Existing SPS and LHC Instrumentation for Crabbed Beams

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Outline

- Dependence of Luminous Region on Crab-Angle – LHC only
  - second-order: beam-beam tune shift (→ BBQ, Schottky)

- Direct Methods – SPS & LHC
  - Fast-Intra-Bunch-Beam-Position-Monitor (aka. Head-Tail)
    - 'single pick-up scheme'
    - 'two pick-up scheme' – one pick-up before and after the cavity
    - Indirect

- Indirect Methods – SPS/LHC
  - Turn-by-Turn Wire-Scanner and Synchrotron Light-Monitor
    - Averaged data looks promising on second scale, but need more experience with turn-by-turn measurements → not directly applicable to SPS
  - Non-zero crab-cavity phase-offset → closed orbit oscillations
    - a priori a non-issue can be picked-up by any BPM for reasonably large (~urad) crab kick angles

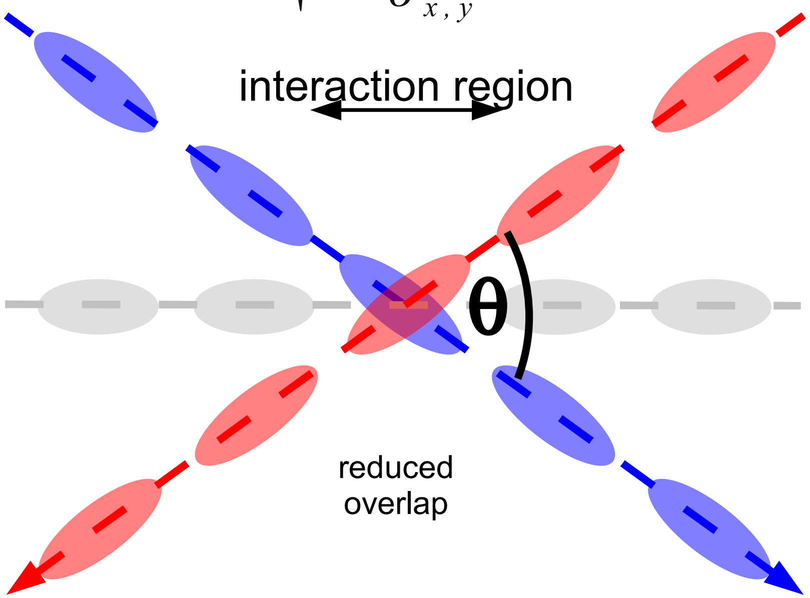
Crab-Cavity Basics

- Crossing angle θ to avoid additional parasitic collisions in the IR
  - Increase angle to avoid long-range beam-beam interaction
    → reduced bunch overlap → reduced luminosity:

$$L = L_0 \cdot F_{crossing} \cdot \ldots$$

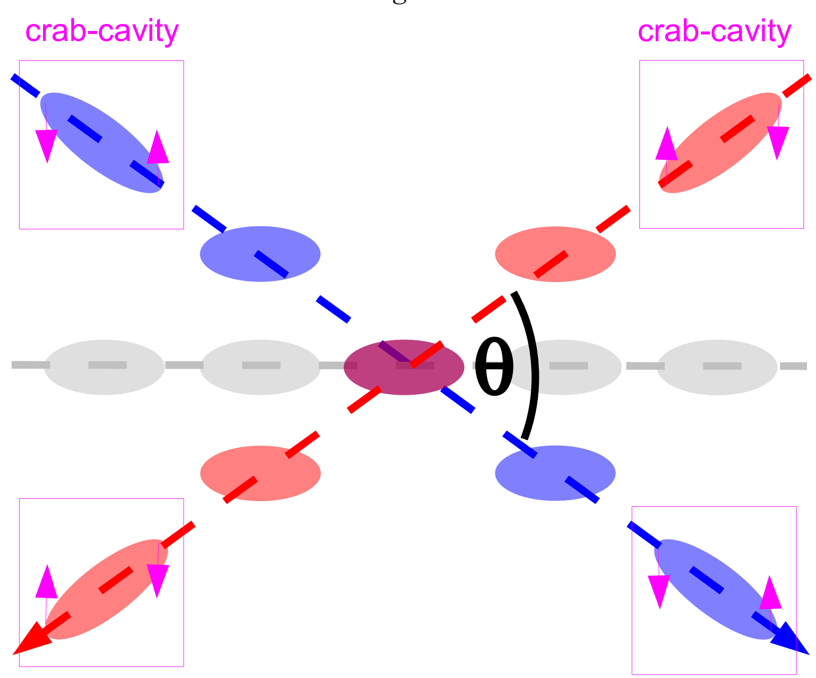
- Without crab-cavity:

$$F_{crossing} = \frac{1}{\sqrt{1 + \frac{\sigma_s}{\sigma_{x,y}} \tan(\theta/2)}}$$



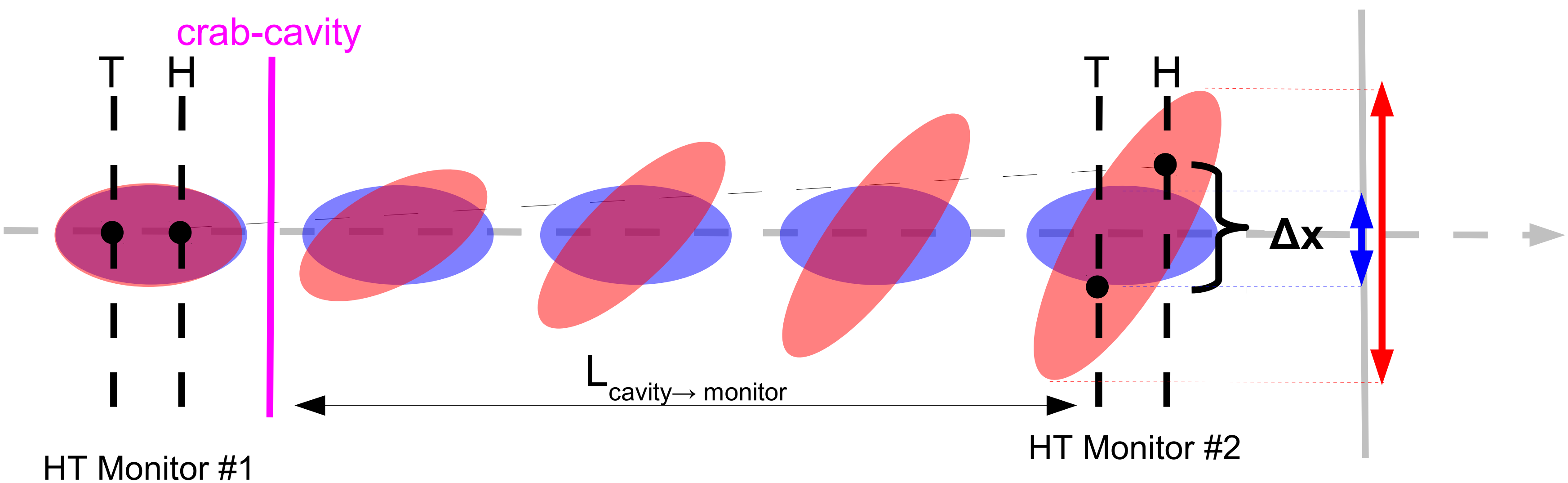
- Aim with crab cavity:

$$F_{crossing} \approx 1$$



Crab-Cavities from a Instrumentation Point-of-View Observables I/II

- A Dependence of luminous region overlap on crab angle (LHC only)
- B Direct: orbit difference Δx between head and tail of the bunch
  - Allows direct measurement of cavity kick angle θ and phase error Δφ
- C Indirect: increased projected beam size Δσ along propagation axis
  - e.g. turn-by-turn wire-scanner, synchrotron light, BGI, ...
  - Potential issue: decoupling of beam size beating due to another effect
- difficult to detect pivoting point (cavity phase) with single monitor location in the ring
  → prefer relative measurement before and a few after cavity (e.g. field free region of 20 m)

