FCC–hh: Transferlines and Injection Insertion

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FCC Week 2018, Amsterdam, 8th – 14th of April

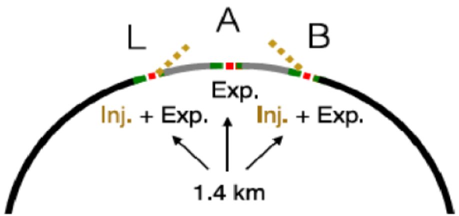
Outline

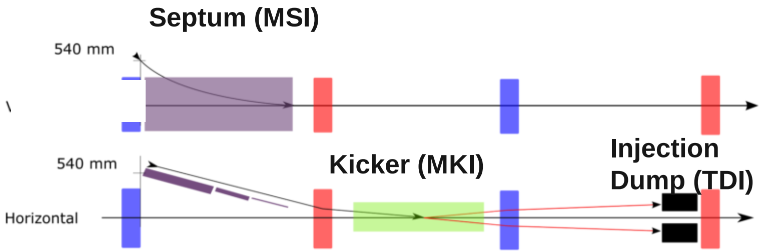
- **Injection Insertion**
  - Update on optics and hardware solutions
  - Kicker failures and injection protection
  - R&D Outlook: massless septum as protection device
- **Transferlines**
  - Layout requirements
  - Proposal for transfer line protection scheme
- **Extraction from HEB**
- **Summary and next steps**

Layout

- **Combined with side experiments (IPB and IPL) in 1.4km**
- **Injection upstream of side experiments**
- **Double plane injection**
  - 100m normal conducting Lambertson septa (simple, robust)
  - 40m fast recharging injection kicker (10Hz), 18 modules

Hardware parameters	Unit	Kicker	Septum
Deflection	mrad	0.18	9.8
Integrated field	T.m	2.0	92
System length	m	40	104
Effective length	m	31.8	84
Rise time	μs	0.43	-
Recharge frequency	Hz	≈ 10	-
Flattop length	μs	2.0	≥ 2.0
Flattop stability		$\pm 5 \cdot 10^{-3}$	$\pm 10^{-5}$
GFR inj. beam h/v (radius)	mm	-	9/-
Beam stay clear circ. beam h/v (radius)	mm	16/16	9/14 (first unit)
Septum width (first unit)	mm	-	8





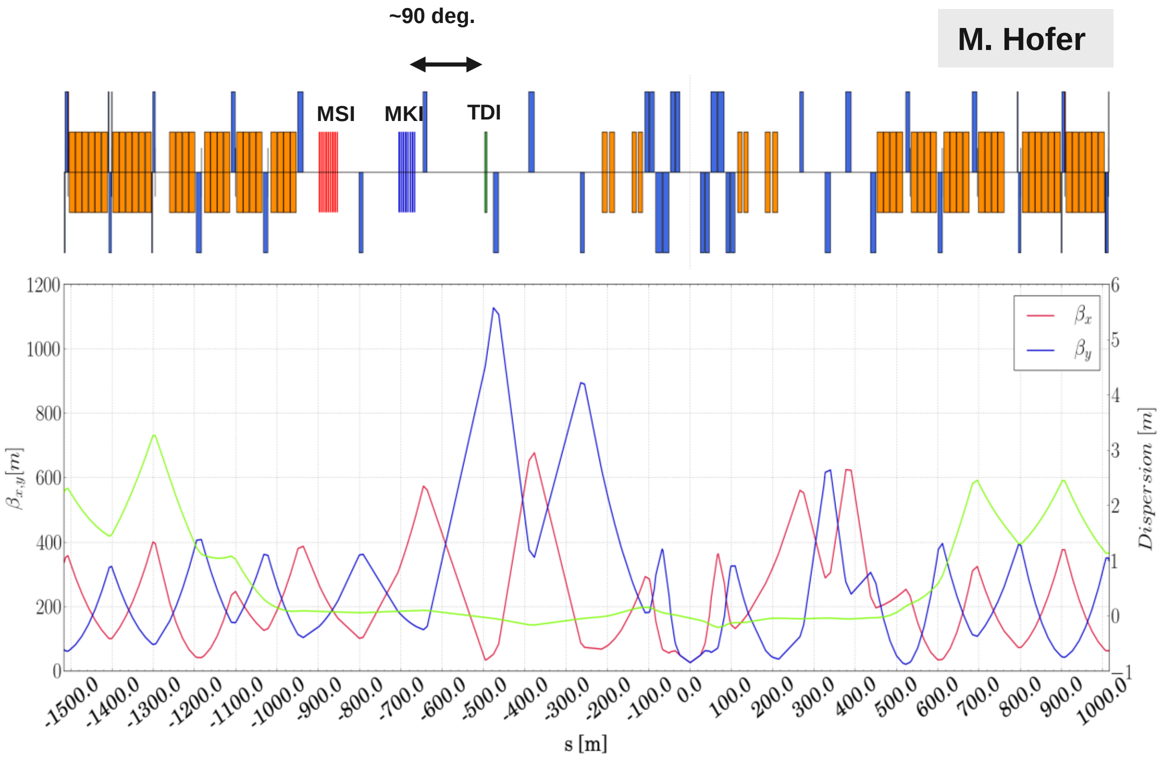
Injection

Status similar to FCCW 2017, main change:

Beam size at injection dump (TDI) increased to stay below damage limit of injection dump in case of kicker failure

- $\sqrt{\beta_x \beta_y}$ factor 1.6 compared to FCCW 2017

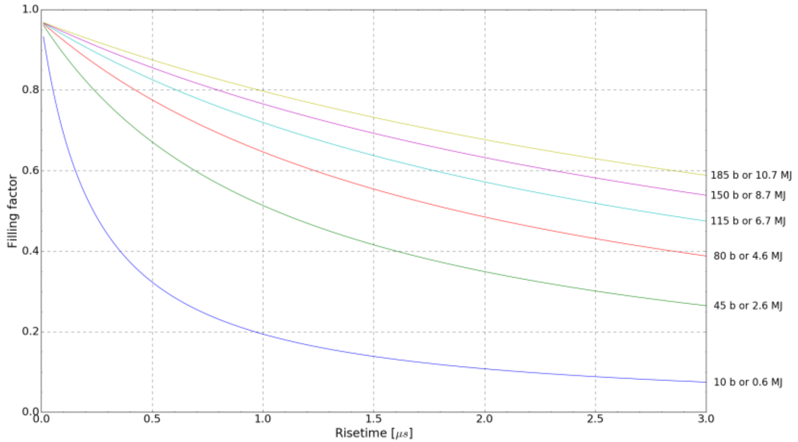
M. Hofer



Challenges for Beam Transfer to FCC

- **Transfer of 550 MJ in total**
- **The injection batch is limited to 80 bunches** to stay below the damage limit of the injection dump (margin of a few 10% [1])
- **130 injections to fill FCC**
- **Complex for kicker system:**
  - Staggered transfer
  - **Fast pulsed injection kicker** (10Hz, frequency reduced compared to 2017: 100Hz**)
  - **Short kicker risetime** (430ns)

⇨ **New generator technologies are necessary and being studied**
- **Marx generator**
- **Inductive Adder**



D.Woog: Inductive adder prototype pulse generator for FCC-hh kickers, Wed. 11:10

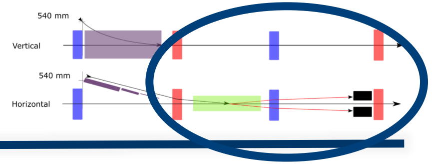
M. Barnes: Marx prototype pulse generator design and initial results, Wed. 0930

M. Barnes: FCC kicker magnet design, impedance and heating aspects Wed. 10:30

A. Lechner: FCC-hh protection absorbers and the dump, Tue 16:40

** additional filling time due to frequency reduction negligible contribution to overall filling time

Injection Failures



Most critical failures are faults of the injection kicker system,

- Miskick of circulating beam
- Missing kick of injected beam

which can both occur ...

- ... at different charging states of generator (full/reduced kick)
- ... for different number of kicker modules

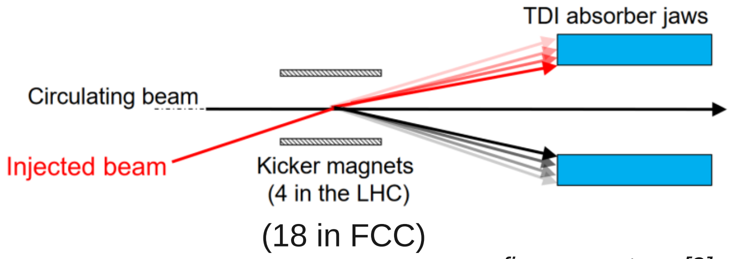
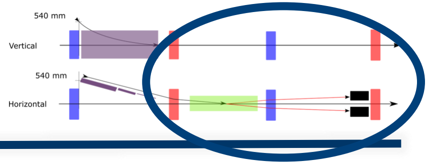


figure courtesy [2]

There are many different failure scenarios to consider:

Technological differences between proposed new pulse generators for injection kicker magnets (Inductive Adder or Marx Generator) and LHC pulse generators (pulse forming networks) [next slides]

Injection Failures



Main message of next slides:
We aim to…

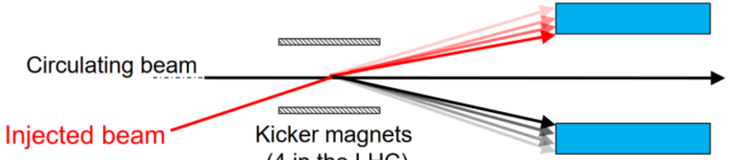


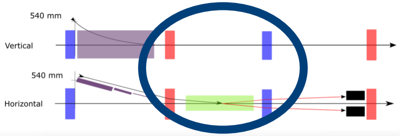
figure courtesy [2]

