Surviving an Asynchronous Beam Dump?

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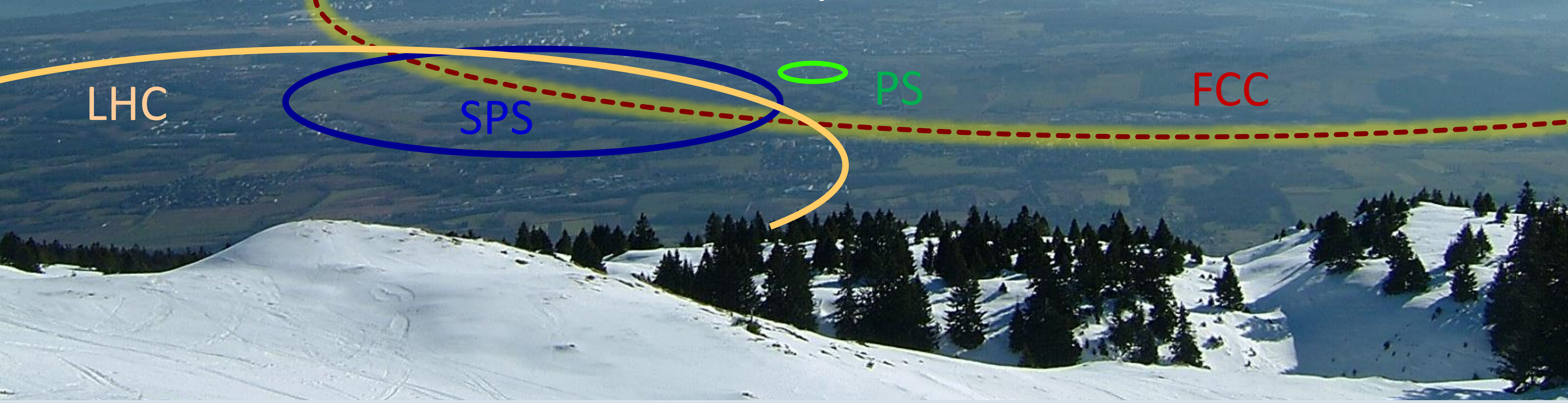
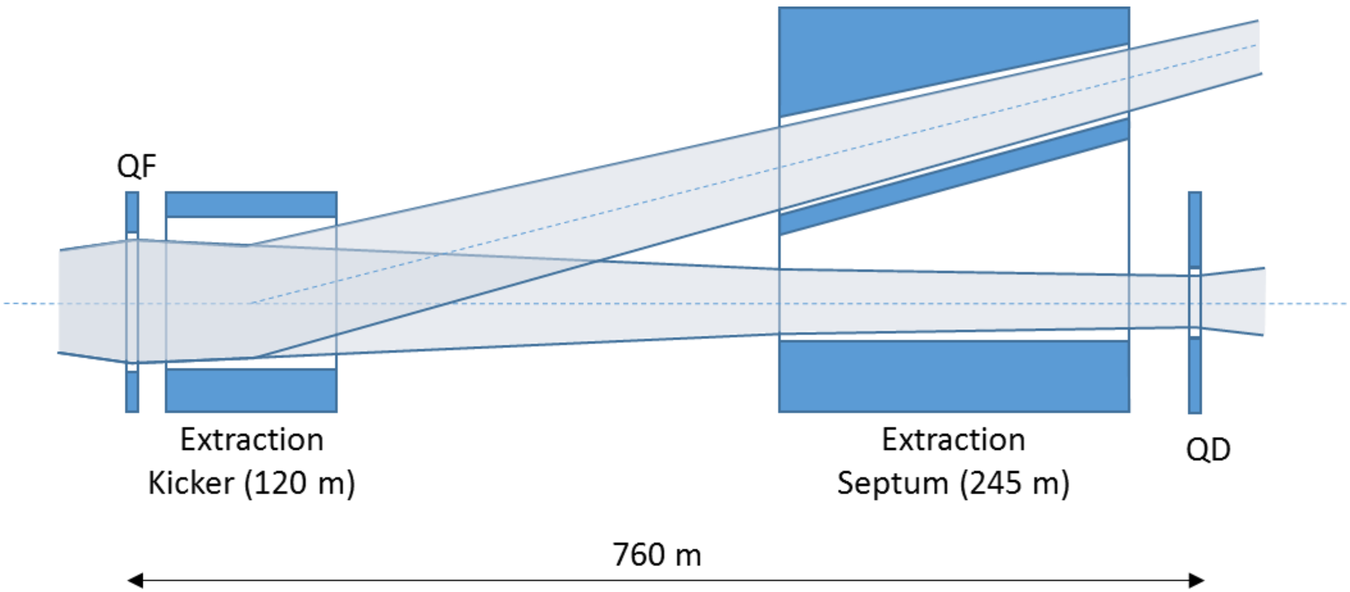


