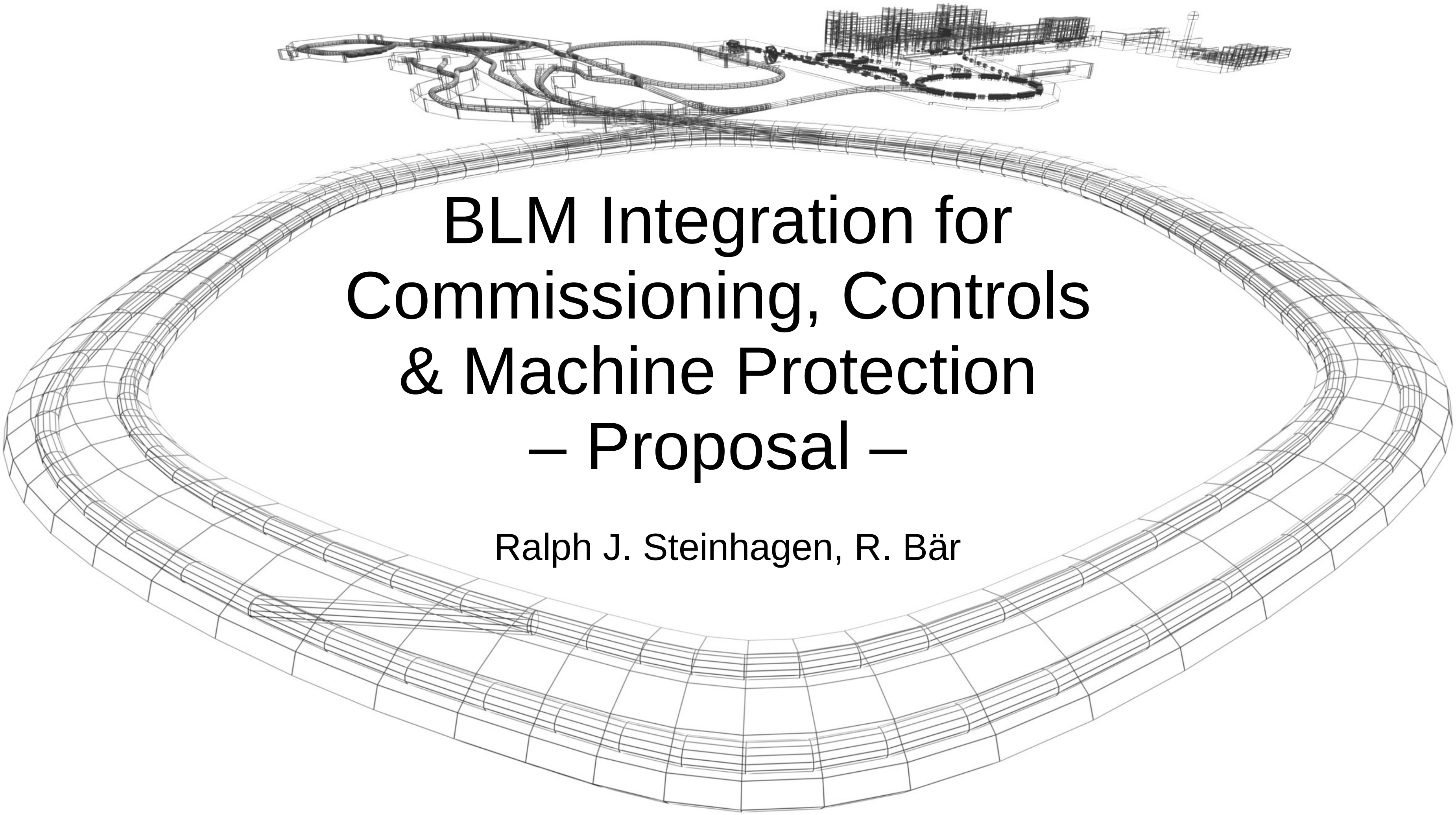


BLM Integration for Commissioning, Controls & Machine Protection – Proposal –

Ralph J. Steinhagen, R. Bär

BLM Topics to be discussed

- Brief summary of what to expect from BLMs @ FAIR
  - sensitivities, ion-species/energy dependence, left-right asymmetry

- Integration into Controls Environment
  - Comparison of FAIR ↔ LHC BLM specification
  - tentative specification: filter, threshold functions, …

- Proposed use-cases:
  - Integration into Transmission Monitoring
    - Relative loss profile measurement → warn/trigger on anomalous losses
      - injection/extraction losses, RF losses, spill monitoring, ...
    - ALARA : BLMs dN/dt more sensitive than beam current transformer based dI/dt measurements
      - monitor integral value (x-calibrated against radiation monitors)
  - Integration into SIS18/100 Machine Protection
    - Collimator hierarchy and passive absorber scheme validation
    - Protection of electro-static septa wires
      - Test with known low intensity losses and record actual BLM signal ↔ a priori quick measurement
    - Protection of sensitive devices
      - provides upper loss/transmission limit for nominal operation

Predicted BLM Sensitivity

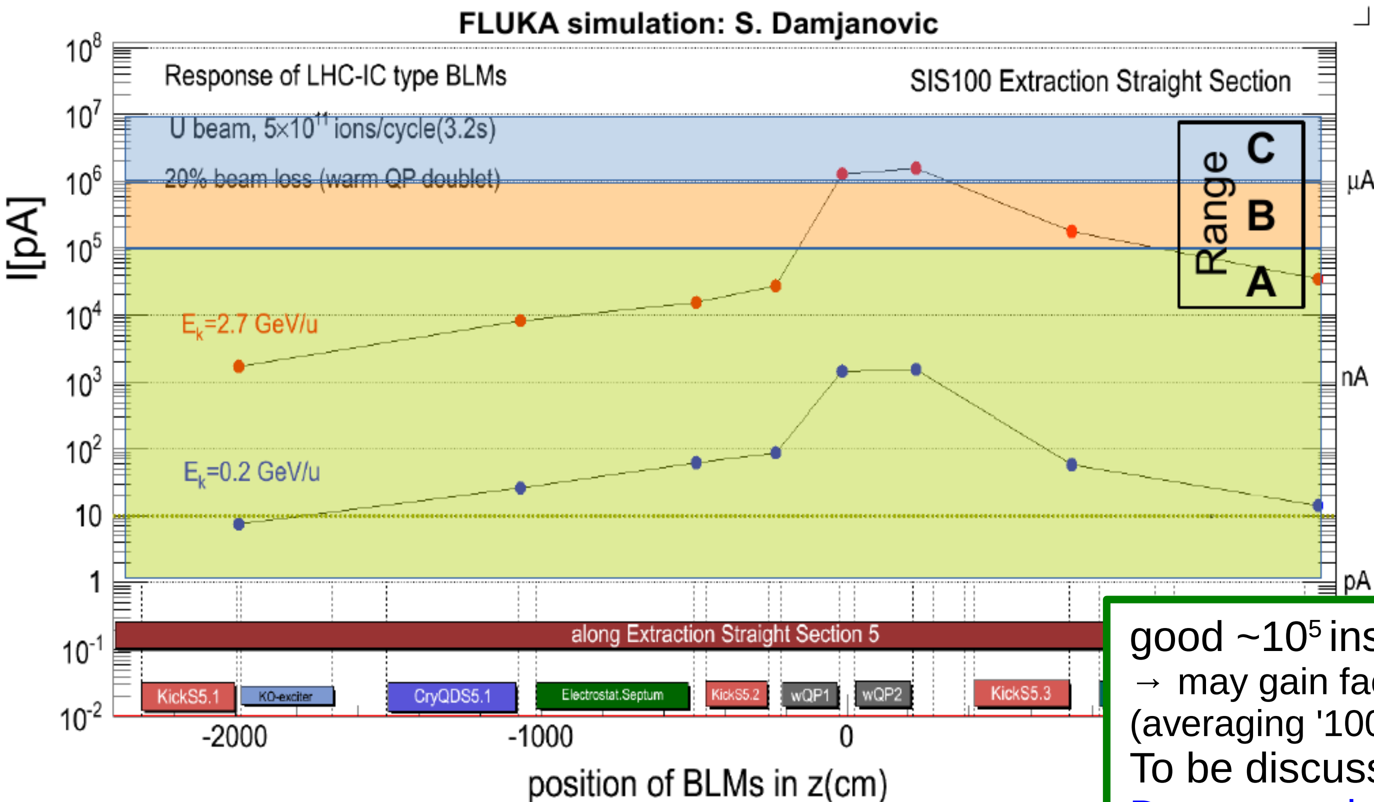
courtesy P. Boutachkov

IFC3: H. Reeg (LOBI)
3 Ranges: A: 100 nA, B: 1uA, C: 10uA

full scale output frequency: 1 MHz
max. frequency, reduced linearity: 2 MHz

converting factor A: 100 fC/pulse
converting factor **B** 1 pC/pulse
converting factor C: 10 pC/pulse

