MONITORING THE MAGNETIC AXIS MISALIGNMENT IN PARTICLE ACCELERATOR SOLENOIDS

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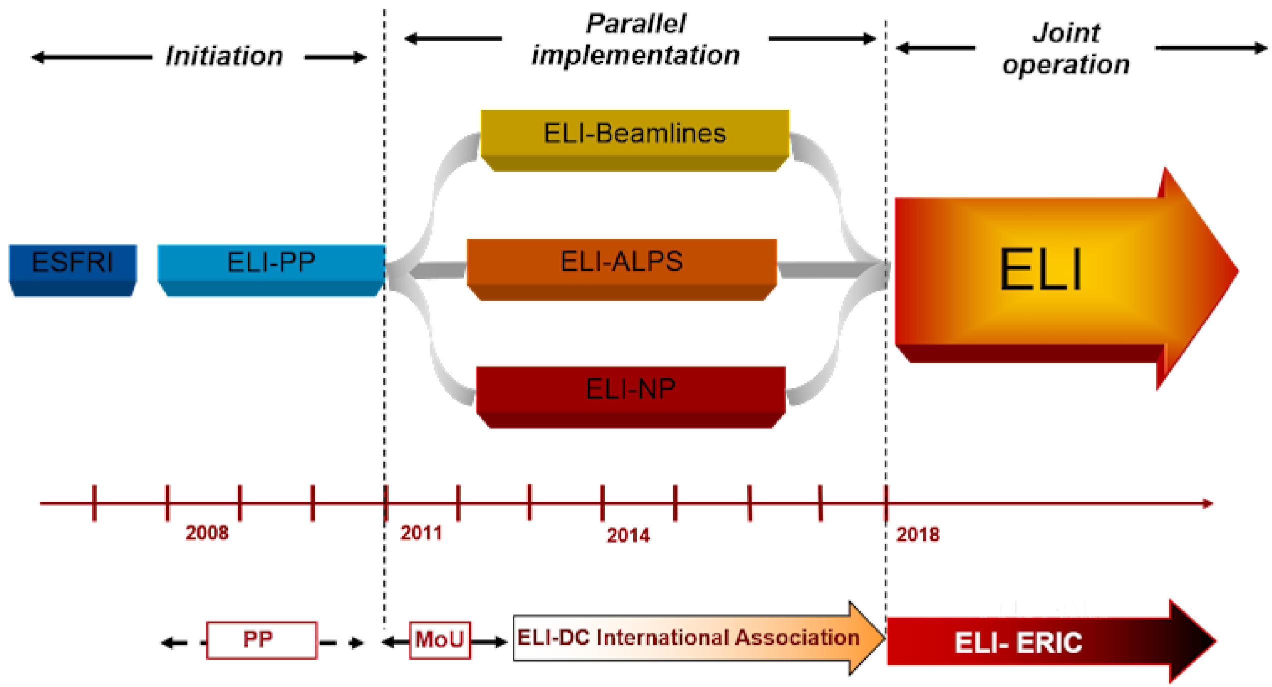
PROLOGUE

EXTREME LIGHT INFRASTRUCTURE

- Extreme Light Infrastructure (ELI) is a new Research Infrastructure of pan-European interest and part of the European ESFRI Roadmap.

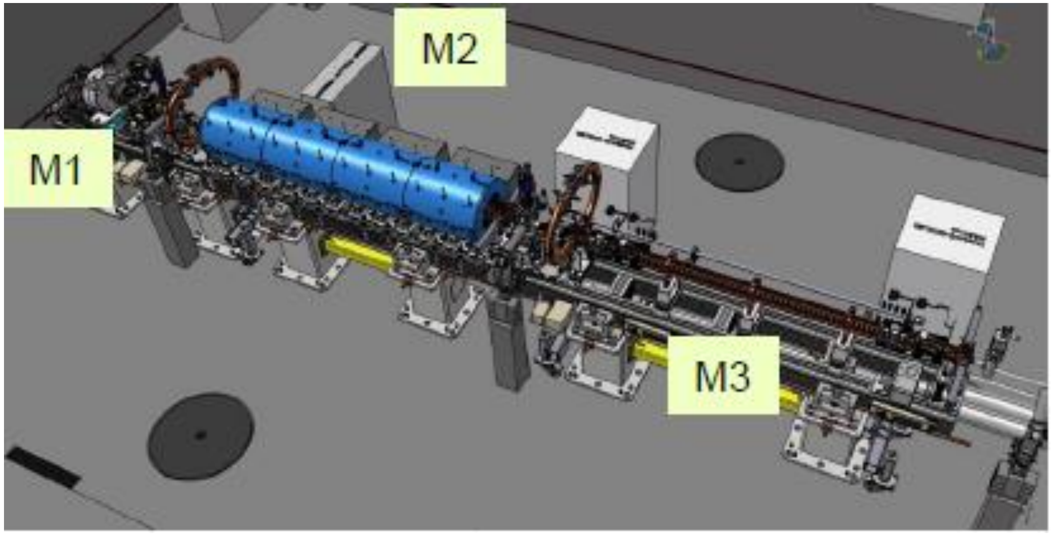


ELI – NUCLEAR PHYSICS

- The ELI Nuclear Physics (ELI-NP) facility focuses on laser-based nuclear physics.
- It will host two machines:
  - a very high intensity laser, where beams from two 10 PW lasers are coherently added to get intensities of the order of 10^{23} - 10^{24} W/cm^2
  - a very intense, brilliant gamma beam, which is obtained by incoherent Compton back scattering of a laser light off a brilliant electron beam from a conventional linear accelerator.

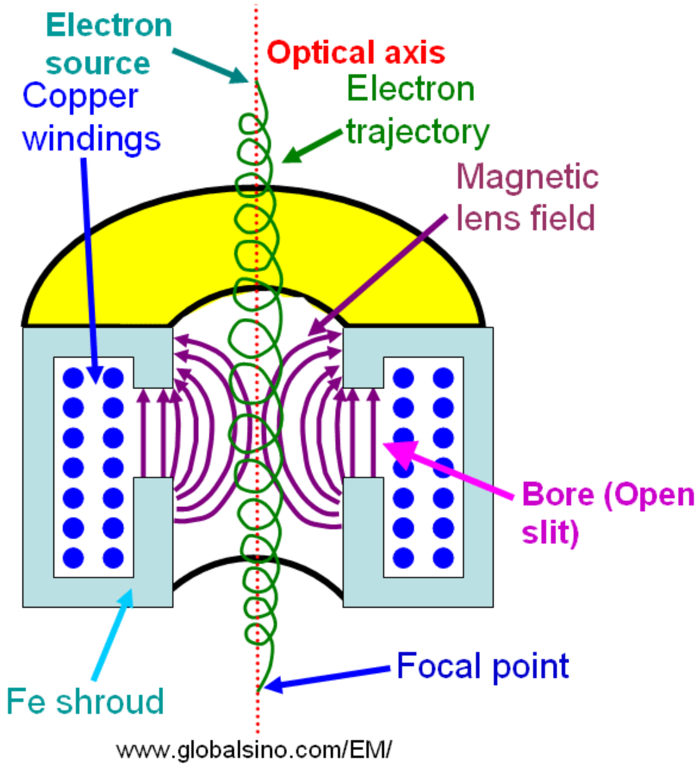
- Applications include nuclear physics experiments to characterize laser – target interaction, photonuclear reactions, and exotic nuclear physics and astrophysics.

ELI-NP SOLENOIDS



- M1: photogun and electron beam extraction components (solenoid A)
- M2: the first S–band accelerating structure and the solenoid B surrounding the S–band structure;
- M3: the second S–band accelerating structure

SOLENOIDS FOR BEAM FOCUSING



- Solenoids are used for beam focusing.
- They behave similarly to converging glass lenses in optical microscopes.
- In order to guarantee an accurate focusing, the magnetic axis of the magnet should be obtained with high precision.

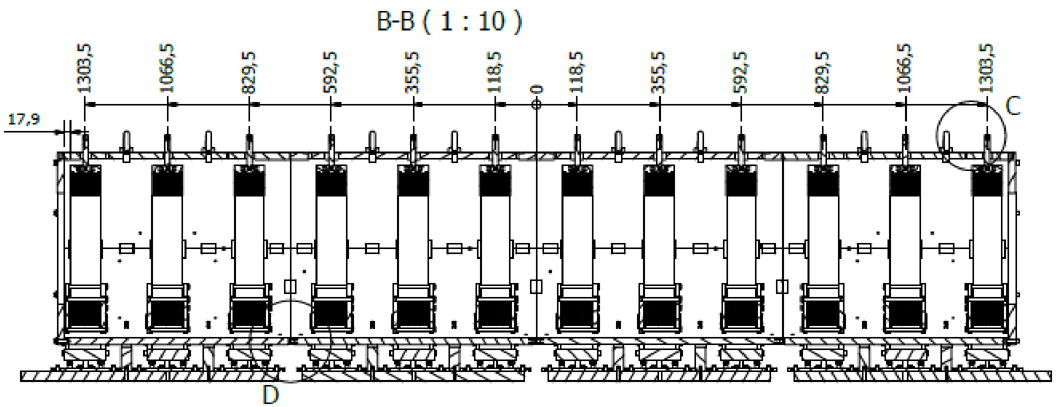
MAGNETIC AXIS MONITORING

- When a magnet is in operation, its coils are constantly subject to an electrodynamic strain. The main reason resides in deformations caused by thermal effects, despite a cooling system is usually installed. This could result in a significant misalignment of the magnetic axis from the geometric axis.
- The thermal effects are especially present at the magnet start-up, but the misalignment can drift also during machine runnings, because of the heat generated by particle beams.

An in-operation monitoring of the misalignment is needed

MULTI-COIL SOLENOIDS

ELI-NP Solenoid B



- Multi-coil solenoids with coaxial coils were studied for producing a uniform magnetic field, or particular field configurations, e.g., a near-linear gradient axial magnetic field.
- The use of multi-coil solenoids as focusing structures is of great interest.

MULTI-COIL SOLENOIDS (2/2)

- When dealing with multi-coil solenoids, each coil may be affected by its peculiar misalignment.
- Hence, these misalignments have to be monitored when a strict constraint on the coils alignment is required, thus allowing to adjust the coils position to achieve/recover the solenoid design parameters.
- In ELI-NP solenoids this can be done with adjustable screws to translate and/or rotate a single coil, even during its operation, with a precision of tens of micrometers.

THE CHALLENGE

ELI-NP MAGNETIC AXIS MONITORING SPECIFICATIONS

- Multi coil solenoid are made by a magnetic yoke that can be imagined as a cylinder 3 m long with a diameter of 60-80 cm and 12 or more coils grouped in three or more sets, individually powered and installed inside the yoke.
- The challenge is to put the resulting magnetic axis inside an ideal cylinder with radius ±5 microns, have the capability to check the magnetic axis precision and if necessary adjust each coil position to achieve/recover the design parameters.
- Very hard specs:
  - we need to measure field difference with very high accuracy
  - field difference in solenoids is very small

WHAT SHOULD WE DO AT THIS STAGE?

