Flux jumps in the HL-LHC IR

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Flux jumps simulations

- Unstable behaviour shown by all type II superconductors when subjected to a magnetic field.
- Likely to happen during ramp.
- The actual magnitude of the jump is unknown.
  - We will take a fixed magnitude to be able to scale.
- The duration of the jump is unknown.
  - Assume the worst case (1 turn) and extrapolate it to higher number of turns.
- It is also unclear if the effect will show up at circuit or magnet level.
  - Simulate both cases: jumps in the circuit and jumps in individual magnets.

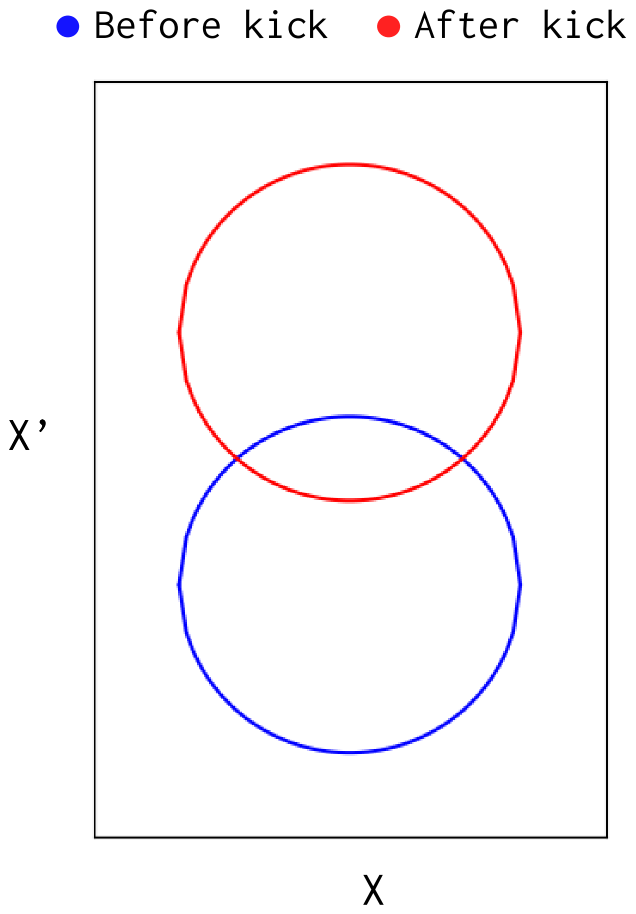
- Only considered the dipolar kicks of D1,D2 dipoles and from triplet quadrupoles with closed orbit (via feeddown).
- The flux jump will appear like a fast error in the field. For dipoles an error in the kick angle.
- The effect of the kick on the emittance if $\epsilon_f = \epsilon_0 + \Delta\epsilon$:

For dipoles

$$\epsilon_f = \epsilon_0 + \beta_{\mathrm{k}}\Delta\theta^2$$

For quadrupoles

$$\epsilon_f = \epsilon_0 + \beta_Q(\Delta kl \cdot x_{co})^2$$



- This is the effect taken into account in the study.

- In quadrupoles the flux jump will appear as a fast change in the strength of the quadrupole Δkl.

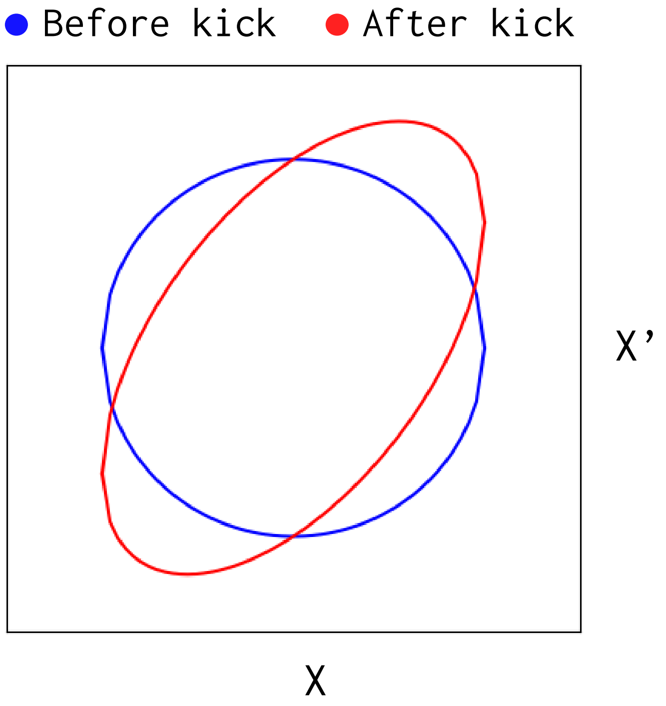
If ϵ_0 is the initial emittance and we start with a distribution $\Psi_0(J)$:

$$\Psi_0(J) = \frac{1}{2\pi\epsilon_0}\exp\left(-\frac{J}{\epsilon_0}\right)$$

Transforming J for a quadrupolar kicks: $J \rightarrow \frac{1}{2\beta}\left[x^2 + \left(p + \beta_Q \Delta klx\right)^2\right] \approx J[1 - \beta_Q \Delta klsin(2\phi)]$

The distribution after the kick:

$$\Psi_1(J,\phi) = \frac{1}{2\pi\epsilon_0}\exp\left(-\frac{J[1 - \beta_Q \Delta klsin(2\phi)]}{\epsilon_0}\right)$$



Averaging the action:

$$< J > = \int_0^\infty \int_0^{2\pi} J\,\Psi_1(J,\phi)dJd\phi = \frac{\epsilon_0}{\left(1 - \left(\beta_Q \Delta kl\right)^2\right)^{\frac{3}{2}}} \approx \epsilon_0 + \overbrace{\boxed{\frac{3\epsilon_o\left(\beta_Q \Delta kl\right)^2}{4}}}^{\Delta\epsilon} + O(\Delta k^4)$$

Looks small compared with dipolar kick -> ignored in this study.

