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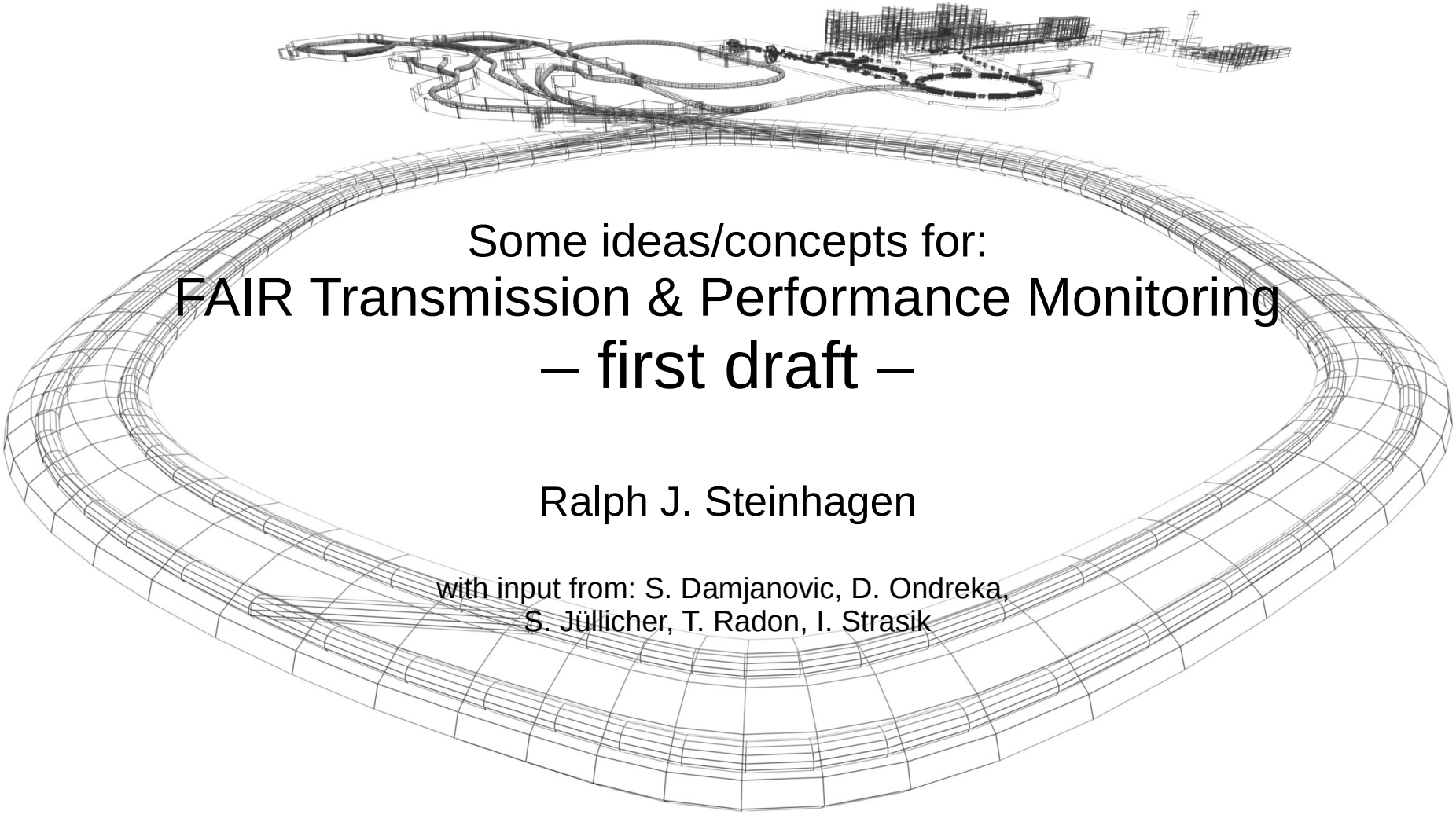


Some ideas/concepts for:
FAIR Transmission & Performance Monitoring
– first draft –

Ralph J. Steinhagen

with input from: S. Damjanovic, D. Ondreka,
S. Jüllicher, T. Radon, I. Strasik

Outline

- Beam Transmission Monitoring – Definition & Time-Scales

- Required tolerances
  – or – “How much losses are acceptable”
  - Optimisation of particles on targets
    - *“Every ion lost in the accelerator is an ion lost for physics”*
    - One* of the key tuning parameters of the accelerator chain
  - ALARA – minimisation of activation and radiation permit compliance
    - How much is 'reasonable'?
  - Minimising risk of combined machine protection failures
    - Less stress on MP system ↔ more clear cut between normal and anomalous operation

→ C. Omet's upcoming FC²WG MP talk

- What could be achieved
  – or – “why FCTs & DCCTs alone may not be sufficient”
  - proposal to include BLMs for fast in-cycle losses + radiation monitors for slow/absolute loss measurements

Beam Transmission Monitoring (BTM) – Problem Definition –

Ion-Source

$$I_{source}(t) = \frac{dN_{source}(t)}{dt}$$

Fast current transfomer (FCT)
DC current transformer (DCCT)

transmission

un-controlled losses

controlled losses

Experiment

primary (secondary)
ions-on-target/s

$$I_{target}(t) = \frac{dN_{target}(t)}{dt}$$

DCCT
/FCT
counter

$$\frac{dN_{collimator}(t)}{dt}$$

dynamic vacuum, ε-blow-up/tails, slow-extraction, ...
→
cryo- & beam-halo collimators, rad-hard magnets, extra shielding, ...

less-avoidable losses
(may need to accept a given amount)

$$\frac{dN_{loss}(t)}{dt}$$

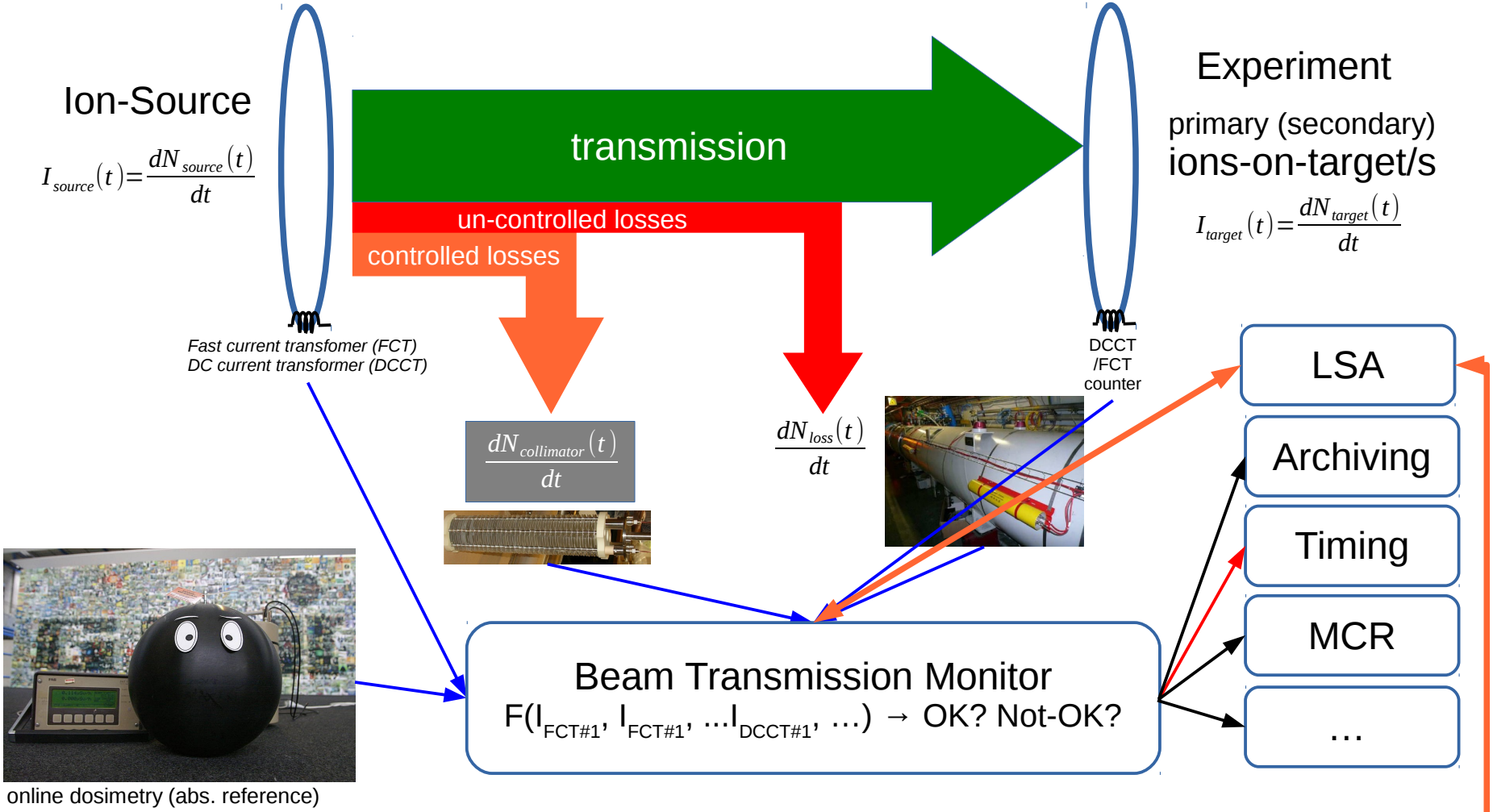
beam instabilities, aperture constraints, slow beam parameter drifts
→
activation & machine protection

avoidable losses
(ALARA: should minimise before MP & Activation limits kick in)

online dosimetry (abs. reference)