W.Bartmann, T.Kramer, A.Lechner, D.Barna, L.Stoel, M.Atanasov, P.van Trappen, D.Woog, J.Rodziewicz, A. Sanz Ull

FCC dump design

- Extraction kicker and septum in ring
- Transfer line with dilution kickers (and possibly quadrupoles) leading to dump block
- Protection devices for asynchronous dump



For full details see talk by W.Bartmann (this session)

Kicker synchronisation

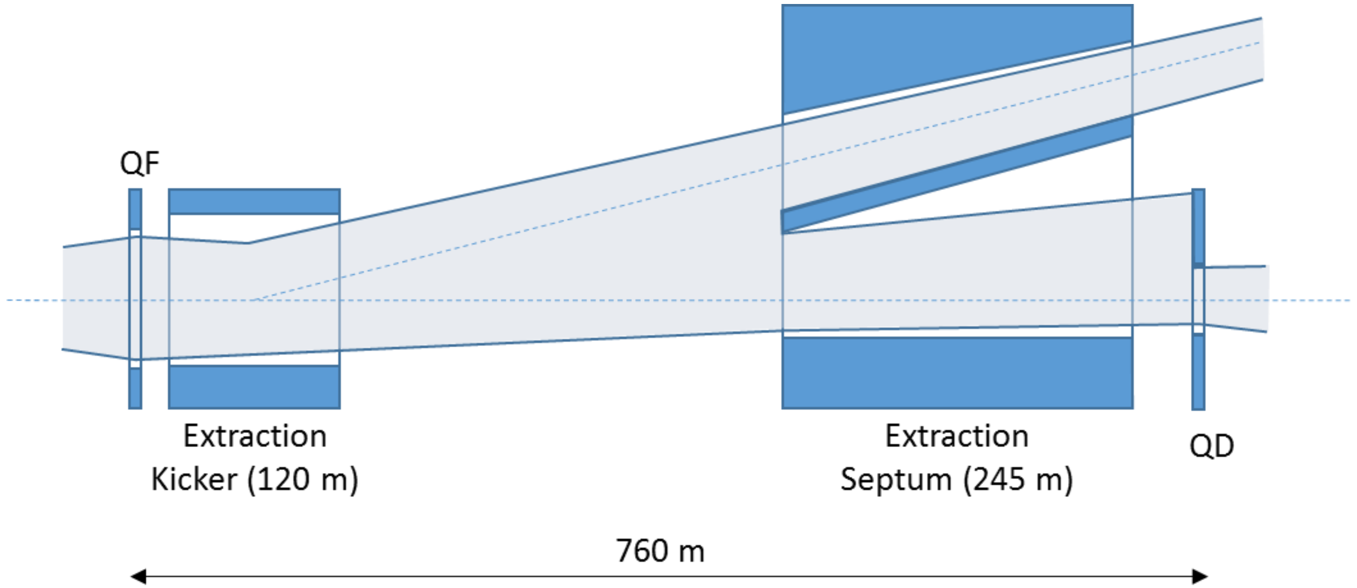
- Extraction kicker has non-zero magnetic field rise time
- Field rise has to be synchronised with abort gap(s) free of particles – hard link to RF clock
  - Kicker triggering and synchronisation is a big topic
- Asynchronous dump: can arise from
  - Failure of synchronisation system
  - Abort gap filling (RF off…)
  - Extraction kicker module pre-fire and (deliberate) retrigger of remaining kickers

