# Magnetic alignment tests of main LHC cryodipoles at CERN

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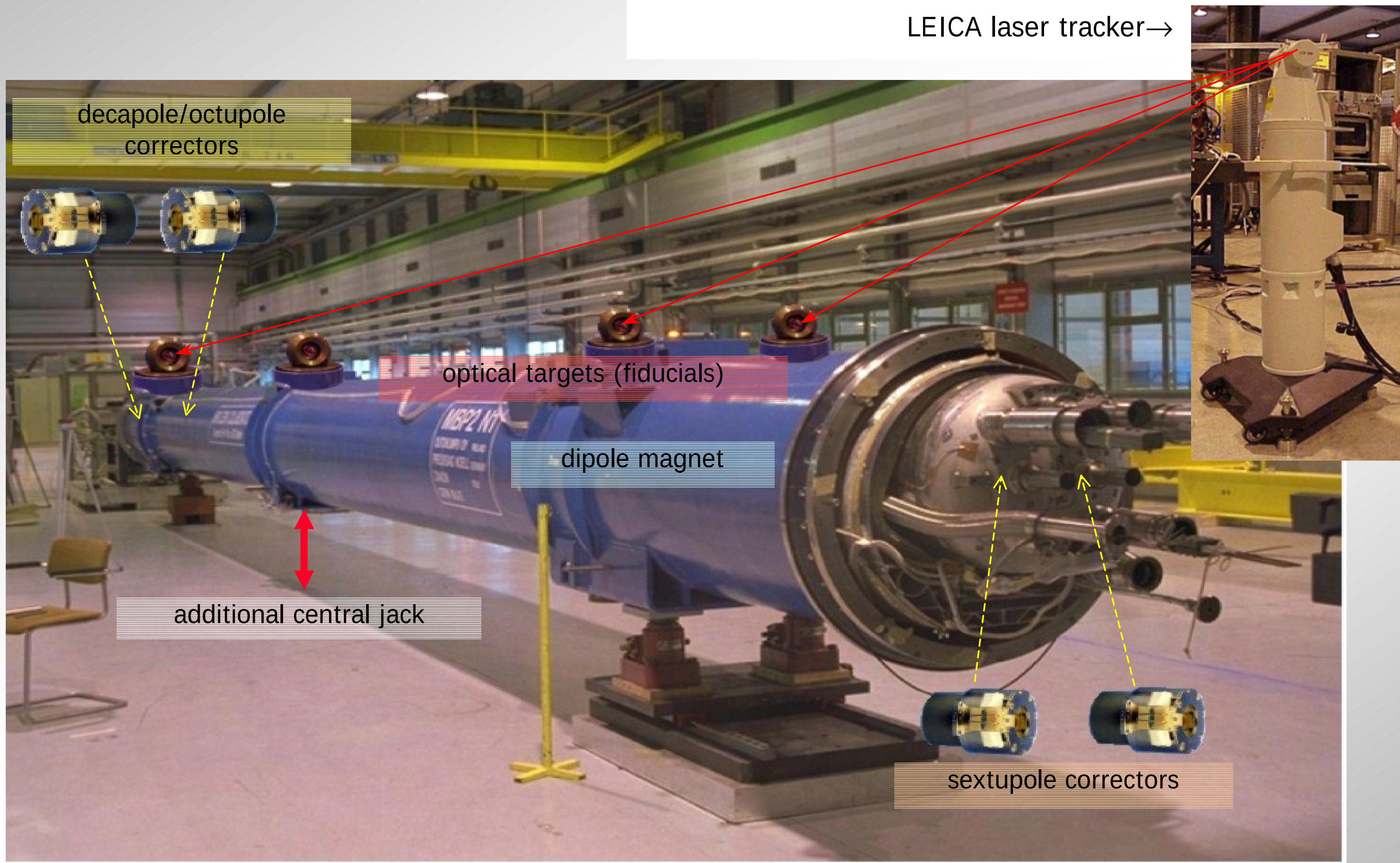
# 1.1 Introduction

## Background

- 1232 dipoles + 430 quadrupoles to be cold tested at CERN upon reception (talk focused on dipoles, but equipment and procedures for quadrupoles are essentially similar – with tighter tolerances)
- cryogenic equipment for magnetic tests works @ room temperature inside an anticryostat⇒ cold mass not accessible to measurements
- all dipoles include sextupole corrector spool pieces at one end
½ include combined octupole/decapole correctors at the other end
- Spool pieces are used to do quasi-local harmonic correction and are aligned mechanically upon installation

# 1.2 Introduction



# 1.3 Introduction

## Main dipole alignment issues related to cryogenic tests

1) **Dipole field angle:**
must be normal to beam orbit

2) **Dipole harmonics:**
(field shape errors) must be expressed w.r.t. reference orbit

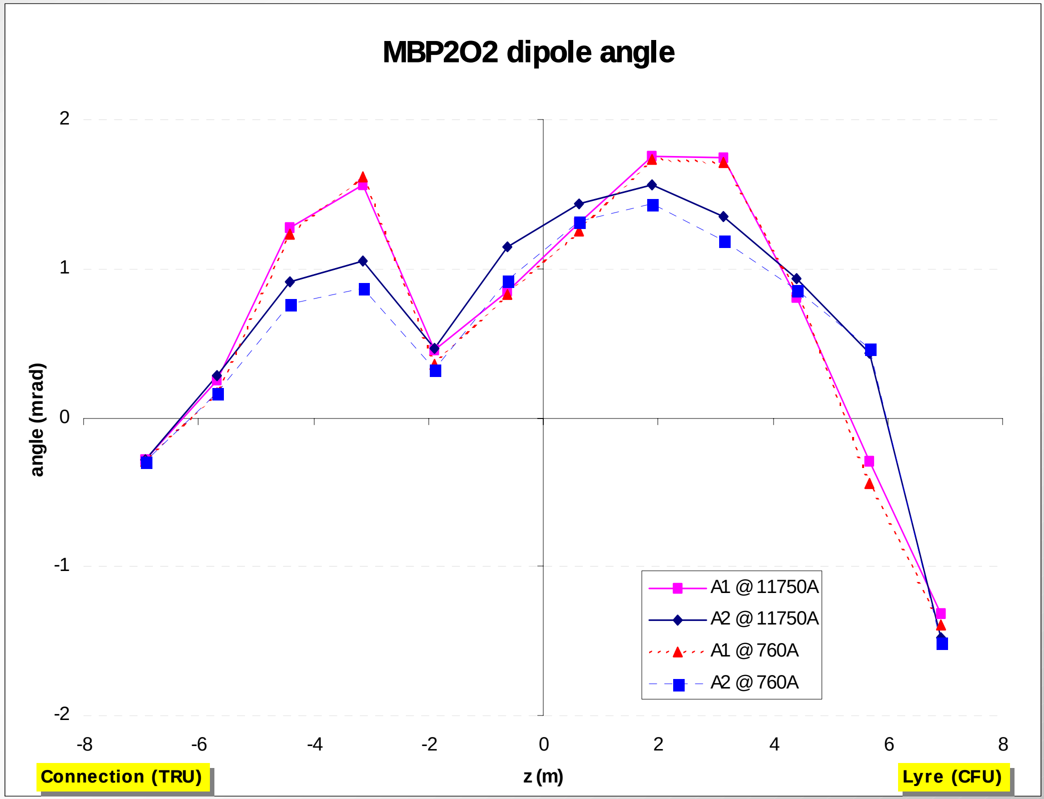
3) **Corrector axis:**
must be aligned w.r.t. dipole ⇒ field errors can be corrected without generating spurious multipoles by feed-down

