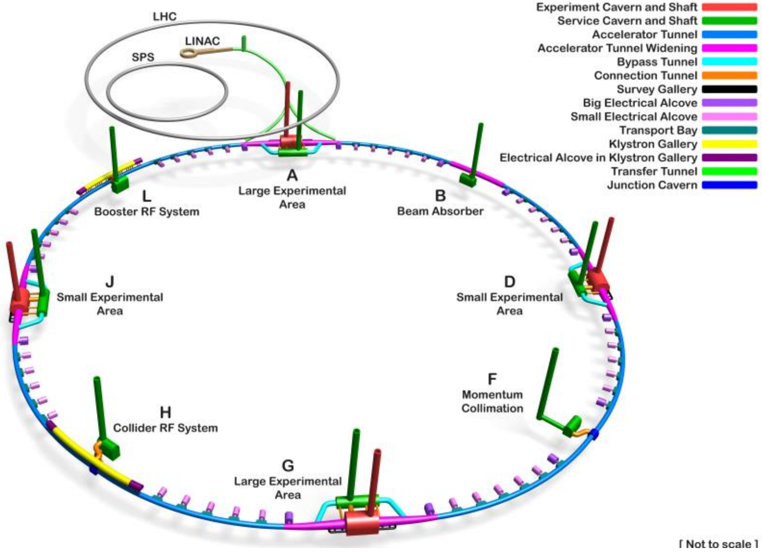
FCC-ee OPTICS EVALUATION

Options, Challenges & Outcome

S. Kostoglou, G. Roy, F. Zimmermann, C. Carli
on behalf of the FCC-ee Layout & Optics Design Working Group

FCC-ee timeline

- **Feasibility Study concluded in 2025,** assessing FCC technical, geological and financial feasibility
- In 2026, **European Strategy** outcome placed **HL-LHC & FCC-ee as first and second highest priorities**
- FCC is now entering **Reference Design Phase**
- Possible **CERN Council decision by 2028**
- **Technical Design Report** foreseen to be completed **by 2033**



Courtesy A. Navascues Cornago

Introduction

- FCC-ee Collider lattice is the **basis for many technical studies & system designs**
- The **choice of baseline optics** extends beyond beam dynamics, performance & luminosity reach
- Selecting baseline optics is on the **critical path** towards a coherent and cost-effective TDR
- **Two optics options**
  - **Global Hybrid Correction (GHC)** by K. Oide, developed over more than 10 years: high-level of maturity, building on KEKB/SuperKEKB experience, hybrid chromaticity correction and strongly relying on lattice super-periodicity
  - **Local Chromaticity Correction (LCC)** by P. Raimondi since 2023: newer modular concept, local chromaticity correction in both planes, common layout across energies

Comparison framework

- **Comparison principles**
  - **Written report** prepared by multiple groups (> 80 contributors)
  - Evaluation by **independent external review panel**
  - **Recommendation** transmitted to FCC study management for a decision

- **Multi-parametric comparison across wide range of evaluation criteria**
  - **Beam physics/performance**: Dynamic Aperture, Momentum Acceptance, lifetime, beam-beam effects, collimation, impedance, top-up injection
  - **Hardware/Infrastructure**: Magnets, Power Converters, RF, BI, MDI, Radiation shielding
  - **Operational aspects**: optics tuning and tolerances, switching between energy points, polarisation and energy calibration, availability

- **Challenges**
  - **Short timescale**
  - **Uneven maturity** or investment of studies between the two optics
  - Results distributed across **multiple teams and tools**, requiring careful consistency checks
  - Where data were missing, expert judgment was used and clearly stated in the report

Review Panel

- **21-23 January 2026 at CERN**
- **Panel members**
  - Philip Bambade (IJCLab)
  - Riccardo Bartolini (DESY), **Chairperson**
  - Alain Blondel (U Geneva)
  - Paul Collier (CERN)
  - Catia Milardi (INFN-LNF)
  - Sergei Nagaitsev (BNL)
  - John Seeman (SLAC)
  - Ye Zou (USTC)
  - Haruyo Koiso (KEK – on Zoom)

- **Mandate**
  - **Assess** methodology, assumptions and **comparison** criteria
  - **Review** performance potential, hardware / infrastructure implications and operational considerations
  - **Identify gaps**, uncertainties and issues requiring clarification
  - Provide a **recommendation** on the preferred optics option
  - Propose **follow-up actions** in the short and longer term

Optics options: Main differences

	GHC	LCC
Chromaticity correction	Global **horizontal chromaticity correction** in the **arcs** + local **vertical correction** near the IP	**Local chromaticity correction** in both planes in the Final Focus
Arc concept	FODO arcs with many **non-interleaved sextupole pairs in –I transformations**. **Preserving –I condition is essential.** Twin aperture dipoles and quadrupoles, QF for one beam corresponds to QD for the other, constrained to have the same length and strength, hence equal phase advances	Repetitive **5-cell FODO structure** with **only 4 sextupole families in 4 nested pairs. Achromatic and anharmonic** lattice. Higher dipole filling factor, twin-aperture quadrupoles powered **separately for the two beams**
Technical insertions	Identical / **universal technical straight sections**, with strong dependence on **superperiodicity.**	**Specialized straight sections** for injection, collimation, RF using **transparency conditions**
Final focus	**Simpler IR**: Crab-waist included in the Y CCS (virtual crab sextupoles)	**More elaborate FF**: dedicated X and Y CCS, dedicated crab sextupoles, additional higher-order magnets for tuning
Switching between energy modes	**Different magnet layout ai different energies**: long 90°/90° FODO cell at Z and W, short (half length) 90°/90° FODO a ttbar	**Common layout across energies**, with phase-advance changes

Impact of Collider optics on overall design

- **Collider optics is not only a beam-dynamics choice**
  - It has major implications for layout, CE, hardware, integration, operation & cost
- **Booster & Collider layout are coupled**
  - Booster layout must follow repetitive Collider arc structure
  - Booster location relative to the experiments (inside vs outside) feeds into tunnel size & CE
  - Common infrastructure (tunnel, experimental caverns..) that serves both FCC-ee & FCC-hh
- **GHC and LCC Final Focus are different**
  - Different available space near the IP → BS dump location, first dipole-IP distance, SR levels → affect detector background & environment
- **Optics in technical insertions are contrained by functionality and overall design of collider (tunes, path lengths)**
  - Flexibility I placement of functionality (Injection, Collimation, Dump, RF) is part of the overall facility optimisation