↔ N.B. instantaneous range



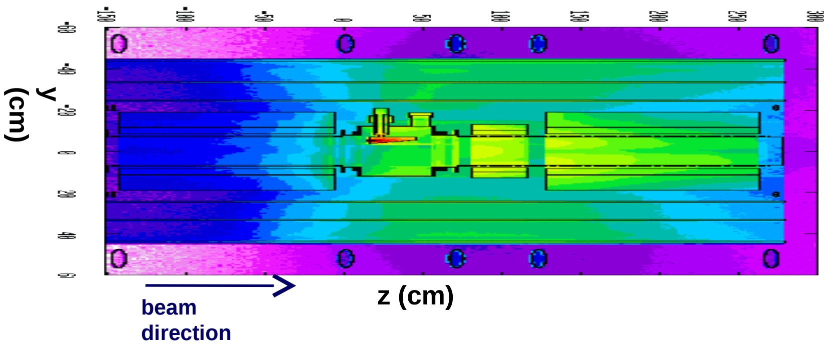
I[pA] = N(particles loss) [1/s] * Q [pC/primary, from FLUKA]
Note: measurements bellow 10 pA require good grounding

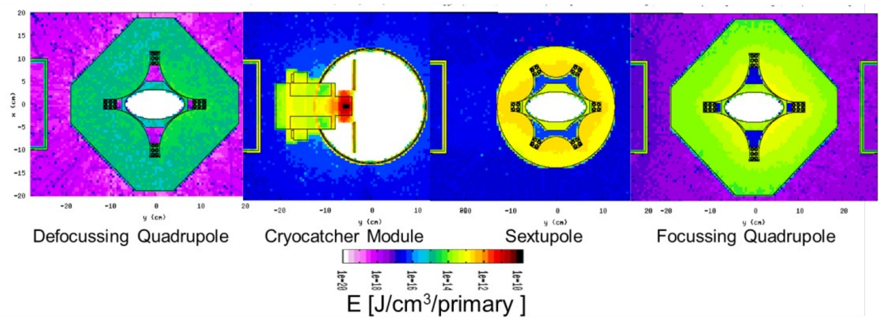
good ~10^5 instantaneous range
→ may gain factor 100 for slow-losses
(averaging '100 us' → '1 s' scale)
To be discussed:
Do we need turn-by-turn resolution?
(100 us → 10 us → 3.6 us? Dedicated diagnostic?)

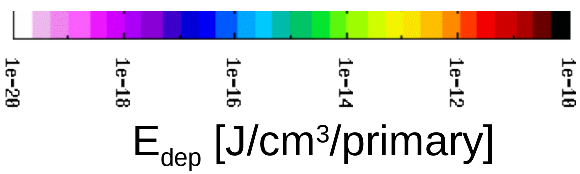
Energy Deposition in QP Module

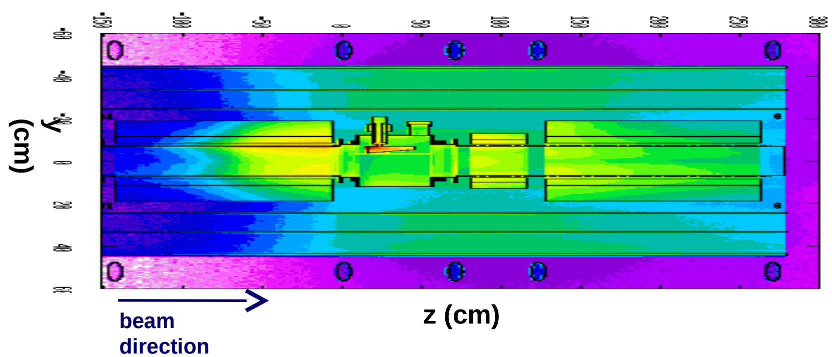
U beam, E_k=2.7 GeV/u (S. Damjanovic)

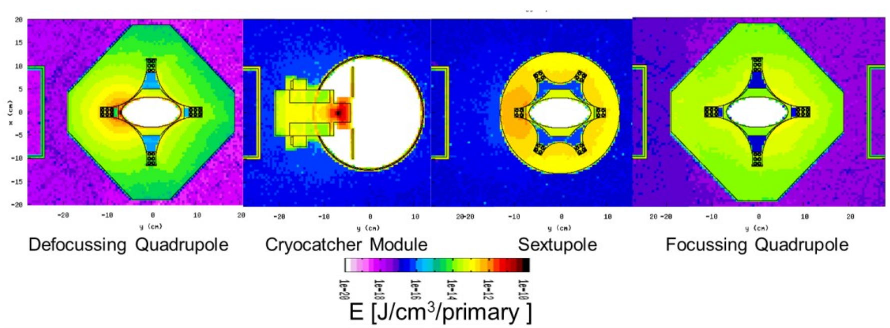
Source I – energy deposition from ions hitting the cryo-catcher







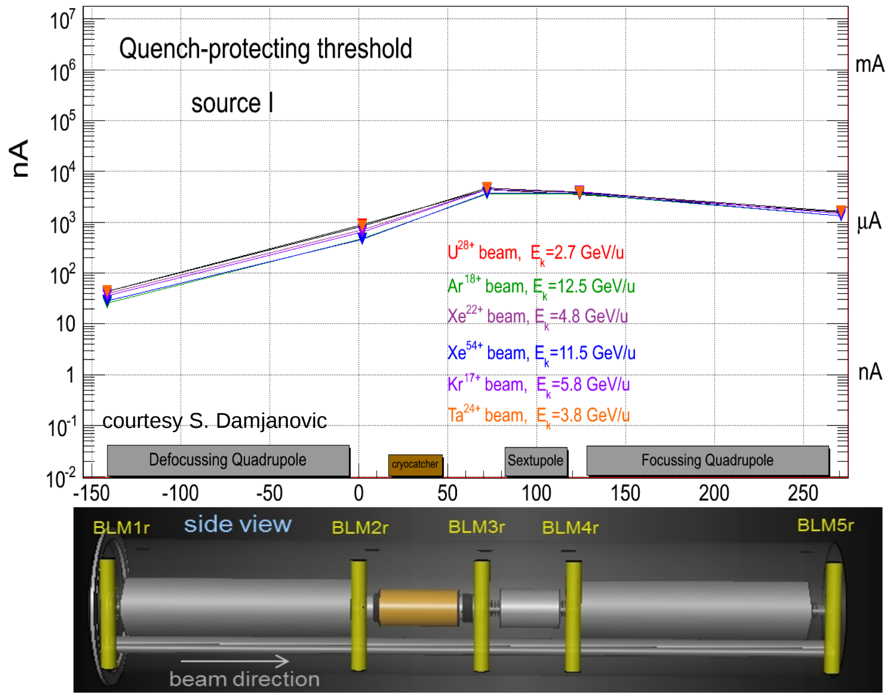


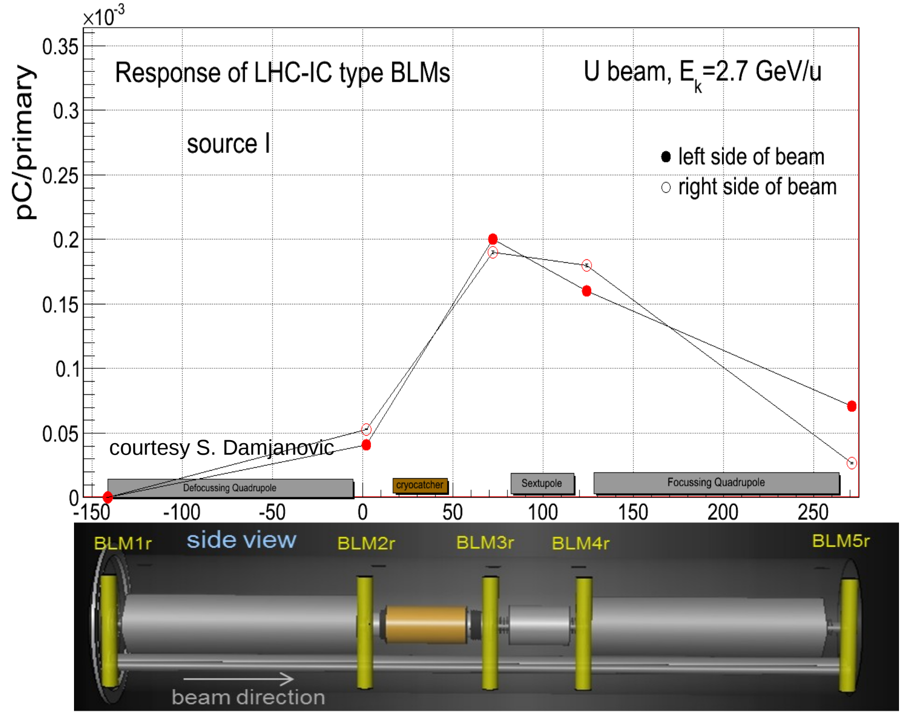


Source II – energy deposition from ions hitting the DQ chamber

Energy Deposition for different
Ions, Energies & Left-Right Asymmetry

- Quench (↔ damage) thresholds similar for considered ions & energies
- little dependence on initial impact angle
  - N.B. large angular spread of secondaries (further spread by material around vacuum pipe)





