Feed-Forward / Feedback required

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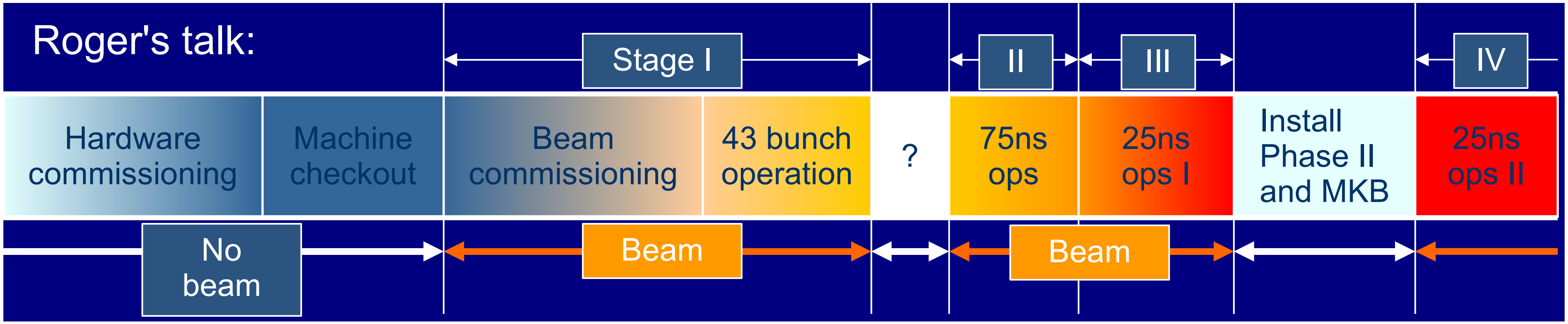
Will cover ...

- stabilisation of key beam parameters:
  - Orbit, Energy, Tune, Chromaticity and Coupling
- Stage I operation (43x43 bunches)
  - Summary of requirements
  - Summary of expected drifts
  - Requirements for feedbacks
- Not covered:
  - Control of higher multipoles (b_4, b_5, ...)
  - Luminosity
  - Fast transverse feedback (→ W. Höfle)
  - Details on instrumentation (BPMs, BBQ, Q-PLL, ...)
    → Providers session on Tuesday

Preliminary Remark:



- Requirements and time-line of key beam parameters control depend on:
  1. Capability to control level/ tolerances of particle losses in the machine
     - Machine protection & Collimation
     - Quench prevention
  2. Commissioning efficiency
  3. Operational efficiency: optimisation of (integrated) luminosity
  4. ...

→ requirements on Orbit, Energy, Tune and Chromaticity scale rather with total beam intensity and beam energy than with stages.

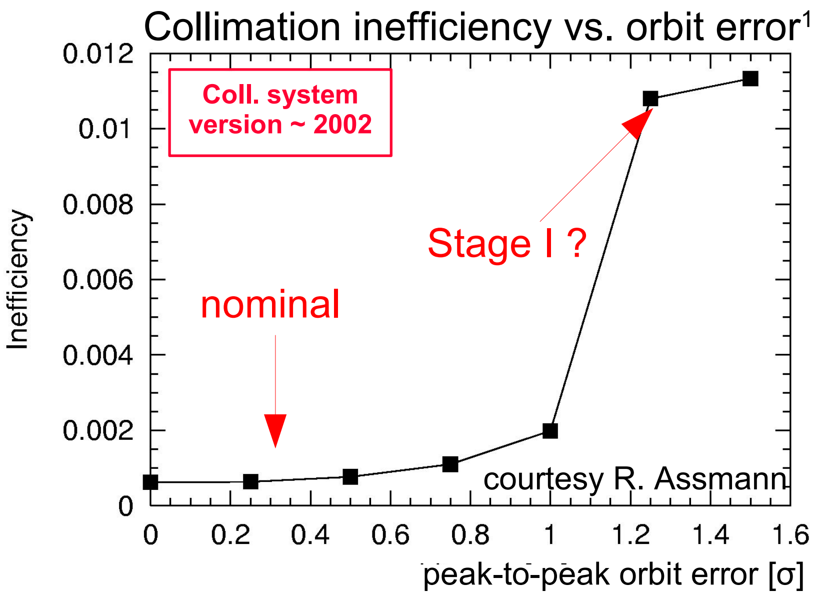
Requirements on Orbit

- Example: Collimation System, Phase I: 43x43 → $N_{max} \approx 5 \cdot 10^{12}$ protons/beam
  - required collimation inefficiency[1,2]:

$$\eta = \frac{\tau_{min} \cdot R_q \cdot L_{dil.}}{N_{max}}$$

  - Min. accept. lifetime: $T_{min} \approx 10$ min.
  - Dilution length: $L_{dil} \approx 50$ m
  - Quench level (@7 TeV) R_q: $R_q \approx 7.6 \cdot 10^6$ prot./m/s

  → η < 0.05 (≈ single stage system)



- Distinction global/local less obvious, expected injection aperture (arc) ~7.5 σ
  → local requirements ≈ global requirements[3]
- Many more less strict requirements → see additional slides for details:
  machine protection, minimisation of feed-down effects, beam instrumentation, [..]
- Orbit stability of < 1 σ sufficient for ≤ 43 bunches ?!?
- Nominal: ≈ 0.3 σ locally (collimation) and ~ 0.3 σ globally (machine protection[3], preserving scrubbing efficiency, ..)

[1] R. Assmann, "Collimation and Cleaning: Could this limit the LHC Performance?", Chamonix XII, 2003
[2] S. Redaelli, "LHC aperture and commissioning of the Collimation System", Chamonix XIV, 2005
[3] R. Steinhagen, "Closed Orbit and Protection", MPWG #53, 2005-12-16

Requirements on Energy

- Energy matching between of SPS → LHC
  - horizontal orbit corrector magnets adjust LHC energy
  - residual non dispersion orbit perturbation needs further correction (e.g. → orbit FB)

- A priori not urgently required for low intensity beams, but
  - may keep capture losses below an acceptable limit
  - minimises abort gap population & feed-down of higher multipoles

→ favourable once running with high intensity

- Required[1] initial momentum stability: $\Delta p/p < 1\cdot 10^{-4}$
  - Simplifies setup of nominal beam after commissioning pilot
- Nominal[2]: $\Delta p/p < 1\cdot 10^{-4}$

