On the Feasibility of (semi-) automated Tune Control in the PS

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with special thanks for their input to
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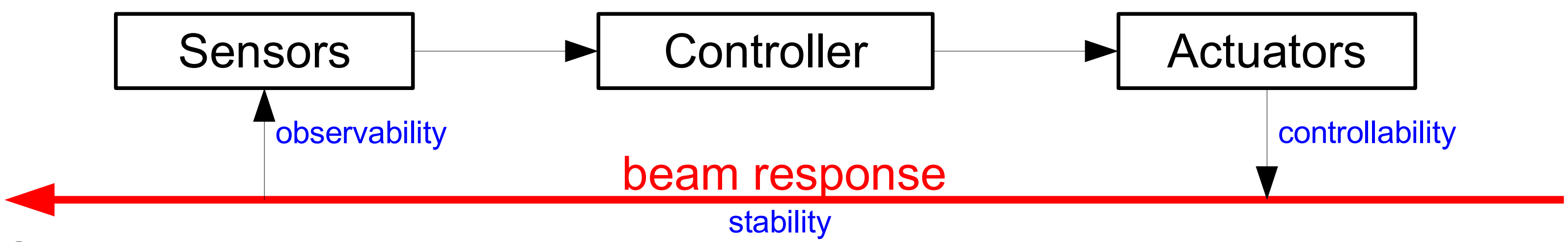
Motivation

- AB Management Board Meeting discussion (2007-08-13):
  - *"Further tests were carried out on the pole face windings during the week and some higher frequency perturbations (100, 150 and 200Hz*) were observed in the beam. "*
  - *"S. Myers asked R. Garoby (for the BI group) to investigate the feasibility and the potential bandwidth of a closed loop control of the tune in the PS."*
  - *(*minimised through power-converter controller optimisation)*



- *Some basic considerations:*
  - *Stability*: *"What are the required stabilities on Q/ξ?"*
  - Controllability: *"Can Q/ξ be controlled without 'hidden parameters'?"*
  - Observability: "Can we measure Q/ξ (and also C^-) robustly?"

  - will comment on staged implementation, steps and possible performance

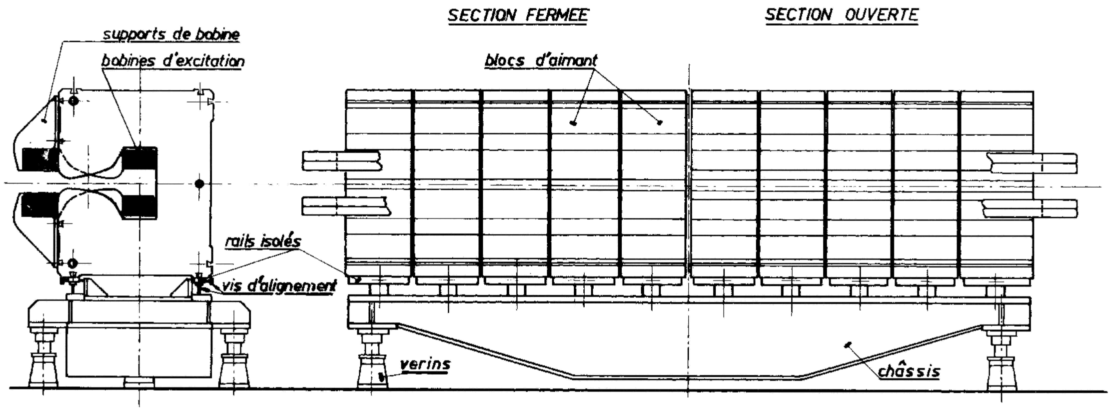
Stability: *"What are the required stabilities on Q/ξ?"*

- Discussion with OP/ABP (Rende, Yannis):
  - main outcome: inconclusive, since most beam parameter (orbit, tune, chromaticity) have/could not be measured systematically in the past
  - most tight requirements during resonant extraction (slow, MTE) 10^{-3}...10^{-4}
  - otherwise: "keep the beam in the pipe"
    - minimisation of resonances, transition crossing, ...
    - to be kept in mind: the PS was/is running without beam-based feedbacks on orbit, tune, coupling and chromaticity for ~ 50 years
      - ... still the slow extraction worked.
  - preliminary: $\Delta Q \sim 10^{-2} \ldots 10^{-3}$, $\Delta\xi \sim 0.1 \ldots 0.2$ units?? (~SPS/LHC!?!)
    - time-scales are unclear – working assumption: ~ SPS (in turn scale!)

- (Ongoing) observation with beam required to quantify PS reproducibility and to cross-check real requirements with physics model prediction
- N.B. "Requirements" are tighter than what is actually achieved in the PS. Many PS cycle show tune stabilities in the order of a few percent (see measurements)

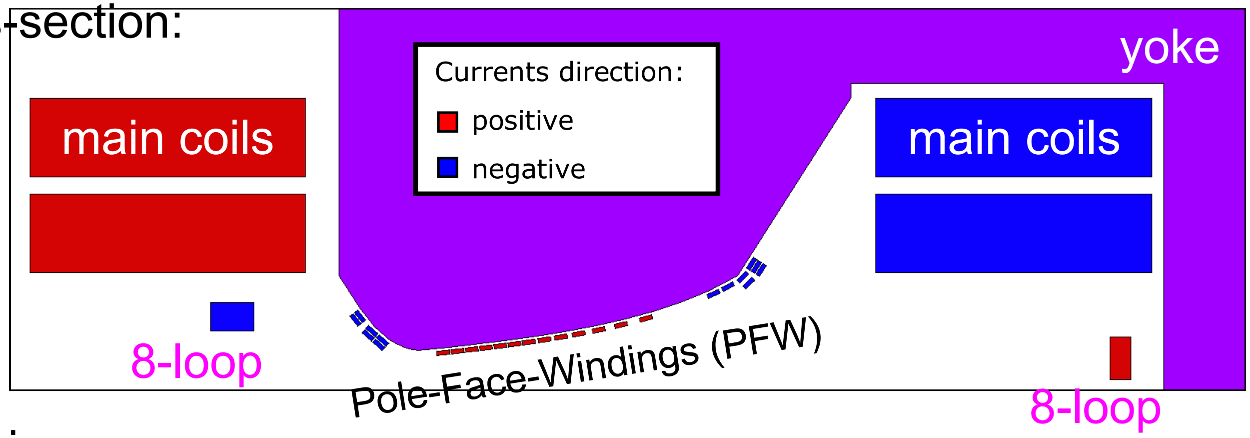
Controllability: PS' Combined Function Magnets - Pole-Face-Winding (PFW, since 1978) I/IV

- *"Recent" 5-current mode implementation eliminates hidden parameters and enables independent control of Q_H, Q_H, ξ_H and ξ_V*

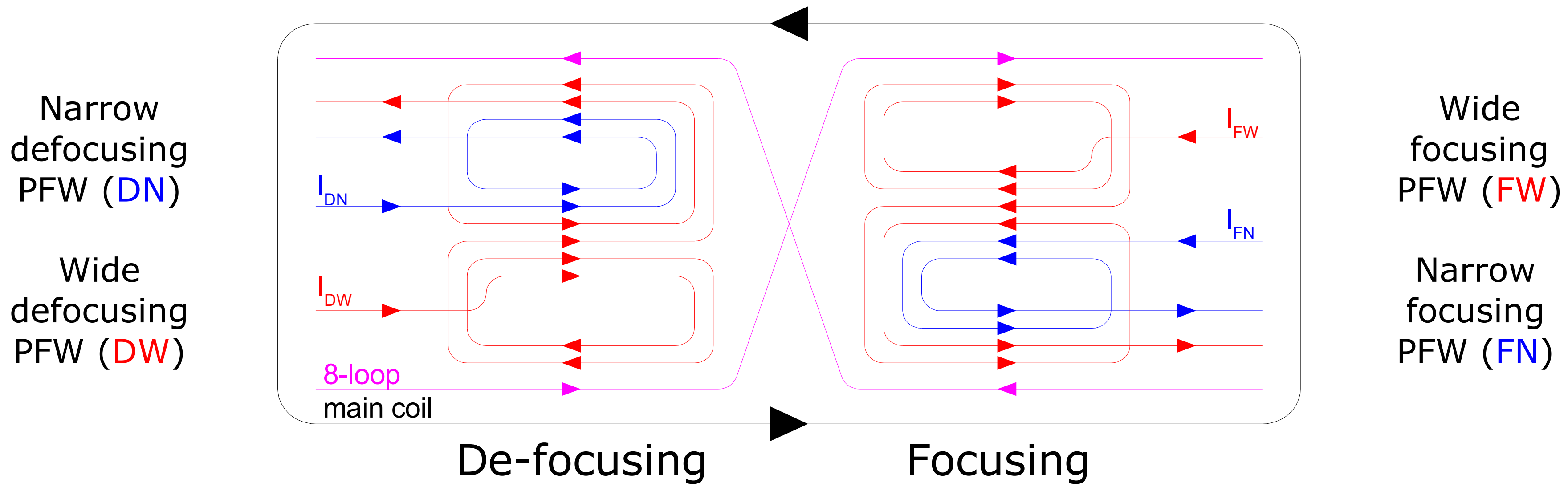


Controllability: PS' Combined Function Magnets - Pole-Face-Winding (PFW, since 1978) II/IV

- Main-magnet cross-section:



- Main-magnet top-view:



- 2x Defocus. (DW, DN), 2x Focus. (FW, FN), 8-loop (~octupole) → 5 circuits
  - orthogonal control of: Q_x, Q_y, ξ_x, ξ_y

(schematics courtesy Mariusz Juchno)

- Response can be cast into beam matrix form, e.g.:

$$p\cdot\begin{pmatrix}\Delta Q_H\\ \Delta Q_V\\ \Delta \xi_H\\ \Delta \xi_V\end{pmatrix} = \begin{pmatrix}+0.0647 & +0.0662 & -0.0352 & -0.0437\\ -0.0345 & -0.0444 & +0.0641 & +0.0668\\ +1.7909 & -0.3109 & +1.0416 & -0.2016\\ -1.2220 & +0.1820 & -1.4866 & +0.3066\end{pmatrix}\cdot\begin{pmatrix}\Delta I_{FN}\\ \Delta I_{FW}\\ \Delta I_{DN}\\ \Delta I_{DW}\end{pmatrix}$$

  - source: R. Gouiran, CERN/PS/SM 76-1, ΔI_{xx} [A], p [GeV/c], p <15 GeV/c
  - Iron yoke saturation makes matrices slightly momentum dependent
    - differences per matrix element are small: < 10...20%
      - does not pose a big problem for feed-back systems
- Main issues/concern:
  - Large differences (>100%) between model and measured response matrix
  - Assumes small betatron-coupled machine
    - Most PS cycle at least partially coupled

      (quality of 5-current MD reponse matrix data?)

→ Any orbit, Q or Q' control requires also control/minimisation of coupling!

