Haisheng Xu, Paolo Craievich, Micha Dehler, Lukas Stingelin :: Paul Scherrer Institut

Study of Resistive-Wall Induced Microwave Instability for SLS-2

Second Topical Workshop on Instabilities, Impedance and Collective Effects (TWIICE 2)

Outline

- The Baseline Design of SLS-2 Storage Ring
- Calculation of Longitudinal Resistive-Wall Impedance (Longitudinal Wake function)
- Analysis of Microwave Instability in SLS-2 Storage Ring
- Summary & outlook on the future work

SLS and SLS-2 lattice parameters

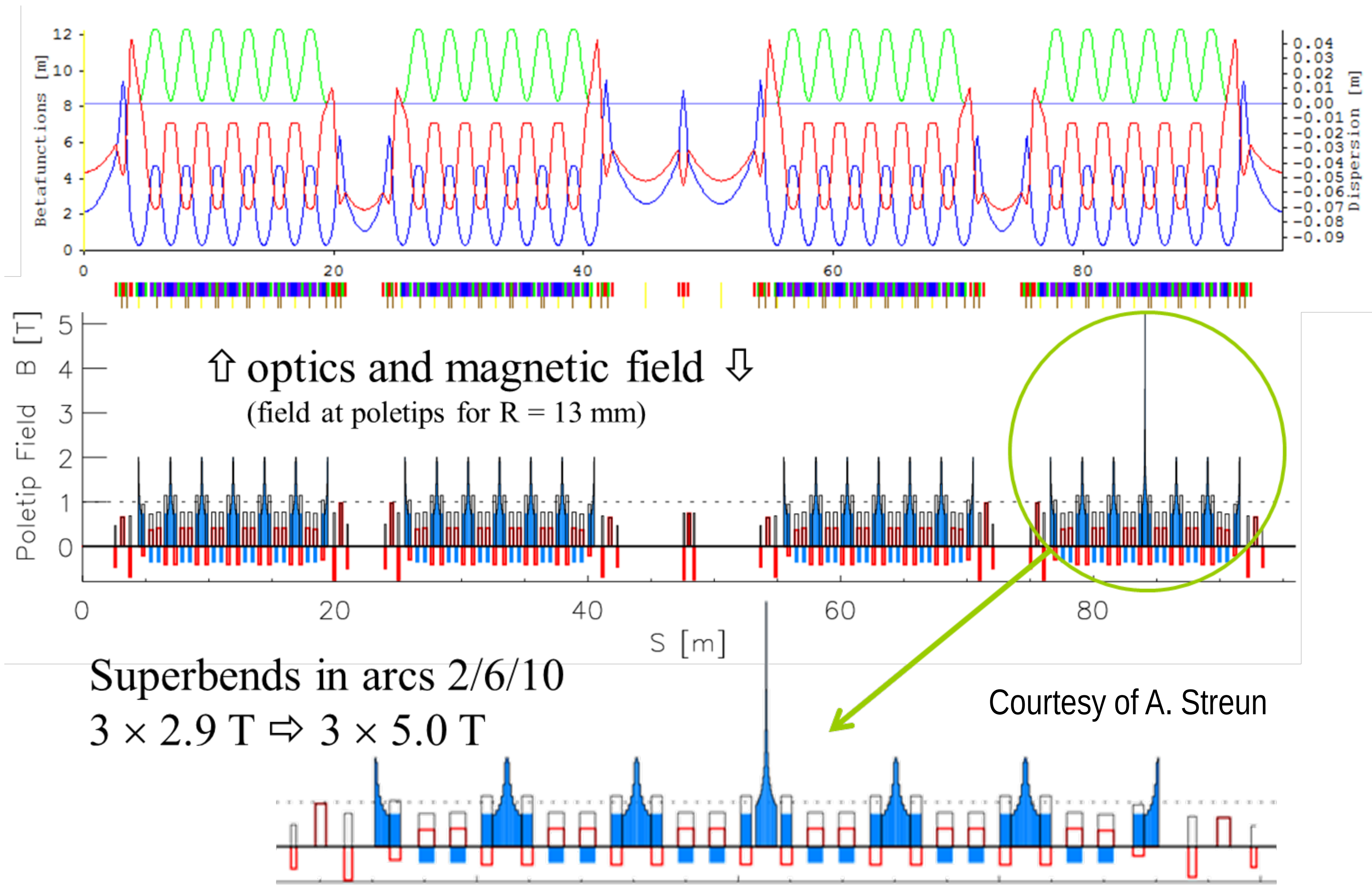
------ with the same circumference, 288 m

Name	SLS*)	SLS-2 (db02l)
status	*operating*	*baseline*
Emittance at 2.4 GeV [pm]	**5022**	**137**
Lattice type	TBA	**7**BA
Total absolute bending angle	360°	585°
Working point $Q_{x/y}$	20.42 / 8.74	38.38 / 11.28
Natural chromaticities $C_{x/y}$	–67.0 / –19.8	–67.5 / –36.0
Optics strain[1)]	7.9	**5.6**
Momentum compaction factor [10^{-4}]	6.56	**–1.39**
Dynamic acceptance [mm.mrad] [2)]	**46**	**10**
Radiated Power [kW][3)]	205	228
rms energy spread [10^{-3}]	0.86	1.05
damping times x/y/E [ms]	9.0 / 9.0 / 4.5	4.5 / 8.0 / 6.4

1) product of horiz. and vert. normalized chromaticities C/Q
2) max. horizontal betatron amplitude at stability limit for ideal lattice
3) assuming 400 mA stored current, bare lattice without IDs
*) SLS lattice d2r55, before FEMTO installation (<2005)

Courtesy of A. Streun

SLS-2 lattice: db02l (one superperiod=1/3 ring)

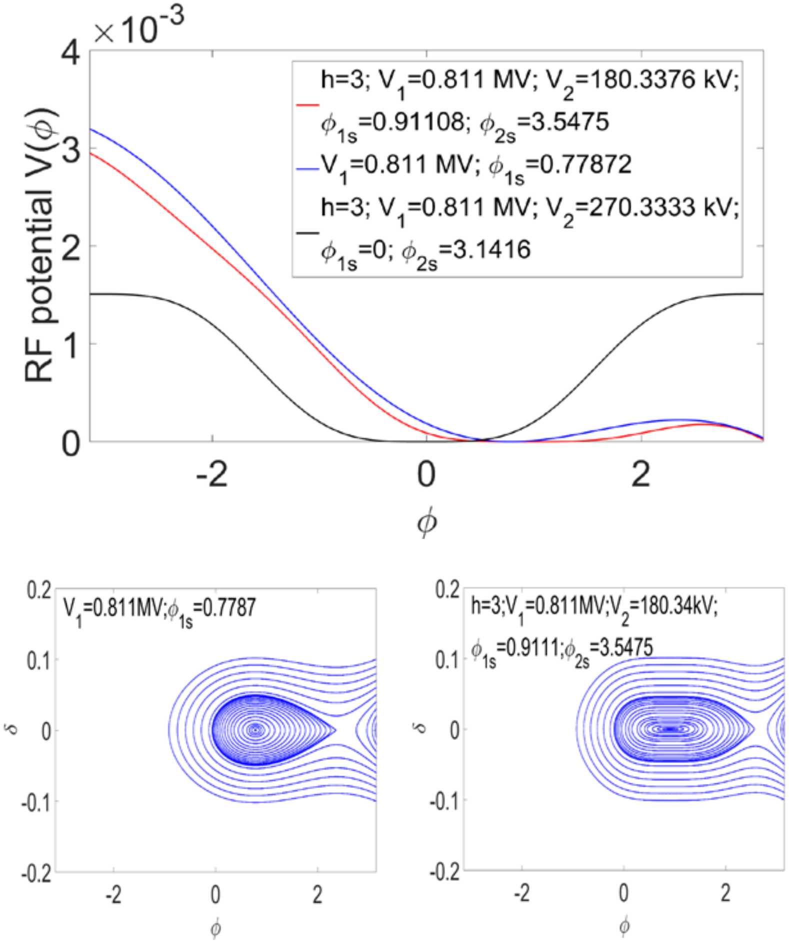


Superbends in arcs 2/6/10

3 × 2.9 T ➩ 3 × 5.0 T

Courtesy of A. Streun

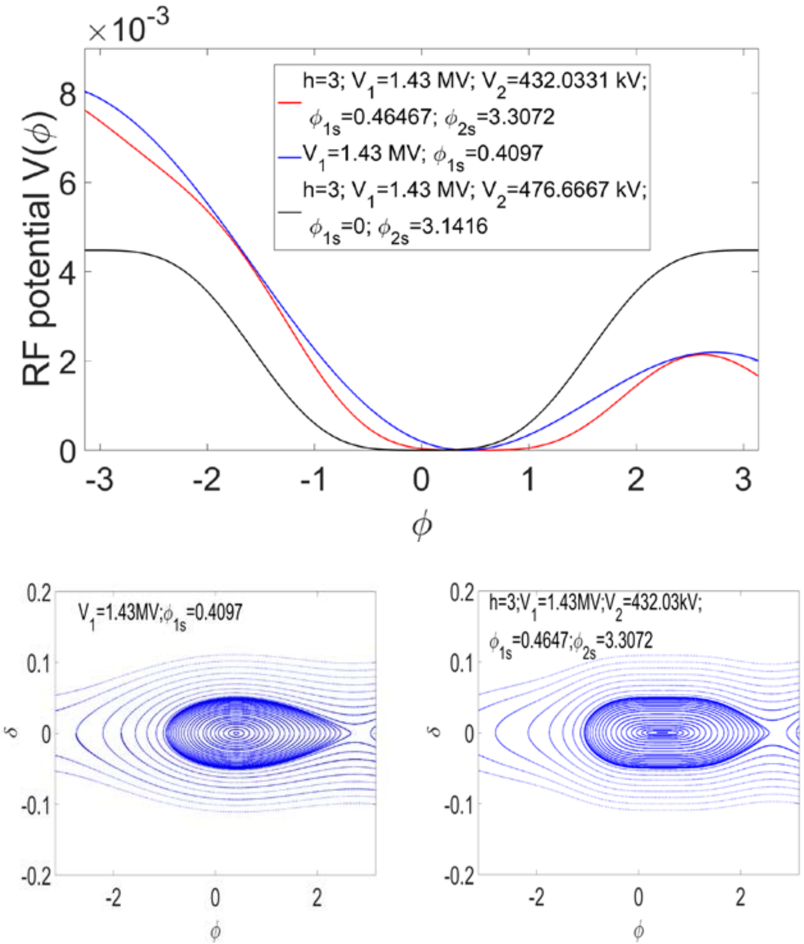
Choices of RF frequencies for SLS-2 ring



