CERN
CH-1211 Geneva 23
Switzerland

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Functional Specification

FUNCTION AND CONCEPT OF TCDI TRANSFER LINE COLLIMATORS

Abstract

The intensities foreseen for injection into the LHC are roughly four orders of magnitude above the quench limit of the superconducting magnets and about one order of magnitude above the expected damage levels. The TI 2 and TI 8 transfer lines will be pulsed with surveillance of power supply currents and beam parameters; nevertheless, failure modes exist which could result in uncontrolled beam loss and serious transfer line or LHC equipment damage. To protect the equipment in TI 2 and TI 8, the LHC injection regions and the LHC machine, TCDI collimators will be installed. This document presents the functional requirements and the preliminary conceptual design.

Prepared by :	***Checked by :***	***Approval Group Leader:***
H. Burkhardt AB/ABP **B. Goddard** AB/BT **V. Kain** AB/CO **W. Weterings** AB/BT	**R. Assmann** AB/ABP **L. Bruno** AB/ATB **J.M. Jimenez** AT/VAC **Y. Kadi** AB/ATB **R. Schmidt** AB/CO **H. Vincke** TIS/RP	**V. Mertens** AB/BT

Approval Group Members:

O.Aberle, J.-F.Arbogast, M.Brugger, O.Brüning, E.Carlier, E.Chiaveri, P.Collier, L.Colly, A.Desirelli, B.Dehning, L.Ducimetière, L.Evans, A.Ferrari, R.Filippini, D.Forkel-Wirth, D.Gerard, D.Grenier, M.Gyr, R.Hänni, B.Jeanneret, W.Kalbreier, J.-P.Koutchouk, M.Mayer, M.Martini, S.Myers, M.Owen, H.Preis, P.Proudlock, J.-P.Quesnel, S.Roesler, F.Ruggiero, M.Sans Merce, P.Sievers, R.Trant, J.Uythoven, A.Verdier, V.Vlachoudis, J.Wenninger.

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1. SCOPE

This engineering specification describes on the passive protection system in the LHC injection transfer lines TI 2 and TI 8. This will be achieved by movable TCDI (Target Collimator Dump Injection) collimator blocks. The performance objectives and operating conditions in relation to the LHC **ultimate** beam intensity will be presented. We describe the functional requirements and technological constraints for the preliminary conceptual design and report on the manufacture, installation and interface requirements of the mechanical design. Finally a summary of all specification data will be given in Appendix 1.

2. INTRODUCTION

Transfer of 450 GeV protons from SPS to LHC will be carried out through two new beam transfer lines TI 2 and TI 8 as shown in Figure 1. Uncontrolled beam loss could result in serious damage of the equipment in the transfer lines, the LHC injection regions or in the LHC machine. Therefore, movable collimator blocks (TCDI) will be installed in the transfer lines in order to protect the transfer line and LHC equipment from damage in case of beam losses.

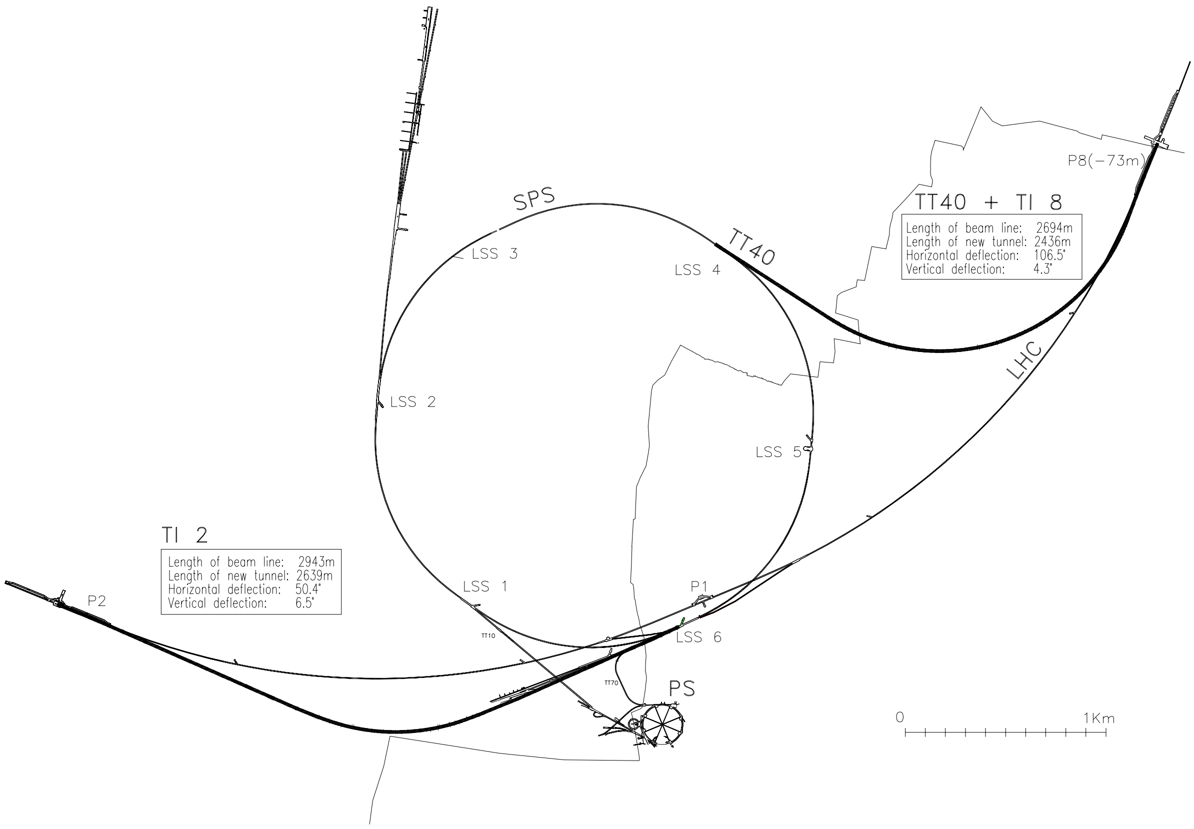

Figure 1- View of the LHC injection transfer lines TI 2 and TI 8.

3. ASSUMED OPERATING CONDITIONS

3.1 LHC FILLING VIA THE TRANSFER LINES TI 2 AND TI 8

In order to fill the LHC, batches of protons will be extracted from the SPS at 450 GeV, to one or other of the two LHC ring, via the transfer lines TI 2 and TI 8. At ultimate intensity, during each cycle, batches of either 3 or 4*72 bunches of $1.7 \cdot 10^{11}$ protons will be required, with normalised horizontal and vertical emittances of 3.5 mm.mrad. The detailed beam parameters for SPS extraction during the LHC operation in proton mode are given in Appendix 1.

3.2 PERFORMANCE OBJECTIVE

The primary collimators in the LHC will be set to 6-7σ at injection and secondary collimators to 7-8.2σ. This reduces the tertiary halo of the circulating beams to below the quench level at physical apertures (at ~10σ). Wrongly injected beams with large excursions could, however, cause damage before they even arrive at the collimation sections in the LHC.

The damage level for fast and localised losses is estimated to be around $2.3 \cdot 10^{12}$ protons [1].

An attenuation of the primary beam by at least a **factor of 20** ($4*72*1.7 \cdot 10^{11}/2.3 \cdot 10^{12}$) is therefore required to prevent damage by the injected LHC ultimate beam [2, 3], assuming that there is no emittance growth with a corresponding reduction in energy density.

Considering a 3.5σ beam size (defined by collimators in the SPS ring) and a maximum offset of 1 σ due to combined effect of closed orbit errors, extraction and transfer line ripples and drifts, a TCDI collimator setting of about 5σ is required [4].

In addition to the need for protection of the LHC machine, the ends of the transfer lines are also critical regions, especially the Injection Septum (MSI) with a very tight aperture of ~7 σ [5]. In order to minimise the risk of damage, to this difficult to replace element, protection for the septum is needed which for cost reasons and simplicity should form part of the overall transfer line collimation system to constrain the possible injection oscillations in the LHC.

Finally, momentum collimators in locations in the high dispersion regions of the lines are proposed, to limit the energy offset to a level of about $\pm 2 \times 10^{-3}$.

3.3 PROPOSED COLLIMATION SCHEME

Momentum collimation should be done in the first available space with high dispersion [3]. The betatron collimation should be able to protect the tight septum aperture and the injection region against bending errors upstream. It should therefore be placed towards the end of the line.

The following strategy is proposed for the transfer line collimation scheme:

- Momentum collimation in the first available place with large dispersion (which is in the vertical plane in TI 2 and in the horizontal plane in TI 8)
- Horizontal and vertical collimation immediately upstream of the MSI septum.
- Vertical collimation at about 90° phase advance upstream of the MSI septum.
- Horizontal collimation at about 90° phase advance upstream of the MSI septum.

This stage 1 installation would require a total of 5 TCDI collimators per line (MSI H/V, 90° H/V and Momentum), and would protect at 7.1 sigma. The protection level for the

LHC could be improved if needed to 5.4 sigma by adding a further 4 stage 2 collimators per line:

- Horizontal and vertical collimation at about 45° (or 225°) phase advance upstream of the MSI septum
- Horizontal and vertical collimation at about 135° (or 315°) phase advance upstream of the MSI septum.

