Stretched-wire measurements of multipole magnets at the ESRF

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Theoretical aspects

Accuracy

Measurement bench

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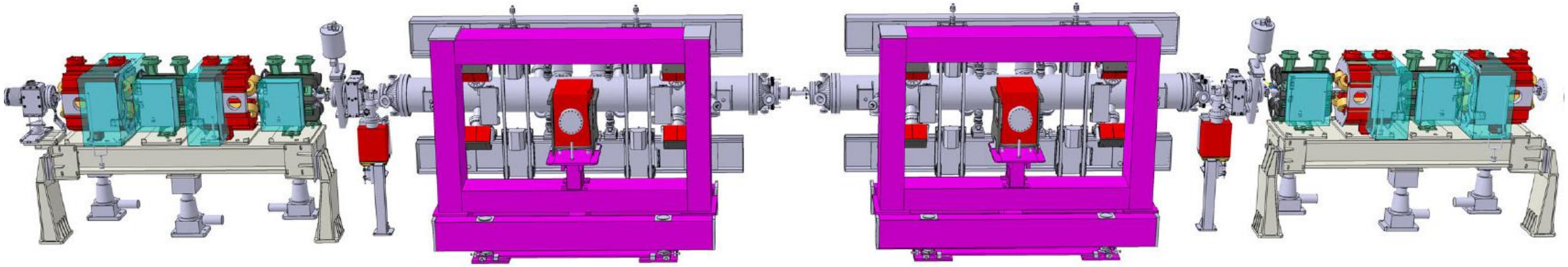
Context

ESRF Upgrade

- Longer straight sections : 5 m → 6 / 7m
- Lower vertical emittance, improved position diagnostics, etc.



Insertion devices straingth section at the ESRF

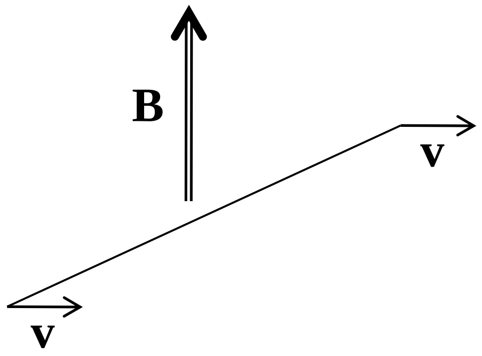
New Magnets

- Shorter quadrupoles and sextupoles
- Permanent Magnet steerers

Introduction

Stretched Wire Measurements

- Moving SW
- Vibrating SW (see next talks)