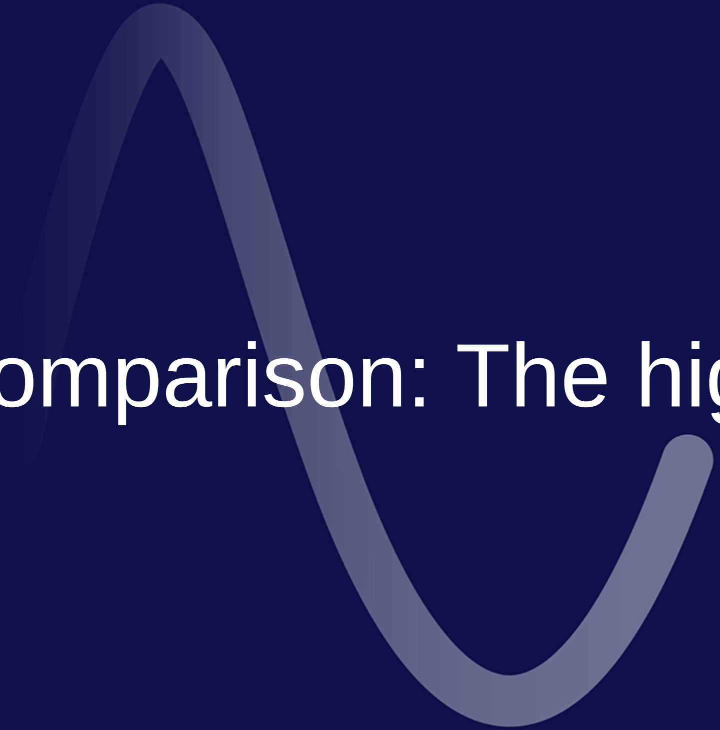
Impact of Collider optics on overall design

- **Both beamlines (e+, e-) must be defined explicitly, 2 machines per Collider optics**
  - Some sections are different for the two beams, cannot be obtained by simple mirroring

- **RF needs and SR losses per turn are optics-dependent**
  - Different dipole filling factors, different levels of SR
  - Different RF requirements feed into infrastructure, cost and performance reach

- **Switching between energy points**
  - LCC keeps common layout across energies (except RF insertion), simplifying energy transitions
  - GHC requires different layout in arcs and RF between energy points → different powering solutions to ensure smooth transitions, additional powering circuits, less operational flexibility

Optics differences propagate into many systems. Keeping both optics options became unsustainable for the Reference Design Phase

