FCC–hh Injection and Extraction: Insertions and Requirements

A. Chmielinska

M. Atanasov, W. Bartmann, D. Barna, M. J. Barnes, F. Burkart, E. Carlier, M. Hofer, B. Goddard, T. Kramer, A. Lechner, E. Renner, N. Magnin, L. Stoel, A. Sanz Ull, P. Van Trappen, D. Woog.

FCC Week 2019, Brussels, June 24 - 28

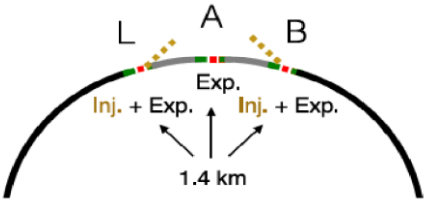
Outline

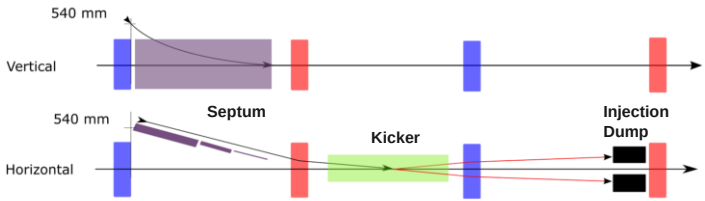
- Injection: Summary of key points
- Extraction: Updates on optics & hardware
- Extraction: Machine protection considerations
- Summary and R&D

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

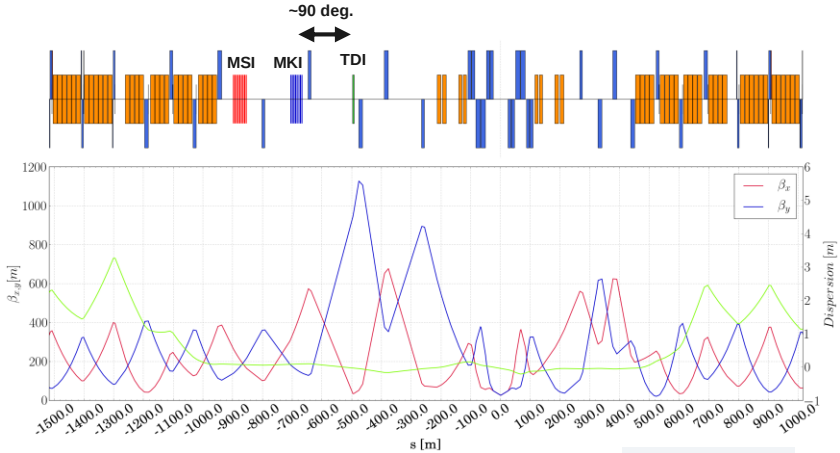
J. Borburgh: FCC-hh Injectior Design, Tue. 17:00





	Septa (nc Lamb.)	Kicker
System Length [m]	104	40
Deflection [mrad/Tm]	9.8/92	0.18/2
Number of Modules	21	18
Flux Field [T]	0.7-1.2	0.062

Injection



M. Hofer

Injection in a Nutshell

T. Kramer: FCC-hh kicker systems: status and R&D plans (injection, extraction, dilution), Wed. 09:10

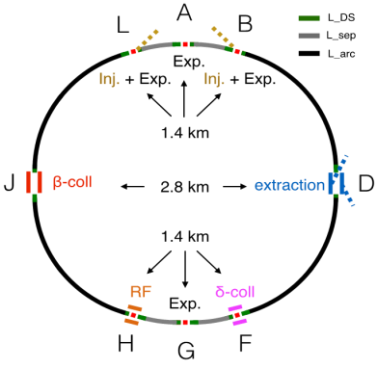
A. Chmielinska: New Spiral Beam Screen Design for the FCC-hh Injection Kicker Magnets, Wed. 09:30

