Chapter 11

Collimation system

2982 11.1 Introduction

In order to achieve a high luminosity at 50 TeV, a high beam current is required in the FCC-hh. Combined with the 50 TeV particle energy, this results in a stored beam energy of about 8.3 GJ, assuming the baseline parameters of 10400 bunches of 10¹¹ protons per bunch. This is about a factor 24 higher than the nominal LHC and a factor 12 higher than the HL-LHC. Therefore, the FCC-hh beams are highly destructive and open up a new regime in terms of machine protection considerations. Absorbing the energy of even very small beam losses becomes challenging.

To achieve the high per particle energy, strong magnetic fields are needed, which demands the usage of superconducting magnets operating at cryogenic temperatures. A loss of a small fraction of the beam can deposit enough energy such that the induced heat in a cold magnet moves it to a normalconducting state, known as a quench. To avoid this, a collimation system must be installed to protect the magnets from beam losses, which is the main topic of this chapter. The development of the design of the various aspects of FCC-hh collimation has been documented in previous publications [15, 26, 27, 86].

In addition to the regular cleaning losses that are expected to occur routinely, the collimation 2995 system must also protect machine elements against damage during irregular and accidental beam losses 2996 that could occur, e.g. injection and extraction kicker miss-fires, or failures of other elements. If needed, 2997 the collimators can be sacrificed in order to prevent beam losses into more critical locations, such as the 2998 experimental detectors. Furthermore, the collimation system should also localise the losses and hence 2999 the radiation dose to controlled areas, and if needed help in reducing machine-induced experimental 3000 backgrounds, all while keeping the machine impedance within acceptable limits. This latter point is 3001 discussed in sections 10.3.5 and 10.3.6. 3002

Beam loss rates in the FCC-hh are very hard to predict and depend on a number of unknowns, but 3003 regular operation and tuning of the machine requires that a reasonable range of beam lifetimes (BLT) can 3004 be handled without a beam dump, quench or collimator damage. For the design and specification of the 3005 collimation system, we assume as a target that the FCC-hh should be able to sustain betatron losses due 3006 to a BLT drop down to 12 minutes over a time period of 10 s, and a BLT of 1 h in steady state. The former 3007 scenario corresponds to an extreme instantaneous beam loss power of 11.6 MW. These design scenarios 3008 have been taken over from the LHC design [194]. Although LHC operation in Run 2 has very rarely 3009 resulted in such pessimistic losses, these criteria are conservatively taken over for the FCC-hh design. 3010

For off-momentum losses, the most critical scenario is taken to be the losses at the start of the energy ramp, where any off-energy tail outside of the RF buckets is rapidly lost as the acceleration starts [195]. Based on LHC experience, we use as a design criterion for the collimation system that the machine should be able to routinely handle losses of 1% of the total beam intensity over 10 s [196]. This

2978

2979

2980

2981

³⁰¹⁵ assumes that the rate of change of the energy at the start of the ramp is similar to that of the LHC.

The baseline FCC-hh collimation system is based on the experience of the design and operation of the LHC system [17–21, 197, 198], as well as foreseen upgrades for HL-LHC [23, 25, 199–201].

The baseline concept and layout of the collimation insertions for FCC-hh are described in 3018 Sec. 11.2, and the geometric considerations for protecting the machine aperture are shown in Sec. 11.3. 3019 The cleaning performance of the system is assessed in Sec. 11.4 through tracking simulations, which are 3020 used to estimate the resulting beam loss pattern and power loads around the ring for various expected 3021 loss scenarios. Detailed energy deposition studies are presented for the most critical cold region in 3022 Sec. 11.5 and for the warm betatron cleaning insertion in Sec. 11.6. The thermo-mechanical response of 3023 the most loaded collimators during expected loss scenarios is investigated in Sec. 11.7, while an outlook 3024 on future developments is given in Sec. 11.8. 3025

3026 11.2 Baseline collimation concept and layout

Two main collimation insertions are used; a betatron system in IRJ for removing particles that have a large amplitude in transverse phase space, and a momentum collimation system in IRF, for removing particles with a large rigidity offset. In addition to these two insertions, collimators exist around each experimental insertion, for both the incoming and outgoing beams. Finally collimators are placed around the injection and extraction regions to protect against failure cases.

In IRJ and IRF, a multi-stage cleaning system is used, which is a scaled-up version of the LHC 3032 system. It has primary collimators (TCP) closest to the beam, followed by secondary collimators (TCS), 3033 and absorbers (TCLA). As for the LHC, the main bottleneck in terms of cleaning losses is expected for 3034 the FCC-hh to be in the dispersion suppressor (DS) downstream of the betatron collimation insertion, 3035 where the dispersion generated due to the superconducting dipoles increases rapidly. Protons that have 3036 lost energy in single diffractive scattering in the TCP and have a small enough angular deviation to bypass 3037 the TCSs are at risk to be lost there [21]. In order to alleviate these losses, it is planned to install DS 3038 collimators (TCLD) in the cold region, similarly to the upgrades planned for HL-LHC [23]. It is planned 3039 to install TCLDs in IRF as well, and also downstream of the experiments in order to catch off-energy 3040 collsion debris that otherwise risk to put a too high load on the DS. The optics and collimator positions in 3041 IRJ and IRF are shown in Figures 11.1–11.4, and the full list of collimators with their names, positions, 3042 materials, settings through the cycle, and orientations are shown in Table 11.1. 3043

The baseline betatron collimation insertion is a scaling of the current LHC system, under the constraint that there is a minimum mechanically feasible jaw gap size. In order to keep similar settings as the LHC in units of beam σ , the smaller geometric emittance of the 50 TeV beam is compensated by a larger β -function.



Fig. 11.1: The optics in the betatron collimation Fig. 11.2: The optics in the betatron collimation ininsertion - (IRJ) at injection configuration. sertion (IRJ) at collision configuration.



Fig. 11.3: The optics in the energy collimation in- Fig. 11.4: The optics in the energy collimation insertion - IRF at injection configuration. sertion (IRF) at collision configuration.

Therefore, all β -functions have been scaled by $\sqrt{\frac{E_{FCC}}{E_{LHC}}} = \sqrt{\frac{50}{7}} \approx 2.67$. To achieve this, all magnet lengths and separations have been increased by 2.67, and the total length of the insertion is 2.7 km. This ensures that the magnetic fields in the warm magnets are of the same magnitude and therefore can be constructed. The increase in focusing required from the energy increase over the LHC comes from the increase in magnetic length.

For the momentum cleaning insertion, the baseline is also a layout similar to the LHC but scaled 3053 up by the same factor as the betatron system. This is the lattice used for the studies presented later in 3054 this report. However, work on alternative designs is underway, and a first version of a new optics for the 3055 off-momentum cleaning insertion has been conceived. This is based on an optimization of the normal-3056 ized dispersion at the off-momentum TCP, while keeping favourable phase advances to secondary and 3057 tertiary collimators. This alternative design has shown some first promising results in terms of geometric 3058 acceptance and protection of the downstream arc, however, more work is needed on the optimization of 3059 potential aperture bottlenecks at injection, as well as tracking studies to optimize the collimator place-3060 ment. 3061

The collimators for the present studies are assumed to be of a design similar to those used in 3062 the LHC, i.e. pairs of movable collimator jaws constructed of sections of amorphous materials, with a 3063 single tank per beam for each collimator. The requirements on infrastructure are also similar. Cooling 3064 water is required, and the controls infrastructure needs to be adequately implemented and no sensitive 3065 electronic components can be placed in areas where they risk radiation damage. A previous design 3066 of the FCC-hh lattice, with the extraction kickers placed close to the collimators, was abandoned due 3067 to the high radiation load to the kickers. Since the collimation insertion will be a high-radiation area, 3068 remote inspection and handling capabilities would be highly beneficial in order to reduce the dose to 3069 personnel. The TCPs and TCSs need to be rather robust. It is foreseen to use carbon-fibre composite 3070 (CFC) for the TCPs and the first TCS, which are the most critical devices in terms of robustness, while 3071 molybdenum-graphite (MoGr) with a 5 μ m coating of Mo is used for the downstream TCSs, which are 3072 less loaded. This allows the machine impedance to be reduced to acceptable levels. This material, which 3073 is foreseen to be used in the HL-LHC [23], has a significantly lower impedance than CFC. In this report 3074 it is assumed that such collimators can be reliably produced within specifications. Using coated graphite 3075 has been considered as a backup solution. Iterations on the mechanical design, with improvements on 3076 the LHC solution, could be done in the future to ensure optimum response from the whole collimator 3077 structure to the expected loads. 3078

Other collimators, such as the TCLAs and the tertiary collimators (TCTs) in the experimental insertions, are further away from the beam center and have lower requirements on robustness but higher requirements on absorption. As in the LHC, these collimators are made of a heavy tungsten alloy (Inermet 180).

Collimator	Material	Number	Injection $(n\sigma)$	Collision $(n\sigma)$
β TCP	CFC	2	7.6	7.6
β TCSG	CFC/MoGr	11	8.8	8.8
β TCLA	W	5	12.6	12.6
β TCLD	W	3	21.0	35.1
δ TCP	CFC	1	10.8	18.7
δ TCSG	MoGr	4	13.0	21.7
δ TCLA	W	5	14.4	24.1
δ TCLD	W	4	21.0	35.1
ТСТ	W	12	14.0	10.5
experimental TCLD	W	8	21.0	35.1
TCDQ	CFC	1	9.8	9.8
extraction TCLA	W	2	11.8	11.8
extraction TCLD	W	1	21.0	35.1

Table 11.1: The FCC-hh collimator materials, numbers (per beam), and settings throughout the cycle. The settings are given for the reference value of 2.2 μ m of the normalized emittance.

After initial simulation results, the design diverged from the LHC system, which has three betatron 3083 TCPs (in the horizontal, vertical and skew planes). Initial energy deposition simulations showed that the 3084 power load from secondary particles on the skew TCP was too high. The collimator would have been 3085 unlikely to survive. To achieve acceptable power loads, some changes have been done to the collimator 3086 materials and design. The length of the primary betatron collimators has been reduced from 60 cm 3087 to 30 cm and their thickness has been increased from 2.5 cm to 3.5 cm. This reduces the power load 3088 inside the collimator jaws and support structure. Removal of the skew TCP allows the secondary particle 3089 showers to expand and reduce their energy density. The subsequent collimator that these secondary 3090 particles will hit is the first secondary collimator. The initial energy deposition simulations found that 3091 the secondary particles would not directly hit the collimator jaw, but the mounting mechanism behind 3092 it. Because of this, the thickness of the jaws of the first secondary collimator has been increased from 3093 2.5 cm to 4.5 cm. 3094

Particles interacting with the collimation system can lose energy, but survive and exit the collima-3095 tion region. Following the collimation insertions, the dispersion is matched to that of the arc region in 3096 the DS. Inside the DS, the dispersion rapidly rises. Any sufficiently off-momentum particles will impact 3097 the beam pipe aperture due to the dispersion. This will quench magnets if dedicated protection is not in-3098 stalled. Because of this, DS collimators, known as TCLDs are installed in this region specifically to catch 3099 these off-momentum particles, as planned for HL-LHC [23]. Each experimental IR has 2 sets of TCLDs 3100 installed, and due to the higher particle load in the collimation regions these have additional TCLDs. In 3101 the betatron insertion, 3 TCLDs are used, and in the energy collimation, 4 are used. In addition, due 3102 to optical changes between injection and collision, the peak dispersion position changes between the 3103 injection and collision optics. The additional TCLD (over the HL-LHC number) is also required to cover 3104 both the injection and collision case. 3105

In the experimental straight sections, it was found that one set of TCT collimators was insufficient. Beam losses were found to take place both inside the matching section, and also between D1 and D2. An extra pair of TCT collimators were installed in the matching part of the straight section, in order to catch these losses. This should also reduce experimental backgrounds.

For the extraction insertion, debris from the extraction protection (TCDQ) was found to impact the beam pipe at the end of the straight section. The level of losses in this region was found to be excessive for a 12 min BLT. To protect the machine, an extra pair of TCLA type collimators were added in the straight section after the TCDQ; one in the horizontal and one in the vertical plane. In addition, a TCLD
type collimator was added at the start of the arc, which provides additional protection in case of a failure
of the dump system.

3116 **11.3 Machine aperture**

For the collimation system to work properly, it must be ensured that the beam-stay-clear around the FCChh ring is sufficient. This is usually most critical at injection energy in the arcs, where the geometric emittance is larger. Aperture bottlenecks usually also arise in the inner triplet at top energy, when the β -functions are squeezed at the collision points.

To study the available aperture, we use the same approach as for the LHC and HL-LHC [93, 202, 203]. The aperture module of MAD-X [91] is used to quantify the smallest distance, in units of beam σ , between the beam centre and the mechanical aperture that is found anywhere on the 2D cross section of the beam screen. The calculations are performed at several longitudinal locations in each element in order to obtain the minimum beam-stay-clear as a function of *s*. Various imperfections are included: a radial closed orbit offset x_{co} , a fractional change k_{β} in beam size from β -beating, a momentum offset δ_p , and a relative parasitic dispersion f_{arc} coming from the arc.

The values assumed for these tolerances are shown in Table. 11.2. Since it is very hard to accu-3128 rately estimate these for FCC-hh, they have been derived from the HL-LHC assumptions [93, 202, 203], 3129 which in turn have been shown to be pessimistic compared to the aperture measurements performed in 3130 the LHC [204–213]. Similarly, the alignment and manufacturing tolerances of each magnet have been 3131 adopted from similar magnets of the HL-LHC. It should be noted that the values of the momentum off-3132 sets are pessimistic compared to the calculated RF bucket height in Sec. 9. This gives a small additional 3133 safety margin, however, it should be noted that these values may change in the future. The last line 3134 of Table 11.2 shows the protected aperture, i.e. the smallest calculated aperture that is allowed in any 3135 machine element. This values has, as working assumption, been re-scaled from HL-LHC by the ratio 3136 of the square-root of the emittances. This assumption is, however, not trivial and needs to be studied in 3137 greater detail. The value of the protected aperture depends on the distribution and intensity of the halo 3138 that escapes the collimation system, as well as the halo that escapes the protection devices during fail-3139 ures, which are combined with detailed knowledge on the quench limit and damage limits of the machine 3140 elements [203]. Such studies have have not yet been performed in detail for the FCC and, pending them, 3141 the HL-LHC parameters are assumed. 3142

Table 11.2: The parameters used in the MAD-X model for FCC-hh aperture studies at top energy and injection.

