BEAM TRANSFER CHALLENGES

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Outline

- Sources of emittance blow-up during beam transfer
    - Implications on hardware for low emittance 5 ns beams

- Machine protection limits
    - Injection protection and implications on injection kicker
    - Extraction protection and implications on dump kicker
    - Dump absorber and implications on dilution system

Error sources for delivery precision

- Correctable errors
  - Magnet misalignment
  - Magnet systematic (different laminations, steel,…) and random errors (different transfer function within a series)
  - Long term drifts due to temperature, humidity,…
  - All these errors lead to trajectory variations that can be corrected
  - Since the transfer function is considered correctable → ΔI/I = ΔB/B

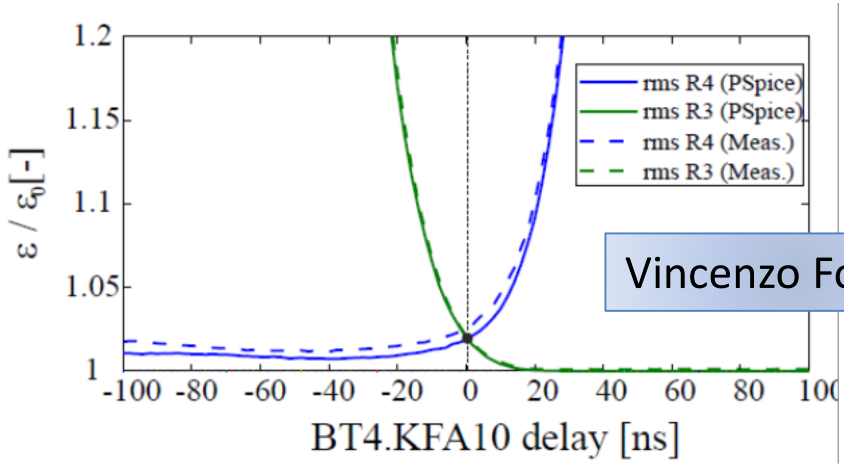
- Uncorrectable (dynamic) errors
  - Random errors:
    Shot-to-shot stability
  - Systematic errors:
    Power converter ripple, kicker waveforms

Example for present PSB-PS transfer

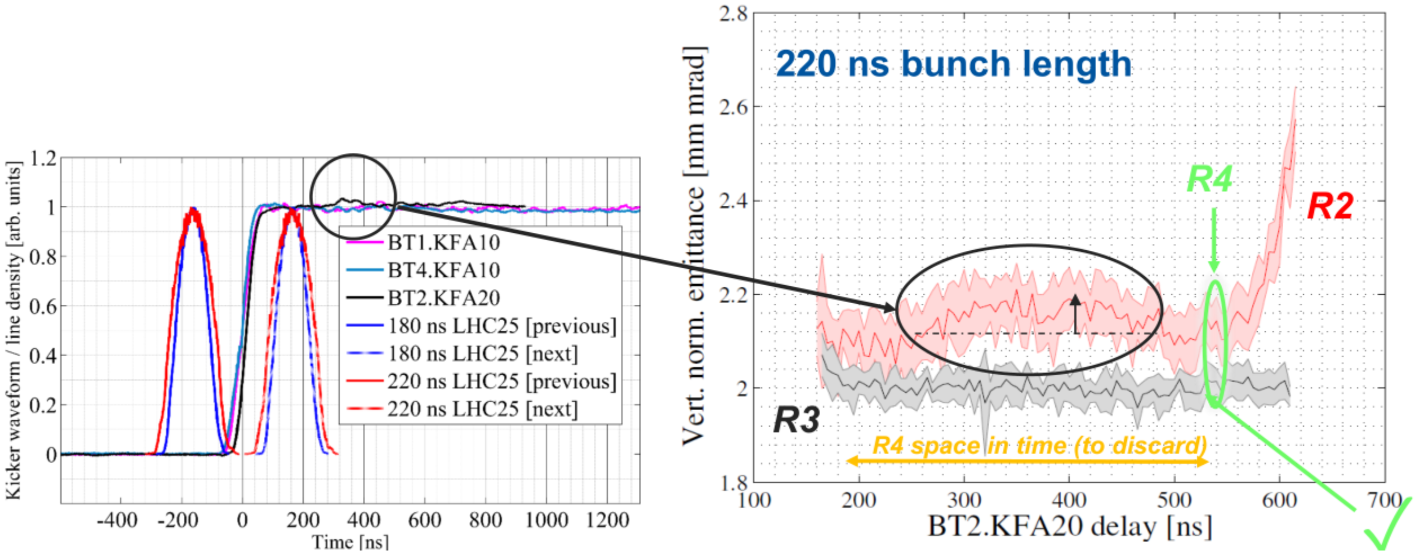
- Extract, recombine four PSB rings and inject into PS via four kicker systems
- Can use TFB to counteract kicker waveform (systematic) and power converter ripple (random)
- No active handle on optics mismatch
- Reduction of dp/p with longitudinal damper helps to reduce dispersion and energy mismatch