SW field integral measurement

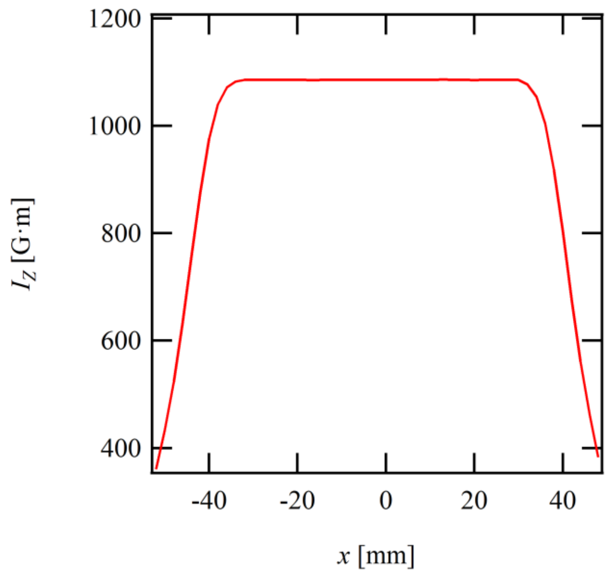
Basic measurements

Longitudinal field integral

$$I = \int B dl = -\frac{e}{v}$$

Integration and time averaging

$$I = \frac{1}{L} \int e \, dt \qquad I \approx -\frac{\langle e \rangle T}{L}$$



PM Steerer field measurement

Applications

Insertion devices

Field gradient, sextupole strength…

Introduction

Multipoles Analysis

Complex potential

$$\boldsymbol{A} = A + iV$$

Multipole expansion

$$\boldsymbol{A} = \sum_{n=0}^{\infty} \boldsymbol{c_n}\, \boldsymbol{z}^n$$

$$\boldsymbol{c_n} = -\frac{b_n + i\, a_n}{n\, \rho_0^{\,n}}$$

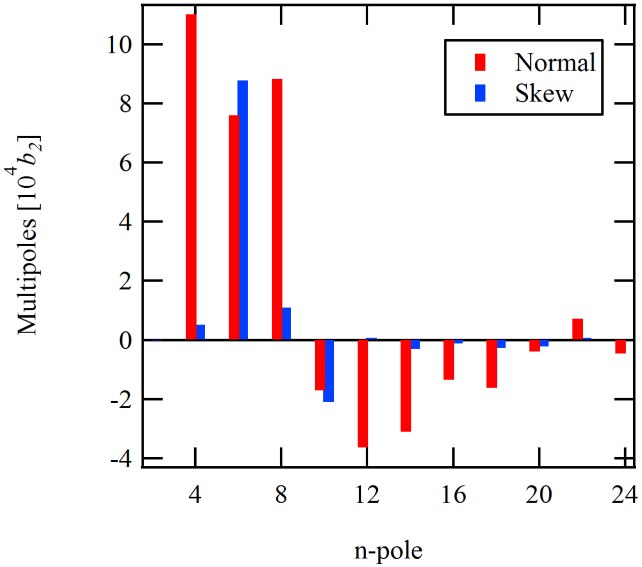
SW basic multipole measurements

- Circular motion
- Fourier analysis
- Wire position errors
- No “bucking” available

Low accuracy

Example

- ESRF Quadrupole
- Parasitic multipoles



Basic SW quadrupole measurement

Theory

Matrix formalism

Complex field integral

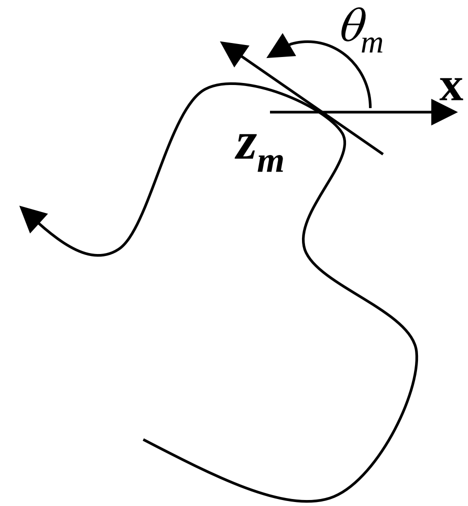
$$\boldsymbol{I}_{//\perp} = I_{\perp} + \boldsymbol{i}\, I_{//}$$

$I_{\perp}$ is $\perp$ to the SW motion, measured

$I_{//}$ is // to the SW motion, not measured

Can be written as

$$\boldsymbol{I}_{//\perp} = -e^{\boldsymbol{i}\theta}(1,\ldots,\boldsymbol{z}^{n-1})(\boldsymbol{c_1},\ldots,N\,\boldsymbol{c_N})^{T}$$



Arbitrary wire trajectory

For a set of measurements:

$$\begin{pmatrix} \boldsymbol{I}^{\boldsymbol{1}}_{//\perp} \\ \vdots \\ \boldsymbol{I}^{\boldsymbol{M}}_{//\perp} \end{pmatrix} = \begin{pmatrix} e^{i\theta_1} & \cdots & e^{i\theta_1}\left(\dfrac{\boldsymbol{z_1}}{\rho_0}\right)^{N-1} \\ \vdots & & \vdots \\ e^{i\theta_M} & \cdots & e^{i\theta_M}\left(\dfrac{\boldsymbol{z_M}}{\rho_0}\right)^{N-1} \end{pmatrix} \begin{pmatrix} b_1 + \boldsymbol{i}\, a_1 \\ \vdots \\ b_N + \boldsymbol{i}\, a_N \end{pmatrix}$$

⇨

The measurements are expressed as:

$$\underbrace{\left(\boldsymbol{I}^{\boldsymbol{1}}_{\perp},\ldots,\boldsymbol{I}^{\boldsymbol{M}}_{\perp}\right)^{T}}_{\mathbf{I}} = \underbrace{\left(\operatorname{Re}\mathbf{Z},\ \operatorname{Im}\mathbf{Z}\right)}_{\mathbf{T}} \underbrace{\left(\ldots,b_n,\ldots,a_n,\ldots\right)^{T}}_{\mathbf{C}}$$

with $\boldsymbol{Z_{mn}} = e^{i\theta_m}\left(\dfrac{\boldsymbol{z_m}}{\rho_0}\right)^{n-1}$