Parameter set	FCC-hh injection (3.3 TeV)	FCC-hh top energy (50 TeV)
Primary halo extension	6 σ	6 σ
Secondary halo, hor./ver.	6 σ	6 σ
Secondary halo, radial	6 σ	6 σ
Normalised emittance ϵ_n	$2.2 \ \mu \mathrm{m}$	$2.2 \ \mu \mathrm{m}$
Radial closed orbit		
excursion $x_{\rm co}$	2 mm	2 mm
Momentum offset δ_p	6×10^{-4}	$2 imes 10^{-4}$
β -beating fractional		
beam size change k_{β}	1.05	1.1
Relative parasitic		
dispersion $f_{\rm arc}$	0.14	0.1
Protected aperture (σ)	13.4	15.5

In the calculations, the present design of the arc beam screen as of July 2018 has been adopted, 3143 as shown in Fig. 11.5. It should be noted that all arc dipoles are straight, which gives rise to a reduction 3144 in aperture due to the sagitta. This aperture reduction has been pessimistically modelled as a constant 3145 decrease of mechanical aperture of half of the sagitta on each side of the beam screen all along the length 3146 of the magnets. A sagitta of 2.524 mm was used for the aperture calculations. About 0.6 m downstream 3147 of every arc dipole a synchrotron radiation absorber protects the interconnection to the next magnet 3148 (see [100, Section 3.3.2]). While dimensions of the inner chamber of this absorber are the same as for 3149 the beam screen, the slits are not as deep and the sagitta is larger due to the longer distance from the 3150 dipole centre, resulting in a horizontal aperture reduction of 1.630 mm at the absorbers. 3151



Fig. 11.5: The transverse cross section of the arc beam screen, the MAD-X model for the aperture calculations is outlined in red.

Several assumptions had to be made on the mechanical aperture, in particular that similar toler-3152 ances on manufacturing and alignment apply as in the LHC [214]. The FCC-hh arc beam screen in 3153 Fig. 11.5 features antechambers to channel synchrotron radiation. This was considered unnecessary for 3154 the straight section magnets, thus a scaled LHC-like beam screen design with a larger free aperture was 3155 assumed. Some detailed studies are required to determine whether this is justified for straight section 3156 magnets close to the arcs that might still receive some synchrotron radiation. The aperture tolerances 3157 were adapted from LHC elements. The vacuum chamber apertures in the warm sections for collimation 3158 and extraction should also be reviewed. 3159

Using the parameters in Table 11.2, the aperture around the FCC-hh was evaluated at injection and top energy using the optics version 10. The results show that the apertures of the full ring, including the triplets in front of the high-luminosity experiments, are above the protected aperture. The top-energy triplet aperture at the high-luminosity experiments in IRA and IRG is shown in Fig. 11.6 for ultimate optics with $\beta^* = 30$ cm, and it can be seen that there is still some margin left. This margin could potentially be used to squeeze the optics further down to around $\beta^* \approx 21$ cm. This includes an increased crossing angle to keep the normalized separation constant.

At injection, most elements around the ring are found within specification, in particular the arcs, in spite of the pessimistic modelling of the beam screen. An example is shown in Fig. 11.7. A few elements do not meet the criterion and have a too small beam-stay-clear. These are listed in Table 11.3. As can be seen, there are only three types of magnets affected: orbit correctors in the extraction and betratron



Fig. 11.6: The calculated aperture at top energy, using the ultimate optics with $\beta^* = 30$ cm, as a function of distance s in the high-luminosity experiments in IRA and IRG, shown together with the criterion for the minimum aperture.

collimation section (elements starting with MCB) as well as matching quadrupoles (MQMO) and tuning
quadrupoles (MQTLH) of the betratron collimation section. Figure 11.8 shows the aperture bottlenecks
in IRJ. The aperture issues of the MCB and MQMO magnets can simply be solved by replacing them
with larger aperture magnets of the MCBY and MQY classes respectively. These magnet classes are
already used in various locations along the ring and provide sufficient strengths. The MQTLH magnet
issues also have to be solved for the final design but are not believed to be serious show-stoppers.

Previous lattice versions showed aperture limitations in the dispersion suppressors where the optics 3177 required a certain degree of freedom in terms of beam size but the aperture is given by the arc dipole 3178 design. Several mitigation measured have been proposed if these issues reemerge as the lattice evolves. 3179 One such measure involves pursuing the studies to refine the aperture criterion and the parameters in 3180 Table 11.2 and to investigate whether any of them can be improved. The mechanical tolerances on 3181 the manufacturing and alignment could possibly also be improved. In particular, in the few concerned 3182 locations, magnets could be installed that are better than the specification, either by sorting the magnets 3183 and simply taking the best ones among the full production, or by designing a special beam screen in these 3184 magnets only. 3185



Fig. 11.7: The calculated aperture at injection energy, as a function of distance s over two arc cells, shown together with the criterion for the minimum aperture.



Fig. 11.8: The calculated aperture at injection, using the standard injection optics with $\beta^* = 4.6$ m, as a function of distance s in IRJ (betatron collimation). It can be seen that a few elements in the dispersion suppressor fall below the criterion for the minimum aperture.

In conclusion, using the preliminary aperture parameters that are taken over, or scaled from the HL-LHC, we demonstrated that the aperture of FCC-hh is adequate for the presently considered optics scenarios, with the vast majority of the elements around the FCC-hh ring meeting the specification. While there are a few outliers, most of them can be cured by a simple switch of magnet type. For the the remaining ones in magnets of the MQTLH type, some further studies are needed on the element design, however, it is not believed to be a serious showstopper. The calculations should be repeated in the future using updated parameters specifically tailored to the FCC-hh.

Element name	s-location (m)	Calculated aperture
MCBV.6RD.H1	25629	10.2σ
MQTLH.[A-F]6LJ.H1	72169	11.5 σ
MCBH.6LJ.H1	71974	11.5 σ
MCBV.6RJ.H1	74659	11.7 σ
MCBH.6LD.H1	23254	12.5 σ
MQMO.6LJ.H1	71974	12.6 σ
MQMO.6RJ.H1	74658	12.8 σ

Table 11.3: Elements found below the minimum aperture at injection energy.

3193 11.4 Simulations of the collimation system performance

In order to evaluate the cleaning performance of the system, tracking simulations of the loss pattern around the ring are performed, which is the topic of this section. Different loss mechanisms are considered, and the output is used for further studies of energy deposition (in Sections 11.5–11.6) and the thermomechanical response (in Sec. 11.7).

³¹⁹⁸ During collisions, the beam is squeezed to a small size at the interaction point, and in doing so, ³¹⁹⁹ the beam size is also blown up in the inner triplet magnets. These become the aperture restriction of the machine. At the same time, the crossing angle is enabled to prevent parasitic head on collisions and long range beam beam effects. This reduces the available aperture. For the studies at top energy, this worst case for the aperture is the configuration that is simulated. Studies were also done at injection with un-squeezed optics, where the aperture restriction is in other regions of the machine, such as the arcs and dispersion suppressors. The optics parameters used in the simulations are summarised in Table 11.4, and the collimator settings in Table 11.1.

Parameter	Unit	Value
Optics version		9
Injection energy	TeV	3.3
Collision energy	TeV	50.0
Injection β^* (IPA,IPG)	m	4.6
Injection β^* (IPB,IPL)	m	27.0
Collision β^* (IPA,IPG)	m	0.3
Collision β^* (IPB,IPL)	m	3.0
Injection crossing angle (all)	µrad	0
Collision crossing angle (IPA,IPG)	µrad	100
Collision crossing angle (IPB,IPL)	µrad	26

Table 11.4: A table showing the FCC-hh optics configuration used in this work.

Additionally an asynchronous dump is simulated at collision energy. This is an accidental loss scenario, where the extraction kicker magnets do not fire at the correct time, or do not fire with sufficient strength, resulting in the beam not being fully extracted from the storage ring correctly.

3209 11.4.1 Simulation method

At both injection and collision, 3 possible beam loss scenarios are simulated. These are beam losses in the horizontal plane, vertical plane, and both planes simultaneously (referred to as skew). Simulations are carried out using the coupling [215–217] between SixTrack [21,43,218,219] and FLUKA [220,221], where the first code tracks the particles through the whole ring and the second describes their interactions in the collimator material, until they are lost in the latter by a nuclear inelastic reaction or they reach elsewhere the machine aperture boundary. This framework has been benchmarked against measurements with LHC beam losses, and the simulations agree well with the measurements [222].

The input beam distribution corresponds to a given loss scenario, while the output gives two components. The first is the energy deposited into each collimator. In addition, the full phase space and location of each particle is dumped if it touches the beam pipe aperture. These particles are considered to be lost. These losses are then histogramed together to produce what is called a loss map. This shows the loss locations around the ring. For this work a longitudinal binning size of 10 cm is used.

In the FLUKA coupling framework, only positively charged stable baryons are tracked around the ring - e.g. protons, and heavy ions. All other particles are killed and are not tracked - their energy is considered to be lost in the collimator or shortly after. An energy cut of 30% was used in FLUKA for this work, meaning that particles below 70% of the initial energy are killed.

In analogy to Ref. [18], the cleaning inefficiency is defined as

$$\eta_c(s) = \frac{E(s)}{E_{tot}\Delta s},\tag{11.1}$$

where η_c is the cleaning inefficiency, Δs is the longitudinal binning size (10 cm in this work), E is the energy that impacts the physical aperture in a given bin, and E_{tot} is the total energy deposited in the full simulation (including inside collimator jaws). The required value of η_c that keeps all magnets below quench level depends on the loss scenario and beam energy

3231 11.4.2 Betatron cleaning

To study the betatron cleaning performance, where the halo is assumed to impact on the primary betatron collimators, a ring of particles is generated in the phase space of the collimation plane (e.g. x,x', y,y') with sufficient amplitude to just touch the primary collimator jaw, usually a with a flat distribution between 7.57 and 7.570001 σ for a primary cut at 7.57 σ . There is no amplitude in the vertical or longitudinal plane; particles are injected on the reference orbit.

The halo, usually containing 100 million particles and generated at IPA, is then tracked for 200 turns, which is sufficient for most particles to be lost on a collimator in an inelastic interaction, or the physical beam pipe aperture.

To calculate the required cleaning performance, a quench limit of 10 mW/cm³ is conservatively assumed for a continuous power load into the magnet coils at 50 TeV, in accordance with the magnet design assumptions

missing ref to sec magnets -> Insert reference to magnet section when merged

This is slightly higher than the design assumption for the LHC magnets at 7 TeV [223], but 3244 it should be noted that recent studies of Nb3Sn magnets have shown significantly higher quench lim-3245 its [224]. The losses at quench can then be calculated to 2.2×10^5 p/m/s by scaling the LHC design 3246 loss rate at quench $(7.8 \times 10^6 \text{ p/m/s} [20])$ by a factor 35, which is the estimated increase in energy 3247 deposition per proton at 50 TeV compared to 7 TeV [225]. Finally, assuming an instantaneous loss 3248 rate corresponding to a 12 minute BLT and full intensity, a maximum allowed cleaning inefficiency of 3249 $\eta_{c,\text{max}} = 3 \times 10^{-7}$ /m is found. Similarly, for a 12 minute BLT at injection energy, the quench limit is 3250 estimated to $\eta_{c,\max} = 3 \times 10^{-5}$ /m. 3251

The simulated betatron cleaning at injection is shown in Fig. 11.9–11.11. The highest cold losses around the ring stay well below $\eta_c = 10^{-5}/\text{m}$ and are thus considered safe.

The estimated losses at collision are shown in Fig. 11.12–11.14. This is considered the most critical scenario. It can be seen that also in this case, the cleaning inefficiency around the ring is below the estimated quench limit of $\eta_{c,\max} = 3 \times 10^{-7}$ /m, which means that for a perfect case, the collimation system should be able to protect the cold aperture even in the rather demanding scenario for a 12 minute BLT. The shown results are for a horizontal beam halo but the results are not substantially different for vertical losses.

With the removal of the skew TCP from the layout, the skew beam halo at collision provides an 3260 interesting test of the performance of the system with this updated layout. Figure 11.16 shows losses 3261 in the betatron collimation insertion with the skew primary removed, for a halo with equal horizontal 3262 and vertical amplitudes. Instead of impacting a TCP, the beam first impacts the less robust TCSs. From 3263 a cleaning perspective, the performance is kept; the losses into the cold regions of the machine are 3264 not excessive thanks to the TCLDs, although significant losses appear downstream of IPA. A potential 3265 concern for these losses is the robustness of the skew secondary collimators. From LHC operational 3266 experience, skew losses are very rare. The solution is to place a stricter limit on the BLT due to losses in 3267 the skew plane, consistent with the damage limit of the TCSs and the LHC operational experience. 3268

3269 11.4.3 Off momentum beam halo

For off-momentum losses, we study first the cleaning efficiency at the start of the ramp. The losses from un-captured beam at the start of the acceleration are simulated by injecting a pencil beam of offmomentum particles without betatron amplitude but with a δ_p/p such that they just impact the primary momentum collimator jaw (an energy of 3294.8025 GeV is used instead of the reference 3300.0 GeV).



Fig. 11.9: Image showing the full ring lossmap at injection for a horizontal beam halo.





Fig. 11.11: Image showing the energy collimation insertion lossmap at injection for a horizontal beam halo.

Fig. 11.10: Image showing the betatron collimation insertion lossmap at injection for a horizontal beam halo.

image converted to pdf -> ask for the good pdf.

The resulting losses are shown in Fig. 11.18. Assuming a 1% beam loss over 10 s, the instantaneous lifetime is about 17 minutes, which requires the inefficiency to stay below $\eta_{c,\max} = 4 \times 10^{-5}/\text{m}$. As can be seen, all losses fulfil the criterion with some margin.

In collision, off-momentum losses can also be caused by uncaptured beam, but these losses are expected to occur at a slow steady rate, and not as a brief impulse. Therefore the cleaning criterion is not as strict as for the betatron case, where faster losses are more likely. Irregular losses could be faster, e.g. during a fault of the RF system, however, such events are expected to be very rare. Dedicated simulations are needed to quantify a limit on the allowed loss rate from off-momentum halo at collision energy.

3282 11.4.4 Asynchronous beam dump

One possible failure scenario is that of the asynchronous beam dump. Here, one or more extraction 3283 kicker could pre-fire asynchronously to the abort gap and hence cause an erroneous deflection of the 3284 circulating beam. This could result in the beam not being correctly extracted from the storage ring to 3285 the beam dump. In case of the LHC, such a failure would almost immediately re-trigger the remaining 3286 extraction kickers. Nevertheless, in an extreme case, the beam risks impacting the machine aperture. For 3287 FCC-hh, the proposed alternative abort strategy proposes a delayed synchronous beam dump, resulting 3288 in part of the mis-kicked beam oscillating for one additional turn. -Dedicated collimators (TCDQ), as 3289 well as septum protection (TCDS), are in place to protect against mis-kicked beam. However, beam 3290 could leak out of the TCDQ or pass it in case of an error on the TCDQ position, or potentially sensitive 3291 collimators or aperture bottlenecks could due to errors arrive at effectively smaller apertures than the 3292



Fig. 11.12: Image showing the full ring lossmap at collision for a horizontal beam halo.



Fig. 11.13: Image showing the betatron collimationFig. 11.14: Image showing the energy collimationsystem at collision for a horizontal beam halo.system at collision for a horizontal beam halo.image converted to pdf -> ask for the good pdf.image converted to pdf -> ask for the good pdf.



Fig. 11.15: Image showing the full ring lossmap at collision for a skew beam halo.



Fig. 11.16: Image showing the betatron collimation Fig. 11.17: Image showing the energy collimation system at collision for a skew beam halo.



Fig. 11.18: Image showing the full ring lossmap at injection for an off momentum beam halo.



Fig. 11.19: Image showing the betatron collima- Fig. 11.20: Image showing the energy collimation system at injection for an off momentum beam tion system at injection for an off momentum beam halo.

³²⁹³ TCDQ. The collimation system should be able to survive such an accident.