Table 3: Emittance growth at PS injection due to different error sources in the PSB to PS transfer.

Mismatch	Emittance growth [%, hor/vert]		
	Pres. LHC	Upgr. LHC	Upgr. HI
Steering	0.3/1.5	0.3/1.5	0.1/0.5
Betatron	4.6/6.8	1.3/0.0	2.0/0.0
Dispersion	4.4/8.8	0.2/2.4	0.0/5.3
Total	**6.3/11.2**	**1.3/2.8**	**2.0/5.3**



Vincenzo Forte



Example for present SPS-LHC transfer

Mismatch in roll angle at injection

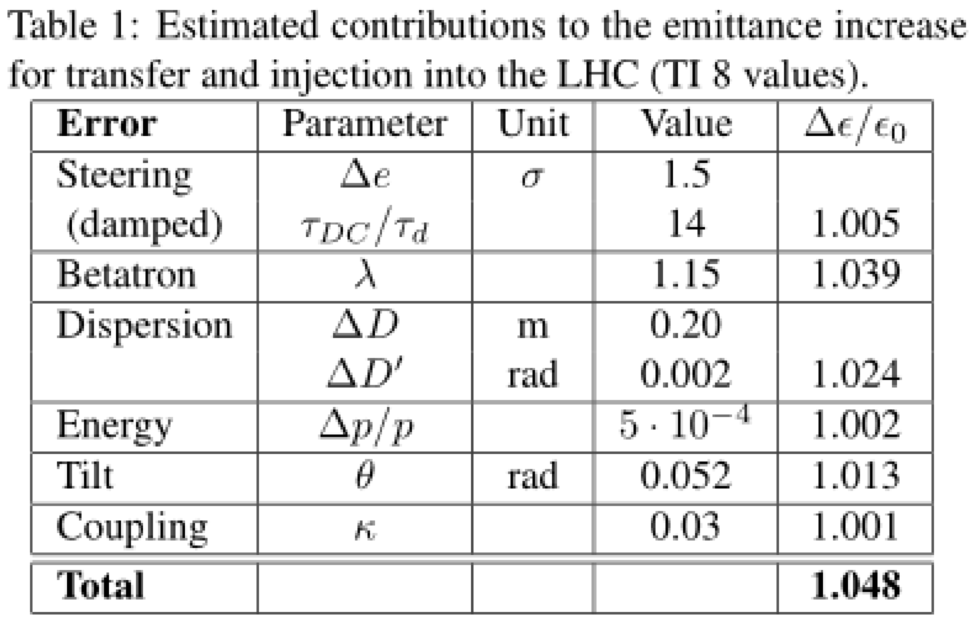


Table 1: Estimated contributions to the emittance increase for transfer and injection into the LHC (TI 8 values).

Error	Parameter	Unit	Value	$\Delta\epsilon/\epsilon_0$
Steering	Δe	σ	1.5	
(damped)	τ_{DC}/τ_d		14	1.005
Betatron	λ		1.15	1.039
Dispersion	ΔD	m	0.20	
	$\Delta D'$	rad	0.002	1.024
Energy	$\Delta p/p$		$5 \cdot 10^{-4}$	1.002
Tilt	θ	rad	0.052	1.013
Coupling	κ		0.03	1.001
Total				**1.048**

Similar contributions from optics and steering errors as for lower energy transfer