Asynchronous dumps

- An asynchronous dump is an ‘allowed’ failure case
  - See no way to exclude it, or reduce probability to ‘beyond design’ level
  - FCC-hh machine must survive this
  - Have to design dump system for it
- Recovery time depends on frequency: should represent maximum ~1 % downtime for collider
  - Few hours is acceptable if ~1 per week
  - Few days is acceptable if ~1 per year (LHC design assumption)
  - Few weeks is acceptable if ~1 per decade

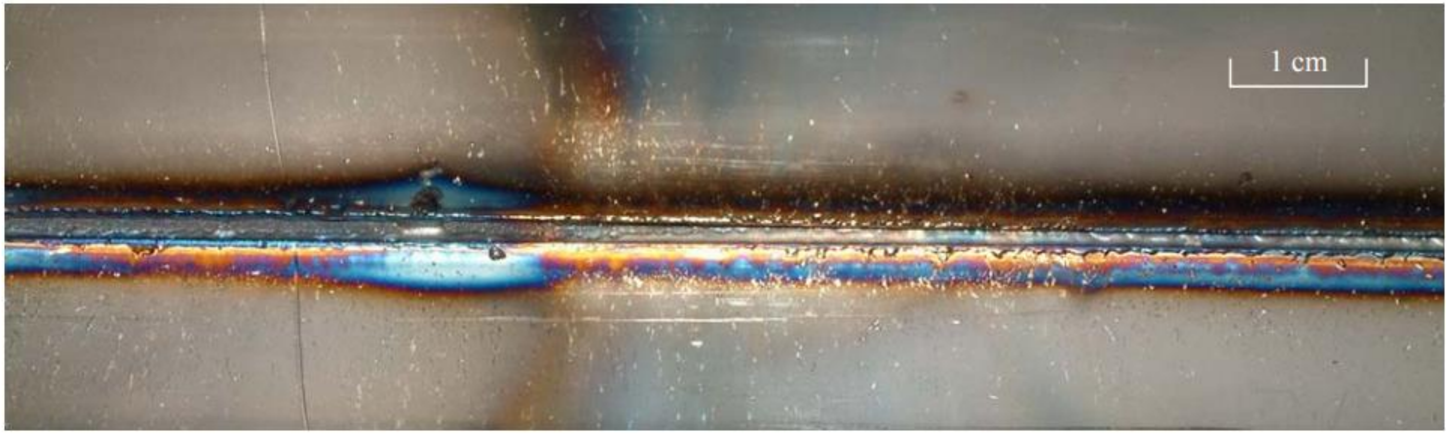
Effect of asynchronous dump

- Bunches miskicked: swept across collimators, aperture and septum



Effect of asynchronous dump

- Stored energy (and transverse energy density) in FCC beam is enormous
  - Cannot allow even small fraction of a single bunch to impact any part of machine aperture
- A 25 ns bunch contains ~1 MJ energy, with density 100 MJ/mm^2 at typical β, some 25× that of LHC
  - 50 TeV: energy deposition scales faster than linear with beam size
- Problem for design of collimators and protection devices to intercept beam – see talk by A.Lechner/F.Cerutti (this session)



SPS transfer line magnet vacuum chamber destroyed over ~1 m length in 2004, by impact of 2 MJ proton beam with transverse energy density of about 4 MJ/mm^2