100 MHz RF

no harmonic cavity

with harmonic cavity



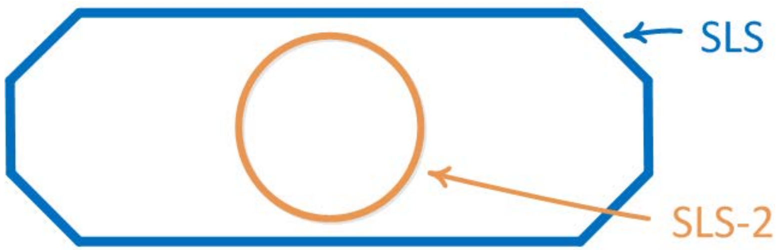
500 MHz RF

no harmonic cavity

with harmonic cavity

Longitudinal Resistive-Wall Wake Functions

Vacuum chamber



- Round chamber with inner gap ~ 20 mm
- Copper chamber ($\rho_{Cu} = 1.68 \times 10^{-8}\ [\Omega \cdot m]$)
- **NEG coating** or **not?**
  ($\boldsymbol{\rho_{NEG} = 9.1 \times 10^{-7} [\Omega \cdot m]}$)
- **ImpedanceWake2D* code**

  or

  Analytical formula?**

	Peak Voltage of the primary RF: V_{RF} [MV]	RMS bunch length @ zero current: σ_z [ps]
100 MHz; no harmonic cavity;	0.811	25.7
500 MHz; no harmonic cavity;	1.43	8.7
100 MHz + 300 MHz cavities #;	0.811	136.1
500 MHz + 1.5 GHz cavities #;	1.43	35.4

#: the ideal flat-potential condition is satisfied.

[*] N. Mounet. **ImpedanceWake2D**. http://impedance.web.cern.ch/impedance/Codes/ImpedanceWake2D/user_manual_todate.txt

[**] Karl L.F. Bane and Matthew Sands, The Short-Range Resistive Wall Wakefields, SLAC-PUB-95-7074, Dec. 1995.

Parameters of Low Emittance Rings

Bunch length

$$\sigma_{t0} = \frac{\alpha}{\nu_s \omega_0} \sigma_\delta$$

Momentum compaction factor:

$$\alpha = \frac{I_1}{C} \qquad I_1 = \oint \frac{\eta_x}{\rho} ds$$

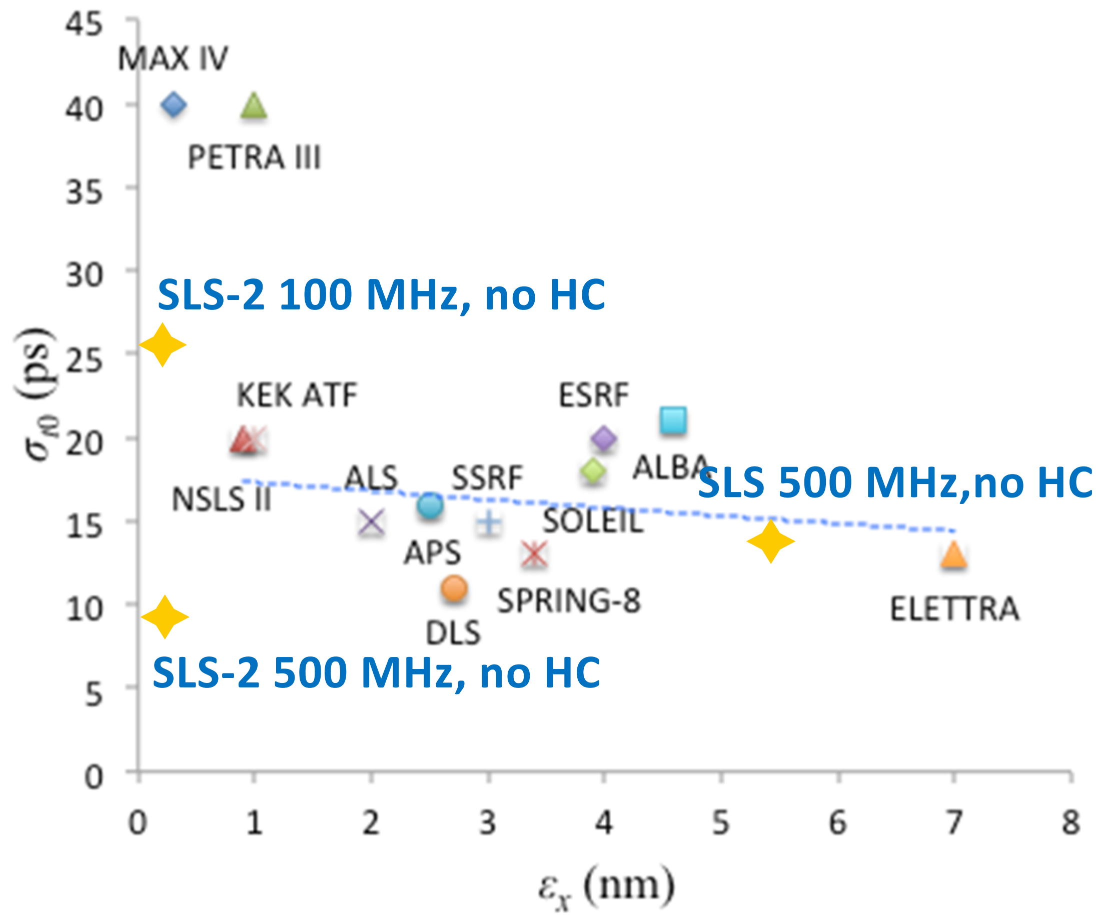
Synchrotron tune:

$$\nu_s^2 = \frac{h_{\mathrm{RF}} \alpha \sqrt{V_{\mathrm{RF}}^2 - U^2 / e^2}}{2\pi E / e} \sigma_\delta$$

Energy loss per turn:

$$U_0 = \frac{2}{3} r_e m_e c^2 \gamma^4 I_2$$

$$I_2 = \oint \frac{ds}{\rho^2}$$

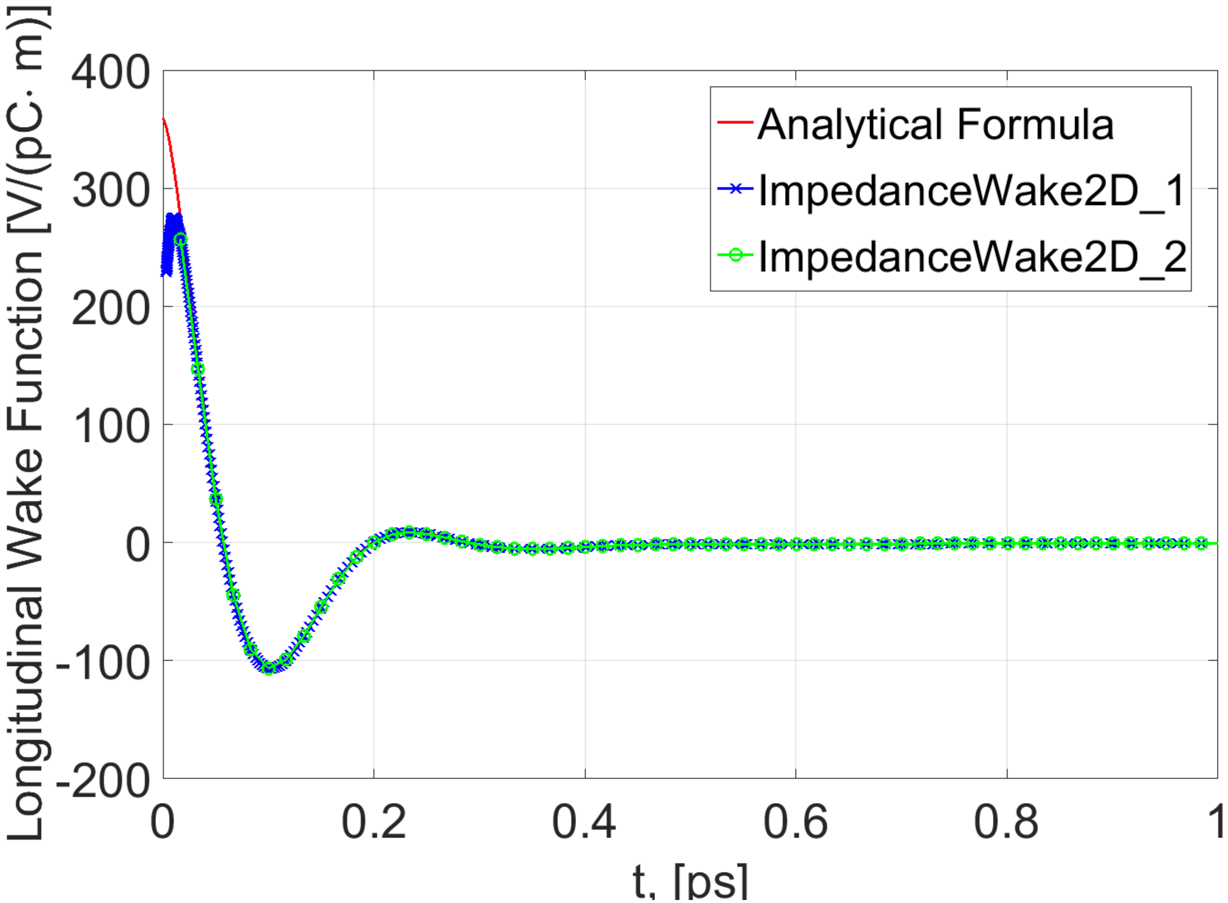


✓ Shorter bunch → higher peak current → stronger collective effects

Courtesy of V. Smaluk

Longitudinal Resistive-Wall Wake Functions

- **without NEG**
- **ImpedanceWake2D* code** or **Analytical formula****



[*] N. Mounet. **ImpedanceWake2D**. http://impedance.web.cern.ch/impedance/Codes/ImpedanceWake2D/user_manual_todate.txt