… STUDYING

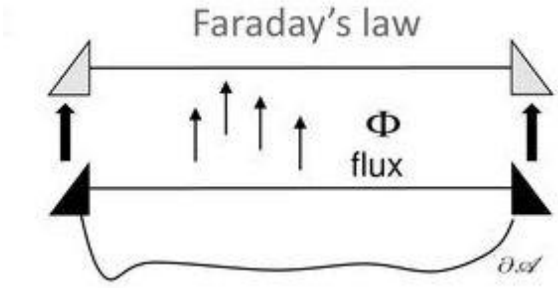
…BUT ALSO MEETING EXPERIENCED PEOPLE

METHODS FOR THE MAGNETIC AXIS MEASUREMENT

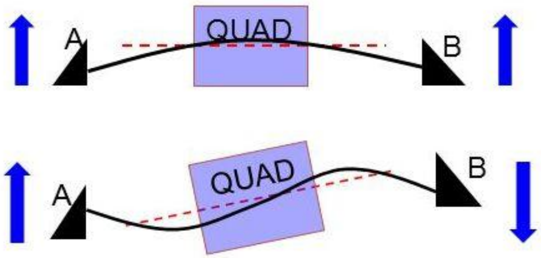
- Current method for magnetic axis determination:

Hall probe mapper

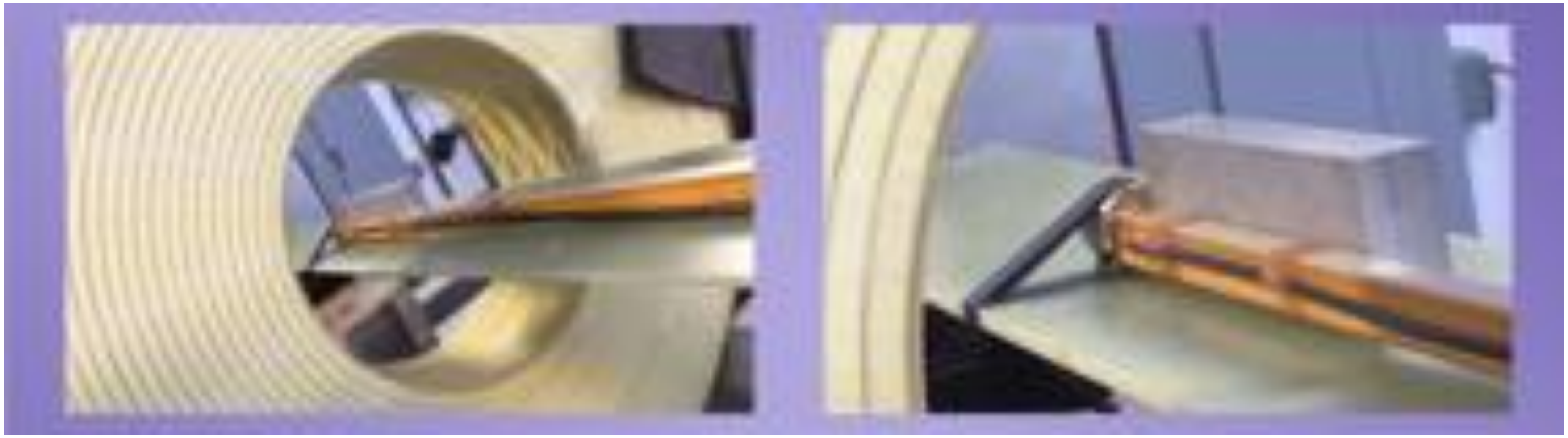
Stretched wire



Vibrating wire

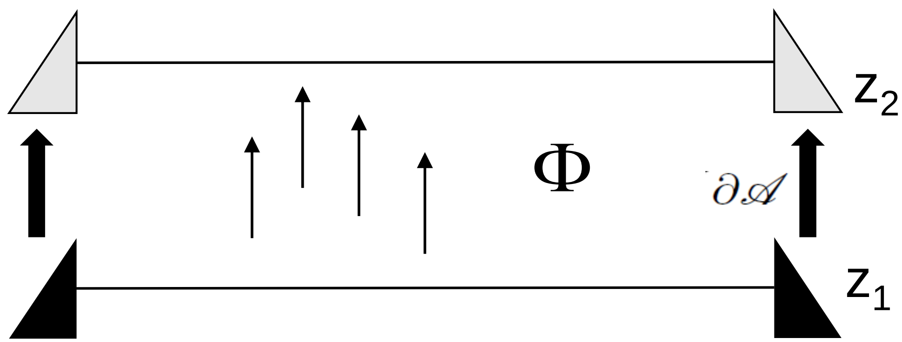


HALL PROBE MAPPER

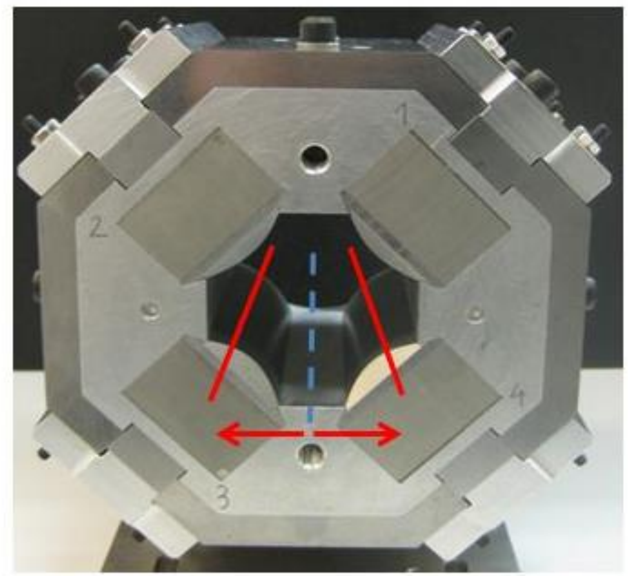


K. H. Park, Y. K. Jung, D.E. Kim, H.G. Lee, S.J. Park, C.W. Chung, B.K. Kang, “Field Mapping System for Solenoid Magnet”, AIP Conference Proceedings, vol. 879, no. 1, pp. 260–263, 2007.

STRETCHED WIRE



$$\int_{\partial\mathscr{A}} \mathbf{E}\cdot \mathrm{d}\mathbf{r} = -\frac{\mathrm{d}}{\mathrm{d}t}\int_{\mathscr{A}} \mathbf{B}\cdot \mathrm{d}\mathbf{a}$$



J. Di Marco, H. Glass, M. J. Lamm, P. Schlabach, C. Sylvester, J.C. Tornpkins, “Field alignment of quadrupole magnets for the LHC interaction regions”, IEEE Transactions on Applied Superconductivity, 2000

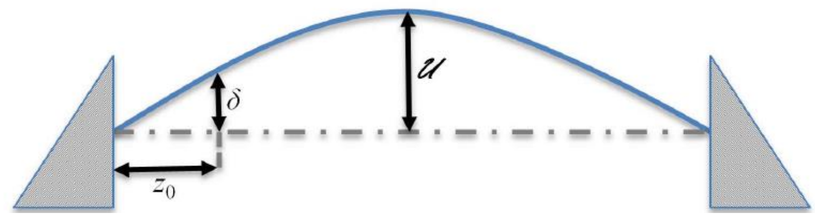
Lorentz force

VIBRATING WIRE (1/2)

Feeding a conducting wire by a sinusoidal current

Wire oscillation amplitude

Magnetic field longitudinal components



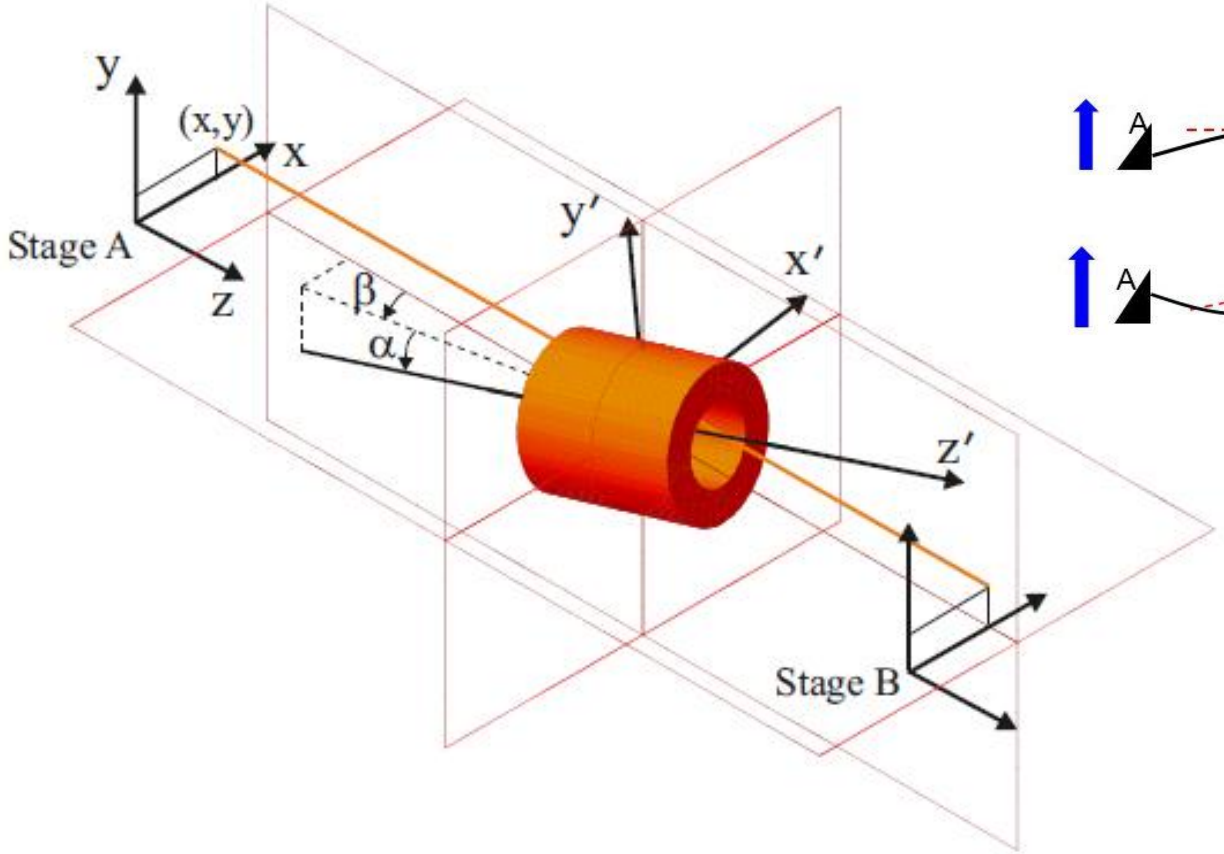
$$F = Q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

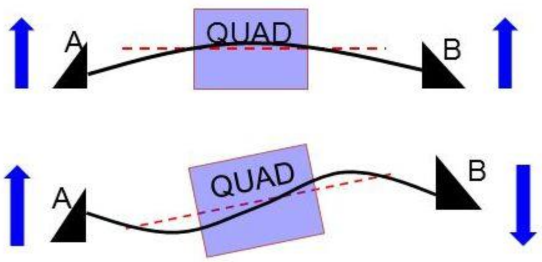
$$u(z,t) = \frac{2I_0}{L}\sum_m \frac{\int_0^L B_n(z)\sin\left(\frac{m\pi}{L}z\right)\mathrm{d}z}{\sqrt{\left[T\left(\frac{m\pi}{L}\right)^2 - \rho\omega^2\right]^2 + (\alpha\omega)^2}}\sin\left(\frac{m\pi}{L}z\right)\sin(\omega t - \varphi_m),$$

$$\varphi_m = \arctan\left(\frac{\alpha\omega}{-\rho\omega^2 + T\left(\frac{m\pi}{L}\right)^2}\right)$$

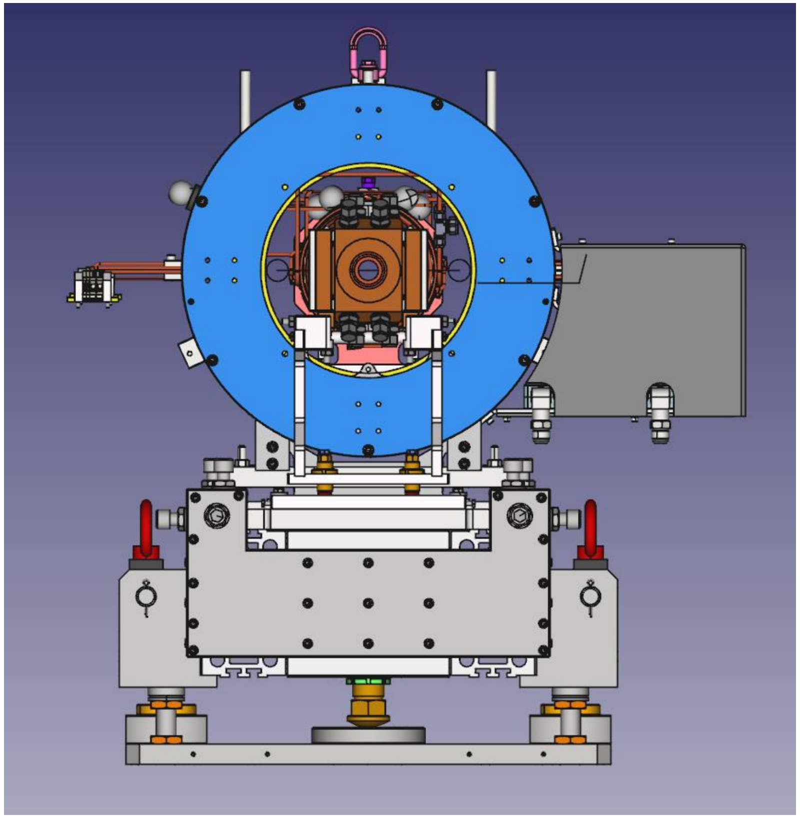
P. Arpaia, C. Petrone, S. Russenschuck, L. Walckiers, “Measuring field multipoles in accelerator magnets with small-apertures by an oscillating wire moved on a circular trajectory”, Journal of Instrumentation, 2012

VIBRATING WIRE (2/2)





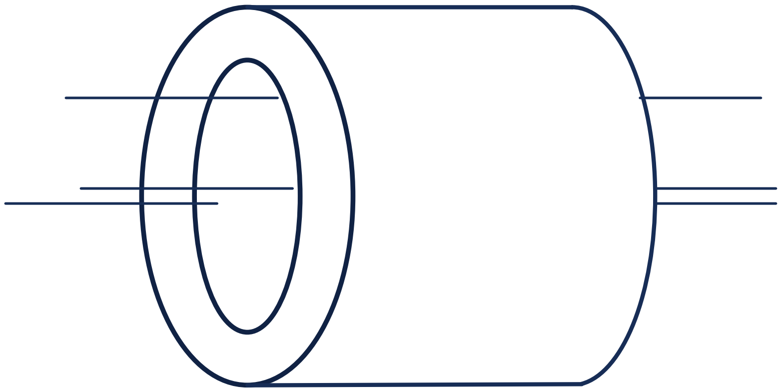
APERTURE NOT ACCESSIBLE!



