FCC – hh Injection and Extraction

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Outline

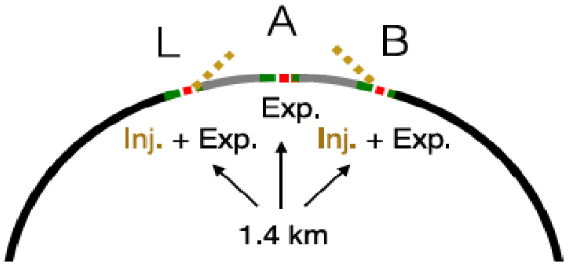
- Injection baseline
- Extraction baseline
- Strategies in case of erratic extraction kickers
  - retrigger strategies
  - alternative kicker layouts with reduced segmentation
  - alternative switch technologies

For a complete summary of the current baseline design please refer to:

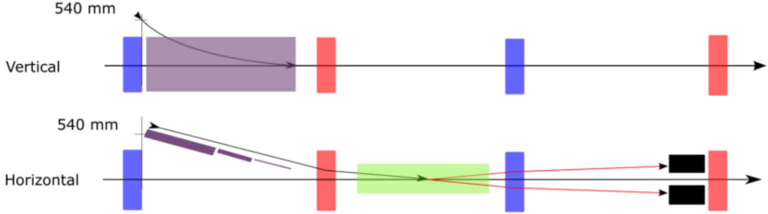
- Injection and extraction insertions and dump lines *(F. Burkart, FCC Week 2017)*
- scSPS as 1.3 TEV HEB *(F. Burkart, FCC Week 2017)*
- Beam transfer technology challenges, including dump and dilution system design *(W. Bartmann, FCC Week 2017)*
- LHC at 3.3 HEB *(W. Bartmann, FCC Week 2017)*

Injection – Status

- same baseline as FCC Week 2017
- **injector options:** LHC at 3.3 TeV and scSPS at ~1.3 TeV
- injection into side-experiments

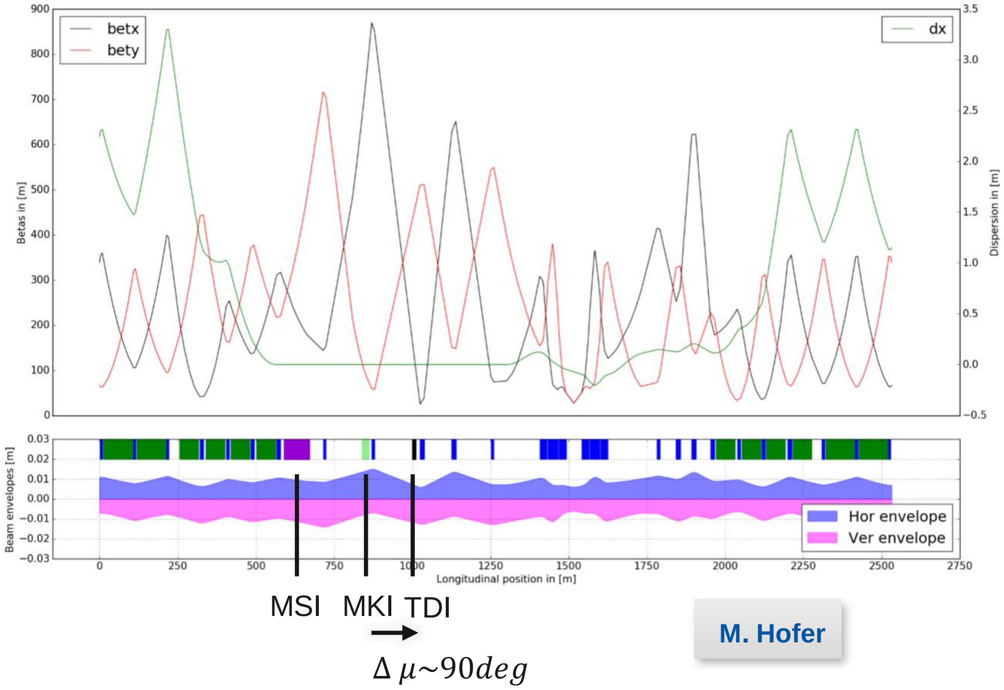


Hardware parameters	Unit	Kicker	Septum
Deflection	mrad	0.18	7.3
Integrated field	T.m	2.0	80.4
System length	m	40	100
Rise time	μs	0.425	-
Recharge frequency	Hz	≈ 100	-
Flattop length	μs	2.0	≥ 2.0
Flattop stability		$\pm 5 \cdot 10^{-3}$	$\pm 10^{-5}$
GFR h/v (radius)	mm	18/18	???
Septum width (first unit)	mm	-	6



