PAUL SCHERRER INSTITUT

Alessandro Citterio on behalf of the Impedance & Instability Team :: Paul Scherrer Institut

Overview of the collective effects in SLS 2.0

ALERT 2019 workshop, 10th-12th July 2019

Contents

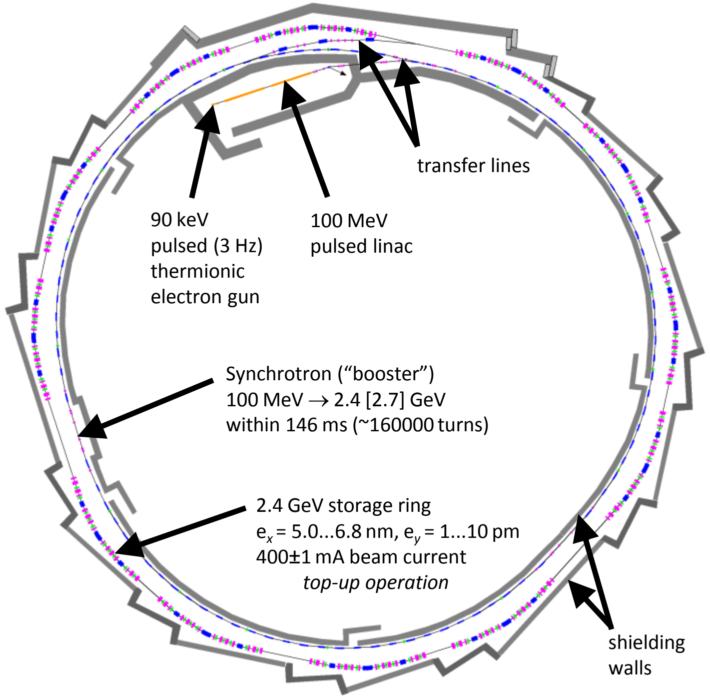
Co-authors: M.Aiba, M.Dehler, S.Dordevic, L.Stingelin

SLS: 17 years of very successful operation...

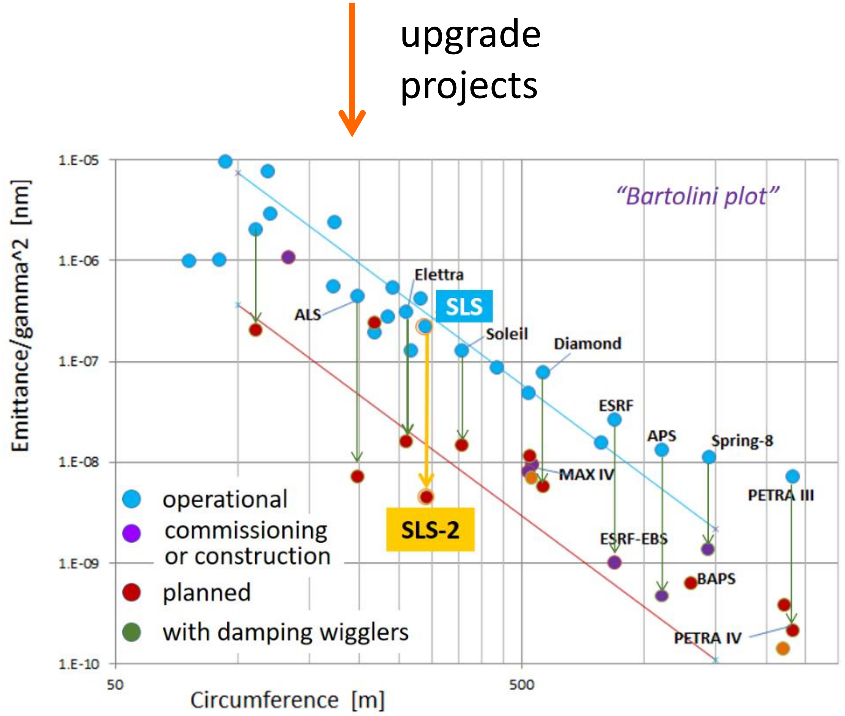
...but emittance **5 nm** at 2.4 GeV not competitive in near future

Name	SLS*)
Emittance at 2.4 GeV [pm]	5069
Lattice type	12×TBA
Circumference [m]	288.0
Total absolute bending angle	360°
Working point $Q_{x/y}$	20.43 / 8.22
Natural chromaticities $C_{x/y}$	-67.0 / -19.8
Optics strain[1]	7.9
Horizontal damping Partition J_x	1.00
Momentum compaction factor [10^{-4}]	6.56
Radiated Power [kW] [2]	208
rms energy spread [10^{-3}]	0.86
damping times x/y/E [ms]	8.9 / 8.9 / 4.4

1) product of horiz. and vert. normalized chromaticities C/Q
2) assuming 400 mA stored current, bare lattice without IDs
*) SLS lattice before FEMTO installation (< 2005)



SLS



⇨ SLS 2.0 *how to ?*

SLS 2.0: Improvement in emittance of at least 40

⇓

novel type of lattice: **state of the art multi bend achromat optics** (but lattice analysis still under optimization!)

⇓

minimum changes in the existing infrastructure

(some modifications in the shielding walls and shifts of the source points of several beamlines may be required)

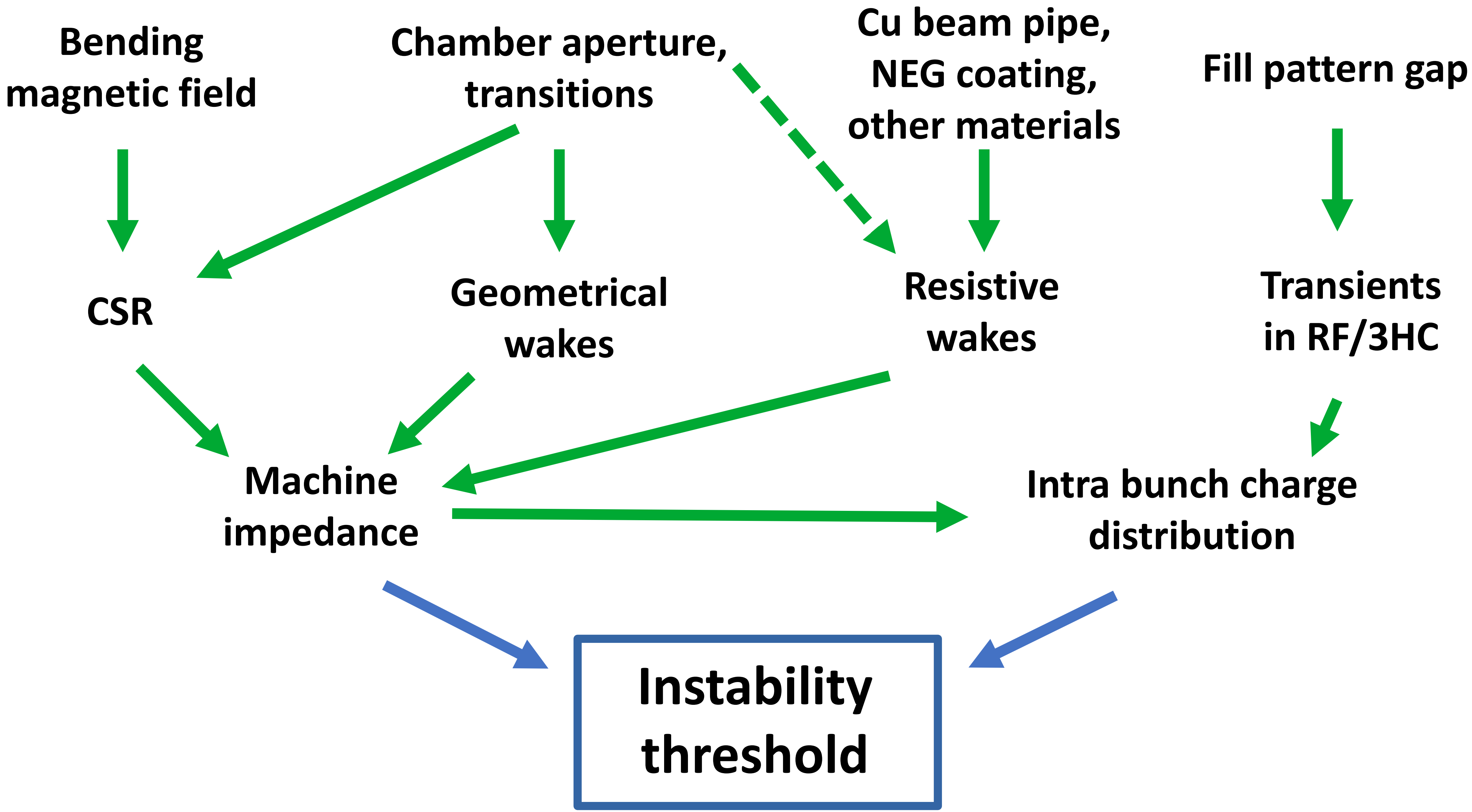
SLS 2.0 Lattices Available in the Analysis of Impedances & Instabilities

As of now, design work on the ring optics is still on going and may result in changes !
Here three solutions with negative momentum compaction factor are presented :

	sls2_june2018_ele.lat	Lattice A a001_000_bri_ele.lat	Lattice B b000_000_ele.lat
Circumference [m]	290.400165	290.4003	288.0002
Beam pipe diameter [mm]	20	20	17
Momentum compaction α	$-1.279883\ 10^{-4}$	$-1.257072\ 10^{-4}$	$-1.222724\ 10^{-4}$
Radiated energy/turn [keV]	529.7455	561.0825	605.9442
Natural energy spread	$1.027936\ 10^{-3}$	$1.062676\ 10^{-3}$	$1.088449\ 10^{-3}$
Damping time E [ms]	7.105005	6.639162	6.107259

- Most of the impedance calculations and tracking simulations (longitudinal MicroWave Instabilities MWI) refers to **sls2_june2018_ele.lat**
  This lattice is also used to analyze some threshold tendencies varying few impedance relevant parameters.
- Recently available Lattice A **a001_000_bri_ele.lat** and B **b000_000_ele.lat** . **Lattice optimization is currently on going** (exploring α > 0).............
- First threshold estimation for longitudinal MWI for Lattice A and B, and preliminary results for transverse MWI for Lattice B.

Interdependencies of Effects with respect to Longitudinal Microwave Instabilities



SLS 2.0 Impedance Budget (as for now) for the Longitudinal Collective Effects

The impedance parameters of this list refers to the lattice **sls2_june2018_ele.lat**

Different impedance budgets must be considered for other lattices (as Lattice A/B, see later) !