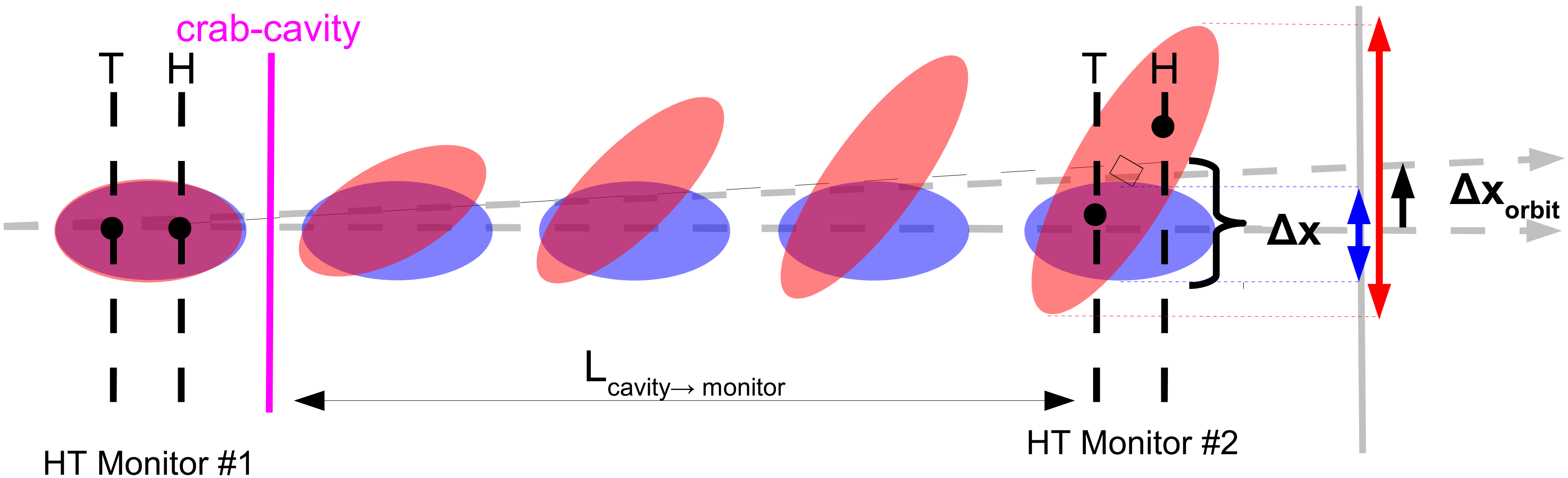


rel. beam size meas.

$$\Delta\sigma = \sigma_w - \sigma_{w/o}$$

D Indirect: closed orbit distortions due to feed-down of imperfect cavity phase

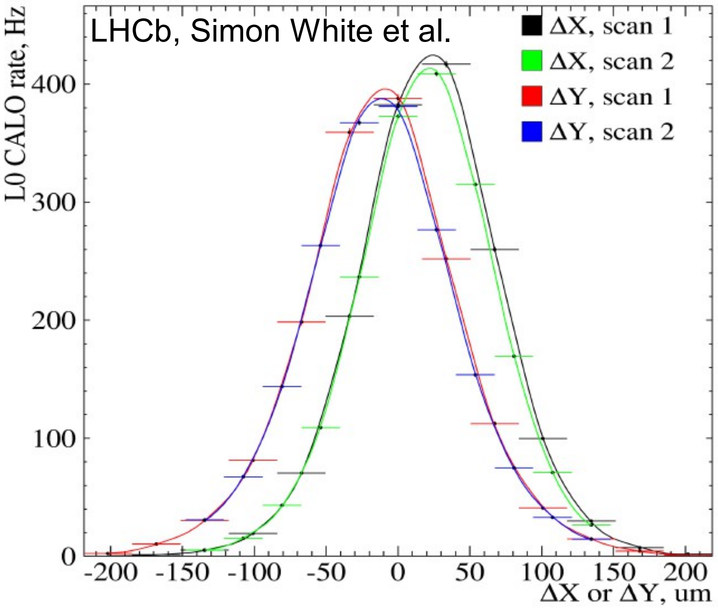
- In case cavity is not phased-in onto the centre of the bunch
- “Easy” diagnostics, particularly for a single de-tuned cavity
  - SPS BPM (>200 H&V): $\Delta x_{res} \approx 200$ μm/turn
  - SPS BPM (~2x 1100): $\Delta x_{res} \approx 50$ μm/turn
- Also covered also by head-tail monitor