W. Bartmann, F. Burkart

Injection – Status

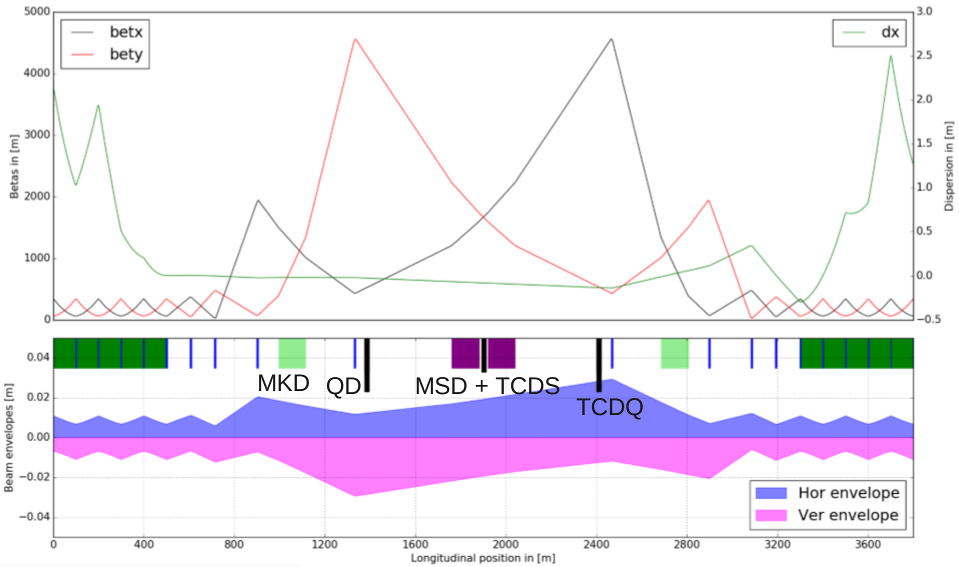


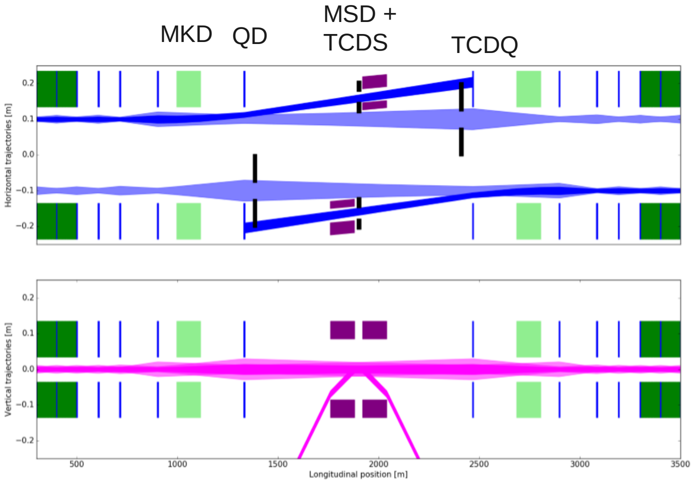
M. Hofer

Current progress + outlook:

- transferline design; drift straight left in transfer line for injection protection collimation scheme
- injection protection design
- tracking studies for injection failures (pycollimate)
- higher beta function on injection protection absorber (TDI) might be needed

Extraction – Status FCC Week 2017





W. Bartmann, F. Burkart

- same baseline as FCC Week 2017
- ✓ optimized to 2.8 km (overlapping septum protection)
- ✓ high beta functions at extraction absorbers