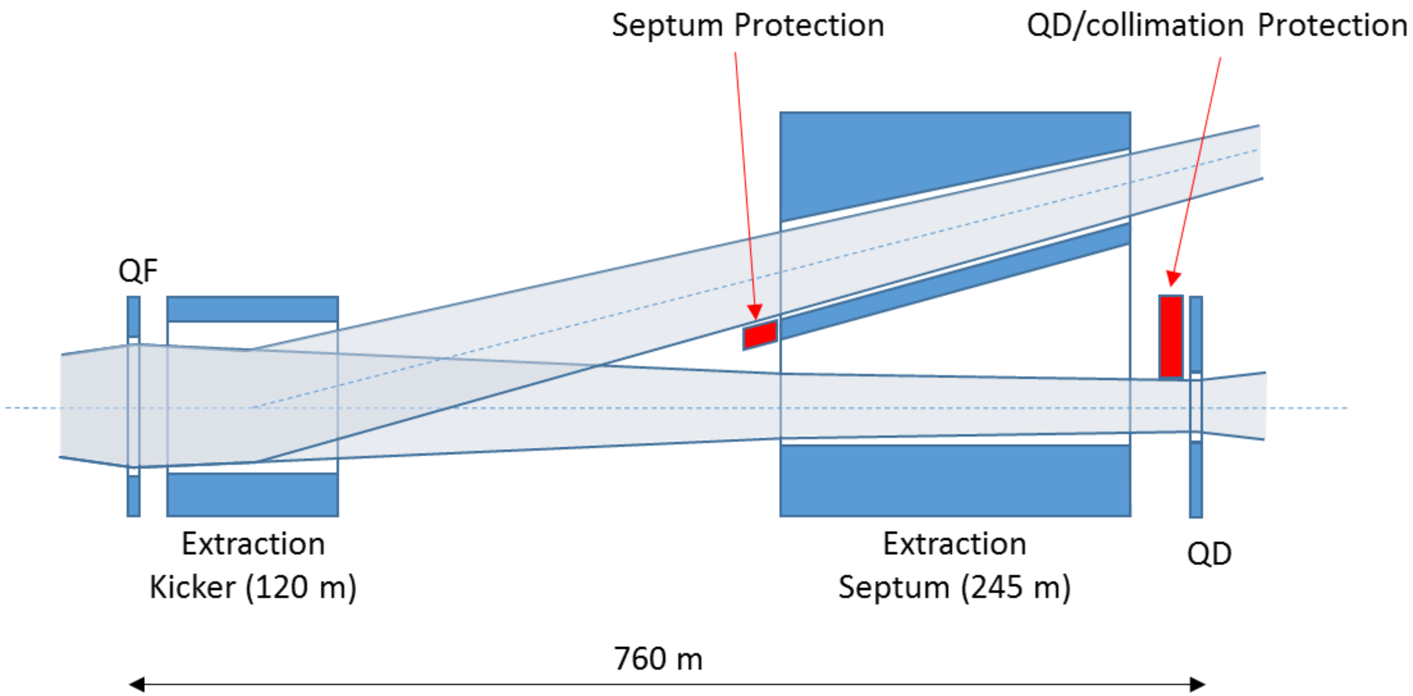
Prevention of asynch dumps

- Kicker switches to be solid-state
- Triggering redundancy and reliability are critical
  - Have to make sure dump ALWAYS fires
  - Can afford some missing modules (if large segmentation)
  - Strongly dependant on HV design: switch, power trigger and enclosure
  - Redundancy (reliability) not always good for asynch rate
- For dump reaction time of 1 turn ~350 μs, fast resonant charging of extraction kickers?
  - Avoid being under HV, reduce possibility of pre-trigger
  - Major reliability concerns, to evaluate…

