FCC–hh Injection and Extraction:

An update due to recent tunnel/layout considerations

W. Bartmann, CERN

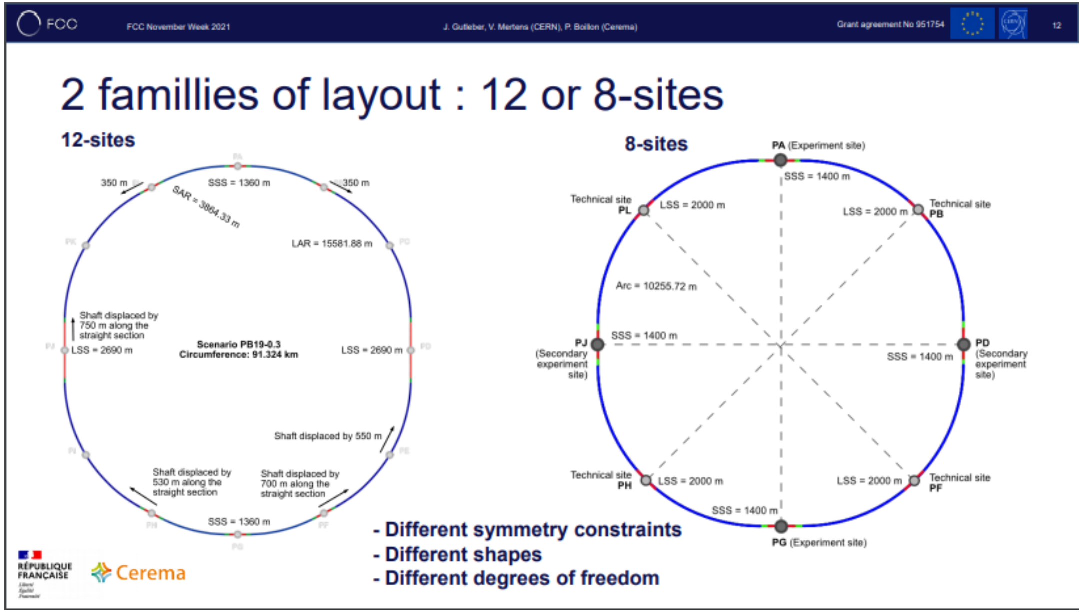
based on the FCC week presentation in 2018 by E. Renner, M. Atanasov, D. Barna, M. J. Barnes, W. Bartmann, F. Burkart, A. Chmielinska, E. Carlier, M. Hofer, B. Goddard, T. Kramer, A. Lechner, N. Magnin, L. Stoel, A. Sanz Ull, P. Van Trappen, D. Woog,...

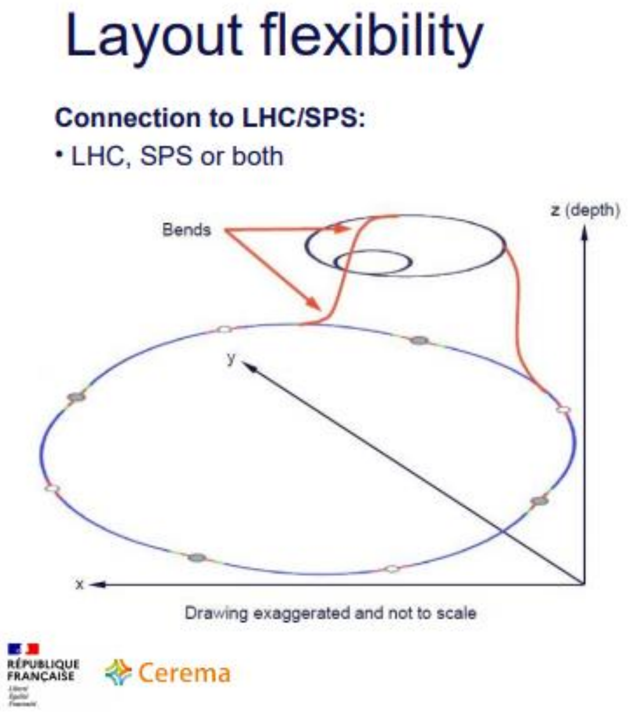
FCC Week 2021, 30th June 2021

Outline

- Recent FCC tunnel options
- Transfer line feasibility
- Impact on CDR layout regarding injection and extraction
- Summary

Various tunnel options impacting collider layout





P. Boillon, Placement review

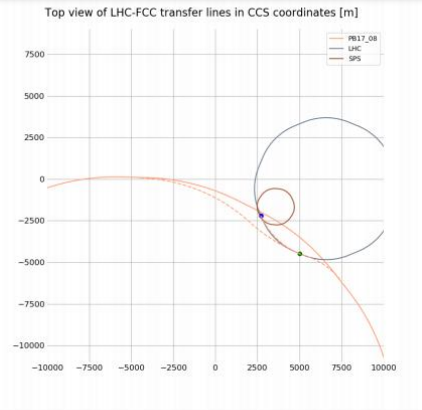
Various tunnel options for transfer lines

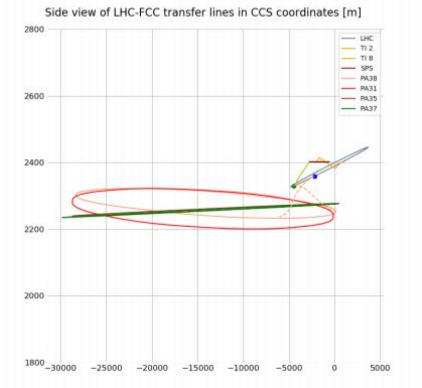
Scenario ID	Circumference	# CELLS ARC		SAFT	LSS PA, PD, PG, PJ	LSS PB, PF, PH, PL
PA31-0.4	90932,686	42		1,000	1400	2100
PA35-0.6	92637,057	43		1,000	1400	2100
PA37-0.3	94823,477	44		1,006	1400	2100
		# CELLS S_ARC	# CELLS L_ARC		LSS PA, PB, PF, PG, PH, PL	LSS PD, PJ
PB17-0.8	96093,614	24	65	1,000	1400	3250
PA38-0-1	90040,501	24	59	1,000	1400	2780
	[m]				[m]	[m]

- PB17-08 and PA38 (12P) - same what concerns beam transfer
- PA31 and PA35 (8P) - similar what concerns beam transfer, PA31 studied
- PA37 (8P) - 45 deg rotated

Transfer lines PB17 and PA38

- Crossing lines: IP8toPL could be NC with 10.8 km TL in completely separate tunnel; reduce TL tunnel to 4 km if injecting into arc tunnel, then SC
- IP1toPB, 6.2 km, SC
- Going directly from IP1 to PL needs 6.2 km, fully separate tunnel required, SC, no shortening possible; just wihtin CE perimeter possible
- IP8toPB, 3.7 km, SC
- Vertical bending by tilting dipoles





Transfer Line Feasibility

	P		Line/tunnel to PB [km]	Line/tunnel to PL [km]	Line/tunnel total [km]	Magnets	Feasible
PB17/PA38	12	xing	10.8/10.8	6.2	17/17	NC + SC	yes
	12	arc	10.8/4	6.2	17/10.2	SC + SC	yes
	12	direct	6.2/6.2	3.7	10./10	SC + SC	yes
PA31/35	8	xing	10./10	>20[1]/6	>30/16	NC + SC	yes
	8	arc	10./4	>20/6	>30/10	SC + SC	yes[2]
PA37	8						no

[1]exact length to be verified with full model in MADX
[2]feasibility of injection into arc tunnel to be studied

Transfer lines conclusions

- All options but PA37 seem feasible re beam transfer
- Total minimum tunnel length 10 - 17 km
- Total line lengths 10 - >30 km
- 12P and 8P similar for tunnel length, significantly longer TL lengths for 8P
- NC magnets for both lines only possible in case of separate tunnel under lake for 8P options, otherwise only for one of the lines possible which is likely not preferred
- All options but PA37 can also be reached from the SPS tunnel, at 1.3 TeV with NC technology and similar length as for LHC lines