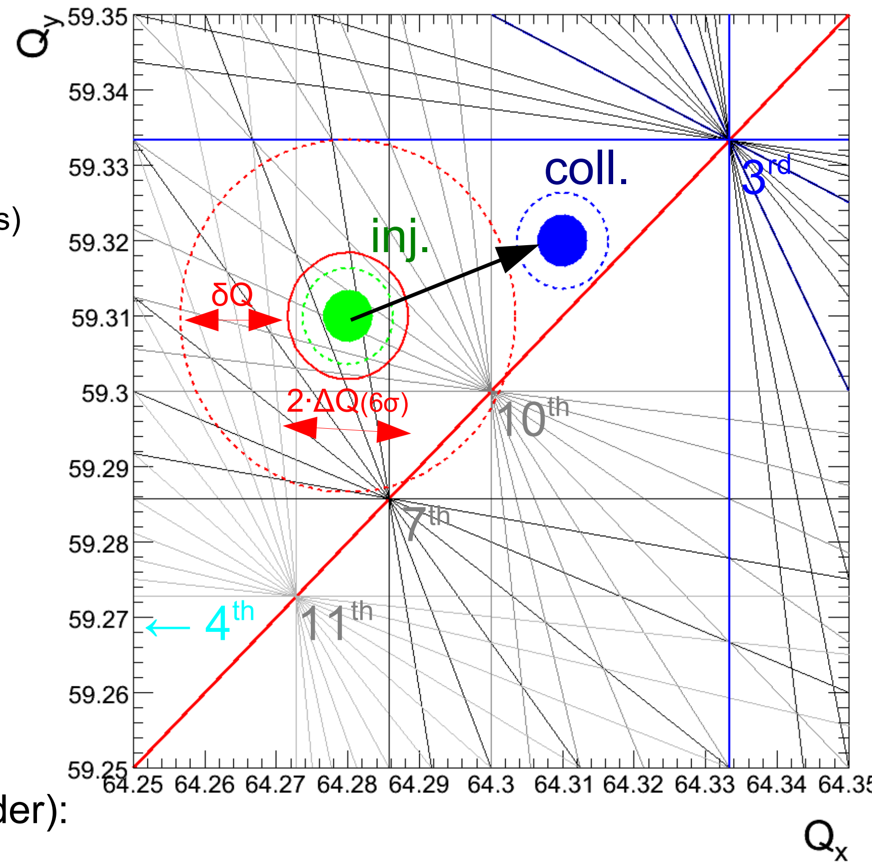
[1] E. Chapochnikova, private communications
[2] E. Shaposhnikova, "Abort Gap Cleaning and the RF System", Chamonix XII, 2003
[3] T. Linnecar, "RF Capture and Synchronisation", Chamonix XII, 2003

Requirements on Tune and Chromaticity

- Tune spread $\Delta Q|_{av} \approx 1.15 \cdot 10^{-2}$
  - fixed by available space in Q-diagram
  - Working assumption: (first order: no non-linear effects, avoid 3rd and 4th order resonances)

$\delta Q \leq 0.015 \rightarrow 0.003$
(early commissioning → 43x43)

  - Nominal[1,2]: $\Delta Q \leq 0.003$ (inj.) $\delta Q \leq 0.001$ (coll)



- Chromaticity
  - SPS: $\Delta p/p$: $2.8 \cdot 10^{-4}$
    (actual $\Delta p/p$ given by SPS → LHC inj.)

→ allowed max lin. chromaticity (5-6 σ, first order):

$$Q'_{max} \propto \frac{\Delta Q_{av}}{\Delta p / p} \quad \rightarrow Q'_{max} \approx 10 \ \& \ Q' > 0 \ !$$

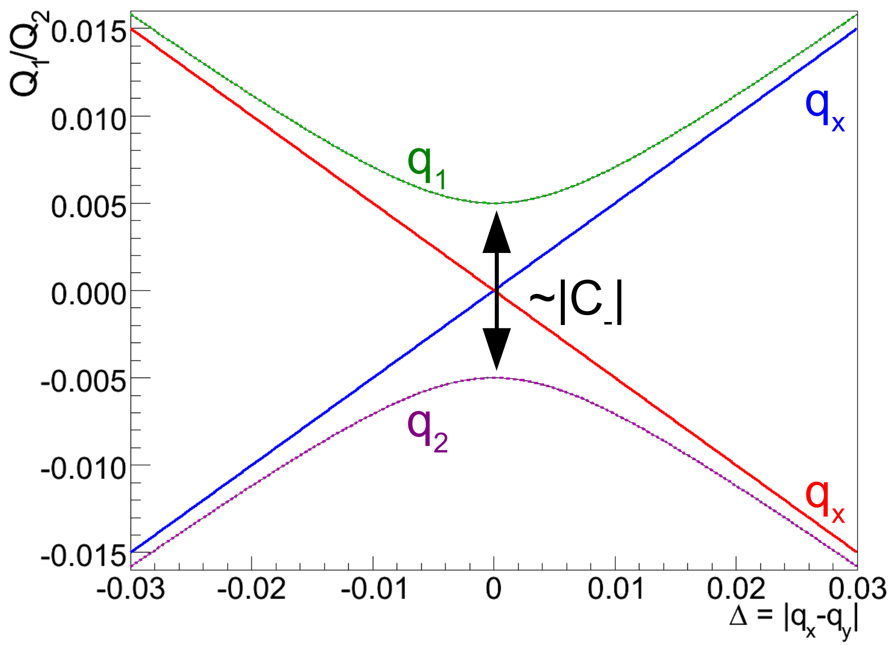
  - Nominal[1,2]: $Q'_{max} \approx 2 \pm 1$

"Numbers are estimates, other more/less strict choices are of course possible – commissioning will clarify real requirements!"

[1] S. Fartoukh, O. Brüning, "Field Quality Specification for the LHC Main Dipole Magnets", LHC Project Report 501
[2] S. Fartoukh, J.P. Koutchouk, "On the Measurement of the Tunes, [..] in LHC", LHC-B-ES-0009, EDMS# 463763

Requirements on Coupling

- Minimum distance Δ_- between tunes given by coupling c_
  - LHC injection: $\Delta_-=|q_x-q_y|=0.03$, collision: $\Delta_-=0.01$



  - Closest tune approach → c_-«0.03 and c_-«0.01 respectively
- Requirement for other feedbacks that rely on decoupled planes
- Proposal for alternate higher tune split[1]: $\Delta_-=0.1$ ($q_x=0.285$, $q_y=0.385$)

[1]S. Fartoukh, “Commissioning tunes to bootstrap the LHC”, LCC #31, 2002-10-23

Expected Dynamic Perturbations vs. Requirements

- From Decay/Snap-back expected dynamic perturbations* (MB & MQ)
  - For details, please see additional slides

	Orbit [σ]	Tune [$0.5 \cdot f_{rev}$]	Chroma. [units]	Energy [Δp/p]	Coupling [c_]
Exp. Perturbations:	~ 0.5	0.014 (0.06)	~ 70 (140)	± 1.5e-4	~0.01 (0.1)
Pilot bunch	-	± 0.1	+ 10 ??	-	-
Stage I Requirements	± ~ 1	±0.015→0.003	> 0 ± 10	± 1e-4	« 0.03
Nominal	± 0.3 / 0.5	±0.003 / ±0.001	1-2 ± 1	± 1e-4	« 0.01

