Effect of spurious quench heater and CLIQ firing on the LHC and the future HL-LHC beams

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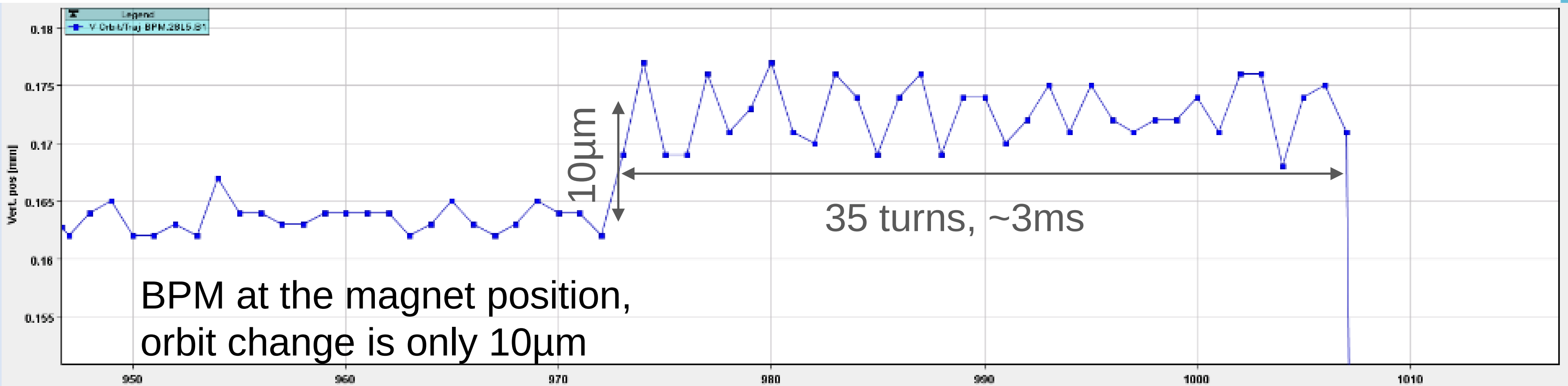
Outline

- Quench Heater effect on the beam
  - Context, 2016 observations
  - MD#1826 on main dipole Quench Heaters
  - Quench Heater parameters and kicks for LHC and HL-LHC magnets
  - Conclusions and possible mitigations
  - Outlook on MD#2186 on triplet Quench Heaters
- CLIQ effect on the beam
  - CLIQ concept
  - CLIQ discharge in the triplet, currents and magnetic fields
  - Spurious discharge in Q1/Q3
  - Spurious discharge in Q2
  - Conclusions on interlocking limits

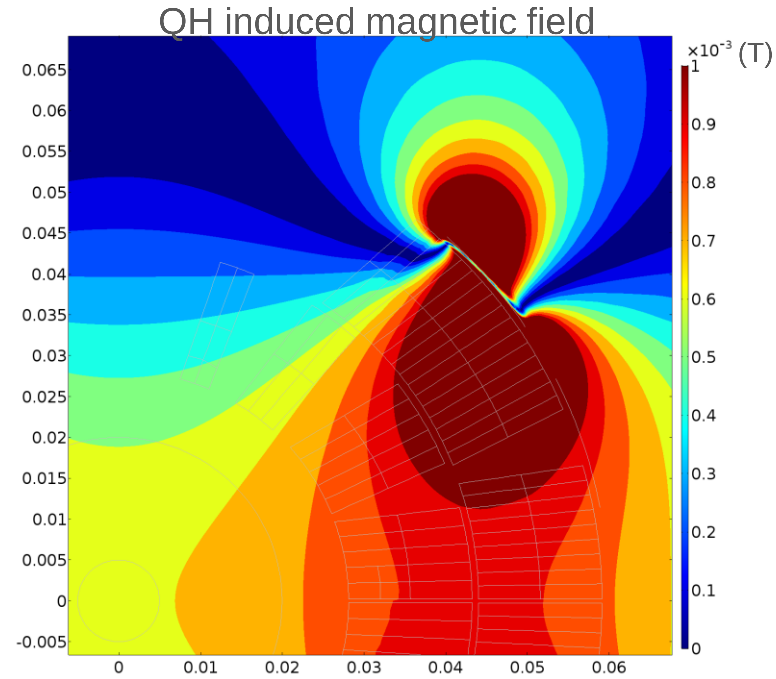
Context: 2016 observations

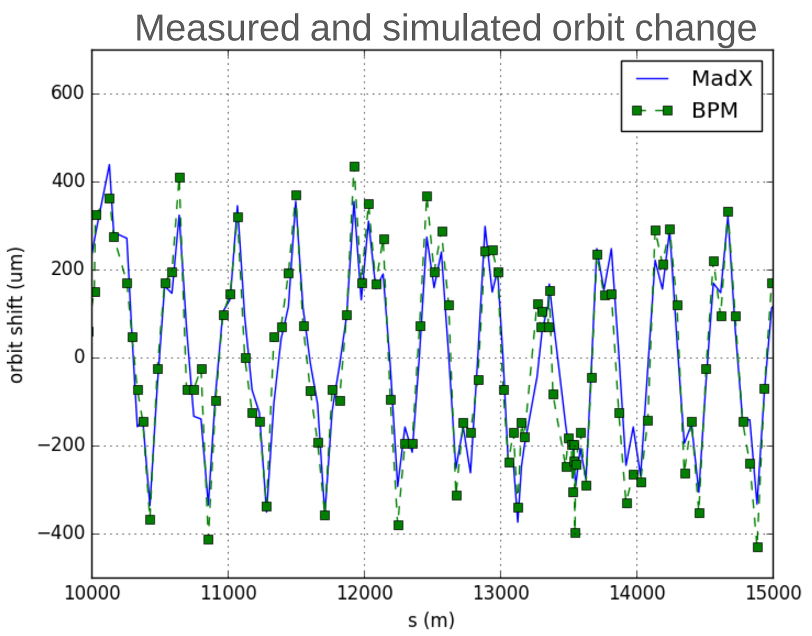
- In 2016, shortly before **dumps** caused by **quenches**, **low level periodic losses** were observed.
- It was associated with a **small shift** and **oscillation of the beam** in the vertical plane.
- The **QH firing** were identified as a potential cause.



