Protection of superconducting elements in the case of injection failures

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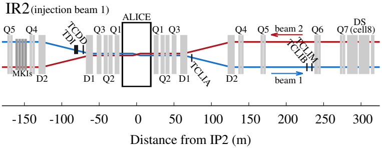
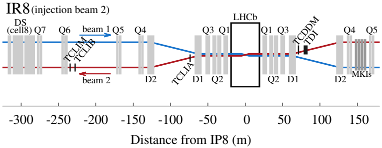
LHC injection protection devices

Protection devices in IR2/8:

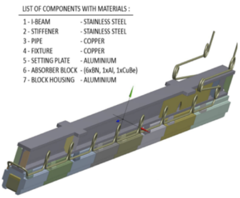
- intercept bunches in case of injection kicker (MKI) failures
  - misinjections (no kick of inj. beam)
  - accidental kicks of the stored beam
  - protect adjacent supercond. magnets
- primary injection beam stopper (TDI) at $\Delta\mu \approx 90^\circ$ from MKIs (vertical)
- auxiliary collimators (TCLIA/TCLIB) at $\Delta\mu \approx n\times 180^\circ \pm 20^\circ$ from TDI (vertical)
- complemented by masks (TCDD/M, TCLIM) intercepting secondary showers from absorbers





Device	Materials	Density	Active length
TDI	BN5000	1.92 g/cm^3	2.85 m
	Al	2.67 g/cm^3	0.6 m
	Cu-Be	8.96 g/cm^3	0.7 m
TCDD	Cu	8.96 g/cm^3	1 m
TCLIA	Graphite R4550	1.83 g/cm^3	1 m
TCLIB	C/C AC150	1.67 g/cm^3	1 m

Table: Materials of present LHC injection protection devices.



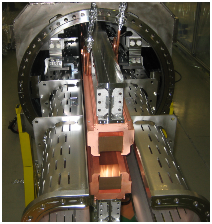


Figure (left): Illustration of TDI jaw (courtesy of J. Hrivnak).
Figure (right): TDI assembly (courtesy of A. Perillo Marcone).

LHC Run I:

- several instances of injection failures happened during LHC operation in 2010-2012
- both insertion regions (IR2 and IR8) were concerned
- up to $\sim 2\times10^{13}$ protons impacting on TDI
- different impact parameters (from grazing up to $\sim$3 cm)
- magnet quenches in all cases where bunches were grazing on jaws (expected and unavoidable)

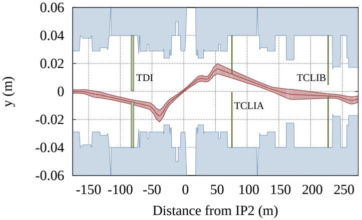
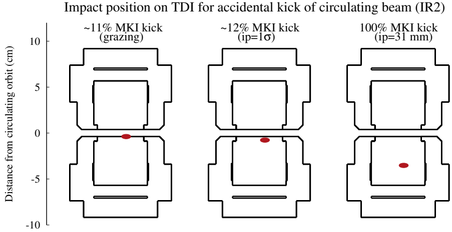


Figure: Vertical beam envelope (3σ) during an injection failure on the 28th of July 2011. More than 160 bunches impacted on TDI with a small impact parameter. Beam=red, machine aperture=blue, absorbers=green.

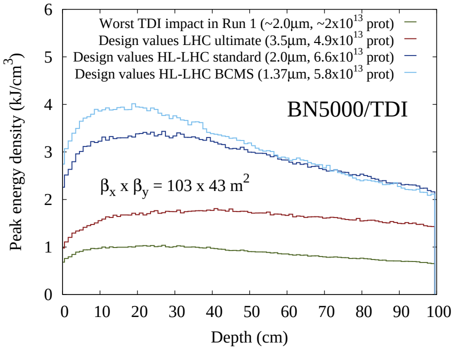


Date	Beam	MKI failure	Applied kick (% nominal)	Lost bunches
2010				
23/10	1/inj.	not firing	0%	32
2011				
18/04	2/inj.	flashover	$\sim$110–125%	36
23/04	1/inj.	not firing	0%	36
27/04	2/inj.	not firing	0%	72
28/07	1/inj.	erratic	0%	144
28/07	1/circ.	erratic	$\leq$12.5%	176
2012				
26/03	2/inj.	erratic	0%	1
15/04	2/inj.	flashover	$\sim$110–126%	108

Table: LHC injection failures (2010–2012) with beam impact (protons) on protection devices.

