Issues and required Improvements related to Feedback Operation after LS1

Ralph J. Steinhagen,

CERN, Beam Instrumentation Group

'Hitchhiker's guide to LHC Feedbacks'

DON'T PANIC

- <u>FBs worked from 'Day-I' for the first three years of LHC</u>
  - early LHC operation took the 'edge off' from otherwise more complicated/demanding issues

    (FIDEL, new machine, model uncertainties, etc.)

    → liberated resources for fast LHC commissioning
  - Pushed envelope w.r.t. required FB performance
  - This review is about identifying technical issues and improving them for post-LS1 LHC operation

Impact Analysis

- Some questions that come to mind:
  - What's not working?
  - What do we want to improve and why?
  - By how much do we want to improve?

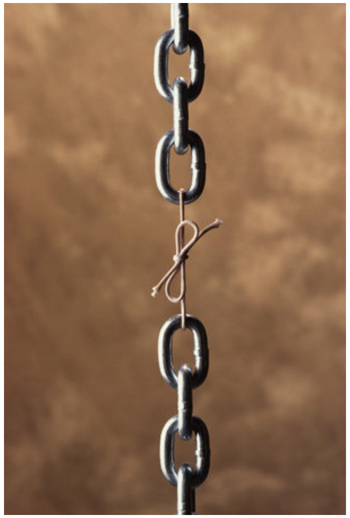
- Scientific/engineering approach: you can only improve what you can measure
  → How to measure/quantify the impact of feedbacks on LHC?

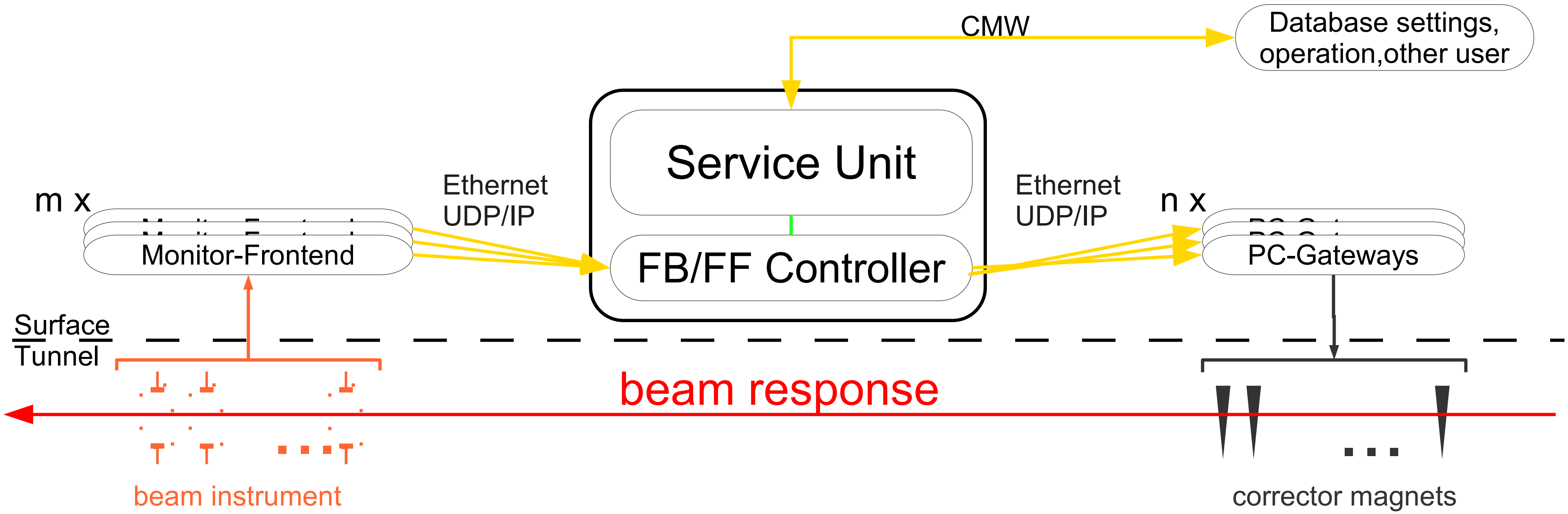
- An attempt of two possible metrics:
  - Impact on machine w.r.t. beam dumps
  - Feedback performance w.r.t. limits on parameter stability and robustness
    - i.e. how much would we gain in terms of bandwidth or stability margin

Common Feedback/Feed-forward Control Layout
Control implementation split into two sub-systems:

- LHC feedback systems most visible faces are:
  - Feedback Controller (OFC): actual feedback controller logic
  - Service Unit (OFSU): Interface to control system/the world

- However 3500+ devices (~130 FE) and many technical services like FESA, CMW, timing, technical network involved
  - Overall strength depends on the reliability of the weakest link
  - One of this review's aim: identify 'what' and 'were' to improve





Feedback & Co. Failure Statistics

- Laurette@Evian'11: "[in 2012] … => Should be left with 2-3 dumps! but what will we find if beams are not dumped?"

- Consider only PM with E>450 GeV, $I_{B1/2}>10^{10}$ protons/beam, and …
  - only dumps, no near-misses, events causing losses without dump, or events that have been recovered by OP or the sequencer
  - PM comment containing "FB", "Feedback", "OFC", "OFSU", "BBQ", "BPM", "RT", "Orbit", "Tune", "Instability"
  - OFC/OFSU crash reports
  - … plus some cleaning up of "no orbit change", unrelated and "OK" statements

	Total PMs:	FB & Co:	Percentage:
2010	453	8	1.7%
2011	684	30	4.4%
2012/13	851	28	3.3%

- Disclaimer: numbers to be taken indicative and not as absolute

Feedback & Co. Failure Statistics
An Attempt to Classify into Sub-Groups & Trends

- Some failures are an interplay between multiple sub-systems (double counting!)

