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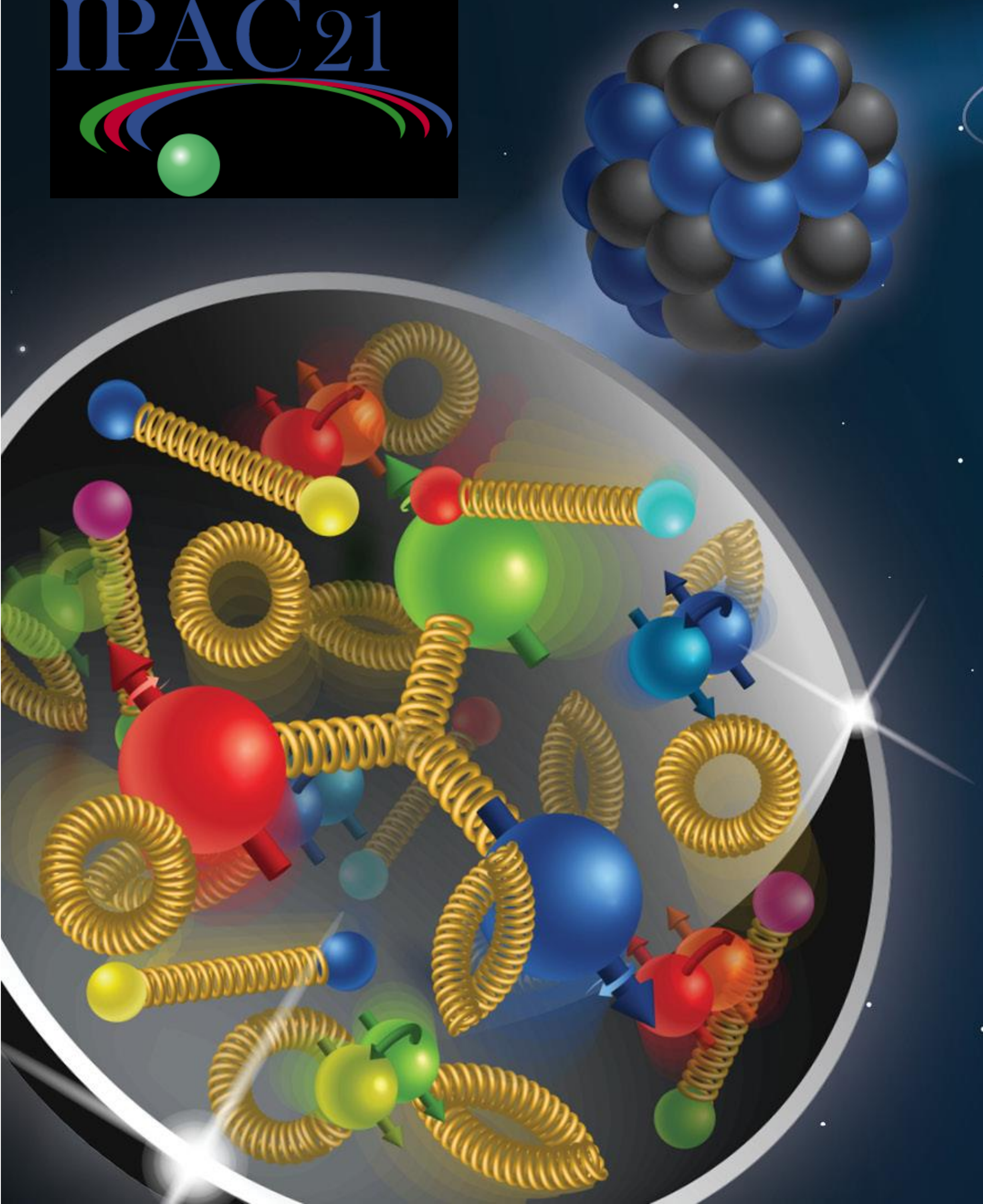

LIMITING COHERENT LONGITUDINAL BEAM OSCILLATIONS IN THE EIC ELECTRON STORAGE RING

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Introduction

We study coherent longitudinal beam oscillations in the Electron Ion Collider (EIC) electron storage ring (ESR). We show that to avoid unacceptable hadron emittance growth due to finite crossing angle, the amplitude of these oscillations needs to be limited to a fraction of a millimeter. Using an analytical model we estimate the amplitude of these oscillations under the two scenarios: 1) the beam is passively stable and the oscillations are driven by RF phase noise only; 2) a coupled-bunch instability, presently expected in the ESR, is damped by a longitudinal feedback system. We show that, for the 2nd scenario, comfortable specifications for RF phase noise and feedback sensor noise will be sufficient to maintain the oscillation amplitude within the required limits.