- Brightness increase in HL era
  - need to employ (new) absorber materials which are robust enough (concerns both lower-Z and higher-Z blocks)
  - need to ensure magnet protection

→ in this presentation, will focus on the second point (for TDI+TCDD only)



Beam parameters and spot sizes@TDI

	ϵ_n	Intensity/train
LHC nominal	3.50 μm	288 $\times$ 1.15$\cdot 10^{11}$
LHC ultimate†	3.50 μm	288 $\times$ 1.7$\cdot 10^{11}$
HL-LHC std.	2.00 μm	288 $\times$ 2.3$\cdot 10^{11}$
HL-LHC BCMS	1.37 μm	288 $\times$ 2.0$\cdot 10^{11}$

† *Presently installed devices designed for LHC ultimate.*

	$\beta_x \times \beta_y$	$\sigma_x \times \sigma_y$
LHC	103×43 m^2	870×560 μm^2
HL-LHC std.	103×43 m^2	660×420 μm^2
HL-LHC BCMS	103×43 m^2	550×350 μm^2

Figure (left): Estimated peak energy density in hBN of the TDI for different beam parameters. The worst impact encountered during Run I (∼160 bunches on TDI) is compared to failure scenarios where 288 bunches impact on the TDI.

Segmenting the TDI (1 → 3 modules, TDI → TDIS)

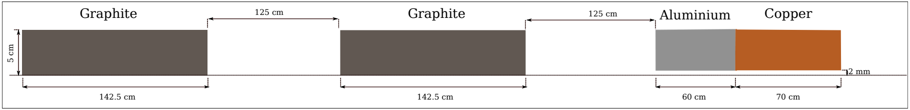


Figure: Illustration of segmented TDI. Materials and/or lengths only indicative, will be subject to change.

3 modules:

- 2×1.5 m low-Z material
- 1×1.5 m higher-Z material
- Material choices to be finalized
- Total number of inelastic interaction lengths retained

Machine protection studies:

- Simulation studies shown in the following were performed for a single module, however expect similar performance for 3 modules (see figure)
- Assumed composite TDI made of GR4550+Al+Cu, with same active length as present TDI

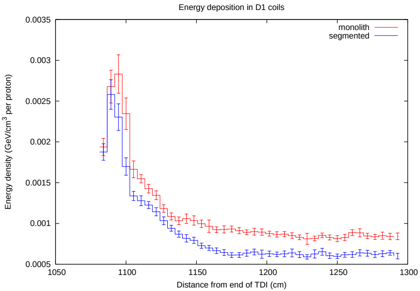
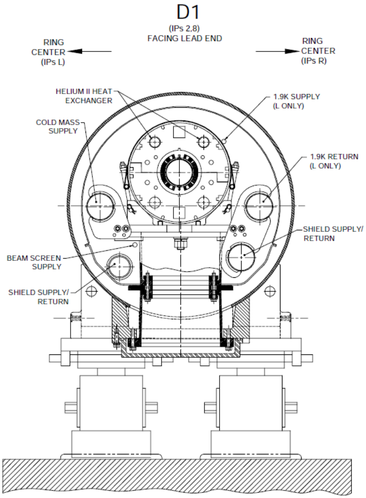


Figure: Peak energy density in D1 coils for beam impact on a single-module TDI compared to beam impact on a 3-module TDI (in both cases, the beam is assumed to graze on the jaws). Results are expressed per incident proton. The simulations are based on an approximative model of the beam pipe between TCDD and D1.