Controllability: PS' Combined Function Magnets - Circuit and PFW Time-Constants

- natural time constants ~ 2 ms (wide) and ~ 9 ms (narrow) resp.
  (wide: R= 1 mΩ, L = 2 mH; narrow: R= 2.1 mΩ, L = 17 mH)
  - natural circuit bandwidth ~ 125 Hz
- PFW are by ±1200V/±250A power converters ($\Delta I/\Delta t|_{max}$ = 5 kA/s)
  - Driven "large signal" bandwidth: ~ 125 Hz
    (ΔI~ 50A ↔ ΔQ ~ 0.1 @26 GeV/c)
  - Driven "small signal" bandwidth: > 1 kHz (theoretical)
    (ΔI~ 5A ↔ ΔQ ~ 0.01 @26 GeV/c, noise: ~ 50 mA ↔ ΔQ ~10^{-4})
- Main limitations:
  - non-linearities due to current rate-limit (similar to LHC PC → easy for FB control)
  - PC sampling frequency (f_s = 1kHz) limits effective Q-loop bandwidth, typically: $f_s \approx 25...40 \cdot f_{bw}$
  - thus, from controllability point of view only Q-loop BW': f_{bw} < 40 Hz
  - or: if f_{bw}:= 100 Hz → f_s > ~ 4 kHz

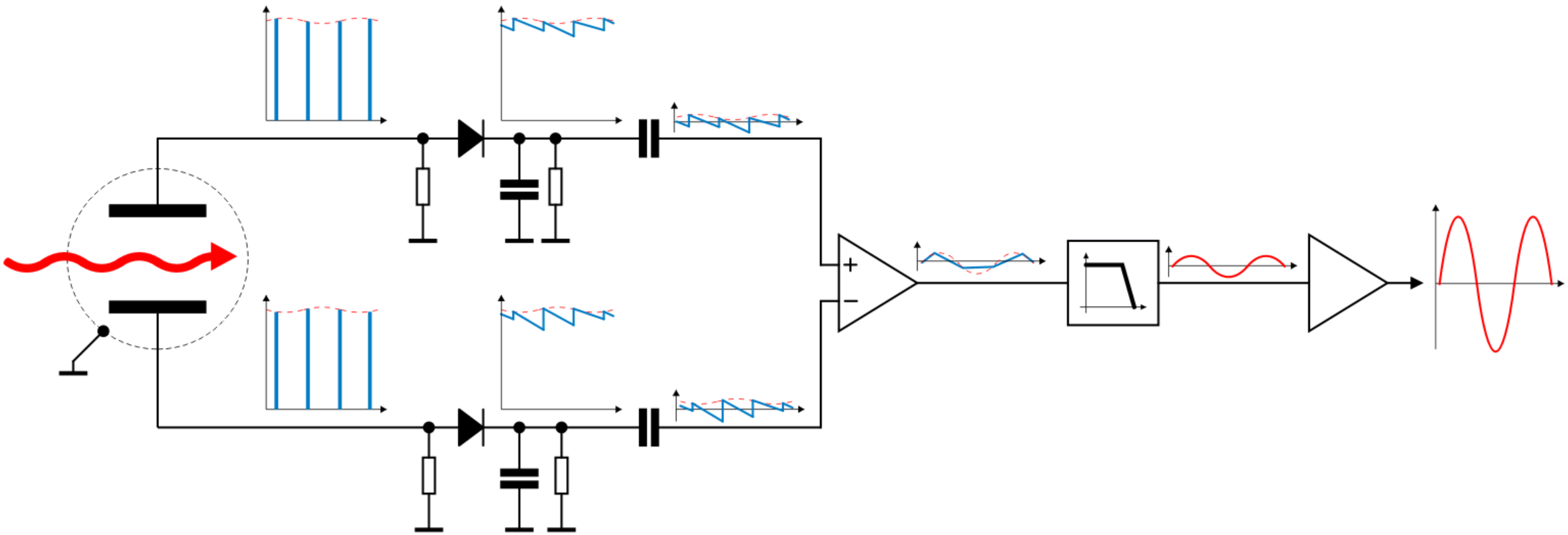
Observability - PS version of the Diode-based Base-Band-Q-meter (BBQ)

- Common approach:
  - Same diode based detection
  - Same digital acquisition system
    - Based on DAB64x
      - developed by TRIUMF (Canada) for the LHC BPM/BLM systems
    - Mezzanine cards house ADCs adapted for machine revolution frequency
  - Same FESA and BI-expert diagnostic tool chain for all CERN accelerators

- Full BBQ acquisition chain available in PS/PSB since beginning of September

PS (section 72)

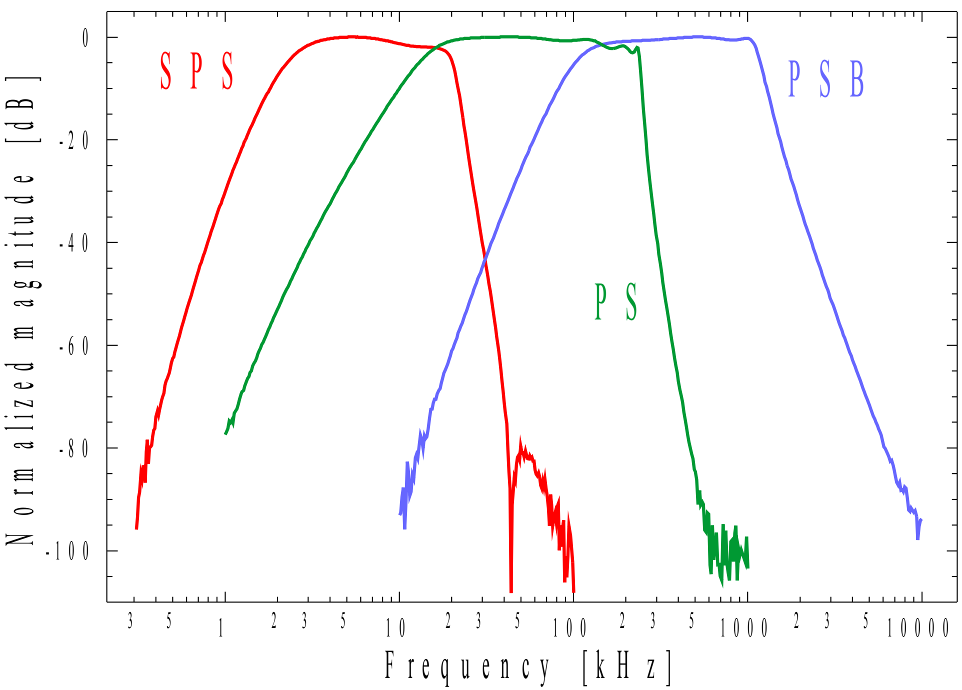
- Detection principle (*M. Gasior, "CERN-LHC-Project-Report-853"*):

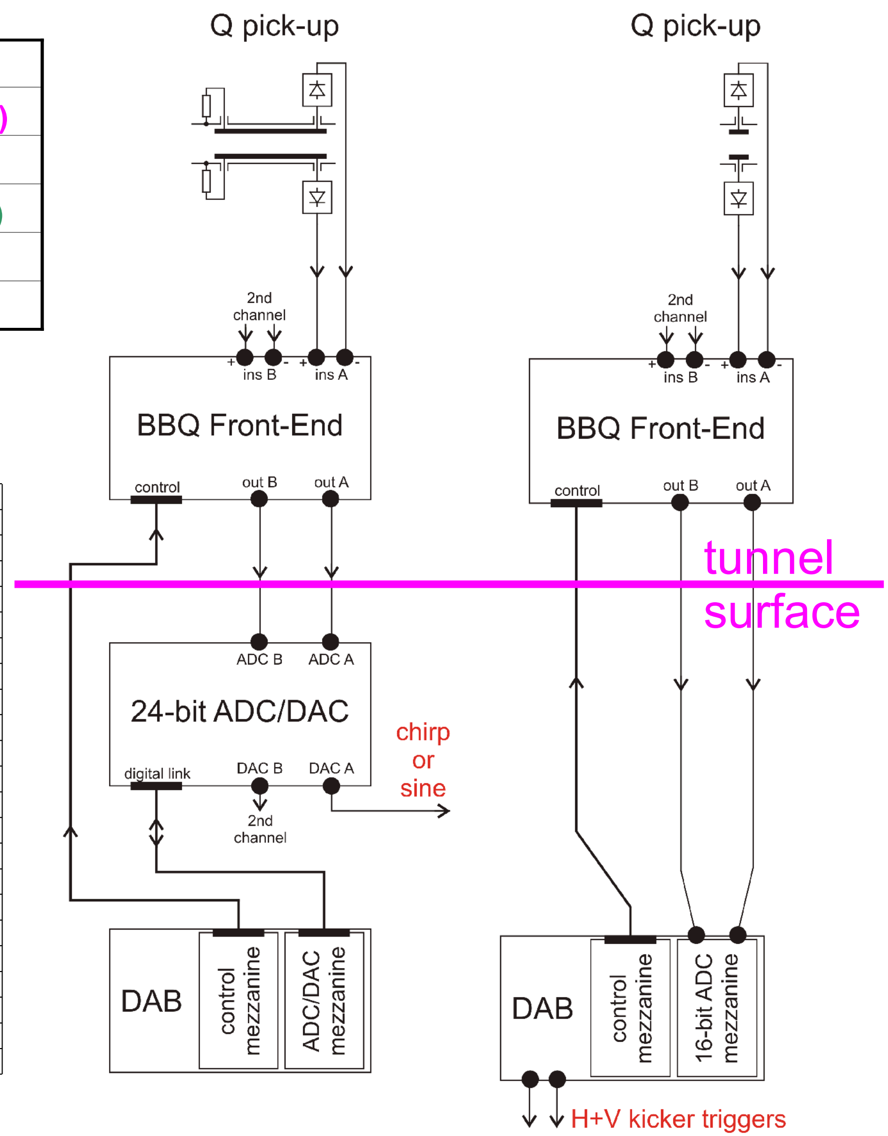


  - Peak detection of position pick-up electrode signals ("collecting just the cream")
  - Revolution frequency content converted to the DC and removed by series capacitors
  - Betatron modulation moved to low frequency range (it is carried by much longer pulses)
  - Impossible to saturate (large f_{rev} suppression already at the detectors + large dynamic range)
  - Large sensitivity
  - Low frequency operation
    - high resolution ADCs available
    - Signal conditioning / processing is easy (powerful components for low frequencies)
  - "New" additional modifications: low-pass filtering in order to reduce longitudinal RF noise
    (N.B. any transverse pickup is intrinsically sensitive to both longitudinal and transverse spectra.)