Various tunnel options impacting collider layout

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	[m]				[m]	[m]

- Reduction of extended LSS length: 2.8 km → 2.1 km for dump system
- Rotated version requires combination of main experiment with injection

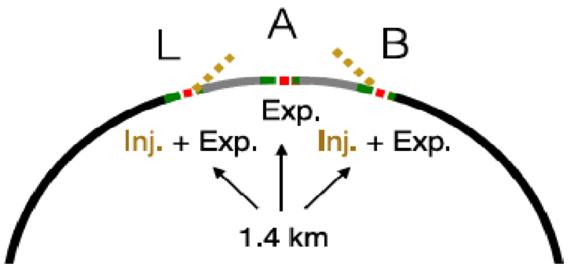
Injection in a Nutshell

Summary of FCC-hh transfer line and injecion design,

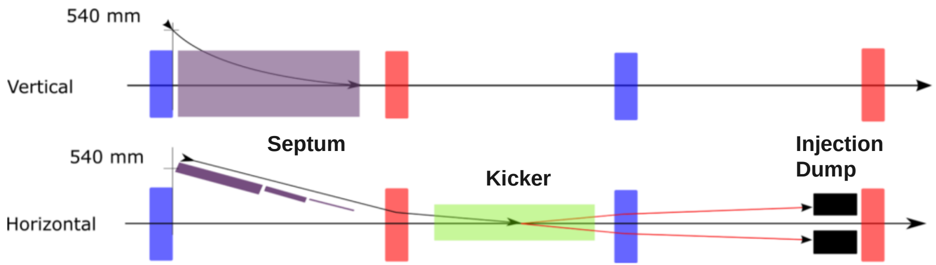
- Challenge: transfer 550 MJ
- Damage limit of injection dump limits **injection batch length to 80 bunches** (LHC: 288, different energy and intensity)
- Short risetime of kicker magnets (430ns) is required to enable FCC-hh filling factor (10400 bunches)
- **Novel pulse generator technologies** (Inductive Adder or Marx Generator) for kicker to enable **short risetime, fast recharging (10Hz)** and have **lower failure rates** due to different concept
- Normal conducting Lambertson **septum: reliable, simple, robust**
- Loss studies for injection failures: protection efficiency ok, but small horizontal beam size at TDI (sigx = 0.15mm) is challenging for TDI settings

Injection - Overview

- Combined with side experiments (IPB and IPL) – 1.4km, ~0.7km for injection
- Baseline: Injection from HEB (LHC) at 3.3 TeV
- 1.3 TeV option studied as well
- Double plane injection

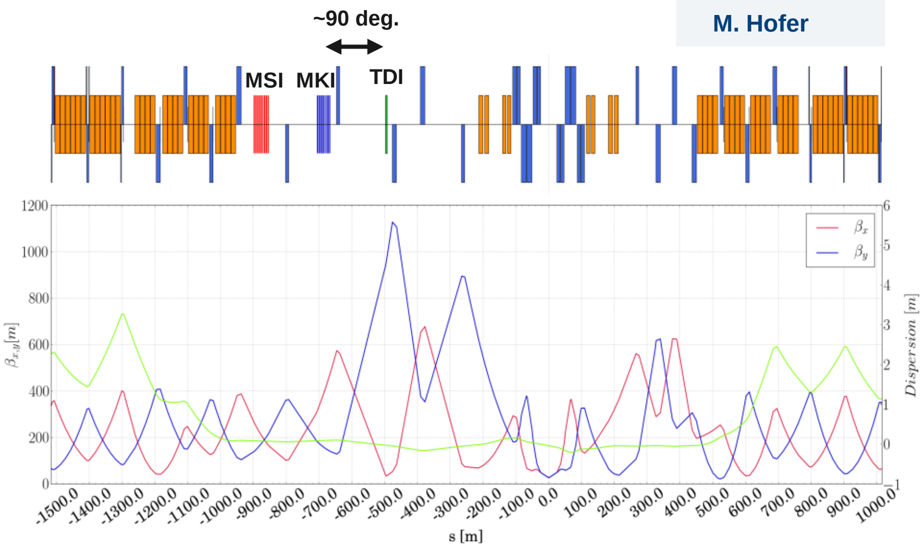


	Septa (nc Lamb.)	Kicker
System Length	104	40
Deflection [mrad/Tm]	9.8/92	0.18/2
Number of Modules	21	18
Flux Field [T]	0.7-1.2T	1



Injection

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

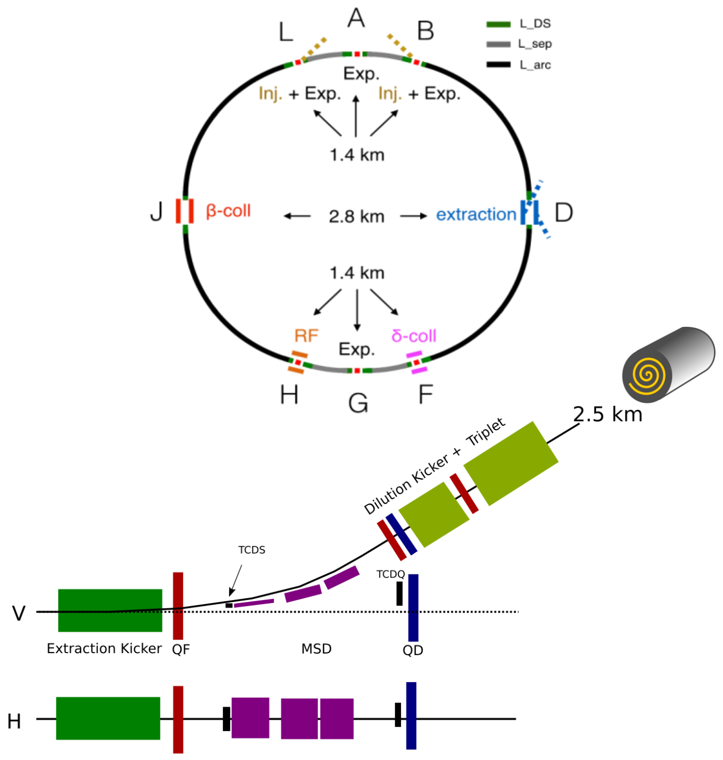


Update wrt CDR:

- Can gain ~250 m in drift space – optics for injection and physics production could be decoupled to reach more matching flexibility
- For injection proper need 450 m in lattice – to be added to LSS in 45 deg rotated tunnel option PA37

Extraction

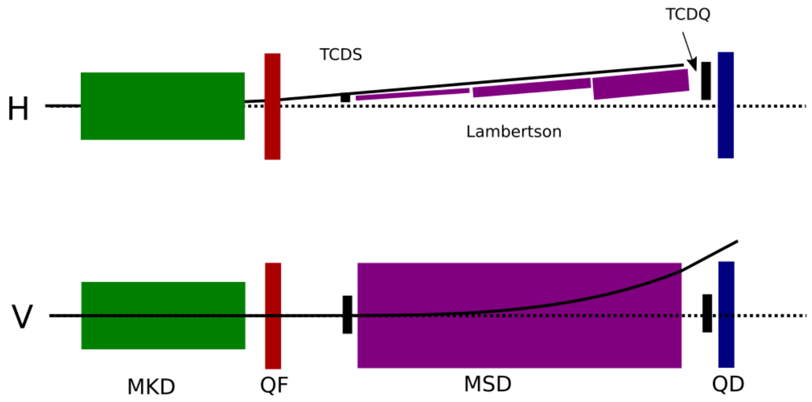
- IPD, 2.8 km for extraction of beam 1 and 2
- 2.5 km dumpline with dilution kicker system to create sweep pattern at graphite beam dump
- Design mainly driven by machine protection
  - Safely extract 8.5 GJ beam
  - Reduce failure probabilities
  - Avoid downtime in case of failure