Talk by P.van Trappen on controls aspects

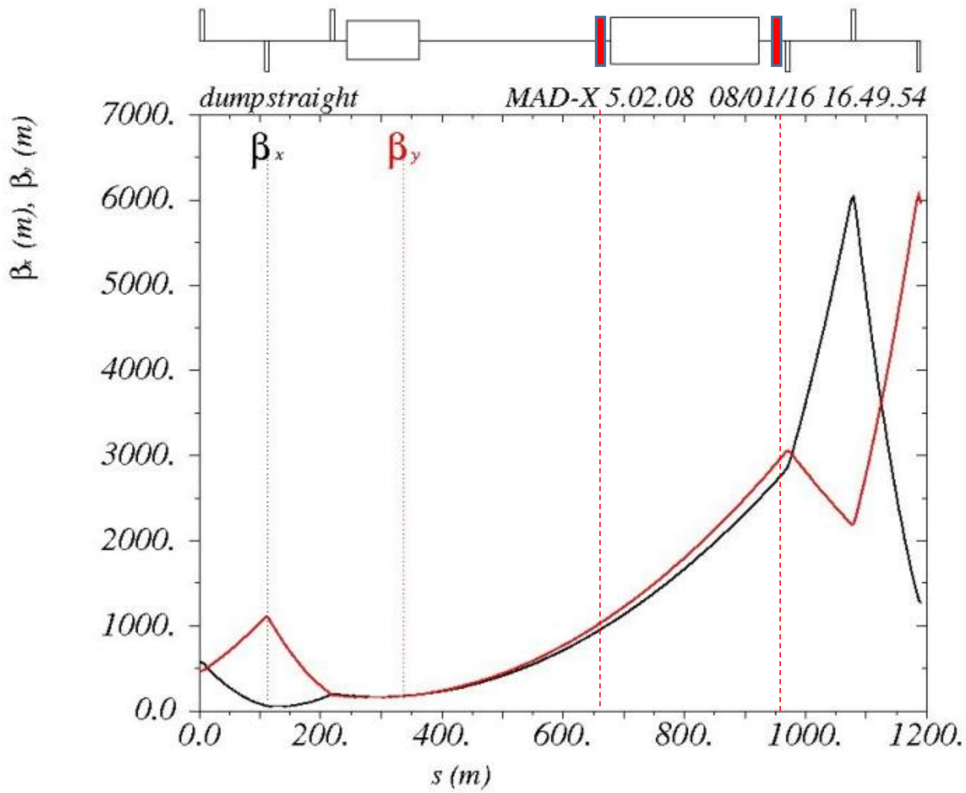
Mitigation of asynch dumps

- Need physical protection devices (septum and QD) to intercept swept bunches and prevent damage
  - Ideally these survive beam impact intact
  - Or…sacrificial design with ‘quick’ replacement (as already investigated for HL-LHC collimators)

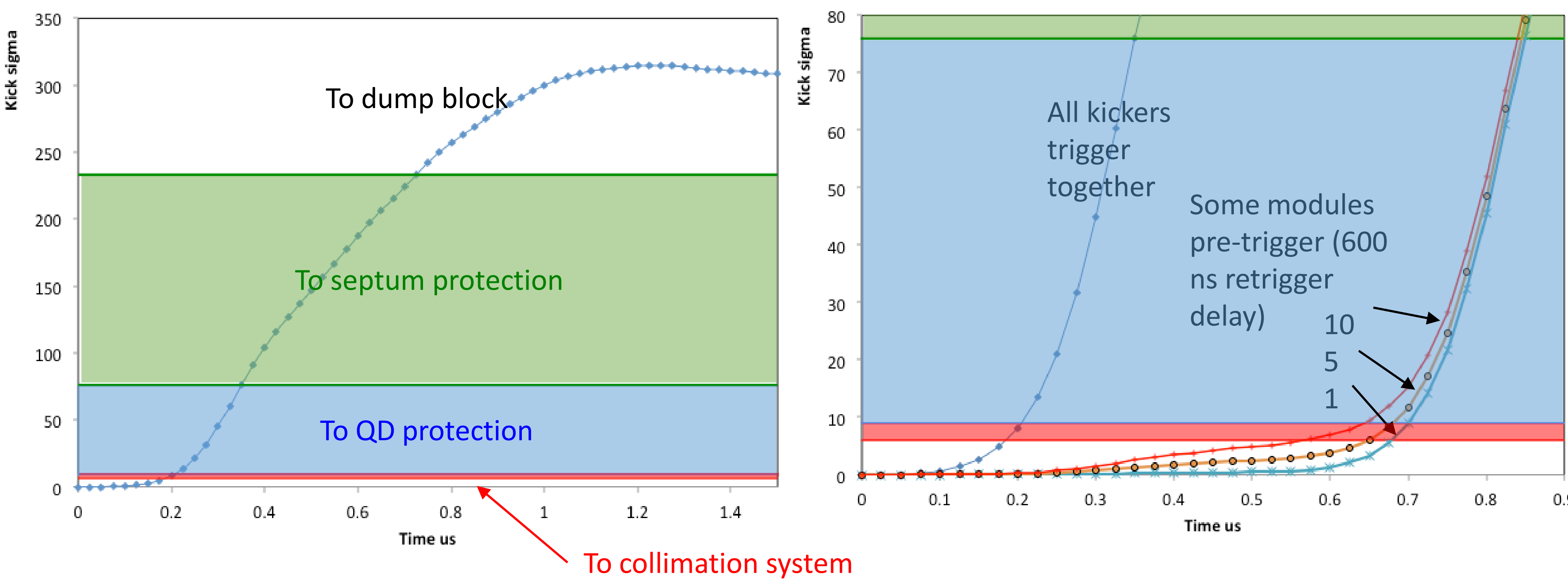


Dump insertion optics

- Large β_x and β_y at protection devices (800 /2700 m)
  - Reduces peak energy density on devices
  - Increases physical separation between swept bunches
- But places important constraints on insertion design…