→ measurement of orbit feed-down effects are a non issue from a diagnostics point of view but may impact machine protection (→ J. Wenninger presentation)

Dependence of Luminous Region on Crab Angle

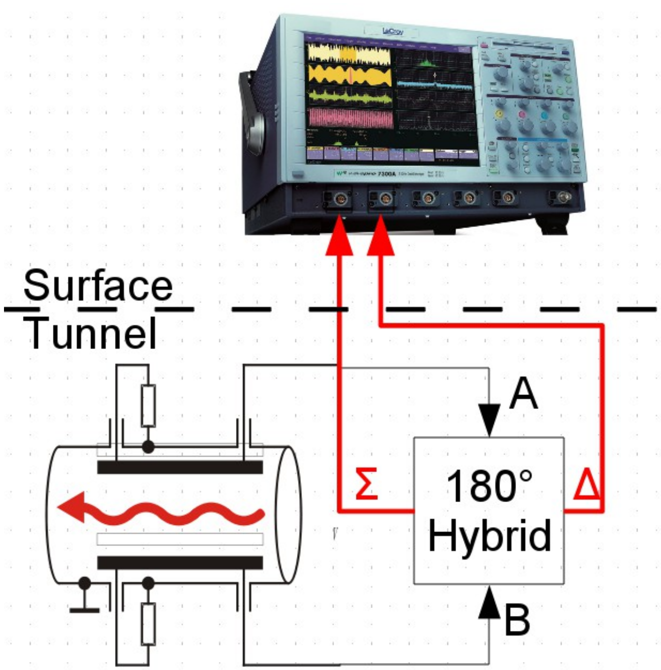
- Could expect similar luminosity resolution as for the Van-der-Meer scans
  - Minute time scale resolution of better than 10^{-3}
  - Should look also at luminous region data from experiments
  - Beam-beam tune shift easily pick-ed up for single colliding bunch pairs (e.g. BBQ)
- Example Lumi Scan:



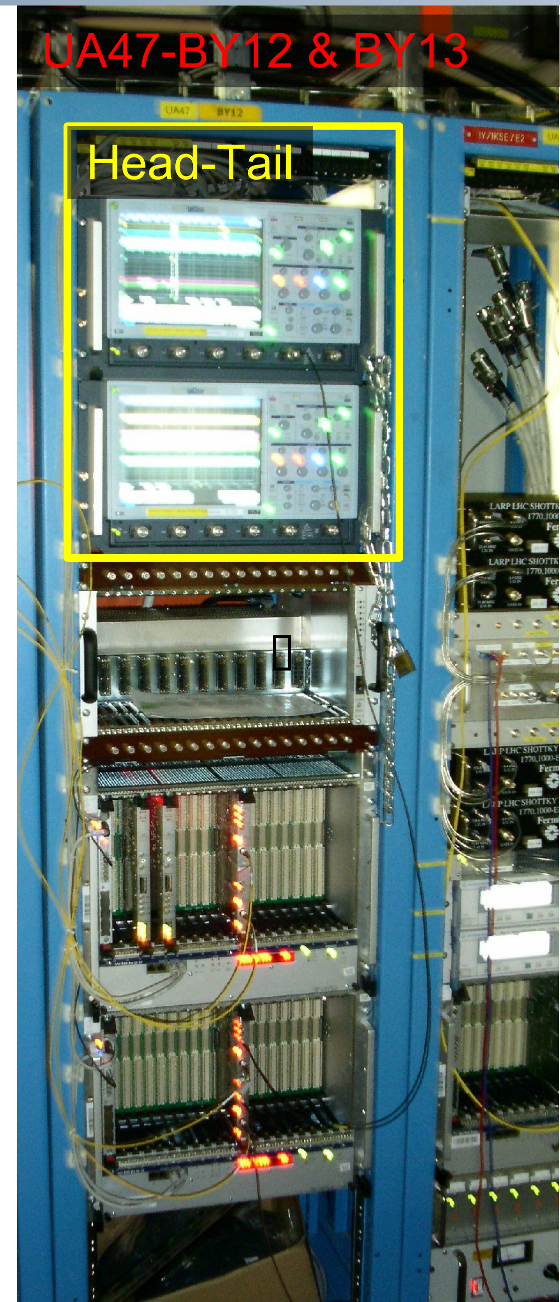
- Pro: direct measurement of the figure of merit (luminosity-increase)
  - nom. crab-cavity effects ~20% (?) of total peak luminosity
- Con:
  - No direct measurement does not tell whether the cavity phase angle is correct or in which direction the angle needs to be adjusted
  - Not applicable for SPS feasibility tests ($\bar{p}$ won't come back soon to the SPS)

