ECR for BETS Upgrade

C. Bracco on behalf of WP14

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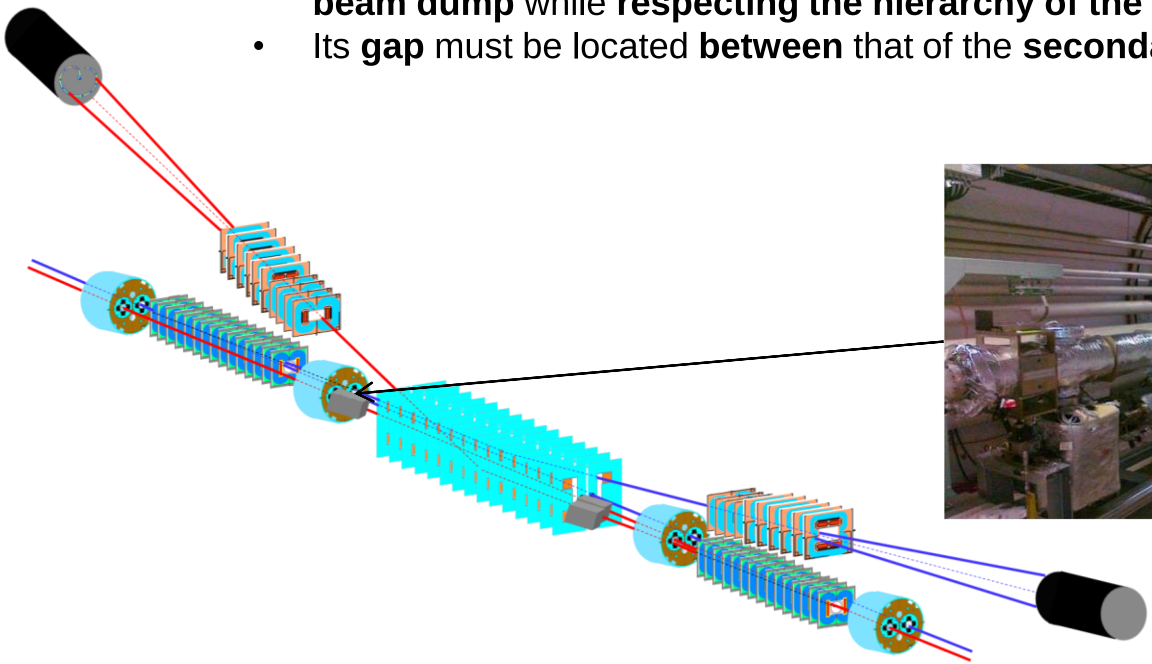
05/04/2024 - MPP

What is the TCDQ

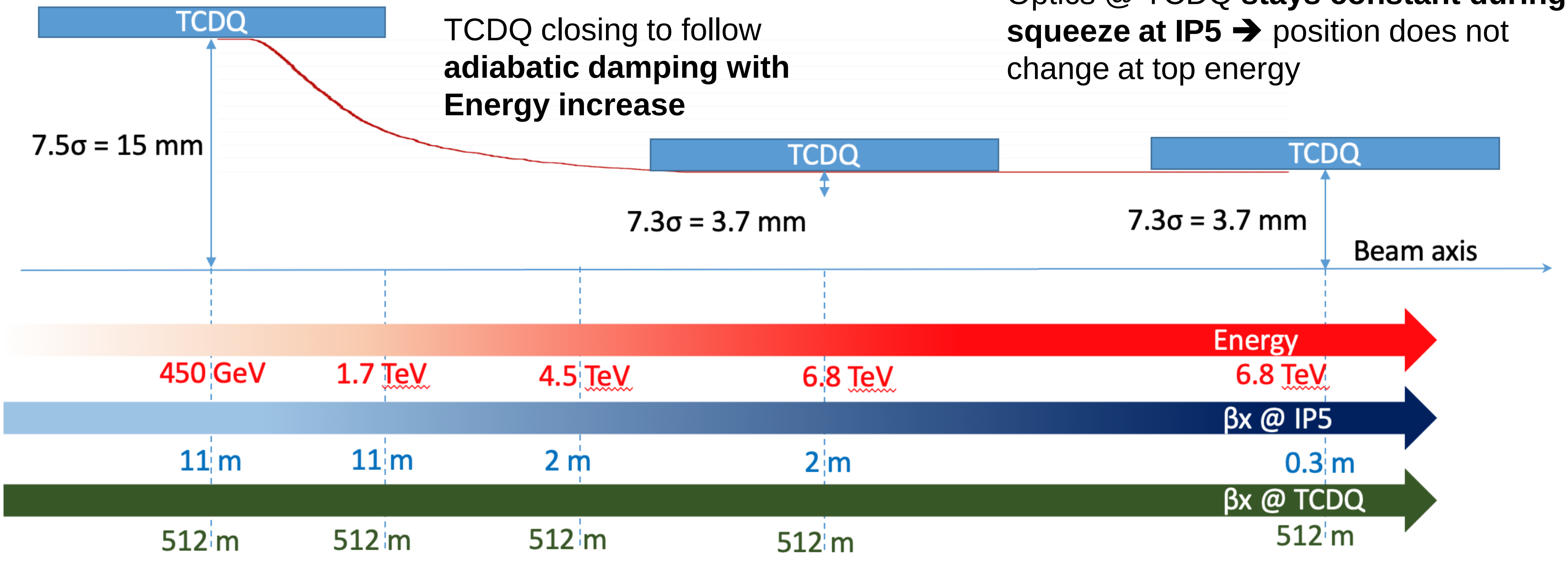
- **TCDQ** is a **mobile single-side diluter** installed **upstream** of the **superconducting quadrupole** magnet **Q4** located after the interaction point in **IR6**.
- The aperture of the TCDQ has to be set to **protect the Q4** in case of an **asynchronous beam dump** while **respecting the hierarchy of the full collimation system**
- Its **gap** must be located **between** that of the **secondary and tertiary collimators**.