Flux jumps simulations

- Assumed a jump of 10^{-6} in the field of the IR magnets relative to nominal. Easy to scale the result for different values.

- Used MAD-X to compute a Twiss of the IR with the flux jumps applied computed emittance as:

$$\gamma(s)y^2 + 2\alpha yy' + \beta(s)y'^2 = \epsilon$$

$$\epsilon_N = \epsilon\gamma_{rel}$$

- Then used the nominal emittance of HL-LHC $\epsilon_{HLLHC} = 2.5\mu m$ to compute the kick in σ:

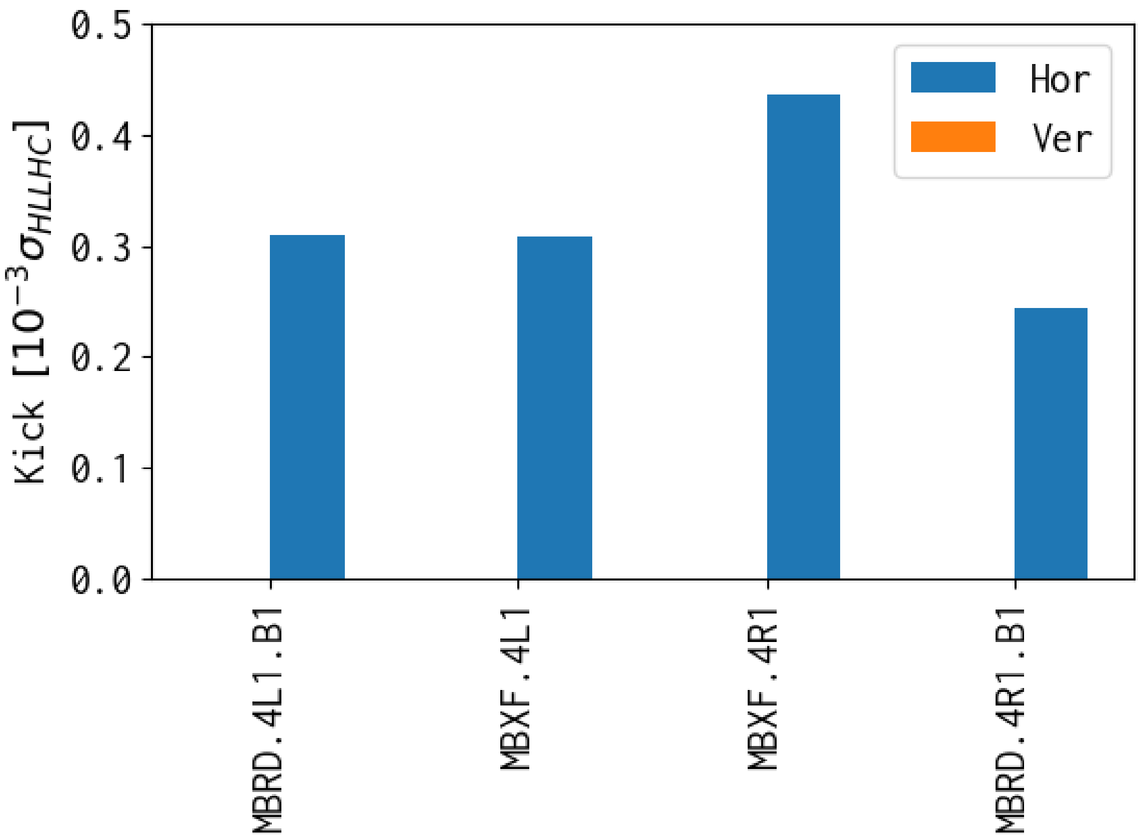
$$k_\sigma = \sqrt{\frac{\Delta\epsilon_N}{\epsilon_{HLLHC}}}$$