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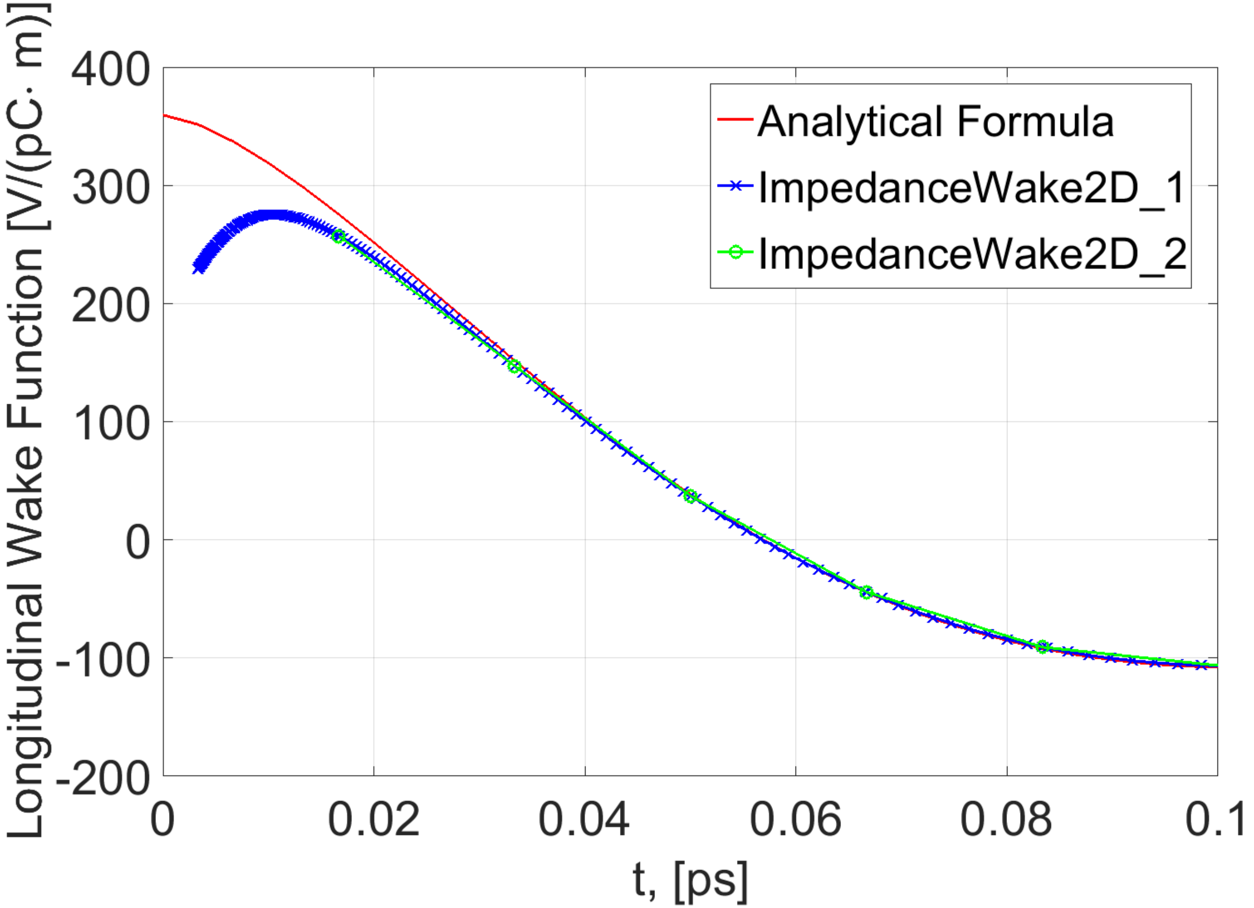

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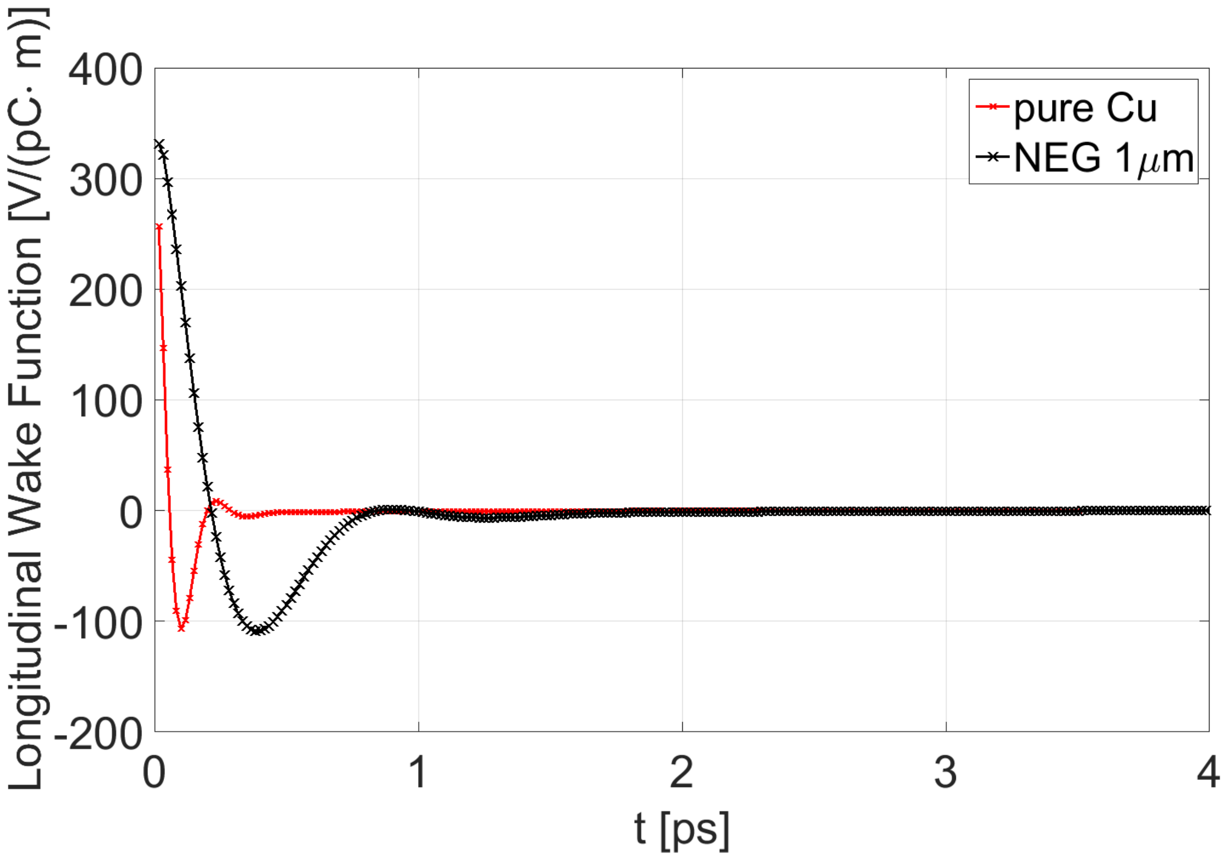
[**] Karl L.F. Bane and Matthew Sands, The Short-Range Resistive Wall Wakefields, SLAC-PUB-95-7074, Dec. 1995.

Longitudinal Resistive-Wall Wake Functions

- **1 μm NEG coating** or **without NEG**
- **ImpedanceWake2D* code**



[*] N. Mounet. **ImpedanceWake2D**. http://impedance.web.cern.ch/impedance/Codes/ImpedanceWake2D/user_manual_todate.txt

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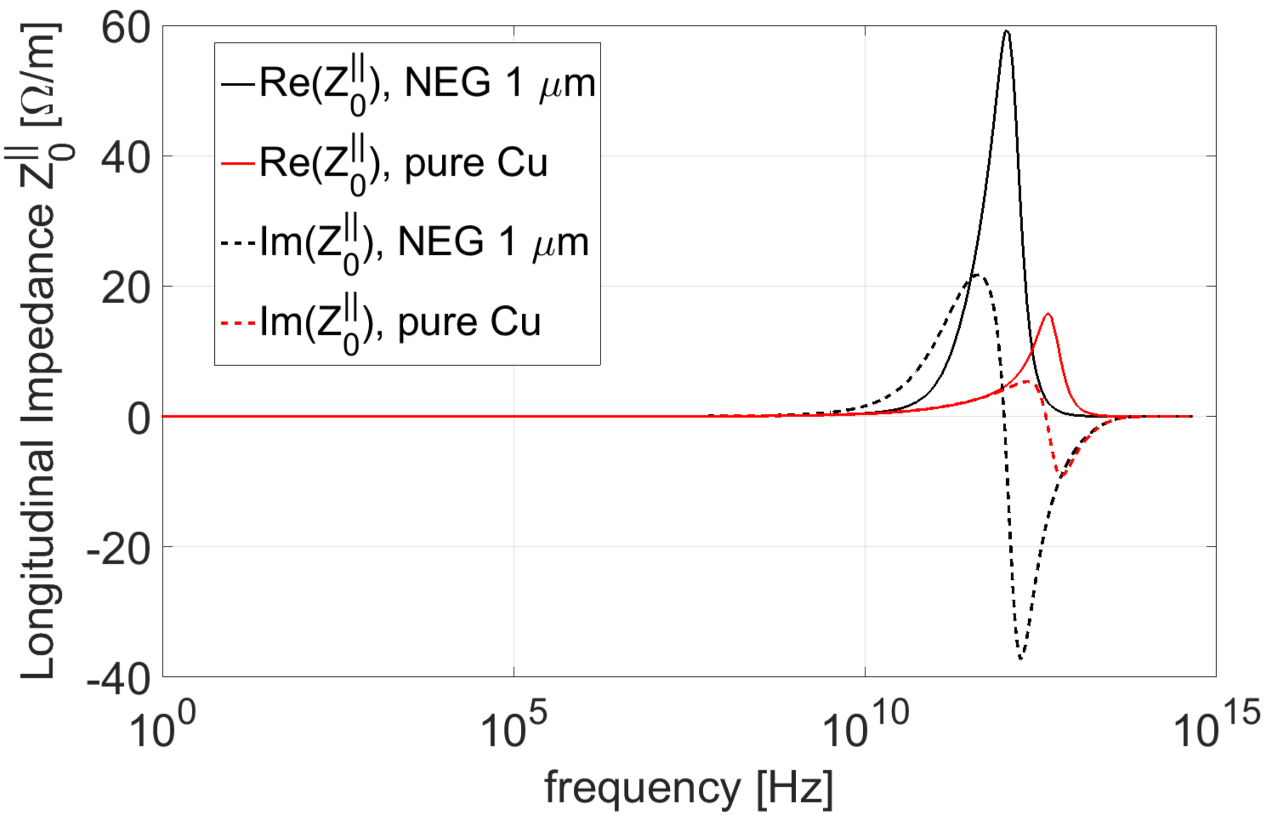