§§ Radiation Permit – limits on total dose per year (facility & external)

Beam Transmission Monitoring (BTM) – Problem Definition –



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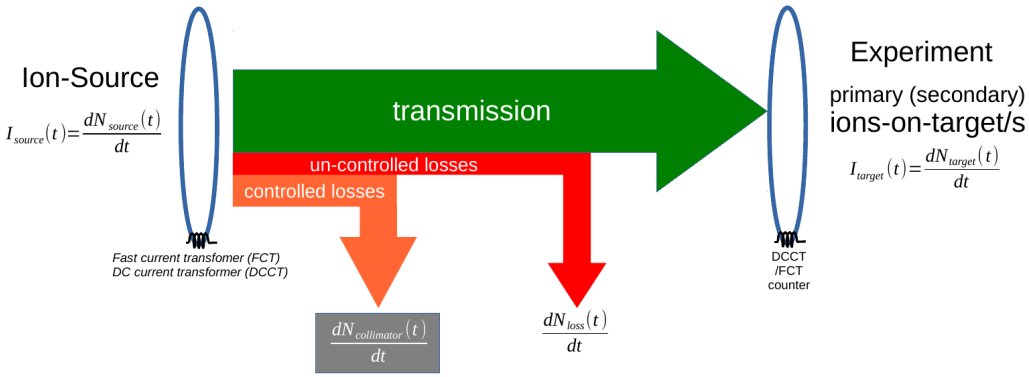
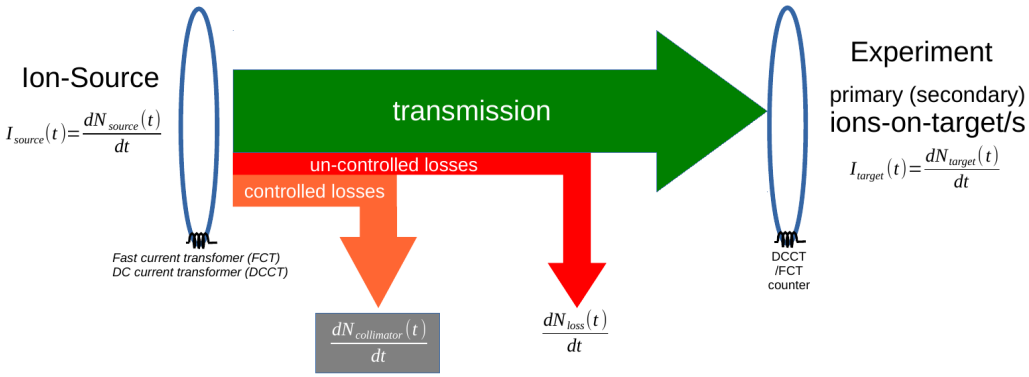
Beam Transmission Monitoring (BTM) – Problem Definition –



- Main usage: reject (dump) beam already at low-energies & low-intensities in pre-injectors before it worsens machine operation/performance upstream
  1. online: one of the performance indicators used to tune the accelerator
  2. prevent recurring (avoidable) losses leading to unnecessary activation
  3. offline: documentation of machine performance (prediction of future runs/performance)
  4. exp. data analysis (e.g. primary → secondary RIB conversion)
  5. large losses indicative that other beam parameters may also be out of tolerance
     - e.g long. or transverse emittance blow (halo formation)
- To note: the BTM is a priori not part of the (fast) MP system, however, still needs to run reliably & continuously

Beam Transmission Monitoring (BTM) – Problem Definition –



- Possible BTM actions:

A) Inhibit next injection for a given beam production chain (via timing system)

- Ideally: should be compatible with SIS18's 3 Hz 'booster mode' ↔ '<100 ms' total response time of BTM
- KISS – Keep it Simple and Safe (with an eye on operational availability):
  - experience with by times flaky injector/source performance
    → may need to consider/keep the option of 'once doesn't count' (aka. “einmal ist keinmal”) policy for SIS18 injection (only)
  - target of '100 ms' is not a hard real-time requirement: OK if achieved with 98-99% probability & hard limit of '1 s'
    - keeps option of SW implementation open (RT Linux)

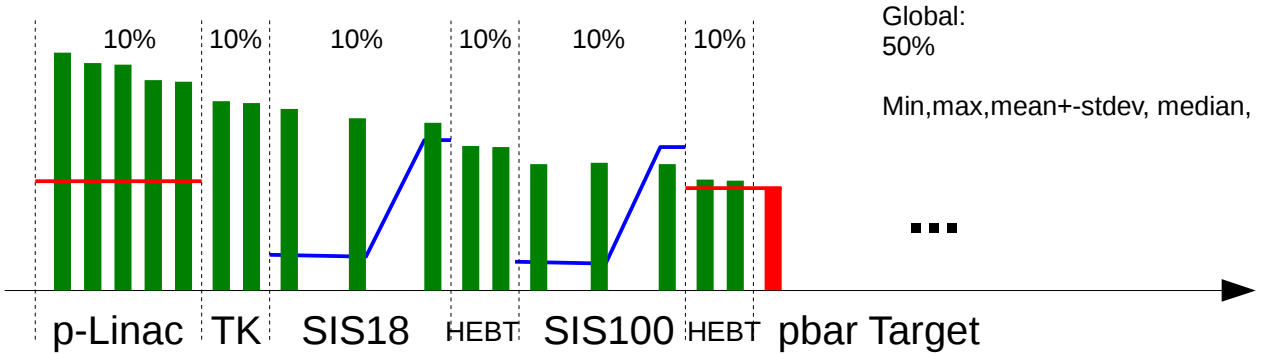
B) Inhibit extraction (via timing system):

- option: repeat cycle
- faster responses required: ~ < 100 ms

C) 'Fast Beam Abort'

- probably too stringent as default ↔ (too?) tight requirement on response time and current transformer sensitivity
  - N.B. < ~1 ‰, possibly too tight based on LHC experience (easier case) & assumption: beam loss continuous after initial detection

Beam Transmission Monitoring (BTM) Examples - Rules



- Four transmission loss scenarios + associated rules

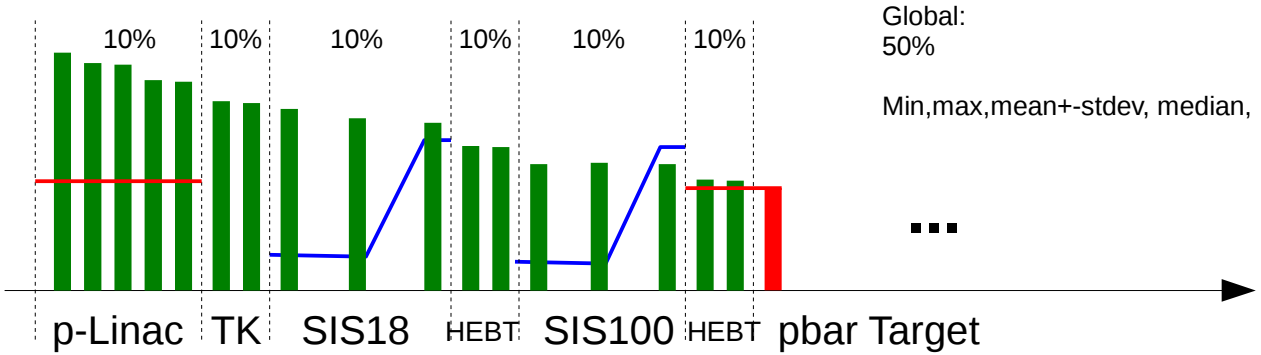
A) Multi-turn injection/accumulation
- Essentially: UNILAC → SIS18 (fast), SIS18 → SIS100 (slower)
- Monitoring goal: '$\int I_{FCT\text{-}TK/HEST}(t)\,dt$' vs. '$I_{fct/dcct}$@ start ramp'
  - easier if using $\langle I_{FCT\text{-}TK}(t)\rangle$ but more precise using '$I_{FCT\text{-}TK}(t)$' and gating on selected injection time window

B) Losses due to RF capture/ramp/instabilities
- transition crossing/instabilities/space-charge
- Monitoring goal: '$I_{fct/dcct}$@ start ramp' vs. '$I_{fct/dcct}$@ end ramp/before (fast) extraction'
  - probably non-issue and mainly dominated by instrument systematics

C) Fast extraction
- Monitoring goal: '$I_{fct/dcct}$@ end ramp' vs. 'I_{fct} at first location in HEST/HEBT'
  - probably non-issue and mainly dominated by instrument systematics

D) Slow extraction
- Monitoring goal: '$I_{fct/dcct}$@ end ramp' vs. '$\int I_{fct??}\,dt$ in HEST/HEBT'
  - Monitoring tool/instrument not clear (↔ counter calibration)