  (*counted only if affecting feedback and/or during RAMP & SQUEEZE)

	FB	OFC	OFSU*	BBQ	BPM*	QPS/ COD	Orbit	Q/Q'
2010	8	2	0	2	0	3	9	0
2011	30	2	5	18	3	14	13	6
2012/13	28	4	10	1	7	1	17**	30**

- BBQ/Tune-FB/QPS interplay may become important again after LS1 if we cannot raise the QPS thresholds … need to preserve this improvement.

- Some system failures related to problems with infrastructure where equipment owner has limited control over (i.e. FESA, CMW, timing, TN network)
  – For what it's worth: indicates the trends and area to be looked further into.

- Marked "**" cases not necessarily attributed to FB failures but illustrate the increased criticality of the control of orbit and Q/Q' during 2012:
  - Smaller β* → tighter collimator tolerances ↔ tighter orbit tolerances
  - Larger bunch intensity/tighter collimators(?) → increased single bunch instabilities

→ Should address this if we want to push the envelope (i.e. through new/better BI diagnostics)

Main Causes of Feedback induced Losses/Stressing of the MPS

A) Measurement quality (BPMs, BBQ) → transients on orbit, tune
→ collimator induced losses/QPS trips of RQT[D/F] → dump
→ outside the scope of this review, but a main issue w.r.t. Tune-FB

B) Front-end/SW infrastructure problems: FESA, CMW, Timing & network
→ covered in detail in Stephane's talk

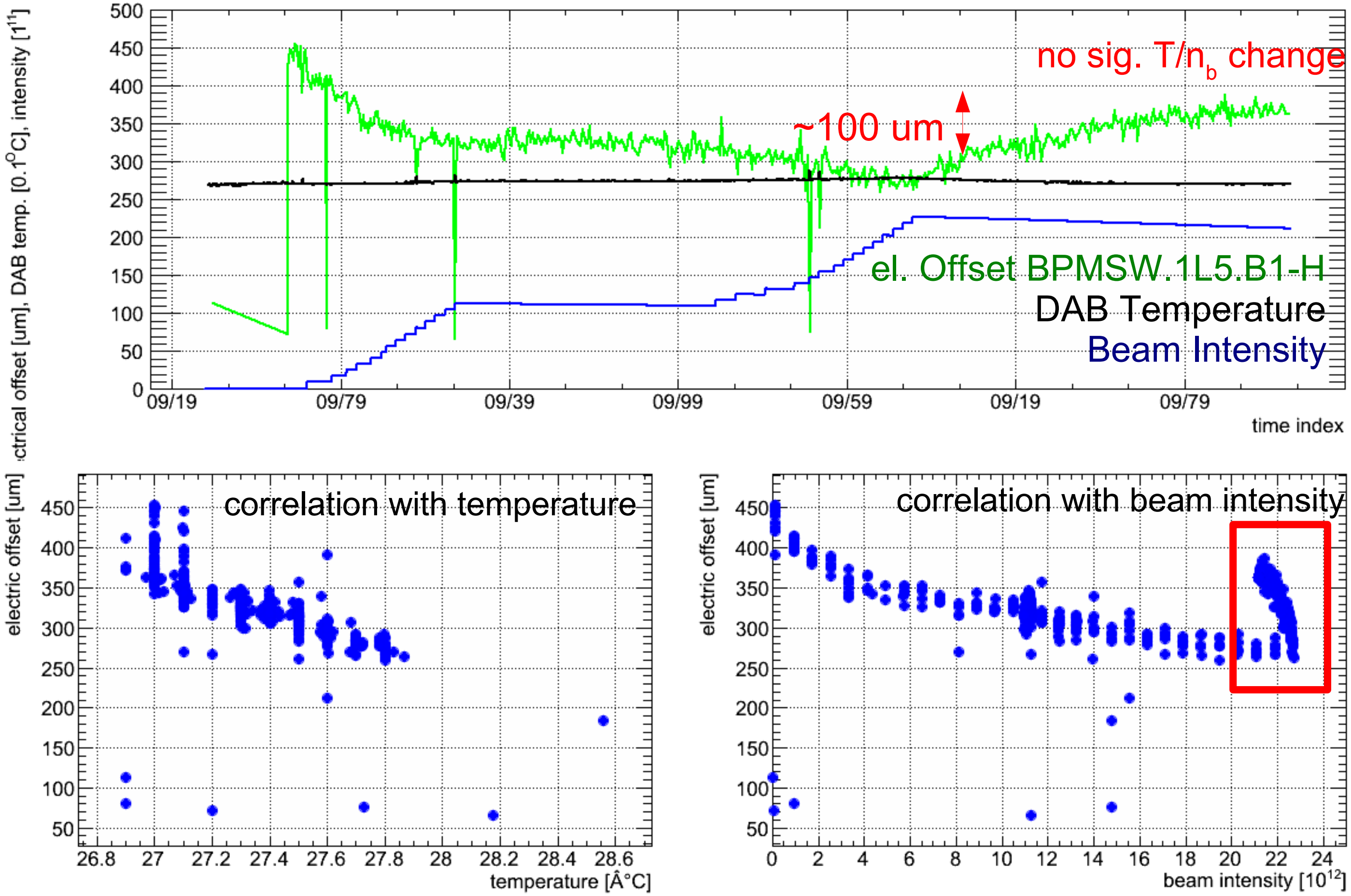
- Threading issues, non-RT behaviour, crashes, external load factor i.e. slow clients, technet switch overloads
- non-RT behaviour of input data stream → no data → pausing feedback → exceeding loop latencies, either
  a) no correction → orbit drift → dump
  b) classical FB instability (too high BW)→ additional orbit drift → dump
- Invalid data – most believed to be/being fixed (i.e. timing, memory corruption)

