ESRF | The European Synchrotron

Equilibrium Bunch Distributions With an Active 4th Harmonic Cavity

Lee Carver

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OVERVIEW

- EBS - a 4th generation light source without a harmonic cavity
- Overview of Simulation Tools
- Cavity Short Range Wake and Bunch Lengthening Factor
- Instability Characterisation in 16 bunch

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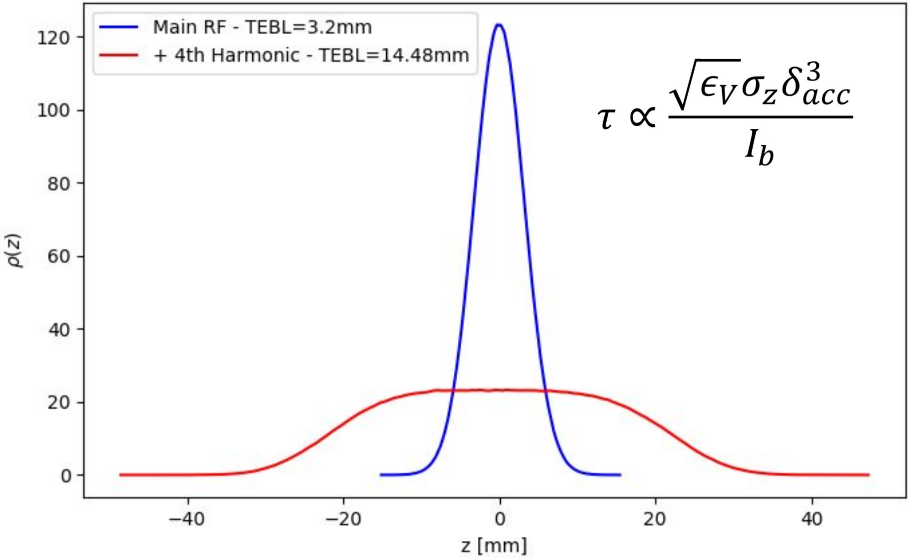
FORESEEN OPERATION IMPROVEMENTS

- **The ESRF plans to install a 4th harmonic cavity (1.4GHz) for bunch lengthening.**
- **2 main motivations:**
  - Allow an increase in lifetime in 16b mode (and then ultimately a reduction in vertical emittance)
  - Significantly increase the performance of uniform filling.
- **Active cavity is needed to allow bunch length manipulation with lower than maximum total current.**
- **ALBA-II proposes an active cavity, but not for high current per bunch modes.**
- **Only the ESRF and HEPS have plans for active cavities in filling modes with high current per bunch.**

Filling Mode	Lifetime [h]	ϵ_y [pm]
7/8 + 1 (200mA)	22	10
Uniform (200mA)	26	10
16b (75mA→92mA)	6	20
4b (40mA)	5	40



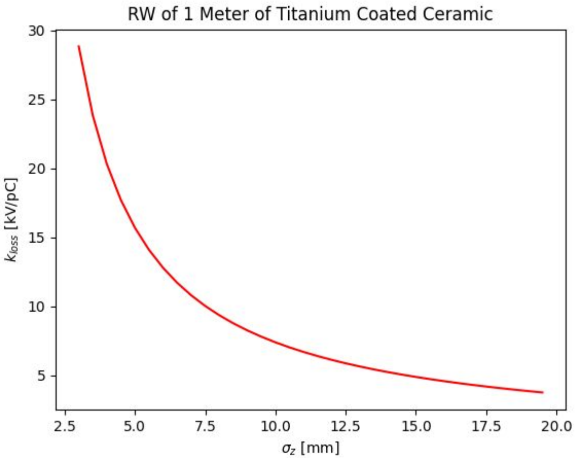
$$\tau \propto \frac{\sqrt{\epsilon_V}\sigma_z\delta_{acc}^3}{I_b}$$

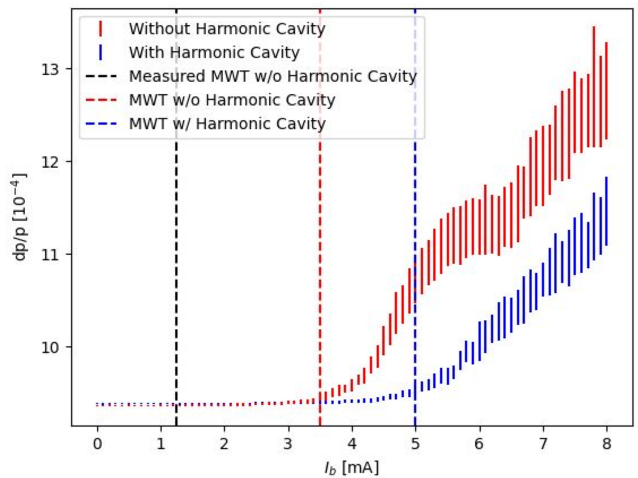
FORESEEN OPERATION IMPROVEMENTS - 16 BUNCH MODE

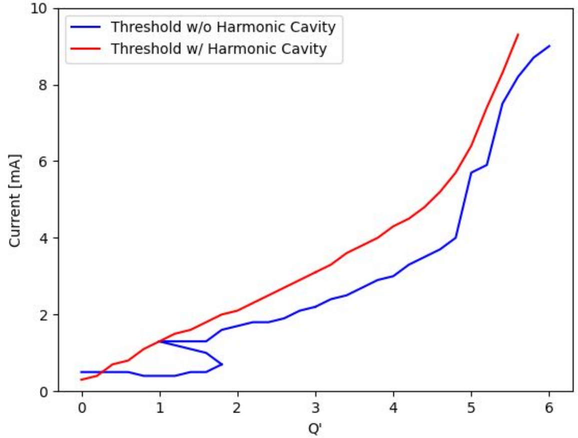
- **EBS ceramic kicker chambers had design flaw.**
  - Replacements and spares are ordered and awaiting delivery.
  - Temperature of the kickers must be kept low until the new chambers are ready for installation. HC would reduce the power deposition.

- **Measured lifetime is 6 hour at 75 mA with 20 pm vertical emittance.**
  - At 92mA with 10pm vertical emittance, we can expect ~3.5 hours (ignoring additional bunch lengthening from impedance)
  - HC will allow this lifetime to be recovered which will provide higher brilliance beam for the timing mode users

- **Increase of MWT would lower the energy spread which increases brilliance for higher harmonic beamlines.**







FORESEEN OPERATION IMPROVEMENTS - UNIFORM MODE

- **Performance in uniform mode is currently restrained.**

- **Lifetime is about 25 hours. Top-up is done every hour.**

- **We use high chromaticity optics for stability in 7/8+1 for stability of the single bunch at injection…but we keep these optics for uniform too.**
    - Only ~3 weeks of uniform mode per year.