Protection of the superconducting D1 (left of IR2/right of IR8)



- The superconducting separation dipole D1 (MBX) is the most exposed magnet in case of beam impact on the TDI
  - Approx. 10 m downstream of the TDI
  - Single-bore with coil aperture of r=40 mm
- Minimum objective
  - No damage to D1 (coils) for any kind of injection failure
- Damage limit of D1 coils?
  - Previous assumption was 87 J/cm^3 [1]
  - Currently assumed safe limit is ~50 J/cm^3 → value might be conservative and is presently being re-evaluated by TE-MPE colleagues (D. Wollmann, A. Verweij, B. Auchmann) → need some estimate this year to conclude on necessary changes of injection protection equipment

[1] O.Brüning, J.B.Jeanneret, LHC-Project-Note-141, CERN, 1998.

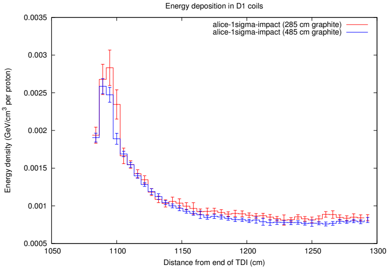
What is the worst case scenario for the D1?

- Protection settings of TDI
  - Jaw half gap (leading low-Z blocks): $6.8\sigma_n = \sim 3.8$ mm ($\sigma_n \rightarrow \varepsilon_n = 3.5\mu$m·rad)
  - Jaw half gap (higher-Z blocks): $6.8\sigma_n + d$ mm (presently $d = 2$ mm) → to avoid direct beam impact
- Impact scenarios
  - Small impact parameters on the TDI (of the order of $\sim \sigma$):
    - → Significant secondary showers can leak through TDI gap
    - → Worst case for D1 (highest energy density in coils)
  - Large impact parameters (max. $\sim$36 mm),
    - → energy density in the D1 is estimated to be orders of magnitude smaller

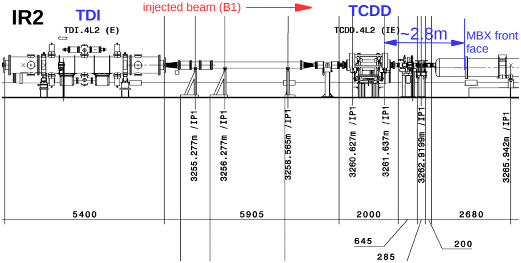
→ In the following, will focus on worst case ($288 \cdot 2.3 \times 10^{11}$ protons @1σ impact parameter, emittance less important for D1 load).

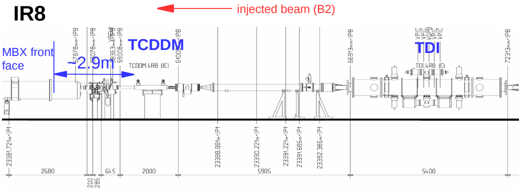
TCDD

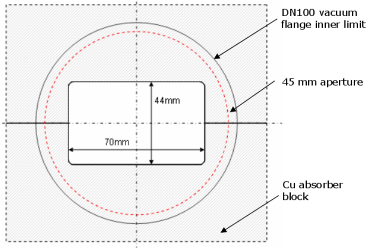
- Small impact parameters: making the TDI longer does not help in reducing the energy density in D1 (see figure below)
- Need for a mask between TDI and D1 to reduce load on D1
- Present TCDD was deemed necessary to prevent damage to D1 for LHC ultimate beams (1.7×10^{11} ppb)



- Present TCDD(M):
  - $70 \times 44\,\text{mm}^2$ (D1 aperture: r=40 mm)
  - TCDD end – D1 front ≈2.8 m

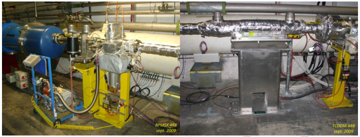




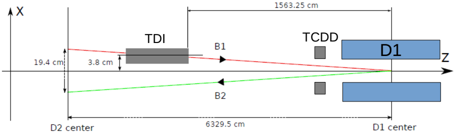


IR2:

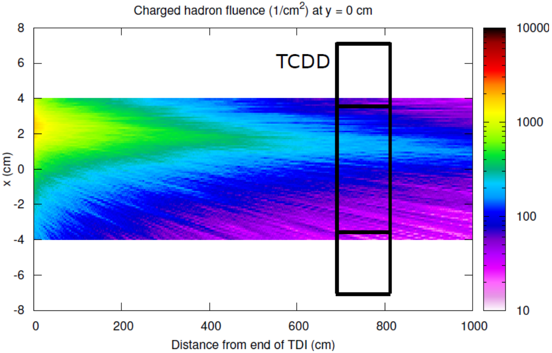
IR8:

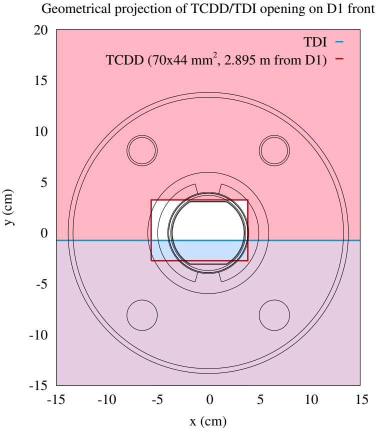


TDI located between separation dipoles:



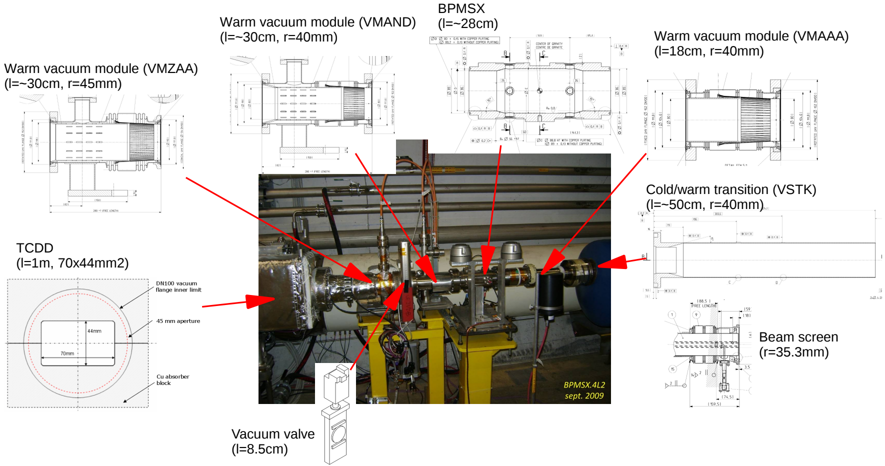
- → Beams have a horiz. angle of ∼1.5 mrad
- → TCDD opening sym. around machine axis
- → Provides asym. protection of D1 coils





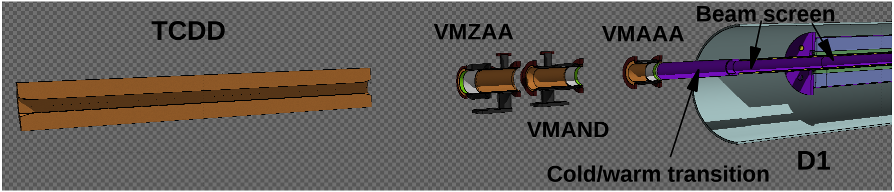
Present vacuum layout between TCDD(M) and D1

- In order to estimate the energy density in D1 coils, one needs to take into account the vacuum equipment just upstream of D1 (like vacuum modules, cold/warm transition tube)
- Even tubes with 1–2 mm thickness and a few 10 cm length can act as shielding for grazing shower particles leaking through the mask