(N.B. LHC IC-BLMs lower sensitivity threshold threshold: < 1 pA)

Tentative FAIR BLM Specification I/II

- Engineering approach: assess, re-use proven concepts, adapt were necessary – also known as: “KISS – Keep it Simple & Save + avoid re-inventing the wheel”
- LHC BLM specification: EDMS #328146, LHC-BLM-ES-0001 Rev 2.0:
  - a posteriori specification: system was largely designed (final engineering checks)
  - However: based upon & many decades of experience with SPS BLM system

Original use-cases (failure-modes)

	Machine status	*Source of Losses*	*Location of Losses*	*Case #*
Steady losses	Nominal losses	Beam halo at collimators	collimators	1
		Tertiary beam halo & Beam-gas	All along	2
		Collision products	Q13.L -> IP -> Q13.R	3
	Partial obstructions	He and air leaks, partial obstruction of a beam channel	Local ± 10 m	6
Slow transient losses	Beam manipulations & measurements	Local orbit bumps, β-beat	Local ± 10 m	4
		Global corrections (tunes,…)	IR3 + IR7	5
		Beam scans with targets (wire, screens,…)	Local ± 10 m	4
Fast transient losses	Obstructions	Complete obstruction of a beam channel	Local + 10 m	7
	Accidental kicks (failures)	Injection errors	TDI, coll. at Q6 downstream of TDI,IR3/IR7	8
		Fastest PC trips (5 turns)	IR3 & IR7	9
		Asynchronous dump kick	Masks in IR6, IR3, IR7	10
	Magnet quench	Drifting beam/machine parameters	Collimators, any local aperture limit	11

Specified accuracies, precision & required sensitivities (LHC specific values)

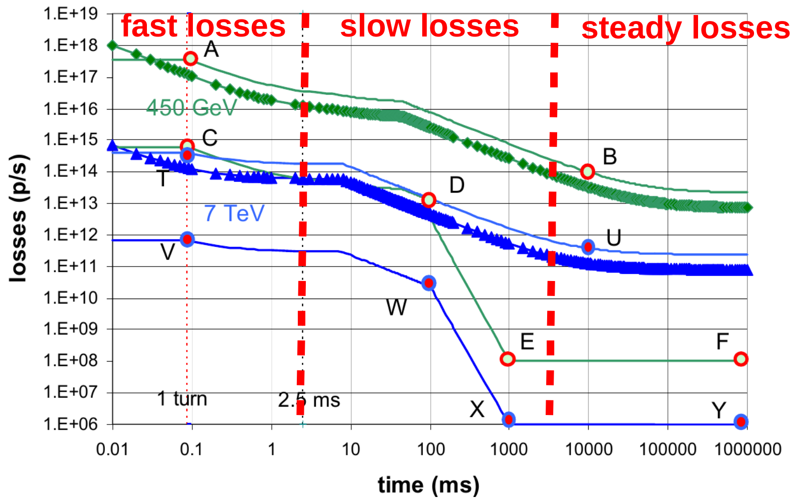


Table 11 : Dynamic range for the BLMC's in p/s.

	0.1 ms		0.1 s		1s		10s		100s	
	MIN	*MAX*	*MIN*	*MAX*	*MIN*	*MAX*	MIN	MAX	*MIN*	*MAX*
450 GeV	6×10^{14} (C)	3.6×10^{17} (A)	$1.3\text{x}10^{13}$ (D)		10^{8} (E)			9.6×10^{13} (B)	10^{8} (F)	
7 TeV	6.5×10^{11} (V)	3.9×10^{14} (T)	$2.3\text{x}10^{10}$ (W)		10^{6} (X)			3.7×10^{11} (U)	10^{6} (Y)	

Tentative FAIR BLM Specification II/II

Start with LHC-type BLM specification, however, with some differences for FAIR:

- most FAIR machines are fast cycling → thresholds need to be function of time in cycle
- 'protons lost/second' impractical → keep native 'Gy/s'
  - permits x-calibration with rad-monitors
  - high uncertainties & unnecessary complexity on primary-loss-to BLM-signal transfer function
    - uncertainty on quench/damage/energy deposition limits
    - ion-mater interaction at low energies folded with loss location uncertainties
    - …

N.B should check some selected key cases but Simulation of all scenarios provides little added value

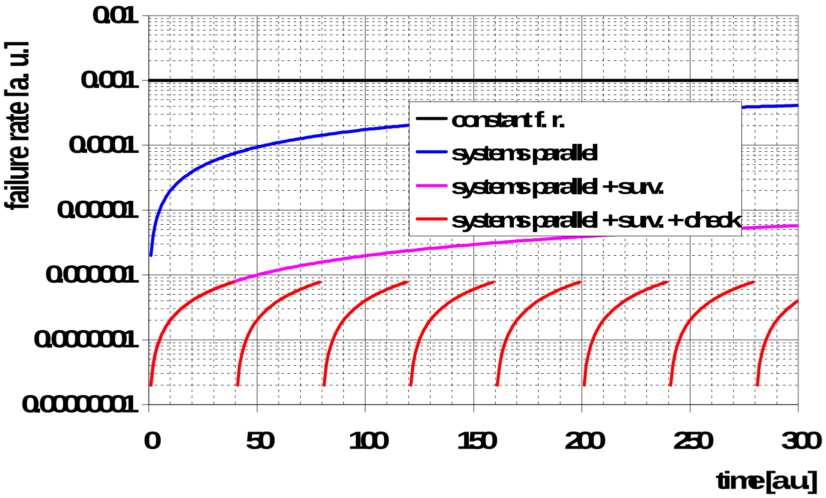
- relative beam-based thresholds are sufficient in most cases
  - fast-cycling SIS's→ (need to) rely upon reproducible performance
    - small continuous losses over long periods more severe than single large losses
  - very limited disastrous single-shot failures at SIS100 energies
    - can check/verify with safe low-intensities and safely extrapolate to nominal
    - N.B. not possible for LHC: smallest intensity ('pilot' beam) is already dangerous at 7 TeV
  - notable exceptions: electro-static septa protection
- may study some specific but cannot study all possible loss scenarios (often little added value) → aim at global concepts that covers also yet-unknown loss mechanisms/scenarios
  - uncertainty on steady-, slow- and fast-loss scenarios → keep flexibility and fix thresholds after having gained some experience with beam in SIS100 (ie. dedicated controlled quenches & material tests)
  - until then (& early operation): define loss thresholds as envelope around known/optimised losses taken during 'Pilot' and 'Intensity-Ramp-up' beam mode phases

BLM System Specification

LHC (EDMS #328146, LHC-BLM-ES-0001 Rev 2.0) → FAIR

- Key LHC BLM(S) parameters (→ FAIR):
  - Sensitivity: 5% of quench level (OK: 0.1% at 0.2 GeV/u and 10^{-6} @2.7 GeV/u @ nom. U^{28+})
  - Dynamic range: about 10^5 for signal integration time 40 µs (SIS100 BLMs similar)
  - Response time ≤ 1 turn (0.1 ms) (FAIR turn scale ~3.6 us<40 us incompatible with LHC-IC time-constant. Dedicated diamond detectors/read-out? For IC → stick to 100 us integration)
  - Accuracy as given in 'p/m/s': < factor 2 (initial < factor 5)
    - FAIR: 'p/m/s' → 'Gy/s' ↔ comparison with radiation monitors
  - Precision: < ± 25 % w.r.t. predicted quench level (less relevant for FAIR)

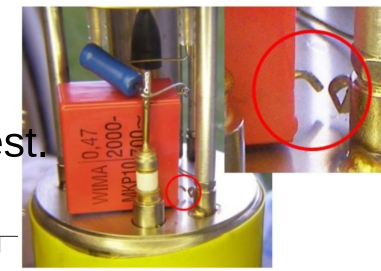
- Failure rate (reliability):
  - SIL1 specified (SIL3 achieved)
  - implies as good as new system validation
    - redundancy only provides limited reliability gain → key to reliability: performance surveillance + checks
  - check procedure improves failure rate by > 10^2 → should consider this option also for FAIR

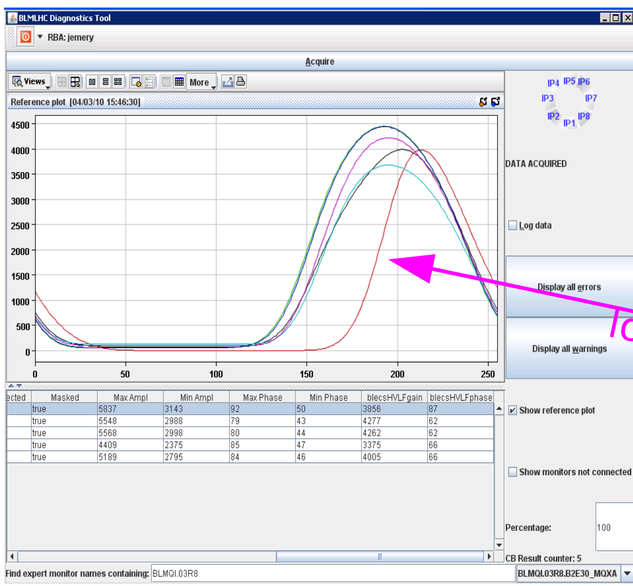


BLM Sanity Checks
(see M. Sapinski's FC2WG-#4 BLM talk for details)