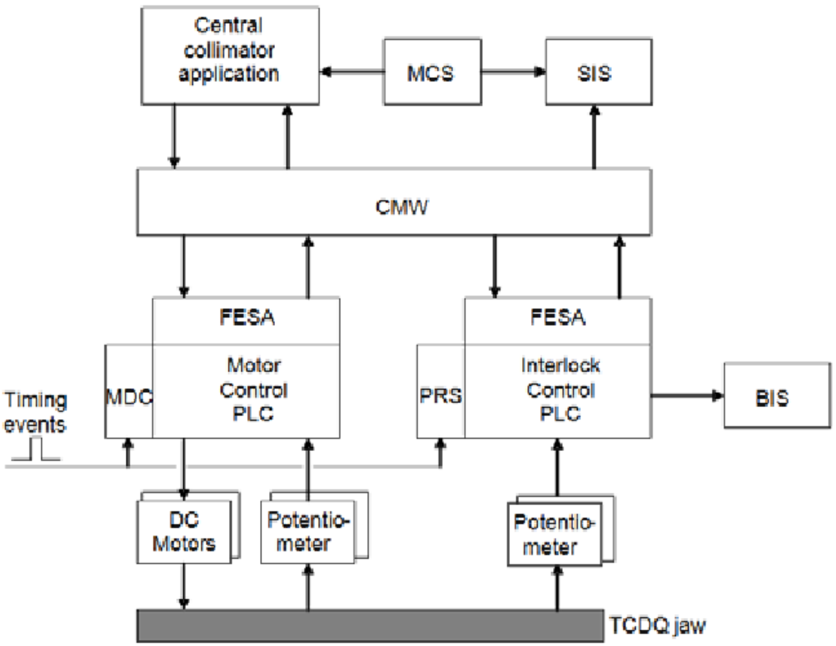
TCDQ Movement During Machine Cycle Now

TCDQ closing to follow **adiabatic damping with Energy increase**

Optics @ TCDQ **stays constant during squeeze at IP5** ➔ position does not change at top energy