Extraction – New Baseline

Old baseline: working backup solution

- Based on superferric Lambertson septa (1.3-1.55T / ~184m with 25 mm septum blade)
- Septa layout requires double plane extraction
- Highly segmented extraction kicker system (300 kicker)



Extraction – New Baseline

→ Higher field with same apparent septum blade thickness (25mm)

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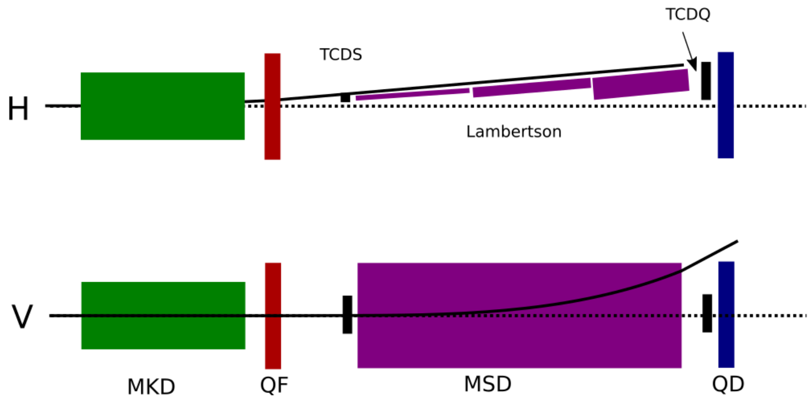
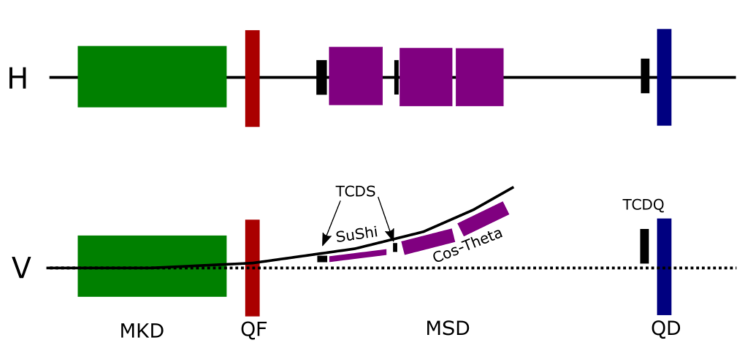


Proposed new baseline:

- Based on novel septa: SuShi (3.2T) and Truncated CosTheta (4T). Total system length ~70m
- Septa Layout requires single plane extraction (vertical)
- Reduced kicker segmentation, still highly segmented (150 kicker)



Extraction – Layout

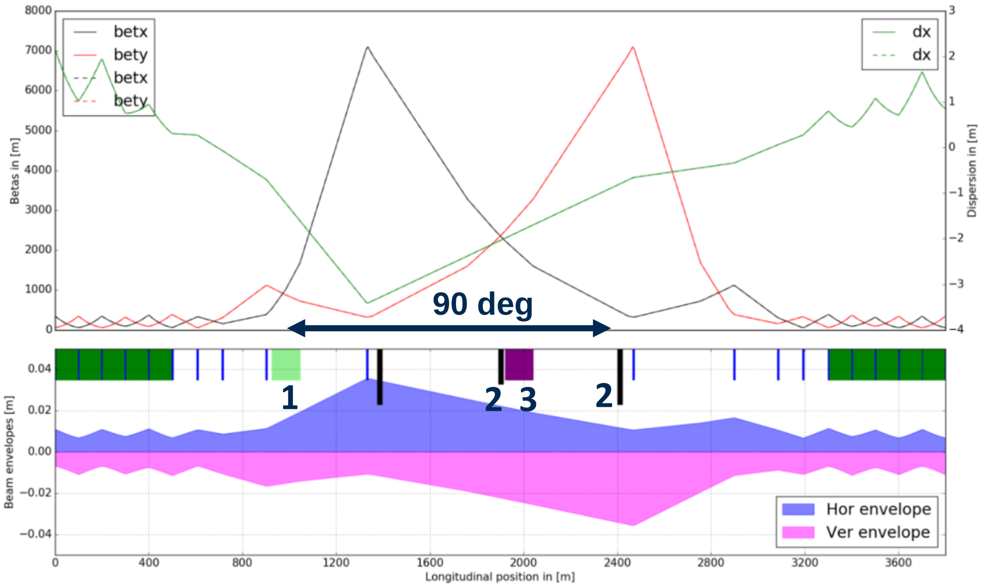
(1) 150 Extraction Kicker (2017: 300)

- System length 120 m
- 1 us risetime

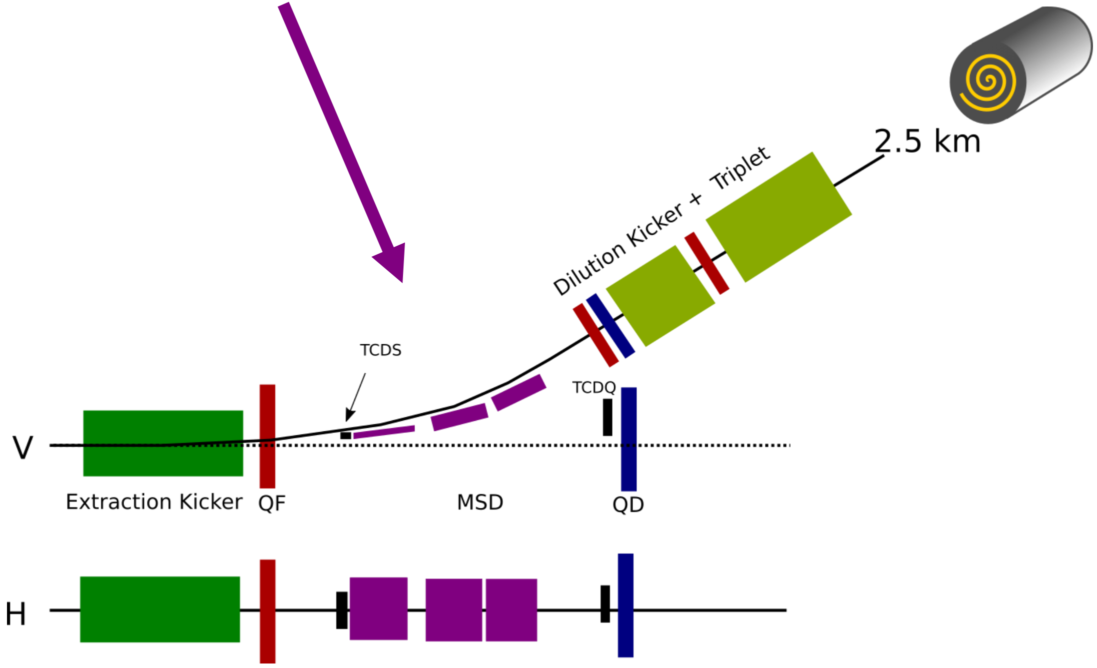
(2) Larger beam size at protection absorber than 2017

(3) SuShi / Cos-Theta Septa instead of superferric Lambertson

- ~70m instead of 180m (2017)



Extraction – Septa



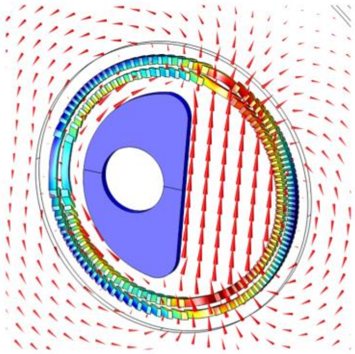
Extraction – Septa (MSD)