# 2.1 Field angle measurements

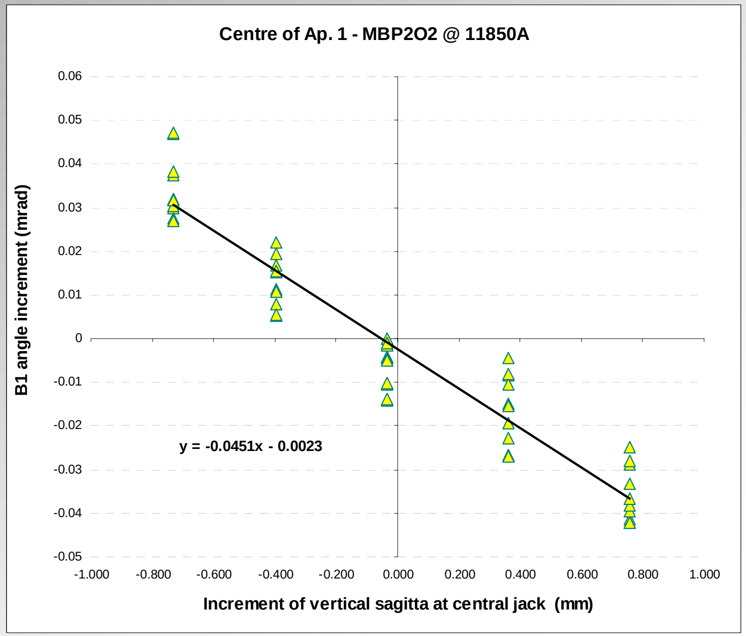
## Field angle measurements

- Main dipole angle measured as the phase of the first harmonic
- Calibration done via a 0.5T reference dipole
- Precision required for the machine:
  **~ 0.5 mrad**
- Measurement accuracy (1 σ):

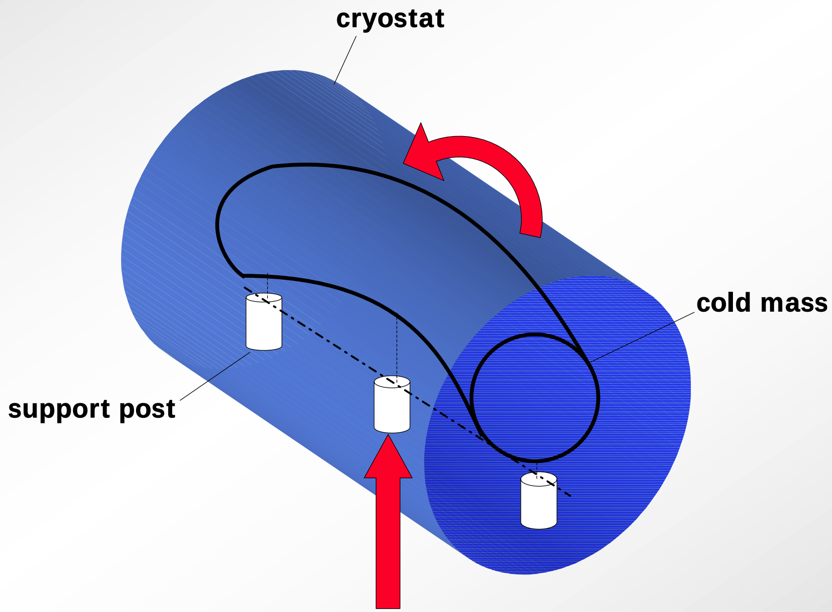
  **0.25 mrad** (local),
  **0.10 mrad** (integrated)



# 2.2 Field direction vs. central support jack




(10 consecutive magnetic measurements at each position of the central jack)




Central jack position is coupled to cold mass twist

- dipole curvature ⇒ vertical displacement at central jack causes cold mass to rotate
- 3 magnets measured so far (results from A001 not fully consistent)
- upper bound:

$$\left|\frac{d\alpha}{d\delta z_{central\_jack}}\right| \leq \begin{cases} 0.05 \dfrac{\text{mrad}}{\text{mm}} & @\,11850\text{ A} \\ 0.07 \dfrac{\text{mrad}}{\text{mm}} & @\,5000\text{ A} \end{cases}$$

# 3.1 Magnetic alignment tests

## Motivations for alignment tests at CERN

I. Magnetic axes are needed in nominal working conditions

II. Mechanical and magnetic axes seem to coincide within 0.1~0.2 mm[1], but mechanical axes are measured are not accessible at 1.9K ⇒ unproved extrapolation from room to cryogenic conditions is necessary

III. Corrector leads accessible only after cold tests

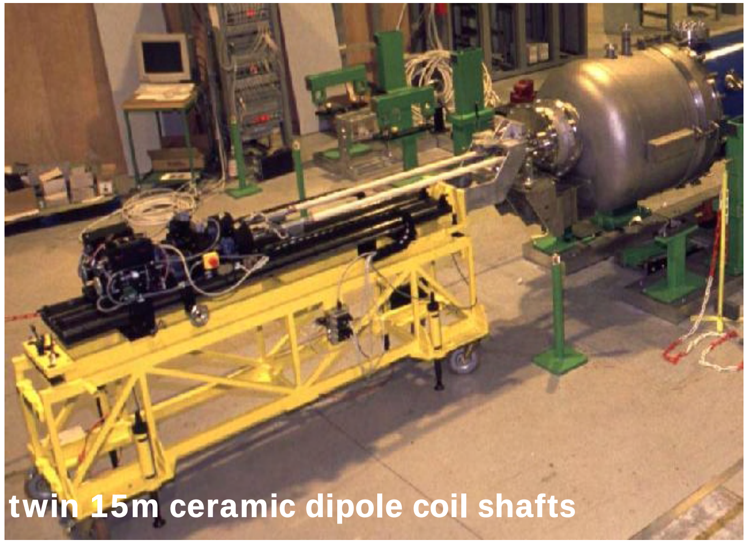
IV. Cross-check with measurements[1] in industry for absolute accuracy and effects due to transportation

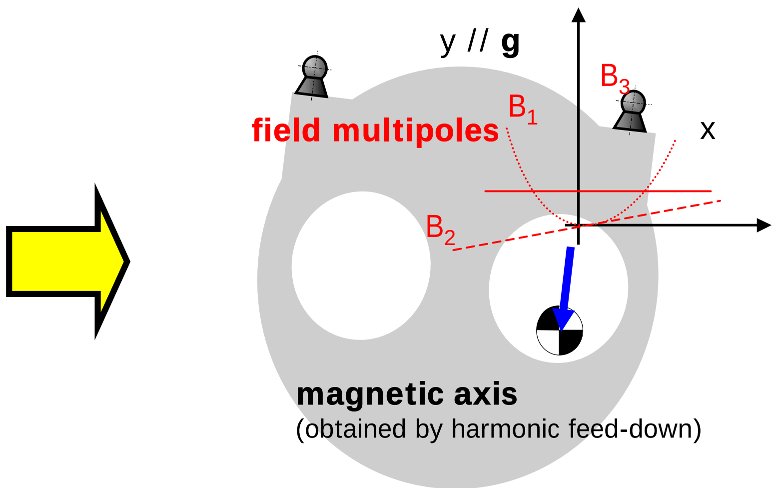
[1] see Juan's talk

# 3.2 Overall alignment test strategy

**Cryogenic magnetic measurements with 15m shaft**

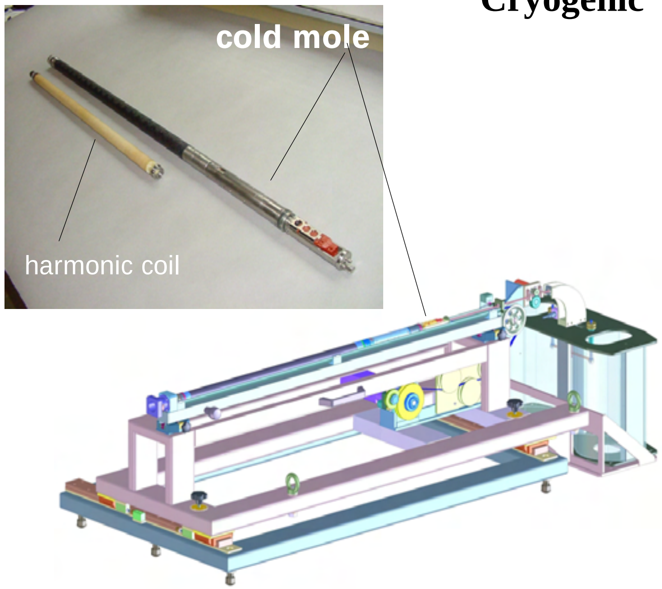
The twin 15m coil shaft system measures dipole axis and field errors (multipoles) vs. excitation and powering history on the cryogenic test bench.
The absolute position of the coil rotation axis is not known with precision.