3.4 TCDI LOADING ASSUMPTIONS FOR ACTIVATION ANALYSIS

For the TCDI loading, 200 days of LHC physics per year and 4 LHC fills per day are assumed. With ultimate intensity per LHC beam of $4.8 \cdot 10^{14}$ protons, the total number of protons injected through each of TI 2 and TI 8 will be $3.8 \cdot 10^{17}$ protons/year (200 x 4 x $4.8 \cdot 10^{14}$).

Three types of losses at the collimators are considered:

a) Regular losses from scraping

The collimators are set at $\pm 5\sigma$ and the beam is assumed to be scraped to $\pm 3.5\sigma$ in the SPS so that in theory there will be no losses for a well-set up line, this even with $\pm 1.5\sigma$ offsets coming from power supply ripples etc.

A worst-case assumption is made that the beam always extends to $\pm 5\sigma$ and is fully intercepted by the TCDI at $\pm 3\sigma$. The total number of particles lost at the 5 collimators is $7.5 \cdot 10^{14}$ protons/year or approximately $2 \cdot 10^{14}$ protons/year per collimator.

b) Regular losses from 'setting up'

From setting up with pilot bunches it might be assumed that, in the absolute worst case, ten pilot bunches impact each collimator for setting up each injection, every day. The total per year is then $4 \cdot 10^{13}$ protons/year per collimator (200 x 4 x 10 x $5 \cdot 10^{9}$).

c) Occasional losses from failures

During LHC filling of the order of one serious failure per year with the full beam of $4.9 \cdot 10^{13}$ protons is expected to be the upper limit for the transfer lines [6]. For instantaneous activation analysis purposes it is assumed that this is concentrated on one collimator. The distributed dose is one-fifth of this value or 10^{13} protons/year per collimator.

An upper limit of $\mathbf{2.5 \cdot 10^{14}}$ protons/year per collimator therefore seems to be a reasonable estimate for the upper limit for regular losses spread through the year from scraping, setting up and accidents, and that $\mathbf{5 \cdot 10^{13}}$ protons should be taken as the figure to calculate cooling times for an instantaneous accidental loss following a failure.

4. DESIGN REQUIREMENTS AND CONSTRAINTS

4.1 MATERIALS

The choice of all materials for the mechanical design must fulfil the constraints of thermal, mechanical, vacuum, radiological and environmental specifications described below.

4.2 VACUUM SYSTEM

The design of the beam vacuum must be compatible with the ultra high vacuum system of the transfer lines, as described in [7].

4.3 COOLING REQUIREMENTS

Cooling of the TCDI is not required due to the very low duty cycle of the transfer lines. In the event of a significant beam impact, the average temperature rise of the absorber block will be around 40K with a maximum of 80K in the ends, see Figure 7, and it is estimated that only a short period of time will be required for the TCDI to cool to a usable level so that subsequent impact would cause no damage. Nevertheless, the TCDI shall be equipped with temperature sensors, as described in 8.1 and if the LHC TCS collimator design is used, as mentioned later in 6.1.1, the cooling channels could be kept and used for water cooling if found to be necessary.

4.4 JAW MOVEMENT RANGE AND SETTING PRECISION

The following values are based on the minimum beam sigma at any of the proposed collimator locations (0.276 mm at TCDIH225 in TI 8).

The **maximum gap** between the jaws to be about 30 mm.

The **minimum gap** between the jaws to be about 1 mm.

The **surface flatness** (including roughness) to be better than ±0.2σ (±0.05 mm).

The **gap between the jaws** to be known to about ±0.5σ (±0.1 mm).

The **jaw position** to be adjustable at the ±0.1σ level (±0.025 mm).

The **reproducibility** of the jaw setting to be at the ±0.2σ level (±0.05 mm).

5. OPTICS, COLLIMATOR LOCATIONS AND PERFORMANCE

5.1 DESCRIPTION OF COLLIMATOR LOCATIONS

The aim in the determination of the collimator position is to obtain the best performance (optimal phase advance differences) compatible with the boundary conditions given by integration issues (available space).

The position of the momentum collimator is chosen at the first available space where the ratio $D/\sqrt{\beta}$ is at a maximum. In **TI 2 this is in the vertical plane** downstream of quadrupole MQIF20600, as shown in Figure 11. In **TI 8 this is in the horizontal plane** close to MQIF81800, as shown in Figure 16.

The positions of the betatron collimators towards the end of the lines are as shown in Figure 2 and Figure 3 and are determined in several steps.

A first set of positions is obtained from optics considerations alone, with as starting point the position of the collimators upstream of the MSI septum (TCDIMSI V, H). The other collimators are positioned upstream of these septum collimators such that the difference in phase advance is as required (90 degrees and 45 and 135).

Due to major interferences with transfer line magnets, several collimators had to be moved upstream by 180 degrees (225 degrees instead of 45 degrees in both planes in TI 2 and in the horizontal plane in TI 8, 315 degrees instead of 135 degrees in H in TI 8).

Other positioning constraints meant that variations of a few degrees with respect to the ideal phase advance distances were necessary in some cases (one degree in phase advance corresponds very roughly to one meter displacement along the line).

Table 1 and Table 2 give the collimator end positions and optical parameters at these positions, both for the stage 1 and 2 collimators. The optics parameters are:

Dx, Dy : horizontal and vertical dispersion;

βx, βy : horizontal and vertical betatron function;

σxd, σyd : horizontal and vertical rms beam size with dispersion;

Δμ : phase advance of the object from TCDIMSI / 2π (1 unit=360 degrees):

The beam sizes are based on a normalized emittance of 3.5 mm mrad [8] and a relative rms energy spread of $3.06 \cdot 10^{-3}$ [9]. It is foreseen to set the collimator jaws at ±5σ of the beam size with dispersion, or 10σ between jaws. As example, the nominal setting for TCDIV90 where σ_{yd} = 0.571 mm corresponds to a distance between the jaws of 5.71 mm. The positions are given at the end positions with respect to s = 0 m at "TI2$START" or "TI8$START" = "EJECTPT".

Table 1 - Optics parameters at chosen collimator locations for the transfer line TI 2.

***Name* [m]**	***s* [m]**	***βx* [m]**	***Dx* [m]**	***σx_d* [mm]**	***βy* [m]**	***Dy* [m]**	***σy_d* [mm]**	***Δμ to TCDI_MSI* [°]**
$TCDI_{Mom}$	403.12	95.39	-0.041	0.834	19.44	-1.490	0.591	29.51 in y
$TCDI_{H225}$	2868.14	37.87	-0.375	0.538	61.90	0.023	0.672	204.40 in x
$TCDI_{V225}$	2902.14	81.89	-1.358	0.878	58.65	-0.266	0.579	225.06 in x
$TCDI_{V135}$	2962.34	96.41	-2.328	1.100	48.52	-0.140	0.597	132.49 in y
$TCDI_{H135}$	2975.58	45.22	-1.649	0.764	95.01	-0.117	0.833	135.02 in x
$TCDI_{H090}$	3006.47	44.42	-1.231	0.683	96.42	-0.084	0.839	87.47 in x
$TCDI_{V090}$	3026.18	122.47	1.413	1.040	44.67	-0.053	0.571	90.06 in y
$TCDI_{HMSI}$	3112.78	43.65	-0.232	0.569	198.38	0.033	1.203	0
$TCDI_{VMSI}$	3114.78	47.23	-0.212	0.591	185.91	0.046	1.165	0

Table 2- Optics parameters at chosen collimator locations for the transfer line TI 8.

***Name* [m]**	***s* [m]**	***βx* [m]**	***Dx* [m]**	***σx_d* [mm]**	***βy* [m]**	***Dy* [m]**	***σy_d* [mm]**	***Δμ to TCDI_MSI* [°]**
$TCDI_{Mom}$	670.67	91.73	-4.437	1.585	22.11	0.000	0.402	23.7 in x
$TCDI_{H315}$	2387.83	17.80	-2.014	0.714	69.92	-0.983	0.775	312.0 in x
$TCDI_{H225}$	2398.24	7.10	-0.508	0.276	149.82	-1.350	1.124	238.8 in x
$TCDI_{V135}$	2436.00	194.51	2.703	1.450	55.44	-0.373	0.646	134.9 in y
$TCDI_{V090}$	2485.90	108.05	2.478	1.168	55.21	0.101	0.636	88.7 in y
$TCDI_{V045}$	2515.01	75.54	2.059	0.974	58.74	0.129	0.656	45.0 in y
$TCDI_{H090}$	2549.08	26.65	1.088	0.553	141.17	0.155	1.016	83.8
$TCDI_{HMSI}$	2623.58	40.74	-0.527	0.569	172.13	-0.029	1.112	0
$TCDI_{VMSI}$	2626.02	44.02	-0.629	0.599	161.82	-0.034	1.087	0