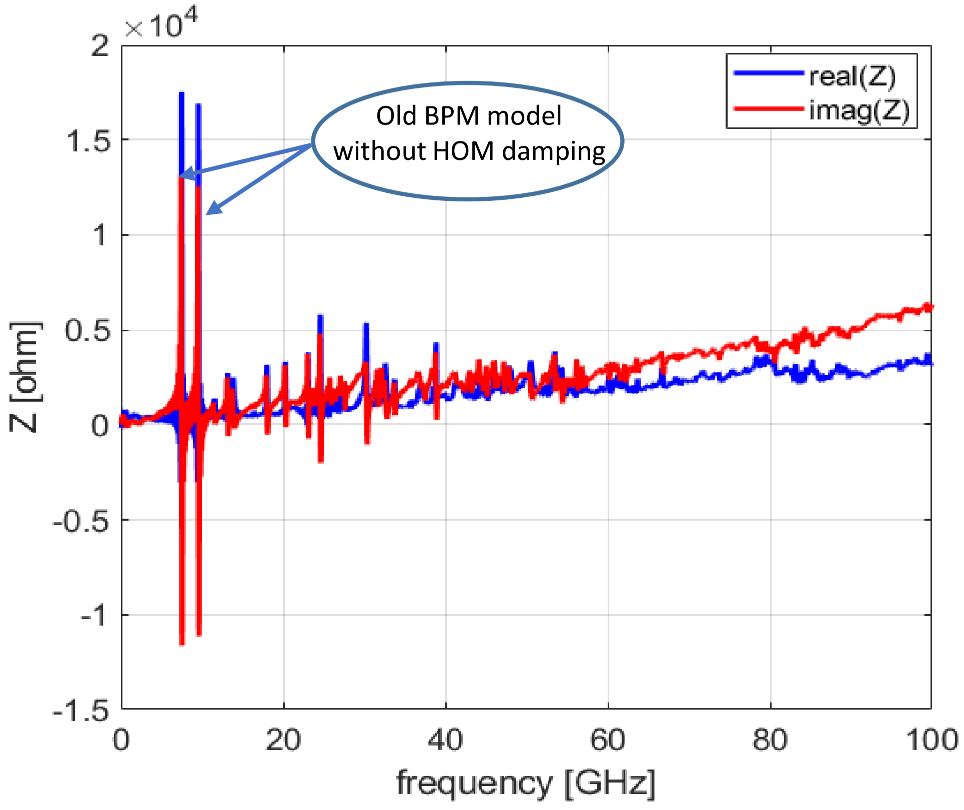
Impedances used in tracking simulations	Lattice June 18
Resistive wall beam pipe (circular cross section)	• L_{tot} = 290.4 - 14 (ID1) -28 (ID2) [m], Diameter = 20 [mm] • Copper with 500 nm columnar NEG coating
Resistive wall insertion device ID1 (circular cross section)	• L_{tot} = 14 [m], Diameter = 4 [mm] • Copper with 500 nm columnar NEG coating
Resistive wall insertion device ID2 (circular cross section)	• L_{tot} = 28 [m], Diameter = 6 [mm] • Copper with 500 nm columnar NEG coating
Tapers for insertion devices (ID1 and ID2)	• N_{tot} = 12 (for ID1) + 6 (for ID2), SLS design based, L_{taper} = 150-450 [mm]
Coherent Synchrotron Radiation	• Infinite parallel plates, steady state regime • Gap = 20 [mm]
Beam Position Monitors	• N_{tot} = 150
500 MHz Cavities	• N_{tot} = 2+2 • Linear tapers 300 [mm] long for the beam pipe transition
SC Harmonic Cavity 1.5 GHz	• As in SLS, but with linear tapers 300 [mm] long for the beam pipe transition

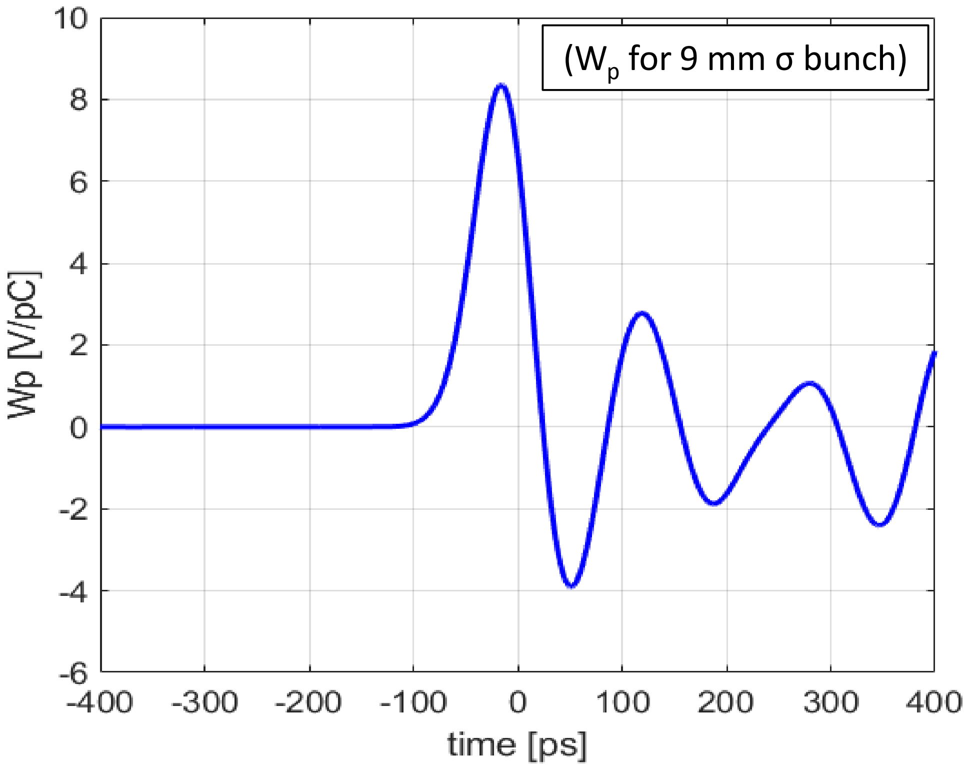
- The vacuum system as well as most of the components as tapers, BPMs etc are not finalized, and still changes and optimizations are expected

- The kind of NEG material (dense versus columnar) and the thickness distribution require a precise characterisation (see slide 21)

Total Impedance for the Microwave Longitudinal Threshold Calculation

sls2_june2018_ele.lat





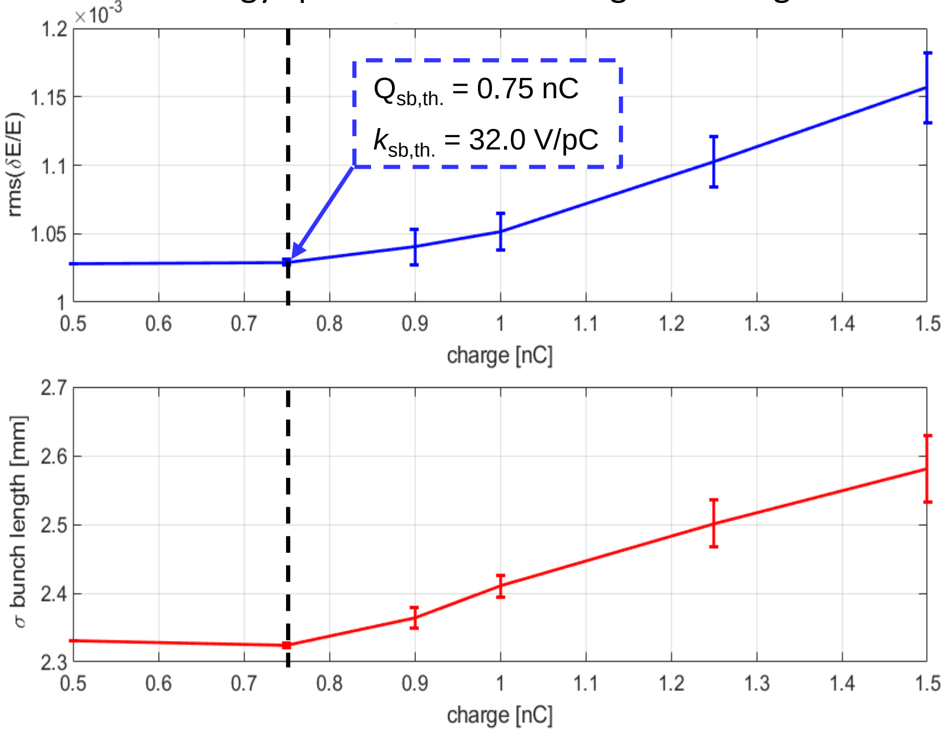
All the tracking simulations performed in **ELEGANT** for the threshold calculations refer to the **impedance computed in the frequency domain**. This impedance is computed looking to the short range wake analysis, then its validity is limited to the single bunch spectrum region, and not the bunch train.

For the tracking code **Mbtrack**, the approach followed to describe the impedance is mixed: part of the impedance is described as a **wake function** in time domain, and the remaining part as a **pure inductance L** in frequency domain.

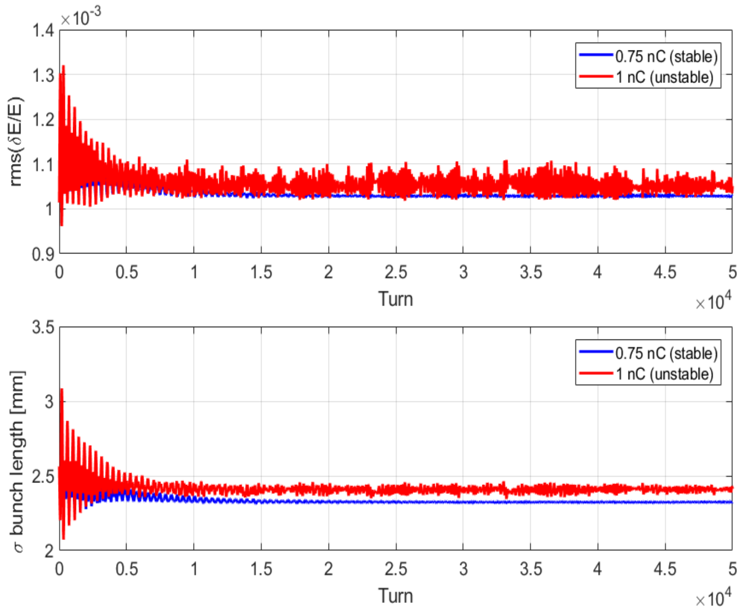
Longitudinal Single Bunch Simulations <u>Without</u> Harmonic Cavity: ELEGANT Results for MWI Threshold

sls2_june2018_ele.lat

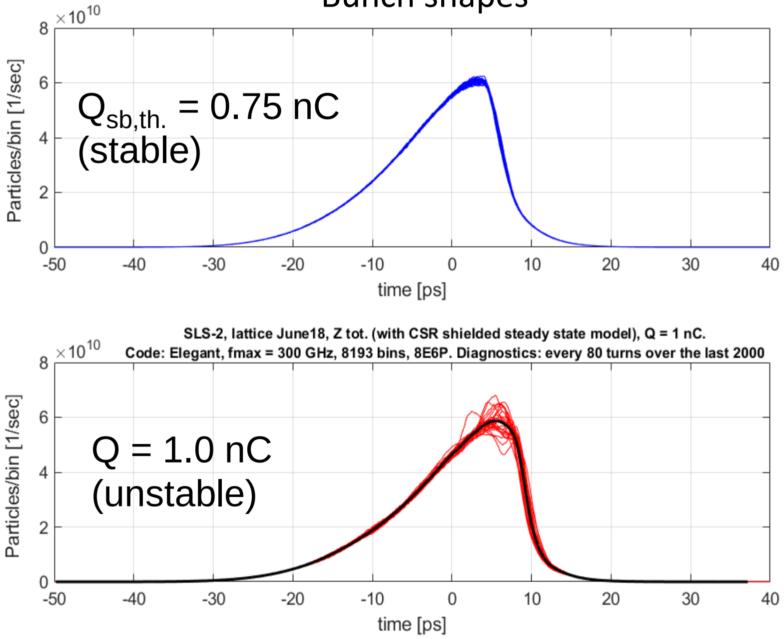
Energy spread and bunch length vs charge