- **IVU gaps are limited to 5mm due to unacceptable losses coming from HALO particles. Beamlines prefer to inject with gaps closer to avoid moving their undulators.**

- **With a harmonic cavity:**
    - Lifetime would be increased by a factor 4
    - Refills can be less frequent e.g. every 4 hours.
    - Scattering rate is reduced → fewer HALO particles → IVU gaps can be reduced

- **These are good motivations for more weeks of uniform mode.**
    - Different optics could then be used, lower Q' -> better damping of injection perturbations -> possibly taking us across the line for transparent injection (after the foreseen septum displacement).

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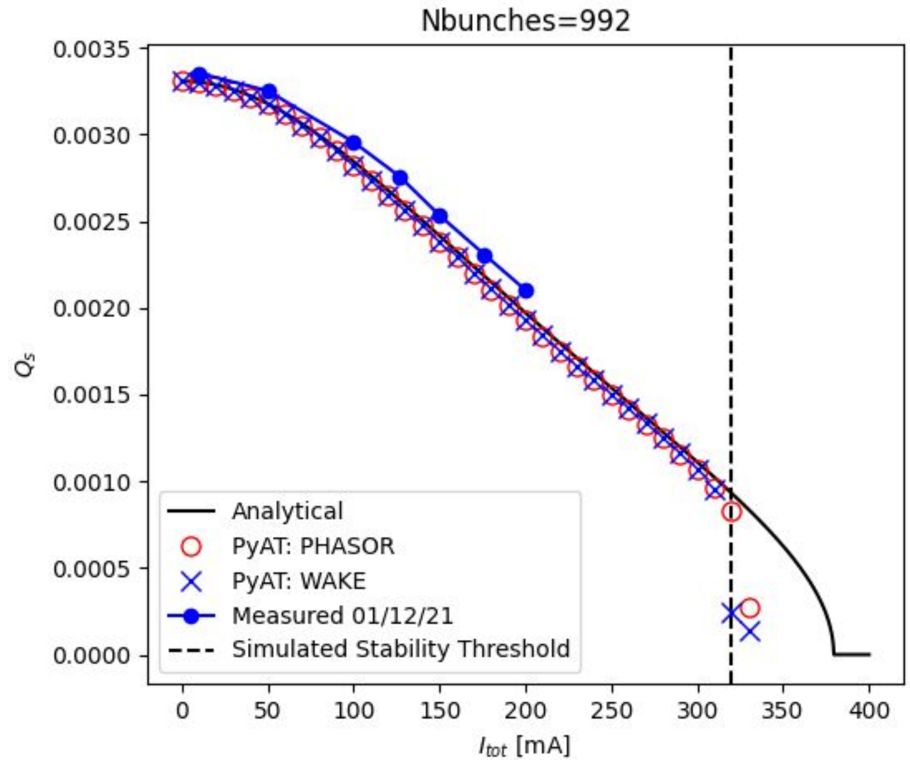
OVERVIEW OF SIMULATION TOOLS - PYAT

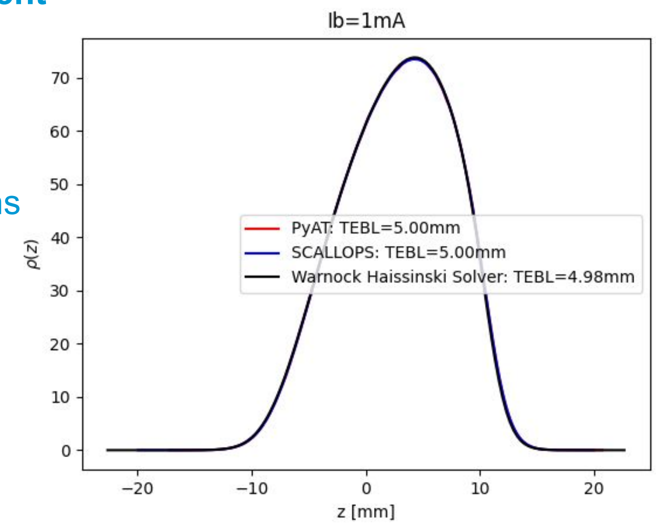
- **All tracking simulations done in PyAT.**
- **Fully self consistent, with significant flexibility on the complexity of the lattice you wish to track (simplified or full lattice).**
- **Multi-bunch collective effects including cavity beam loading has been added and benchmarked.**
- **For now, only one RF feedback model is implemented, more will follow.**



More details can be found in contributions at the AT workshop:
L.R. Carver, 'Collective Effects Development in AT'
T. Olsson, 'AT/Elegant for Harmonic Cavities'
Or on the AT github repository: https://github.com/atcollab/at

OVERVIEW OF SIMULATION TOOLS - SCALLOPS

- **We also developed a distribution solver specifically high current per bunch filling patterns - SCALLOPS (Solver to CALculate LOngitudinal ProfileS)..**
  - Define some fixed z positions around each filled bucket.
  - Define a starting distribution and populate slices.
  - Compute the beam induced voltage on each slice over Nturns (user defined).
  - Compute the Vgen and psi for beam loading compensation.
  - Sum all of the voltages (Vgen, Vbeam, Vwake)
  - Compute the potential and therefore the distribution for each bunch.
  - Recompute the beam induced voltage and iterate until convergence.
- **Provides an alternative to tracking and deeper insight, faster than tracking for few bunch filling…but it is not parallelised.**



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OVERVIEW OF ESRF PARAMETERS

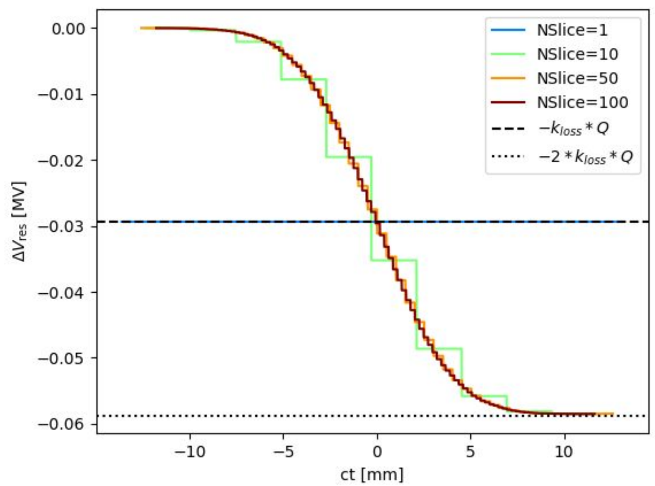
Ring Parameters	Value	Unit
Energy	6	GeV
L	843.977	m
α_c	8.85e-5	
Vrf	5.5	MV
U0	2.53	MeV/turn
h	992	
σ_e	9.3566e-4	
τ_z	3229	turns