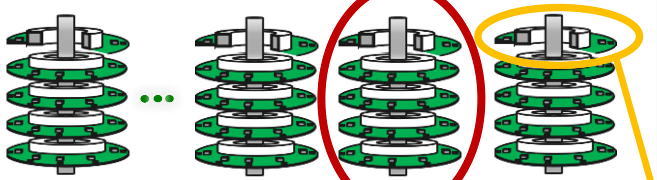
… reduce failure probabilities of kicker magnets due to novel generators

…still provide protection

(also for grazing impact [worst case] - which, can potentially be excluded at hardware level → post CDR)

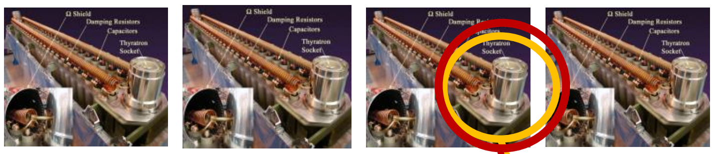
Injection – Failure Scenarios of the Inductive Adder I





FCC: MKI 1

FCC: MKI 18



LHC: MKI 1

LHC: MKI 4

(1) 18 kicker magnets /generators

(2) 20 layer per generator

(3) 24 semiconductor switches per layer

(1) 4 kicker magnets /generators

(3) 1* thyratron switch per generator

*1 main switch and 1 dump switch

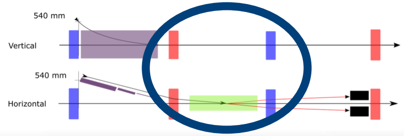
- 1 failing switch has negligible impact
- Capacitors only partly discharged for each inj. batch (~1-2% discharge)

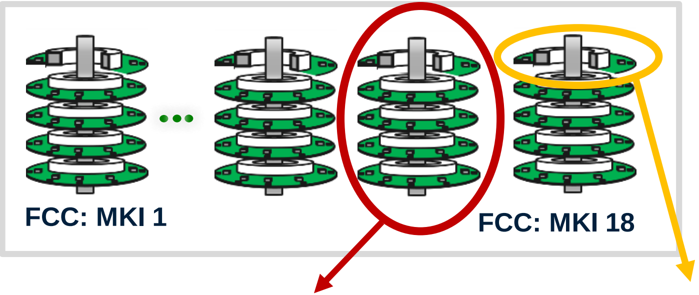
→**Thus kicker pre-firing (nearly always) with max. kick,**

- 1 failing switch: 25% of the kick
- Energy for 1 single injection pulse stored in generator

→ Recharging of capacitors for each inj. batch, **pre-firing at any charging state/kick (>0-100%) possible**

Injection – Failure Scenarios of the Inductive Adder II



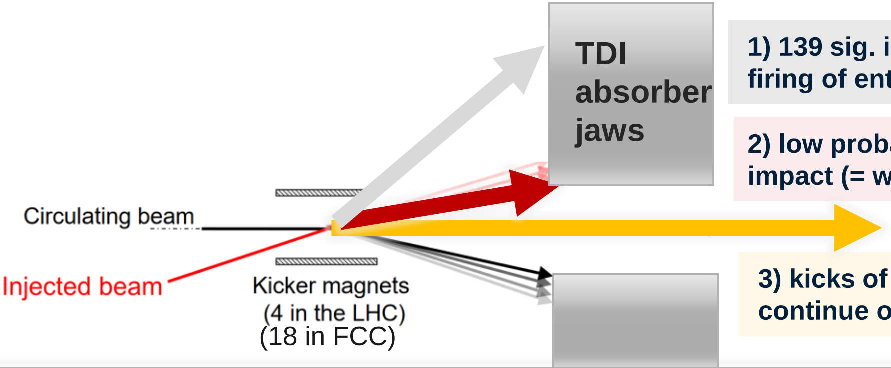


(1) Entire system missing/pre-firing

(2) 1 generator missing/pre-firing

(3) 1 switch/layer missing/pre-firing

- kicks of <0.3sig (→ no impact) and full kick most likely
- low probability of grazing impact (= worst case)

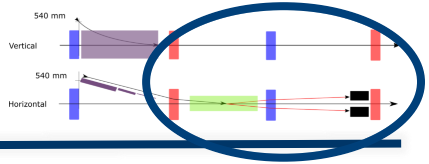


1) 139 sig. impact of missing/pre-firing of entire system

2) low probability of grazing impact (= worst case)