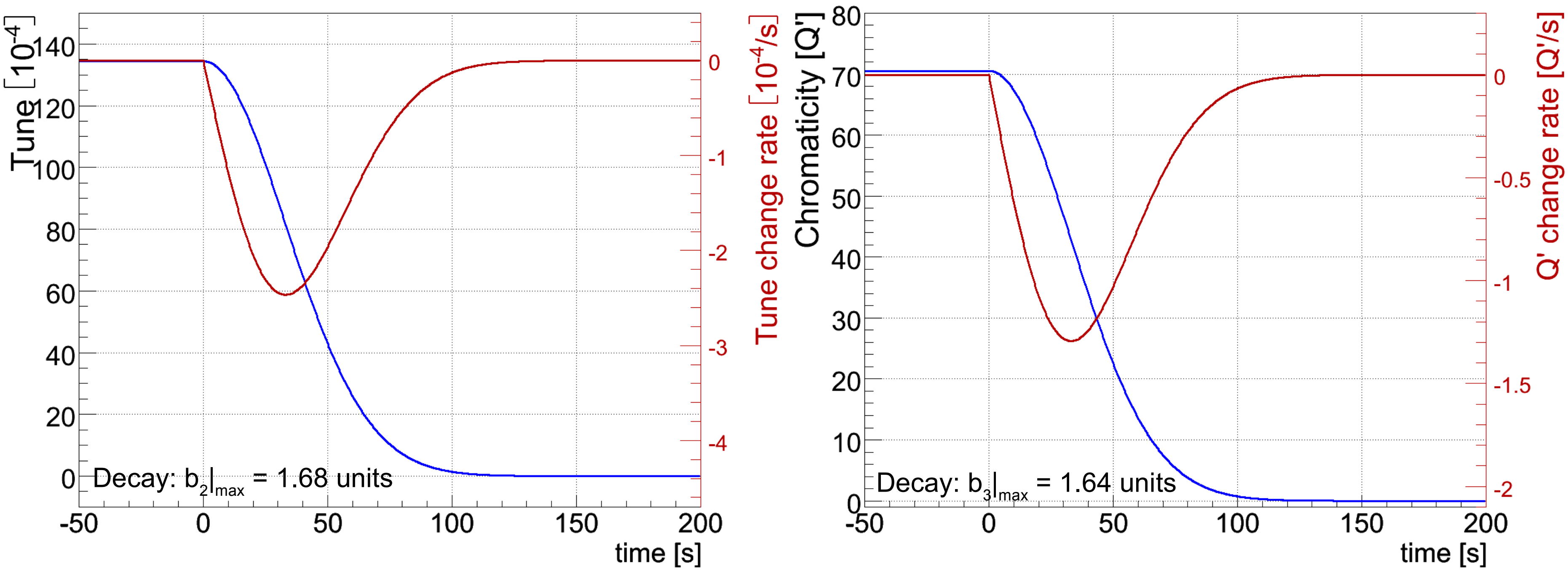
- Chromaticity is the most critical parameter to control
  - defines lifetime and dynamic aperture (= losses) inside the ring
  - Tune is less critical but its measurement a pre-requirement for above
- Require coupling control esp. at start of ramp to enable other controls

- Control of orbit is the easiest one
  - Measurement and correction scheme well established
  - consequence of having BPM with 100k turn acquisition: → Energy feedback
- Stage I: injection more relaxed (except Chromaticity)

* numbers in brackets are 'worst case'

Expected Time-Scales of Perturbations

- Orbit & Energy:
  - Injection (ground-motion, Δb_1): ~ 0.4 σ/10 h → Control @1 Hz sufficient
  - Snap-back: 0.3 σ/100 s → Control @1-10 Hz ??
  - β*-Squeeze: 0.1 σ/s → Control @10++ Hz OK

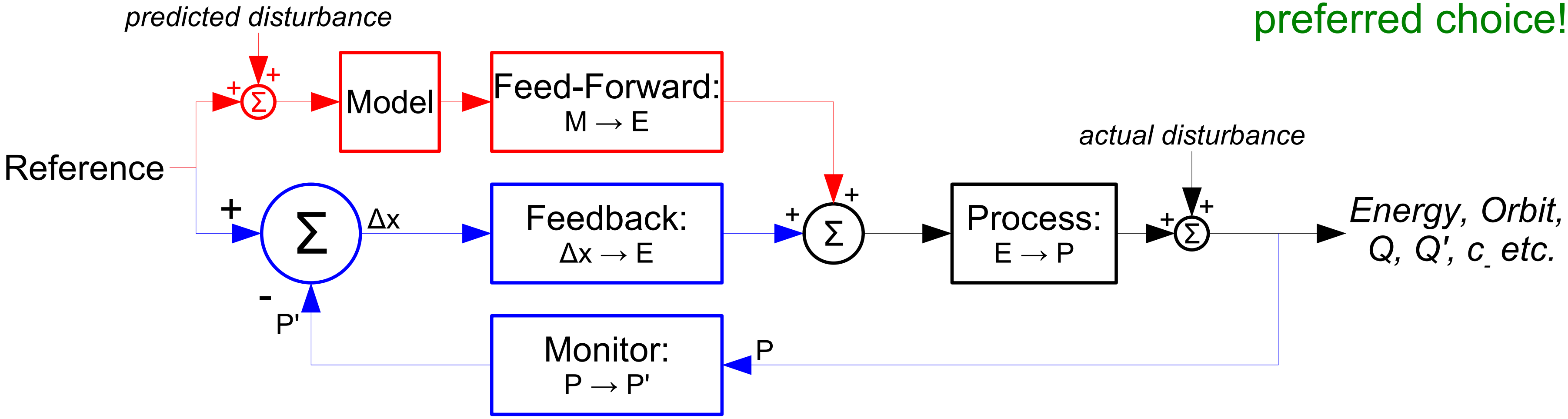


- $(\Delta Q'/\Delta t)_{max}$ < 1.3 units/s & $(\Delta Q')_{max}$ < ~ 10 units
  → (measure &) control chromaticity every ≈ 10 seconds (or faster)

Parameter control, either through...

- **Feed-Forward**: (FF)
  - Steer parameter using precise process model and disturbance prediction
    - mostly using magnet model predictions based on magnet measurements
    - The (only) choice for the sector test and very first LHC injection
- **Feedback**: (FB)
  - Steering using <u>rough</u> process model and measurement of parameter
  - Two types: within-cycle (repetition Δt<<10 hours) or cycle-to-cycle (Δt>10 hours)

preferred choice!



- From the steering point of view: → All control schemes possible (see Massimo's talk)
- Choice of Feedback vs. Feed-forward
  - depends on available robust beam parameter measurements

Feed-Forward vs. Feedback: Which first?

- In principle: → Work of an operator = manual feedback!
  - (Semi)-automated FB → liberates operators/EIC for more important tasks
  - Expected LHC turn around time is long (hours)
  - Trial-and-Error optimising/learning of “injection, ramp, squeeze...” may
    - potentially cause quenches (→ further delays)
    - will delay total commissioning till first collisions

- Experiences during LEP commissioning, Engineers In Charge (EIC[1]):

  “Many beams lost during ramp due to absence of Orbit & Tune feedback”
    - un-anticipated movement of low-beta quadrupoles....
  - Let's learn from EIC experience:

  → Establish parameter measurement and feedbacks at an early stage!

[1]J. Wenninger, M. Lamont, M. Jonker, G. Roy, P. Collier, H. Burkhardt, ...

Orbit Feedback

- Most advanced feedback[1], main "clients": Collimation & Machine Protection
- Measurement[2,3] and correction scheme well established
  - successful SPS Prototype[4]
  - BPM available from early startup (required for threading the beam!)
  - Does not necessarily require LHC wide BPM/COD synchronisation (slow timing)
    - Either self-triggered @ 1-2 Hz or semi-automatic steering program (coded!)
  - For-free: minimises dynamic feed-downs due to moving orbit

    (e.g. moving orbit in sextupoles and coupling, many other snap-back related effects)