Direct Measurement of Crab-Cavity Kick-Angle
Existing SPS & LHC Instrumentation

- Head-Tail or Fast-Intra-Bunch-Position Monitor:
  - Long strip-line (60 cm, to avoid signal-reflection mixing)
  - Σ-Δ hybrid (removes common mode signal)
  - Fast-sampling to resolve bunch structure
    - ~ ns bunch length → GHz scope bandwidth
  - Mandatory compensation for non-beam effects:
    - pickup- & hybrid response, cable dispersion, …
    - done and used for year(s) in the LHC (SPS)

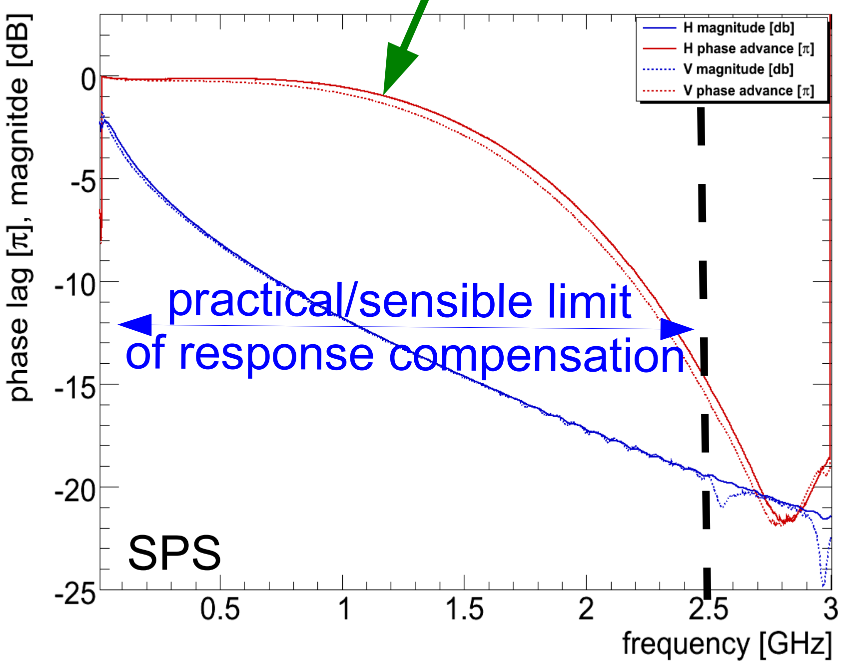


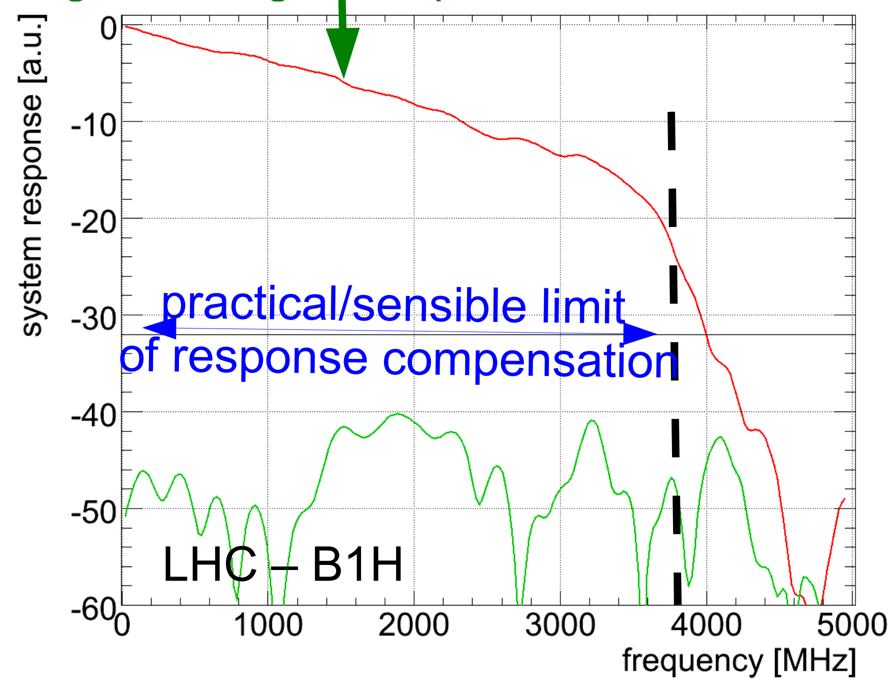
- direct measurement of all observables
- poor resolution, in particular for short bunches
- single monitor, difficult to dis-entangle:
  crab vs. Q' vs. impedance effects causing HT oscillation
  → two monitor scheme



Compensation of HT System Response

- True longitudinal bunch profile measurement is distorted by:
  - pick-up response
  - hybrid-response
  - Dispersion due to 7/8” Heliax cabling & analogue scope bandwidth





  - SPS good up to about 2.5 GHz
  - LHC has much shorter cables and thus better performance → ~4GHz
- Accuracies below 10% require compensation (i.e. short bunches)
  - Fourier space deconvolution with measured system response
    - Good compensation to first order but relative measurements preferable