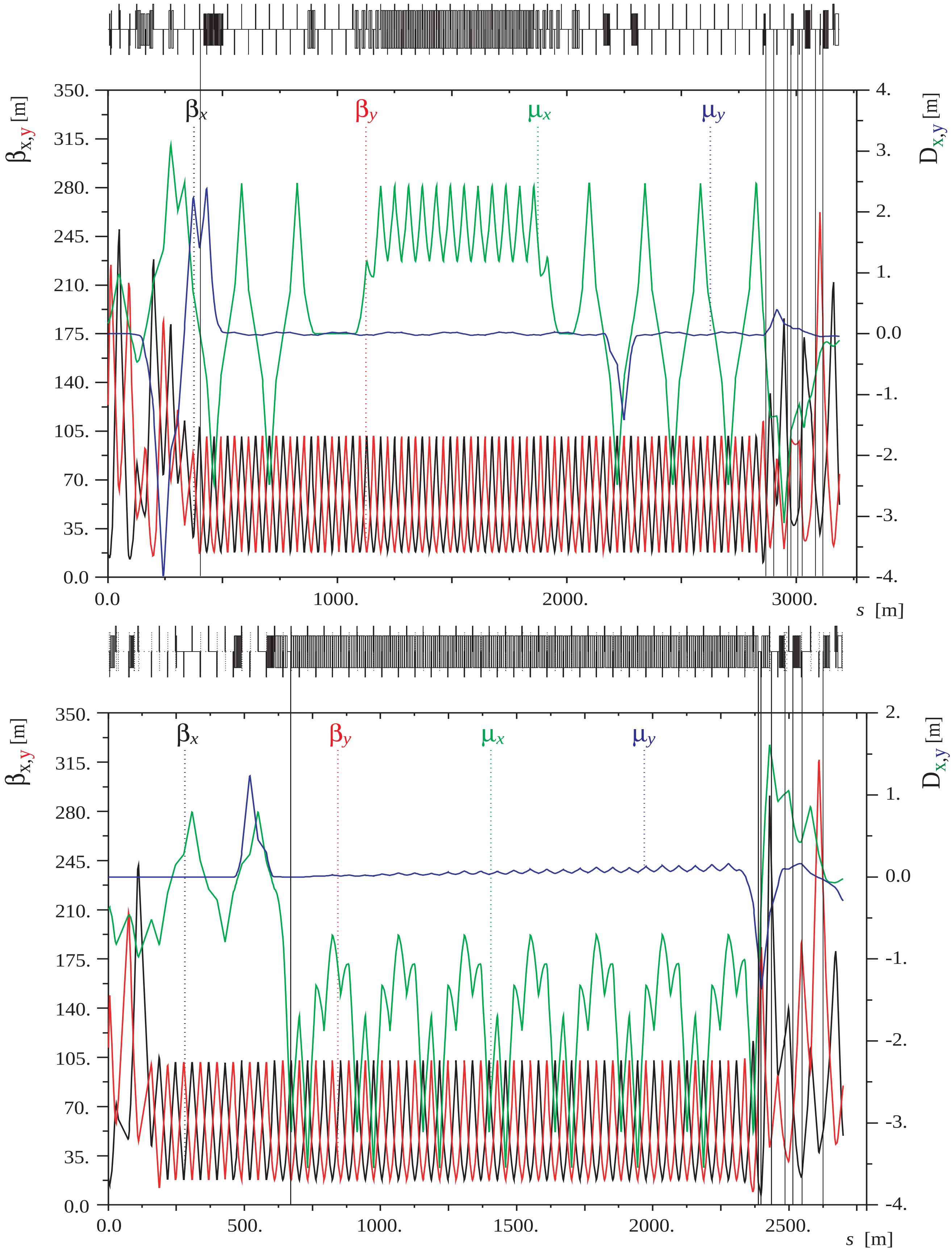

Figure 2 - Sequence of elements, betatron and dispersion functions in TI 2 (top) and TI 8 (bottom). The position of the TCDI collimators is shown by vertical lines. More detailed views towards the end of TI 2 and TI 8 are shown in Figure 3.

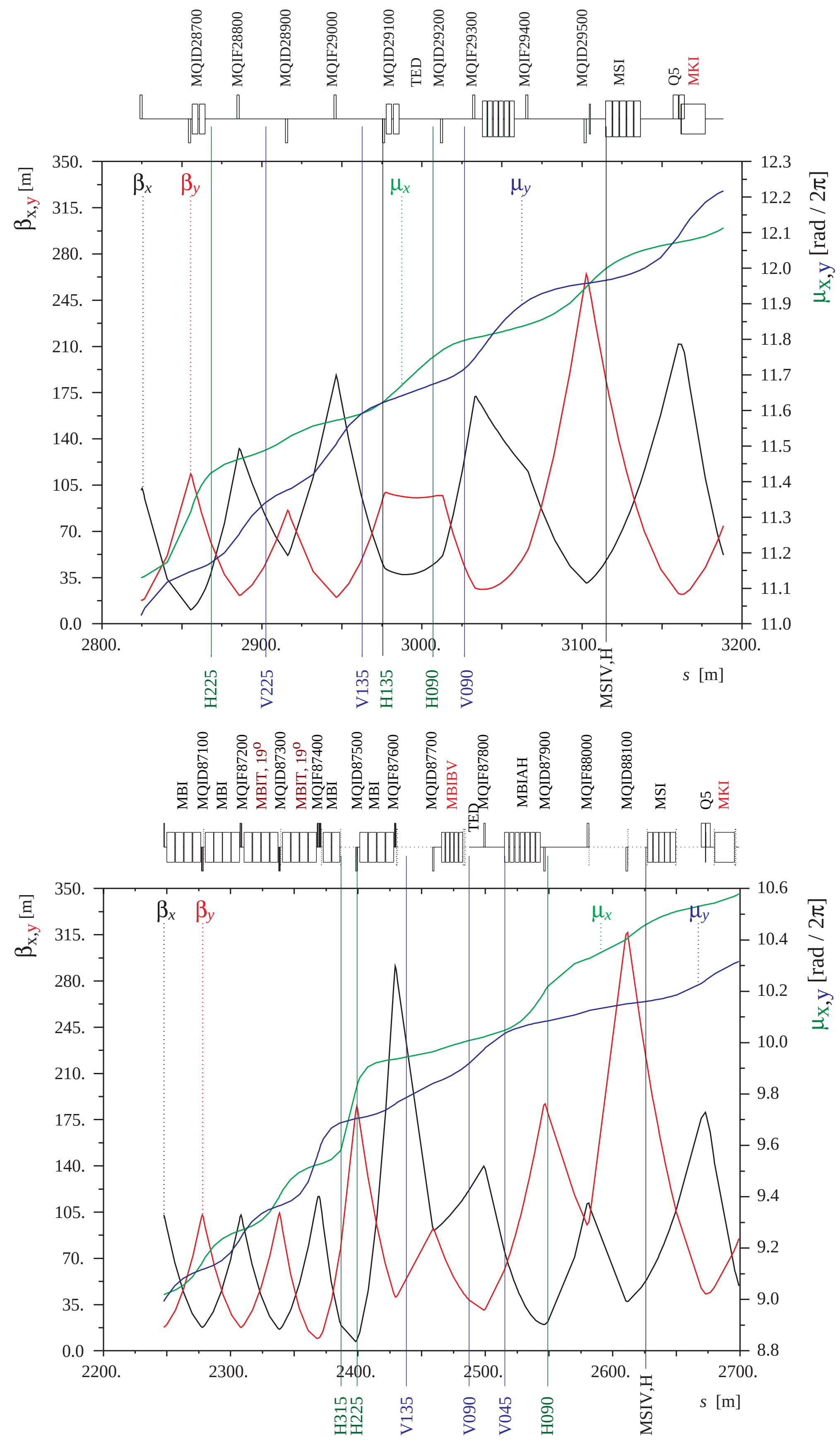

Figure 3 - Sequence of elements, betatron functions and phase advance towards the end of TI 2 (top) and TI 8 (bottom). The position of the TCDI collimators is shown by vertical lines.

5.2 COLLIMATOR PERFORMANCE

Figure 4 illustrates the boundaries in normalized phase space obtained from collimation at 5σ. In stage 1, the normalized phase space is reduced by the 0 (TCDIMSI) and 90 degree collimators to a square with limits at 5σ. The diagonal extends to 7.1σ (5 σ / cos 45°). The collimators in stage 2 at 45 and 225 degrees reduce the maximum amplitude from 7.1 to 5.4σ (5σ / cos 22.5°).

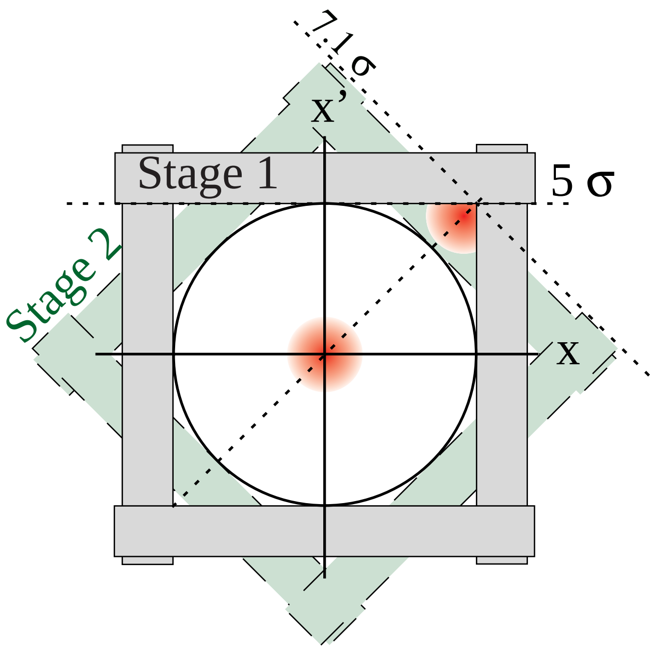

Figure 4 - Illustration of the phase space limits obtained with the collimators of stage 1 and 2.