Observability - BBQ Systems at CERN

Machine	Front-End	Acquisition
LHC	"constant f_{rev} type"	24 bits (up to 100 kHz)
SPS	"constant f_{rev} type"	24 bits
PS	"constant f_{rev} type"	16 bits (up to 40 MHz)
LEIR	"varying f_{rev} type"	16 bits
PSB	"varying f_{rev} type"	16 bits





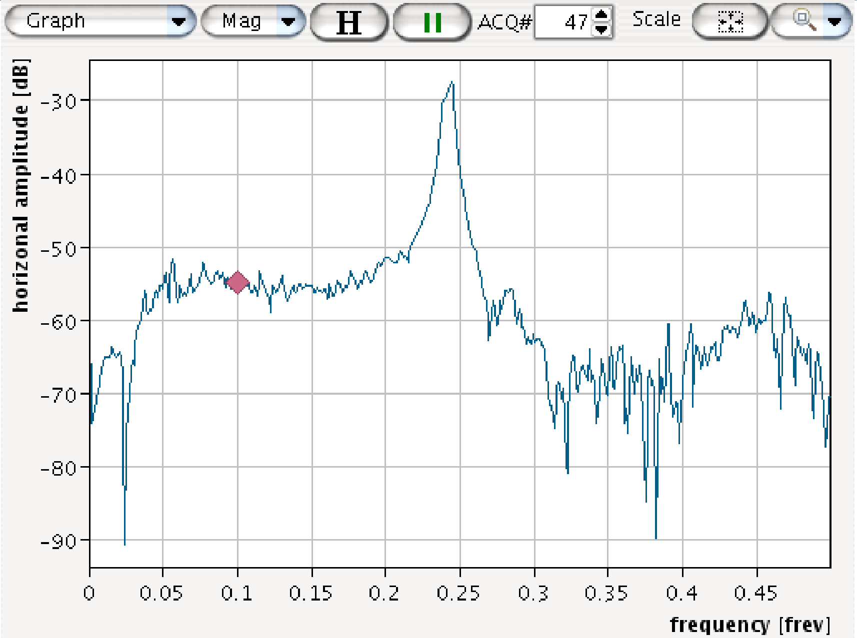
Observability - Diode-based Base-Band-Q-meter (BBQ)

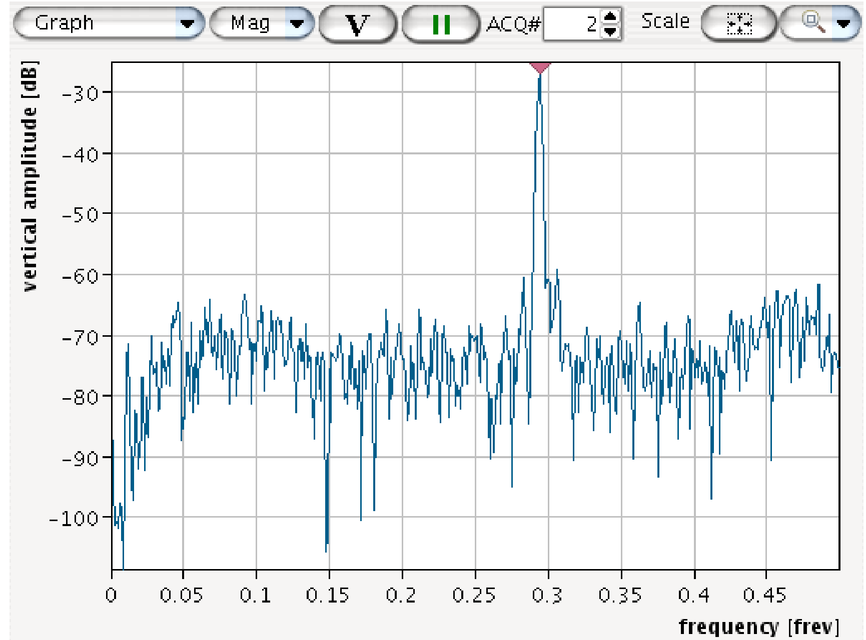
Some measurements with beam in the PS available

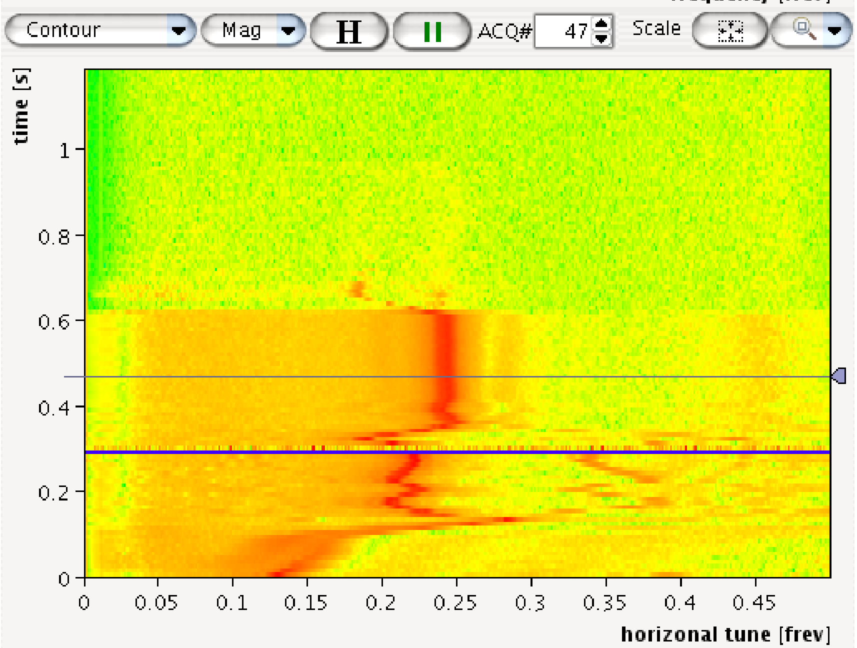
- Preliminary observations:
  - seems to be compatible with PS' "RF-gymnastics" at least with those seen on the SFTPRO, CNGS, EASTB, LHC25ns and MD2 cycle (see plots)
  - in contrast to SPS: no "tune-spectra-guarantee" without excitation → kicks (though they can be small) seem to be mandatory
  - works with un-bunched beam (see attachment)
  - transparent to slow bunch length variations
  - of course: further tests/optimisation are required and will be done!

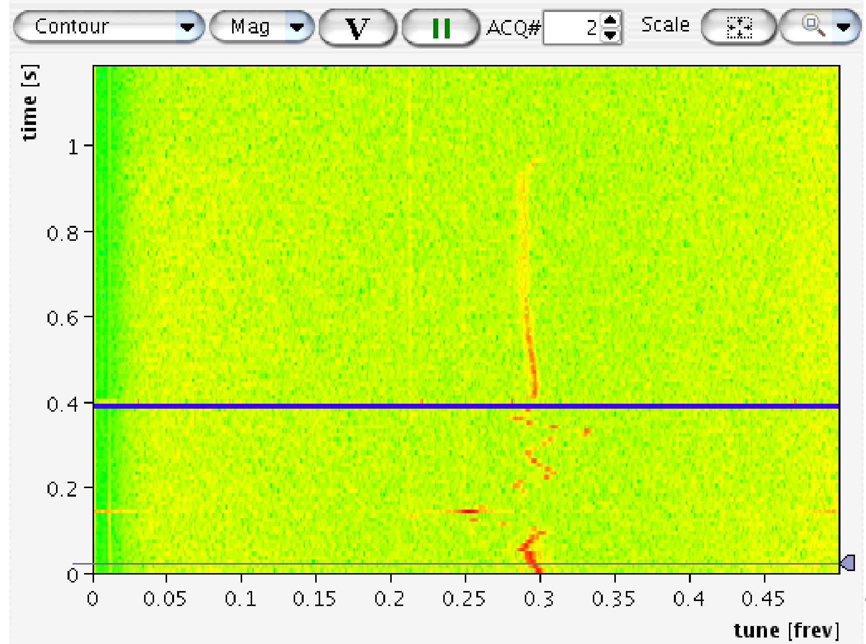
- Outstanding Issues (in progress):
  - excitation chain is controlled in a different way on each machine
    - (re-design) of PS/PSB kicker amplitude control
    - re-phasing of kick vs. bunch arrival (mainly for single ion bunch beams)
  - S/N improvements for low-signal beam (= small bunch-peak signals)
    - single ion bunches are at the limit but visible
- Most of these issues are driven by the large observed ΔQ (~Q') variations

DAB based BBQ acquisition: PS examples
PS-MD2, H/V kicks, “free-running mode”

