An Alternative Processing Algorithm for the Tune Measurement System in the LHC

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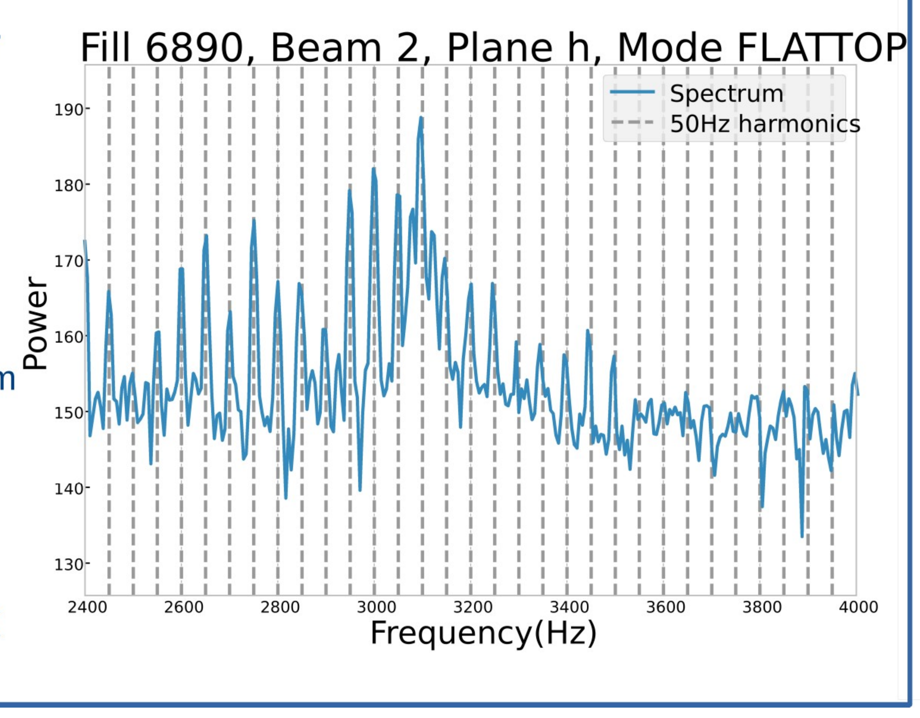
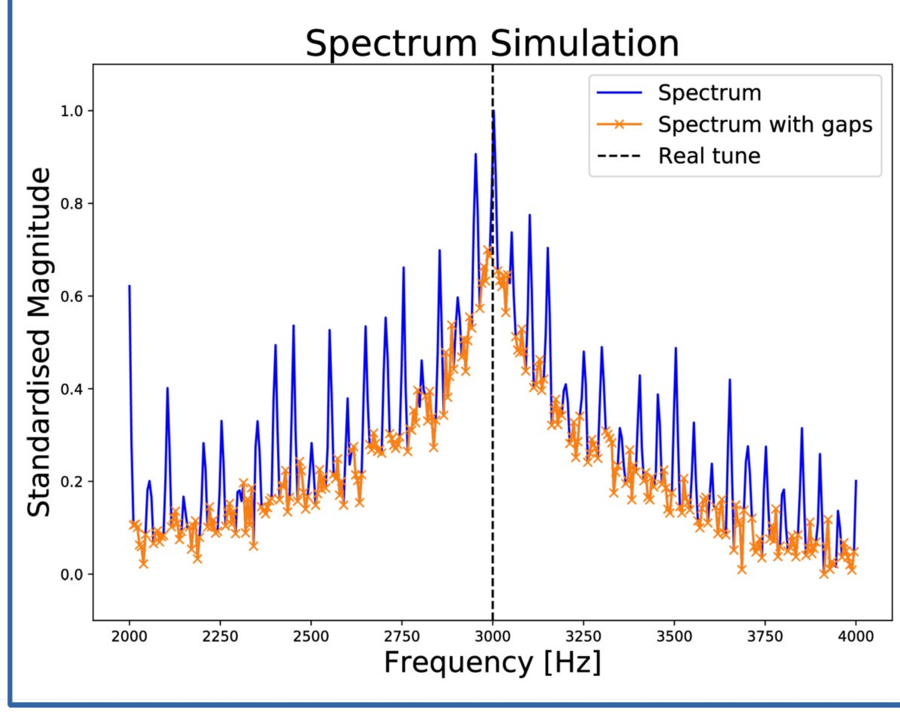
Abstract: The betatron tune in the Large Hadron Collider (LHC) is measured using a Base-Band-Tune (BBQ) system. Processing of these BBQ signals is often perturbed by 50 Hz harmonics present in the beam. This causes the tune measurement algorithm, currently based on peak detection, to provide tune estimates during the acceleration cycle with values that clearly oscillate between neighbouring harmonics. The LHC tune feedback cannot be used to its full extent in these conditions as it relies on stable and reliable tune estimates. In this work we present two alternative tune measurement algorithms, designed to mitigate this problem by ignoring small frequency bands around the 50 Hz harmonics and estimating the tune from spectra with gaps. One is based on Gaussian Processes and the other is based on a weighted moving average. We compare the tune estimates of the new and present algorithms and put forward a proposal that can be implemented during the renovation of the BBQ system for the next physics run of the LHC.