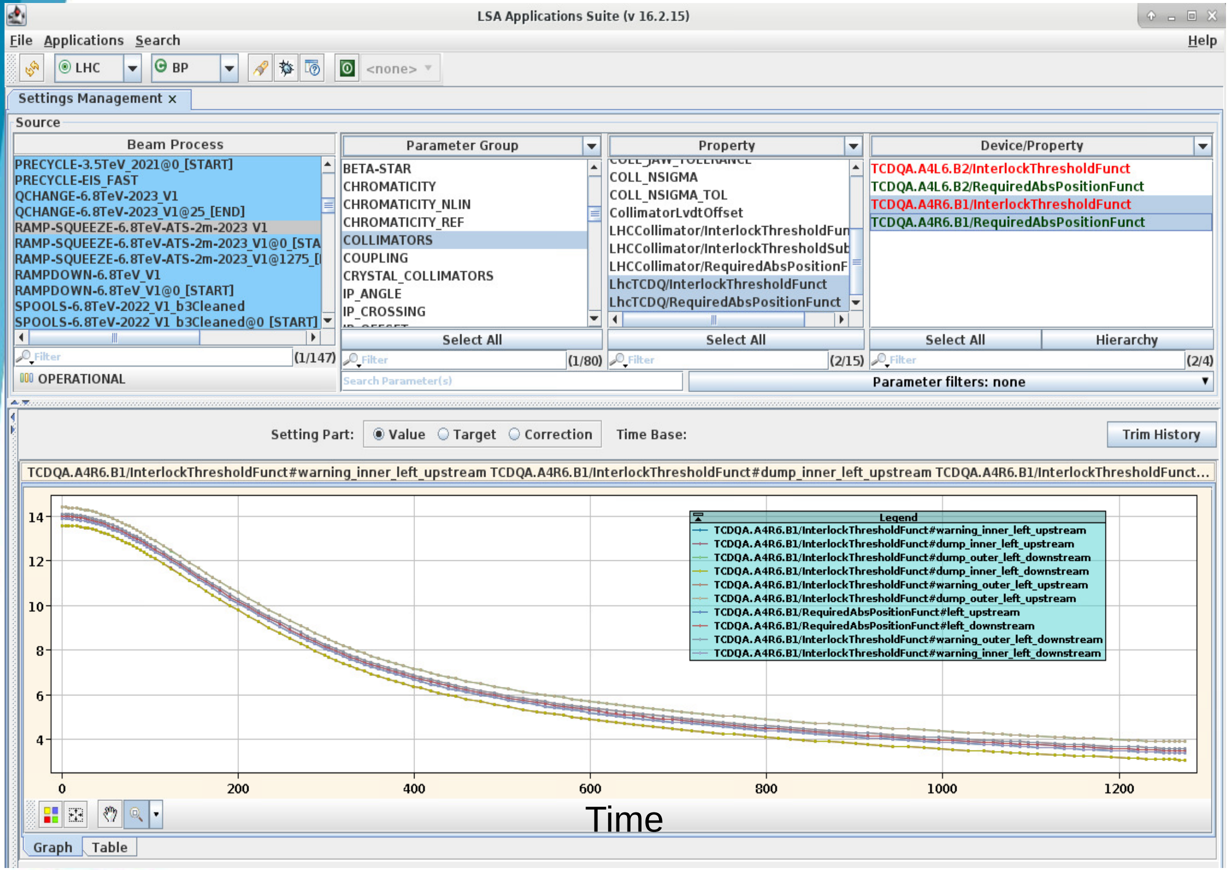
TCDQ Control System



- The TCDQ control system consists of **two separate functional units based on independent PLCs**: the **Motor Drive and Control** (MDC) and the **Position Readout and Survey** (PRS).
- The **MDC** controls the **positioning systems** and its **protection logic**. The position is acquired by **potentiometers** used as **feedback** within the **positioning regulation loops**.
- The **PRS surveys the relative position of the jaw w.r.t. interlock limits** defined by operational conditions and **managed as machine critical settings** (MCS). It is **connected** to the **LHC Beam Interlock System** (BIS) in order to request a **beam dump** in case of an **incorrect position**.

*https://cds.cern.ch/record/1194053

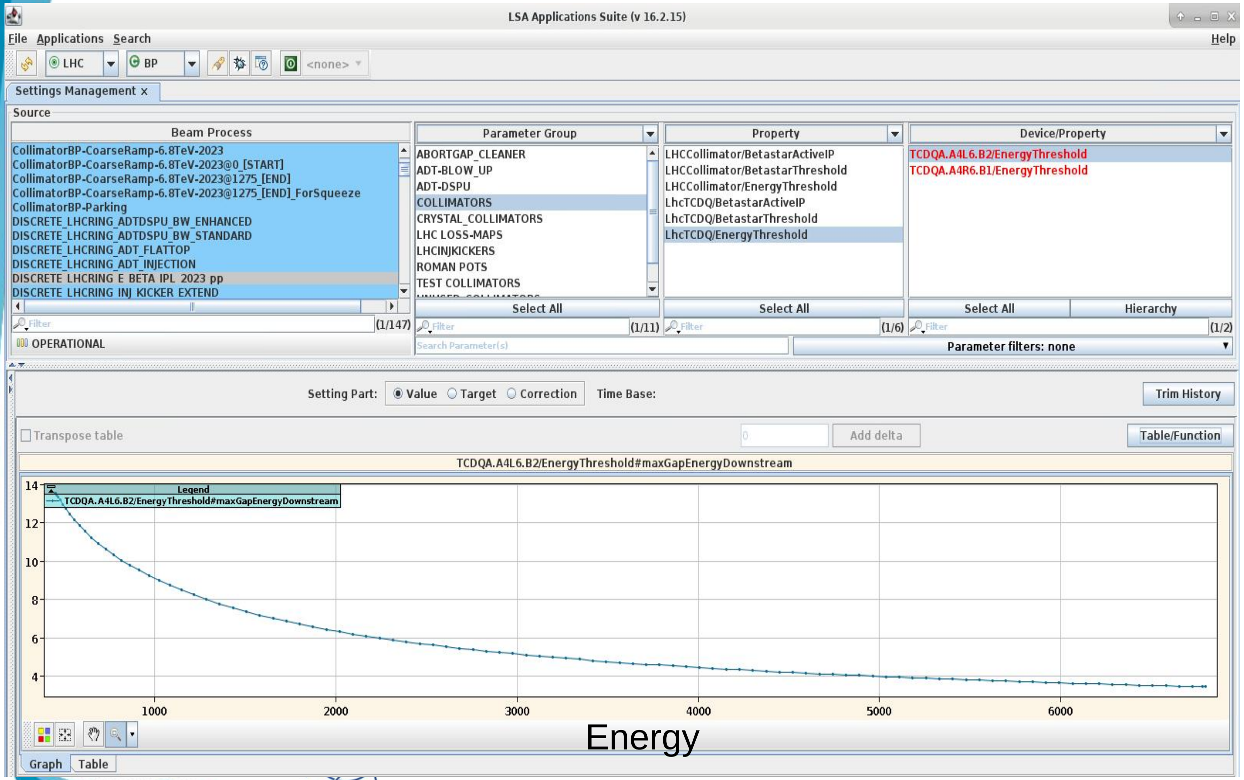
Interlocks (Completely Equivalent to Collimators)