In the version of the FCC used, the extraction takes place in the horizontal plane, and the system

uses 300 segmented kicker magnets. It should be noted that a newer version exists, where the extraction
is instead vertical, and that these studies should be redone for that case. The goal of this study was to
obtain the maximum number of kicker magnets that could fire at the same time before damage occurs at
a collimator.

In the simulation, the beam was tracked for 1 turn, *n* extraction kickers were enabled on turn 2, the beam was then tracked for one further turn and extracted. The initial conditions are for a full beam, including also the core. The distribution corresponds to the sum of two gaussians: The core consists of 95% of particles, with a 1σ standard deviation, while the halo makes up the remaining 5%, with a 1.8σ standard deviation as from the Van der Meer scans in Ref. [226]. Particles are generated up to the TCP cut.

The resulting losses, for different number of kickers firing and normalized to the absolute number of impacting protons, are shown in Fig. 11.21–11.24. This can be compared to an estimated damage limit of 1×10^{11} protons. From the plots, it can be seen that up to 3 kickers can fire safely. For more than 3 kickers, e.g. 4 or 5, it can be seen that this is potentially not safe. The updated layout of the extraction insertion comprises 150 kicker magnets instead of 300. Furthermore, considering the impact of the updated optics with a vertical kick the limit would be reduced to just 1 kicker pre-firing. For final conclusions, studies on the influence of imperfections on the TCDQ position should also be carried out.

3312 11.4.5 Influence of imperfections

The results of previous sections refer to an ideal machine. In reality, unavoidable imperfections of the collimators and the rest of the machine affect the cleaning performance of the collimation system. In order to evaluate their influence, several cases with combined imperfections have been simulated. The error model is introduced in SixTrack following the procedure and experimental data used for the LHC [20,21]:

3318

Imperfections of the jaw flatness can reduce the length of material seen by the impacting protons.
 The jaw flatness error is modelled by a second order polynomial applied over a number of slices:

$$\pm 4 \cdot 10^{-4} (\frac{s^2}{l} - s)[m] \tag{11.2}$$

- where s is the longitudinal position along the jaw and l is the jaw length in m. In this study four slices are used with the deformation bent outwards the beam as shown in Fig.11.25.
- ³³²³ 2. The beam orbit and center of the collimator gap are not always perfectly aligned, which were ³³²⁴ modelled through random offsets of the centers of collimators with a standard deviation of 100 μ m ³³²⁵ (see Fig. 11.26).
- 3326 3. Angular misalignments of the collimator jaws with respect to the beam axis are added with an rms 3327 tilt angle of 200 μ rad (see Fig. 11.26).
- 4. Random errors on collimator gaps were applied with a standard deviation of 0.17 σ , corresponding to an rms β -beating of 4% as assumed for FCC-hh [227].
- 5. Tolerances of aperture misalignments for the different type of magnets are used to introduce imperfections in the alignment of the accelerator elements.

A full study of optics imperfections, adding magnetic and alignments errors in the lattice through MAD-X and partially correcting them to get a realistic β -beating and orbit, has not been performed but is foreseen as future work. Phase advance and dispersion beating can only be introduced with this second method. Apart from the jaw flatness error, all the imperfections follow a Gaussian distribution cut at 3 σ and are controlled by a seed. Twenty seeds are used for each scenario with combined imperfections. The number of seeds is limited by computational time, which represents several decades of computer CPUtime for this study.

The FCC-hh lattice used in this study is V9 for the beyond ultimate case with $\beta^* = 15$ cm at 3339 collision to investigate the most challenging scenario. The horizontal betatron loss maps have been sim-3340 ulated for multiple imperfection scenarios. The SixTrack version used for this study relies on the internal 3341 scattering module [218] and the cleaning inefficiency in the following plots represents the fraction of 3342 protons lost in a longitudinal bin normalised by the bin length ($\eta = N_{lost}^{\Delta s} / [N_{lost} \Delta s]$). The collimation 3343 system considered is the one of Table 11.1, however, in an earlier version with the skew TCP in IRJ still 3344 in and all the TCSs made of CFC. The length of the TCPs is 60 cm, the TCDO is 10 m in length whereas 3345 other collimators are 1 m. The simulation setup is identical to the one in Sec. 11.4, but with an impact 3346 parameter of 0.0015 σ . 3347

In Figs. 11.27-11.28 we present the loss maps for the ideal case and an example with all imper-3348 fections. As expected, most protons are lost in the collimation regions IRF and IRJ. These results allow 3349 us to predict where possible quenching events may occur, and give an indication about how to modify 3350 the collimator settings along the accelerator in order to improve the system performance. The loss map 3351 for the ideal machine in Fig. 11.27 shows very few cold losses compared with several blue spikes present 3352 in the loss map with imperfections. Most of the cold losses appear between the detector IRA and IRB. 3353 around the dump insertion region IRD and downstream the RF insertion IRH. The majority of loss maps 3354 with all imperfections activated show a similar behaviour. 3355

The influence of different imperfection types on the losses on collimators is summarised in 3356 Fig. 11.29 where ratio of losses on different collimator families to the TCP losses is presented. In 3357 the horizontal axis the different cases are indicated starting from the ideal case and then adding the 3358 imperfection types in steps. Each point represents an average over the 20 seeds with their standard 3359 deviation. For all cases the ratio below one indicates that no hierarchy breaking has been observed in 3360 simulations, including the error bars. For TCLAs, TCDQ, and TCLDs, a slight increase can be observed 3361 with wider error bars. In Fig. 11.30, we present the ratio between the TCT losses and the TCP losses. 3362 In this case, the TCT losses increase as more imperfections are included. It can be seen that with all 3363 imperfections, losses in tertiaries are about 4 times higher with respect to the ideal case, which could 3364 have a potential impact on the machine-induced background. 3365

The warm and cold global inefficiencies, defined as the sum of all inefficiencies in warm and cold apertures of the machine, are shown in Fig. 11.31. The changes to the global inefficiency for warm elements is within the error bars. For cold elements an increase of factor 2 with respect the ideal case is observed after introducing offsets errors of the collimator gaps. Including tilt errors, the global inefficiency is about a factor 5 higher than in the ideal case, while adding gap and flatness errors gives as final increase a factor of about 6.

The highest cold losses in a single 10 cm bin are presented in Fig. 11.32. Most of the simulations 3372 with imperfections show an almost complete loss of all protons (more than 95%). For the ideal case 3373 the number of simulated protons was increased to 140M to get a similar amount of total losses and a 3374 comparable η_c for a loss of a single particle in the simulation. Fig. 11.32 indicates that on average only 3375 a single proton is lost in a single longitudinal bin for the ideal case and for the offset-tilt cases. When 3376 adding gap errors and flatness imperfections the inefficiency in a single location increase up to 3 times 3377 the single event inefficiency, however, most seeds stay within the estimated requirement of $\eta_{c \max}$ = 3378 3×10^{-7} /m, which gives confidence in the system performance. For the ultimate optics case of this 3379 study, the highest cold peak increases by a factor 2 on average and the global cold inefficiency by a 3380 factor 4. 3381



 Fig. 11.21: Image showing the loss distribution Fig. 11.22: Image showing the loss distribution with 1 extraction kicker pre-firing.

 image converted to pdf -> ask for the good pdf.



Fig. 11.23: Image showing the loss distribution Fig. 11.24: Image showing the loss distributionwith 4 extraction kickers pre-firing.178 th 5 extraction kickers pre-firing.

image converted to pdf ->	ask for the good pdf.
---------------------------	-----------------------

image converted to pdf -> ask for the good pdf.

Fig. 11.25: Jaw deformation for 1 m long colli-mator modelled by a 2^{nd} degree polynomial in red and the 4 slices approximation used in SixTrack in simulation.

Fig. 11.27: Horizontal loss map for the ideal case without imperfections.

Fig. 11.28: Example of horizontal loss map with all imperfections considered.

Fig. 11.29: Influence of imperfections on different horizontal collimator losses as simulated by Six-Track.

Fig. 11.30: Influence of imperfections on different horizontal tertiaries collimator losses as simulated by SixTrack.

Fig. 11.31: Global cold inefficiency calculated as sum of all collimator imperfections for all combined scenarios.

Fig. 11.32: Highest cold inefficiency in a single longitudinal bin of 10 cm for different combined scenarios.

3382 11.5 Energy deposition in cold magnets

The tracking simulations described in the previous sections give as output the distribution of protons lost 3383 on the apertures around the ring. Based on this, an approximate estimation was made on whether the 3384 protection of the cold aperture is adequate. For a detailed assessment of particularly critical locations, 3385 it is required to perform local energy deposition studies. In particular, the impacts on the collimators 3386 cause secondary particle showers that are not evaluated in the tracking simulations and which can extend 3387 into neighbouring magnets. In this section we therefore examine the expected energy deposition in the 3388 dispersion suppressor of IRJ, which is the most critical cold part of the machine, and in particular in the 3389 cold magnets installed downstream of the TCLDs. 3300

The Monte Carlo program FLUKA [220, 221] was used in order to evaluate the energy deposition in the cold region around a TCLD, downstream of the betatron cleaning insertion straight section [228]. The distribution of protons leaking out of the upstream betatron collimators at the start of cell 8 was used as starting conditions. They were extracted from tracking simulations carried out at 50 TeV using the MERLIN code [229, 230], and the FCC-hh lattice as of 2017 [231]. Only cell 8, including the TCLD, was simulated, in the assumption that the situation around the other TCLD in cell 10 would be similar or better. An identical result and mitigation strategy can thus be assumed for cell 10.

A 3D geometry of the region was implemented as shown in Fig. 11.33, including the TCLD and 3398 two downstream magnets (a quadrupole and a dipole). Since at the time of the study a detailed geometry 3399 of the dipole was not available, simplified models based on the current LHC magnets were used with the 3400 addition of the FCC coil design and beam screen [232]. Magnetic fields were included in both magnets, 3401 modelled as perfect quadrupolar or dipolar fields, extending over the vacuum chamber, beam screen and 3402 cold bore. The collimators were modelled as two parallel blocks of the tungsten alloy Inermet 180, 3403 including a tapering part. The masks were modelled as cylinders of the same material. Full details can 3404 be found in Ref. [228]. 3405

In the FLUKA simulations, typically 4×10^6 protons were simulated, and the energy deposition was scored in the coils of the dipole and quadrupole. To normalise the simulated energy deposition per lost proton, a 12 minute BLT was assumed for the nominal FCC-hh beam parameters at 50 TeV, with all losses impacting on the primary collimator, in order to obtain a power load in the superconducting coils.

For the studies, several layouts of TCLDs and masks were tested and iteratively adjusted until a satisfactory solution was found. The final proposed layout includes a main 1.0 m long TCLD, followed by a second 1.5 m TCLD, and a 0.5 m mask in front of the quadrupole. An additional 1.5 m TCLD and a 0.15 m mask were placed in front of the dipole. For this layout, labelled "Updated design", the resulting energy deposition along the length of the coils of the quadrupole and dipole is shown in Fig. 11.34. For every longitudinal position, the figure shows the maximum over all bins transversely.

In the figure, the simulated power load has been scaled up by a safety margin of a factor 8. This factor includes both the effect of imperfections, not included in the tracking simulations used here, and the underestimation of the measured energy deposition found in previous studies of the LHC [21], even after imperfections were included.

It can be seen in Fig. 11.34 that for a previous layout iteration consisting of only two 1 m TCLDs 3420 and a single mask, the power load exceeds the estimated quench limit of 10 mW/cm³, while for the final 3421 layout with 3 TCLDs and two masks, it is well below. As noted before, this limit is likely pessimistic in 3422 view of the recent estimates of a 100-200 mW/cm³ guench limit of the 11 T magnet [224], developed for 3423 HL-LHC and also based on Nb3Sn technology. This gives a significant safety margin in the final design, 3424 which based on these simulation results should be able to protect the cold aperture of the ring against 3425 quenches for a 12 minute BLT. Although these studies should be redone for the latest version of the 3426 FCC-hh lattice, which might cause minor layout changes, it is unlikely that the qualitative conclusions 3427 will change. 3428

Fig. 11.33: FLUKA geometry as implemented in cell 8 in the dispersion suppressor of IRJ, including three TCLDs and two fixed masks [228]. The collimators and masks are shown in green, the quadrupole in red, and the dipole in blue.

image converted to pdf -> ask for the good pdf.

Fig. 11.34: Peak power density along the quadrupole (left) and dipole (right) in cell 8 for the final protection design and the previous solution with the a factor 8 safety margin included [228].

3429 11.6 Energy deposition in warm betatron section

The power deposition is of high importance not only on the superconducting magnets, but also on the collimators themselves and on other elements in the warm section. The extreme load during a 12 minute BLT drop corresponds to a beam loss power of 11.6 MW, which is 24 times higher than for the nominal LHC and it should be sustained up to 10 s. This represents a severe challenge for the robustness of the collimators and other exposed elements. Therefore, this section presents energy deposition studies of all elements in the warm section using FLUKA.

A cut of the initial part of the FLUKA model of the whole 2.7 km insertion is shown in Figure 11.35. An earlier version of the collimator configuration was used, which is identical to the one in Table 11.1 except that all TCSs are made of CFC. As in the LHC, three passive absorbers (TCAP), made of tungsten and copper, with lengths of 1.5 m, 0.4 m and 1 m, respectively, are placed in front of the most exposed magnets. Figure 11.36 shows the components of the collimator jaws as modelled, while a 3D view of a part of the tunnel is given in Figure 11.37.

In order to perform particle shower simulations and calculate energy deposition in the various 3442 beam line elements, maps of beam halo protons touching the collimator jaws are fed to FLUKA. These 3443 are produced by the above-mentioned online coupling between SixTrack and FLUKA. The relevant phase 3444 space details of each collimator hit is dumped as input for the second step of the simulation, performed 3445 by FLUKA only over its geometry model, as partially shown in Figure 11.35. Before being removed 3446 from the halo by either hitting the aperture or inelastic interactions inside a collimator, a halo proton 3447 touches the collimators on average more than once. Its hits are kept in the maps only if they occur in 3448 distinct turns, since possible multiple hits in the same turn are replicated in the course of the shower 3449 propagation. 3450

As a representative case, the vertical halo scenario, where hits are concentrated in the first TCP, 3451 was investigated through successive iterations. This case is more critical than horizontal losses, since the 3452 vertical TCP is most upstream and there is thus more distance within the section of the TCPs over which 3453 the shower can develop. In order to limit the power deposition on the jaws, three design measures were 3454 implemented. First, the TCP active length was halved with respect to the LHC (from 60 cm to 30 cm), 3455 this way reducing the shower development inside the absorbing material. Then the jaw thickness was 3456 increased (from 2.5 cm to 3.5 cm and 4.5 cm, for TCPs and TCSGs, respectively), since the metallic 3457 parts of the jaw cooling circuit turned otherwise out to be subject to the highest power density, being too 3458 close to the secondary particle shower core. Finally, the skew primary collimator, still collecting a total 3459 power significantly exceeding 100 kW for the design BLT of 12 minutes, due to its downstream position 3460 from the horizontal and vertical primaries, was removed. 3461

The amount of the power deposition on the beam line elements and the infrastructure for the resulting configuration is reported in Figure 11.38. Almost half of the power is taken by the tunnel walls, while a significant fraction is absorbed by the beam pipes, along 2.7 km.