The present ESR design is expected to have longitudinal coupled bunch instability, driven primarily by a narrow-band impedance due to the RF cavity HOM absorbers. A strategy needs to be developed to cure this instability, either by passive damping with re-designed HOM absorbers, or with a longitudinal feedback system. Separately, to avoid unacceptable hadron emittance growth, the electron beam arrival time jitter in the crab cavities must be maintained below 1.1 ps rms, which imposes 0.33 mm rms limit on the amplitude of coherent longitudinal oscillations in the ESR, derived below. These oscillations are expected to be primarily driven by the RF phase noise. However, in the case that a feedback system is used to cure the instability, they can also come from the feedback system itself, which, in a certain frequency range, could amplify its own sensor noise. In this paper we analyse the expected magnitude of these oscillations for both approaches. For more in-depth treatment of this problem see our technical note.

Beam arrival position jitter tolerance for the ESR

- Longitudinal motion of e-bunches causes dipole beam-beam kicks on the hadrons due to crossing angle (2 θ= 25 mrad)
- The offset from the ideal orbit is

$$\Delta x(z) = \theta z - \theta \sin\left(kz\right)/k$$

Distance from 0-crossing $\qquad$ ω_{crab}/c

- Assume centroid jitter, $z_0(t)$. Averaging over the beam distribution get beam-average transverse offset

$$\langle \Delta x(t) \rangle = \theta k^2 < (s - z_0(t))^3 >_s /6 \cong -\theta k^2 \sigma_l^2 z_0(t)/2$$

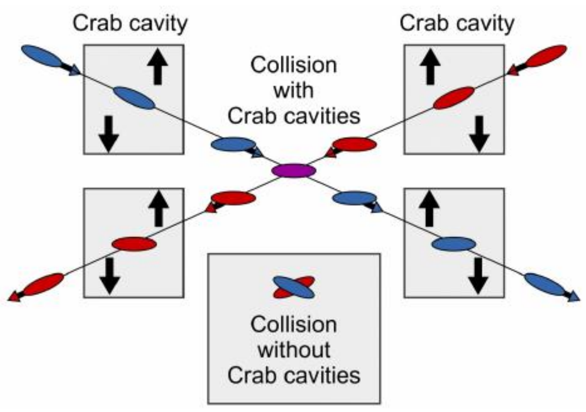
rms bunch length

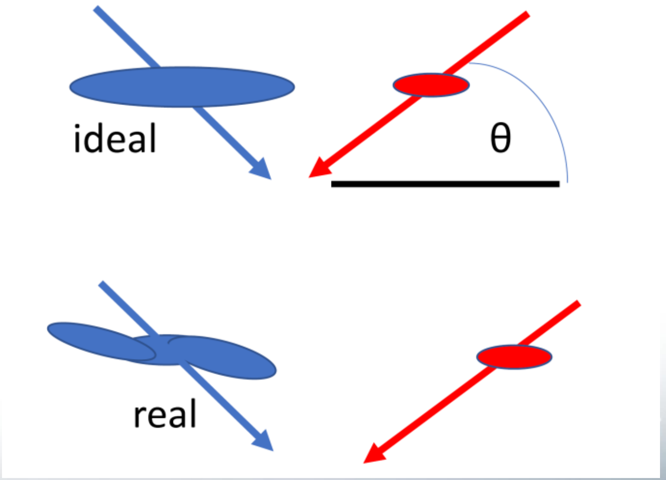
- Hadron beam size growth at the IP

$$\frac{d}{dn}\sigma_x^2 = 2(2\pi\Delta Q_{bb}\sigma_{xe})^2 \sum_{m=-\infty}^{\infty} \rho(m)\cos(2m\pi Q_x)$$

rms of <$\Delta x(t)$> $\qquad$ Correlation function

- Take the sum to be 1. Take the initial beam size σ_{x0}=0.1 mm, σ_l=1cm, ΔQ_{bb}=0.015, and n=10 hours/12.8 μs, for the beam emittance to double => estimate σ_{xe} => estimate rms of $z_0(t)$.