- Methods actually used for magnet alignment cannot ne used for in-operation monitoring.
- When in operation, most part of the solenoid aperture (in particular near the magnetic axis) is obstructed by the beam pipe and other equipment.

BRAIN STORMING (1/3)

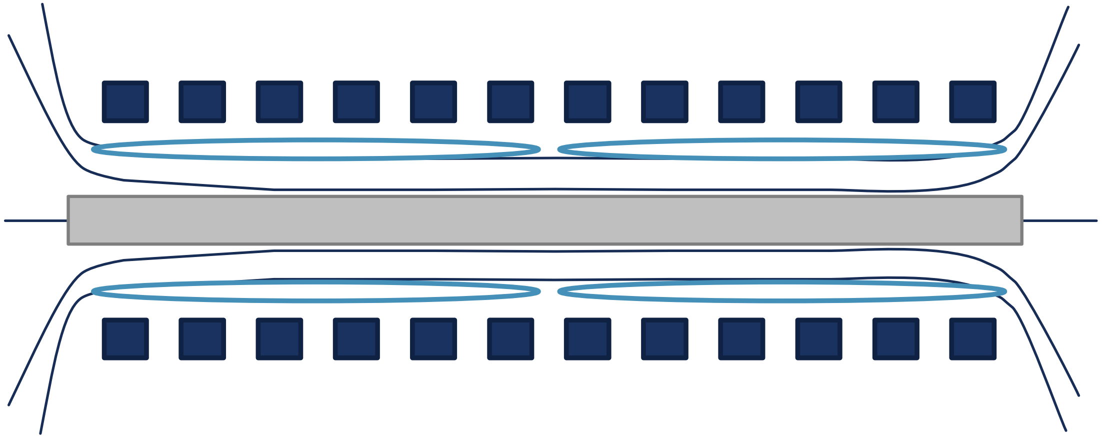
- Idea 1: To use multiple (3 or 4) vibrating wires.



- PRO: Sensitivity (Significant vibrations also with low field)
- CONS: Hard to obtain several wires with identical mechanical behavior.

BRAIN STORMING (2/3)

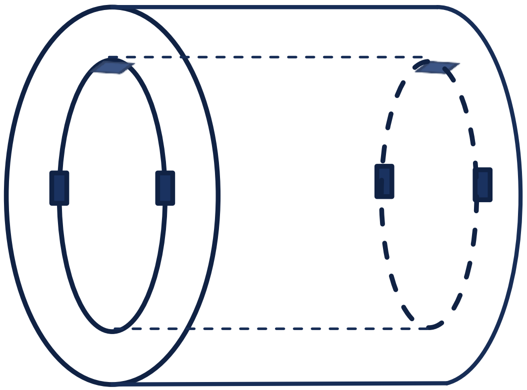
- Idea 2: To use coils.



- PRO: Easy to build, high accuracy.
- CONS: Require field gradient. Static coils can be only in the case of pulsed magnets (NOT the case of ELI-NP!). Not enough space for rotating/translating coils.

BRAIN STORMING (3/3)

- Idea 3: To use several Hall transducers
  (thanks to Carlo Petrone for the discussion!)



- PROS: Measuring directly the magnetic field, small, no motion.
- CONS: Lower accuracy, possibly damaged by radiation (monitoring during working).

RADIATION RESISTANCE FOR ELI-NP

Oscar Frasciello <oscar.frasciello@lnf.infn.it> 25 set 2017, 12:35

a Alessandro, Tomassini, Luca, prof, Alessandro, Biase, Nicola, Oscar

Cari tutti,

come già specificato in altre occasioni, il danno da radiazione è un effetto a soglia. La più bassa soglia di danneggiamento si osserva per l'elettronica a semiconduttore ed equivale a circa 10 Gy. Integrando il più alto valore di picco per il rateo di dose a mia disposizione - calcolato per il dump a 840 MeV - su 3000 h/y di funzionamento della macchina, si ottiene un valore di dose di circa 0.12 Gy, quindi ben al di sotto (3 ordini di grandezza) della minima soglia specificata sopra. WARNING: la zona cui si riferisce il dato testé riportato NON corrisponde a quella in cui si desidererebbe installare le sonde. Costituisce, tuttavia, un ragionevole valore di riferimento. Nel caso fosse necessaria una più specifica e completa caratterizzazione ai fini dell'installazione, occorrerebbe procedere con simulazioni dedicate.

A vostra disposizione per ulteriori chiarimenti,

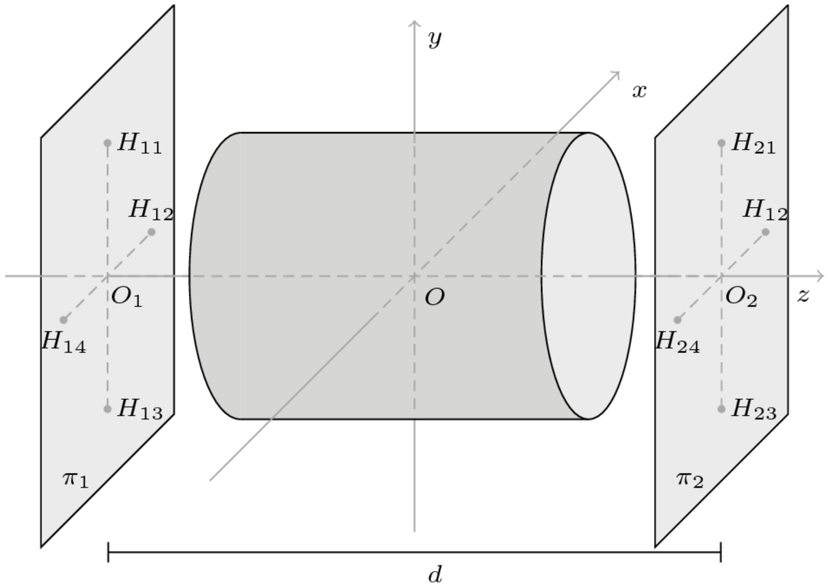
un caro saluto

Oscar

WE KNOW NOW ENOUGH TO START WORKING

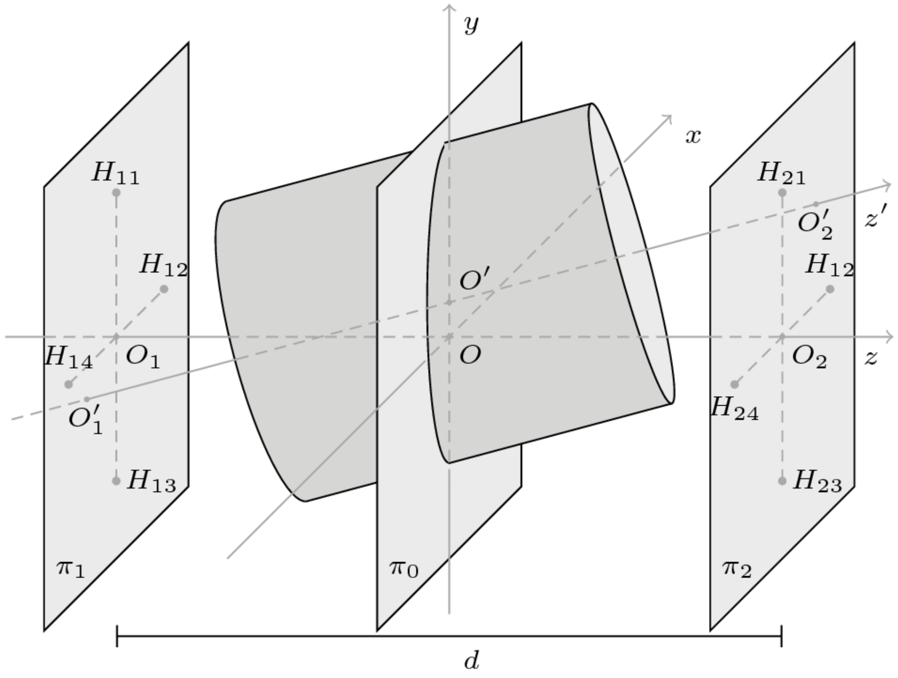
LET'S GO WITH HALL TRANSDUCERS! (1/2)

- 4 Hall transducers on two planes perpendicular to the mechanical axis;
- Due to the axisymmetry of the field, in the aligned case, the Hall transducers would measure the same field magnitude.

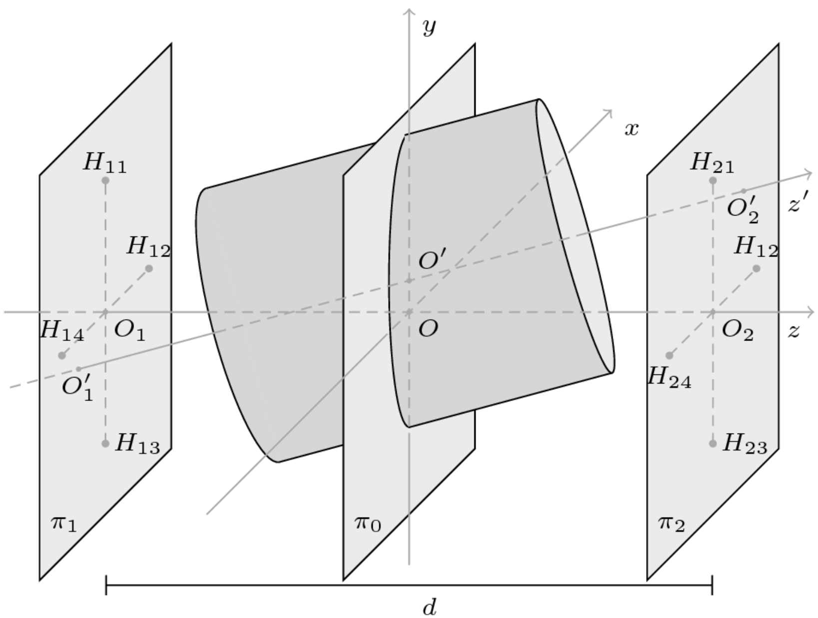


LET'S GO WITH HALL TRANSDUCERS! (2/2)

- If misaligned, the Hall transducers will not measure the same magnitude.
- The method aims to derive the equation of the misaligned axis from the Hall transducer measurements.