C) Insufficient loop stability margin

- mismatch between actual optics and the one used by the OFC
- Optics re-computation errors – being fixed in OFSU
- FB running at the design stability limit

BPM Stability

- Installed RF commutation switches directly after BPMSW.1[L/R]5.B[1/2] to assess electrical offset drifts (RF cables, WBTN front-end, integrator, etc.):

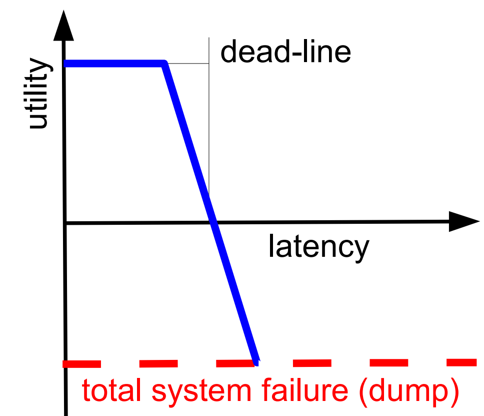


- Measurement drifts ~100 um/h w/o significant temperature changes
→ Orbit-FB may convert these measurement errors into real orbit shift

Definition of 'Real-Time'

- … "A system is said to be real-time if the total correctness of an operation depends not only upon its logical correctness, but also upon the time in which it is performed. [..] are classified by the consequence of missing a deadline:
  - Hard – Missing a deadline is a total system failure.
  - Firm – Infrequent deadline misses are tolerable, but may degrade the system's quality of service. The usefulness of a result is zero after its deadline.
  - Soft – The usefulness of a result degrades after its deadline, thereby degrading the system's quality of service."

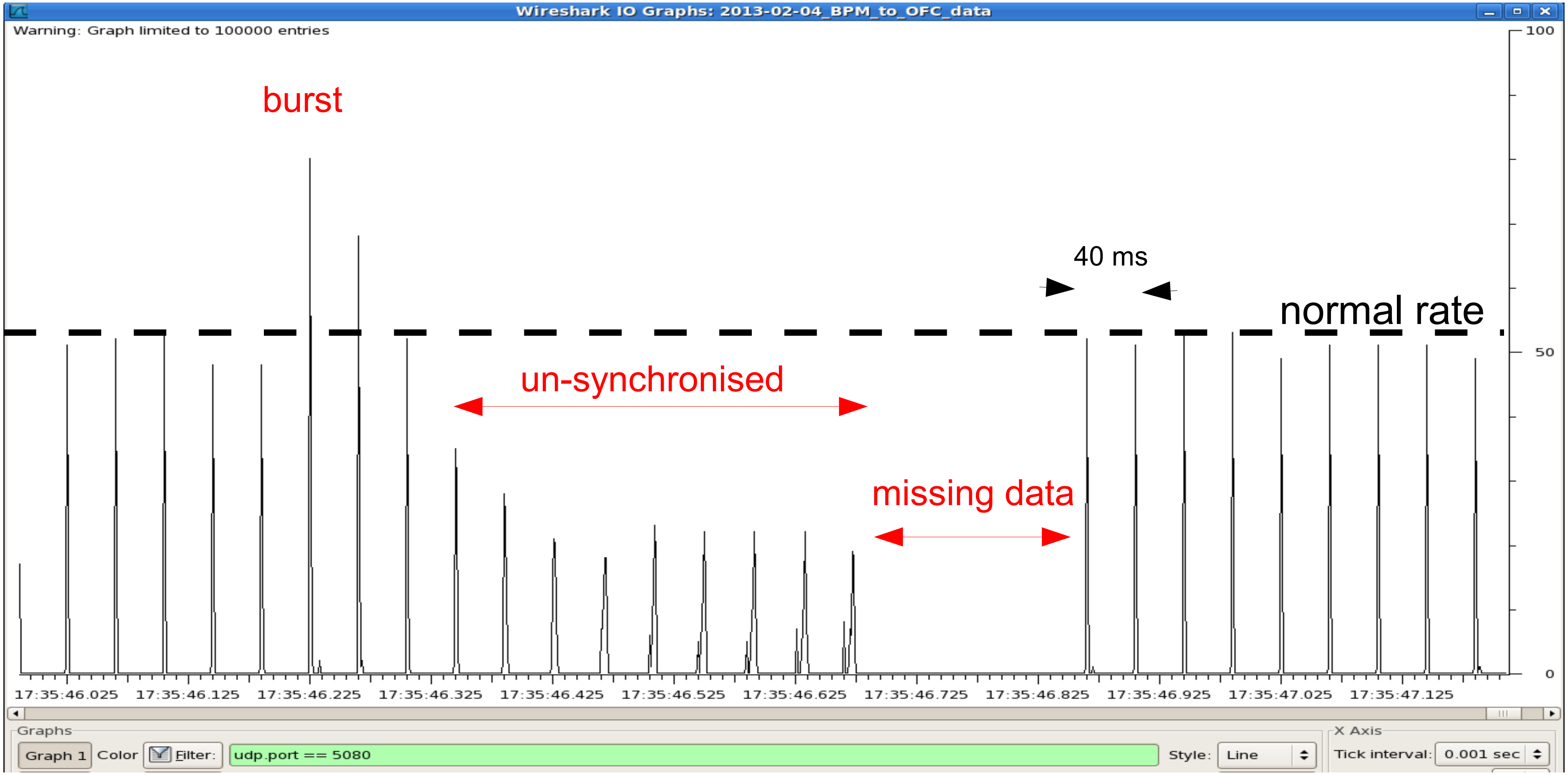
- LHC feedbacks are 'firm real-time systems'
  - some (limited) margin on occasional missing data
  - additional latencies are critical for loop stability, e.g. missing packet reduces phase margin by ~15°@1Hz (0° < stable < 90°< unstable < 180° – max. instability)