Error sources with Transverse Feedback as mitigation

- Kicker ripple, PC stability
- Presently contributes with 0.5% emittance growth assuming flattop ripple (the kicker rise fits well between bunches)
- In case of LIU rise time contributes and gives emittance growth of 2-3%
- Mitigations
  - Assuming extra effort in HW design (manpower and budget for R&D)
    - Faster systems – reduce rise time by ~10%
    - Factor ~5 reduction of waveform ripple
      - e.g. systems in PS complex with same B.dl requirement from +/-2% ripple → +/- 0.4%
      - e.g. systems in LHC from +/-0.5% → +/-0.1%
    - Aggressive damping times of 5-10 turns (instead of several 10s of turns) without injecting more noise into circulating beam
    - Build linear machines (e.g. scSPS) to keep detuning for higher amplitudes low

- Relative emittance growth can probably be controlled to ~1e-3 → most likely not even in FCC times measurable!

Error sources without active mitigation

- Betatron mismatch
  - No active handle, but independent of adiabatic shrinking
  - Presently have at least 20% error
  - Results in emittance growth of 1-3% per transfer
  - Very difficult to control since it relies on optics measurement with single passage of at least a factor 10 better or to control contribution from each magnet via HW specification

- This could present the main issue concerning emittance growth

- Mitigations
  - Huge improvement in optics measurement
  - Rebuild existing lines with HW much tighter specified, requires control of transfer functions within magnet series , heavy measurement campaign – time!
    - Same for power converters

Error sources without active mitigation

- Dispersion mismatch, energy error
- Dispersion relatively well measurable
- Mostly important for large dp/p – can be difficult if this is required for space charge mitigation

- → Could be issue for LIU/Hilumi

- Mitigations
  - Building new PSB recombination lines
  - Replacing PSB by Rapid cycling synchrotron
  - Replacing PSB by SPL

Error sources without active mitigation 2

- Energy mismatch
    - Can work on dp/p but might be needed for space charge forces

- Geometrical mismatch
    - Accounts for 1.3% emittance growth at LHC injection (B2)
    - Can be mitigated by skew compensation scheme or building a new TI 8 line

- Coupling
    - Considered to be in the noise of all the other errors

- → Smaller contributors

Summary for errors from transfer systems I

- Present machines should operate in the range of 2-5% relative emittance growth per transfer from simulations
  - This includes damping from transverse feedback systems – otherwise emittance growth >50%
  - This does not account for emittance growth during cycle (e.g. transition crossing)

- **However, in daily operation emittance growth of 20% can easily occur – without knowledge of the source**

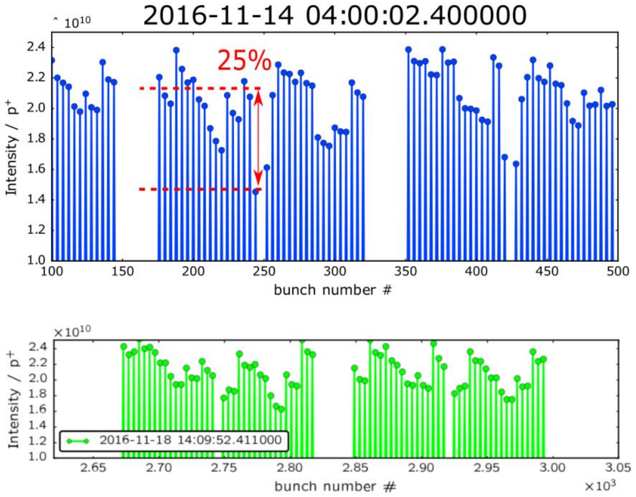


Figure 2: Intensity along the batch in the SPS without transverse damper (top) and with transverse damper (bottom).