MD#1816
MB Quench Heaters

- From **simulations**: the QH cause a **0.7 mT** field in the beam area.
- Associated **orbit change**: **+/- 400 µm**, confirmed experimentally.
- A **delay** of up to **3 ms** (35 turns) between **QH firing and dump** was also confirmed.

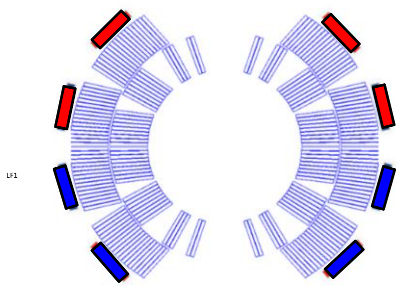




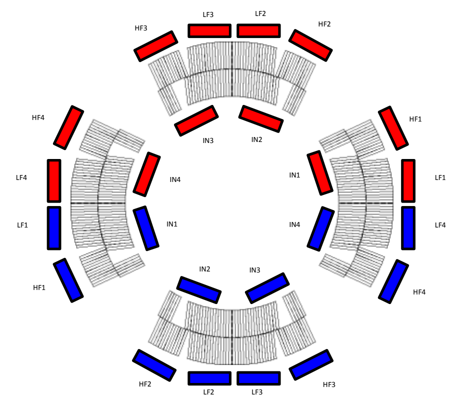
Quench heaters in other magnets

- **MB QH** are powered with **80 A**, some **QH in the LHC** are powered with **300 A** (e.g. D1 in IP2 & 8).
- Some **HL-LHC magnets** will be protected by up to **12 QH circuits**.

11 T dipole



MQXF

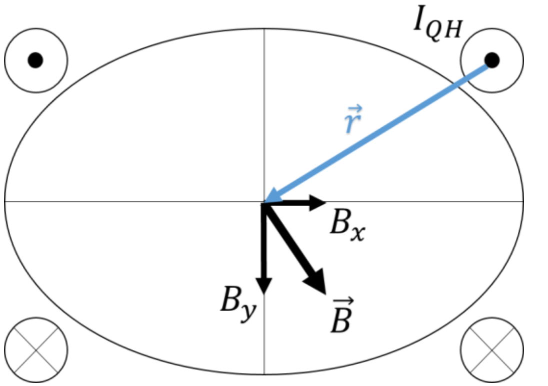


- A **broader analysis** of the QH of LHC and HL-LHC magnets was performed:
  - The **triplet and IPDs** are long magnets with large local β-functions => **large kicks**.
  - **IPQs** (MQM, MQY, …) with short magnetic lengths and smaller β functions were **ignored**.

Derivation of kicks

- In the following:
  - ~~Many numerical simulations~~, magnetic field is derived analytically (<1% ≠ simulations):

$$B_x = \frac{4\sin(\theta)\,\mu_0\, IQH}{2\pi\, r}$$



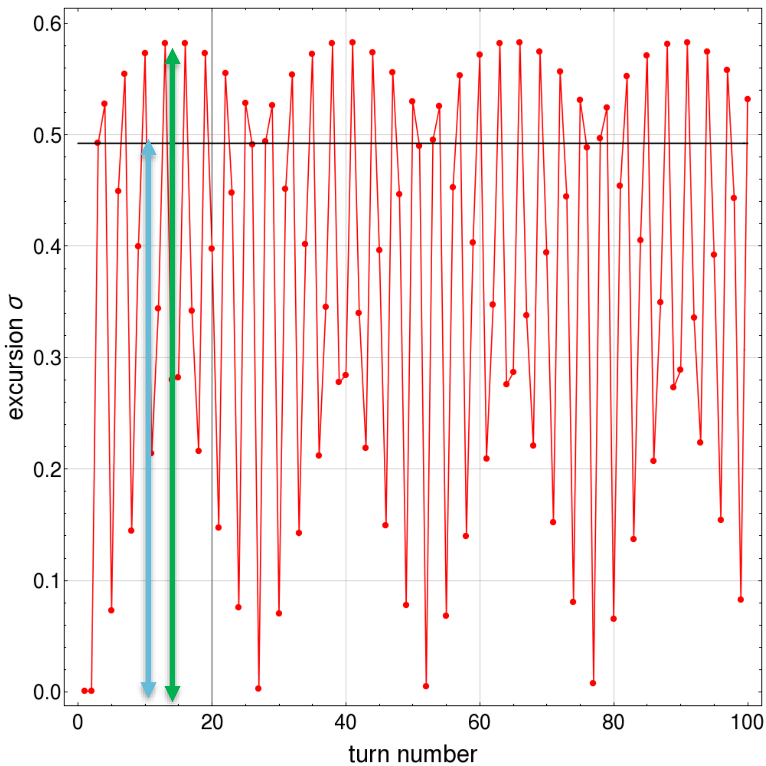
  - Associated kick:

$$Kick = \frac{B_x L_{magnet}}{B\rho}\sqrt{\frac{\beta_{magnet}}{\varepsilon}}$$

  - Orbit excursion:

$$\sigma_{max} \cong Kick * 1.185$$

(confirmed with MAD-X)