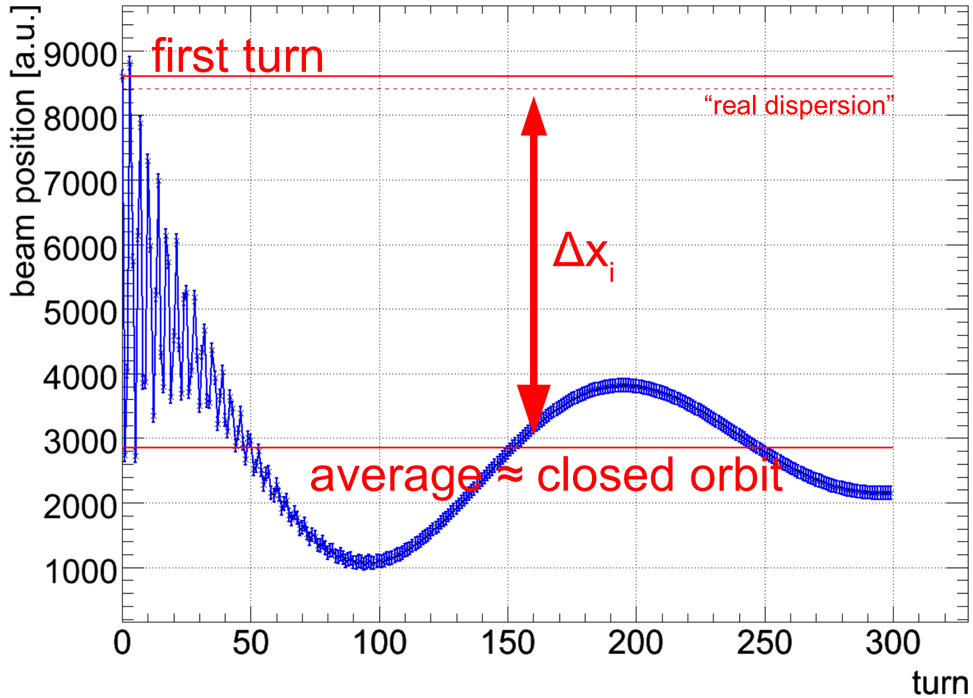
- Proposed baseline should and can be used at an early stage (circulating beam)

  → latest before ramping

- nominal performance (bandwidth f_{bw}≈1Hz, $\Delta x<0.2\ \sigma$) requires:
  - slow timing and beta-beat <20%, coupling is an issue

[1] J. Wenninger, "LHC Orbit Feedback Specification", available on request
[2] E.B. Holzer: "BDI Commitments and Major Issues for Individual Instrumentation" (this workshop)
[3] H. Schmickler: "Running in the Diagnostics", Chamonix XIII
[4] R. Steinhagen, "LHC Orbit Stabilisation Tests at the SPS", PAC05 & CERN-AB-2005-052

- Injection oscillation to estimate injection mismatch $(\Delta p/p)_{inj}$



$$\left(\frac{\Delta p}{p}\right)_{inj} = \frac{\sum_i^N D_i \cdot \Delta x_i}{\sum_i^N D_i^2}$$

local dispersion: D_i
average over
N ≈ 300 arc monitors

- Robust measurement: BPM systematics on Δx_i and D_i cancel!
  - "no" high-precision calibration required
  - Moderate turn-by-turn acquisition Δx ≈ 200 µm (pilot) @ ~300 arc monitors
  - Δp/p resolution ≈ few 10^{-6} → sufficient for nominal operation! (COD hysteresis → Δp/p ≈ $6 \cdot 10^{-7}$)
- Horizontal arc corrector dipole magnets used to adjust LHC energy

Energy Feedback II/II

- Later: Tide compensation (FF or FB possible) to optimise (preserve) aperture
- Minimal requirements for stage I:
  - BPMs:
    - BST (Beam synchronous timing) to trigger on injection of individual batch
    - Turn-by-turn acquisition should not affect (block) orbit acquisition
  - Orbit correction (FB) required to minimise non-dispersion orbit (2^{nd} order effect)
  - someone who actually implements the algorithm in the front-end

- Could be used at an early stage (circulating beam)
  → latest before RF capture losses become an issue

- Traditional tune measurement method: kick and 'BPM 100k turn' acquisition
  - Emittance blow-up, not ideal for continuous feedback
  - Kick is an issue w.r.t. machine protection and collimation:
    Collimation $\Delta x_{max} < 0.3\ \sigma$ vs. desired kick $\Delta x_{min} > 1\text{mm} \sim 1\ \sigma$
    - scrapes the beam!
      → move collimator out → require dedicated low intensity runs
      → worse BPM performance & cycle-to-cycle reproducibility issues
  - backup solution on day 0: comes for free while threading the beam[1]!

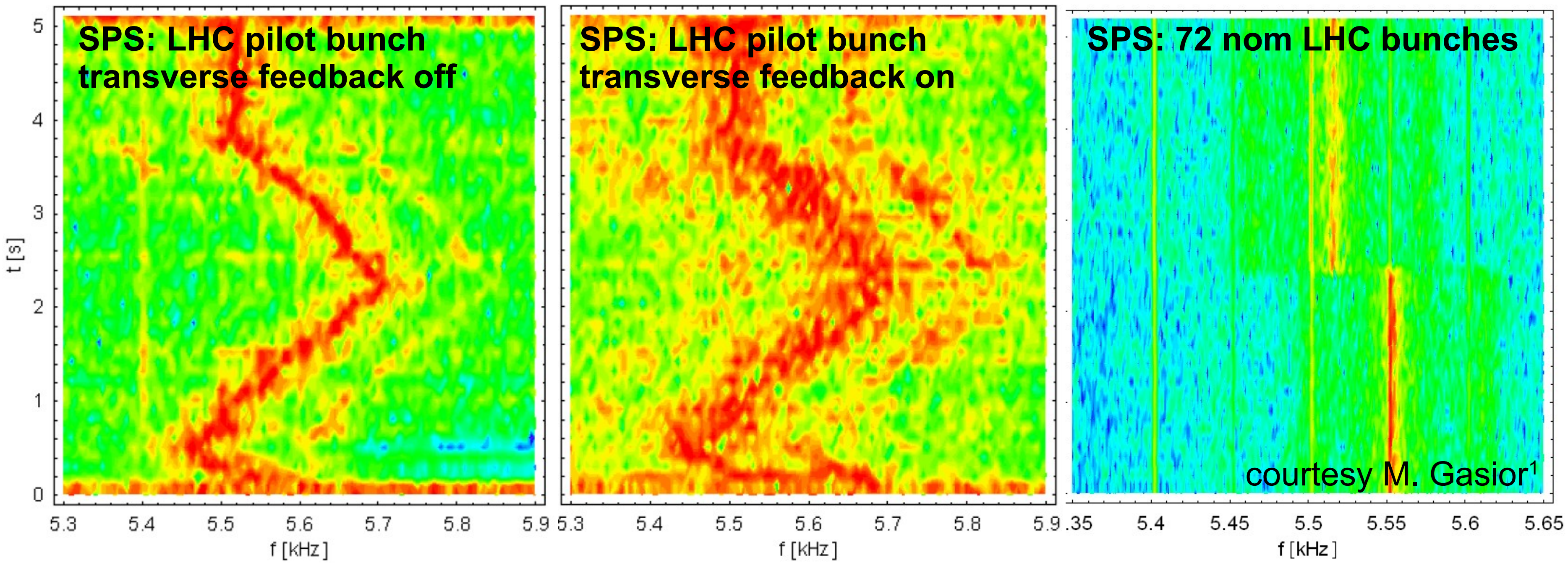
- New method (BI baseline): Base-Band-Q Meter (BBQ)
  - Can measure tune without (or very small) excitation and resolution in the 10^{-4} range
  - Phase Look Loop to enhances S/N ratio of tune signal
    - 0.1 - 10 µm level excitation (depending on beam noise level) → negligible ε-blow up
    - Q-kicker rate limit: PLL-tune measurement @ < 2 Hz → sufficient for Stage I

  → The candidate for feedback use!