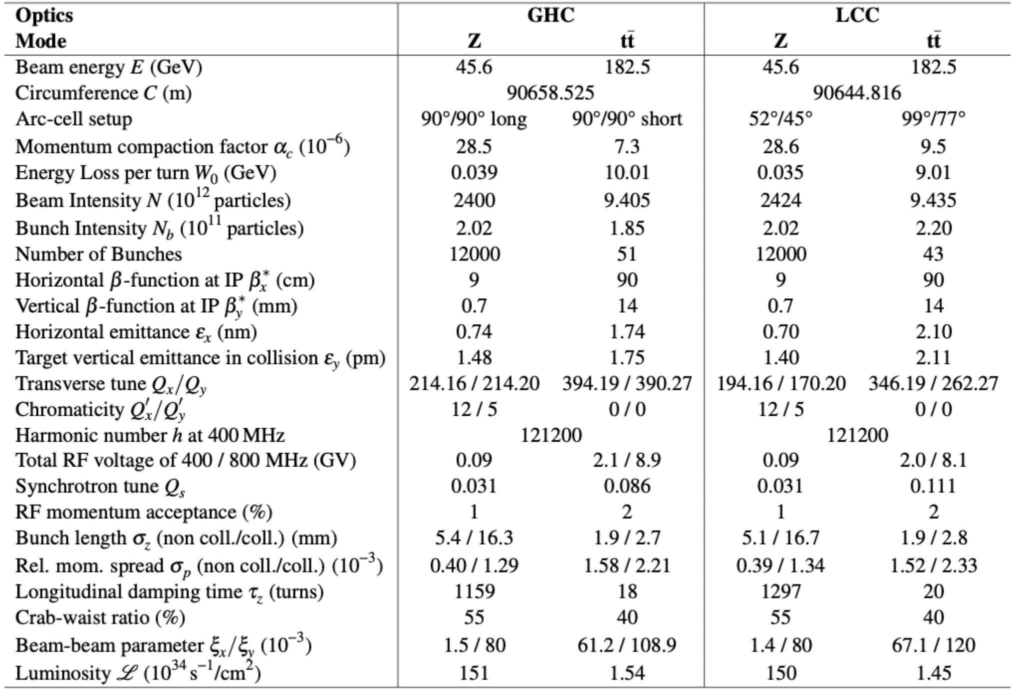


Optics comparison: The highlights

Comparison parameters

X. Buffat, M. Jebramcik, I. Karpov,
K. Oide, P. Raimondi, K. Skoufaris

Preliminary set of beam & machine parameters used as basis for the comparison



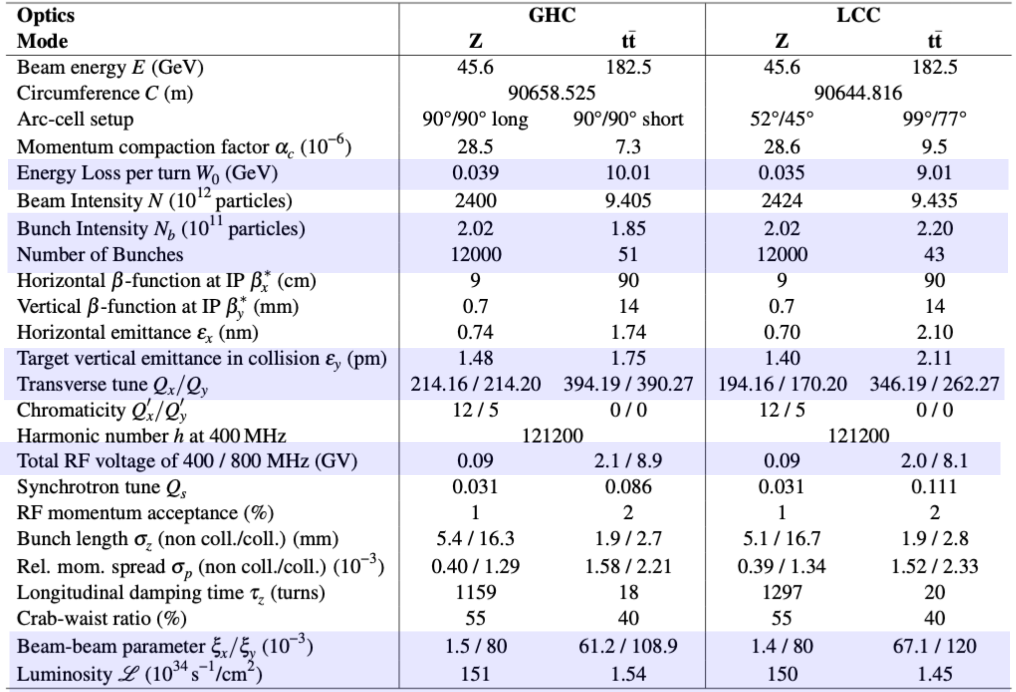
Optics	GHC		LCC	
Mode	Z	$t\bar{t}$	Z	$t\bar{t}$
Beam energy E (GeV)	45.6	182.5	45.6	182.5
Circumference C (m)	90658.525		90644.816	
Arc-cell setup	90°/90° long	90°/90° short	52°/45°	99°/77°
Momentum compaction factor α_c (10^{-6})	28.5	7.3	28.6	9.5
Energy Loss per turn W_0 (GeV)	0.039	10.01	0.035	9.01
Beam Intensity N (10^{12} particles)	2400	9.405	2424	9.435
Bunch Intensity N_b (10^{11} particles)	2.02	1.85	2.02	2.20
Number of Bunches	12000	51	12000	43
Horizontal β-function at IP β_x^* (cm)	9	90	9	90
Vertical β-function at IP β_y^* (mm)	0.7	14	0.7	14
Horizontal emittance ε_x (nm)	0.74	1.74	0.70	2.10
Target vertical emittance in collision ε_y (pm)	1.48	1.75	1.40	2.11
Transverse tune Q_x/Q_y	214.16 / 214.20	394.19 / 390.27	194.16 / 170.20	346.19 / 262.27
Chromaticity Q'_x/Q'_y	12 / 5	0 / 0	12 / 5	0 / 0
Harmonic number h at 400 MHz	121200		121200	
Total RF voltage of 400 / 800 MHz (GV)	0.09	2.1 / 8.9	0.09	2.0 / 8.1
Synchrotron tune Q_s	0.031	0.086	0.031	0.111
RF momentum acceptance (%)	1	2	1	2
Bunch length σ_z (non coll./coll.) (mm)	5.4 / 16.3	1.9 / 2.7	5.1 / 16.7	1.9 / 2.8
Rel. mom. spread σ_p (non coll./coll.) (10^{-3})	0.40 / 1.29	1.58 / 2.21	0.39 / 1.34	1.52 / 2.33
Longitudinal damping time τ_z (turns)	1159	18	1297	20
Crab-waist ratio (%)	55	40	55	40
Beam-beam parameter ξ_x/ξ_y (10^{-3})	1.5 / 80	61.2 / 108.9	1.4 / 80	67.1 / 120
Luminosity $\mathscr{L}$ (10^{34} s^{-1}/cm^2)	151	1.54	150	1.45

Table 2.1: Parameter table for the GHC and LCC lattices at Z and $t\bar{t}$ mode.

Comparison parameters

**X. Buffat, M. Jebramcik, I. Karpov,
K. Oide, P. Raimondi, K. Skoufaris**

- Beam current set by **50 MW SR power per beam** for **GHC**
  - 10% less radiation power for LCC for the same beam current
- $\varepsilon_y=\varepsilon_x/1000$ after optics corrections
- $\xi_y=0.08$ at Z, 0.12 at ttbar per IP
- $N_b \leq 12000$ from e-cloud
- Q_y from tracking simulations
- Q_x between synchro-betatron sidebands
- $V_{RF}(Z)=90$ MV for beam loading and depolarization constraints



Optics	**GHC**		**LCC**	
Mode	**Z**	**$t\bar{t}$**	**Z**	**$t\bar{t}$**
Beam energy E (GeV)	45.6	182.5	45.6	182.5
Circumference C (m)	90658.525		90644.816	
Arc-cell setup	90°/90° long	90°/90° short	52°/45°	99°/77°
Momentum compaction factor α_c (10^{-6})	28.5	7.3	28.6	9.5
Energy Loss per turn W_0 (GeV)	0.039	10.01	0.035	9.01
Beam Intensity N (10^{12} particles)	2400	9.405	2424	9.435
Bunch Intensity N_b (10^{11} particles)	2.02	1.85	2.02	2.20
Number of Bunches	12000	51	12000	43
Horizontal β-function at IP β_x^* (cm)	9	90	9	90
Vertical β-function at IP β_y^* (mm)	0.7	14	0.7	14
Horizontal emittance ε_x (nm)	0.74	1.74	0.70	2.10
Target vertical emittance in collision ε_y (pm)	1.48	1.75	1.40	2.11
Transverse tune Q_x/Q_y	214.16 / 214.20	394.19 / 390.27	194.16 / 170.20	346.19 / 262.27
Chromaticity Q'_x/Q'_y	12 / 5	0 / 0	12 / 5	0 / 0
Harmonic number h at 400 MHz	121200		121200	
Total RF voltage of 400 / 800 MHz (GV)	0.09	2.1 / 8.9	0.09	2.0 / 8.1
Synchrotron tune Q_s	0.031	0.086	0.031	0.111
RF momentum acceptance (%)	1	2	1	2
Bunch length σ_z (non coll./coll.) (mm)	5.4 / 16.3	1.9 / 2.7	5.1 / 16.7	1.9 / 2.8
Rel. mom. spread σ_p (non coll./coll.) (10^{-3})	0.40 / 1.29	1.58 / 2.21	0.39 / 1.34	1.52 / 2.33
Longitudinal damping time τ_z (turns)	1159	18	1297	20
Crab-waist ratio (%)	55	40	55	40
Beam-beam parameter ξ_x/ξ_y (10^{-3})	1.5 / 80	61.2 / 108.9	1.4 / 80	67.1 / 120
Luminosity $\mathscr{L}$ (10^{34} s^{-1}/cm^2)	151	1.54	150	1.45

Table 2.1: Parameter table for the GHC and LCC lattices at Z and $t\bar{t}$ mode.