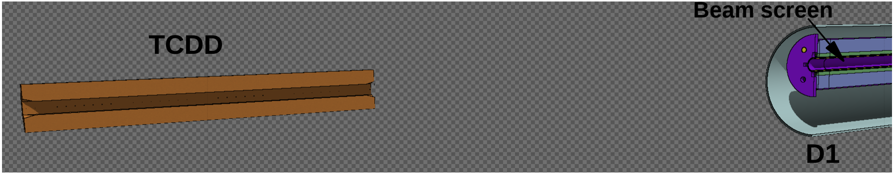


- To quantify the effectiveness of the mask and the contribution of vacuum equipment, simulations were run with and without vacuum equipment/tubes between TCDD and D1
- Beam pipe between TDI and TCDD less relevant since it has a much larger aperture (r=10.6 cm) and only shields particles with larger angles (which would not make it through mask opening) → for first design studies this beam pipe is neglected

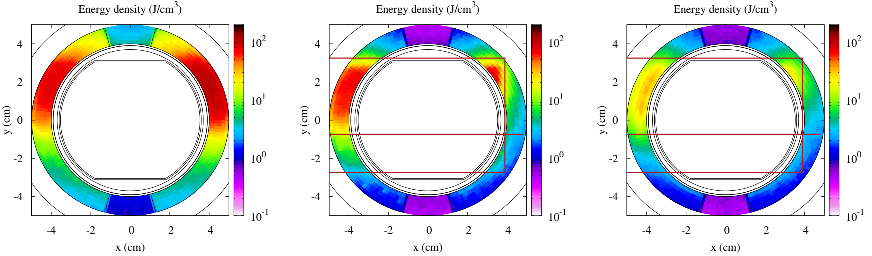
Model with vacuum elements between TCDD and D1:



Model without vacuum elements:



No mask: Present mask: Present mask+vacuum tubes:

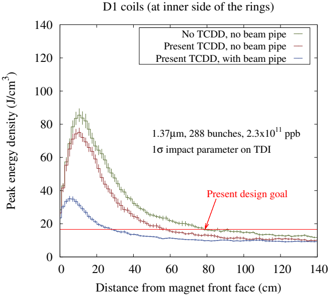


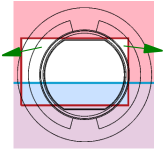
Figures: Transverse energy density profile at longitudinal maximum in D1 coils, for 288 bunches (2.3×10^{11} ppb) impacting on lower TDI jaw with an impact parameter of 1σ. No mask (left), present TCDD (center), and present TCDD + vacuum modules/transition tubes between TCDD and D1 (right).

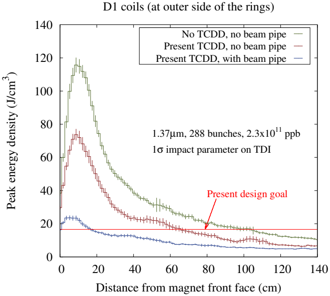
The simulation results suggest:

- Mask does not reduce much the load on D1 coils at inner side of the ring (@negative x)
  - → due to asymmetry, quite large mask aperture, and large distance from D1 front face
- Significant shielding by vacuum modules and cold-warm transition tube
  - → yields a factor ∼2–3 reduction compared to case with TCDD only
  - → results depend on details of FLUKA geometry model of vacuum layout

Small impact parameter ($\sim \sigma$) on TDI: effectiveness of the present TCDD (IR2)







- Design goal: energy density in D1 coils $\leq$ assumed damage limit $\times$ 1/3 (the latter is a safety factor for energy deposition calculations)
- Even with vacuum tubes, cold/warm transition etc., we obtain an energy density above our design goal

Ideally, should find a solution where we depend less on shielding by vacuum equipment

How could we reduce the energy density in D1 coils?

$\rightarrow$ *Reduction of TCDD aperture, moving mask closer to D1?*

$\rightarrow$ *Complementing present TCDD with another passive protection element (inside cryostat)?*

Can we reduce the TCDD aperture?