METHOD DEFINITION (1/4)



- Description of the magnetic axis:

$$P(t) = O' + t(O_2' - O_1')$$

$$\begin{cases} x = x_{O'} + v_x t \\ y = y_{O'} + v_y t \\ z = t \cdot d \end{cases} \qquad \begin{aligned} v_x &= x_{O'_2} - x_{O'_1} \\ v_y &= y_{O'_2} - y_{O'_1} \end{aligned}$$

- Assumption of no longitudinal shift:

$$O' \in \pi_0$$

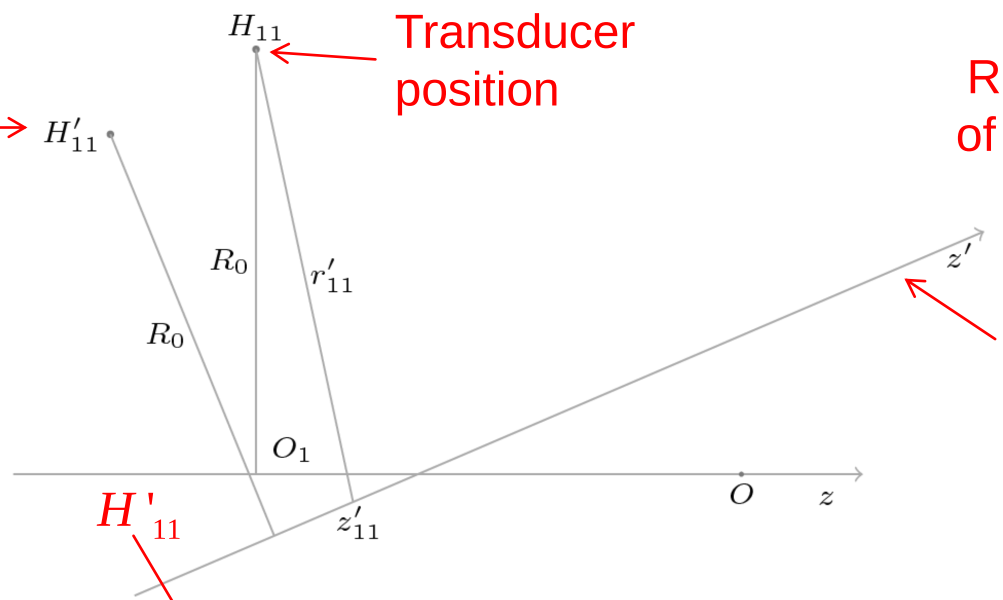
METHOD DEFINITION (2/4)

- Under the assumption of a small misalignment: $x_{O'}, y_{O'}, v_x, v_y \ll R_0$

Radial position of the tranducer

Misaligned transducer position

Transducer position



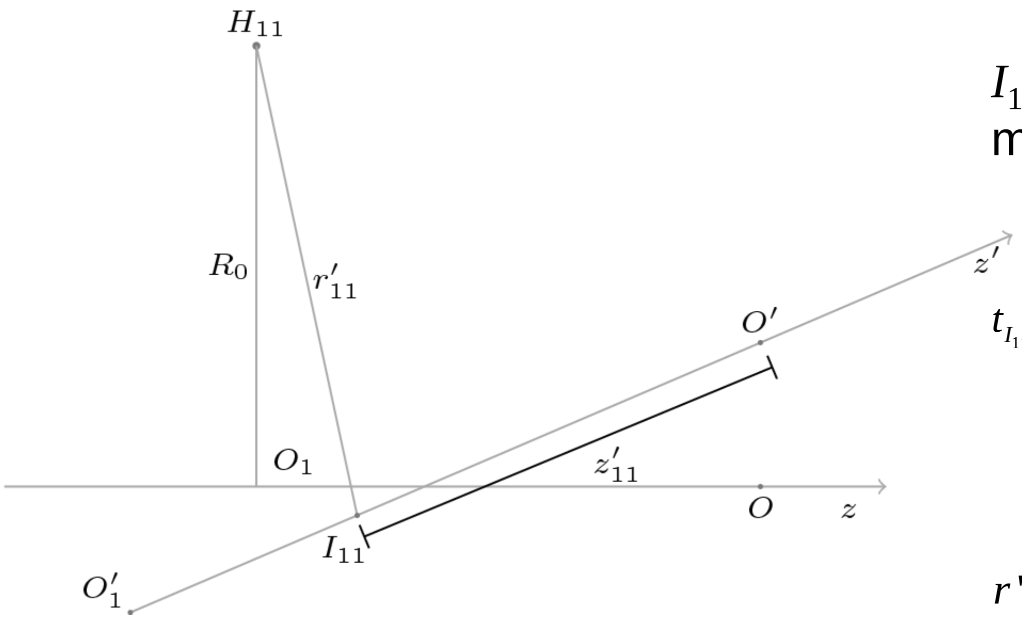
Magnetic axis

Field magnitude

H_{11} H'_{11}

$$B\left(r'_{hk}, z'_{hk}\right) \approx B\left(R_0, z_h\right) + \left.\frac{\partial B}{\partial r}\right|_{R_0, z_h} \left(r'_{hk} - R_0\right) + \left.\frac{\partial B}{\partial z}\right|_{R_0, z_h} \left(z'_{hk} - z_h\right)$$

METHOD DEFINITION (3/4)



I_{11} belongs to the magnetic axis

$$\begin{cases} x_{I_{11}} = x_{O'} + t_{I_{11}} v_x \\ y_{I_{11}} = y_{O'} + t_{I_{11}} v_y \\ z_{I_{11}} = t_{I_{11}} d \end{cases}$$

$$t_{I_{11}} \approx \frac{1}{d^2}\left[v_x \left(x_{H_{11}} - x_{O'} \right) + v_y \left(y_{H_{11}} - y_{O'} \right) + d \cdot z_{H_{11}} \right]$$

$$z'_{11} = z_1 + \left(t_{I_{11}} + \frac{1}{2} \right) d$$

$$r'_{11} = \sqrt{x_{I1}^2 + \left(R_0 - y_{I1} \right)^2 + \left(z_1 - z_{I1} \right)^2} \approx R_0 - y_{I1}$$

METHOD DEFINITION (4/4)

- Repeating for all probes…

$$B(H_{13}) - B(H_{11}) = 2\left.\frac{\partial B}{\partial r}\right|_{R_0,-d/2}\left(y_{O'} - \frac{1}{2}v_y\right) - 2\frac{R_0}{d}\left.\frac{\partial B}{\partial z}\right|_{R_0,-d/2} v_y$$

$$B(H_{14}) - B(H_{12}) = 2\left.\frac{\partial B}{\partial r}\right|_{R_0,-d/2}\left(x_{O'} - \frac{1}{2}v_x\right) - 2\frac{R_0}{d}\left.\frac{\partial B}{\partial z}\right|_{R_0,-d/2} v_x$$

$$B(H_{23}) - B(H_{21}) = 2\left.\frac{\partial B}{\partial r}\right|_{R_0,d/2}\left(y_{O'} + \frac{1}{2}v_y\right) - 2\frac{R_0}{d}\left.\frac{\partial B}{\partial z}\right|_{R_0,d/2} v_y$$

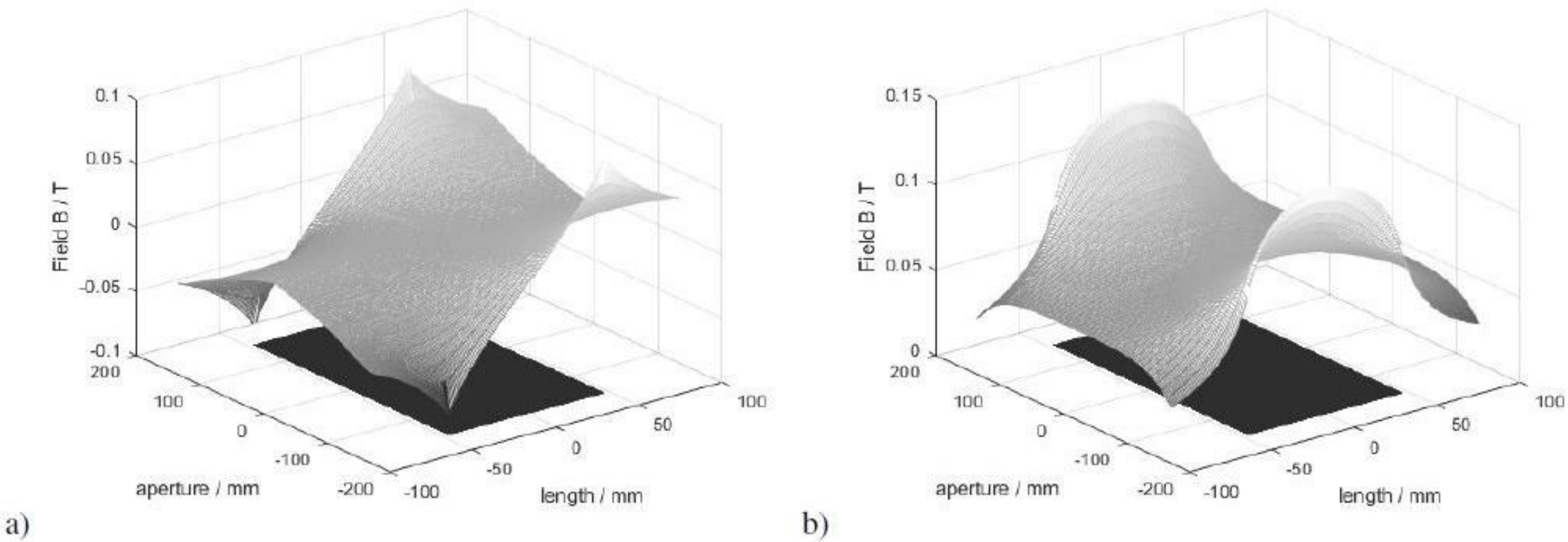
$$B(H_{24}) - B(H_{22}) = 2\left.\frac{\partial B}{\partial r}\right|_{R_0,d/2}\left(x_{O'} + \frac{1}{2}v_x\right) - 2\frac{R_0}{d}\left.\frac{\partial B}{\partial z}\right|_{R_0,d/2} v_x$$

We need:

- Measured field magnitude values (from triaxial Hall transducers)
- Derivatives of the field magnitude in the aligned case (from solenoid mapping or FEM)

P. Arpaia, B. Celano, L. De Vito, A. Esposito, N. Moccaldi, and A. Parrella, "Monitoring the magnetic axis misalignment in axially-symmetric magnets," in *Proc. of 2018 Int. Instrum. and Meas. Tech. Conf.*, 2018, pp. 1726–1731.

SOLENOID ANALYTICAL MODEL



N. Derby, S. Olbert, "Cylindrical magnets and ideal solenoids", American Journal of Physics, vol. 78, 2010

UNIAXIAL TRANSDUCERS VS. TRIAXIAL TRANSDUCERS

- In order to evaluate the magnetic field magnitude we need 3D Hall transducers.
- However, 1D Hall transducers show a better accuracy than the 3D ones
- Can we modify the method to work with 1D sensors?

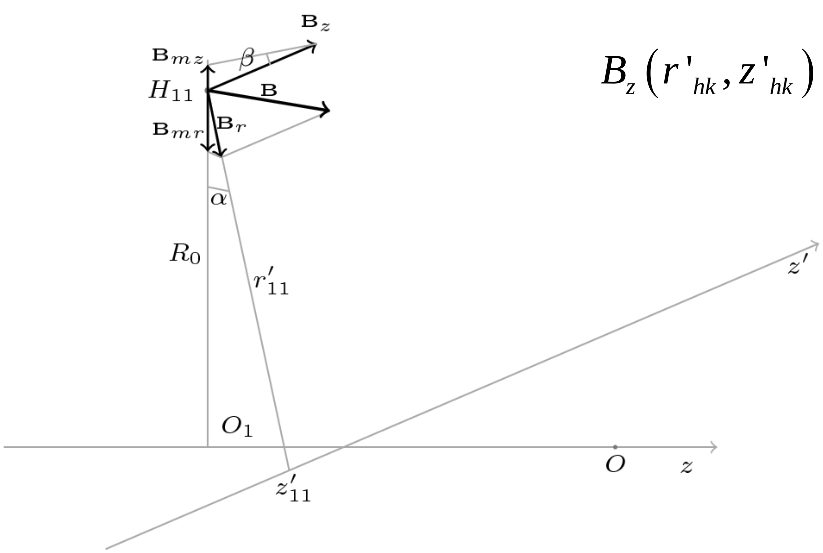
USING UNIAXIAL PROBES (1/7)

Expansion of the B vector

$$\mathbf{B}(r'_{hk}, z'_{hk}) \approx \mathbf{B}(R_0, z_h) + \left.\frac{\partial \mathbf{B}}{\partial r}\right|_{R_0, z_h} (r'_{hk} - R_0) + \left.\frac{\partial \mathbf{B}}{\partial z}\right|_{R_0, z_h} (z'_{hk} - z_h)$$

$$B_r(r'_{hk}, z'_{hk}) \approx B_r(R_0, z_h) + \left.\frac{\partial B_r}{\partial r}\right|_{R_0, z_h} (r'_{hk} - R_0) + \left.\frac{\partial B_r}{\partial z}\right|_{R_0, z_h} (z'_{hk} - z_h)$$

$$B_z(r'_{hk}, z'_{hk}) \approx B_z(R_0, z_h) + \left.\frac{\partial B_z}{\partial r}\right|_{R_0, z_h} (r'_{hk} - R_0) + \left.\frac{\partial B_z}{\partial z}\right|_{R_0, z_h} (z'_{hk} - z_h)$$



$$B_m = B_{mr} + B_{mz} \approx B_r + B_z \sin\beta$$

Uniaxial probe measurement

$$\sin\beta_{11} \approx \frac{v_2}{d} \quad \sin\beta_{13} \approx -\frac{v_2}{d}$$

$$\sin\beta_{12} \approx \frac{v_1}{d} \quad \sin\beta_{14} \approx -\frac{v_1}{d}$$