Energy spread and bunch length vs turns



Bunch shapes



Criterion for threshold value:
Growth of the rms energy spread by 1% w.r.t. zero current value

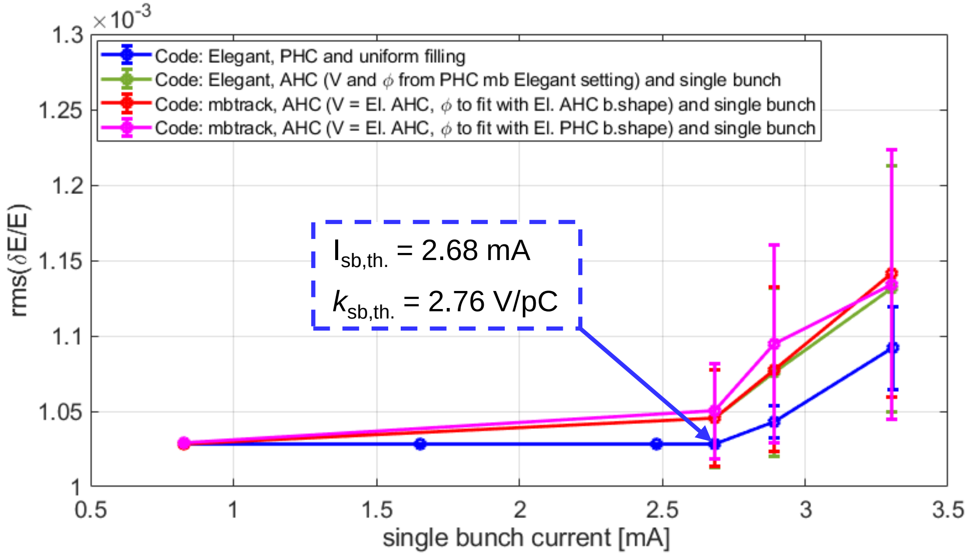
Operation: $Q_{sb,nom.}$ = 0.80 nC (400 mA, 484 buckets)

Threshold: $Q_{sb,th.}$ = 0.75 nC.

The **harmonic cavity is mandatory in SLS 2.0** for stable operations

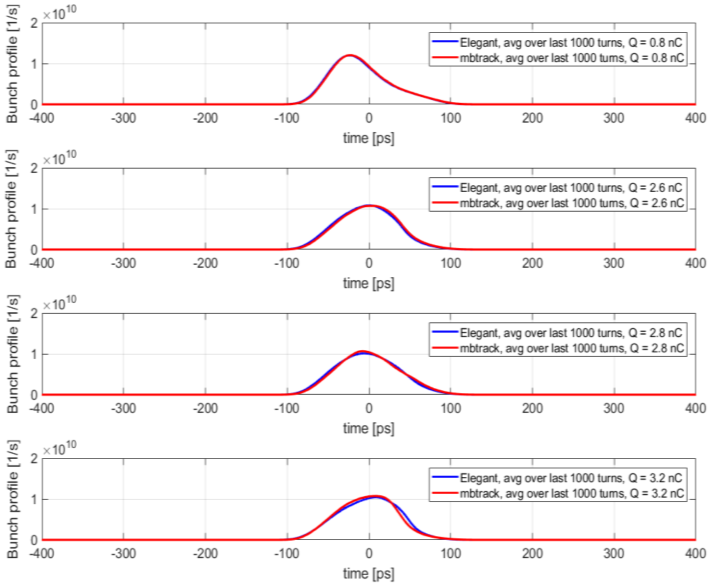
MW Longitudinal Simulations With the Harmonic Cavity: the Uniform Filling Pattern Comparison in ELEGANT and Mbtrack

Focusing on the **uniform filling pattern**, both ELEGANT and Mbtrack simulations are performed.
In particular, the initial multibunch ELEGANT simulation with uniform filling is compared with three sets of single bunch simulations using a dedicated Active Harmonic Cavity to reproduce the results of the simulated multibunch uniform filling case.

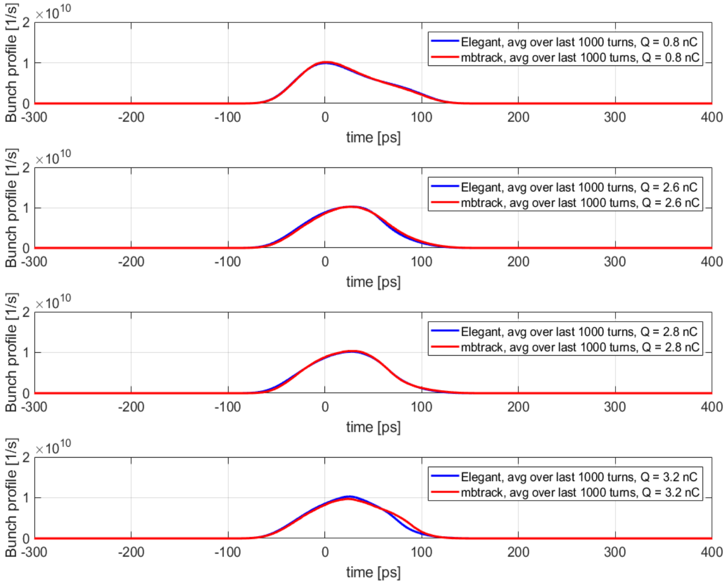


sls2_june2018_ele.lat

Elegant AHC single bunch vs Mbtrack AHC single bunch (setting 1)



Elegant PHC multibunch vs Mbtrack AHC single bunch (setting 2)



Set of tracking simulations:

1. **ELEGANT** multibunch (mb) with Passive Harmonic Cavity (PHC)
2. **ELEGANT** single bunch (sb) with Active Harmonic Cavity (AHC)
3. **Mbtrack** single bunch (sb) with Active Harmonic Cavity (AHC, **setting 1**)
4. **Mbtrack** single bunch (sb) with Active Harmonic Cavity (AHC, **setting 2**)

Operation: $I_{sb,nom.}$ = 0.83 mA (400 mA, 484 buckets)

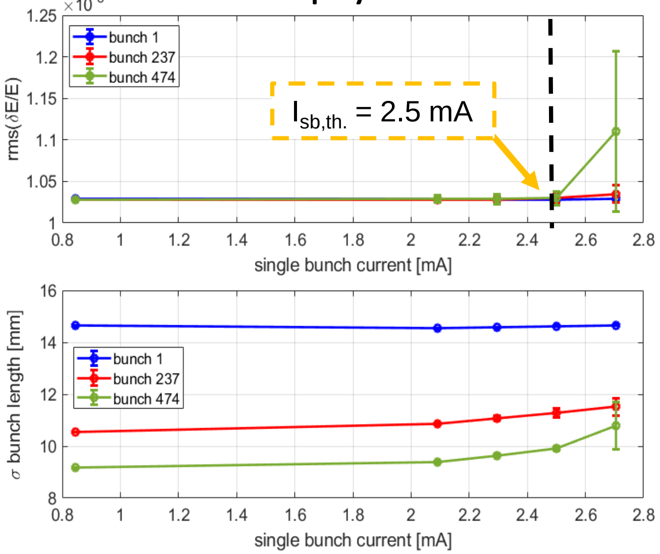
Threshold: $I_{sb,th.}$ = 2.68 mA = $\mathbf{I_{sb,nom.}}$ **× 3.23** .

Mbtrack Longitudinal Simulations With the Harmonic Cavity: the Filling Pattern With Gaps (Empty Buckets)

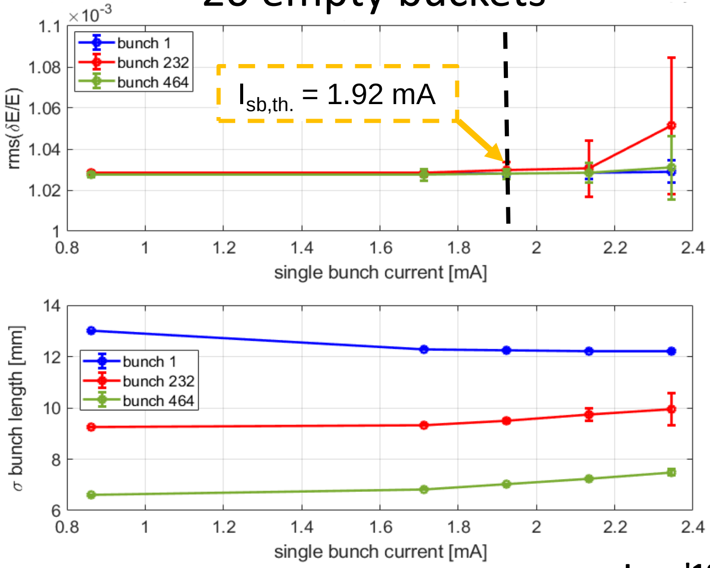
The **Mbtrack** code is used for these Passive Harmonic Cavity multibunch simulations because of the possibility provided by the code to vary the relative charge of the bunches.
Then, in order to keep constant the RF detuning parameters, the overall 400 mA beam current is not changed, and the scan in current is obtained just varying the relative charge of (typically) only three bunches - initial, middle and final – into the chosen pattern.
The transient effects assume operation with three RF cavities and using only 1 cell of the 3HC module (the other is detuned).

