# CLIQ and Quench Heater firing: effect on the beam

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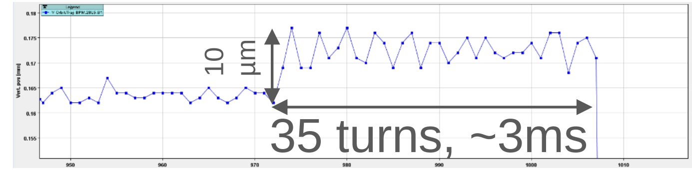
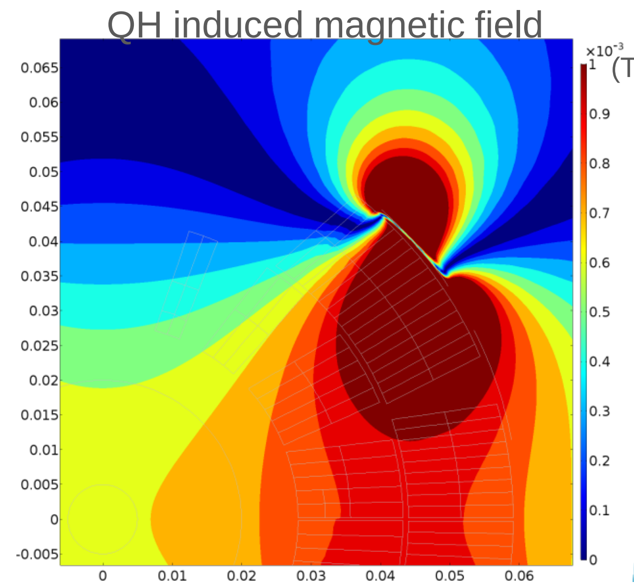
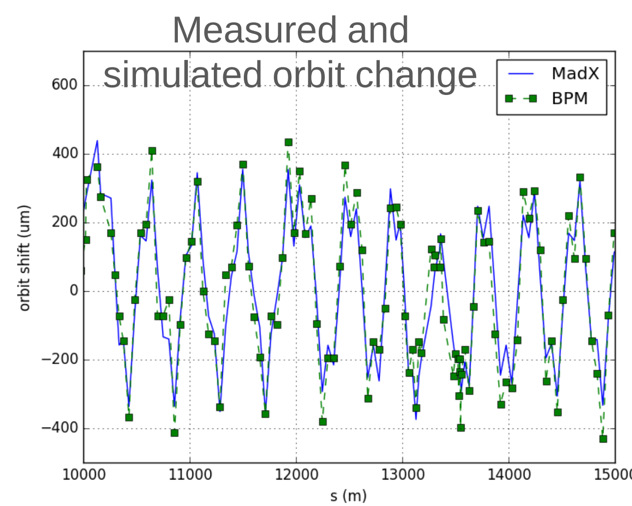
7th HiLumi meeting – Madrid - 15 November 2017

# From observation to LHC tests

- In 2016, before **dumps with quenches**: fast (<1 turn) but small **vertical orbit shift** of the LHC beam.
- **QH firing** is a potential cause, the **induced magnetic field** was simulated in COMSOL.
- Confirmed in an **LHC test** and fits the MAD-X simulations.

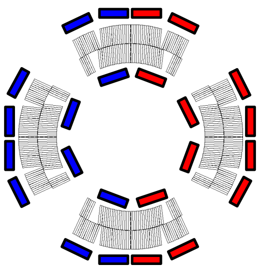


# Simulation results

- The LHC MB is protected by **4 QH strips** powered with **80 A**.
- Some HL-LHC magnets will be protected with up to **24 strips with 134/200 A,** e.g. MQXF:



- An analysis was done for the QH kicks of HL-LHC magnets.