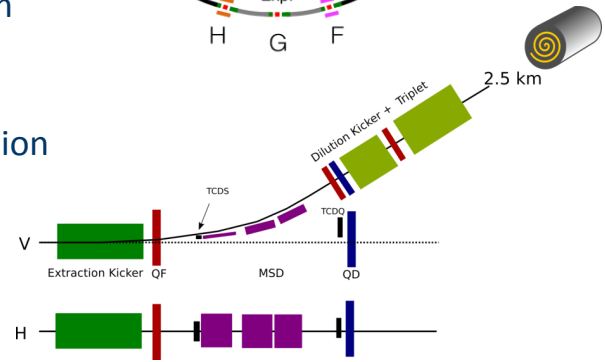
- Challenge: transfer 550 MJ
- Damage limit of injection dump limits **injection batch length to 80 bunches** (LHC: 288, different energy and intensity)
- Fast rise time of the kicker magnets (430ns) is required to enable FCC-hh filling factor (10400 bunches)
- **Novel pulse generator technologies** (Inductive Adder or Marx Generator) are required to achieve **short rise time, fast recharging (10Hz)** and **lower failure rates** due to different concept
- Beam screen for the kicker magnets must provide **low beam coupling impedance, fast field rise time, good high voltage performence** and **low impact on beam stability**
- Normal conducting Lambertson **septum: reliable, simple, robust**
- **Loss studies for injection failures are ongoing,** first conclusions:
  - Protection efficiency is not a limitation, but small horizontal beam size at TDI (sigx = 0.15mm) is challenging for TDI settings

Extraction

New Baseline:

- 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



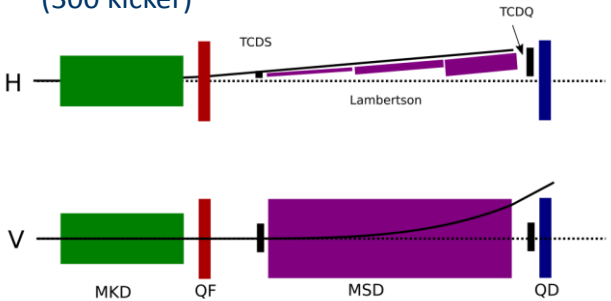


Extraction – New Baseline

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

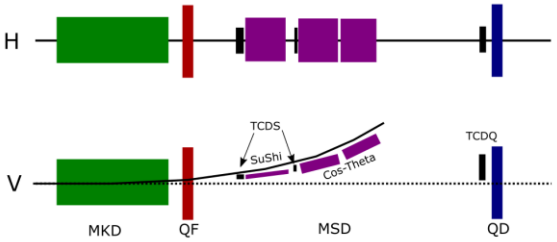
Old baseline: working backup solution

- 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)