6. CONCEPTUAL DESIGN

6.1 CONFIGURATION, SIMULATION RESULTS AND EXPECTED PERFORMANCE

Detailed simulations have been carried out to optimise the protection level and define the overall collimation concept, using FLUKA [10]. A simplified geometry was considered for a typical collimator position. The protection elements and magnets were defined as parallelepipeds or concentric cylinders with a fairly realistic vacuum chamber configuration. Different materials and dimensions were investigated and a preliminary solution defined. A range of beam impact parameters was considered, as defined by an estimate of the expected failure modes. A full description of the studies is given in [11]. The chosen version is described below.

6.1.1 PRELIMINARY CONCEPT

The preliminary conceptual design study results favour using mobile plane parallel carbon diluter jaws, with 2 jaws in either the H or V plane. An independent movement in vacuum of the jaws should be accomplished by 4 motors per collimator.

The length of the block is defined primarily by the interaction length required to achieve the necessary attenuation of the primary proton beam energy density. Using a 1.2m jaw made of 2.0g/cc carbon, with a 41 cm nuclear inelastic interaction length, an attenuation at the magnet of the primary proton beam by a factor of about 22 is obtained. For realistically-available carbon grades of 1.77g/cc this attenuation will be reduced to about a factor of 16. However, in addition to the primary beam attenuation, scattering of the remaining transmitted protons (via multiple Coulomb and nuclear inelastic scattering) produces an additional and significant reduction in the energy density on downstream elements, due to the very large increase in the beam emittance, such that the energy density is reduced well below the damage threshold after a few metres drift distance.

This is an important result, since diluter blocks of maximum 1.2m length are strongly preferred in order to profit from the reuse of the design of the LHC secondary collimators. In order to allow such short collimator jaws it is, however, necessary to include secondary iron shielding, just upstream of the transfer line magnets and outside the vacuum chamber, of around 0.5 m in length. This shielding protects the magnets from the high flux of particles which in the simulation is observed to scatter out of the face of the collimator for shallow (~1σ) impact parameters.

6.1.2 LAYOUT

The TCDIH090 upstream of MQID292 (TI 2), Figure 5 below, was used for the FLUKA modelling. The exit face of the collimator is about 6 m from the entrance of the magnet, with a horizontal gap between the collimator jaws of 6.8 mm (10 σ). A jaw 4 cm high and 5 cm wide was assumed, with a length of 1.2 m.

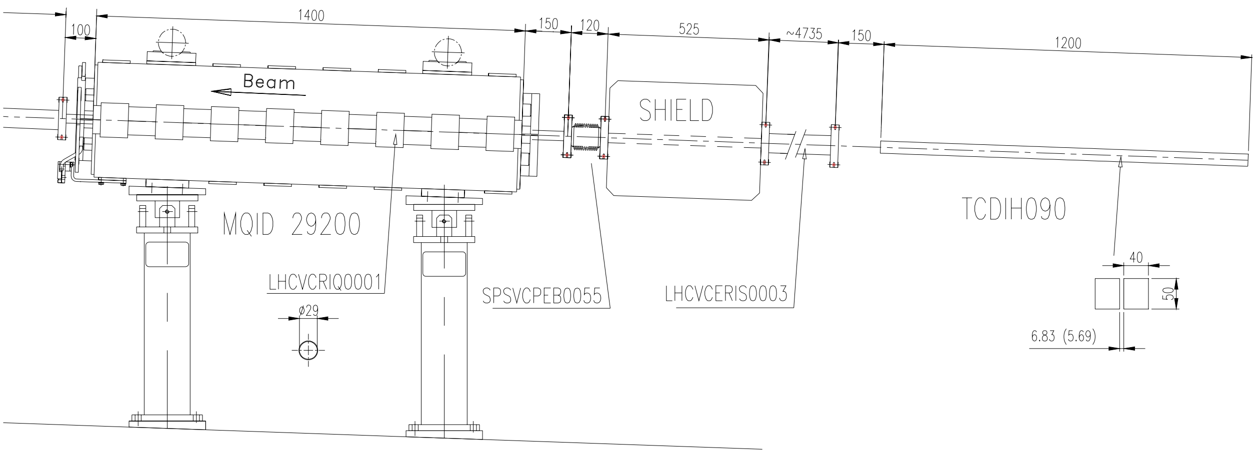

Figure 5 - Machine layout for TCDIH090 upstream of MQID29200.

6.1.3 SIMULATION PARAMETERS

The beam and simulation parameters used are summarised in Appendix 1. A monochromatic beam was assumed, with a full Gaussian beam distribution of positions in H and V for the specified emittance.

6.1.4 ENERGY DEPOSITION AND HEATING IN THE CARBON COLLIMATOR

The energy deposition in GeV/cm3/proton was calculated for the parameters given in Appendix 1, with a beam impact at 15 mm from the chamber axis, corresponding to the maximum possible defined by the aperture of the transfer line magnets. The binning used was 5 cm longitudinally and 0.2 mm in the X and Y planes. The energy deposition in the bins on the beam axis was used to calculate the expected temperature rise in the carbon. The heat capacity C_v [J/K/kg] was assumed to vary with temperature in °C [12] as:

$$C_v(T) = 528.75 - 205.9\,T^{1/3} + 154.21\,T^{1/2} - 1.53\,T + 9.15\times10^{-5}\,T^2$$

The results are shown in Figure 6. The maximum local instantaneous temperature rise is 990 K for the ultimate beam, some 20-25cm from the entrance face of the collimator jaw.

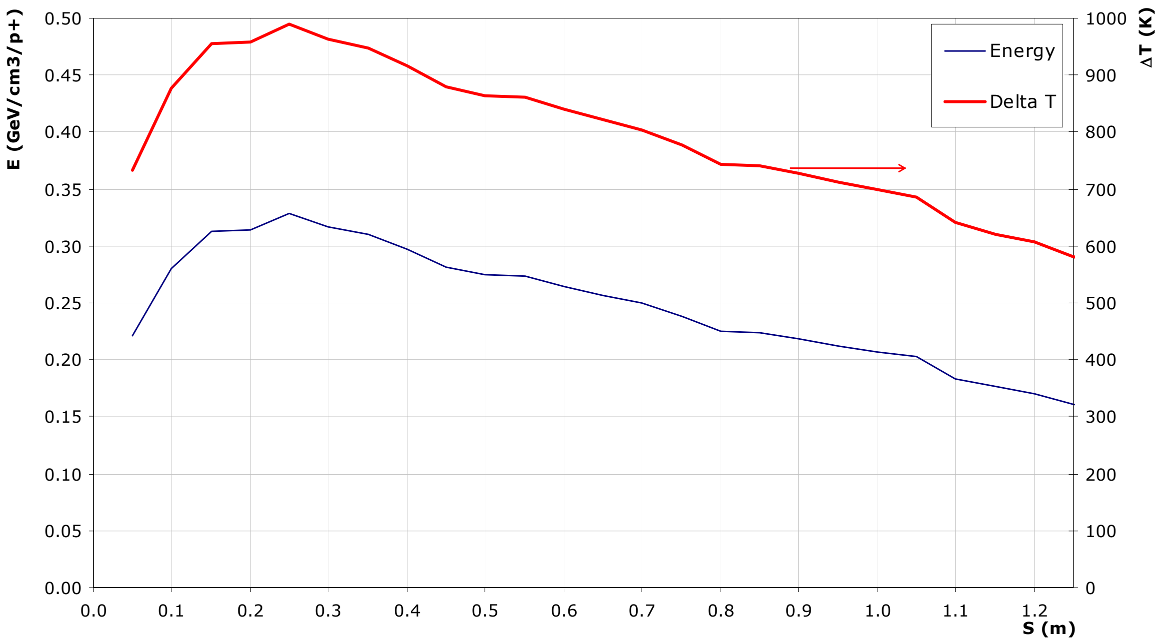

Figure 6 - Energy deposition per proton [GeV/p+/cm^3] and resulting temperature rise [K] for ultimate LHC beam intensity.

The total energy deposited in each 5cm longitudinal bin was summed and the average calculated for each segment (100 cm^3). The results are shown in Figure 7, with the resulting temperature rise per segment, from which the overall thermal dilatation after a full beam loss can be derived.