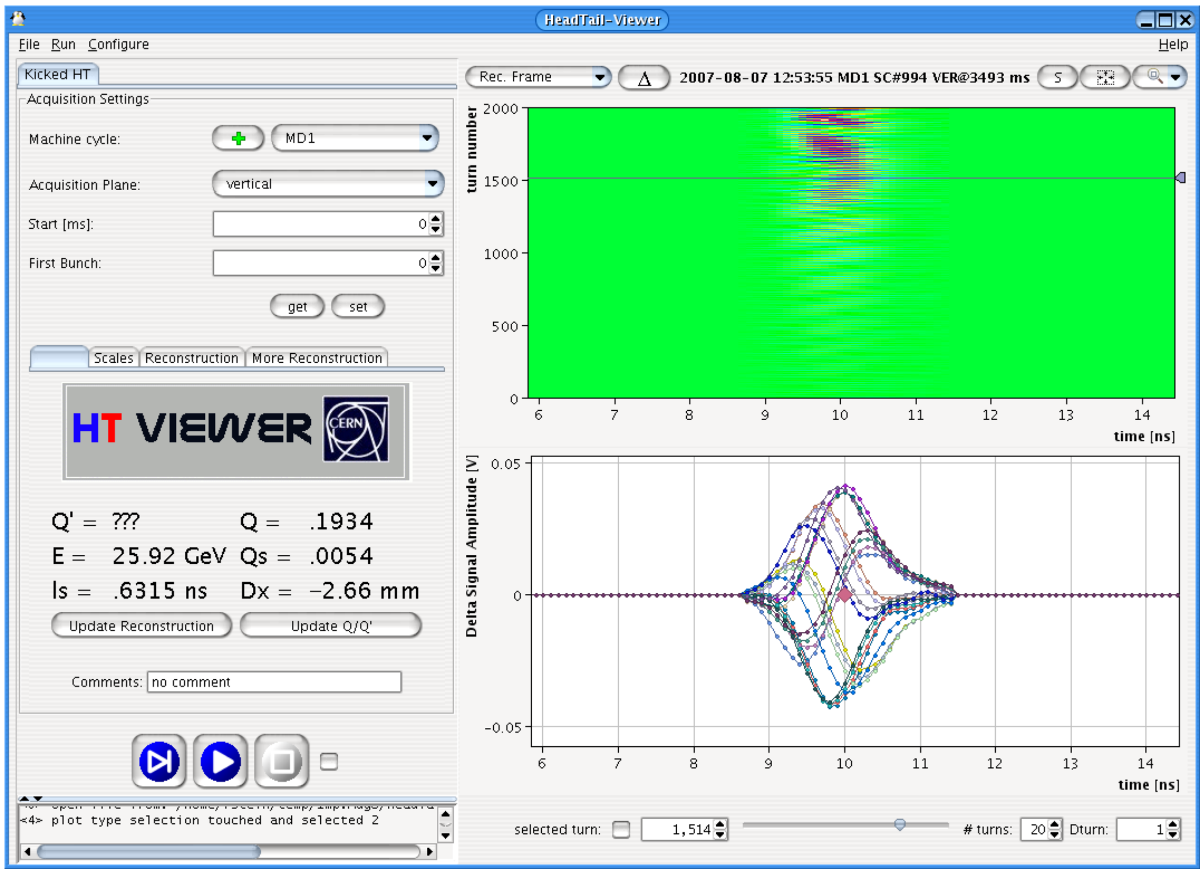
Some Head-Tail Facts and Figures

- Head-Tail Monitor: fast turn-by-turn acquisition a few dozen bunches or trains
  - minimum separation between bunches/train ~1 μs, one scope/beam
  - Can be re-triggered within the same turn, re-triggering delay ~2 us
  - Sum- and Delta- 'frame-length x number of turns' limited by scope memory, e.g.: 100 us x 10 turns, 500 ns x 5000 turns or 2 trains of up to 500 ns x 2500 turns
  - Gains needed to adjust for pilot/nominal bunches
  - 8 bit scope but actual resolution depends more on given parameter and in particular bunch-length

- Various beam parameter estimates already implemented:
  - Fast intra-bunch beam position measurement of head-tail modes
    → crab-cavity specific angle and phase can be "easily" added/extracted
    - Bunch orbit is sliced in minimum chunks of 0.1 ns (sampling), however: actual independent bunch slices are much wider due to limited analogue BW
    - For the time being: designed/calibrated for 2.5 GHz ↔ 0.2..0.4 ns
      - Need a bit of development & resources to push this limit higher
  - Bunch intensity estimates → nice for fast losses / self-consistent measurement
  - Bunch length estimates: Cos^2-, Parabolic-, Gaussian-distribution
  - Bunch power-bandwidth containing 50/95/99% of bunch power/intensity
  - Bunch peak voltage

Head-Tail Example

- Processing and analysis a priori very similar to head-tail analysis
  - However: need to decouple what is head-tail (or impedance) driven and what is crab-cavity induced → favours two-HT pick-up scheme
- Example measurements (here head-tail m=1 mode):



Head-Tail Monitor Limitations

- Brief discussion of
  - Crab-cavity phase resolution ↔ long resolution along the bunch
    - 10 GHz Sampling → 0.1 ns
    - much lower limit due to effective analogue bandwidth of 2.5 GHz
    - Improving this is not obvious → favours long bunches
  - Crab-cavity kick angle → orbit resolution of individual bunch slice