Beam Transmission Monitoring (BTM) Functional Requirements



- additional requirements:
  - Global + local trending (inj, ramp, extr): <min, max, mean ± stdev, median, ...>
    - stimulate some “healthy” BTM optimisation competition: add. traces for 'best cycle' for given beam configuration and 'worst cycle' (e.g. over last hour/day, excluding injector failures)
  - Post-processed & predictive thresholds:
    - normalised per process ('A)', 'B)', 'C)', resp. 'D)')
    - normalised per machine ($BTM_{'A)'}$*$BTM_{'B)'}$*$BTM_{'C)', resp. 'D)'}$)
    - absolute w.r.t. total particle lost (↔ activation, radiation permit)
      - predictive losses during intensity ramp-up (e.g. prevent 'low-transmission, low-intensity' → 'low-transmission, high-intensity' transition)
  - Archiving (in addition to direct logging from FCT/DCCT devices)
    - re-use common archiving system (under preparation)
    - Data retention for at least 10 years ↔ needed also from experiment/legal point of view
    - group data into one system that re-publishes the data to the timing system (interlock), MCR, archiving system, …
  - Threshold, settings, reconfigurability via LSA, …, details:
    - S. Jülicher, G. Fröhlich, “Detailed Specification of [..] 'Beam Transmission Monitor System' ” 2012-08-29, F-DS-C-12e, V3.1

Beam Transmission Monitoring (BTM)
S. Jülicher et al: Controls Specification

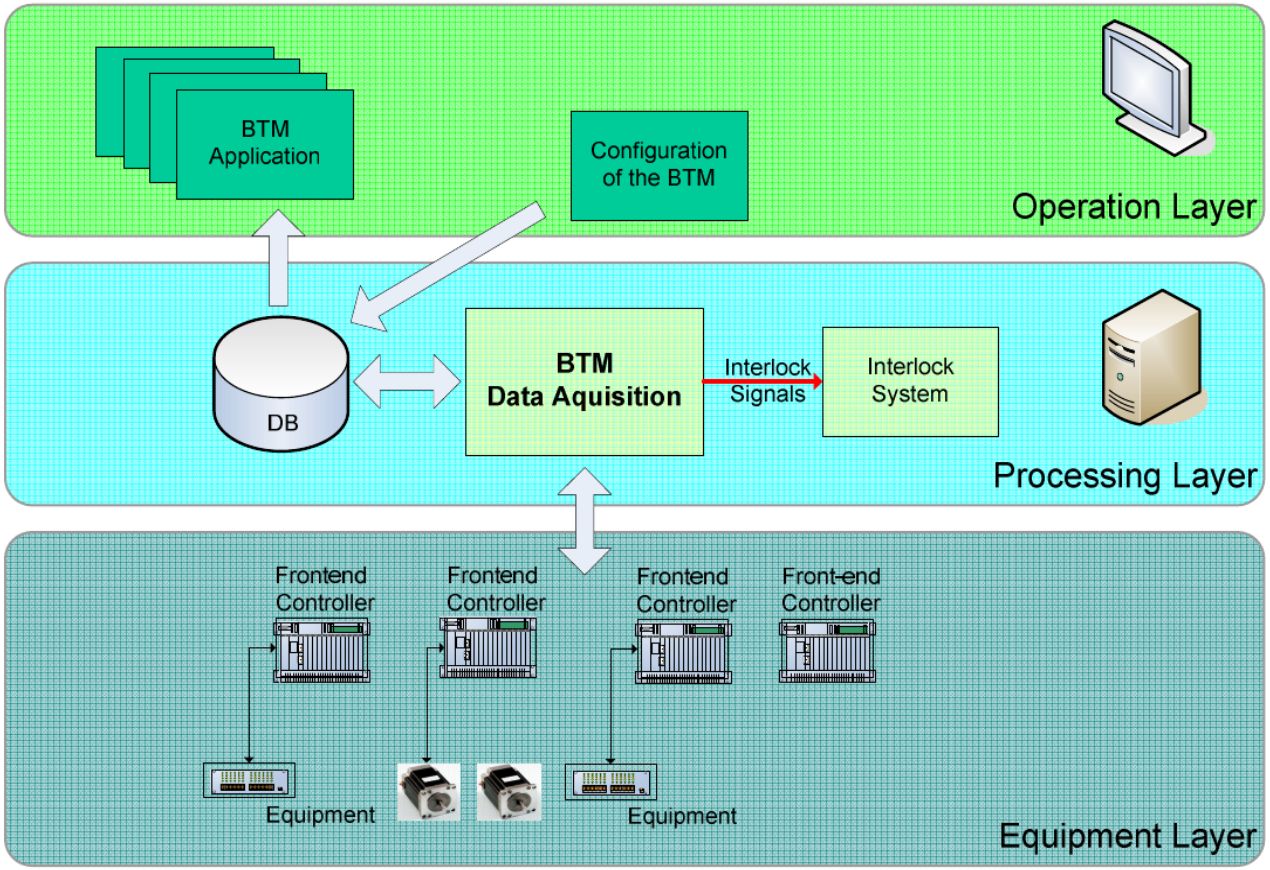


Figure 1: System Overview

S. Jülicher, G. Fröhlich, “Detailed Specification of [..] 'Beam Transmission Monitor System' ” 2012-08-29, F-DS-C-12e, V3.1

“… how much losses are acceptable?”

- In a perfect world: none
- In the real world: cannot avoid certain beam losses
  - operating close to the space-charge limit
  - Touschek scattering
  - finite machine acceptance/aperture
  - finite vacuum/rest-gas interactions
  - optics errors: beta-beat, dynamic aperture, ...
  - …

- Why do we care about this now:
  - setting realistic goals, expectations and limits
    - gain experience for high-intensity operation with low-intensity beam
  - defines required accuracy, resolution and robustness of beam instrumentation
    - FCTs, DCCTs, BLMs, radiation monitors, ...
  - defines time-scales we have to act if transmission gets worse

Ivan Strasik @ HIC4FAIR'2015: Tolerable Beam Losses of the Proton Beam

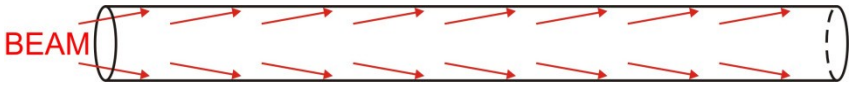
"uncontrolled beam losses of 1 W/m should be a reasonable limit for hands-on maintenance"

[Ref] N.V. Mokhov and W. Chou, The 7th ICFA Mini-workshop on High Intensity High Brightness Hadron Beams, USA, 1999.

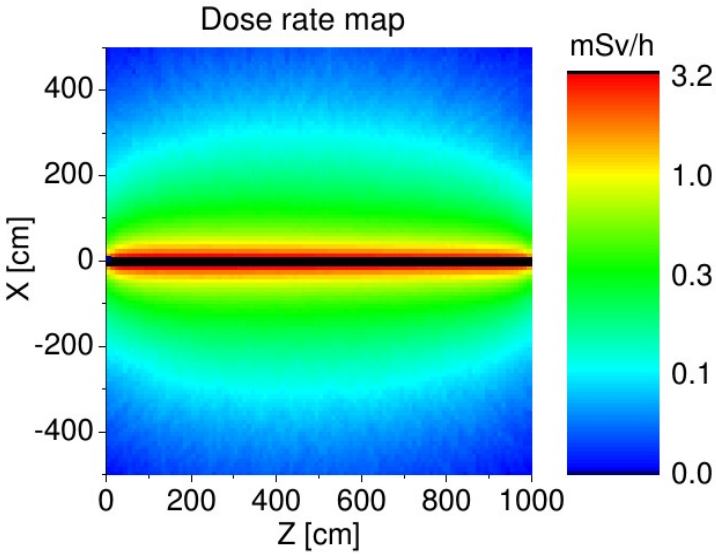
1 W/m → 6.2×10^9 protons/(m·s) of energy 1 GeV (uniformly distributed)

Simulation of the steel beam pipe residual activity induced by beam losses of 1 W/m

- Simulation tool: FLUKA
- Irradiation time: 100 days
- Cooling time: 4 hours



Effective dose rate at 30 cm is about 1 mSv/h



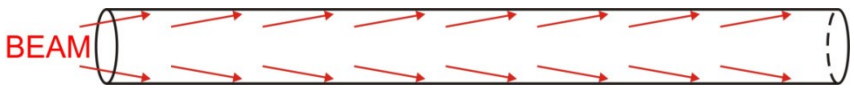
- possibly may need to accept 1 mSv/h due to unavoidable losses at e.g. septa, collimators, ...
- However, should
  - not take this as a 'carte blanche' that high losses are OK ↔ ALARA principle (**A**s **L**ow **A**s **R**easonable **A**chievable)
  - aim at much lower global target < 0.1 mSv/h resp. < 0.1 W/m