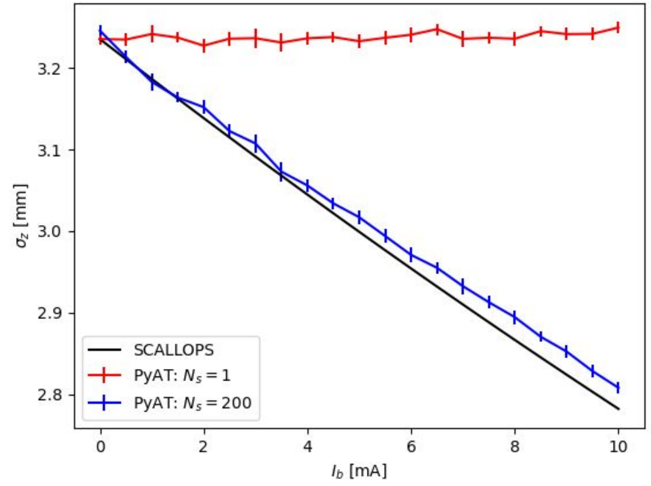
Main RF	Value	Unit
# Cavities	13	
Q0	37500	
beta	2.8	
R/Q per cavity (unloaded)	145	Ω

4th Harmonic	Value	Unit
# Cavities	4	
Q0	29735	
beta	1	
R/Q per cavity (unloaded)	86.8	Ω

CAVITY SHORT RANGE WAKE

- **When considering high current per bunch. The short range cavity wakefield can not be ignored.**
- **The top plot is the cumulative voltage experienced by a gaussian beam passing through a cavity resonator.**
- **This additional voltage provides a local modification to the slope of the total RF voltage and can modify the bunch lengthening.**
- **This is shown for a single bunch single mode case on the bottom plot.**
  - In this case the slope is increased, resulting in a shorter bunch.





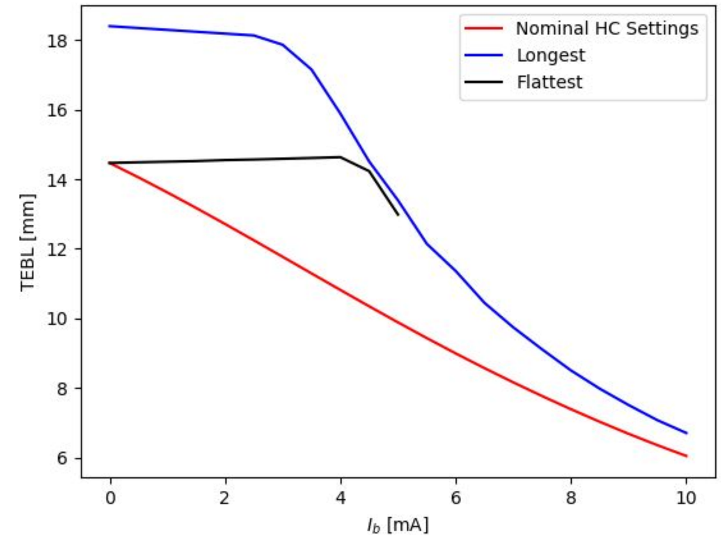
CAVITY SHORT RANGE WAKE WITH HARMONIC CAVITY - SINGLE BUNCH

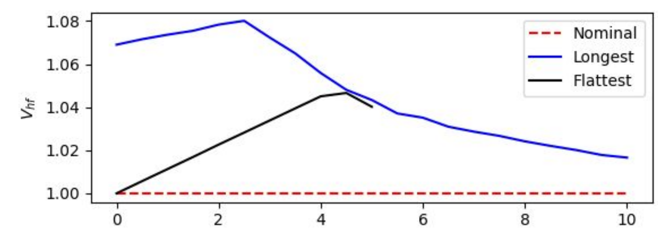
- **When including a harmonic cavity (for now with no machine wake), the additional short range harmonic cavity voltage also must be included.**
  - Predicting the distribution becomes tricky due to dependence on cumulative integral of distribution

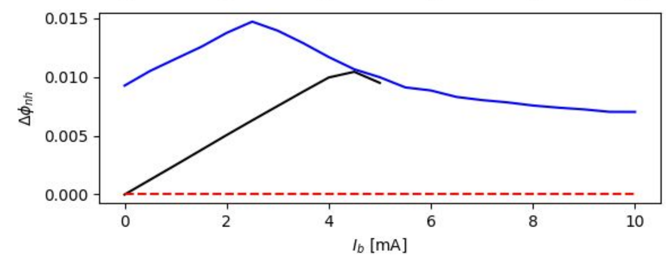
- **Simulation results still for only 1 single bunch (so very small beam loading effects).**

- **For each current, optimize the bunch length either for length (maximum possible) or flatness (minimize the difference between the flat potential distribution and the current distribution).**
  - Vhf is a multiplication factor applied to the HC voltage.
  - Δφnh is a phase shift applied to the HC phase.

- **By increasing the harmonic settings and shifting the phase, flat potential can be maintained up until a point.**
  - Beyond 4mA the flat potential and the longest distributions are the same.