Emittance variation of 20% along the batch in LHC

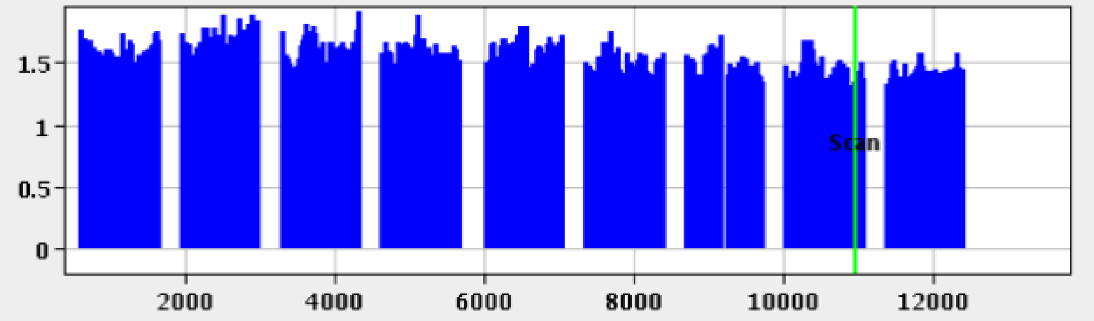


Figure 4: Vertical normalised emittance for several injections of bunch trains with 800 ns batch spacing.

Summary for errors from transfer systems II

- Compressable error sources (kicker with feedback systems) are not the big contributors
- Contribution from optics is important – and barely compressible when manpower, budget and schedule are of consideration…
- Assuming SPL as injector and 0.3 um at PS extraction (see Elena Chapochnikova's presentation)
- 2 or 3 additional transfers – scSPS or LHC as injector
  - Transfer including errors from extraction kickers, TL hardware, injection kickers
- **With aggressive improvements in the CERN injector chain, one can probably reach 1-2% emittance growth per transfer**

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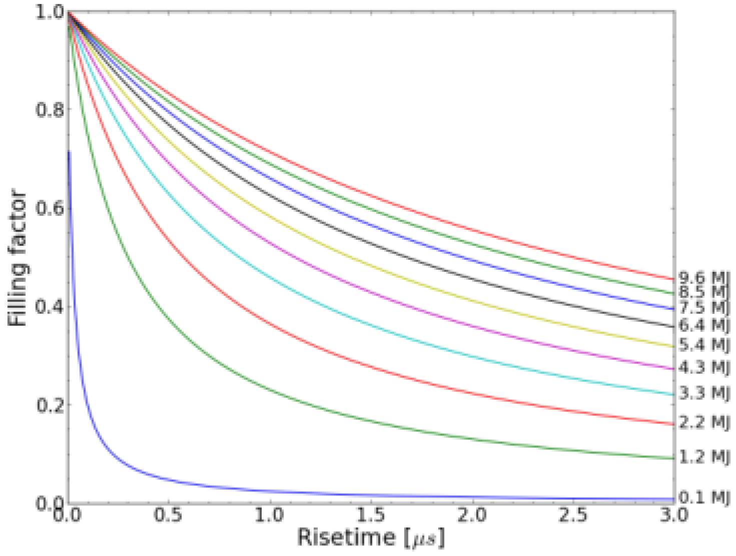
Machine protection during injection

- Injection protection elements for LHC will have to be upgraded for Hilumi era
  - Damage of collimators
  - Attenuation of beam
- Extensive studies for transfer line collimators and injection dump – profit for FCC
- Limit of around 5 MJ – depends on beam parameters, optics at injection



- Maximum # circulating bunches in FCC defined by synchrotron radiation impact
- Maximum # injected bunches defined by damage/attenuation limits of absorbers
- Definition of injection kicker rise time: 425 ns (see David Woog's talk)

Machine protection during injection

- Damage limit of absorbers well studied
- Attenuation limit requires max allowed energy deposition on superconducting strands, worst case beam parameters
- Tracking studies to quantify shower impact will define
  - Conceptual design - phase space coverage by how many collimators in transfer line
  - Collimator settings – close collaboration with collimation team to preserve collimator hierarchy
- Particular importance of these studies due to unfortunate design of injecting into the experiment in FCC

Machine protection at extraction – dump kickers

- Extraction concept driven by machine protection
  - 8 GJ - correct functioning of beam dumping system is not a performance feature but imperative
  - See F. Burkart's presentation

- Dump kickers
  - Reduction of kick strength to lower single switch voltage and reduce probability of self-trigger
  - Fast rise time for bunch separation on extraction absorbers – absorber survival
  - Investigation of switch architectures to avoid self-trigger (see P. van Trappen's poster)
    - Detecting self trigger and short-circuiting charge to ground – crowbar
    - Series connection of two switches to inhibit current over magnet in case of single self-trigger

