Magnets cross-talk and impact on the lattice for ESRF-EBS

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Outline

1. Introduction
2. Evidences for quad cross-talks
3. Models
4. Measurements
5. Impact on the lattice
6. Conclusion
1. Introduction
The Extremely Brilliant Source

- New generation 6 GeV synchrotron light source
- Low emittance storage ring
- Restarted end 2019
- User mode since end of August
THE EBS LIGHT SOURCE

The Extremely Brilliant Source

- New storage ring
- 130 pm·rad horizontal emittance
- 10 pm·rad vertical emittance
- 6 GeV electrons
- 200 mA current
- Same buildings and infrastructures

How to decrease the emittance?

- More dipoles (7 per cell)
- Strong quadrupoles between dipoles
Main magnets

Dipoles

128 PM magnets

0.17 T < \( B \) < 0.67 T

Dipole-quads (DQs)

96 magnets

0.39 T < \( B \) < 0.57 T

31 T/m < \( G \) < 37 T/m
THE EBS MAGNET SYSTEM

Main magnets

Quads
- 521 magnets
- 50 T/m < B < 90 T/m
- 25 mm < φ < 33 mm

Sextupoles
- 192 magnets
- \( S = 1700 \text{T/m}^2 \)
- \( \phi = 38.4 \text{mm} \)

Octupoles
- 64 magnets
- \( O = 57 \text{kT/m}^3 \)
- \( \phi = 38.2 \text{mm} \)
Other magnets

Correctors

96 magnets
Dipoles + skew quad (+sextupole)

Injection
Specific magnets
SBM sources
Short PM dipoles
Some specificities of the EBS magnets

*PM dipoles*

No trimming coil (tunning in lab)

*High gradient quads*

Saturated at nominal current

*Combined magnets*

Dipole-quads
Sextupoles + dipole correctors + skew quads
Combined correctors + skew quads
A very compact storage ring!
Short distances between magnets

- PM dipole: 47 mm
- Sextupole yoke: 75 mm
- Octupole yoke: 60 mm
THE EBS MAGNET SYSTEM

A very compact storage ring!
Short distances between magnets

Coil to coil distance < 1 cm

PM dipole
Sextupole yoke
Octupole yoke
Quadrupole yoke
Quadrupole yoke

75 mm
60 mm
All ingredients for strong cross-talks

**Between magnets**
- Short distances
- Saturation
- Cross-talk induced PM dipole error pre-corrected in lab

**Between channels of combined magnets**
- Not in the scope of this talk

Dipole to quad crosstalk
[LER2013, Oxford]
2. Evidences for quad cross-talks
28th November 2019

First turns

Tune measurements from turn-by-turn data

Large discrepancies between measurements and model

\[ \Delta \nu_X = -0.4 \]
\[ \Delta \nu_Y = -1.4 \]
EVIDENCES FOR QUAD CROSS-TALK

Mid-December 2019

*Quadrupole calibrations*

- Excitation curves for quad families
- Individual calibration coefficients for quadrupoles (close to 1)
- Bugs found, e.g. divisions instead of multiplications…
- Two sets of measurements available (by suppliers and at ESRF)
Mid-December 2019

Quadrupole calibration errors

Calibration coefficients for one magnet family
Mid-December 2019

*Quadrupole calibration errors*

- Excitation curves for quad families
- Individual calibration coefficients for quadrupoles (close to 1)
- Bugs found, e.g. divisions instead of multiplications…
- Two sets of measurements available (by suppliers and at ESRF)

*Calibration uncertainties*

- Estimated to $U = 3.2 \times 10^{-4}$
  (supplier vs ESRF, accounting for benches, power supplies, etc.)

**Much larger errors expected from lattice measurements!**
EVIDENCES FOR QUAD CROSS-TALK

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Much larger errors expected from lattice measurements!

Can cross-talks generate large quadrupole errors?
Preliminary measurements in 2017

- Dipole to quadrupole cross-talk
- Needed for PM dipole tuning
- Focused on dipole errors due to quads
- Impact on gradient not investigated in details at that time

Integrated dipole vs dipole-to-quad distance
Preliminary measurements in 2017

- Dipole to quadrupole cross-talk
- Needed for PM dipole tuning
- Focused on dipole errors due to quads
- Impact on gradient not investigated in details at that time

A later analysis of the data shown a 1% gradient error at nominal distance
3. Models
Magnetic simulations

- Non-linear 3D models
- Strong dependence in current (magnets are saturated)
- Radia software used