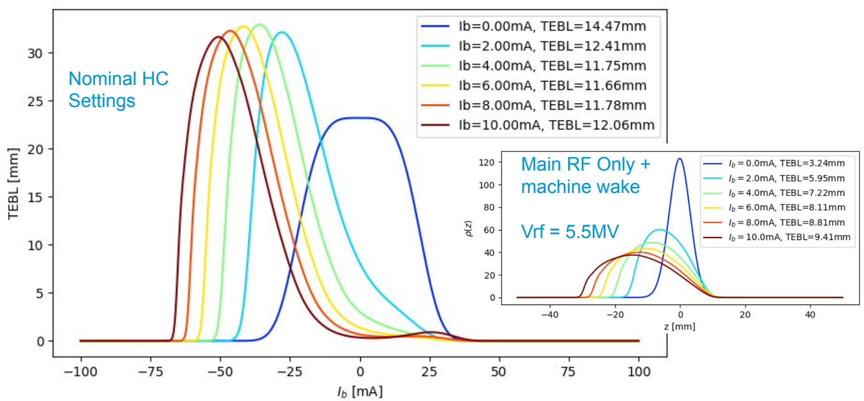
CAVITY SHORT RANGE WAKE WITH HARMONIC CAVITY AND MACHINE WAKE

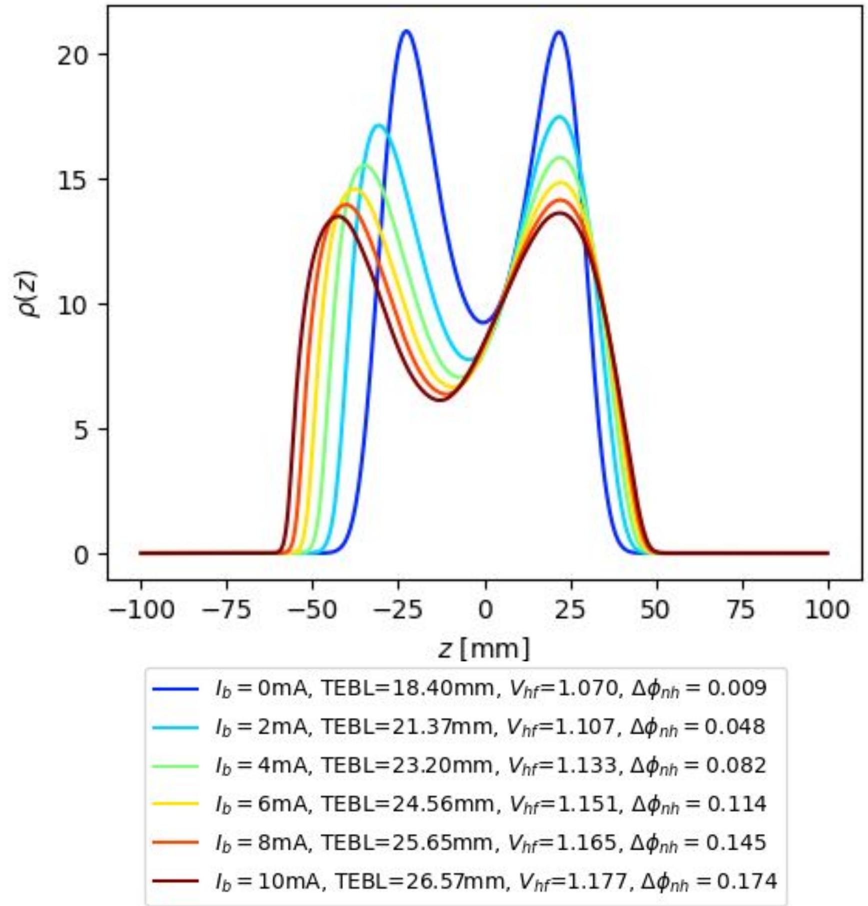
- **When machine wake is included, flat potential condition is non-existent.**

- **Most likely operational scenario: optimize for lifetime -> longest bunch length -> double bump profile.**
  - Can optimize for TEBL with a single bunch.

- **Below: bunch distributions with nominal harmonic voltage and phase with SR wake.**

- **Right: Each step optimized for maximum TEBL.**

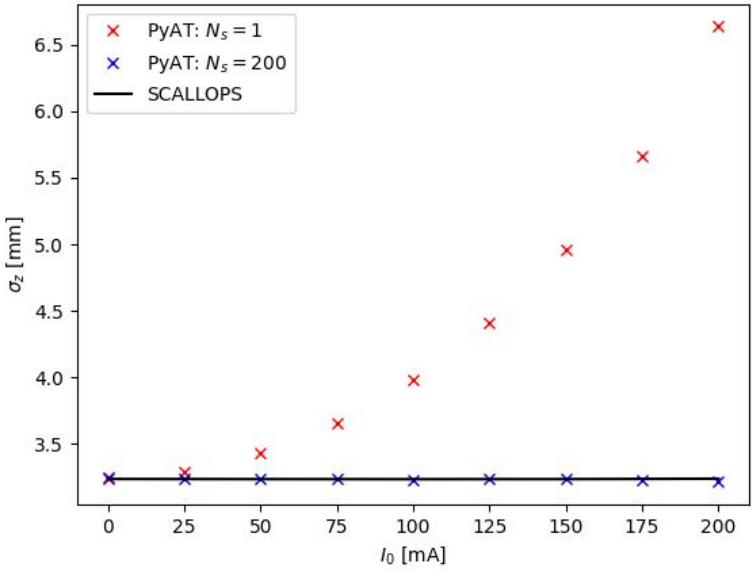


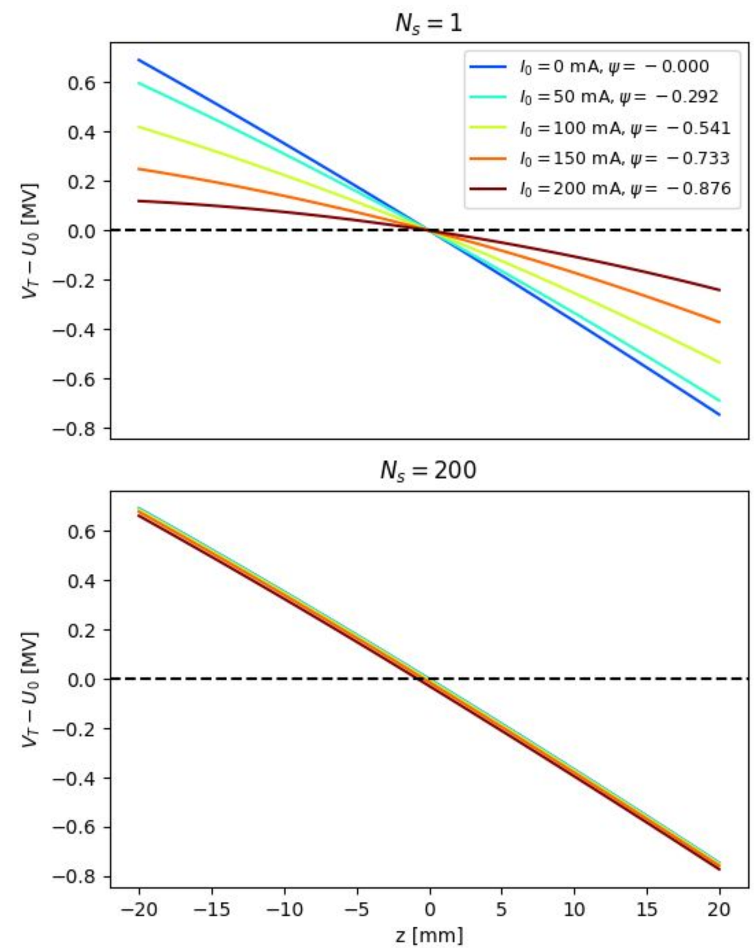


For optimum conditions with a single bunch 10mA, 18% more voltage is needed than for the flat potential condition.