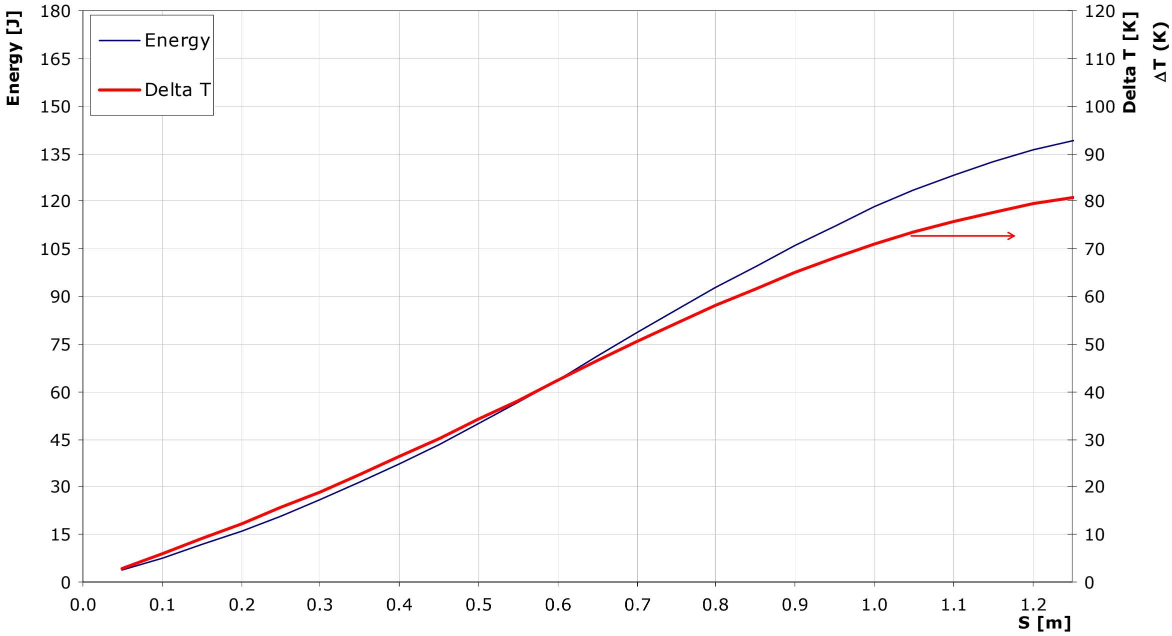

Figure 7 - Total energy deposited [J] per 5 cm, average 100 cm^3, long block, and resulting temperature rise [K], for ultimate LHC beam intensity.

6.1.5 VACUUM ELEMENT AND IRON SHIELD HEATING

For an impact parameter of 1 σ, the temperature rise in the vacuum elements upstream of the shield is around **75 K** for ultimate beam intensity. For the iron shield itself the temperature increases is about **205 K**, see Figure 8 and Figure 9, which is acceptable for this passive element.

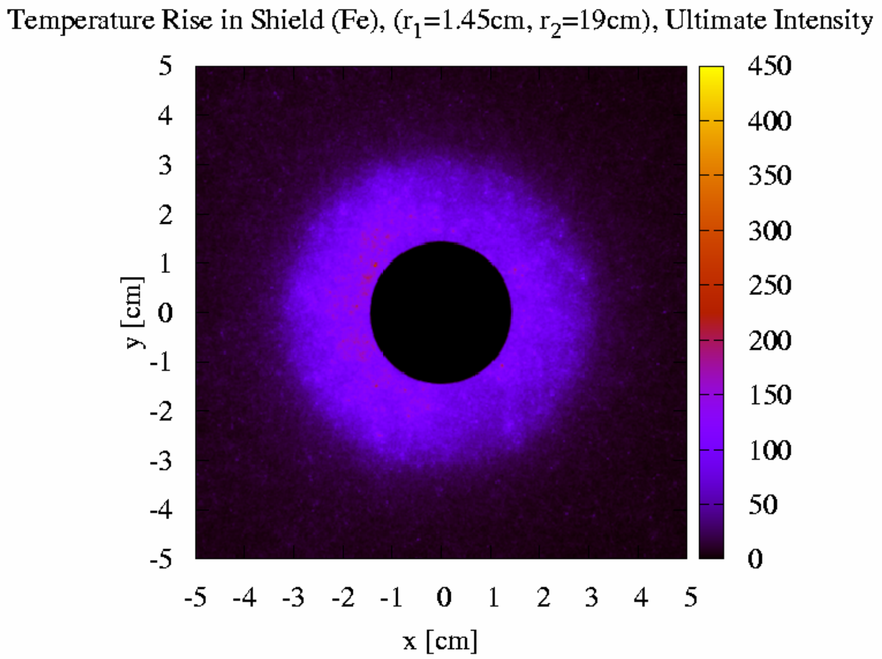

Figure 8 - Temperature rise in Fe shield for 1.2 m C jaw at ultimate intensity.

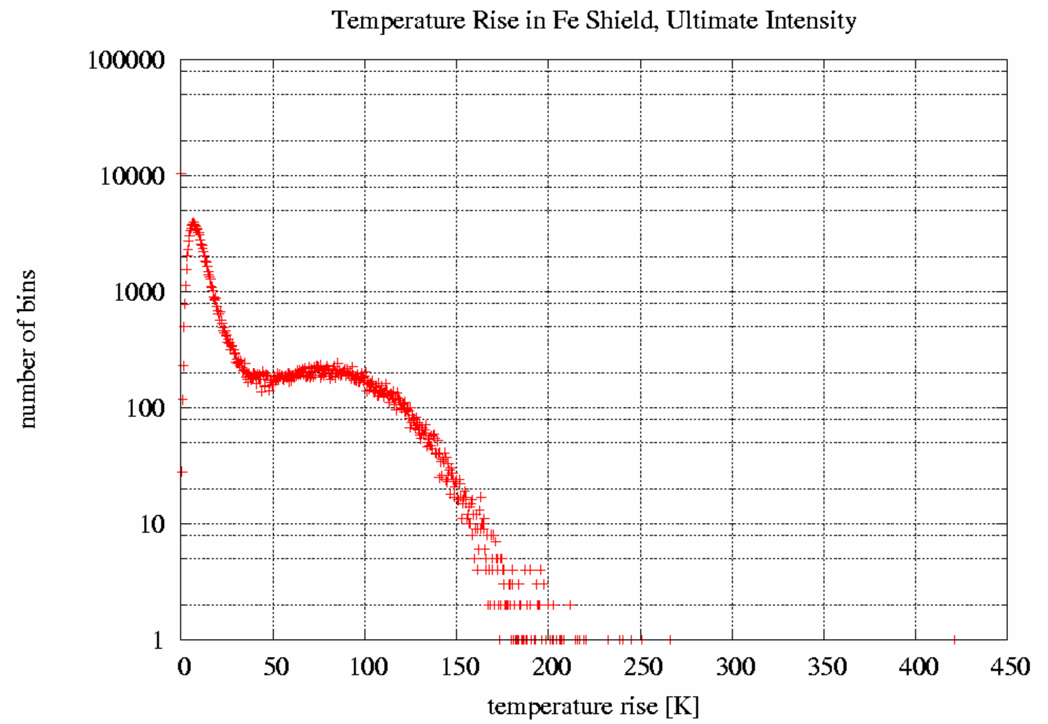

Figure 9 - Distribution of bins with a given temperature rise in Fe shield for 1.2 m collimator jaws for ultimate intensity. Peak temperatures of about 205K are observed.

6.1.6 TRANSFER LINE MAGNET HEATING

For an impact parameter of 1 σ, the maximum temperature rise in the Cu part of the magnet downstream of the shield is **80K** for ultimate beam intensity. The temperature rise in the Fe part is **15K** respectively, as shown in Figure 10.

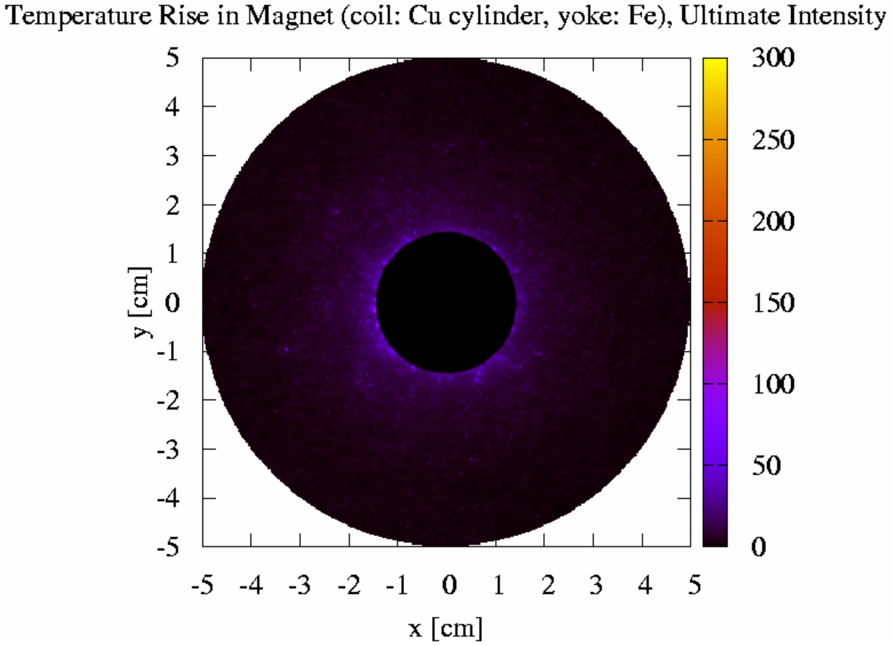

Figure 10 - Temperature rise in magnet coil (Cu) and yoke (Fe) for 1.2m C jaw with 50cm Fe shield, at ultimate intensity.

