Operational Limits from Intercepting Devices

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Outlines

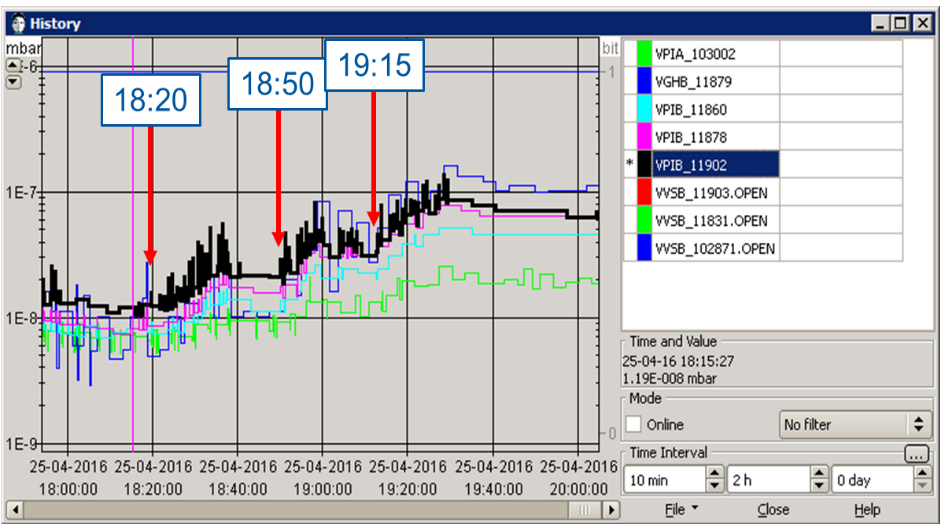
- 2017 intensity limits from intercepting devices SPS→ LHC injection → LHC extraction (robustness and transmission):
  - SPS dumps, beam stoppers, collimators and protection elements
  - TL collimators
  - LHC injection protection
  - LHC extraction protection

- Conclusions

Maximum Intensity from SPS

- Achievable beams

	ppb	Norm. Emittance [mm mrad]	# bunhces
25 ns	1.3e11	2.7-2.8	288
BCMS	**1.3e11**	**1.4**	**288**
80 bunches	1.2e11	2.8	240 (320*)



- High pressure recorded at the TIDVG#3 on April 25th 2016 ➔ leak identified inside the TIDVG shielding ➔ limit SPS intensity to:
  - 96 LHC-type bunches
  - 2.2e13 ppp for FT (4-6e11 residual protons dumped per cycle.)
  - No high intensity MDs or HiRadMat

* 10% higher brightness than ultimate LHC ➔ Ok (t.b.c). MKI Flattop to be adapted accordingly (if possible!!)

Possible 2017 Scenarios

	Advantages	Disadvantages
Scenario 1 (new TIDVG#4 installed)	1. Designed to relief operational constraints of TIDVG#3 (risk of melting Al) 2. Allow LHC plus full fixed-target physics, MDs & HiRadMat	1. New dump concept 2. Large number of screws 3. Outgassing/conditioning time also with beam (probably comparable to TIDVG#3)
Scenario 2 (present TIDVG#3 kept)	No delays	1. Current operational limitations remain valid 2. Higher risk of catastrophic failure during 2017 (2 weeks stop plus NOT ALARA) 3. Conditioning with beam of new one during physics in case of failure
Scenario 3 (refurbished TIDVG#2 reinstalled)	No delays	1. Unknown operational limitations also compared to 2016 2. Possible aperture limitations of SPS
Scenario 4 (TIDVG#4 delayed but baseline)	Same as of Scenario 1	Impact of cold check out if readiness >March 24th

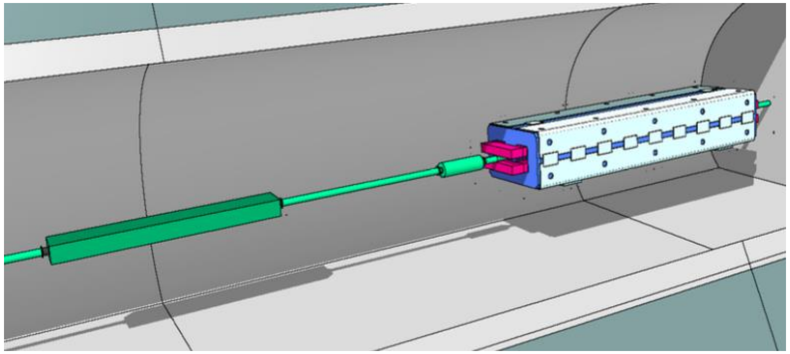
M. Calviani, LMC 02/11/2016

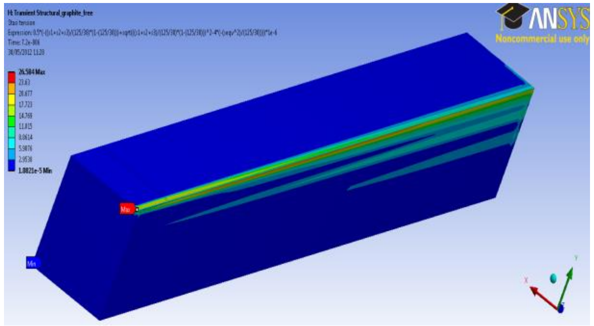
If Scenario 1 OK, any other limitation from intercepting devices?