Machine protection at extraction – dilution system

- Dilution system vital if solid graphite dump block considered (see Anton Lechner’s talk)
- Alternative of water beam dump without dilution being investigated (see N. Tahir’s talk)

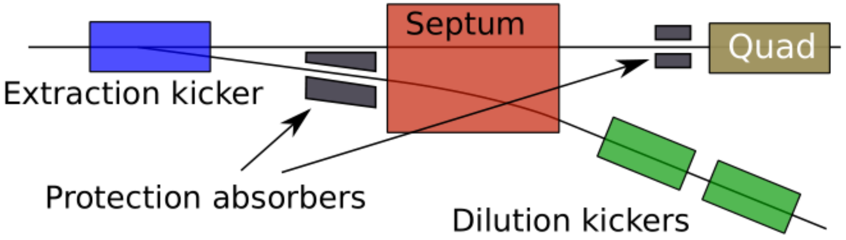
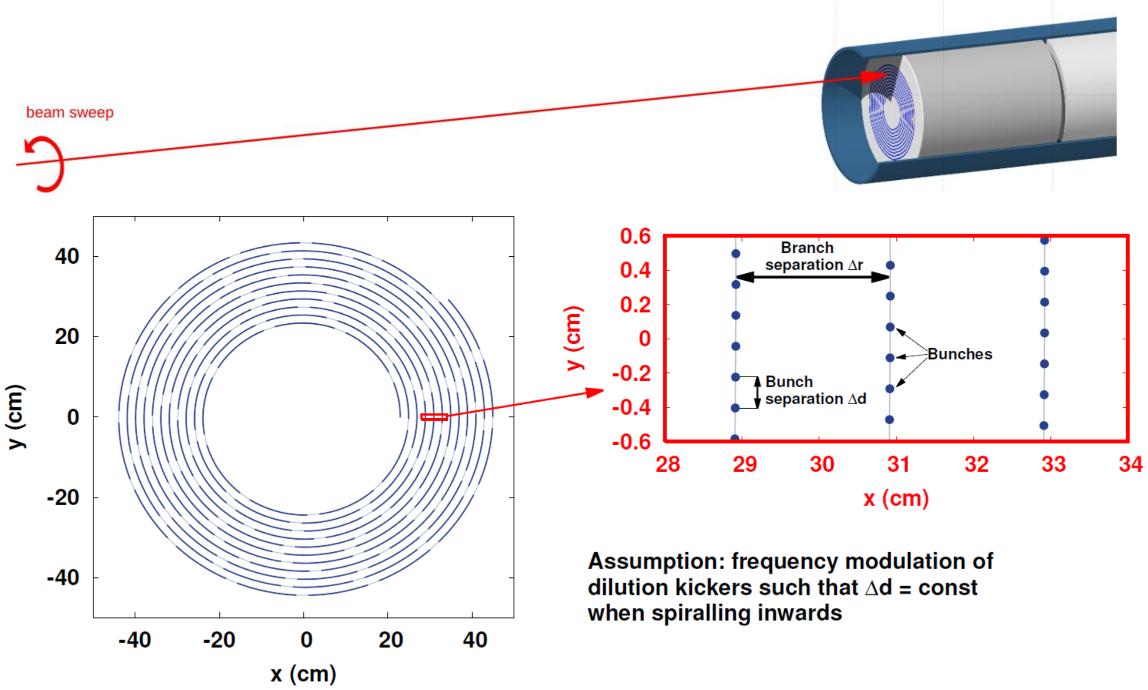


FIG. 1: Extraction layout scheme



Assumption: frequency modulation of dilution kickers such that Δd = const when spiralling inwards