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

kicks > 1.2 σ are dangerous

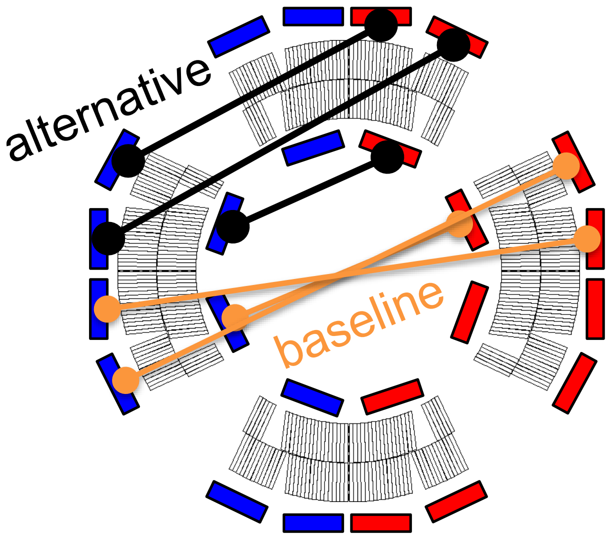
| Magnet | BL (T.m) | β (m) | kick (σ) |
|---|---|---|---|
| MB | 0.01 | 420 | 0.49 |
| MQ | 0.002 | 575 | 0.15 |
| **D1** | **0.008** | **18 km** | **1.98** |
| **D2** | **0.0125** | **5.8km** | **2.44** |
| 11T | 0.02 | 144 | 0.42 |
| **Triplet** w/out IL | **0.11** | **4.5km - 21km** | **28.8** |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

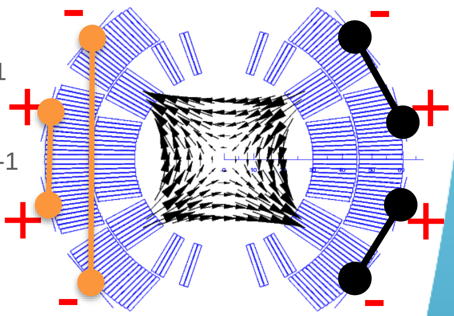
Optics: HLLHCv1.2

**The 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** and are fired at the same time.
- Can be **mitigated** by the triggering causing a dump and delays.
- Remaining failure case: **spurious triggering** of one circuit.
- **Alternative connection schemes** would allow:
  - **reducing the kick** from the Q2b
    - IL QH from 2.4 σ to 1.7 σ
    - OL QH from 1.7 to 1.2 σ
  - having a **quadrupole field** in the 11 T-dipole instead of a dipole kick