Table 11.5 details the loads on the collimation system elements. Among those in CFC, the first secondary collimator represents the most critical case. However, despite an integral load 14 times lower, the primary collimator directly impacted by the beam halo (TCP.D) is the one exposed to the highest power density, due to the multi-turn ionization by primary protons at extremely small impact parameters.

Figures 11.39 and 11.40 show the power density distribution in the vertical TCP. For the design BLT of 12 minutes, the maximum value is at 50 kW/cm³ on the jaw surface layer, but 100 μ m inside one already gets one order of magnitude less.

The horizontal TCP, which in the considered scenario is rather exposed to the particle shower from the upstream collimator, takes a total power 12 times higher than the latter, but its peak power densities are dramatically lower, up to 55 W/cm³, albeit extended to a well larger area.

As pointed out above, the first TCS is affected by more severe conditions. Figure 11.41 illustrates the 3D distribution of its nearly 100 kW, showing also the picture obtained with the standard LHC jaw

Fig. 11.35: FLUKA model of the first 800 meters of the betatron collimation insertion.

Fig. 11.36: FLUKA model of a collimator jaw.

image converted to pdf -> ask for the good pdf.

thickness of 2.5 cm that induces power density values up to 800 W/cc in the cooling pipes and an integral load almost 2.5 times higher. With the proposed thickness increase to 4.5 cm, a maximum of 115 W/cc is found in the absorbing material. For the following collimators, this measure is less critical. Further studies of the thermo-mechanical response of the most critical collimators are shown in Sec. 11.7.

The two 17 m long warm dipoles that close the dogleg are particularly impacted, being exposed 3481 to the particle showers from the primary collimators. The second module, in the presence of the shortest 3482 passive absorber in front of it, collects more than 1 MW for a 12 min BLT. For reference, the LHC 3483 module, which is 5 times shorter, takes 22 kW assuming the same BLT with nominal beam parameters. 3484 As shown in Figure 11.42, the MBW.A6 non-IP face reaches 270 kW/m, while over most of its length the 3485 absorbed power is at about 60 kW/m, which translates into a linear load from 10 kW/m to 100 W/m for 3486 more regular BLTs of 1 to 100 hours. This calls for a suitable cooling system and a further optimisation 3487 of the front face protection, considering that the first meter of the magnet absorbs more than 10 % of the 3488 total power. 3489

Looking at the dose accumulated in the coils, it is clear from Fig. 11.43 that a critical gain is provided by the mechanical design, where the return coils are kept as far as possible from the beam pipe. If the LHC design would have been kept, with return coils closer to the beam, a one order of magnitude higher localised peak dose is expected.

Fig. 11.37: 3D view of the FLUKA model of the Betatron cleaning insertion dogleg, hosting the primary collimators.

3494 11.6.1 Ozone production

From the calculation of energy deposition in air, one can estimate the resulting concentration of ozone through the formula:

$$N_{O_s}(ppm) = 9.28 \times 10^{-15} \times G(eV^{-1}) \frac{P_{eV}(\frac{eV}{s})\tau(s)}{V(cc)} [1 - e^{\frac{-t}{\tau}}]$$
(11.3)

where the numerical constant is the ratio between the O_2 concentration and the number of air molecules per cm³, G is the number of O_3 molecules produced by the absorption of 1 eV (typically 0.06 to 0.074eV⁻¹) and

$$\tau(s) = \frac{1}{\left(\alpha + \frac{1}{\tau_{vent}} + \frac{kP_{eV}}{V}\right)}$$
(11.4)

3500 being

$$\alpha(\frac{1}{s}) = 2.3e - 4$$
 & $k(eV^{-1}cm^3) = 1.4 \times 10^{-16}$ (11.5)

Fig. 11.38: Power sharing in the betatron collimation insertion. The missing energy fraction refers to the energy spent in endothermic nuclear reactions as well as carried away by generated neutrinos.

Fig. 11.39: Peak power density profile along the length of the two jaws of the vertical TCP.

Fig. 11.40: Transverse power density distribution in the most impacted area (1 mm x 1 mm) of the vertical TCP. The jaw surface is at y=0. Values are given for 12 min BLT, with a transverse (x/y) resolution of 5 μm and a longitudinal (z) resolution of 1 cm.

the ozone dissociation and decomposition constants, respectively. The second addend of the sum in 11.4 is the air renewal rate, i.e. the inverse of the ventilation time τ_{vent} needed to fully renew the considered volume of air V.

In our model, the assumption of an average loss rate corresponding to 10^{16} protons per beam lost in the collimation system over an annual operation time of 5000 beam-hours yields a power deposition of 100 W in an air volume of 58000 m³. Since $\frac{1}{\alpha} = 1.2$ h, a ventilation time larger than several hours would give for this power density in air an ozone concentration of 0.03 ppm. To achieve a factor 10 reduction, a ventilation time of 8 minutes would ideally be required.

Primaries	Power (kW)
TCP.D6L	6.5
TCP.C6L	80
Scondaries	Power (kW)
TCSG.A6L	92
TCSG.B5L	9.8
TCSG.A5L	41
TCSG.D4L	33
TCSG.B4L	6.4
TCSG.A4L	12
TCSG.A4R	14
TCSG.B5R	3.3
TCSG.D5R	7.2
TCSG.E5R	12.5
TCSG.6R	2.3
TCSG.6R Active absorbers	2.3 Power (kW)
TCSG.6R Active absorbers TCLA.A6R	2.3 Power (kW) 36.5
TCSG.6R Active absorbers TCLA.A6R TCLA.B6R	2.3 Power (kW) 36.5 2.0
TCSG.6R Active absorbers TCLA.A6R TCLA.B6R TCLA.C6R	2.3 Power (kW) 36.5 2.0 2.2
TCSG.6R Active absorbers TCLA.A6R TCLA.B6R TCLA.C6R TCLA.D6R	2.3 Power (kW) 36.5 2.0 2.2 1.6
TCSG.6R Active absorbers TCLA.A6R TCLA.B6R TCLA.C6R TCLA.D6R Passive absorbers	2.3 Power (kW) 36.5 2.0 2.2 1.6 Power (kW)
TCSG.6R Active absorbers TCLA.A6R TCLA.B6R TCLA.C6R TCLA.D6R Passive absorbers TCAPA.6L	2.3 Power (kW) 36.5 2.0 2.2 1.6 Power (kW) 545
TCSG.6R Active absorbers TCLA.A6R TCLA.B6R TCLA.C6R TCLA.D6R Passive absorbers TCAPA.6L TCAPB.6L	2.3 Power (kW) 36.5 2.0 2.2 1.6 Power (kW) 545 78

Table 11.5: Total power on collimators and absorbers for 12 min BLT

Fig. 11.41: Power density distribution in the first secondary collimator for 12 min BLT. Left: LHC jaw thickness of 2.5 cm. Right: proposed jaw with thickness of 4.5 cm.

Fig. 11.42: Integral power profile on the two warm dipoles after the primary collimators, for 12 min BLT.

Fig. 11.43: Transverse dose distribution at the MBW.B6 non-IP end, for a cumulative loss amount on the collimation system of 10^{16} top energy protons. Left: Return coil layer. Right: First internal layer. The coil position is indicated. Values are averaged over the respective layer length of 8 cm.

3509 11.7 Collimator robustness

Preliminary finite element analyses have been conducted on the most loaded TCS and TCP jaws. Simulations were carried out using the finite element software Ansys v18.2. To begin with, a thermal analysis was performed, using as input the beam-induced energy deposition from FLUKA, described in Sec. 11.6. A static structural analysis was then coupled to the thermal study to obtain the mechanical response of the system. A detailed explanation of the method and of the adopted relevant assumptions can be found in Ref. [233].

Starting from LHC specifications, CFC is adopted as constitutive material for the most loaded 3516 collimators. In this study, losses during both 1 h and 12 minute BLT are considered for the secondary 3517 collimator, while only the 12 minute BLT scenario is taken into account for the TCP. This choice is 3518 driven by the fact that the 1h BLT scenario for the TCP involves a smaller amount of power than the 1 h 3519 BLT case for the TCS (which features the same overall geometry of the TCP), resulting in a less severe 3520 case regarding the assessment of the global response of the system (e.g. in terms of thermally-induced 3521 deflections of the jaws). Since the goal is to analyse the robustness of the TCP components, which is 3522 mainly affected by energy deposition density peaks, only the more severe case of 12 minute BLT is 3523 considered for TCPs. 3524

In the 1 h BLT scenario, the beam-induced power deposition is applied in steady state. For the minute BLT scenario, starting from this steady condition, the associated losses are ramped up during 10 ms and then kept for 10 s, to be subsequently ramped down again in 10 ms to the 1 h BLT load (see Fig. 11.44).

Fig. 11.44: Load profiles considered in the thermo-structural analyses for a) the 1h BLT and b) the 0.2h BLT load case.

All analyses are carried out considering heat loads associated to a design scenario with the skew TCP removed, the TCPs shortened to 30 cm and the thickness of TCPs and TCSs increased to 3.5 cm and to 4.5 cm respectively. Moreover, given the preliminary nature of the study, some simplifying assumptions are made: a perfect bonding between the CFC absorbers and the Glidcop housing is assumed, as well as a linear constitutive law for the absorbers and a constant temperature profile for the water flowing inside the cooling circuit. The following sections discuss the results.

3535 11.7.1 TCS collimator

The design of LHC TCSP collimators is considered as base design for the analysis on the most loaded TCS, namely the TCSG.A6L: the only difference among the two designs is that the former has Glidcop taperings to host the beam position monitors (BPMs), while the latter features CFC taperings (and no BPMs), and that the CFC thickness is increased by 2 cm.

The peak temperatures found on the jaw for the 1 h and 12 minute BLT cases are about $164 \degree C$ and $330 \degree C$, respectively, as shown in Fig. 11.45. This induces thermal deformations, strains and stresses on the different components, because of the temperature gradient and the thermal-expansion coefficient

Fig. 11.45: Beam-induced temperature fields on the first TCS for 1 h BLT (left) and 12 minute BLT (right).

mismatch among the different materials constituting the jaw. Temporary beam-induced deflections of up to $185 \,\mu\text{m}$ and $246 \,\mu\text{m}$ are obtained for the 1 h and 0.2 h BLT cases, respectively (see Fig. 11.46). Non-negligible strains are present in the contact region between the CFC absorbers and the housing: these values are mostly due to the bonded contact introduced in the model (perfect bonding) and to the linear character of the constitutive law considered in the analyses for the absorbers, which both lead to an overestimation of the rigidity of the structure.

Fig. 11.46: Normal deflections of the TCS jaw for 1 h BLT (left) and 12 minute BLT (right).

Finally, the cooling pipes are found to experience plasticity (see Fig. 11.47). The elastic limit of the constituting material, CuNi 90-10, is about 100 MPa and it is largely exceeded both in the 1 h and in the 12 minute BLT case. This issue is not a showstopper, as it can be mitigated by adopting a higher yield-strength material for the cooling circuit.

3553 11.7.2 TCP collimator

As done for TCS collimators, with which they share the same geometry apart form the absorber thickness, the design of LHC TCSP collimators is considered as base design to carry out the analyses also on the vertical TCP, which is exposed to the highest power deposition density peak. In this case, however, only a 30 cm long region of the 3.5 cm thick absorbers has been considered to be subject to power deposition. The maximum temperature found on the CFC is about 660 °C, as shown in Fig. 11.48: as a result, a

Fig. 11.47: Stress intensity for the first TCS in the CuNi 90/10 cooling pipes for 1 h BLT (left) and 12 minute BLT (right).

maximum stress of 45 MPa is induced in the absorber-housing contact region along the direction normal to the planes constituting the CFC absorber, with an estimated associated strain of about $8000 \,\mu$ m/m,

theoretically leading to failure (see Fig. 11.49).

³⁵⁶² However, similar temperatures have already been achieved repeatedly on CFC absorbers during

past experimental campaigns, without reporting any sign of failure [234, 235]. In the HRMT-23 experiment, CFC absorbers reached a peak temperature of 685 °C when impacted by 288-bunches with a total intensity of 3.79×10^{13} protons and σ =0.35mm. Furthermore, in the HRMT-36 experiment, CFC samples experienced a grazing pulse of 288 bunches, with a total intensity of 3.72×10^{13} protons and σ =0.25 mm. No failure was found in either case, despite thermal gradients which largely exceed those at hand in the present study shown in Fig. 11.50.

Fig. 11.50: The temperature field over the CFC absorbers in HRTM-23 [234] (left) and the Mo-coated CFC sample impacted by a grazing shot which melted the coating leaving the CFC substrate unbroken [235] (right).

image converted to pdf -> ask for the good pdf

The obtained high values of stress and strain are therefore thought to be largely due to the simpli-3569 fied nature of the absorber-housing contact adopted in the analysis, as well as to the hypothesis of linear 3570 elasticity considered for CFC. Both these assumptions cause a much stiffer structure than the real case. 3571 For the same reason, the obtained beam-induced bending deflection of $155\,\mu\text{m}$ shown in Fig. 11.51 is 3572 believed to underestimate the real deformation of the jaw. Regarding the cooling circuit, a maximum 3573 stress of 26 MPa is found, much below the elastic limit for CuNi 90-10. No plasticity is observed in the 3574 housing either, where a stress peak of 106 MPa is estimated against a yield stress for Glidcop of 294 MPa 3575 (see Fig. 11.52). 3576

Fig. 11.52: Stress intensity in the CuNi 90/10 cooling pipes (left) and the Glicop housing (right) of the vertical TCP during 12 minute BLT losses.

image converted to pdf -> ask for the good pdf.

3577 11.7.3 Result assessment

Thermo-mechanical analyses conducted on the most loaded TCS and TCP collimators highlighted some critical points which, without representing any clear showstopper at this stage, will need to be addressed in future design developments. The only case where permanent deformations occur is in the cooling pipes of the TCS, however, it is believed that this can be mitigated in a straight-forward way by a different material choice for the pipes.

Temperature peaks up to $660 \degree C$ are observed in the CFC absorber of the vertical TCP, theoretically 3583 leading to failure. However, past tests have shown that no failure occurred in CFC absorbers at these 3584 simulated temperatures [234, 235]: the numerical overestimation of stresses and strains is thought to be 3585 largely ascribable to the simplifying hypotheses introduced in the numerical models, leading to a stiffer 3586 structure. For the same reason an underestimation of the beam-induced bending deflections must be 3587 considered for both the case of TCS and TCP, where temporary deformations stay above $100\mu m$ for all 3588 the analysed load cases. It should be assessed in future studies if this has an impact on the cleaning 3589 inefficiency. Another potential concern is that the outgassing from graphitic materials such as CFC risks 3590 to be very high at the simulated temperatures. The resulting beam vacuum and the possible need for 3591 additional pumping should be evaluated in future studies. 3592

³⁵⁹³ Different directions of improvement could be considered to address the points raised above. A ³⁵⁹⁴ summary of proposals would include:

- lighter absorbers, to minimise the energy density on the jaw, e.g. carbon foams [236]
- more rigid housing and stiffener;
- higher water flow in the cooling pipes;
- monitoring, and possibly deformation-correcting, systems. A project in this sense is already
 launched between CERN and the University of Huddersfield [237]

3600 11.8 Advanced concepts and key R&D

The studies presented above are based on a collimation system that is scaled up from the LHC but using similar physical hardware. The simulations show that special measures have to be taken to ensure safe operation with acceptable collimator loads during BLT drops, such as the removal of the skew TCP. One important path for general improvements of the collimation system is to study novel materials with improved robustness and acceptable impedance. A more optimized and robust system design could be obtained with such materials if the skew TCP could be kept. A novel mechanical collimator design could also be investigated as an option to further improve the robustness. Furthermore, the cleaning performance might be improved through design iterations on the optics and layout of the two dedicated collimation insertions, and the potential addition of more fixed masks.