F. Burkart, Anton Lechner

Dilution hardware

Dani Barna

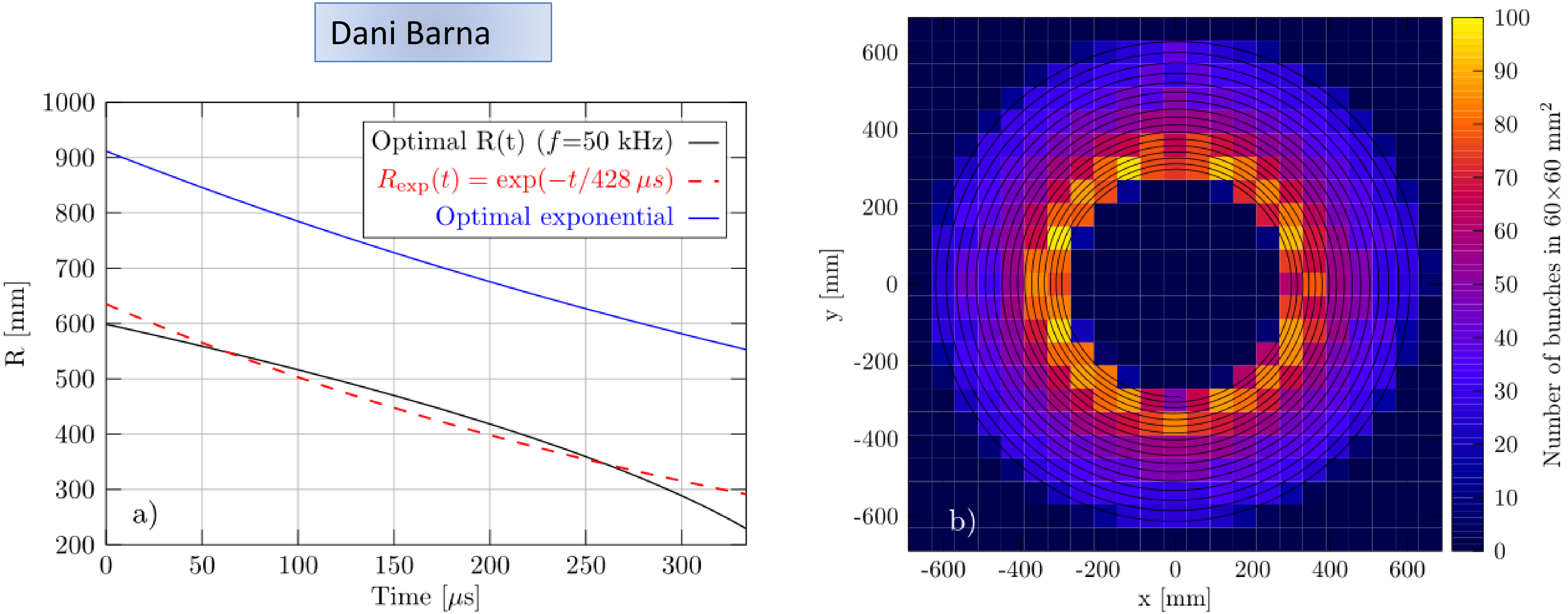


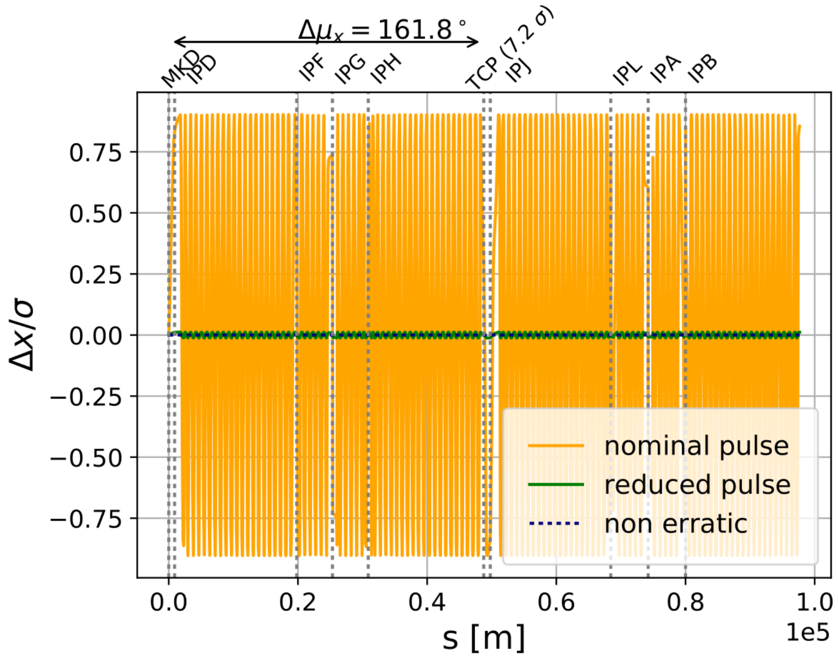
FIG. 3: a) The optimal pattern $R_i(t)$ eq. (3) (solid black line), a fitted exponential (dashed red line), and the optimal exponential (solid blue line) waveforms. b) The dump pattern with the fitted exponential time-dependence of the kickers.