USING UNIAXIAL PROBES (2/7)

$$B_r(H_{11}) \approx B_r\left(R_0, -\frac{d}{2}\right) - \frac{\partial B_r}{\partial r}\bigg|_{R_0,-\frac{d}{2}} (y_{O'} + t_{I_{11}} v_2) + \frac{\partial B_r}{\partial z}\bigg|_{R_0,-\frac{d}{2}} \left(t_{I_{11}} + \frac{1}{2}\right) d$$

$$B_r(H_{13}) \approx B_r\left(R_0, -\frac{d}{2}\right) + \frac{\partial B_r}{\partial r}\bigg|_{R_0,-\frac{d}{2}} (y_{O'} + t_{I_{13}} v_2) + \frac{\partial B_r}{\partial z}\bigg|_{R_0,-\frac{d}{2}} \left(t_{I_{13}} + \frac{1}{2}\right) d$$

$$t_{I_{11}} = \frac{v_1(-x_{O'}) + v_2(+R_0 - y_{O'}) + d(-d/2)}{d^2} \approx \frac{v_2(+R_0 - y_{O'})}{d^2} - \frac{1}{2}$$

$$t_{I_{13}} = \frac{v_1(-x_{O'}) + v_2(-R_0 - y_{O'}) + d(-d/2)}{d^2} \approx \frac{v_2(-R_0 - y_{O'})}{d^2} - \frac{1}{2}$$

EXPLOITING FIELD SYMMETRIES IN THE ALIGNED CASE

$$B_r(H_{2k}) = -B_r(H_{1k}) = B_{r0} \qquad B_z(H_{2k}) = +B_z(H_{1k}) = B_{z0}$$

$$\left.\frac{\partial B_r}{\partial r}\right|_{R_0,+\frac{d}{2}} = -\left.\frac{\partial B_r}{\partial r}\right|_{R_0,-\frac{d}{2}} = \left.\frac{\partial B_r}{\partial r}\right|_0 \qquad \left.\frac{\partial B_z}{\partial r}\right|_{R_0,+\frac{d}{2}} = +\left.\frac{\partial B_z}{\partial r}\right|_{R_0,-\frac{d}{2}} = \left.\frac{\partial B_z}{\partial r}\right|_0$$

$$\left.\frac{\partial B_r}{\partial z}\right|_{R_0,+\frac{d}{2}} = +\left.\frac{\partial B_r}{\partial z}\right|_{R_0,-\frac{d}{2}} = \left.\frac{\partial B_r}{\partial z}\right|_0 \qquad \left.\frac{\partial B_z}{\partial z}\right|_{R_0,+\frac{d}{2}} = -\left.\frac{\partial B_z}{\partial z}\right|_{R_0,-\frac{d}{2}} = \left.\frac{\partial B_z}{\partial z}\right|_0$$

USING UNIAXIAL PROBES (3/7)

$$B_m(H_{13}) - B_m(H_{11}) \approx [B_r(H_{13}) - B_r(H_{11})] - \frac{v_2}{d}[B_z(H_{13}) + B_z(H_{11})]$$

$$= -\frac{\partial B_r}{\partial r}\bigg|_0 \left[2y_{O'} + \left(t_{I_{13}} + t_{I_{11}}\right)v_2\right] + \frac{\partial B_r}{\partial z}\bigg|_0 \left(t_{I_{13}} - t_{I_{11}}\right)d$$

$$- \frac{v_2}{d}\left[2B_{z0} + \frac{\partial B_z}{\partial r}\bigg|_0 \left(t_{I_{13}} - t_{I_{11}}\right)v_2 - \frac{\partial B_z}{\partial z}\bigg|_0 \left(t_{I_{13}} + t_{I_{11}} + 1\right)d\right]$$

$$B_m(H_{13}) - B_m(H_{11}) \approx -\frac{\partial B_r}{\partial r}\bigg|_0 \left[2y_{O'}\left(1 - \frac{v_2^2}{d^2}\right) - v_2\right] - 2\frac{\partial B_r}{\partial z}\bigg|_0 \frac{v_2}{d}R_0$$

$$- \frac{v_2}{d}\left[2B_{z0} - 2\frac{\partial B_z}{\partial r}\bigg|_0 \frac{v_2^2}{d^2}R_0 - 2\frac{\partial B_z}{\partial z}\bigg|_0 \frac{v_2}{d}y_{O'}\right]$$

$$\approx -2\frac{\partial B_r}{\partial r}\bigg|_0 \left(y_{O'} - \frac{v_2}{2}\right) - 2\frac{R_0}{d}\frac{\partial B_r}{\partial z}\bigg|_0 v_2 - 2\frac{v_2}{d}B_{z0}$$

USING UNIAXIAL PROBES (4/7)

Transducers placed along the radial direction:

$$B_m(H_{13}) - B_m(H_{11}) = -2\frac{\partial B_r}{\partial r}\bigg|_0\left(y_{O'} - \frac{v_2}{2}\right) - 2\frac{R_0}{d}\frac{\partial B_r}{\partial z}\bigg|_0 v_2 - 2\frac{v_2}{d}B_{z0}$$

$$B_m(H_{14}) - B_m(H_{12}) = -2\frac{\partial B_r}{\partial r}\bigg|_0\left(x_{O'} - \frac{v_1}{2}\right) - 2\frac{R_0}{d}\frac{\partial B_r}{\partial z}\bigg|_0 v_1 - 2\frac{v_1}{d}B_{z0}$$

$$B_m(H_{23}) - B_m(H_{21}) = +2\frac{\partial B_r}{\partial r}\bigg|_0\left(y_{O'} + \frac{v_2}{2}\right) - 2\frac{R_0}{d}\frac{\partial B_r}{\partial z}\bigg|_0 v_2 - 2\frac{v_2}{d}B_{z0}$$

$$B_m(H_{24}) - B_m(H_{22}) = +2\frac{\partial B_r}{\partial r}\bigg|_0\left(x_{O'} + \frac{v_1}{2}\right) - 2\frac{R_0}{d}\frac{\partial B_r}{\partial z}\bigg|_0 v_1 - 2\frac{v_1}{d}B_{z0}$$

P. Arpaia, B. Celano, L. De Vito, A. Esposito, A. Parrella, and A. Vannozzi, "Measuring the magnetic axis alignment during solenoids working," *Nature Scientific Reports*, no. 8, 2018.

nature SCIENTIFIC REPORTS

USING UNIAXIAL PROBES (5/7)

Transducers placed along the radial direction:

$$x_{o'} = \frac{[B_m(H_{24}) - B_m(H_{22})] - [B_m(H_{14}) - B_m(H_{12})]}{4\left.\frac{\partial B_r}{\partial r}\right|_0}$$

$$y_{o'} = \frac{[B_m(H_{23}) - B_m(H_{21})] - [B_m(H_{13}) - B_m(H_{11})]}{4\left.\frac{\partial B_r}{\partial r}\right|_0}$$

$$v_1 = \frac{[B_m(H_{24}) - B_m(H_{22})] + [B_m(H_{14}) - B_m(H_{12})]}{2\left(\left.\frac{\partial B_r}{\partial r}\right|_0 - 2\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 - 2\frac{B_{z0}}{d}\right)}$$

$$v_2 = \frac{[B_m(H_{23}) - B_m(H_{21})] + [B_m(H_{13}) - B_m(H_{11})]}{2\left(\left.\frac{\partial B_r}{\partial r}\right|_0 - 2\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 - 2\frac{B_{z0}}{d}\right)}$$

USING UNIAXIAL PROBES (6/7)

Transducers placed along the axial direction:

$$
\begin{aligned}
B_m(H_{13}) - B_m(H_{11}) &= 2\frac{\partial B_z}{\partial r}\bigg|_0 \left(y_{O'} - \frac{v_2}{2}\right) + 2\frac{R_0}{d}\frac{\partial B_z}{\partial z}\bigg|_0 v_2 + 2\frac{B_{r0}}{d}v_2 \\
B_m(H_{14}) - B_m(H_{12}) &= 2\frac{\partial B_z}{\partial r}\bigg|_0 \left(x_{O'} - \frac{v_1}{2}\right) + 2\frac{R_0}{d}\frac{\partial B_z}{\partial z}\bigg|_0 v_1 + 2\frac{B_{r0}}{d}v_1 \\
B_m(H_{23}) - B_m(H_{21}) &= 2\frac{\partial B_z}{\partial r}\bigg|_0 \left(y_{O'} + \frac{v_2}{2}\right) - 2\frac{R_0}{d}\frac{\partial B_z}{\partial z}\bigg|_0 v_2 - 2\frac{B_{r0}}{d}v_2 \\
B_m(H_{24}) - B_m(H_{22}) &= 2\frac{\partial B_z}{\partial r}\bigg|_0 \left(x_{O'} + \frac{v_1}{2}\right) - 2\frac{R_0}{d}\frac{\partial B_z}{\partial z}\bigg|_0 v_1 - 2\frac{B_{r0}}{d}v_1
\end{aligned}
$$

P. Arpaia, B. Celano, L. De Vito, A. Esposito, A. Parrella, and A. Vannozzi, "Measuring the magnetic axis alignment during solenoids working," *Nature Scientific Reports*, no. 8, 2018.

nature

SCIENTIFIC REPORTS

USING UNIAXIAL PROBES (7/7)

Transducers placed along the axial direction:

$$x_{O'} = \frac{[B_m(H_{24}) - B_m(H_{22})] + [B_m(H_{14}) - B_m(H_{12})]}{4\left.\frac{\partial B_z}{\partial r}\right|_0}$$

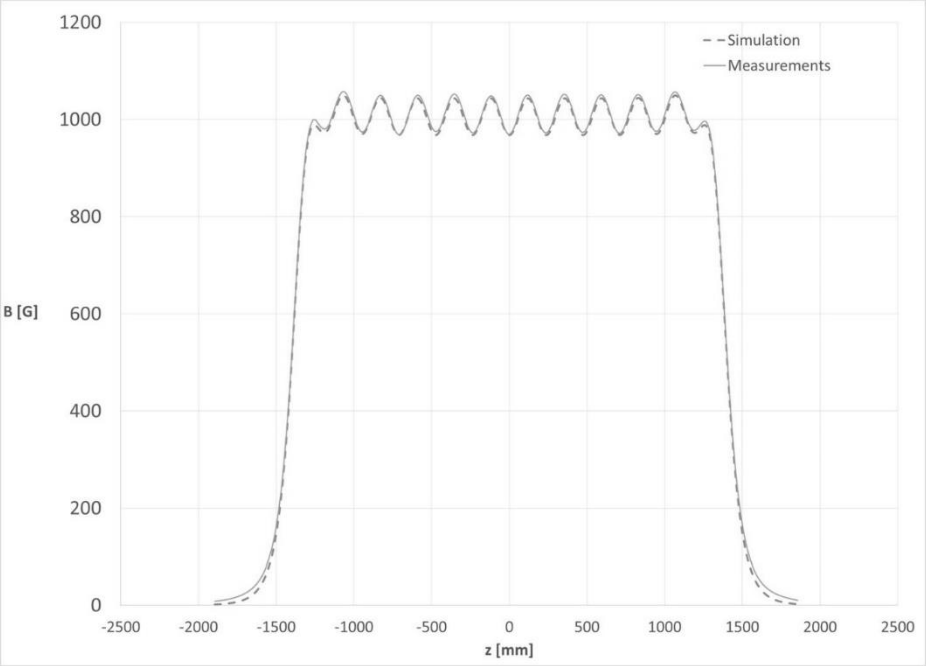
$$y_{O'} = \frac{[B_m(H_{23}) - B_m(H_{21})] + [B_m(H_{13}) - B_m(H_{11})]}{4\left.\frac{\partial B_z}{\partial r}\right|_0}$$

$$v_1 = \frac{[B_m(H_{14}) - B_m(H_{12})] - [B_m(H_{24}) - B_m(H_{22})]}{2\left(2\frac{R_0}{d}\left.\frac{\partial B_z}{\partial z}\right|_0 - \left.\frac{\partial B_z}{\partial r}\right|_0 - 2\frac{B_{r0}}{d}\right)}$$

$$v_2 = \frac{[B_m(H_{13}) - B_m(H_{11})] - [B_m(H_{23}) - B_m(H_{21})]}{2\left(2\frac{R_0}{d}\left.\frac{\partial B_z}{\partial z}\right|_0 - \left.\frac{\partial B_z}{\partial r}\right|_0 - 2\frac{B_{r0}}{d}\right)}$$

FEM EVALUATION

- We would like to evaluate the derivates and the field in the aligned case by FEM and not only by the analytical model.