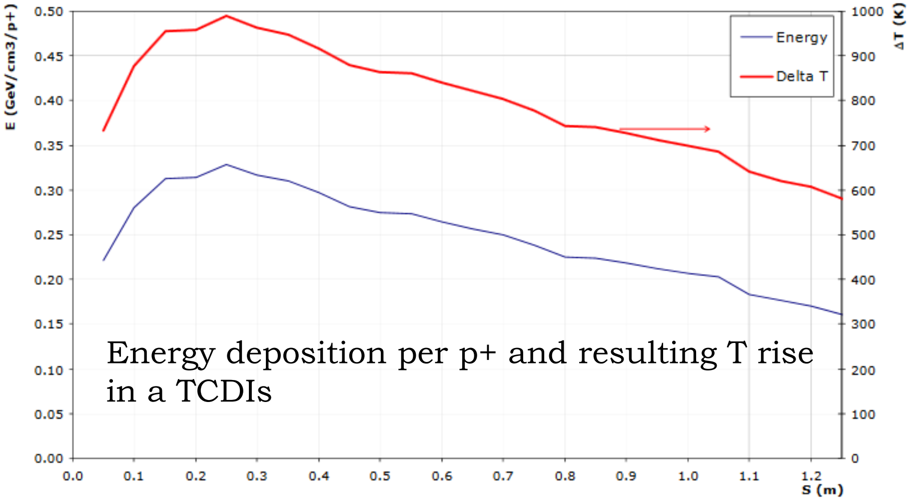
Needed Assessments and Studies

- **Attenuation** to guarantee the **protection of the downstream components** (tanks, masks and magnets)
- **Robustness** of the **protection elements themselves**

FLUKA and **ANSYS** calculations to define the **longitudinal** and **transverse energy density profile ➔ Temperature ➔ stresses** and **strains** distribution

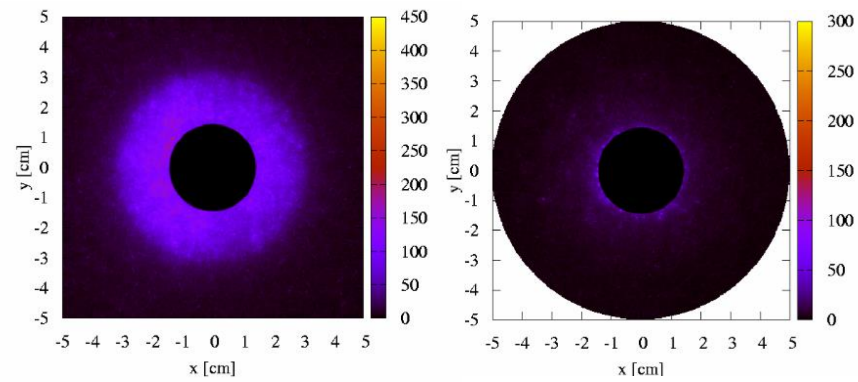






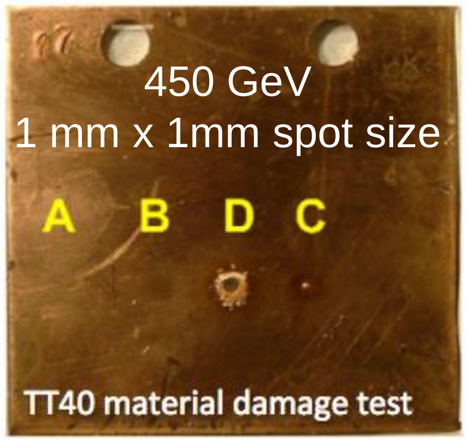
Energy deposition per p+ and resulting T rise in a TCDIs

T rise at Fe shield and in magnet coil and yoke < 100 °C!



Damage Limit and Attenuation Factor

Present assumptions based on simulations and “TT40 material damage test” performed in 2004



Intensity	# protons	Comment
A	1.2e12	No effect
B	2.4e12	Decolouration
C	4.8e12	Melting
D	7.2e12	Fragment ejections

Setup beam flag at 450 GeV: $5x10^{11}$p+ (~1/4 damage limit)

Attenuation factor A:

$$\frac{I_{after}}{\varepsilon_{after}} = \frac{1}{A} \cdot \frac{I_{beam}}{\varepsilon_{beam}}$$

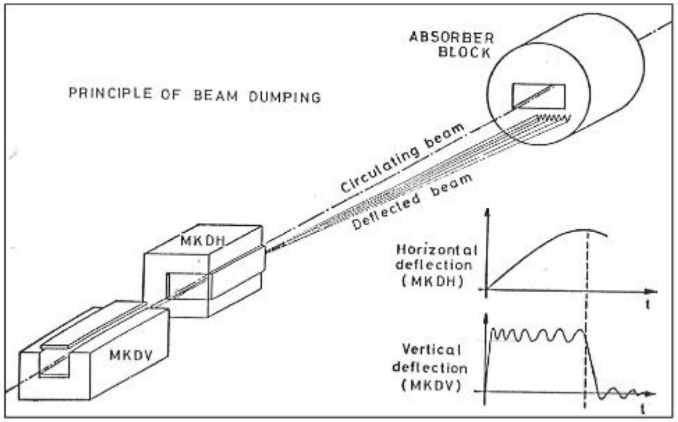
LHC TL collimation system designed to **attenuate impacting intensity to $2x10^{12}$ p+:**

