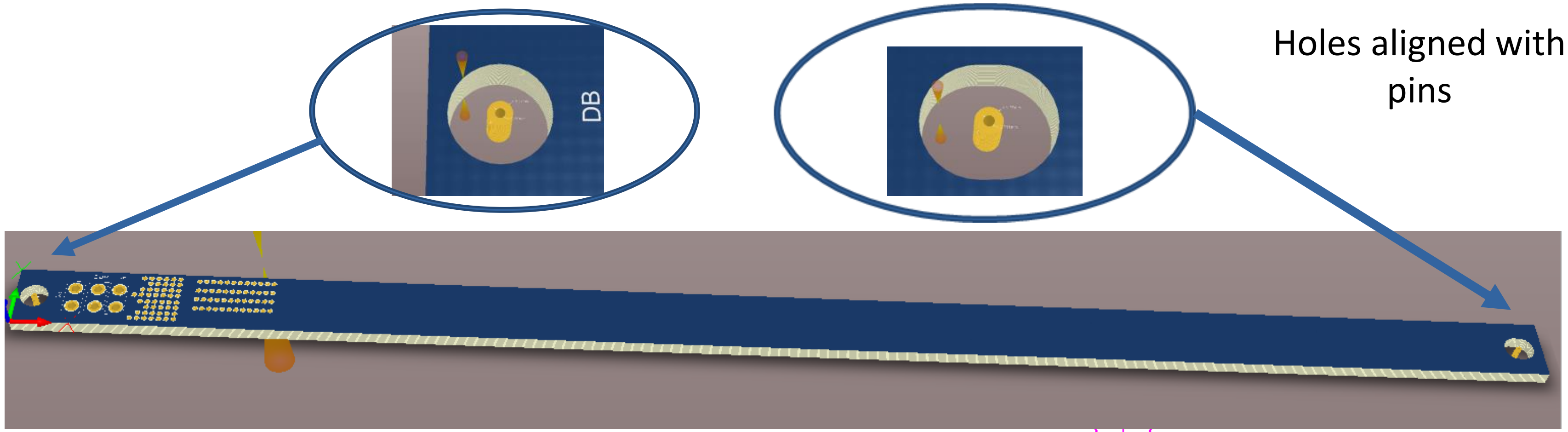
-UB1 UB2 UB3 UB4
-DQB DB



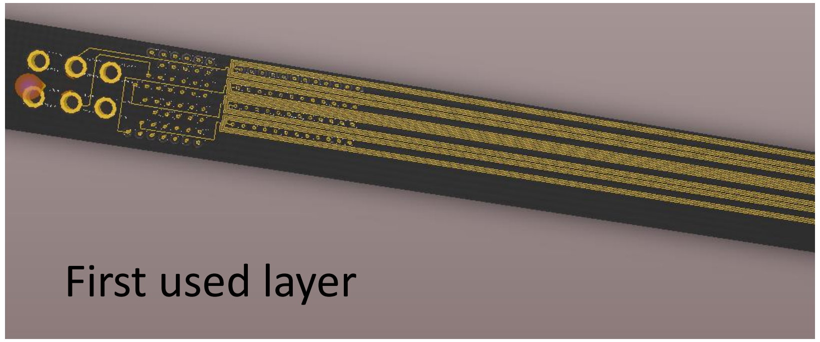
4 Signal Layers
Output signals:

-UB1/A UB2/A UB3/A
-DQB/A DB
-DQB/B UB1/B UB2/B UB3/B
-DQSB

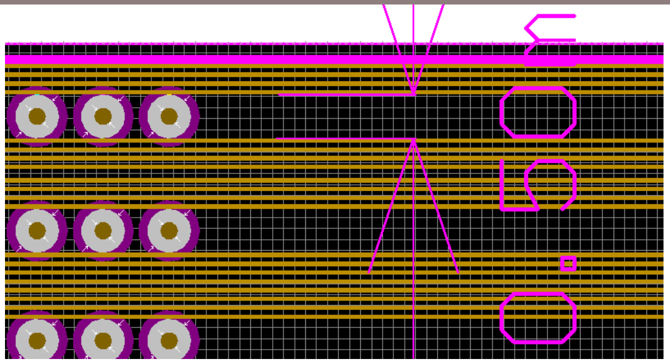
New coil and shaft design: Radial coil with on board dipole and quadrupole bucking