EFFECT OF HIGH TOTAL CURRENT ON THE BUNCH DISTRIBUTION

- **What about the total current? We can return to a case of a single RF system.**
- **Right plot shows a current scan in uniform filling.**
- **If a simplified beam loading model is used with Nslice=1, the slope of the main RF is modified from the phase shift of Vgen.**





INTERIM CONCLUSIONS

- **When considering even moderate single bunch currents, the short range cavity wake degrades the bunch lengthening.**
  - Can be recovered with different HC settings, but only up to a certain point.
  - Of course, reducing the loss parameter k can help. [$k=\omega R_s / (2Q)$]

- **Simulation models that include only 1 slice for the whole bunch are not accurate when studying beam equilibrium profiles (but probably for Vbeam and psi comparisons it's ok).**

- **Studying equilibrium distributions can become quite challenging as stability becomes an issue when increasing the total current.**
  - Unfortunately, SCALLOPS is not a true Haissinski solver and therefore is susceptible to the same stability problems as with tracking.
  - Nonetheless we can characterise the instability we see in 16b mode, and then begin to discuss RF feedback models.

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INSTABILITY CHARACTERISATION

- **In 16 bunch mode, we are at the intersection between these two effects**
  - Current per bunch = 92mA/16 = 5.75mA
  - Total current = 92mA - Single RF System DC Robinson limit = 330mA.

- **Moderate current per bunch, moderate total current.**

- **Some tracking simulations have been made with PyAT to try and characterize the beam behaviour in 16 bunch mode.**

- **SCALLOPS is a useful tool for final distributions, and it does indeed have problems with convergence, but due to the way it is coded it is not really possible to extract details of the instability.**

SETUP FOR TRACKING SIMULATIONS

- **Full ring is lumped into several elements:**
  1 x main RF cavity,
  1 x harmonic RF cavity,
  1 x 6x6 linear map,
  1 x non-linear element (chromaticity and amplitude detuning),
  1 x lumped diffusion element.

- **RF cavities have a Proportional Feedback Loop with gain_voltage = gain_phase = 1e-4**
  - Gain needs to be kept low otherwise the RF voltage is too sensitive to beam centroid motion.

- **16 bunches with 48k particles per bunch, Nturns=100k with a current ramp of 10k turns.**

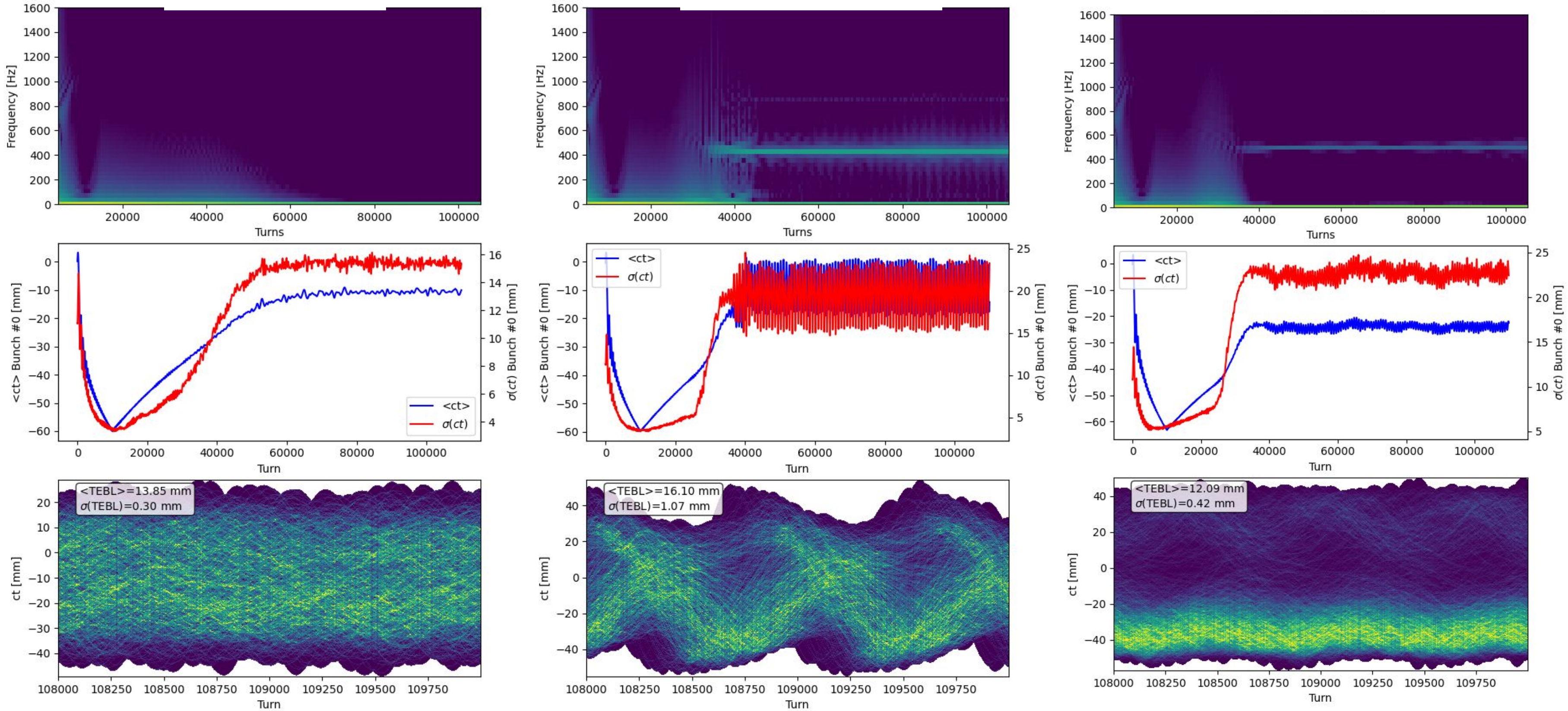
- **Nslice per bunch = 200 (but for interest I have also run with Nslice per bunch = 1)**