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

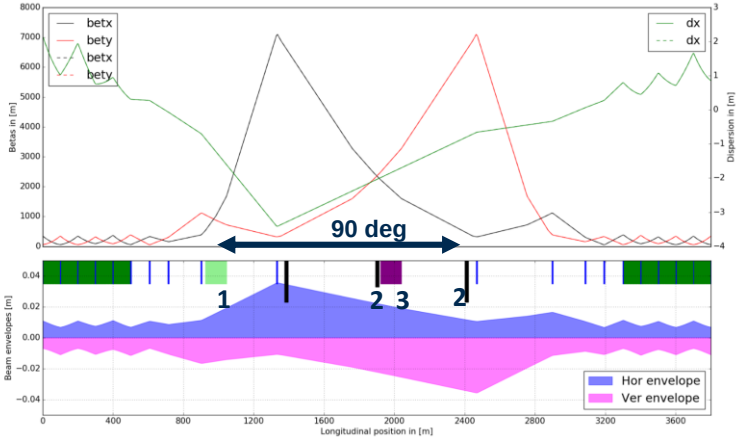
(1) 150 Extraction Kickers

- System length 120 m
- 1 us risetime

(2) Protection absorbers

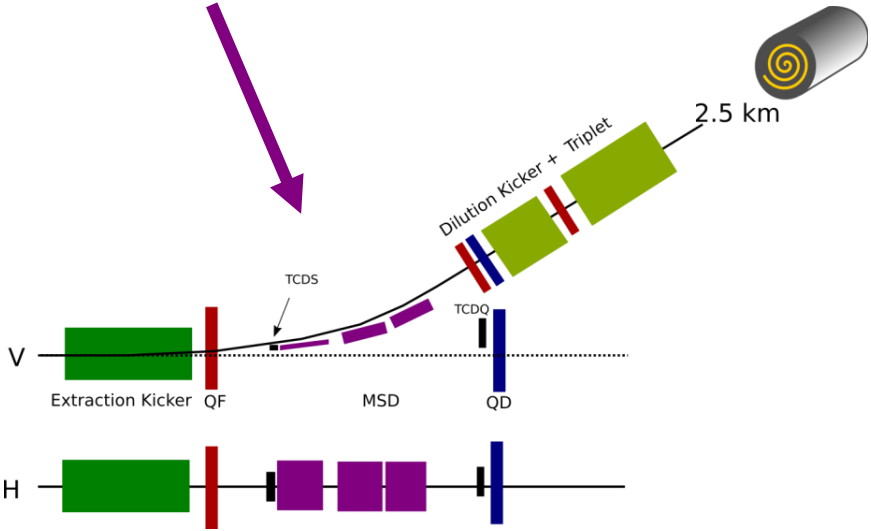
(3) SuShi / Cos-Theta Septa

- ~70 m



W. Bartmann

Extraction – Septa



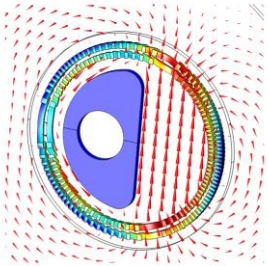
Extraction – Septa (MSD)

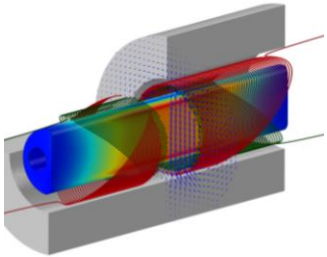
SuShi

Barna et al. (2019). NbTi/Nb/Cu Multilayer Shield for the Superconducting Shield (SuShi) Septum. *IEEE Transactions on Applied Superconductivity*, *29* (1).

- 3.2 T
- Apparent septum blade: 25mm

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



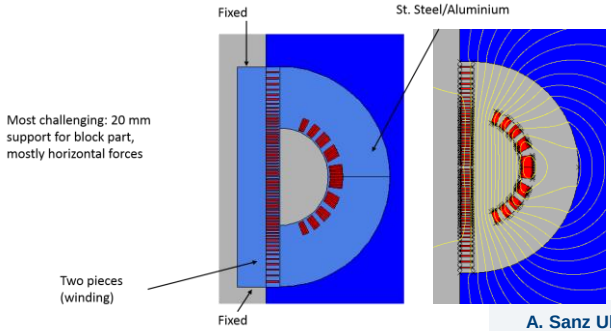


D. Barna

Truncated Cos-Theta

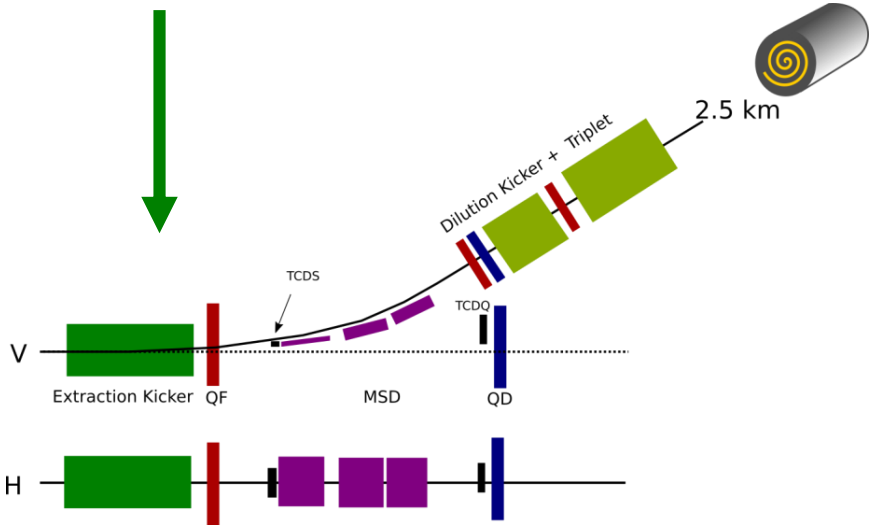
K. Sugita: Advanced design study of superconducting septum magnet for FCC, Wed. 08:50