sls2_june2018_ele.lat

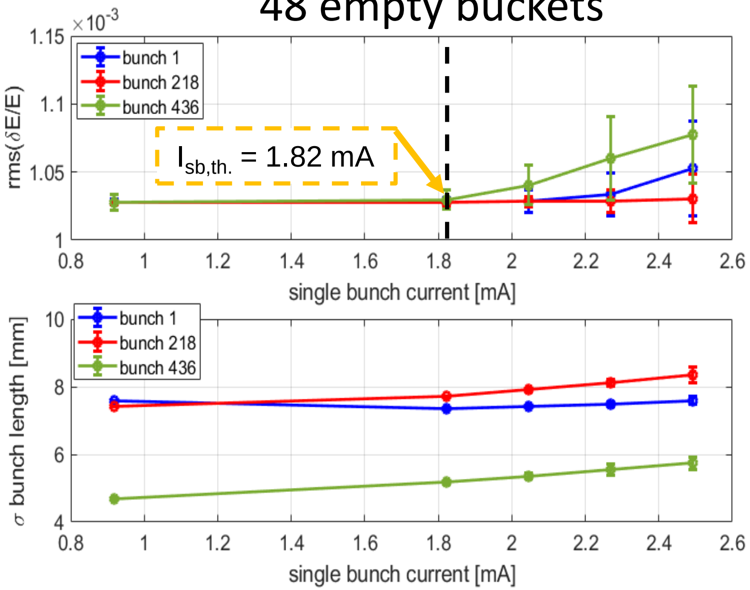
10 empty buckets



20 empty buckets



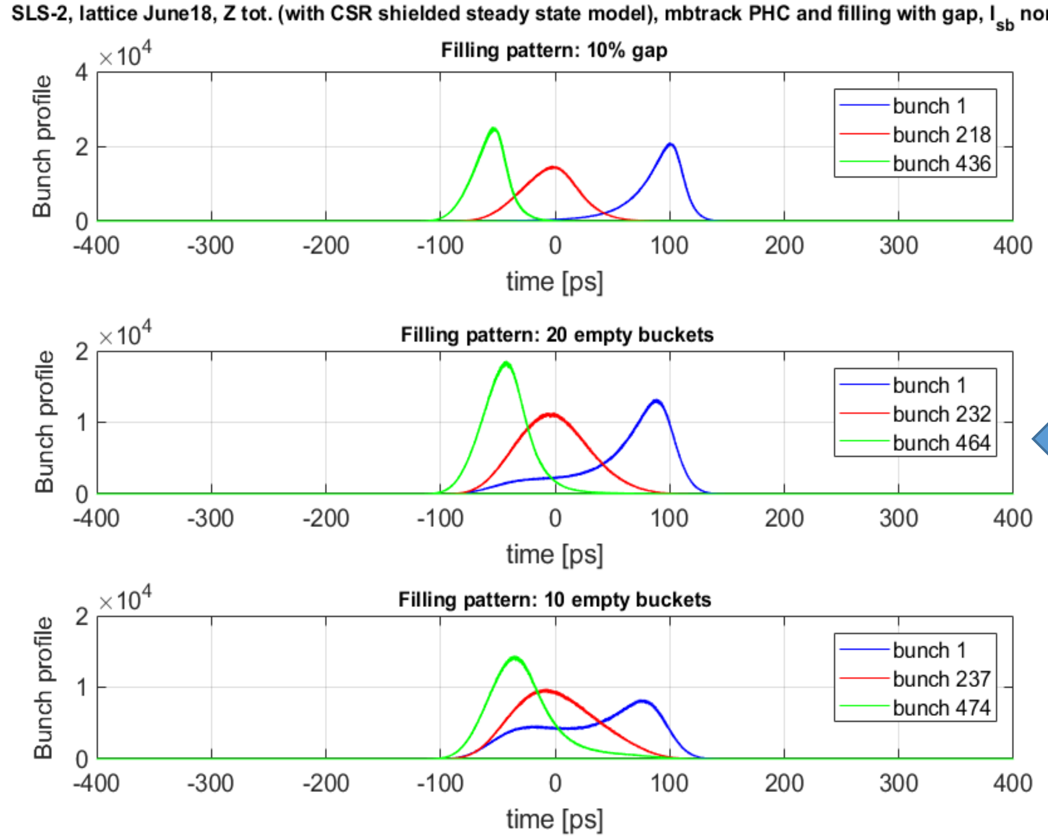
48 empty buckets

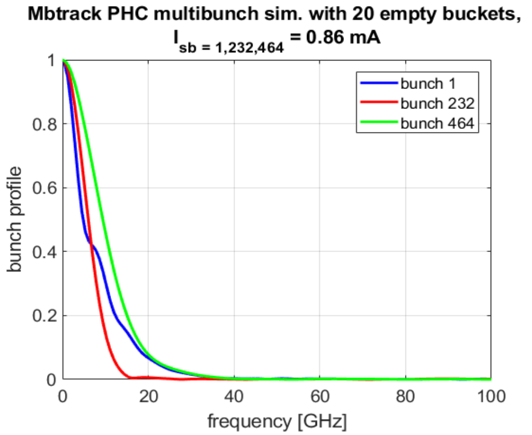


June '18 baseline

	Uniform filling	10 empty buckets	20 empty buckets	48 empty buckets (10% gap)
Nominal single bunch current $I_{sb,nom.}$ [mA]	0.83	0.84	**0.86**	0.92
Threshold single bunch current $I_{sb,th.}$ [mA]	2.68	2.5	**1.92**	1.82
Safety margin $I_{sb,th.}$ / $I_{sb,nom.}$	3.23	2.98	**2.25**	1.98

Mbtrack Longitudinal Simulations With the Harmonic Cavity: the Landau Cavity





sls2_june2018_ele.lat

- Harmonic cavity beneficial for thresholds due to longer bunch lengths.
- Ion clearing gap in fill pattern causes transient beam loading in both main RF and harmonic cavity.
- Transients reduce stretching of bunches in buckets near to gap.

- Minimize gap:
  assuming 20 buckets now
- Reduce beam loading in HC:
  use only one cell of std SLS 3HC.
- Reduce beam loading in main RF:
  operating with 3 cavities (SLS: 4).

Ion Clearing in SLS 2.0 for small Gaps in Bunch Train

Conclusions from the analysis about minimum gap:

1. Most effective ion clearing can be achieved by introducing a gap in the bunch pattern.
   For the operational parameters of SLS-2.0 of 400 mA beam current and 0.1 emittance coupling **full ion clearing is guaranteed with a gap in the bunch pattern of 10 empty buckets only**.

2. Having some random fluctuations in the bunch charges as they happen anyway in Top Up operations may allow even smaller gaps, less transient effects in the RF and so higher thresholds. **Currently**, we apply a safety margin of two and use a **gap size of 20** as a reference value

3. During the **initial operations phase** only lower beam currents can be stored which would require **larger gaps for beam clearing**.

Mbtrack Longitudinal Simulations With the Harmonic Cavity: Scan of Impedance Relevant Parameters for sls2_june2018_ele.lat

sls2_june2018_ele.lat
with impedance variations

Few baseline parameters are changed and the threshold behavior investigated:

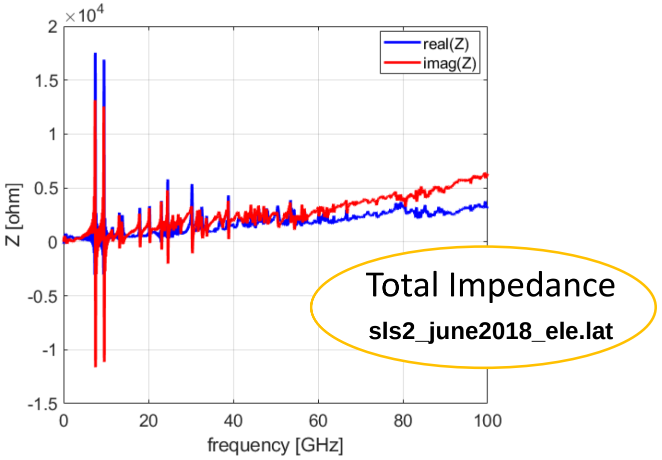
1. the thickness of the NEG coating (➡ changing in RW impedance),
2. the NEG conductivity (➡ changing in RW impedance),
3. the beam pipe diameter (➡ changing in RW impedance and CSR, tapers were kept the same),
4. n. of cells used of the HC (→ act on transient beam loading ➡ changing in RF detuning).

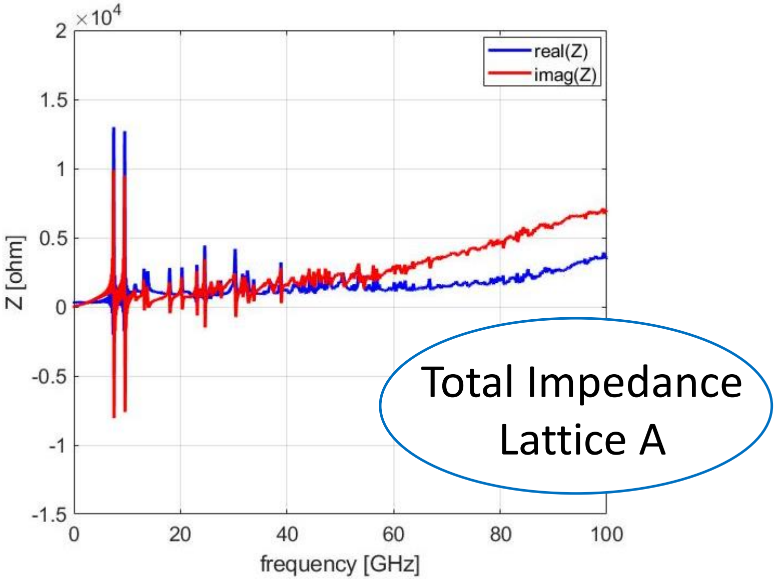
All the tracking simulations, performed in **Mbtrack** with Passive Harmonic Cavity, refer to the case of **20 empty buckets filling pattern**.

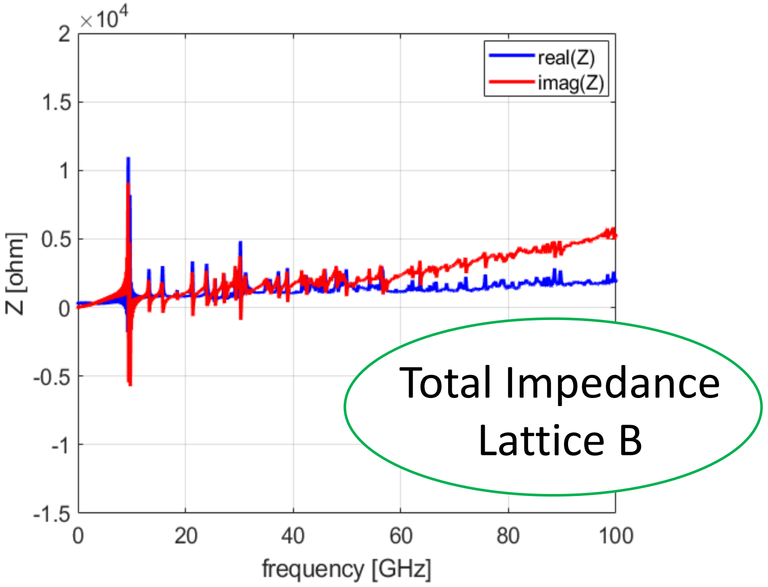
	NEG parameters & properties (20 mm diameter beam pipe)				**geometry**	**Harmonic cavity: n. of cells**
	No NEG coating	1 µm, bulk NEG coating	500 nm, columnar NEG coating	1 µm, columnar NEG coating	17 mm diameter beam pipe *(500 nm bulk NEG)*	2 cells, δf = -115 kHz
$I_{sb,th.}/I_{sb,nom.}$	2.85	1.75	2.25	1.5	2.25	2.25
Relative gain to sls2_june2018_ele.lat	**+27.6%**	**-22.2%**	0	**-32.8%**	0	0

($\sigma_{NEG,\ colum.}$ = 1.4 10^4 S/m) (like Lattice B) (1 HC cell → δf = -56 kHz)

