Synchronous phase shift measurements for evaluation of the longitudinal impedance model at the CERN SPS

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Abstract

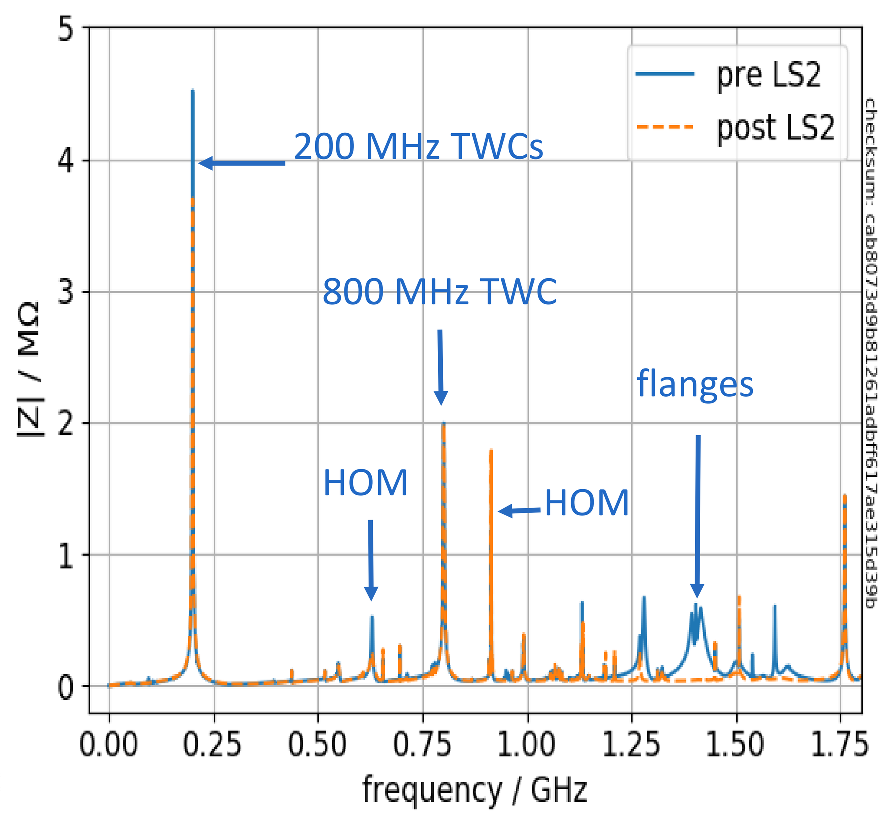
The High Luminosity LHC (HL-LHC) requires 2.3e11 protons per bunch (ppb) at LHC injection. For the SPS, the injector to the LHC, this goal requires a doubling of the injected intensity to 2.6e11 ppb. Longitudinal instabilities were observed in the SPS for intensities below the required 2.6e11 ppb. Identifying, and ultimately mitigating, the impedance sources driving the instabilities requires an accurate impedance model. Here, we report on measurements of the synchronous phase shift and corresponding energy loss. Using the loss factor to compute the energy loss from the measured bunch spectrum and the SPS impedance model leads to significant disagreements with measurements. This disagreement is investigated for the simplified case of a single resonator. However, simulating matched bunches using the SPS impedance model yields better agreement with measurements.

Longitudinal SPS Impedance Model

- SPS impedance model [1] comprised of many elements
  - Main 200 MHz Travelling Wave Cavities (TWC) and 800 MHz TWC as 'Landau cavity'
  - Higher Order Modes (HOM) of TWC
  - Flanges, beam instrumentation, …
- On-going impedance reduction campaign during the long shutdown 2 (LS2)
- Energy loss U due to impedance Z related bunch position/phase $\phi = \omega_{RF}\tau$ as

$$\frac{U}{eV_{RF}} = \sin(\phi) \simeq \phi(N,\sigma)$$

- Measurements of the bunch position used to measure resistive part of machine impedance (e.g. [2,3,4,5])