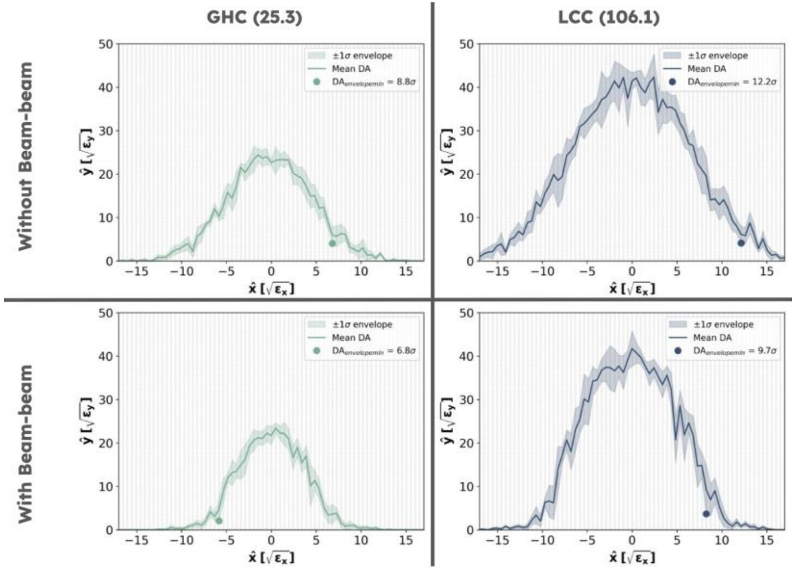
Dynamic Aperture & Momentum Acceptance

- DA & MA comparison including SR effects, cases without beam-beam or with weak-strong beam-beam and beamstrahlung (BS)

- Overall, **LCC shows a higher DA** and MA for Z
  - Tune scans: **larger stable tune space** with acceptable **lifetime** & lower **vertical emittance** for LCC

- At ttbar, both optics suffer from a **significant luminosity degradation (20-30%)** at nominal beam–beam parameter, requiring further studies
  - GHC degradation related to loss of superperiodicity
  - LCC degradation related to strong BB effects, larger emittances and resonance crossing

DA at Z pole



K. Skoufaris, X. Buffat, M. Jebramcik

Magnets: Differences in Arc layout

J. Bauche, I. Garcia Aguirrebeitia-Sanchez,
A. Vorozhtsov, L. von Freeden

Main dipoles

- **Length**
  - LCC: ~30m dipoles, split in 3 units of ~10m
  - GHC: ~24m dipoles, split in 2 units of ~12m
- **Field**: Slightly lower field for LCC (5%)
- **Quantity**: 17% more in LCC to support & align
- **Design**: Identical magnet cross-section
- **Powering**: -2.5% busbar lengths in LCC

Main quadrupoles

- **Length**
  - LCC: 1.86 m QD, 2.89 m QF
  - GHC: 2.7 m QF and QD
- **Field**: Much lower for LCC
- **Quantity**: 24% less in LCC
- **Design**:
  - LCC: Twin aperture but separate powering of each aperture
  - GHC: Coupled twin aperture with opposite polarities for the two beams

Magnets: Differences in Arc layout

J. Bauche, I. Garcia Aguirrebeitia-Sanchez, A. Vorozhtsov, L. von Freeden

Main sextupoles

- **Length**
    - LCC: 0.52 m SD, 0.3 m SF
    - GHC: 1.3 m SF and SD (double for Zh & ttbar)
- **Quantity**: 27% less in LCC
- **Design**: Similar magnet cross-section
- **Powering**:
    - GHC: Many independently powered sextupole pairs
    - LCC: Fewer sextupole families / circuits in the arcs

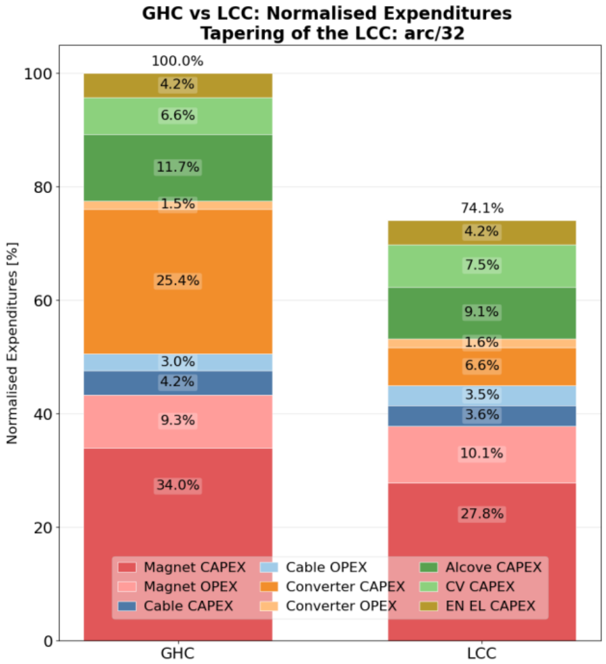
Overall

- Quadruople and Sextupoles arc magnets are the **most complex and costly** to manufacture
- LCC shows clear potential for magnet CAPEX savings thanks to its shorter Quadrupoles and Sextupole arc magnets
- Preliminary estimate for total arc-magnet CAPEX: about **17% lower for LCC than for GHC**
- Manufacturing is expected to be easier for LCC, especially because the **sextupoles are much smaller and less numerous**

Global system optimization

**D. Aguglia, N. Pinillos Zamorano,
A. Rankovic, S. Pittet**

- Subsystems **cannot be optimized independently.** Local choice in one subsystem propagates to many others
- System optimisation objective is to minimize total cost (CAPEX & OPEX), while respecting some constraints
- Comparison performed on Collider arcs only, including magnets, power converters, cabling, electrical equipment, cooling & ventilation, alcoves..
- **LCC gives substantially lower cost than GHC**
    - Main contributor are the power converters
    - In LCC, sextupole powering is centralized in the big alcoves, which **reduces the number of converters**
    - GHC **needs more converters to support energy-stage transitions** with fixed magnet layout