Quench Heater kicks for LHC and HL-LHC magnets

LHC

Magnet	BL (T.m)	β (m)	kick (σ)
MB	0.01	135	0.28
MQ	0.002	181	0.08
D1	**0.022**	**622**	**1.37**
D2	**0.014**	**1244**	**1.18**
D3	0.009	304	0.38
D4	0.015	441	0.74
11T	0.02	145	0.44
Triplet	**0.017**	**1400-5800**	**2.51**

HL-LHC

Magnet	BL (T.m)	β (m)	kick (σ)
MB	0.01	420	0.49
MQ	0.002	575	0.15
D1	**0.008**	**18 km**	**1.98**
D2	**0.0125**	**5.8km**	**2.44**
11T	0.02	144	0.42
Triplet w/out IL	**0.11**	**4.5km - 21km**	**28.8**
Triplet with IL	**0.20**		**52.0**

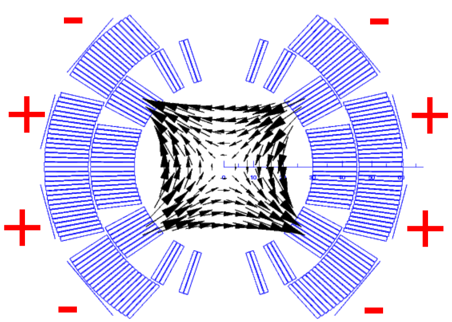
*With 40 cm ATS optics and HL-LHC v1.3 optics

- MQX & IPDs QH have **kicks > 1 σ** => dump via the BLMs.
- If **QH of all 3 MBs** connected to an **nQPS** crate were to fire: kick up to **2.5 σ**.
- **HL-LHC triplet QH have very large kicks**, beam would end up in aperture if fired before the dump.

=> Ensure the beam is dumped before these QH are fired.

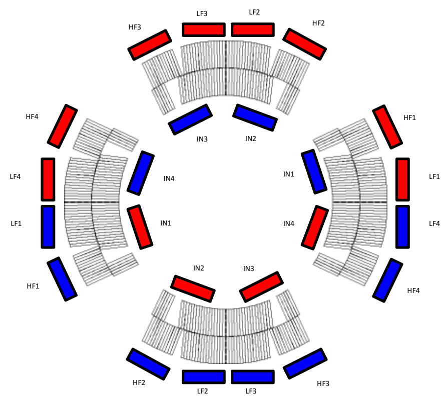
Possible mitigations

- In the previous table: **all QH kicks add up**, for magnets with multiple circuits.
  - Could be **mitigated** by using **other connection schemes** with HL-LHC magnets: quadrupole, compensating dipoles, …

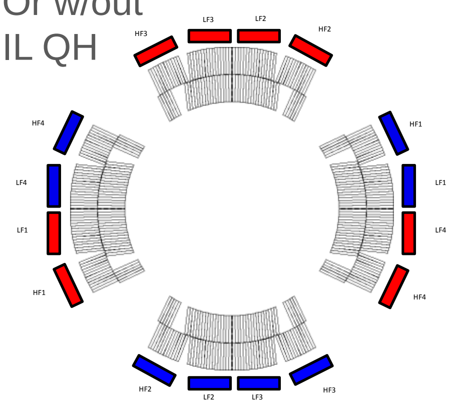


~0.11 T.m^{-1} Compared to 200 T.m^{-1} for the arc quads with similar β

Courtesy S. Izquierdo



Or w/out IL QH



=> Has to be brought to the circuit forum to verify compatibility with magnet protection.

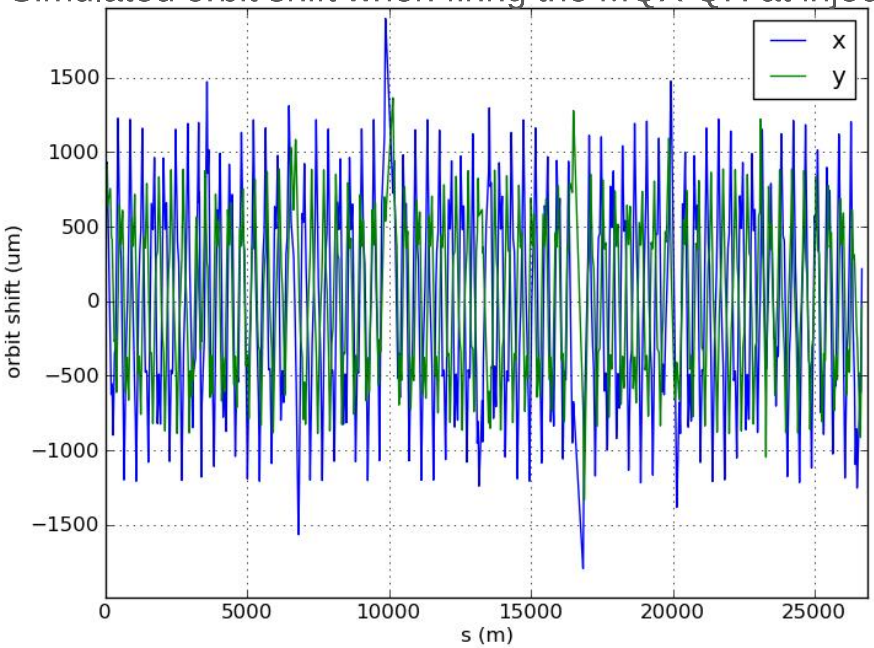
Conclusions

- The **kick from QHs** in **most LHC and HL-LHC superconducting magnets** were **calculated**, with some assumptions.
- **Very large kicks** are to be expected for the **triplets and IPDs**.
- This effect can be **mitigated** by **faster interlocking** on QH firing.
- **Alternative mitigation:** lower the dipole kick of QH by using different **connection schemes**.