- The FeM of the ELI-NP Solenoid B was evaluated (multicoil)
- The result of the FEM ws compared with the experimental data from the magnet characterization (by the manufacturer)
- The actual FEM used was obtained then by simulating a single active coil.

METHOD CONFIGURATION

- Where to place the Hall probes? Positions minimizing uncertainty

- Considered uncertainty sources:
  - Measurement uncertainty of the Hall transducers (u_B)
  - Uncertainty related to the transducers placing (u_g)
  - Uncertainty of the derivatives of B_r (u_∂)
  - Uncertainty of the B_{z0} value (u_f)

UNCERTAINTY EVALUATION (1/3)

$$u_{x_{O'}}^2 = \frac{u_B^2}{4\left(\left.\frac{\partial B_r}{\partial r}\right|_0\right)^2} + \left(\frac{x_{o'}}{\left.\frac{\partial B_r}{\partial r}\right|_0}\right)^2 u_\partial^2$$

$$u_{v_1}^2 = \frac{u_B^2}{\left(\left.\frac{\partial B_r}{\partial r}\right|_0 - 2\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 - 2\frac{B_{z0}}{d}\right)^2} + \left(\frac{v_1}{\left.\frac{\partial B_r}{\partial r}\right|_0 - 2\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 - 2\frac{B_{z0}}{d}}\right)^2$$

$$\times\left[\left(1 + 4\frac{R_0^2}{d^2}\right)u_\partial^2 + \frac{4}{d^2}u_f^2\right] + \left(\frac{v_1}{\left.\frac{\partial B_r}{\partial r}\right|_0 - 2\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 - 2\frac{B_{z0}}{d}}\right)^2$$

$$\times\left[4\left(\frac{B_{z0}}{d^2} + \frac{R_0}{d^2}\left.\frac{\partial B_r}{\partial z}\right|_0\right)^2 + \frac{4}{d^2}\left.\frac{\partial B_r}{\partial z}\right|_0^2\right]u_g^2$$

UNCERTAINTY EVALUATION (2/3)

- Considering the order of magnitude of the uncertainties:
  - $u_B \approx 10^{-4}\,\mathrm{T}$ typical uncertainty of uniaxial Hall transducers
  - $u_g \approx 10^{-5}\,\mathrm{m}$ placement by laser tracker
  - $u_\partial \approx 10^{-2}\,\mathrm{T/m}$, $u_f \approx 10^{-3}\,\mathrm{T}$, field model accuracy 1%
- In the case of the ELI-NP solenoid, only u_B and u_∂ give significant contribution:

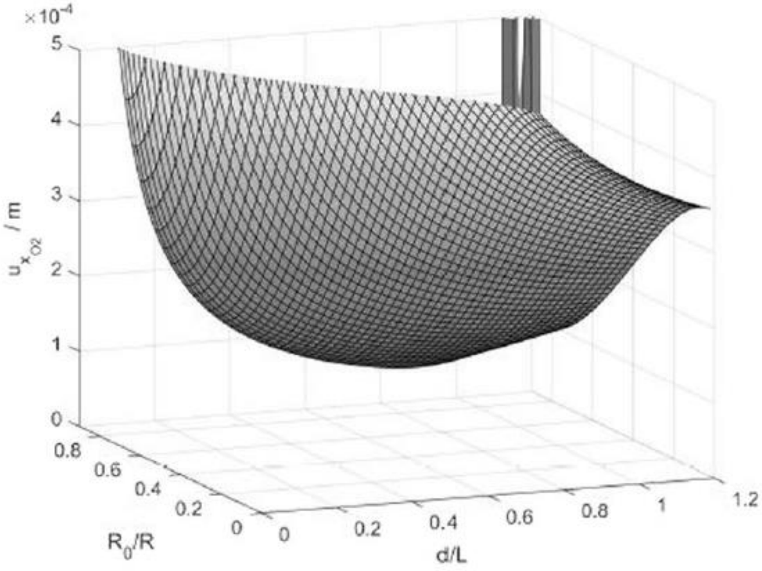
$$u_{xo'}^2 \approx \frac{u_B^2}{4\left(\left.\frac{\partial B_r}{\partial r}\right|_0\right)^2}$$

$$u_{v1}^2 \approx \frac{u_B^2 + v_1^2\left(1 + 4\frac{R_0^2}{d^2}\right)u_\partial^2}{\left(\left.\frac{\partial B_r}{\partial r}\right|_0 - 2\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 - 2\frac{B_{z0}}{d}\right)^2}$$

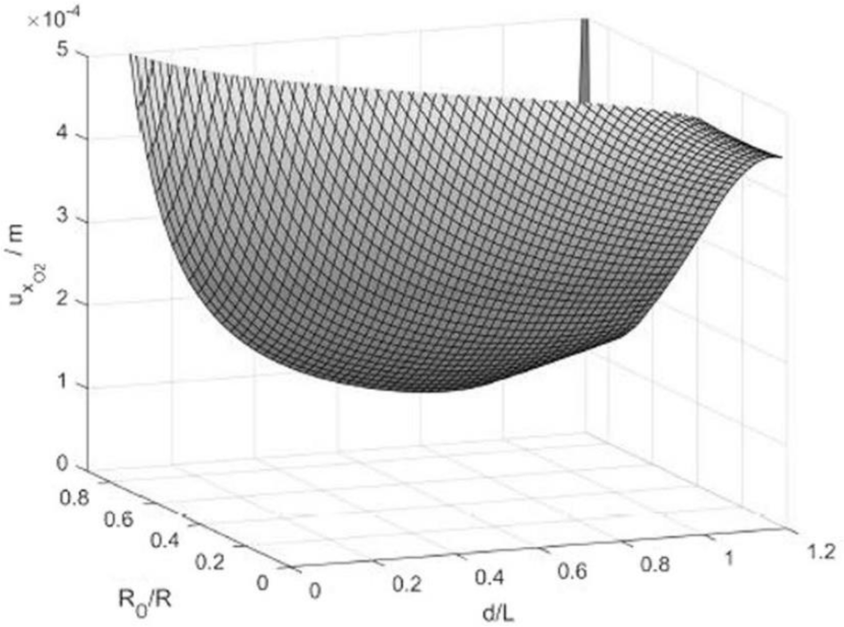
$$u_{x_{O_2'}} = \sqrt{u_{x_{O'}}^2 + \frac{u_{v1}^2}{4}}$$

UNCERTAINTY EVALUATION (3/3)

Analytical model



FEM (one coil)

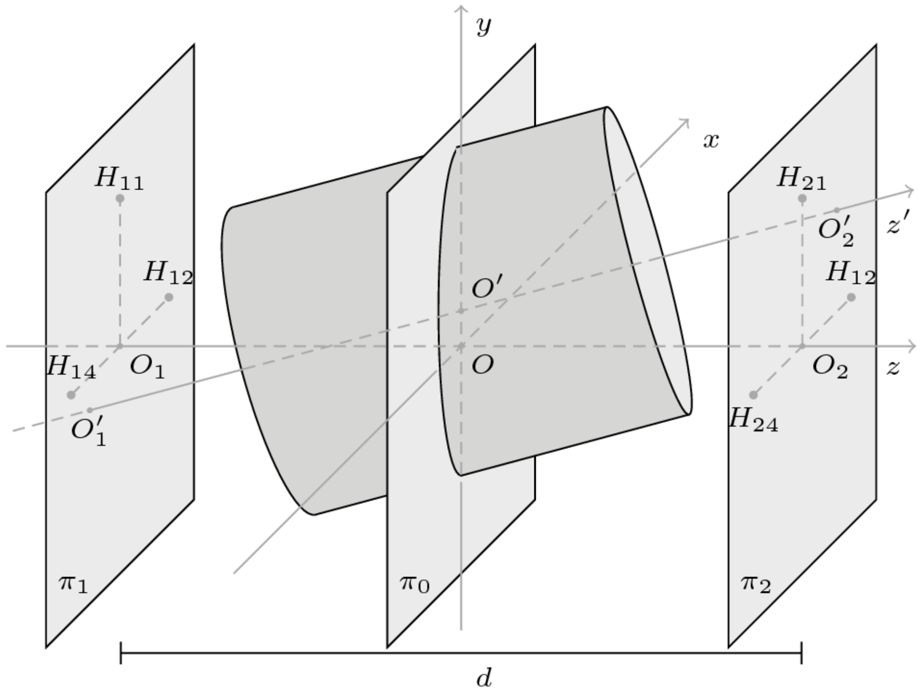


Minima are located for R_0/R close to 1 and $d \approx 0.9L$

Uncertainty is slightly more than $50\ \mu\mathrm{m}$

3 TRANSDUCERS PER SIDE (1/3)

- In some cases, only 3 positions per side are accessible for probe positioning.



3 TRANSDUCERS PER SIDE (2/3)

Transducers placed along the radial direction:

$$B_m(H_{14}) - B_m(H_{12}) = -2\frac{\partial B_r}{\partial r}\bigg|_0 \left(x_{O'} - \frac{v_1}{2}\right) - 2\frac{R_0}{d}\frac{\partial B_r}{\partial z}\bigg|_0 v_1 - 2\frac{v_1}{d}B_{z0}$$

$$B_m(H_{24}) - B_m(H_{22}) = +2\frac{\partial B_r}{\partial r}\bigg|_0 \left(x_{O'} + \frac{v_1}{2}\right) - 2\frac{R_0}{d}\frac{\partial B_r}{\partial z}\bigg|_0 v_1 - 2\frac{v_1}{d}B_{z0}$$

$$B_m(H_{14}) - B_m(H_{11}) = -\frac{\partial B_r}{\partial r}\bigg|_0 \left[x_{O'} - \frac{v_1}{2} + y_{O'} - \frac{v_2}{2} + \frac{R_0}{d^2}(v_2^2 - v_1^2)\right] - \left(\frac{R_0}{d}\frac{\partial B_r}{\partial z}\bigg|_0 + \frac{B_{z0}}{d}\right)(v_1 + v_2)$$

$$B_m(H_{24}) - B_m(H_{21}) = +\frac{\partial B_r}{\partial r}\bigg|_0 \left[x_{O'} + \frac{v_1}{2} + y_{O'} + \frac{v_2}{2} + \frac{R_0}{d^2}(v_2^2 - v_1^2)\right] - \left(\frac{R_0}{d}\frac{\partial B_r}{\partial z}\bigg|_0 + \frac{B_{z0}}{d}\right)(v_1 + v_2)$$

3 TRANSDUCERS PER SIDE (3/3)

$$x_{o'} = \frac{[B_m(H_{24}) - B_m(H_{22})] - [B_m(H_{14}) - B_m(H_{12})]}{4\left.\frac{\partial B_r}{\partial r}\right|_0}$$

$$y_{o'} = \frac{K_2 - K_1}{2\left.\frac{\partial B_r}{\partial r}\right|_0}$$

$$v_1 = \frac{[B_m(H_{24}) - B_m(H_{22})] + [B_m(H_{14}) - B_m(H_{12})]}{2\left(\left.\frac{\partial B_r}{\partial r}\right|_0 - 2\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 - 2\frac{B_{z0}}{d}\right)}$$

$$v_2 = \frac{K_2 + K_1}{\left.\frac{\partial B_r}{\partial r}\right|_0 - 2\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 - 2\frac{B_{z0}}{d}}$$

$$K_1 = -\left.\frac{\partial B_r}{\partial r}\right|_0\left(y_{O'} - \frac{v_2}{2}\right) - \left(\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 + \frac{B_{z0}}{d}\right)v_2$$

$$K_2 = +\left.\frac{\partial B_r}{\partial r}\right|_0\left(y_{O'} + \frac{v_2}{2}\right) - \left(\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 + \frac{B_{z0}}{d}\right)v_2$$