Machine availability

J. Heron, J. Uythoven, D. Domange

- Availability is driven mainly by failure rate & repair duration
- The dominant optics-dependent factor is the **power converter configuration**
- **LCC has a clear availability advantage due to sextupole powering**: Fewer critical sextupole circuits means larger MTBD, fewer dumps, better availability

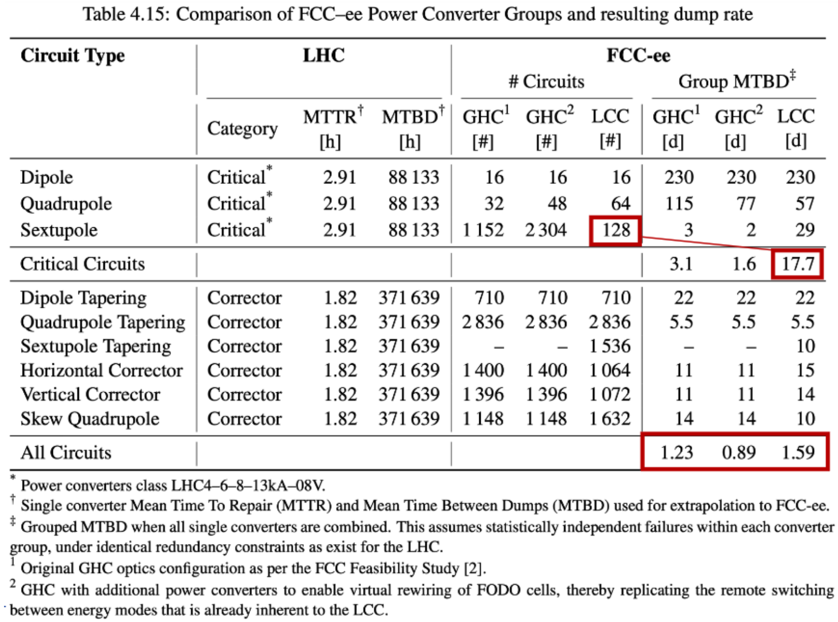


Table 4.15: Comparison of FCC–ee Power Converter Groups and resulting dump rate

Circuit Type	**LHC**			**FCC-ee**					
				# Circuits			Group MTBD[‡]		
	Category	MTTR[†] [h]	MTBD[†] [h]	GHC[1] [#]	GHC[2] [#]	LCC [#]	GHC[1] [d]	GHC[2] [d]	LCC [d]
Dipole	Critical[*]	2.91	88 133	16	16	16	230	230	230
Quadrupole	Critical[*]	2.91	88 133	32	48	64	115	77	57
Sextupole	Critical[*]	2.91	88 133	1 152	2 304	128	3	2	29
Critical Circuits							3.1	1.6	17.7
Dipole Tapering	Corrector	1.82	371 639	710	710	710	22	22	22
Quadrupole Tapering	Corrector	1.82	371 639	2 836	2 836	2 836	5.5	5.5	5.5
Sextupole Tapering	Corrector	1.82	371 639	–	–	1 536	–	–	10
Horizontal Corrector	Corrector	1.82	371 639	1 400	1 400	1 064	11	11	15
Vertical Corrector	Corrector	1.82	371 639	1 396	1 396	1 072	11	11	14
Skew Quadrupole	Corrector	1.82	371 639	1 148	1 148	1 632	14	14	10
All Circuits							1.23	0.89	1.59

[*] Power converters class LHC4–6–8–13kA–08V.

[†] Single converter Mean Time To Repair (MTTR) and Mean Time Between Dumps (MTBD) used for extrapolation to FCC-ee.

[‡] Grouped MTBD when all single converters are combined. This assumes statistically independent failures within each converter group, under identical redundancy constraints as exist for the LHC.

[1] Original GHC optics configuration as per the FCC Feasibility Study [2].

[2] GHC with additional power converters to enable virtual rewiring of FODO cells, thereby replicating the remote switching between energy modes that is already inherent to the LCC.

MTBD = Mean Time Between Dumps
(larger is better)

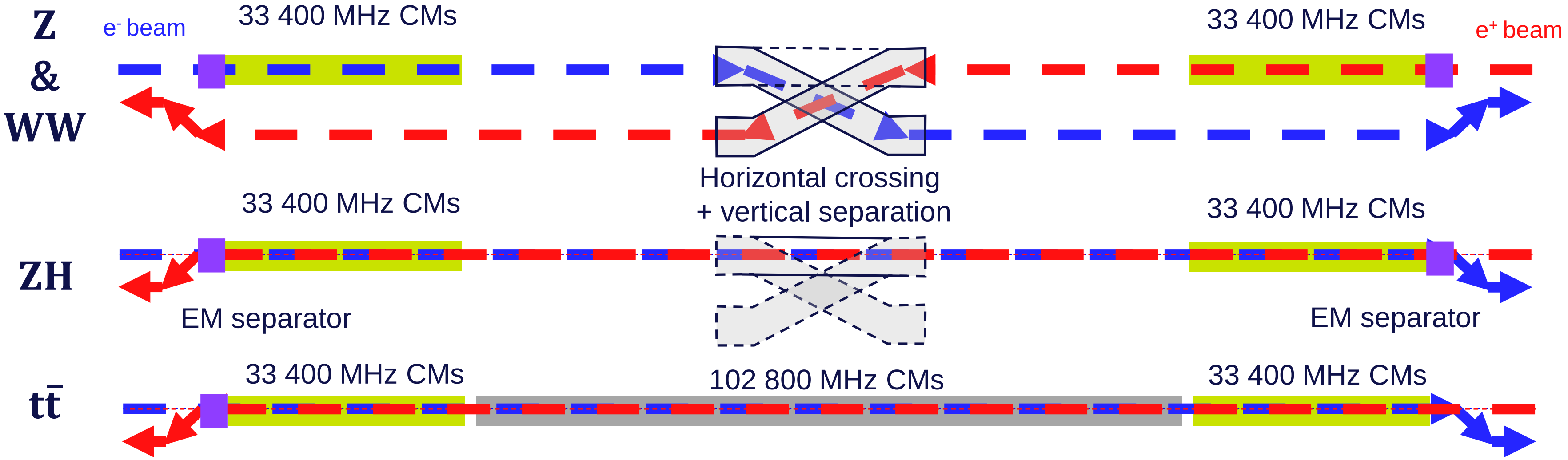
Huge advantage for LCC critical ciruits

With corrector circuits, advantage is reduced. Needs detailed criticality study.