Outlook on MD#2186

- **Follow-up MD** will be performed at the end of the year on **triplet QH**.
- Allows **verifying the kicks** from the quench heaters and the **delay before dump**.
- Simulations suggest **kicks up to 2 σ** (both planes)
- Will be performed on the **ALICE triplet**.

Simulated orbit shift when firing the MQX QH at injection



Quench Heater parameters for LHC and HL-LHC magnets

LHC

Magnet	L (m)	I_{QH} (A)	B_x (mT)
MB	14.3	80	0.71
MQ	3.1	80	0.86
D1	9.45	300	2.4
D2	9.45	190	1.4
D3	9.45	123	0.95
D4	9.45	200	1.5
11T (HF)	5.5x2		1.4
11T (LF)	5.5x2		0.47
MQXA	6.37	80	0.72
MQXB	5.5	80	0.72

HL-LHC

Magnet	L (m)	I_{QH} (A)	B_x (mT)
D1 (HF)	6.27	168	0.93
D1 (LF)	6.27	168	0.36
D2 (HF)	7.78	122	1.25
D2 (LF)	7.78	122	0.38
MQXFA	4.2	200	
MQXFB	7.15	200	
HF1		200	1.28
HF2		200	0.6
LF1		200	1.4
LF2		200	0.25
IL1		200	1.9
IL2		200	0.94

CLIQ – Coupling Loss Induced Quench

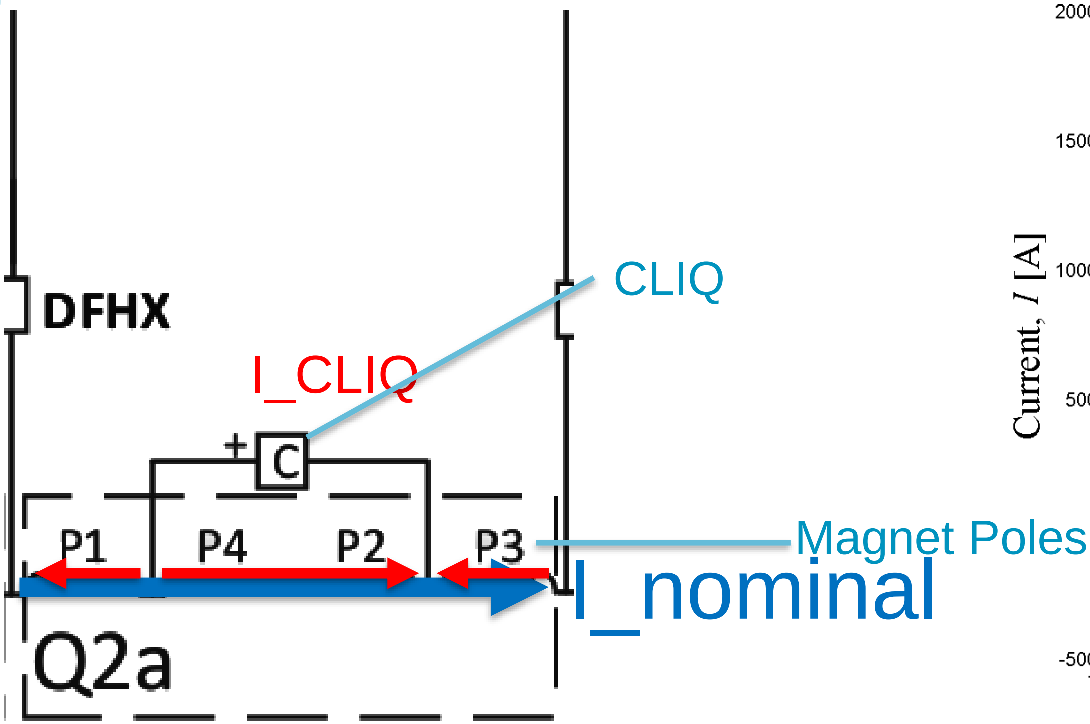
- CLIQ – a new type of quench protection system
- Discharges 2 kA into magnet coils, heating the whole mass
  - Changes the magnetic field in the beam region
- Current and magnetic field simulations done in STEAM [1]
  - Tool for multi-physics simulations – see reference for more info
- Effect on beam simulated in MAD-X*

* Optics: HLLHCV1.2: lhc_hllhc12_round

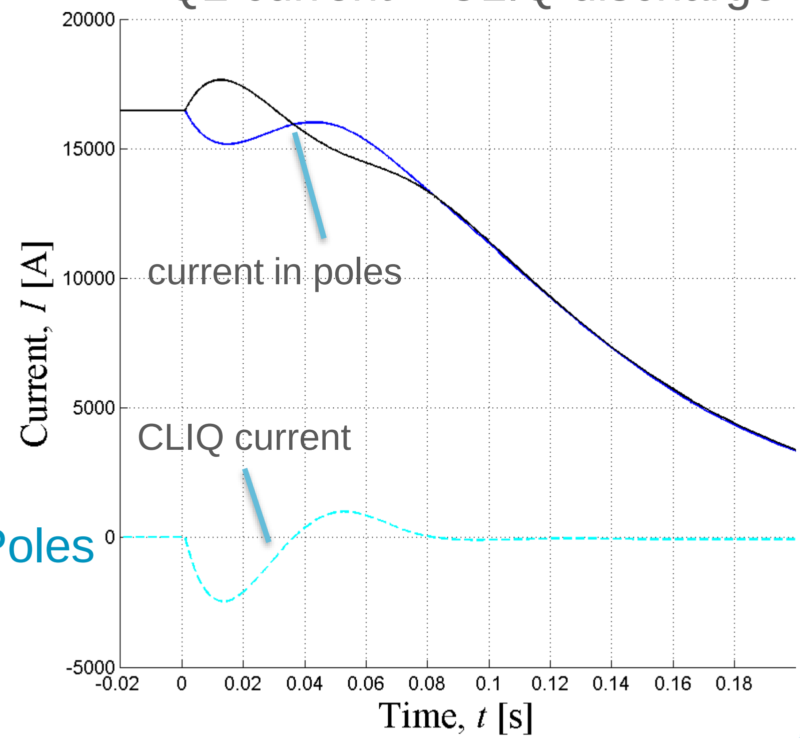
[1] L. Bortot et al. "A Consistent Simulation of Electrothermal Transients in Accelerator Circuits." *IEEE Transactions on Applied Superconductivity* 27.4 (2017): 1-5.