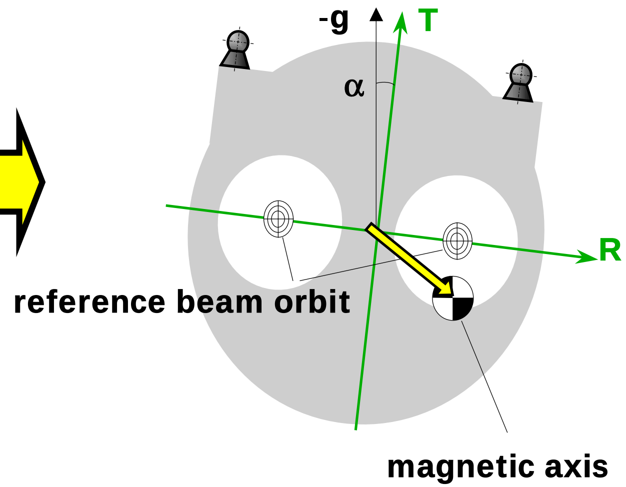



# 3.3 Overall alignment test strategy

**Cryogenic “cold mole” tests**



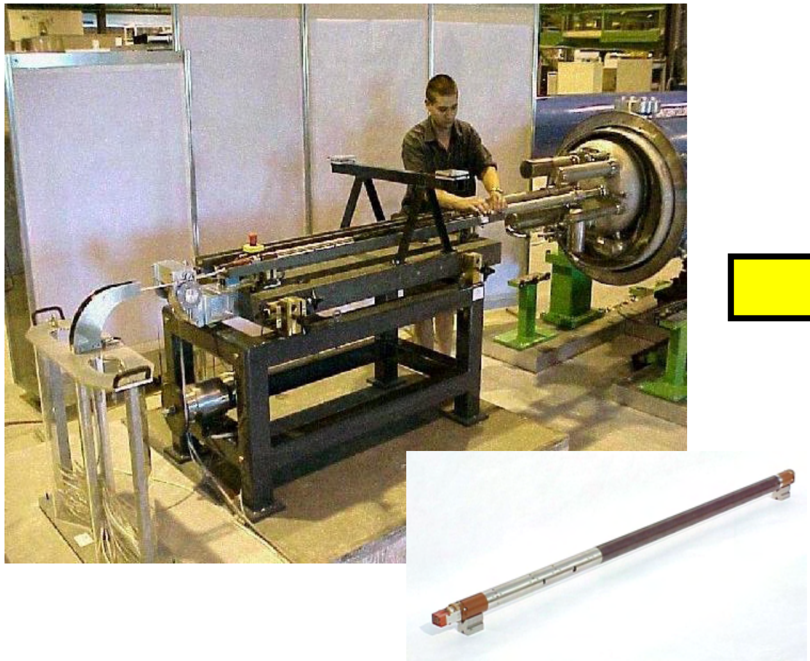

**mole parking + reference bench**

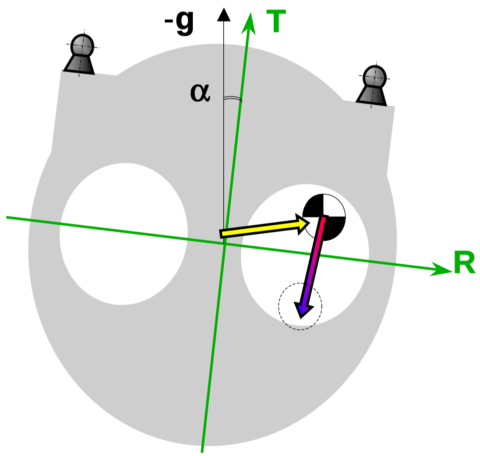



The dipole is measured a second time with a traveling probe (“cold mole”), which detects the position of the magnetic axis of both dipole and correctors w.r.t. the standard {R,S,T} MAD dipole reference system (based on the reference beam orbit).

# 3.4 Overall alignment test strategy

**Room-temperature “warm mole" tests**






For most dipoles there will be no time to carry out mole measurements on the cryogenic test bench. Instead, the magnetic axis will be measured with a simpler room-temperature probe and extrapolated via a suitable warm/cold correlation.

# 3.5 Overall alignment test strategy

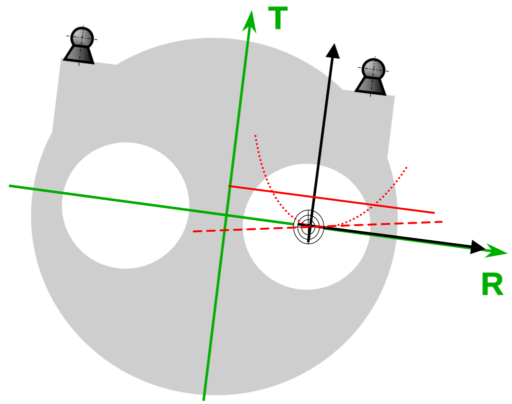
**Cryogenic magnetic tests with 15m shaft**
(100% of dipoles)

**Cryogenic "cold mole" tests**
(100% of pre-series dipoles,
10% of full series production)

**Room-temperature "warm mole" tests**
(100% of dipoles)

**Warm-cold correlation**

**Result**




The measurements are finally combined via harmonic feed-down to get the desired multipoles (along with corrector axes) referred to the beam orbit.

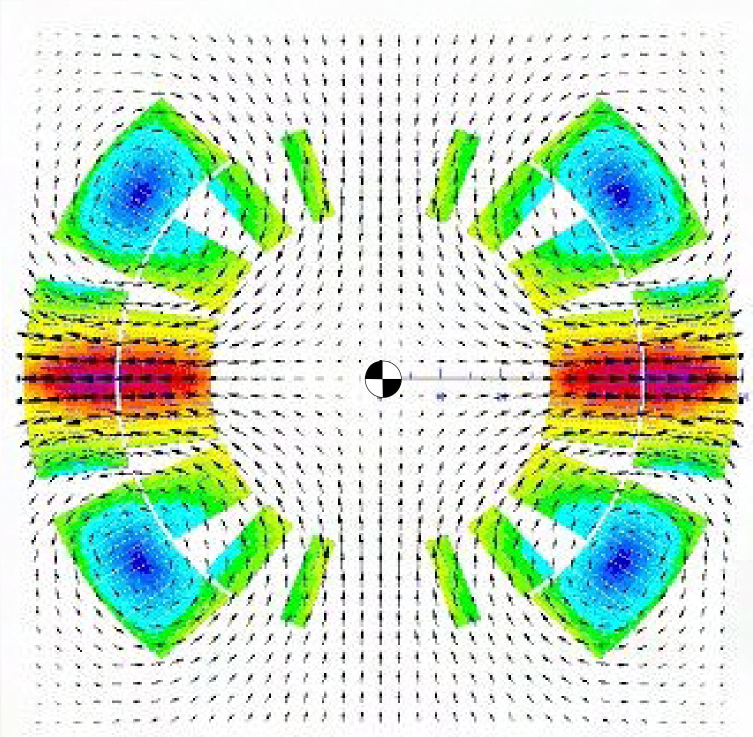
# 4.1 Definition of dipole axis

## How to define a dipole axis ?

- A perfect dipole has no axis, but a conventional one can be defined based on field errors.
- Axes based on high-order harmonics (defined by zeroing e.g. $C_{10}$ $C_{12}$ $C_{14}$, which can be assumed to be generated by feed-down from strong $C_{11}$, $C_{13}$ and $C_{15}$) lie close to the mechanical axis but correlate poorly in different magnets.
- Note that the axes of the harmonics needing corrections ($C_3$, $C_4$, $C_5$) are ill-defined (they move with dynamic effects)