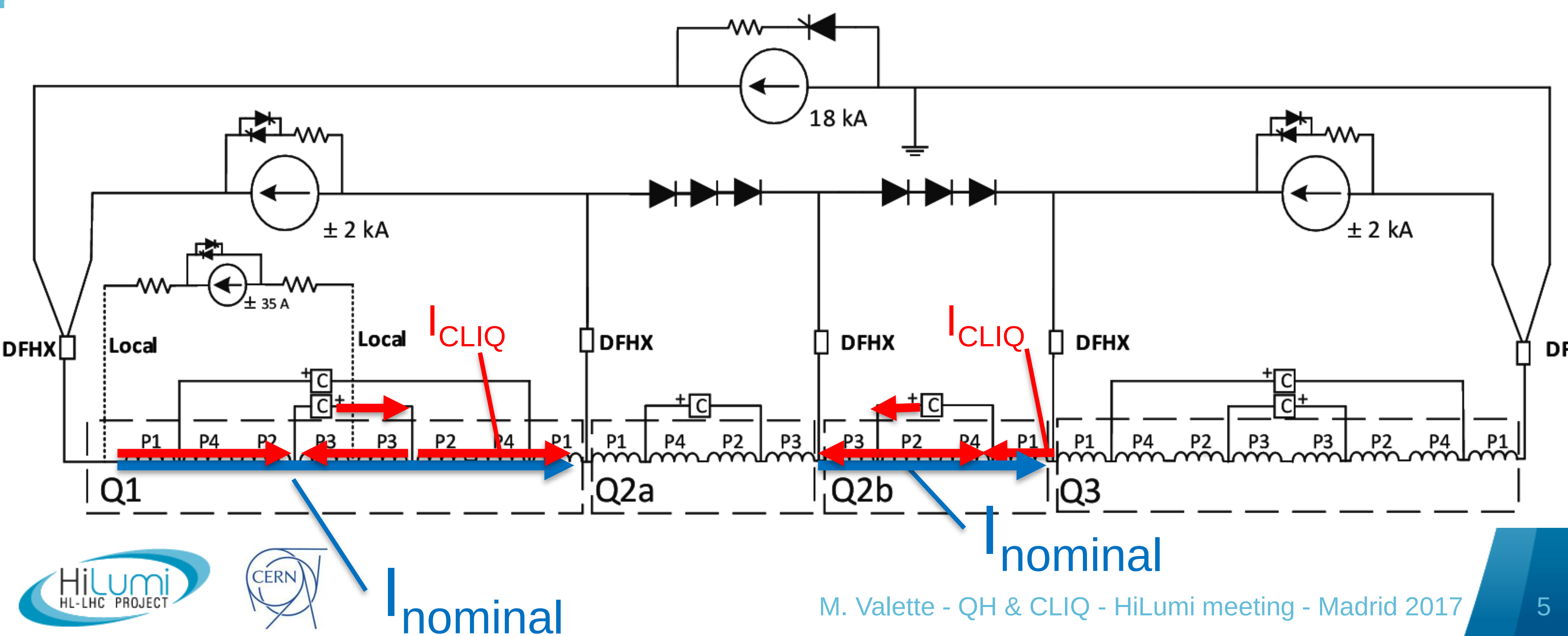



Courtesy S. Izquierdo

# Spurious CLIQ discharge

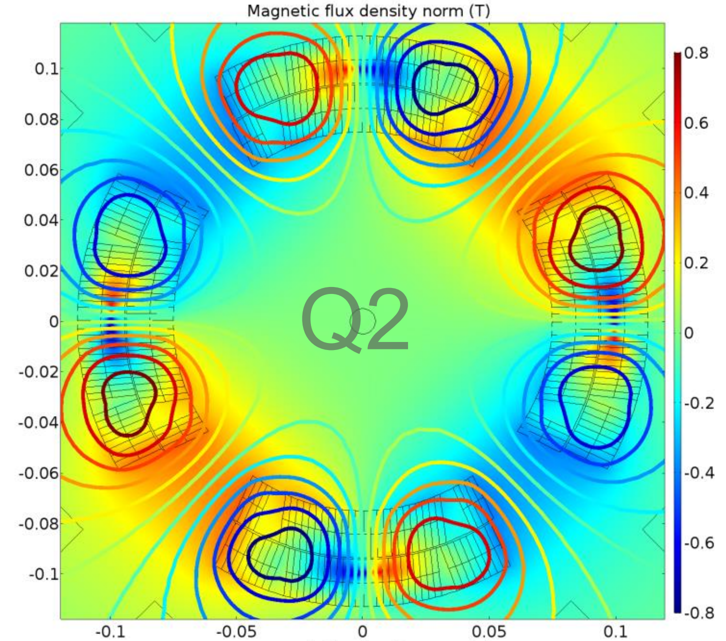
- The triplet will also be protected by **CLIQ**.
- **2 kA** discharged **in the coils** if fired.
- Same considerations as for the QH: **spurious firing** as the main failure case.