CLIQ – Coupling Loss Induced Quench

- Capacitor discharges current in magnet circuit
- 2 kA of current going into the magnet coils – imperative to study its criticality
- Poles P3 and P1 see lower current
- Poles P4 and P2 see higher current
- Heat is deposited in the copper matrix via inter-filament and inter-strand coupling losses, causing a quench

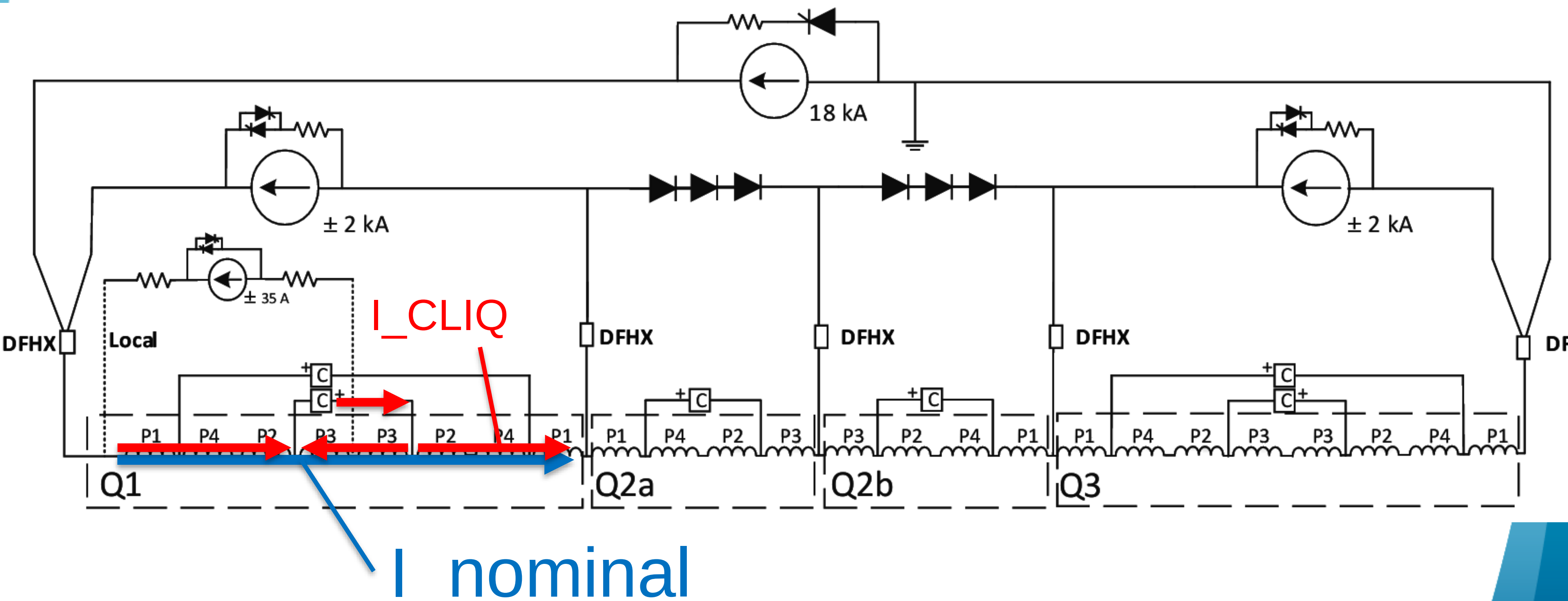


Q2 current – CLIQ discharge



CLIQ in Triplet (Q2 and Q3)

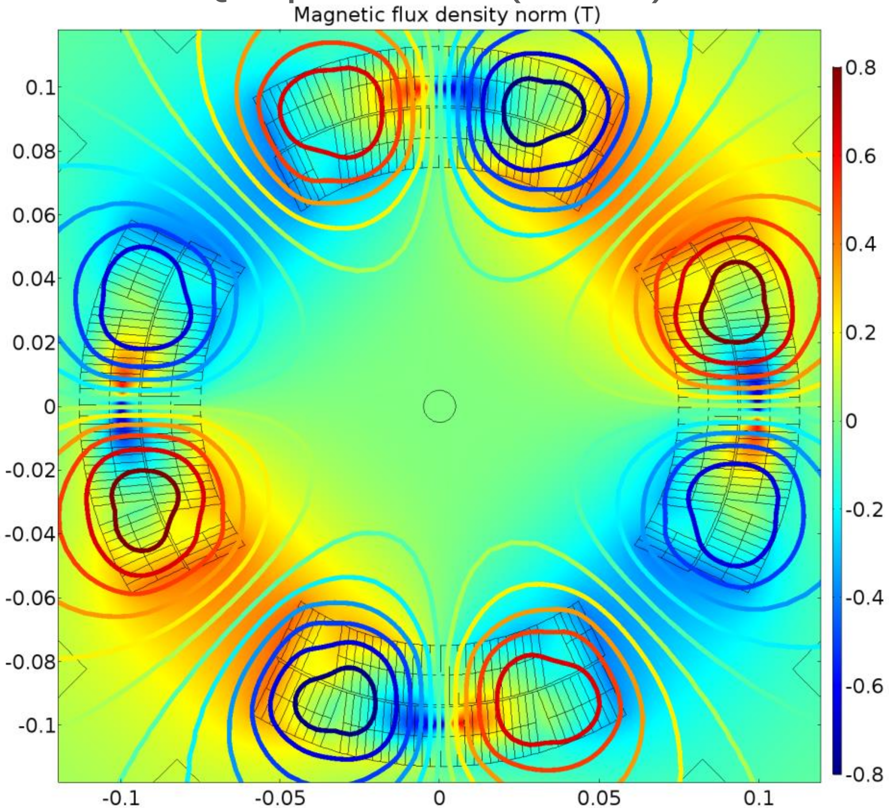
- Differences in connection, different magnetic fields.
- Q1 electrically same as Q3
- From optics, Q3 has larger beta function, and is thus more critical
- **Q2**: **Symmetric** discharge *(opposite poles, same current change)*
- **Q1/Q3**: **Asymmetric** discharge *(one pole increased current, three poles decreased)*