[1] J. Wenninger, "Quadrupole Error Localization using Response Fits", LHC-OP #38, 2005-05-08

Tune and Chromaticity Feedback II/III

- Base-Band-Q Meter[1] (BBQ) available from day 0-1 (see R. Jones' talk on Tue.)
- Issues: Potential locking on
  - Synchrotron side bands, however: predicted error δQ~0.005 → maybe OK for Phase I ?
  - Multiple of mains (50 Hz) signal, error δQ~0.002 → OK for Phase I ?
  - H/V-coupling (issue @ HERA → "BLL" and RHIC) & coupled bunch modes[2]
    - Coupling control: pre-requirement for safe tune feedback during ramp



[1] M. Gasior, R. Jones, "The Principle and First Results of Betatron Tune Measurement [..]", LHC Proj. Rep. 853
[2] S. Fartoukh, J.P. Koutchouk, "On the Measurement of the Tunes, [..] in LHC", LHC-B-ES-0009, EDMS# 463763

- Day 0 - workhorse: Classic approach
  - Slow Δp/p modulation and tune tracking: $$Q' \propto \frac{\Delta Q}{\Delta p/p}$$
  - Method used in LEP → proven & robust[1]
  - Requires moderate radio-frequency changes ($\Delta p/p \sim 10^{-4}$) and tune tracking
    - similar issues as tune feedback
  - May be enough to cope with snap-back and ramp induced b_3 drifts (at least during Phase I)

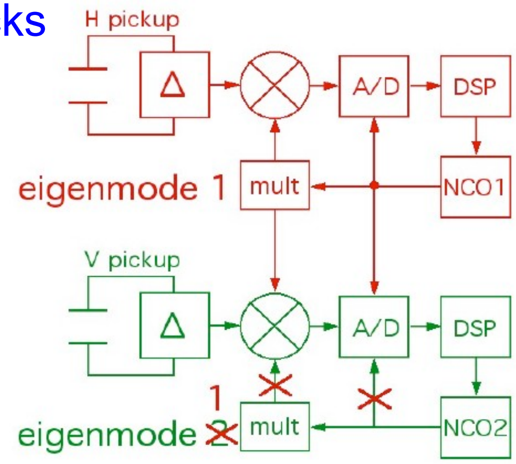
- Day N - new approach: Head-Tail-Chromaticity
  - Presently requires large kicks (ε blow-up, machine protection issues)
  - envisaged to move to a BBQ similar principle

    → continuous Q' measurement without notable ε blow-up
  - Requires time for commissioning and may be not available on 'day 0'!

Coupling Feedback I/II

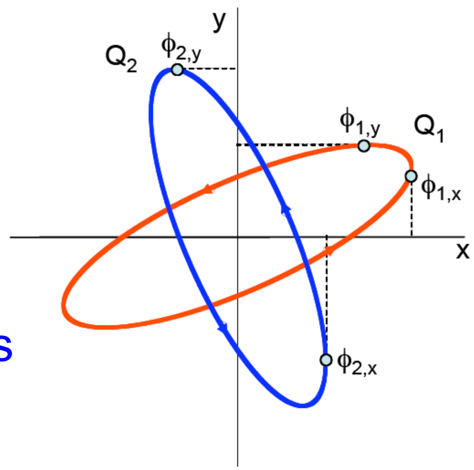
- Experiences from RHIC[1]:
  - Coupling during ramp breaks tune (and other) feedbacks
  - potential quick-fixes: “no/stop feedbacks” during ramp

Tune-PLL & coupling measurement scheme:



- PLL Coupling measurement exists[2] (R. Jones):
  - Info on unperturbed tunes Q_x and Q_y - ideal for tune FB
  - Measures coupling amplitude $|C_-|$ as well as its phase locally
  - → real-time data at the same rate as tune data

- Common FB “Chicken-Egg-Problem”:
  1. Measurement breakdown due to uncontrolled coupling/chroma.
  2. Feedback control breakdown due to failing measurement

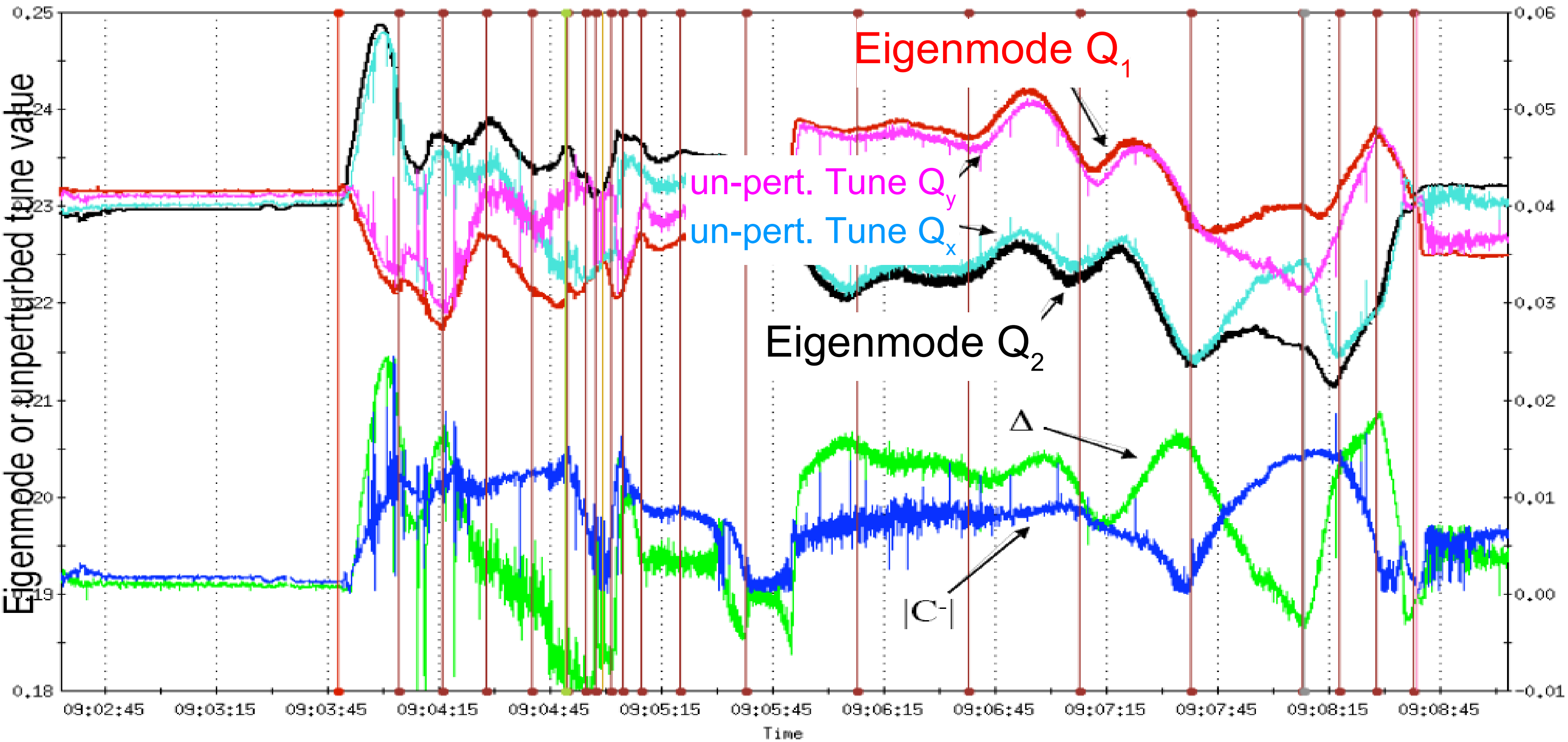


My proposed solution: Control coupling (& chroma) before its measurement becomes an issue