Interlock on position:

- **Functions of time** in LSA database (each corner position, **warning** and **dump thresholds**)
- Sent via **timing event**

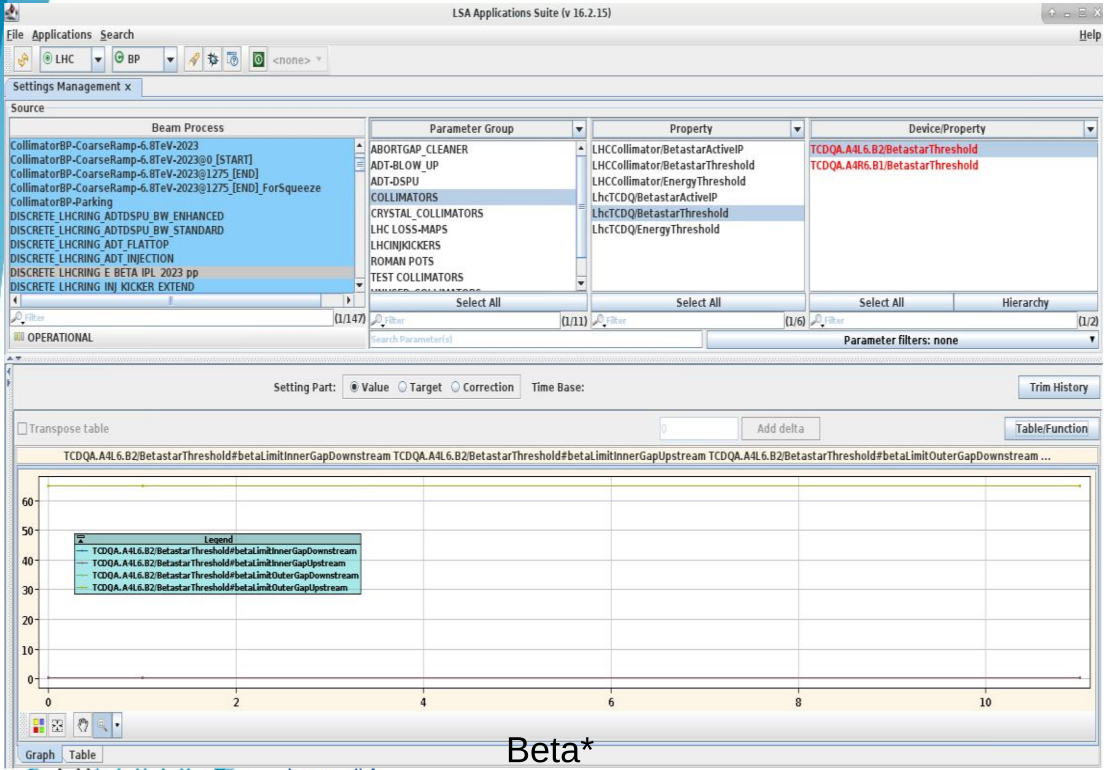
Interlocks (Completely Equivalent to Collimators)



Beam process always resident (timing independent)

- **Discrete settings**: table with **Outer threshold for Gap vs Energy** checks in LSA
- **PRS** receives **Energy from the SMP** with **1Hz** frequency
- If no Energy received for **3 s ➔ maximum energy** taken by default (most conservative case)