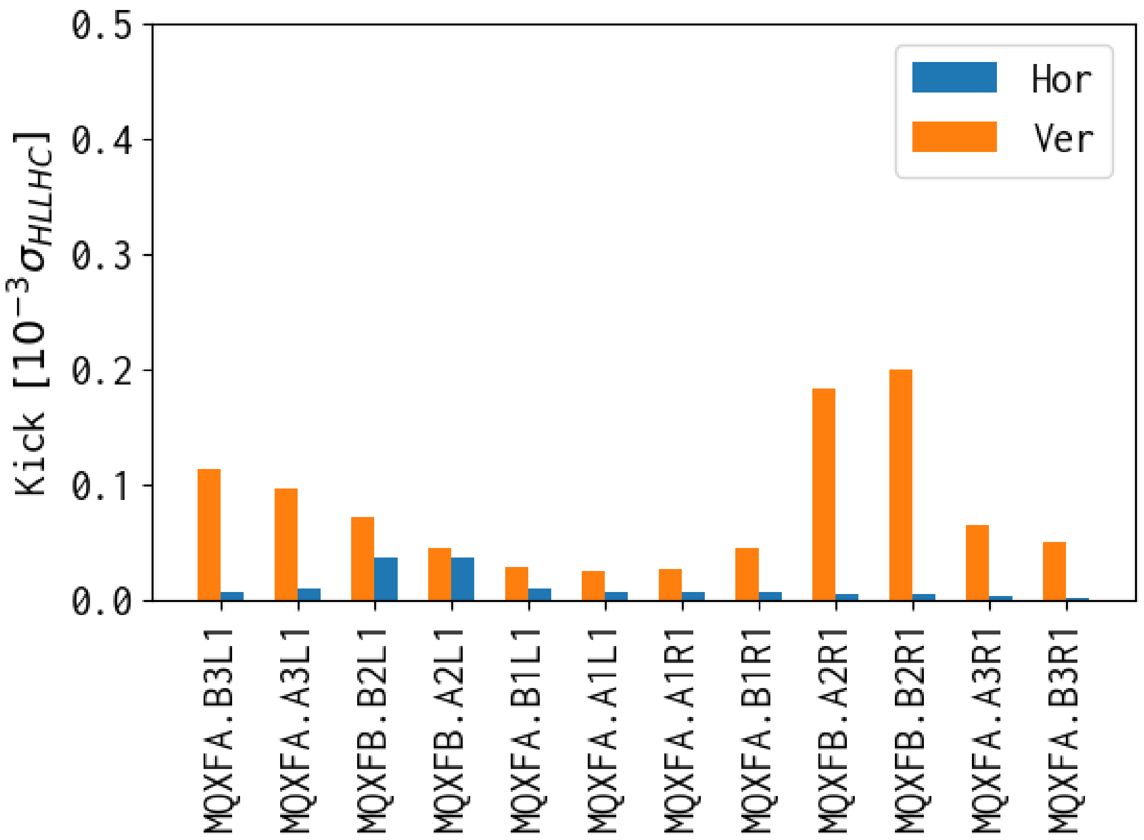
- Simulations made magnet-by-magnet and circuit-by-circuit.

- Studied only IP1 (different separation and crossing planes)

Flux jumps simulations

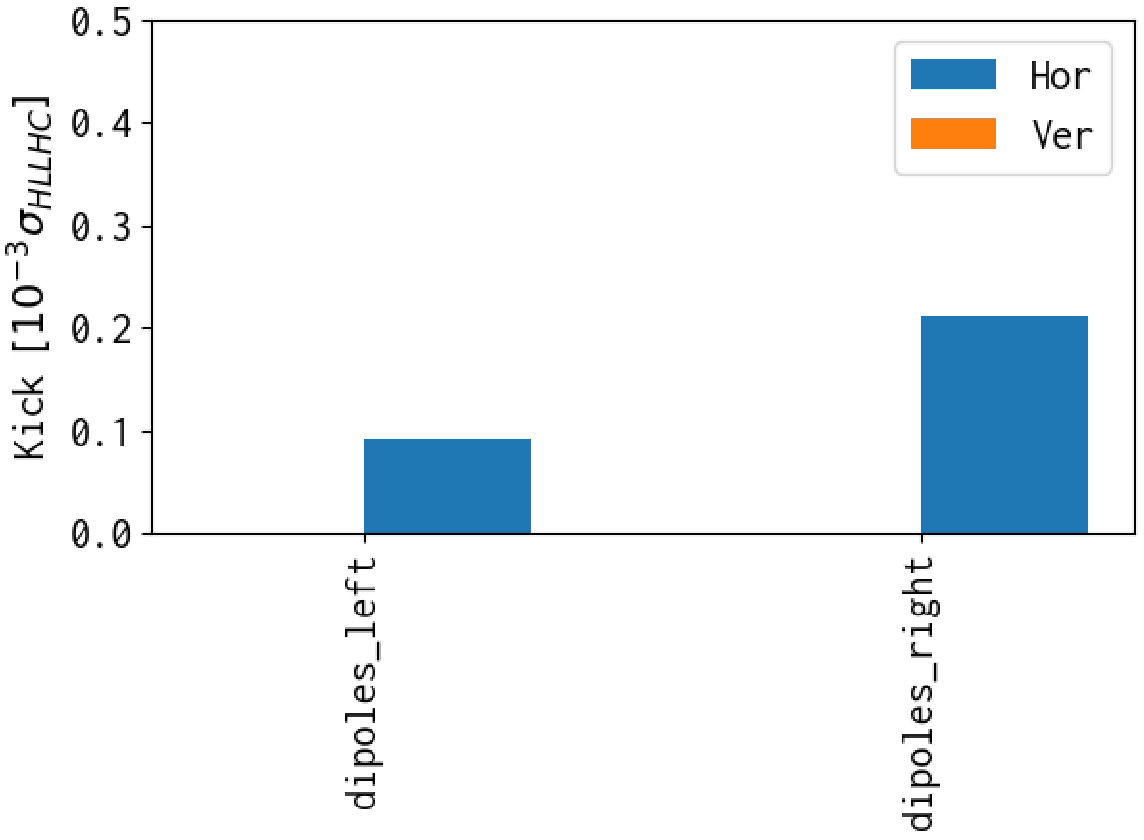
- Considering every magnet individually:

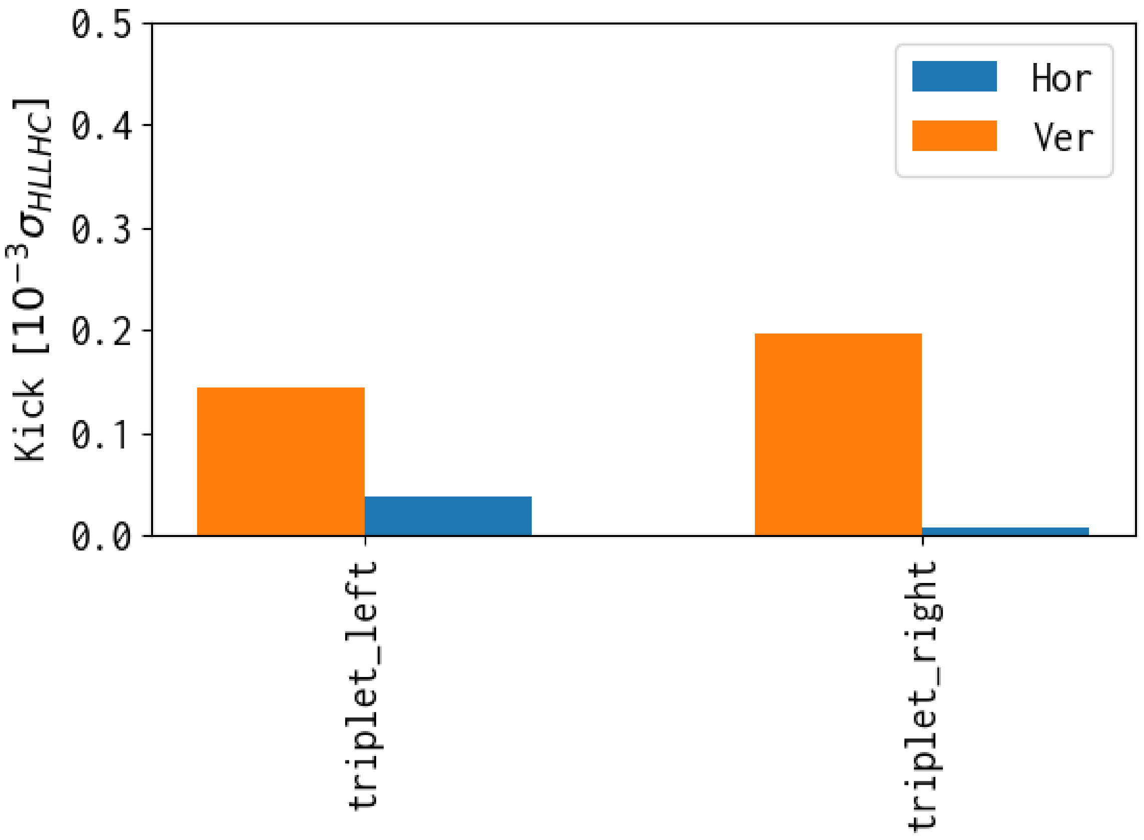




- For 0.45TeV and injection optics.

- Considering the circuits:

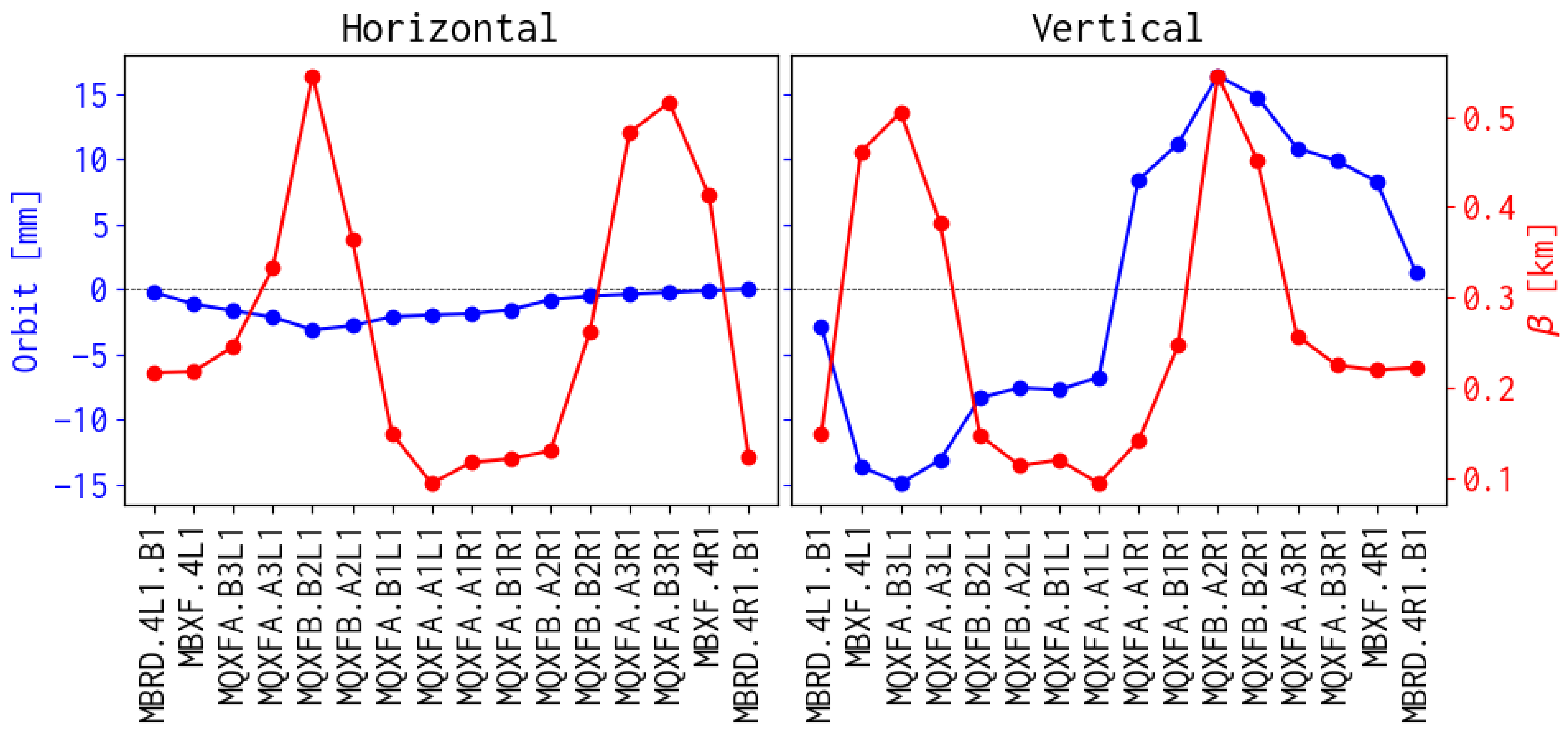




- For 0.45TeV and injection optics.

Flux jumps simulations

- β and orbit in the segment:



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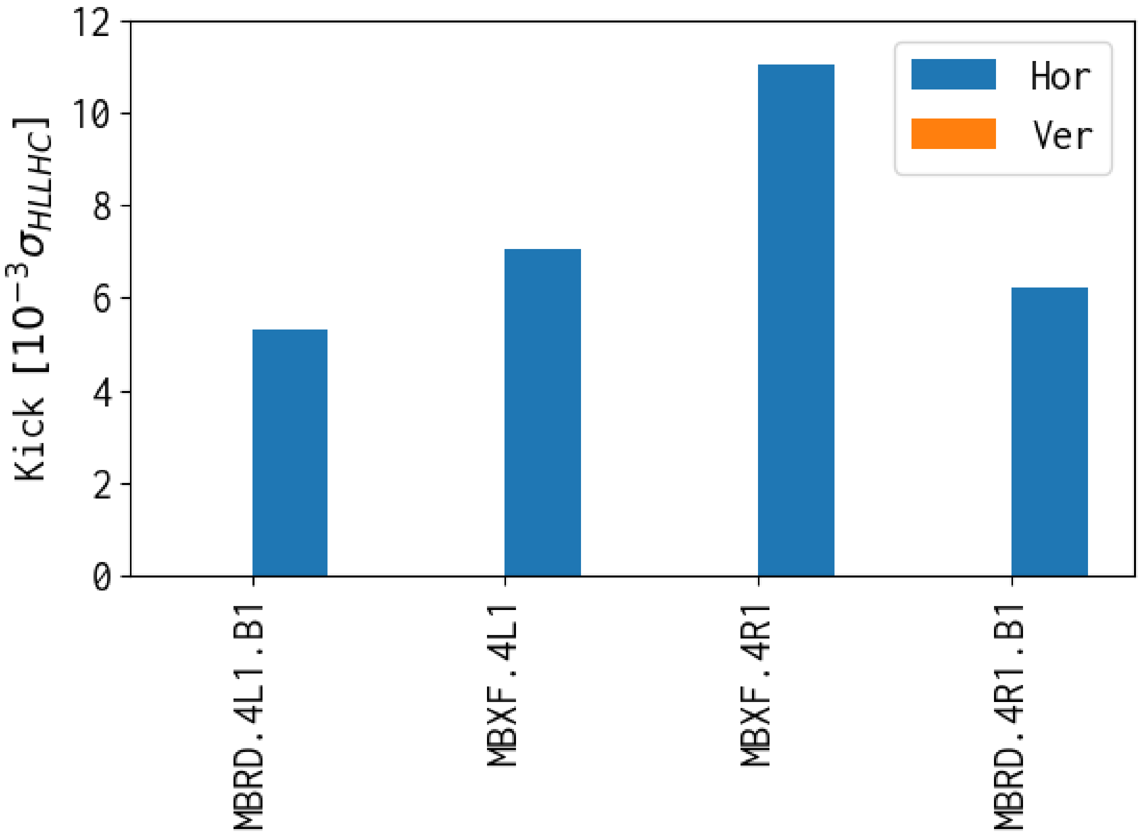
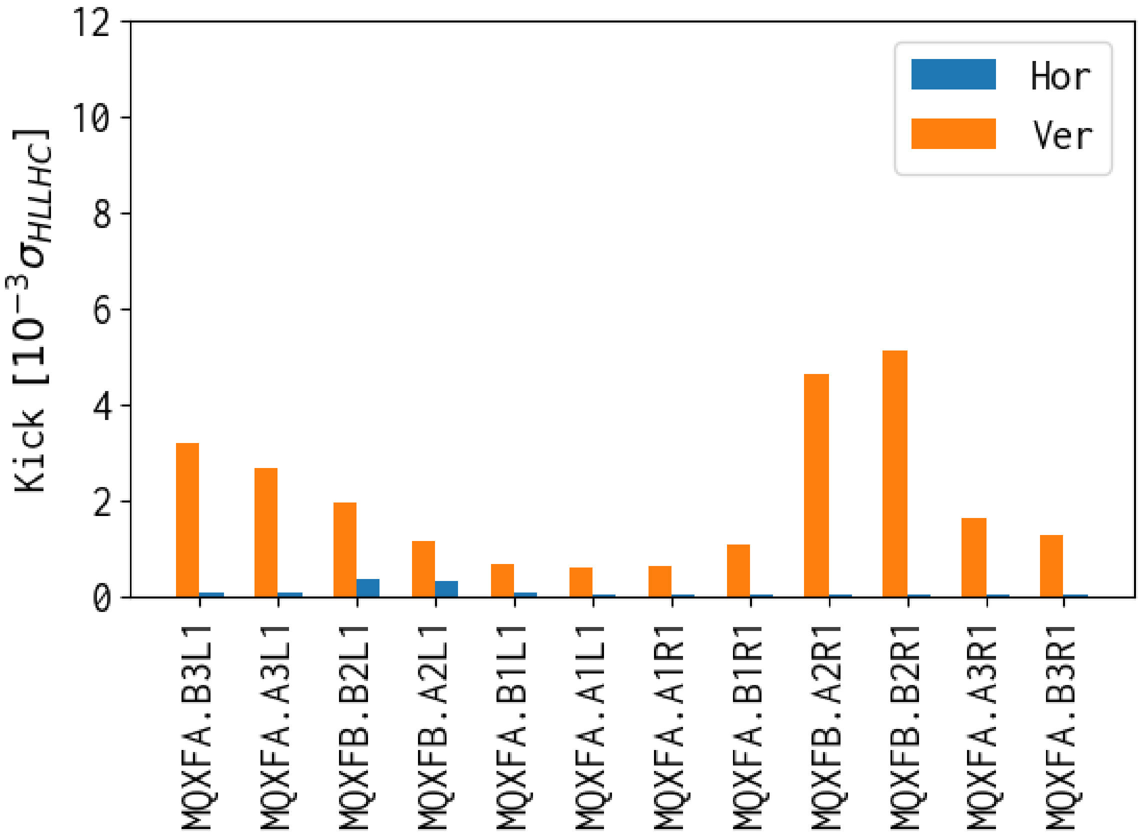
Flux jumps simulations