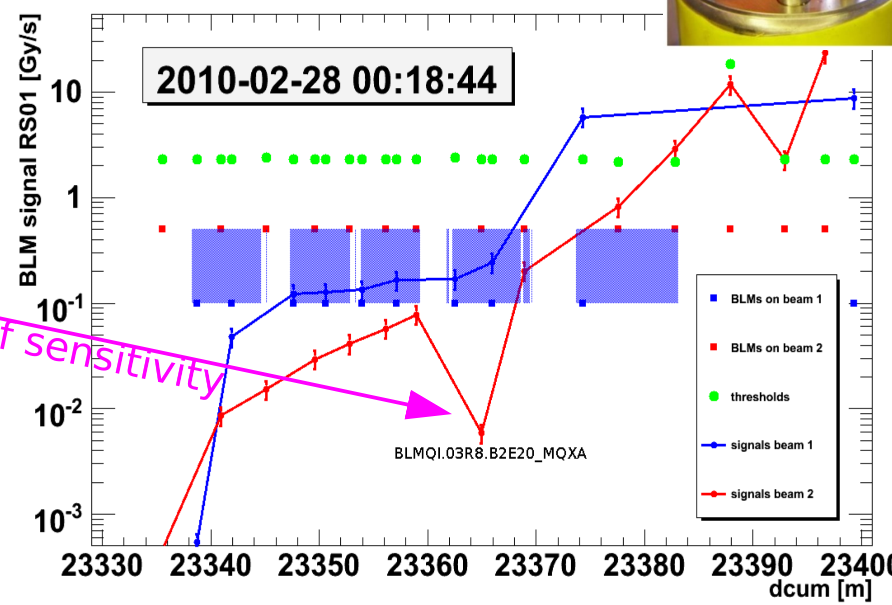
Check which runs before every fill (for FAIR: once per day?):

- Connectivity check:
  - Detects non-conformities of cabling, verify HV, can detect issues in the tunnel electronics. (J. Emery et al., Journal of Instrumentation, Vol. 5, C12044, 2010)
- Internal beam permit check
  - Verify ability of every threshold comparator to send beam dump request.

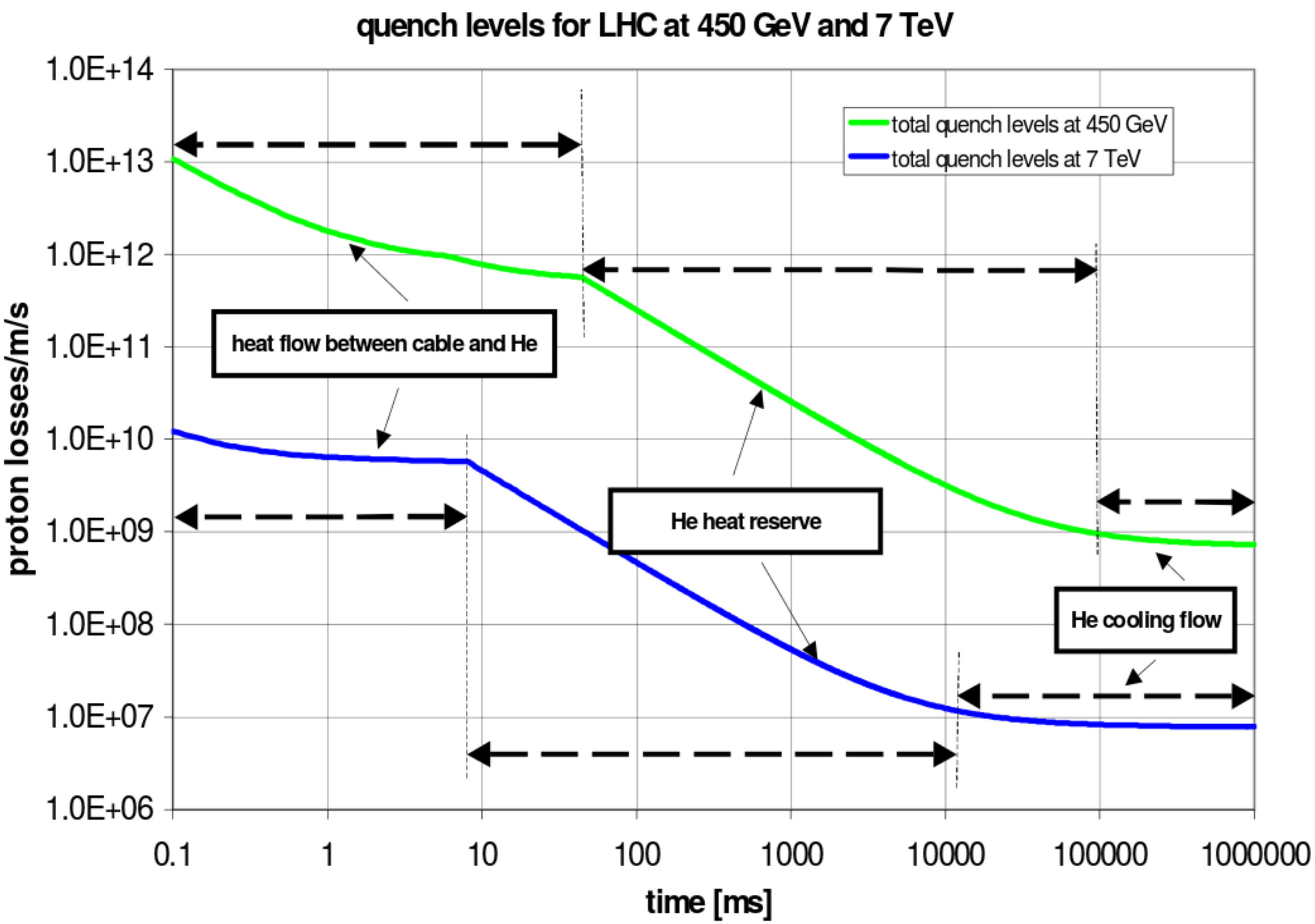




channel response to HV modulation



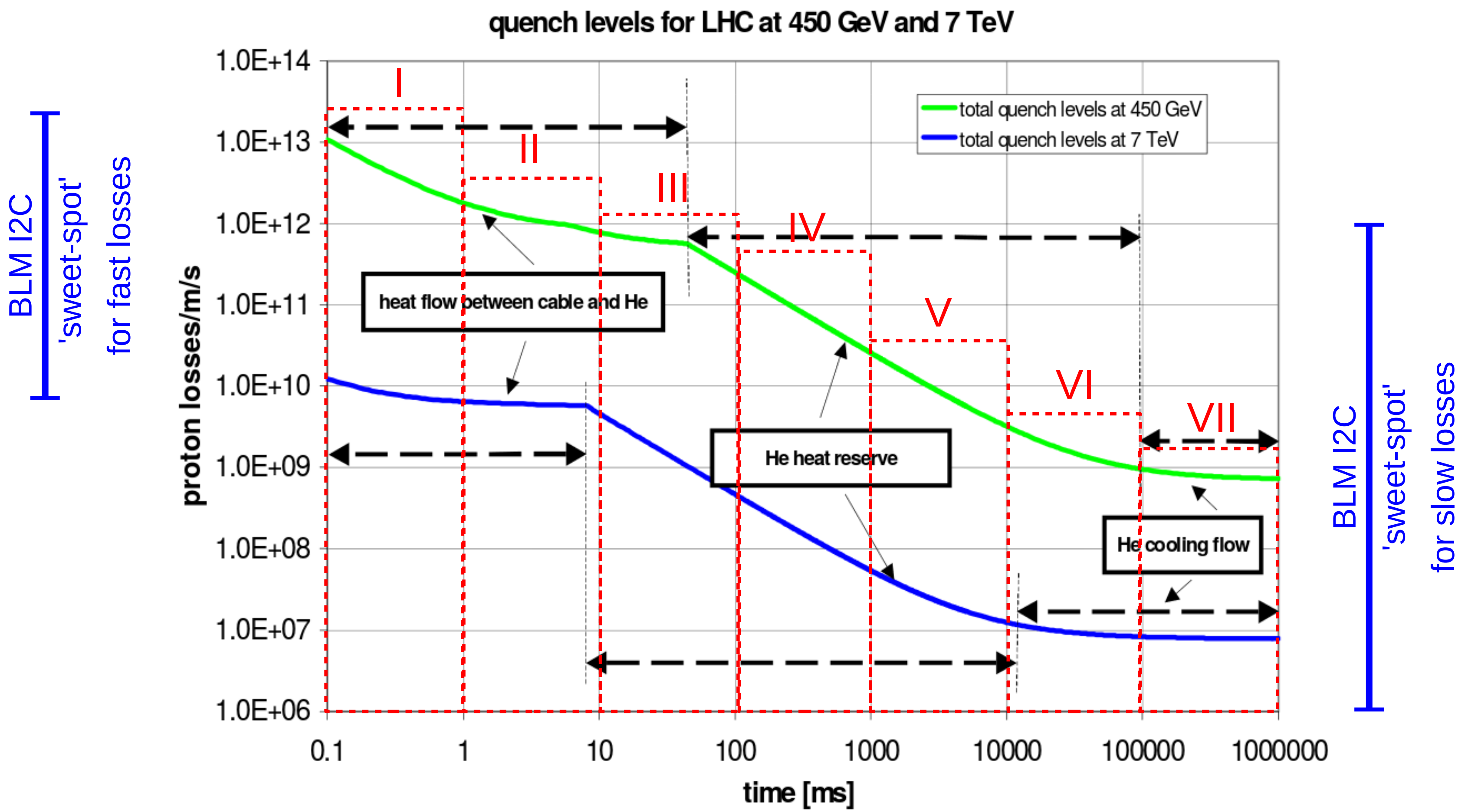
Example: LHC BLM Thresholds
(original design)