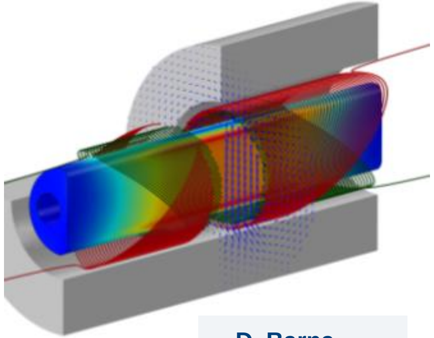
SuShi

D. Barna: Superconducting Shield (SuShi) septum

- 3.2 T
- Measurements on first prototype conducted
- Apparent septum blade: 25mm

  → can potentially be reduced to 20mm using NbTi for the shield **(reduced kick strength)**



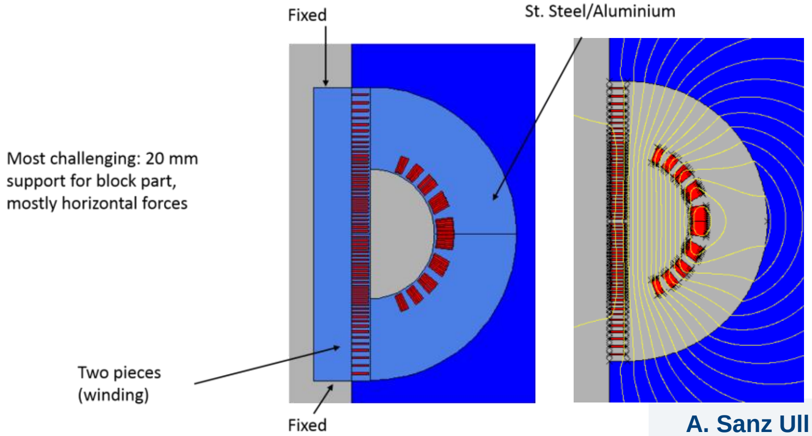


D. Barna

Truncated Cos-Theta

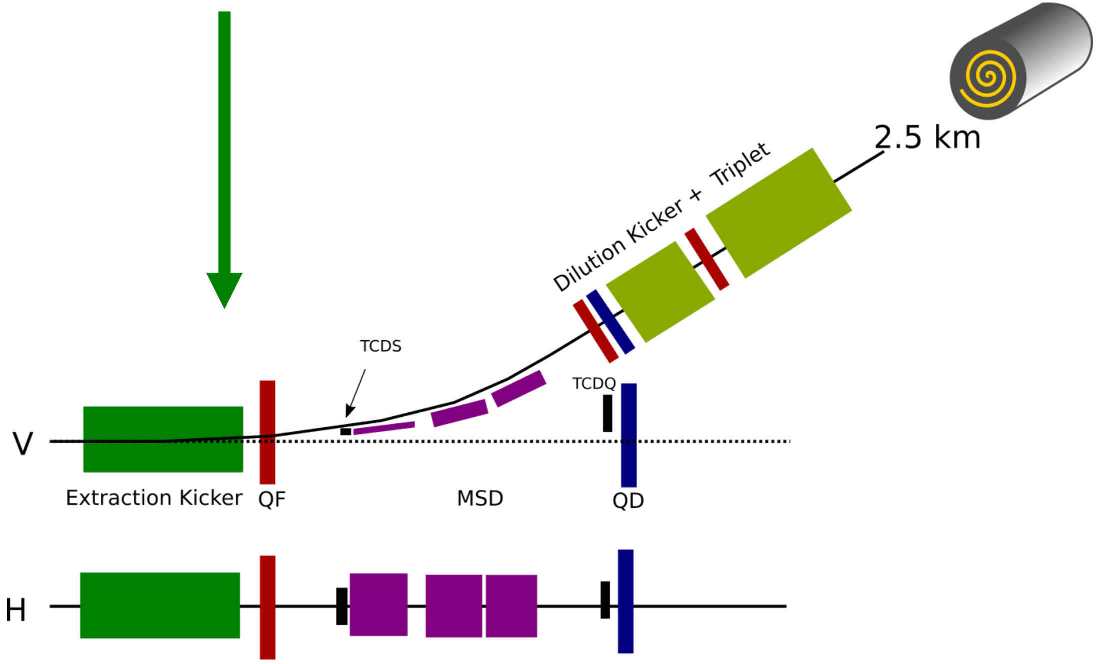
K. Sugita: Status of truncated cosine-theta septum magnet study

- 4T
- 35mm app. septum blade
- Very flexible geometry for larger separation of circulating and extracted beam



A. Sanz Ull

Extraction Kicker



Extraction and Dilution Kicker Strategy

Go a step back and remember the idea behind the kicker system layout…

FCC-hh beam dump extraction and dilution kicker systems

- To **increase availability** the main idea is, that in case of a faulty kicker magnet **normal operation can continue with a reduced number of kickers** and **repair is only required during the next scheduled technical stop**

- Septa apertures, kicker segmentations etc. are designed to allow operation with at least 10% missing dilution or/and extraction kicker

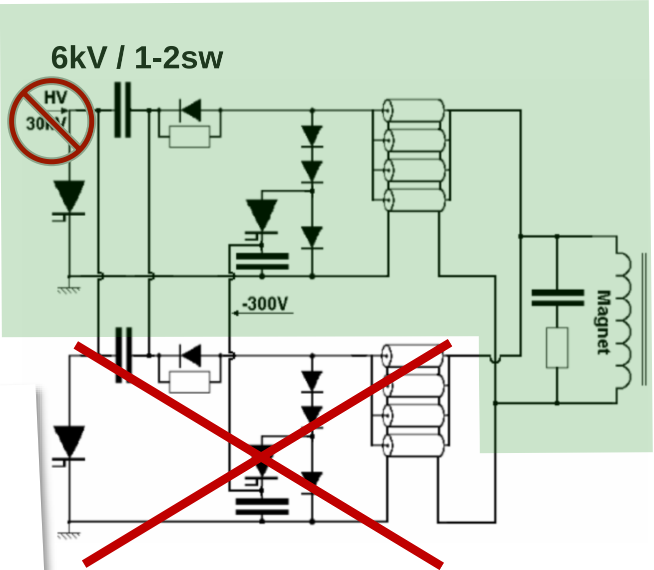
- Furthermore, **failure probabilities for and the impact of a single failing element should be reduced**

► A **highly segmented** system is envisaged
  - 150* extraction kicker per beam (LHC: 15)
  - 30 horizontal + 55 vertical dilution kicker per beam (LHC: 10)

**2017: 300 kicker. 2018: Number of segments reduced, see next slide*

Extraction Kicker

- Highly segmented system: 150 kicker compared to 15 in LHC (l = 0.6m)*
- Main design restriction: 1 us risetime required to survive asynch. dump
- ▶ 3.3 kA / ~6kV per kicker (LHC: 30kA / 27kV)



▶ Relaxed hardware parameters / simpler systems than LHC:

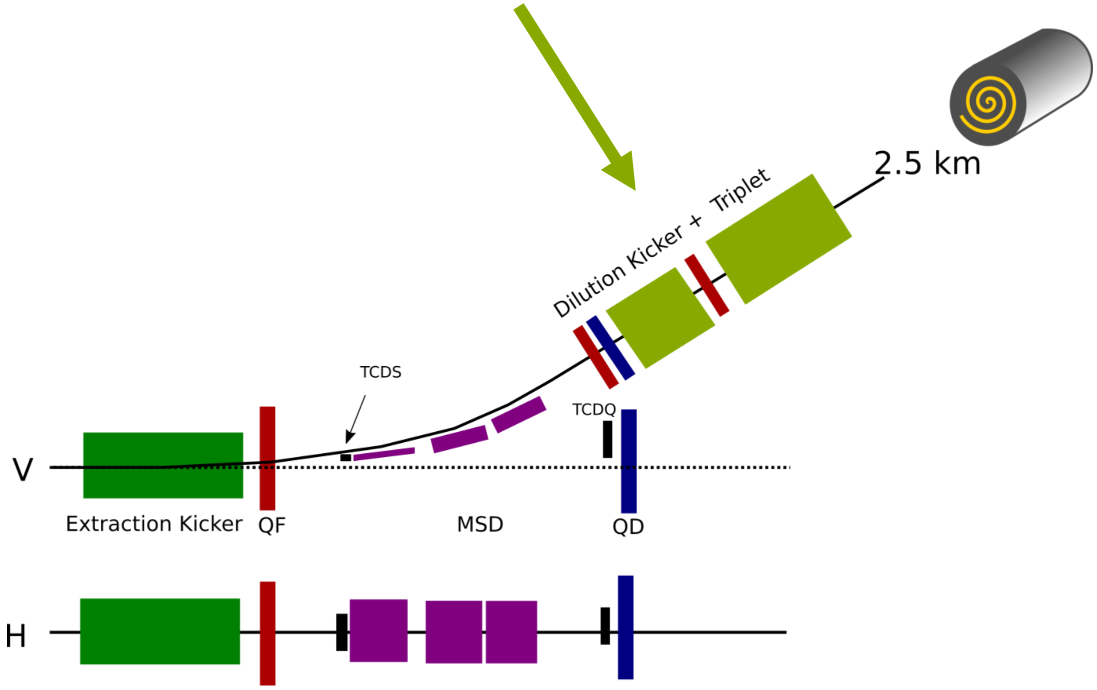
- 1 generator per kicker (LHC: 2)
- 1-2 switches per generator (LHC: 10)**

Overall complexity regarding failure/availability comparable to LHC

**2017: 300 kicker. 2018: Number of segments reduced, while still allowing for '1. sigma oscillation'(slide 17) in case of erratic, keeping hardware requirement reasonable and enable operation with reduced number of modules*

***: 2 switches with current technology. R&D necessary to enable generator with 1 switch.*

Extraction – Dilution Kicker and Dumpline



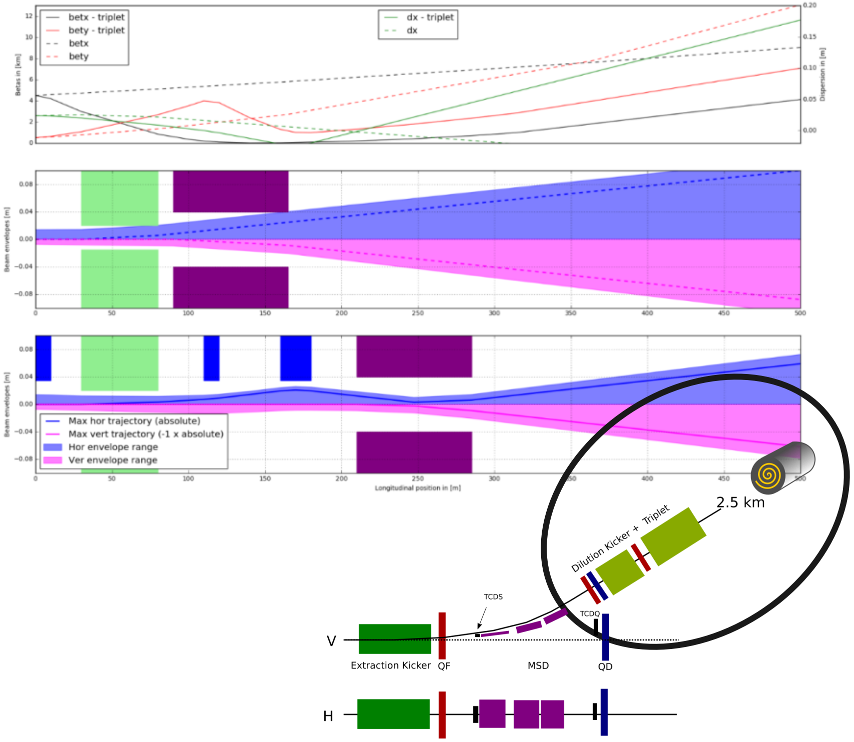
Extraction – Dilution Kicker and Dumpline

2017: Dilution system envisaged kickers with modulated frequency to minimize size of dumpcore (max. 50kHz)

+ Sweeppattern r=45 cm
– Very challenging for kicker system
– **Problematic for survival of asynchronous beam dump**

2018: Constant frequency of the dilution system (50kHz)

- Sweeppattern r=55 cm
- **Energy deposition in case of asynch. dump acceptable**
- Large deflection by dilution kicker necessary
  - ▶ Either increase tunnel length to 3km or increase BdL of MKBs
  - ▶ **Focusing triplet in the dumpline** helps to reduce the aperture in the dilution kickers and hence relax the hardware requirements.



Dilution Kicker (MKB)

- 30 horiz. / 55 vertical magnets to keep hardware requ. acceptable
- Hardware relaxed by triplet in dumpline
  - reduced gap height and width in vertical dilution kicker
  - reduced horizontal kick strength
- 10% less horizontal / vertical dilution acceptable

Complex system, e.g.:

- max. frequency mismatch of ~0.2-0.5% allowed

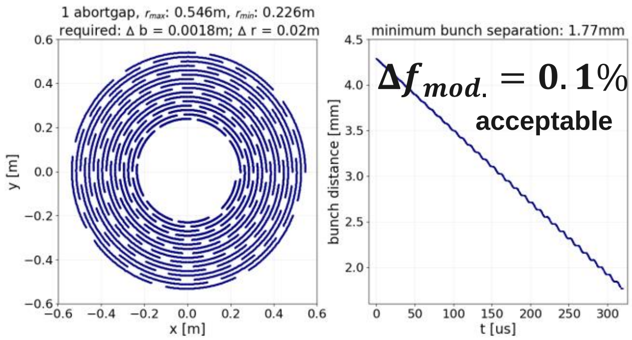
Impact on availability?

- time dependent damping constant, …

	triplet		w.o triplet	
	MKBH	MKBV	MKBH	MKBV
frequency [kHz]	50	50	50	50
risetime [us]	5	5	5	5
Installed L [m]	60	110	100	110
Gap field [T]	0.5	0.5	0.5	0
Modules	30	55	50	50
BdL [Tm]	22	42	38	39
gap height [m]	0.03	0.046	0.026	0.046
gap width [m]	0.03	0.04	0.046	0.086
Current [kA]	12	16	10	34
Voltage [kV]	8	12	12	12

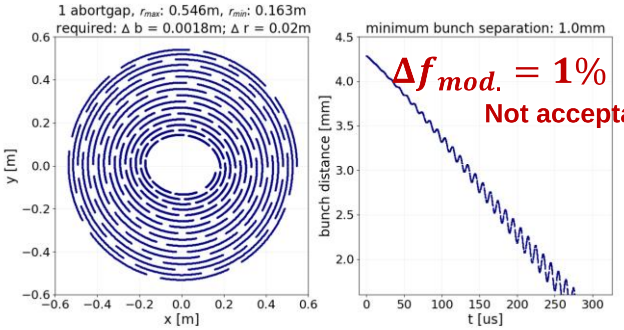
Dilution Kicker – Frequency Mismatch

Mismatch between single generators



$\Delta f_{mod.} = 0.1\%$

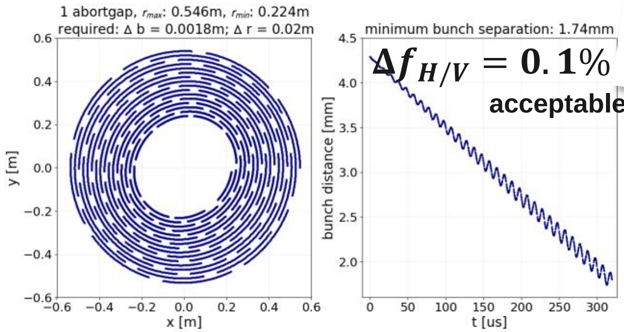
acceptable



$\Delta f_{mod.} = 1\%$

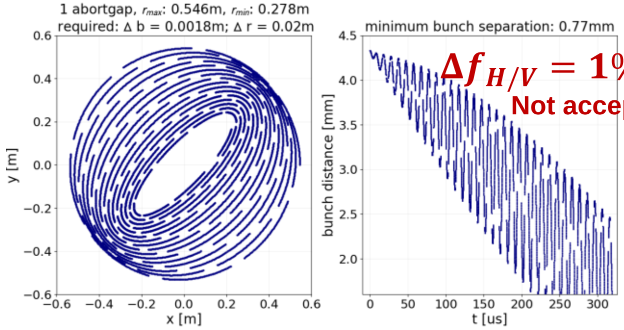
Not acceptable

Mismatch between horizontal and vertical system



$\Delta f_{H/V} = 0.1\%$

acceptable



$\Delta f_{H/V} = 1\%$

Not acceptable

To be studied beyond the CDR – avoid impact on availability due to strict interlocking.