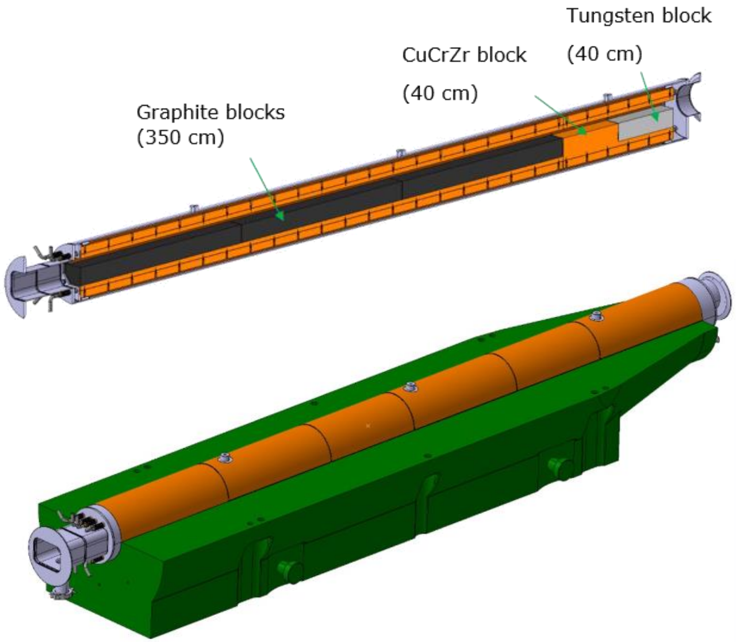
A =20 for ultimate LHC beams ($1.7x10^{11}$ppb, 288 bunches and 3.5 mm mrad normalized emittance)

Intercepting Devices ≤ 450 GeV

Device	Comment	Material
TIDVG#4	Sweep, intensity limitation not brightness. Continuous dumping problematic	Sandwich: Graphite, CuCrZr and W
TIDH	Sweep. Dump at 28 GeV	Al
TBSJ	Injection dump: 26 GeV. Max intensity: 72 (48) bunches per shot	Stainless steel
TED LHC	450 GeV. Continuous dumping problematic. Graphite not in vacuum	Sandwich: Graphite, Al, Cu-Be, Cu
TED HiRadMat	450 GeV	
TBSE	450 GeV. Should never be impacted by the beam but should still survive one shot	
Scraper		Graphite
TIDP	Momentum collimator. n/a	
TPSG	450 GeV: Assume all beam in one spot	Sandwich: graphite <-> CfC, Ti, Inconel
TCDIs	450 GeV.	Graphite
TDI	450 GeV	Sandwich: Graphite and CuCrZr

SPS internal dumps





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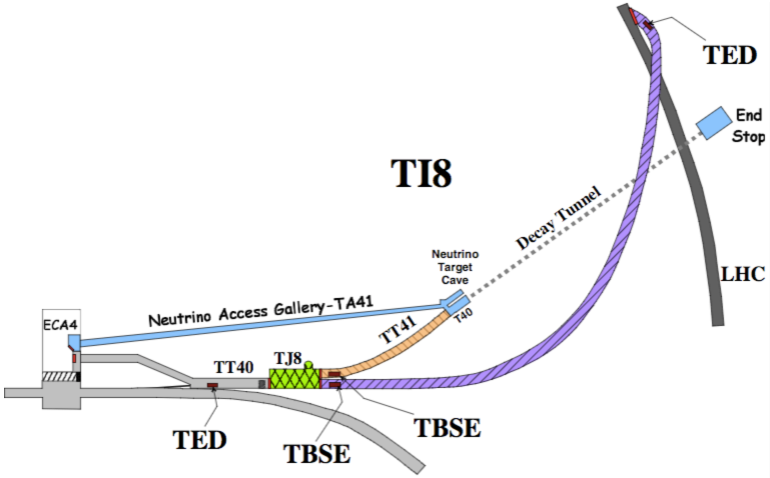
TL dump and stoppers



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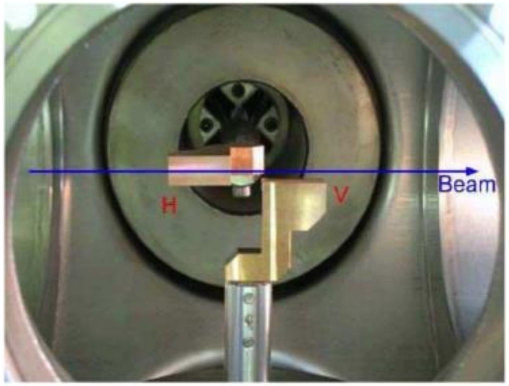
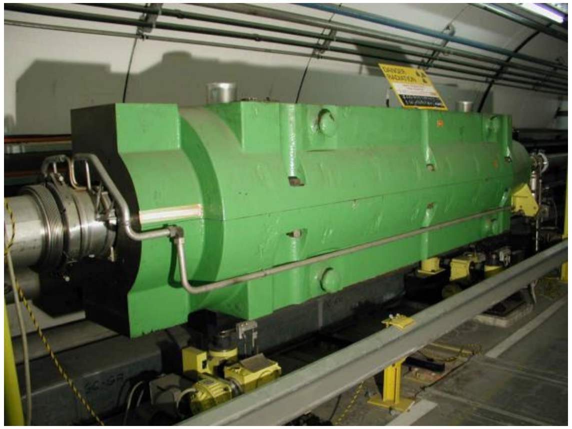
SPS betatron and momentum (TIDP) scrapers