Ivan Strasik @ HIC4FAIR'2015: Beam Loss Criteria for Heavy Ions

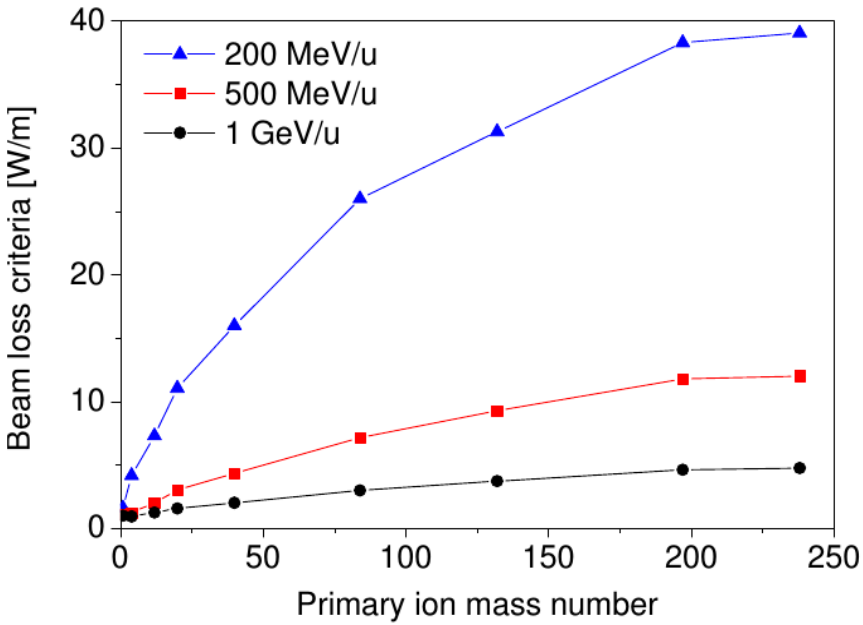
Simulation performed by using FLUKA

Beam loss criteria: A_p/A_i

A_p – activity induced by 1 W/m of protons
A_i – activity induced by 1 W/m of ions



Primary ions (E = 1 GeV/u)	Equivalent to 1 W/m [ions/(m·s)]
^{1}H	6.2×10^{9}
^{4}He	1.6×10^{9}
^{12}C	5.2×10^{8}
^{20}Ne	3.1×10^{8}
^{40}Ar	1.6×10^{8}
^{84}Kr	7.4×10^{7}
^{132}Xe	4.7×10^{7}
^{197}Au	3.2×10^{7}
^{238}U	2.6×10^{7}

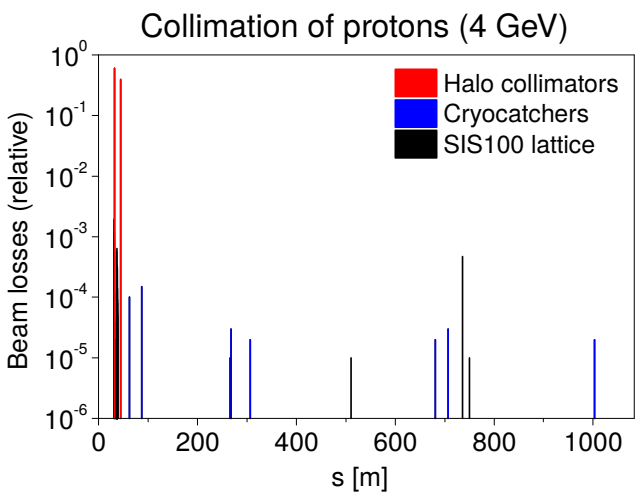


Ivan Strasik @ HIC4FAIR'2015: Tolerable Beam Losses in SIS100

- SIS100 beam parameters and equivalent to 1 W/m (number of particles)

Beam	Injection energy	Extraction energy	1 W/m equivalent (injection)	1 W/m equivalent (extraction)	Beam intensity
Protons	4 GeV	29 GeV	1.5×10^{9}	2.1×10^{8}	2×10^{13}
$^{40}Ar^{18+}$ ions	1.6 GeV/u	12 GeV/u	1×10^{8}	1.3×10^{7}	1×10^{11}
$^{238}U^{92+}$ ions	1.3 GeV/u	10 GeV/u	2×10^{7}	2.5×10^{6}	1.5×10^{10}

- From the beam loss maps tolerable beam losses* (% of the beam) can be identified.



*assumes 10s proton cycle & activation limit only

Beam	Loss criteria (injection)	Loss criteria (extraction)	Tolerable losses (injection)	Tolerable losses (extraction) *
Protons	1 W/m	1 W/m	10 %	5 %
$^{40}Ar^{18+}$ ions	2 W/m	1 W/m	30 %	6 %
$^{238}U^{92+}$ ions	4 W/m	2 W/m	20 %	10 %

Caution: '1 W/m' is only indicative!
existing operation, shielding and radiation permit limits proton losses to <3% @ 29 GeV and nominal intensities!
→ should aim to be significantly below that limit (ALARA)

*for comparison: CERN-PS: 4-8% losses achieved (data courtesy R. Steerenberg, 19th March 2012)
Caution: for protons this implies near-perfect two-stage collimation system

Beam Transmission & ALARA

"As-Low-As-Reasonably-Achievable" Losses – a buzz-word?

- 'golden standard': should exhaust reasonable common operation practices of controlling beam parameter known to induce particle loss ("KISS in mind" – 'actual risk mitigation' vs. 'operational availability'):

Low-intensity beams:

A. Extraction/Injection Matching

- first-turn trajectory steering (BPMs),
- energy matching (BPMs & Schottky),
- coarse collimation (IPMs) (removing excessive tails at low energy before propagating them to higher-energy machines)
- bunch-length to bucket-space matching (FCTs)

B. Closed-Orbit Cycle-to-Cycle Feedback (BPMs)

- aperture optimisation (coarse, circulating beam)

C. Tune & Chromaticity Correction (BPMS, BBQ)

- optimises space charge, ΔQ spread, dyn. aperture, beam stability

D. Emittance (blow-up) Monitoring (IPMs, FCTs)

- frequent cause for loss changes

High-intensity beams:

All on the left, with tighter limits, plus

E. Optics Correction

- Inj./extr. mismatch (Δβ, Δμ) correction (ε-blow-up optimisation)
- ring beta-beat correction (aperture opt. & linearises/restores symmetry of the optics → suppresses driving terms)
- detailed aperture optimisation (tune β bottlenecks)

F. Detailed Collimation (e.g. 2-stage for protons)

- see Ivan Strasik's talk @ HIC4FAIR'2015

G. Quantitative slow-extraction optimisation

- eval. 'Hardt condition', step-width measurement, …

H. ...

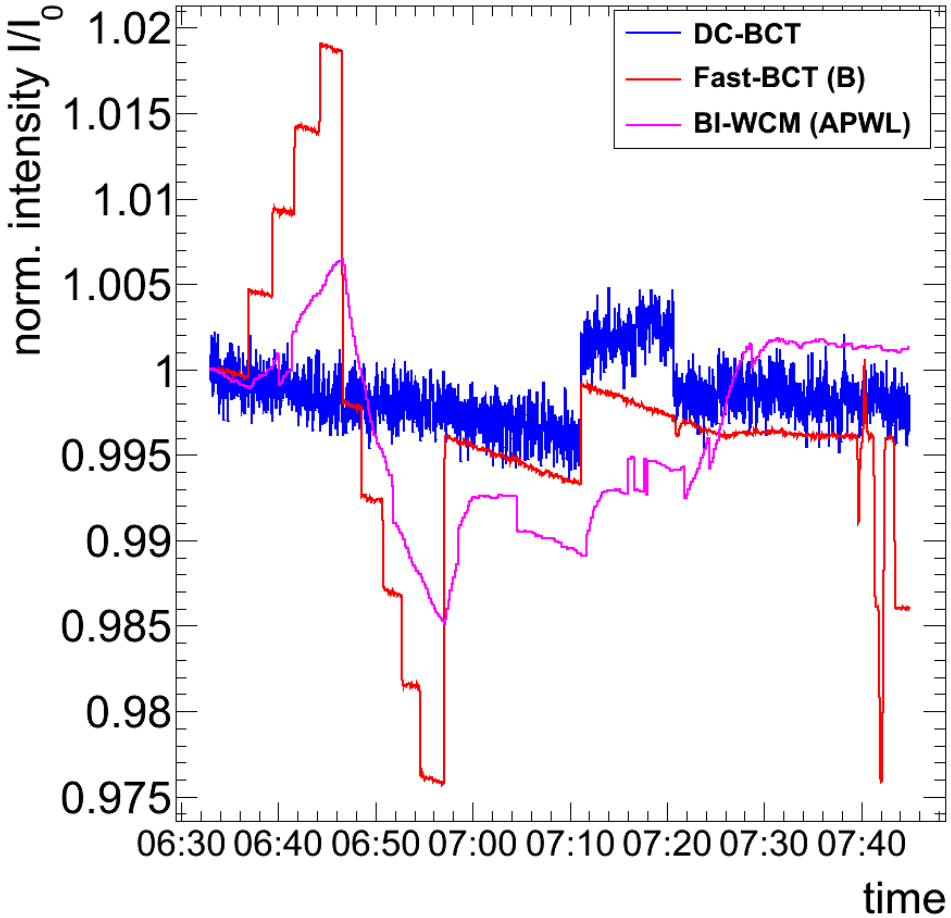
for discussion: 'acceptable losses' := losses remaining after having performed above steps