Theory

Effect of measurement length

$$\boldsymbol{Z}_{\boldsymbol{mn}} = \frac{1}{L}\int e^{\boldsymbol{i}\theta_m}\left(\frac{\boldsymbol{z_m}}{\rho_0}\right)^{n-1} d\boldsymbol{z}$$

Measured field integral

$\mathbf{I} = \mathbf{TC}$ → Simulation from SW trajectory and multipoles

Field multipoles

Least square inversion

$$\hat{\mathbf{C}} = (\mathbf{T}^T\mathbf{T})^{-1}\mathbf{T}^T\mathbf{I}$$

Advantages

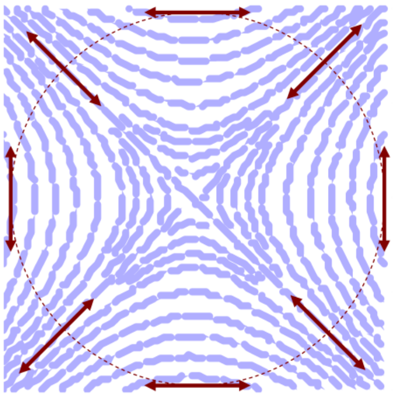
- Valid for any trajectory
- Position errors are taken into account

Theory

Multipole Compensation

- SW parallel to the main multipole field lines
- Measurements at two radii at least

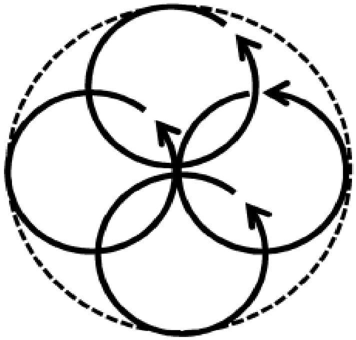
Similar to "bucked" coils



Compensation of the 4-pole

Extension to rotating coils

- Simulation of coil errors
- Combining several rotating coil measurements



Multiple rotating coil measurements

Accuracy

Linear measurements

Field Integral

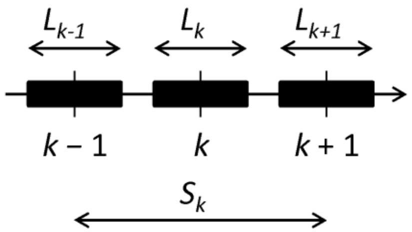
$$\frac{\Delta I}{I} = \frac{\Delta L}{L}$$

Gradient

$$G_k^{meas} = \frac{I_{k+1}^{meas} - I_{k-1}^{meas}}{s_k} = G_k + \Delta G_k$$

with $$\left|\Delta G_k\right| \leq \left|G_k \frac{\Delta S}{S}\right| + \frac{1}{S}\left|\frac{\Delta L}{L}\right| \left(\left|I_{k+1}\right| + \left|I_{k-1}\right|\right)$$