Acknowledgement: Serge Pittet

RF system

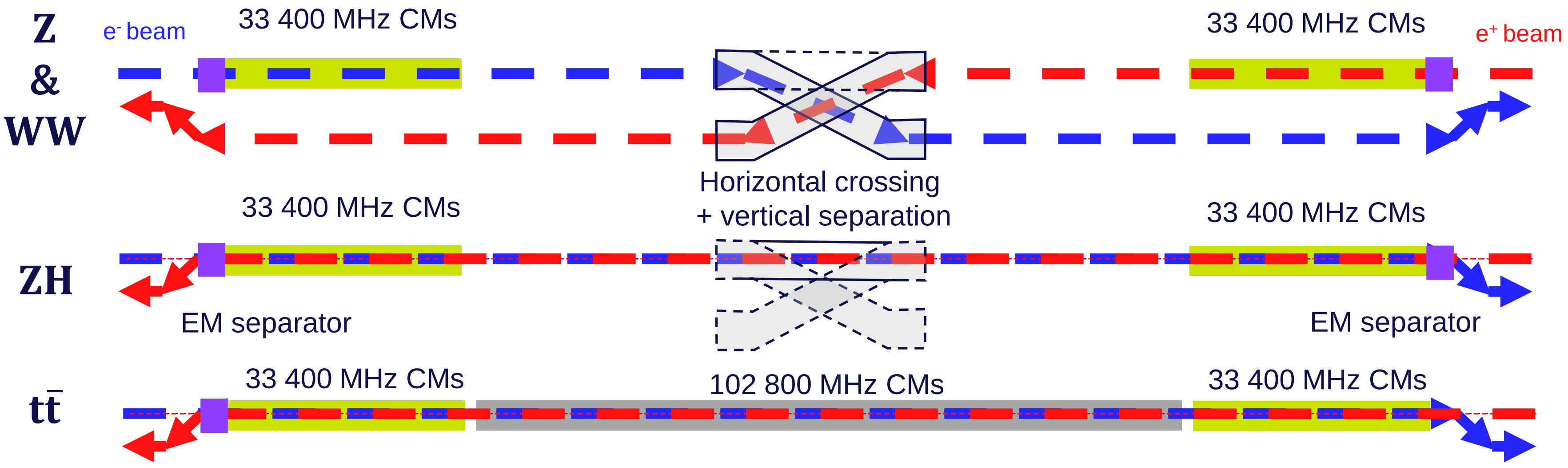
I. Karpov, O. Brunner, K. Canderan,
W. Hofle, V. Parma, F. Peauger, D. Sittard



- Identical number of 400 MHz SRF modules for Z, WW, Zh
- Separate per beam for Z (with Reverse Phase Operation) and WW, common to both for Zh
- Additional 800 MHz modules, common to both beams, for ttbar
- Vertically separated beam pipes to avoid long-range beam-beam effects
- Electromagnetic separators and dipoles to steer back to arc trajectories

RF system

**I. Karpov, O. Brunner, K. Canderan,
W. Hofle, V. Parma, F. Peauger, D. Sittard**



- LCC has about **10% lower SR energy loss per turn than GHC**. Lower RF voltage needs, fewer cavities, beneficial for integration of cryomodules
- Beam parameters in the comparison were chosen to maintain 50 MW SR power per beam for GHC. Under this assumption, same total beam current assumed for both optics but lower RF voltage requirements at ttbar for LCC

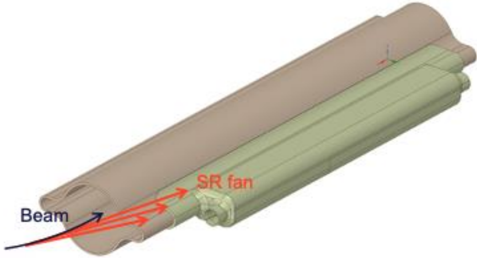
Synchrotron Radiation Absorbers

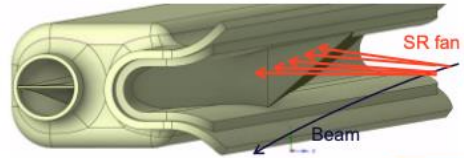
**B. Humann, A. Lechner, M. Ady, C. Garion,
V. Giovinco, M. Morrone, P. Krkotic et al**

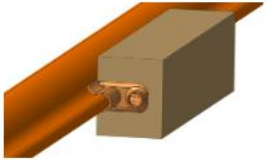
- **SRAs integrated into vacuum chamber winglets to intercept SR**
  - Placed only in **dipoles**
  - Spaced so that no direct photons from the beam hit the downstream chamber wall

- **Placement is driven by dipole spacing and dipole-free regions**
  - **GHC:** Longer short straight sections**,** longer dipole-free regions & non-uniform dipole pattern (short and long dipoles) make shadowing more difficult. Some absorbers must protrude into the chamber aperture to maintain full shadowing
  - **LCC:** more uniform, long-drift shadowing problem is avoided

- Overall, the LCC layout is **more favorable for SR absorber integration**: fewer absorbers, more uniform placement and no absorber intrusion into nominal aperture