Holes aligned with pins



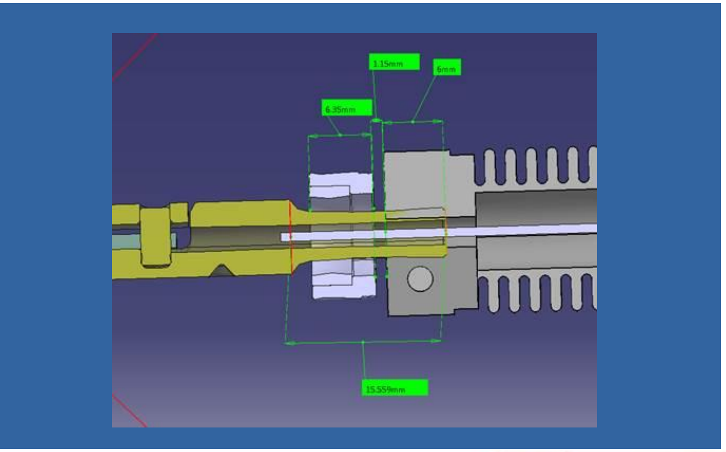
First used layer

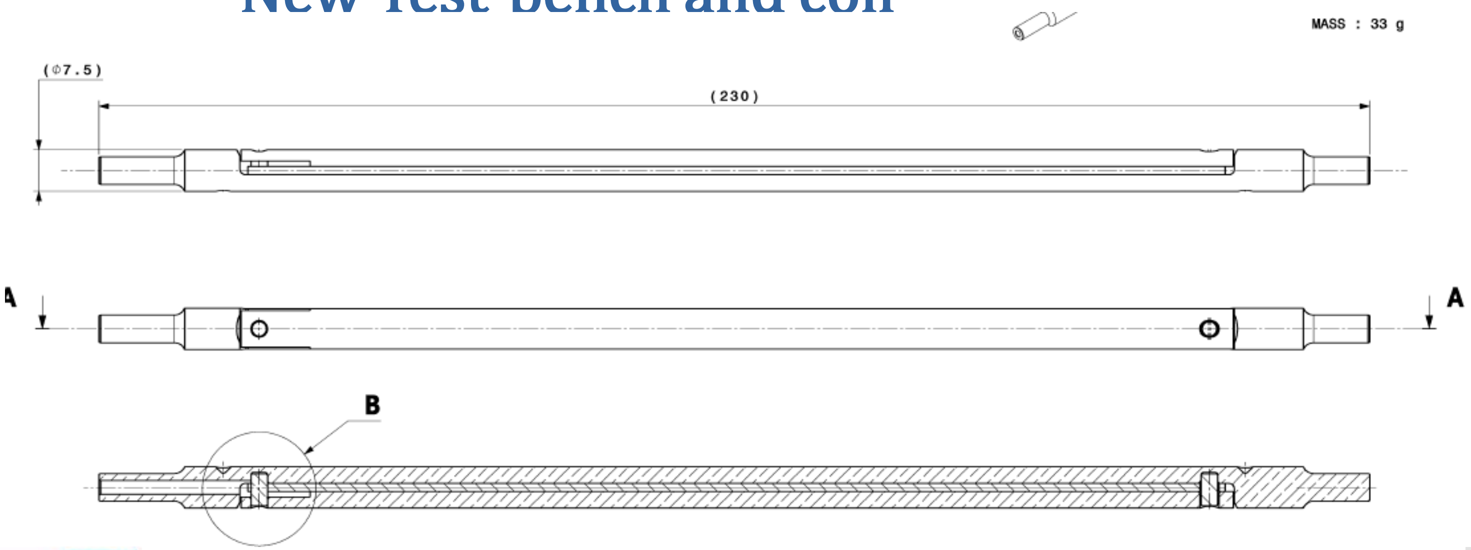


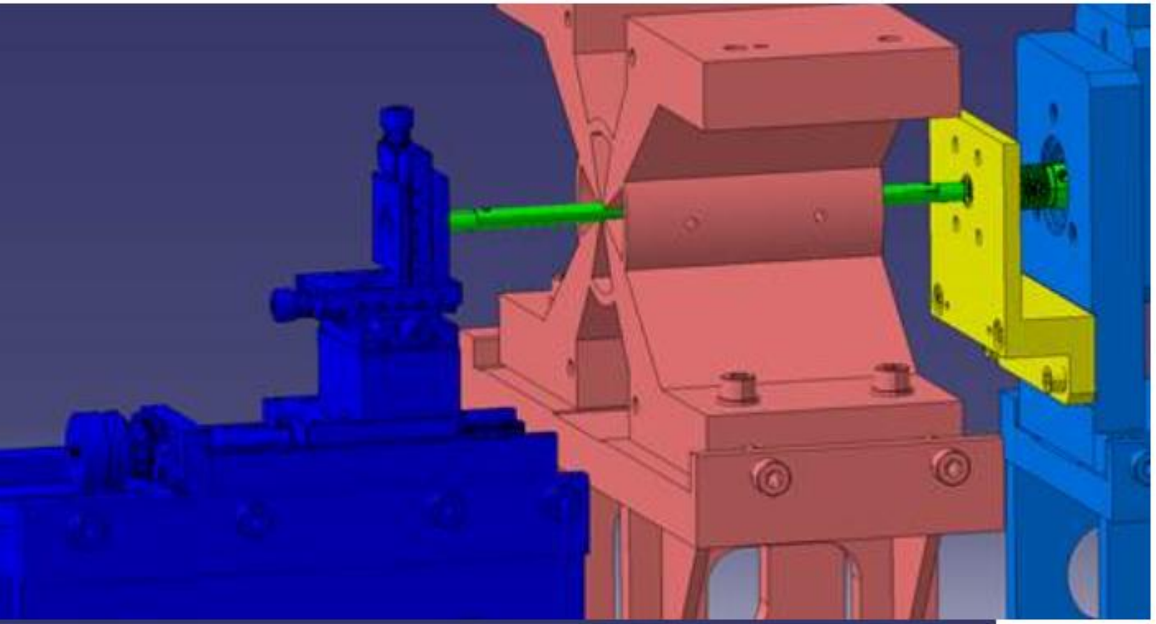
Thickness : 1.38mm worst case tolerance usually is of +/-10% (The tolerance expected by PCB service maximum 5%)