- Normalized energy loss $\bar{U}$ from impedance model:
  - Coherent energy loss [6]

$$\bar{U}_\kappa = e\,N\,\kappa,\ \text{loss factor}\ \kappa = 2\int_0^\infty \Re[Z(f)]|\Lambda(f)|^2 df$$

  - Synchronous phase shift (unperturbed bunch spectrum $\Lambda_0(f)$) [7]

$$\bar{U}_{\phi_s} = e\,V_{RF}\Delta\phi_s/N, \quad \Delta\phi_s = \frac{2N}{eV_{RF}\cos\phi_{s0}}\int_0^\infty \Re[Z(f)\Lambda_0(f)]df$$

  - $\bar{U}_{\phi_s,approx}$ calculated from $\Delta\phi_s$ using perturbed bunch spectrum $\Lambda(f)$

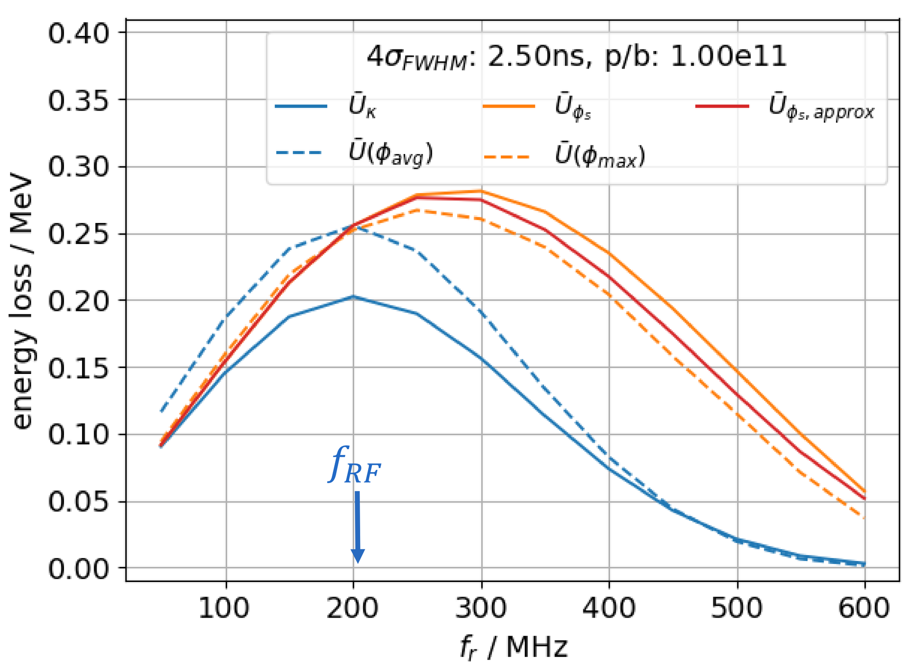
Narrowband Resonator Model

- Narrowband resonator impedance R, Q, f_r
- Create matched (static) particle distribution including intensity effect with BLonD [8]
- Obtain maximum τ_{max} and average τ_{avg} of profile
- Normalized energy loss (dashed curves)

$\bar{U}(\phi_{avg}) = e\,V_{RF}\omega_{RF}\tau_{avg}$,

$\bar{U}(\phi_{max}) = e\,V_{RF}\omega_{RF}\tau_{max}$,

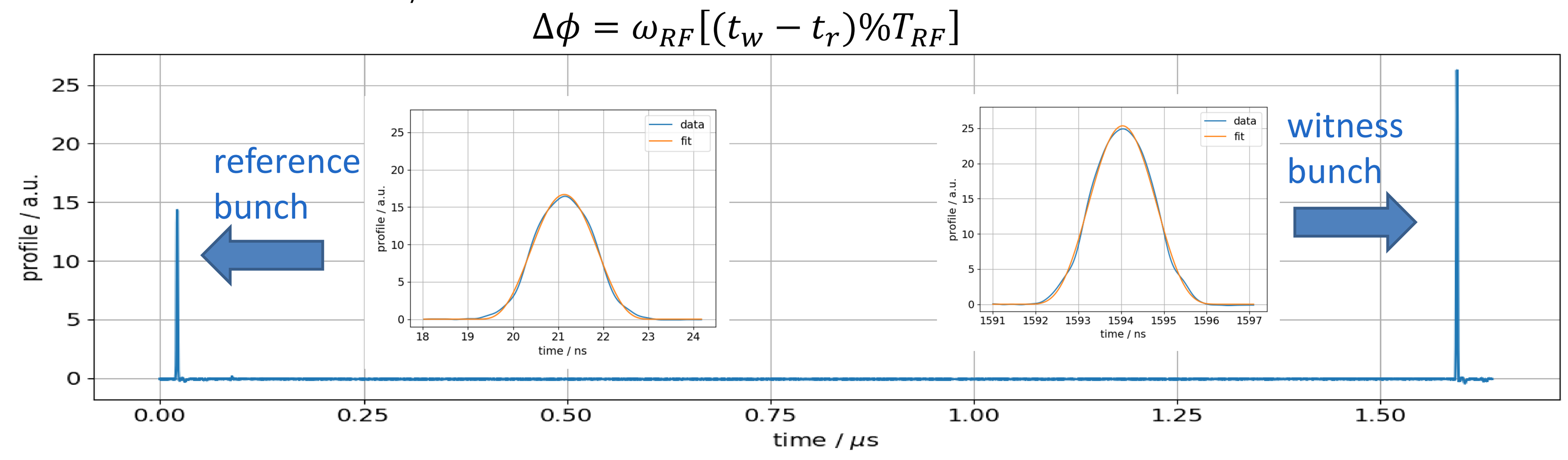
- $\phi_{max} = \phi_s$ for matched distribution → $\bar{U}(\phi_{max})$ follows $\bar{U}_{\phi_s}$
- Asymmetric profile → average position ≠ position of synchronous particle and $\bar{U}_\kappa \neq \bar{U}_{\phi_s}$
- $\bar{U}(\phi_{avg})$ follows $\bar{U}_\kappa$ if $f_r > f_{RF} = 200\text{MHz}$
- $\bar{U}_{\phi_s,approx}$ follows $\bar{U}_{\phi_s}$



Measurement of Synchronous Phase

- Reference bunch (leading) with fixed intensity
- Vary intensity of witness bunch (trailing)
- Obtain bunch positions $t_{r/w}$ from profiles and relative phase between bunches

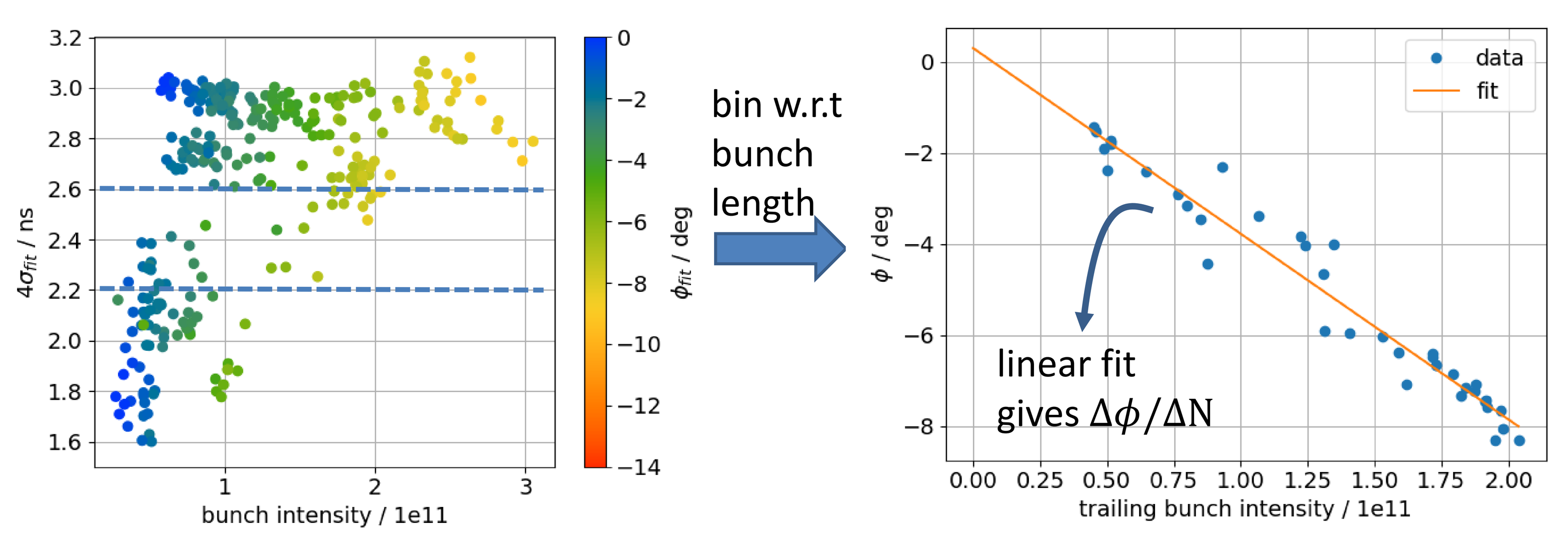
$$\Delta\phi = \omega_{RF}[(t_w - t_r)\%T_{RF}]$$



- Phase w.r.t. RF-bucket (for same bunch shape, i.e. same bunch length 4σ)

$$\phi(N) \simeq N\,\Delta\phi/\Delta N$$

- Scan intensity N and bunch length (4σ)

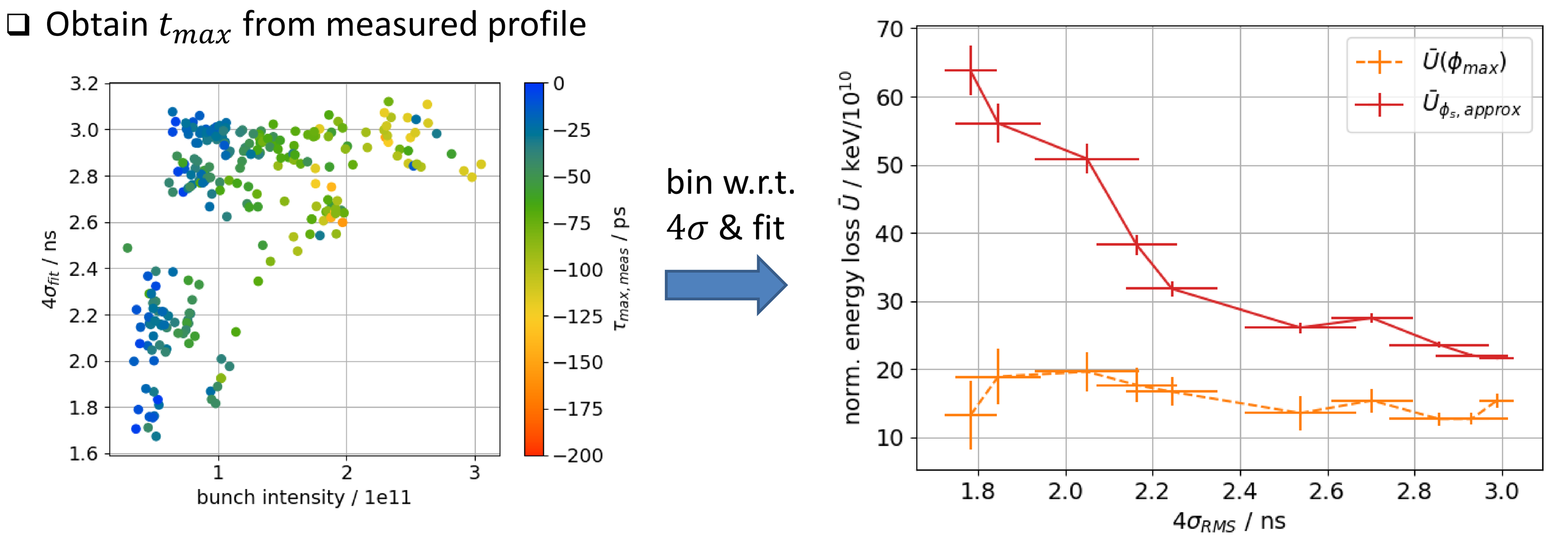


- Measured normalized energy loss given as $\bar{U}(4\sigma) = eV_{RF}\Delta\phi/\Delta N$

Measured Energy Loss

Using maximum position

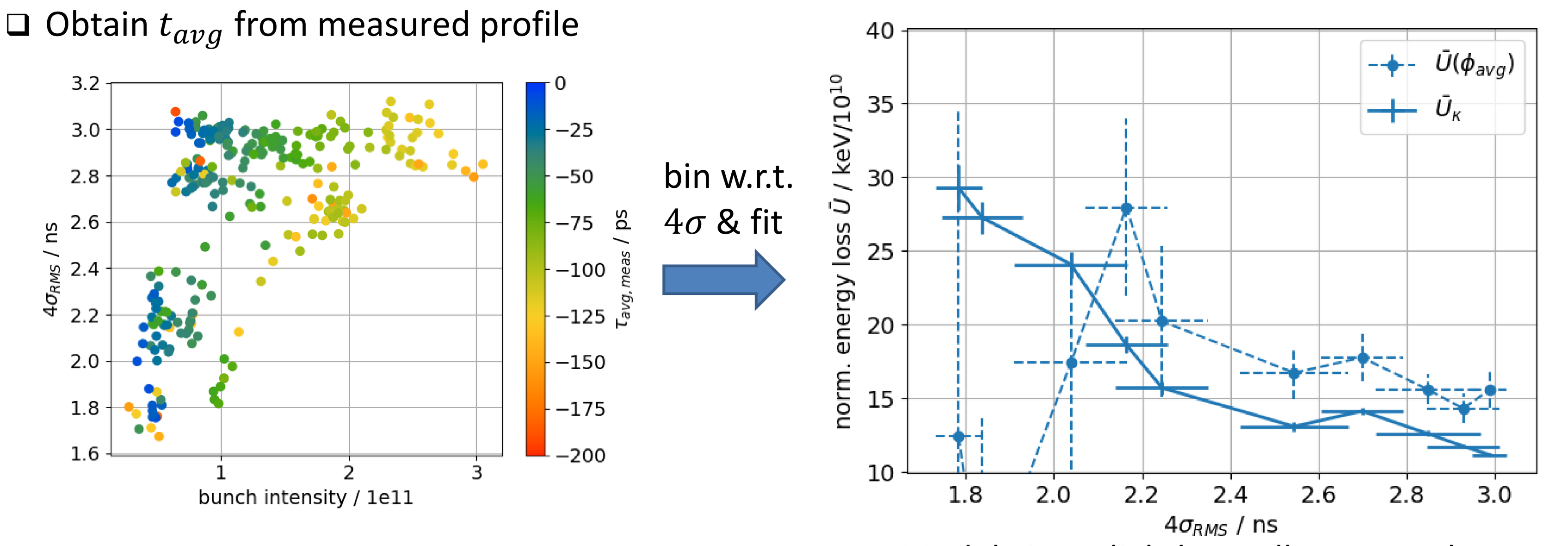
- Obtain t_{max} from measured profile



- Use measured bunch profile and SPS impedance model to compute $\bar{U}_{\phi_s,approx}$
- Model gives significantly larger energy loss
- Measured (perturbed) profile in $\bar{U}_{\phi_s,approx}$ not applicable?

Using average position

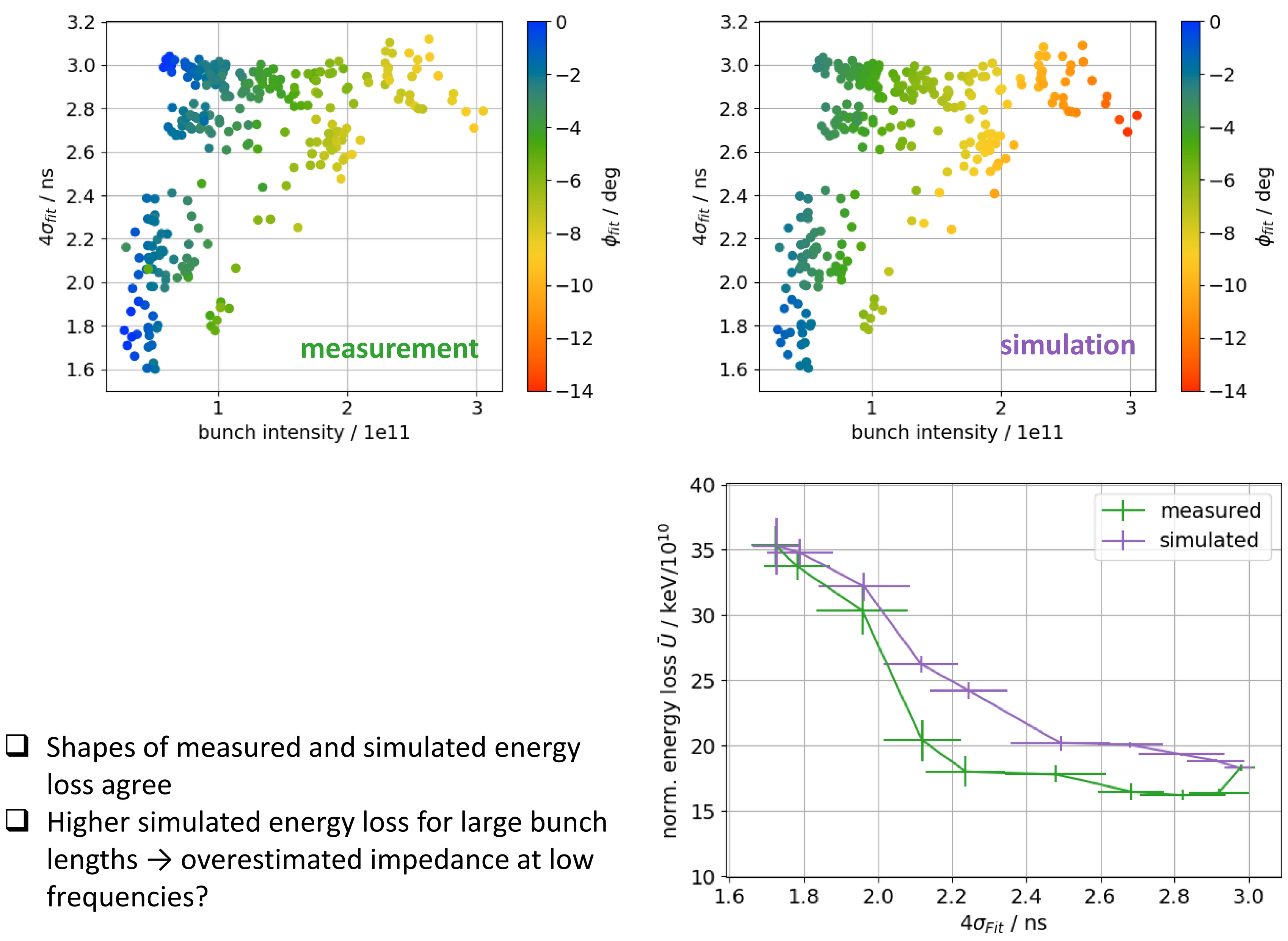
- Obtain t_{avg} from measured profile



- Use measured bunch profile and SPS impedance model to compute $\bar{U}_\kappa$
- Model gives slightly smaller energy loss
- Similar behavior in single-resonator model when f_r is close to f_{RF}

Simulated Stationary Bunches

- Fit measured profiles to binomial distribution $\lambda(\tau) = A\left[1 - \left(\frac{2(\tau-\tau_{max})}{4\sigma\sqrt{1+\mu/2}}\right)^2\right]^{\mu+1/2}$
- Use fit parameters to create bunches in BLonD using Abel transform (matched using SPS impedance model)



- Shapes of measured and simulated energy loss agree
- Higher simulated energy loss for large bunch lengths → overestimated impedance at low frequencies?

Conclusions & Outlook

- SPS impedance dominated by fundamental impedance of TWCs
- Reasonable agreement between measurements and model
- Higher simulated energy loss at large bunch length due to impedance at low frequencies?

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