MW Longitudinal Multibunch Simulations With Lattice A and B



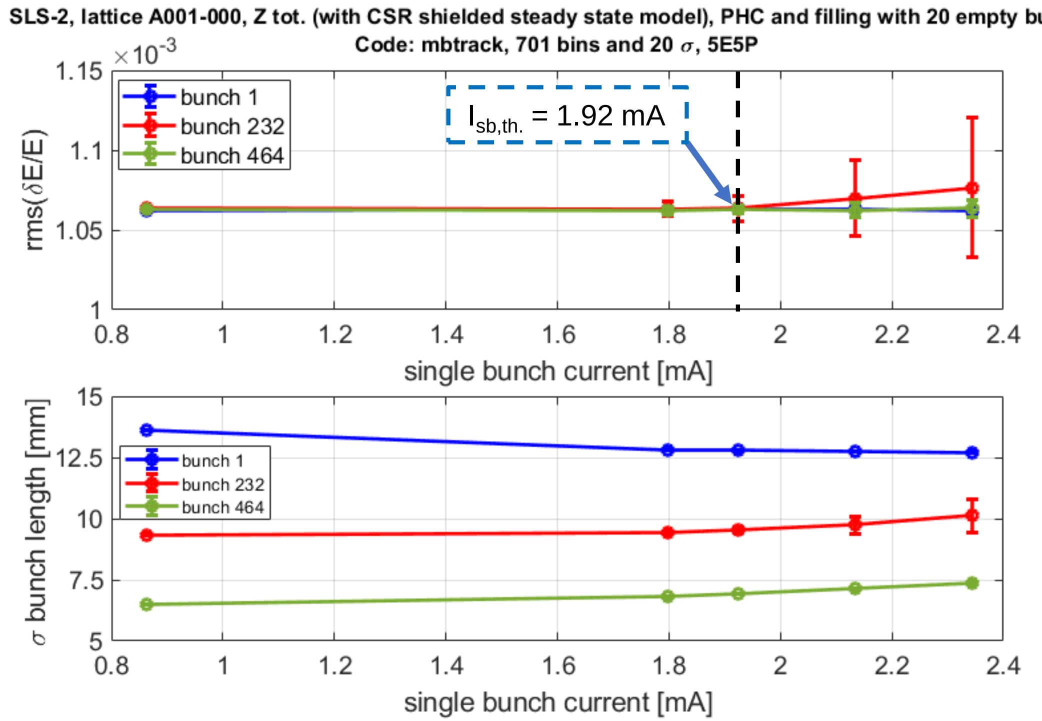




Impedances used in tracking simulations	**Design Lattice A**	**Design Lattice B**
Resistive wall beam pipe (circular cross section)	• L_{tot} = 290.4 - 12 (ID1) -23.2 (ID2) [m], Diameter = 20 [mm] • Copper with 500 nm columnar NEG coating	• L_{tot} = 288 - 12 (ID1) -33.2 (ID2) [m], Diameter = 17 [mm] • Copper with 500 nm columnar NEG coating
Resistive wall insertion device ID1 (planar cross section)	• L_{tot} = 12 [m], Gap = 4 [mm] • Copper	• L_{tot} = 12 [m], Gap = 4 [mm] • Copper
Resistive wall insertion device ID2 (elliptical cross section)	• L_{tot} = 23.2 [m], Minor axis = 8 [mm], Major axis = 15 [mm] • Copper with 500 nm columnar NEG coating	• L_{tot} = 33.2 [m], Minor axis = 8 [mm], Major axis = 15 [mm] • Copper with 500 nm columnar NEG coating
Tapers for insertion devices (ID1 and ID2)	• N_{tot} = 12 (for ID1) + 22 (for ID2) linear tapers, L_{taper} = 100 [mm]	• N_{tot} = 12 (for ID1) + 22 (for ID2) linear tapers, L_{taper} = 100 [mm]
Coherent Synchrotron Radiation	• Infinite parallel plates, steady state regime • Gap = 20 [mm]	• Infinite parallel plates, steady state regime • Gap = 17 [mm]
Beam Position Monitors	• N_{tot} = 108	• N_{tot} = 111
500 MHz Cavities	• N_{tot} = 1+1+1 • Linear tapers 100 [mm] long for the beam pipe transition	• N_{tot} = 2+1 • Linear tapers 100 [mm] long for the beam pipe transition
Harmonic Cavity	• As in SLS, but with linear tapers 100 [mm] long for the beam pipe transition	• As in SLS, but with linear tapers 100 [mm] long for the beam pipe transition

	sls2_june2018_ele.lat	Lattice A
Filling pattern	20 empty buckets	20 empty buckets
Nominal single bunch current $I_{sb,nom.}$ [mA]	0.86	0.86
Threshold single bunch current $I_{sb,th.}$ [mA]	1.92	1.92
Safety margin $I_{sb,th.}$ / $I_{sb,nom.}$	2.25	2.25

≈ same safety margin



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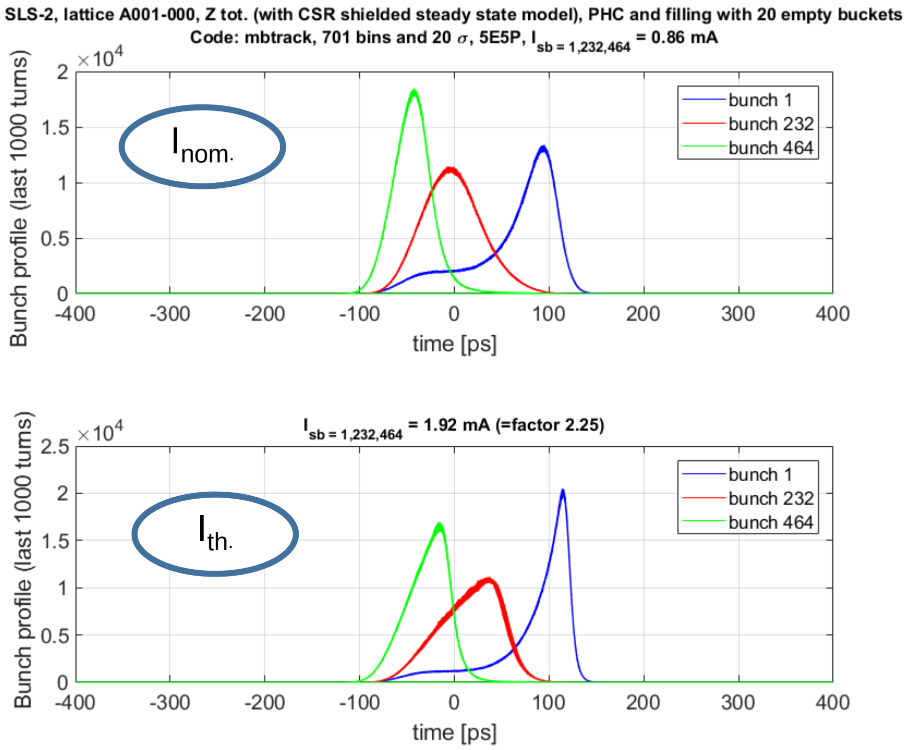
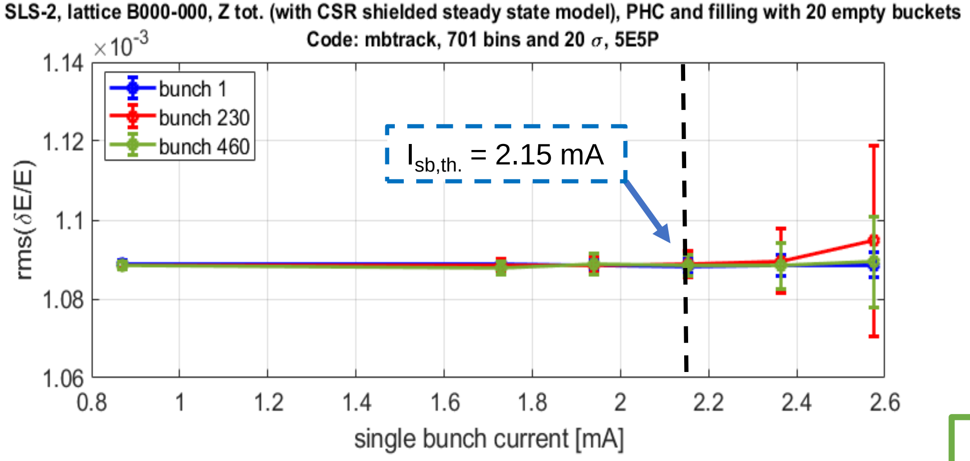
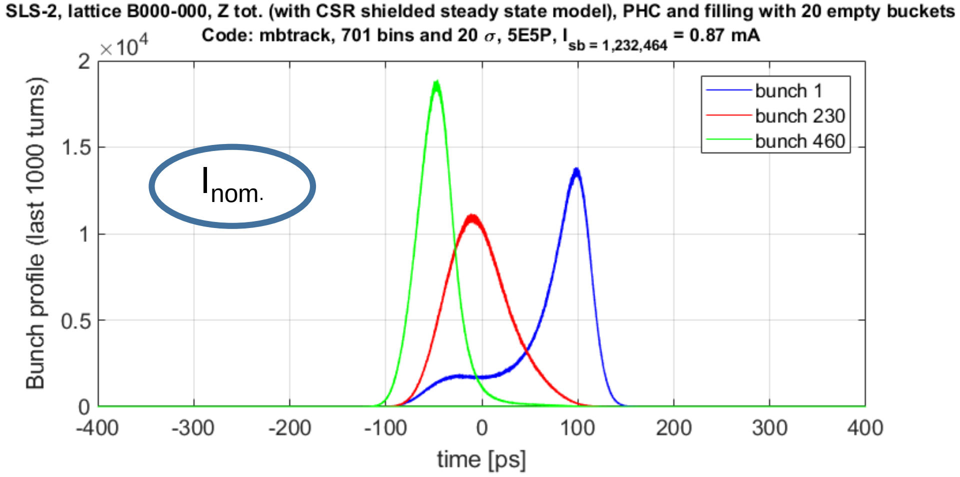


	sls2_june2018_ele.lat	Lattice B
Filling pattern	20 empty buckets	20 empty buckets
Nominal single bunch current $I_{sb,nom.}$ [mA]	0.86	0.87
Threshold single bunch current $I_{sb,th.}$ [mA]	1.92	2.15
Safety margin $I_{sb,th.} / I_{sb,nom.}$	2.25	2.5