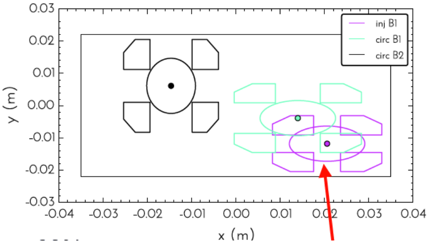
- Aperture for circulating beams:
  - TCDD.4L2:
    - → Horizontally: could gain 6–7 mm on each side
    - → Vertically: no decrease possible (polarity change)
  - TCDDM.4R8:
    - → Horizontally: could gain 6 mm on internal side
    - → Vertically: could gain 5 mm up and down
- Aperture requirements for injected beam to be finalized

Assumptions for circulating beams:

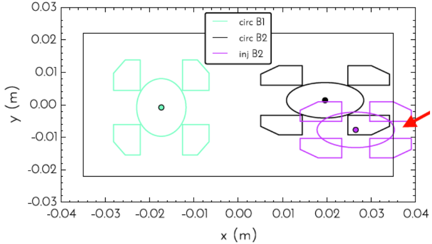
$$\delta^{al} = 0.1\ mm$$
$$k_\beta = \sqrt{1.2}$$
$$CO^{peak} = 4\ mm$$
$$k_D = 0.27$$
$$D_{QF} = 2.1\ m$$
$$\beta_{QF} = 177.5\ m$$
$$\epsilon^N = 3.5\ \pi.\text{mm.mrad}$$
$$\delta_p = 1.5 \times 10^{-3}$$

$$n_1 = 7.0$$
$$n_r = 9.8$$
$$n_a = 8.5$$

IR2 (polarity change: y → -y):

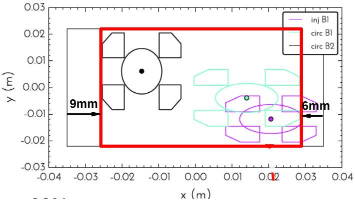


IR8:



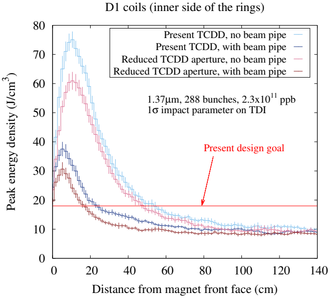
Figures: Circulating beam apertures at TCDD(M) in IR2 and IR8. Injected beam aperture (red arrows) corresponds to failure scenario of ±0.5% MSI error (its current is interlocked for bigger errors) and ±20% MKI error (very extreme case because a large part of the beam is intercepted by the TDI before reaching the TCDD. Figure courtesy by F.M. Velotti (WP14 Meeting of 7th Oct. 2014).

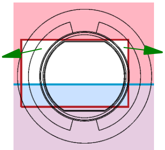
Case study I: TCDD aperture horizontally reduced (IR2)

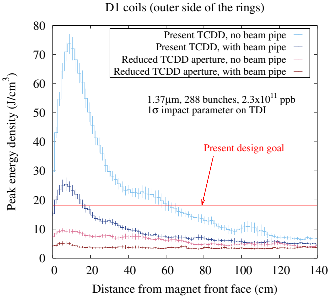


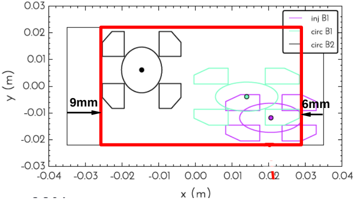
Reducing the IR2 TCDD horizontally (on both sides):

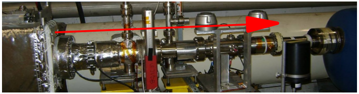
- Neglecting for the moment aperture requirements for injected beam (which still have to be finalized)
- Energy density significantly reduced in coils at outer side of ring (achieving present design goal)
- However, limited gain (10–20%) on inner side of the ring