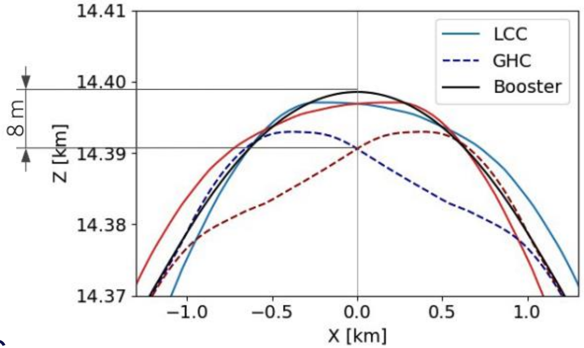




Machine Detector Interface

M. Boscolo, G. Broggi, G. Nigrelli,
F. Palla, F. Van der Veken

- MDI includes the experimental cavern & the interplay with the final-focus matching section (~1 km from the IP on each side)
- Same high-level parameters: L^*=2.4 m, 30 mrad crossing angle, SR masks at exits of final doublet (QC1, QC2) quadrupoles
  - Similar QC1 lengths & gradients, -30% QC2 gradient in LCC, potentially allowing normal-conducting magnet design
- No show-stopper MDI issue for either optics, **but different tunnel footprint, cavern integration, SR levels & beam intercepting device layout**
  - LCC places **dipoles in the cavern** (possibility to move them away under discussion), GHC does not
  - GHC uses **reverse bends**, LCC does not, but SR only on one side of tunnel
  - Beams start **separating at different locations** for the two optics
  - **BS dump location** differs: ~500 m downstream in GHC, likely closer in LCC but requires further assessment

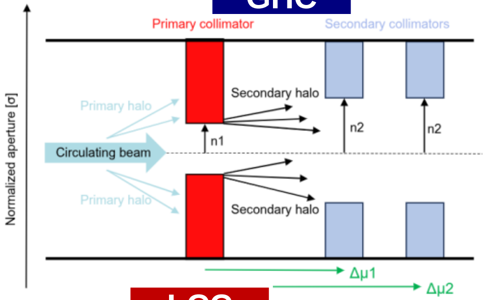


Collimation/Impedance

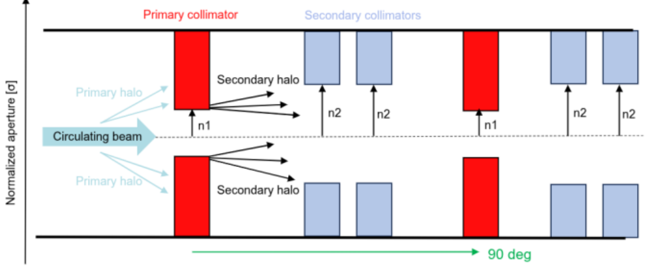
G. Broggi, A. Bessenay, R. Bruce, S. Redaelli, F. Van der Veken
C. Zannini, D. Gibellieri, M. Migliorati

- Two-stage collimation (primary & secondary) for both optics
- GHC is contrained by the universal technical insertion & superperiodicity requirements, limited freedom to optimize
- LCC has **more flexibility**:
  - Higher β-functions, wider collimation gap → beneficial for impedance
  - **Double-phase collimation** (primary collimators with 90° phase advance) can be implemented naturally: Significantly improves suppression of fast losses, protects against hierarchy breakage, improves background
  - Collimation insertion has essentially **zero dispersion:** off-momentum collimation requires another dedicated region and is **not yet fully defined / optimized**
- **Overall, LCC is favored for betatron collimation & impedance**

GHC



LCC



Optics comparison: The outcome

Outcome of the review

- The panel acknowledged that parallel development of GHC and LCC is **unsustainable**
- Both lattice strategies were judged to be **clearly defined**
- GHC was recognized as the FCC-ee historical backbone. LCC was recognized as building on that foundation
- **Recommendation: adopt LCC as the new FCC-ee optics baseline**
- Main reasons:
  - **Modular approach** & greater insertion flexibility, enabled by transparency conditions
  - **Common layout** across all operating energies
  - Superior **DA and MA**
  - Lower **SR loss per turn**, either reduced RF needs or higher luminosity at fixed RF power
  - Fewer sextupole families, significantly **reduced number of power converters and cost**

Outcome of the review

- The panel also stressed that many areas require **more systematic & in-depth analysis**
- Several **near-term and longer-term** studies were identified
  - **Consistent** use of **tools** across simulations
  - Field quality, tolerances and misalignments. Robustness against **realistic machine imperfections**
  - **Correctors** strategy and performance
  - Integrated simulations **including beam-beam and collective effects**
  - **Top-up** injection efficiency
  - Understanding **luminosity loss at ttbar** in LCC
  - **Collimation optimization** in LCC, including momentum collimation
  - Interplay between **Booster and Collider fields**
- Panel also emphasized that the two optics were compared at the same total beam current, not at the same SR power and that these **comparison assumptions should be revisited**

Study decision following optics review

- **LCC becomes the new reference optics for all ongoing studies**
- It will be used in particular for:
    - the short-term follow-up actions identified by the review panel
    - deriving specifications for hardware
    - analysing the implications for infrastructure, technical systems and the entire project
- **Goal**: **confirm LCC as the new baseline optics after FCC Week 2026**
- **By end of 2026**: update all relevant specifications & requirements

Next steps

- **By FCC Week 2026**
  - Make optics available at **all energy points**
  - First **reference table** of beam & machine parameters
  - Studies of all groups with LCC as common reference for FCC Week 2026

- **By end of 2026**
  - Consolidate **layout for CE studies** (Booster placement, tunnel widening in insertions, beam separations)
  - Reference to surface & **FCC-hh compatibility**
  - Consolidate **hardware**: magnet specifications, circuits & power converter specifications
  - Consolidate collimation, injection/dumps, RF, solenoid compensation

- **Reference Design Phase**
  - Fully **consolidated design**, supported by **realistic simulations** including most important beam dynamics effects & refine **equipment specifications**
  - Continue **optimizations of performance & integrated luminosity**

Summary

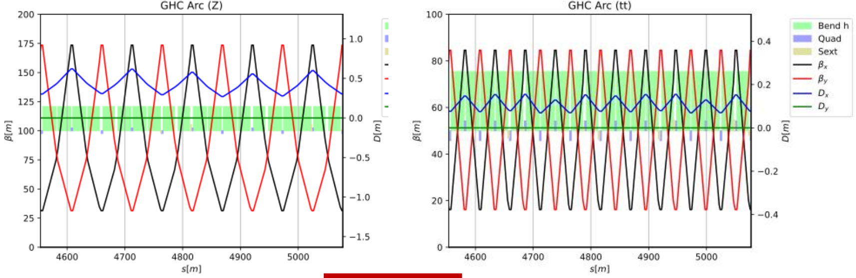
- The optics comparison required a **very large effort from many teams**, across many technical areas, in a very short timescale
- LCC was recommended, it offers real advantages in performance and cost.
  The collaboration is now focusing on consolidating it into a **coherent design**. Target is to confirm the new baseline optics **after FCC Week 2026**
- Our goal now is to keep the momentum, maintain a **strong flow of information** across groups and help align the work plan for the Reference Design Phase
- The next phase is **extremely challenging** as many aspects now couple optics, hardware, integration, CE, MDI, RF, collimation, vacuum, operation, machine protection..
- The key objective is to make all of these studies converge into a **coherent and technically feasible design**

Thank you
for your attention.