Extraction Design Requirements – Safety and Availability

- ❑ Safely extracting the beam (8.5 GJ stored beam energy)
- ❑ Surviving asynch. beam dump
- ❑ Avoiding an asynch. beam bump (main cause: erratic kicker)
  - ➢ reduce risk of spontaneous triggering → minimize failure rate, relaxed hardware parameters (current baseline design: 300 kicker segments with relaxed hardware requirements), reduced number of modules
  - ➢ avoid asynchronous beam dump in case of spontaneous triggering
  - ➢ reduce impact of spontaneous triggering

Requirements to Survive an Asynch. Beam Dump

- **Extraction protection (TCDQ, TCDS):**
  Bunch separation $> 2mm$ for $\sqrt{\beta_x \beta_y} > 1\ km$.

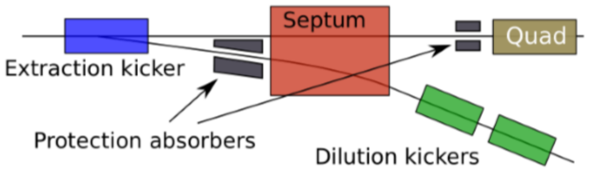
  ✓ TCDQ: not problematic
  ~ TCDS: $\tau_r \leq 1\mu s$ required

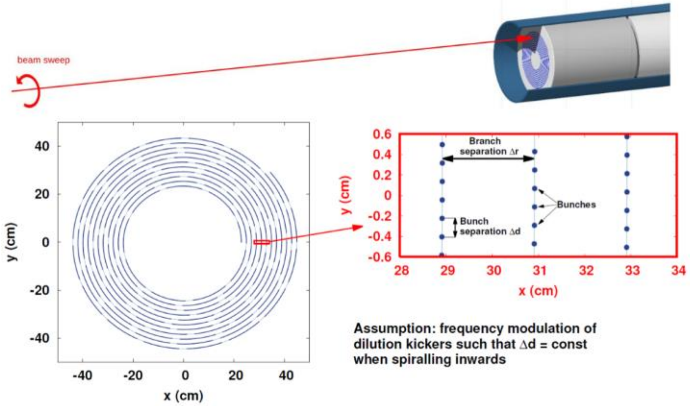
- **Beam dump (TDE):**
  dilution system needs to provide a bunch separation of 1.8mm (spiral branch separation of 20mm).

  Dilution kicker (MKB) risetime 5us → extraction kicker (MKD) risetime ~ 1us

  ➢ Insufficient bunch separation at beam dump in case of asynch. dump, potential damage of beam dump

Aim: Reduce probability of asynch. dump





F. Burkart, A. Lechner, D. Barna

Further information: Design Studies for the FCC-hh beam dump, A. Lechner, FCCW 17)

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Avoiding an Asynch. Beam Dump in Case of Erratic Triggering

Different strategies to respond to an erratic extraction kicker

- **Retrigger instantaneously (as in LHC, delay 0.7 – 0.8 us)**
  - **(1) Immediate asynch. dump**
- **Retrigger with a delay**
  - **(2) Wait 5 us (risetime dilution system)**
    = delayed asynch. dump
  - **(3) Retrigger with next abort gap**
    = semisynchronus dump

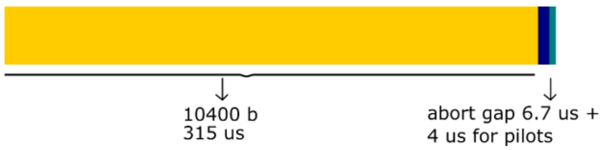
Semisynchronous Dump

= wait for the next abort gap to retrigger remaining kicker modules

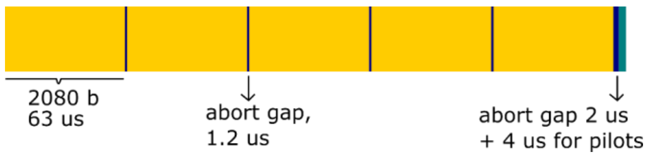
- Evaluate impact on the machine due to oscillating beam in the collider (losses, beam-beam effects, impact on extraction after one turn, impact on sweep pattern)

<u>Impact can be relaxed by introducing multiple abort gaps:</u>

- ❑ 1 abort gap: 10400 bunches



- ❑ 5 abort gaps: 2080 bunches



- Consider RF synchronization

Impact of Alternative Retrigger Strategies

- Assessing the **feasibility of a semisynchronous dump** for the baseline design (300 kicker modules, each with a kick of 0.15 urad)
- How far can the **modularity be reduced** to still stay below the damage limits in case of different failure scenarios?