- **Nominal HC Voltage and Phase.**

- **Machine wake, when used, has had its short range fundamental cavity wake removed (due to the fact that the resonator itself will include it in the cavity beam loading).**

16 BUNCH ITOT=23mA

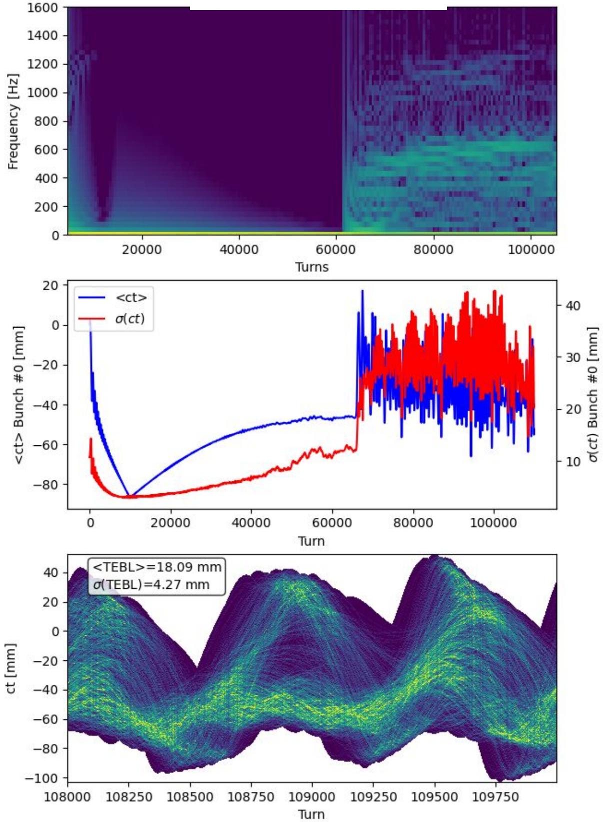
Nslice=1 | Nslice=200 | Nslice=200 + Machine Wake



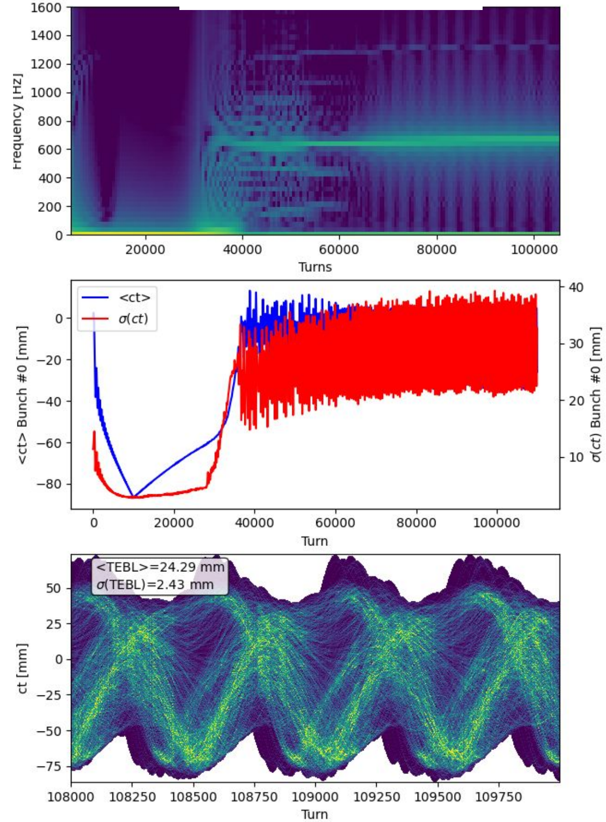
No losses seen at any point. Always pseudo-stable.