# 4.2 Definition of dipole axis

## QCD dipole axis



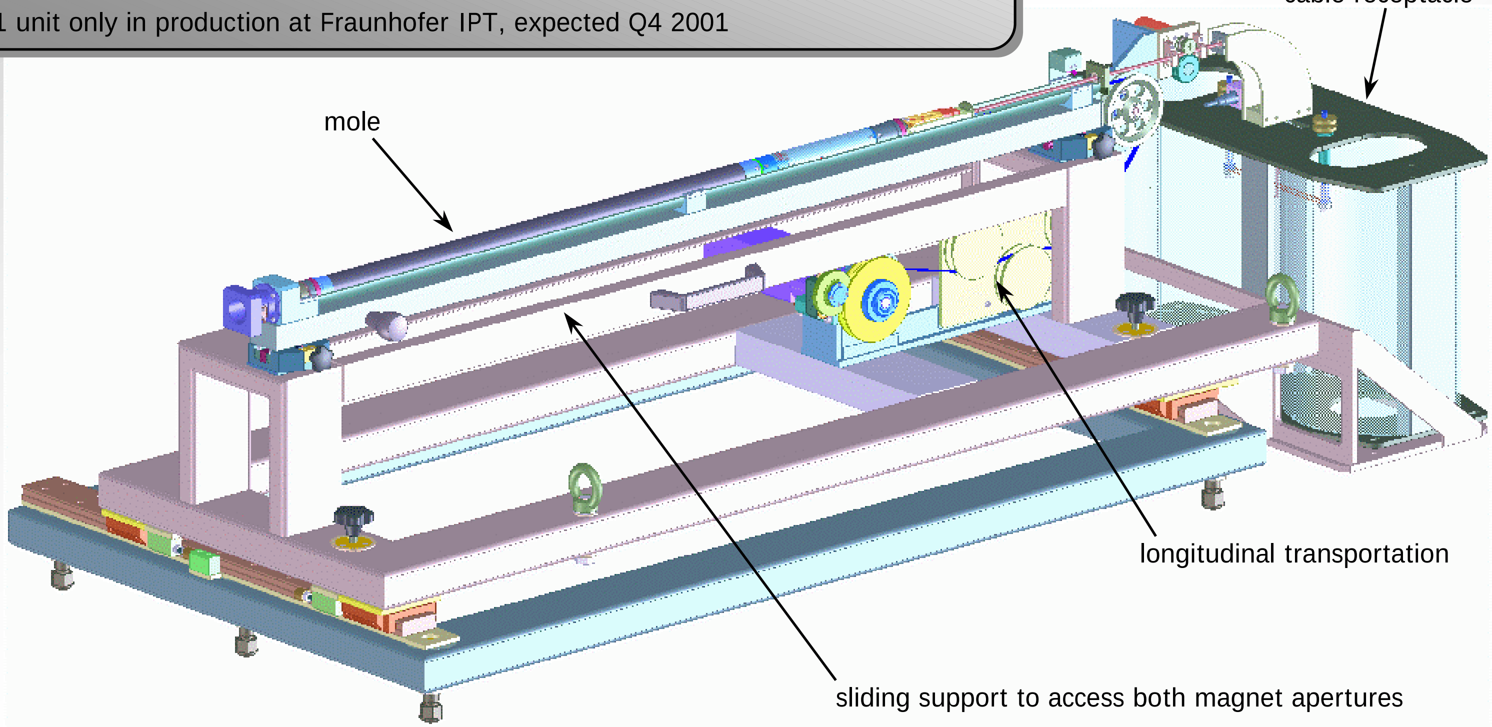
The Quadrupole-Configured Dipole (**QCD**) is obtained by feeding opposite current in each half-coil through the voltage taps.

QCD axis has been chosen as the most convenient reference because of the following advantages:

- Depends on the global coil shape (represents the geometry of the cold mass ⇒ long term stability)
- Close (<200 μm) to cold bore geometrical axis (to be confirmed on a statistical basis)
- Easy to measure with precision from feed-down even at extremely low current (<10 μm @ ±0.5A)

# 5.1 Cold mole: test bench

- fully automatic motorized travelling probe
- 750 mm × ∅ 20 mm coil for QCD and harmonic measurements
- telescope+CCD camera transversal coil position sensor (same as for warm mole)
- <u>operating in a vacuum</u> for high optical accuracy despite large thermal gradients
- absolute coil position is recovered at external reference quadrupoles via laser tracker survey
- not optimised for mechanical axis measurement
- no on-board tilt sensor ⇒ cannot be used to measure field direction
- 1 unit only in production at Fraunhofer IPT, expected Q4 2001

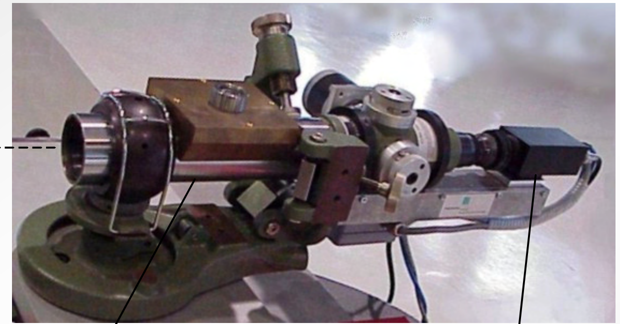



# 5.2 Optical position sensor

travelling probe (mole)

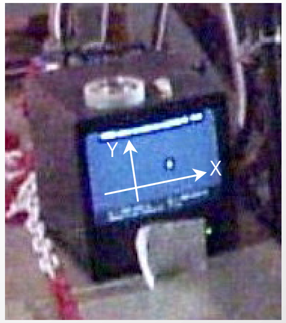
LED light spot

(optically projected in the centre of the coil)



telescope

CCD camera + DSP




XY measurement

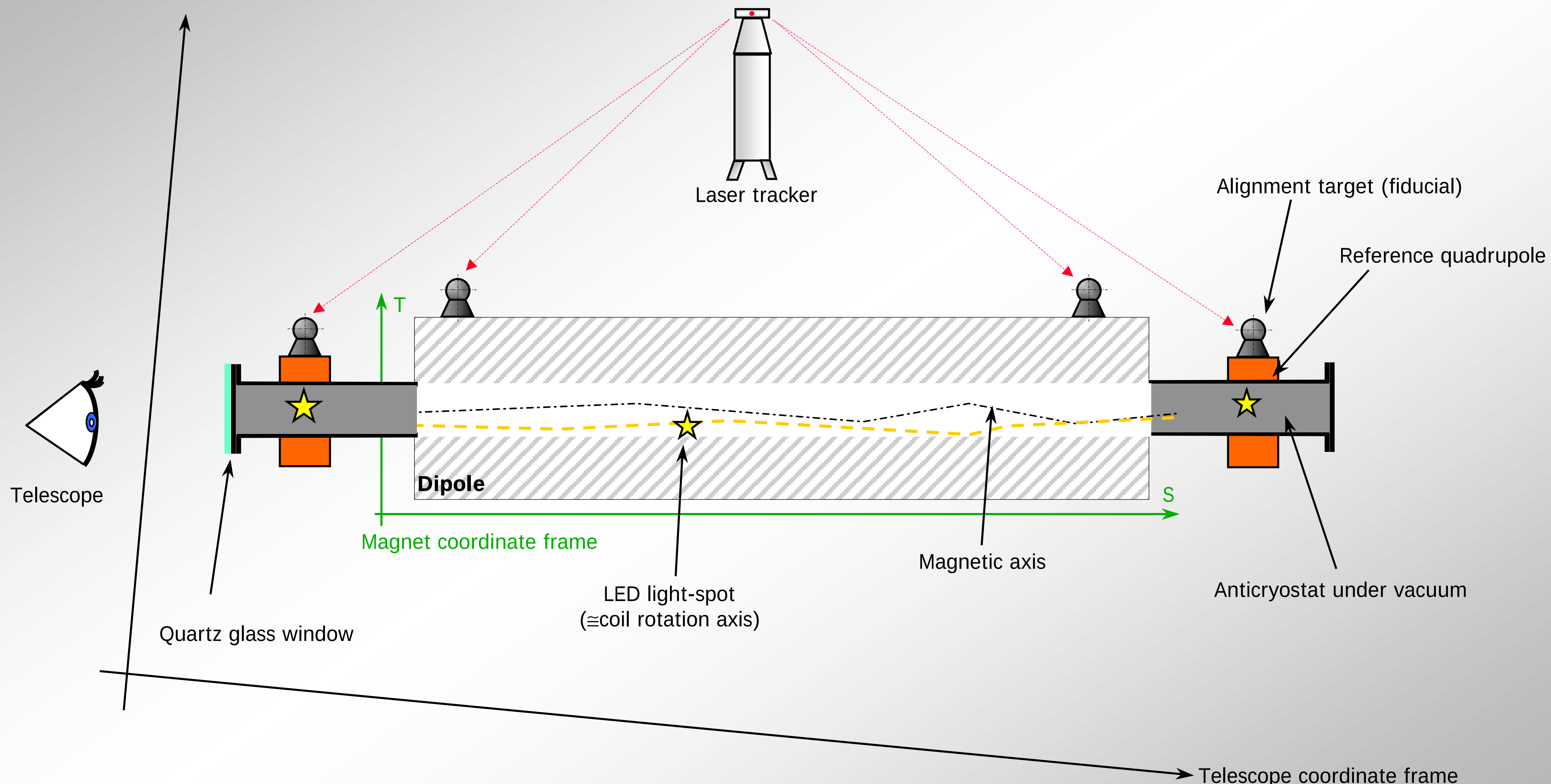
(in the transversal plane)