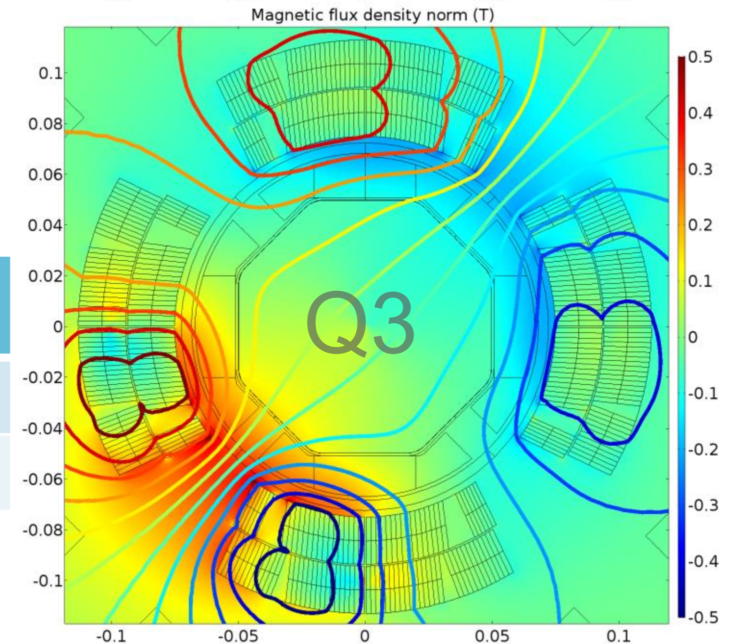


# Magnetic Field Simulations

- A **CLIQ discharge** in one of the **Q2** magnets would **reduce its focusing gradient**.
- Due to **asymmetry**, a discharge in a **Q1 or Q3** magnet would have **dipole components** in the beam area.

| | Bn [mT] | Bs [mT] | $\frac{dB}{dx}$ [$mT.m^{-1}$] | $\frac{d^2B}{dx^2}$ [$mT.m^{-2}$] |
|---|---|---|---|---|
| **Q2** | **~0** | **~0** | **229** | **203** |
| **Q3** | **47.5** | **47.5** | **49.6** | **27000** |

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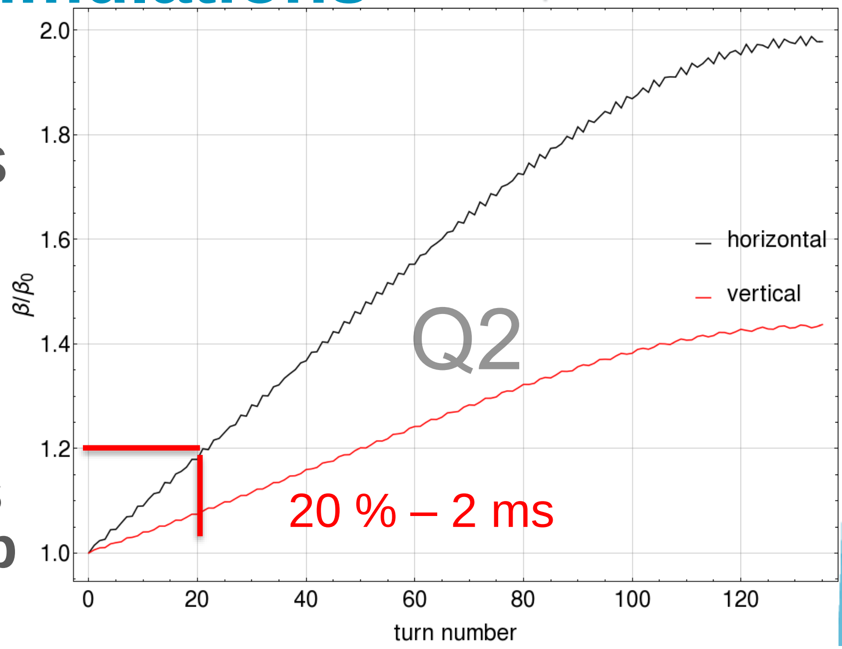
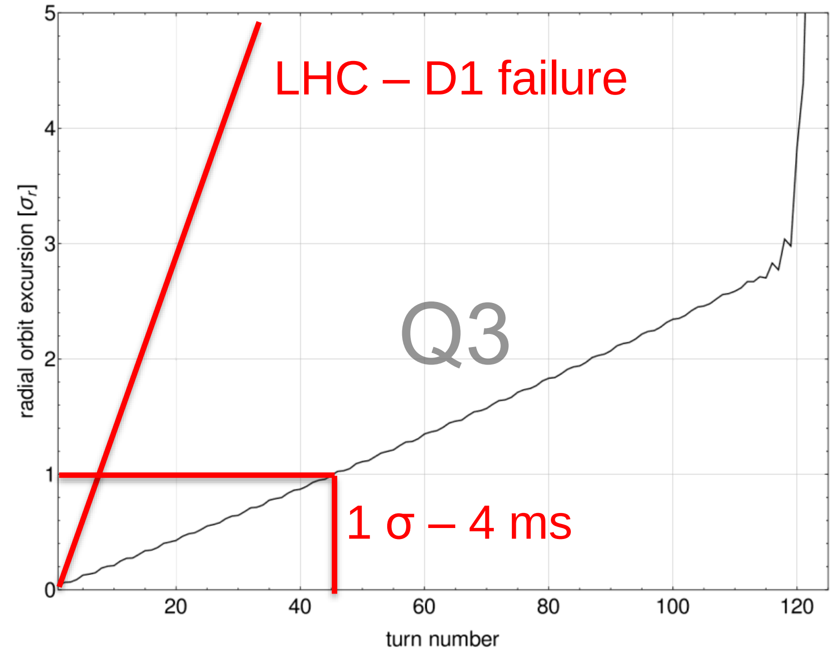
# Beam Tracking Simulations