≈ +11% in safety margin in Lattice B





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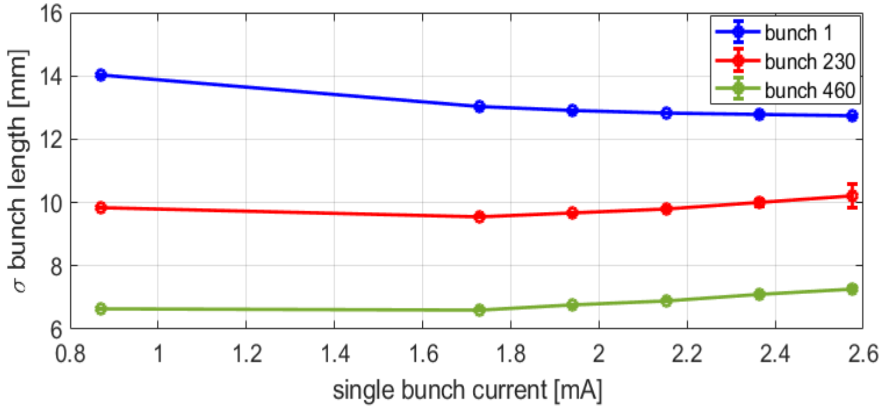
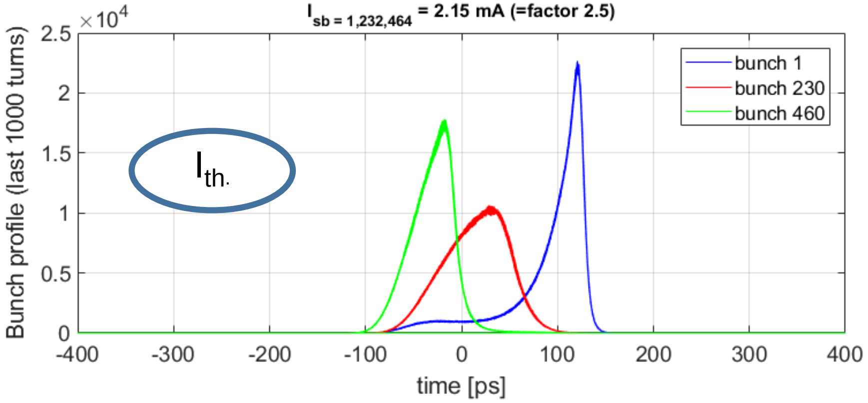
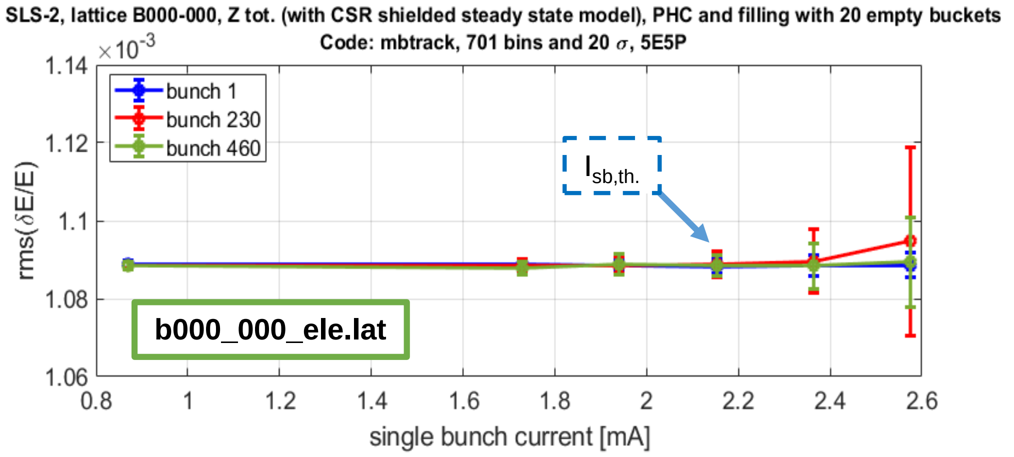
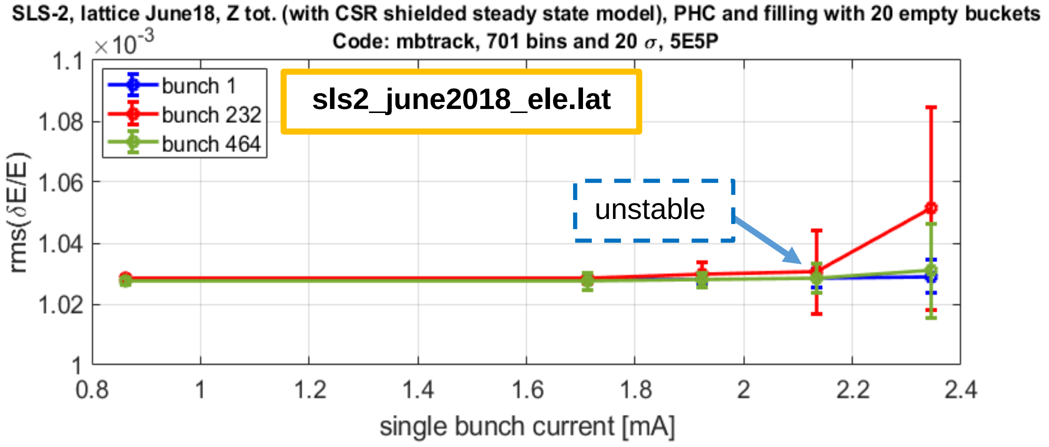








Because the two global impedances are pretty similar (slide 14), is it possible to change the threshold of Lattice B into the first unstable point of sls2_june2018_ele.lat just varying few Lattice B parameters ?

Possible candidates: rms(δE/E), α_c

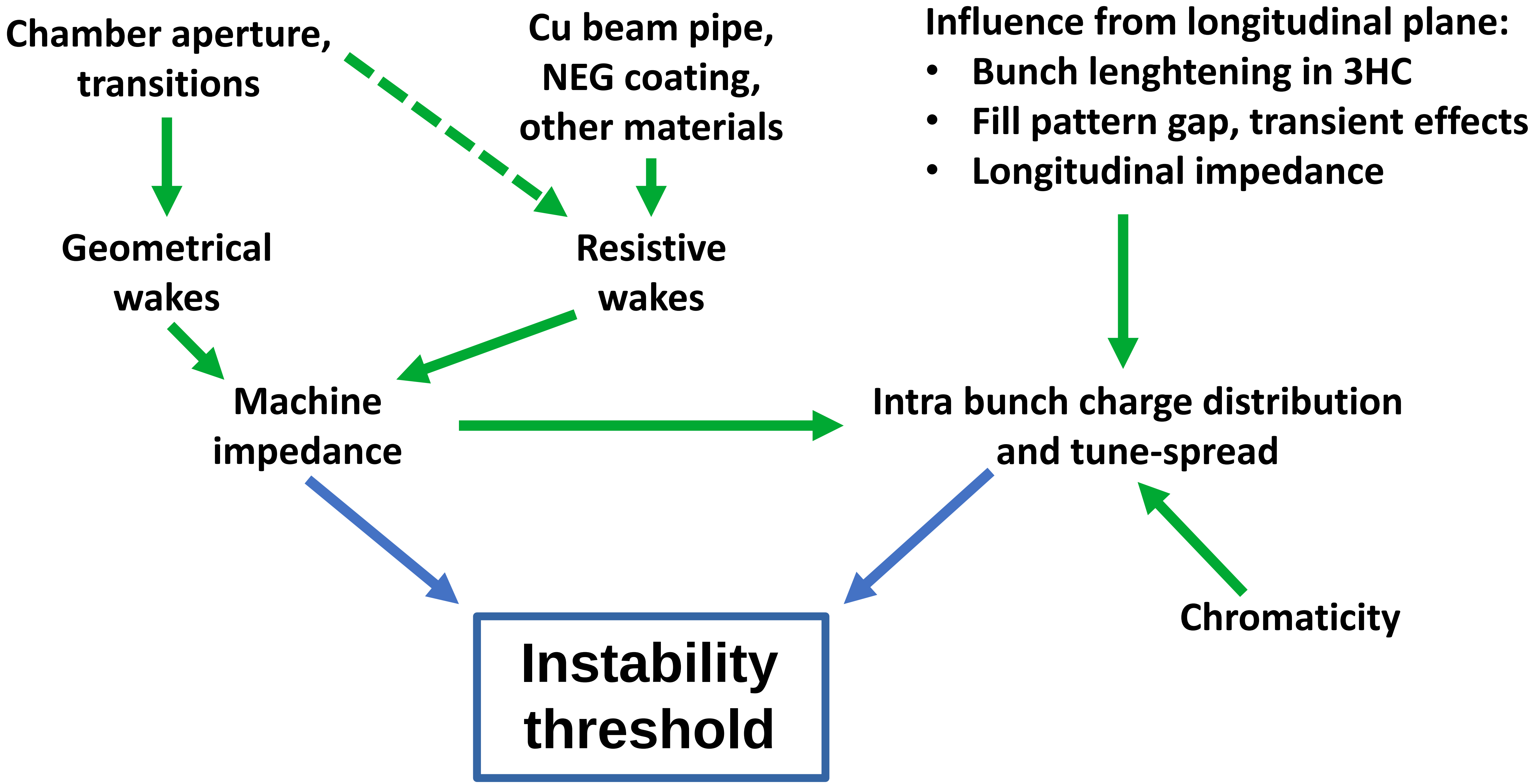
	sls2_june2018_ele.lat	Lattice B b000_000_ele.lat
Circumference [m]	290.400165	288.0002
Beam pipe diameter [mm]	20	17
Momentum compaction	$-1.279883\ 10^{-4}$	$-1.222724\ 10^{-4}$
Radiated energy/turn [keV]	529.7455	605.9442
Natural energy spread	$1.027936\ 10^{-3}$	$1.088449\ 10^{-3}$
Damping time E [ms]	7.105005	6.107259

Relative amplitude oscillations of rms(δE/E) at I_{sb} = 2.15 mA

Lattice	Bunch n. 1	Bunch n. 230	Bunch n. 460
Lattice B	0.17%	0.31%	0.24%
Lattice B, with rms(δE/E) from sls2_june2018_ele.lat	0.25%	1.63%	0.65%
Lattice B, with rms(δE/E), α_c from sls2_june2018_ele.lat	0.22%	0.67%	0.42%

Tendencies confirm the Boussard criterion

Interdependencies of Effects with respect to Transverse Microwave Threshold

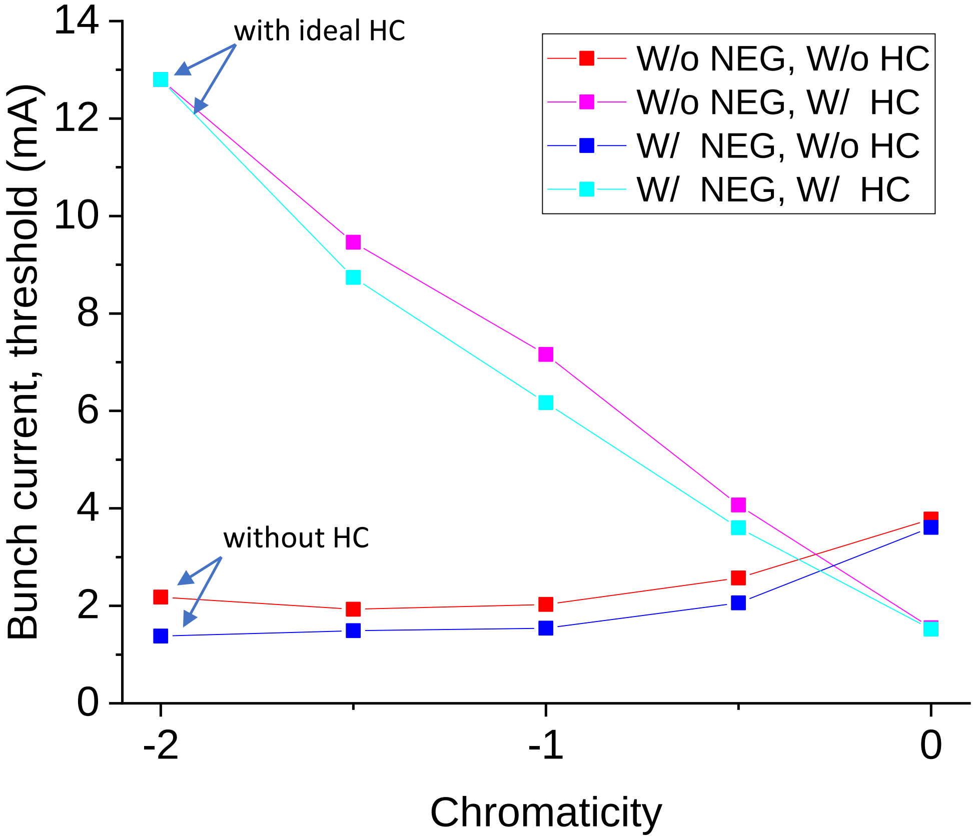


Transverse Single Bunch Effects: ELEGANT with Analytic RW Wakes

sls2_june2018_ele.lat
with impedance variations

Lattice September 2018	Design
Beam energy [GeV]	2.4
Circumference [m]	290.4
β_y average [m]	4.09
β_y at straight [m]	3.5
Synchrotron tune	0.0023 (V_{RF} = 1.4 MV)
Bunch length w/o HC [mm]	2.68
Vertical damping time [ms]	8.7
ID length [m]	12/20
ID gap [mm]	4/7.5
Chamber diameter[mm]	20

basic model:
resistive losses in the beam pipe, comparing the uncoated copper tube to a coated one with 500 nm NEG (excluding the insertion devices)