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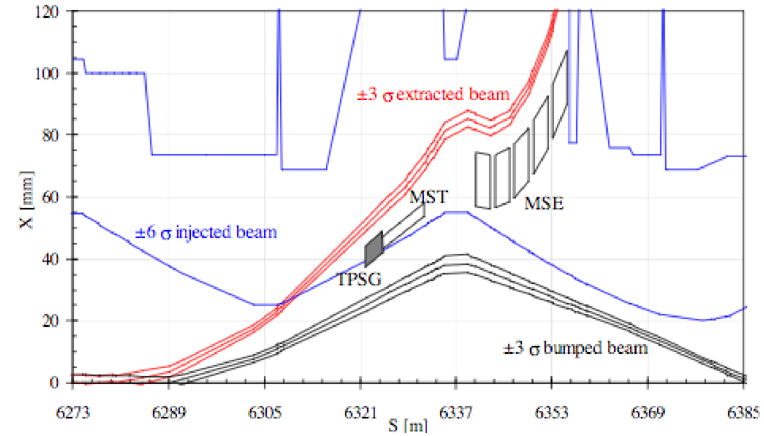
SPS protection elements (TPSG)



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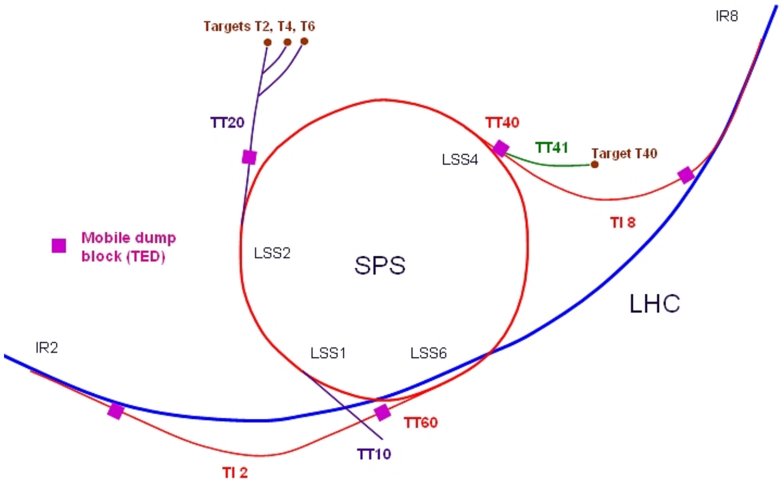
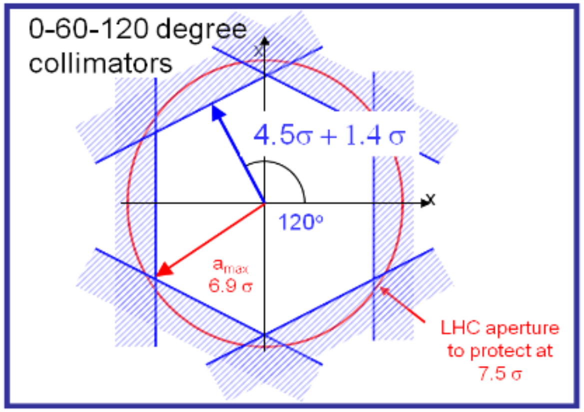
TL collimators





Aim: protect injection septum (MSI) and LHC aperture

Intercepting Devices ≤ 450 GeV

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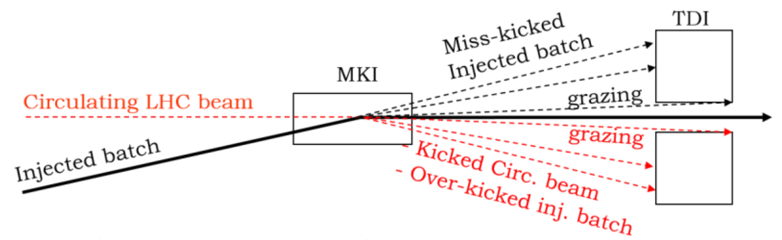
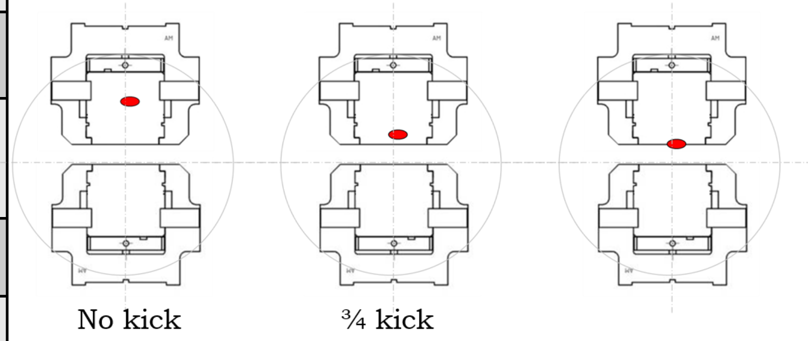
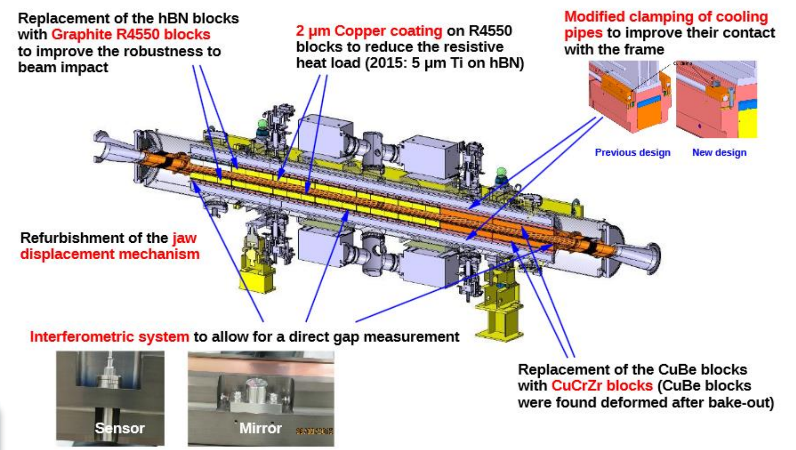
TDI	450 GeV	Sandwich: Graphite and CuCrZr