- N.B. quench prevention @ FAIR not critical/driving requirement!
- However, heating/cooling model similar for material stress/destruction → 1st order: <damage threshold> ≈ n·<quench threshold>

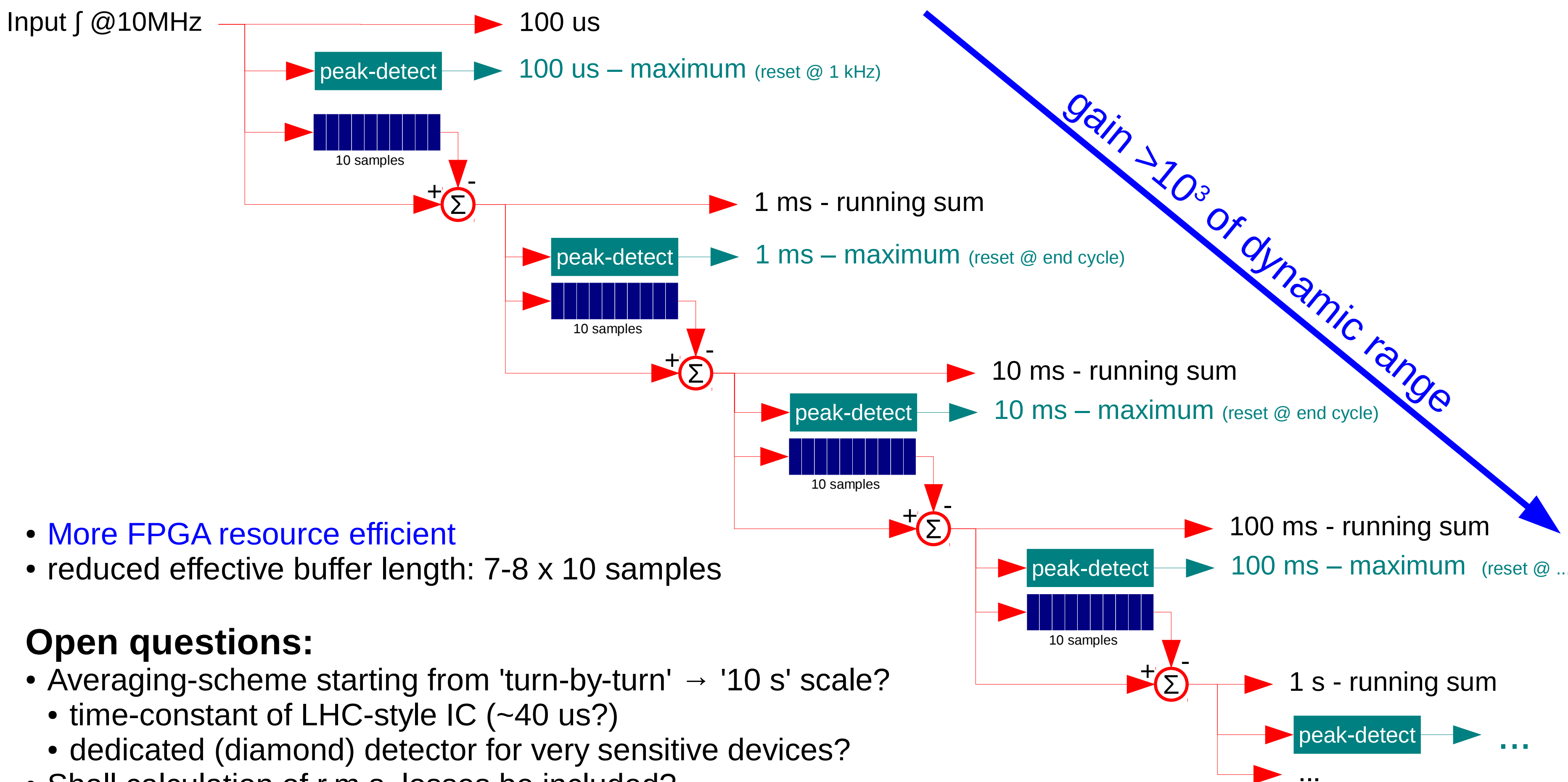
E. Geschwendtner et al., “LHC Beam Loss Monitors”, CERN-SL-2001-027 BI, DIPAC2001, Grenoble, France, 2001

Example: LHC BLM Thresholds
(original design)



- Large uncertainty on shape of expected op. loss scenario, damage thresholds & rates → multiple sliding averages (FIR filter)
  - Group into decades from 'turn' scale (fastest losses) to steady-state losses '1 ... 10 s' (cryo-plant limits)
  - N.B. quench threshold is not the driving limit for SIS100! Windows merely intended to distinguish between fast and slow losses.

Running Sum Averaging



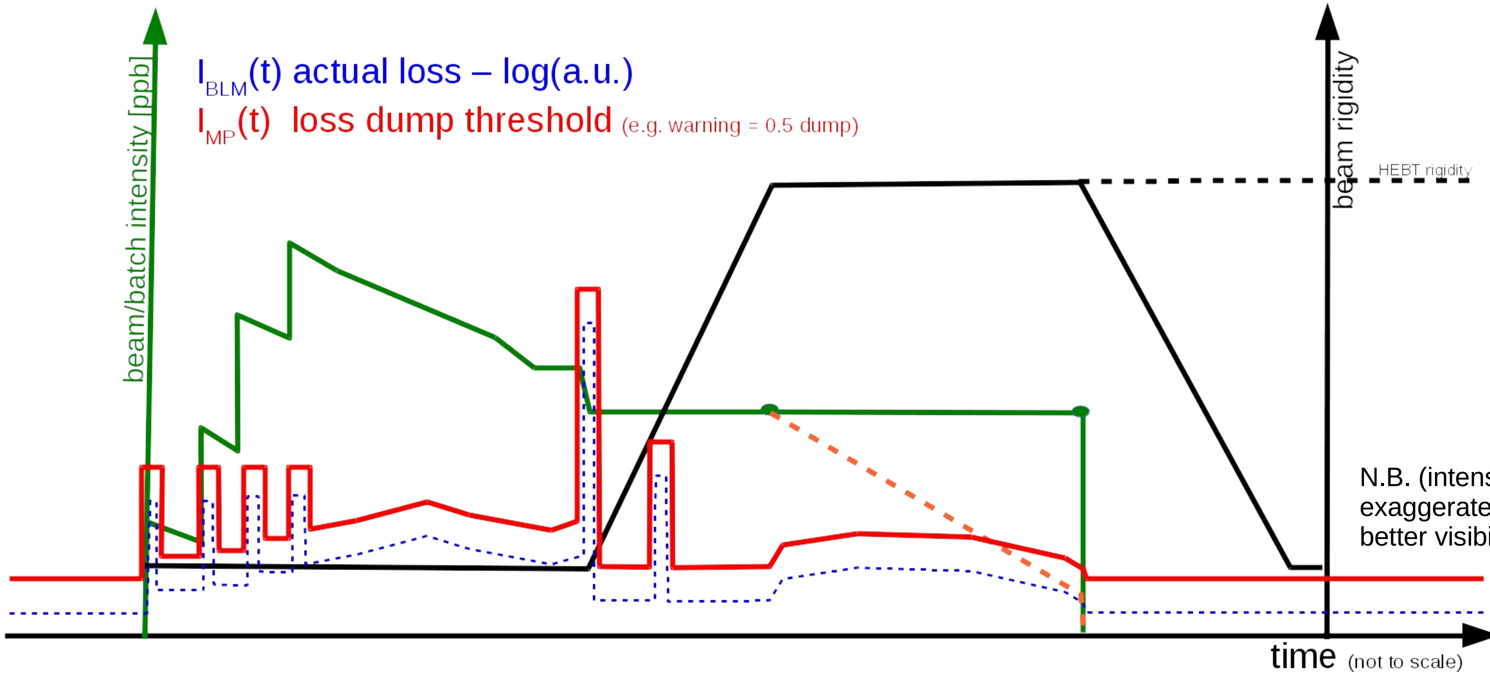
- More FPGA resource efficient
- reduced effective buffer length: 7-8 x 10 samples

Open questions:

- Averaging-scheme starting from 'turn-by-turn' → '10 s' scale?
  - time-constant of LHC-style IC (~40 us?)
  - dedicated (diamond) detector for very sensitive devices?
- Shall calculation of r.m.s. losses be included?
  → option of using temporal stability of losses (noise)estimation to refine thresholds
- ...