⇒ **Field dependence**



Parameters for gradient calculations

Accuracy

Numerical simulations

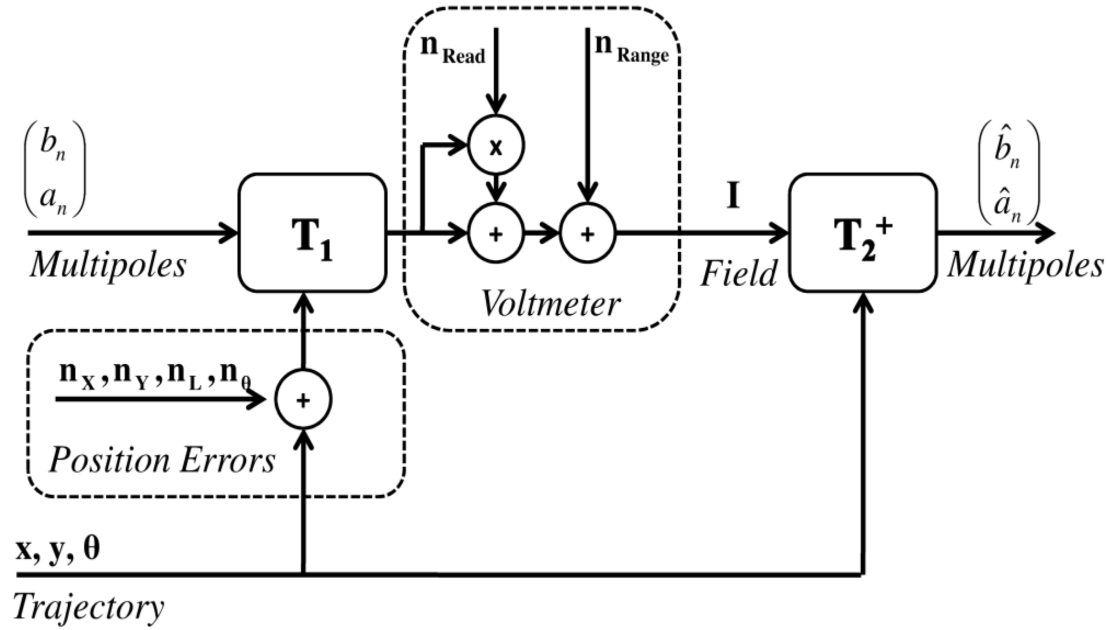
Multipoles and Trajectory

⇩

Several sample Fields and Estimated Multipoles

⇩

Sensitivities



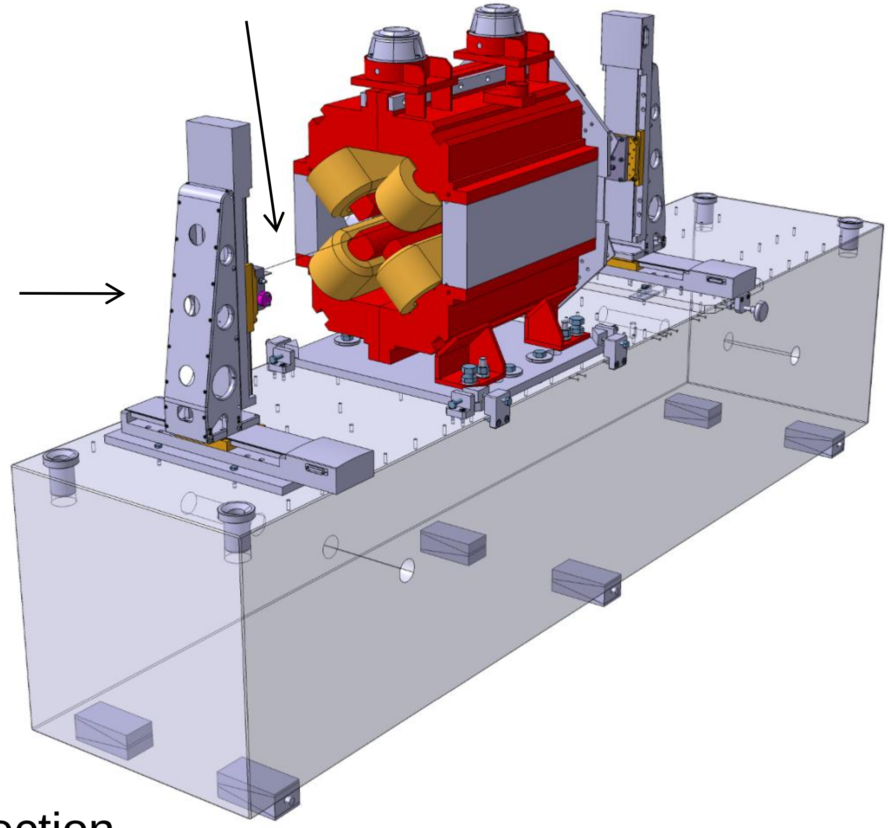
Block diagram of the measurement model

Measurement bench

Wire
100 um x 1.4 m

Linear stages
Newport ILS-250CC

Motion Controller
Newport XPS



Nanovoltmeter
Keitley 2182 A

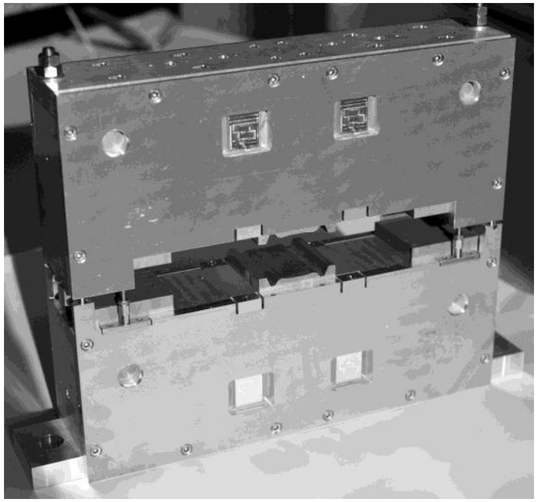
FARO Arm

Granite Table
60 x 60 cm^2 cross section

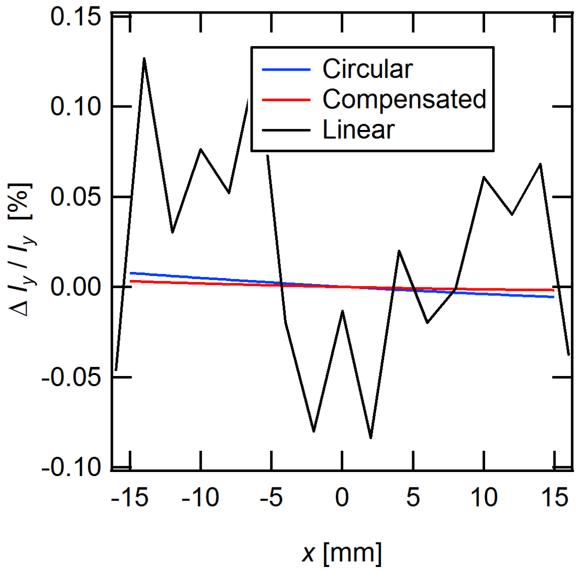
Measurements

Dipole

Max. field integral: 5 10^{-2} Tm



PM Steerer