- Q2: focusing change causes **β-beating** up to 20% in 2.2 ms @TCPs and TCTs:
  - The **TCTs would not be exposed** (√2 increased beam size vs 5.2 σ retraction)
  - Similar β-changes @TCDQ does **not expose the TCTs to a dump**
  - **TCPs** would see **large losses**
- Q3: **fast dipole kick** to the beam of **1 σ in 4 ms**.
- A beam **dump must be triggered** when a CLIQ unit fires.

Optics: HLLHCv1.2




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

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# Conclusions & outlook

- **Kicks from QHs** in most **HL-LHC superconducting magnets** were calculated: **very large kicks** are to be expected for the **triplets and IPDs**.
- This effect can be **mitigated** by **faster interlocking** on QH firing.
- **Spurious firing** can not be interlocked against and is very fast (<1 turn for MB)
  - **Additional mitigation:** lower the dipole kick of QH by using **different connection schemes**.
  - **Extra reaction time** might come **from long cables** to the power supply for MQXF, to be studied.

- **CLIQ discharge in Q2:** slowly rising β-beating, no exposure of TCTs to be expected, but **large losses in IR7**.
- **CLIQ discharge in Q3:** Orbit changes too fast to rely on QPS.

=> It is necessary to **interlock the CLIQ units** on discharge.