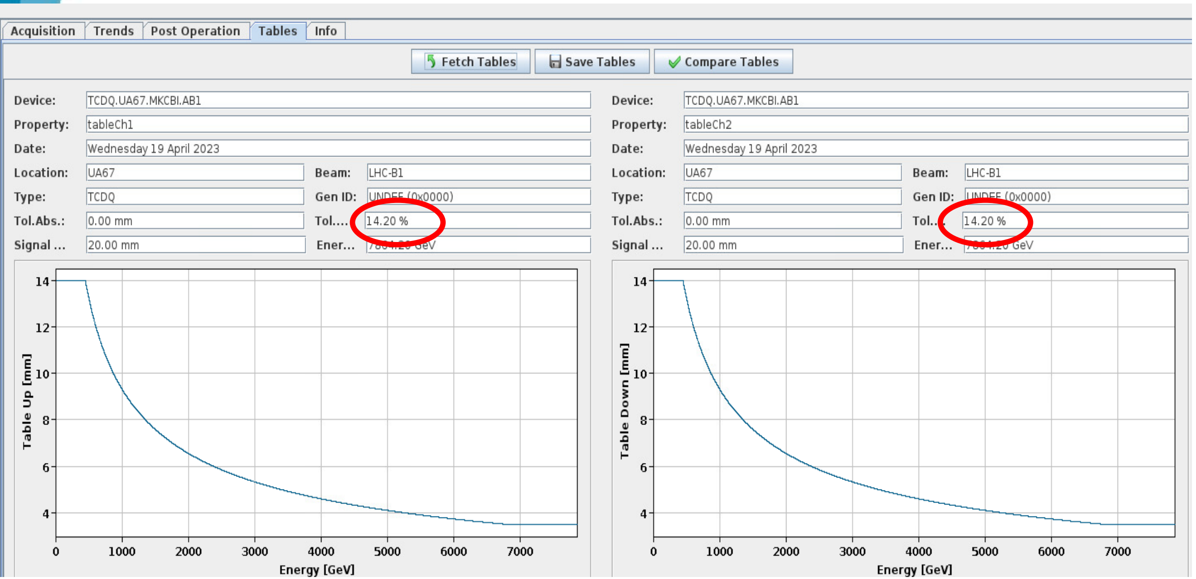
Interlocks (Completely Equivalent to Collimators)



Beam process always resident

- **Discrete settings**: Table with **Outer/Inner threshold** for **Gap vs β*** checks in LSA
- **PRS** receives **β*** **from SMP** with **1Hz** frequency
- If no **β*** received for **3 s ➔ minimum β*** taken by default (most conservative case)
- **Energy thresholds more relaxed** to allow for movements at fixed energy (as done for TCTs). Presently **β*** limits for TCDQ fully open

BETS TCDQ



Due to criticality of correct positioning of TCDQ to ensure the protection of the machine in the rare event of an asynchronous beam dump ➔ additional **fully independent verification of TCDQ position with respect to the energy done by the Beam Energy Tracking System (BETS) using an additional potentiometer**

- **Discrete settings**: Table with **Outer/Inner threshold for Gap vs Energy** checks (value in table ± fixed %*) ➔ locally **uploaded into BETS cards** (access needed)
- It **prevents any movement of the jaw outside thresholds at fixed Energy ➔ not compatible with movements during the β* squeeze or levelling**