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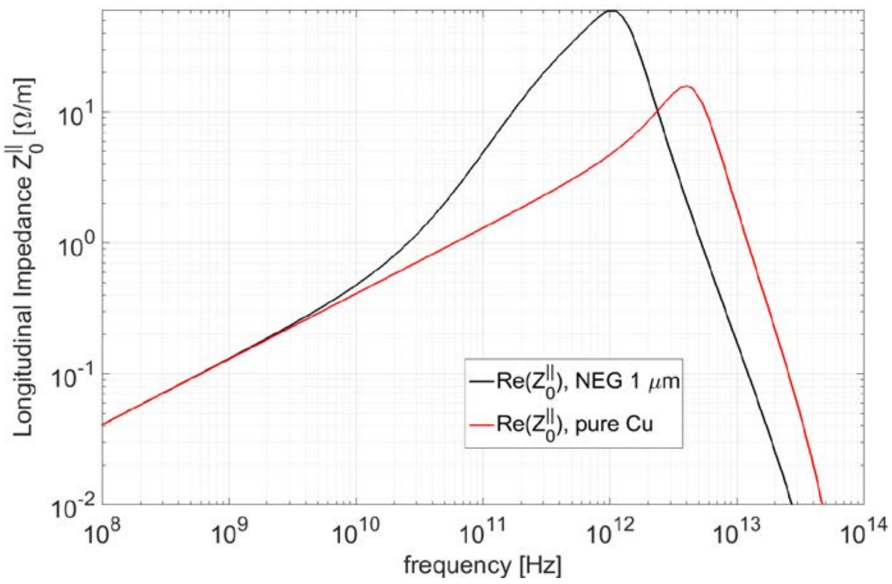
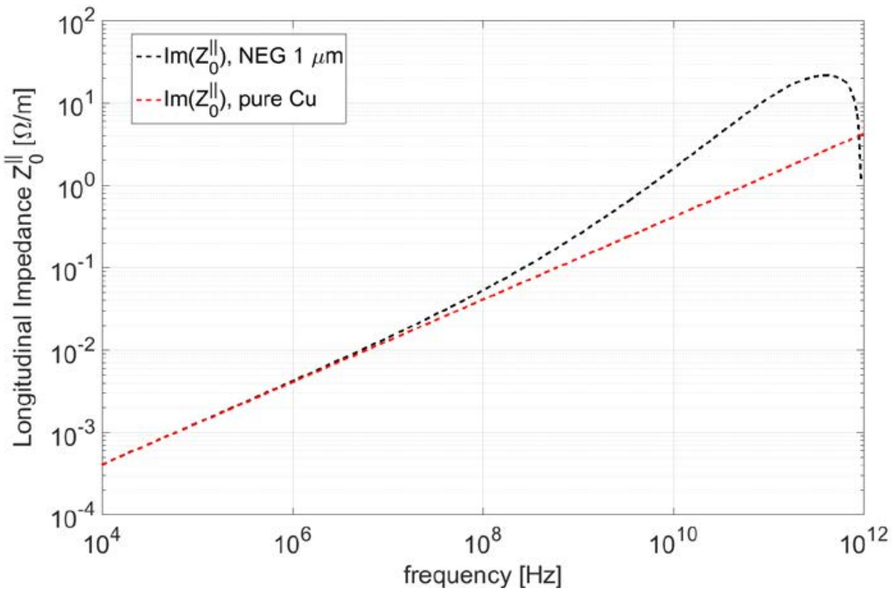
Longitudinal Resistive-Wall Wake Functions

- **1 μm NEG coating** or **without NEG**
- **ImpedanceWake2D* code**

ZOOM IN





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Longitudinal Resistive-Wall Wake Functions

- **Longitudinal Short-Range Wake Function** has been calculated by both analytical formula and ImpedanceWake2D code.
  - Good agreement has been shown when $t > 20$ [fs];
  - RMS bunch length (minimum is 8.7 [ps]) >> 20 [fs], we therefore keep the difference in mind and still use this code to calculate the wake function in the cases with NEG coating.
- NEG coating (e.g., $\rho_{NEG} = 9.1 \times 10^7\ [\Omega \cdot m]$) gives longitudinal impedance in high frequency.
  – $\mathrm{Re}\left(Z_0^{\parallel}\right)$ → above ~ 10 [GHz]
  – $\mathrm{Im}\left(Z_0^{\parallel}\right)$ → above ~ 0.1 [GHz]

Microwave instability

- Average current → **400 mA**
  - @ 100 MHz RF, uniform filling pattern, **I_b = 4.17 mA (2.5×10^{10} e/bunch)**
  - @ 500 MHz RF, uniform filling pattern, **I_b = 0.833 mA (5.0×10^{9} e/bunch)**
  - @ 500 MHz RF, 390 normal bunches + 1 'camshaft', **$I_{normal}\approx$ 1.015 mA (6.0×10^{9} e/bunch)**, **$I_{camshaft}\approx$ 4 mA (2.4×10^{10} e/bunch)**
- The threshold of microwave instability can be given by **Boussard criterion***

$$\left|\left(\frac{Z_{\parallel}}{n}\right)_{eff}\right| \le F'\frac{E_0}{e}\frac{|\eta|\gamma}{I_b}\frac{\sigma_z}{cT_0}\left(\frac{\Delta p_{FWHM}}{p_{\parallel}}\right)^2$$

where effective impedance** can be calculated in two ways:

(1) → $$\left(\frac{Z_{\parallel 0}}{n}\right)_{eff} = \omega_0\cdot\left(\frac{Z_{\parallel 0}}{\omega}\right)_{eff} = \omega_0\cdot\frac{\sum_{p=-\infty}^{\infty}\frac{Z_{\parallel 0}(\omega_p)}{\omega_p}h_m(\omega_p)}{\sum_{p=-\infty}^{\infty}h_m(\omega_p)}$$

The spectral density $h_m(\omega_p) = (\omega\sigma_\tau)^{2m}e^{-\omega^2\sigma_\tau^2}$ with assumption of Gaussian bunch. Consider the m=1 mode only.

(2) → $\left(\frac{Z_{\parallel 0}}{n}\right)_{eff} = \frac{Z_{\parallel}(\omega_b)}{\omega_b/\omega_0}$; $\omega_b = \frac{2\pi c}{\sigma_z}$ is a typical bunch frequency; ω_0 is angular revolution frequency;

- [*] Alexander Wu Chao, et.al, Handbook of Accelerator Physics and Engineering (Second Edition), World Scientific Publishing Co. Pte. Ltd. 2013, p148
- [**] Alexander Wu Chao, et.al, Handbook of Accelerator Physics and Engineering (Second Edition), World Scientific Publishing Co. Pte. Ltd. 2013, p262

Estimation by Boussard Criterion

- Longitudinal RW Wake;
- Gaussian Bunch Assumption;
- Zero-Current Bunch Length (shown on slide 6);

			(1)Effective Impedance	(1)Threshold *	(2)Effective Impedance	(2)Threshold *
100 MHz RF	**without harmonic cavity**	Analytical impedance, no NEG	40.80 mΩ	1.30 mA	22.65 mΩ	2.33 mA
		ImpedanceWake2D, 1 μm NEG	253.76 mΩ	0.21 mA	193.05 mΩ	0.27 mA
	With 3rd harmonic cavity	Analytical impedance, no NEG	92.89 mΩ	2.99 mA	51.22 mΩ	5.43 mA
		ImpedanceWake2D, 1 μm NEG	318.96 mΩ	0.87 mA	259.82 mΩ	1.07 mA
500 MHz RF	**without harmonic cavity**	Analytical impedance, no NEG	23.84 mΩ	0.75 mA	13.68 mΩ	1.30 mA
		ImpedanceWake2D, 1 μm NEG	202.93 mΩ	0.09 mA	131.11 mΩ	0.14 mA
	With 3rd harmonic cavity	Analytical impedance, no NEG	47.69 mΩ	1.52 mA	26.39 mΩ	2.74 mA
		ImpedanceWake2D, 1 μm NEG	264.99 mΩ	0.27 mA	210.27 mΩ	0.34 mA