$$\Delta\varphi = 2\pi f_{bw} \cdot \Delta t_{delay}$$

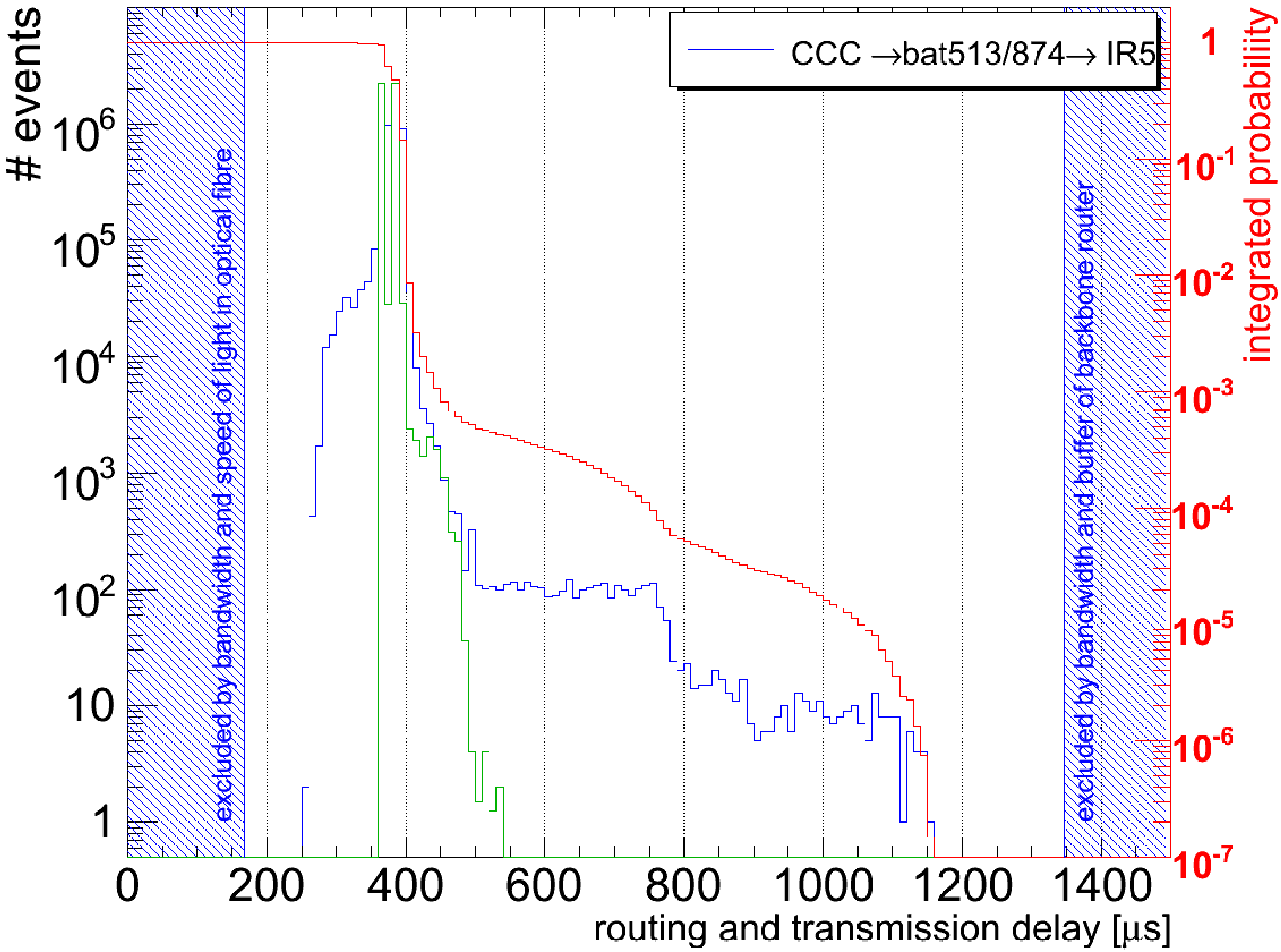
BPM-to-OFC UDP Transmission Errors – Example

- … perceived in the CCC as 'BPM disco' effect (since 2010)
- Low-level: bursts, non-synchronised or missing data at the OFC