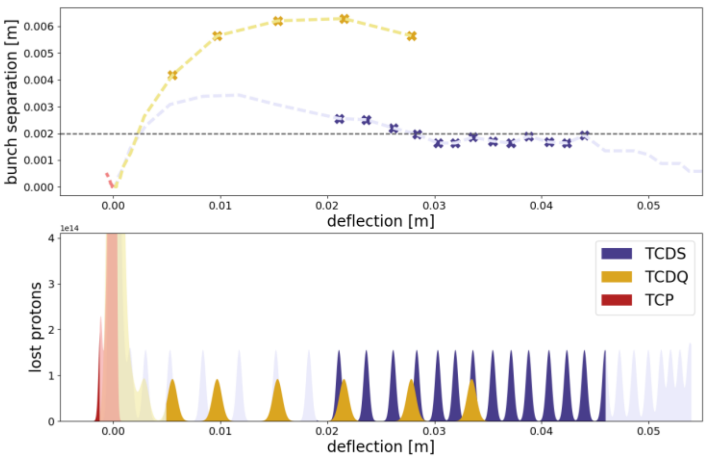
Considered damage limits

- **Extraction protection:** bunch separation of ~ 2mm
- **Primary collimator*:** loss of ~ $1.5\ to\ 2 \cdot\ 10^{11}\ p+$

**Remark: only estimations of damage limit for primary collimators are considered (1-2 FCC bunches) → FLUKA studies for damage limits are started by collimation, FLUKA team and EN/MME*

Extraction Kicker Baseline (A) – Semisynchronous Dump

	A: 300 kicker modules
l [m]	0.3
U [kV]	1.2
I [kA]	2.1
Z [Ohm]	0.33
L [uH]	0.38
tau [us]	1
Single erratic kicker module (MKD)	✓ **semisynch. dump (0.9 sigma osc.) *** ✓ **Absorber/collimator/Dump: OK**
Common cause failure	**<5 erratic modules: semisynch. (5 ag)*** **≥5 erratic modules: asynch. dump**
Asynch. dump:	✓ **Absorber/collimator: OK** × **Dump: ?**

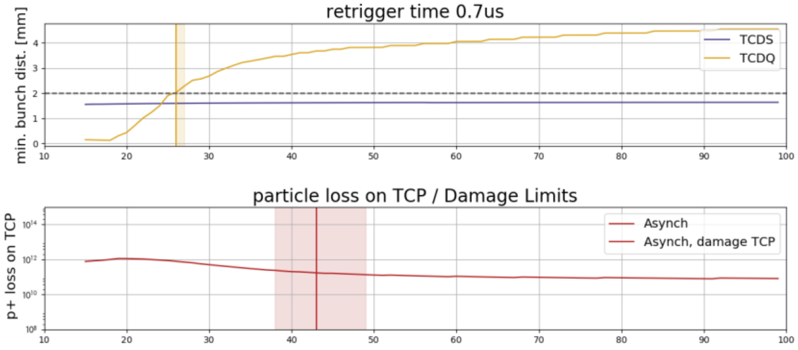


Load on and bunch separation at extraction absorber and primary collimator for 1 us risetime (shaded areas: by absorbers not intercepted p+)

*) Taking a loss of $1.5\ to\ 2\ 10^{11}$ p+ at the primary collimator as a limit