Injection protection: TDI







Intercepting Devices ≤ 450 GeV

Device	Comment	Material	Ok for Run 2 BCMS Beam?
TIDVG#4	Sweep, intensity limitation not brightness. Continuous dumping problematic	Sandwich: Graphite, CuCrZr and W	YES
TIDH	Sweep. Dump at 28 GeV	Al	YES
TBSJ	Injection dump: 26 GeV. Max intensity: 72 (48) bunches per shot	Stainless steel	YES
TED LHC	450 GeV. Continuous dumping problematic. Graphite not in vacuum	Sandwich: Graphite, Al, Cu-Be, Cu	YES (interlock on intensity for TED in TT60?)
TED HiRadMat	450 GeV		YES
TBSE	450 GeV. Should never be impacted by the beam but should still survive one shot		YES
Scraper		Graphite	YES
TIDP	Momentum collimator. n/a		YES
TPSG	450 GeV: Assume all beam in one spot	Sandwich: graphite <-> CfC, Ti, Inconel	YES
TCDIs	450 GeV.	Graphite	Limited to 144 BCMS bunches
TDI	450 GeV	Sandwich: Graphite and CuCrZr	YES

TCDI Robustness

- FLUKA and ANSYS studies defined as a maximum allowed intensity: **240 Run 2 BCMS bunches**
- 1 σ impact parameter at TCDI location with smallest $\sigma_x \times \sigma_y$

Beam status	Emittance [Pi.mm.mrad]	Spot Size (βx*βy) [m^2]	Bunch Intensity	Material	Number of Bunches	Max. Temperature [°C]	Tens. Strength /Max Tens. Stress	Comp. Strength /Max Comp. Stress	Mohr-Coulomb S.F.	Status
Run2 BCMS	1.39	1238.8	1.3e11	Graphite	**288**	1400	30/32	118/81	**0.9**	✗
					240	1250	30/24	118/75	**1.44**	✓
					192	1043	30/18	118/58	**1.75**	✓
Run2 Standard	2.6	1238.8	1.3e11		**288**	862	30/15	118/42.5	**2**	✓

New HiRadMat tests next year ➔ can we revise this limit?

TCDI Attenuation

Limitation defined as from Attenuation formula: **144 Run 2 BCMS bunches**. TCDIs 1 m long quasi-transparent collimator (compare to 4 m long TDI with higher Z at the end). They **only attenuate by factor 20**.

TCDI Philosophy: in case of any possible failure and consequent impact of the “transmitted beam” (scattered primary protons by TCDIs) on the MSI and/or LHC aperture ➔ no damage!

- Do we need to revise this philosophy?
- What is the gain wrt the risk?
- How do we decide if we are too conservative:
  - Simulate all possible failures (feasible?)
  - **Try to identify the worst failure scenario** (really the worst?)

Failure Scenarios SPS-to-LHC

SPS Fast Extraction Interlock (**FEI**) combined with Fast Current Change Monitors (**FMCM**) and Beam energy Tracking System (**BETS**) on critical extraction and transfer line magnet circuits

- **Single failure ➔** grazing or quasi-grazing (0σ and 1σ impact parameter respectively)
- **Double failures** (discarded) **➔ large impact parameter** if reaching the TCDIs depending on where the failure occurs in the line

MKE failures:

- Erratic or asynchronous **➔ beam swept and diluted over the TCDI jaws**
- **Internal breakdown** when pulsing ➔ possible escaping edge of TPSG with 80% nominal amplitude ➔ all extracted beam on one TCDIH with **fixed impact parameter (between grazing and ~7σ).** BUT the **recent reconfiguration** with short-circuit terminations **reduced the MKE voltage and thus the risk of flashover.**

Energy error (BIS limits ±0.6%) ➔ beam extracted on a dispersive trajectory:

- ±0.6%: beam lost on upstream aperture of TI2 and TI8
- **±0.16% - ±0.20% : TCDI grazing in TI2 and TI8 respectively**
- **±0.5%** (limit from BPMs interlock): **large impact parameter** (~5σ) at one TCDIH (largest dispersion: TCDIH.29050 and TCDIH.87441).

Possible any impact parameter from 0σ up to 7σ ➔ up to 12σ oscillations

LHC Aperture

Newest calculations, very close to present LHC at injection

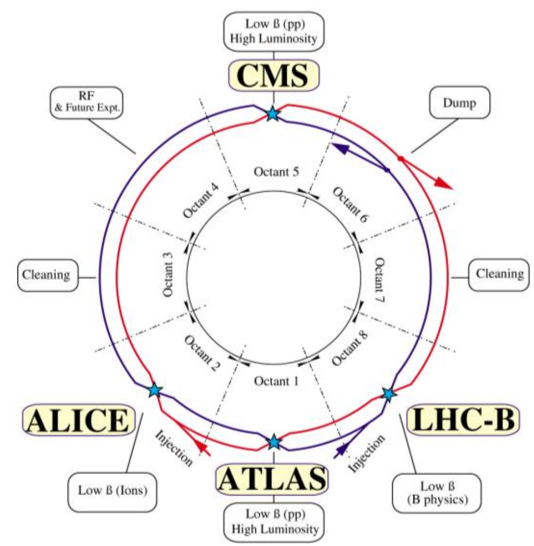
Table 2: Calculated apertures at injection in HL-LHC, using optics version 1.2 and the new HL-LHC parameters in Table 1. The table shows for each section of the machine, the minimum calculated aperture in each beam, as well as the element where this aperture is found. All values assume a normalized emittance of 2.5 μm.

