Stretched-wire measurements of multipole magnets at the ESRF

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ESRF Upgrade

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

New Magnets

- Shorter quadrupoles and sextupoles
- Permanent Magnet steerers
Introduction

Stretched Wire Measurements

• Moving SW
• Vibrating SW (see next talks)

Basic measurements

Longitudinal field integral

\[ I = \int Bdl = -\frac{e}{v} \]

Integration and time averaging

\[ I = \frac{1}{L} \int e \, dt \quad \Rightarrow \quad I \approx -\frac{\langle e \rangle T}{L} \]

Applications

Insertion devices
Field gradient, sextupole strength…
Introduction

Multipoles Analysis

Complex potential

\[ A = A + iV \]

Multipole expansion

\[ A = \sum_{n=0}^{\infty} c_n z^n \]

\[ c_n = -\frac{b_n + i a_n}{n \rho_0^n} \]

SW basic multipole measurements

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

Example

- ESRF Quadrupole
- Parasitic multipoles

Low accuracy

Example graph of multipole measurements.
Theory

Matrix formalism

Complex field integral

\[ I_{\parallel \perp} = I_{\perp} + i I_{\parallel} \]

\( I_{\perp} \) is perpendicular to the SW motion, measured

\( I_{\parallel} \) is parallel to the SW motion, not measured

Can be written as

\[ I_{\parallel \perp} = -e^{i\theta} (1, \ldots, z^{n-1})(c_1, \ldots, N c_N)^T \]

For a set of measurements:

\[
\begin{pmatrix}
I^1_{\parallel \perp} \\
\vdots \\
I^M_{\parallel \perp}
\end{pmatrix}
= \begin{pmatrix}
e^{i\theta_1} & \cdots & e^{i\theta_1} (z_1) & \cdots & b_1 + i a_1 \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
e^{i\theta_M} & \cdots & e^{i\theta_M} (z_M) & \cdots & b_N + i a_N
\end{pmatrix}
\]

The measurements are expressed as:

\[
\begin{pmatrix}
I^1_{\perp}, \ldots, I^M_{\perp}
\end{pmatrix}^T = (\text{Re} Z, \text{Im} Z)(b_n, \ldots, a_n)^T
\]

with

\[ Z_{mn} = e^{i\theta_m} \left( \frac{z_m}{\rho_0} \right)^{n-1} \]
Theory

Effect of measurement length

\[ Z_{mn} = \frac{1}{L} \int e^{i\theta_m} \left( \frac{z_m}{\rho_0} \right)^{n-1} dz \]

Measured field integral

\[ \mathbf{I} = \mathbf{T}\mathbf{C} \quad \rightarrow \text{Simulation from SW trajectory and multipoles} \]

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

Extension to rotating coils

• Simulation of coil errors
• Combining several rotating coil measurements

Compensation of the 4-pole

Multiple rotating coil measurements
Accuracy

Linear measurements

Field Integral

\[ \frac{\Delta I}{I} = \frac{\Delta L}{L} \]

Gradient

\[ G_{k}^{\text{meas}} = \frac{I_{k+1}^{\text{meas}} - I_{k-1}^{\text{meas}}}{s_{k}} \]

\[ = G_{k} + \Delta G_{k} \]

with

\[ |\Delta G_{k}| \leq G_{k} \frac{\Delta S}{S} + \frac{1}{S} \frac{\Delta L}{L} \left( |I_{k+1}| + |I_{k-1}| \right) \]
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

- **Granite Table**
  - 60 x 60 cm² cross section

- **Nanovoltmeter**
  - Keitley 2182 A

- **FARO Arm**
Measurements

Dipole
Max. field integral: $5 \times 10^{-2}$ Tm

PM Steerer

Results
- Linear measurement $\rightarrow$ poor accuracy
- Multipole measurements are better
Measurements

Quadrupole

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

Results:
- Multipole compensated trajectory gives better accuracy
- Poor accuracy of linear measurements
Measurements

Sextupole
Strength: 76.7 Tm/m²; Max. field integral: 3.45 \times 10^{-2} \text{Tm}

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