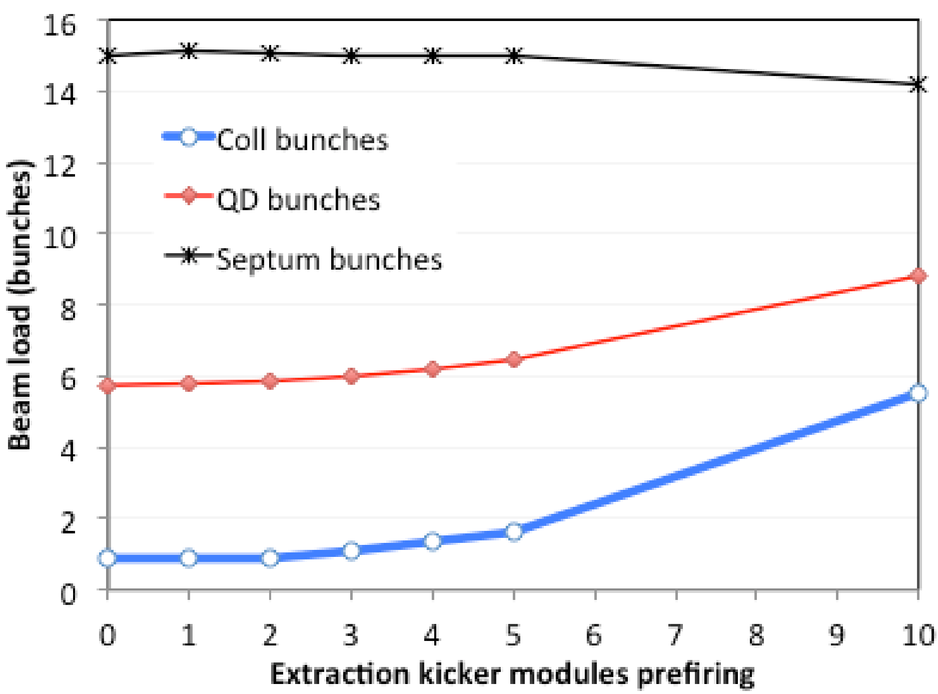


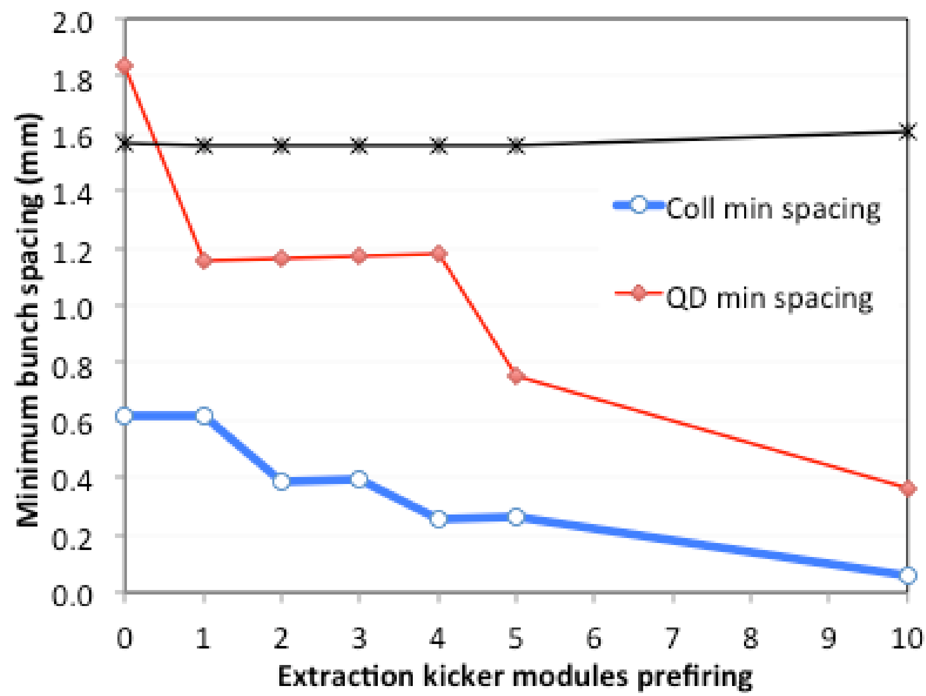
- Depends strongly at low amplitudes on whether single kicker has pre-fired, or all kickers together
- Pretrigger produces highest densities close to beam core
- Faster rise time (and faster retriggering) means less beam swept across downstream aperture
  - Aiming for 1 μs for FCC (to compare with 3 μs for LHC)