***Thank you for your attention,***
***any questions ?***

| MQXFB. | A2L1 | B2L1 | A2R1 | B2R1 | A2L5 | B2L5 | A2R5 | B2R5 |
|---|---|---|---|---|---|---|---|---|
| TCP.C/D6L7.B1 | **1.62 / 0.98** | **1.72 / 0.98** | **0.91 / 1.33** | **0.85 / 1.39** | **1.72 / 0.88** | **1.81 / 0.80** | **0.84 / 1.72** | **0.73 / 1.82** |
| TCDQA.C4R6.B1 | **1.35 / 0.89** | **1.42 / 0.82** | **0.98 / 1.63** | **0.98 / 1.72** | **1.77 / 0.99** | **1.86 / 1.02** | 0.83 / 1.24 | 0.71 / 1.29 |
| TCTH/V.6L1.B1 | 0.96 / 1.07 | 0.96 / 1.17 | 1.07 / 0.96 | 1.16 / 0.96 | **1.71 / 1.20** | **1.80 / 1.40** | 0.86 / 0.66 | 0.77 / 0.64 |
| TCTPH/V.4L1.B1 | 0.93 / 1.10 | 0.93 / 1.22 | 1.08 / 0.90 | 1.18 / 0.90 | **1.69 / 1.22** | **1.77 / 1.43** | 0.87 / 0.60 | 0.78 / 0.58 |
| TCTPH/V.4L2.B1 | **1.87 / 0.85** | **2.00 / 0.74** | **0.84 / 1.78** | **0.72 / 1.89** | 0.59 / 1.13 | 0.56 / 1.27 | 1.19 / 0.87 | **1.39 / 0.87** |
| TCTH/V.6L5.B1 | **1.68 / 1.21** | **1.78 / 1.42** | 0.89 / 0.58 | 0.81 / 0.55 | 0.95 / 1.10 | 0.95 / 1.21 | 1.08 / 0.95 | 1.17 / 0.94 |
| TCTPH/V.4L5.B1 | **1.71 / 1.20** | **1.81 / 1.40** | 0.88 / 0.61 | 0.80 / 0.59 | 0.93 / 1.12 | 0.93 / 1.25 | 1.09 / 0.90 | 1.19 / 0.90 |
| TCTPH/V.4L8.B1 | 0.89 / 0.85 | 0.89 / 0.75 | **1.10 / 1.74** | **1.22 / 1.85** | **1.63 / 0.94** | **1.71 / 0.92** | **0.88 / 1.42** | **0.81 / 1.49** |

| MQXFB. | A2L1 | B2L1 | A2R1 | B2R1 | A2L5 | B2L5 | A2R5 | B2R5 |
|---|---|---|---|---|---|---|---|---|
| TCP.C/D6R7.B2 | 0.84 / 0.54 | 0.72 / 0.51 | **1.87 / 1.21** | **1.99 / 1.44** | 0.94 / 0.63 | 0.91 / 0.61 | **1.46 / 1.18** | **1.52 / 1.36** |
| TCDQA.C4L6.B2 | 0.84 / 0.64 | 0.73 / 0.62 | **1.85 / 1.19** | **1.97 / 1.38** | 1.01 / 0.54 | 1.05 / 0.50 | 1.21 / 1.20 | **1.25 / 1.41** |
| TCTH/V.6R1.B2 | 1.07 / 0.95 | 1.16 / 0.95 | 0.96 / 1.08 | 0.95 / 1.18 | 0.88 / 0.57 | 0.80 / 0.55 | **1.66 / 1.19** | **1.74 / 1.39** |
| TCTPH/V.4R1.B2 | 1.08 / 0.91 | 1.18 / 0.90 | 0.94 / 1.10 | 0.94 / 1.22 | 0.87 / 0.61 | 0.79 / 0.58 | **1.68 / 1.19** | **1.77 / 1.37** |
| TCTPH/V.4R2.B2 | 0.96 / 0.56 | 0.94 / 0.53 | **1.42 / 1.21** | **1.49 / 1.43** | **1.16 / 1.39** | **1.33 / 1.45** | 0.71 / 0.96 | 0.70 / 0.95 |
| TCTH/V.6R5.B2 | 0.87 / 0.66 | 0.78 / 0.64 | **1.76 / 1.18** | **1.87 / 1.37** | 1.08 / 0.95 | 1.17 / 0.95 | 0.96 / 1.07 | 0.95 / 1.16 |
| TCTPH/V.4R5.B2 | 0.88 / 0.61 | 0.79 / 0.59 | **1.73 / 1.19** | **1.84 / 1.40** | 1.09 / 0.90 | 1.19 / 0.90 | 0.93 / 1.10 | 0.93 / 1.21 |
| TCTPH/V.4R8.B2 | 0.88 / 0.81 | 0.79 / 0.81 | **1.73 / 1.13** | **1.84 / 1.28** | 1.09 / 1.23 | 1.20 / 1.28 | 0.93 / 1.01 | 0.93 / 1.05 |