3) kicks of <0.3sig → no impact / no dump / continue operation

Injection Failures



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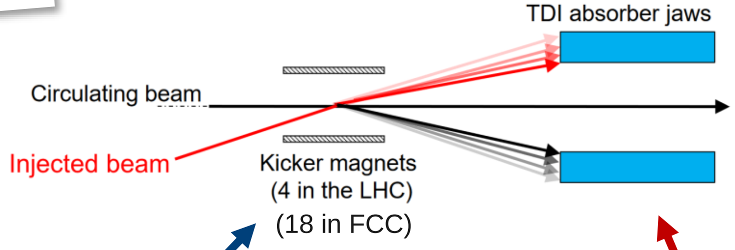


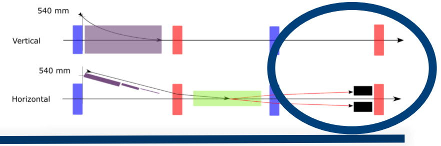
figure courtesy [2]

… reduce failure probabilities of kicker magnets due to novel generators

…still provide protection

(also for grazing impact [worst case] - which, can potentially be excluded at hardware level → post CDR)

Injection – Protection Strategy



Proposed protection system similar to LHC

Injection dump (TDI):

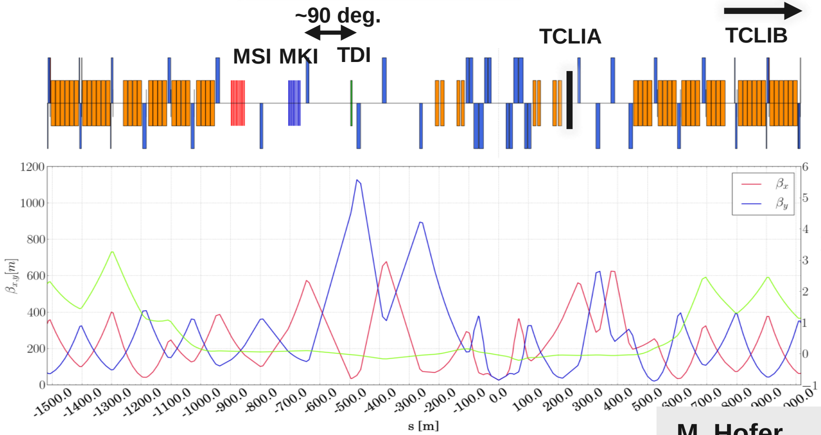
- 6m, graphite (2.5m with $1.4\ g/cm^3$+ 3.5m with $1.8\ g/cm^3$)

Auxiliary absorber (TCLIs)

- TCLIA: with $180 - 20deg$ to TDI (or multiple)
- TCLIB: with $360 + \ 20deg$ to TDI (or multiple)

Currently not possible to provide +-20deg phase advance to the TCLIs (-10deg, +20deg):

→ If not sufficient, the phase advance to be optimized to accommodate auxiliary absorbers **(post CDR)**



M. Hofer

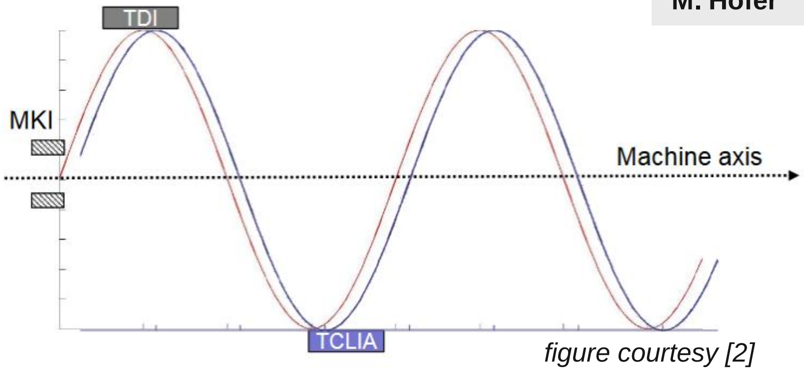
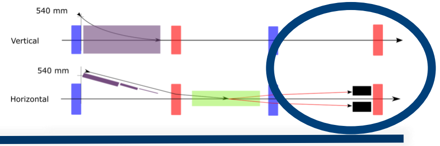


figure courtesy [2]

Injection Dump (TDI) Settings



- Preliminary setting of injection dump: 8.5 sigma

→ Beam size at TDI still small → half gap is 1.3mm

→ **Small horiz. beam size has large impact on alignment tolerances, to be considered for TDI settings**

Maximum errors (not exhaustive) assumed to evaluate the worst case halo escaping the injection protection system

	HL-LHC [4] 4m	FCC 6m
Mech. tolerances	+- 0.2mm/0.3	+- 0.3mm → 2 sig
Injection precision	0.3sig	~1-1.5sig → to be quantified more precisely**