Introduction

- Tune (Q) of a circular machine is the number of betatron oscillations per turn
- Base-Band Q (BBQ) system measures the tune in the LHC
  - $F_s = f_{rev} \sim 11245.55$ Hz
  - Tune is the frequency of the maximum of the spectrum baseline
- Spectral components at harmonics of 50 Hz perturb the spectrum
- Detrimental to performance of tune feedback controller in the LHC

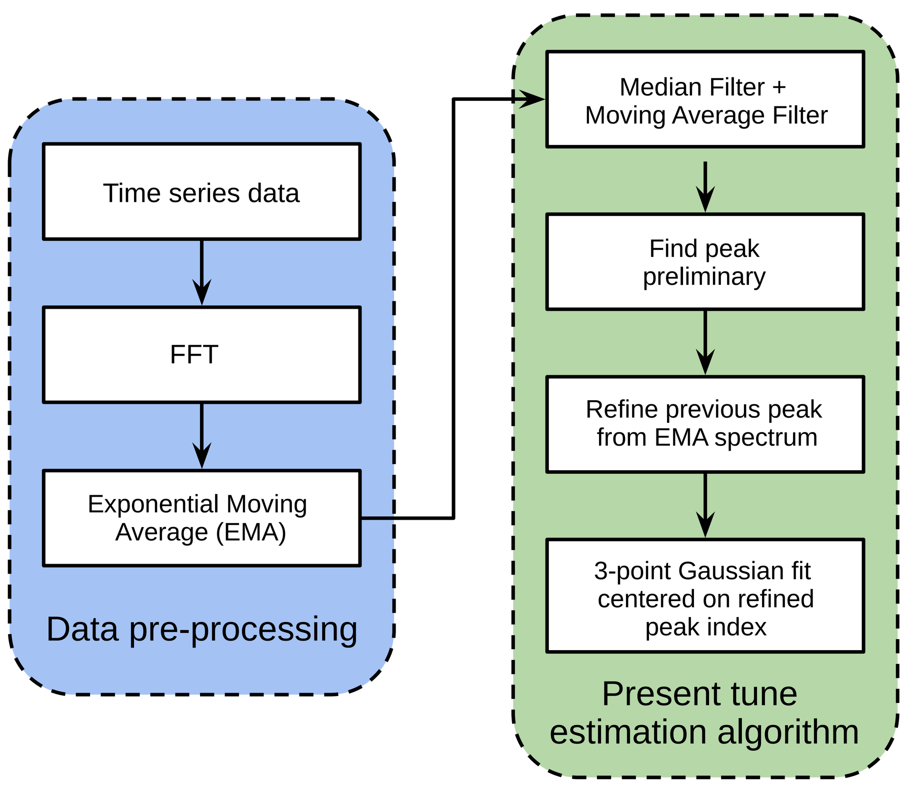


Benchmarking



- **Recorded experimental data is available**
- **Accurate tune value is not known**
- Spectrum of a second order system can model tune resonance
  - $G(\omega) = \frac{\omega_{res}^2}{\sqrt{(2\omega\omega_{res}\zeta)^2 + (\omega_{res}^2 - \omega^2)^2}} + \mathcal{N}(0, \sigma)$
  - $\omega_{res}^{true} = \sqrt{1 - 2\zeta^2}\omega_{res}$
- Monte Carlo simulation creates different spectra
  - $f_{res}^{true} \sim \mathcal{N}(3\text{ kHz}, 200\text{ Hz})$
  - $\zeta \sim 10^{\mathcal{U}(-4,-1)}$

Present Tune Algorithm



- BBQ continuous data acquisition received in blocks of 2048 points at 6.25 Hz
- Fourier Transform gives frequency **spectrum**
  - Frequency resolution ~ 5.49 Hz
- EMA filter bank attenuates incoherent spectral noise
- Median + average filters + Gaussian fit are used to estimate the tune
  - Spectral spikes at 50 Hz harmonics are not removed
  - Tune estimates are affected by harmonics
  - Too many hyperparameters

Alternative Algorithms

- Spectral regions affected by 50 Hz harmonics are constant and can be masked
- Masking out 50 Hz harmonics creates spectra with gaps
- Three algorithms were tested as alternatives to the present algorithm
  - Need to handle unevenly sampled data