6.1.7 ATTENUATION OF PRIMARY PROTON BEAM

The attenuation of the primary proton beam energy density should be at least a factor of 20 for protection of the LHC machine elements.

The FLUKA results with 2.0 g/cc graphite show that an attenuation in the primary beam of a factor of **~19** (exp(l/λ) is achieved at the exit face of the C jaw. With the 1.2 m jaw length, this implies an inelastic nuclear interaction length λ of ~0.41 m, in agreement with quoted values [13]. (An attenuation of ~14 is expected for 1.77 g/cc graphite.)

The results also show that the surviving 5.4 % of the protons exit the C jaw with large angles (typically several 100 μrad) due to multiple coulomb and nuclear elastic scattering, which produces an emittance growth of a factor of **>400** in each plane. This produces a large additional attenuation of the energy density on the beam axis for downstream elements – in a test ellipse spanning ±5 σ in both H and V at the entrance face of the downstream quadrupole, 4.5 % of the primary protons were counted, corresponding to a total attenuation factor of **22**. (A total attenuation of ~16 is expected for 1.77 g/cc graphite.)

These results were cross-checked with simple nuclear and elastic scattering formulae, which predict that the beam emittance increases by a factor of between 40 (multiple Coulomb) and 600 (elastic) in each plane [14], in broad agreement with the FLUKA results.

Overall, even for 1.77 g/cc graphite the primary beam attenuation is already near the required level due to inelastic scattering in the collimator jaw, and the emittance growth of a factor >400 for the remaining protons provides significant additional safety margin in the design.

6.2 SIMULATION CONCLUSIONS

The main results of the simulations for the test geometry with a 1.2m long C jaw and 0.5m long Fe shield are shown in Table 3.

Table 3 - Summary of main simulation parameters and results for 1.2m jaw made from 2.00 g/cc graphite, and 0.5m Fe shield, at ultimate beam intensity.

	Graphite Density	*g/cm³*	2.00
	Attenuation factor primary p+ beam		~19
	Attenuation of primary p+ beam at magnet		~22
	Increase in beam emittance (X,Y)		~400
	Maximum energy deposition in C jaw	*[GeV/p+/cm³]*	0.33
	Maximum energy deposition in C jaw	*[J/g]*	1450
Maximum temperature rise in:	C jaw	*[K]*	990
	Vacuum system	*[K]*	75
	Fe shield	*[K]*	205
	Magnet coil Cu	*[K]*	80
	Magnet yoke Fe	*[K]*	15
Average temperature rise in:	C jaw	*[K]*	40

In view of the above results, a 1.2 m jaw length is recommended to achieve the required primary beam attenuation, combined with a 0.5 m long secondary Fe shield outside the vacuum chamber, to intercept particles out-scattered from the collimator face. A diluter density of 2.00 g/cc will ensure the required protection level even neglecting any emittance growth effects; if 1.77 g/cc graphite is preferred, the attenuation factor combined with the emittance growth should also guarantee adequate protection after a short drift distance.

6.3 THERMO MECHANICAL STRESSES AND DILATATION

The subject of thermal mechanical stresses will be treated in a separate technical specification for study of the thermal behaviour of the TCDI collimator block [15]. Nevertheless, the design of the TCDI system must take into account the estimated thermal expansion of the TCDI absorber elements due to bake-out and beam impact.

Table 4 - Estimated thermal expansion due to bake-out and beam impact at nominal intensity (h·w·L=40·50·1200 mm).

Material	**Impact** [°C]	Coefficient α [K^{-1}]	Δh [mm]	Δw [mm]	ΔL [mm]
Graphite	40	2-3.8 x 1E-6	0.01	0.01	0.18

Material	**Bake-out** [°C]	Coefficient α [K^{-1}]	Δh [mm]	Δw [mm]	ΔL [mm]
Graphite	250	2-3.8 x 1E-6	0.04	0.05	1.14

The estimated thermal expansion due to bake-out and beam impact at ultimate intensity are shown in **Error! Reference source not found.**, based on the total energy deposited and average temperature rise along a 1.2 m graphite TCDI collimator blocks as shown in Figure 7.

6.4 RADIOLOGICAL AND ENVIRONMENTAL ISSUES

In case of an accidental beam loss in the collimator, no machine intervention close to the affected equipment should be performed during the following 12. After this waiting time a detailed work planning has to be prepared in order to minimize the dose which will be received by the personnel [16]. The intervention time in areas showing a dose rate above 2 mSv/h must be severely limited. After one week of cooling, access for personnel qualified to work in radioactive zones can be granted to most areas. However, work close to the collimator and the downstream equipment still has to be well prepared and limited in time.

For machine interventions after 200 days of normal operation, access can be granted already after one hour of cooling. Only personnel qualified to work in radioactive areas will be allowed to enter this zone. For work in this area job and dose planning should be performed in order to minimize the dose collected by the personnel.

7. LAYOUT AND INTEGRATION

The positions of the collimators are optimised and determined as described in section 5.1 and the proposed positions of the collimator are given in Table 1 for TI 2 and Table 2 for TI 8.

7.1 INTEGRATION TI 2

7.1.1 TI 2 STAGE 1

The proposed collimator positions for the stage 1 installation in TI 2 are as shown in Figure 11, Figure 12, Figure 13 below. Sufficient space will be available for the integration of TCDIMom, TCDIH090 and TCDIV090. The reserved space for cryo-magnet transportation in UJ22 needs to be taken into account, the critical distance between this space and the beam axis being ~400 mm.

The integration of the TCDIMSI will be more complicated due to the fact that in this area the injected beam-pipe will be in close proximity to the vacuum chamber of the circulating beam.

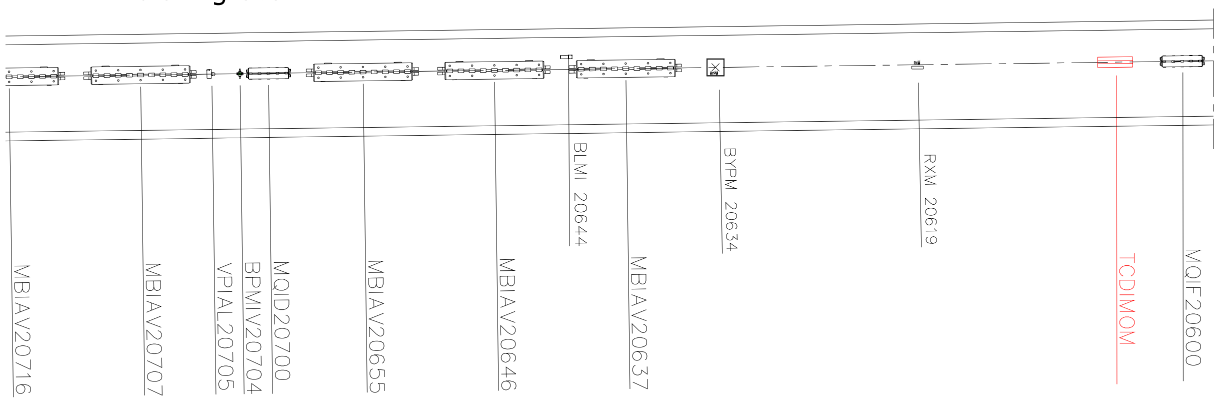

Figure 11 – Position of TCDIMom in TI 2.

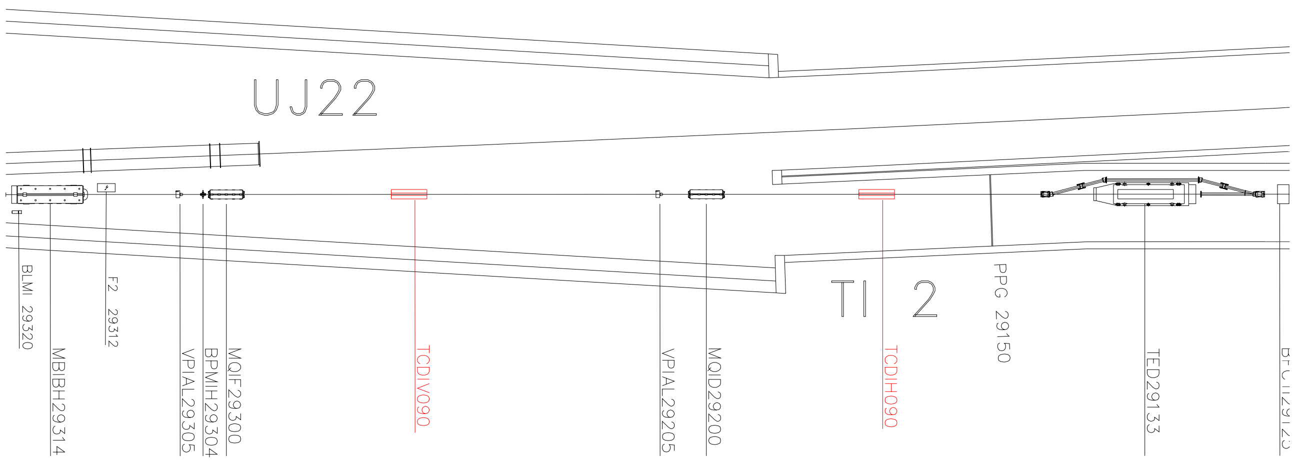

Figure 12 – Position of TCDIH090 and TCDIV090 in TI 2.