Systems need to be set up accurately but no showstopper

Summary and Next Steps

Transfer lines

- All options look feasible but the 45 deg rotated one – here we would need to extend the LSS by ~ 450 m
- 8 point options will require significantly more TL magnets
- Joining the collider tunnel as early as possible is considered – this requires a careful consideration of integration and cross-talk in terms of future availability

Injection

- Optics updated to fulfill machine protection requirements
- New generator technologies required and studied
- Failure scenarios analyzed
- Update wrt CDR: Can reduce system length to 450 m for injection equipment – might not allow for direct LSS length reduction – depending on optics matching for low beta optics

Summary and Next Steps

Extraction:

- **Vertical single plane extraction** based on **SuShi and Truncated Cos-Theta Septa** → reduced system length wrt NC septa solution
- Highly segmented extraction kicker system (150 modules)
  - Impact of **1.5 sigma oscillation in case of single erratic was found acceptable (extraction at next abort gap arrival)**
  - Hot spare approach → **continue operation in case of faulty generator until next stop**

⇨ Challenges: Trigger / Re-trigger system; Dilution system

⇨ **Reduction in length from 2.8 km to 2.1 km → likely possible to find a challenging yet feasible concept; additional challenge put on the HW systems with risk of reduced reliability/availability → given the project's timescale, bet on sufficient technology advancement**

Thank you!

Extraction – Machine Protection Strategy

Machine protection requirements to be considered for the design are …

1. Safely extract the beam – always guarantee kicker triggering [See appendix]
2. Survive asynchronous dump
3. Avoid asynchronous dumps
4. Avoid other failures with damage potential [See appendix]
5. Avoid failure impacting availability / avoid necessity for immediate repair

Survival of Asynchronous Dump

A. Lechner: FCC-hh protection absorbers and the dump

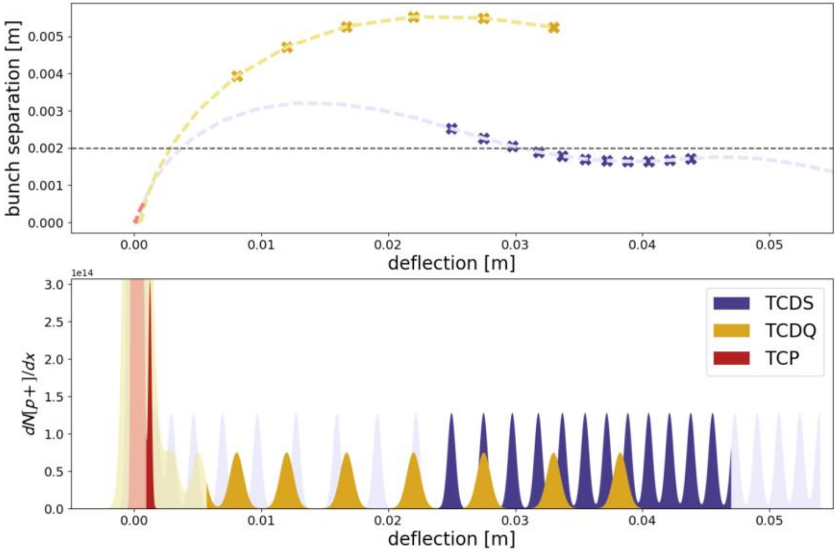
Extraction kicker:

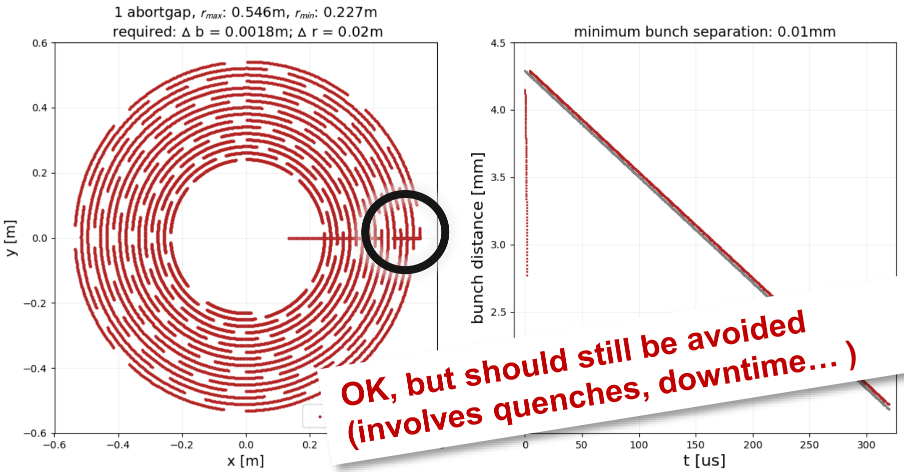
1 us risetime of extraction kicker to guarantee bunchspacing of ~1.8mm at septum protection ✓

Dilution kicker:

Increased energy deposition at the beginning of the asynch. dilution pattern

OK With new dilution pattern, but larger dump core (r ~70-80cm) ✓





OK, but should still be avoided
(involves quenches, downtime…)

Avoid Asynch. Dump/ ‘1.5 Sig Oscillation’

► **LHC:** Main cause for asynch. dumps are erratic extraction kicker

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► **FCC:** 150 MKDs, 1 MKD: ~1.5 sigma (worst case MKD1)

avoid asynch. dump

Idea: Do not re-trigger immediately in case of an erratic kicker, but **wait until the next abort gap and dump beam synchronously.**

→ Part of beam oscillates **1 turn with ~1.5 sigma 1 turn before being extracted.**

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2017/2018: Evaluating implications of ‘1.5 sig oscillation’

- Tracking studies conducted: up to ~2.7 sig oscill. OK for losses in collider

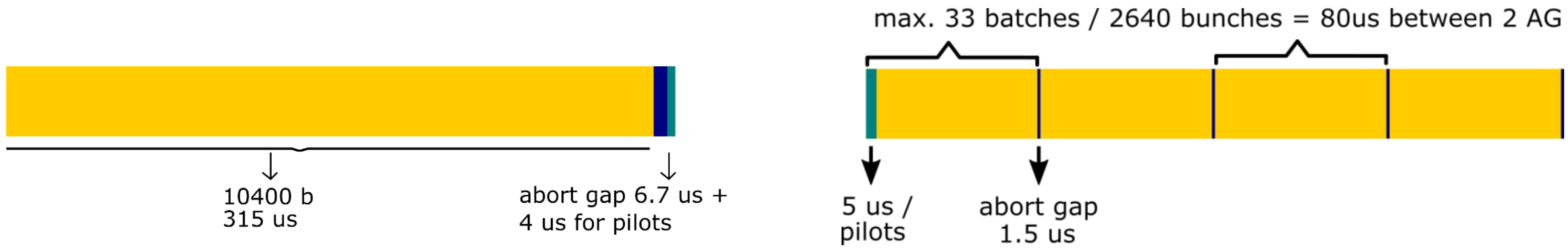
J. Molson: Betatron collimation system insertions, Tue. 13:55

- 1.5 sig oscillation leaves margin for correction factors (need to be quantified more precisely) e.g.
  - beta beating 20%
  - horizont. offset in Crab Cavities / phase offset in CC
  - ...
- ~Same deflection as failure of sep. dipole (1.5sig in 2ms)

Y. Nie: Overall machine protection, Wed. 16:40

Multiple Abort Gaps

Impact of 1.5-sigma oscillation can be reduced in case of multiple abort gaps:



- Abort gaps need to be equally distributed
- Simple for abort gap synchronization
- Abort gap ~1.5us, injection gap: 0.43us. → Abort gap = 3x injection gap (advantage for RF cavities?)