[1]P. Cameron et al.: “Advances towards the measurement and control of LHC Tune and Chromaticity”, DIPAC'05

[2]R. Jones, P. Cameron, Y. Luo, “Torwards a Robust Phase Locked Loop Tune Feedback System”, Brookhaven Nat. Lab., C-A/AP/#204, May 2005,

- Tune and coupling measurement @ RHIC (will use FB this year!):



- control strategy - ideas exist but require more analysis:
  - Feedback might work assuming coupling due to many distributed sources (global optimisation)
  - Coupling feedback not easy, hope to gain from RHIC experience
- Should have coupling feedback at an early stage (preferably before ramping)

Executive summary

- Which feedback first:
  - Coupling correction is a pre-requirement for FBs during ramp
  - Orbit: easiest to implement but not most important
  - Chromaticity: most important but not easiest feedback (requires tune!)
  - Energy FB is a logical consequence having a 100k turn acquisition
  - Tune FB is a logical consequence having a Q-meter (-PLL)

- Feedback priority list: Tune → Chromaticity → Orbit → Energy

- Feedback list of "what's easiest to commission":
  - 1rd: Orbit → functional BPM system → OK
  - 1½: Energy → consequence of 100k turn acquisition → OK
  - 2nd: Tune → functional Q-meter (-PLL) → soso
  - 3rd: Chromaticity → functional Q-meter and Δf/f modulation → ??

- Foresee time to commission feedbacks at an early stage
  - Most instruments can be commissioned parasitically with first circulating beam
  - Foresee semi-automatic control (measure→correct) implementations (poorman's feedbacks)
  - Investment now (!!) will help later with and save time while ramping the beam

Conclusions

- Parameter stability requirements and perturbation predictions:
  - Need automated control of: Energy, Orbit, Tune, Chromaticity and Coupling
  - requirements scale rather with total beam intensity and beam energy

- Feedback are most useful and efficient at an early commissioning stage
  - Cope well with random effects and machine uncertainties
  - Parameter measurement is an issue
    - BPM system available at 'day 0' → no problem for orbit and energy feedback
    - Tune, Chromaticity and Coupling are more difficult

- Two reasons to use feedbacks at an early stage:
  1. Give EICs, operators, ... the time to take care of more important things
  2. Without control of coupling and chromaticity, Q/Q' measurements become an issue

- ~~Santa-Claus~~ Early LHC wish-list: operational PLL + coupling measurement
  - Tune and Q' feedback with Δf/f modulation as a workhorse

Reserve Slides

Expected Dynamic Perturbations

- Current decay in main bends[1,2] (b_1 & b_3) and lattice quadrupoles (b_2):

	Main Dipoles				MQ
	Δb_1	Δa_1	Δa_2	Δb_3	Δb_2
Decay/Snap-back	0.78 ± 0.72	-0.75 ± 2.61	-0.01 ± 0.22	1.64 ± 0.42	1.68 ± 0.56

  – ...LHC injection optics (v6.5, MAD-X)
    - Orbit (H/V): $\Delta x \approx 0.28\cdot\sigma \cdot \Delta b_1(R)$ → $\Delta x(y) \sim 0.2\ \sigma$
    - Energy: $\Delta p/p \approx 10^{-4} \cdot \Delta b_1(S)$ + tides → $\Delta p/p \sim 1.3\cdot 10^{-4}$
    - Tune(MQ): $\Delta Q_{x(y)} \approx 8\cdot 10^{-3} \cdot \Delta b_2(S)$ → $\Delta Q \sim 0.014$
    - Chromaticity: $\Delta Q'_{x(y)} \approx 44(-39) \cdot \Delta b_3(S)$ → $\Delta Q' \sim 62 - 70$
    - Coupling $\Delta c\_ \approx 0.46 \cdot \Delta a_2(S)$ → $\Delta c\_ \sim 0.005$
    - Coupling $\Delta c\_ \approx 0.014 \cdot \Delta a_2(R)$ → $\Delta c\_ \sim 0.003$

  – + feed-downs of higher multipoles, energy, orbit ... depend on operational conditions
    - Tune[3] $\Delta Q_{x(y)} \approx 0.06$
    - Coupling[4] $\Delta c\_ \approx 0.1$ (worst case)

  – However it is unclear (lots of non-evident assumptions): static ↔ dynamic components
    → commissioning will show

- Machine intrinsic effects: Squeeze (raw uncorrected orbit drift ~ 30 mm)
- Environmental sources & machine element failures (ground motion, girder, cryogenics, ...)

[1] L. Bottura, “Cold Test Results: Field Aspects”, Proceedings of Chamonix XII, 2003
[2] L. Bottura, “Superconducting Magnets on Day I”, Proceedings of Chamonix XI, 2002
[3] S. Fartoukh, J.P. Koutchouk, “On the Measurement of the Tunes, [..] in LHC”, LHC-B-ES-0009, EDMS# 463763
[4] S. Fartoukh, “Commissioning tunes to bootstrap the LHC”, LCC #31, 2002-10-23

Exp. Perturbations:		Orbit [σ]	Tune [0.5·f_{rev}]	Chroma. [units]	Energy [Δp/p]	tau
Inj. Energy mismatch		0.25	0.0017	~ 1.3	1.0E-4	sev. days
Moon/Sun Tides 1		0.14	0.0009	~ 1.2	5.0E-5	~ 10 hours
Random Ground Motion 2		0.3 – 0.5	-	-	-	~ 10 hours
Decay/Snapback 3	b_1 ≈0.75	0.11	0.0030		7.5E-5	~ 1200/100 s
	b_2 & b_3	0.03	-	~ 70 – 140	-	
	MQ: b2≈1.7		0.014			
Ramp induced* 3	b_1 ≈ 1.50	0.22	0.0019	~ 8	1.5E-4	Start of ramp
MCB Hysteresis 4		0.01	-	-	Xx	
MCB/PC stability 5	±7mA/60A GeV	0.1	-	-		
β* Squeeze	0.5 mm misalign.	~ 30 mm	??	??	-	~ 1200 s