Alternative collimation techniques, such as crystal collimation [238] are another path of future study. With this technique, bent crystals are used to channel impacting halo particles and give them an angular kick that is large enough to make them impact deeply at a downstream absorber. Experiments using an LHC test installation [239] have shown a significant improvement of the cleaning efficiency with Pb, Xe, and proton beams [240]. However, since the power deposition of the lost particles will be concentrated on the absorber, its design is very challenging.

Another area of future studies is the control of the beam halo. It has been estimated that for the HL-3616 LHC, the amount of energy present above 3.5 σ in betatron amplitude is 35 MJ [241]. With a factor 12 3617 higher total stored beam energy in the FCC-hh, the total energy in the halo alone risks to be of the order 3618 of 400 MJ, which is more than the total 362 MJ design stored energy of the LHC beam. Any movement 3619 or jitter in the orbit risks to cause large losses and beam dumps, that reduce the machine availability. One 3620 solution could be to use a hollow electron lens, as studied for HL-LHC [23]. By controlling the diffusion 3621 speed of halo particles, one can act on the time profile of the losses, for example by introducing a steady 3622 and controlled halo depletion, so that static halo population is significantly reduced. This would reduce 3623 the amount of beam scraped during any orbit movement. The parameters and feasibility of a hollow 3624 electron lens for FCC-hh remain to be studied. 3625

3626 11.9 Conclusions

In this document, a detailed design of the FCC-hh collimation system has been presented, including both the needed collimators and the beam optics. The assumed hardware design of the collimators is based on concepts from the LHC and HL-LHC but with some further developments to cope with the very high power loads expected during the FCC-hh beam loss scenarios. Infrastructure requirements include, as for the LHC, cooling water circuits, controls, and remote inspection and handling and high-radiation areas.

The performance of the FCC-hh collimation system has been studied in detail through particle 3632 tracking, energy deposition, and thermo-mechanical simulations. In spite of a stored beam energy of 3633 8.3 GJ, it has been shown that the cleaning performance largely meets the requirements and that the ma-3634 chine can be protected from quenches during lifetime drops down to 12 minutes, which is pessimistically 3635 taken as a specification for the betatron cleaning. This has been achieved through the use of a system 3636 based on the LHC design but with the addition of extra dispersion suppressor collimators as well as local 3637 protection to alleviate losses at some critical locations. The cleaning of off-momentum losses at the most 3638 critical scenario, where the unbunched beam is lost rapidly at the start of the ramp, has also been found 3639 to be within the estimated limits. 3640

The collimators themselves will be subject to very high loads during sharp BLT drops and this is a major challenge for the system design. Energy deposition studies and thermo-mechanical simulations have been used to study and optimize the loads, and through changes in the collimator design the resulting peak power load can be brought down to tractable levels. Some issues still remain to be solved but they are not believed to be showstoppers. Other elements in the warm collimation section, such as the passive absorbers and the warm dipoles, receive very high instantaneous power loads, and the design and cooling of these elements need further study and optimization.

4257 **References**

[1] L. A. Aamport, "The gnats and gnus document preparation system," *G-Animal's Journal*, 1986.

- 4259 [2] missing.
- 4260 [3] missing.
- 4261 [4] missing.
- 4262 [5] missing.
- 4263 [6] missing.
- 4264 [7] missing.
- 4265 [8] missing.
- 4266 [9] missing.
- 4267 [10] missing.
- 4268 [11] missing.
- 4269 [12] missing.
- 4270 [13] missing.
- ⁴²⁷¹ [14] O. S. Brüning, *et al.*, "LHC design report v.1 : The LHC main ring," *CERN-2004-003-V1*, 2004.
- [15] M. Fiascaris, *et al.*, "First Design of a Proton Collimation System for 50 TeV FCC-hh," *Proceed- ings of the International Particle Accelerator Conference 2016, Busan, Korea*, p. 2425, 2016.
- [16] M. Fiascaris *et al.*, "Conceptual solution for a beam halo collimation system of the future circular
 hadron-hadron collider (FCC-hh)," *submitted to Nucl. Instr. Meth. Phys. Res. A*, 2018.
- [17] R.W. Assmann, "Collimators and Beam Absorbers for Cleaning and Machine Protection," *Proceedings of the LHC Project Workshop Chamonix XIV, Chamonix, France*, p. 261, 2005.
- [18] G. Robert-Demolaize, *Design and Performance Optimization of the LHC Collimation System*.
 PhD thesis, Universite Joseph Fourier, Grenoble, 2006.
- [19] R.W. Assmann *et al.*, "The Final Collimation System for the LHC," *Proc. of the European Particle* Accelerator Conference 2006, Edinburgh, Scotland, p. 986, 2006.
- [20] C. Bracco, *Commissioning Scenarios and Tests for the LHC Collimation System*. PhD thesis,
 EPFL Lausanne, 2008.
- [21] R. Bruce, *et al.*, "Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 081004, Aug 2014.
- 4286 [22] missing.
- [23] G. Apollinari, *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Re- port V. 0.1.* CERN Yellow Reports: Monographs. CERN-2017-007-M, Geneva: CERN, 2017. R.
 Bruce, https://cds.cern.ch/record/2284929.
- 4290 [24] missing.
- [25] A. Lechner *et al.*, "Power Deposition in LHC Magnets With and Without Dispersion Suppressor
 Collimators Downstream of the Betatron Cleaning Insertion," in *Proceedings of the International Particle Accelerator Conference 2014, Dresden, Germany*, 2014. MOPRO021.
- [26] J. Molson, et al., "Status of the FCC-hh collimation system," Proceedings of the International
 Particle Accelerator Conference 2017, Copenhagen, Denmark, p. 64, 2017.
- [27] M. I. Besana, *et al.*, "Energy deposition in the betatron collimation insertion of the 100 TeV
 future circular collider," *Proceedings of the International Particle Accelerator Conference 2017*,
 Copenhagen, Denmark, p. 68, 2017.
- 4299 [28] missing.
- 4300 [29] missing.
- [30] R. Martin, *et al.*, "Interaction region design driven by energy deposition," *Phys. Rev. Accel. Beams*,

- vol. 20, p. 081005, Aug 2017.
- [31] S. Fartoukh, "Achromatic telescopic squeezing scheme and application to the lhc and its luminosity upgrade," *Phys. Rev. ST Accel. Beams*, vol. 16, p. 111002, Nov 2013.
- ⁴³⁰⁵ [32] "Future Circular Collider Study. Volume 3: The Hadron Collider (FCC-hh) Conceptual Design
 ⁴³⁰⁶ Report." preprint edited by M. Benedikt et al. CERN accelerator reports, CERN-ACC-2018-0058,
 ⁴³⁰⁷ December 2018. Submitted to Eur. Phys. J. ST.
- [33] E. Cruz-Alaniz, *et al.*, "Design of the large hadron electron collider interaction region," *Phys. Rev. Accel. Beams*, vol. 18, p. 111001, Nov 2015.
- [34] R. de Maria, "Layout design for final focus systems and applications for the LHC interaction
 region upgrade." CERN-LHC-PROJECT-REPORT-1051, 2007.
- [35] J. B. García et al., "Beam-beam studies for FCC-hh." FCC week 2018, Amsterdam, April, 2018,.
- [36] W. Herr, et al., "Long Range Beam-beam Effects in the LHC," in Proceedings, ICFA MiniWorkshop on Beam-Beam Effects in Hadron Colliders (BB2013): CERN, Geneva, Switzerland,
 March 18-22 2013, pp. 87–92, 2014.
- [37] T. Pieloni *et al.*, "Two Beam Effects," in *Proc. 2014 Evian Workshop on LHC Beam Operation*,
 (Geneva), pp. 69–79, CERN, CERN, 2014.
- [38] X. Buffat, *et al.*, "Long-range and head-on beam-beam: what are the limits?," in *7th Evian work- shop on LHC beam operation: Evian-les-Bains, France.*, (Geneva), pp. 133–140, CERN, CERN,
 2017.
- [39] T. Pieloni, A study of beam-beam effects in hadron colliders with a large number of bunches. PhD
 thesis, Ecole Polytechnique Federale de Lausanne (EPFL), 2008.
- [40] W. Herr, *et al.*, "Observations of beam-beam effects at high intensities in the lhc," 01 2011.
- [41] W. Herr, "Features and implications of different LHC crossing schemes," Tech. Rep. LHC-Project Report-628. CERN-LHC-Project-Report-628, CERN, Geneva, Feb 2003.
- 4326 [42] http://sixtrack.web.cern.ch/SixTrack/, 2016.
- 4327 [43] F. Schmidt, "Sixtrack User's Reference Manual," tech. rep., CERN, 1994.
- 4328 [44] W. Herr and T. Pieloni. http://lhc-beam-beam.web.cern.ch/lhc-beam-beam/ 4329 combi_welcome.html.
- [45] T. Pieloni and W. Herr, "Coherent beam-beam in the CERN large hadron collider (LHC) for
 multiple bunches, different collision schemes and machine symmetries," in *Proceedings of 2005 Particle Accelerator Conference*, 2005.
- [46] T. Pieloni and W. Herr, "Models to study multi bunch coupling through head-on and long-range
 beam-beam interactions," cern lhc project report 937 and proceedings of EPAC06, edinburgh,
 united kindom, 2006, CERN, 2006.
- [47] M. Crouch, *Luminosity Performance Limitations due to the Beam-Beam Interaction in the Large* Hadron Collider. PhD thesis, Manchester University, 2017.
- [48] M. Giovannozzi, "Proposed scaling law for intensity evolution in hadron storage rings based on dynamic aperture variation with time," *Phys. Rev. ST Accel. Beams*, vol. 15, p. 024001, Feb 2012.
- [49] X. Buffat, *et al.*, "Stability diagrams of colliding beams in the large hadron collider," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 111002, Nov 2014.
- [50] H. Grote, F. Schmidt, and L. H. A. Leunissen, "LHC Dynamic Aperture at Collision," Tech. Rep.
 LHC-PROJECT-NOTE-197, CERN, Geneva, Aug 1999.
- 4344 [51] Y. Luo and F. Schmidt, "Dynamic Aperture Studies for LHC Optics Version 6.2 at Collision,"
 4345 Tech. Rep. LHC-PROJECT-NOTE-310, CERN, Geneva, Jan 2003.
- 4346 [52] M.Crouch *et al.*, "Dynamic aperture studies of long-range beam-beam interactions at the LHC,"
 4347 in *Proceedings*, 8th International Particle Accelerator Conference (IPAC 2017): Copenhagen,
 4348 Denmark, p. THPAB056, 2017.

- [53] J. B. García *et al.*, "Beam-beam studies for FCC-hh," in *Proceedings*, 8th International Particle
 Accelerator Conference (IPAC 2017): Copenhagen, Denmark, p. TUPVA026, 2017.
- [54] J. B. García *et al.* EuroCirCol Meeting Oct 2017, Presentation at the LHC machine committee,
 October, 2017.
- [55] J. Gareyte, J. Koutchouk, and F. Ruggiero, "Landau damping, Dynamic Aperture and Octupoles
 in the LHC," Tech. Rep. LHC Project Report 91, CERN, Geneva, Switzerland, 1997.
- [56] J. Shi, O. Kheawpum, and L. Jin, "Global compensation of long-range beam-beam interactions with multipole correctors," in *Proc. of EPAC 2002, Paris, France, Paris, France, June, 2002*, pp. 1296–1298, EPS-IGA and CERN, June 2013.
- [57] T. Pieloni *et al.*, "Colliding High Brightness Beams in the LHC," in *Proceedings*, *HB2012*, *Beijing*,
 China, p. MOP250, 2012.
- 4360 [58] X. Buffat, *et al.*, "Probing the behaviour of high brightness bunches in collision at 6.5 TeV and the
 4361 interplay with an external source of noise (MD1433)." https://cds.cern.ch/record/2261037,
 4362 Apr 2017. CERN-ACC-NOTE-2017-0030.
- [59] S. V. Furuseth and X. Buffat, "Modeling of nonlinear effects due to head-on beam-beam interactions," *Phys. Rev. Accel. Beams*, vol. 21, p. 081002, Aug 2018.
- [60] A. Ferrari, *et al.*, "FLUKA: a multi-particle transport code." https://cds.cern.ch/record/
 898301, 2005. CERN-2005-10.
- [61] T. Böhlen, *et al.*, "The FLUKA code: Developments and challenges for high energy and medical applications," *Nuclear Data Sheets*, vol. 120, pp. 211–214, 2014.
- [62] G. Apollinari, *et al.*, "High-luminosity large hadron collider (HL-LHC) technical design report
 v.0.1." http://cds.cern.ch/record/2284929, 2017. CERN-2017-007-M.
- [63] E. Skordis, *et al.*, "Impact of beam losses in the LHC collimation regions," in *Proc. 6th Interna- tional Particle Accelerator Conference (IPAC'15)*, 2015. CERN-ACC-2015-271.
- 4373 [64] F. Cerutti *et al.*, "Beam loss studies in IP." talk, FCC week 2018, Amsterdam, Netherlands, April
 4374 2018, 2018.
- [65] A. Infantino, B. Humann, and F. Cerutti, "Energy deposition from collision debris in FCC-hh
 EIR," 2018.
- [66] D. Schoerling, "Review of peak power limits for high-luminosity IR triplet magnets," 2017.
- 4378 [67] L. Bottura, "11T magnet operating margin," 2018.
- [68] R. Walker, "Synchrotron radiation," in CAS CERN Accelerator School : 5th General Accelerator
 Physics Course, vol. 1, pp. 437–454, Geneva, Switzerland: CERN, 1992. doi: 10.5170/CERN 1994-001.437.
- [69] M. Boscolo and H. Burkhardt, "Tools for flexible optimisation of IR designs with application to FCC.," in *Proc. 6th International Particle Accelerator Conference IPAC15*, pp. 2072–2074 TUPTY031, 2015.
- [70] L. Deniau, et al., The MAD-X program: Methodical Accelerator Design User's Reference Manual.
 CERN, Geneva, Switzerland, 10 2018. http://cern.ch/madx/.
- [71] A. Naumann, *et al.*, *ROOT: Data Analysis Framework User's Guide*. CERN, Geneva, Switzerland,
 5 2018. https://root.cern.ch/.
- [72] S. A. et al., "Geant4âĂŤa simulation toolkit," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, pp. 250 303, 2003.
- [73] F. Collamati, *et al.*, "Synchrotron radiation backgrounds for the fcc-hh experiments," *Journal of Physics: Conference Series*, vol. 874, no. 1, p. 012004, 2017.
- [74] R. Kersevan, M. Ady, and J. Pons, *Molflow–SynRad: A Monte Carlo Simulator package developed at CERN*. CERN, Geneva, Switzerland. https://molflow.web.cern.ch/.