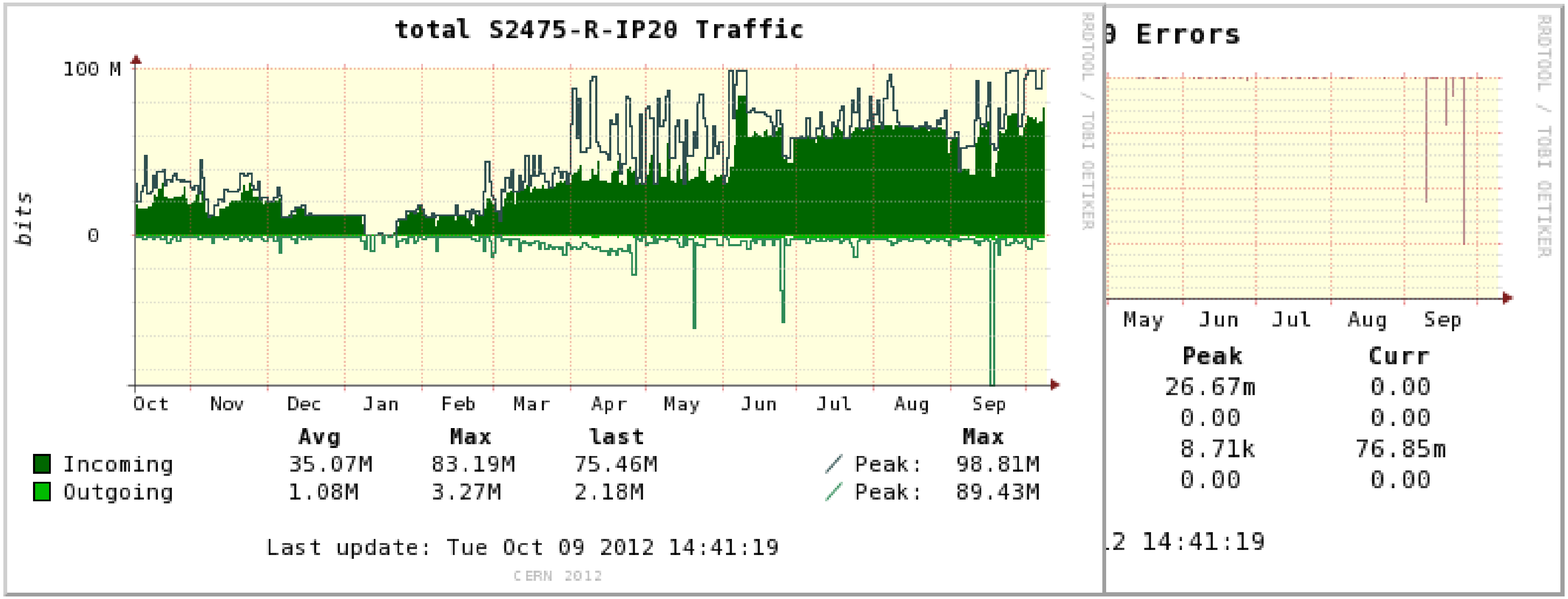
- Compromises OFC data concentration → latencies → FB loop instability (missing packet ≈ 15° loss of phase margin @1 Hz) → losses on collimators → dump

Tracking of detailed Real-Time Latencies per Sub-System
Example: Technical Network



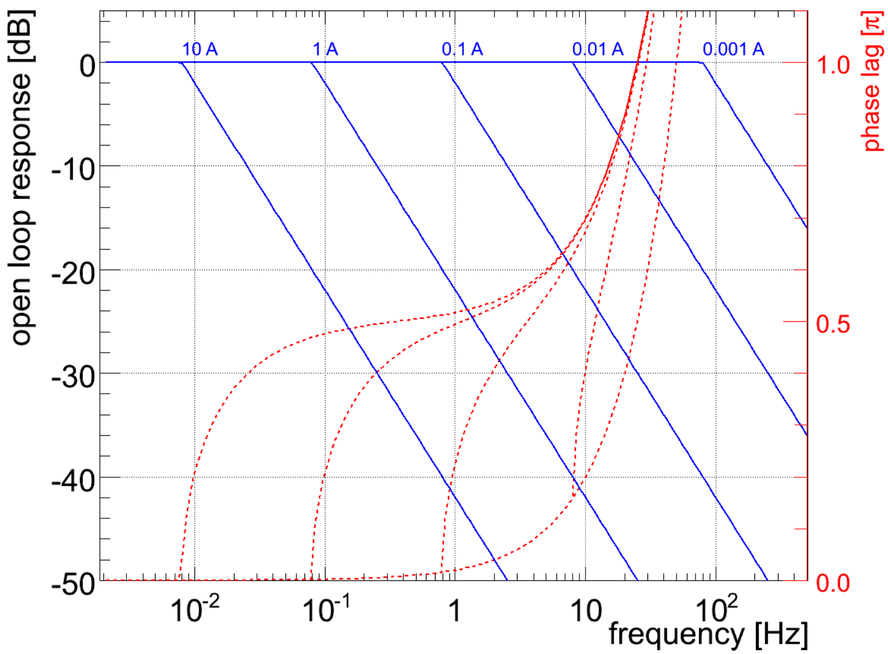
Overload of LHC's Technical Network Infrastructure

- Increased demand of data, new instrument and prototype systems increased the overall technical network load,
  - i.e. LSS4 real-time data competing with other clients causing loss of BBQ data and affecting Q' measurement (sign errors)