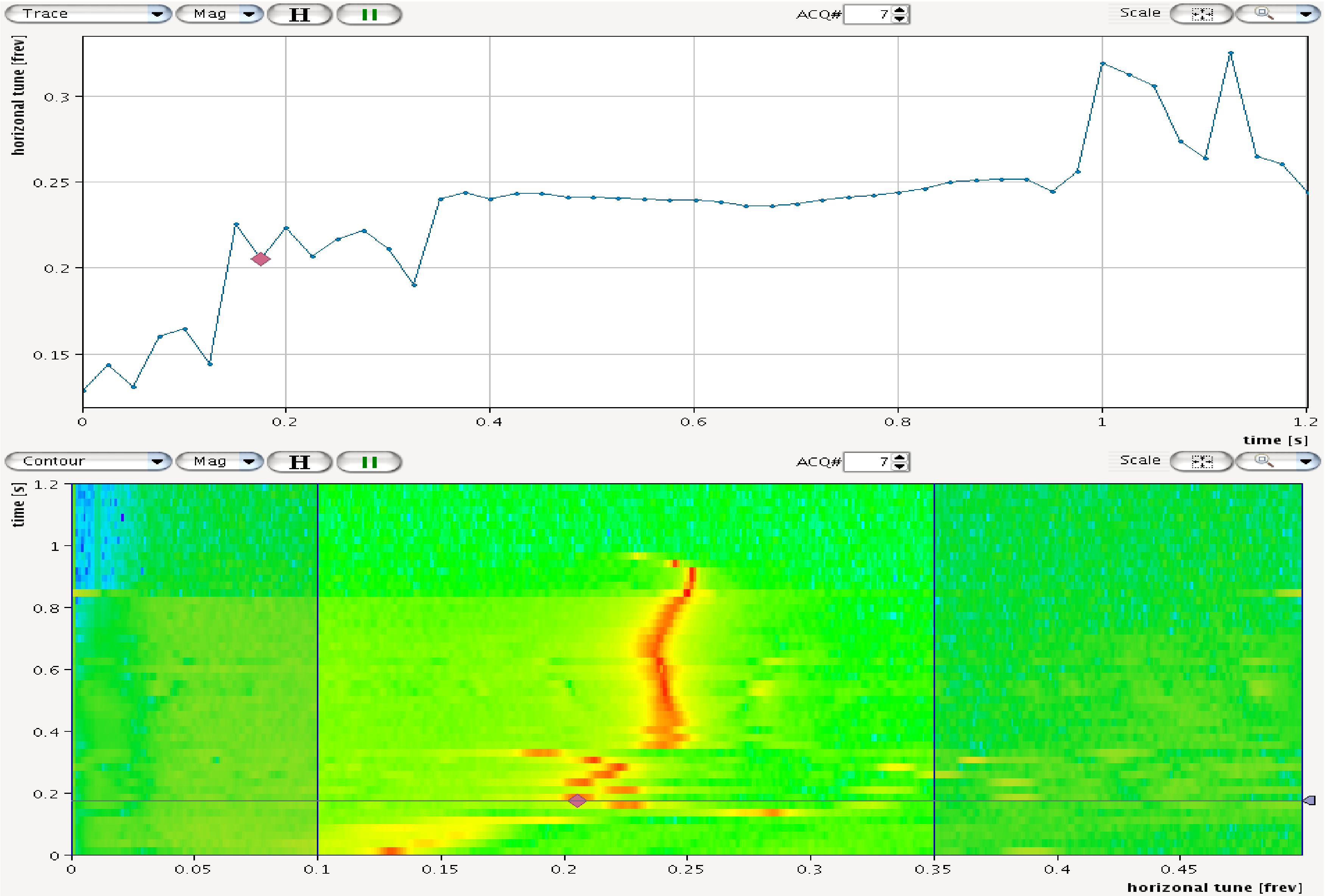






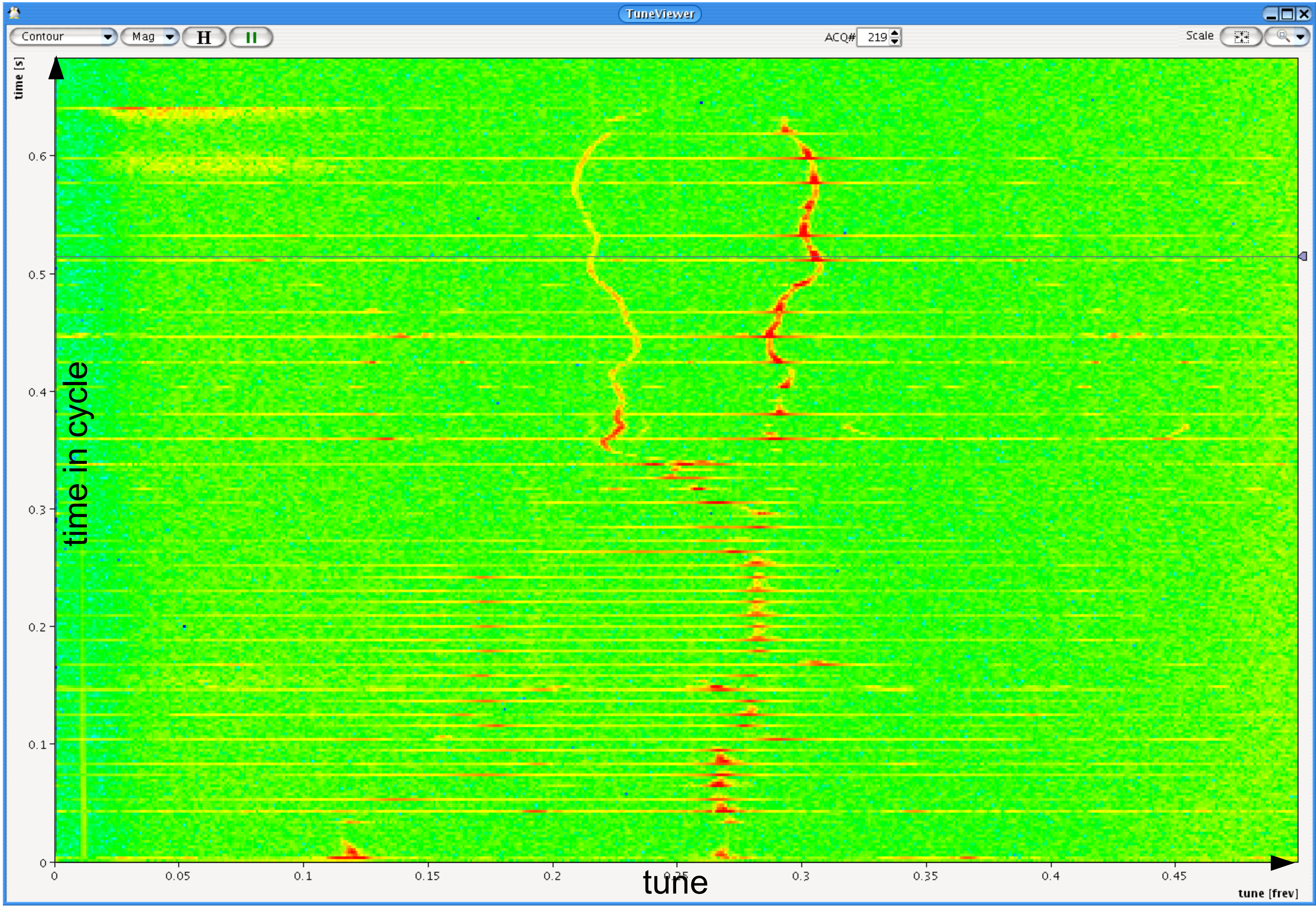


DAB based BBQ acquisition: PS examples SFTPRO, H kicks only,

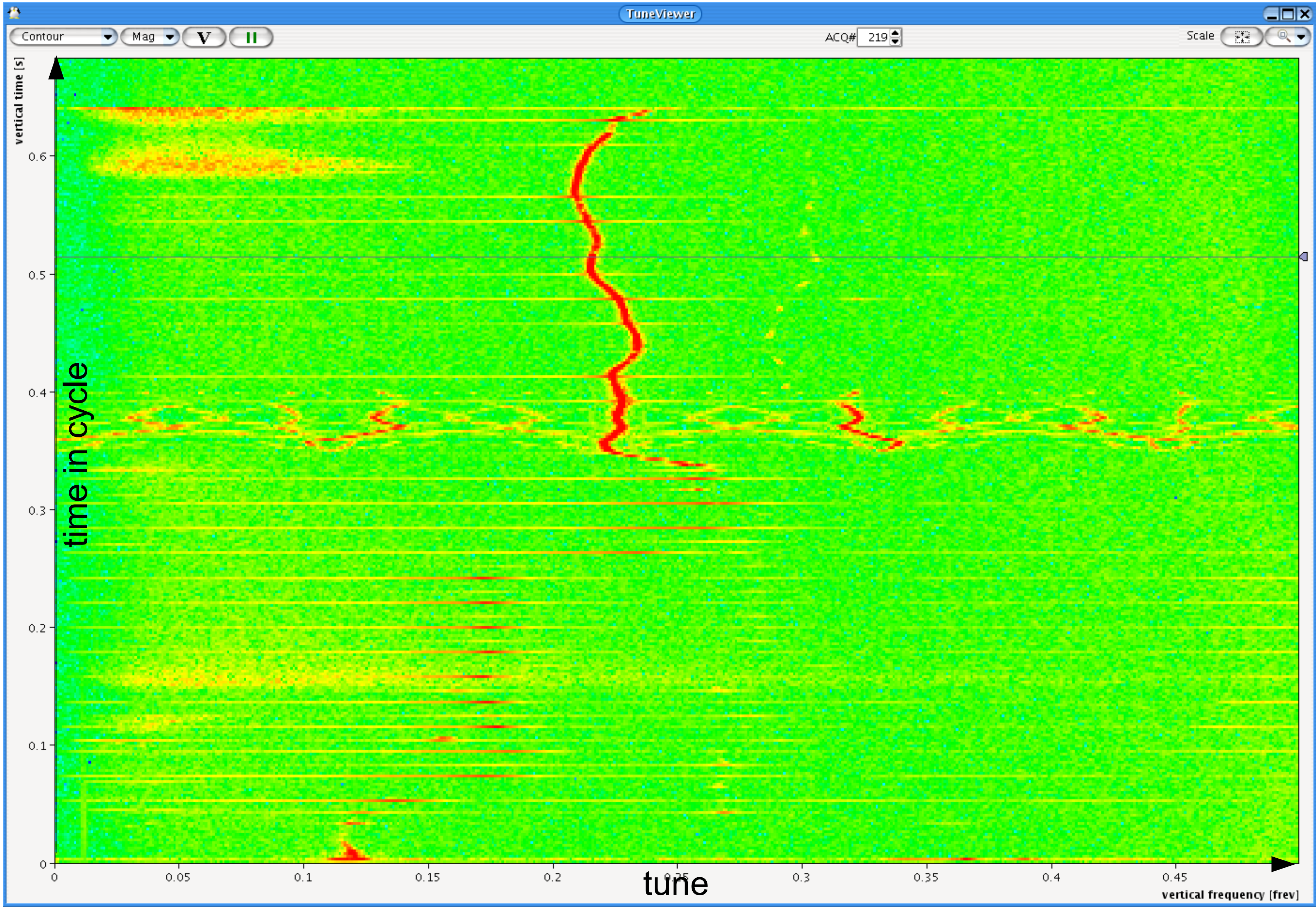


- Simple peak detection: "highest peak" or "highest S/N ratio"

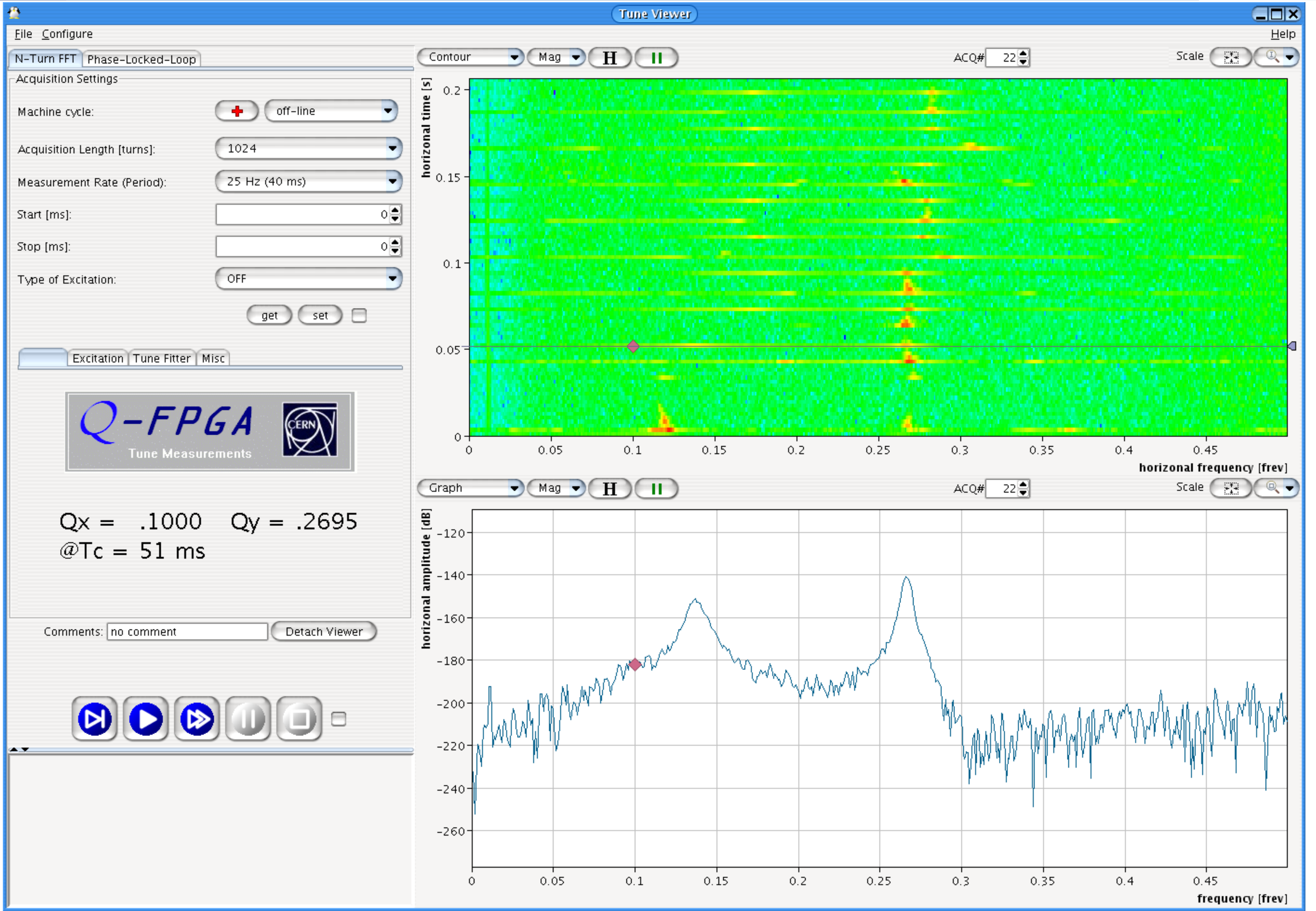
PS-SFTPRO cycle, back-to-back acquisition, H/V kicks every 5 ms, horizontal plane