- Considering every magnet individually:

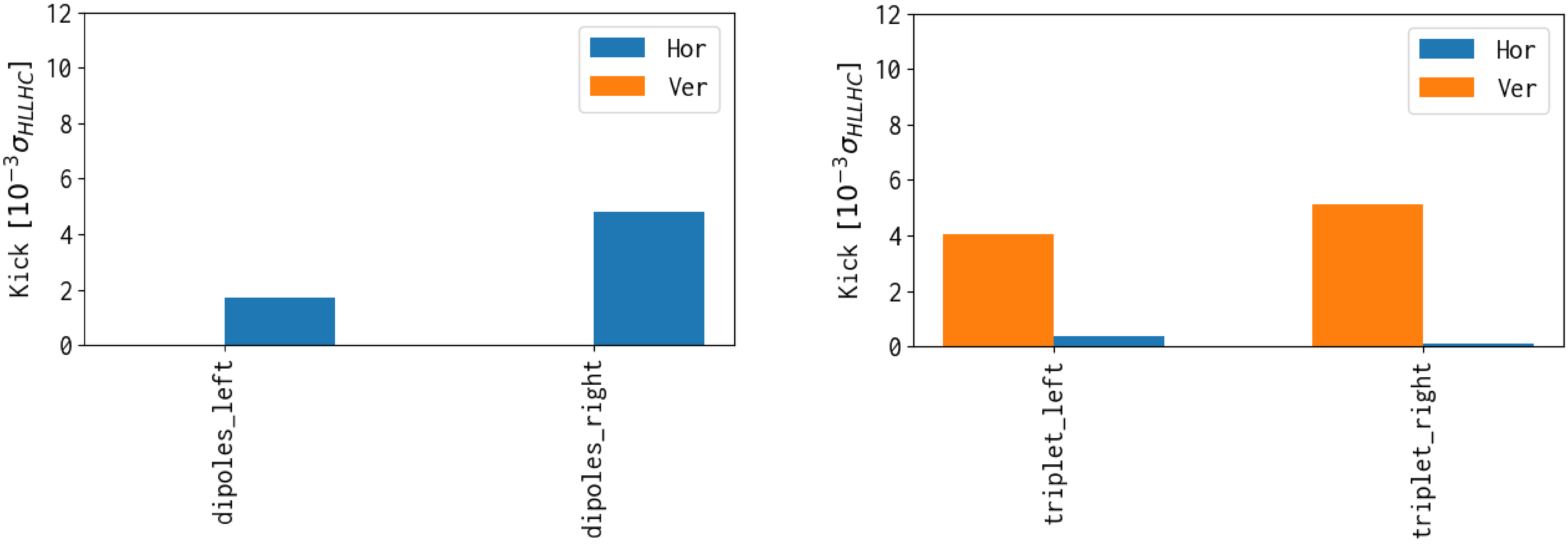




- For 7TeV and 15cm optics.