- telescope+CCD camera transversal coil optical position sensor
- common to warm and cold MB moles + SSS scanning system
- LED light-spot generated in the front of the probe optically projected into coil centre (follows probe pitch and yaw)
- Range: XY up to ±7 mm @ 3 m distance – distance<20 m
- absolute accuracy:

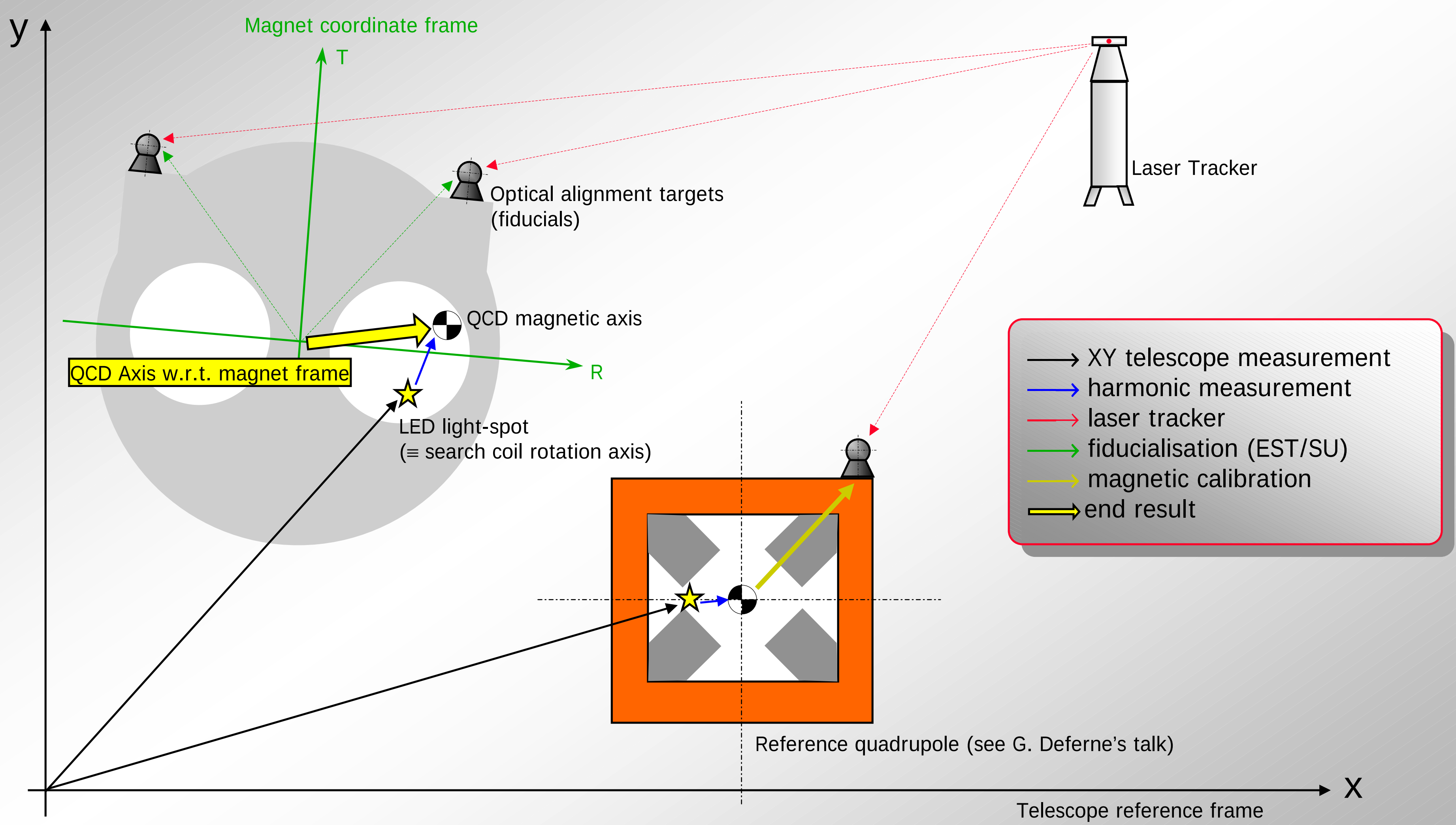
  20 µm @ 3 m distance (air)
  60 µm @ 20 m distance (air)
  30 µm @ 20 m distance (vacuum)

Note: the same system is used for warm/cold dipole moles & quadrupole scanning machine

# 5.3 cold mole: axis transfer overview



# 5.4 cold mole: axis transfer detail



# 5.5 Cold mole: summary

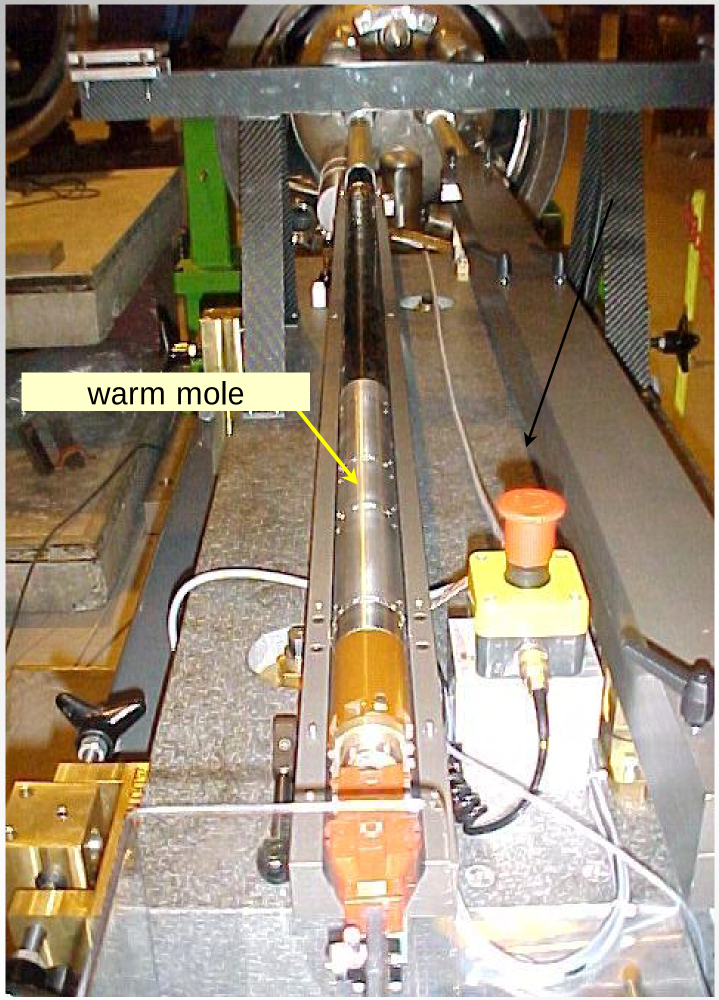
## Main benefits of cold mole measurements

1) **Indispensable tool** to transport axes and multipoles to the reference orbit frame.