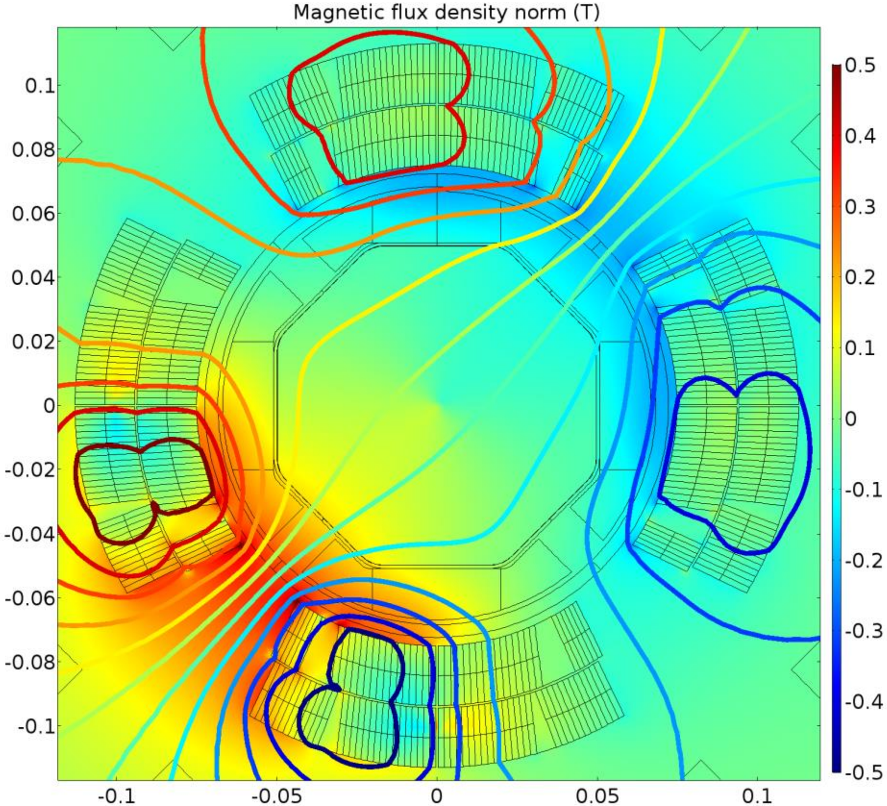
CLIQ in Triplet (Q2 and Q3)

- Differences in connection, different magnetic fields.
- Q1 electrically same as Q3
- From optics, Q3 has larger beta function, and is thus more critical
- **Q2**: **Symmetric** discharge -> **Quadrupolar** field -> **beta beating**
- **Q1/Q3**: **Asymmetric** discharge -> **Skew dipolar** field -> **orbit excursion**

Q2, peak field (12 ms)



Q3, peak field (20 ms)