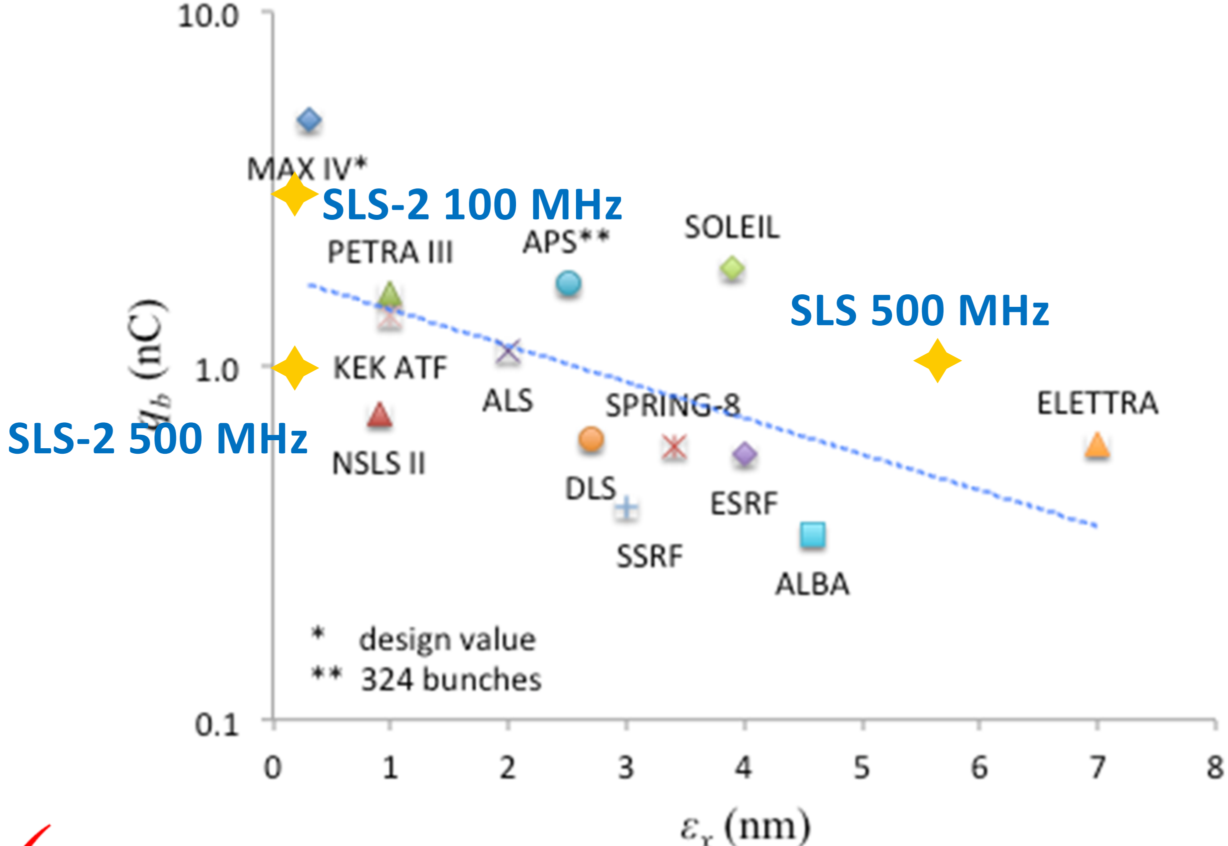
* Form factor F’ is assumed as 1;

Parameters of Low Emittance Rings

Beam intensity

Beam current
for regular operation

	I_{aver} (mA)	number of bunches
MAX IV	500*	176
NSLS II	300 (500*)	1080
KEK ATF DR	300	100
PETRA III	100	960
ALS	500	300
APS	150	324 (24)
DLS	300	900
SSRF	200	720
SPRING-8	100	812
SOLEIL	500	312
ESRF	200	992
ALBA	120	320
ELETTRA	300	432



Courtesy of V. Smaluk

✓ Higher bunch charge ➔

higher peak current ➔ $I_p = \dfrac{q_b}{\sqrt{2\pi}\sigma_t}$

stronger collective effects $V_{wake} = I_p Z$

Microwave instability

- PyHEADTAIL*
  - 1 million macroparticles, 500 slices/bunch
  - Synchrotron radiation effects have not yet been built in the code. We implemented the SR effects by the following manner**:

$$\delta\Big|_{n+1} = \frac{\Delta p}{p_0}\Big|_{n+1} = \delta\Big|_n \cdot e^{-\frac{2T_0}{\tau_E}} - \frac{U_0}{\beta^2 E_0} + rand \cdot \sigma_\delta \cdot \sqrt{3 \cdot \left(1 - e^{-\frac{4T_0}{\tau_E}}\right)}$$

Radiation damping Average energy loss per turn Quantum excitation

- *mbtrack****
  - 5×10^4 macroparticles, 80 slices/bunch
  - Synchrotron radiation is included in the code

- [*] CERN PyHEADTAIL simulation code for simulation of multi-particle beam dynamics and collective effects
- [**] Andreas Streun, PhD Thesis, 1992
- [***] R. Nagaoka, et.al, Studies of Collective Effects in SOLEIL and DIAMOND Using the Multiparticle Tracking Codes sbtrack and mbtrack, FR5RFP046, Proceedings of PAC09, Vancouver, BC, Canada, 2009; Galina Skripka, et.al, Simultaneous computation of intrabunch and interbunch collective beam motions in storage rings, Nuclear Instruments and Methods in Physics Research Section A, 806 (2016), 221-230.

First Study and Questions of Microwave Instability

			Boussard Criterion *		PyHEADTAIL**	*mbtrack***
			(1)	(2)		
100 MHz RF	**without harmonic cavity**	**Analytical wake, no NEG**	**1.30 mA**	**2.33 mA**	**5.0 mA**	**33.3 mA**
		ImpedanceWake2D, no NEG			5.0 mA	
		ImpedanceWake2D, 1 μm NEG	0.21 mA	0.27 mA	0.33 mA	
	With 3rd harmonic cavity	**Analytical wake, no NEG**	**2.99 mA**	**5.43 mA**	**50.0 mA**	
		ImpedanceWake2D, no NEG			66.7 mA	
		ImpedanceWake2D, 1 μm NEG	0.87 mA	1.07 mA	10.0 mA	
500 MHz RF	**without harmonic cavity**	**Analytical wake, no NEG**	**0.75 mA**	**1.30 mA**	**0.67 mA**	**15.0 mA**
		ImpedanceWake2D, no NEG			0.67 mA	
		ImpedanceWake2D, 1 μm NEG	0.09 mA	0.14 mA	0.67 mA	
	With 3rd harmonic cavity	**Analytical wake, no NEG**	**1.52 mA**	**2.74 mA**	**16.7 mA**	
		ImpedanceWake2D, no NEG			16.7 mA	
		ImpedanceWake2D, 1 μm NEG	0.27 mA	**0.34 mA**	0.83 mA	

* Form factor F' is assumed as 1;

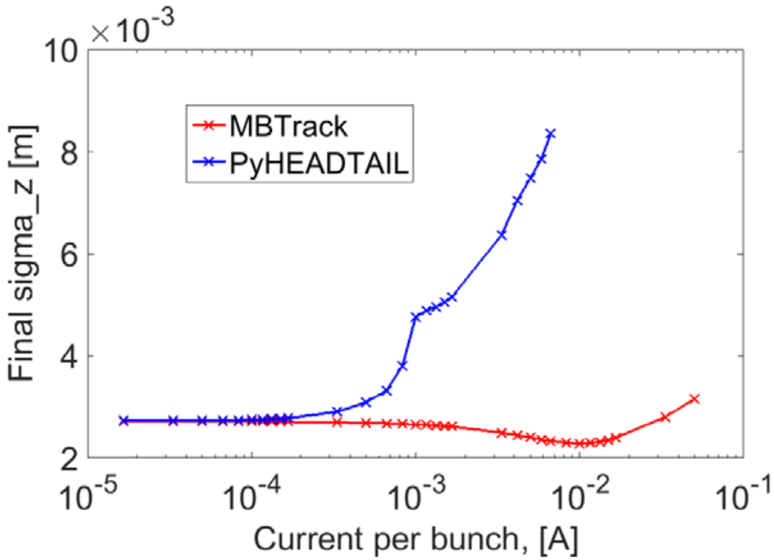
** Threshold criterion: $\sigma_\delta > 1.01\ \sigma_{\delta-zero-current}$; above mentioned settings are used.

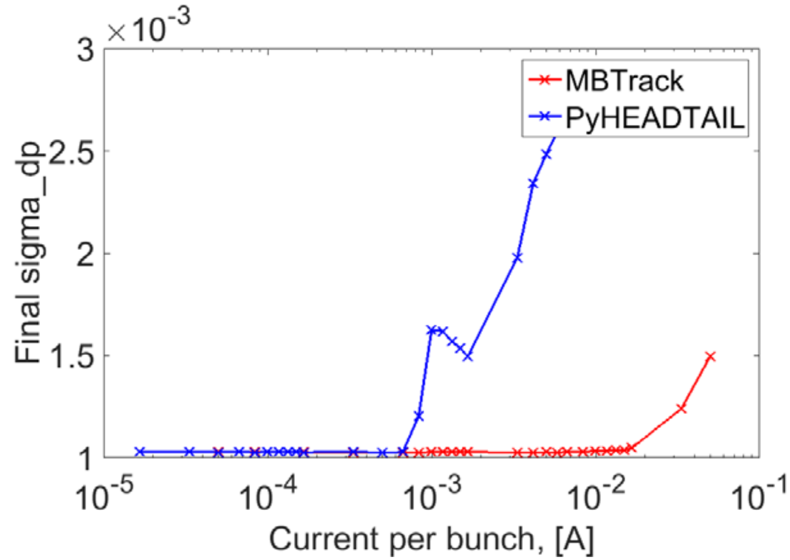
First Study and Questions of Microwave Instability

- **Questions:**
  - Our estimations by Boussard Criterion show lower threshold than the results we obtained from the simulation codes PyHEADTAIL and *mbtrack*;
  - We don’t understand some results from our simulation by PyHEADTAIL.
  - PyHEADTAIL and *mbtrack* give different thresholds;

Comparison between PyHEADTAIL and *mbtrack*

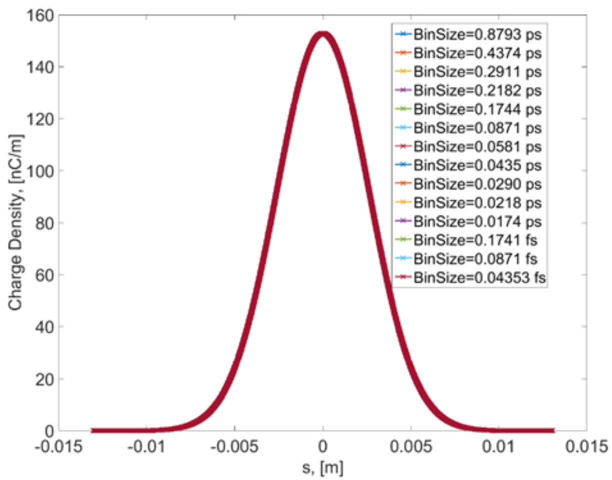
We keep doing the comparison...