*Needs a lot of CPU time on the ESRF cluster!*

~ 1 CPU hour / current settings

Radia magnetic model of a dipole and a quadrupole
MODELS

About the Radia code

- Magnetostatic simulation code
- Initially developed for PM insertion device simulations
- It does not rely on FEM, but on a boundary integral approach, i.e. it computes the magnetization of small elements using currents and magnetizations of other elements

This is convenient for cross-talk problems, as it allows to separate easily the contribution of the different magnets

[https://github.com/ochubar/Radia]
Dipole to quadrupole cross-talk

- 0.8 to 0.9% decrease of integrated gradient (depending on magnets)
- Effect localized on the dipole edge
- Almost no change in the quad
- Can be modelled by a thin lens with opposite polarity

Gradient distribution in a dipole and a quadrupole
Sextupole to quadrupole cross-talk

- 0.3 % decrease of integrated gradient
- Effect localized on the sextupole edge

Gradient distribution in a sextupole and a quadrupole
Sextupole to quadrupole cross-talk

<table>
<thead>
<tr>
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<th>QF4A</th>
<th>SF2-ext</th>
<th>SF2</th>
<th>SF2-ext</th>
<th>QF4B</th>
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<td>Gradient error</td>
<td>−0.03</td>
<td>−0.27</td>
<td>−0.27</td>
<td>−0.03</td>
<td>%</td>
</tr>
</tbody>
</table>
Sextupole to quadrupole cross-talk

Integrated gradient error from sextupole edge

Integrated gradient error from quadrupole

(All errors in (%) of the integrated gradient without sextupole)
Octupole to quadrupole cross-talk

- 1.7 % increase of integrated gradient
- Gradient error all along the octupole

Errors distribution and sign are magnet dependent
Octupole to quadrupole cross-talk

Integrated gradient error from octupole

Integrated gradient error from quadrupole

(All errors in (%) of the integrated gradient without octupole)
4. Measurements
MEASUREMENTS

Magnetic measurements

- Integrated gradient
- Stretched wire method used
- Crosstalk with dipole, sextupoles and octupoles measured

Main purpose
To check the simulations in a few sample configurations

Octupole and quadrupole installed on a measurement bench
PM Dipole / quadrupole

Measured in 2017 (focused on field)

Discrepency:

\[
\frac{\text{Sim} - \text{Meas}}{\text{Meas}} < 7 \times 10^{-4}
\]

(Magnet positioning could have been improved)

Quadrupole gradient vs distance between quad and PM dipole (nominal value: 47 mm, first point)
MEASUREMENTS

Sextupole / quadrupole

*Simulation*

\[ \Delta G / G = -0.30 \% \]

*Measurements*

\[ \Delta G / G = -0.306 \% \]

(Quad at 85 A, sextupole at 0 A, distance 75 ± 0.5 mm, \( UG \approx 10^{-4} \))
Octupole / quadrupole

Simulation (quad current: 85 A)
\[ \frac{\Delta G}{G} = 1.78\% \]

Measurements
\[ \frac{\Delta G}{G} = 1.77\% \]

Simulation (quad current: 100 A)
\[ \frac{\Delta G}{G} = 1.69\% \]

Measurements
\[ \frac{\Delta G}{G} = 1.76\% \]

(Octupole at 0 A, distance 60 \( \pm \) 0.5 mm, \( UG \approx 10^{-4} \))
5. Impact on lattice
Optics with cross talk quadrupole fields

- Cross-talks (thin elements) introduce $\Delta \beta_X / \beta_X \approx 10\%$ and $\Delta \beta_X / \beta_X \approx 20\%$
- Recovered after matching
- Changes in quadrupole setting points up to 1.7\%
DA and off-energy

Ideal lattice model
DA : -8.7 +/- 0.3 mm
T.L.T. : 19.6 +/- 0.7 h
I.E. : 85 +/- 5 %

Ideal lattice model
+ cross talks
DA : -8.3 +/- 0.4 mm
T.L.T. : 19.7 +/- 1.4 h
I.E. : 88 +/- 7 %
Horizontal dispersion measurements

09 Dec 2019, first measurement

- calibrations, cross-talks, steering with more singular values than foreseen, \textit{BBA},
- NO quadrupole correction (except tunes)

30 Jan 2020, “uncorrected”
6. Conclusion
Causes of cross-talks

- Short distances between magnets

Effect on the lattice

- Similar to magnet calibration issues
- Large discrepancies between model and real lattice at the restart
- Recovered by inserting cross-talk effects in the model
- No change in lattice performances at the end
Simulations

- 3D magnet models at several currents
- Fine localization of the errors (at magnet edges or not)
- Used to update the lattice model

Magnetic measurements

- Stretched-wire measurements of the integrated field
- Good agreement with simulations