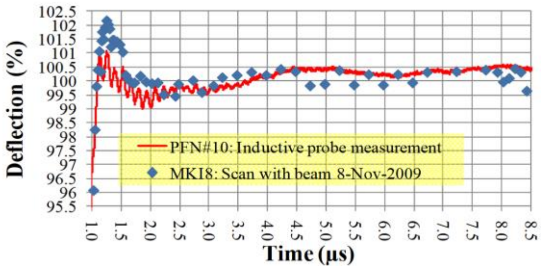
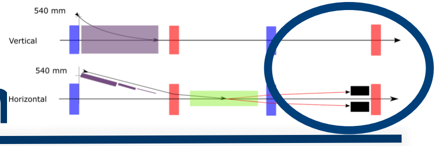


figure courtesy [8]

Biggest contributor is kick due to **flattop ripple of injection/extraction kicker: ~ 0.7 sigma with current pulse generator specifications (+-0.5%, as in LHC)

→ **Generator specifications will be updated to reduce injection errors (very challenging for 5ns beam)**

Injection Dump (TDI) – Protection Validation



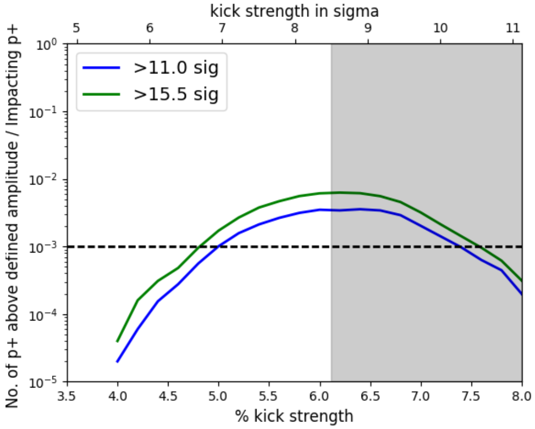
- FLUKA simulations conducted for **impact of 80 bunches in grazing impact** to validate local protection efficiency → **OK**

A. Lechner: FCC-hh protection absorbers and the dump, Tue 16:40

- **Tracking studies ongoing** to refine required TDI settings → First results to be validated for the CDR

→ Preliminary results for grazing impact: ~0.5% of impacting p+ are scattered with large angle

→ **Larger horiz. beam size at the TDI would be of advantage to reduce alignment tolerances and # of p+ with large scattering angle**



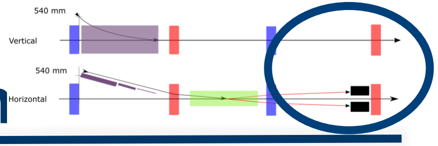
Cooperation with the CERN collimation team and EN-STI

Attenuation requirement: $O(10^{-3})$ (HL-LHC: 1/70)

- Injection batch: $80 \cdot 10^{11} p +$
- non-closing switch → magnetic saturation after ~3us: $\sim 100 \cdot 10^{11} p +$
- Safe beam flag (M. Zerlauth, based on[7]) $1 \cdot 10^{10} p +$

To be revised

Injection Dump (TDI) – Protection Validation



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A. Lechner: FCC-hh protection absorbers and the dump, Tue 16:40

Protection for worst case kicker failure OK, but with difficult TDI settings etc.

→ **could be improved by** larger betX at TDI (to be studied beyond CDR)

→ Protection studies ongoing

- **Tracking studies ongoing** to refine required TDI settings → First results to be validated for the CDR

  → Preliminary results for grazing impact: ~0.5% of impacting p+ are scattered with large angle

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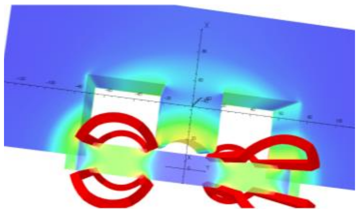
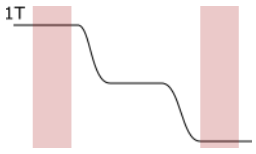
To be revised

Outlook: Massless Septum as Protection Device

Main idea: Use a massless septum to further deflect the miskicked beam between the injection kicker (MKI) and the injection dump (TDI) without impacting the circulating beam

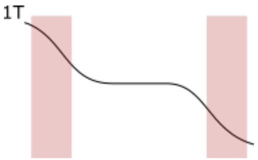
Two options, (B) seems more feasible → To be studied in detail post-CDR





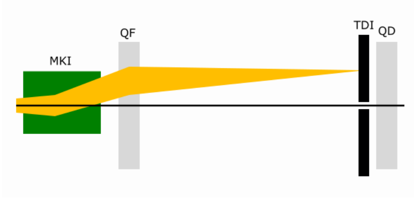
(A) Use a massless septum to extract beam to an external TDI to avoid showers after TDI

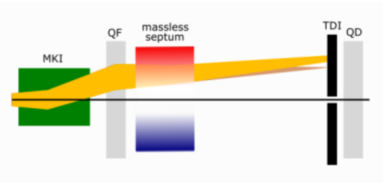
- very challenging, ~100m of MLS (1T) needed to bypass Q6
- Challenge: steep slope, tolerances in zero field region