- ⁴³⁹⁶ [75] J. Abelleira, L. Van-Riesen Haupt, *et al.*, "An alternative final-focus system for the fcc-hh: triplet ⁴³⁹⁷ optimization with energy deposition studies," *submitted for publication*, 2018.
- [76] L. van Riesen-Haupt, *et al.*, "A Code for Optimising Triplet Layout," in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, 14–19 May, 2017*, no. 8 in
 International Particle Accelerator Conference, (Geneva, Switzerland), pp. 2163–2166, JACoW,
 May 2017. https://doi.org/10.18429/JACoW-IPAC2017-TUPVA043.
- I. Abelleira, *et al.*, "Energy Deposition Studies and Luminosity Evolution for the Alternative FCChh Triplet," in *Proc. 9th International Particle Accelerator Conference (IPAC'18), Vancouver, BC, Canada, April 29-May 4, 2018*, no. 9 in International Particle Accelerator Conference, (Geneva,
 Switzerland), pp. 352–355, JACoW Publishing, June 2018. https://doi.org/10.18429/JACoWIPAC2018-MOPMK003.
- [78] L. van Riesen-Haupt, *et al.*, "An Optimised Triplet for the Final Focus of the FCC-HH with a 40m
 Final Drift," in *Proc. 9th International Particle Accelerator Conference (IPAC'18), Vancouver, BC, Canada, April 29-May 4, 2018*, no. 9 in International Particle Accelerator Conference, (Geneva,
 Switzerland), pp. 364–367, JACoW Publishing, June 2018. https://doi.org/10.18429/JACoWIPAC2018-MOPMK007.
- [79] T. Pieloni *et al.*, "Beam-beam effects." FCC week 2018, Amsterdam, Netherlands, April 2018, 2018.
- [80] A. Chancé *et al.*, "Status of the Beam Optics of the Future Hadron-Hadron Collider FCC-hh,"
 in *Proc. of International Particle Accelerator Conference (IPAC'16), Busan, Korea, May 8-13,*2016, no. 7 in International Particle Accelerator Conference, (Geneva, Switzerland), pp. 1470–
 1472, JACoW, June 2016. doi:10.18429/JACoW-IPAC2016-TUPMW020.
- [81] H. M. Durand *et al.*, "HL-LHC Alignment Requirements and Associated Solutions," in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, 14–19 May,*2017, no. 8 in International Particle Accelerator Conference, (Geneva, Switzerland), pp. 1893–
 1896, JACoW, May 2017. https://doi.org/10.18429/JACoW-IPAC2017-TUPIK085.
- [82] D. Boussard and T. P. R. Linnecar, "The LHC Superconducting RF System," Tech. Rep. LHC Project-Report-316. CERN-LHC-Project-Report-316, CERN, Geneva, Dec 1999.
- [83] E. Shaposhnikova, "Longitudinal beam dynamics and RF requirements," *Longitudinal beam dynamics and RF requirements, The third Annual Meeting of the Future Circular Collider Study,* Berlin, 2017.
- [84] E. Shaposhnikova and I. Karpov, "Longitudinal beam dynamics and RF requirements," *Longitu- dinal beam dynamics and RF requirements, The fourth Annual Meeting of the Future Circular Collider Study, Amsterdam*, 2018.
- [85] E. Renner, "Machine Protection of the Future Circular Hadron Collider FCC-hh: Injection and
 Extraction," 2018. Diploma thesis, to be published.
- [86] M. Fiascaris, R. Bruce, and S. Redaelli, "A conceptual solution for a beam halo collimation system
 for the Future Circular hadron-hadron Collider (FCC-hh)," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*,
 vol. 894, pp. 96 106, 2018.
- [87] T. T. Böhlen, *et al.*, "The FLUKA Code: Developments and Challenges for High Energy and
 Medical Applications," *Nucl. Data Sheets*, vol. 120, pp. 211–214, 2014.
- [88] A. Ferrari, *et al.*, "FLUKA: A multi-particle transport code (Program version 2005)," 2005.
 CERN-2005-010, SLAC-R-773, INFN-TC-05-11.
- [89] I. L. Garcia *et al.*, "HiRadMat TCDI / TDI material tests (3D Carbon/Carbon and graphic
 75/50)," 2017. presented at 7th HL-LHC Collaboration Meeting, Madrid, Spain, 2017, https:
 //indico.cern.ch/event/647714/contributions/2646536/. [Accessed: 10- Aug- 2018].
- [90] V. Raginel *et al.*, "First Experimental Results on Damage Limits of Superconducting Accelerator

- Magnet Components Due to Instantaneous Beam Impact," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 4, p. 8800310, 2018.
- 4446 [91] "MAD-X program." http://cern.ch/mad/.
- [92] F. M. Velotti, *Higher brightness beams from the SPS for the HL-LHC era*. PhD thesis, EPFL,
 Lausanne, Switzerland, 2017. CERN-THESIS-2017-041.
- [93] R. Bruce, *et al.*, "Updated parameters for HL-LHC aperture calculations for proton beams,"
 CERN-ACC-2017-0051, 2017.
- [94] Y. Nie, *et al.*, "Numerical simulations of energy deposition caused by 50 MeVâĂŤ50 TeV proton
 beams in copper and graphite targets," *Phys. Rev. Accel. Beams*, vol. 20, no. 8, p. 081001, 2017.
- [95] A. Chance, *et al.*, "Updates on the optics of the future hadron-hadron collider FCC-hh," in *Proceedings*, 8th International Particle Accelerator Conference (IPAC 2017): Copenhagen, Denmark,
 p. TUPVA002, May 2017.
- [96] A. Chance, *et al.*, "First results for a FCC-hh ring optics design," Tech. Rep. CERN-ACC-2015 0035, CERN, Geneva, Apr 2015.
- [97] A. Chance, *et al.*, "Overview of Arc Optics of FCC-hh," in *Proceedings*, 9th International Particle
 Accelerator Conference (IPAC 2018): Vancouver, BC, Canada, p. MOPMF025, May 2018.
- [98] C. Tambasco *et al.*, "Landau damping studies for the fcc: Octupole magnets, electron lens and
 beam-beam effects," in *9th Int. Particle Accelerator Conf.(IPAC'18), Vancouver, BC, Canada, April 29-May 4, 2018*, p. thpaf074, JACOW Publishing, Geneva, Switzerland, 2018.
- [99] Proceedings of the 9th International Particle Accelerator Conference, 2018.
- [100] M. Benedikt, *et al.*, "Future Circular Collider Study. Volume 3: The Hadron Collider (FCC-hh)
 Conceptual Design Report," Tech. Rep. CERN-ACC-2018-0058, CERN, Geneva, Dec 2018. Submitted for publication to Eur. Phys. J. ST.
- ⁴⁴⁶⁷ [101] D. Schoerling, "Magnet status towards the cdr." FCC week 2017, Berlin, Germany, 2017.
- [102] C. Lorin, *et al.*, "Design of a Nb₃Sn 400 T/m Quadrupole for the Future Circular Collider," in
 MT-25, *Amsterdam*, *Netherlands*, 2017.
- [103] B. Dalena, *et al.*, "Advance on Dynamic Aperture at Injection for FCC-hh," in *Proceedings*, 8th International Particle Accelerator Conference (IPAC 2017): Copenhagen, Denmark, p. TUPVA003, 2017.
- [104] B. Dalena, *et al.*, "Dipole field quality and dynamic aperture for FCC-hh," in *Proceed- ings*, 9th International Particle Accelerator Conference (IPAC 2018): Vancouver, BC, Canada,
 p. MOPMF024, 2018.
- [105] O. S. Brüning and S. D. Fartoukh, "Field Quality Specification for the LHC Main Dipole Magnets," Tech. Rep. LHC-Project-Report-501. CERN-LHC-Project-Report-501, CERN, Geneva, Oct 2001.
- [106] A. Chao and M. Tigner, *Handbook of Accelerator Physics and Engineering*. Handbook of Accelerator Physics and Engineering, World Scientific, 1999.
- [107] Y. Nosochkov and D. M. Ritson, "The provision of IP crossing angles for the SSC," in *Proceedings* of International Conference on Particle Accelerators, pp. 125–127, May 1993.
- [108] S. Fartoukh and O. Bruning, "Lhc-project-report-501," tech. rep., CERN, 2001.
- 4484 [109] "Sixtrack."
- 4485 [110] P. Hagen, "Magnetic model of the normal-conducting magnets mbw, mbxw(h) and mcbw(h/v)."
- [111] G. Sabbi and E. Todesco, "Hilumilhcmil-ms-33," tech. rep., CERN, 2012.
- 4487 [112] Proceedings of the 7th International Particle Accelerator Conference, 2016.
- ⁴⁴⁸⁸ [113] Proceedings of the 8th International Particle Accelerator Conference, 2017.
- [114] A. Fedynitch, Cascade Equations and Hadronic Interactions at Very High Energies. PhD thesis,

- 4490 KIT, 2015. CERN-THESIS-2015-371.
- [115] P. K. Skowronski et al., "Advances in MAD-X using PTC," 2007. LHC-Project-Report-1016.
- [116] S. Tygier, et al., "Recent development and results with the MERLIN tracking code," in Proceed-
- ings, 8th International Particle Accelerator Conference (IPAC 2017): Copenhagen, Denmark,
 p. MOPAB013, May, 2017.
- 4495 [117] E. Todesco. Private Communication, 2017.
- [118] R. K. Adair and H. Kasha, "The range of muons in rocks," in *Proceedings*, 13th International Conference on Cosmic Rays, Denver, Colorado, 1973.
- [119] Particle Data Group. Passage of particles through matter http://durpdg.dur.ac.uk/lbl/
 index.html, 2005.
- [120] M. I. Besana, "Evaluation of the radiation field in the future circular collider detector," *Phys. Rev. Accel. Beams*, vol. 19, p. 111004, 2016.
- [121] H. Rafique, *et al.*, "Proton cross-talk and losses in the dispersion suppressor regions at the FCChh," in *Proceedings*, 8th International Particle Accelerator Conference (IPAC 2017): Copenhagen, Denmark, p. TUPIK037, May, 2017.
- In the second sec
- 4508 [123] N. Mounet, The LHC Transverse Coupled-Bunch Instability. PhD thesis, EPFL, 2012.
- [124] E. Metral, "Beam screen issues," in *Proceedings, EuCARD-AccNet-EuroLumi Workshop: The* High-Energy Large Hadron Collider (HE-LHC10): Villa Bighi, Malta, Republic of Malta, Octo ber 14-16, 2010, 2011.
- [125] N. Mounet, N.Biancacci, and D.Amorim, "Impedancewake2d code." https://twiki.cern.ch/
 twiki/bin/view/ABPComputing/ImpedanceWake2D.
- 4514 [126] "Code cst particle studio wakefield solver."
- [127] U. Niedermayer, O. Boine-Frankenheim, and H. D. Gersem, "Space charge and resistive wall impedance computation in the frequency domain using the finite element method," *Physical Review Special Topics Accelerators and Beams*, vol. 18, mar 2015.
- [128] D. Hynds, *et al.*, "Amorphous-carbon thin films for the mitigation of electron clouds in particle
 accelerators," 2009.
- 4520 [129] P. C. Pinto. Private Communication, 2018.
- [130] S. Arsenyev and D. Schulte, "Broadband Impedance of Pumping Holes and Interconnects in the
 FCC-hh Beamscreen," in *Proceedings, 9th International Particle Accelerator Conference (IPAC* 2018): Vancouver, Canada, April 29 May 4, 2018.
- [131] B. Riemann and S. Khan, "Resistive-Wall Impedance of Insertions for FCC-hh Location of Pre sentation," in *Proceedings*, 9th International Particle Accelerator Conference (IPAC 2018): Van *couver*, Canada, April 29 May 4, 2018.
- [132] G. Stupakov, "Low frequency impedance of tapered transitions with arbitrary cross sections,"
 Phys. Rev. ST Accel. Beams, vol. 10, p. 094401, 2007.
- ⁴⁵²⁹ [133] D. Angal-Kalinin, "Review of coupled bunch instabilities in the lhc," 2002.
- [134] O. Brüning, *et al.*, *LHC Design Report, Vol I.* CERN Yellow Reports: Monographs, Geneva:
 CERN, 2004.
- [135] S. Arsenyev, D. Schulte, and O. Boine-Frankenheim, "FCC-hh transverse impedance budget," in
 Proceedings, 9th International Particle Accelerator Conference (IPAC 2018): Vancouver, Canada, April 29 May 4, 2018.
- [136] F. J. Sacherer, "A longitudinal stability criterion for bunched beams," *IEEE Transactions on Nuclear Science*, vol. 20, pp. 825–829, June 1973.

- [137] V. I. Balbekov and S. V. Ivanov, "Thresholds of longitudinal instability of bunched beam in the presence of dominant inductive impedance." https://inis.iaea.org/collection/
 NCLCollectionStore/_Public/23/019/23019505.pdf?r=1&r=1, 1991. IHEP-OUNK-91-14.
- [138] J. Esteban Muller, E. Shaposhnikova, and L. Rivkin, "Longitudinal intensity effects in the CERN
 Large Hadron Collider," Master's thesis, Ecole Polytechnique, Lausanne, Apr 2016. Presented 28
 Jun 2016.
- [139] E. Shaposhnikova, "Longitudinal beam parameters during acceleration in the LHC.," Tech. Rep.
 LHC-PROJECT-NOTE-242, CERN, Geneva, Dec 2000.
- [140] E. Shaposhnikova, "Beam dynamics: RF requirements for the FCC-hh," *Beam dynamics: RF requirements for the FCC-hh, The second Annual Meeting of the Future Circular Collider Study, Rome*, 2016.
- ⁴⁵⁴⁹ [141] S. Y. Lee, *Accelerator Physics*. WORLD SCIENTIFIC, 3rd ed., 2011.
- [142] D. Boussard, "rf power requirements for a high intensity proton collider ; parts 1 (chapters I, II,
 III) and 2 (chapters IV, V, VI)," Tech. Rep. CERN-SL-91-16-RFS, CERN, Geneva, May 1991.
- [143] T. Mastoridis, P. Baudrenghien, and J. Molendijk, "Cavity voltage phase modulation to reduce the
 high-luminosity Large Hadron Collider rf power requirements," *Phys. Rev. Accel. Beams*, vol. 20,
 p. 101003, oct 2017.
- [144] I. Karpov and P. Baudrenghien, "Transient beam loading and rf power evaluation for future circular
 colliders." Submitted to PRAB in Feb. 2019.
- [145] W. S. E. Keil and P. Strolin, *Feedback damping of horizontal beam transfer errors*. CERN Yellow
 Reports: Monographs, Geneva: CERN, 1969.
- [146] A. V. G. Rochepeau, L. Thorndahl and C. C. Zettler, "Damping of transverse oscillations in the ISR." http://cds.cern.ch/record/352804, 1971. CERN-ISR-RF-71-42. ISR-RF-71-42.
- [147] W. Höfle, "Progress In Transverse Feedbacks and Related Diagnostics for Hadron Machines."
 https://cds.cern.ch/record/1595483, May 2013. CERN-ACC-2013-0193. CERN-ATS-2013-0193.
- [148] K. Li *et al.*, "Code Development for Collective Effects," in *Proc. of ICFA Advanced Beam Dynam- ics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'16), Malmö, Sweden, July 3-8, 2016*, no. 57 in WEAM3X01, pp. 362–367, Aug. 2016.
- [149] J. Komppula, "Optimization algorithms for pyheadtail multibunch simulations." PyHEADTAIL
 Meeting #18 15.06.2018, CERN, 2018, https://indico.cern.ch/event/735184/.
- [150] J. Komppula, W. Höfle, and K. Li, "Simulation Tools for the Design and Performance Evaluation of Transverse Feedback Systems," in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, May, 2017*, no. 8 in TUPIK091, (Geneva, Switzerland), pp. 1912–1915, JACoW, May 2017.
- [151] P. B. et al., "LHC Transverse Feedback System and Its Hardware Comissioning," *Proc. 11th European. Particle Accelerator Conf. (EPAC'08)*, pp. 3266–3268, June 2008.
- [152] D. Valuch, "ADT operation. a cook book of black magic." LBOC Meeting No 61 24.05.2016,
 CERN, 2018, https://indico.cern.ch/event/527889/.
- [153] N. Klinkenberg, "Computational studies of collective effects in particle beams in the future circular collider," Master's thesis, Westfälische Hochschule in cooperation with CERN, 2018. Bachelor
 thesis.
- [154] E. Koukovini-Platia, *et al.*, "Study of Single Bunch Instabilities with Transverse Feedback at Diamond," in *Proceedings*, *8th International Particle Accelerator Conference (IPAC 2017): Copen- hagen, Denmark*, pp. 4489–4492, May 14-19, 2017.
- 4583 [155] S. A. N. B. X. B. E. Metral, D. Amorim and K. Li, "Destabilizing effect of the LHC transverse