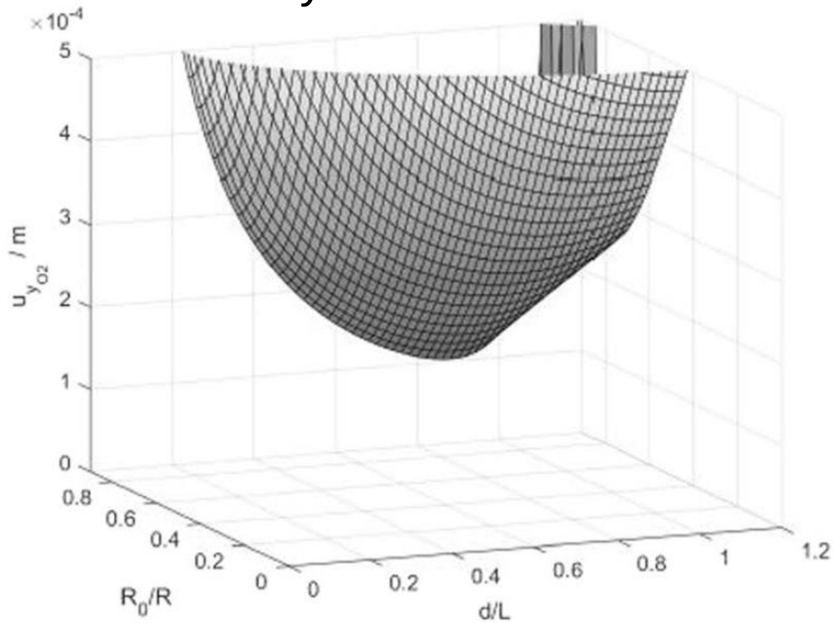
UNCERTAINTY FOR 3 TRANSDUCERS

$$u_{yo'}^2 \approx \frac{5u_B^2}{4\left(\left.\frac{\partial B_r}{\partial r}\right|_0\right)^2}$$

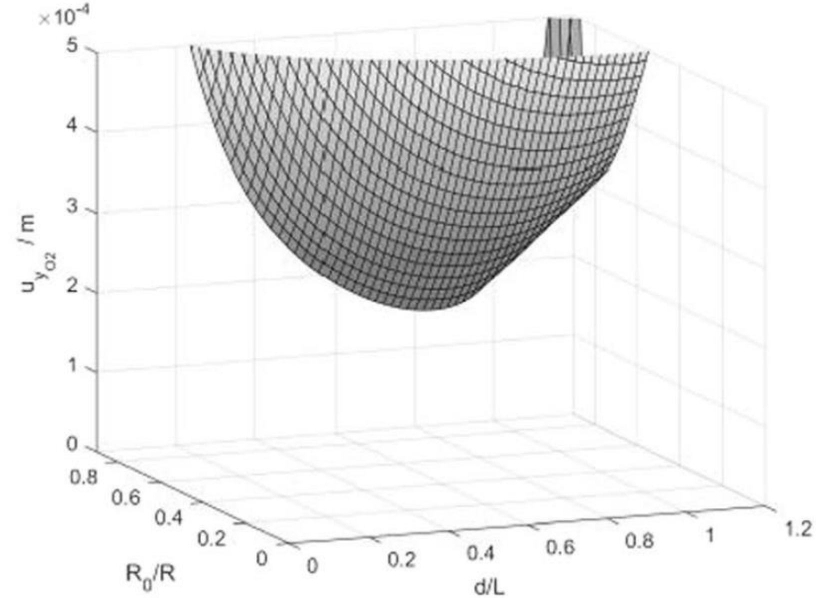
$$u_{v2}^2 = \frac{8.5u_B^2 + v_2^2\left(1 + \frac{4R_0^2}{d^2}\right)u_\partial^2}{\left(\left.\frac{\partial B_r}{\partial r}\right|_0 - 2\frac{R_0}{d}\left.\frac{\partial B_r}{\partial z}\right|_0 - 2\frac{B_{z0}}{d}\right)^2}$$

UNCERTAINTY FOR 3 TRANSDUCERS

Analytical model



FEM



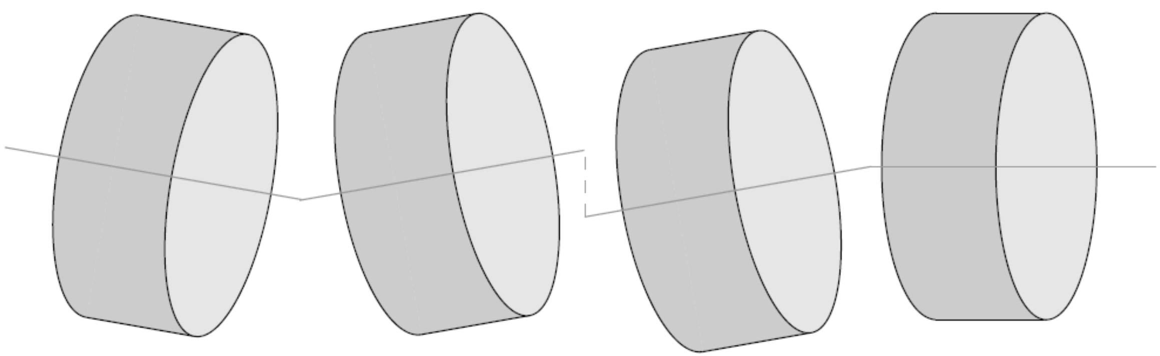
Minima are again located for R_0/R close to 1 and $d \approx 0.9L$

Uncertainty of the vertical coordinate is doubled to about $100\ \mu\text{m}$

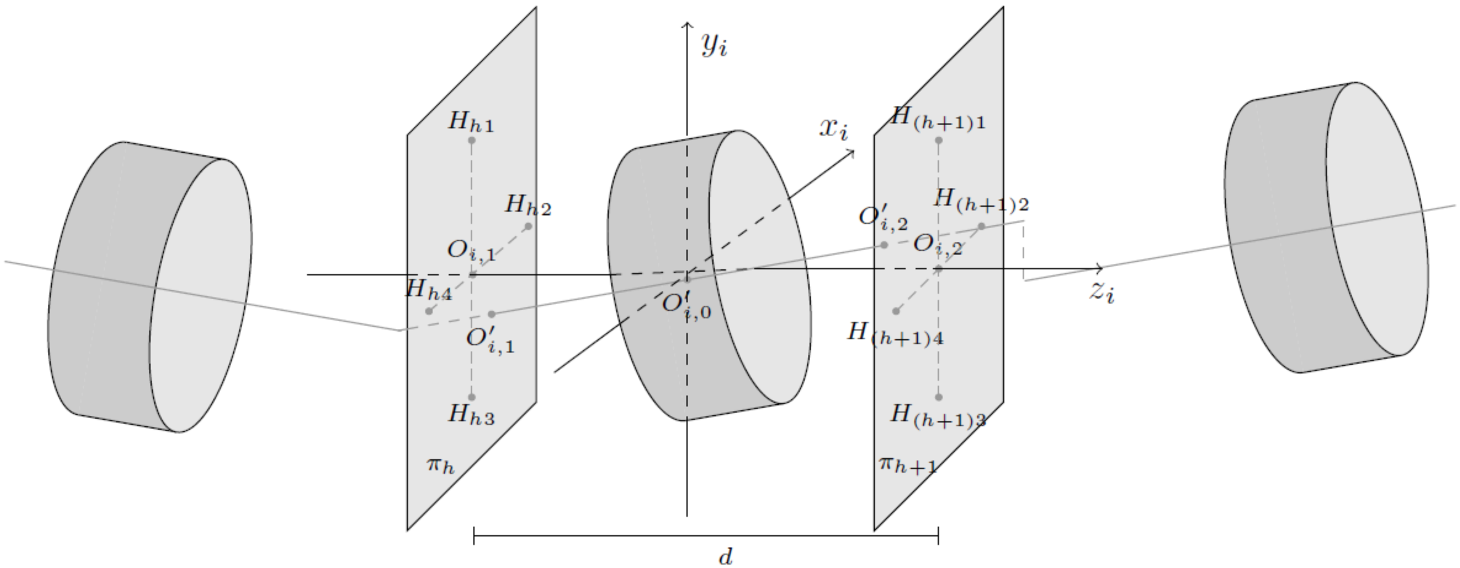
WHAT ABOUT MULTI-COIL SOLENOIDS?

MULTI-COIL SOLENOIDS

- For a single cylindrical coil, assuming that the magnetic field is axially symmetric, the magnetic axis is a straight line and coincides with the symmetry axis of the magnetic field.
- Even assuming the magnetic field of each coil as axially symmetric, the actual misalignments of such fields make the overall magnetic field not axially symmetric.
- We approximate approximated it with a polygonal chain, composed by as many segments as the number of the coils, where each segment is part of the magnetic axis of the corresponding coil.



EXTENSION TO MULTI-COIL SOLENOIDS (1/4)



$$\begin{cases} x_i = x_{O'_{0,i}} + t v_{x,i} \\ y_i = y_{O'_{0,i}} + t v_{y,i} \\ z_i = t d \end{cases}$$

EXTENSION TO MULTI-COIL SOLENOIDS (2/4)

$$B_m(H_{hk}) \approx \sum_{i=1}^{N} \left[B_{r,i}(H_{hk}) + \sin\beta_{hk,i} B_{z,i}(H_{hk})\right]$$

$$B_m(H_{h3}) - B_m(H_{h1}) = \sum_{i=1}^{N} \left\{\left[B_{r,i}(H_{h3}) - B_{r,i}(H_{h1})\right] - \frac{v_{y,i}}{d}\left[B_{z,i}(H_{h3}) + B_{z,i}(H_{h1})\right]\right\}$$

$$B_m(H_{h4}) - B_m(H_{h2}) = \sum_{i=1}^{N} \left\{\left[B_{r,i}(H_{h4}) - B_{r,i}(H_{h2})\right] - \frac{v_{x,i}}{d}\left[B_{z,i}(H_{h4}) + B_{z,i}(H_{h2})\right]\right\}$$

$$B_{r,i}(r'_{hk}, z'_{hk}) \approx B_{r,i}(R_0, z_h) + \left.\frac{\partial B_{r,i}}{\partial r}\right|_{R_0, z_h} (r'_{hk} - R_0) + \left.\frac{\partial B_{r,i}}{\partial z}\right|_{R_0, z_h} (z'_{hk} - z_h)$$

EXTENSION TO MULTI-COIL SOLENOIDS (3/4)

for odd h:

$$B_m(H_{h3}) - B_m(H_{h1}) = \sum_{i=1}^{N} \left\{ 2 \left.\frac{\partial B_r}{\partial r}\right|_{-\frac{d}{2}+\left(\frac{h+1}{2}-i\right)D} y_{O'_{0,i}} + \left[\left.\frac{\partial B_r}{\partial r}\right|_{-\frac{d}{2}+\left(\frac{h+1}{2}-i\right)D} \left(-1 + (h+1-2i)\frac{D}{d}\right) - 2\frac{R_0}{d} \left.\frac{\partial B_r}{\partial z}\right|_{-\frac{d}{2}+\left(\frac{h+1}{2}-i\right)D} - 2\frac{B_z|_{-\frac{d}{2}+\left(\frac{h+1}{2}-i\right)D}}{d} \right] v_{y,i} \right\}$$

for even h:

$$B_m(H_{h3}) - B_m(H_{h1}) = \sum_{i=1}^{N} \left\{ 2 \left.\frac{\partial B_r}{\partial r}\right|_{+\frac{d}{2}+\left(\frac{h}{2}-i\right)D} y_{O'_{0,i}} + \left[\left.\frac{\partial B_r}{\partial r}\right|_{+\frac{d}{2}+\left(\frac{h}{2}-i\right)D} \left(+1 + (h-2i)\frac{D}{d}\right) + - 2\frac{R_0}{d} \left.\frac{\partial B_r}{\partial z}\right|_{+\frac{d}{2}+\left(\frac{h}{2}-i\right)D} - 2\frac{B_z|_{+\frac{d}{2}+\left(\frac{h}{2}-i\right)D}}{d} \right] v_{y,i} \right\}$$

P. Arpaia, L. De Vito, A. Esposito, A. Parrella, and A. Vannozzi, "On-field monitoring of the magnetic axis misalignment in multi-coils solenoids," *Journal of Instrumentation*, vol. 13, 2018.