Result: rms jitter of 0.33 mm, equivalent to arrival time jitter of 1.1 ps rms.

Analytical model: noise-driven harmonic oscillator with feedback

driving force (white noise)

derivative feedback

$$\ddot{x} + 2\Gamma\dot{x} + \omega_0^2 x = \sigma\,\eta(t) - g \times (\dot{x} + \dot{\xi}(t))$$

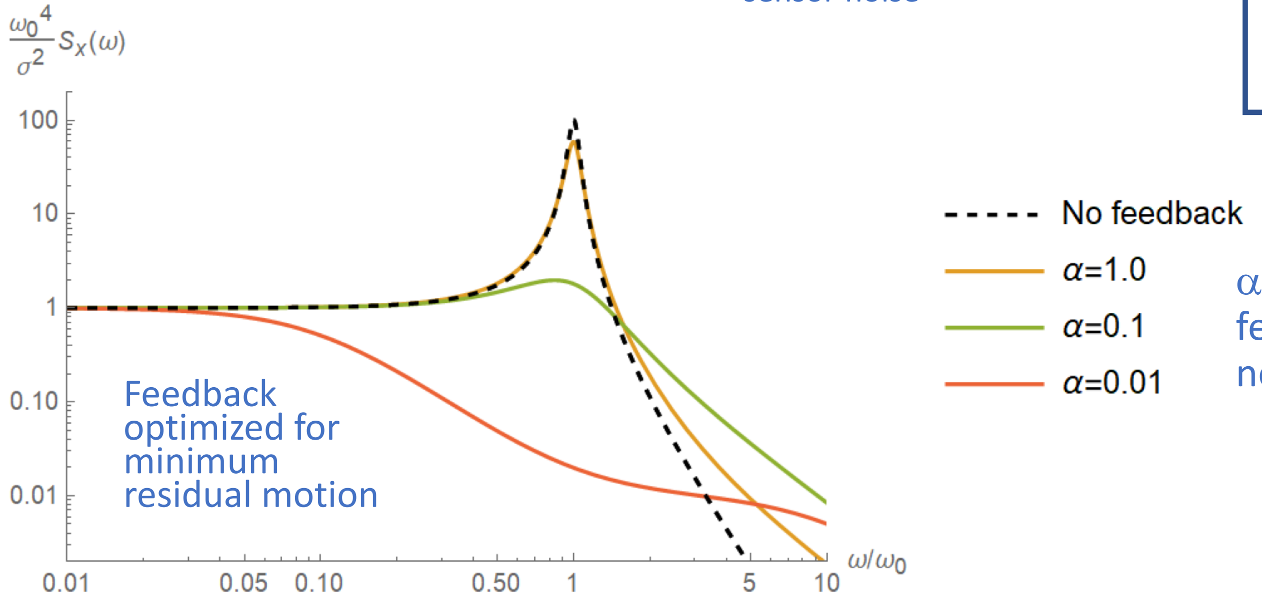
Feedback sensor noise

Expected Power Spectral Density (PSD)

$$S_x(\omega) = \frac{\sigma^2}{(\omega_0^2-\omega^2)^2+(2\Gamma+g)^2\omega^2} + \frac{g^2\omega^2}{(\omega_0^2-\omega^2)^2+(2\Gamma+g)^2\omega^2}\sigma_\xi^2$$

driving noise

sensor noise



Feedback optimized for minimum residual motion

α is "normalized feedback sensor noise"

Figure 1: PSD of residual oscillations at the optimum feedback gain plotted for different feedback sensor noise levels and $\Gamma/\omega_0 = 0.05$.

Beam instability damped by optimized derivative feedback

- Add instability to the model by $\Gamma \to \Gamma_d - \Gamma_i$
- Require feedback gain $g > \Gamma_i - \Gamma_d$ for overall stability