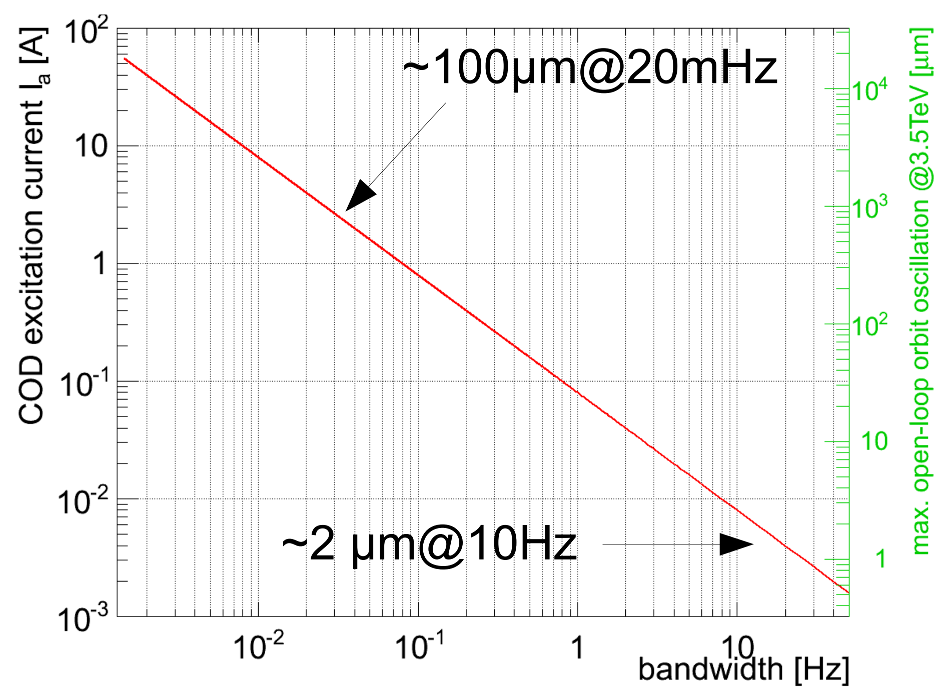


- Given switch has been upgraded during the last Christmas TS
  - may possibly discover other (new) bottlenecks after LS-1 due to new systems being installed/commissioned

- Closed-loop bandwidth and phase margin depend on excitation amplitude:
  - + non-linear phase once rate-limiter kicks in...



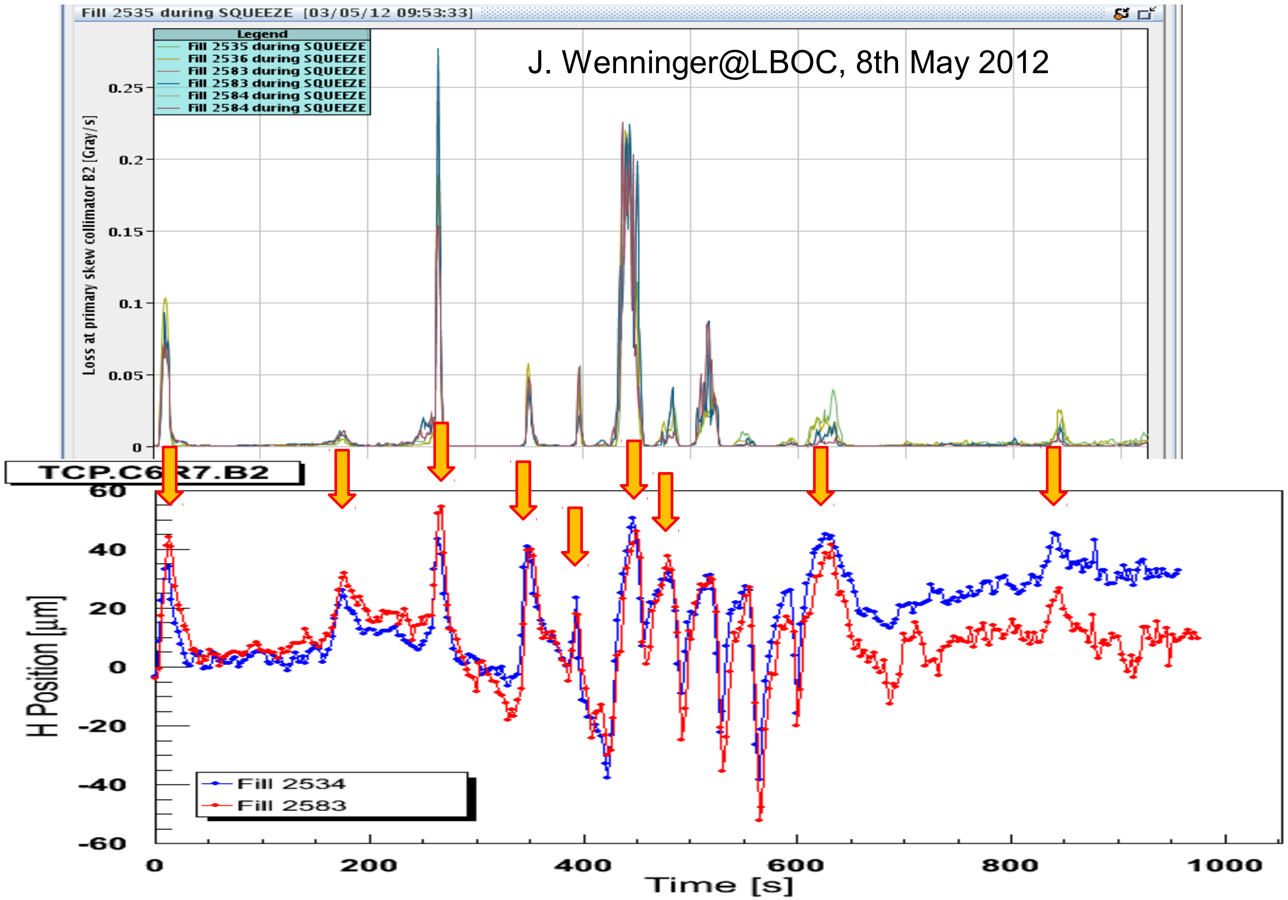
ΔI=0.1A ↔ Δx≈32 μm@β=180m



- Consider ~35μm@1Hz as effective bandwidth @4TeV (assuming 3C bump)
- Many latencies become a non-issue for f_{bw} < 0.1 Hz