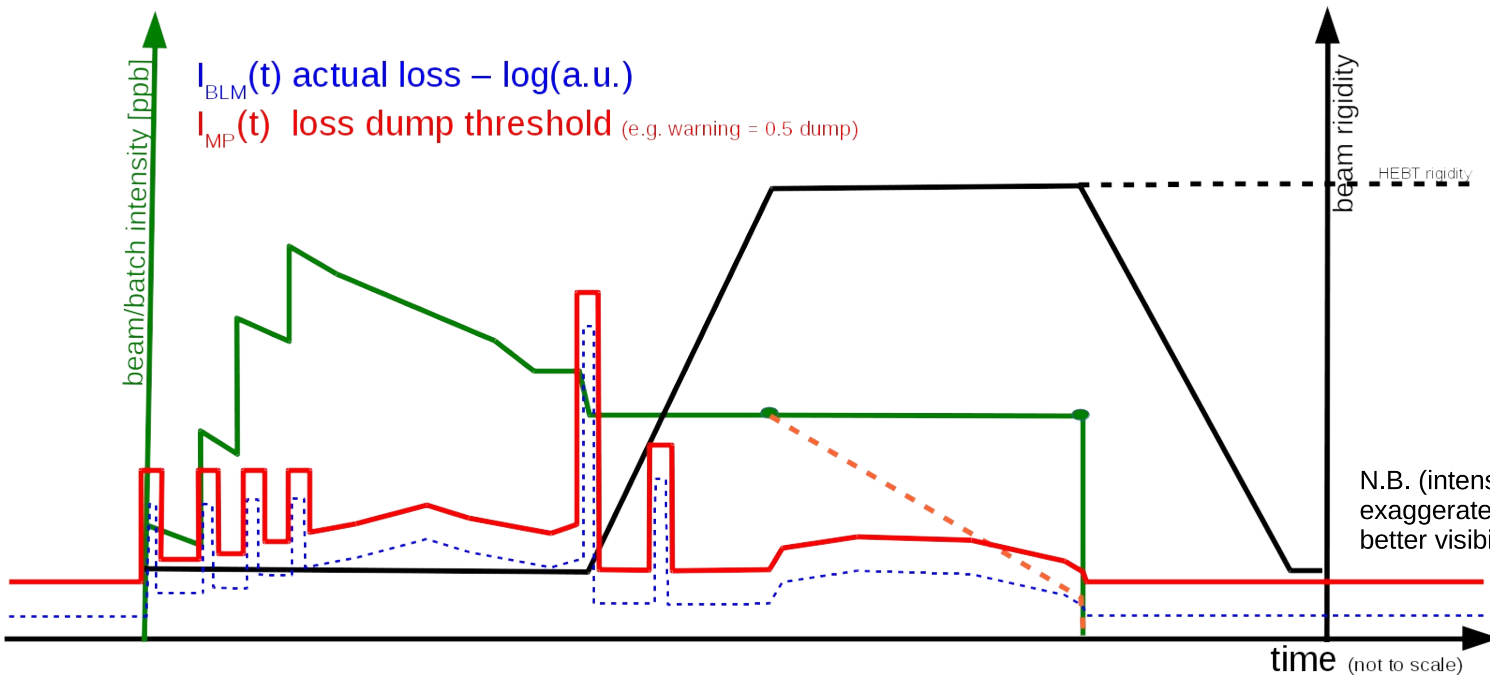
BLM Thresholds I/II
→ Function-of-Cycle-Time

- One threshold function (of time) per integration window
  - folds energy, ion species, and other effects into one function
    - aimed at simplicity from a BLM integration point of view
  - Initial setup strategy:
    - top-level integration to unfold and propagate to other new cycles (with different energy cycles, ion species)
    - Derive thresholds from actual measurements ↔ includes what can be achieved, actual machine stability, ...
      - → warn/dump if nominal operation deviates from known set-up scenario
      - warning-level = n-% of dump threshold (linear scaling)



BLM Thresholds III/II
→ Function-of-Cycle-Time – Data Rates

- minimum distance 1 ms to mask/increase thresholds during injection
- most loss-inducing beam physics/OP scenarios are during the first 1-2 seconds → 2000 points
  - Injection, RF gymnastic, ramp, transition, more RF gymnastic (bunch rotation, de-bunching), slow extraction
- SIS100 slow-extraction is typically 10 – 100 s long, however, loss-rates changes only slowly during that time:
  - brute force: 12000 data points x (7 thresholds) x 4 bytes/threshold → 330 kB per threshold table
    - easiest set-up to generate thresholds: use actual measurement data for 10-20 cycles → averaging+scaling → threshold
  - reduced: 2000 points for first 2 seconds, then threshold rate @10 Hz or non-equidistant sampling
  - optimised: limit to e.g. 1000 threshold samples → harder (but not impossible) to setup table



BLM Use-Case Examples & Proposals

A) Integration into Transmission Monitoring

- Relative loss profile measurement → warn/trigger on anomalous losses
  - assumes reproducible machine after initial set-up
  - does not require detailed BLM signal ↔ loss pattern ↔ energy calibration
- ALARA : BLMs dN/dt more sensitive than DCT/FCT-based dI/dt measurements
  - Simple/robust cycle-to-cycle intensity (loss) diagnostic
  - calibration against radiation monitoring system (provides absolute 'Gray scale')
    - estimation/prediction of activation potential of given in-cycle losses

B) Integration into FAIR Machine Protection concept (SIS18/100, linacs, ...)

- Collimator hierarchy & cleaning efficiency verification
  - aperture scan
- Intensity ramp-up concept/procedure
  - dedicated losses on septa wires with acceptable low intensity (↔ mapping to BLM signals) ↔ a priori quick measurement
  - Test of collimator hierarchy and absorber scheme
    - via: controlled emittance blow-up at primary collimator
  - Upper limit for nominal operation

ALARA: 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

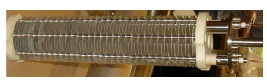
DCCT
/FCT
counter

Experiment

primary (secondary)
ions-on-target/s

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

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



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

BLMs & RadMons Extension Proposal (see FC²WG #6)

- May not achieve required BTM using beam current transformers alone, or would need to impose unrealistic BI design parameters
  - ‰-level resolutions for stable beam conditions achievable but accuracy typically only 1-3% abs.
- Include BLMs and RadMons as complementary input to BTM system
  - single BLM resolution: 0.1%@inj. to 10^{-6}@extr. for $1.5\cdot10^{11}$ U^{28+}/s lost on septa wires

Proposed operational procedure/scenarios:

A) Low-intensity beams:
  - cycle-to-cycle time scale: mainly rely on beam current transformer and tune beam parameter to transmissions on 2-3%-level around established 'acceptable loss' scenario

B) High-intensity beams (steps mask-able by SBF):
  - use current-transformer as for low-intensity beams
  - In addition: minimise global/localised losses using integrated BLM signals
    - N.B. a priori qualitative process: no quantitative primary-loss-to-BLM transfer function needed (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

“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 ($\Delta\beta$, $\Delta\mu$) 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)