- 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

- 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 and the impact of a single failing element should be reduced**

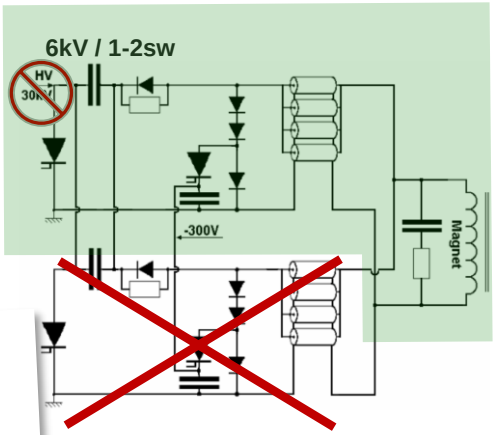
► A **highly segmented** system is envisaged

- 150 extraction kicker per beam (LHC: 15)
- 30 horizontal + 55 vertical dilution kicker per beam (LHC: 10)

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)

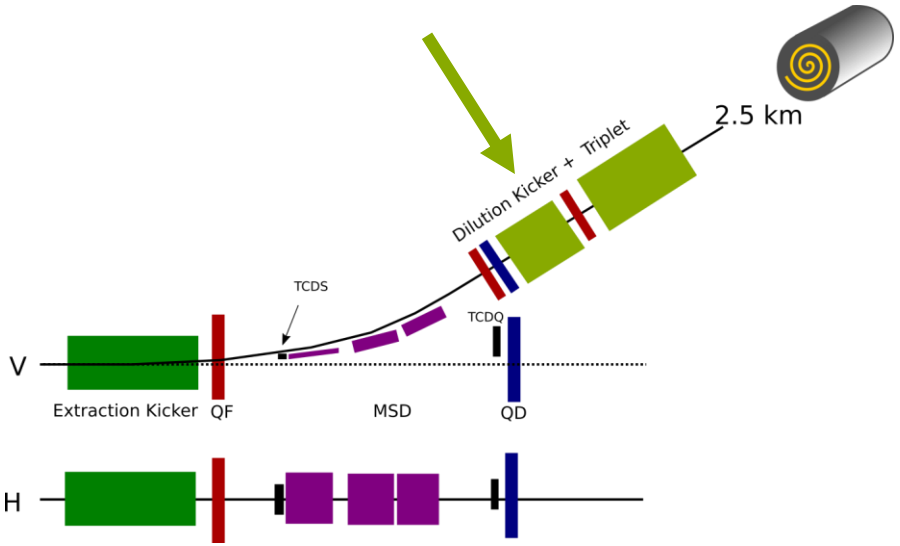


►Relaxed hardware parameters / simpler systems than LHC:

- 1 generator with 1 branch per kicker (LHC: 1 generator with 2 branches)
- 1-2 switches in a single branch (LHC: 10 switches per branch)

Overall complexity regarding failure/availability comparable to LHC

Extraction – Dilution Kicker and Dumpline



Extraction – Dilution Kicker and Dumpline

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

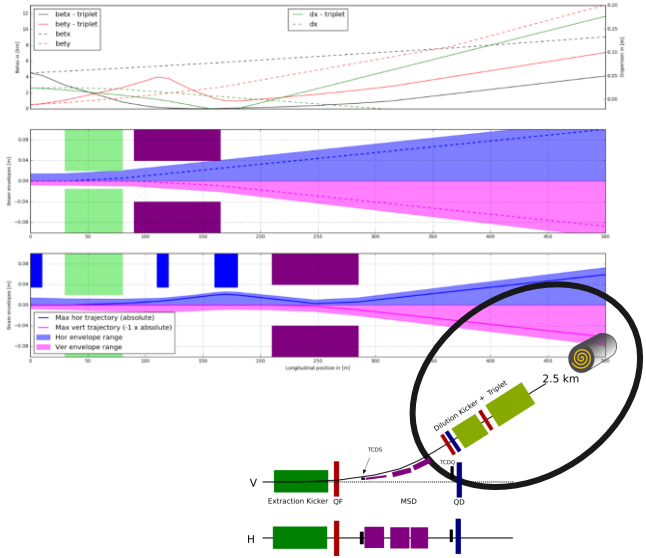
\+ Sweeppattern r=45 cm

– Very challenging for kicker system

– **Problematic for survival of asynchronous beam dump**

2018: <u>Constant frequency</u> 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

