Measurements of Collective Effects Related to Beam Coupling Impedance at SIRIUS

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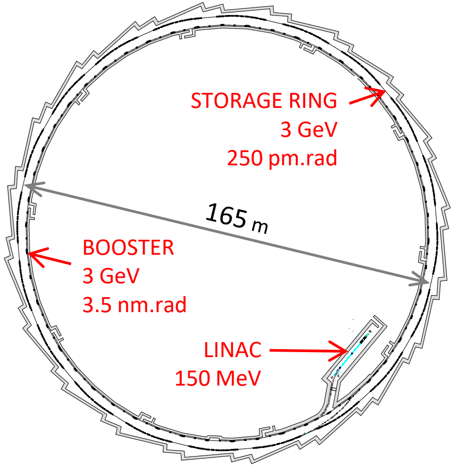
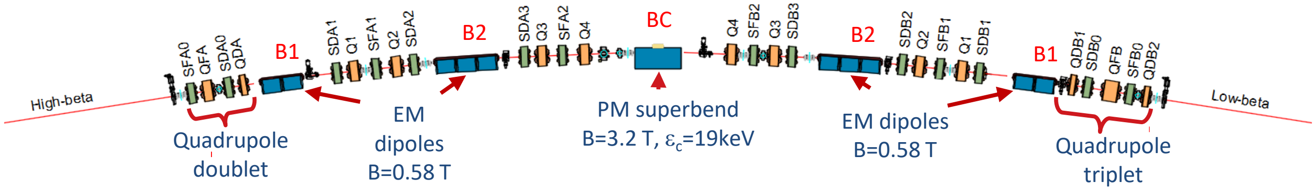
Outline

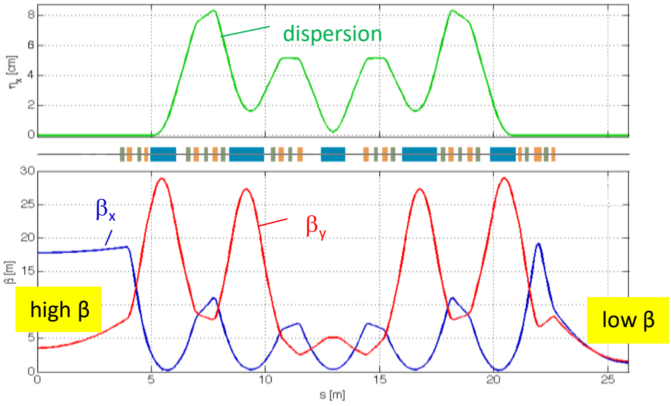
- SIRIUS main parameters and timeline overview;
- SIRIUS Impedance Budget:
  - Methods employed in impedance and wake calculation;
  - Longitudinal Impedance: Effective Impedance and Loss Factor;
  - Transverse Impedance Budget: Tune-shifts with current;
- Longitudinal Single-Bunch Effects:
  - IBS Model and Calculation;
  - Wakes+IBS iteration algorithm;
  - Streak Camera measurement: setup and analysis;
  - Comparison of results with simulation;
- Transverse Single-Bunch Effects:
  - Model calculations and measurement setup;
  - Results and comparison with model;
- Summary and Next Steps.

Main Design Parameters



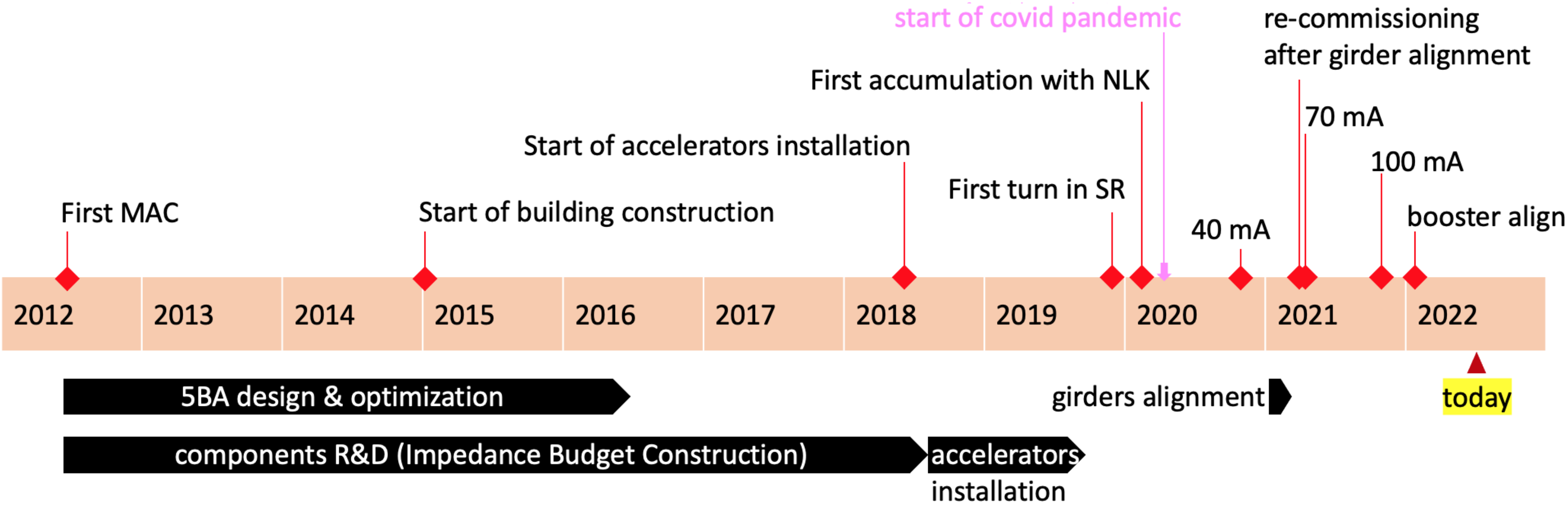


Storage Ring parameters	
Beam energy	3.0 GeV
Circumference	518.4 m
Lattice	**20 x 5BA**
Current, top up	350 mA
Hor. emittance (bare ⇢ w/ids)	**250 ⇢ 150 pm.rad**
Energy spread	0.084 %



5-fold symmetric optics { 15 low β sections, 5 high β sections

Brief timeline overview



Impedance and collective effects measurements started only very recently

[1] L. Liu et al., “Status of Sirius Operation”, **TUPOMS002**, this conference.
[2] X. R. Resende, M. B. Alves, F. H. de Sá, L. Liu, A. C. S. Oliveira, and J. V. Quentino, “Sirius Injection Optimization”, **THPOPT038**, this conference.

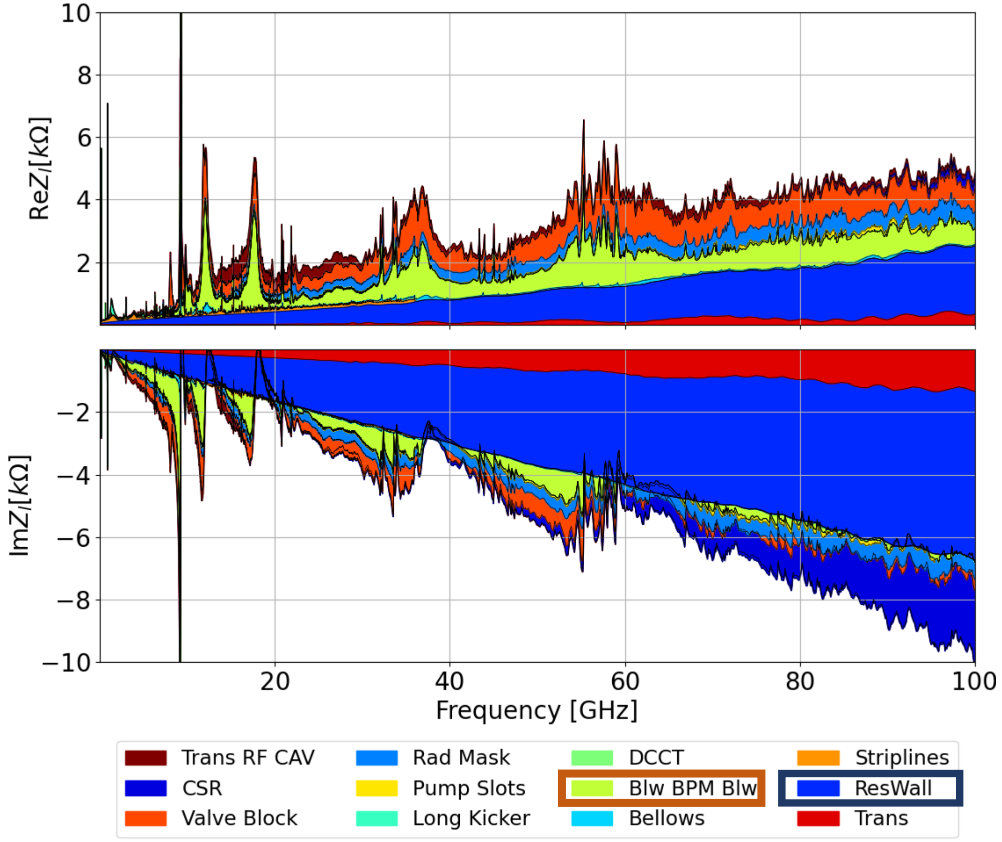
SIRIUS Impedance Budget

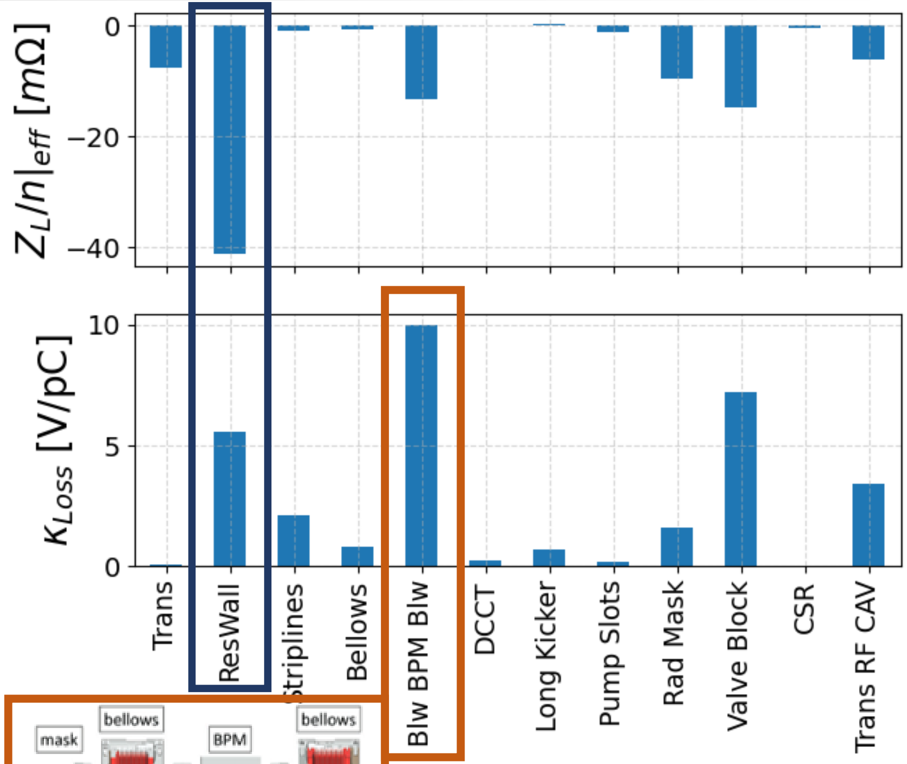
- All in-vacuum components design were optimized considering its impedance contribution whenever possible;
- All of them have 2D or 3D-model-based impedance calculations included in the budget;
- Multi-bunch dynamics is very influenced by Petra 7-Cell temporary cavity (coupled-bunch instabilities and tune-shifts).
- Only broadband contributions will be considered in this work (single-bunch measurements). Wake-lengths of 0.5 m;

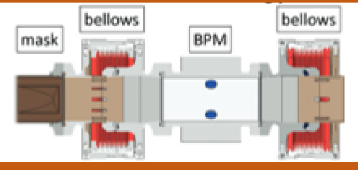
Type of Impedance	Method of Calculation	Wake source	Impedance used in frequency-domain calculations	Wake used in time-domain simulations
ResWall [1] and CSR [2]	Semi-analytical formulas	Wake-function of point-like charge	Use impedance as it was calculated	Obtained from convolution of wake-function with small Gaussian bunch (σ = 40 µm) to filter out high frequencies
Geometric	Numeric Solvers [3, 4]	Wake-potential of Gaussian bunch (σ = 500 µm)	Obtained from deconvolution of wake and source-bunch spectrum (f_{max} = 150 GHz)	Use wake as it was calculated

[1] N. Mounet, “The LHC Transverse Coupled-Bunch Instability”, Ph.D. thesis, École Polytechinique Fédérale de Lausanne, Lausanne, Swiss, 2012.
[2] J. B. Murphy, S. Krinsky, and R. L. Gluckstern, “Longitudinal wakefield for an electron moving on a circular orbit”, *Particle Accelerators*, v. 57, n. BNL-63090, p. 9–64, 1997.
[3] ECHO web site, https://echo4d.de/.
[4] GdfidL web site, http://www.gdfidl.de/.

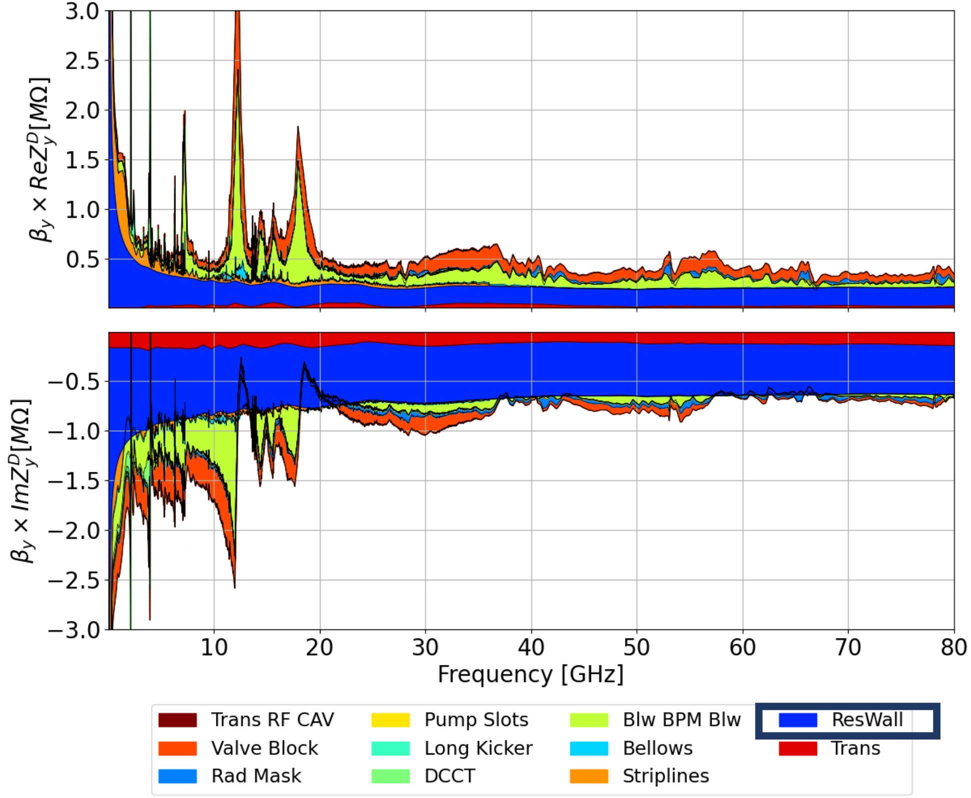
Longitudinal Impedance Budget

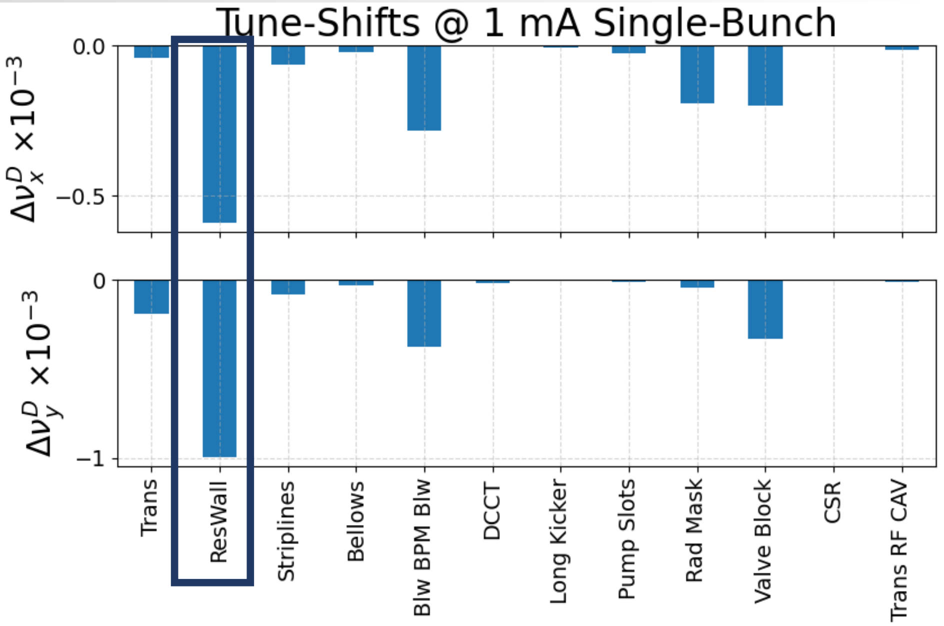






Transverse Impedance Budget

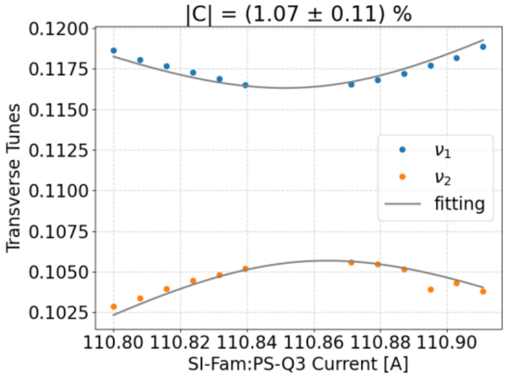


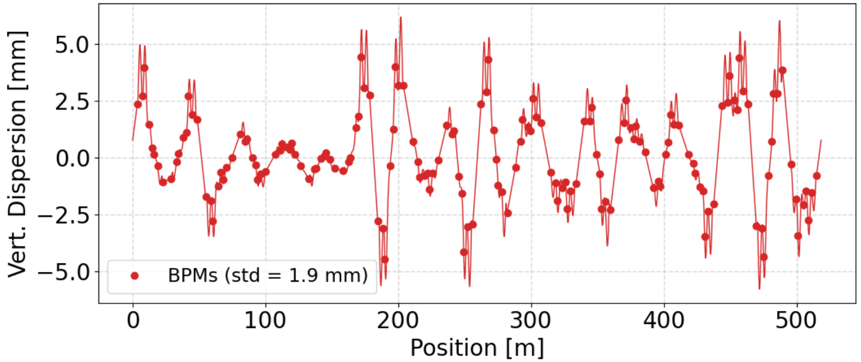


Chamb. Type	Length	Gap, Shape	Material	NEG?
Standard	>500 m	24 mm, cylinder	Copper	Yes (1 µm)
5 APUs	5x1.2 m	6.0 mm, flat	Aluminum	Yes (0.6 µm)
1 Delta Und.	2.6m	6.4 mm, rhombus	Copper	Yes (0.6 µm)

IBS Model and Calculation

- Storage ring linear optics and equilibrium parameters model:





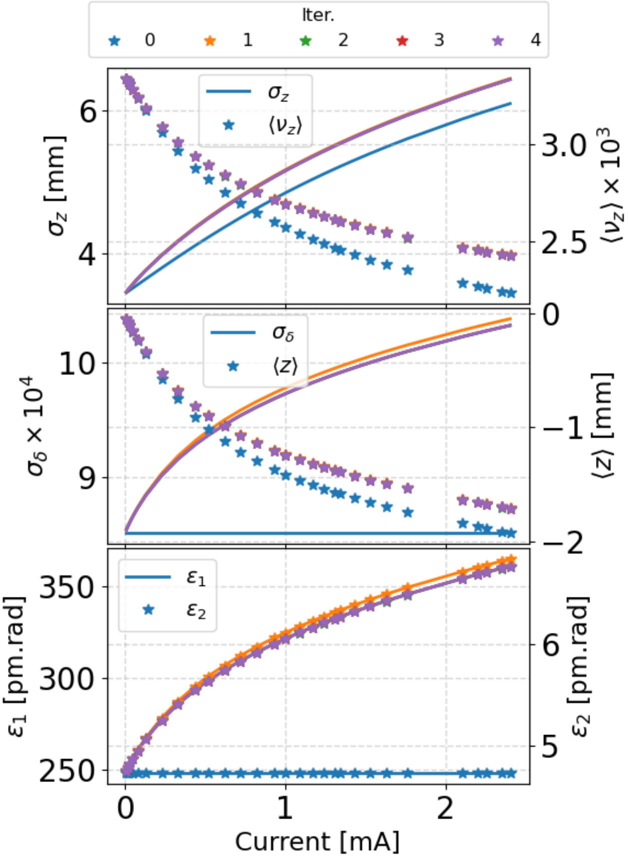
Params	Value
ε_{10}	247.9 pm.rad
(ν_x, ν_y)	(49.0777, 14.1414)
ε_{20}	4.7 pm.rad
$\varepsilon_{20}/\varepsilon_{10}$	1.9 %
$\sigma_{\delta 0}$	0.0851 %
RF Gap Volt.	1.575 MV
σ_{s0}	3.423 mm

- IBS Algorithm:
  - Starts with ε_{10}, ε_{20}, $\sigma_{\delta 0}$ and some current-dependent value for σ_s;
  - Calculate $\tau_{IBS}(s)$ with Bjorken-Mtingwa [1] formulas, using β_1, β_2, α_1, α_2, η_1, η_2, η'_1, η'_2 from Edwards-Teng modes;
  - Use $\langle\tau_{IBS}\rangle$ at each time-step to update ε_1, ε_2 and σ_δ and evolve them in time until stationary state.

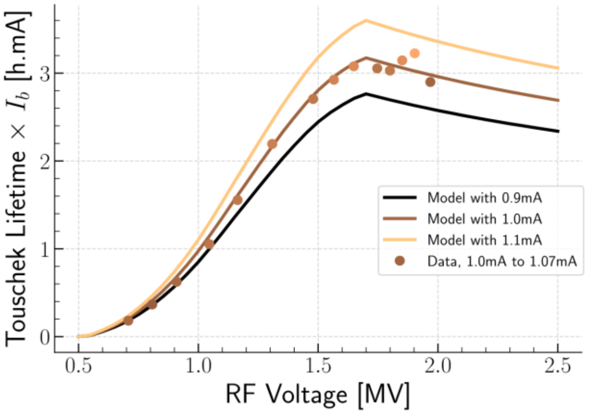
- This way ε_1 and ε_2 will evolve independently in time with no need to force coupling ratio between x-y planes on each iteration and contribution of η_y is considered through η_1 and η_2.

[1] K. Kubo, S. K. Mtingwa, A. Wolski, “Intrabeam scattering formulas for high energy beams”, *Phys. Rev. ST Accel. Beams*, vol. 8, issue 8, p. 081001, Aug. 2005.

Wakes+IBS Iteration Algorithm

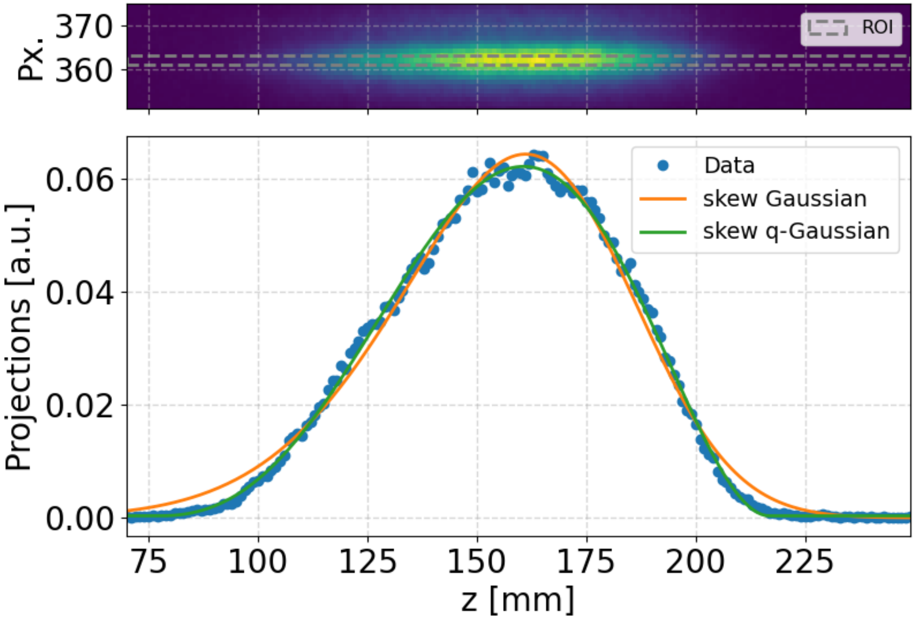


- For each current:
  1- Solve Haissinski equation with wakes, using natural energy spread;
  2- Use resulting longitudinal distribution to supply initial bunch length for IBS calculation (keep initial values of other equilibrium parameters equal to their natural values);
  3- Use resulting energy spread to solve Haissinski equation again;
  4- Iterate 2 and 3 until energy spread converges.
- Diagnostic beamline to measure energy spread and emittances not available yet.
- Resulting current-dependent equilibrium parameters explain well lifetime measurements [1];
- Limitations:
  - Only works below microwave instability threshold;
  - Assume Gaussian distribution in growth rates calculations.



[1] M. B. Alves, F. H. de Sá, L. Liu, and X. R. Resende, “Beam Lifetime Measurements in Sirius Storage Ring”, **WEPOTK055**, this conference.

Analysis of Streak Camera Measurements



- Streak-camera from previous LNLS machine (diff. RF freq.)

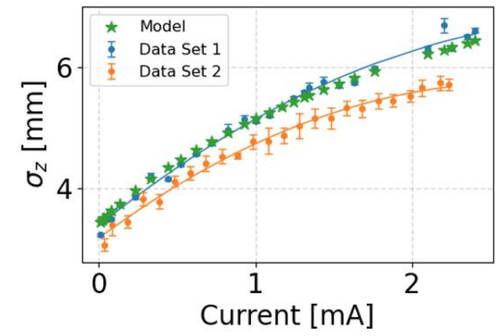
- Data acquired for 100 ms of exposure time. Effect of synchrotron oscillations expected to be small (10% of natural bunch length);

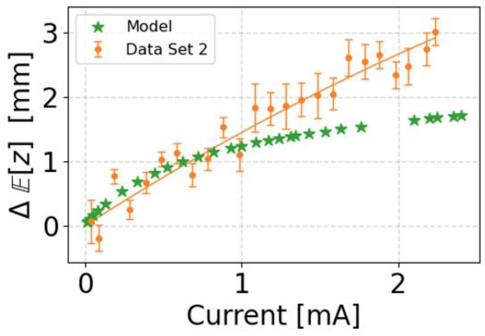
- Data analysis from streak camera to calculate moments:
  - Offline conversion (pixels to mm) and analysis;
  - Projection of a very thin Region Of Interest (ROI);
  - Fitting of known probability density functions:
    - Try to fit the distribution tails as well as possible;
    - Capture the skewness of the distribution;
  - Deconvolve variance with measured slit size;

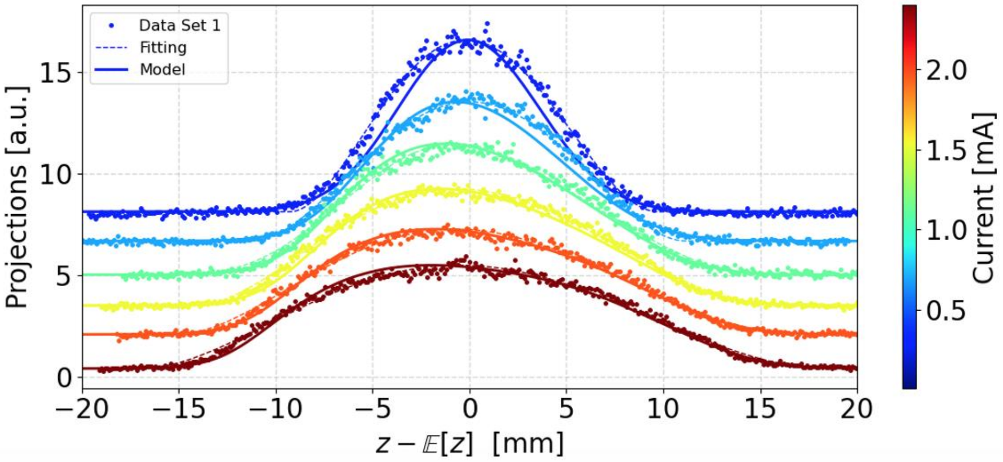
- Data tails and skewness captured by fitting a skew q-Gaussian [1]:

[1] M. Tasaki, K. Koike, “On skew q-gaussian distribution”, *International Journal of Statistics and Systems*, vol. 12, num. 4, pp. 773–789, 2017.

Measurements and Comparison with Model







- Two data sets acquired (one month apart):
  - Data Set 1: Single-bunch in the machine, maximum measurement resolution scale used;
  - Data Set 2: Two bunches, one test bunch (high charge) and one reference bunch (low charge, 20 µA). Allow synchrotron phase shift measurement, lower resolution for bunch length measurement.
- Large difference in bunch length for both measurements, including zero-current bunch length. Possible conversion scale error.
- Synchronous phase shift well explained at low currents but diverges above 1 mA. More measurements needed.
- Impedance budget fits well bunch-lengthening data, but no resolution so far to check validity of iterative Wakes+IBS scheme;
- Model does not predict microwave instability for this current range. Need of energy spread measurement to check this prediction.

Transverse Single-Bunch Tune-shifts

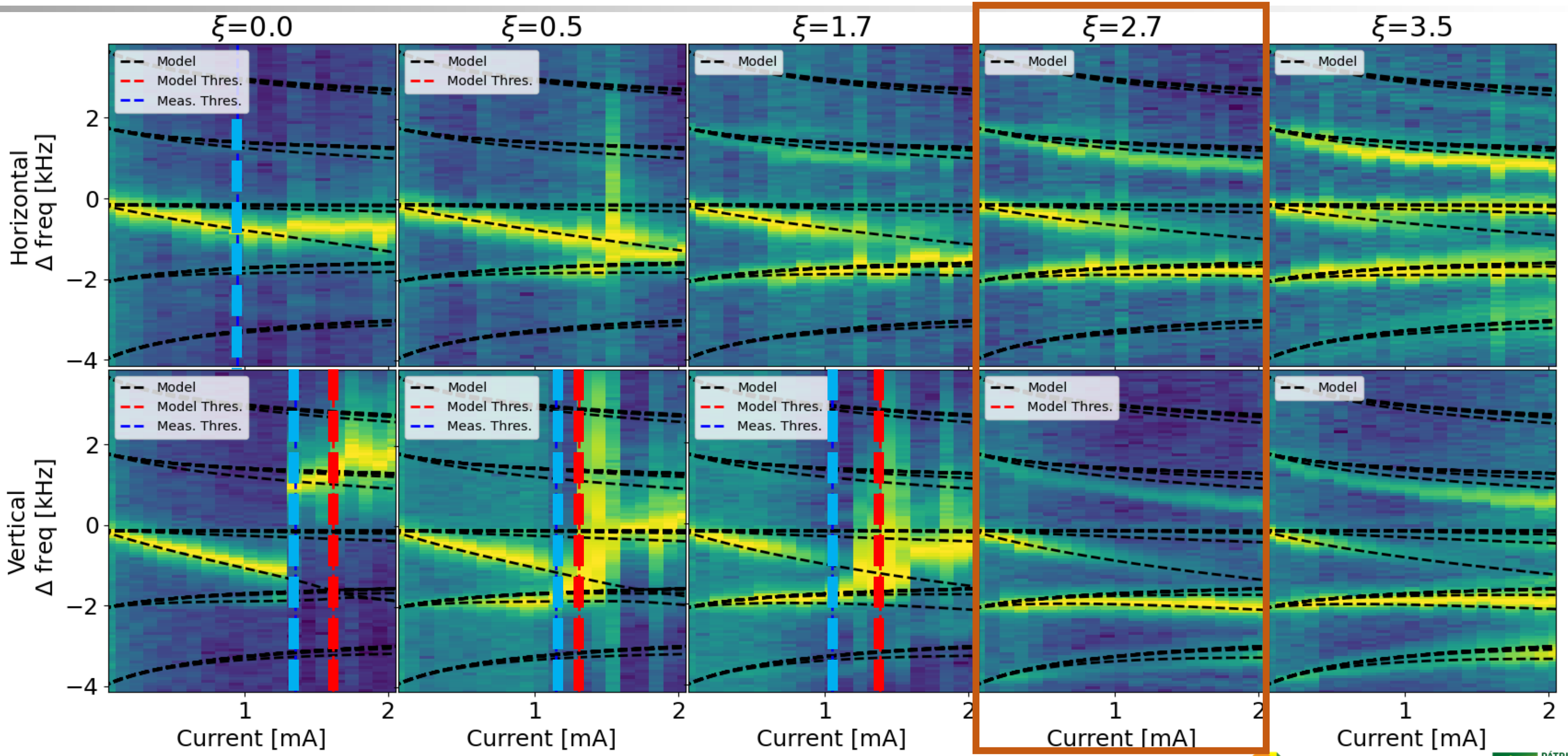
- Model Calculations:
  - Standard mode-coupling theory used (solution of linearized Fokker-Planck equation) [1];
  - Assumes beam is gaussian and does not account for synchrotron or betatron tune-spread;
  - Current-dependent bunch length and average synchrotron tune were taken from model with Wakes+IBS discussed previously.

- We performed measurements for several values of chromaticity with current ranging from 2.1 mA down to 0.05 mA.

- Setup for horizontal/vertical measurements:
  - For each current and chromaticity, kick the beam with the horizontal/vertical pinger;
  - Measure turn-by-turn data with the bunch-by-bunch system (Dimtel iGp12 processor);
  - Take the DFT of the data.

[1] T. Suzuki, "Fokker-Plank theory for transverse mode-coupling instability", Particle Accelerators, Vol. 20 pp. 79-96, 1986.

Measurements and Comparison with Model



Summary and Next Steps

- Good agreement between experimental data and model (no fitting parameters)
  - Impedance budget was obtained from 2D and 3D models of every in-vacuum component;
  - Emittances and energy spread from nominal values + measurements of linear optics (betatron coupling and vertical dispersion);
  - Effects of Wakes and IBS considered simultaneously with simplified approach;
  - Tune-shifts calculated with a simple and well-known theory;
  - Inclusion of Wakes+IBS scheme necessary for good agreement.

- Next steps:
  - Measure the energy spread and emittances;
  - Perform further synchrotron phase shift measurements;
  - Measure localized impedance;
  - Characterize multi-bunch dynamics;

IPAC22

Thank you for your attention!

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