- damper," in *Proceedings*, 9th International Particle Accelerator Conference (IPAC 2018): Vancouver, Canada, p. THPAF048, April 29 - May 4, 2018.
- ⁴⁵⁸⁶ [156] S. Berg and R. D. Ruth, "Transverse Multibunch Instabilities for Non-Rigid Bunches," in *Proceedings, Particle Accelerator Conference: Dallas, TX, USA*, pp. 3076–3078, May 1-5, 1995.
- [157] X. Buffat, *Transverse beams stability studies at the Large Hadron Collider*. PhD thesis, Ecole
 Polytechnique Federale de Lausanne (EPFL), 2015.
- [158] W. Herr, "Introduction to landau damping," in *Accelerator School: Advanced Accelerator Physics*,
 Trondheim, Norway, 19–29 August 2013 (W. Herr, ed.), no. CERN-2014-009 in CAS-CERN,
 CERN, 2014.
- ⁴⁵⁹³ [159] "DYNAP: Tunes, Tune Footprints, Smear and Lyapunov Exponent, MAD-X user's guide." http:
 ⁴⁵⁹⁴ //madx.web.cern.ch/madx/madX/doc/usrguide/dynap/dynap.html.
- [160] W. Herr, "Particle tracking with MAD-X including LHC beam-beam interactions," LHC project
 note 344, CERN, 2004.
- [161] J. Barranco Garcia and T. Pieloni, "Global compensation of long-range beam-beam effects with octupole magnets: dynamic aperture simulations for the HL-LHC case and possible usage in LHC and FCC.." https://cds.cern.ch/record/2263347, May 2017. CERN-ACC-NOTE-2017-0036.
- [162] X. Buffat *et al.*, "Our understanding of transverse instabilities and mitigation tools/strategy," in *8th LHC Operations Evian Workshop 12-14 December 2017 Evian, France*, CERN, Geneva, Switzerland, 2017.
- ⁴⁶⁰⁴ [163] X. Buffat *et al.*, "Md 3288: Instability latency with controlled noise." To be published.
- ⁴⁶⁰⁵ [164] C. Tambasco *et al.*, "Triggering of instabilities by BTF measurements." LBOC March, 2018.
- [165] A. G., *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1.* CERN Yellow Reports: Monographs, Geneva: CERN, 2017.
- [166] E. Metral *et al.*, "Update of the HL-LHC operational scenarios for proton operation." http://
 cds.cern.ch/record/2301292, Jan 2018. CERN-ACC-NOTE-2018-0002.
- [167] V. Shiltsev, *et al.*, "Landau damping of beam instabilities by electron lenses," *Phys. Rev. Lett.*,
 vol. 119, p. 134802, Sep 2017.
- [168] W. Fischer, *et al.*, "Compensation of head-on beam-beam induced resonance driving terms and tune spread in the relativistic heavy ion collider," *Phys. Rev. Accel. Beams*, vol. 20, p. 091001, Sep 2017.
- [169] Y. H. Chin, "Landau damping of a multi-bunch instability due to bunch-to-bunch tune spread,"
 in *Proc. of 1987 IEEE Particle Accelerator Conference (PAC1987), Washington (DC), USA*,
 pp. 1213–1215, IEEE, Mar 1987.
- [170] S. Sakanaka and T. Mitsuhashi, "Construction of an RF Quadrupole Magnet for Suppressing
 Transverse Coupled-Bunch Instabilities," in *Proc. of 1991 IEEE Particle Accelerator Conference* (*PAC1991*), *San Francisco (CA), USA*, pp. 1836–1838, IEEE, May 1991.
- [171] V. V. Danilov, "Increasing the transverse mode coupling instability threshold by RF quadrupole,"
 Phys. Rev. ST Accel. Beams, vol. 1, p. 041301, Aug 1998.
- [172] E. A. Perevedentsev and A. A. Valishev, "Synchrobetatron dynamics with a radio-frequency quadrupole," in *Proc. of European Particle Accelerator Conference 2002 (EPAC'02), Paris, France*, pp. 1574–1576, JACoW, Jun 2002.
- [173] L. D. Landau, "On the vibration of the electronic plasma," *Zh. Eksp. Teor. Fiz.*, vol. 16, p. 574,
 1946.
- [174] A. W. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerators*. Wiley Series
 in Beam Physics and Accelerator Technology, Wiley, 1993. ISBN: 978-0-47-155184-3.
- 4630 [175] A. Grudiev, "Radio frequency quadrupole for Landau damping in accelerators," Phys. Rev. ST

4631 Accel. Beams, vol. 17, p. 011001, Jan 2014.

- [177] M. Schenk, *et al.*, "Analysis of transverse beam stabilization with radio frequency quadrupoles,"
 Phys. Rev. Accel. Beams, vol. 20, p. 104402, Oct 2017.
- ⁴⁶³⁵ [178] M. Schenk, *et al.*, "Vlasov description of the effects of nonlinear chromaticity on transverse co-⁴⁶³⁶ herent beam instabilities," *Phys. Rev. Accel. Beams*, vol. 21, p. 084402, Aug 2018.
- [179] M. Schenk, *et al.*, "Experimental stabilization of transverse collective instabilities in the LHC with
 second order chromaticity," *Phys. Rev. Accel. Beams*, vol. 21, p. 084401, Aug 2018.
- [180] K. Papke and A. Grudiev, "Design of an rf quadrupole for Landau damping," *Phys. Rev. Accel. Beams*, vol. 20, p. 082001, Aug 2017.
- [181] J. Scott Berg and F. Ruggiero, "Stability diagrams for Landau damping," in *Proc. of Particle Accelerator Conference 1997 (PAC'97), Vancouver (British Columbia), Canada*, pp. 1712 1714,
 May 1997.
- [182] E. Métral, *et al.*, "Beam Instabilities in Hadron Synchrotrons," *IEEE Transactions on Nuclear Science*, vol. 63, pp. 1001–1050, Apr 2016.
- [183] S. Calatroni and R. Vaglio, "Surface resistance of superconductors in the presence of a dc magnetic
 field: frequency and field intensity limits," *IEEE Trans. Appl. Supercond.*, vol. 27, p. 3500506,
 2017.
- [184] S. Calatroni, *et al.*, "Thallium-based high-temperature superconductors for beam impedance mitigation in the future circular collider," *Supercond. Sci. Technol.*, vol. 30, p. 075002, 2017.
- [185] P. Krkotić, U. Niedermayer, and O. Boine-Frankenheim, "High-temperature superconductor coating for coupling impedance reduction in the fcc-hh beam screen," *Nuclear Instruments and Meth- ods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equip- ment*, vol. 895, 03 2018.
- [186] J. Gutierrez, "Hts ybacuo coated conductors for the fcc-hh beam screens, contribution to the fcc
 week 2018," 2018.
- [187] V. Reza, *et al.*, "Low secondary electron yield of laser treated surfaces of copper, aluminium and
 stainless steel," in *Proceedings*, 7th International Particle Accelerator Conference (IPAC 2016):
 Busan, Korea, pp. 1089–1092, May 8-13, 2016.
- ⁴⁶⁶⁰ [188] R. Valizadeh, *et al.*, "Reduction of secondary electron yield for e-cloud mitigation by laser ablation ⁴⁶⁶¹ surface engineering," *Applied Surface Science*, vol. 404, no. Supplement C, pp. 370–379, 2017.
- ⁴⁶⁶² [189] S. Calatroni, "Proposals for impedance measurements at cern," 2017.
- [190] S. Arsenyev and D. Schulte, "Modeling coupling impedance of a rough surface," in *Proceedings*, *9th International Particle Accelerator Conference (IPAC 2018): Vancouver, Canada*, April 29 May 4, 2018.
- In Fox *et al.*, "Control of Intra-Bunch Vertical Instabilities at the SPS Measurements and Technol ogy Demonstration," in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, May, 2017*, no. 8 in TUPIK119, (Geneva, Switzerland), pp. 2005–2007, JACoW,
 May 2017.
- ⁴⁶⁷⁰ [192] W. H. K.S.B. Li and G. Rumolo, "Modelling and studies for a wideband feedback system for ⁴⁶⁷¹ mitigation of transverse single bunch instabilities," in *Proc. of International Particle Accelera-*⁴⁶⁷² *tor Conference (IPAC'13), Shanghai, China , May, 2013*, no. 4 in WEPME042, pp. 3019–3021, ⁴⁶⁷³ JACoW, May 2013.
- 4674 [193] K. L. et al., "Wideband feedback demonstrator system selected results from 2017." LIU MD
 4675 Days 15.03.2018, CERN, 2018, https://indico.cern.ch/event/706213/contributions/
 4676 2897740/.
- ⁴⁶⁷⁷ [194] R. W. Assmann, "Preliminary Beam-based specifications for the LHC collimators," Tech. Rep.

^{4632 [176]} missing.

- 4678 LHC-PROJECT-NOTE-277, CERN, Geneva, Jan 2002.
- [195] J. B. Jeanneret, "Momentum losses in LHC : the special case of RF uncaptured protons," CERN
 SL-Note-92-56-EA, 1992.
- [196] S. Wretborn, *et al.*, "Study of off-momentum losses at the start of the ramp in the Large Hadron
 Collider," *CERN-ACC-NOTE-2017-0065*, Sep 2017.
- [197] R. Bruce, R. W. Assmann, and S. Redaelli, "Calculations of safe collimator settings and β^* at the CERN Large Hadron Collider," *Phys. Rev. ST Accel. Beams*, vol. 18, p. 061001, Jun 2015.
- [198] R. Bruce, *et al.*, "Reaching record-low β^* at the CERN Large Hadron Collider using a novel scheme of collimator settings and optics," *Nucl. Instr. Meth. Phys. Res. A*, vol. 848, pp. 19 – 30, Jan 2017.
- [199] R. Bruce, A. Marsili, and S. Redaelli, "Cleaning Performance with 11T Dipoles and Local Dispersion Suppressor Collimation at the LHC," in *Proceedings of the International Particle Accelerator Conference 2014, Dresden, Germany*, 2014. MOPRO042.
- [200] A. Marsili, R. Bruce, and S. Redaelli, "Collimation Cleaning for HL-LHC Optics Scenarios with
 Error Models," *Proceedings of the International Particle Accelerator Conference 2014, Dresden, Germany*, p. 163, 2014.
- 4694 [201] G. Valentino, *et al.*, "Successive approximation algorithm for beam-position-monitor-based LHC
 4695 collimator alignment," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 021005, 2014.
- ⁴⁶⁹⁶ [202] R. Bruce, *et al.*, "Parameters for HL-LHC aperture calculations and comparison with aperture measurements," *CERN Report CERN-ACC-2014-0044*, 2014.
- ⁴⁶⁹⁸ [203] R. Bruce, *et al.*, "Parameters for aperture calculations at injection for HL-LHC," *CERN-ACC-*⁴⁶⁹⁹ 2016-0328, 2016.
- [204] C. A. Pons, *et al.*, "LHC aperture measurements," *Proceedings of IPAC 10, Kyoto, Japan*, p. 477, 2010.
- 4702 [205] C. A. Pons, et al., "IR1 and IR5 aperture at 3.5 TeV," CERN-ATS-Note-2011-110 MD, 2011.
- [206] R. Assmann, *et al.*, "Aperture Determination in the LHC Based on an Emittance Blowup Technique with Collimator Position Scan," *Proceedings of IPAC11, San Sebastian, Spain*, p. 1810, 2011.
- [207] S. Redaelli, *et al.*, "Aperture measurements in the LHC interaction regions," *Proceedings of IPAC12, New Orleans, Louisiana, USA*, p. 508, 2012.
- 4708 [208] C. A. Pons, et al., "IR2 aperture measurements at 3.5 TeV," CERN-ATS-Note-2012-017 MD, 2012.
- [209] R. Bruce, *et al.*, "IR8 aperture measurements at injection energy," *CERN-ATS-Note-2013-026 MD*, 2013.
- ⁴⁷¹¹ [210] R. Bruce, *et al.*, "IR2 aperture measurements at 4.0 TeV," *CERN-ACC-NOTE-2013-0011 MD*, 2013.
- [211] P. Hermes, *et al.*, "Improved Aperture Measurements at the LHC and Results from their Application in 2015," *Proceedings of the International Particle Accelerator Conference 2016, Busan, Korea*, p. 1446, 2016.
- [212] N. Fuster-Martinez, R. Bruce, and S. Redaelli, "LHC β^* -reach MD: aperture measurements at small β^* ," *CERN-ACC-NOTE-2017-0064*, Nov 2017.
- [213] N. Fuster-Martinez and E. Maclean and J. Dilly and R. Bruce and R. Tomas and S. Redaelli and T.
 Persson and L. Nevay, "Aperture measurements with AC dipole," *CERN-ACC-NOTE-2018-0008*,
 Feb 2018.
- [214] J.B. Jeanneret, "Geometrical tolerances for the qualification of LHC magnets," *LHC Project Report 1007, CERN*, 2006.
- ⁴⁷²³ [215] A. Mereghetti *et al.*, "Sixtrack-FLUKA active coupling for the upgrade of the SPS scrapers," in ⁴⁷²⁴ *Proceedings of the International Particle Accelerator Conference 2013, Shanghai, China*, 2013.