Extraction: Challenges for the Re-Triggering System

Inherently different to LHC, FCC-hh requires …

- … **an active system:**

  distinguish single erratics (no re-trigger) and multi-erratics (re-trigger)

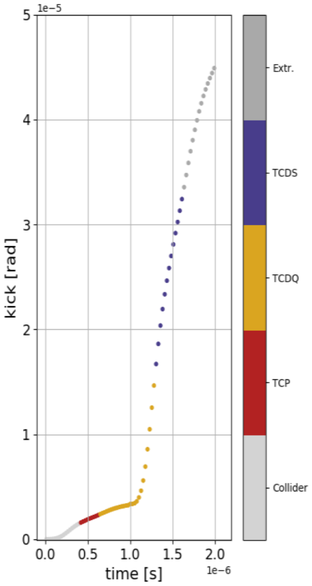
- … **a fast system**

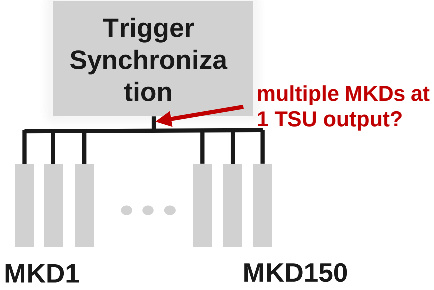
  despite long system length (120m, signal propagation)

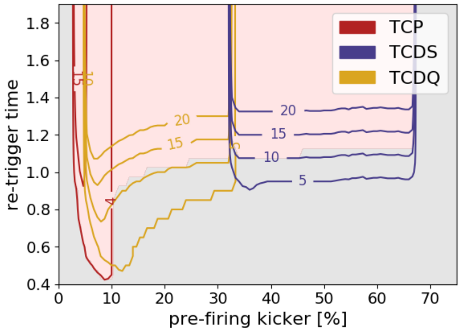
- **… exclusion of partial pre-triggering (3-67%) due to failure in output of trigger distribution.**

Impact of pre-triggering of X% of all extraction kickers with subsequent re-trigger of remaining modules after re-trigger time. → not problematic in LHC

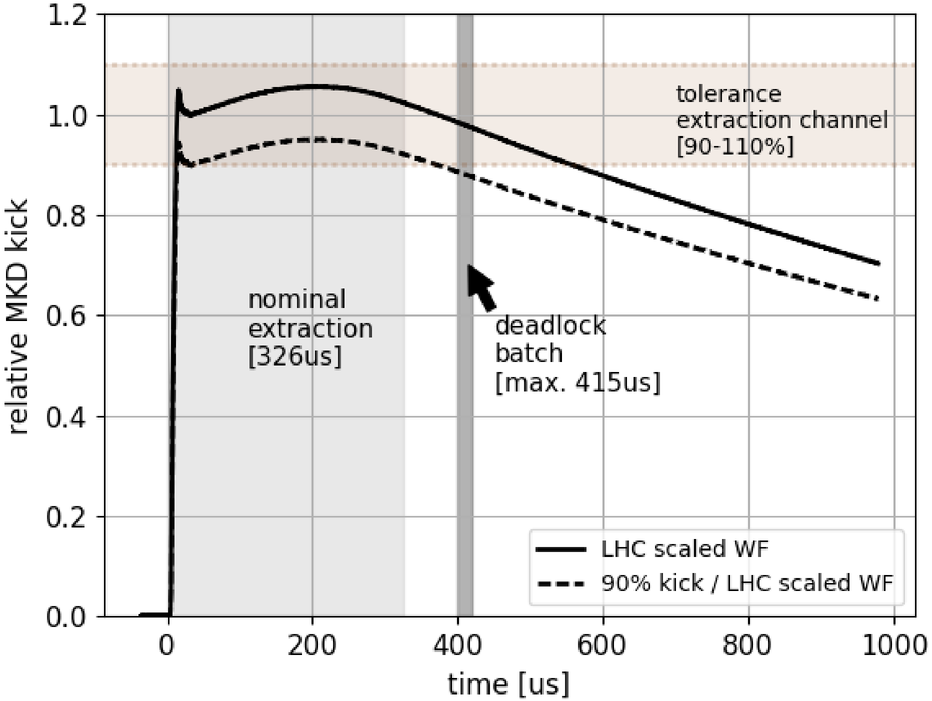
N. Magnin, Laser triggering of thyristor swiches, Wed. 1050