(B) Massless septum to increase beam size of miskicked beam at TDI

- make use of slope
- ~10 meters of MLS (1T) to increase horizontal beam size at TDI by factor ~1.5-2
- Challenge: tolerances in zero field region





Outline

- Reminder of baseline
- Injection Insertion
  - Update on optics and hardware solutions
  - Failure scenarios and injection protection
  - R&D: massless septum as protection device
- Transferlines
  - Layout requirements
  - Proposal for transfer line protection scheme
- Extraction from HEB
- Summary and next steps

Layout of transferline depends on protection scheme / requirements

→ Understand protection requirements to understand transferline layout

Transferlines (TL) - Layout

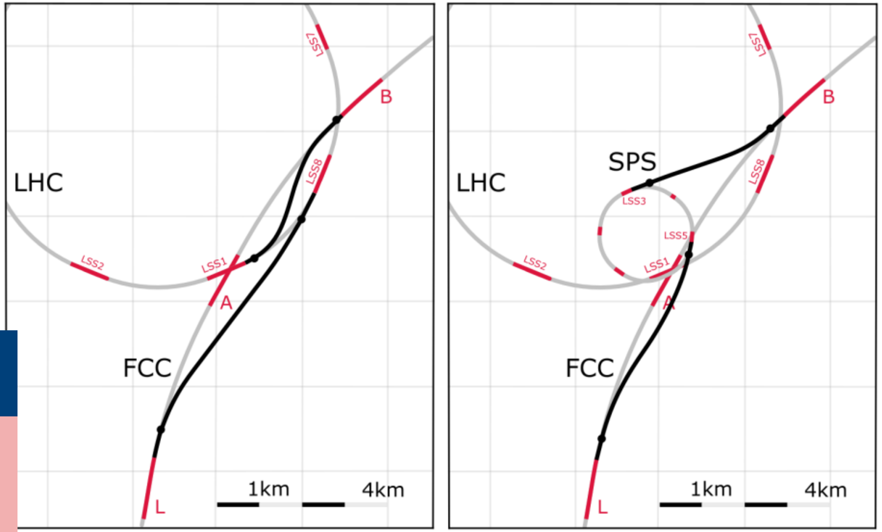
New transferline layout

→ longer straight sections at start and end of the TL were necessary for appropriate protection from extraction / TL failures

→ Increased dipole strength

	total length [km]	Dipole Field / Length	straights length [km]
LHC1 – FCCB	4.2	SC: 7.2T/3.9km	**0.3 (challenging TL collimation!)***
LHC8-FCCL	8	SC: 7.2T/ 1.5km	6.5
SPS3-FCCB	3.3	NC: 1.8T /1.9km	2.4
SPS5-FCCL	5.8	NC: 1.8T/ 4.4km	1.4

* additional straight length to be gained from LHC extraction



- LHC-FCC: only sc to not mix different machine protection strategies
- scSPS to FCC: only normal conducting
- (2017: mixed sc and nc TLs, Bmax = 6T)

Transferlines – Failure Scenarios / Proposed Prot. Scheme

- Transferline collimation system must protect the downstream TL and FCC injection from any failure during the 3-4ms after the injection permit is given

LHC-FCC: sc transferline**

Quench: **~1sig**

Power converter: **<< 1sig**

Dedicated absorber

with specific phase advance to LHC extraction kicker/septum at the beginning of the TL

scSPS- FCC: nc transferline**

Power converter trip of single dipole: ~1-2 sig

*value for single dipole; power conv. trip of entire circuit needs to be considered

Phase space covering

at end of TL. More space needed.