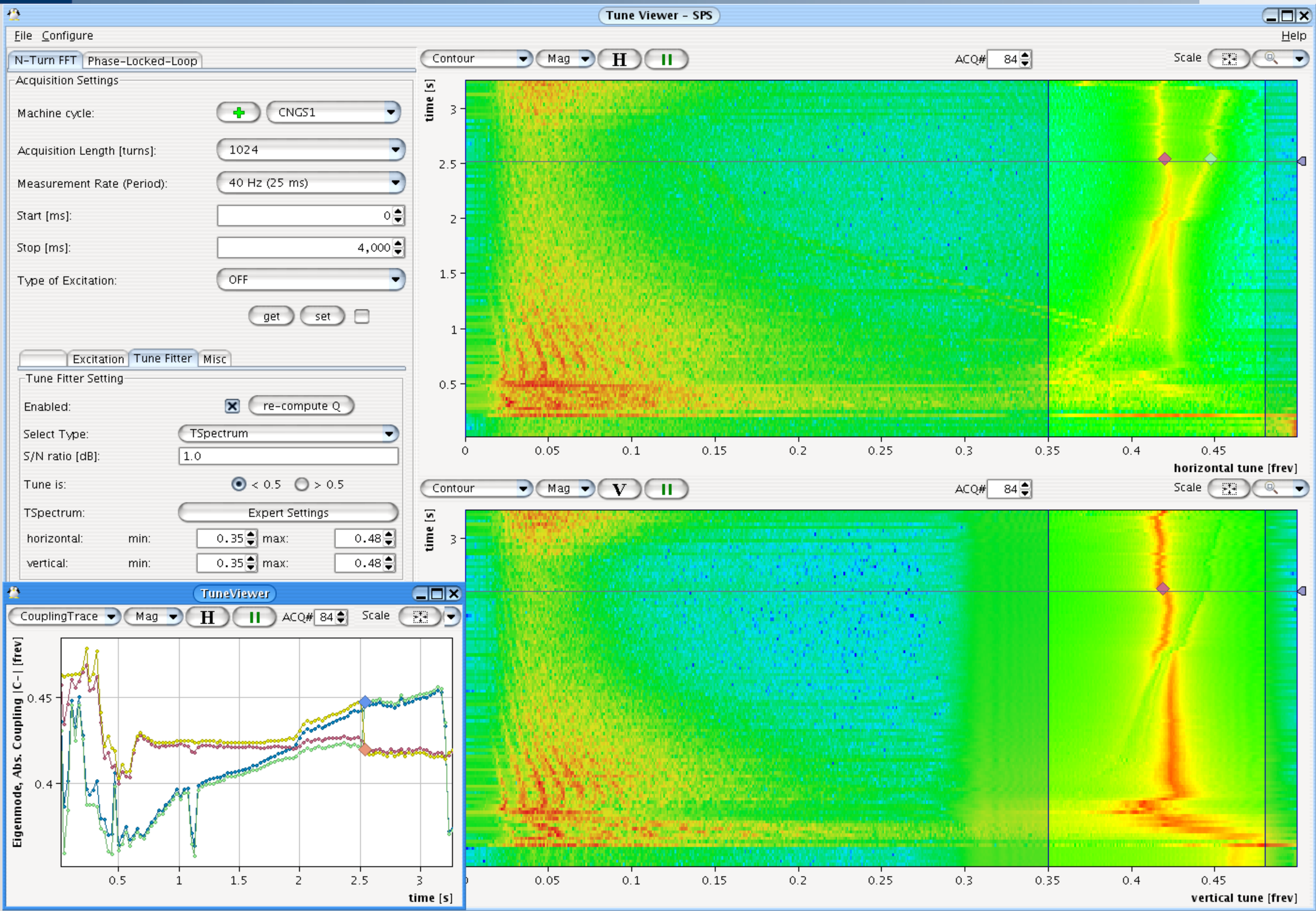
PS-SFTPRO cycle, back-to-back acquisition, H/V kicks every 5 ms, vertical plane



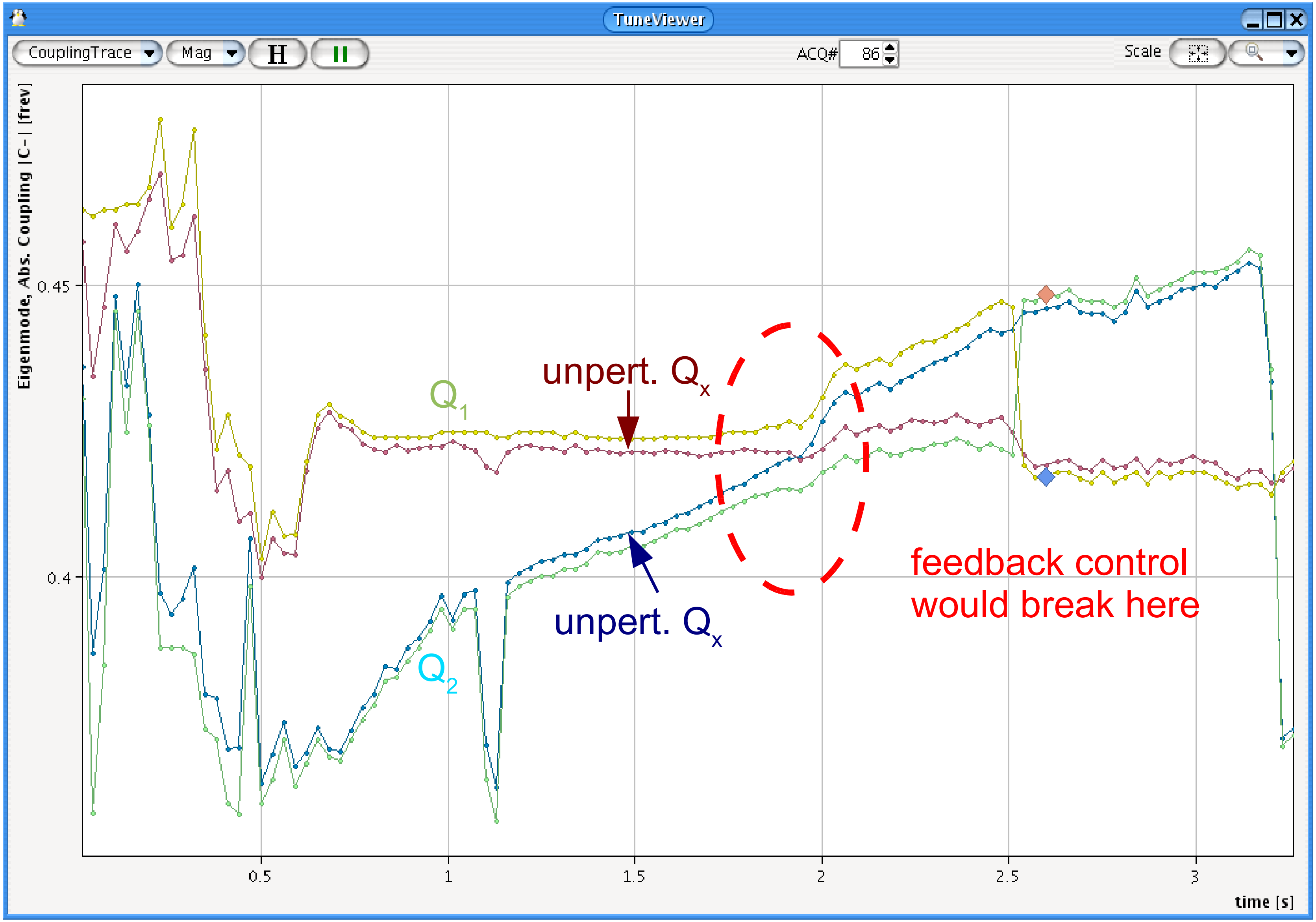
PS-SFTPRO cycle
Betatron-Coupling after Injection



Betatron-Coupling: CNGS1 (SPS) I/II



Betatron-Coupling: CNGS1 (SPS) II/II after reconstruction



What if.... (the nearish future) I/II

- Provided that betatron-coupling is not required and minimised to zero....
- ...a semi-automated slow 'cycle-to-cycle' feedback control could
  - correct for fast intra-cycle perturbations due to
    - current overshoots, b_1/b_2 mismatches, ramp systematics, ...
  - correct for slow environmental induced cycle-to-cycle perturbations:
    - girder movements, temperature drifts of magnetic fields (iron), slow intensity variations, ...
  - be useful for the fast setup of new user/cycles
  - reach an “intra-cycle” correction bandwidth” of ~ 100-200 Hz

  - possible implementation:
    - could be based on the already available BBQ instrumentation (the necessary tools are there!)
    - top-level GUI that performs an automated measure-and-correct principle using chirped FFT data
      - e.g. 1024 turn-FFT every 5 ms
      - similar to what is known in the SPS as 'Auto-Pilot' in case of trajectory/orbit steering

- Provided that betatron-coupling is not required and minimised to zero....
- ...a fully-automated intra-cycle feedback control could in addition
  - correct for fast intra-cycle perturbations due to:
    - power converter (mains) harmonics,
    - fast intensity driven tune changes (beam loss + impedance)
    - other 'truly random'/incoherent noise sources
  - reach a feed-back bandwidth of ~ 100-200 Hz
    (provided PC sampling frequency is increased to 4 kHz (to minimise PID phase lag))
  - possible implementation:
    - PLL is not the ideal candidate for a robust Q-loop in the PS since RF bunch splitting, gymnastics, coupling and other effects 'skews up' the beam-transfer function which is required to be reasonably stable
    - Propose: (narrow bandwidth) chirp-based excitation with continuous FFT detection is preferable (e.g. 1024-turn FFT every 100 turns)
      - robust peak-detection needs further assessment
      - control logic could be fairly easily implemented within a FPGA once the digital power converter input interface is established