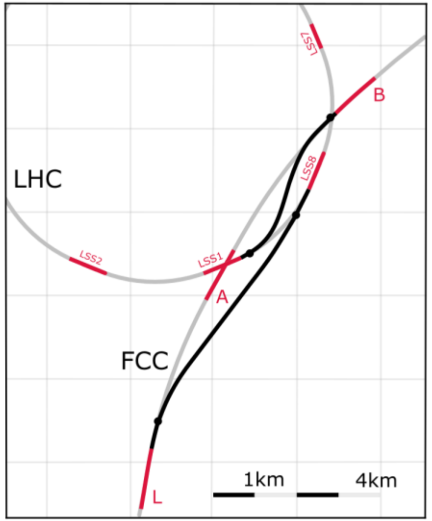


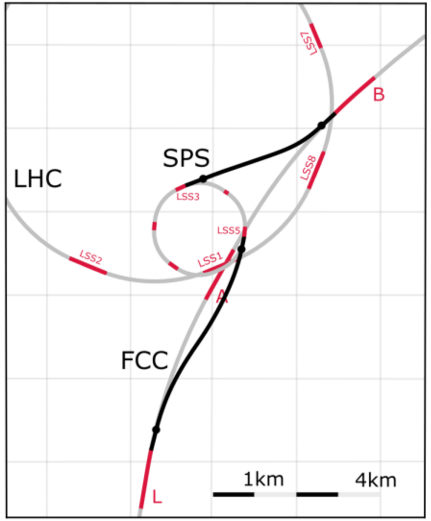


Spare: Injection Deadlock



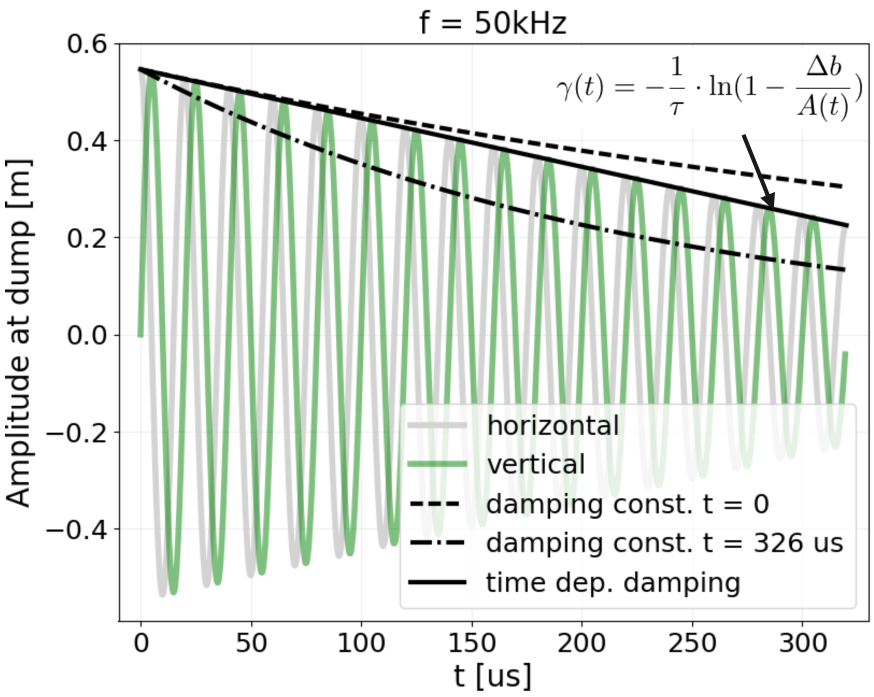
Spare: Transferlines





	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

Spare: Dilution Kicker – Time Dependent Damping



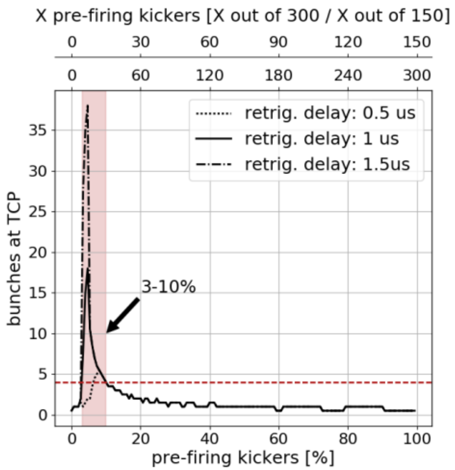
Spare: Extraction – Machine Protection

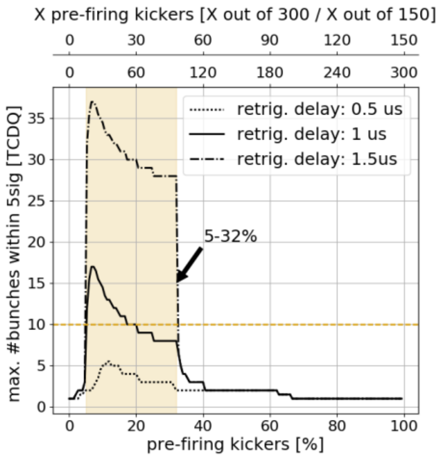
Category	Primary Failure Scenario	*Consequence / Potential Effect*	Comment	Dump Line sc DL	class
Abort gap	Abort gap population out of tolerance	Quench of MSD?	Define AG threshhold. Sushi / superferric Lamb.	Quench?	2
Abort gap	Synchronisation error	asynch. dump	asynch. dump	Quench?	2
Fast kicker	Dilution kicker erratic (spurious) trigger	synch. dump, less dilution			2
Fast kicker	>10% dilution kicker magnets missing	TDE damage	self announcing		2
Fast kicker	Extraction/injection deadlock	injection batch on TCDS (3.3 TeV)	check impact on TCDS only critical for 0.9%MKD kick	Quench?	2
Fast kicker	1 Ext. kicker erratic (spurious) trigger	semi-synchr. dump (next abort gap)	check bunch position at TDE		2
Fast kicker	> 1 Ext. kicker erratic (spurious) trigger	re-trigger	active / intelligent re-trigger system	Quench?	2
Fast kicker	3-10% extr. kicker magnet multierratic	collider damage	• to be excluded in re-trigger system • re-trigger time <0.5us		1
Fast kicker	7-67% extr. kicker magnet multierratic	extraction absorber damage	• to be excluded in re-trigger system • re-trigger time <1us • sacrificial absorber (new optics)		1-2
Fast kicker	>= 10% dilution kicker magnets missing	Challenging max. energy dep. In TDE	self announcing, 10% to be quantified more precisely		1
Fast kicker	>= ~12% extraction kicker missing	Potential MSD / TCDS damage	self announcing 12% to be quantified more precisely		1
BETS	Energy tracking error	Faulty extraction			1
MPS	No trigger received from BIS	No extraction			1

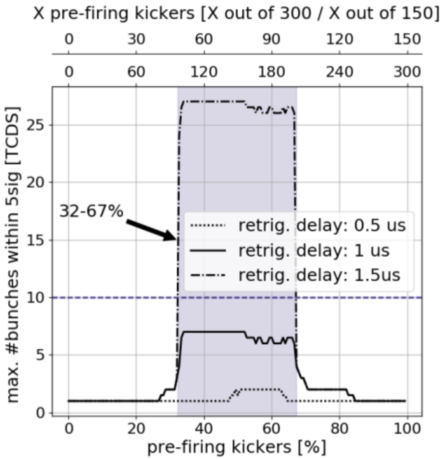
Spare: Extraction - Challenges for the Re-Triggering System

- **simultaneous pre-triggering of multiple kickers due to fault at higher level in trigger system (spurious output going to multiple modules)** results in a 'step in the waveform'

- **depending on re-trigger time and % of pre-firing kicker, losses in collider / at extraction absorber would not be acceptable**







Spare: Extraction - Challenges for the Re-Triggering System

3-10% sim. pre-firing:

- Damaging losses in the collider
- Nearly independent of re-trigger time

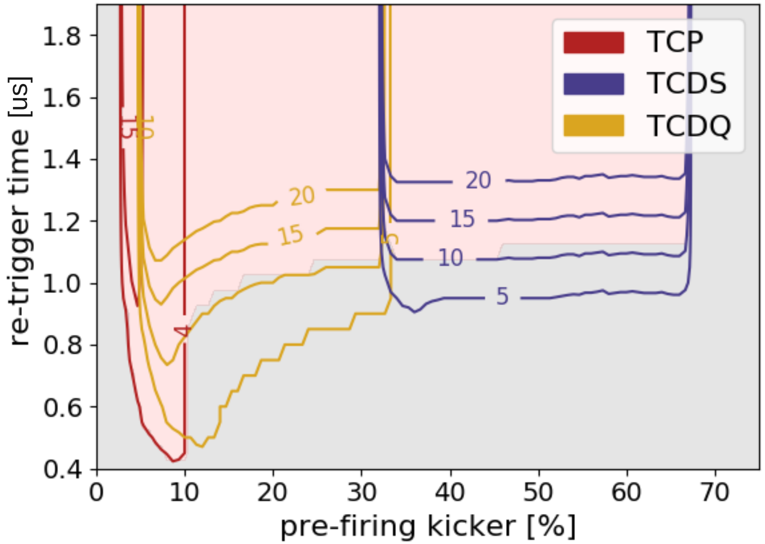
Has to be avoided

10-67% sim pre-firing:

- losses ok for collider
- damage of extraction protection (TCP / TCDQ)
- sacrificial absorber
- dependency on re-trigger time

Should be avoided

→ otherwise: sacrificial absorber, requires new optics layout as longer drifts are is necessary



hardware solution seems feasible – no showstopper

Spare: Safety – Risk of Missing MKD

Unsafety = Probability to have less than (here) 93% of MKDs firing (equiv. to 14 out of 15) missing MKDs → no safe extraction

- Failure rates scaled from studies conducted for LHC [1] [us]
- Above 30 modules U<<10^{-14} for 1 generator branch (redundancy ≥ 2 modules)

> ✓ **LHC, 2 generator branches: U = $3 \cdot 10^{-7}$/yr**
>
> ✓ **FCC (300 MKDs), 1 branch: U → 0**
>
> ✓ **~ 30 MKDs, 1 branch: U = 10^{-14}/yr**

[1] R. Filipi, **Dependability analysis of a safety critical system: the LHC beam dumping system at CERN**, CERN-Thesis 2007