* Defined in order to have 1 σ at top energy

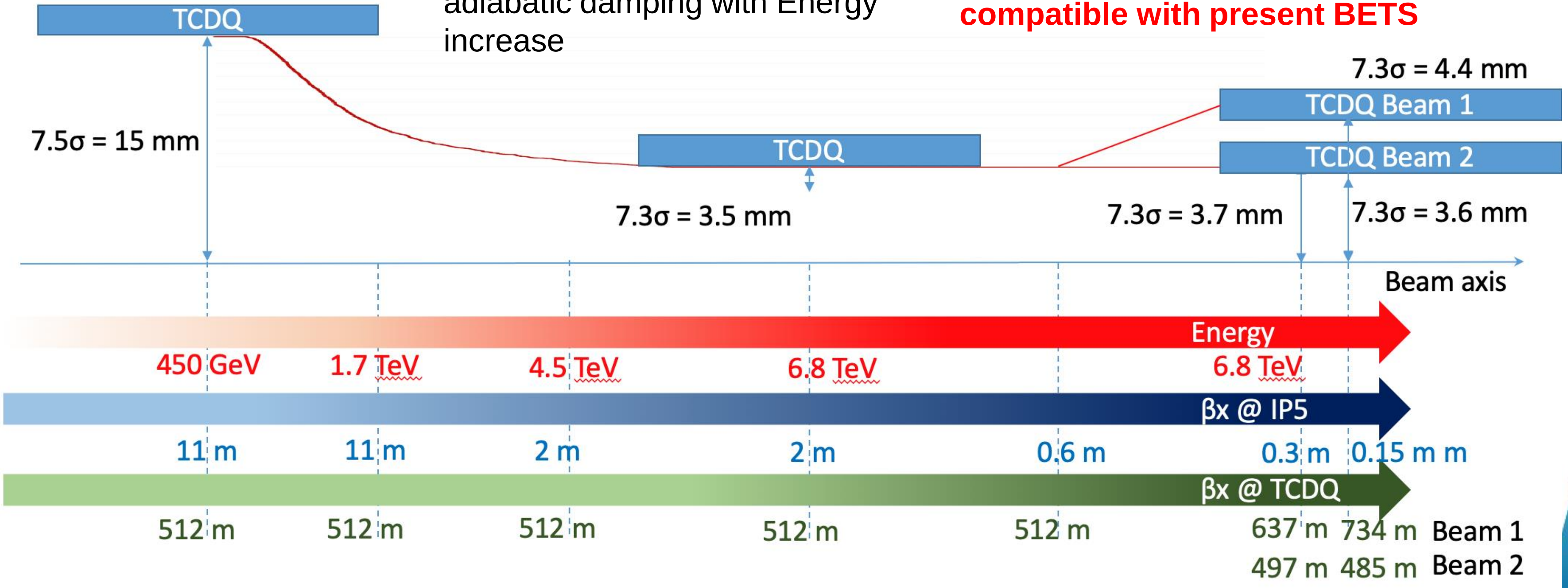
Reason for Change

- The **HL-LHC baseline** foresees to operate the machine at **minimum values of β* = 15 cm** while the initial performance ramp-up baseline does not foresee the need of pushing β* beyond a value of 20 cm already in Run 4.
- Initial Run 3 experience with increased bunch intensity, following the LIU upgrade, has however shown an **important risk of bunch intensity limitations in the HL-LHC era due to electron cloud and heat load.** In view of this potential limitations, **pushing β* to the nominal value of 15 cm or even beyond is an important risk mitigation for the performance ramp-up baseline already in Run 4.**
- Moreover, a **large variety of β*** is needed (during flat top, collapse, lumi ramp from cryo, lumi levelling, end of levelling etc.) during commissioning and regular physics operation.
- The **optics in Point 6 is very constrained** and **dependent on the MQTL magnets** (Q6) that are **limited in current and sometimes show detraining**.
- It becomes **particularly challenging to keep the β_x-function at the TCDQ unchanged for all the required optics scenarios**. **The actual β* squeeze in IP5 with HL-LHC ATS optics affects the β_x-function at the TCDQ, especially for Beam 1, already for β* < 60 cm**

TCDQ Movement During Machine Cycle for β*<20cm

Optics @ TCDQ varies during squeeze at IP5 ➔ **position changes at top energy, different for Beam 1 and Beam 2. Not compatible with present BETS**

TCDQ closing to follow adiabatic damping with Energy increase



BETS Upgrade

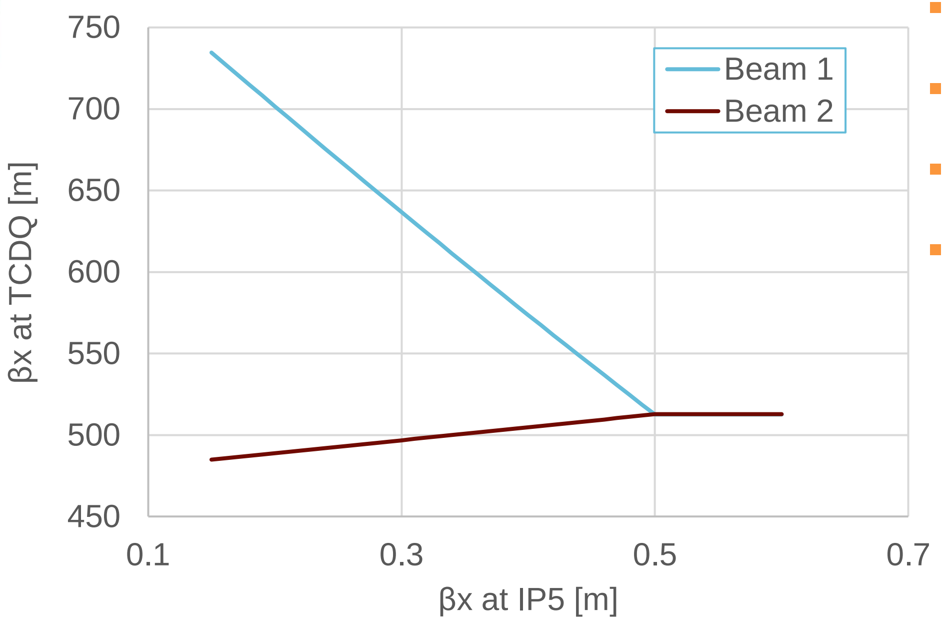
- The BETS will be **upgraded during LS3** in order to receive, **from the SMP**, either **the β* in IP5 or the β at the TCDQ (preferred option) as calculated by the SIS**.
- The SIS β* signal is presently **already used as a critical MP parameter** for the collimator gap interlock, the "Safe Stable Beam Flag" declaration and the collimator BPM SIS interlock.
- After extensive discussions with several experts (ABT, OP and MPE) experts, it was agreed that the **use of the β* signal calculated by the SIS and transmitted by the SMP perfectly fulfils the safety level required to the system.**
- To further enhance the reliability, the **SIS could provide the β* to the SMP via two separate processes onto separate boards**. The final implementation will be the scope of a detailed functional specification to be written.
- The **logic** will then be **modified to ensure compatibility of the change of TCDQ position with β* in IP5 at fixed energy.**
- The **movement of the TCDQ during levelling** will likely be orchestrated by the **levelling tool as implemented and used already for the TCTs** in the present LHC run.