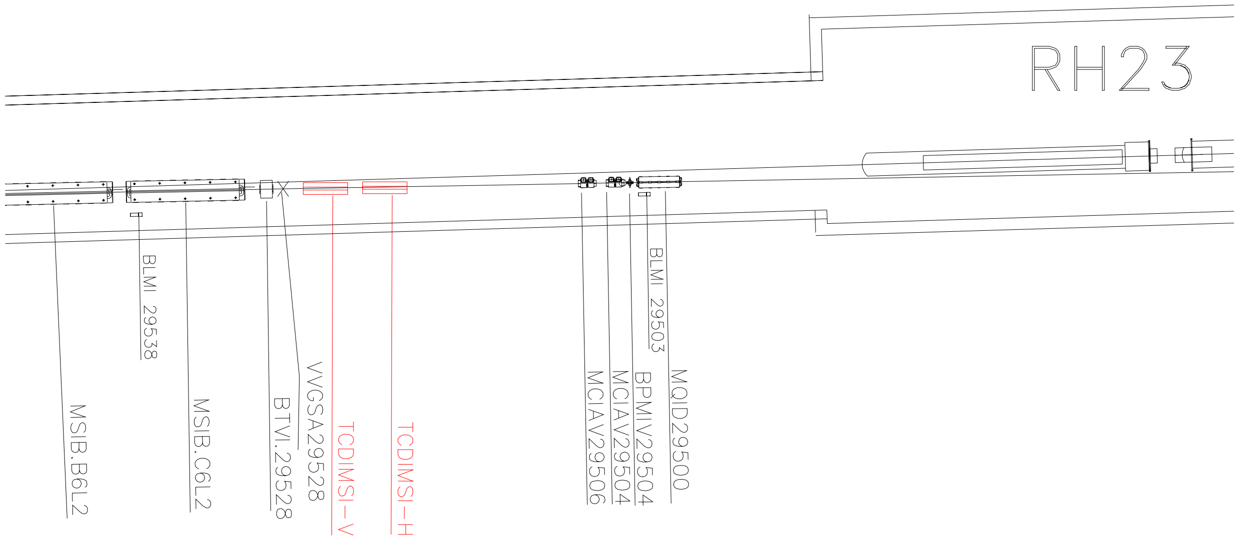

Figure 13 – Position of TCDIMSI in TI 2.

7.1.2 TI 2 STAGE 2

The proposed collimator positions for a latter upgrade in TI 2 are shown in**Error! Reference source not found.** Figure 15 and Figure 14 below. As mentioned in 5.1, integration of the initial forseen 45 degrees position was not possible and 225 degrees is choosen instead. The situation of TCDIH135, TCDIV135, TCDIH225 and TCDIV225 is identical as for TCDIMom in stage 1 and sufficient space for integration will be available.

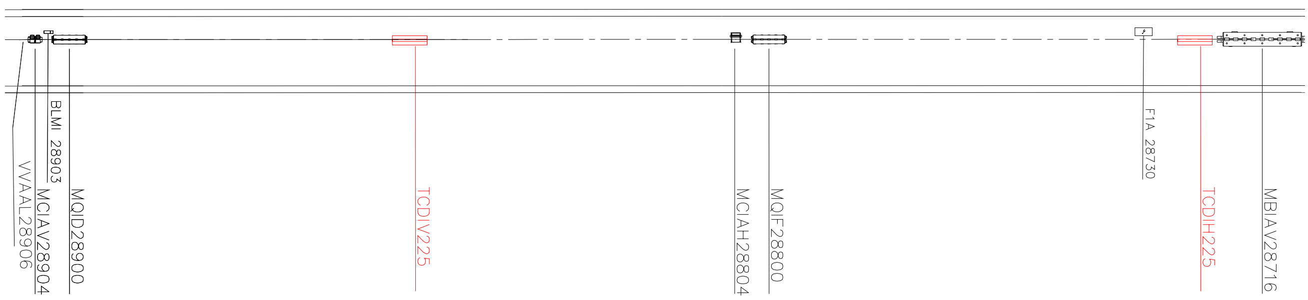

Figure 14 – Position of TCDIV225 and TCDIH225 in TI 2.

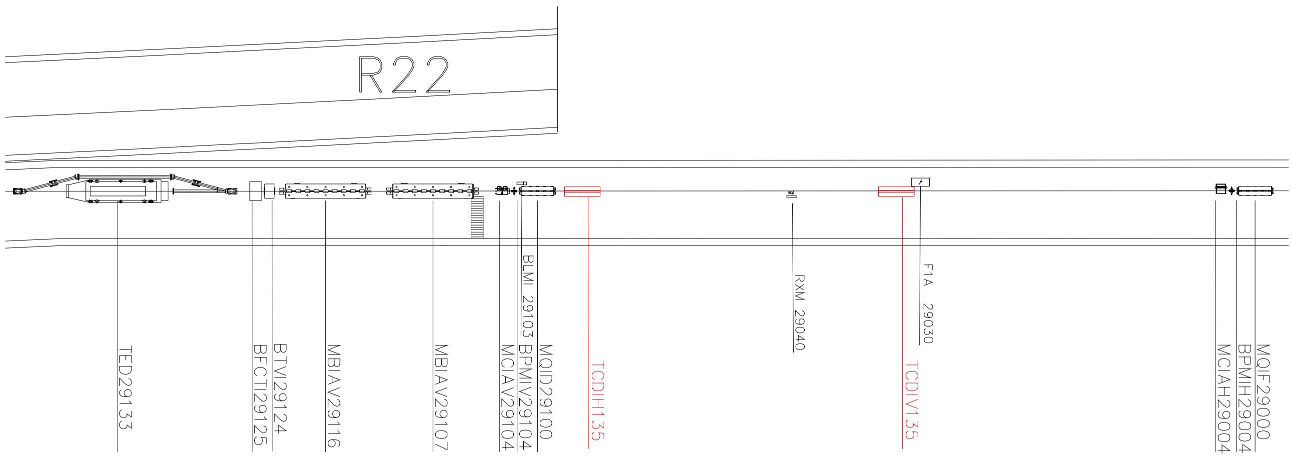

Figure 15 – Position of TCDIH135 and TCDIV135 in TI 2.

7.2 INTEGRATION TI 8

7.2.1 TI 8 STAGE 1

The proposed collimator positions for the initial installation in TI 8 are as shown in Figure 16, Figure 17, Figure 18 and Figure 19 below. The proposed position of the TCDIMom is directly downstream of MQF81800. As shown in Figure 16, integration is possible but tight due to the position of BYPM81756, which could slightly be moved downstream in case of interference.

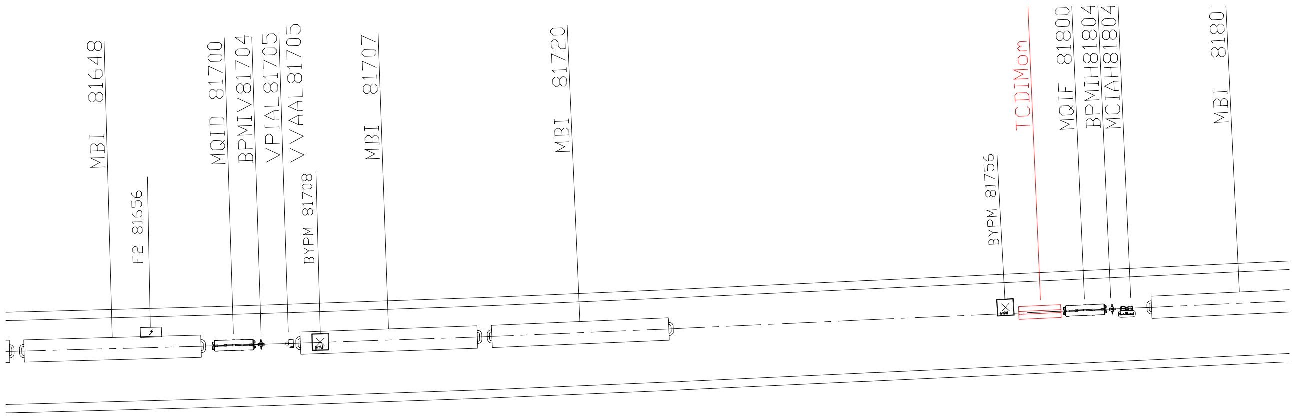

Figure 16 – Position of TCDIMom in TI 8.

Taking into account the reserved space for magnet transportation, sufficient space will be available for the integration of TCDIH090 and TCDIV090, although the tunnel wall is at near proximity at position TCDIH090. Also the integration of the TCDIMSI in TI 8 will be more complicated due to the fact in this area the injected beam-pipe will be in near proximity to the stored LHC beam-pipe. In some cases, the ideal collimator position is already taken by other beam line equipment and a nearby compromise position was found.