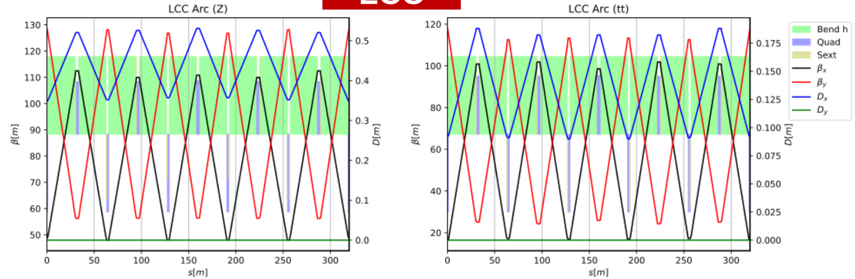
Comparison parameters

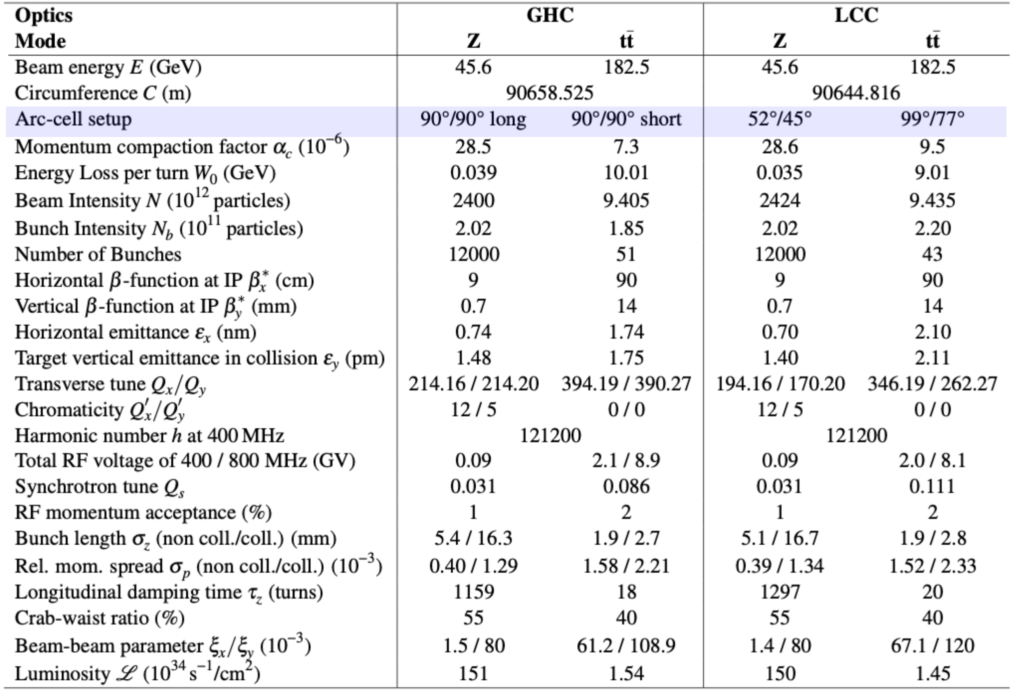
**X. Buffat, M. Jebramcik, I. Karpov,
K. Oide, P. Raimondi, K. Skoufaris**

GHC



LCC





Optics	GHC		LCC	
Mode	**Z**	**$t\bar{t}$**	**Z**	**$t\bar{t}$**
Beam energy E (GeV)	45.6	182.5	45.6	182.5
Circumference C (m)	90658.525		90644.816	
Arc-cell setup	90°/90° long	90°/90° short	52°/45°	99°/77°
Momentum compaction factor α_c (10^{-6})	28.5	7.3	28.6	9.5
Energy Loss per turn W_0 (GeV)	0.039	10.01	0.035	9.01
Beam Intensity N (10^{12} particles)	2400	9.405	2424	9.435
Bunch Intensity N_b (10^{11} particles)	2.02	1.85	2.02	2.20
Number of Bunches	12000	51	12000	43
Horizontal β-function at IP β_x^* (cm)	9	90	9	90
Vertical β-function at IP β_y^* (mm)	0.7	14	0.7	14
Horizontal emittance ε_x (nm)	0.74	1.74	0.70	2.10
Target vertical emittance in collision ε_y (pm)	1.48	1.75	1.40	2.11
Transverse tune Q_x/Q_y	214.16 / 214.20	394.19 / 390.27	194.16 / 170.20	346.19 / 262.27
Chromaticity Q'_x/Q'_y	12 / 5	0 / 0	12 / 5	0 / 0
Harmonic number h at 400 MHz	121200		121200	
Total RF voltage of 400 / 800 MHz (GV)	0.09	2.1 / 8.9	0.09	2.0 / 8.1
Synchrotron tune Q_s	0.031	0.086	0.031	0.111
RF momentum acceptance (%)	1	2	1	2
Bunch length σ_z (non coll./coll.) (mm)	5.4 / 16.3	1.9 / 2.7	5.1 / 16.7	1.9 / 2.8
Rel. mom. spread σ_p (non coll./coll.) (10^{-3})	0.40 / 1.29	1.58 / 2.21	0.39 / 1.34	1.52 / 2.33
Longitudinal damping time τ_z (turns)	1159	18	1297	20
Crab-waist ratio (%)	55	40	55	40
Beam-beam parameter ξ_x/ξ_y (10^{-3})	1.5 / 80	61.2 / 108.9	1.4 / 80	67.1 / 120
Luminosity $\mathscr{L}$ ($10^{34}\,\mathrm{s}^{-1}/\mathrm{cm}^2$)	151	1.54	150	1.45

Table 2.1: Parameter table for the GHC and LCC lattices at Z and $t\bar{t}$ mode.