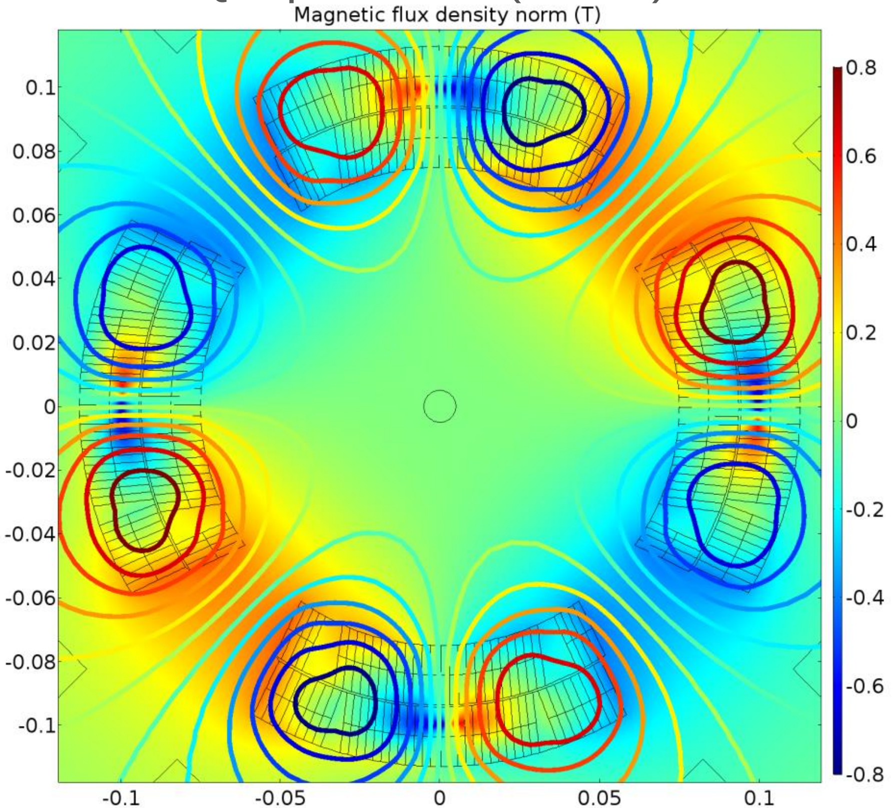


Magnetic Field Decomposition

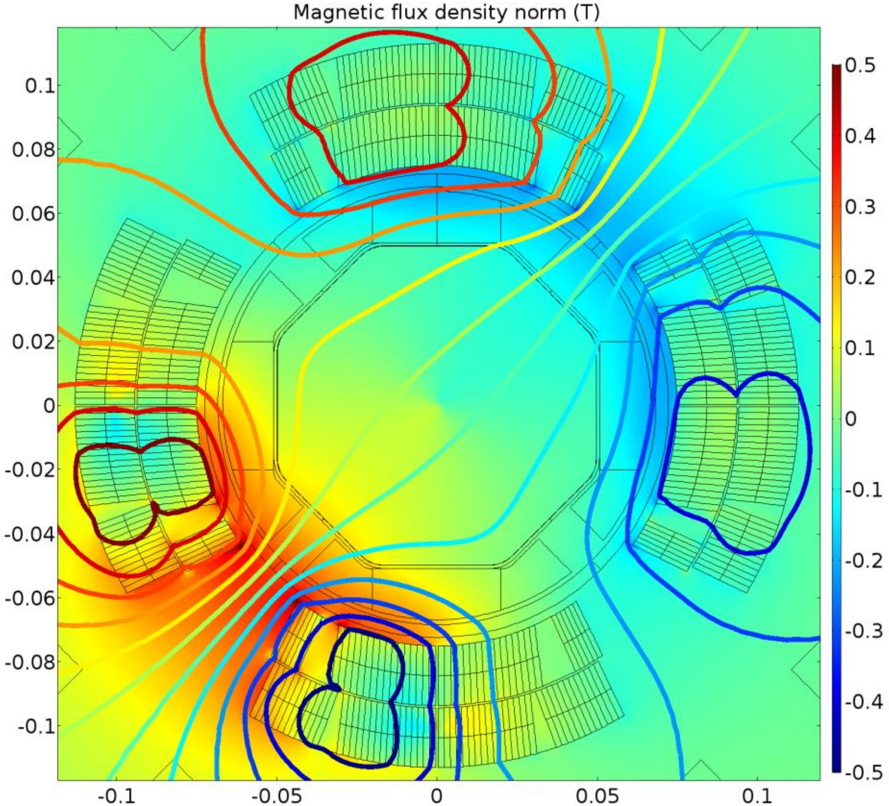
	Bn [mT]	Bs [mT]	dB/dx [mT/m]	dB/dxx [mT/m^2]
Q2	~0	~0	229	203
Q3	47.5	47.5	49.6	27000

- CLIQ current approximated by a sinus until first peak (12 / 20 ms)

Q2, peak field (12 ms)