Dipole field measurements

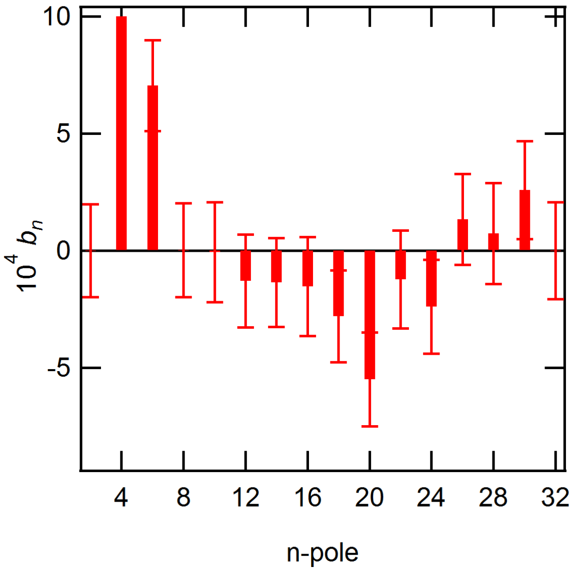
Results

- Linear measurement → poor accuracy
- Multipole measurements are better

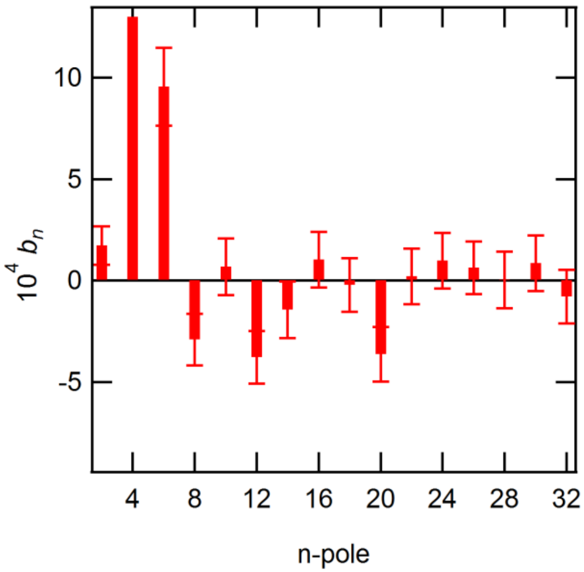
Measurements

Quadrupole

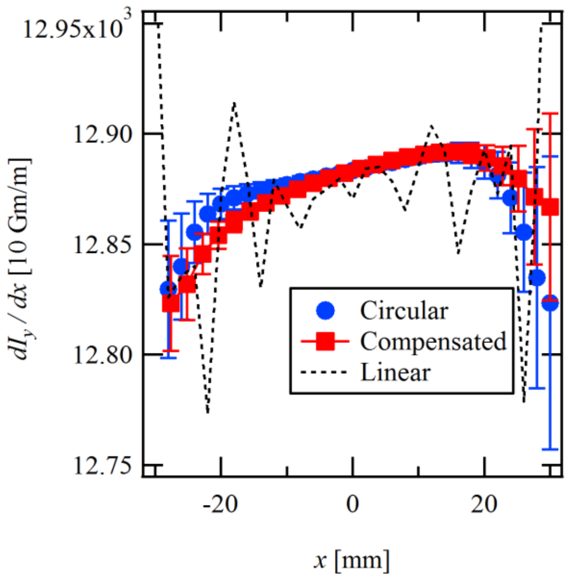
Gradient: 12.8 Tm/m; Max. field integral: 0.386 Tm



Normal multipoles Circular trajectory



Normal multipoles Multipole compensated trajectory



Gradient

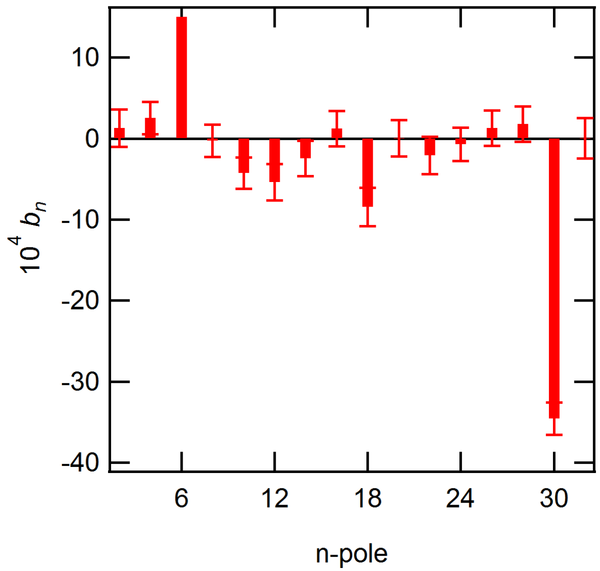
Results:

- Multipole compensated trajectory gives better accuracy
- Poor accuracy of linear measurements

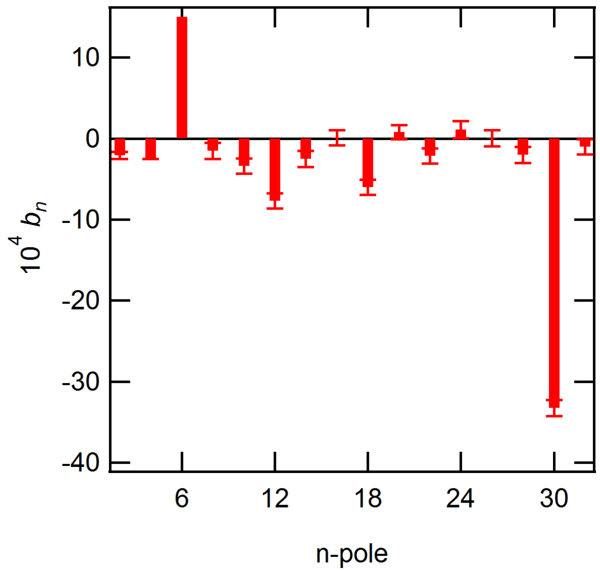
Measurements

Sextupole

Strength: 76.7 Tm/m^2 ; Max. field integral: 3.45 10^{-2} Tm



Normal multipoles
Circular trajectory



Normal multipoles
Multipole compensated trajectory

Results:
- Multipole compensated trajectory is better
- Circular trajectory gives acceptable accuracy

Conclusion

Theory

- Matrix formalism & least square approach
- Analysis of arbitrary trajectory
- SW “bucking” is available (compensated trajectories)
- Numerical simulations for sensitivity and accuracy analysis

Measurements

- Linear measurements are not accurate
- Multipole compensated trajectories give the best results
- No reference magnet used

Perspective

- Elliptic multipoles
- Non-circular trajectories