New BETS Logic

- A typical operational year of an LHC run includes both **nominal proton physics** and **special optics** (Van Der Meer, ions, etc.). It is assumed that, at a defined energy, the **position in σ units of the TCDQ is fixed and that the βx at the TCDQ changes only for the proton physics squeeze and β* levelling** while it stays constant for all the other optics.
- Electronics should be modified to allow loading two tables:
  - The standard Energy-Position table
  - A new β*@IP5-Offset@TCDQ table or βx@TCDQ-Offset@TCDQ table

Energy [TeV]	TCDQ Position [mm]	β@IP5 [m]	Offset@TCDQ [mm]	βx@TCDQ [m]	Final value in BETS [mm]
0.45	15	11	0	512.618	15
7	3.696	0.60	0	512.618	3.696
7	3.696	0.49	0.022	518.603	3.718
7	3.696	0.25	0.526	669.001	4.222
7	3.696	0.24	0.547	675.496	4.243
7	3.696	0.23	0.567	682.006	4.263
7	3.696	0.22	0.587	688.531	4.283
7	3.696	0.21	0.608	695.07	4.304
7	3.696	0.20	0.628	701.622	4.324
7	3.696	0.19	0.648	708.189	4.344
7	3.696	0.18	0.668	714.769	4.364
7	3.696	0.17	0.688	721.362	4.384
7	3.696	0.16	0.708	727.967	4.404
7	3.696	0.15	0.728	734.586	4.424

New BETS TCDQ Logic – Option 1



- Unique relation between β_x at IP5 and at the TCDQ
- Possible using β_x at IP5 (already available for SMP)
- **Final position and thresholds given by sum of position plus offset from the two tables**
- The possibility of switching ON and OFF the addition of the offset via software should be allowed and protected by an RBAC role. This would guarantee full compatibility when operating with special optics where the β_x at the TCDQ doesn't vary during the squeeze but, for a certain β*@IP5, could differ from the one of the proton physics optics (VdM, ions, etc.). Adequate additional checks should be implemented to ensure that the correct operational conditions and settings are applied when operating with unsafe beam. Even in case the switch ON/OFF accidentally not applied when needed ➔ beam dump if outside thresholds (availability more than MP risk)

New BETS TCDQ Logic – Option 2

- Further flexibility and improved protection would be gained if possible to use, as a **direct input for the BETS, the β_x at the TCDQ with the relative fixed offset**.
- In this case, the only constraint would be to **keep the position in σ units** of the TCDQ unmodified, for a defined pair of Energy and β_x, while the logic would be valid for any optics and any β_x@TCDQ/β*@IP5 relation.
- This would remove the need of the “offset ON/OFF” option and any associated risk.
- This is the preferred option as it allows different optics cycles to be implemented throughout an operational year (for instance cycle for production and cycle for machine studies).
- Feasibility to calculate and use β_x@TCDQ to be assessed

New BETS TCDQ Reliability

- The most critical failure scenario is when the following two conditions appear simultaneously within a fill:
  1. An **asynchronous beam dump** with a critical beam happens. By specification, this is expected to happen once per year.
  2. The **TCDQ is not correctly positioned**. Based on experience, this possibly happened only once in more than ten years of operation (**and detected by the BETS**).
- In the **worst case** the **combination of these two conditions leads to damage** that results in **a recovery time of weeks to months ➔ <1 failure in 1000 years as reliability target**.
- Based on this target and the assumption of one asynchronous dump per year, one can calculate an upper bound on the frequency of the second condition (TCDQ incorrectly positioned) to occur.
- Assuming **400 LHC fills** with critical beam per year, calculations show that the **TCDQ is allowed to be in the wrong position for a single fill up to 0.4 times per year.**
- **For the TCDQ to move to the wrong position 0.4 times a year without dumping the beam, both its positioning system and the energy & ß* cross-checks would need to fail simultaneously**. The **upper limit** on the **tolerable probability for the cross-check to fail ~66 % per fill.**
- Given that the cross-check is based on a reliable implementation and an XPOC check in parallel, the **actual probability** for the cross-check to fail is expected to be **lower than 1 % per fill**. Hence, it is considered that the **proposed solution is sufficiently reliable** when systematic and common mode failures can be excluded.
- All calculations assume **no systematic nor common mode failures**.