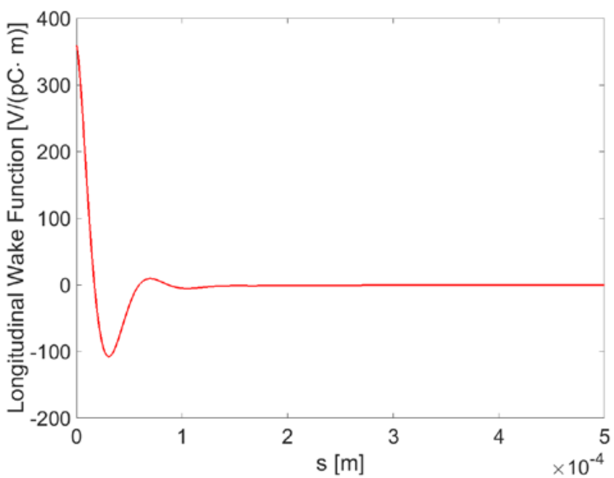


- PyHEADTAIL: $\mathbf{1 \times 10^6}$ macroparticles, **500** [bins/bunch];
- *mbtrack*: $\mathbf{5 \times 10^4}$ macroparticles, **80** [bins/bunch];
- Only Longitudinal Resistive-Wall Wake Function is included;
  - PyHEADTAIL: imported RW wake, calculated by **ImpedanceWake2D**;
  - *mbtrack*: built-in model, calculated by ***mbtrack***;
- RF 500 MHz, round copper chamber without NEG, inner radius 10 [mm];
- Synchrotron radiation damping time is ~ 6.63 [ms];
- 50000 turns (~7 damping time) in total;
- Both sigma_z and sigma_dp are average values of the last 10000 turns.

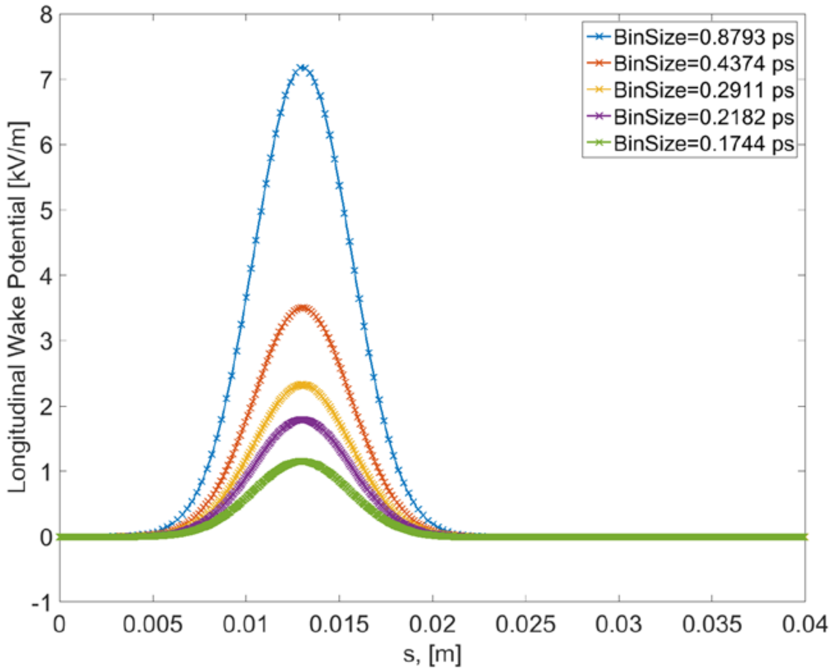
Wake Potential Calculation in Time Domain



Normalized Gaussian Distribution

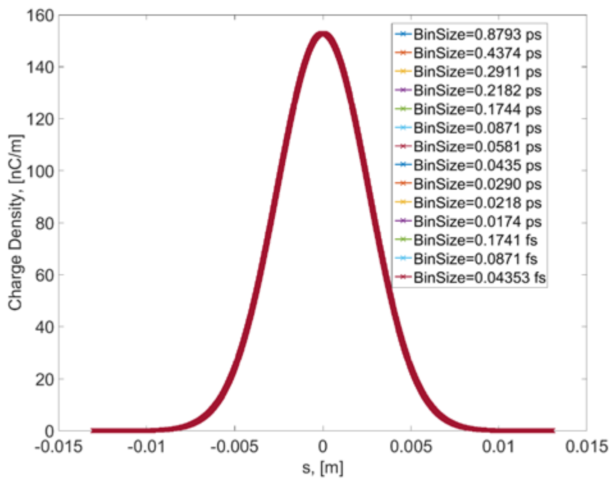


Longitudinal Wake Function



Time-Domain Convolution

Wake Potential Calculation in Time Domain



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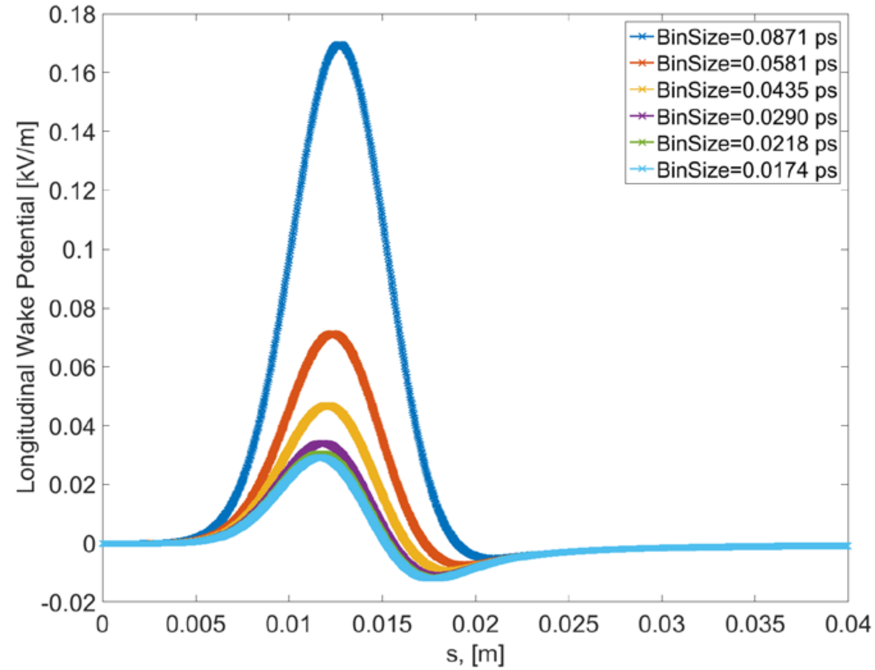

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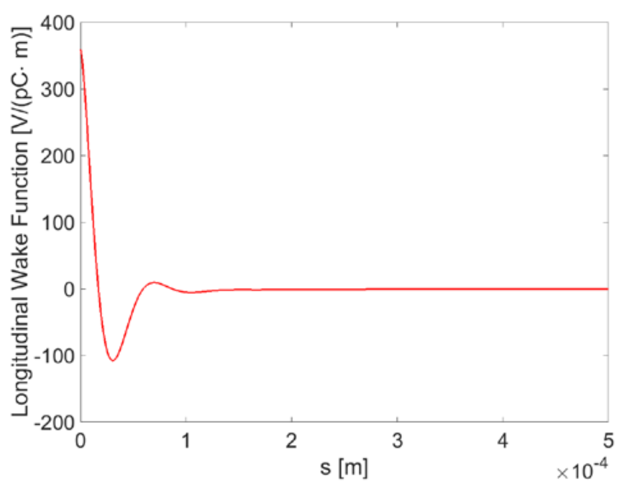
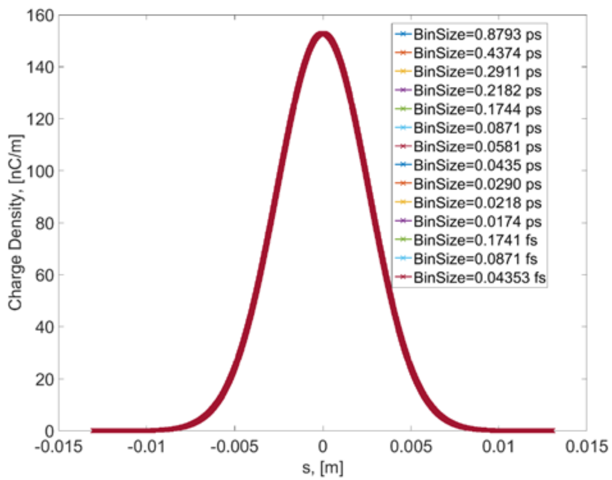


Longitudinal Wake Function

Wake Potential Calculation in Time Domain



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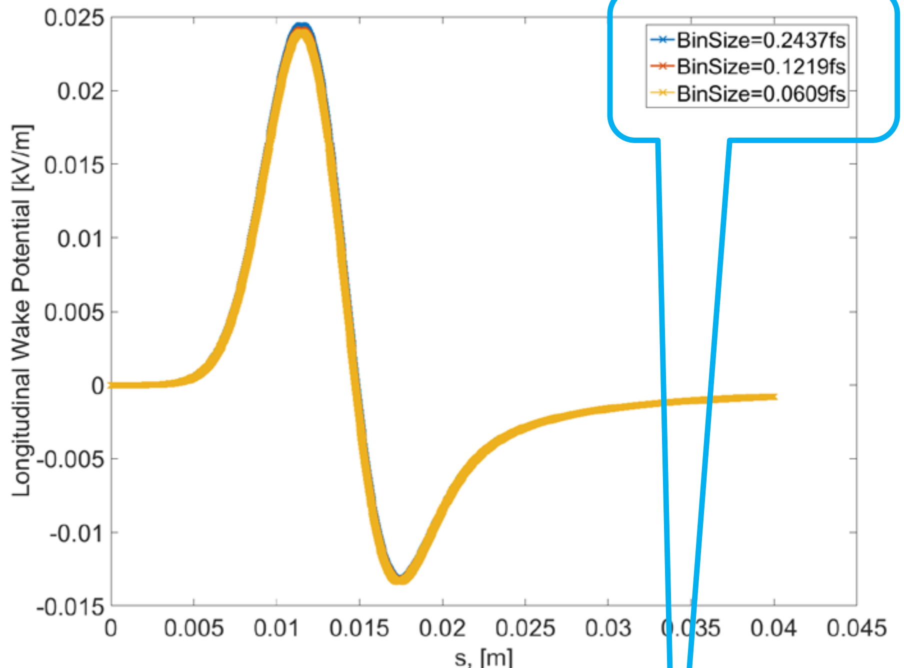
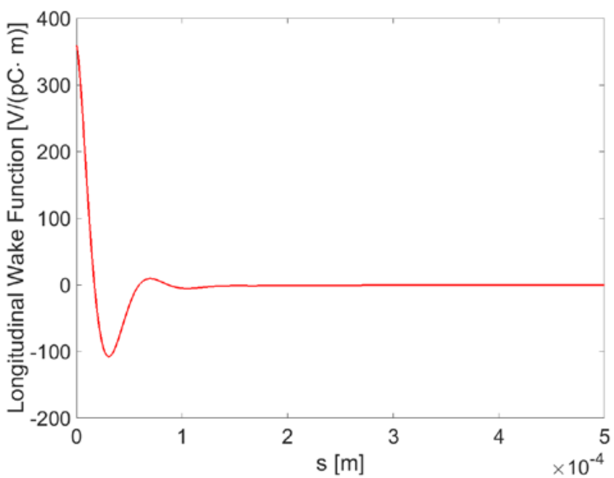


Time-Domain Convolution

difficult to converge!