4725 WEPEA064.

- [216] A. Mereghetti, *Performance Evaluation of the SPS Scraping System in View of the High Luminos- ity LHC*. PhD thesis, University of Manchester, 2015.
- [217] E. Skordis, *et al.*, "FLUKA coupling to Sixtrack," *CERN-2018-011-CP*, *Proceedings of the ICFA Mini-Workshop on Tracking for Collimation, CERN, Geneva, Switzerland*, p. 17, 2018.
- 4730 [218] G. Robert-Demolaize, *et al.*, "A new version of SixTrack with collimation and aperture interface,"
 4731 *Proc. of the Particle Accelerator Conf. 2005, Knoxville*, p. 4084, 2005.
- 4732 [219] "Sixtrack web site." http://sixtrack.web.cern.ch/SixTrack/.
- 4733 [220] A. Ferrari, et al., "FLUKA: a multi-particle transport code," CERN Report CERN-2005-10, 2005.
- 4734 [221] G. Battistoni *et al.*, "Overview of the FLUKA code," *Annals Nucl. Energy*, vol. 82, pp. 10–18, 2015.
- 4736 [222] B. Auchmann, *et al.*, "Testing beam-induced quench levels of LHC superconducting magnets,"
 4737 *Phys. Rev. ST Accel. Beams*, vol. 18, p. 061002, 2015.
- 4738 [223] J. B. Jeanneret *et al*, "Quench levels and transient beam losses in LHC magnets," *LHC Project* 4739 *Report 44, CERN*, 1996.
- ⁴⁷⁴⁰ [224] L. Bottura *et al.*, "Expected performance of 11T and MB dipoles considering the cooling perfor-⁴⁷⁴¹ mance," *Presentation at 8th HL-LHC collaboration meeting, CERN, Geneva Switzerland*, 2018.
- 4742 [225] M. Varasteh *et al.*, "Cold loss studies for the quench limit assessment," in *4th EuroCirCol Meeting*,
 4743 Oct 2018.
- 4744 [226] C. Collaboration, "Absolute Calibration of Luminosity Measurement at CMS: Summer 2011 Up 4745 date," Tech. Rep. CMS-PAS-EWK-11-001, CERN, Geneva, 2011.
- 4746 [227] R. Tomas, private communication.
- 4747 [228] A. Krainer, "Design and Simulation of new protection devices in the dispersion suppressor regions
 4748 for the Future Circular Collider Project (to be published)," Master's thesis, Graz University of
 4749 Technology, Austria, 2019.
- I. Molson, *et al.*, "Simulating the LHC collimation system with the accelerator physics library
 MERLIN," *Proceedings of ICAP12, Rostock-Warnemünde, Germany*, pp. 12–14, 2012.
- [230] M. Serluca *et al.*, "HI-LUMI LHC collimation studies with MERLIN code," *Proceedings of the International Particle Accelerator Conference 2014, Dresden, Germany*, p. 784, 2014.
- [231] A. Chancé *et al.*, "Updates on the Optics of the Future Hadron-Hadron Collider FCC-hh," *Proceedings of the International Particle Accelerator Conference 2017, Copenhagen, Denmark*, p. 2023, 2017. TUPVA002.
- [232] D. Tommasini *et al.*, "Status of the 16 T Dipole Development Program for a Future Hadron Collider," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, p. 4001305. 5 p, 2018.
- [233] A. Dallocchio, *Study of thermomechanical effects induced in solids by high-energy particle beams: analytical and numerical methods*. PhD thesis, CERN-THESIS, 2008.
- [234] F. Carra, *et al.*, "New TCSPM Design Outcome of HRMT-23: Robustness of HL-LHC jaws."
 Special LHC Collimation Upgrade Specification Meeting: Material and design readiness for LS2
 productions, CERN, 2017.
- 4764 [235] A. Bertarelli, *et al.*, "HRMT-36 (Multimat) Experiment: Preliminary Results." LHC Collimation
 4765 Upgrade Specification Meeting N° 96, CERN, 2017.
- [236] E. Quaranta, *et al.*, "Towards optimum material choices for the HL-LHC collimator upgrade."
 IPAC16, Busan, Korea, 2016.
- [237] T. Furness, "Design and integration of an active dynamic compensation for the collimator jaw in
 the Multimat experiment." Eucard2 WP11 topical meeting, CERN, 2017.
- [238] D. Mirarchi, *Crystal Collimation for LHC*. PhD thesis, Imperial College London, 2015.

- [239] D. Mirarchi, *et al.*, "Design and implementation of a crystal collimation test stand at the Large
 Hadron Collider," *The European Physical Journal C*, vol. 77, p. 424, Jun 2017.
- 4773 [240] W. Scandale, *et al.*, "Observation of channeling for 6500 GeV/c protons in the crystal assisted
 4774 collimation setup for LHC," *Physics Letters B*, vol. 758, pp. 129 133, 2016.
- [241] R. Appleby *et al.*, "Report from the Review Panel," *Review of the needs for a hollow electron lens for the HL-LHC, CERN, Geneva, Switzerland*, 2016.
- ⁴⁷⁷⁷ [242] F. Bordry, *et al.*, "Machine parameters and projected luminosity performance of proposed future colliders at CERN," tech. rep., CERN, 2018. https://arxiv.org/abs/1810.13022.
- 4779 [243] R. Alemany Fernandez, *et al.*, "FCC-hh turn-around cycle," tech. rep., CERN, 2016. 4780 https://cds.cern.ch/record/2239138.
- ⁴⁷⁸¹ [244] M. Pojer, "LHC operation," in *8th LHC Operations Evian Workshop* (T. Argyropoulos, ⁴⁷⁸² S. Dubourg, and G. Trad, eds.), pp. 47 – 50, CERN, 2019. https://cds.cern.ch/record/2654224.
- [245] M. Solfaroli Camillocci, *et al.*, "Combined ramp and squeeze to 6.5 TeV in the LHC," in *Proc. of International Particle Accelerator Conference (IPAC'16), Busan, Korea, May 8-13, 2016*, (Geneve), pp. 1509–1512, JACoW, 2016. http://dx.doi.org/10.18429/JACoW-IPAC2016-TUPMW031.
- ⁴⁷⁸⁶ [246] D. Jacquet, "Injection," in *6th Evian Workshop on LHC beam operation* (B. Goddard and ⁴⁷⁸⁷ S. Dubourg, eds.), (Geneve), pp. 49–52, CERN, Oct. 2016. https://cds.cern.ch/record/2156966.
- [247] M. Solfaroli Camillocci, "Scope and results of hardware commissioning to 3.5 TeV and lessons learnt," in *Proceedings of the Chamonix 2010 workshop on LHC performance* (C. Carli, ed.),
 (Geneve), pp. 34–36, CERN, Apr. 2010. https://cds.cern.ch/record/1236824.
- [248] V. Shiltsev, "On performance of high energy particle colliders and other complex scientific systems," *Modern Physics Letters A*, vol. 26, no. 11, pp. 761–772, 2011.
 http://dx.doi.org/10.1142/S0217732311035699.
- [249] R. Steerenberg and J. Wenninger, "Operational challenges and performance of the LHC during run II," in *Proceedings of the 61st ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams*, (Geneve), pp. 357–361, JACoW, 2018.
 https://doi.org/10.18429/JACoW-HB2018-THA2WD01.
- [250] F. Bertinelli, *et al.*, "Towards a consolidation of LHC superconducting splices for 7 TeV operation," in *Proc. of International Particle Accelerator Conference (IPAC'10), Kyoto, Japan*, (Geneve), pp. 367–369, JACoW, 2010. https://cds.cern.ch/record/1277711.
- [251] O. Brüning, *et al.*, "LHC full energy exploitation study: Operation at 7 TeV," tech. rep., CERN,
 2017. https://cds.cern.ch/record/2284549/.
- [252] B. Todd, L. Ponce, and A. Apollonio, "LHC availability 2016: Proton run," tech. rep., CERN,
 2016. https://cds.cern.ch/record/2237325/.
- ⁴⁸⁰⁵ [253] B. Todd, *et al.*, "LHC availability 2017: Proton run," tech. rep., CERN, 2017. ⁴⁸⁰⁶ https://cds.cern.ch/record/2294852.
- [254] A. Niemi, *et al.*, "Availability modeling approach for future circular colliders based on the LHC
 operation experience," *Physical Review Accelerators and Beams*, vol. 19, p. 121003, Dec. 2016.
 https://doi.org/10.1103/PhysRevAccelBeams.19.121003.
- [255] J. Penttinen, A. Niemi, and J. Gutleber, "An open modelling approach for availability and reliabil ity of systems OpenMARS," tech. rep., CERN, 2018. https://cds.cern.ch/record/2302387.
- ⁴⁸¹² [256] J. Penttinen, *et al.*, "An open modelling approach for availability and reliability of
 ⁴⁸¹³ systems," *Reliability Engineering & System Safety*, vol. 183, pp. 387 399, 2019.
 ⁴⁸¹⁴ https://doi.org/10.1016/j.ress.2018.11.026.
- ⁴⁸¹⁵ [257] M. Schaumann, "Potential performance for Pb-Pb, p-Pb, and p-p collisions in a future circular ⁴⁸¹⁶ collider," *Phys. Rev. ST Accel. Beams*, vol. 18, September 2015.
- ⁴⁸¹⁷ [258] M. Schaumann and J.M. Jowett, "A First Look at the Performance for Pb-Pb and p-Pb collisions

- ⁴⁸¹⁸ in FCC-hh," in FCC Study Kickoff Meeting, Geneva, Switzerland, Feb 2014.
- [259] M. Mangano, ed., *Heavy ions at the Future Circular Collider*, *Chapter 4*, vol. Vol.3/2017 of *CERN Yellow Reports: Monographs*. CERN, Geneva, 2017. CERN–2017–003–M.
- [260] J.M. Jowett *et al.*, "FCC-hh as a heavy-ion collider," in *FCC week 2015*, Washington DC, USA,
 2015.
- [261] A. Dainese *et al.*, "Heavy-ion physics studies for the Future Circular Collider," in *FCC Week 2016*,
 Rome, Italy, 2016.
- ⁴⁸²⁵ [262] M. Schaumann et al., "Heavy-ions at the FCC-hh," in FCC week 2017, Berlin, Germany, 2017.
- [263] J.M. Jowett *et al.*, "The 2016 proton-nucleus run of the LHC," in *Proceedings of the International Particle Accelerator Conference, IPAC2017, Copenhagen, Denmark*, 2017. TUPVA014.
- [264] M. Schaumann, "Semi-Empirical Model for Optimising Future Heavy-Ion Luminosity of the LHC," in *Proceedings of the International Particle Accelerator Conference, IPAC14, Dresden, Germany*, 2014. TUPRO014.
- ⁴⁸³¹ [265] D. Manglunki. private communication.
- [266] K. Fuchsberger, "Turn-around analysis and possible improvements," in *Proceedings of the 7th Evian Workshop on LHC beam operation*, 2016. CERN-ACC-2017-094.
- ⁴⁸³⁴ [267] A.J. Baltz, M.J. Rhoades-Brown, and J. Weneser, "Heavy-ion partial beam lifetimes due to
 ⁴⁸³⁵ Coulomb induced processes," *Phys. Rev. E*, vol. 54, no. 4233, 1996.
- [268] I.A. Pshenichnov and S. Gunin, "Electromagnetic interactions of nuclei at the FCC-hh," in *Talk given at the XV International Seminar on Electromagnetic Interactions of Nuclei, Moscow*, October 2018.
- [269] H. Meier, *et al.*, "Bound-free electron-positron pair production in relativistic heavy-ion collisions,"
 Phys. Rev. A, vol. 63, no. 032713, 2001.
- [270] H.H. Braun, *et al.*, "Hadronic and electromagnetic fragmentation of ultrarelativistic heavy ions at
 LHC," *Phys. Rev. ST Accel. Beams*, vol. 17, no. 021006, 2014.
- [271] R. Bruce, *et al.*, "Beam losses from ultraperipheral nuclear collisions between ²⁰⁸Pb⁸²⁺ ions in the Large Hadron Collider and their alleviation," *Phys. Rev. ST Accel. Beams*, vol. 12, no. 071002, 2009.
- I.M. Jowett, M. Schaumann, and R. Versteegen, "Heavy ion operation from Run 2 to HL-LHC,"
 in *Proceedings of RLIUP: Review of LHC and Injector Upgrade Plans, Centre de Convention,* Archamps, France (B. Goddard and F. Zimmermann, eds.), 2014. CERN-2014-006.
- [273] A. Zlobin *et al.*, "Status of 11T 2-in-1 Nb3Sn dipole development for LHC," in *Proceedings of the 5th International Particle Accelerator Conference, IPAC-2014, Dresden, Germany*, 2014. p. 2722.
- [274] P.D. Hermes *et al.*, "Measured and simulated heavy-ion beam loss patterns at the CERN Large
 Hadron Collider," *Nucl. Instrum. Methods Phys. Res. A*, 2016.
- [275] H.H. Braun *et al.*, "Collimation of heavy ion beams in LHC," in *EPAC '04, Lucerne, Switzerland*,
 July 2004. MOPLT010.
- [276] D. Mirarchi *et al.*, "Cleaning Performance of the Collimation System of the High Luminosity
 Large Hadron Collider," in *Proceedings of the International Particle Accelerator Conference* 2016, Busan, Korea, 2016. WEPMW030.
- [277] P.D. Hermes *et al.*, "Simulation of heavy-ion beam losses with the SixTrack-FLUKA active coupling," in *IPAC '16, Busan, Korea*, June 2016. WEPMW029.
- [278] T. Bohlen, *et al.*, "The FLUKA Code: Developments and Challenges for High Energy and Medical
 Applications," *Nuclear Data Sheets*, no. 120, pp. 211–214, 2014.
- [279] P. Hermes, *Heavy-ion collimation at the Large Hadron Collider simulations and measurements*.
 PhD thesis, Phys. Dept., Westfälischen Wilhelms-Universität Münster, 2016.
- 4864 [280] Z. Citron et al., "Future physics opportunities for high-density QCD at the LHC with heavy-ion

- and proton beams," *arXiv e-prints*, 2018.
- [281] D. Manglunki *et al.*, "CERN's Fixed Target Primary Ion Programme," in *Proceedings of the 7th International Particle Accelerator Conference, IPAC-2016, Busan, Korea*, 2016. TUPMR027.
- 4868 [282] D. Küchler. private communication.
- [283] E.V. Karpechev *et al.*, "Emission of forward neutrons by 158A GeV indium nuclei in collisions
 with Al, Cu, Sn and Pb," *Nuclear Physics A*, no. 921, pp. 60–84, 2014.
- [284] U.I. Uggerhoj *et al.*, "Charge-changing interactions of ultrarelativisic In nuclei," *Physical Review C*, vol. 72, no. 057901, 2005.
- [285] I.A. Pshenichnov, "Electromagnetic excitation and fragmentation of ultrarelativistic nuclei,"
 Phys. Part. Nuclei, vol. 42, no. 2, pp. 215–250, 2011.
- 4875 [286] I.A. Pshenichnov. private communication.
- [287] R. Alemany Fernandez, "News and progress of turn-around time studies," in *FCC-hh meeting on extraction, insertion and turn-around time studies*, March 2016.
- ⁴⁸⁷⁸ [288] B. Todd *et al.*, "LHC Availability 2017: Proton Physics Setting the Scene," in *8th Evian Work-*⁴⁸⁷⁹ *shop on LHC beam operation*, 2017.