Orbit Stability during β*-Squeeze

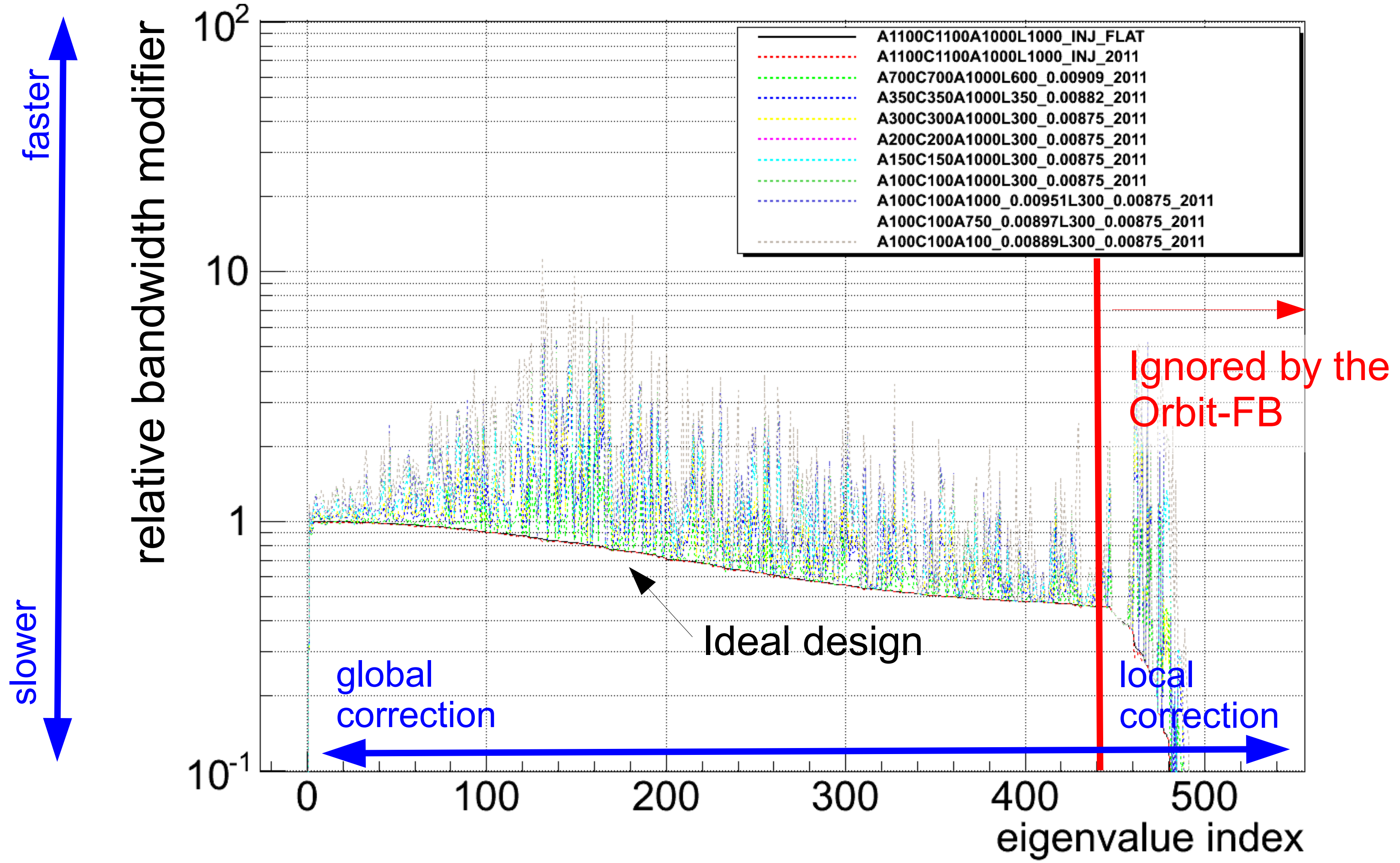
- Losses and orbit movement at H-TCP.C6R7.B2 well correlated



- Maximum drift rates of 40 um/s → (close to) limit of Orbit-FB at 4 TeV
  - Underpinned by FB instability observation for 5x bandwidth increase
- At this speed, OFC needs to operate with correct optics

Correction during Squeeze with imperfect Optics

- Bandwidth modifier w.r.t. eigenvalue index (<1 more stable, >1 diminishes stability margin)



- Typ. opertional bandwidth <10% of maximum possible (sometimes too slow)

Planned Improvements for after LS-1 I/III
Measurement Data Integrity

- Temperature stabilised BPM racks (should minimise but not remove systematic drifts)
- BPM signal RF commutation switches on BPMSW's (already deployed in IP5)
  → identify and compensate measurement errors w.r.t. real orbit drifts
- Redundant IR-BPM read-out electronics (Diode-Orbit acquisition), tbd:
  – naming convention of additional channels
  – integration w.r.t. WBTN-based BPMs
  – initial deployments only at BPMSW.1[L/R][1,5,8,2].B[1/2] (vs. full Q1-Q7)
- BPMs in TCTP collimator – non-trival integration to be discussed/agreed upon
  – Orbit computation needs settings of gap centre, opening and angle
  – new orbit reference management (collimators are moving targets vs. collimator move according to the target? ColUS?)
- ADT as Q/Q' source (important SW integration effort)
- Split BBQ use-cases into independent chains, i.e. optimised parameters for Q', Tune-FB, coupling, beam-beam/stability studies – implementation tbd.