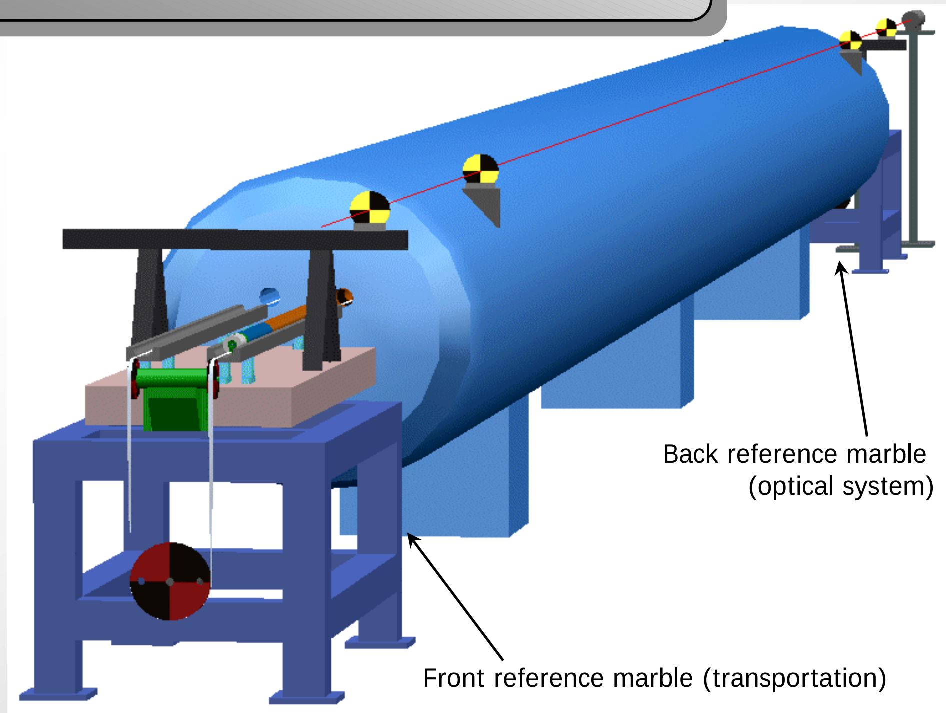
2) Cold magnetic axes (of both dipole and correctors) can be given **directly w.r.t. magnet fiducials**, bypassing mechanical extrapolations used to define the cold reference orbit

3) **Relative alignment between dipole and correctors** can be verified **directly** with one instrument (bypassing the transformations to the fiducial and to the reference orbit frames)