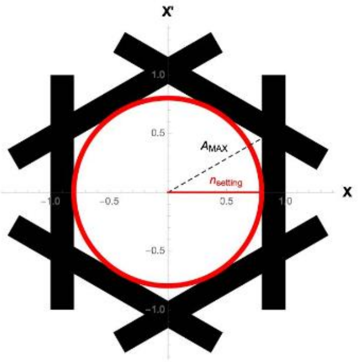
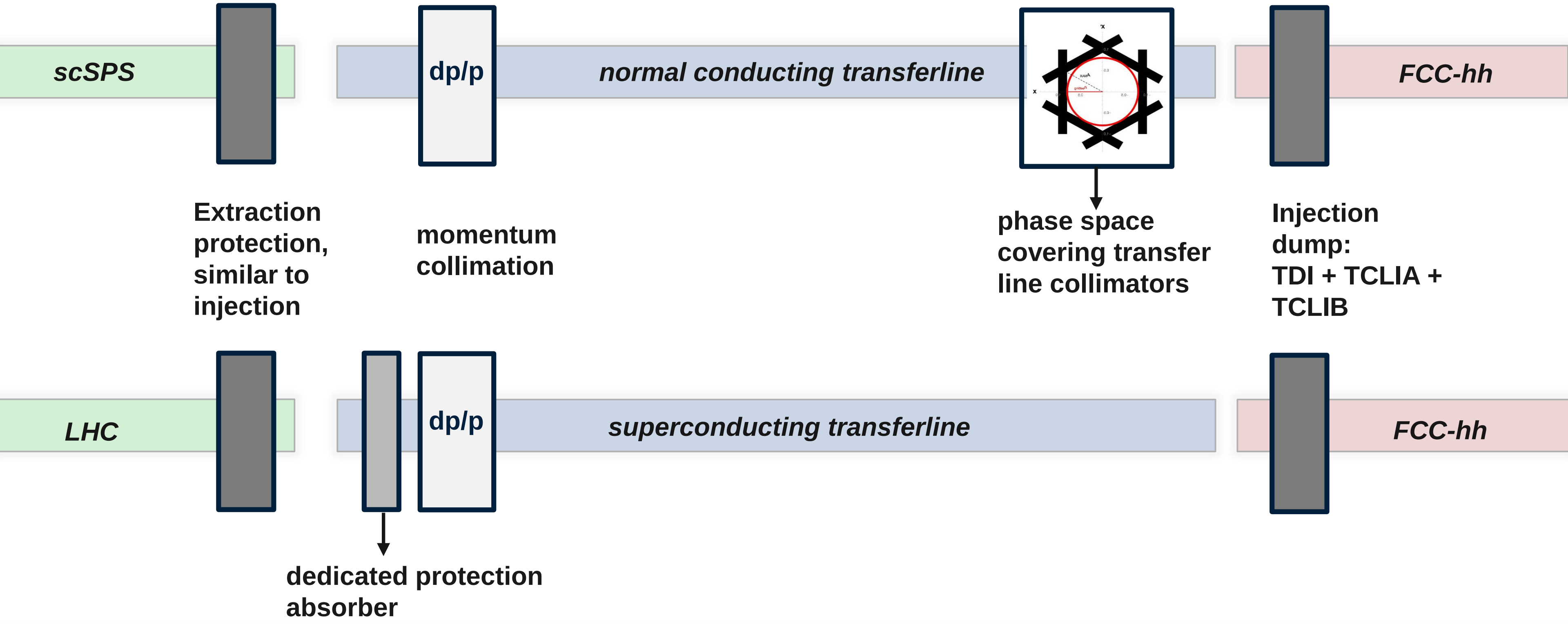


figure courtesy [4]

** preliminary estimations based on optics estimates and time constants for LHC magnets

Transferline Protection

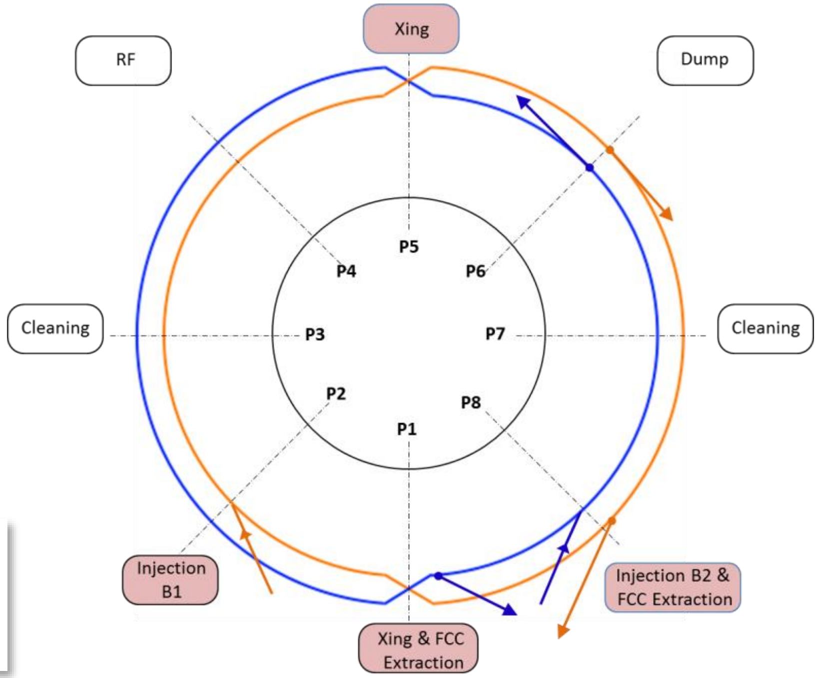


Machine Protection for Extraction from LHC as Injector

P1 and P8: Extraction to transferline is similar to FCC injection system

P6: LHC beam dump system

- **Same studies as for injection for failures of LHC to TL extraction necessary**
- **Same mitigation strategies, however…**
  - …avoid losses in superconducting transferline in case of failure e.g. extraction kicker failure



Post CDR:

→ Detailed loss and strategy studies for extraction failures necessary

Conclusions

- Working optics design with feasible hardware solutions
- FLUKA studies for grazing impact at injection dump show sufficient local protection [1]
- New kicker generator topologies to enable fast risetime, staggered transfer (fast recharging) and low failure probabilities are studied and prototypes are being built
- The beam size at the injection dump is small, resulting in large set-up errors (halfgap only 1.3mm) and scattered p+
- Transferline geometry updated to fulfill protection requirements (LHC-FCC: 7.2T, superconducting / scSPS-FCC: 1.8T, normal conducting)

To be studied beyond the CDR:

- Optimization of optics insertion regarding horiz. beam size at the injection dump and location of auxiliary absorber
- Revisit attenuation requirements in case of inj. failures
- Evaluate necessity of a secondary inj. dump in case of grazing impact injection errors
- Optimize new kicker generator layout to avoid grazing impact
- Reduce flattop ripple of injection kicker
- Detailed protection studies for super conducting transferline
- Detailed protection studies for extraction of LHC as High Energy Booster

Thank you!

Bibliography

[1] A. Lechner, “Injection/extraction protection devices and the dump”, FCC Design Meeting, 2017-12-07

[2] C. Bracco, “Injection: Hadron Beams”, Beam Transfer CAS 2017, Erice

[3] T. Kramer et al. “Considerations for the injection and extraction kicker systems of a 100 TeV centre of mass FCC-hh collider”, IPAC’16, Busan, Korea (2016)

[4] F. Velotti, “Higher brightness beams from the SPS for the HL-LHC era”, CERN-THESIS 2017

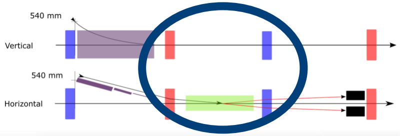
[5] V. Kain, “Machine Protection and Beam Quality during the LHC Injection Process”, CERN-THESIS 2005

[6] D. Woog, “Design of an Inductive Adder for the FCC Injection kicker pulse generator”, IPAC’17, Copenhagen, Denmark (2017)

[7] Y. Nie et al, “Numerical simulations of energy deposition caused by 50MeV to 50TeV proton beams in copper and graphite targets”, Physical Review Accelerators and Beams, 20081001 (2017)

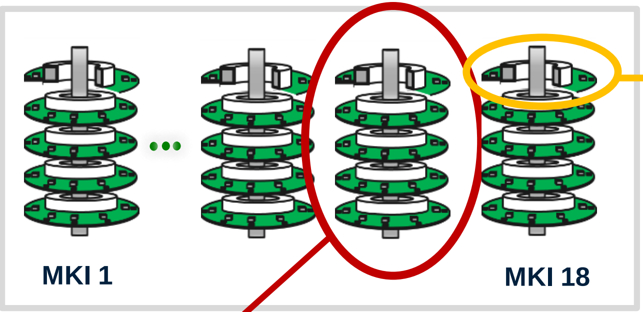
[8] M. J. Barnes et. al, “Beam-based measurement of the waveform of the LHC injection kickers”, IPAC’10, Kyoto, Japan (2010)

Injection – Failure Scenarios of the Inductive Adder II



(1) entire system:

Full impact at TDI [139 sigma)



(3) branch/layer:

missing or pre-fire:

- 0.01 - 0.3 sig. deflection
- **Continue OP, no need to dump**

most likely failure case

(2) single IA:

Pre-fire: very low probability

missing: most critical failure case in current design due to grazing impact at TDI [7.7 sigma]

Efforts to avoid this by design change (different segmentation, trigger system, spare layers etc.)

- **kicks of <0.3sig and full kick most likely → no impact**
- **low probability of grazing impact (= worst case)**

... however: pulse length needs to be limited to O(80b). Normal operation: switch closes after 2us

- Pulse limitation in case of non closing switches needs to be guaranteed

► Limitation of pulse length proposed by saturation of magnetic core

Relevant failure scenarios for transferline protection

- **Interlock System prohibits beam transfer in case of non-nominal system parameters. (LHC: last check ~4ms before SPS extraction. To be revised for FCC)**
  - → Thus, the system can only fail with impact on beam during those 4ms
  - → Failures during this time result in field changes impacting the beam → only fast/ultrafast failures relevant
  - → Consider time constants of field decay (NC vs SC)
  - → Active protection systems for fast failures (occurring <4ms before extraction; FMCCM for e.g. extraction septum, BETS for injection kicker)

Location	Comp.	Failure	Protection Absorber	Time
Extraction	**Septum**	e.g. power converter trip	**TL-TCDI**	Fast
Extraction	**Kicker**	erratic	**HEB-TCDQ / TL-TCDI**	Ultra fast
Transfer line	**NC Dipoles**	e.g. power converter trip	**Before TCDI: TCDI / After TCDI: pot. TDIV (vertical TDI) if necessary**	Fast
Injection	**Septum**	e.g. power converter trip	**pot. TDIV (vertical injection dump) if necessary → not in baseline**	Fast
Injection	**Kicker**	erratic	**Injection dump (TDI=**	Ultra fast

Table of components leading to main failure scenarios. Not exhaustive