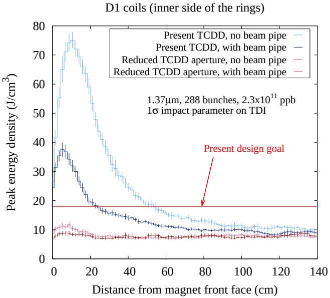


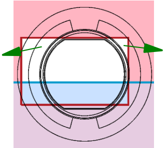


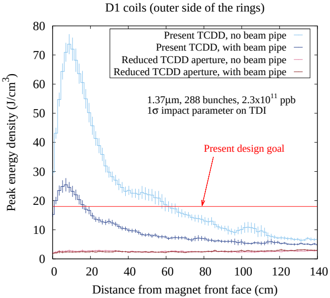


Reducing the IR2 TCDD horizontally (on both sides) and moving the TCDD closer to the D1 (by 1 m):

- Would imply moving the vacuum valve and BPM*)
- Very efficient overall reduction, less dependent on vacuum tubes







*) Feasibility of changing layout to be studied.

- Magnet protection provided by TDI/TCDD:
  - Reducing the aperture&displacing the TCDD provides a handle to reduce the load on D1 coils in case of grazing beam impact on TDI (worst case for D1)
  - Only IR2 results were shown, but one can expect similar results for IR8
  - Decision of redesigning the TCDD to be taken this year, depends on D1 damage limit
  - If it is decided to modify mask, need to finalize aperture requirements and study integration possibilities
  - Alternatively, we could think of complementing the TCDD with another passive element inside the cryostat

TCLIA/TCLIB

- Need to complete tracking (+scattering) studies in order to estimate:
  - the beam fraction which can leak through TDI gap and impact on the TCLIA/TCLIB (considering also orbit errors etc.)
  - the fraction of scattered protons from the TDI which can impact on on the TCLIA/TCLIB, in particular in case one low-Z TDI module is misaligned
- For the moment, we don't expect any risk of damage for magnets downstream of the TCLIA/TCLIB (to be verified by FLUKA simulations)

Backup

Surviving protons from TDI/TCDD (1/2)

1. For small impact parameters on TDI (∼mm), the beam only traverses the leading low-Z blocks, with a proton survival probability of:

$$P_s = exp(-N_\lambda^{TDI,light})$$

- → Present survival (for 288·2.3×10[11]): $N_\lambda^{TDI,light}$ =6.6, $P_s \cdot I_{HL}$= 9.1×10[10] protons
- → these protons should primarily impact on the TCLIA/TCLIB
- → Modular TDI: the number of surviving protons could increase if one low-Z jaw is mis-aligned (to be studied in more detail)

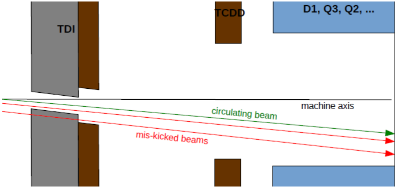


Figure: Illustration of mis-kicked beams (vertical cut).

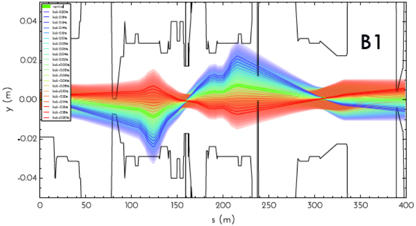


Figure: Trajectories of mis-kicked beams (IR2), incl. imperfections and errors. Courtesy of F.M. Velotti.

Surviving protons from TDI/TCDD (2/2)

2. For impact parameters >2 mm and <10–20 mm, the beam traverses all TDI absorber materials but still remains within TCDD aperture. Survival probability:

$$P_s = exp(-N_\lambda^{TDI,light} - N_\lambda^{TDI,heavy})$$

→ Present survival (for 288·2.3×10^{11}):
$N_\lambda^{TDI,light} + N_\lambda^{TDI,heavy}$ =13.0,
$P_s \cdot I_{HL}$=1.5×10^{7} protons

→ depending on optics and polarity, these protons can be lost locally in the triplet