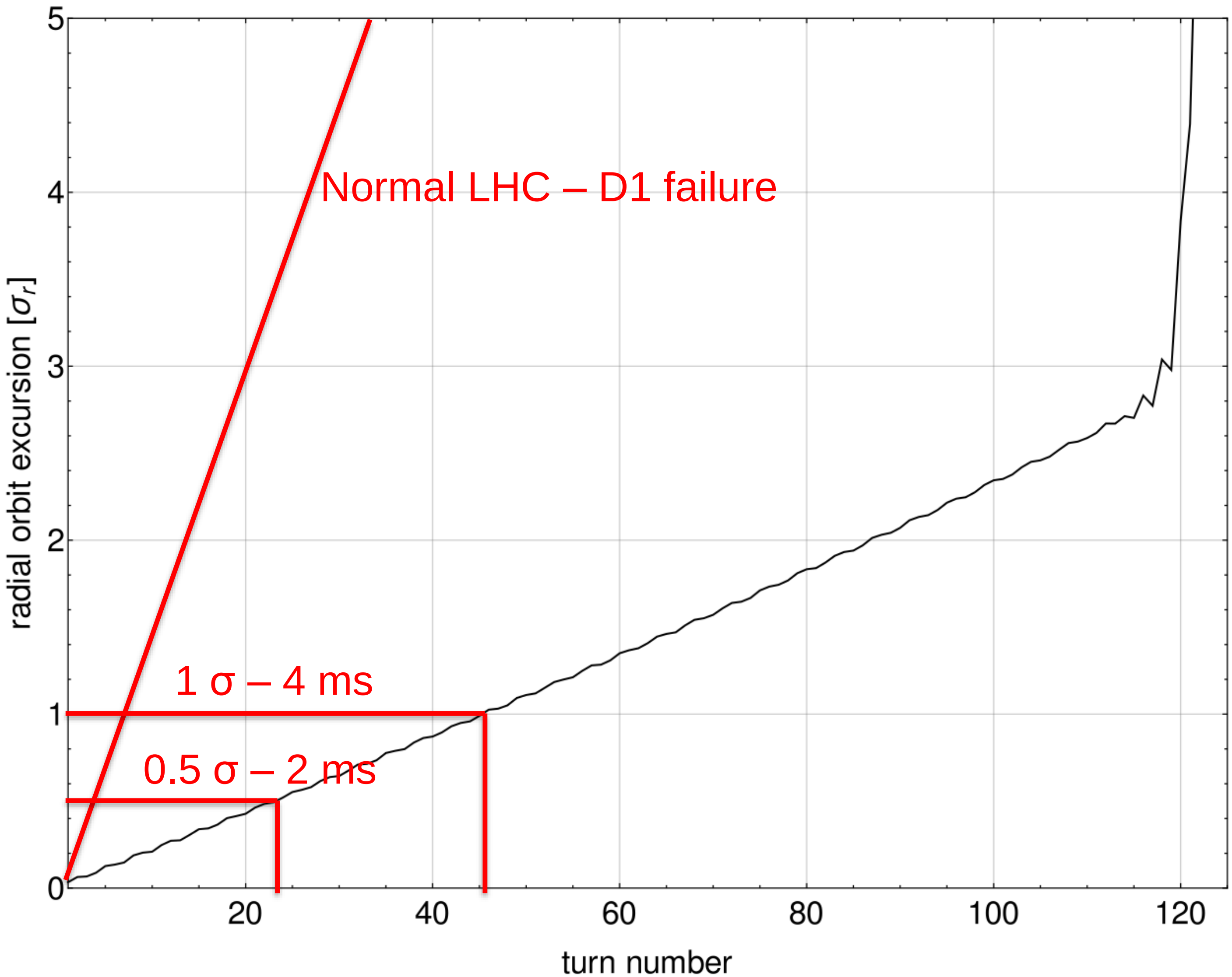


Q3, peak field (20 ms)



Q3 – orbit excursion

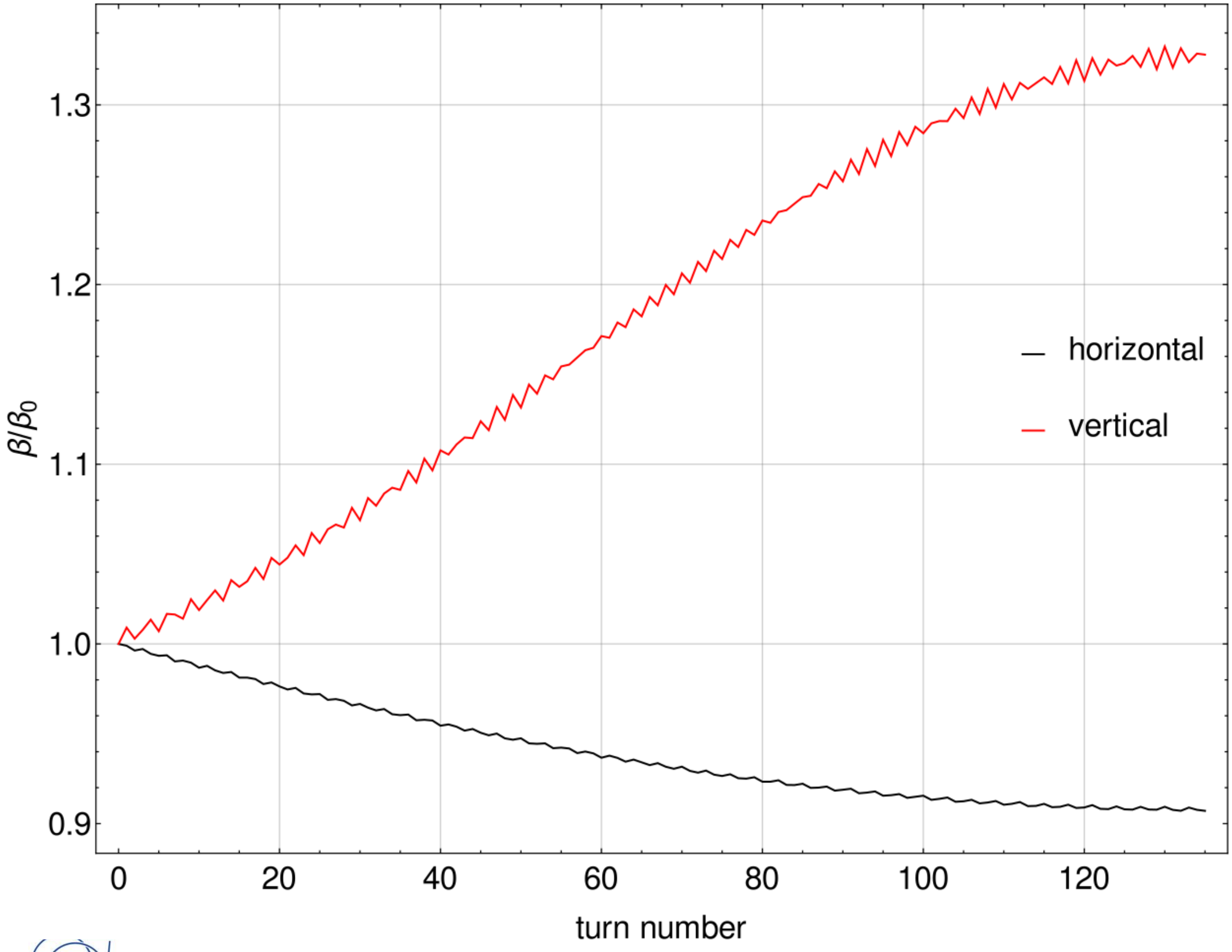
- Beam lost shortly after turn 100



Time [ms]	I_CLIQ [A]	Relative current change
2	310	1.9%
4	620	3.8%

Q2 – Beta Beating

- Beta beating of ~30 % at the TCPs



Conclusions

- **CLIQ in Q3:** Orbit changes too quick to rely on QPS, should be interlocked against:
  - **0.5 σ** after ~2 ms (~**310 A** of CLIQ current, i.e. **1.9%** current change)
  - **1 σ** after ~4 ms (~**620 A** of CLIQ current, i.e. **3.8%** current change)
- Could also be mitigated by changing the connection scheme, but must be weighted against magnet protection constraints

- **CLIQ in Q2:** Beta beating of ~30 % at TCPs. Need be verified with collimation how critical this is for the passive protection

Q3 – Compensating case

- Maximum orbit offset for compensating connection scheme (Q3a and b) smaller than baseline scheme; beam is not lost into aperture
- Less losses on skew collimators