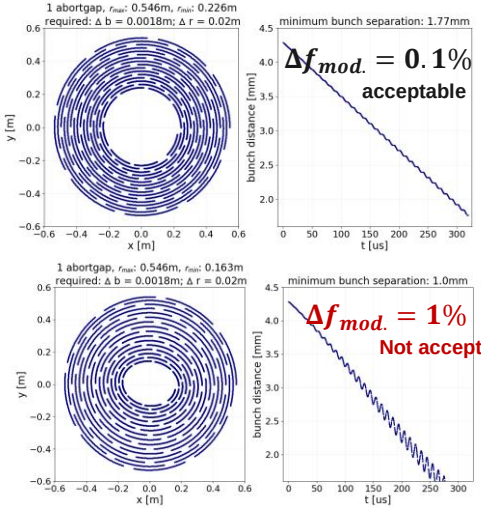
Complex system, e.g.:

- max. frequency mismatch of ~0.2-0.5% allowed
  Impact on availability?
- time dependent damping constant, …

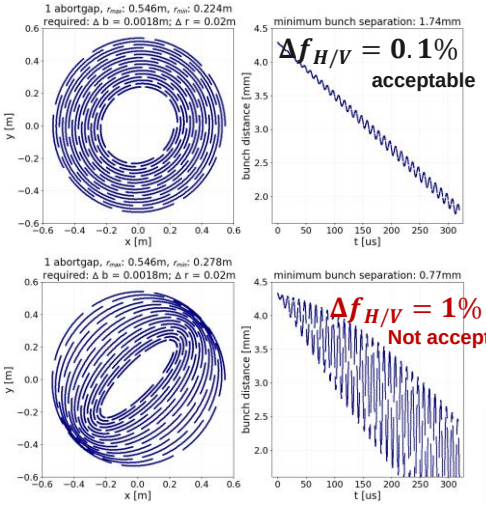
	triplet		w.o triplet	
	MKBH	MKBV	MKBH	MKBV
frequency [kHz]	50	50	50	50
risetime [us]	5	5	5	5
Installed L [m]	60	110	100	110
Gap field [T]	0.5	0.5	0.5	0
Modules	30	55	50	50
BdL [Tm]	22	42	38	39
gap height [m]	0.03	0.046	0.026	0.046
gap width [m]	0.03	0.04	0.046	0.086
Current [kA]	12	16	10	34
Voltage [kV]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

Dilution Kicker – Frequency Mismatch

Mismatch between single generators



Mismatch between horizontal and vertical system



Systems need to be set up accurately but no showstopper

B. Facskó: Optimal beam dilution pattern of the FCC-hh ring using beating frequencies, Tue. 15:30

Extraction – Machine Protection Strategy

Machine protection requirements to be considered for the design are …

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

Survival of Asynchronous Dump

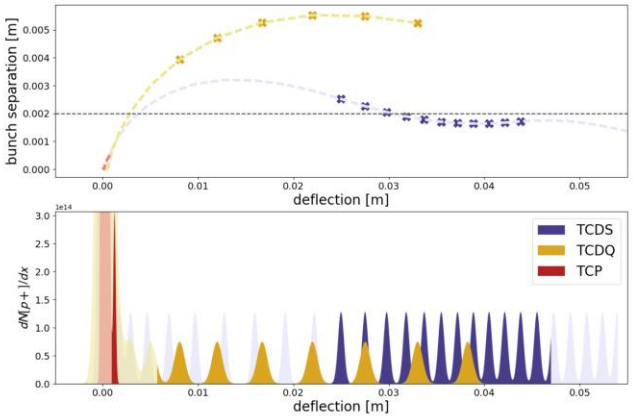
Extraction kicker:

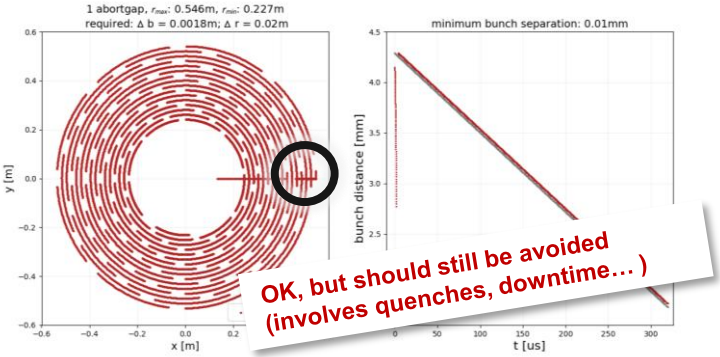
1 us risetime of extraction kicker to guarantee bunch spacing of ~1.8mm at septum protection ✓

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) ✓





Avoid Asynch. Dump/ ‘1.5 Sig Oscillation’

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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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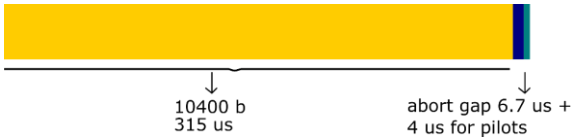
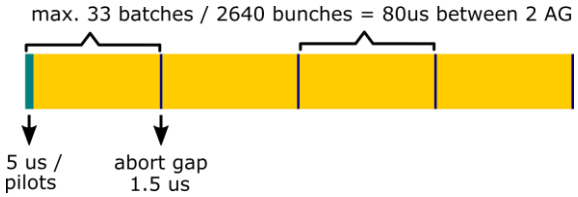
2017/2018: Evaluating implications of '1.5 sig oscillation'

- Tracking studies conducted: 1.5 sig oscill. OK for losses in collimator
- 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)

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)

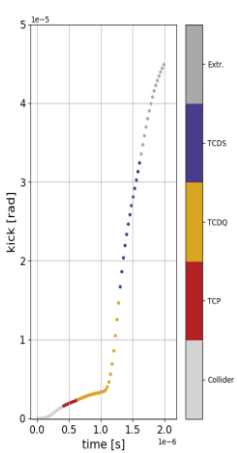
- … **a fast system**

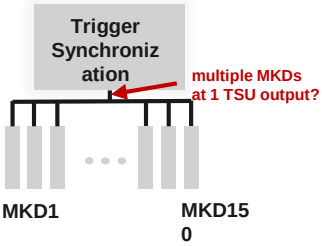
  despite long system length
  (120m, signal propagation)

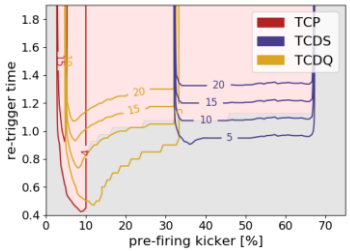
- **partial pre-triggering within 3 % to 67% must be avoided**

  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 switches, FCC Week 2018







Summary (I)

Injection:

- Optics updated to fulfill machine protection requirements
- New generator technologies required and studied
- Failure scenarios analyzed → Inherently different strategy due to different failure modes of new generators / reduced failure probabilities

Summary (II)

Extraction:

- **New proposed baseline: vertical single plane extraction** based on **SuShi and Truncated Cos-Theta Septa** → reduced system length, pot. less kick strength required
- Highly segmented extraction kicker system (150 modules). Impact of **1.5 sigma oscillation in case of single erratic was studied**
  → acceptable [dump beam with next abort gap]
- System designed to run with min. 10% less dilution/kick strength
  → **continue operation in case of faulty generator until next stop**
- **4 abort gaps** with 1.5 us proposed to reduce machine impact in case of failure

Future studies

- ⇨ Continuous update regarding protection
- ⇨ Injection kicker magnet (MKI) – measurements of the FCC beam screen
- ⇨ Extraction kicker magnet (MKD) – new switch topologies
- ⇨ Dilution system (MKB) – frequency offset, constant damping, margin for reduced kick strength
- ⇨ Triggering systems

T. Kramer: FCC-hh kicker systems: status and R&D plans (injection, extraction, dilution), Wed. 09:10

Thank you for your attention.