Extraction – Limits for Reduction of Kicker Segmentation

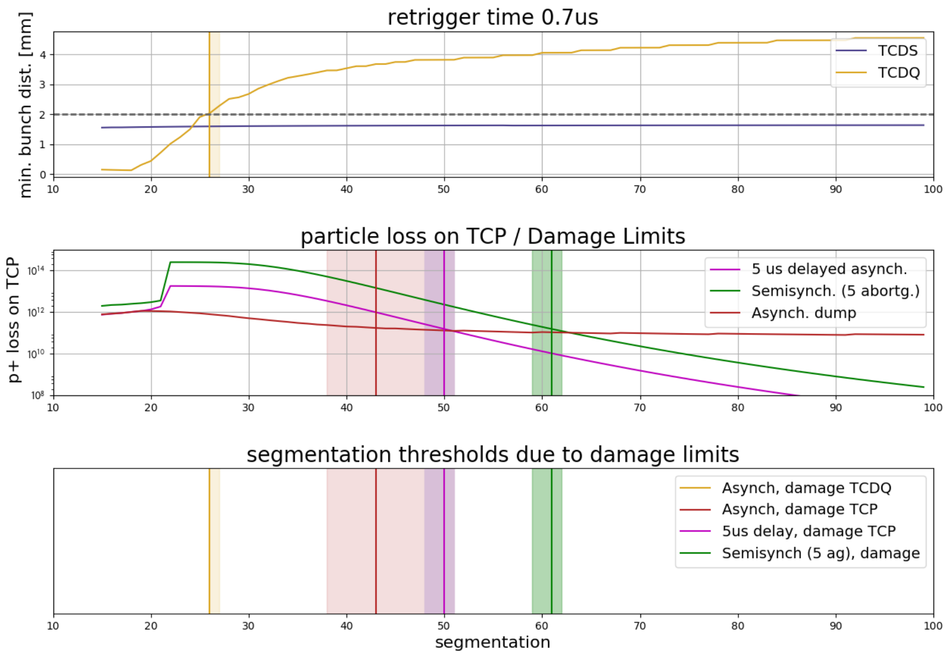
Ad 1) Asynch. dump



- **Load on quadrupole protection limits to ~28 segments**
- **Load on primary collimator limits to ~45 segments**

	Mean	**Deviation**
$\tau\ [us]$	1	[0.9 to 1.2]
TCDS [mm]	20 to 46	[21 to 46 / 19 to 27]
TCDQ [sig]	11.4	[11 to 12]
TCP [sig]	7.2	
$\Delta\mu_{\{MKD-TCDS\}}$	66 deg	
$\Delta\mu_{\{MKD-TCDQ\}}$	78 deg	
$\Delta\mu_{\{MKD-TCP\}}$	280 deg	

Extraction – Limits for Reduction of Kicker Segmentation



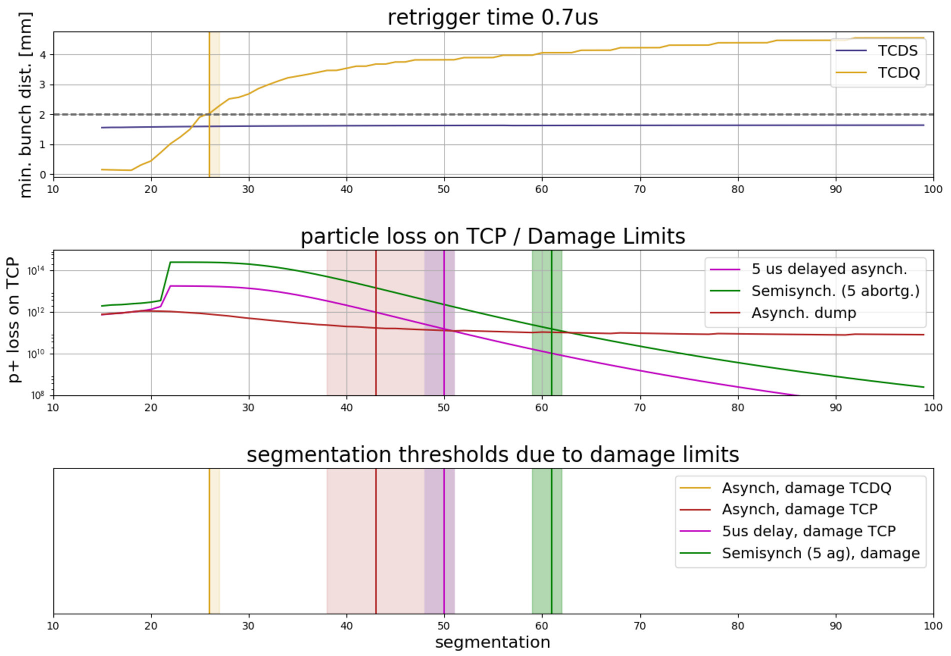
Ad 2) 5 us retrigger time (dilution system rise time)