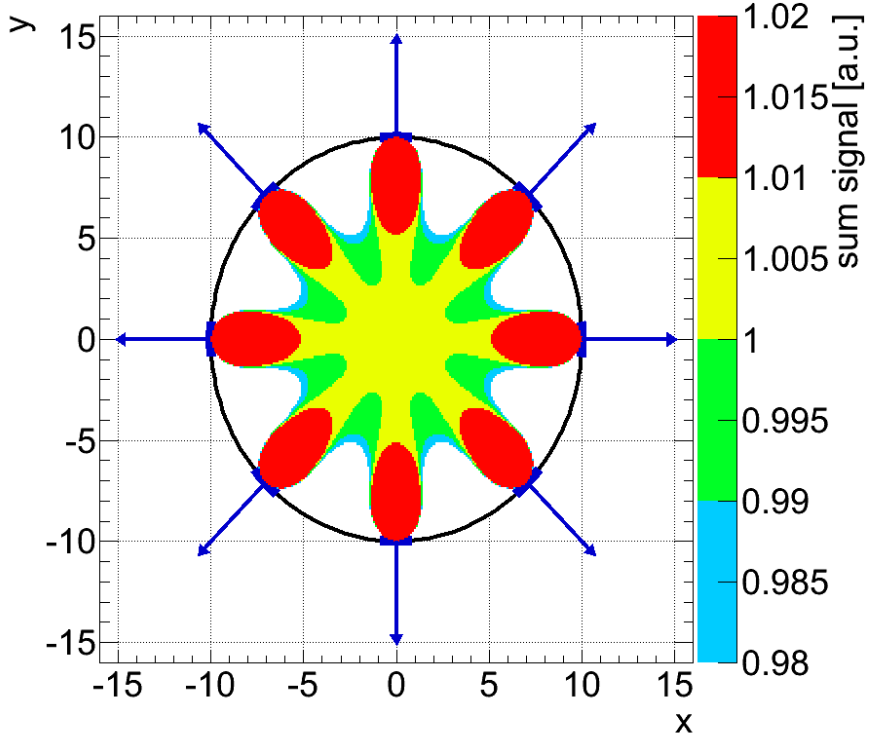
BTM using only FCTs & DCCTs

- May not achieve required BTM using FCTs & DCCTs alone, or would need to impose unrealistic BI design parameters
- Underlying measurement systematics
  - Coarse spacial resolution: locate losses per accelerator/transfer-line scale but only limited diagnostics where and how the particles are being lost
  - N.B. more challenging to measure pulsed RF compared to DC currents
  - permille-level resolutions can be achieved for stable beam parameters but absolute accuracy is typically limited to 1-3%, some dependencies:
    - electronic/reference-source temperature
    - EM-Interferences, cable-reflections, ...
    - RF bunch phase (FCTs, needed integration)
    - finite magnetic quantisation of ferrite core (DCCTs, weiss-domains)
    - Bunch-length (notably BMCS @ SIS100), beam position, ...
  - May improve upon some of these limitation but some are may be unreasonable below the 1% level (cost vs. reliability vs. performance → R&D, some examples)
- Real-World operational problem:
  - FCT/DCCT transmission measurement accuracy limited to about 2-3%
  - ALARA (activation) transmission control aimed ideally on the sub-% level

Position and Time-of-Flight Dependencies

- "Re-discovered" expected position dependence while doing a ±4 mm orbit bump around LHC-Pt4 (RF, BI insertion):





- Usually suppressed by ±200 um orbit stability during regular operation

Beam Transmission Monitoring (BTM) – Problem Definition –

$\frac{dN_{collimator}(t)}{dt}$

dynamic vacuum, ε-blow-up/tails, slow-extraction, ...
→
cryo- & beam-halo collimators, rad-hard magnets, extra shielding, ...

less-avoidable losses
(may need to accept a given amount)

$\frac{dN_{loss}(t)}{dt}$

beam instabilities, aperture constraints, slow beam drifts across e-septa
→
activation & machine protection

avoidable losses
(ALARA: should minimise before MP & Activation limits kick in)

online dosimetry (abs. reference)

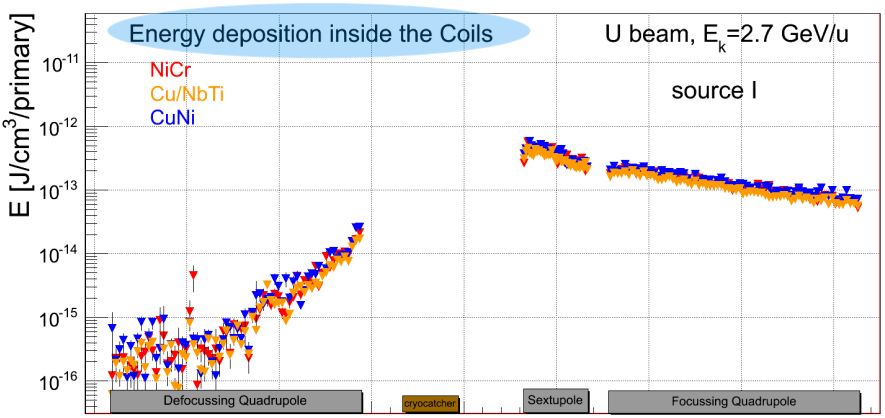
§§ Radiation Permit – limits on total dose per year (facility & external)

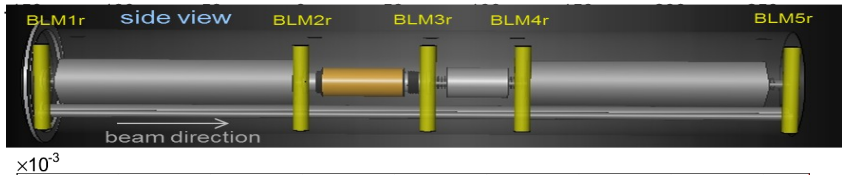
Beam Transmission Monitoring (BTM) – BLMs & RadMons Extension Proposal

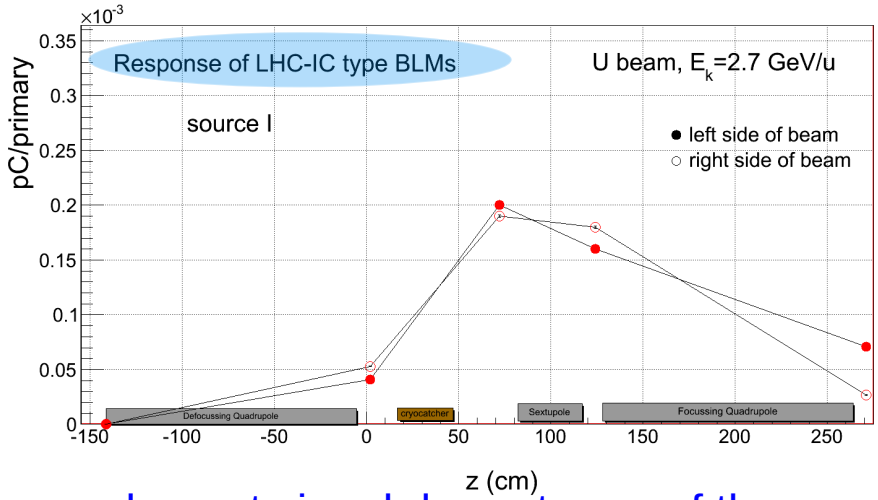
- Include BLMs and RadMons as complementary input[1] to BTM system; operational procedure/scenarios:
- Low-intensity beams:
  - cycle-to-cycle time scale: mainly rely on FCTs & DCCTs and tune beam parameter to transmissions on 2-3%-level around established 'acceptable loss' scenario
- High-intensity beams (steps maskable by SBF):
  - use FCTs & DCCTs as for low-intensity beams
  - In addition: minimise global/localised losses using integrated BLM signals
    - N.B. qualitative not quantitative process, i.e. no hard quantitative primary-loss-to-BLM transfer function (holes in coverage, physics uncertainties, …)
    - However, some experience with BLM vs. FCT calibration at FNAL
  - On larger time-scale: cross-correlate FCT/DCCTs & BLM-based loss optimisation with absolute 'd/dt(RadMons)' reference
    (diagnostics/calibration to be worked out – example FNAL: $\int \Sigma(\mathrm{BLM})\, dt := \int \Sigma(\mathrm{RadMons})\, dt$)

[1]BLMs & RadMons also helps localising transmission losses and assessment w.r.t. uncontrolled and losses

S. Damjanovic: Energy Deposition in Coils vs. IC-type BLM Signals







If quenching would occur, it would first be the two innermost coils of the Sextupole/ Steerer:

maximum energy deposition

E_d^{max}=4.5×10^{-13}J/cm^3/(lost primary)

max E_{dep} [J/cm^3/primary]	BLM signal [pC/primary]				
	BLM1	BLM2	BLM3	BLM4	BLM5
4.5×10^{13}	2×10^6	4×10^5	2×10^4	1.6×10^4	7×10^5