Required Improvements for after LS-1 II/III
Improvements of Loop Stability

- Establish true 'firm real-time' constraints on input data
  - review BPM/BBQ UDP transmission robustness and implementation (in particular the interplay with CMW, FESA, proxies etc.)
  - decouple RT traffic from those needed for operation and others (TN QoS, IT-CS)
- Operate feedback settings closer to actual machine parameters/requirements
  - Optics/reference changes during squeeze
  - Gain scheduling based on beam mode/operational scenario
- Impact of LHC mode-operation changes on feedbacks (reference management)
  - 'Collide & Squeeze', 'Ramp & Squeeze', dynamic vs. in-steps???
- validate BPM functionality at least once per fill – foreseen but not executed systematically (takes < 1 min and detects dead BPMs)
- Should re-visit option of having a dedicated full feedback test-bed

Required Improvements for after LS-1 III/III Diagnostics and Tracking

- Attribute errors to the specific sub-systems
  - Finer granularity of post-mortem reports (i.e. system expert feedback and sub-categories)
  - better monitoring of technical infrastructure (FESA, CMW, timing, network) – bits and pieces are there but expert-only features

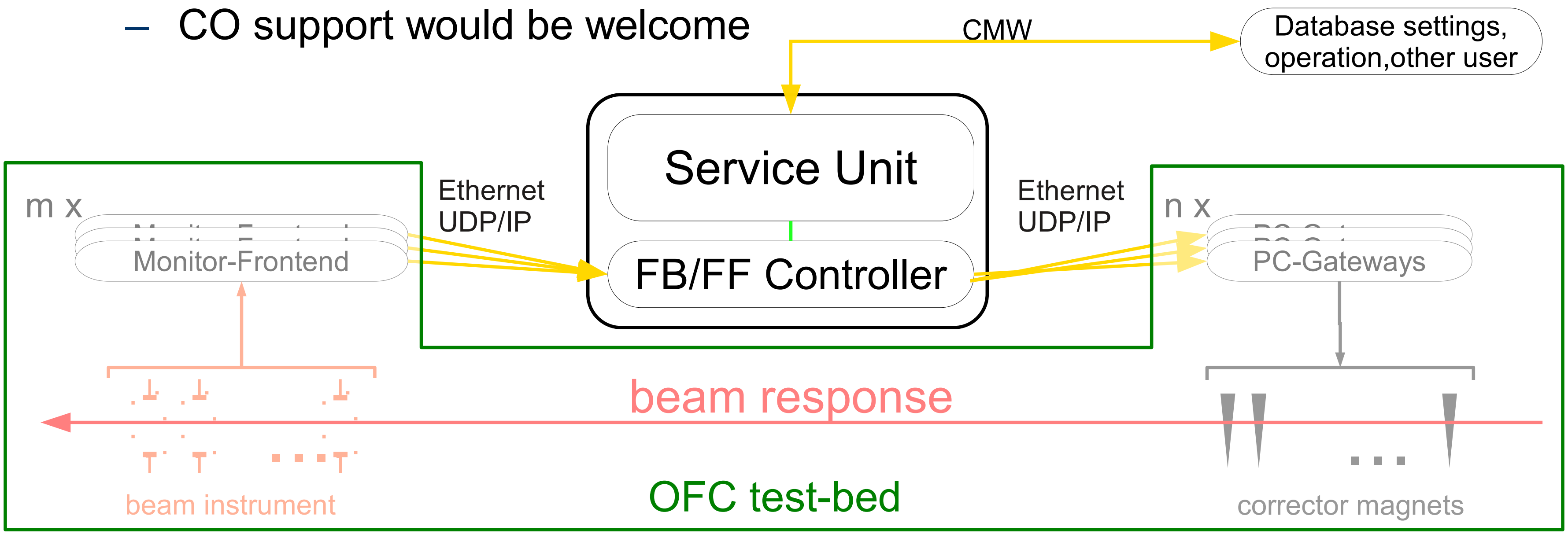
- Better pre-warning, better GUI integration, particularly concerning overview (needs input from OP concerning level of detail)

- Re-establish 'OFC testbed' – real-time beam physics simulation to test closed-loop FB, latency footprints, error recovery etc.

- Miscellaneous (pending since 2011):
  - move remaining blocking TCP-based OFC↔OFSU comm. to UDP
  - more rigorous CPU shielding (including driver & non-FB services)
  - OFSU: user accessible 25 Hz data & PM buffer of all feedback states/data
  - Improve transparent full recovery after an OFC/OFSU crash
  - Orbit, Q/Q' and optics reference control, hot spare/additional systems
  - remove OFC functionality that should be covered in the OFSU (i.e. ORM recalc.)

Proposal to revive LHC OFC Test-Bed Concept

- Old Concept and used at the SPS to assess controls aspects, orbit control strategies and possible issues prior to LHC operation.
  - Numerically expensive (10x OFC f_s): OK for SPS but was out-of-reach with avail. HW for simulating full LHC beam response in 2004/2005 (what concerns orbit, Q/Q')
  - 2013: memory bandwidth and CPU performance improved → an option post-LS1?
- Would allow to test performance, control and integration aspects (+OP training)
- Additional validation tests prior to deploying a new OFC/OFSU version at LHC
  - CO support would be welcome



Summary

- Generally, feedback performed their designed job. Pushing LHC machine parameter envelope also implied increased performance constraints on Feedback operation (notably orbit stability during squeeze)
  → Need to improve FB sub-systems to keep up with LHC progress post-LS1

- Main issues of 2012 dumps with beam related to:
  - Beam measurement quality
  - Front-end/SW infrastructure problems: FESA, CMW, Timing & network
  - Insufficient loop stability margin (tighter constraints than in 2010/11)

- A lot of progress and issues have been already addressed during 2012/13
- A set of important improvements are under way during LS1, notably
  - Temperature controlled racks & new Diode-Orbit ACQ for the IR BPMs
  - Improvements in the service infrastructure (CMW, TechNet, etc.)

- Need better diagnostics, warning and status indication of overall infrastructure, and better tracking and finer granularity of error assessment