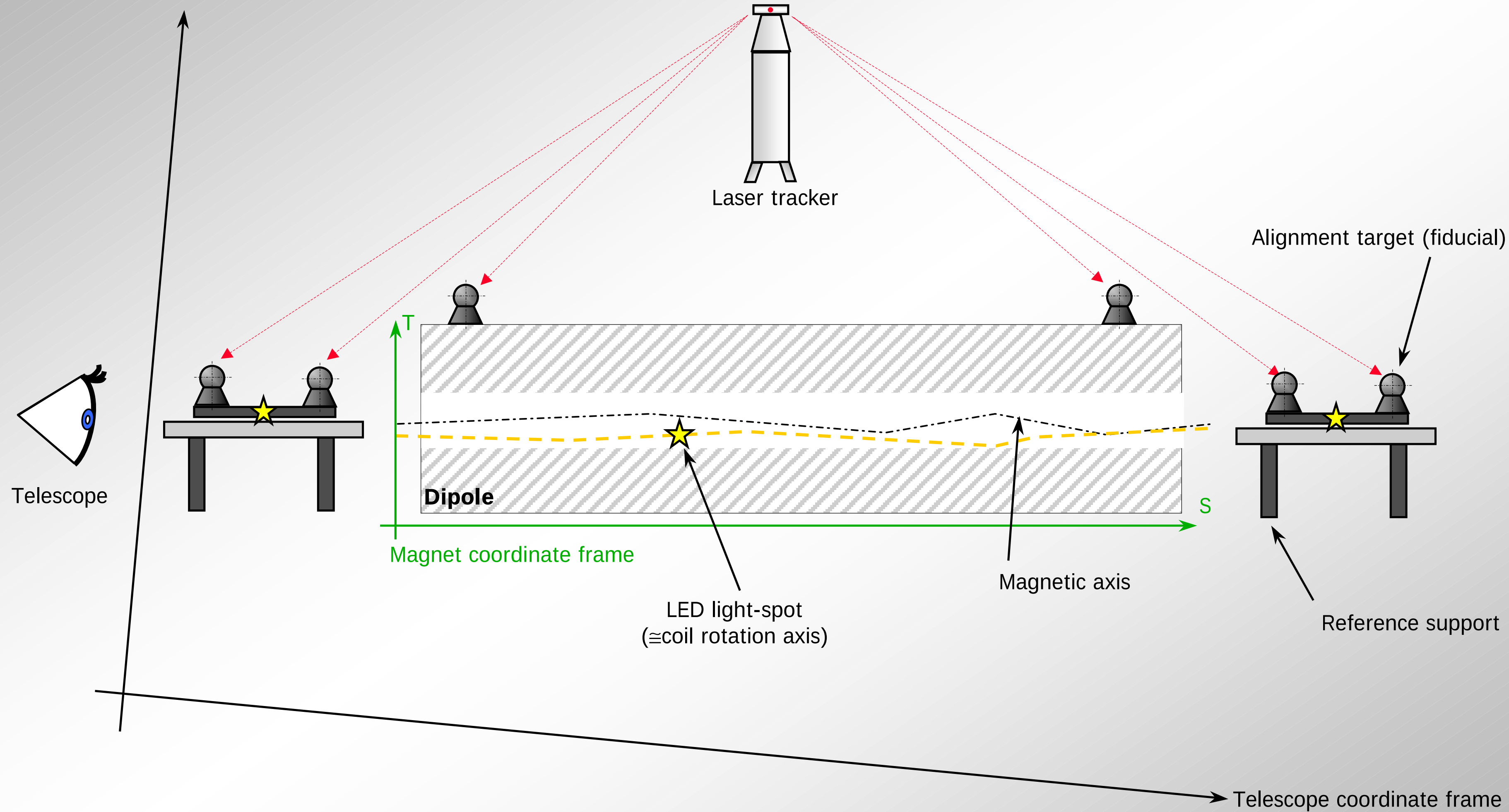
# 5.6 warm mole



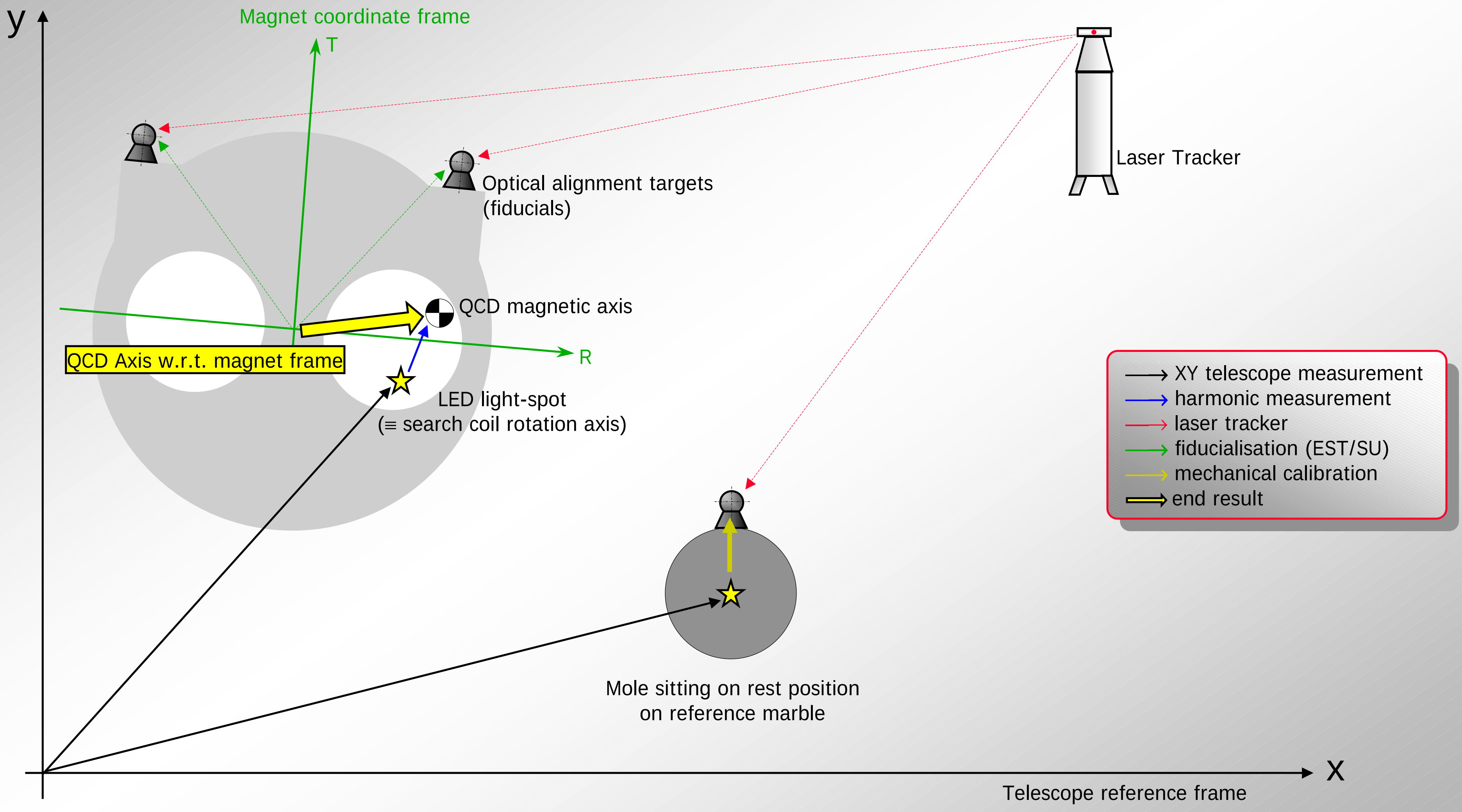

- fully automatic motorized travelling probe
- 750 mm × 400 turns dipole-compensated harmonic coil
- telescope+CCD camera transversal coil position sensor
- absolute coil position recovered at external reference marbles via laser tracker survey
- not optimised for mechanical axis measurement
- 1 unit operational + 1 expected Q1 2002