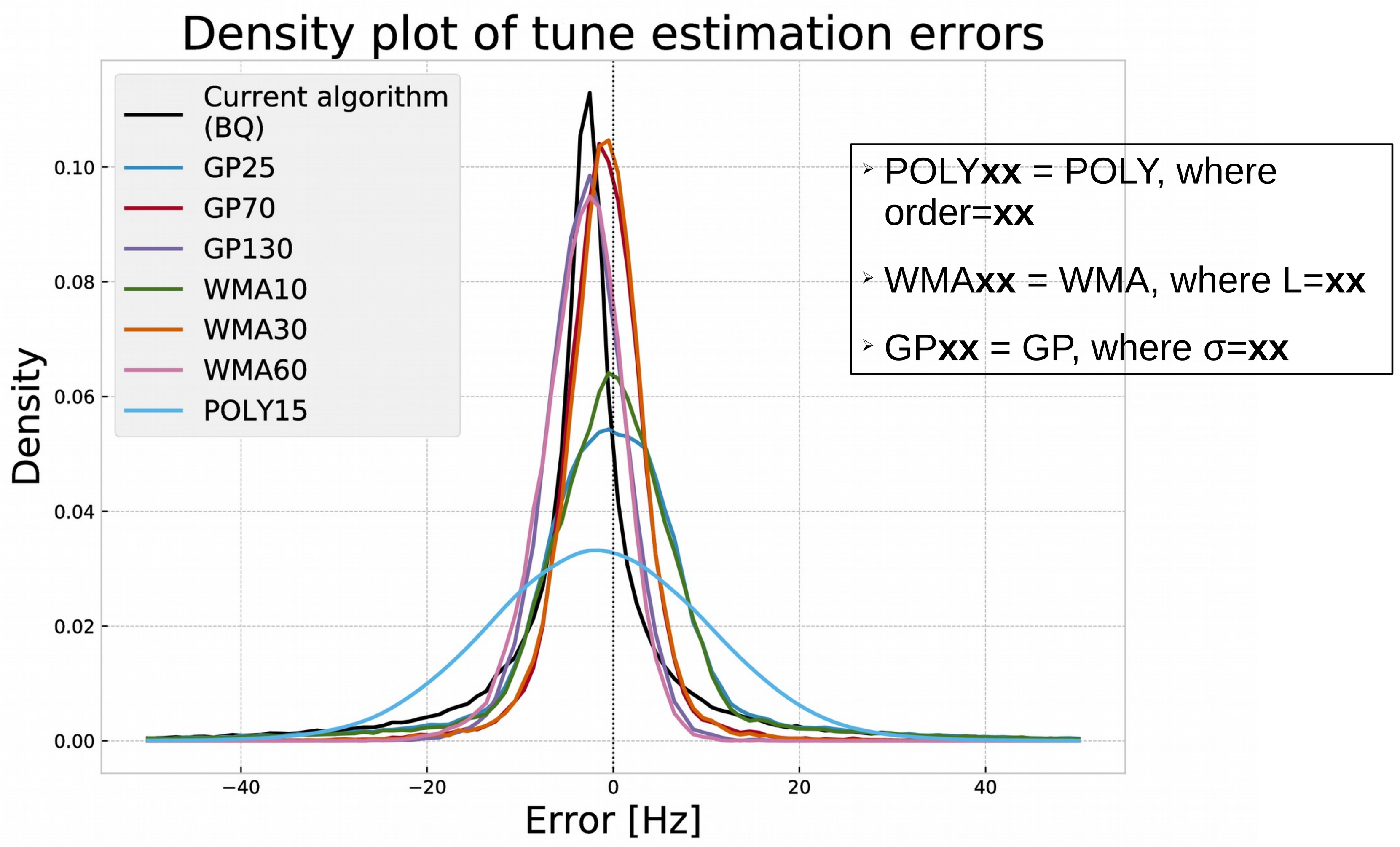
- Polynomial fit >10th order

- Weighted Moving Average (WMA) with a window length, L

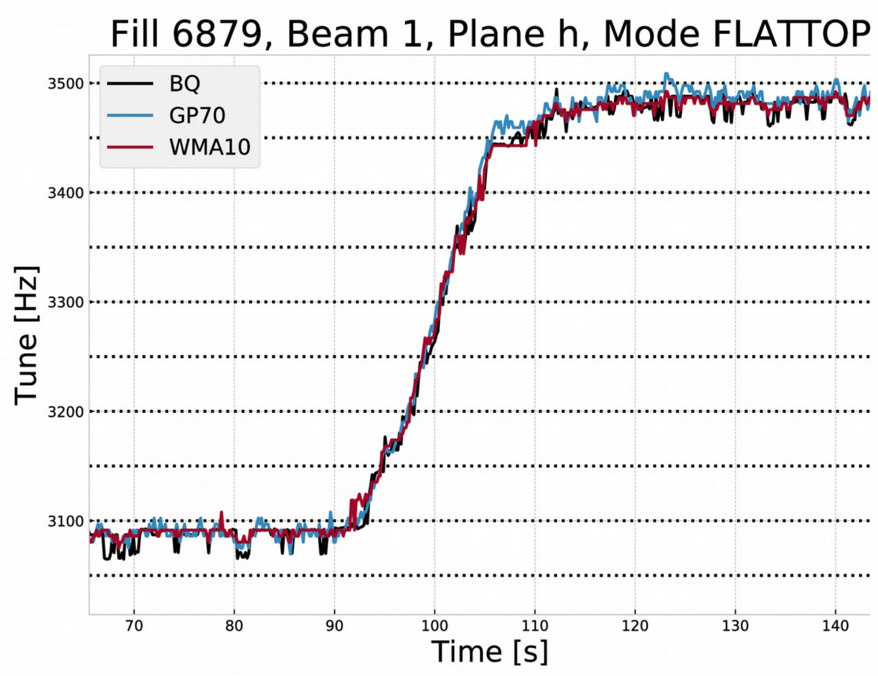
$$\hat{y}_i(L) = \frac{\sum_{j=-L}^{L} w(j, L) \times y_{i+j}}{\sum_{j=-L}^{L} w(j, L)} \qquad w(k, L) = \begin{cases} L - |k| & \text{, if } \exists\, y_{i+j} \\ 0 & \text{, if } \nexists\, y_{i+j} \end{cases}$$