Longitudinal Wake Function

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Summary & Discussion

- We calculated the **longitudinal resistive-wall wake function** in the cases **with-** and **without- NEG coating** for SLS-2 ring.
  - Cu chamber → analytical formula and ImpedanceWake2D code;
  - NEG-coated chamber → ImpedanceWake2D code;
- We calculated the **threshold of microwave instability** induced by **longitudinal resistive-wall wake field** using **analytical method (Boussard Criterion)**, **PyHEADTAIL** and ***mbtrack***.
  - different RF frequencies (100 MHz, 500 MHz);
  - with or without third harmonic cavities (only PyHEADTAIL);
- **Questions and on-going studies:**
  - Is fully NEG-coated chamber rolled out for SLS-2?
  - 100 MHz or 500 MHz?
  - Multi-bunch effects!
  - Questions to simulation:
    - Convolution in PyHEADTAIL? time-domain convolution
    - Model of short-range longitudinal resistive-wall wake function in *mbtrack*?

    Dr. Nagaoka's team is kindly working on it.

Acknowledgement

- The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n.º290605 (PSI-FELLOW / COFUND).
- We thank people in SLS-2 team for the comments and discussions.
- We thank Eirini Koukovini-Platia, Kevin Shing Bruce Li, Adrian Oeftiger, Michael Schenk for their support and discussion on the usage of PyHEADTAIL.
- We thank Ryutaro Nagaoka, Francis Cullinan, Galina Skripka for their support and discussion on the *mbtrack* code.

Thank you very much for your attention!

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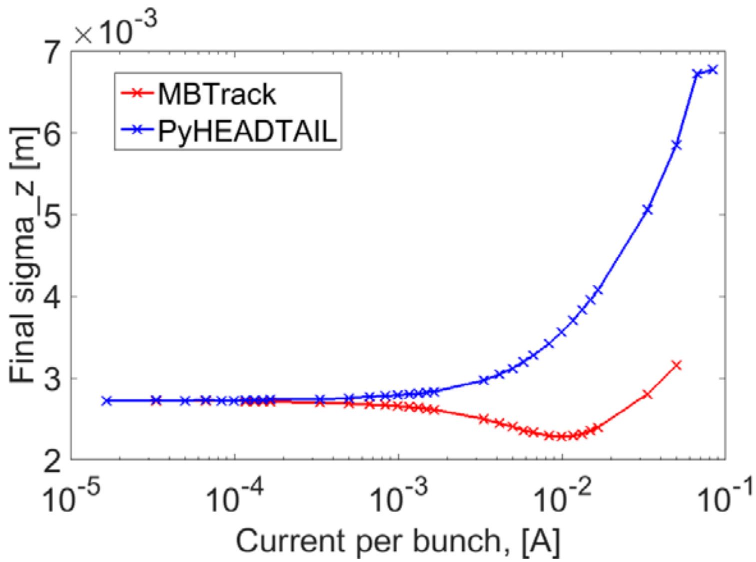
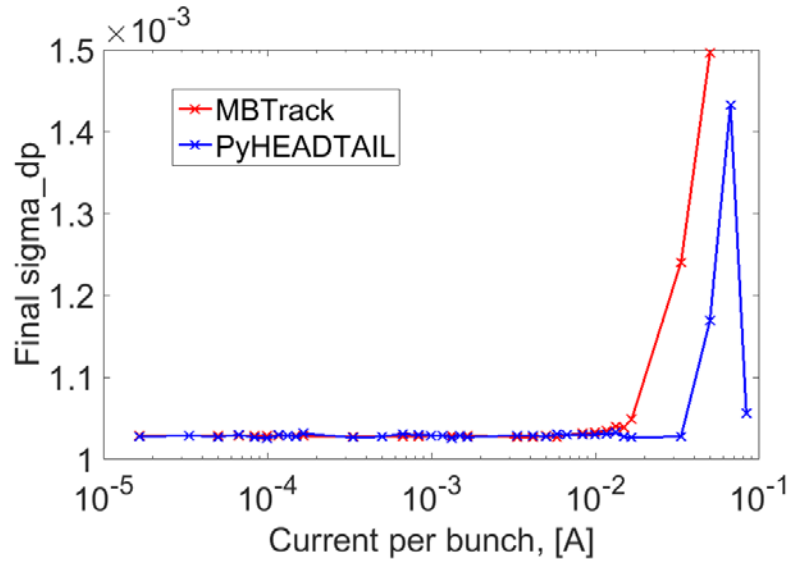
Backup slides

Comparison between PyHEADTAIL and *mbtrack*





- PyHEADTAIL: $\mathbf{5 \times 10^4}$ macroparticles, **80** [bins/bunch];
- *mbtrack*: $\mathbf{5 \times 10^4}$ macroparticles, **80** [bins/bunch];

- Only Longitudinal Resistive-Wall Wake Function is included;
  - PyHEADTAIL: imported RW wake, calculated by ***mbtrack***;
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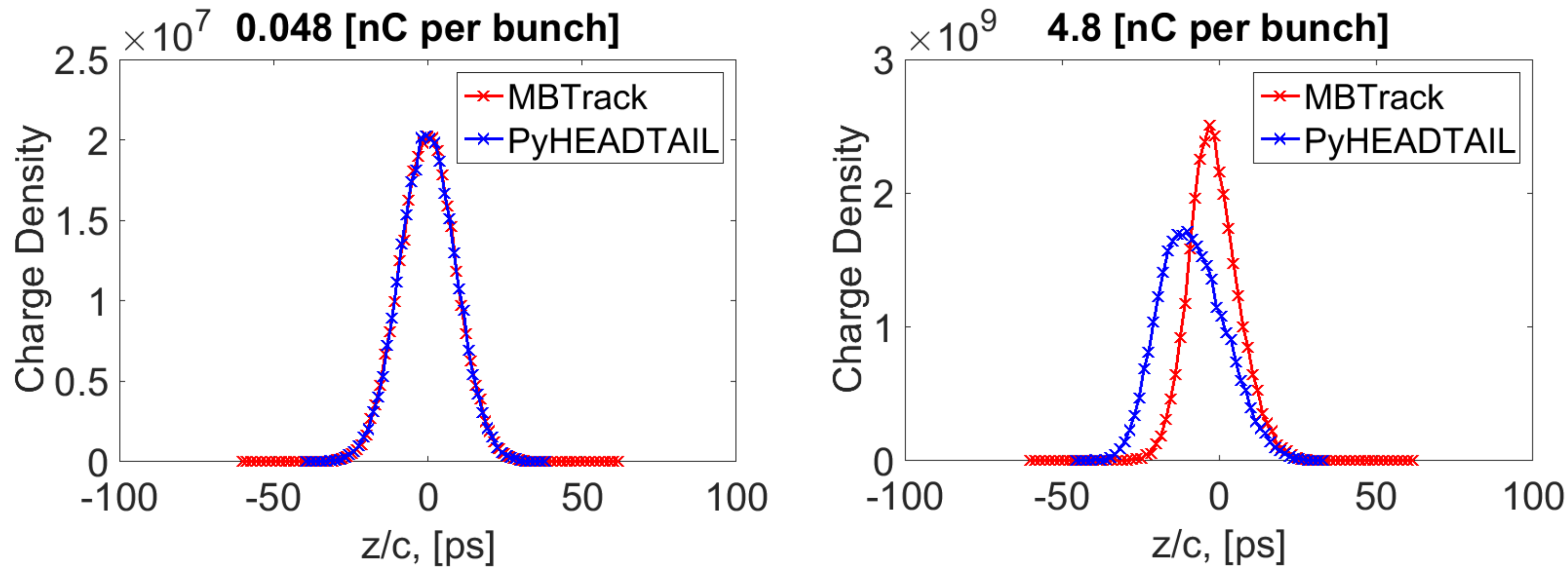
- Other conditions are kept the same.