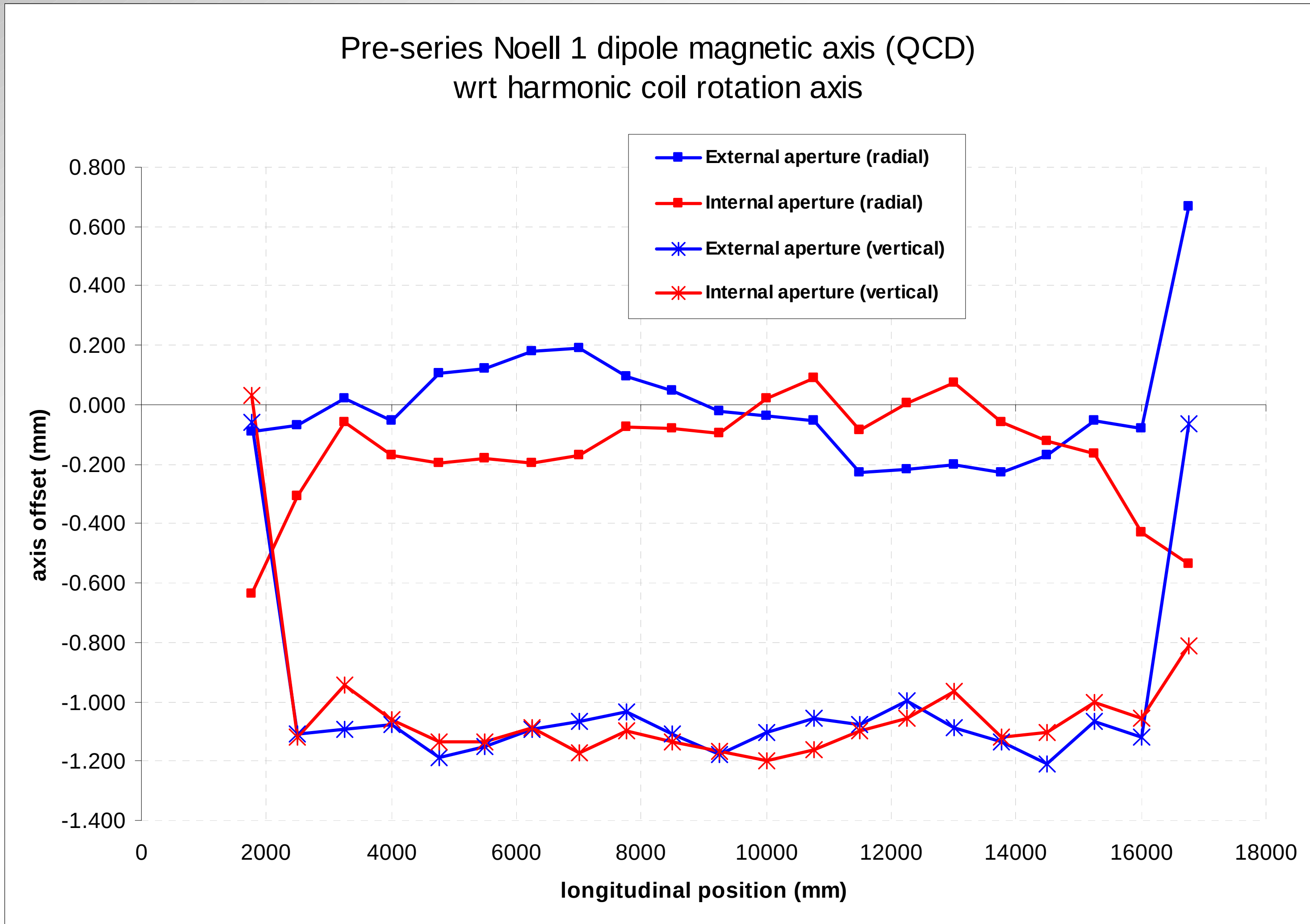
# 5.7 warm mole: axis transfer overview



# 5.8 warm mole: axis transfer detail



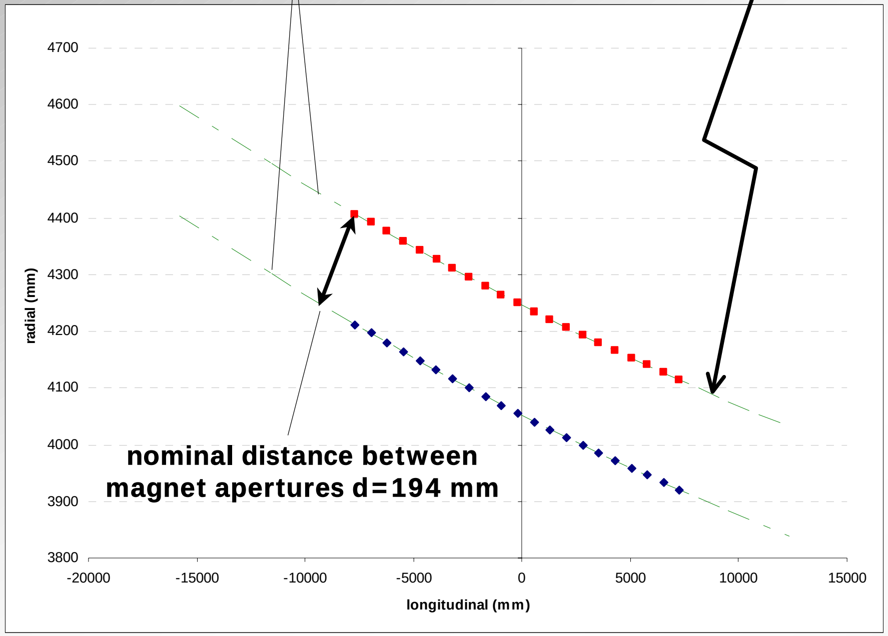
# 5.9 warm mole: results



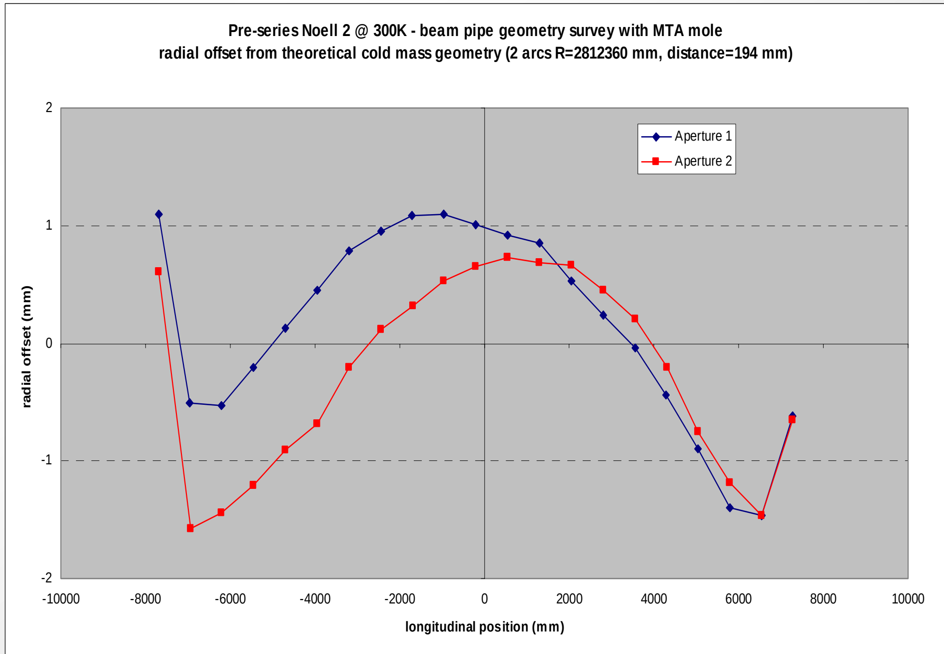
# 5.10 warm mole: results

reference beam orbit arcs
positioned via least-squares best fit w.r.t. measured points

**Nominal bending radius @ 300K**
**R=2812.36 m**




**Residuals from best-fitting theoretical arcs**

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# 5.11 random axis error summary

**Standard deviation (1 σ) of magnetic axis w.r.t. magnet fiducial coordinate system**

(conservative estimates based on reproducibility of preliminary measurements)

| values in μm | Dipole (QCD) | | MCS ($b_3 \equiv 0$) | | MCD ($b_5 \equiv 0$) | |
|---|---|---|---|---|---|---|
| | Cold vac. 1A | Warm air 1A | Cold vac. ≤550A | Warm air 0.5A | Cold vac. ≤550A | Warm air 0.5A |
| Magnetic axis to coil rotation axis (feed-down calculation) | 40 | 10 | 10 | 20 | 5 | 20 |
| Coil rotation axis to telescope (mech. tol., CCD+camera precision, thermal effects) | 33 | 61 | 32 | 61 | 32 | 61 |
| Reference fiducials to coil rotation axis (× 2) | 46 | 50 | 46 | 50 | 46 | 50 |
| Coil rotation axis to telescope (× 2) (at reference positions) | 65 | 61 | 65 | 61 | 65 | 61 |
| Reference fiducials to magnet fiducials (survey, overall stability) | 115 | 115 | 115 | 115 | 115 | 115 |
| **σ RMS** | **167** | **170** | **163** | **155** | **162** | **155** |

# 6.1 conclusions

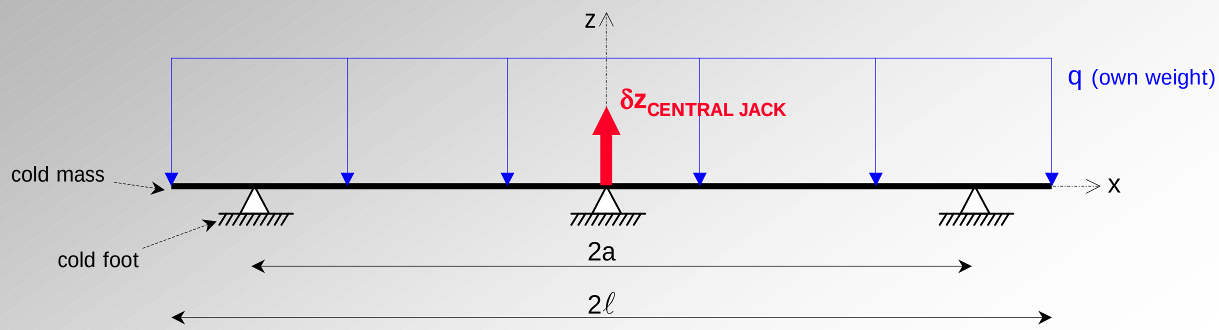
- **Outlook**

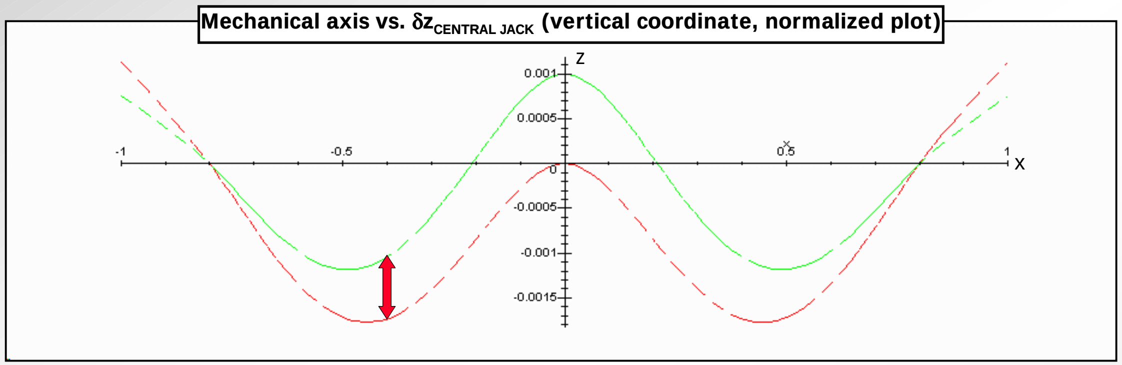
  — alignment test equipment needed for detailed study of pre-series dipole fully available as of end 2001
  — critical measurements will be cross-calibrated with multiple systems and cross-checked with results from other groups (LHC/MMS, EST/SU)
  — estimated accuracy in line with requirements and with comparable results in other superconducting accelerators

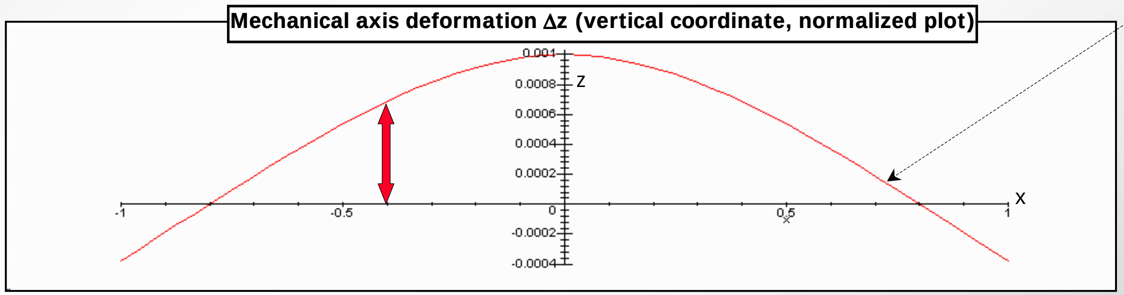
- **Issues still to be assessed**

  — reproducibility of warm-cold QCD correlation
  — dependence of axis deformation and field rotation upon thermal cycling, central jack position, magnet current etc..
  — cross-talk between apertures in QCD mode ⇒ radial shift of QCD axis

# Magnetic axis vs. central support jack




- Problem: $z_{CENTRAL\ JACK}$ on test benches ≠ than in the tunnel ⇒ QCD axis is incorrect
- Assumption: QCD axis follows mechanical axis during a bending deformation
- Mechanical model: standard linear beam theory, uniform load, 3×simple supports
- Result: QCD axis deformation is parameterised in the difference $\delta z_{CENTRAL\ JACK}$:

$$\Delta z = \delta z_{central\_jack} \begin{cases} 1 - \dfrac{3x^2}{2a^3}\left(a - \dfrac{x}{3}\right) & |x| \le a \\ -\dfrac{3}{2}\left(\dfrac{x}{a} - 1\right) & a < |x| \le \ell \end{cases}$$