Load downstream

- Depends on fraction of kickers prefiring
- Assume 300 kickers modules: high segmentation
- Load on collimators and QD protection critical
- Total bunches AND minimum spacing get worse for more modules pre-firing





Dealing with pre-triggers

- Retriggering of all other kicker modules as fast as possible is one option – assume 600 ns is possible
  - Then load for single module pre-fire is similar to that of full ‘synchronous’ sweep’
- Or…do nothing until abort gap “arrives”?
  - Accept ~1 σ oscillation around ring from 1 kicker then trigger “synchronously”.
  - Could have multiple (4-8?) abort gaps to limit this effect (impact on filling factor is low, for ~μs rise time)
  - Questions of load on collimators, beam-beam, background, …

Loads on protection devices

- Are bunch separation and number on protection devices are acceptable? If not:
  - Kicker: A steeper rise (e.g. same strength and shorter risetime or higher strength and same risetime) reduces number of bunches and increases spacing.
  - Septum: A thinner blade allows for a thinner protection device and thus fewer bunches (but same density)
  - QD Quadrupole: If need less separation (triple aperture quad?), can decrease septum length and move protection device downstream, increasing bunch spacing.
  - Insertion length: If increase insertion length, placing a larger drift between kicker and septum, can increase bunch spacing

Orbit bump for dump?

- In LHC, no extraction bump
  - Sweep amplitude to fixed septum protection at high energy is very large, in beam σ (~50).
  - Need protection of downstream aperture at around 9 σ.
- Could consider bump for FCC dump: keep beam close to fixed septum protection, avoid need for (or reduce load on) mobile QD protection device
  - Would have important by-product of reducing kicker strength needed by maybe a factor 2
  - Or could use this to reduce kick rise time by factor 2, for same peak voltage
  - Aspects of reliability, losses, operation, setup, impedance, … to study

Lessons from LHC

- Total of two asynchronous dumps in ~4 years of actual LHC beam operation (with others during testing)
  - Once at injection, with a few bunches
  - Once at 6.5 TeV, with a single low intensity bunch
  - Average of ~0.12 per year per beam at high energy
  - Both ‘unexpected’ failure modes (failure of common power components on retrigger fan-out, HV switch breakdown)
  - Both through pre-trigger followed by retriggering
- Not yet happened at top energy with machine full of beam
  - No experience of effectiveness of protection devices, quench extent and required recovery time
- LHC system has 60 individual switches, so rate of 10^{-3} per switch per year is achievable
  - For FCC, ~300 switches per system would imply ~1 asynch dump per year
  - Reduction of spontaneous triggering to 10^{-4} per switch per year highly desirable, assuming ~weeks recovery time with sacrificial absorbers

Conclusions

- Surviving asynchronous dump is dominant consideration in design of FCC dump insertion
- Beam loading on protection devices key design aspect
  - Impacted by kicker system parameters, kicker segmentation and failure modes and insertion design
  - Need highly segmented system to minimise effect of single kicker pretrigger (with or without retriggering)
- Balance between insertion/kicker complexity and a move to sacrificial protection devices to weigh up
- Many aspects to investigate in continued study…

Study directions

- Can kicker triggering ensure $\leq 10^{-4}$ spontaneous triggers per switch per year?
- What kicker retriggering strategy is best, linked to bunch filling pattern and number of abort gaps
- Can fast resonant charging be considered?
- Can machine survive 1 turn (or fraction of a turn) with one beam kicked by ~1.0 sigma?
- Utility of an extraction orbit bump
- Damage limits for protection devices
- Sacrificial protection devices design and tests
- Are two protection devices sufficient?
- Quench protection system for downstream SC magnets