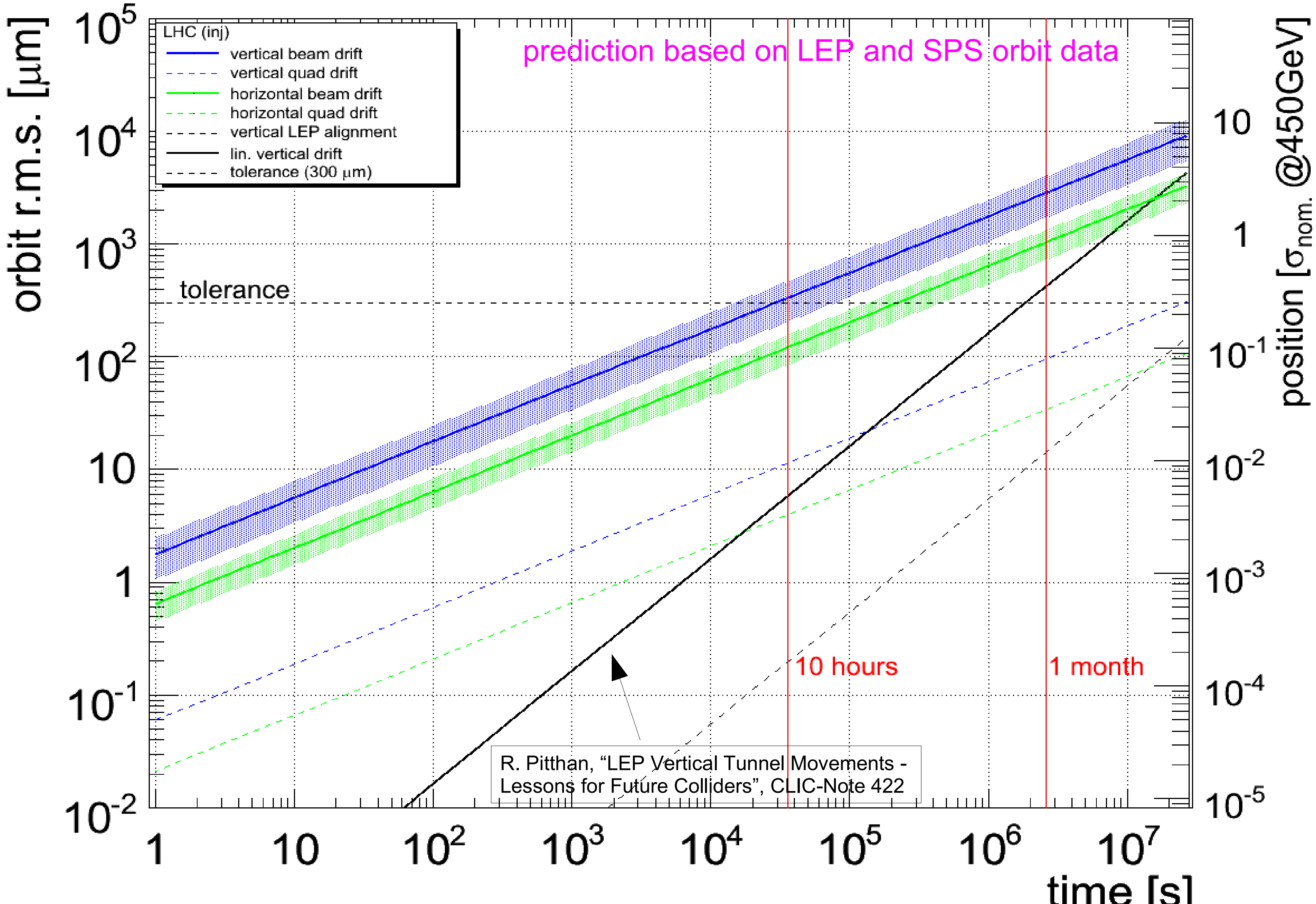
*assuming lin. Ramp at 10A/s, optimised ramp (7) reduces it by a factor ~16)

Requirements: 6

Pilot	N_p ≈ 5e9	± 1-2 mm	± 0.1	± 10	-
Stage I (43x43)	N_p > 5e10	± 1.8 σ / 1 σ	± 0.015	± 1-10 ??	± 1e-4

1: J. Wenninger: “Observation of Radial Ring Deformation using Closed Orbits at LEP”
2: RST, “Analysis of Ground Motion at SPS and LEP, implications for the LHC”, CERN-AB-XX (to be published)
3: M. Haverkamp, “Decay and Snapback in Superconducting Accelerator Magnets”, CERN-THESIS-2003-030
L. Bottura, “Cold Test Results: Field Aspects”, Proceedings of Chamonix XII
L. Bottura, “Superconducting Magnets on Day 1”, Proceedings of Chamonix XI
FQWG-Homepage: http://fqwg.web.cern.ch/fqwg/
4: W. Venturini: “Hysteresis measurements of a twin aperture MCB orbit corrector”, 19th October 2005
5: Q. King, L. Ceccone: private communications
6: T. Wijnands, “Requirements for Real Time Correction of Decay and Snapback [...]”, EPAC'00, Vienna, 2000
7: L. Bottura, “LHC Main Dipoles Proposed Baseline Current Ramping”, LHC Project Report 172

"Analysis of Ground Motion at SPS and LEP, Implications for the LHC", AB Report 2005-087



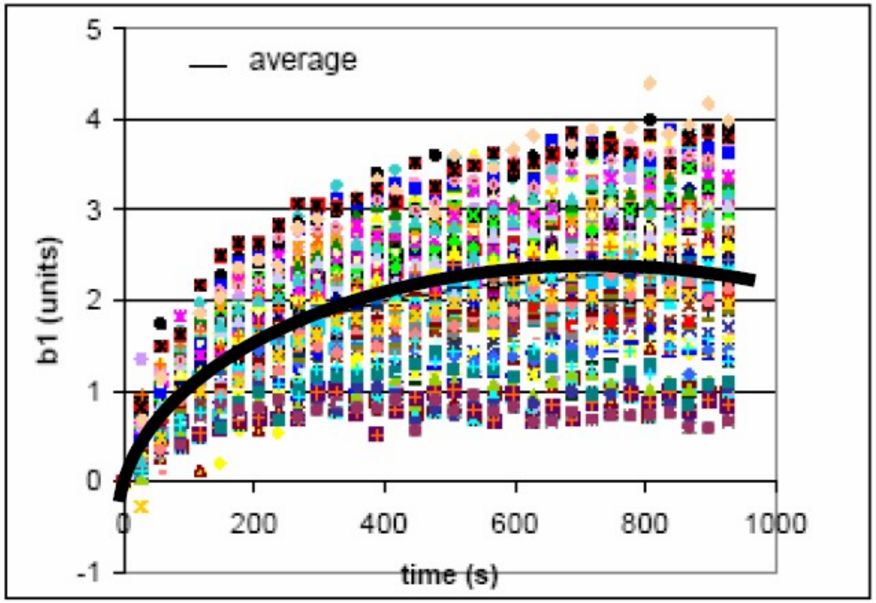
- → closed Orbit drifts after 10 hours ≈ 0.3 σ

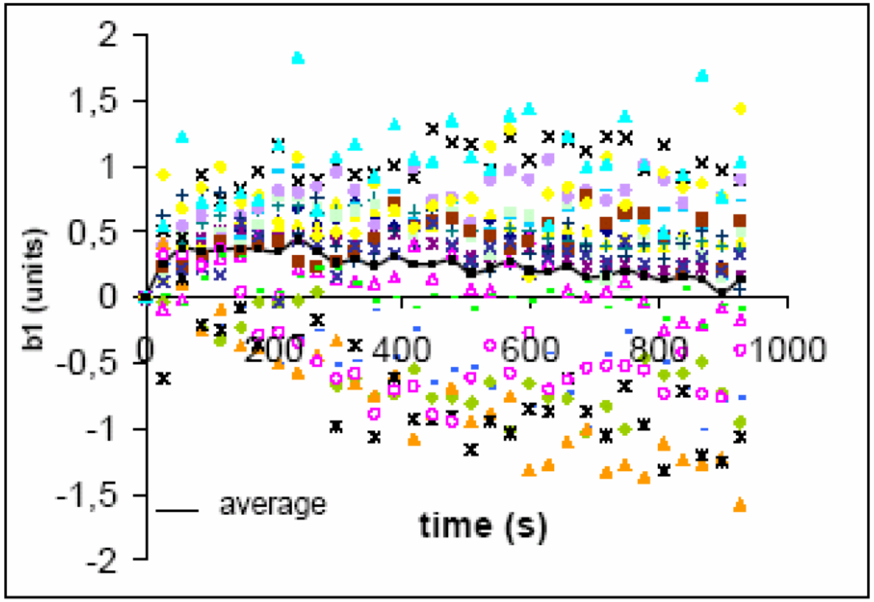
Orbit Requirements

▪ LHC cleaning System:	< 0.3 σ	IR3,IR7
▪ Machine protection & Absorbers:		
– TCDQ (prot. asynchronous beam dumps)	< 0.5 σ	IR6
– Injection collimators & absorbers	~ 0.3 σ	IR2,IR8
– Tertiary collimators for collisions	~ 0.2 σ	IR1,IR5
• absolute numbers are in the range: ~100-200 μm		
▪ Inj. arc aperture w.r.t. prot. devices and coll.:	< 0.3-0.5 σ (??)	global
(estimated arc aperture 7.5 σ vs. Sec. Coll. @ 6.7 σ)		
▪ Active systems :		
– Transverse damper, Q-meter, PLL BPM	~ 200 μm	IR4
– Interlock BPM	~ 200 μm	IR6
▪ Performance :		
– Collision points stability	minimize drifts	IR1,2,5,8
– TOTEM/ATLAS Roman Pots	~ 10 μm	IR1,IR5
– Reduce perturbations from feed-downs	~ 0.5 σ	global
– Maintain beam on clean surface (e-cloud)	~ 1 σ ??	global

... requirements are similar → distinction between local/global less obvious!