New BETS TCDQ Reliability

- Having **2+1 independent “paths**” for positioning and cross-checking allows to avoid systematic and failure modes:
- ***The TCDQ positioning*** is done via a PLC that determines the TCDQ position from an optics-LUT (look-up-table) taking timing signals as input.
- ***The BETS cross-check*** determines the target position based on optics-LUTs taking the energy and the ß* as input. It is separated in one LUT relating energy with position and another LUT relating ß* with position offset. If the actual TCDQ position is outside the defined threshold margins, the BETS dumps the beam. These thresholds in the position of the TCDQ are applied in both directions to cover both cases of the ß* position offset being ON when it should be OFF and vice versa.
  - **Almost all failure scenarios of the TCDQ positioning or the cross-check will result in a beam dump**.
  - One critical but extremely unlikely not leading to a beam dump is when the TCDQ positioning drives the TCDQ into a wrong position that happens to be in line with a **failure in the cross-check leading it to calculating the very same wrong target position**. Only possible if **the position error margins are miscalculated and significantly too large**. Any TCDQ position would be within the allowed error margin. Solved having a simple and robust way to define the thresholds + additional XPOC check should catch this problem.
- **An independent check implemented in XPOC** (or SIS) to independently verify that the TCDQ was at the right position at the time of dump.
- Finally, a **full re-validation of any changes in the optics LUTs should avoid that the same but wrong TCDQ target positions are being shared between the 2+1 paths.**

Conclusions

The functional specification outlines upgrades to the Beam Energy Tracking System (BETS) for the TCDQ (single-jaw mobile diluter) within the Large Hadron Collider (LHC). These upgrades aim to **enhance operational flexibility and protection against asynchronous beam dumps**. The document emphasizes the critical importance of precise TCDQ positioning to prevent damage and minimize downtime. Proposed enhancements include **adapting the BETS to allow TCDQ position adjustments based on the β* at IP5 or β_x@TCDQ, as calculated by the SIS, during the squeeze at fixed energy, offering more flexibility in optimizing optics configurations**. Additionally, considerations for BETS reliability and minimizing failure scenarios are addressed, ensuring robust protection against potential damage from beam dumps. Overall, these upgrades aim to improve operational efficiency and reliability within the LHC system.

EDMS approval: comments

Accepted by ZERLAUTH Markus (ATS-DO) Created on 2024-03-25, 11:02

OK, thanks for editing this detailed functional spec. A few comments already included in this version.

Accepted by VAN TRAPPEN Pieter (SY-ABT) Created on 2024-03-25, 16:10

OK some minor comments given by mail

Accepted by SECONDO Raffaello (TE-MPE) Created on 2024-03-26, 10:42

Thanks a lot for the very detailed documents.
Some notes sent by email separately.
A couple minor ones given here:
- The "CISV" is renamed "CISU" (User) in the future, to be renamed in chapter three.
- The BETS and PRS will receive the Beta and Energy from the SMP at a rate of 1 kHz, assuming WhiteRabbit connection is available, the readout can then be downsampled to 1 Hz on the BETS/TCDQ side.

Seen by WOLLMANN Daniel (TE-MPE) Created on 2024-03-28, 16:44

Thanks a lot for preparing this functional specification for the BETS TCDQ Upgrade for HL-LHC.

Page comments

Page 3

MQTL: I would propose to remove the statement `sometimes show detraining¿, as term of detraining is not well defined and is already covered b the previous statement that the current in the MQTL is limited.

Page 10 Safe stable beam flag

Chapter 4: The `safe beam flag¿ and is not derived from the beta* values provided by the SIS, but directly by the SMP based in BCT readings and distributed via GMT and in the future via WRT. So I think, it should be removed here.

Page 11

Chapter 5: `The chance of this failure should be minimised by having a simple and robust way to define the thresholds¿ ¿> I would propose to add that the definition of the thresholds / threshold setting should also be verified with automatic tools to identify these type of failures as early as possible.

Already done today, thresholds are calculated from settings defined in LSA. Dry ramps then allow to check settings and limits plus coherency with position and energy thresholds, what more?