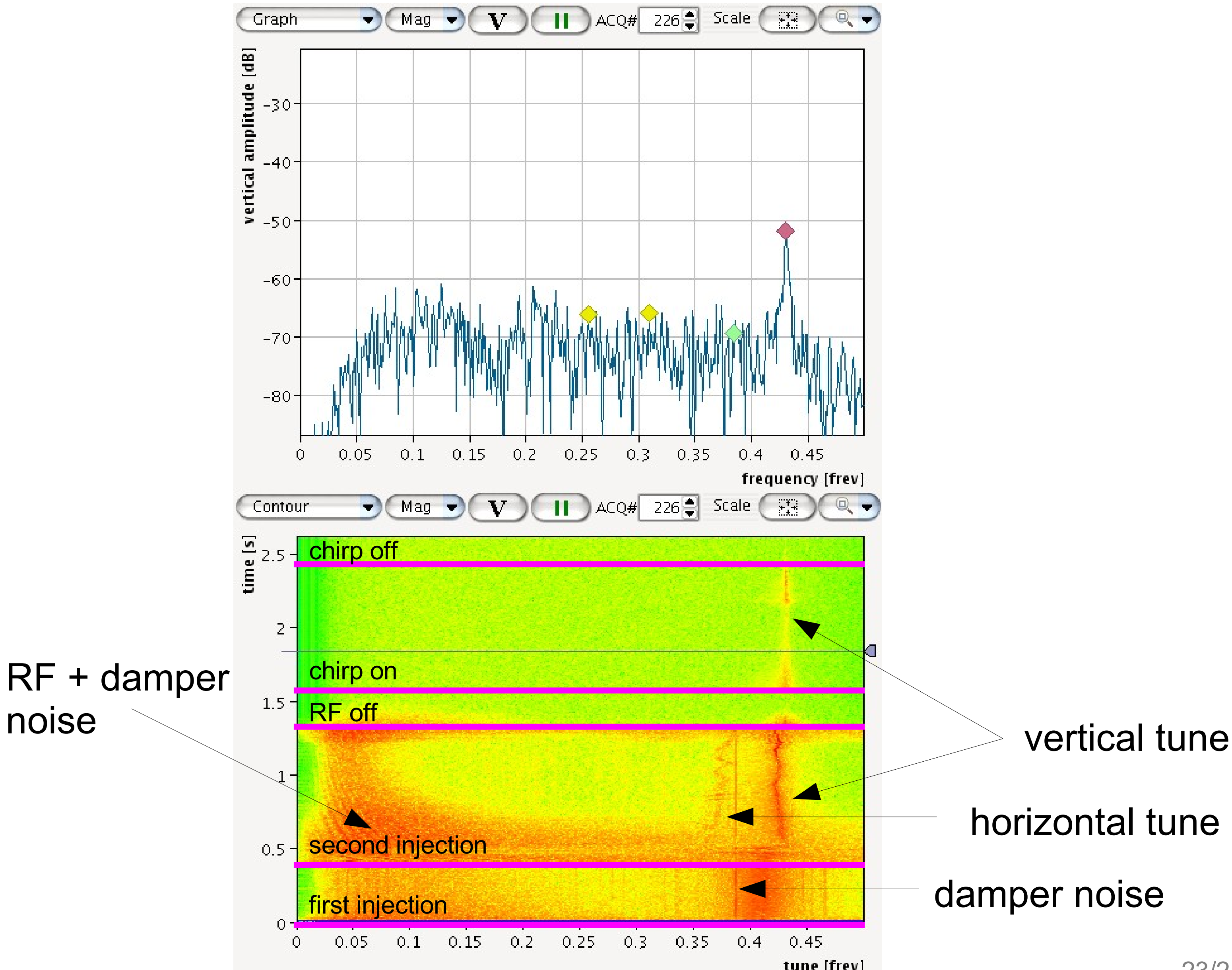
- The actual implementation of the five current scheme enables (new) possibilities for the control of tune and chromaticity in the PS
  - requires control/minimisation of coupling!

- However the need and/or requirements for a fast Q-loop control are unclear

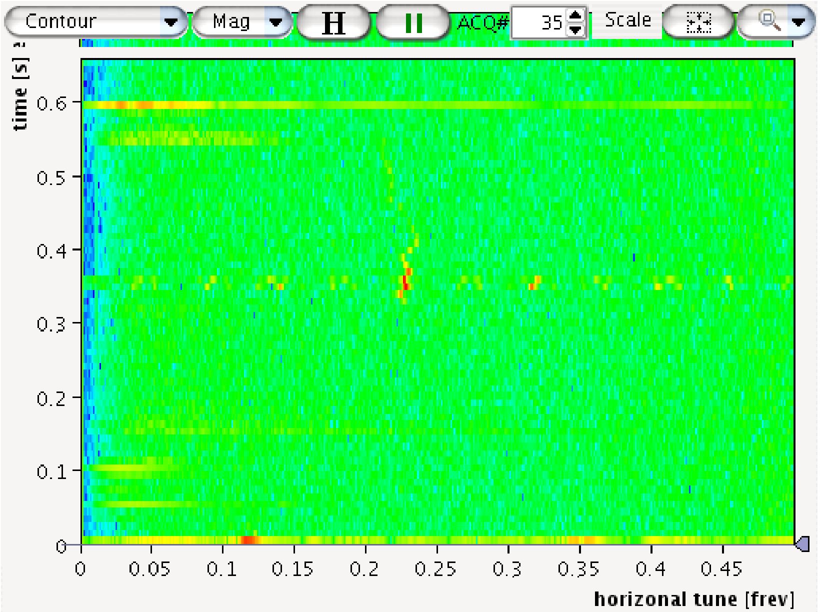
- Proposed feedback implementation/deployment steps:
  - 1. Quantification of parameter requirements based on robust measurements (ongoing)
  - 2. Semi-automated cycle-to-cycle feedback control
    - could reach a intra-cycle bandwidth of about 100-200 Hz
    - could be implemented on the basis of already available hard-/software
  - 3. Fully automated in-cycle feedback within in the Q-meter FPGA
    - could reach a true closed-loop bandwidth of about 100-200 Hz

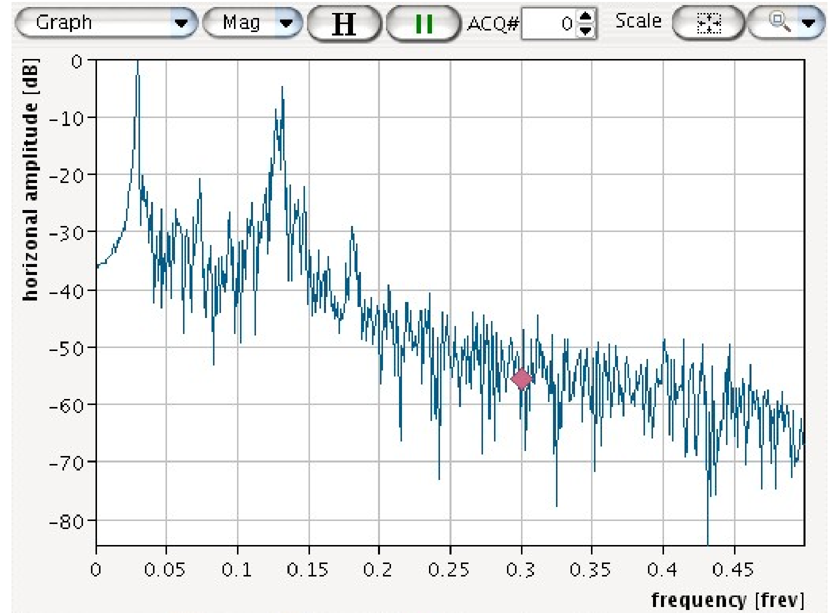
additional supporting slides

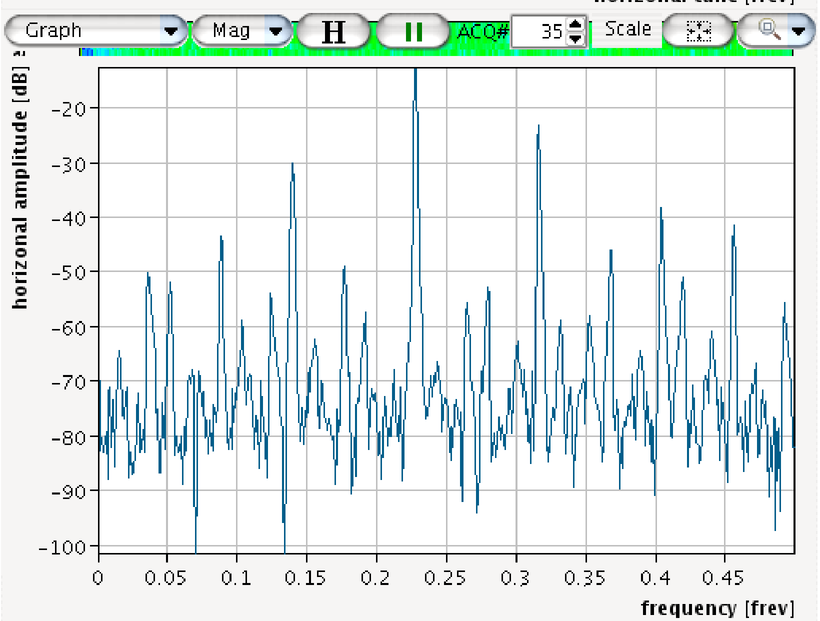
Tune Measurement with slowly-extracted un-bunched Beam in the SPS