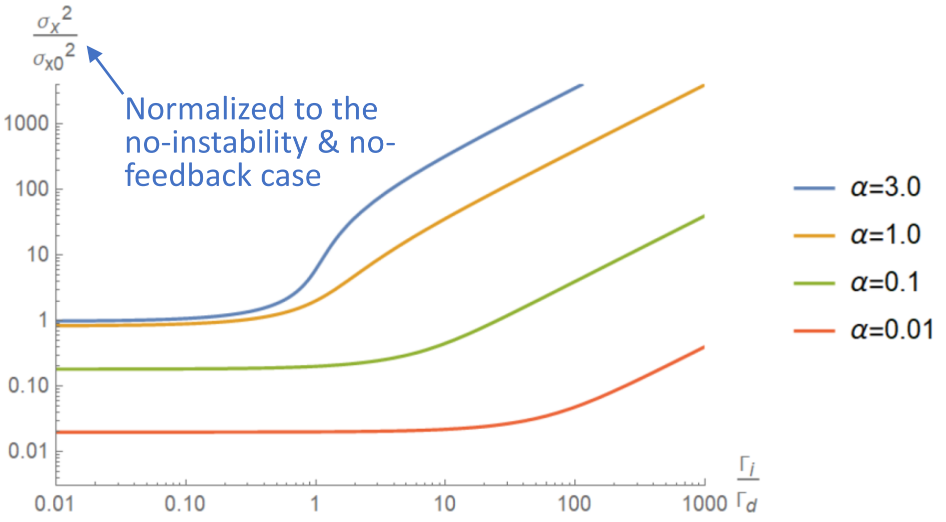


Figure 2: Residual oscillation power with the derivative feedback set to the optimum gain plotted for different feedback sensor noise levels.

Feedback Sensor Noise Parameter

$$\alpha^2 = \frac{\Gamma_d^2}{\omega_0^2} \frac{S_\xi}{S_x(0)} = \frac{\pi \Gamma_d}{2 B_\xi} \frac{\sigma_s^2}{\sigma_{x0}^2}$$

Sensor PSD; Sensor; Beam PSD @ low freq.; Sensor bandwidth; beam

Γ_i instability growth rate

Γ_d radiation damping rate

ω_0 synchrotron frequency

- Feedback is effective when its sensor noise is low, $\alpha \ll 1$.
- Compared to the no-instability & no-feedback case, the feedback can reduce the residual beam noise power by a factor of $\sim 2\alpha \ll 1$, as long as the instability growth rate is limited by $\Gamma_i < \Gamma_d/(2\alpha)$.

Implications for ESR: arrival position jitter when instability is damped by the feedback

- Can we meet 0.33 mm arrival position rms jitter in the crab cavities in the presence of longitudinal coupled bunch instability?
- Yes, by using active feedback. Required RF phase noise specs are relaxed, feedback sensor noise specs are not very challenging (see EXTRAS below)

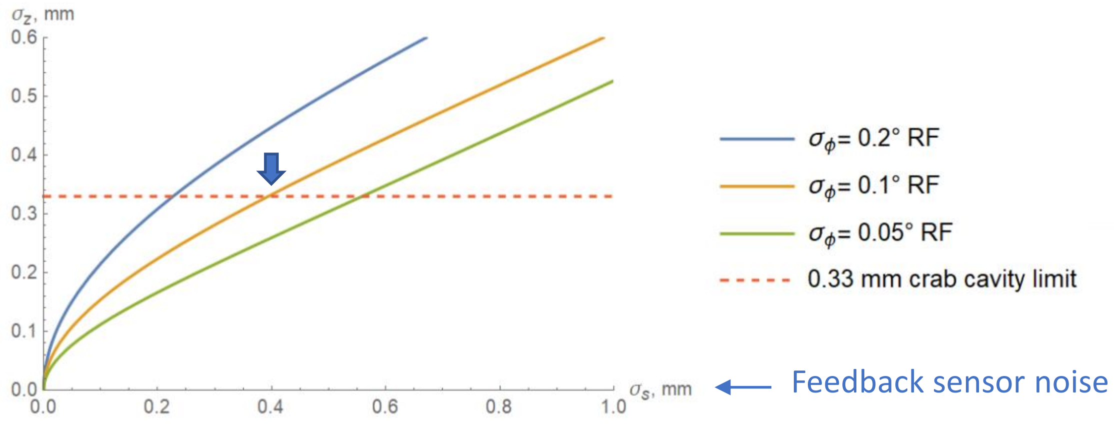


Figure 5: Beam arrival position jitter vs. integrated feedback sensor noise for several rms values of RF phase noise, σ_ϕ. Bandwidth of $[0.5\ 1.5]\omega_s$ is assumed for both the RF and sensor noise.