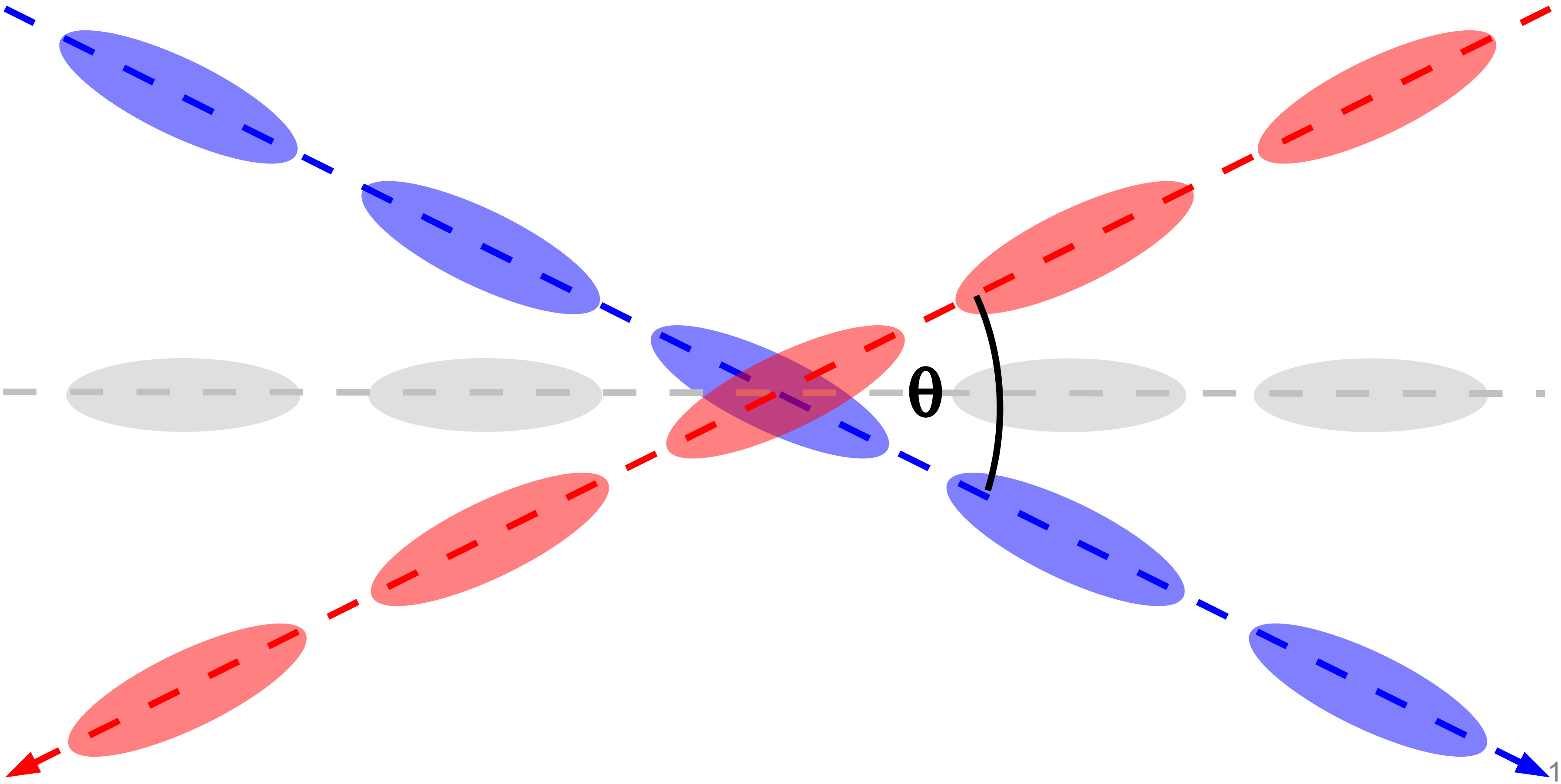
$$\Delta\theta_{meas} \propto \frac{\Delta x_{HT}}{\tau_{HT}} \cdot L_{cavity \rightarrow monitor}$$

~ 20 m (proposal)

- The larger the distance τ_{HT} between the head- and tail-slice of the bunch the better leverage arm but also the worse the S/N of the difference and sum signal
  - keep in mind that the ADC is only 8 Bit and
  - has to swallow closed orbit signal offset of the center slice
    - » Electrical/magnetic/mechanical re-centering of pick-up?

Summary

- Detecting the crab-cavity induced deflection:
  - Direct – cleanest but difficult in terms of BW and S/N
    - Head-Tail monitors already available in SPS and LHC (one per beam)
    - two-pick-up scheme to disentangle other non-crab effects
      - less sensitive to long./impedance driven turn-by-turn effects
  - Indirect – better signals but uncertainties on cavity phase, beam size vs. bunch oscillations, etc.
    - orbit feed-down effects could be picked-up by existing BPM installation
- Thing that would ease diagnostics (for the SPS tests)
  - centering of orbit in pick-up and cavities
  - long bunches, e.g. 5 ns (SPS: injection only)
    - less constraints on timing
    - better resolution/separation between individual bunch slices
  - larger bunch population → more S/N in the head and tails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