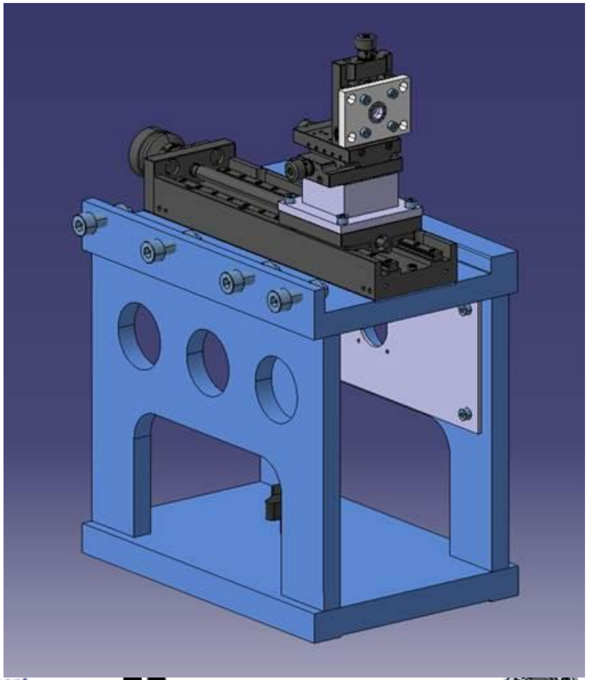
- Copper height of 5 um
- Internal vias pads 0.25 mm (hole 0.2 mm)
- Two external layer with 0.5 mm vias pad (hole 0.2 mm)
- 0.25 mm distance between most external track and cut
- 24 layers

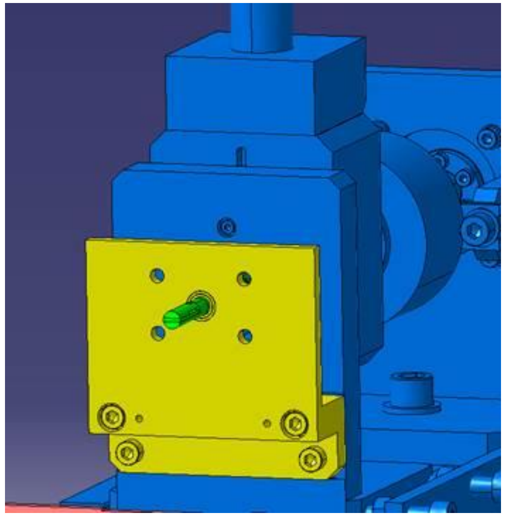
New Test-bench and coil











PACMAN

Eltos
circuiti stampati professionali

SIGMAPHI
MAGNETS AND BEAM TRANSPORT

Instrumentation & Measurement for Particle Accelerator Lab
IMPALAB

Fermilab

Università degli Studi del Sannio

CLIC

CERN

European Commission

COIL CALIBRATION

CLASSIC CALIBRATION:

- **Done one time**
- **Must be repeated as needed due to the coil ageing effects**
- **Needs both a Dipole and a quadrupole reference magnets**

CERN IN SITU-CALIBRATION:

Advantages:

- **Needs only a quadrupole**:
  - The dipole variation obtained with a linear displacement done with high precision linear stages is used for the rotation radius calibration

Disadvantages:

- **Must be repeated after some time**:
  - To prevent errors due to the coil ageing effects
  - The PCB can be involuntarily displaced from its location
  - If the magnet is shorter than the coil, calibration values can change due to the coil longitudinal positioning variations
- **Needs Linear stages:**
  - Linear stages precision determine the quality of calibration
- It is not planned for PCB coils with on-board bucking

COIL CALIBRATION

FERMILAB IN-SITU CALIBRATION:

Advantages:

- Implemented for PCB coil with on-board dipole and quadrupole bucking
- **Only needs a quadrupole**
- **Does not need linear stages**

Disadvantages:

- **Must be repeated as needed:**
  - To prevent errors due to the coil ageing effects
  - The PCB can be involuntarily displaced from its location
  - If the magnet is shorter than the coil, calibration values can change due to the coil longitudinal positioning variations

SELF - CALIBRATION CONCEPT:

Used to calibrate the whole PCB position:

- DB signal (radius independent)
- UB signal (radius dependent)

A metrological crosscheck measurement can be done to verify PCB calibration results and real displacement