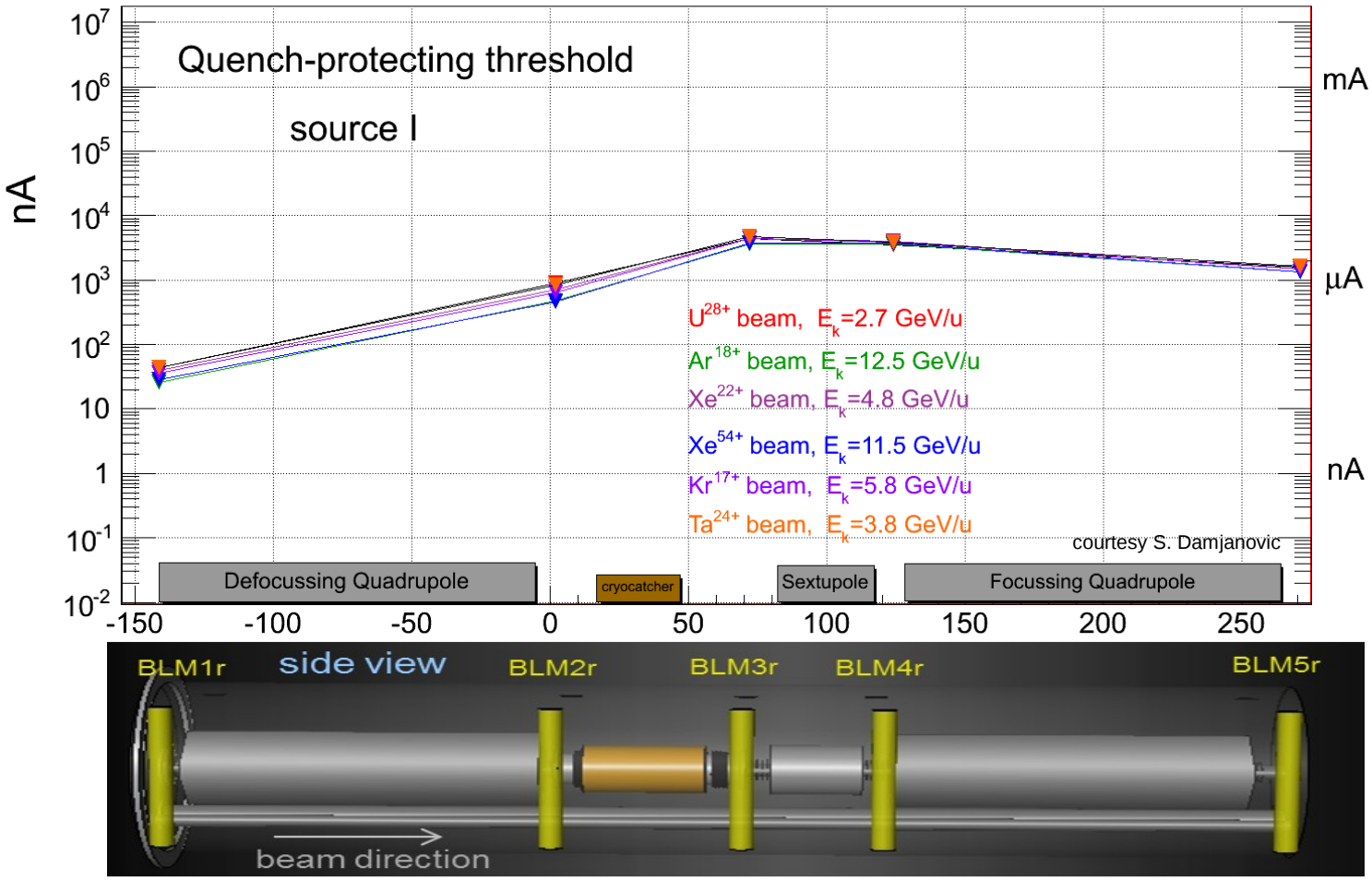
max P_{dep} [W/cm^3]	BLM signal [pA]				
	BLM1	BLM2	BLM3	BLM4	BLM5
1×10^{-3}	3900	8×10^4	3.7×10^5	3×10^5	1.3×10^5

(N.B. LHC IC-BLMs lower sensitivity threshold threshold: ~10 pA)

I_{det} ~ 5·10^4 ions/s

largest signal downstream of the cryocatcher module, at the position of BLM3

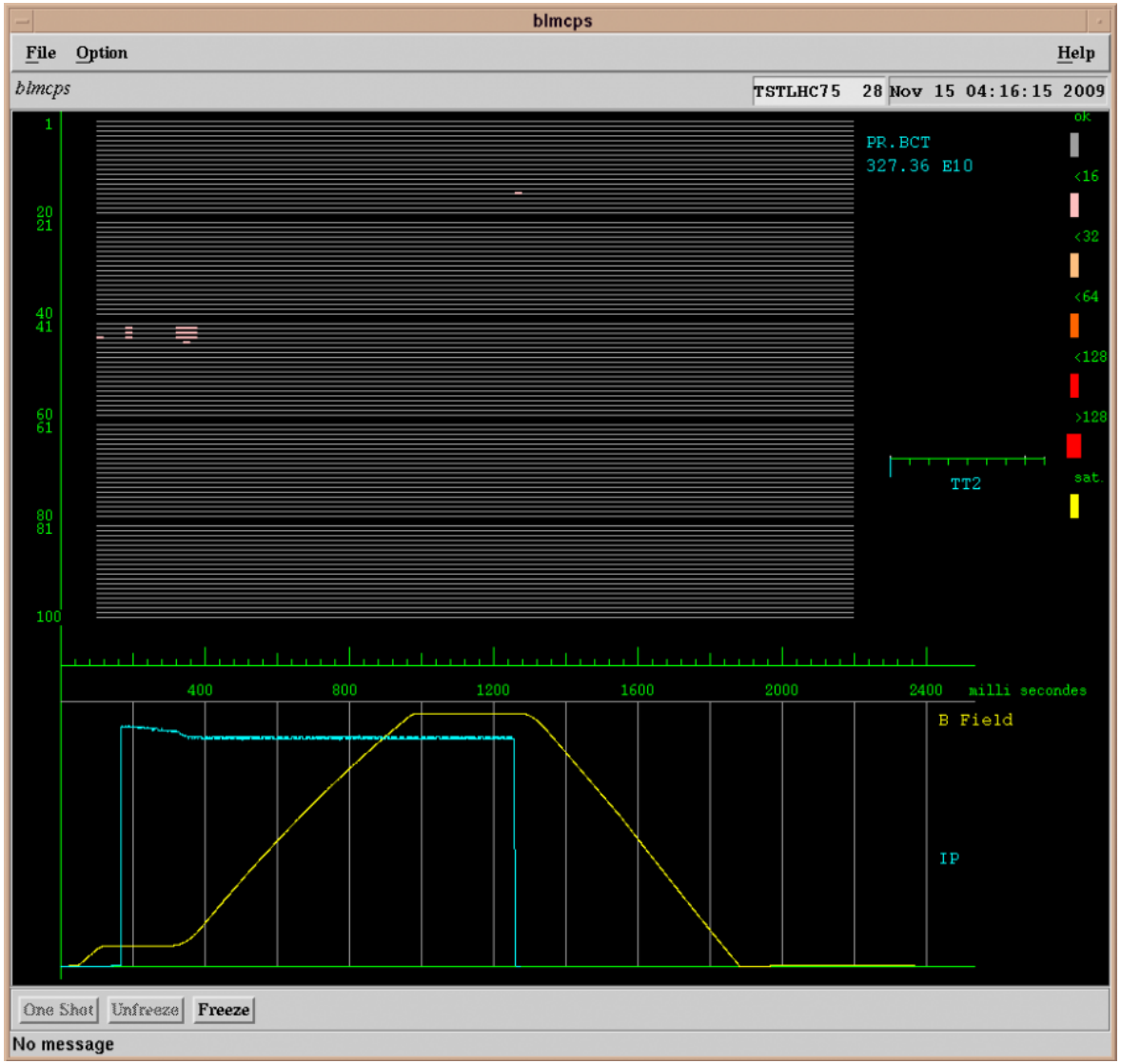
S. Damjanovic: Quench-prevention threshold for different ion beams and energies



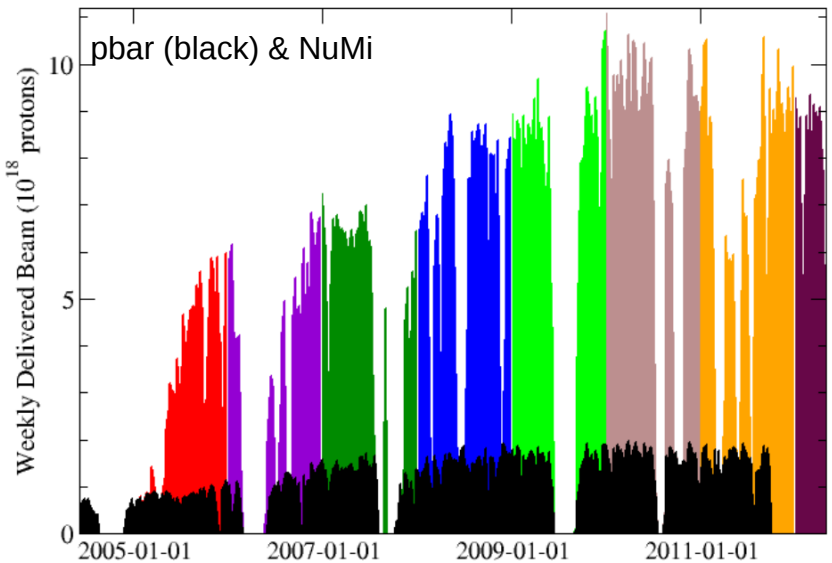
Quench-prevention thresholds the same for all ions/energies considered