16 BUNCH ITOT=51mA

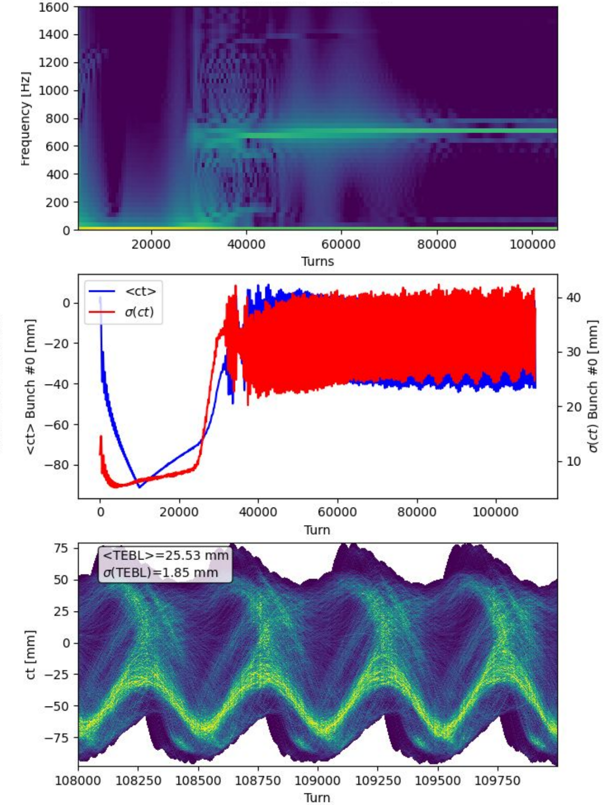
Nslice=1



Nslice=200



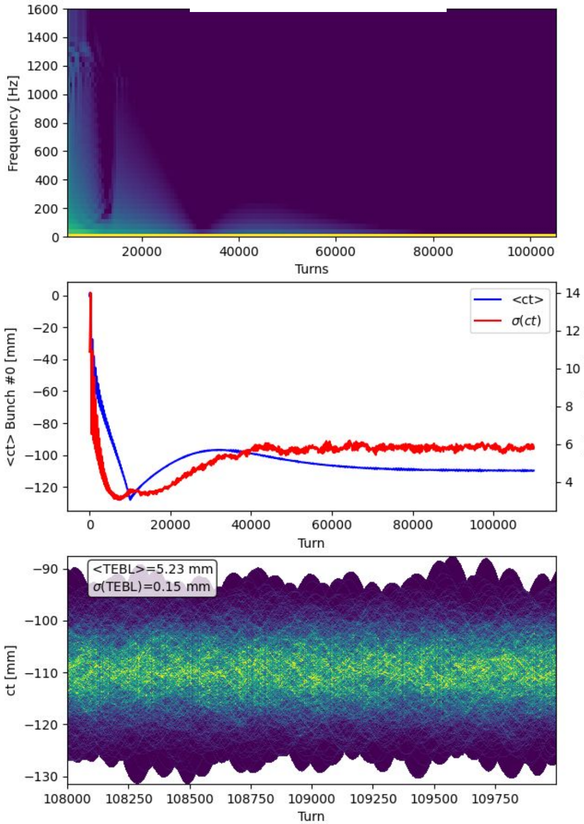
Nslice=200 + Machine Wake



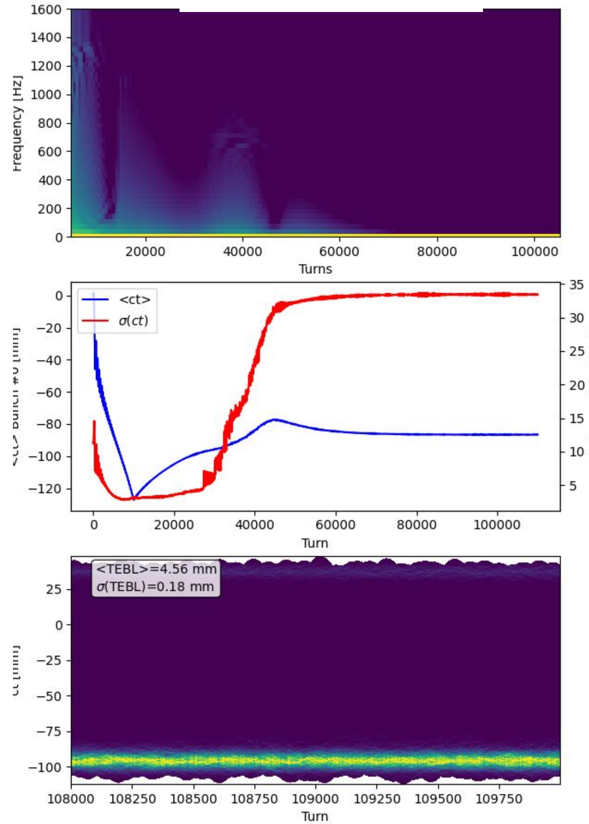
No losses seen at any point. Always pseudo-stable.

16 BUNCH ITOT=92mA

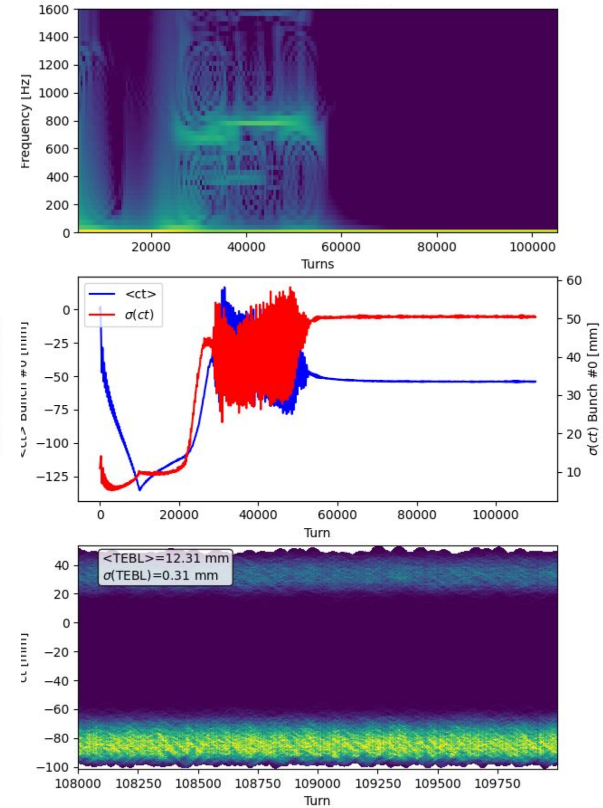
Nslice=1



Nslice=200

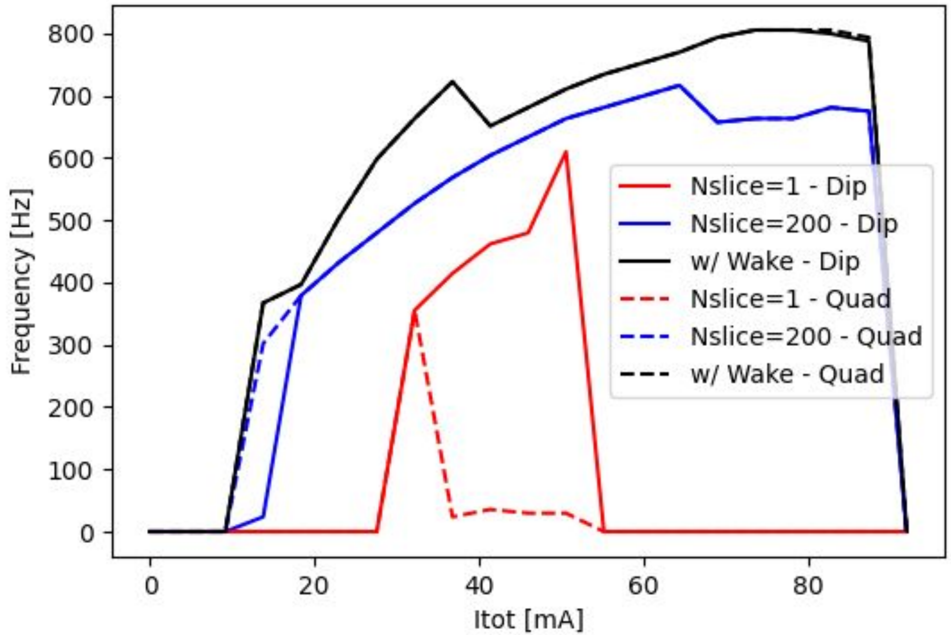


Nslice=200 + Machine Wake



No losses seen at any point. Always pseudo-stable.