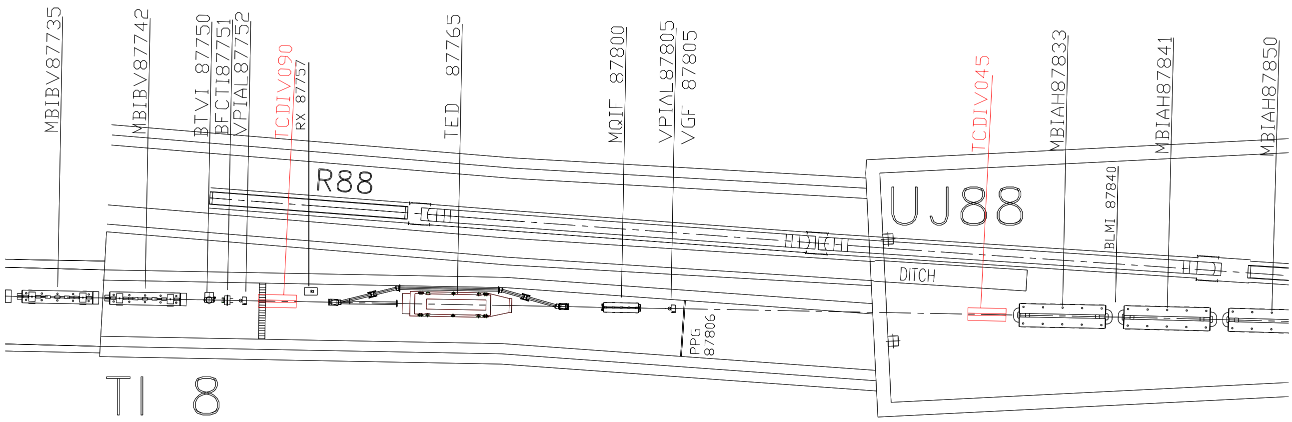

Figure 17 – Position of TCDIV090 in TI 8, the position of TCDIV045 for stage 2 is also shown.

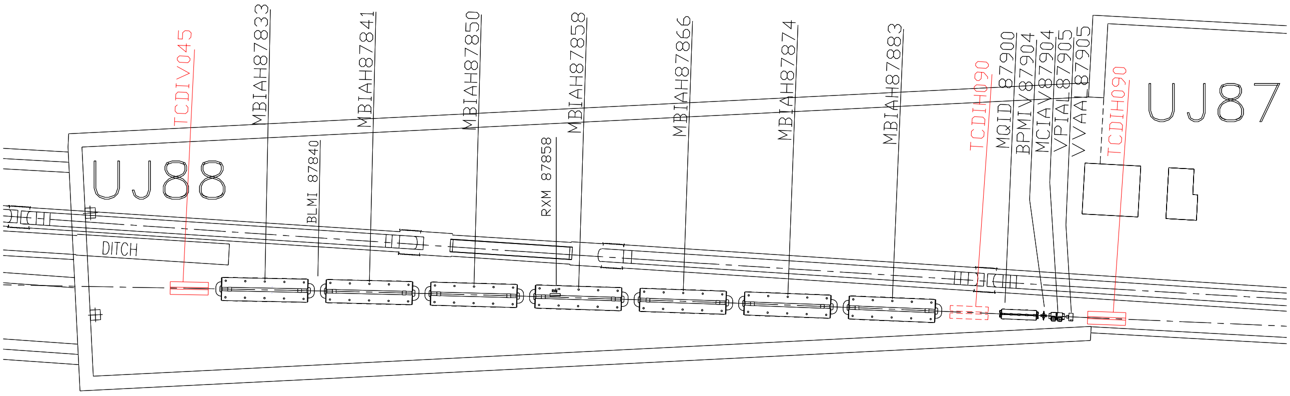

Figure 18 – Position of TCDIH090 in TI 8 (the altenative dashed position just downstream of MQID87900 gives a phase advance of about 84 degrees just upstream would give 96 degrees), the position of TCDIV045 for stage 2 is also shown.

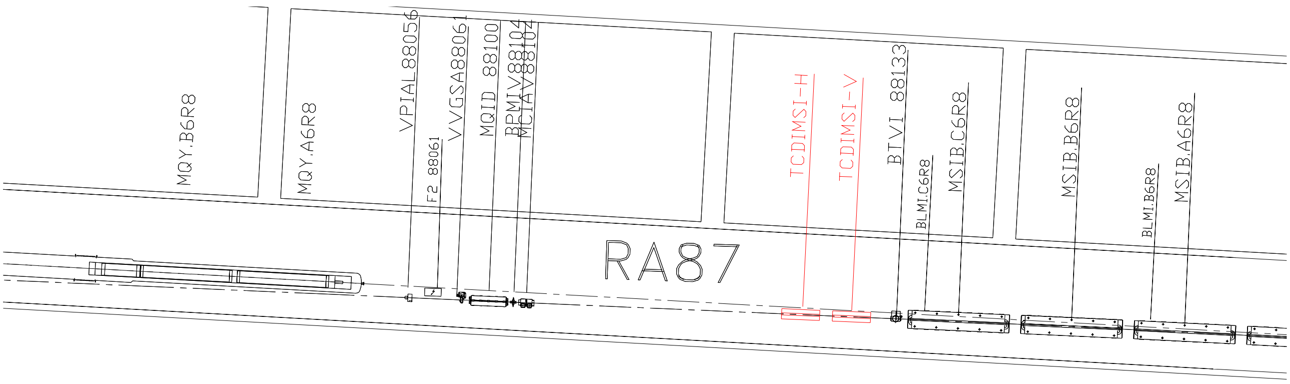

Figure 19 – Position of TCDIMSI in TI 8.

7.2.2 TI 8 STAGE 2

The proposed collimator positions for a latter upgrade in TI 8 are as shown in Figure 18 above and Figure 20 below. Integration of these objects will inflict no major problems. In order to match the optimal phase advance, TCDIH315 should be placed as close as possible downstream of MBI87424 and TCDIH225 as close as possible upstream of MQID87500.

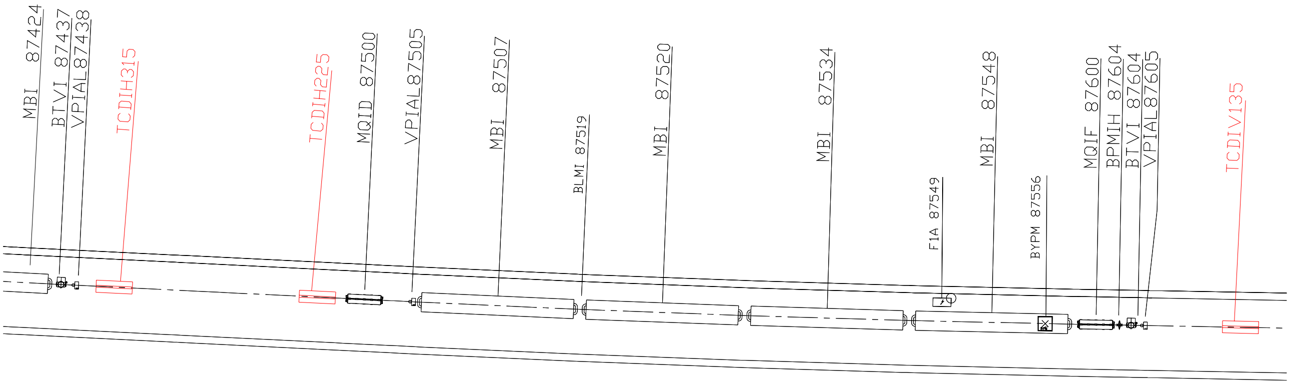

Figure 20 – Position of TCDIV135, TCDIH225 and TCDIH315 in TI 8.

8. INSTRUMENTATION

8.1 EQUIPMENT SURVEILLANCE

The TCDI shall be equipped with temperature sensors in such a way that the temperature profile of the collimator blocks can be monitored.

8.2 BEAM INSTRUMENTATION

In order to control the correct jaw settings, each TCDI collimator shall be equipped with Beam Loss Monitors (BLMs), in sufficient numbers and adequately positioned. Alternatively, BLM's installed at other positions of the transfer lines could be moved closer to the TCDI positions.

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APPENDIX 1– TCDI SPECIFICATION DATA SHEET

Operation Conditions		
Beam parameters		
Proton energy	450	GeV
Nominal emittance (ε_N)	3.5	mm.mrad
Emittance (ε)	7.82	nm
Number of batches	3 or 4	
Bunches per batch	72	
Protons per bunch (nominal)	$1.1 * 10^{11}$	
Protons per bunch (ultimate)	$1.7 * 10^{11}$	
Number of bunches	288	
Beta function (H/V)	44 / 96	m
Energy spread $\Delta E/E$	$3.06 * 10^{-4}$	
Simulation parameters and results		
Graphite density	2	g/cm^3
Attenuation of primary p+ beam	~19	
Attenuation of primary p+ beam at magnet	~22	
Increase in beam emittance (X,Y)	~400	
Maximum energy deposition in C jaw	0.33	[GeV/p+/cm^3]
Maximum energy deposition in C jaw	1450	[J/g]
Maximum temperature rise in: C jaw	990	K
Vacuum system	75	K
Fe shield	205	K
Magnet coil Cu	80	K
Magnet yoke Fe	15	K
Average temperature rise in: C jaw	40	K