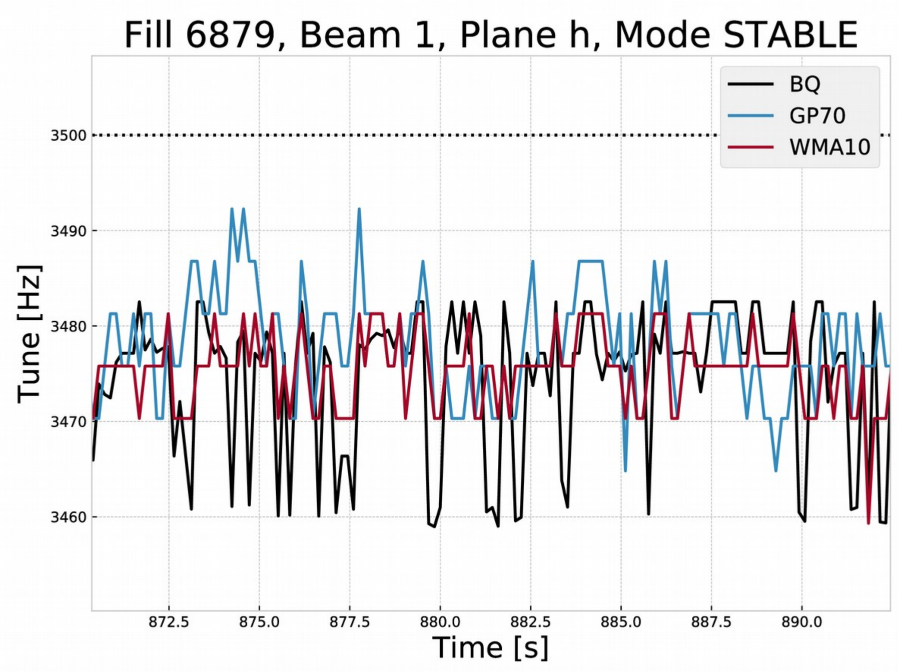
- Gaussian Processes (GP)
  - Bayesian modelling approach
  - Distribution of functions: $f(X) \sim \mathcal{N}(\mu = m(x), \Sigma = k(X, X))$
  - Kernel: $k(x_a, x_b) = e^{-\frac{1}{2\sigma^2}\|x_a - x_b\|^2}$

Results



- Different configurations of new algorithms were tested
  - POLY15 poor precision and small systematic error
  - Density plot of errors show systematic error in BQ, similar for WMA60 and GP130
  - WMA30 & GP70 more precise but small systematic error
  - WMA10 & GP25 less precise but more accurate





- Performance on real BBQ data compared
  - Comparable accuracy of tune estimates across selected algorithm configurations
  - BQ downward spikes are artifacts due to 50 Hz harmonics; WMA10 and GP70 unaffected

Conclusion

A new approach based on the rejection of spectral points affected by 50 Hz harmonics is proposed to improve tune measurements at the LHC. In line with this approach, three methods were benchmarked against the presently implemented tune estimation algorithm which is known to under-perform in the presence of these polluting harmonic components. A Monte-Carlo simulation of second-order system frequency spectra was performed in order to generate spectra which mimic real beam spectra but for which the tune value is exactly known. The results obtained indicate that when properly configured both the weighted moving average (WMA) and Gaussian Process (GP) algorithms can achieve a better performance than the current algorithm in terms of accuracy and precision. Examples using real experimental spectra confirm this observation, with the WMA algorithm performing best. This study will now be extended to more algorithms with the aim of selecting the most robust, accurate and precise one for real-time implementation on the LHC.

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Code

WEPP27

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