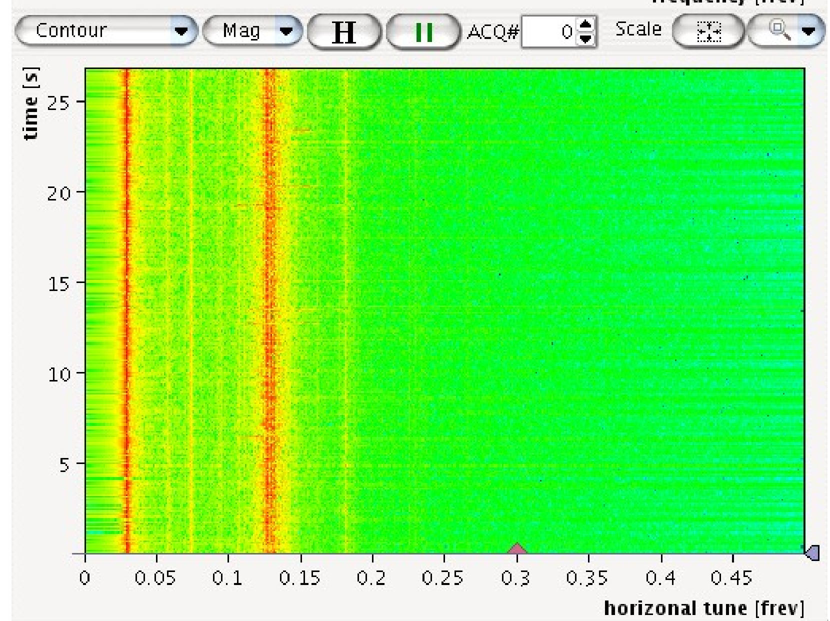


PS-SFTPRO(1) cycle

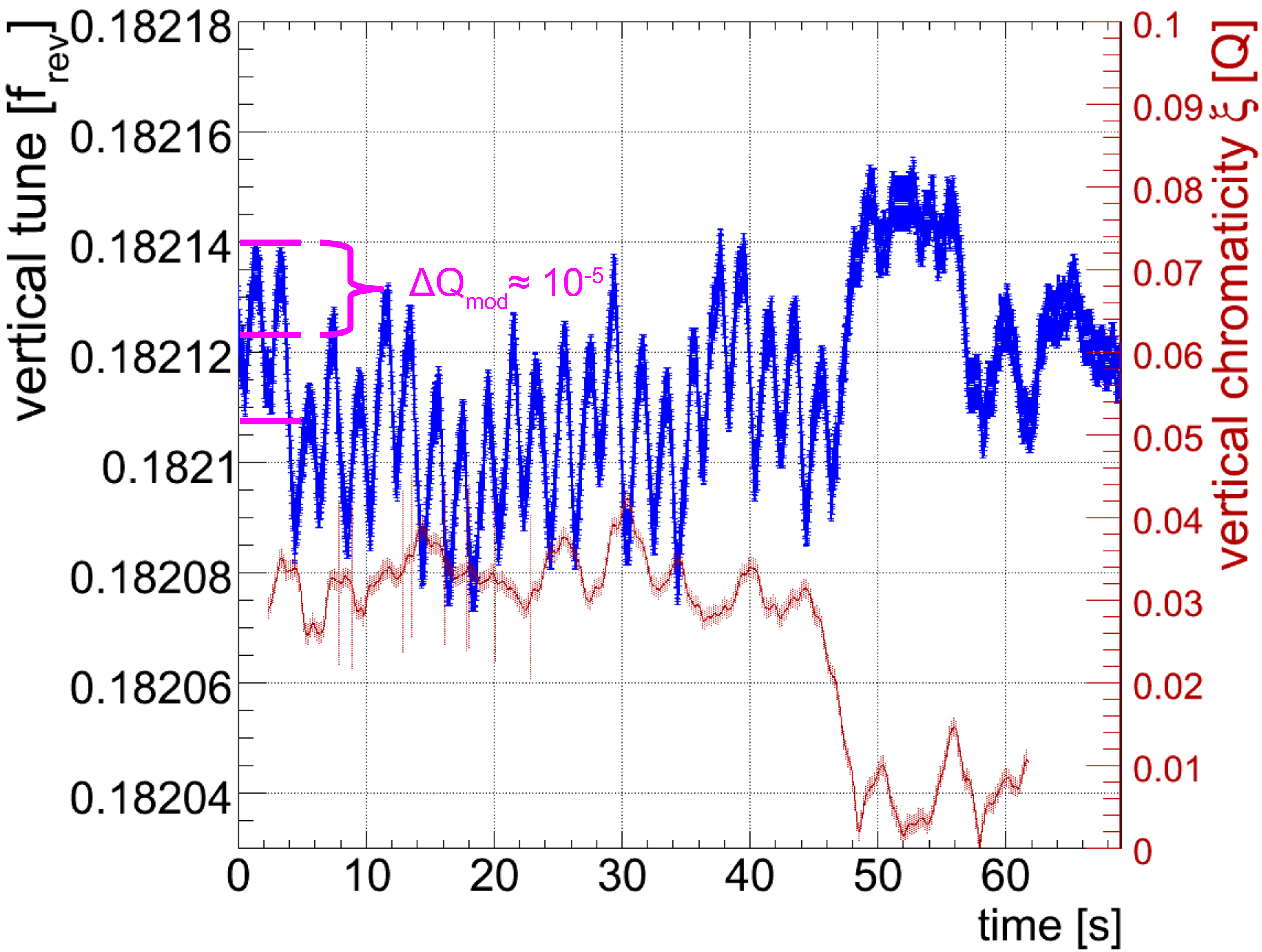






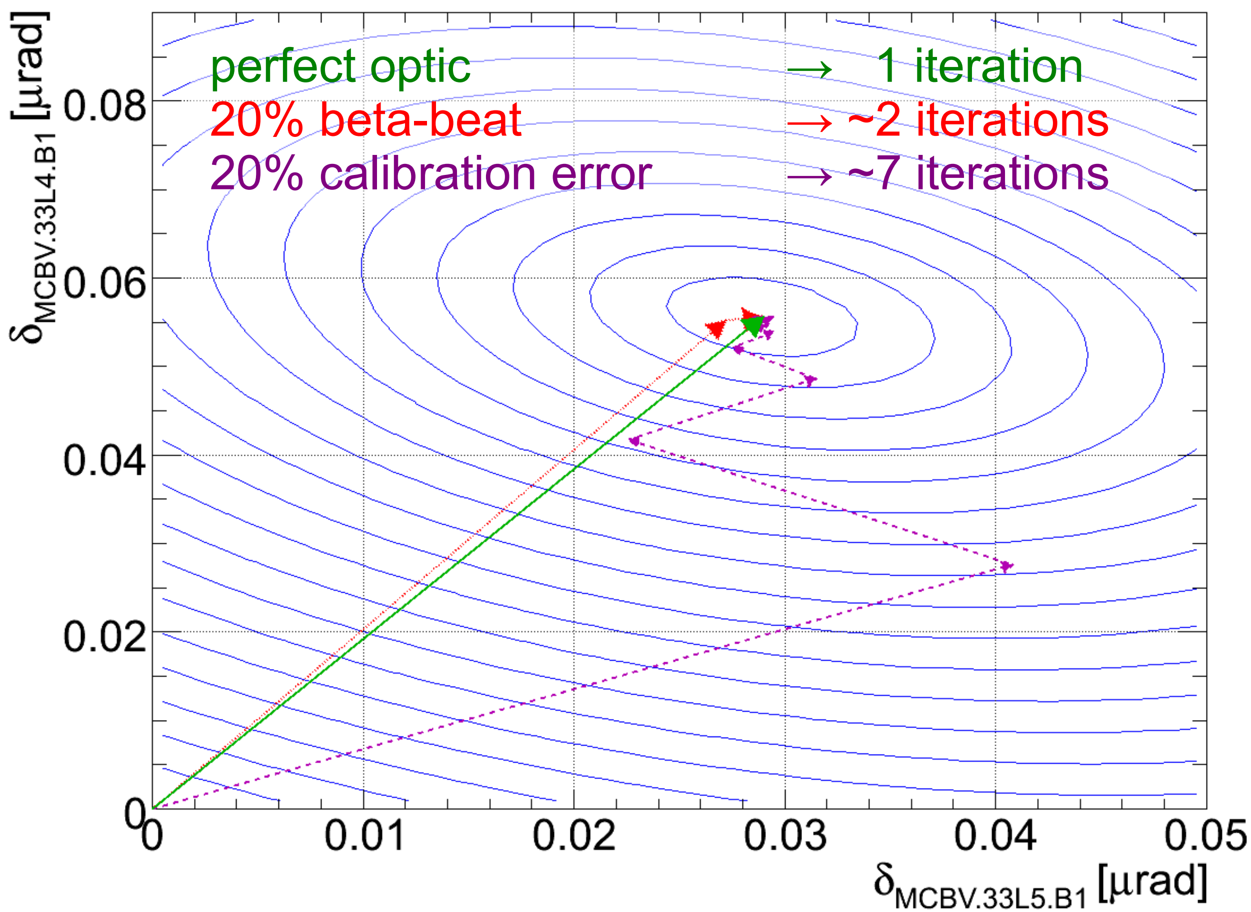


HOT: SPS Q' tracking study
Radial RF modulation $dp/p=1.6\cdot10^{-5}$, set $\xi := 0.05$

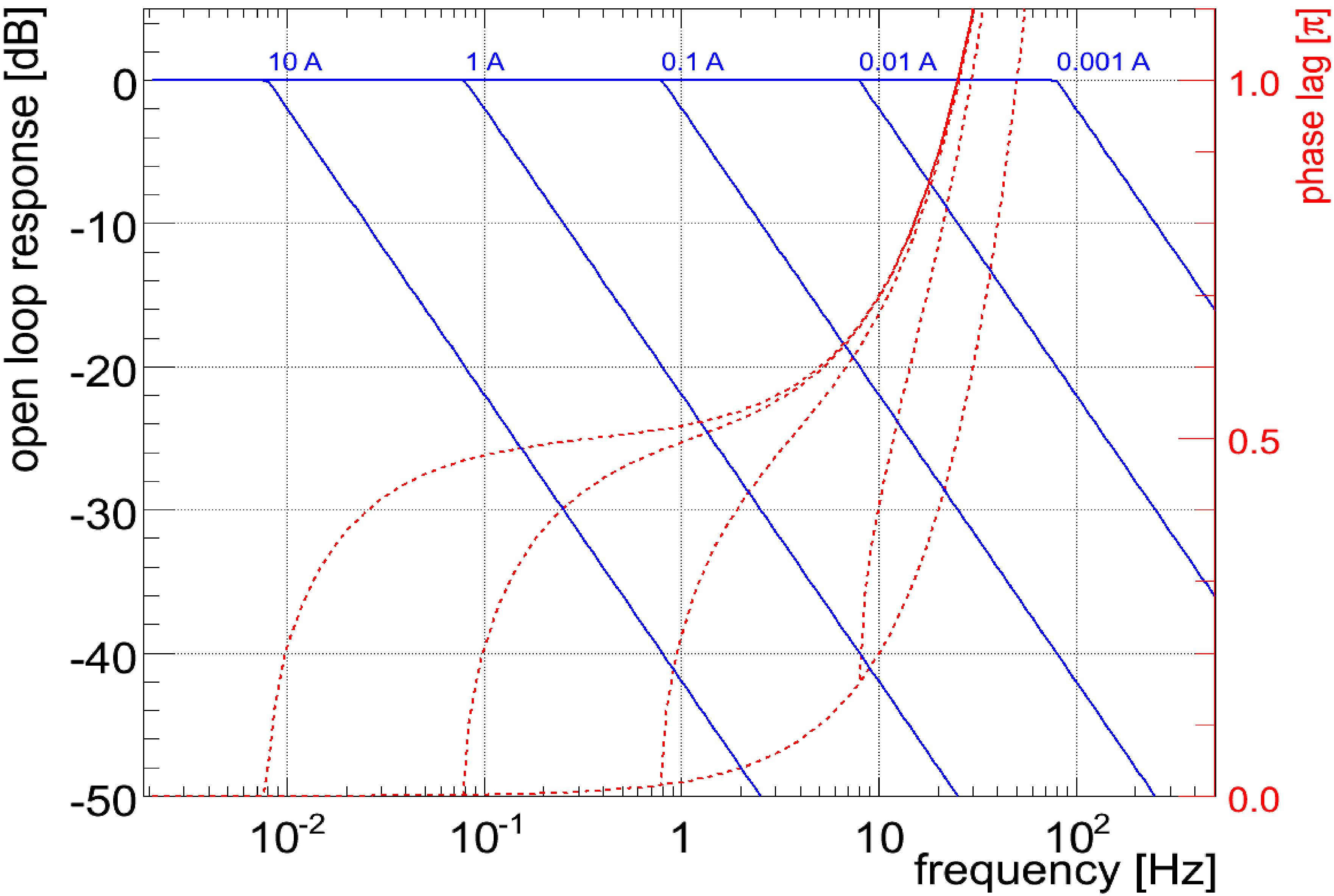


Q/ξ Beam Response Matrix Uncertainties

- Uncertainties in the beam response matrix reduced the effective control/feedback bandwidth but does not affect the steady-state precision
- E.g. LHC orbit feedback:



Non-linear Slew-rate Limited Exciter Response

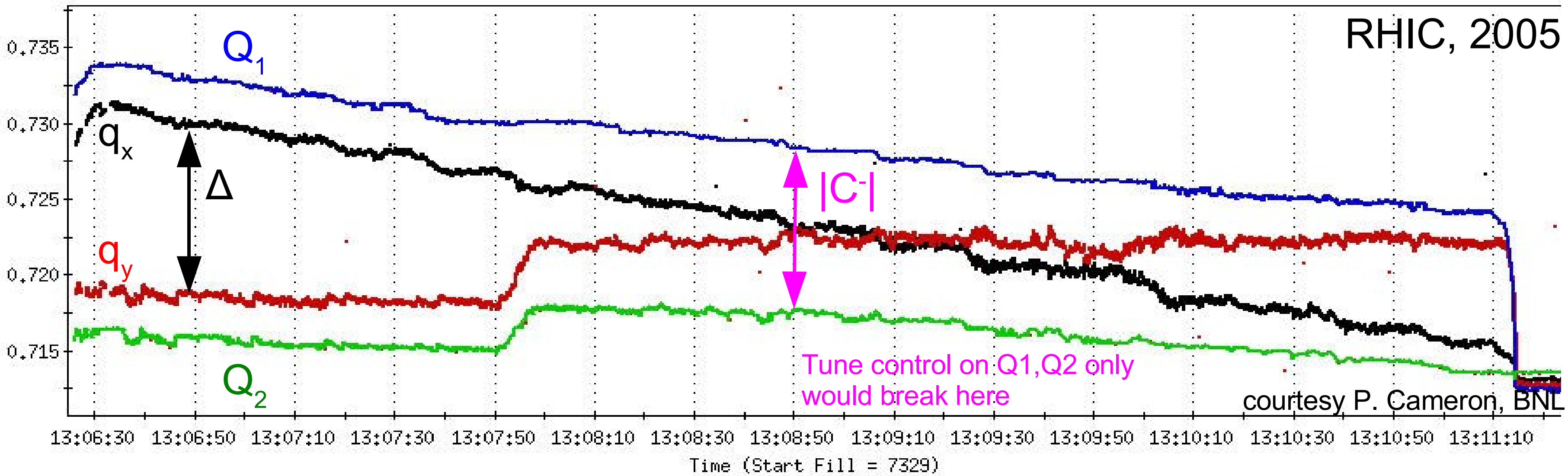


LHC orbit dipole corrector: ΔI=0.01 ↔ Δx ≈ 15 μm @7TeV

Cross-Dependability and Constrains of FB Loops II/III - Coupling I/II

- Strictly speaking: PLL measures eigenmodes (Q_1, Q_2) which in the presence of coupling may be rotated w.r.t. unperturbed tunes (q_x, q_y, $\Delta = |q_y - q_y|$):

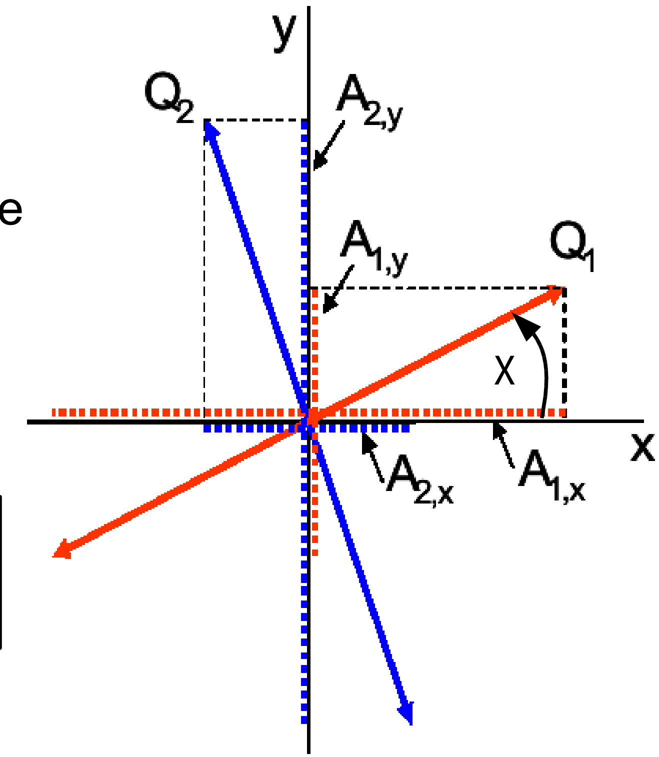
$$Q_{1,2}=\frac{1}{2}\left(q_x+q_y\pm\sqrt{\Delta^2+|C^-|^2}\right)$$



- Possible improvement:
  - optimise tune working point (larger tune-split),
  - vertical orbit stabilisation in lattice sextupoles,
  - active compensation and correction of coupling

Cross-Dependability and Constrains of FB Loops II/III - Coupling II/II

- Measure ratio between regular and cross-term:
  - $A_{1,x}$: "horizontal" eigenmode in vertical plane
  - $A_{1,y}$: "horizontal" eigenmode in horizontal plane



$$r_1 = \frac{A_{1,y}}{A_{1,x}} \quad \wedge \quad r_2 = \frac{A_{2,x}}{A_{2,y}}$$

$$\Rightarrow \quad \left|C^-\right| = \left|Q_1 - Q_2\right| \cdot \frac{2\sqrt{r_1 r_2}}{(1 + r_1 r_2)} \quad \wedge \quad \Delta = \left|Q_1 - Q_2\right| \cdot \frac{(1 - r_1 r_2)}{(1 + r_1 r_2)}$$

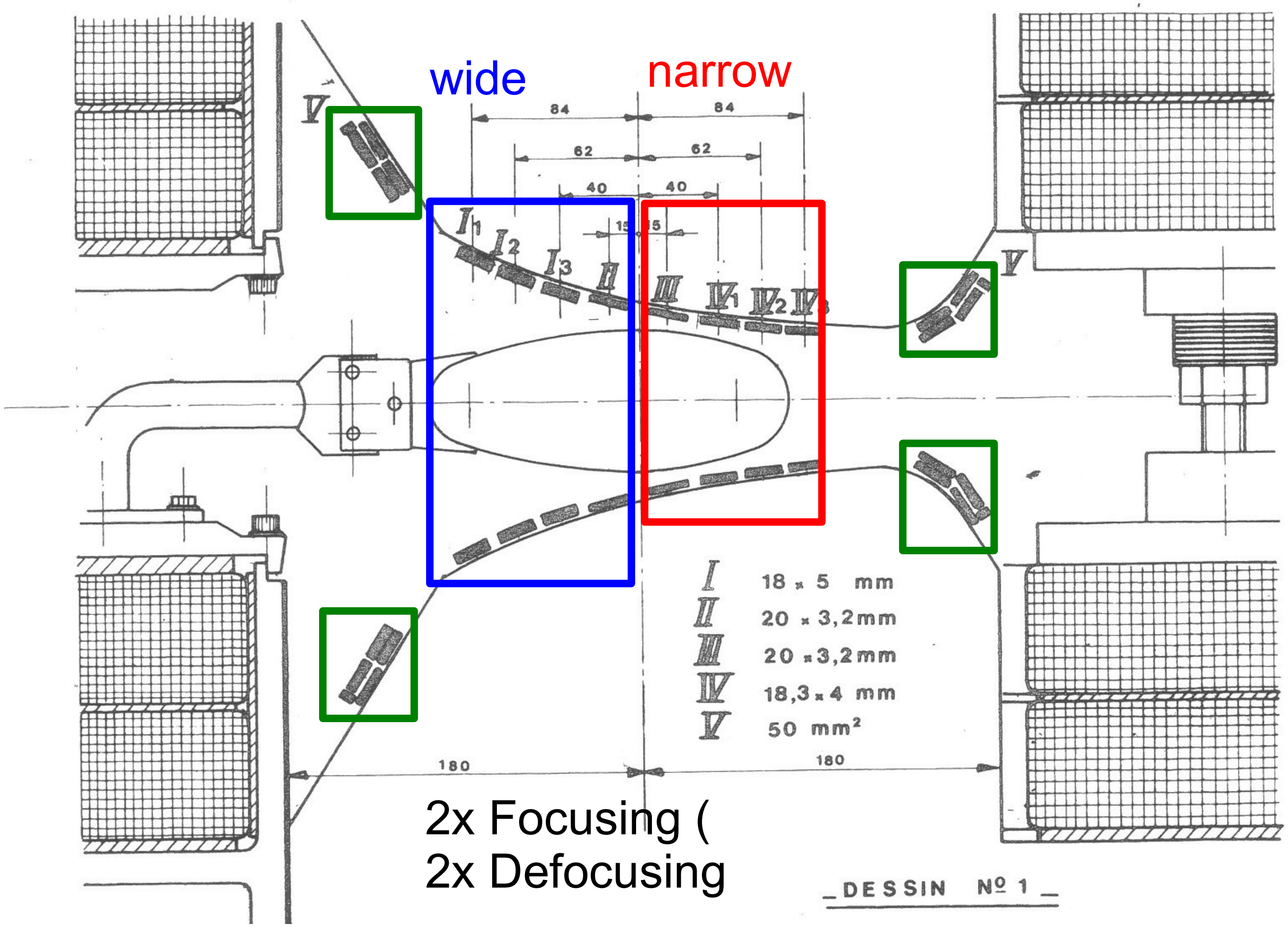
- Decoupled feedback control
  - q_x, q_y → quadrupole circuits strength
  - $|C^-|$, χ → skew-quadrupole circuits strength

implemented and tested at RHIC

R. Jones e.al., "Towards a Robust Phase Locked Loop Tune Feedback System", DIPAC'05, Lyon, France, 2005
P. Cameron, this workshop's Poster Session

Controllability -
PS' Combined Function Magnets

- Main Dipole's Pole-Face-Winding (PFW) Schematic (before 1978)



- 1x Focus. (FW, FN), 1x Defocus. (DW, DN), 8-loop (~octupole) → 3 circuits