Machine section	Element B1	Aperture B1 (σ)	Element B2	Aperture B2 (σ)
IR1	MQML.10R1.B1	13.3	MQML.10L1.B2	12.8
IR2	TCLIM.6R2.B1	12.9	MQML.8R2.B2	13.0
IR3	MQ.8R3.B1	13.2	MQ.11R3.B2	12.9
IR4	MQ.11R4.B1	13.1	MQML.8R4.B2	13.0
IR5	MQ.11L5.B1	13.1	MQML.10L5.B2	12.9
IR6	MQY.B5L6.B1	12.8	TCDQM.B4L6.B2	12.8
IR7	MQTLI.11L7.B1	13.0	MQ.8L7.B2	13.0
IR8	MQXA.1L8	13.0	TCLIM.6L8.B2	13.1
Arc12	MCBV.16L2.B1	13.4	MCBV.15L2.B2	13.4
Arc23	MCBV.15R2.B1	13.3	MCBV.26L3.B2	13.3
Arc34	MCBV.14R3.B1	13.3	MCBV.17R3.B2	13.3
Arc45	MCBV.17R4.B1	13.4	MCBV.16R4.B2	13.4
Arc56	MCBV.14R5.B1	13.4	MCBV.17R5.B2	13.4
Arc67	MCBV.17R6.B1	13.3	MCBV.16R6.B2	13.3
Arc78	MCBV.16R7.B1	13.3	MCBV.15R7.B2	13.3
Arc81	MCBV.17L1.B1	13.4	MCBV.14L1.B2	13.3

(Nominal norm. emittance)

Arc aperture: 11.2 σ

Global bottleneck:
Beam 1= 10.8 σ @ MQY.B5L6
Beam 2 = 11 σ @ MQ.8L7.B2



among other errors: **2 mm orbit** and 2σ injection oscillations

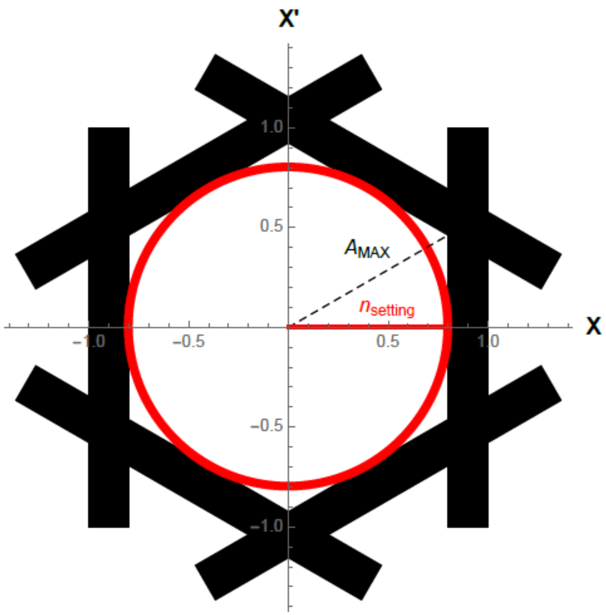
Possible hit LHC Aperture?

Fundamental assumptions:

- One of the mentioned failures occurs
- The beam intercepts only **one TCDI**
- **"Enough" beam** goes **through the MSI** (0-180° phase advance from intercepted TCDI, upstream mask aperture: $10\sigma_x \times 7\sigma_y$)

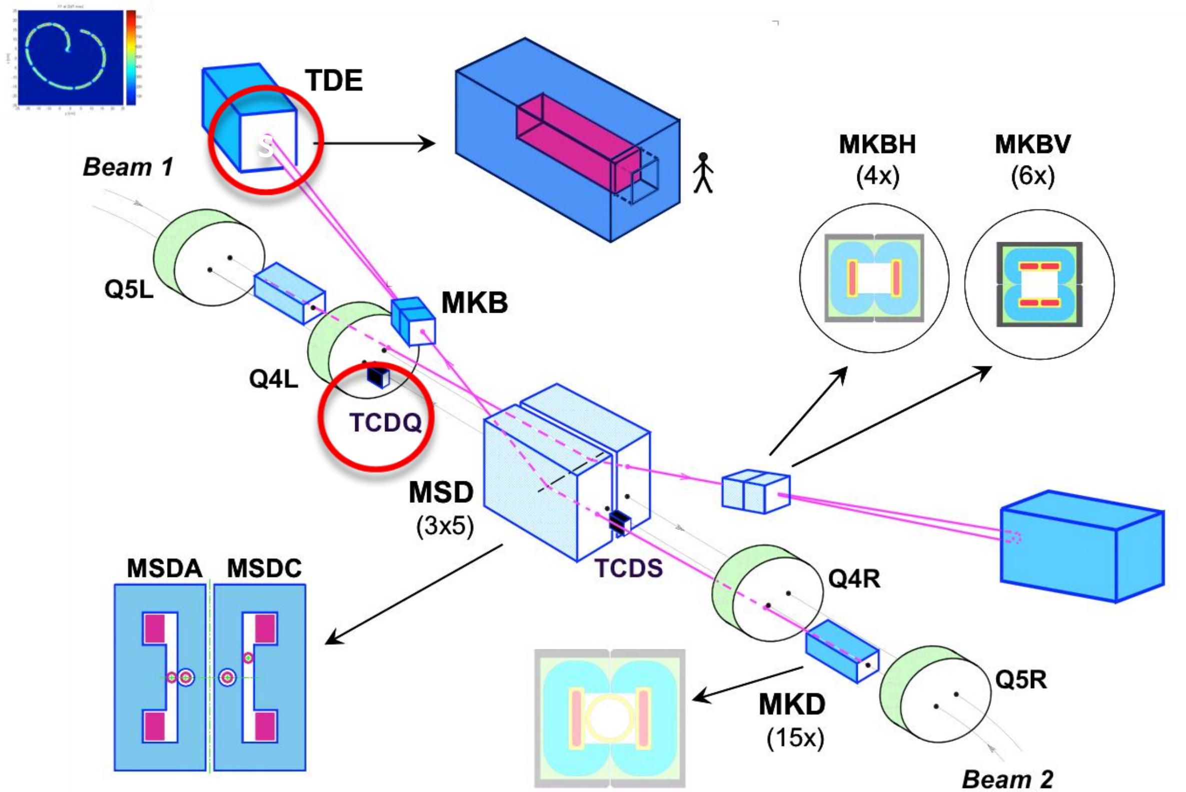
TCDIs at 5σ:

- Maximum escaping amplitude (including errors) **A_{max} = 7.4σ**
- **Quasi-grazing** (1σ impact parameter) ➔ **8.4σ** oscillation ➔ **2.4σ margin to LHC aperture**
- **Worst case TCDI impact parameter to be identified (indicatively 3.4σ-5.8σ)**
- One should not neglect **local orbit bumps** in the LHC!



To be studied in details if possible!
Any other (worse) case possible?

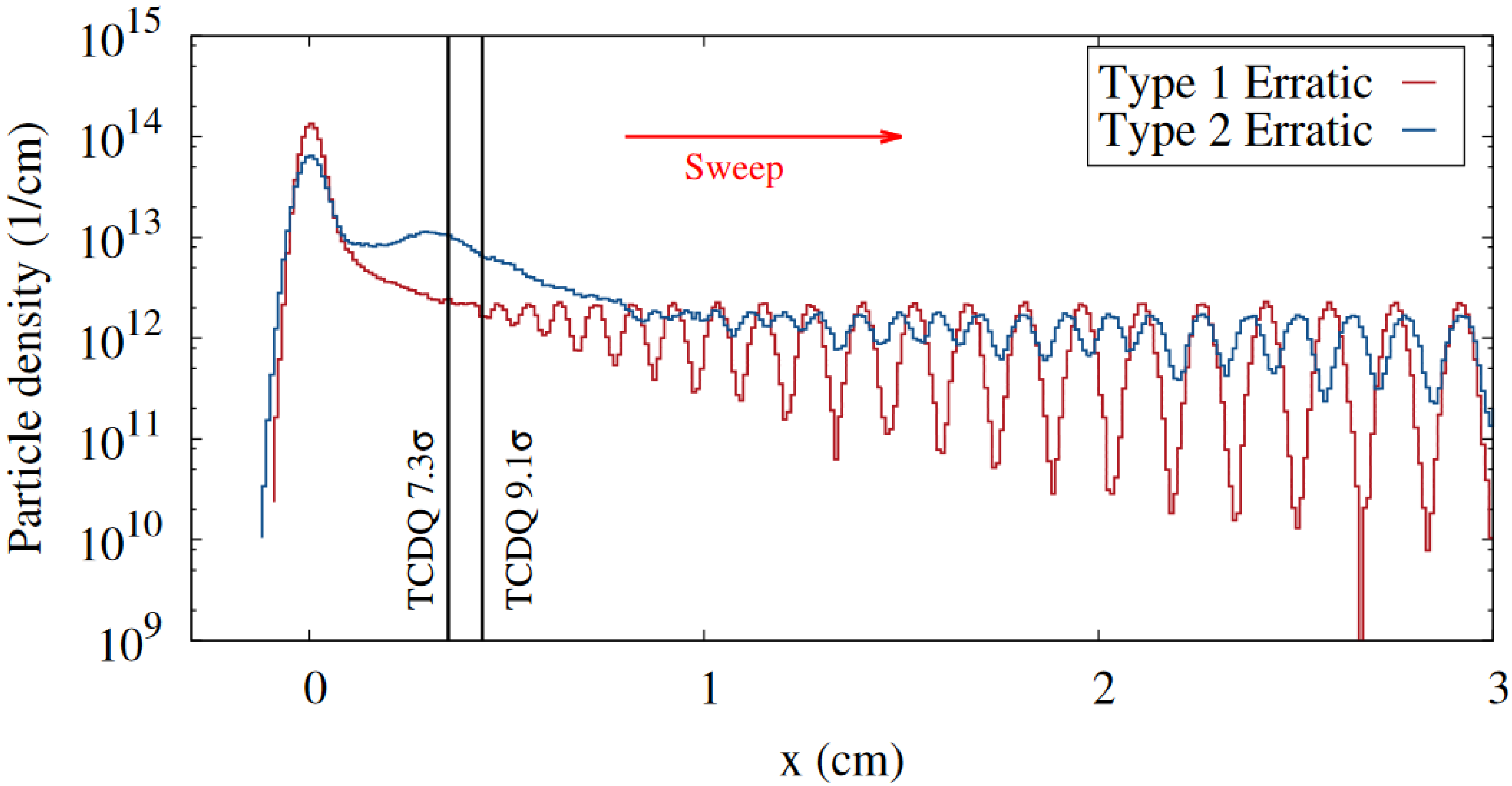
Any Limitation at Top Energy?