Comparison between PyHEADTAIL and *mbtrack*



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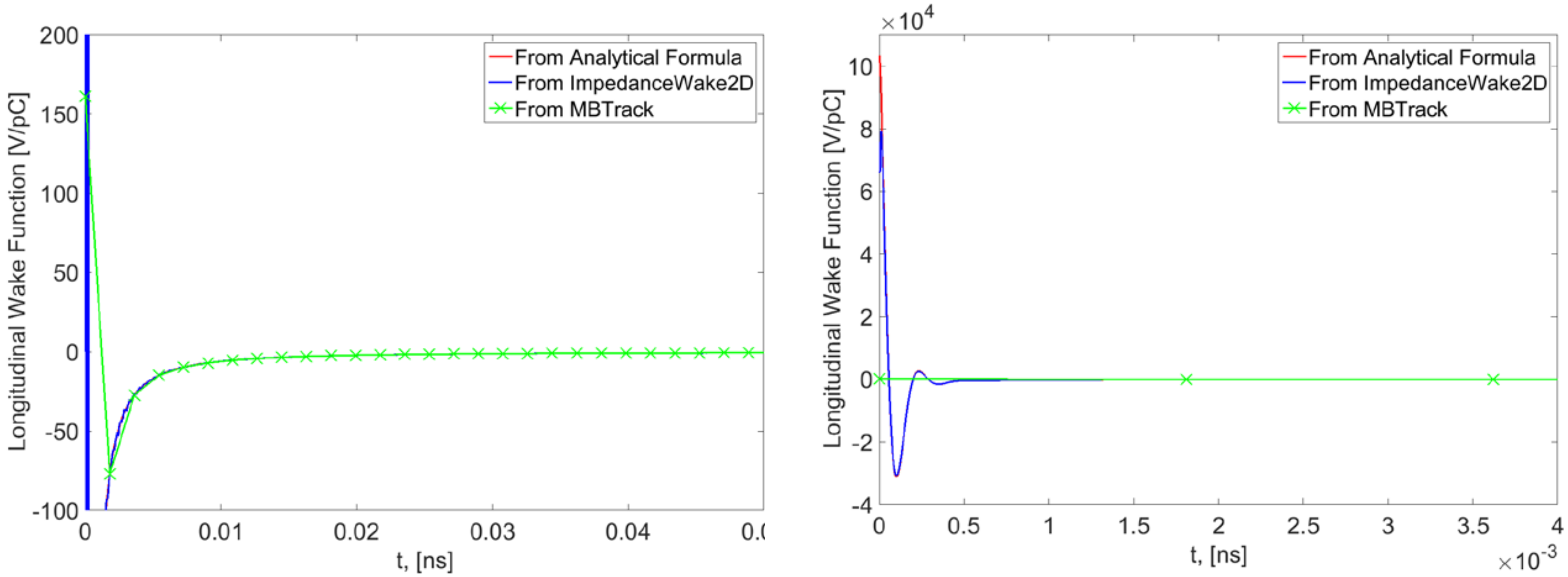
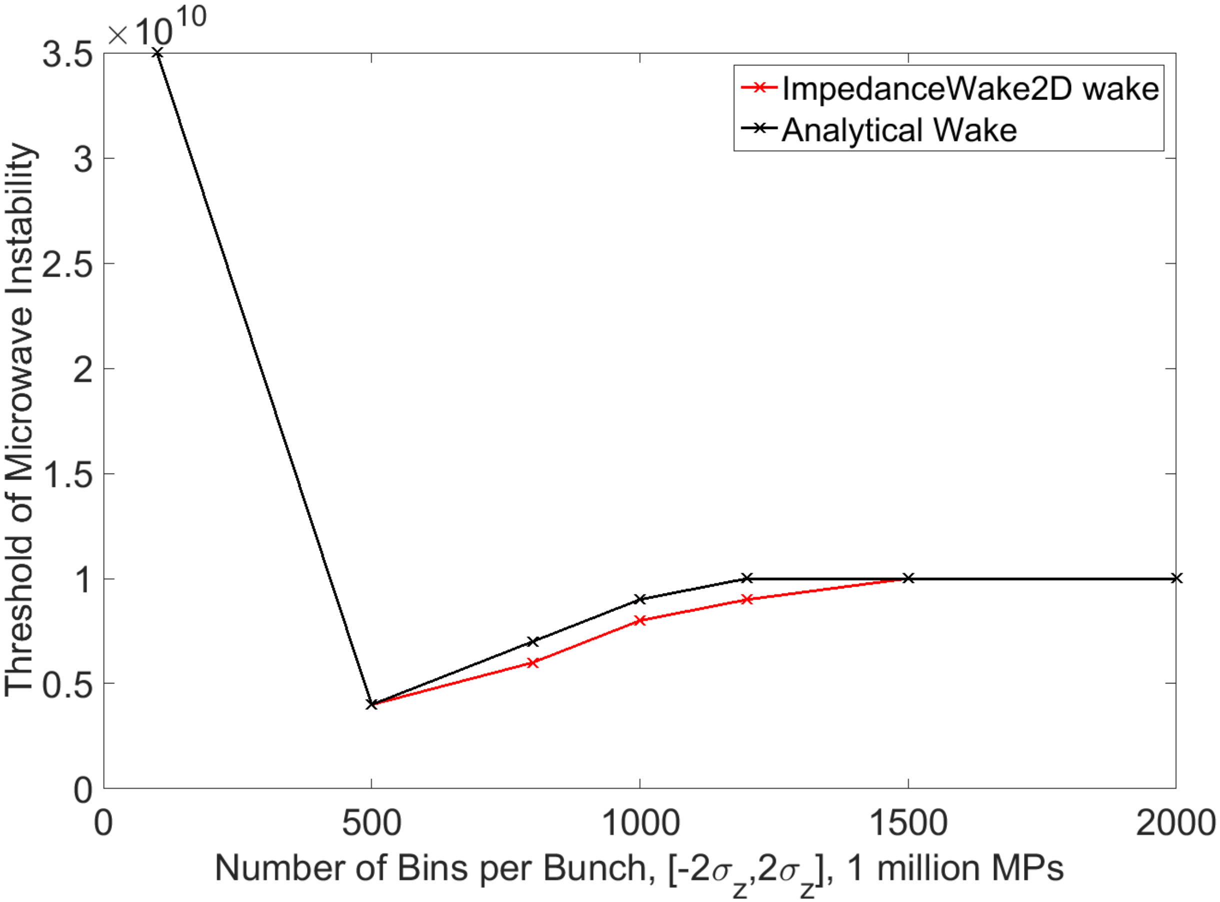


- *mbtrack:*
  - In my simulation, bin size = 1.82 [ps];
- PyHEADTAIL:
  - In my simulation, longitudinal wake function is calculated by ImpedanceWake2D.
  - Bin size ≈ 0.07 [ps] (initial bin size);
- Zero-Current RMS Bunch Length @ 500 MHz: $\sigma_z \approx 2.6\ [mm] \approx 8.7\ [ps]$

PyHEADTAIL: Different Number of Bins per Bunch



- In this simulation, longitudinal wake function is included.
- Zero-Current RMS Bunch Length @ 500 MHz: $\sigma_z \approx 2.6 \times 10^{-3}\ [m] \approx 8.7\ [ps]$

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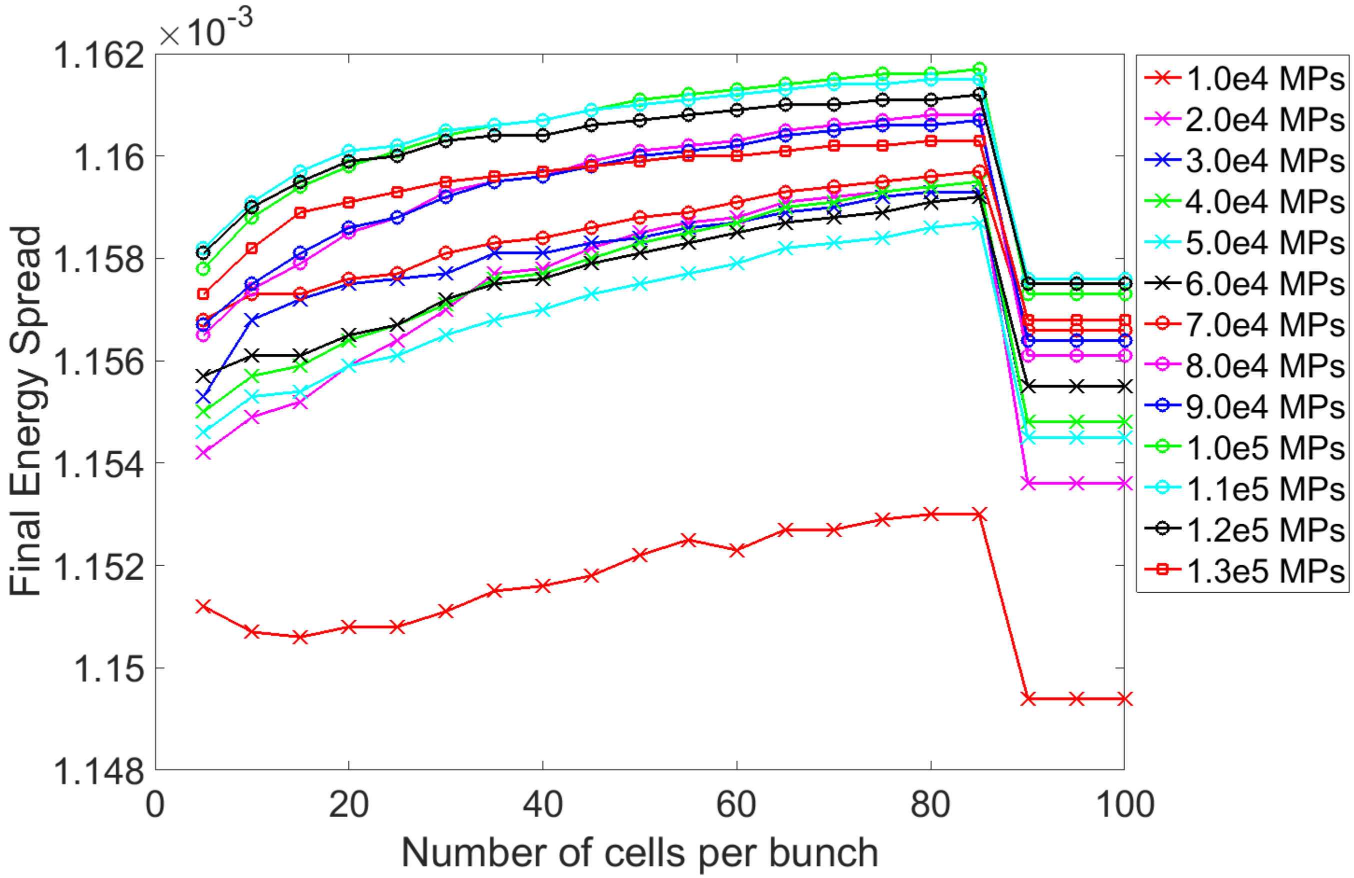
mbtrack: Different Number of Bins per Bunch



- In this simulation, longitudinal wake function is included.
- Zero-Current RMS Bunch Length @ 500 MHz: $\sigma_z \approx 2.6 \times 10^{-3}\ [m] \approx 8.7\ [ps]$