CDR Parameters	
radiation damping rate:	1/2000 turn^{-1}
Instability growth rate:	2π/1000 turn^{-1}
RF frequency:	591 MHz
Synchrotron freq., f_s :	0.05 f_{rev}=3.9 kHz

1 degree RF = 1.41 mm

- For example, for RF phase noise of 0.1 deg rms the sensor noise of 0.4 mm rms is adequate (@ zero margin)

Implications for ESR: arrival position jitter with passively damped instability

- Can we meet 0.33 mm arrival position rms jitter in the crab cavities if we passively damp the instability (via HOM damper redesign)?
- Yes, but it could be challenging
- Even at zero margin we need RF phase noise below 0.02 degrees rms

Residual rms jitter, no feedback

$$\sigma_{z0} = \sigma_{\phi} \frac{c}{f_{RF}\,360} \frac{1}{4} \sqrt{\frac{\pi B_{RF}}{\Gamma_d}}$$

Bandwidth

Phase noise, deg. rms

- Passively damping the instability will also require meeting more challenging RF phase noise specs
- This is a seemingly inferior option to the one with feedback

Summary

- To avoid unacceptable hadron emittance blow-up, electron bunch arrival position jitter in the crab cavities must be maintained below 0.33 mm rms
- This specification can be met in the presence of longitudinal coupled bunch instability by using a feedback damper
- Our analysis predicts fairly relaxed specs for the RF phase noise (achieved at NSLS-II and elsewhere) as well as for the maximum allowable feedback sensor noise (also achieved)
- In addition to damping the unstable mode(s) the feedback will greatly reduce the amplitude of the (stable) m=0 mode that usually dominates the noise in the longitudinal plane
- An alternative option is to passively damp the instability (cavity damper redesign) but this will also require meeting challenging RF phase noise specs; a seemingly inferior option

EXTRAS

Other mechanisms potentially causing hadron emittance growth

- Beam-Ion instability

  M. Blaskiewicz, “Beam-Beam Damping of the Ion Instability”, in *Proc. North American Particle Acc. Conf. (NAPAC2019)*, Lansing, MI, Sep. 2019, pp. 391-394.

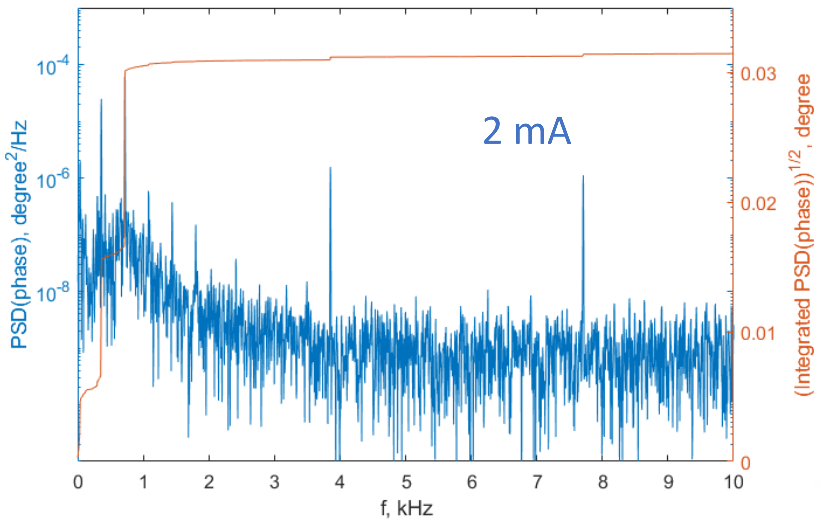
- Main cavity RF noise + dispersion

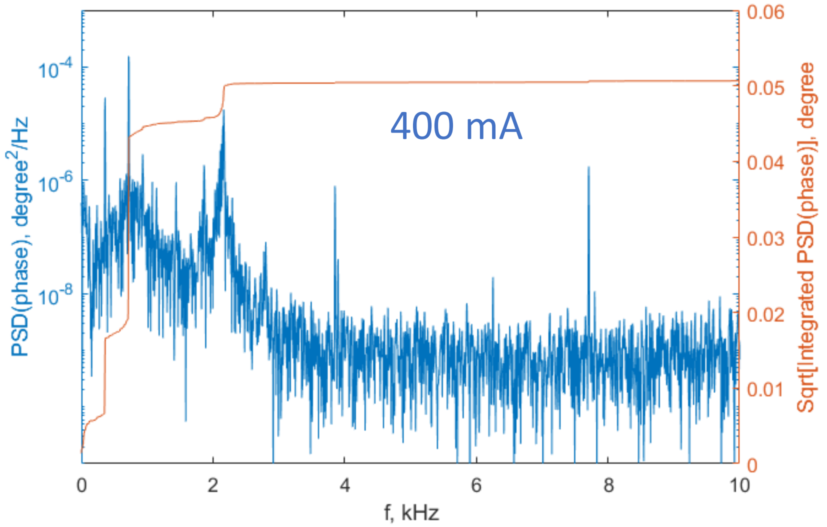
  R. Brinkmann, “Proton Emittance Growth Caused by Electron rf-Noise and the Beam-Beam Interaction in HERA”, in *Proc. First European Particle Acc. Conf. (EPAC 88)*, Rome, Italy, June 1988, pp. 657-659.