- Border is rather fuzzy.... injection likely won't require RT-feedbacks
- S. Sanfilippo (SM18 Review): “Decay of these magnets not scalable yet.”
  - b_3 & b_1 decay prediction:



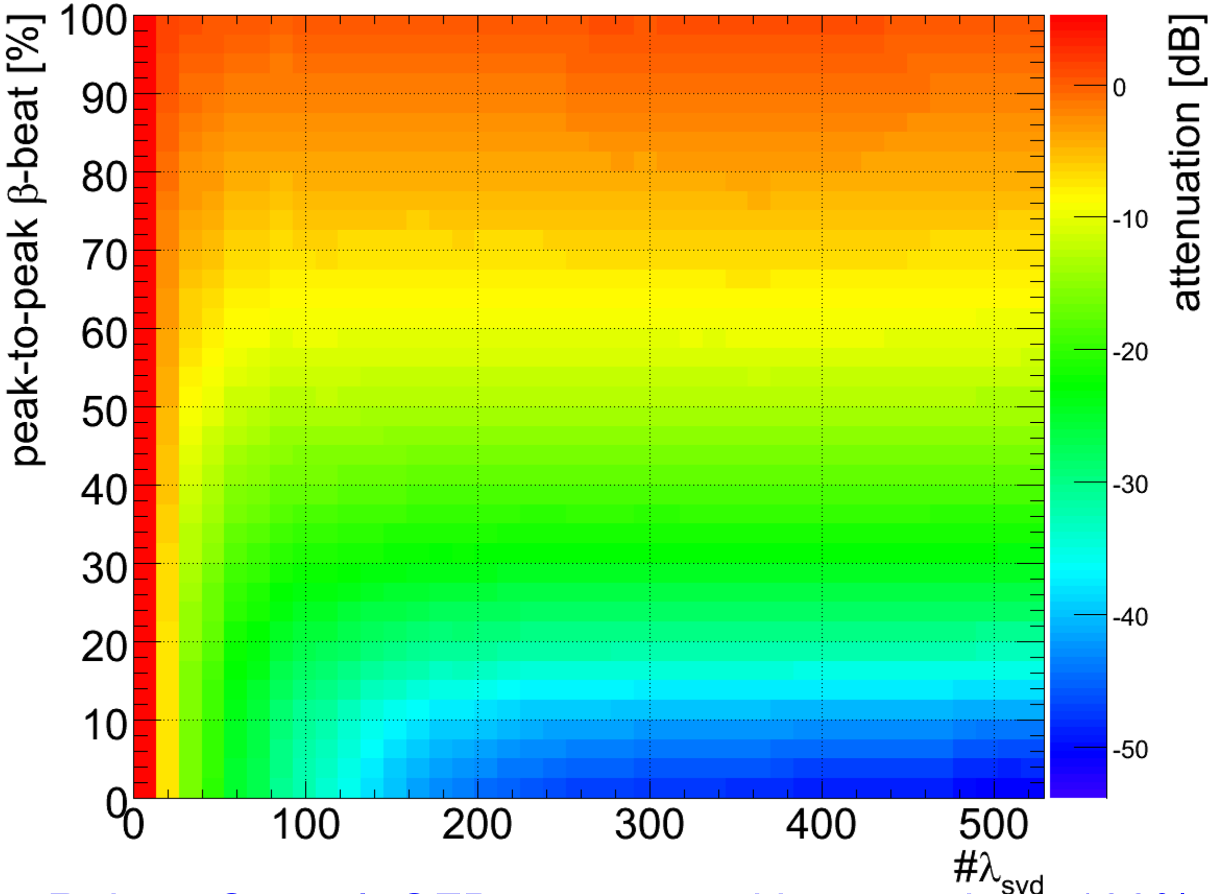


random b_3 → negligible effect
systematic b_3 → seem to be reproducible
→ constant feed-forward function may be established at some point of time

random b_1 → perturbs orbit
systematic b_1 → Δp/p shift
→ both require feedback control for each fill

Orbit Feedback Disturbance Rejection

- Low sensitivity to optics uncertainties = high disturbance rejection:
  - LHC simulation: Inj. Optics B1&B2 corrected



$\#\lambda_{svd}$ controls correction precision

attenuation =

$$20 \cdot \log \left| \frac{orbit\ r.m.s.\ after}{orbit\ r.m.s.\ before} \right|_{ref}$$

- Robust Control: OFB can cope with up to about 100% β-beat!! (we will do better!?!)
  - Available aperture and collimation inefficiency w.r.t. β-beat is clearly more an issue
- Similar for BPM and COD calibration constants (hysteresis, see later talk)

- Induced noise on orbit[1]:
  - BPM failure (undetected electronics drift): $\Delta x|_{max} < 0.01\ (\beta_{min})\ /\ 0.4\ \sigma\ (\beta_{max})$
  - BPM systematic (intensity, bunch length, 450 Gev): $\Delta x|_{max} < 0.02\ (\beta_{min})\ /\ 0.01\ \sigma\ (\beta_{max})$
  - White BPM noise (single bunch): $\Delta x|_{max} < 10^{-3}\ \sigma$ (inj) / $0.02\ \sigma$ (coll)
  - COD power converter ripple (~7mA/55A): $\Delta x|_{max} < 0.1\ \sigma$
  - COD circuit failure (e.g. quench): $\Delta x|_{max} \sim 0.8\ \sigma$

→ compatible with nominal → should not pose problems for Stage I++

- Some comments:
  - BPM resolution scales reciprocal with collimation requirement
    - Increased number of bunches
      - → Tighter collimation tolerances
      - → better BPM resolution Δx:

$$\Delta x = \frac{1}{\sqrt{N_{turns} \cdot N_{bunch}}} \sum^{N_{turns} \approx 224} \sum^{N_{bunch}} \Delta x_{turn}$$

(Nominal performance: beta-beat < 20 %, reasonable BPM calibration)

[1] R. Steinhagen, “Closed Orbit and Protection”, MPWG #5x, 2005-12-16

Technical implementation:

- Simple streaming task for all feed-forwards/feedbacks:
  - (Monitor → Network $)_{FB}$→ Data processing → Network → PC-Gateways
- Feed-forward/Feedback choice mainly depends on available measurement
- Assumption on hardware present during startup of commissioning with beam:
  - General infrastructure (network, databases, controls software....)
  - Corrector circuits with rough (~20%) calibration and correct polarity
  - Either: beam diagnostics or: good model for the to be steered parameter
  - Timing on second level sufficient