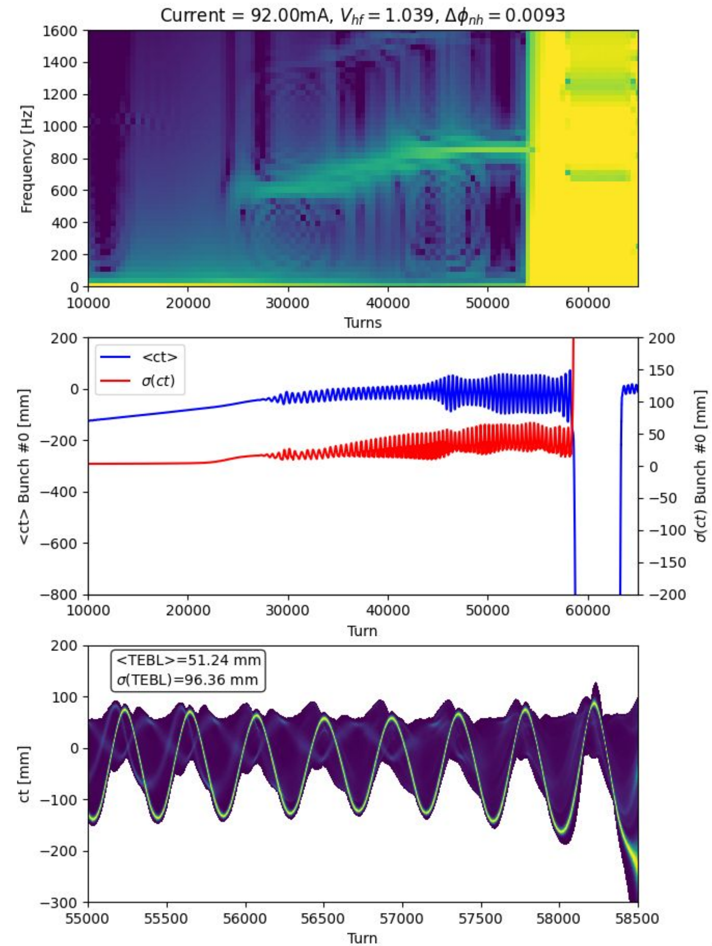
INSTABILITY FREQUENCIES



- Dipole and quadrupole frequencies identical. (Quadrupole instability with dipole component?)
- Nslice=1 reduces unstable region.
- Wake increases frequency a bit, but not significantly.
  - Stability studies don’t need wake to be approximately accurate.

HIGHER VOLTAGE

- Taking values from slide 13 for the optimum HC settings for bunch length (for 5.75mA).
- Rerun simulation with 92mA.
- No longer pseudo stable, at a certain point the stable bucket is completely lost.
- Much more well defined secondary buckets. They seem to merge and become unstable, but this needs more studies.

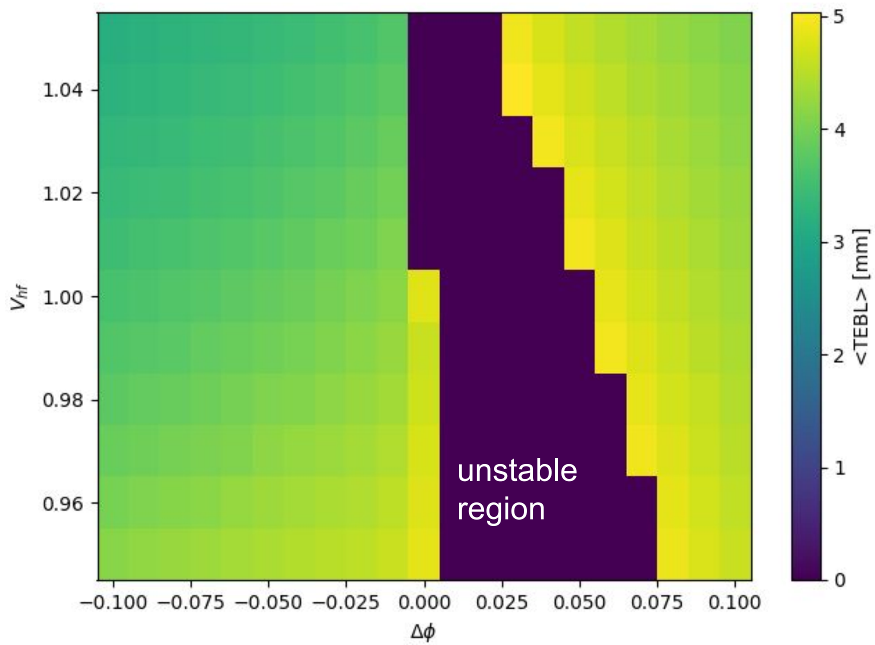


SOME OTHER NOTES

- Beam still pseudo-stable (unstable) when the gain of the harmonic voltage and phase is set to 0.
  - Not a regulation problem

- We saw that increasing the harmonic voltage made the situation worse (losses began to appear), we have also seen that reducing the harmonic voltage by 10% stabilises the situation.

- Below, scan of stability region for 16b with no machine wake at 92mA.
  - Stable region clearly defined, but bunch lengthening far from optimal.



CONCLUSIONS

- **Cavity short range wake can not be ignored when considering high currents per bunch**
  - SCALLOPS was developed to allow a deeper insight into this.

- **For a single bunch, cavity short range wake can be compensated with higher HC voltage and a phase shift, but only up to ~5mA.**
  - Higher harmonic cavity voltage (1.18*nominal) is needed for maximum bunch length with machine wake.

- **Pseudo-stable oscillations observed in 16b mode starting from ~20mA going up to 92mA.**
  - Even switching the harmonic cavity RF feedback off does not help. Something more clever is needed.

- **Hard to predict the expected equilibrium distribution without first solving the problem of stability.**

FUTURE PLANS AND QUESTIONS

- **How to properly characterise the instability?**
- **What type of bunch length can I really expect in the realistic conditions?**
  - All signs pointing towards the bunch lengthening being much less than desired.
- **What is the most appropriate type of RF feedback for the harmonic cavity?**
  - Several available, but not sure on the direction to take for this type of problem.
- **How can I stabilise the instability?**
  - Is it a question of RF feedback on the HC or an additional longitudinal feedback?
  - Can Landau damping help?
  - All simulations assume load angle $\Phi L=0$. Could this be adjusted to mismatch the generator and stabilise?
- **Benchmarking the instability with mbtrack2 is ongoing.**
  - Single RF beam loading and distributions with cavity short range wake and HC have both been benchmarked and agree extremely well.