- OK down to ~50 segments for damage limit of primary collimator

Ad 3) Semisynchonous dump (5 abort gaps – 2080 bunches)

- OK down to ~60 segments for damage limit of primary collimator

Extraction – Alternative Kicker Design (B)



	B: ~70 kicker modules
l [m]	1.6
U [kV]	6.75
I [kA]	1.7
Z [Ohm]	2
L [uH]	2.03
tau [us]	1
Single erratic kicker module	✓ **semisynch. dump (3.9 σ osc.).** ✓ **Absorber/collimator/Dump: OK**
Common cause failure	**> 1 erratic modules: asynch. dump**
Asynch. dump:	✓ **Absorber/collimator: OK** × **Dump: ?**

Extraction Design Requirements – Safety and Availability

- ❑ Safely extract beam (8.5 GJ stored beam energy)
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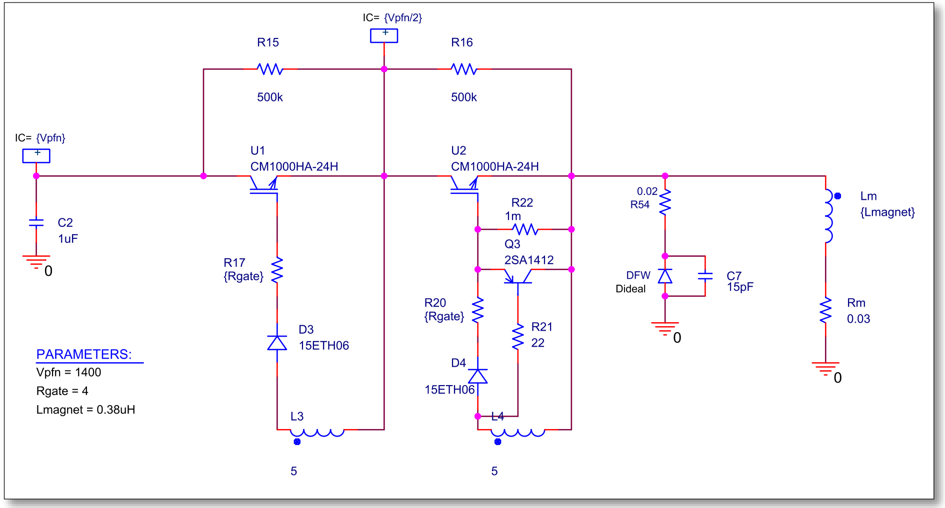
→ **alternative switch architecture** to inhibit the current over the magnet in case of an erratic

Alternative Switch Topologies

- Alternative switch topologies can limit the current in the kicker magnet in case of an erratic with the aim to reduce or eradicate the impact of an erratic trigger on the beam

- Two alternative generator topologies:
  - **Series connection of two switches** to inhibit current over magnet in case of single self-trigger (simulation: reduction of pulse strength to ~1%)
  - **Shorting crowbar switches**

Concept to prove



Above: PSpice Model for Series Switch Architecture, P. Van Trappen:
Further information: New design concepts for suppressing erratic triggering of solid state switch stacks (P. Van Trappen et al, FCCWeek 2017)

Extraction – Alternative Kicker Design (C)

- ~ 30 modules: number limited by hardware requirements
- IGBT switch should be operated at low blocking voltage, to limit transient amplitude if one switch has an erratic
- Long risetime (6 us) to lower required voltage
- risetime: 6 us > 5 us:
  - ✓ Beam dump survives asynch. dump
  - × Extraction protection / primary would be damaged → sacrificial absorbers
  - × Probability of and asynch. dump (due to both switches failing) should be minimized