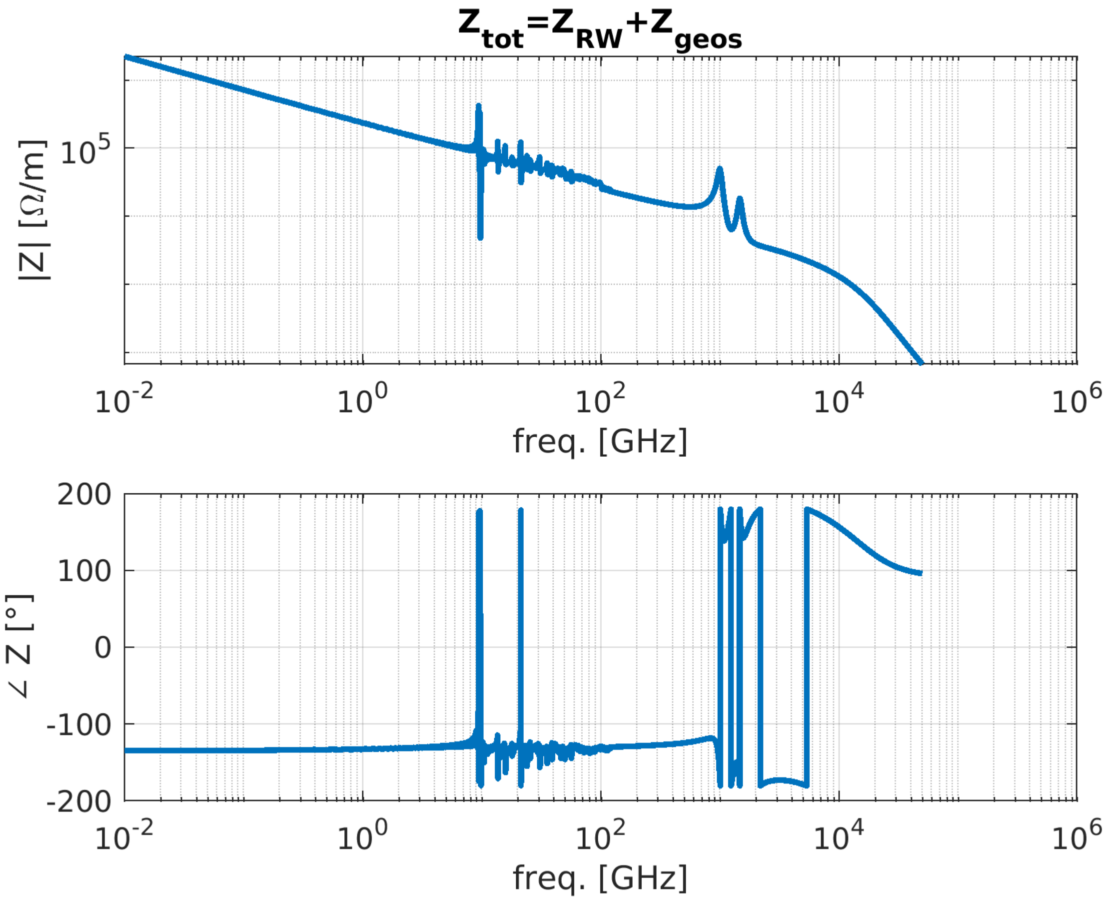


- **First approach**: no radiation damping is included in the tracking, and the growth rate from tracking is compared to the radiation damping rate determined by the lattice.
- **Without HC**, the threshold is rather insensitive to the chromaticity.
- **With** the deformation of the potential well by **HC**, threshold can be controlled.
- **Positive alpha** was also examined and it gives almost identical results with positive chromaticity.

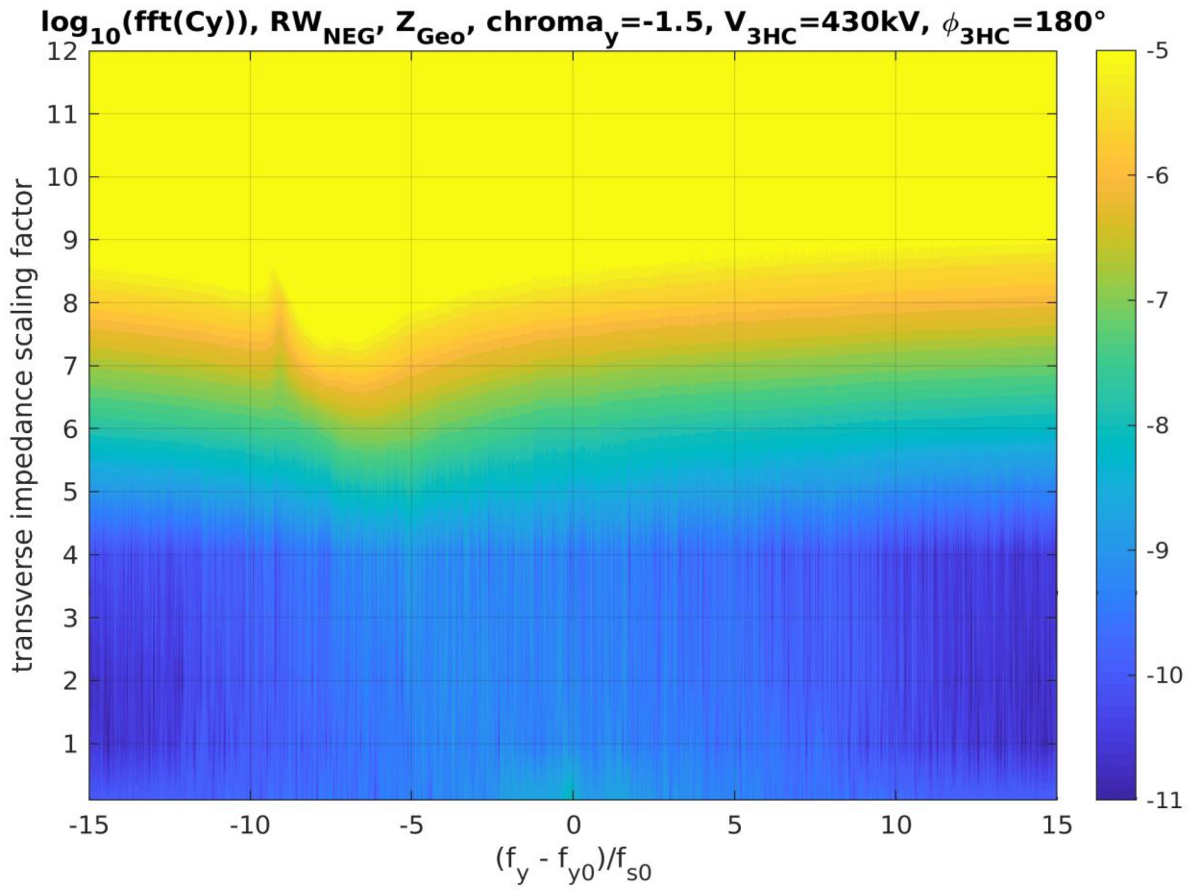
Preliminary Vertical Single Bunch Stability Analysis for Lattice B

b000_000_ele.lat

Single Turn Vertical Impedance ($\beta_{ref,y}$ = 13.38 m):



Vertical Oscillation Spectrum, for almost ideally lenghtened bunch:



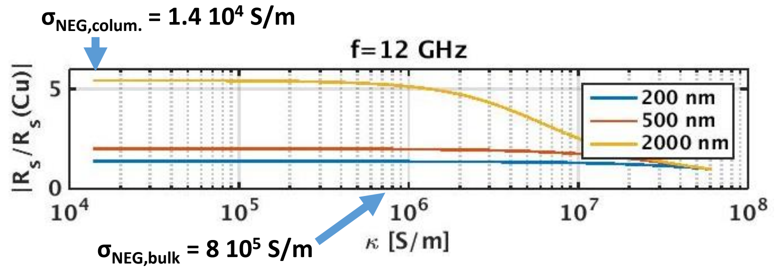
- Impedance budget → see slide 18.
- Remark: RF Cavity impedances are not included in this analysis.

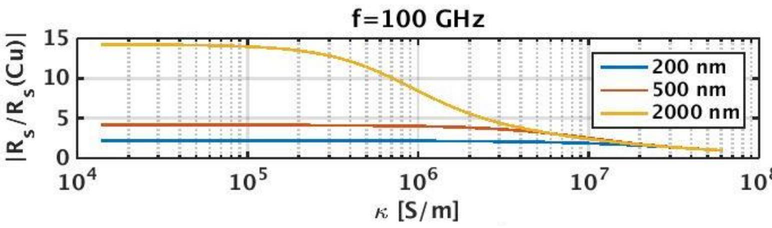
- fft(Cy) = fourier of vertical diplacement of the bunch centroid
- No unstable oscillation mode are visible

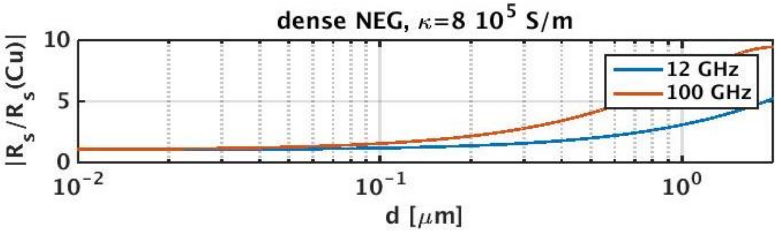
Characterization of NEG Coatings for SLS 2.0 (presented as poster at IPAC19, M.Dehler *et al.*)

Small aperture beam pipe (17-20 mm):

- Challenge vacuum conductance: using fully Ti-Zr-V NEG coated chamber,
- Challenge machine impedance contribution from resistive wall effects, exacerbated by low conductivity of NEG layers,
- Motivation for thin coatings (200-500 nm), electrical characterization to test fabrication process, material properties,



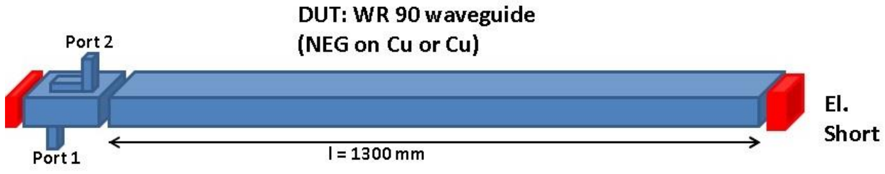


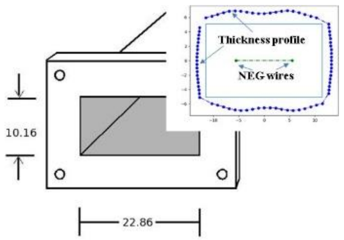


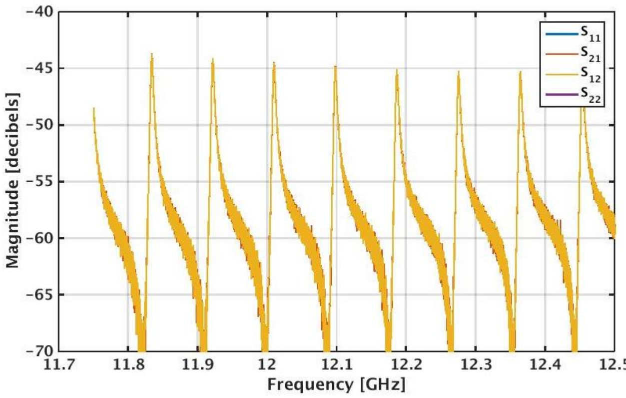
two measurement aproaches

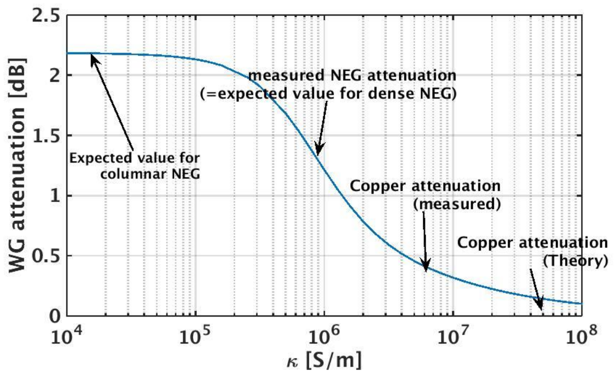
1. Measurement in X band region (12 GHz)