- Crab cavity RF noise

  P. Baudrenghien and T. Mastoridis, “Transverse emittance growth due to rf noise in the high-luminosity LHC crab cavities”, Phys. Rev. ST Accel. Beams 18, 101001, (2015).

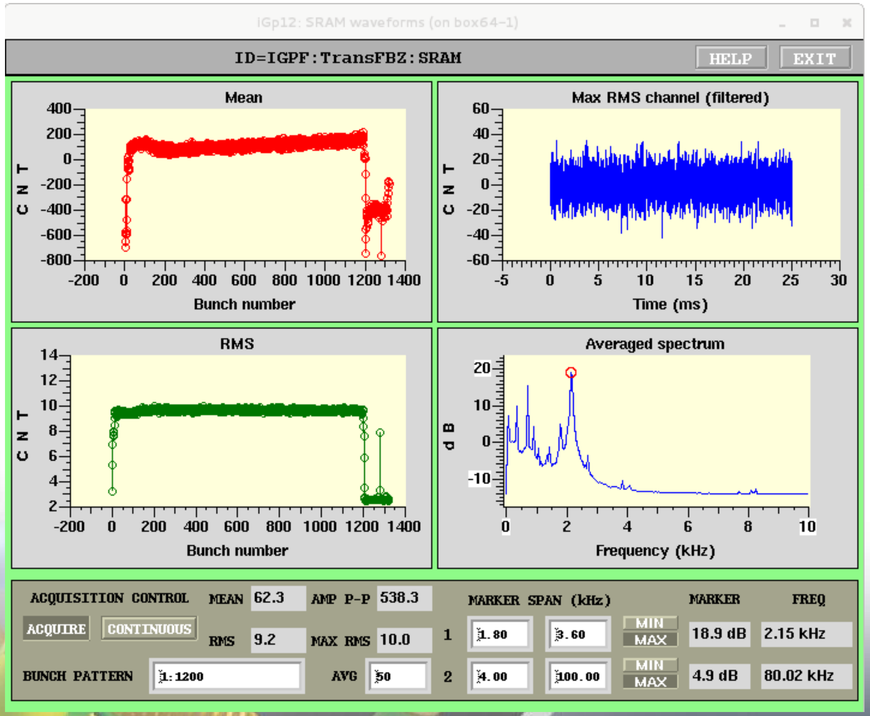
RF phase noise at NSLS-II





- The spec of 0.16° rms RF phase jitter at NSLS-II light source came from the timing users
- It has been achieved by a high margin. Could be optimized further but no need yet.
- Cavity probe signals shown are routinely monitored during Ops
- At high current beam operations these signals include substantial contribution from the beam => low current setup gives better estimate of phase noise
- Typical integrated phase noise at 400 mA is 0.1-0.2 deg. rms in 2 MHz bandwidth, and 0.05 degree rms in 10 kHz bandwidth

Longitudinal feedback BPM noise performance from NSLS-II



- NSLS-II is stable longitudinally
- => no need for feedback, monitor only
- Plot shows each bunch's phase, and its rms, also train-average motion spectrum
- 400 mA, f_s=2.2 kHz, f_{RF}=500 MHz
- 1200 + 1 bunches
- Calibration: 540 cnts/deg. RF
- Full buckets:
  - 9.8 counts rms/540 => 0.018 deg. rms beam jitter (driven mainly by m=0 mode)
- Empty buckets:
  - 2.6 counts => 0.005 deg. rms
    - => 8 μm rms sensor noise
- This would be more than adequate for the ESR needs