	C: ~30 kicker modules
with 2 switch stacks in series (Concept to prove)	
l [m]	1.6
U [kV]	4.6
I [kA]	3.9
Z [Ohm]	0.33
L [uH]	2.03
tau [us]	6.1
Single erratic kicker module	✓ series blocking switch → semisynch. dump
Common cause failure	✓ series blocking switch → semisynch. dump
Asynch. dump:	× absorber/collimator: sacrificial ✓ dump: OK ✓ minimized probability

	A: 300 kicker modules	B: ~70 kicker modules	C: ~30 modules (Concept to prove)
Length [m]	0.3	1.6	1.6
U [kV]	1.2	6.75	4.6
I [kA]	2.1	1.7	3.9
Z [Ohm]	0.33	2	0.33
L [uH]	0.38	2.03	2.03
risetime [us]	1	1	6.1
Switch topo.	Single IGBT	Stacked IGBT (2-4)	2 stacks in series (each 2-3)

Single erratic kicker module	✓ semisynch. dump Abs./Coll/Dump: OK	✓ semisynch. dump (3.85 sigma osc.) → 8 a.g.!	Series blocking switch → ✓ semisynch. dump
Common cause failure	<5 erratics.: semisynch. ≥5 erratics: → asynch. × Probability to minimize	≥1 erratic module → asynch. dump × Probability to minimize	Series blocking switch → ✓ semisynch. dump
Asynch. dump	✓ Absorber/collimator: OK × Dump: ? ✓ Minimzed probability*	✓ Absorber/collimator: OK × Dump: ? ✓ Minimzed probability*	× Absorber/coll.: sacrificial ✓ Dump: OK ✓ Minimzed probability*

*) Asynch dump only in case of RF synchronization loss, multiple erratic kickers (common cause), abort gap population,..

* As only for multiple erratics and other failures

Conclusion and Outlook

- **Injection:**
  - ✓ Injector options and injection optics are completed
  - ➢ **Ongoing:** Studies on transfer line design, injection protection and failures ongoing

- **Extraction:**
  - ✓ Extraction straight and dump line optics are completed
  - ➢ Extraction design driven by failure case of asynchronous dump, due to impact on extraction protection and dump.

    Therefore: Study on impact of alternative extraction kicker design on RAMS is ongoing.
    - Baseline design with 300 extraction kicker modules: **Possibility to avoid asynchronous dump in case of an erratic kicker module by waiting for the next abort gap (semi synchronous dump).**
    - **Ongoing:** Compare baseline to alternative designs (~70 kicker modules or ~30 kicker modules with 2 switches in series to mitigate impact of erratic kicker [Concept to prove]) regarding failure impact and probability
  - ➢ Studies starting in cooperation with the collimation team for injection and extraction failures

Thank you!

- Injection and extraction insertions and dump lines *(F. Burkart, FCC Week 2017)*
- scSPS as 1.3 TEV HEB *(F. Burkart, FCC Week 2017)*
- Beam transfer technology challenges, including dump and dilution system design *(W. Bartmann, FCC Week 2017)*
- LHC at 3.3 HEB *(W. Bartmann, FCC Week 2017)*
- Surviving an Asynchronous Dump? *(B. Goddard, FCC Week, Rome 2016)*
- Dump system concepts for the Future Circular Collider *(W. Bartmann, et al, Physical Review Accelerators and Beams, 2017)*
- Dependability analysis of a safety critical system : the LHC beam dumping system at CERN *(R. Filipini, CERN-Thesis 2007)*
- New design concepts for suppressing erratic triggering of solid state switch stacks *(P. Van Trappen et al, FCCWeek 2017)*
- Design Studies for the FCC-hh beam dump *(A. Lechner, FCCW 17)*

Extraction

Safety:

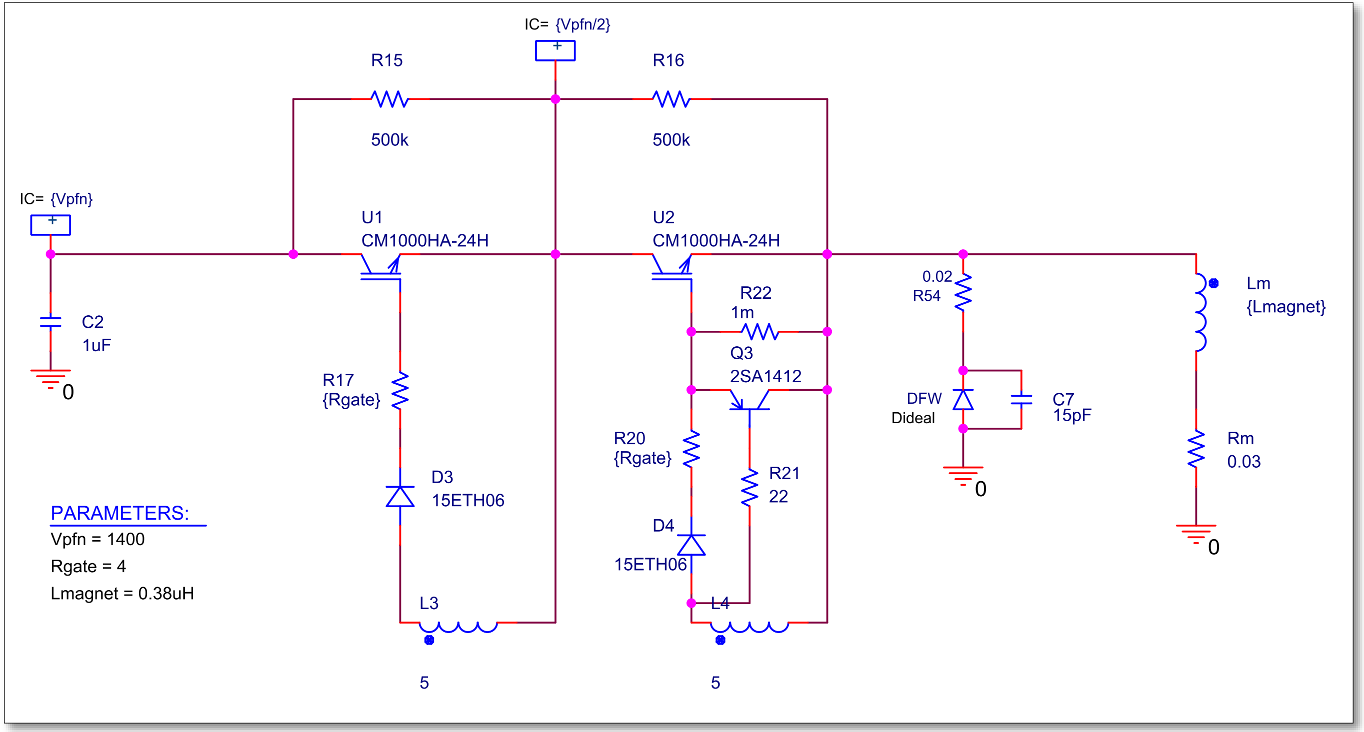
Unsafety (Not being able to extract due to missing kicker) << 10^{-11} yr

(scaled from LHC: 10^{-7}/yr) [R. Filipi, **Dependability analysis of a safety critical system : the LHC beam dumping system at CERN**, CERN-Thesis 2007]

Hardware parameters	Unit	Kicker	Septum
Deflection	mrad	0.045	1.15
Integrated field	T.m	7.5	192
System length	m	120	120
Effective septum thickness	mm	-	25
Maximum leak field	T.m	-	< 0.6
Rise time	μs	1	-
Flattop length	μs	≥ 333	≥ 333
Flattop stability	%	$\pm$ 5	$\pm$ 1
GFR h/v (radius)	mm	18/18	23/19

Beam parameters	Unit	Injection	Extraction
Kinetic energy	TeV	3.3	50
β_{rel}		≈ 1	≈ 1
γ_{rel}		3518	53290
Revolution period	μs	333	333
Magnetic rigidity	T.m	11011	166785
Bunch spacing	ns	25 (5)	
# bunches		10400 (52000)	
Bunch intensity	10^{11}	1 (0.2)	
Transverse emittances	μm	2.2 (0.44)	
Total beam energy	GJ	0.55	8.3

Series Connected Switches



Crowbar Connected Switches