3. For large impact parameters (>10–20 mm), the protons surviving the TDI will be intercepted by the TCDD. Total survival probability:

$$P_s = exp(-N_\lambda^{TDI,light} - N_\lambda^{TDI,heavy} - N_\lambda^{TCDD})$$

→ Present survival (for 288·2.3×10^{11}):
$N_\lambda^{TDI,light} + N_\lambda^{TDI,heavy} + N_\lambda^{TCDD}$ =19.8,
$P_s \cdot I_{HL}$=1.6×10^{5} protons

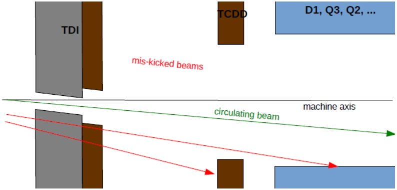


Figure: Illustration of mis-kicked beams (vertical cut).

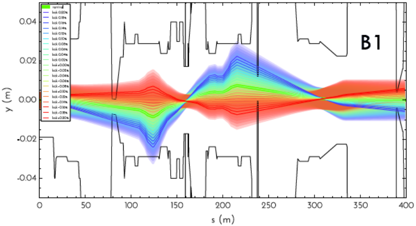
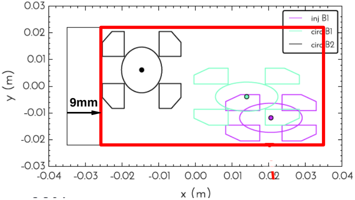


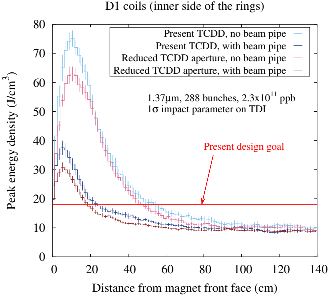
Figure: Trajectories of mis-kicked beams in IR2, incl. imperfections and errors. Courtesy of F.M. Velotti.

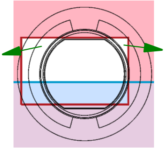
Case study I.b: reduced-aperture TCDD (IR2)

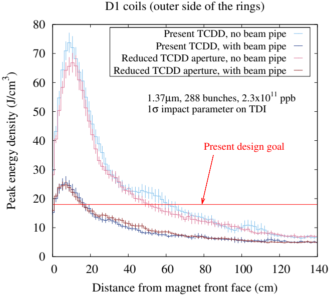


Reducing the IR2 TCDD horizontally (on one side only):

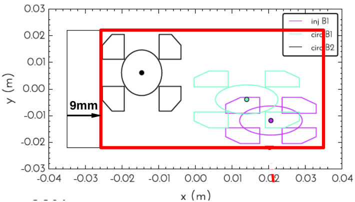
- As expected, energy density reduces mainly in coils at inner side of ring
- However, limited gain (10–20%) with respect to present mask

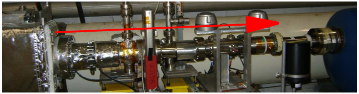






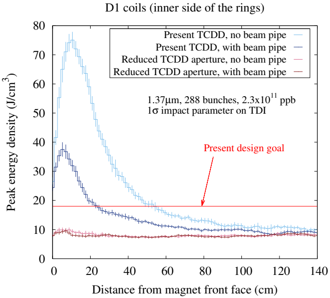
Case study II.b: reduced-aperture TCDD, 1 m closer to D1 (IR2)

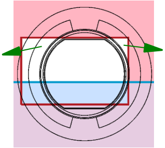


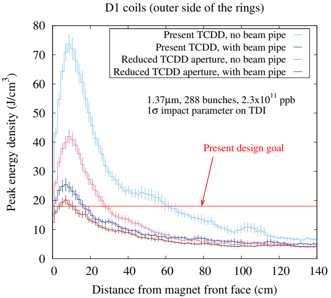


Reducing the IR2 TCDD horizontally (on one side) and moving the TCDD closer to the D1 (by 1 m):

- Would imply removing the vacuum valve and BPM*)
- Very efficient reduction for coils on the inner side







*) Feasibility of changing layout to be studied.