EXTENSION TO MULTI-COIL SOLENOIDS (4/4)

$$\mathrm{A}\mathbf{x} = \mathbf{B}$$

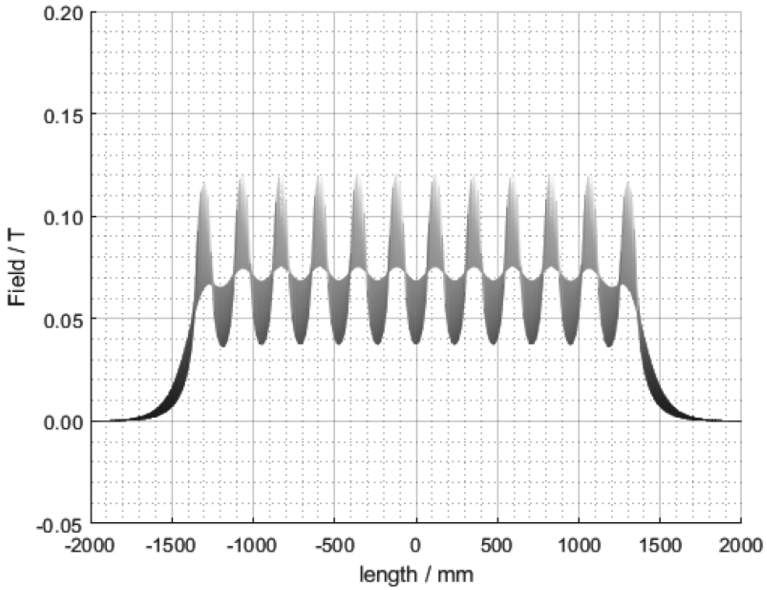
$$\mathbf{x} = \begin{bmatrix} x_{O'_{0,1}} \\ y_{O'_{0,1}} \\ v_{x,1} \\ v_{y,1} \\ \dots \\ x_{O'_{0,N}} \\ y_{O'_{0,N}} \\ v_{x,N} \\ v_{y,N} \end{bmatrix}, \qquad \mathbf{B} = \begin{bmatrix} B_m(H_{13}) - B_m(H_{11}) \\ B_m(H_{14}) - B_m(H_{12}) \\ B_m(H_{23}) - B_m(H_{21}) \\ B_m(H_{24}) - B_m(H_{22}) \\ \dots \\ B_m(H_{2N-1,3}) - B_m(H_{2N-1,1}) \\ B_m(H_{2N-1,4}) - B_m(H_{2N-1,2}) \\ B_m(H_{2N,3}) - B_m(H_{2N,1}) \\ B_m(H_{2N,4}) - B_m(H_{2N,2}) \end{bmatrix}$$

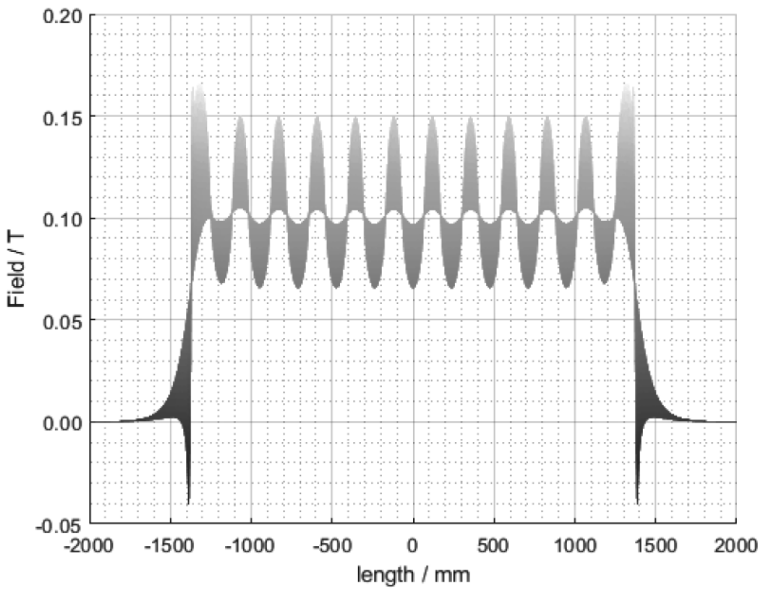
$$\mathbf{x} = \mathrm{A}^{-1}\mathbf{B}$$

MAGNETIC FIELD SIMULATION (1/2)

Analytical model
(overposition of the single coil fields)

FEM





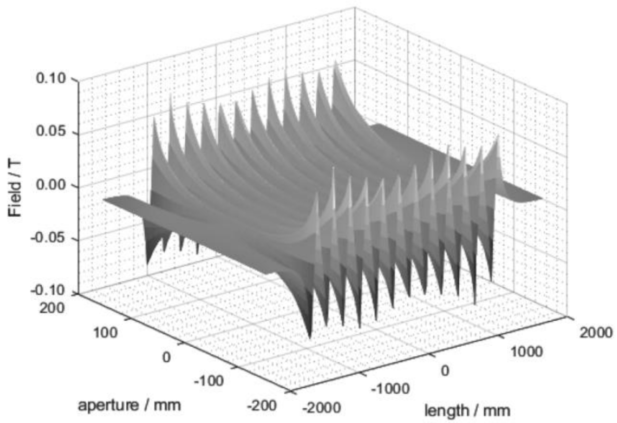
- Differences are due to the magnetic shield that in solenoids is often employed to limit fringe flux, and to reduce the number of ampere-turns for a given focal length.

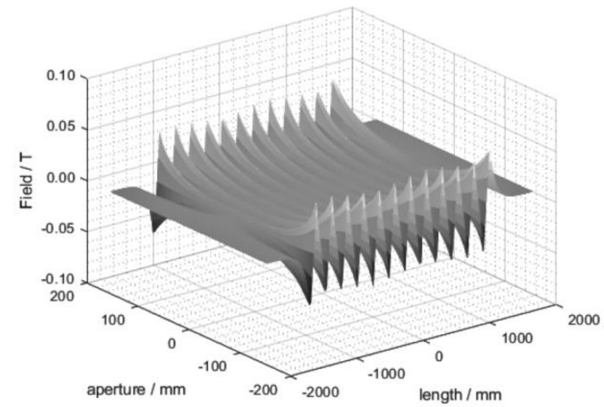
MAGNETIC FIELD SIMULATION (2/2)

Analytical model

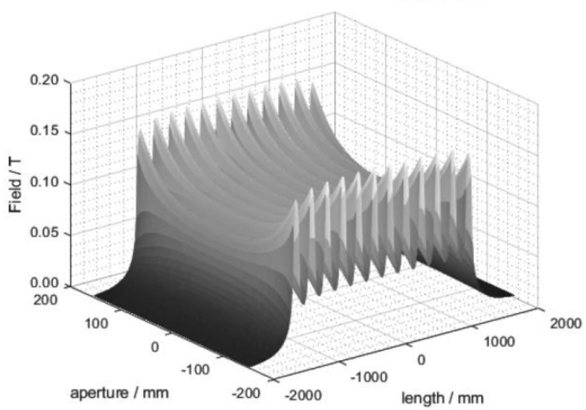
FEM without shield

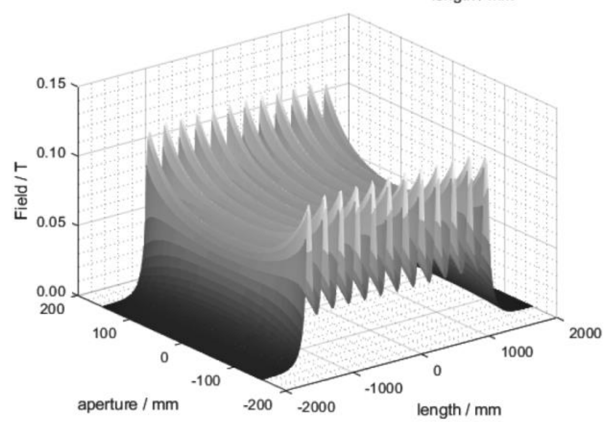
Radial





Longitudinal



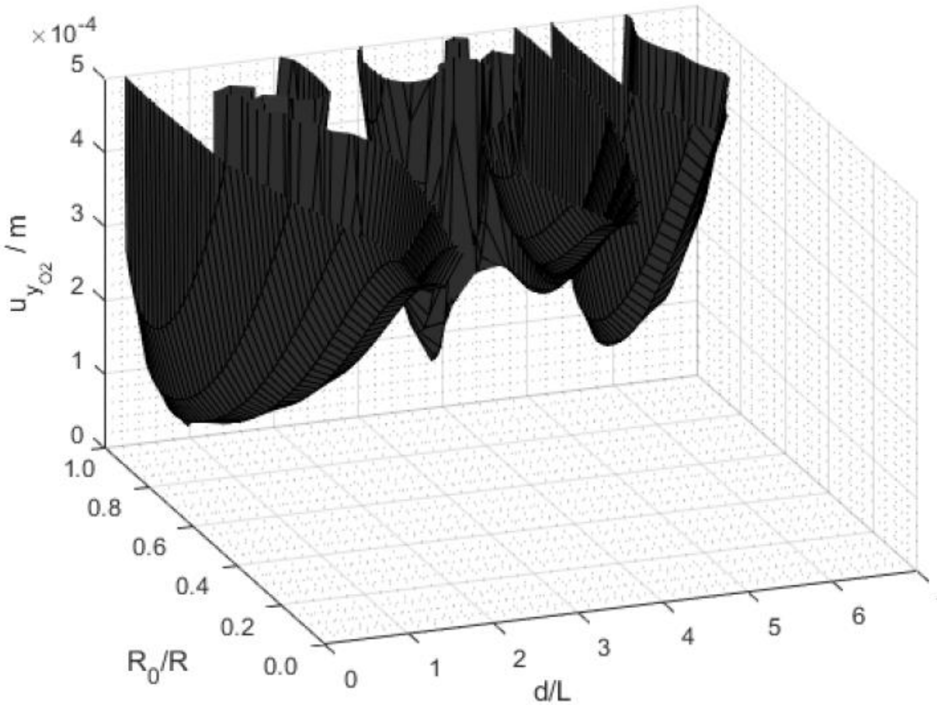


UNCERTAINTY EVALUATION (1/2)

$$\mathbf{u}_{\mathbf{x}}^2 = \sum_i \left(\frac{\partial \mathbf{x}}{\partial c_i}\right)^2 u_{c_i}^2 = \Gamma + \Delta = \sum_{h=1}^{2N} \sum_{k=1}^{4} \left(\frac{\partial \mathbf{x}}{\partial B_{hk}}\right)^2 u_{B_{hk}}^2 + \\ + \sum_{j=1}^{N} \left[\left(\frac{\partial \mathbf{x}}{\partial c_{r_j}}\right)^2 u_{\partial r_j}^2 + \left(\frac{\partial \mathbf{x}}{\partial c_{z_j}}\right)^2 u_{\partial z_j}^2 + \left(\frac{\partial \mathbf{x}}{\partial c_{f_j}}\right)^2 u_{f_j}^2 \right]$$

- A closed form of the uncertainty is difficult to obtain in this case.

UNCERTAINTY EVALUATION (2/2)



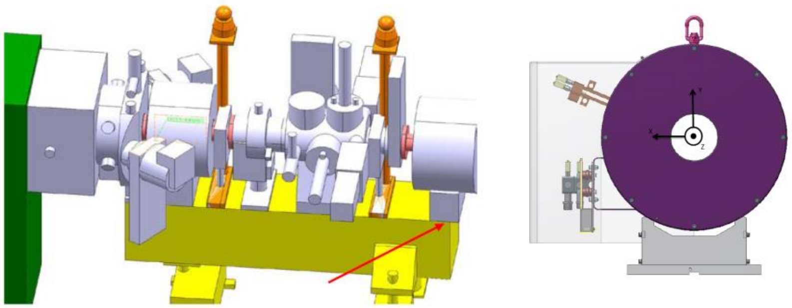
- The optimal placing of the N planes couples is approximatively the same for all the N coils. It corresponds to R_0 equal about to the 90% of the aperture, and d equal to about 75% of the coil length L

STILL TO DO…

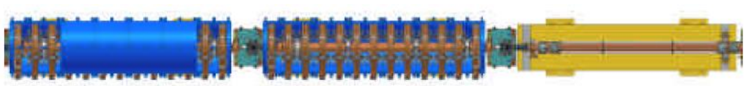
PLANNED EXPERIMENTAL EVALUATION

- To carry experimental tests:

@ CERN
on LINAC4 Low Energy Beam Transport (LEBT) (single coil) Solenoid



@ INFN / LNF
on SPARC focusing solenoid (multi-coil, similar to the ELI-NP one)



CONCLUSION

- I presented a problem of designing a monitoring method for the magnetic axis misalignment in solenoids.
- Measurement specifications were very challenging and current method for magnetic axis determination were not suitable due to the inaccessibility of the magnet aperture.
- We designed a new method based on several Hall transducers placed on two planes orthogonal to the nominal axis of the solenoid (of each coil in the multi-coil case).
- We carried out an uncertainly analysis of the method.
- We are now going to realize the experimental evaluation of the method.

PROJECT TEAM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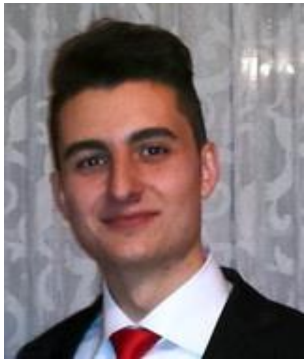
University of Lisbon
and CERN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BUT ALSO THANKS TO…

- Carlo Petrone, CERN
- Stephan Russenschuck, CERN
- Sandro Tomassini, INFN
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