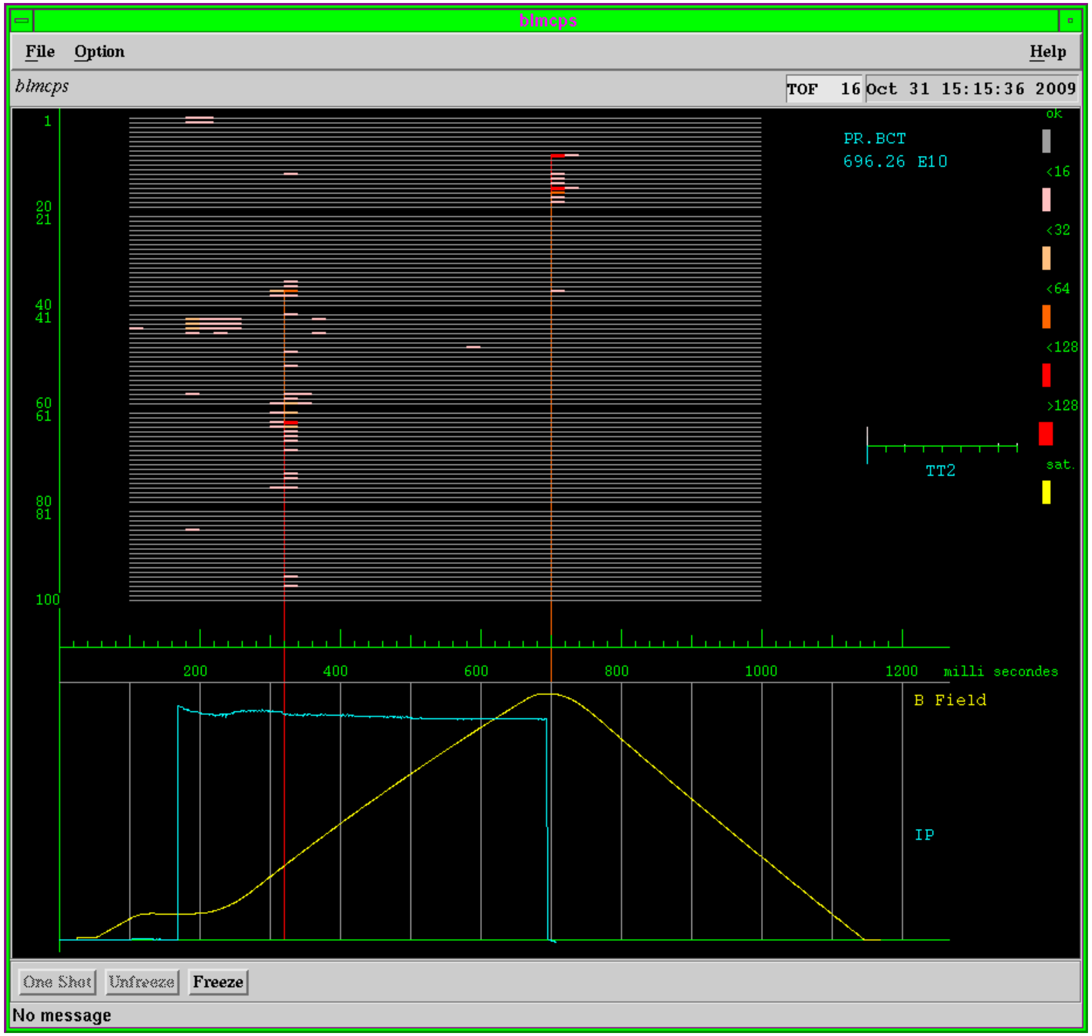
F. Detailed Collimation (e.g. 2-stage for protons)
- see Ivan Strasik's talk @ HIC4FAIR'2015

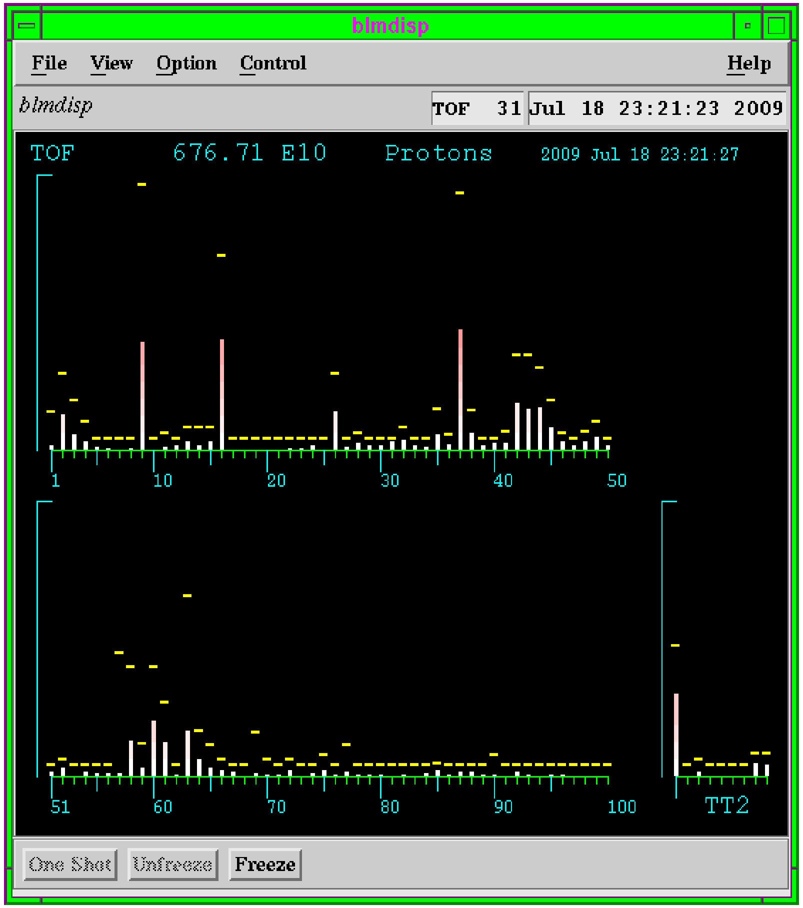
G. Quantitative slow-extraction optimisation
- eval. 'Hardt condition', step-width measurement, …