- Very little dependence on beam size (intensity plays the main role)
- TCDS designed for ultimate intensity and energy deposition for Type 2 erratic equivalent to type 1 ➔ OK (only plastic deformation for Ti part for HL-beams)
- TDE and Window designed for ultimate intensity ➔ OK
- Type 2 erratic ➔ energy deposition on TCDQ (tight settings!)

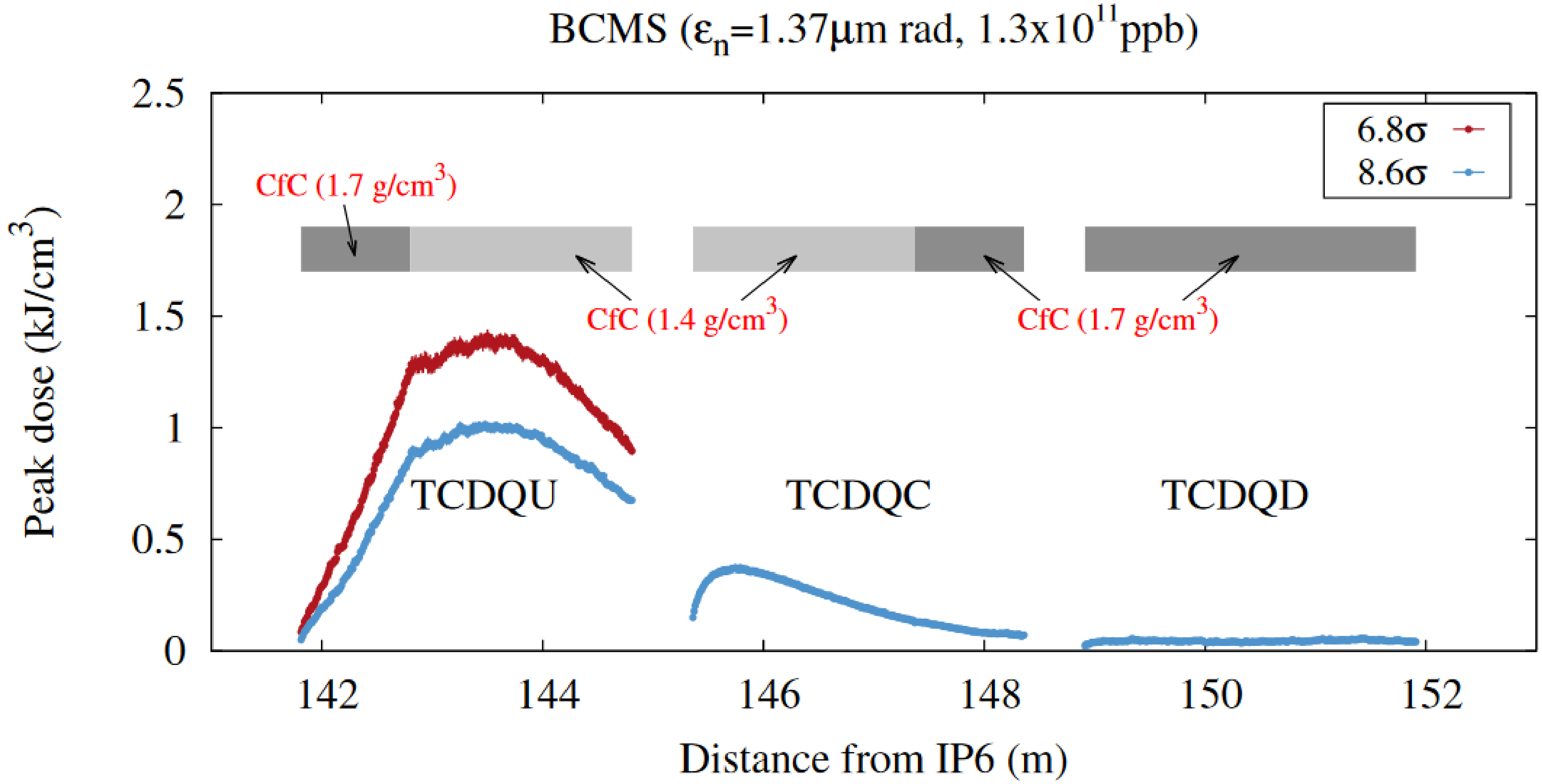
TCDQ: 2017 settings

9.1σ *vs* **7.3**σ*:*



TCDQ: 2017 settings

9.1σ *vs* **7.3**σ *(-0.5*σ *misalignment):*



TCDQ: **stresses expected to be within limits** (as suggested by HL simulations)
Q5 coils: energy density expected to reach **20-25 J/cm³** (damage limits of NbTi being assessed)

Conclusions

- **No intensity limitation** is expected in the SPS **if** the **TIDVG#4** will be ready and installed during the EYETS ➔ 288 nominal and Run II BCMS bunches
- **Only intensity limitation** for **Run II BCMS** beams comes from the **TCDIs** (TT40 damage test):
  - **Robustness: 240 bunches**(foreseen HiRadMat tests)
  - **Attenuation:144 bunches ➔ basic principle of passive protection system: guarantee no damage of LHC components for any possible (even unknown..) failure scenario (present design and upgrade!)**
  - Are **currently assumed damage** limit at 450 GeV **too conservative?**
  - **Large oscillations** down the line **cannot be excluded**. What are the **consequences** for the injection region (including the MSI) or further downstream in the LHC?
  - Detailed tracking and FLUKA studies will follow (impact parameter scan)
  - Need to insure that **worst failure scenario correctly identified!**
  - Does the **low probability justify** the taken precautions and **limits on high brightness beams**?
- No limitation for high energy operation with 2017 beam parameters and settings (TCDQ,TCDS and TDE)

Thank you!

80% MKE Strength