- It allows to test geometries similar to SLS 2.0 chamber (chamber cutoff !!)
- Sensitive only for coatings > 2 µm



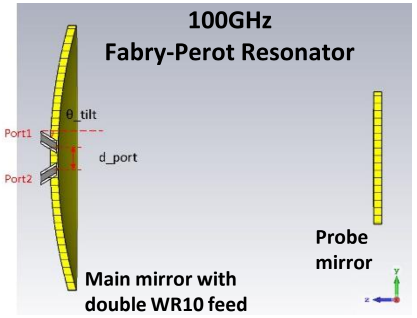


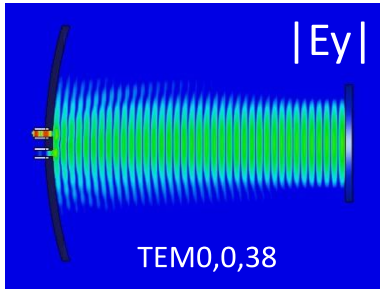


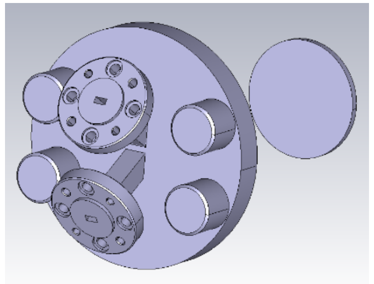


2. Measurement using mm waves (100 GHz)

- only possible for small test samples (e.g. plates)
- only option to characterize super thin coatings in the sub micron range as required for SLS 2.0

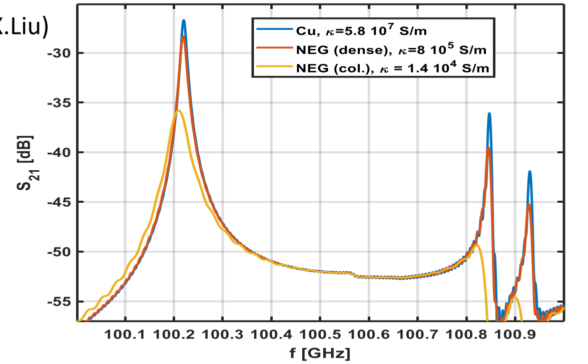






(court. of X.Liu)

Technical specifications	
mirror separation	60 mm
curvature spherical mirror	83.7 mm
Ø spherical mirror	48 mm
Ø planar probe	24 mm
coupling	WR10 tilted at 30°
loaded Q (spherical mirror in Cu)	
Copper probe ($\kappa = 5.8 \cdot 10^7 S/m$)	8489
dense NEG ($\kappa = 8 \cdot 10^5 S/m$)	6967
column. NEG ($\kappa = 1.4 \cdot 10^4 S/m$)	2657



SLS 1: Validation of Simulation Model for MWI on Running Machine

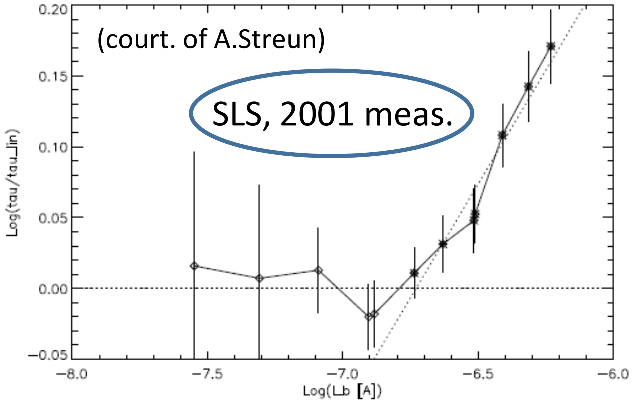
To better estimate the required margin of safety between theoretical calculated thresholds, we are currently working on an experimental validation using the existing SLS, setting up an impedance model of the accelerator as it is now, which will be used to calculate thresholds, subsequently to be validated with beam at the accelerator.

Proposed strategy:
Observation of lifetime for high single bunch currents may provide information on bunch lengthening thresholds and the impedance involved.

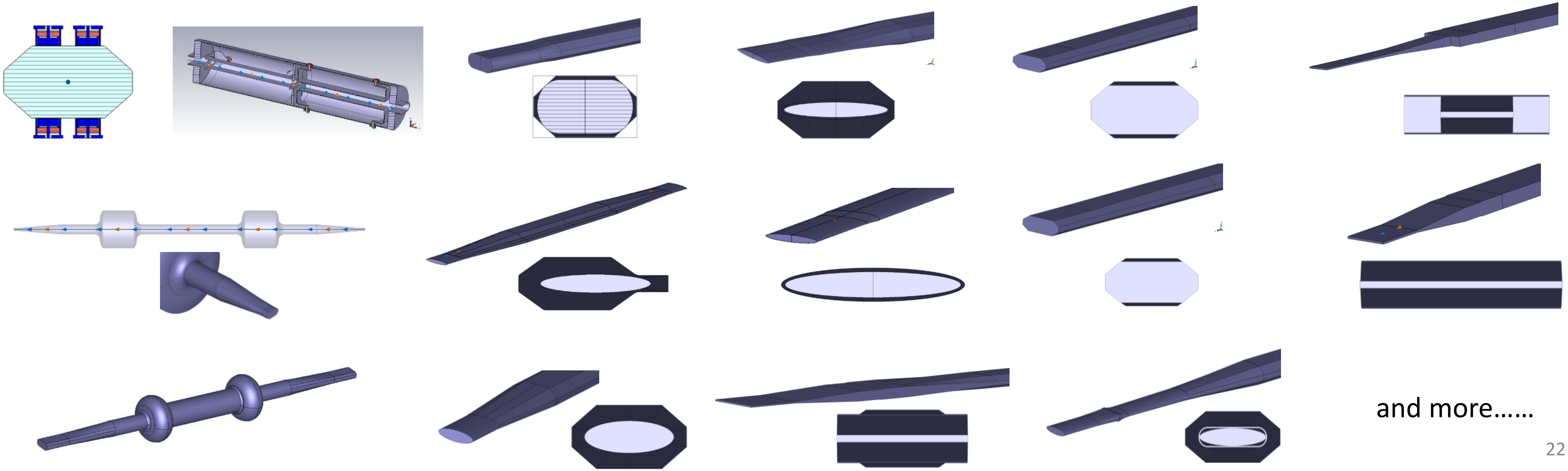
TBL equation

$$\ln x = \underbrace{A \ln \left(K \left| \frac{Z_\parallel}{n} \right|_o^{\mathrm{bb}} \right)}_{B} + A \ln I_b$$

x = bunch lengthening parameter (ratio of Touscheck lifetime to linear fitted lifetime)



Impedance budget, currently on going:



Conclusions and Outlook

	Uniform filling	10 empty buckets	**20 empty buckets**	48 empty buckets (10% gap)
Nominal single bunch current $I_{sb,nom.}$ [mA]	0.83	0.84	0.86	0.92
Threshold single bunch current $I_{sb,th.}$ [mA]	2.68	2.5	**1.92**	1.82
Safety margin $I_{sb,th.}$ / $I_{sb,nom.}$	3.23	2.98	**2.25**	1.98

sls2_june2018_ele.lat

- Gap size of 20 buckets as reference value
- Margin of safety of two is satisfied

	NEG parameters & properties (20 mm diameter beam pipe)				**geometry**	**Harmonic cavity: n. of cells**
	No NEG coating	1 µm, bulk NEG coating	500 nm, columnar NEG coating	1 µm, columnar NEG coating	17 mm diameter beam pipe	2 cells, δf = -115 kHz
Safety margin $I_{sb,th.}$ /$I_{sb,nom.}$	2.85	1.75	2.25	1.5	2.25	2.25
Relative gain to the baseline	**+27.6%**	**-22.2%**	0	**-32.8%**	0	0

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with impedance variations

NEG thickness is an important issue

	sls2_june2018_ele.lat	**Lattice A**	**Lattice B**
Filling pattern	20 empty buckets	20 empty buckets	20 empty buckets
Nominal single bunch current $I_{sb,nom.}$ [mA]	0.86	0.86	0.87
Threshold single bunch current $I_{sb,th.}$ [mA]	1.92	**1.92**	**2.15**
Safety margin $I_{sb,th.}$ / $I_{sb,nom.}$	2.25	**2.25**	**2.5**

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Both Lattice A and B look feasible looking to the longitudinal impedance limitations. The final decision must take into account the details of the final design of SLS 2.0 !

- As a rule of thumb, **we assume to require a margin of safety of two between predicted and required threshold currents**. For the current baseline parameters as described above, this is fulfilled and **the accelerator is expected to run stable at nominal current**. **The harmonic cavity is mandatory** for both longitudinal and transverse instabilities.

- Since there is not yet a final design of the vacuum system**, we are using a kind of generic model of the machines**. This includes all components (e.g. tapers, BPMs etc), but it should be clear that the designs and their contributions to the machine impedance may still change.

- **The thickness of the NEG coating is an important issue**. Strong efforts are strongly suggested in order to **make the coating as transparent (= thin) as possible: we are now looking towards 200 nm NEG thickness** (vs 500 nm reference in the simulations). The chamber geometry is rather complex, bent longitudinally with antechamber and possibly tapering at the location of the superbends, so the NEG layer can be expected to vary quite a bit.
  A program of measurements of test pieces and samples is foreseen starting from the second half of 2019 for both thinner 2 µm and 200-500 nm coatings.

- A second important parameter for the threshold is the **size of the gap in the fill pattern**. A gap size of 10 buckets may be already sufficient for ion clearing. Having some random fluctuations in the bunch charges as they happen anyway in Top Up operations may allow even smaller gaps, less transient effects in the RF and so higher thresholds. **Currently, we use a gap size of 20 as a reference value**.

- The **good correspondence of the threshold curves and of the bunch shapes for ELEGANT and Mbtrack** prove the consistency of our approach both in terms of the impedance preparation and of the tracking calculations for the analysis of the longitudinal microwave instabilities.

- **An experimental validation is under way using SLS 1**, which, together with the results above and a refined impedance model, may allow to apply a smaller margin of safety for the calculated thresholds.
  Lot of efforts in impedance simulations and design cross-checking of SLS 1 !!!

- The **latest results** on impedances and instabilities have been presented at the IPAC19 conference in two posters:
  - M.Dehler *et al.*, “**Overview of collective effects at SLS 2.0**”,
  - M.Dehler *et al.*, “**Characterization of NEG coatings for SLS 2.0**”

Wir schaffen Wissen – heute für morgen

My thanks go to

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