H. ...

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

Relative Loss Profile Measurement
Example: CERN-PS n-TOF Operation



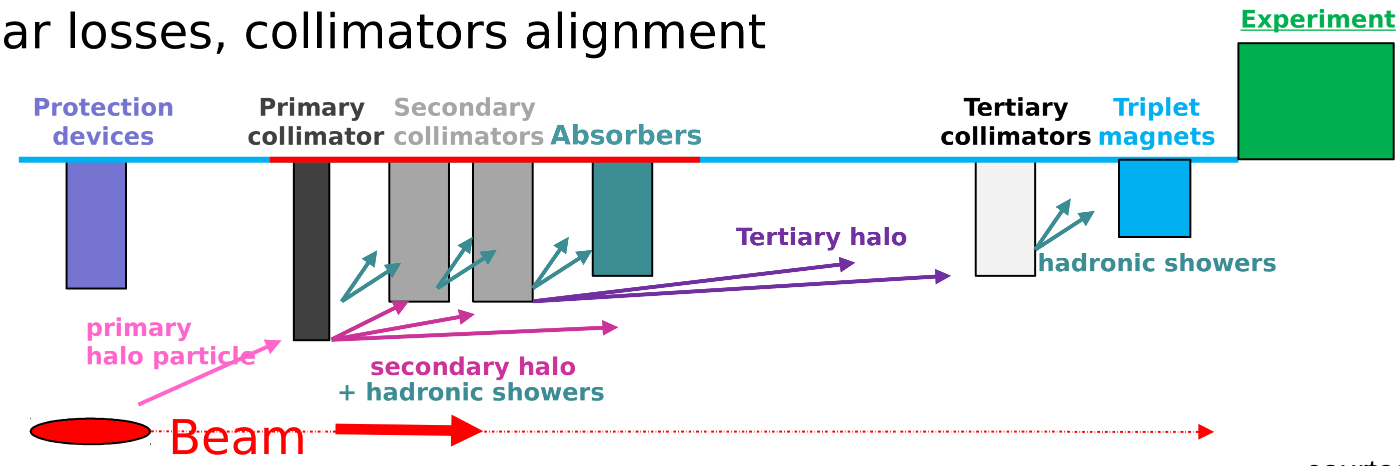


Courtesy F. Chapuis & S.Mataguez, CERN

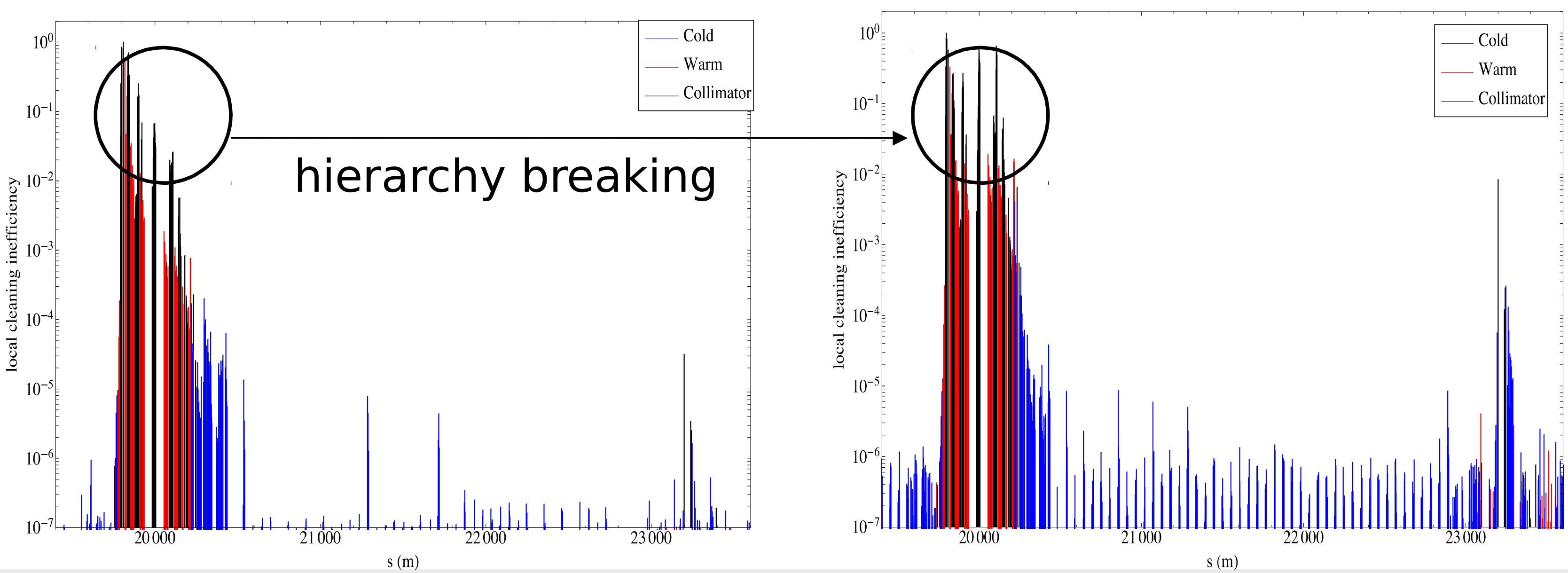
Collimator Hierarchy Verification

N.B. checks cleaning (in-)efficiency ↔ MP checks

Regular losses, collimators alignment

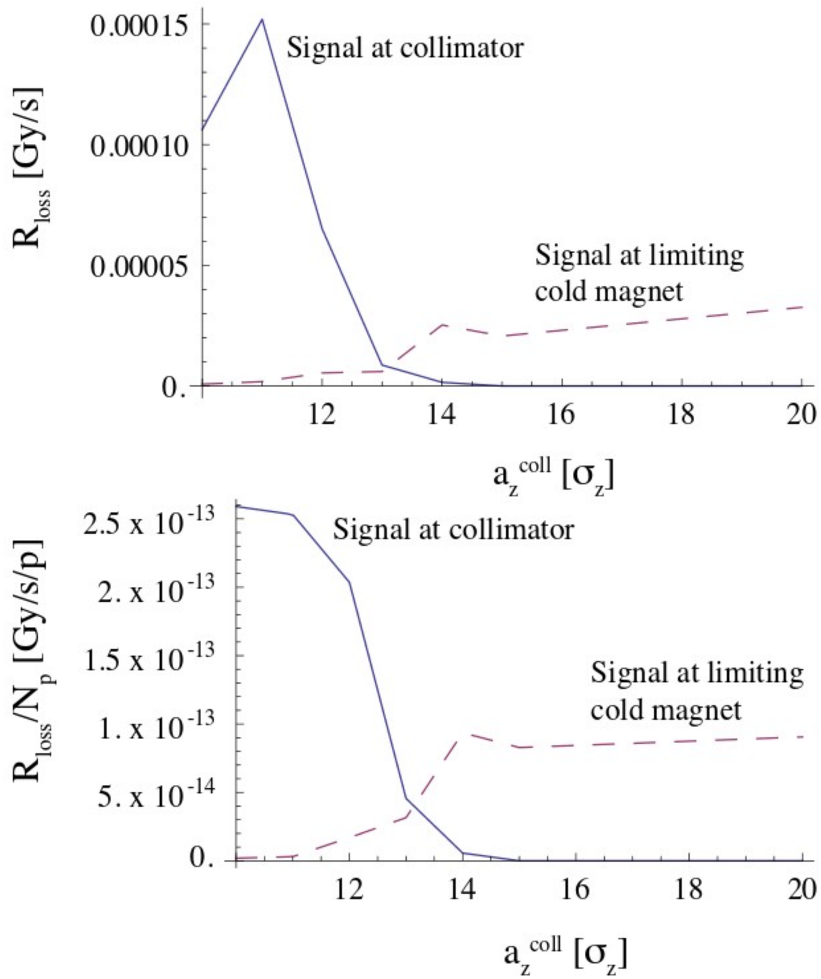


courtesy R. Schmidt



BLM Examples: Machine Aperture

N.B. checks collimator hierarchy ↔ MP checks



Measurement Procedure:

1) Store the beam and record beam intensity N_{ion}.
2) Determine overall aperture bottleneck in the machine with collimators open and emittance blow-up.
3) Close primary collimator in plane of interest by a step to a known value of a^{coll}_z.
4) Store again the beam, record beam intensity N_{ion} and blow-up the emittance in the plane of interest.
5) Record beam loss rates R_{loss} around the ring.
6) Go to 3) until the machine aperture bottleneck is in the full shadow of the primary collimator

R. Assmann et al., "Aperture Determination in the LHC based on an Emittance Blowup Technique with Collimator Position Scan", IPAC2011

Proposal: SIS100 Septa-Protection I/II
System Identification & Calibration

$$E(s) \xrightarrow[\text{(known)}]{\text{exciter signal}} \boxed{G(s)} \xrightarrow[\text{signal}]{\text{beam pickup}} X(s)$$

beam/machine response

- Similar to collimator hierarchy problem/verification:
  1) Generate known loss signal
     - lose full beam on septa wires within known time interval, e.g. using (for e.s. wire) safe intensity of ~10^{10} ions lost in '1 s', '0.1 s', or '10 ms'
       a) Option I: using transverse emittance blow-up based method (K.O./TFS exciter)
          - minimises orbit/optics uncertainties and feed-down effects
          - can be done with squeezed slow-extraction separatrix (extract on wire with nom. Emittance)
       b) Option II: using closed-orbit bump into septa
          - some impact due to bump non-closure and feed-down effects
          - simulates machine failures causing closed-orbit drifts
       c) Option III: keep size/angle of separatrix constant and reduce step size across septa wire to < 100 um (N.B. a ~ (Q-Qres)/g)
       d) Option IV: driving beam through (e.g. third-order) lattice resonances
  2) Record signal of all BLMs (esp. those down-stream of the septa)
     - monitor orbit bump amplitude (↔ beam size measurement)
     - monitor effective beam size with IPM (↔ control for the blow-up process)
  3) FAIR 'Intensity Ramp-Up': repeat at specified energies & for new ion species/cycles
     - Measure losses at $1{\cdot}10^{10}$,($1{\cdot}10^{10}$) and $2{\cdot}10^{10}$ ions/s on wire → tests scaling of intensity effects
     - Interpolate in between measurement points
     - Fairly 'quick' measurement procedure taking few minutes only
       - estimate: 3 cycle (statistic) x 3 (1?) loss options + some cycles for no-beam references/lost injection etc.

Proposal: SIS100 Septa-Protection II/II
Wire- vs. BLM-based Surveillance

- Direct wire monitoring
  - N.B. predicted wire operation temperature '~1500 K' vs. '~1700 K' degradation/breakage
  - wire scanner experience: difficult to get this robust on the 10-20% level
  - some issues using thermal-radiation- or resistance-based observables:
    - calibration w.r.t. actual individual wire (peak) temperature
      - wire breaks at the weakest link – highest not average temperature
      - effective wire diameter – sublimation near beam axis over time
      - ρ(T) non-linear dependence (+ wire diameter)
    - wire emissivity changes at those temperature & changes over time
    - uncertainties due to cooling via secondaries
    - sensor/electronics EMI due to beam wake fields & trapped modes, ...

- Advantages of beam-based BLM procedure:
  - intrinsically includes and is insensitive to actual optics and orbit errors
    - assumes machine reproducibility ↔ main working assumption for SIS18/100
  - relative calibration, little dependence on:
    - actual beam impact parameter (linearisation around working point)
    - BLM electronic gain (as long as it is stable in time ↔ determines frequency of re-calibration)
    - particle species & extraction energy
  - Provides a lower (safe) threshold limit
    - N.B. other sources may produce similar loss patterns/signals – however, wire is still protected under these circumstances (trade-off between 'protection vs. availability' may be required though)

Summary

- Integration into Commissioning/Controls Environment
  - 'protons(ions) lost/second' impractical → keep native 'Gy/s' observable
    - permits x-calibration with rad-monitors
  - proposed BLM sensitivity and dynamic range sufficient for FAIR ~10^4 U^{28+}/s @ 2.7 GeV/u
  - Trigger/threshold comparison based on running averages
    - 6 sum-filter (one per decade) from 100 us → 10 s (+10^3 sensitivity/dyn. range, $\tau_{BLM\text{-}IC}$≈40 us)
    - One threshold function of time per sum-filter (@ 1 kHz, $R_{warning} = (n<1) \cdot R_{dump}$)
      - brute force table ~ 330 kB/cycle vs. optimised (1000 samples) 30 kB/cycle
    - max/peak-detection for running sums
  - Relative beam-based thresholds (i.e. fix losses around established set-up performance)
    - target: 'Day I' (SIS100, 2020) – with open thresholds → 'Day-N': activate threshold comparison as needed

- Proposed use-cases:
  - Integration into Transmission Monitoring
    - Relative loss profile measurement → warn/trigger on anomalous losses
    - ALARA : BLMs dN/dt more sensitive than transformer-based dI/dt measurements (& cross-calibration with rad-mons)
  - Integration into SIS18/100 Machine Protection
    - protection of sensitive devices, e.g. electro-static septa wires
    - Test of collimator hierarchy and absorber scheme

- N.B. need to evaluate BLM-MP integration for machines/transfer-lines/targets after SIS100 where primary beam intensities/energies might be extracted into (HEBT, CBM, SuperFRS, APPA, ...)