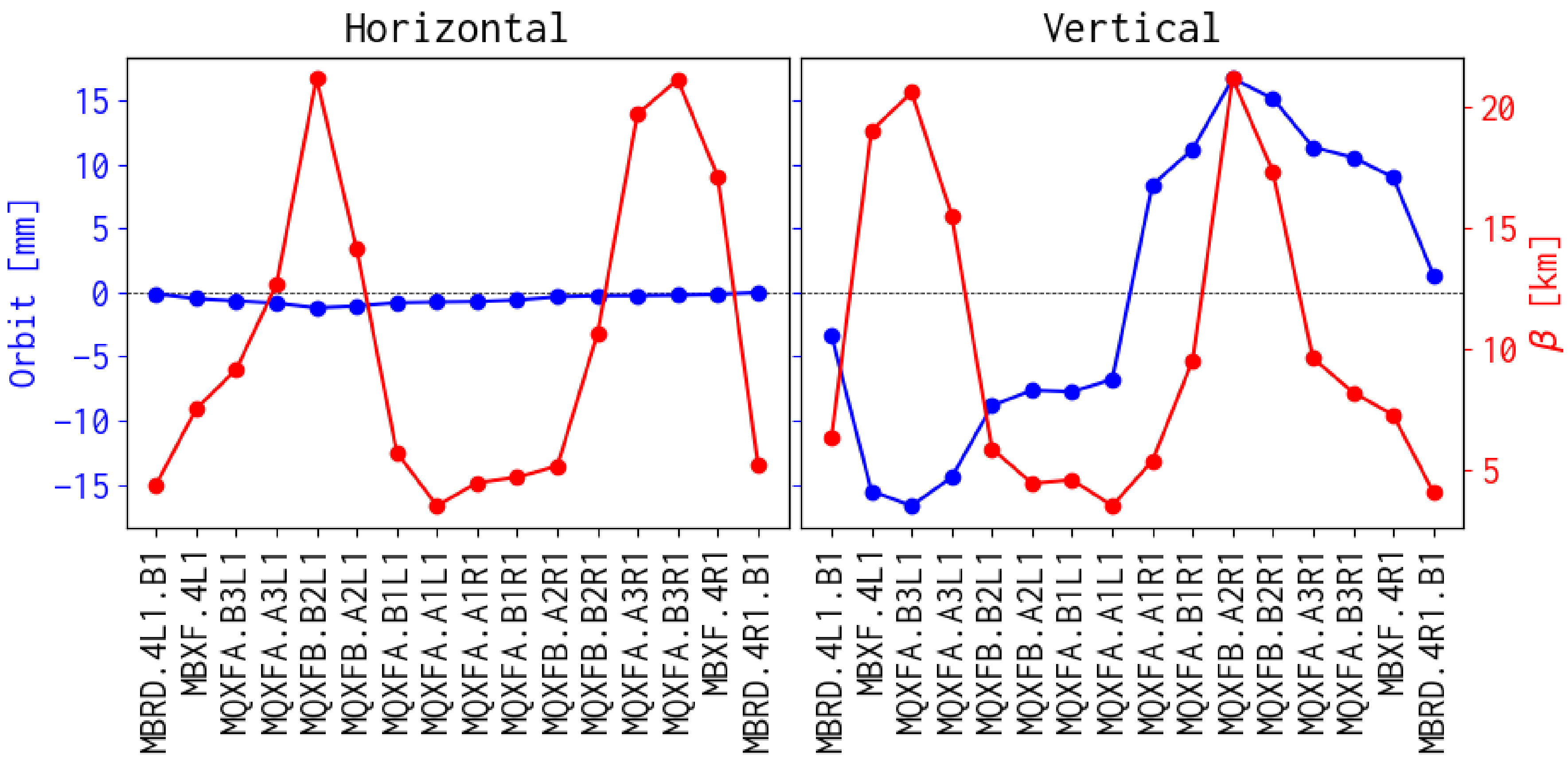
Flux jumps simulations

- Considering the circuits:



- For 7TeV and 15cm optics.

- β and orbit in the segment:

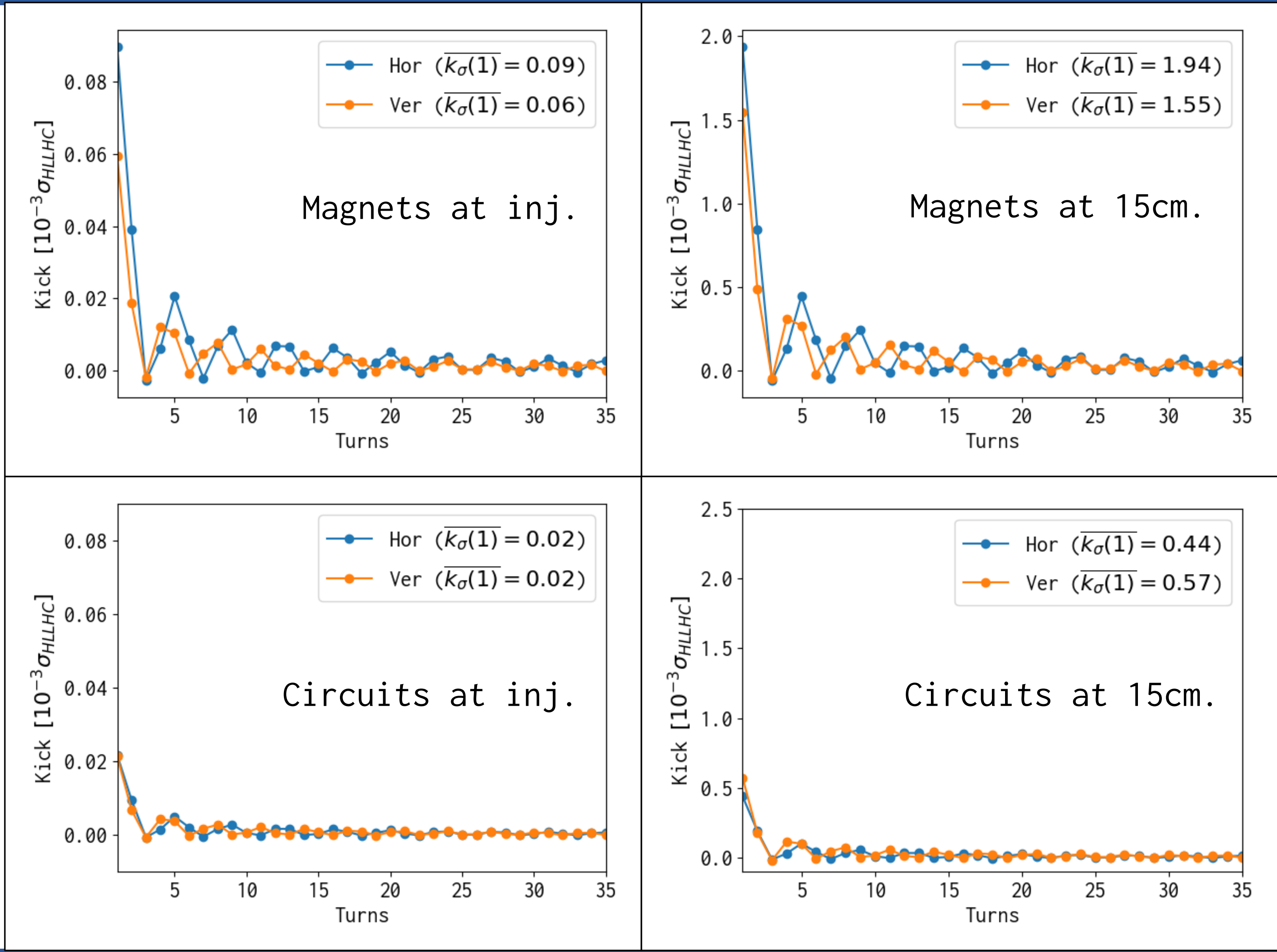


- For 7TeV and 15cm optics.

Flux jumps simulations

- Assuming dipoles and quadrupoles equally likely to have a flux jump.

- If the 10^{-6} kick develops over N turns assuming a linear increase gives:



Flux jumps simulations

- Also assuming all 16 dipoles and quadrupoles equally likely to have a flux jump.
- The total number of individual 1-turn 10^{-6} kicks to get a 1% emittance growth is:

	Horizontal	Vertical
Inj. Magnets	1115	1682
Inj. Circuits	4594	4676
7TeV Magnets	**52**	**65**
7TeV Circuits	229	175

Flux jumps simulations

- At lowest β^* and top energy 52 jumps ($\frac{\Delta k}{k} = 10^{-6}$ 1-turn) in D1,D2 and triplet in IR1 will produce a 1% emittance blow up.
- At injection tolerances are a factor ~20 larger.
- If the jump takes more than one turn the effect decays $\sim\frac{1}{N}$
- The effect of the quadrupolar kick seems small, but should be confirmed in further studies.
- Maybe worth checking the effect on IP5, where crossing and separation orbits will add up.

- D1,D2 and triplet fields across the IR:

NAME	θ	K1L
MBRD.4L1.B1	-0.001499	0
MBXF.4L1	0.001499	0
MQXFA.B3L1	0	-0.023444471
MQXFA.A3L1	0	-0.023444471
MQXFB.B2L1	0	0.039308297
MQXFB.A2L1	0	0.039308297
MQXFA.B1L1	0	-0.023720678
MQXFA.A1L1	0	-0.023720678
MQXFA.A1R1	0	0.023720678
MQXFA.B1R1	0	0.023720678
MQXFB.A2R1	0	-0.039308297
MQXFB.B2R1	0	-0.039308297
MQXFA.A3R1	0	0.023444471
MQXFA.B3R1	0	0.023444471
MBXF.4R1	-0.001499	0
MBRD.4R1.B1	0.001499	0

Flux jumps simulations (Appendix)

- Total number of individual 1-turn 10^{-6} kicks to get a 1% emittance growth.

- Quadrupoles alone (12 magnets):

	Horizontal	Vertical
Inj. Magnets	8643	1262
Inj. Circuits	26422	3507
7TeV Magnets	887	49
7TeV Circuits	2611	132

- Dipoles alone (4 magnets):

	Horizontal	Vertical
Inj. Magnets	309	-
Inj. Circuits	1321	-
7TeV Magnets	14	-
7TeV Circuits	62	-