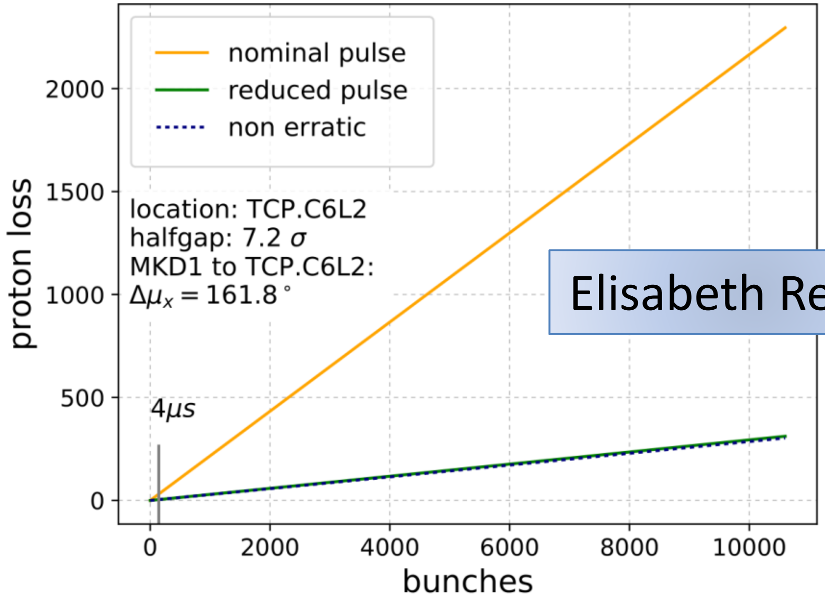
Dilution hardware

- Damped LC circuit with 50 kHz frequency (see D. Barna, T. Kramer, FCC week 2016)
- Spiral from outside → max deflection reached after ¼ f = 5 us
- Dump kicker has rise time of 1 us – immediate retrigger causes beam not sufficiently diluted
- Different rise times can be taken into account for programmed dump – not for async.
- → Adapt retriggering time to dilution kicker rise time in case of asynchronous beam dump
    - Single self-trigger with LHC retriggering time leads to ~30 bunches oscillating before clean extraction
    - Adapting the retrigger time causes ~145 bunches oscillating

Asynchronous dump

- Oscillation of a self-trigger 0.9 sig
  - Iterate on phase advance between extraction kickers and primary collimators
- With series-switch architecture down to 0.01 sig
- Retrigger asap ~several 100 ns
  - Dump block needs to be exchanged
  - 30 bunches oscillating
  - 6 bunches swept
- Retrigger after ~4 us
  - → dump block OK
  - 145 bunches oscillating
  - 6 bunches swept
- Re-trigger when next abort gap in sync





Elisabeth Renner

Beam impact on extraction equipment

- Self-trigger of kicker switches due to beam impact could trigger several modules at once
  - switches in gallery, dedicated shielding

- Beam rigidity requires most likely SC septum technology (see A. Sanz Ull's talk)
  - Energy deposition studies on septum current leads
  - Design of passive septum protection
  - Combination of nc and sc septa technologies

Conclusions

- Emittance growth in the CERN injector chain
  - With a new dedicated low emittance injector chain, one can probably reduce the theoretical emittance growth from 2-5% to 1-2% emittance growth per transfer
  - Main limitation is the measurement and therefore operational control of these values
- Machine protection during beam transfer
  - Defines rise time and repetition rate of injection kicker
  - Careful study of injection protection since experiments will catch the shower of injection failures
  - Baseline design of extraction protection including dump absorber OK for programmed dump
  - Several scenarios studied for asynchronous dump – need to go into details of trigger delays between dump and dilution kickers
  - Switch architecture studies to limit impact of beam on machine in case of self-trigger
  - Alternative solutions (water beam dump, very low density graphite, powder) under consideration