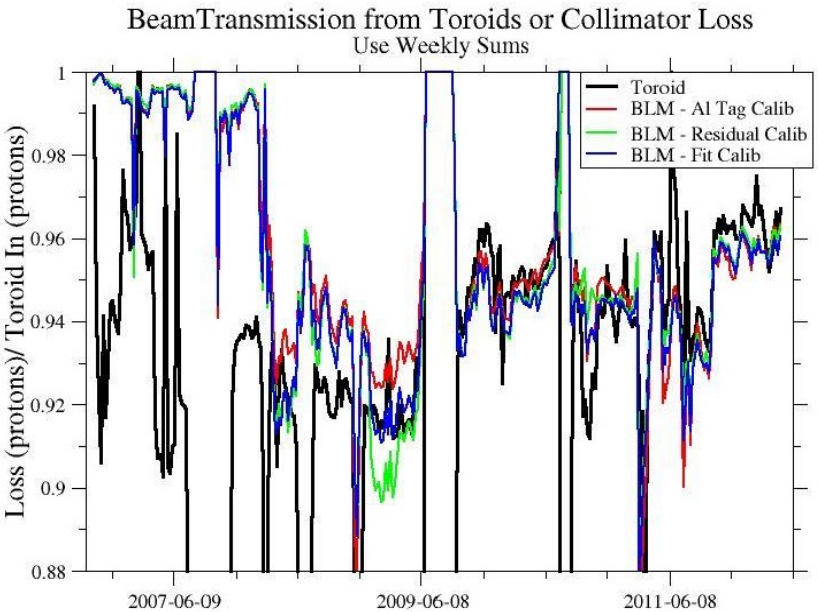
(N.B. LHC IC-BLMs lower sensitivity threshold threshold: ~10 pA)

Possible BLM integration in the MCR: CERN PS – BLM display



Possible BLM integration in the MCR: FNAL example





Courtesy Bruce C. Brown, FNAL

(example FNAL: ∫ Σ(BLM) dt := ∫ Σ(RadMons) dt, details tbc.)

FNAL reference

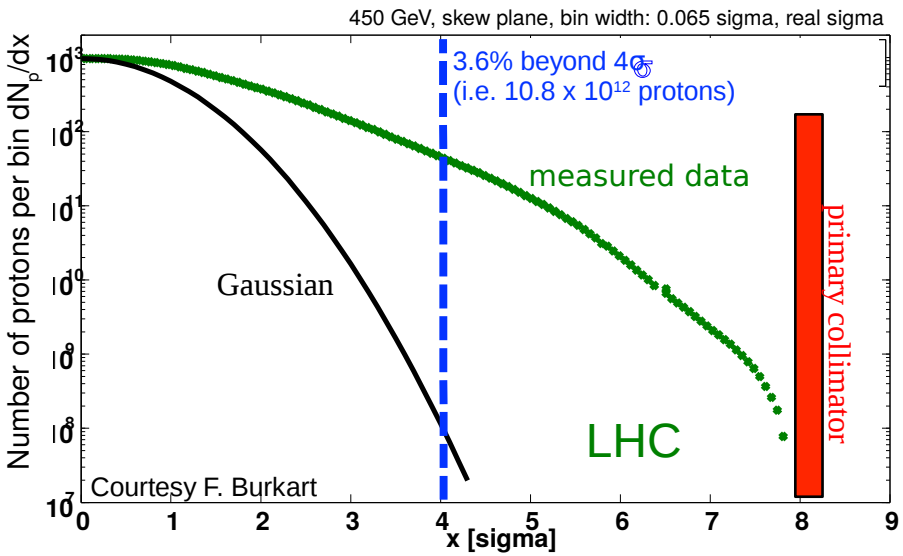
Beam Transmission Monitoring (BTM) Open Technical Questions

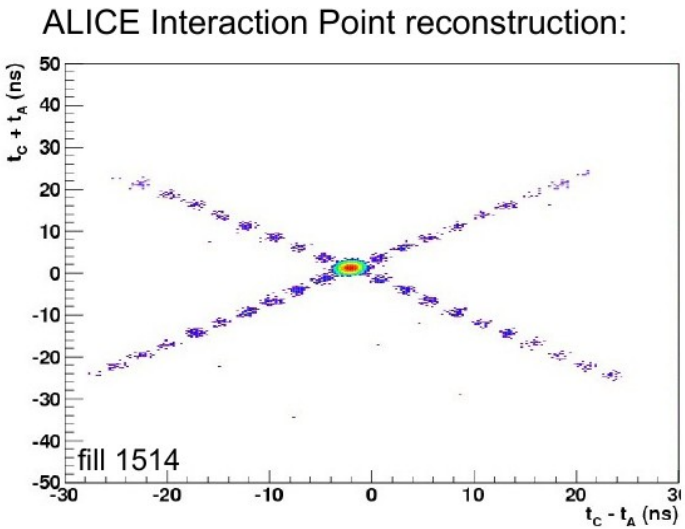
- Signal Sources:
  - Ring-FCTs, Ring-DCCTs + all (??) TK, HEST, HEBT FCTs?
  - Which Counters? Intensity signal from experiments (Calibration?)??
- Beam Current Normalisation (DCCTs)
  - Ideally should provide normalised currents/particle intensities
  - Performed on 'FESA front-end' or already on 'DAQ-HW'?
    - LSA function driven (settings)? (easy Day-I SW solution)
    - Dedicated SDDS? (better for HW solution)
    - Beam-based-f_{rev} generation? (good for commissioning/in case of problems)
- Total 'FCT/DCCT → BTM → Injection Inhibit' Latency
  - Is a soft real-time dead-line < 100 ms (hard limit: < 1 s) achievable by pure SW?
  - CMW subscription? Dedicated SW-Link between FCTs/DCCTs-FE and BTM?
  - Is a HW solution necessary (ala. UNILAC BTM)?
- Beam-Presence-Flag (BPF) & Setup-Beam-Flag (SBF)
  - certain BTM features are similar to BPF & SBF, however, 'SBF' is MP sensitive (dedicated HW solution?)
  - Interface for BPF (FCT derived?) and SBF (DCCT derived?) to Fast-Abort/MP-System?

Beam Transmission Monitoring (BTM) & Emittance Monitoring

... more complex subject but equally important to beam transmission control

- "Good" vs. "Bad" intensity:
  - particles outside the acceptance of up-stream accelerators
    - Mechanical and dynamic aperture!!
    - halo-particle interactions with experiment's target → background
  - prone to be lost due to or causing beam instabilities
    - "dark currents" → RF capture losses
    - abort-gap beam population → fast extraction particle across many elements
  - satellites around main bunches (inherent to BCMS) → impact on physics with bunched beam





Summary

- Beam Transmission Monitoring
  - Performance: key accelerator tuning parameter & *"Every ion lost in the accelerator is an ion lost for physics"*
  - ALARA – minimisation of activation and radiation permit compliance
  - Minimising risk of combined failures & reducing MP stress before losses become an MP/operation issue
- Definition of 'acceptable losses – setting realistic goals, expectations and limits
  - 'In a perfect world: none' vs. 'In the real world: cannot avoid certain beam losses'
  - should keep (well) below upper limit given by facility's radiation permit and activation considerations
  - for discussion: 'golden standard of acceptable losses' := losses remaining after having applied reasonable common operation practices of controlling beam parameter known to induce particle loss:
    - Extr./inj. matching, cycle-to-cycle Orbit-FBs, Q/Q' correction, ε-blow-up monitoring → optics correction, detailed collimation, slow-extraction, ...
- Real-World operational problem:
  - 'FCT/DCCT accuracy limited to about 2-3%' vs. 'ALARA transmission control aimed ideally on the sub-% level'

  → proposal to include BLMs for fast in-cycle losses & RadMons for slow, absolute loss measurements

    - N.B. BLM thresholds to be used as relative indicators w.r.t. given setup reference
- Some ToDos (dedicated task groups): CO architecture, SW/HW implementation, CSCO and BI system interfaces, ...

Appendix

Hazard and Risk for accelerators

- **Hazard:** a situation that poses a level of threat to the accelerator. Hazards are dormant or potential, with only a theoretical risk of damage. Once a hazard becomes "active“: **incident / accident**. **Consequences** and **possibility** of an incident interact together to create **RISK**, can be quantified:

RISK = Consequences · Probability

Related to accelerators

- Consequences of an uncontrolled beam loss
- Probability of an uncontrolled beam loss
- The higher the **RISK**, the more **Protection** is required

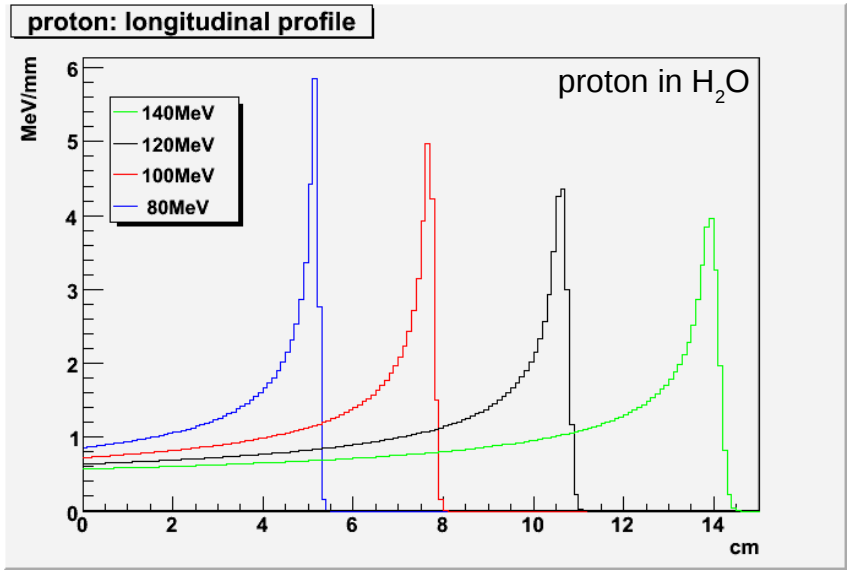
Risk Management Gradient

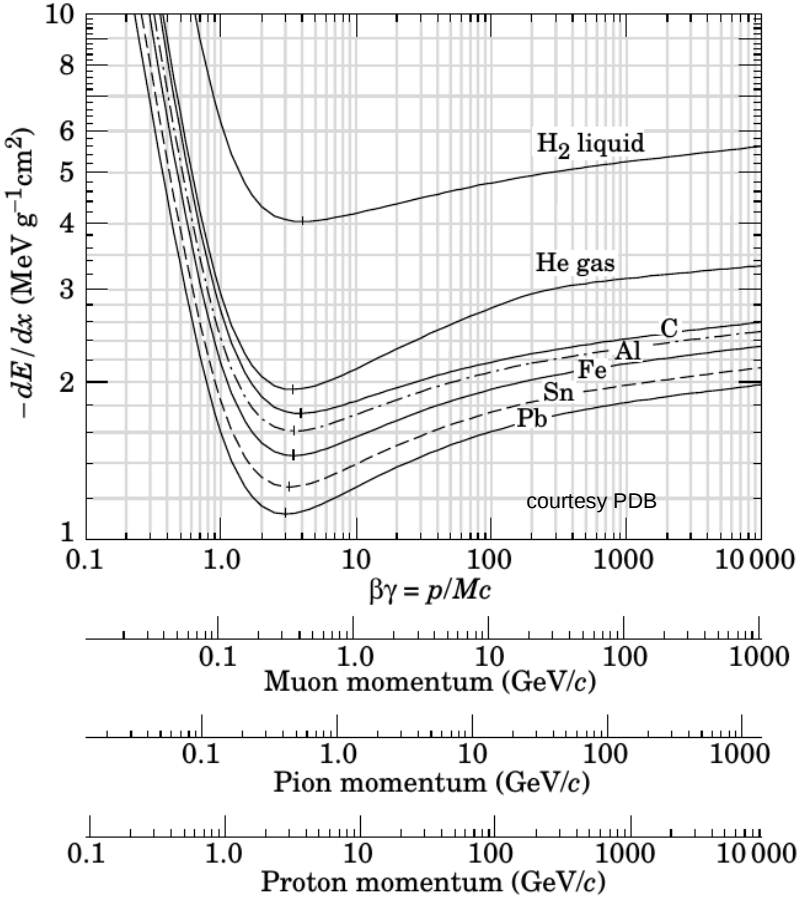
	Poka-Yoke 'Mistake Proofing'	???		Machine Protection
Use-cases:	*intercepting common mistakes, procedural errors, etc. affecting machine performance*	*minimising machine activation (ALARA principle)*	*preventing quenches*	*investment protection*
Devices:	*LSA, settings monitoring, ...*	PC, FMCM (?), QPS, FCT, BLMs, ...		*passive absorbers, machine optic, material choices*
Systems:	Sequencer & operational procedures	FAIR (SW) Interlock System	FAIR-SIS100 Fast Beam Abort Sys. (HW Interlock System)	FAIR Machine & System Design
time-scales:	10s of seconds → minutes/hours	100 ms	50 us	< turn

Poka-Yoke (ポカヨケ) – 'Mistake-Proofing'

- … to avoid (yokeru) inadvertent errors (poka)
- … industrial processes designed to prevent human errors
  - Concept by Shigeo Shingo: 'Toyota Production System' (TPS, aka. 'lean' systems)
- common mistakes, procedural errors, etc. affecting machine performance
- Real-World Examples:
  - Polarity protection of electrical plugs (e.g. phone, Ethernet cable)
  - Procedures: e.g. ATM machine: need to retrieve card before money is released (↔ prevents missing card)

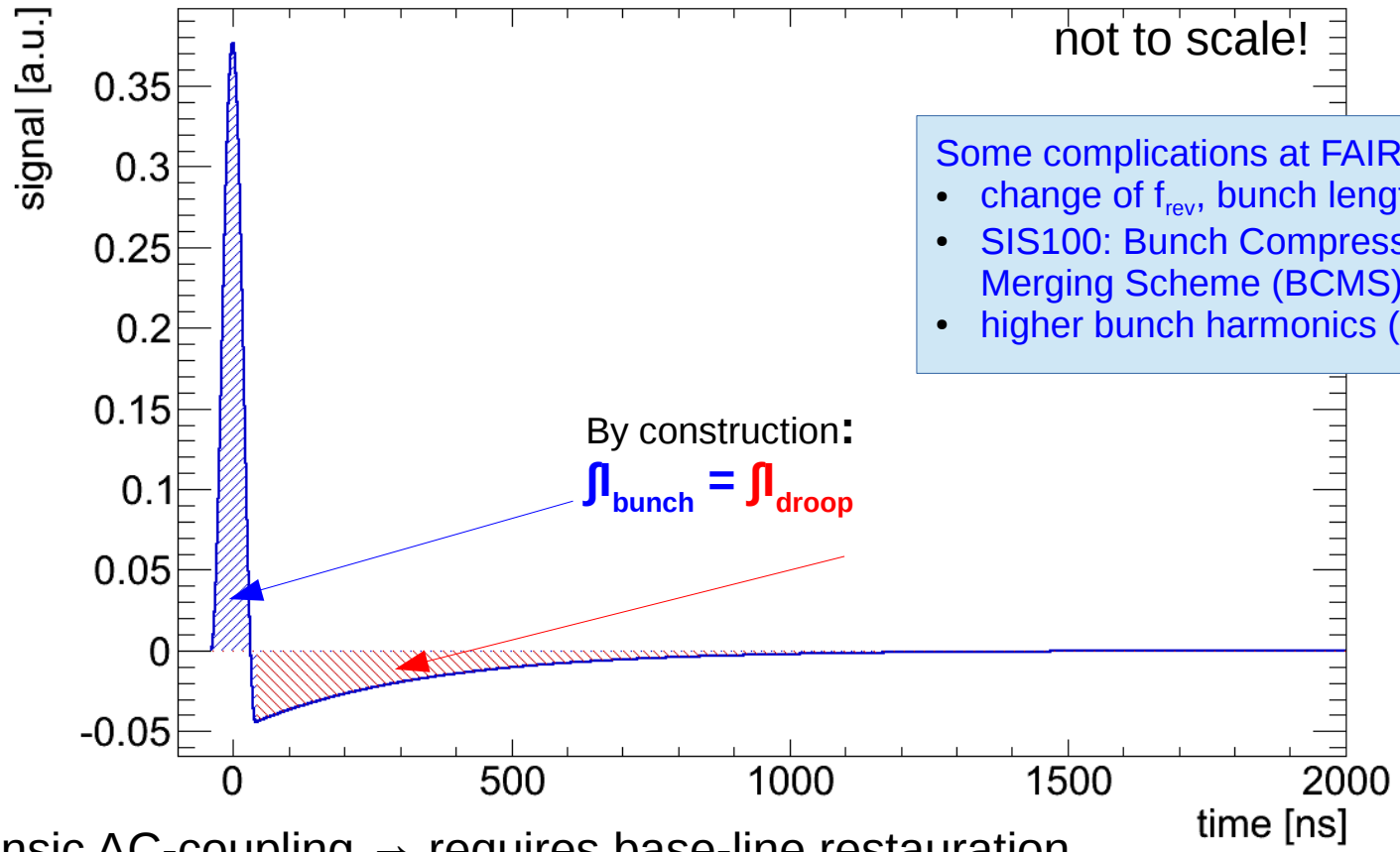
FCTs/DCCTs
Better choice as BTM for Low Energy Ion Beams





Reconstruction Requirements I/II
Typical WCM response – Low-Frequency Base-Line

- Naive approach: Fourier Integral definition for 'ω:=0': $F(\omega)=\int_{-\infty}^{+\infty} f(t)\, e^{-i\omega t}\, dt$
- However: DC information is in-accessible:



Some complications at FAIR:
- change of f_{rev}, bunch length & shape
- SIS100: Bunch Compression & Merging Scheme (BCMS)
- higher bunch harmonics (Landau)

- Intrinsic AC-coupling → requires base-line restauration
  - typ. 1rd-order zero-pole IIR filter works fine on %-level
    - Particularly important for filling patterns with many bunches (LHC: <2808)
  - observed sub-%-level drifts related bunch-filling pattern, bunch charge,...

III. Base-Line Restoration – SNIP Algorithm
Example PS WCM Signal

- Satellites have been deliberately produced for better proof-of-principle: