Momentum Slip-Stacking Simulations for SPS Ion Beams with Collective Effects

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Acknowledgements:

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Contents

Motivation

- The HL-LHC requirement for ion beams is to double the peak luminosity after LIU Upgrade [1] increasing the number of bunches in the LHC

- The LIU baseline to achieve that is to decrease bunch spacing from 100 ns to 50 ns in SPS through slip-stacking (already used at Fermilab to double beam intensity [2])

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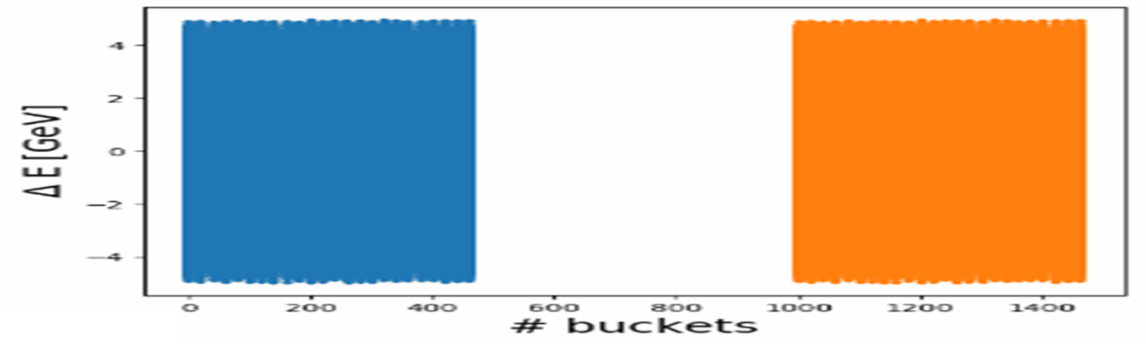

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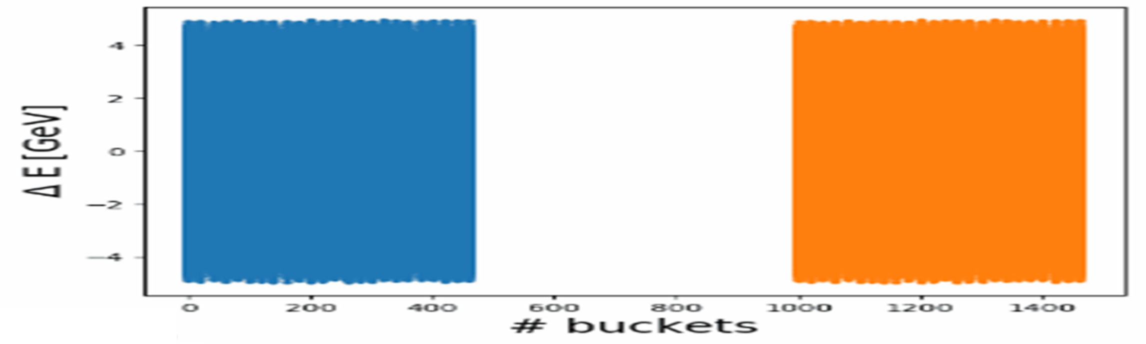

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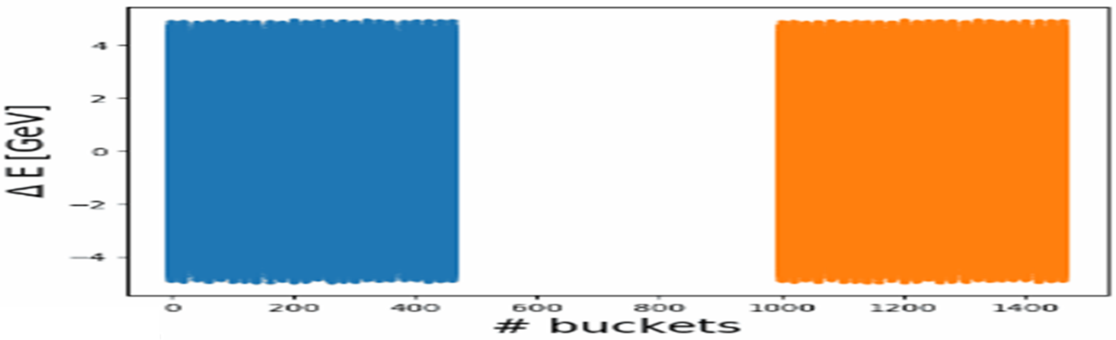

In longitudinal phase space two batches are interleaved using two independent RF systems.

- In SPS slip-stacking can be tested only after Upgrade
  - ➢ Low Level RF of the 200 MHz RF system has to be upgraded

- Therefore simulations are the only means to check slip-stacking feasibility (see also [3])

- For the first time simulations (with the CERN BLonD code [4]) have been done using:
  - ➢ Full SPS longitudinal impedance model
  - ➢ Measured beam parameters
  - ➢ Optimization with respect to the most significant parameters involved

Slip-stacking principle

Fundamental equations for slip-stacking dynamics (at constant magnetic field)

$$\boxed{\frac{\Delta f_{rf}}{f_{rf,0}} = -\eta_0 \frac{\Delta p}{p_0}}$$

$$\boxed{\frac{\Delta p}{p_0} = \gamma_{tr}^2 \frac{\Delta R}{R_0}}$$

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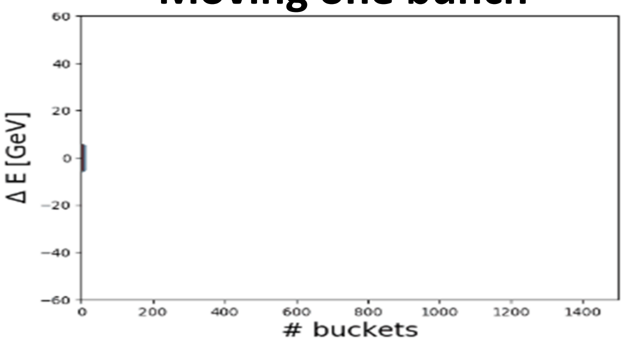

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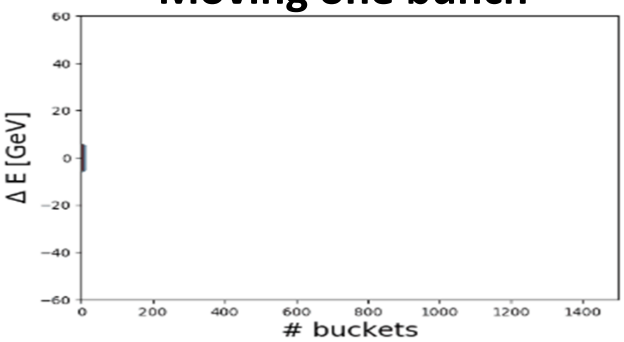

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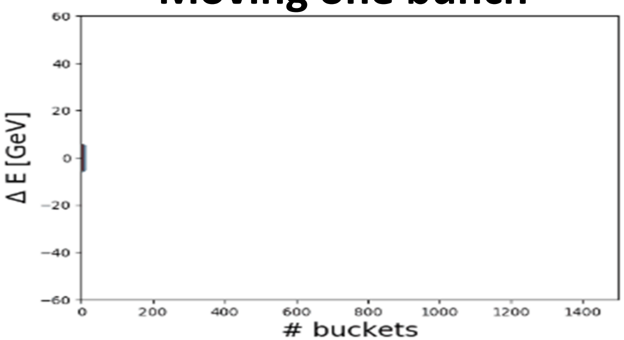

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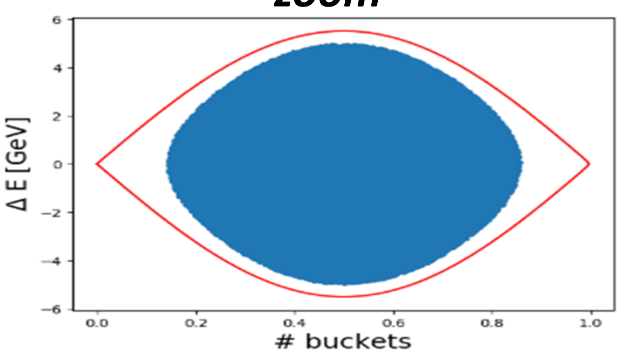

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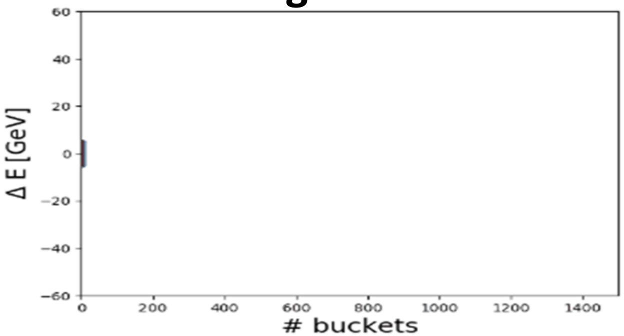

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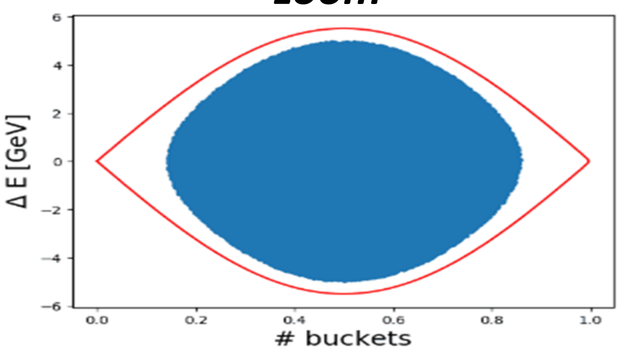

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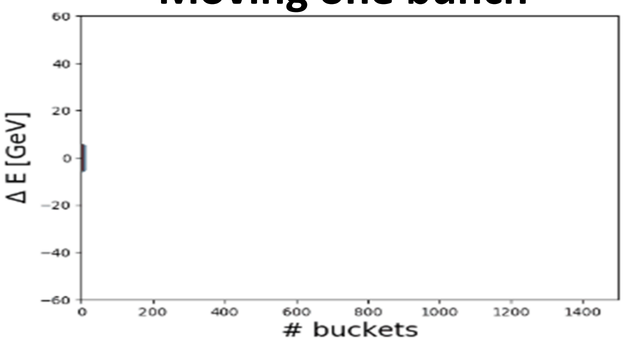

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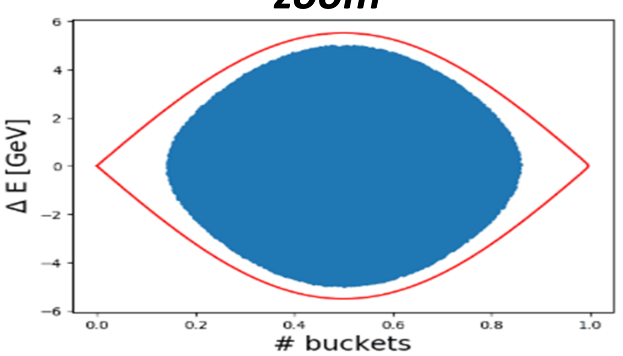

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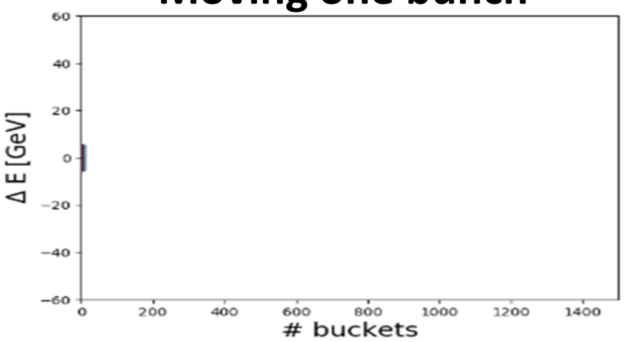

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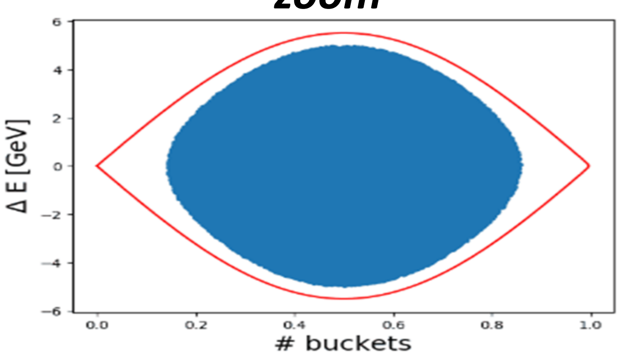

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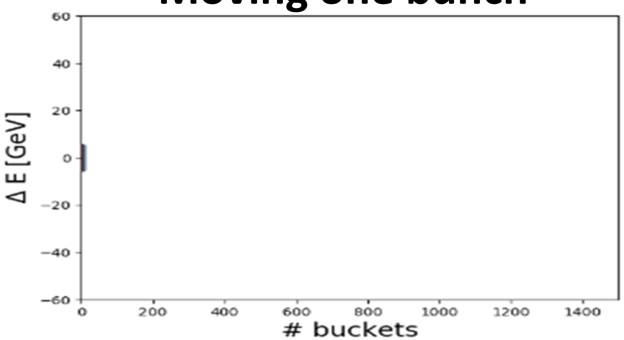

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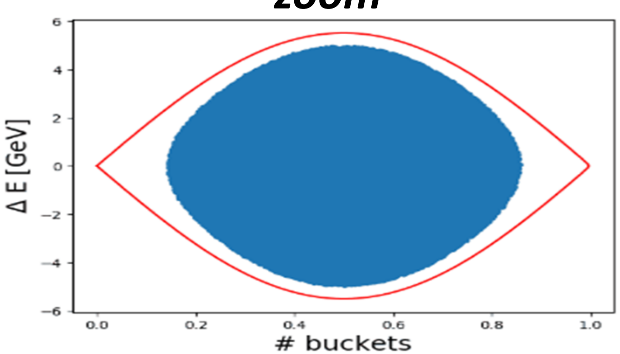

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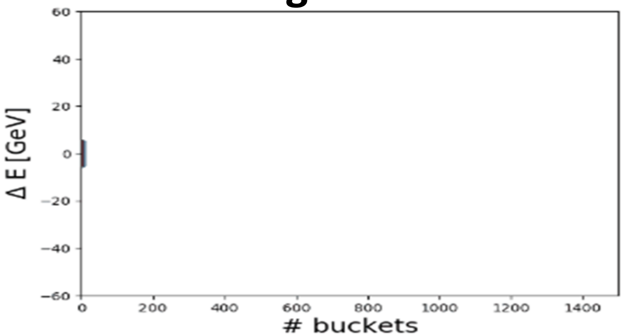

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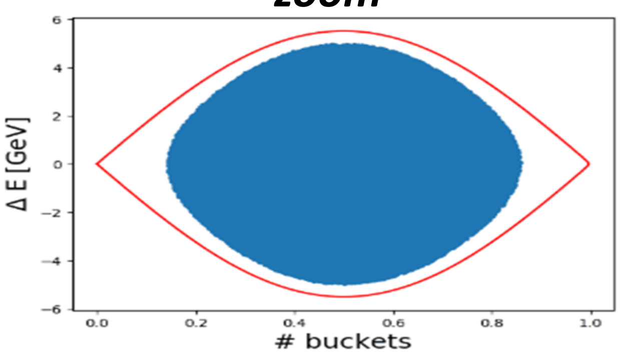

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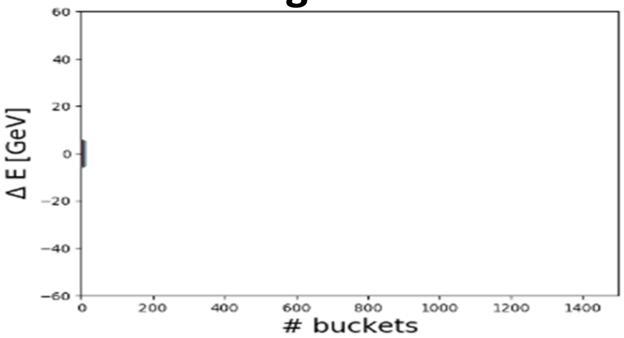

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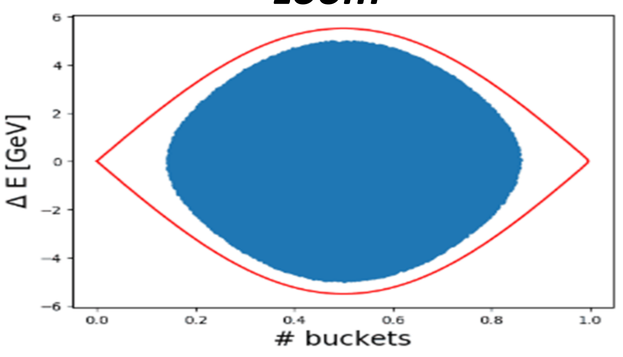

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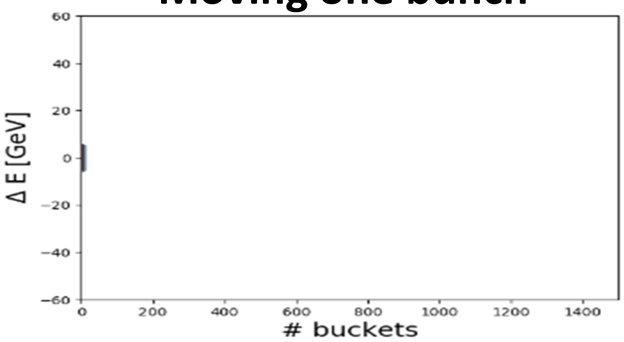

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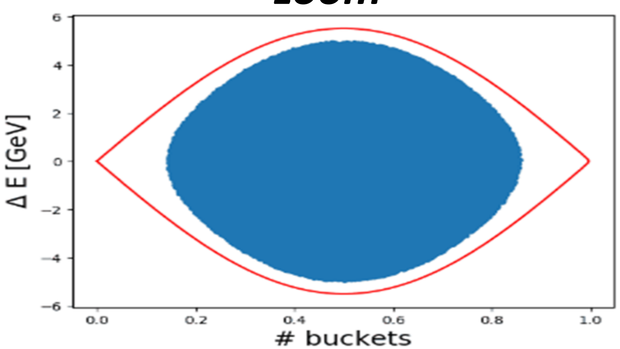

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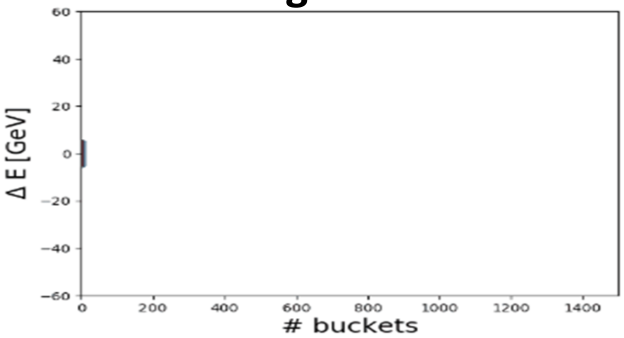

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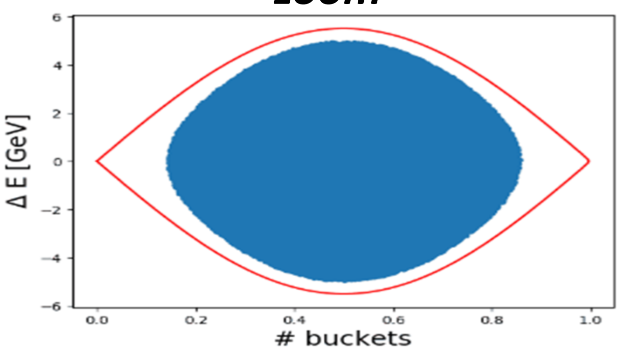

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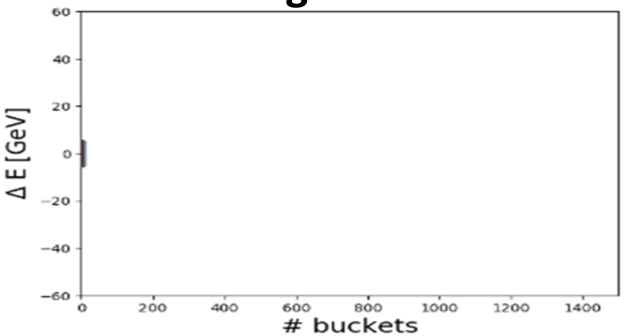

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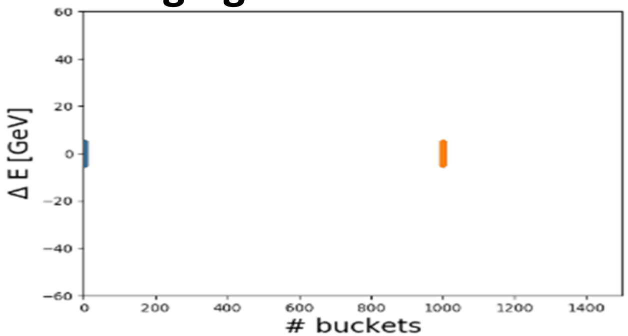

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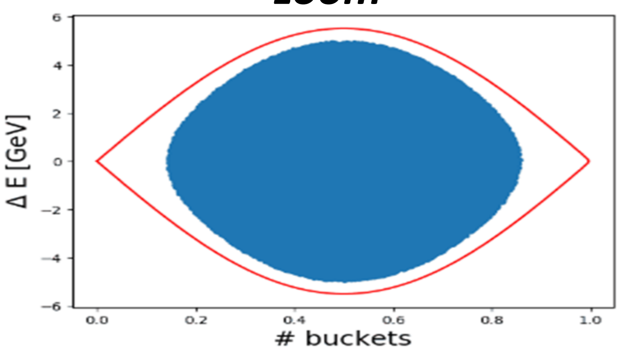

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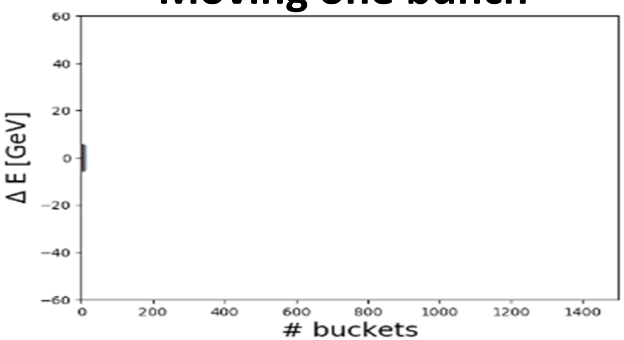

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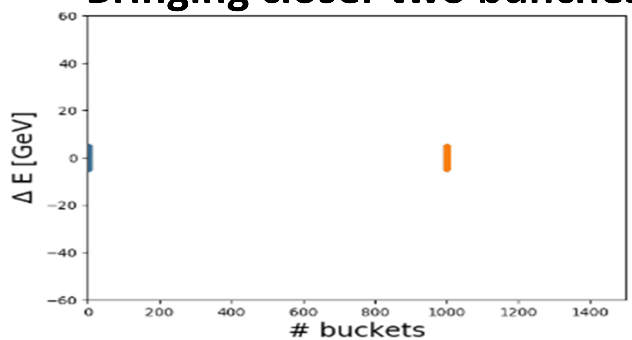

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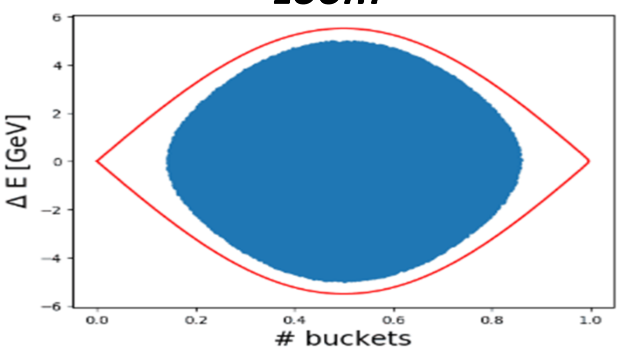

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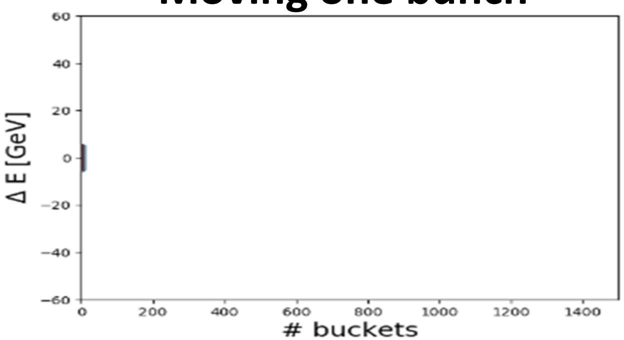

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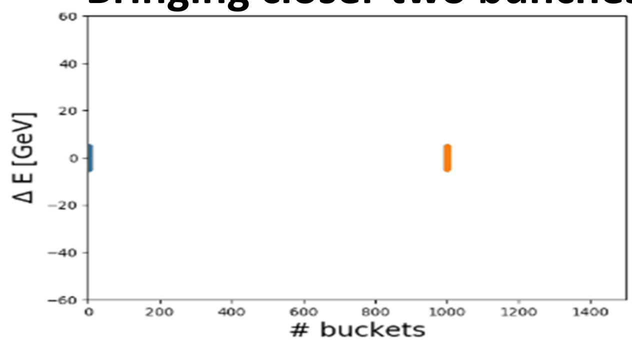

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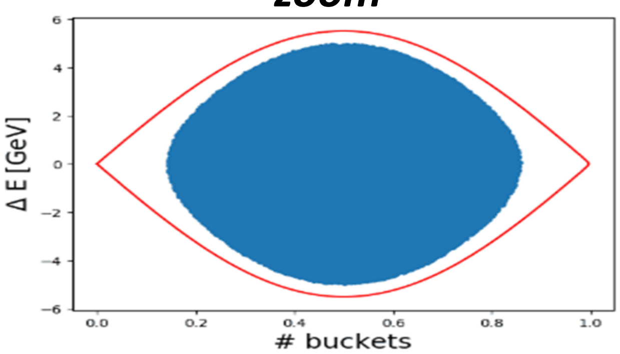

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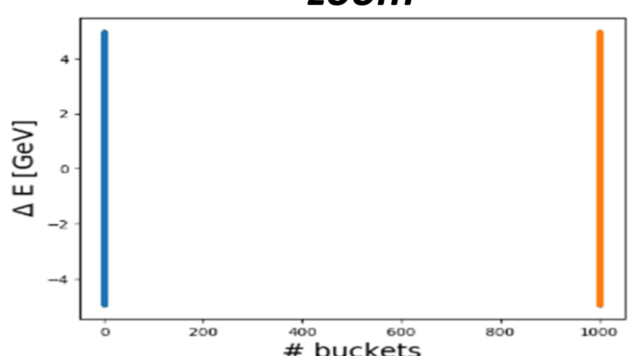

Slip-stacking principle

Fundamental equations for slip-stacking dynamics (at constant magnetic field)

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Examples above transition ($\eta_0>0$)

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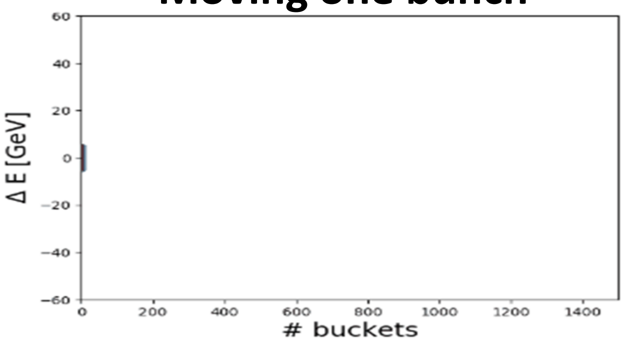
Moving one bunch



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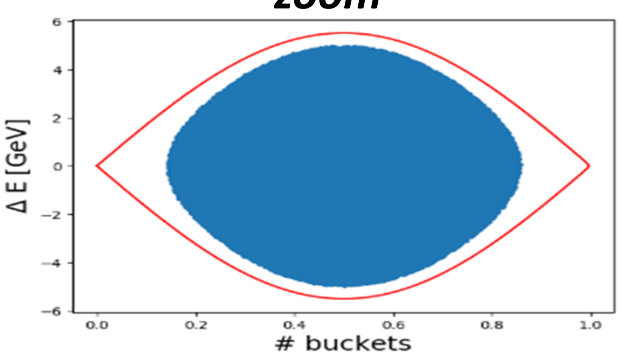
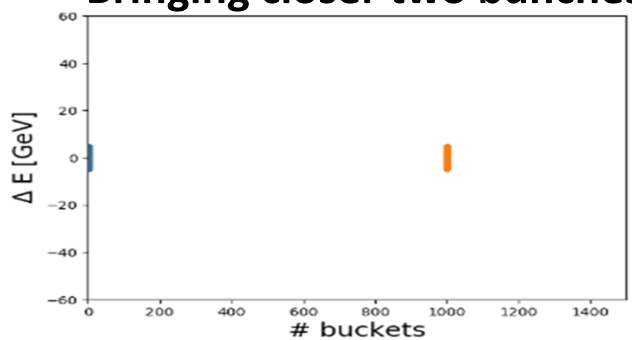


Bringing closer two bunches



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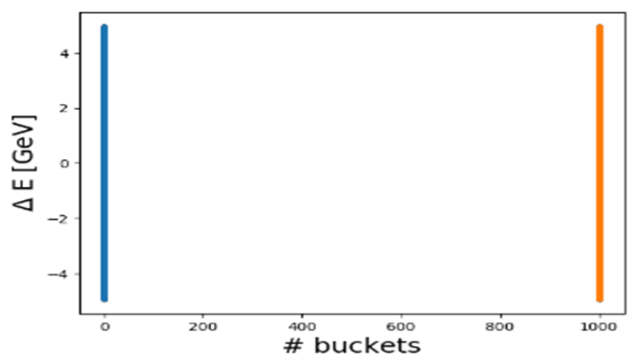

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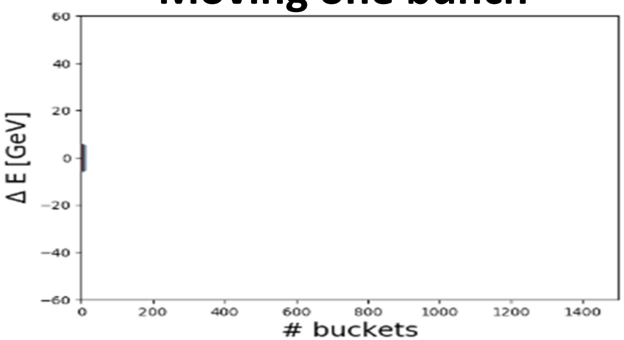

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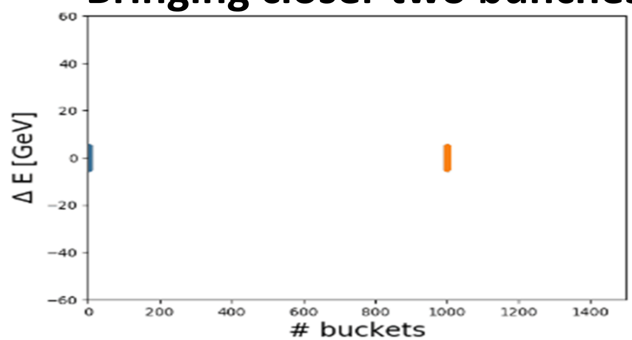

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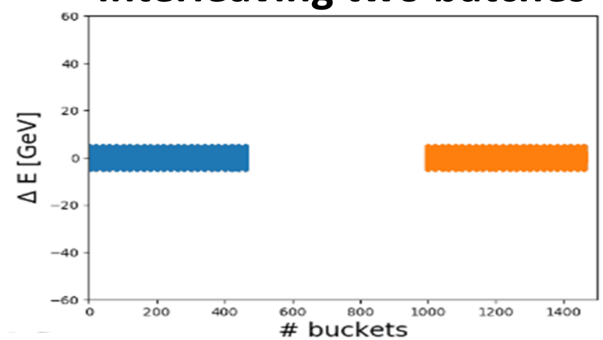

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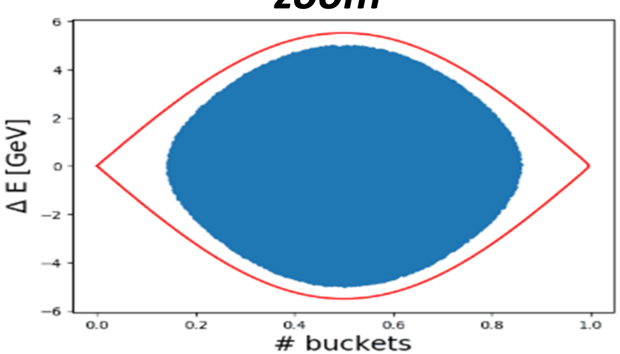

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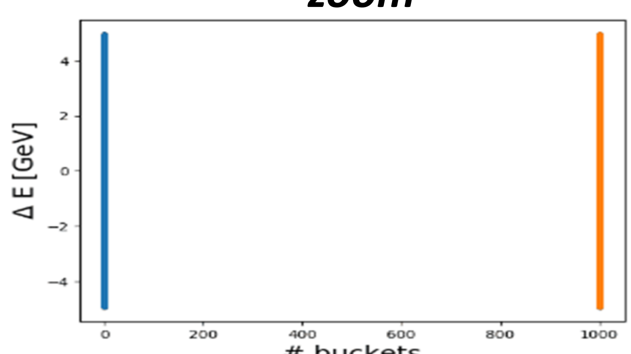

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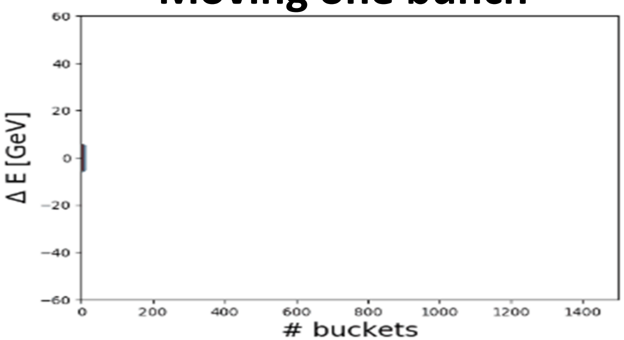

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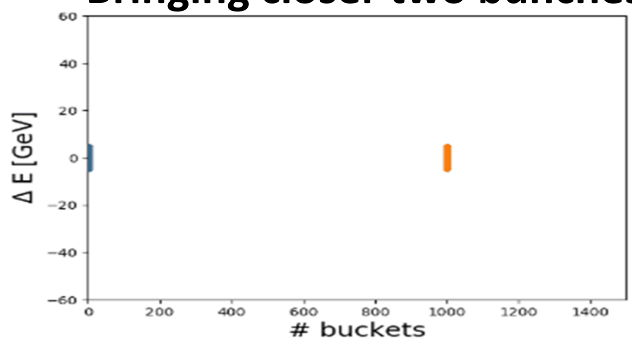

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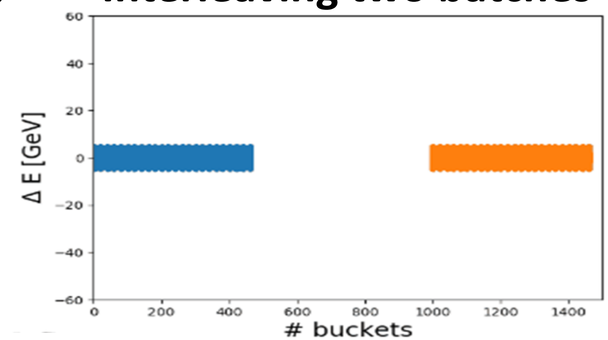

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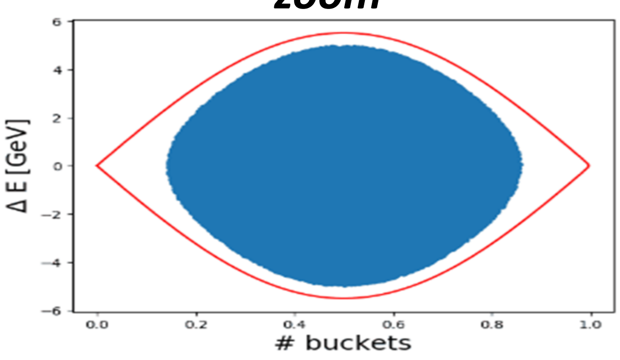

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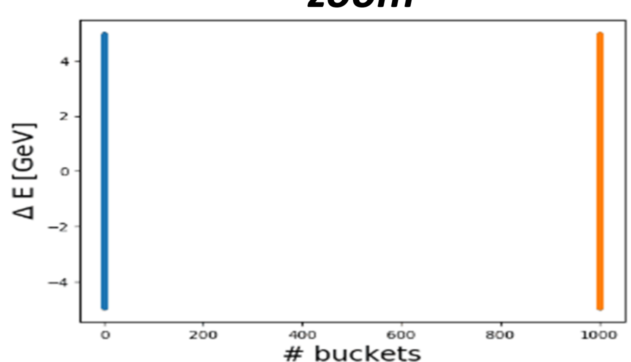

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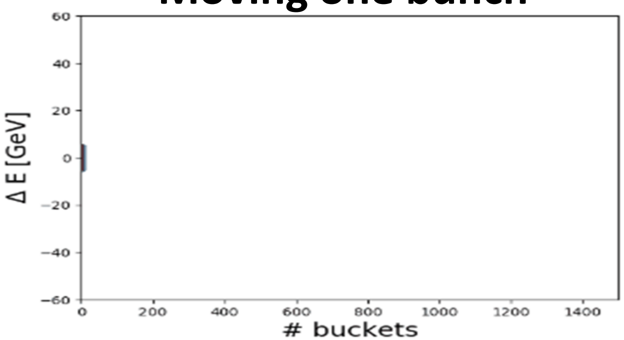

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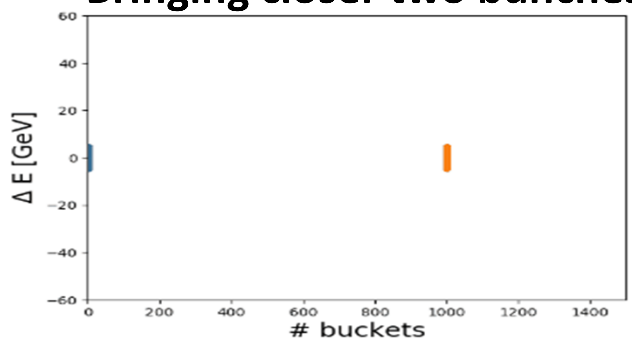

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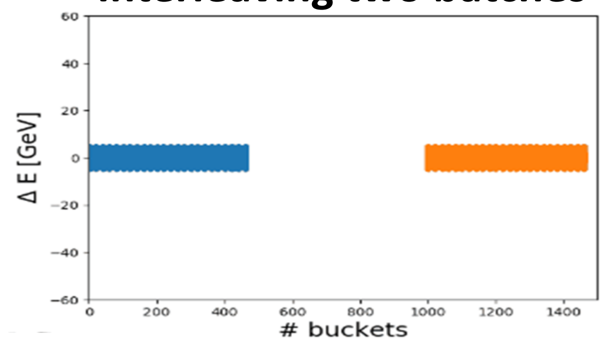

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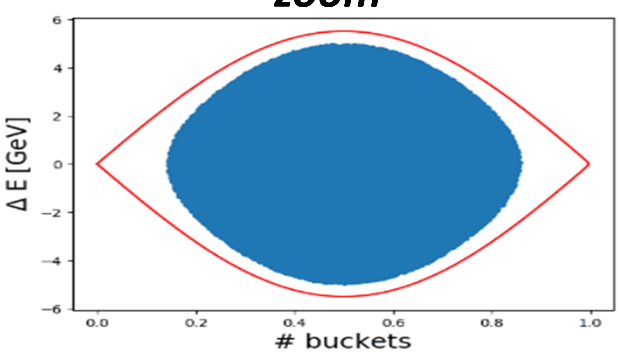

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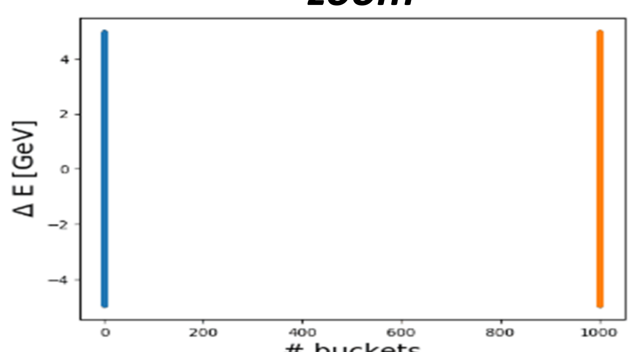

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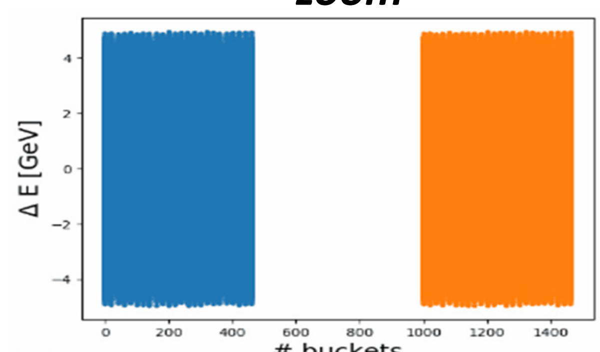

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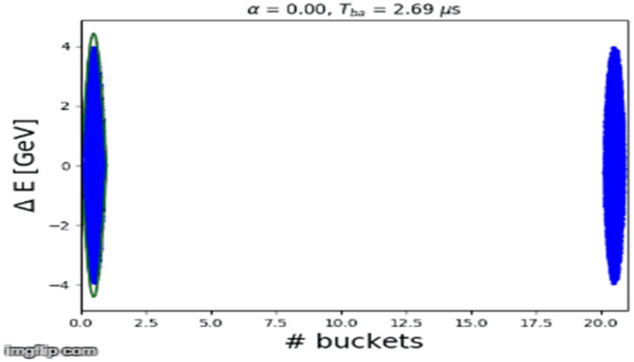

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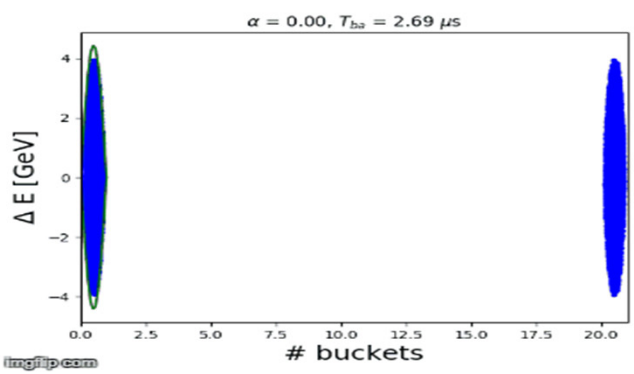

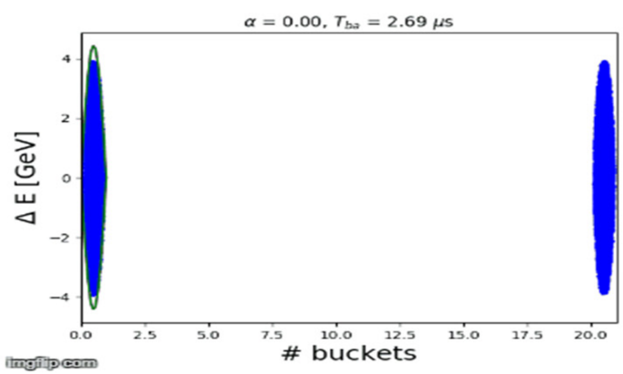

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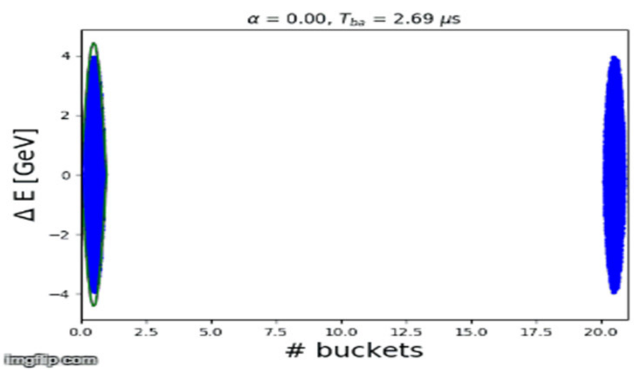

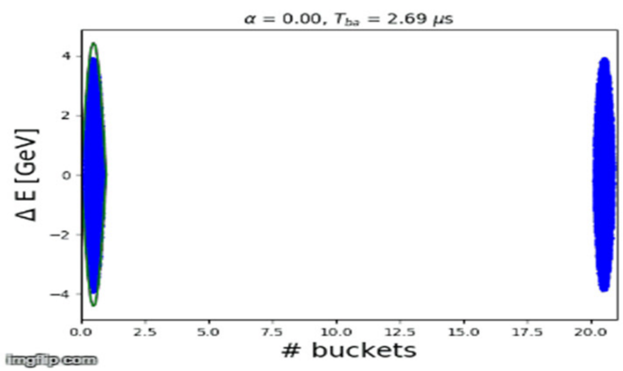

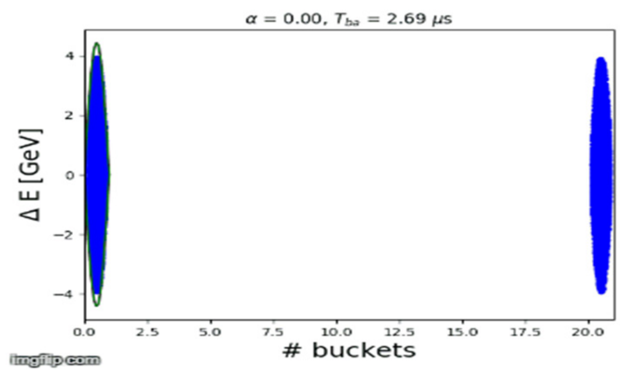

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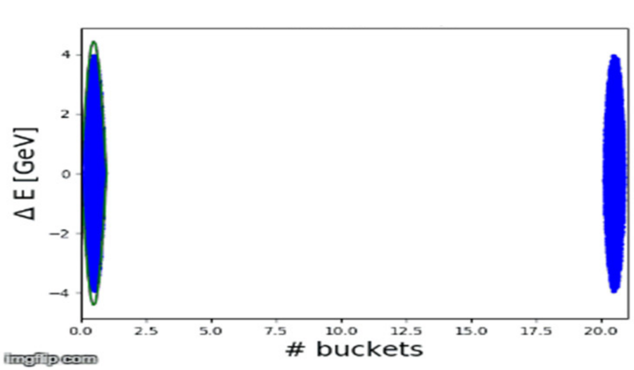

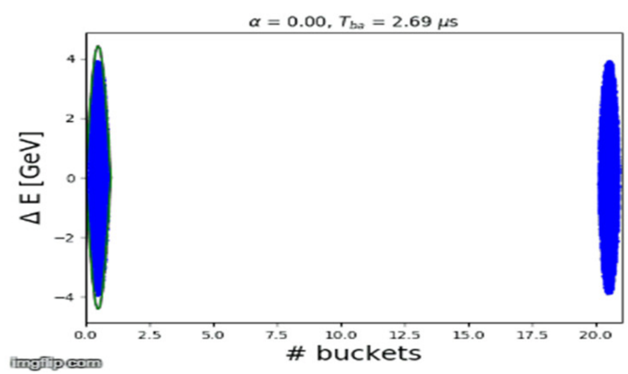

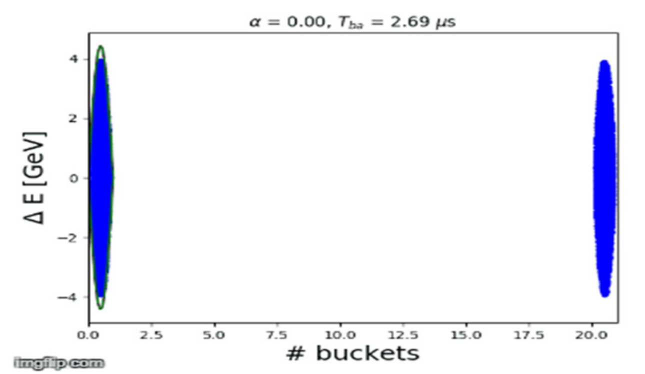

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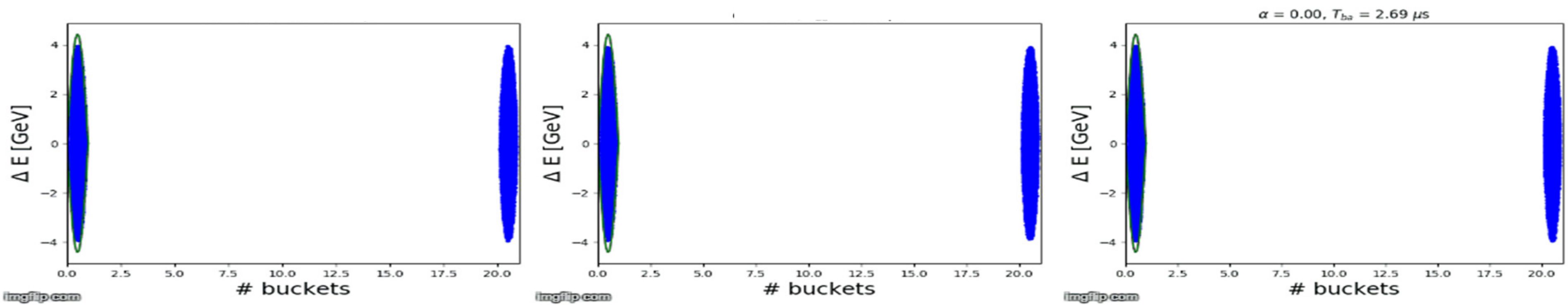

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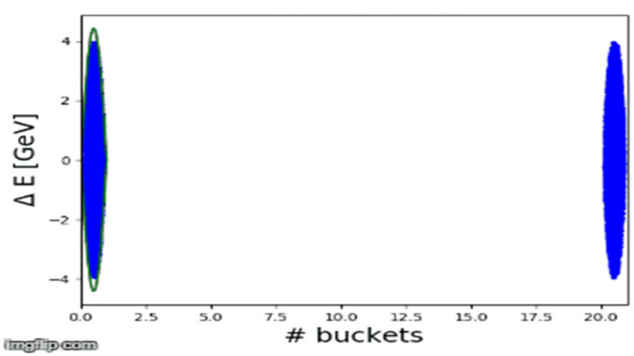

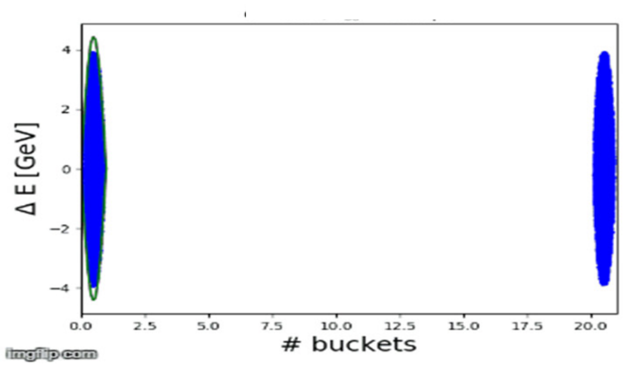

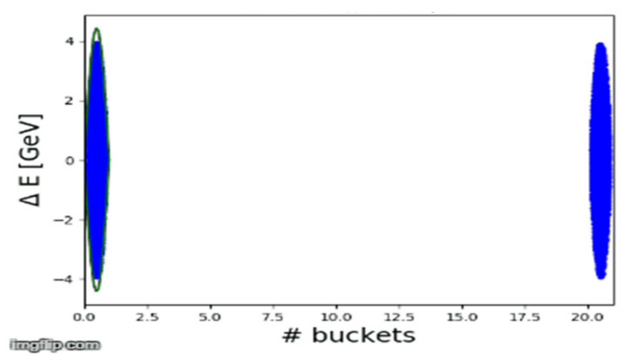

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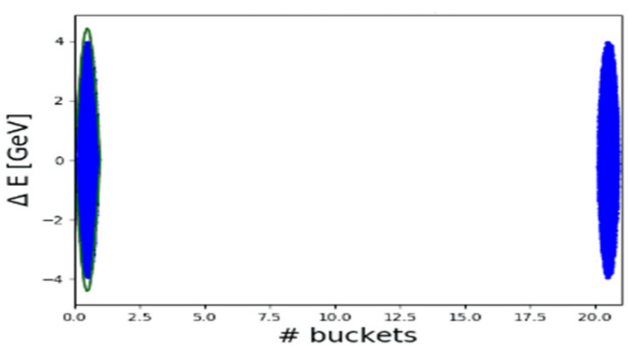

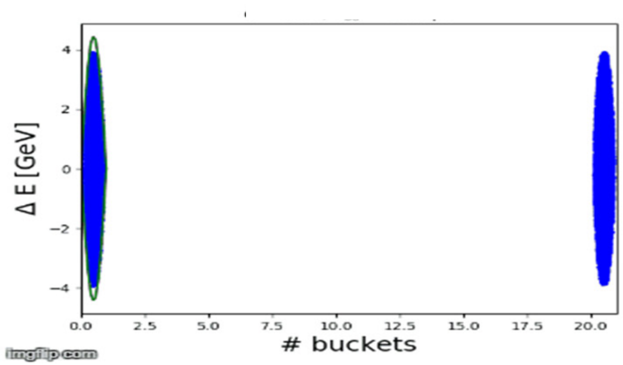

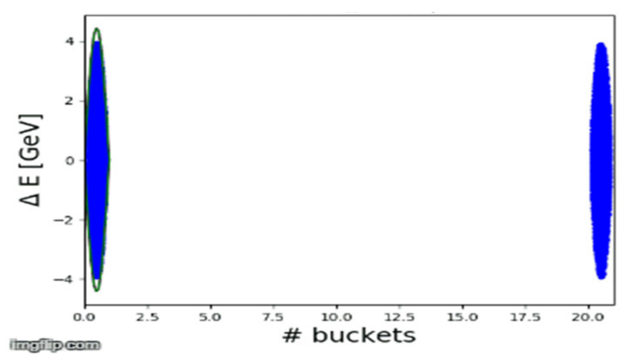

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- Perturbation severity $\boxed{\alpha \doteq \frac{\Delta f_{rf}^{b}}{f_{s0}} = 2\frac{\Delta E^{b}}{H_b}}$

Difference in RF frequency and absolute energy between the two batches

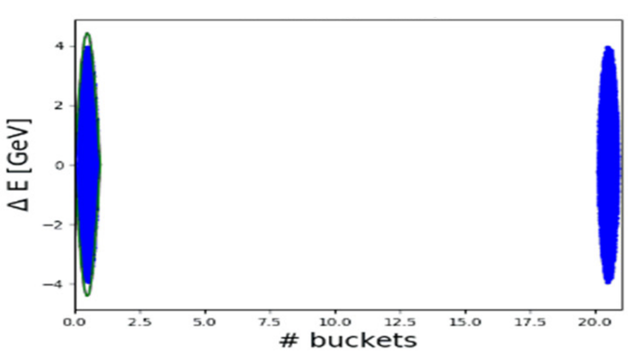
Core synchrotron frequency and bucket half height

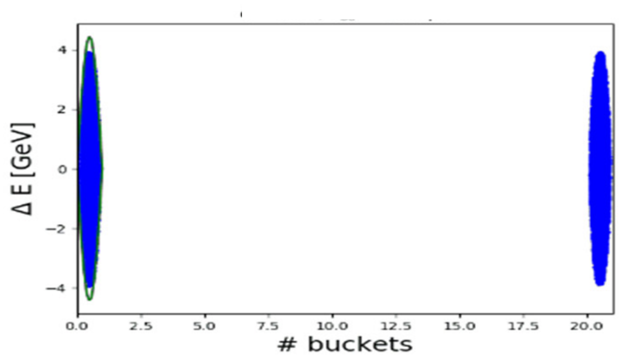
- It has been proven [5] that a lower limit for stable motion is defined by $\alpha = 4$

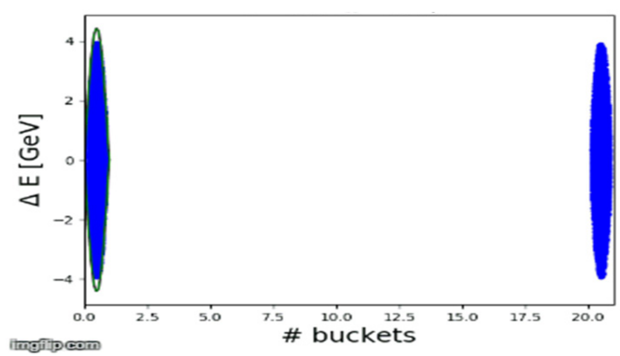
$\alpha = 8$ -> small perturbation effect but large needed recapture voltage and large emittance after filamentation

$\alpha = 4$ -> smaller recapture voltage needed (and small emittance growth after recapture) but the perturbation has more effect

$\alpha = 0$ -> bunches are lost, large quantity of satellite particles after recapture due to chaotic motion in ΔE=0







RF perturbation

- Each RF system, while accelerates one batch, perturbs the other batch.

- The perturbation is zero when the batch distance T_b is greater than the time T_b^{th} needed to switch alternatively the two RF systems on and off depending on which batch passes by.
- The perturbation has less damaging effects when Δf_{rf}^{b} is large relative to f_{s0}
  - ➢ the perturbation averages within a synchrotron oscillation period

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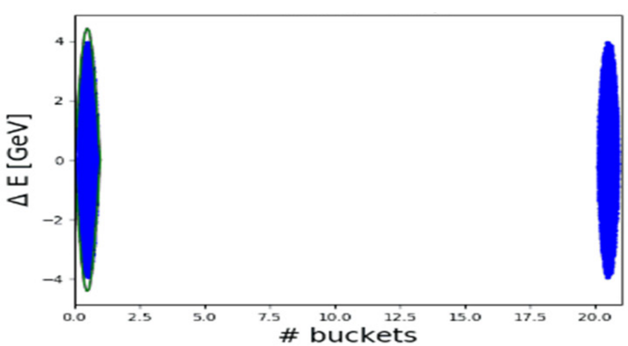

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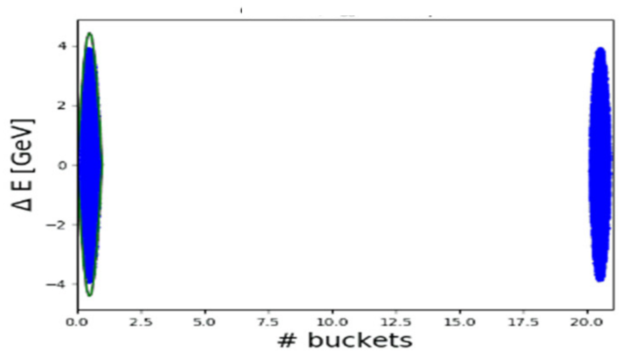

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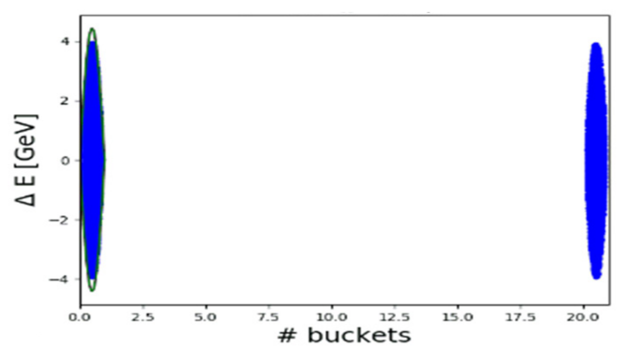
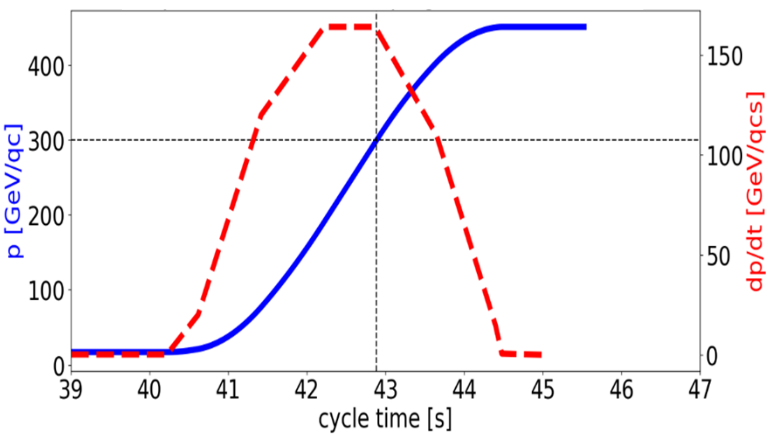


Slip-stacking energy in SPS

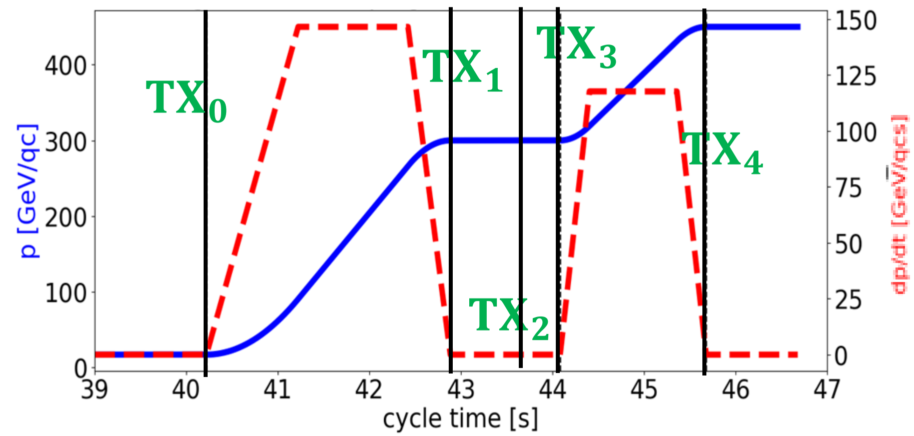
- At which energy should slip-stacking be performed?
  - Flat bottom: strong space charge effects, IBS and RF noise (observed during operation)
  - Flat top: uncaptured beam is transfered to the LHC and lowest instability threshold
  - **Intermediate energy plateau**: good compromise (the energy 300 GeV/qc is chosen)

- Only multiples of 1.2 s (PSB cycle length) can be added to the SPS cycle for slip-stacking
  - 1.2 s are added at 300 GeV/c (0.8 s for slip-stacking and 0.4 s for filamentation after recapture)

Operational momentum program and derivative



Momentum program with slip-stacking and derivative



- Simulations started at TX_1 (beginning of slip-stacking)

- In measurements [6] significant bunch by bunch variation in intensity and emittance at 300 GeV/qc due to losses at SPS flat bottom.

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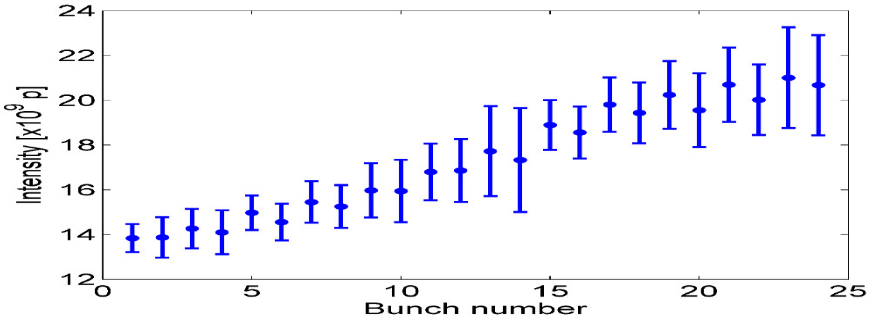

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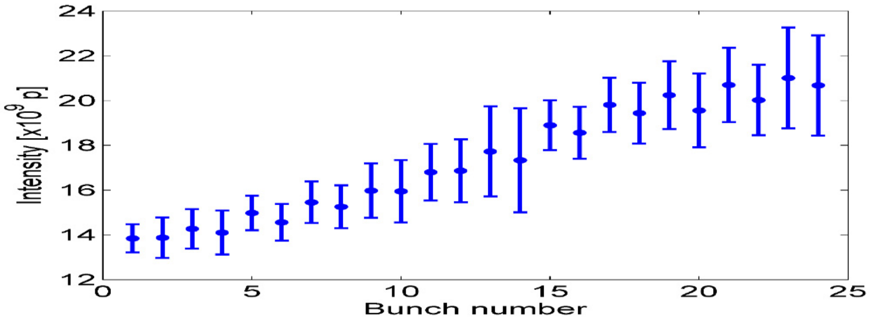

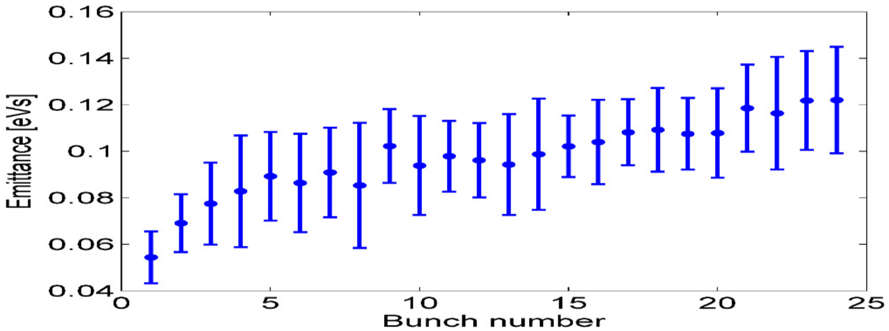

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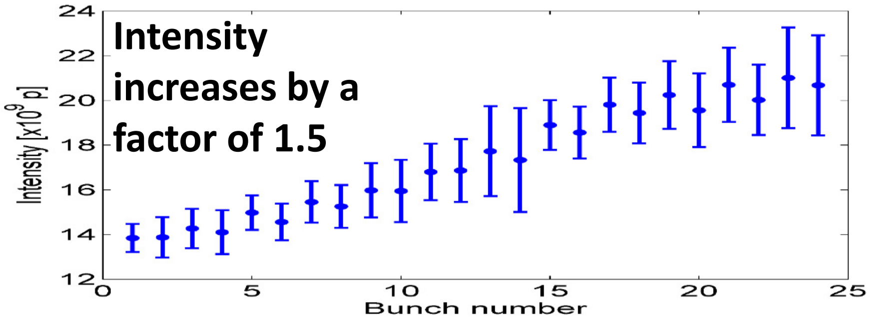

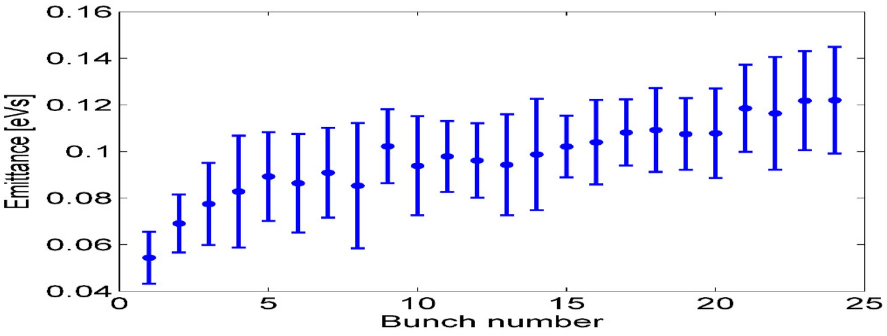

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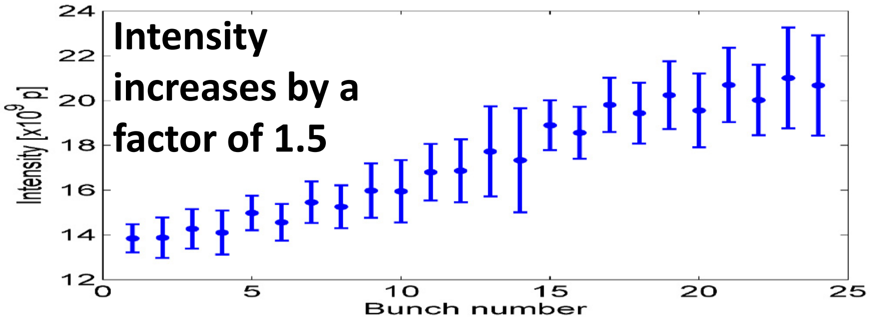

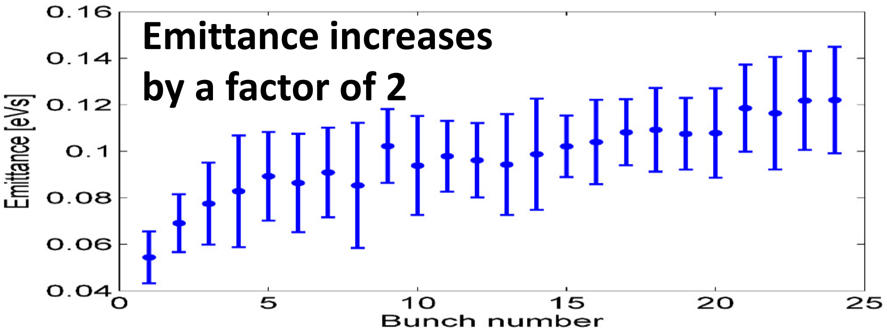

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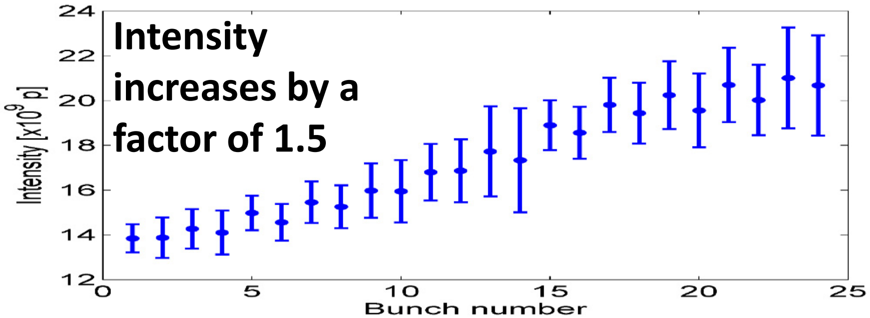

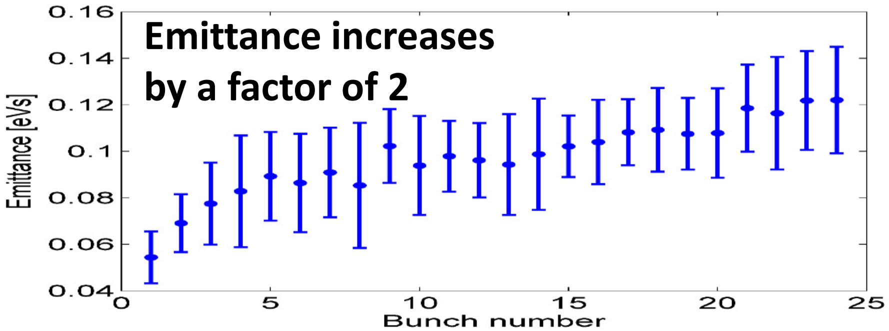

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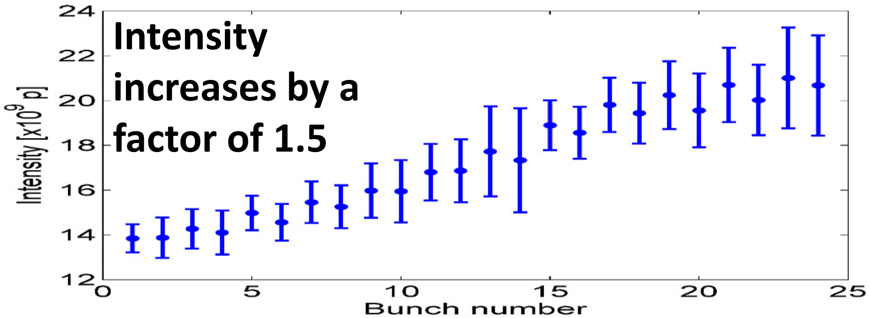

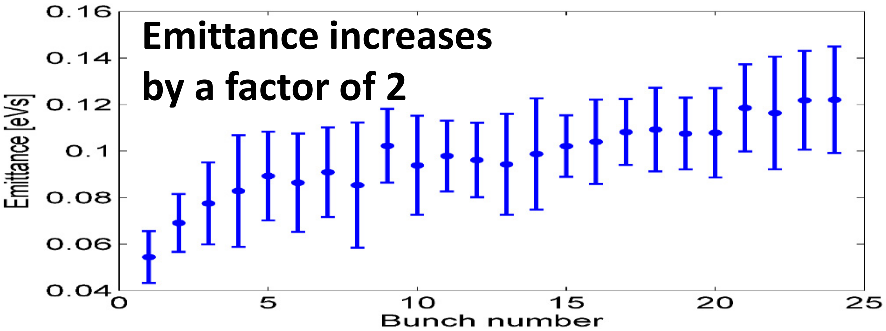

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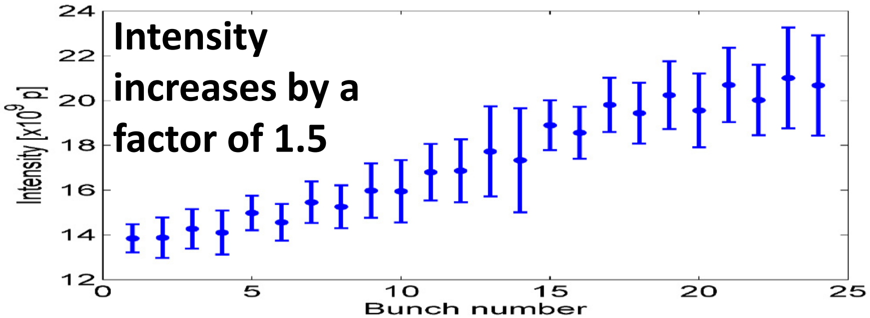

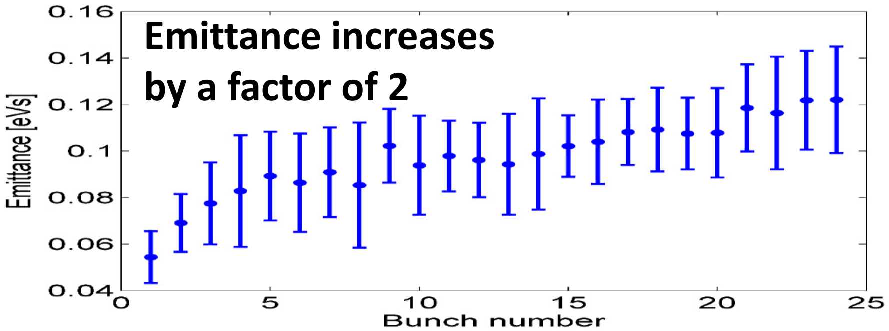

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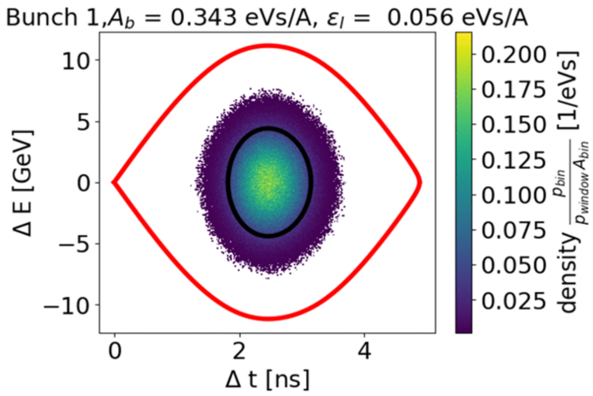

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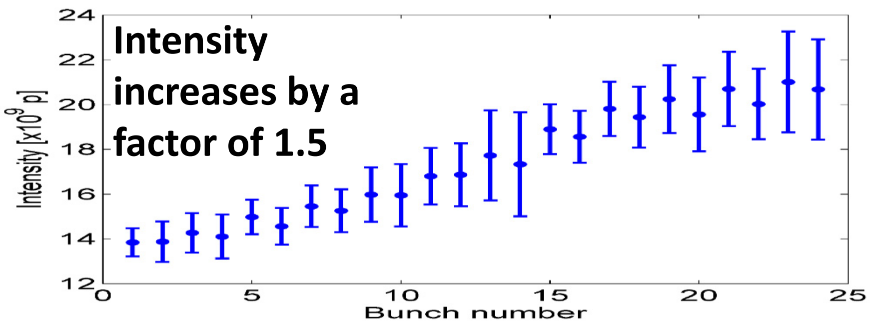

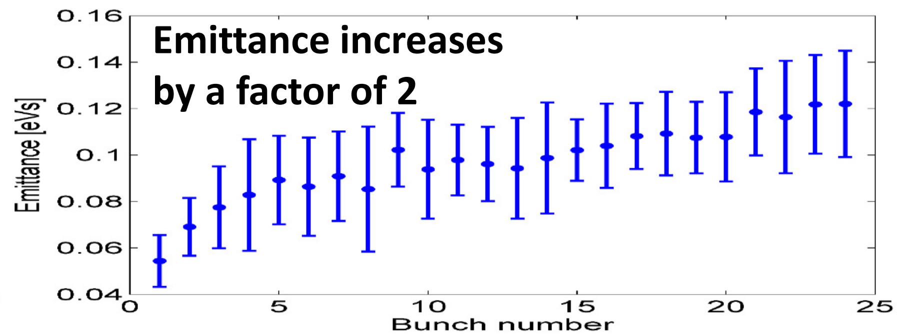

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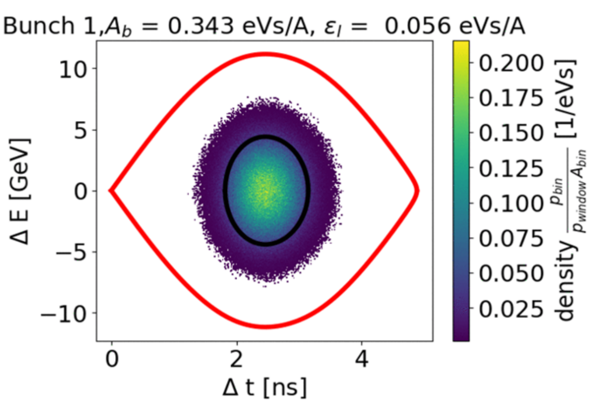

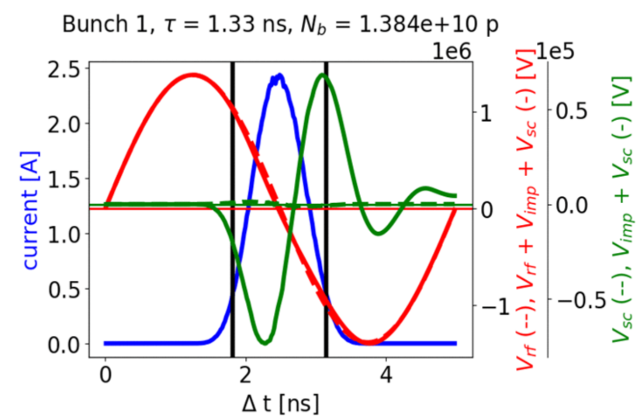

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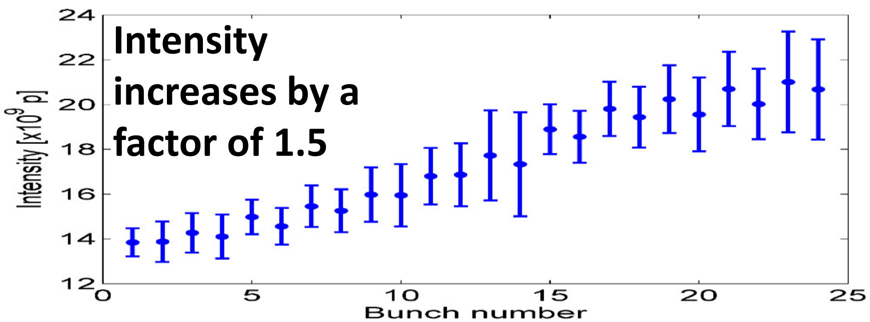

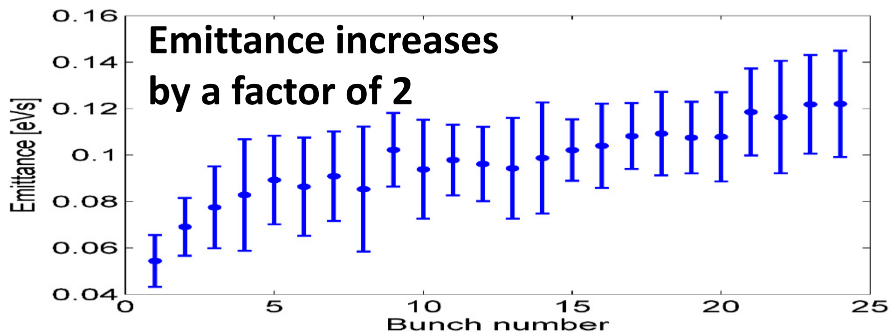

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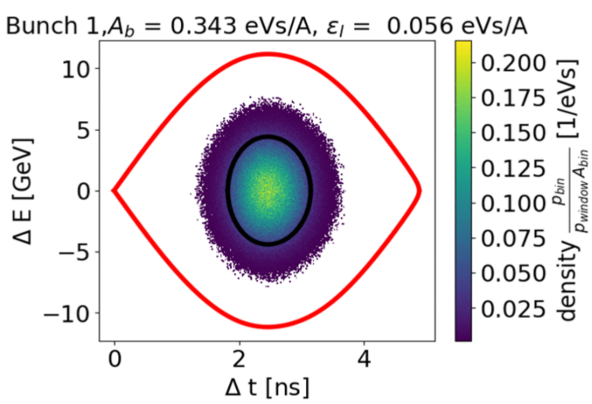

EXAMPLE

- ‘Low’ RF voltage needed (1.4 MV) relative to current operational one (7 MV)
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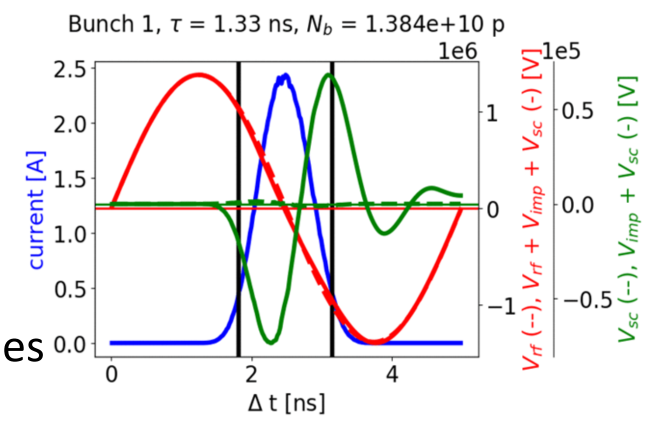

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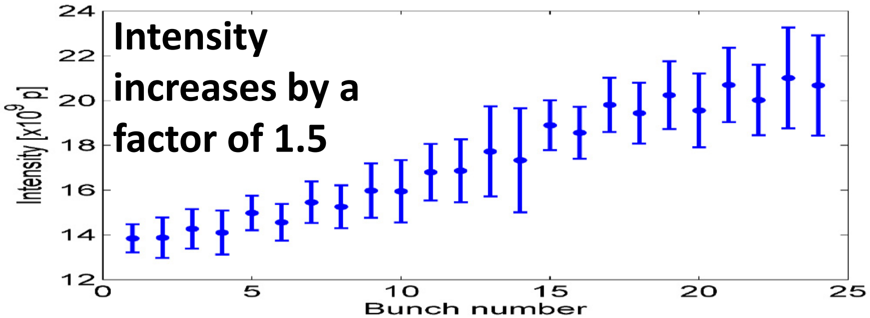

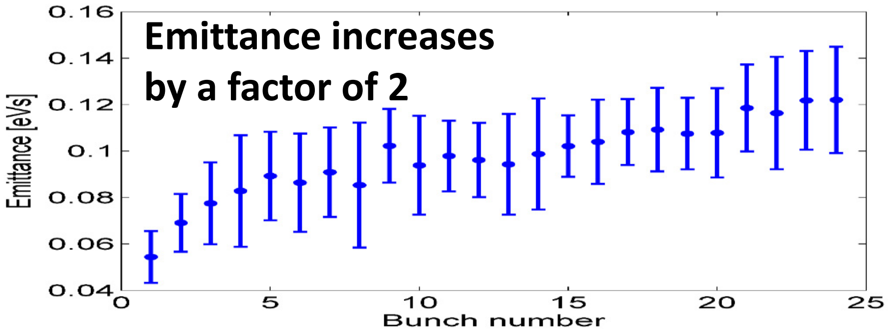

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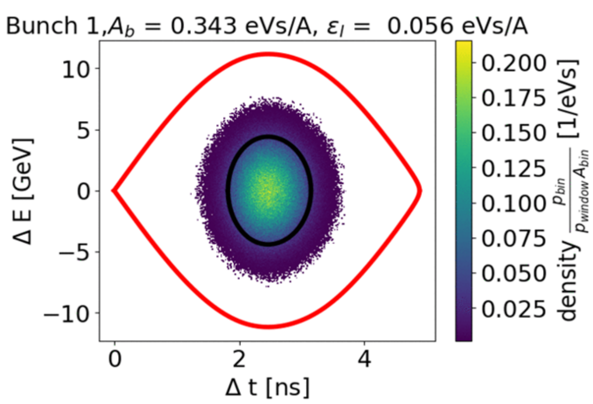

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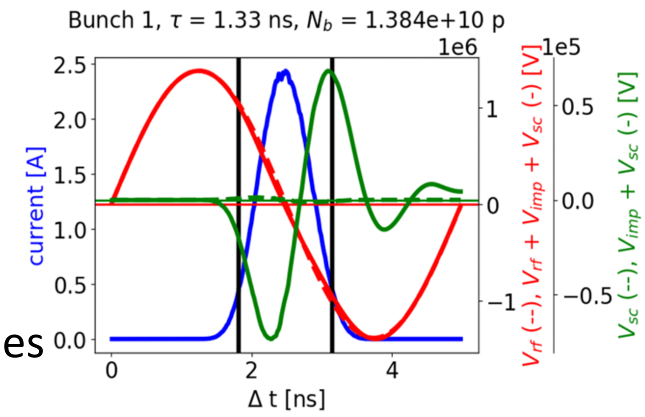

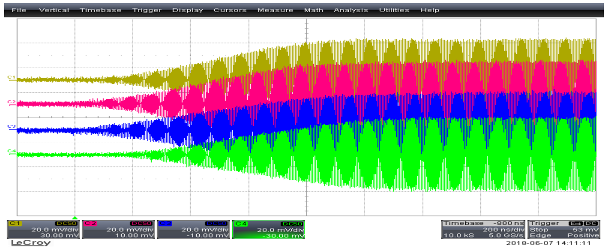

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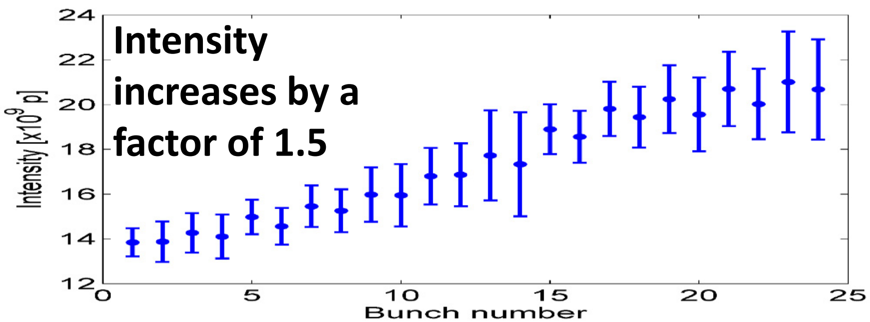

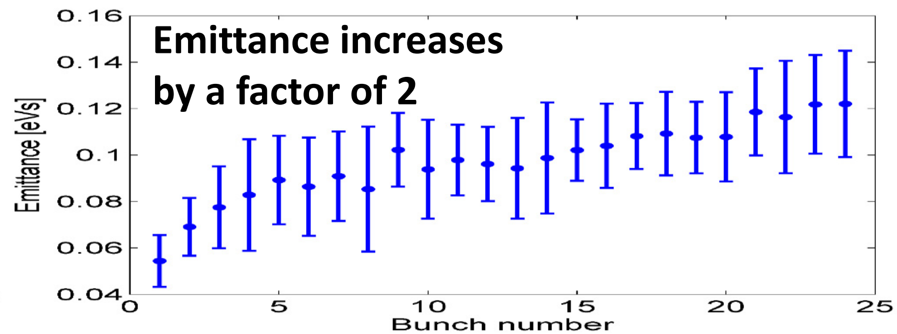

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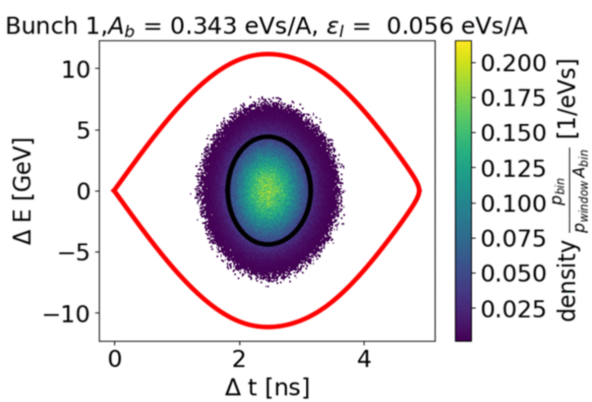

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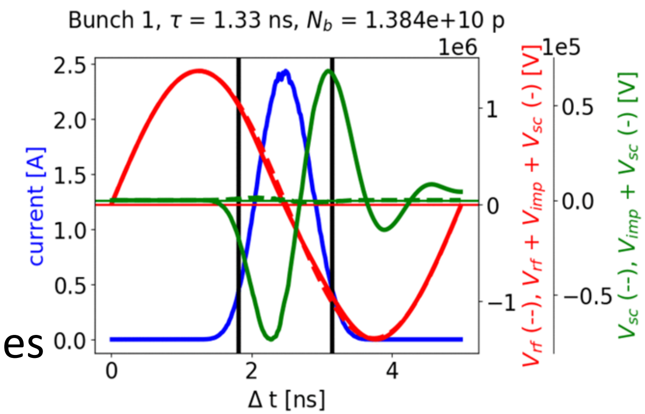

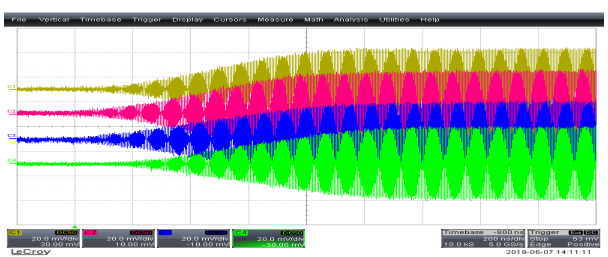

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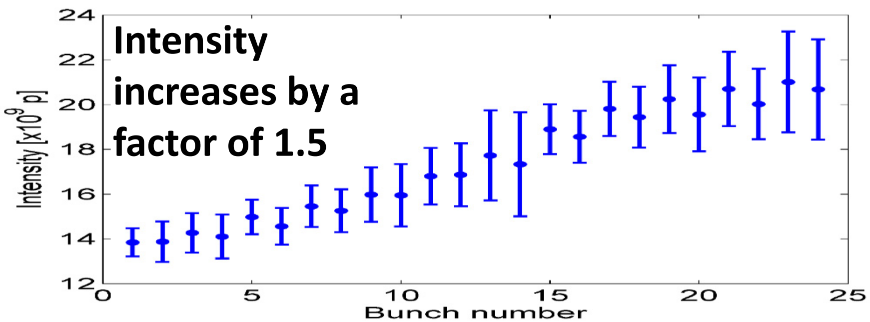

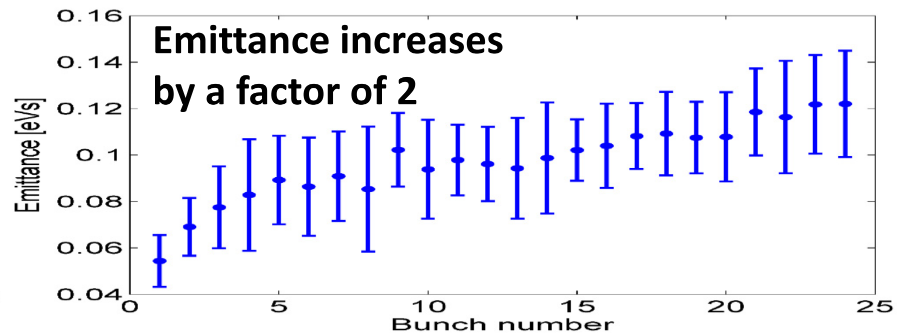

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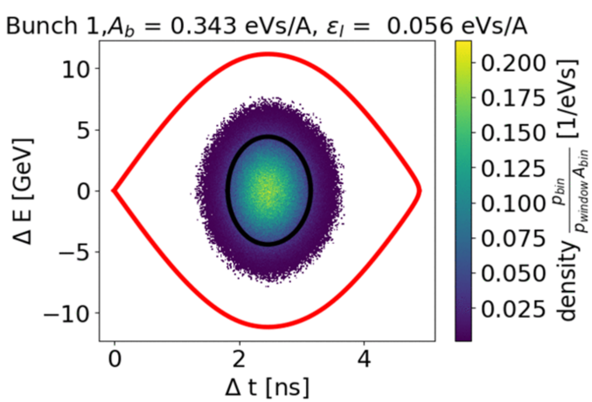

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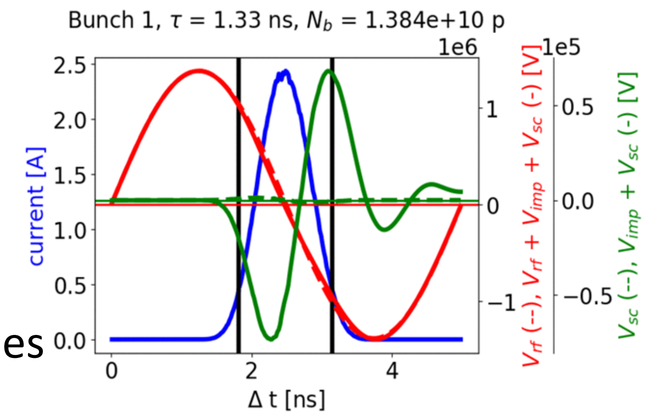

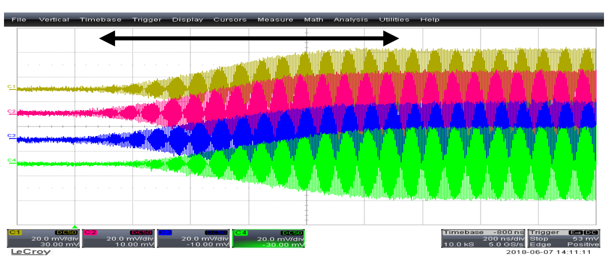

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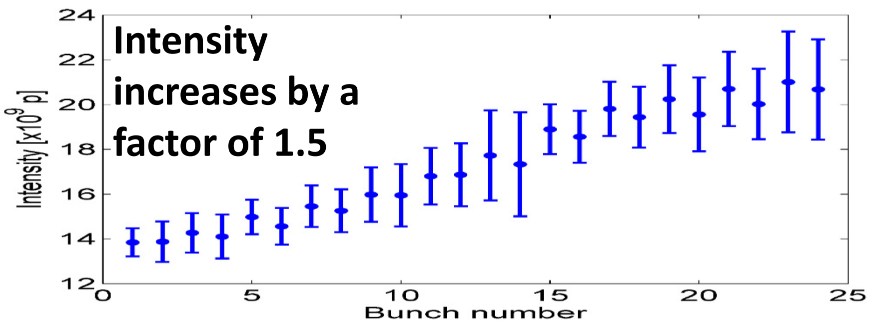

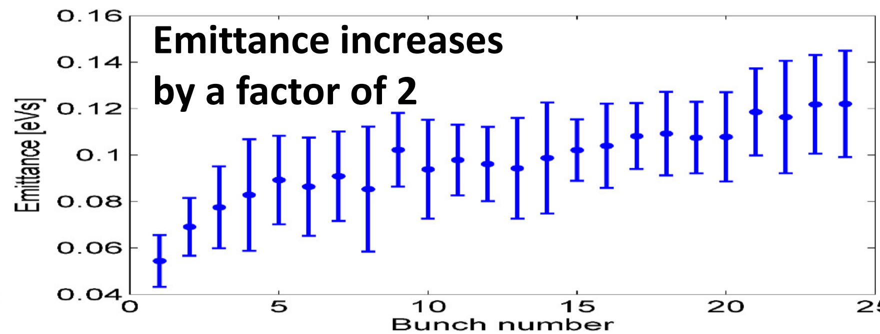

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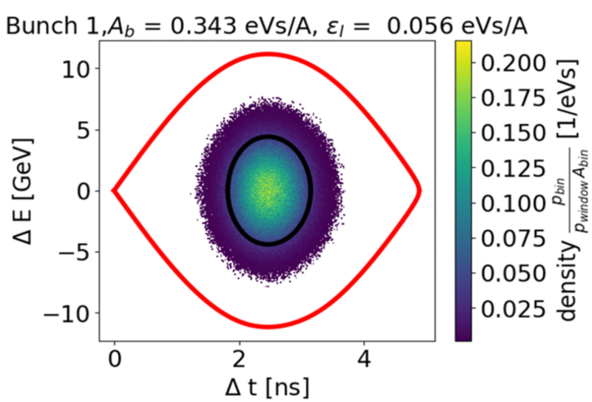

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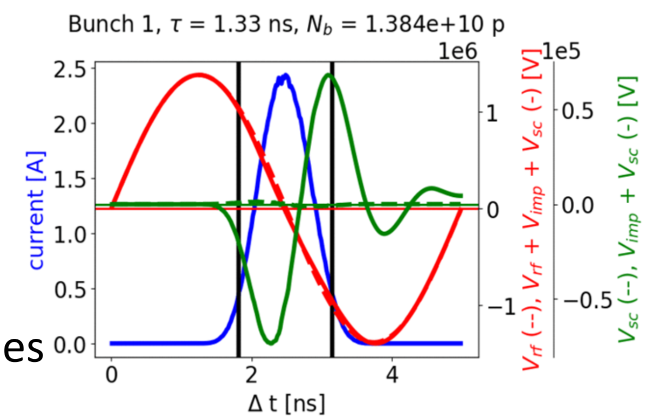

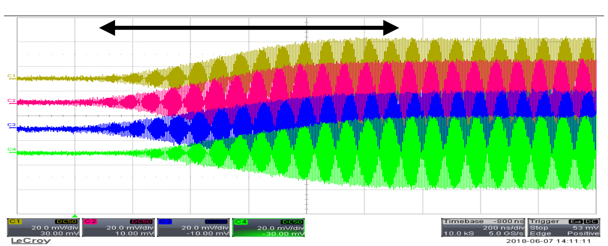

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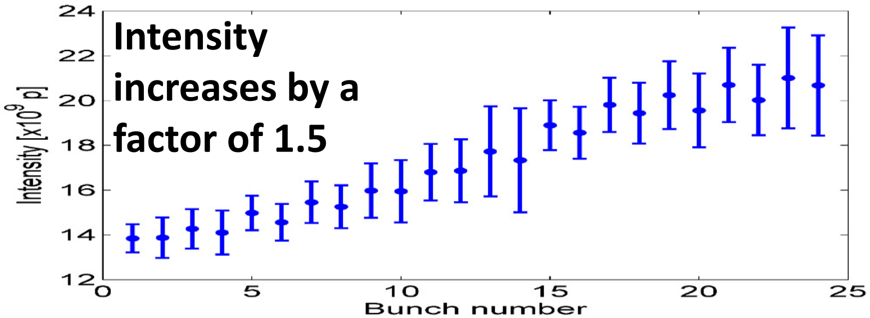

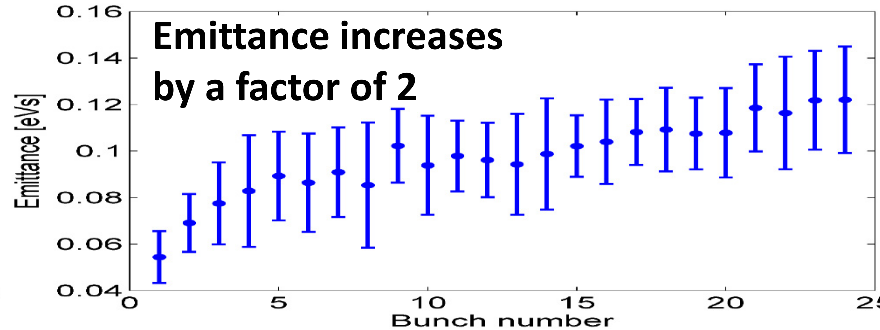

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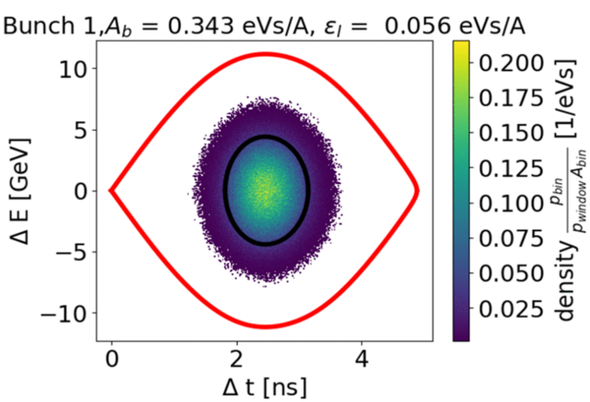

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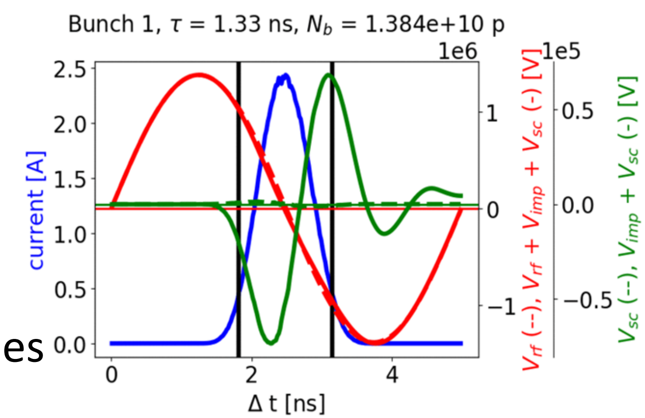
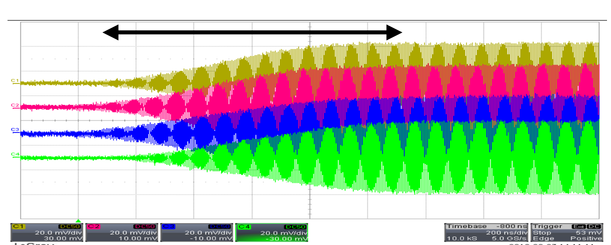


- The two batches are separated by large T_b= 2.7 μs (T_b^{th}= 1 μs)
  - ➢ In this way $\alpha \gg 4$ when T_b=T_b^{th} and adiabaticity is preserved



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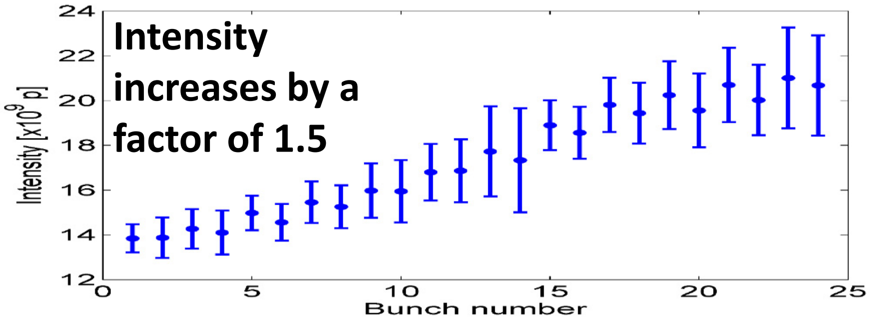

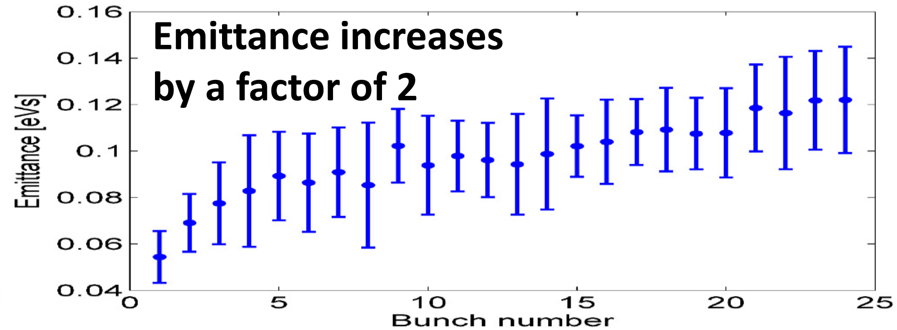

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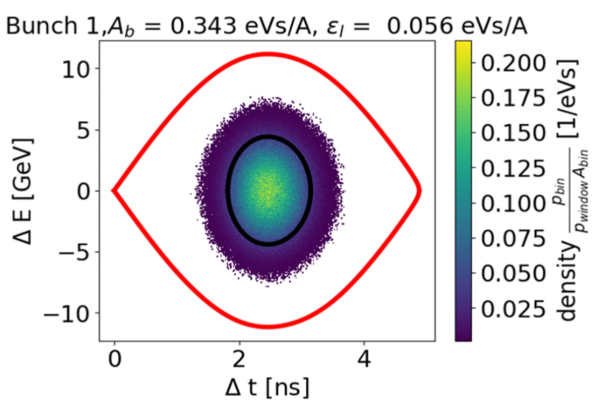

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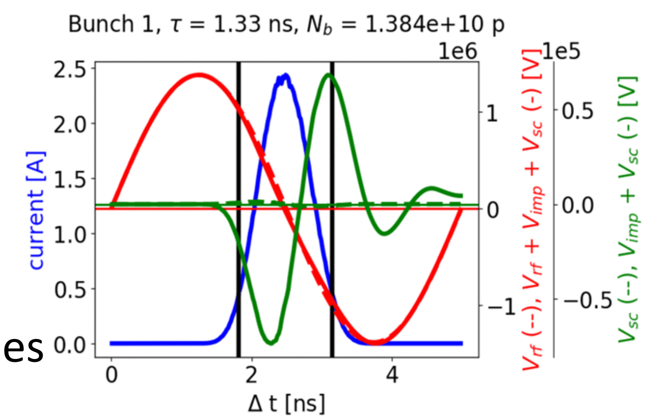
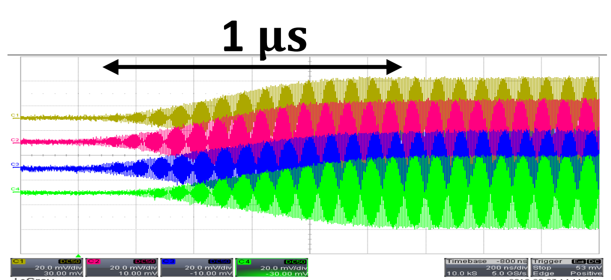
- ➢ 'Low' RF voltage needed (1.4 MV) relative to current operational one (7 MV)
- ➢ Induced voltage cumulates along each batch of 24 bunches



- The two batches are separated by large T_b= 2.7 μs (T_b^{th}= 1 μs)
  - ➢ In this way $\alpha \gg 4$ when T_b=T_b^{th} and adiabaticity is preserved

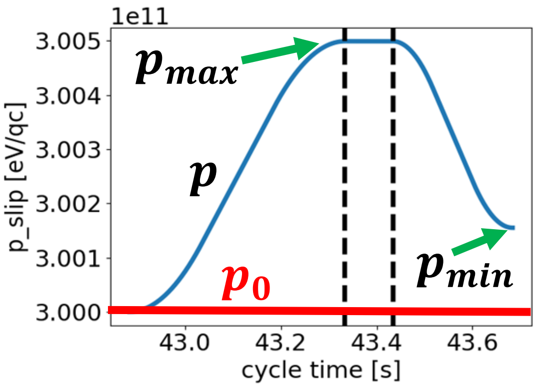


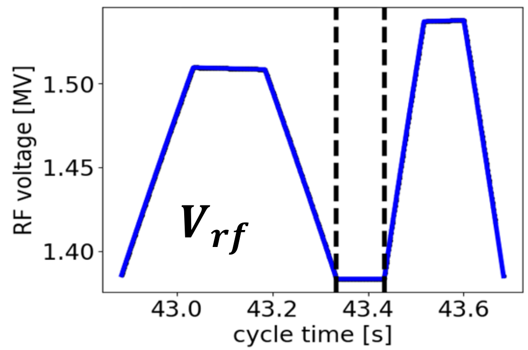
Measurements of cavity voltage rise during batch passage (courtesy T. Bohl)

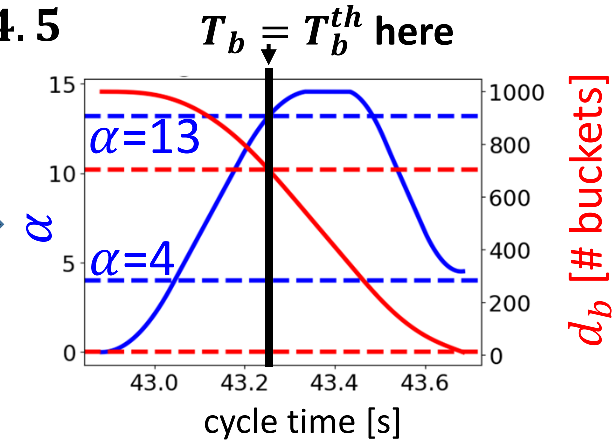
Design of RF programs

- The RF voltage program during slip-stacking is calculated from the momentum program for constant filling factor of bucket in energy $\boldsymbol{q_e^{mss}}$
- The batches move in opposite directions relative to ΔE=0 ($f_{rf}^1 + f_{rf}^2 = 2f_{rf,0}$, $V_{rf}^1 = V_{rf}^2$)

EXAMPLE with $\boldsymbol{q_e^{mss} = 0.65}$ and $\boldsymbol{\alpha_{TX2} = 4.5}$

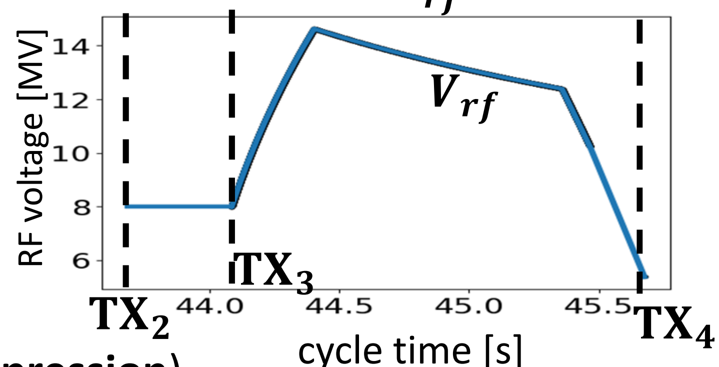






- The capture voltage $\boldsymbol{V_{rf}^{rc}}$ is used in [TX_2,TX_3], then the filling factor in energy at TX_3 of the highest emittance bunch is computed and used to calculate the voltage program in [TX_3,TX_4].

EXAMPLE with $\boldsymbol{V_{rf}^{rc}} = 8$ MV

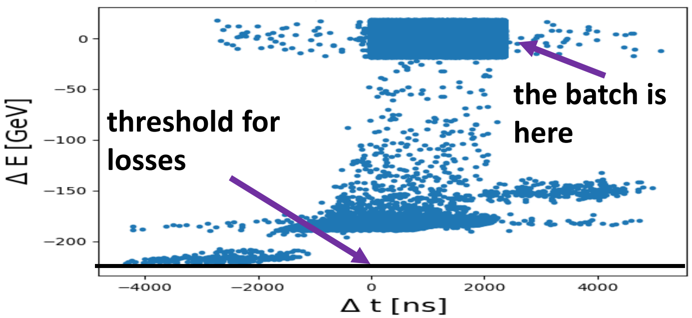


- At flat top two options are considered:
  - V_{rf} is increased adiabatically to 15 MV (**bunch compression**).
  - V_{rf} is increased in few turns to 15 MV (**bunch rotation**).

Constraints and optimizations

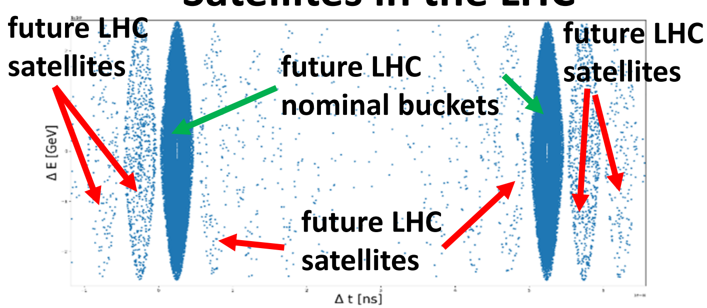
- **Two constraints to take into account**
  - $L_{tot} < 5\ \%$ **(total losses due to momentum slip-stacking, LIU constraint)**
  - $\tau_{max} < 1.65$ **ns (maximum bunch length at SPS extraction, 400 MHz LHC buckets cannot accept more)**
- We divide the total losses in $L_{tot} = L_{SPS} + S_{LHC}$

Losses in the SPS



EXAMPLE

Satellites in the LHC

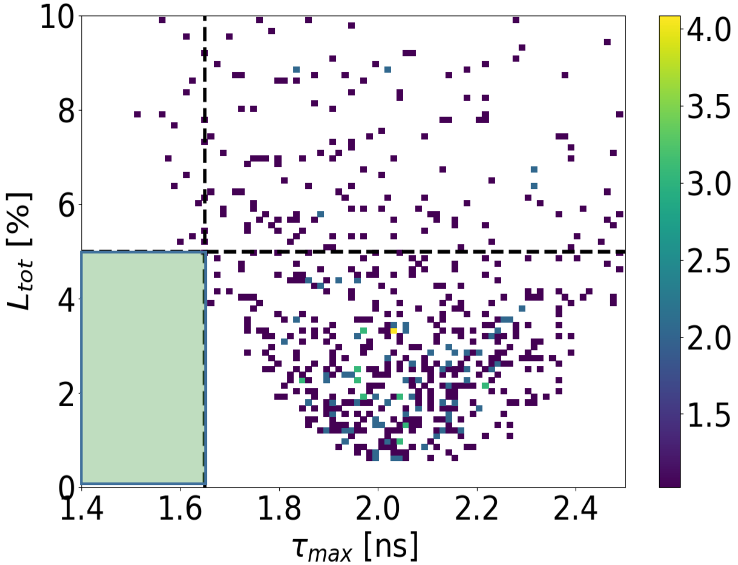


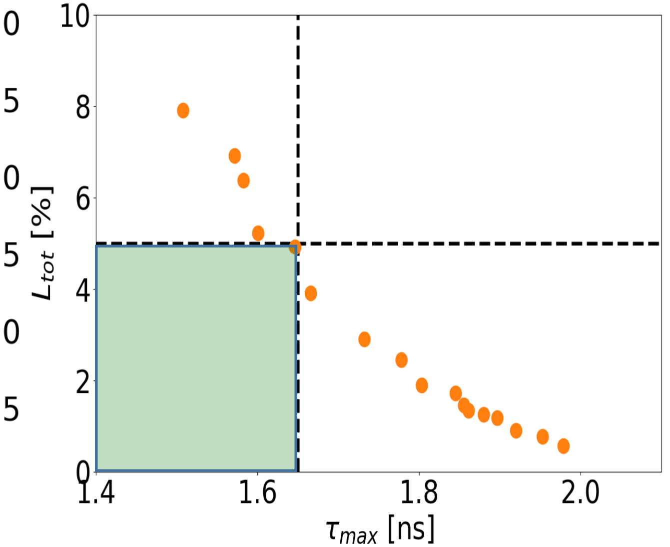
- With all the assumptions given before, simulations are completely defined fixing $\boldsymbol{\alpha_{TX2}}$, $\mathbf{q_e^{mss}}$, $\mathbf{V_{rf}^{rc}}$ and the RF manipulation at flat top (**compression** or **rotation**)
  - It is important to find the combinations which give the lowest L_{tot} and τ_{max} (optimal solutions)
  - The dynamics are too complex to rely only on qualitative studies
  - Parameter scan: $\boldsymbol{\alpha_{TX2}}$ (3.5->8), $\mathbf{q_e^{mss}}$ (0.45->9), $\mathbf{V_{rf}^{rc}}$ (1 MV->9 MV)
- The Q20 optics (γ_{tr}=18) is currently used in operation (detailed analysis)
  - The other two optics (Q22, γ_{tr}= 20), (Q26, γ_{tr}= 23) are briefly mentioned

Q20 optics: bunch compression

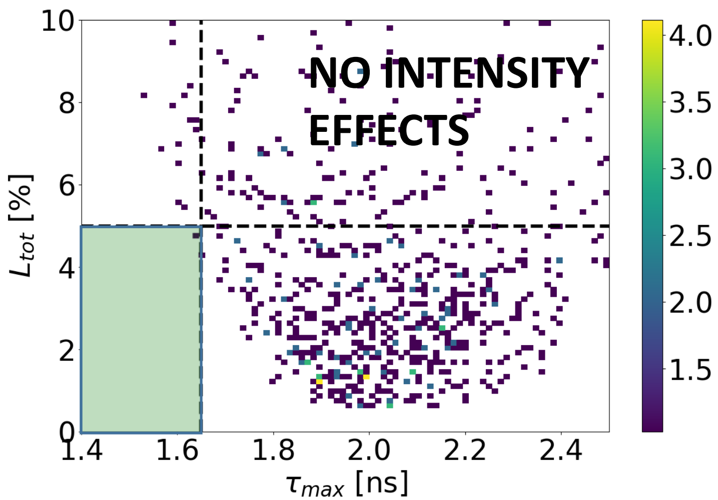
Scan results

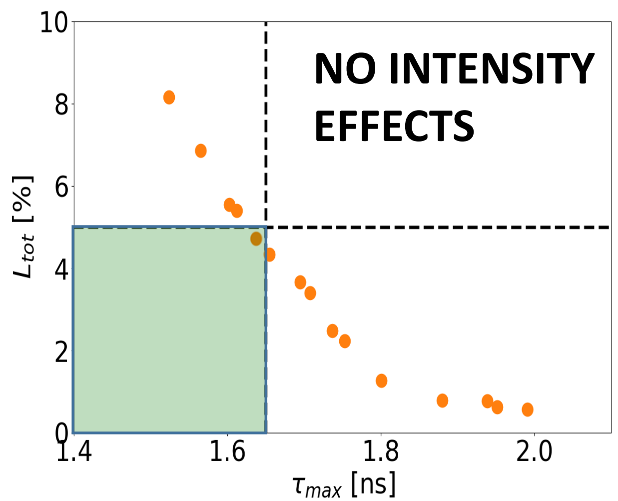
Optimal solutions





- **Constraints are practically not satisfied**
- **Strong limitation on τ_{max} rather than on L_{tot}**



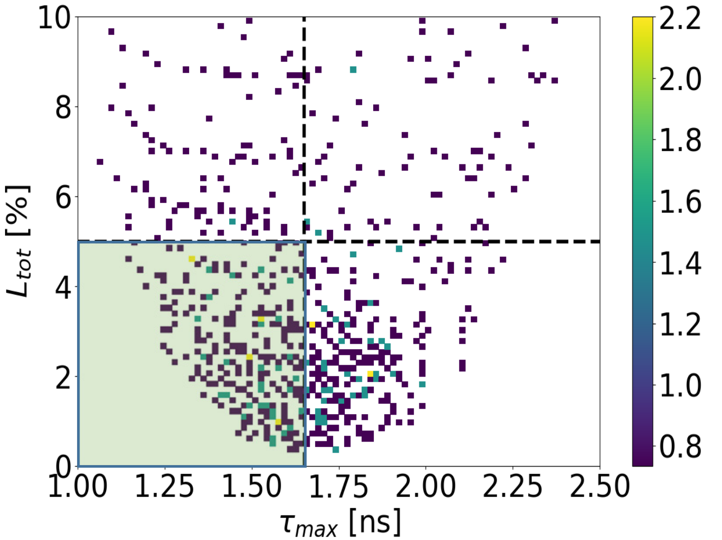


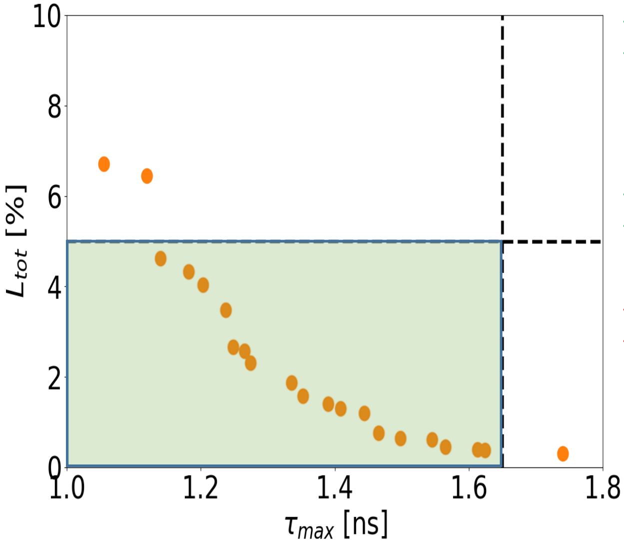
- **No significant difference if intensity effects are off**
- **Intensity effects don't cause additional losses or blow-up**

Q20 optics: bunch rotation

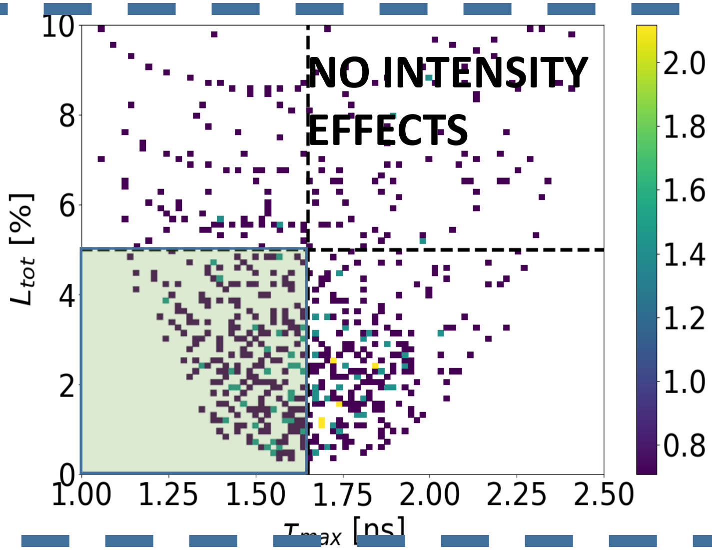
Scan results

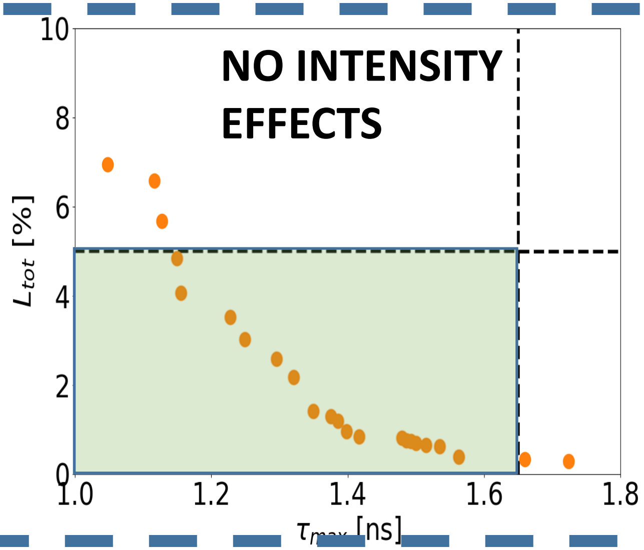
Optimal solutions





- **Bunch rotation allows to significantly reduce τ_{max} without increasing L_{tot}**
- **Constraints satisfied by half of the combinations**
- **However 'S' shape at extraction could complicate transmission into LHC**



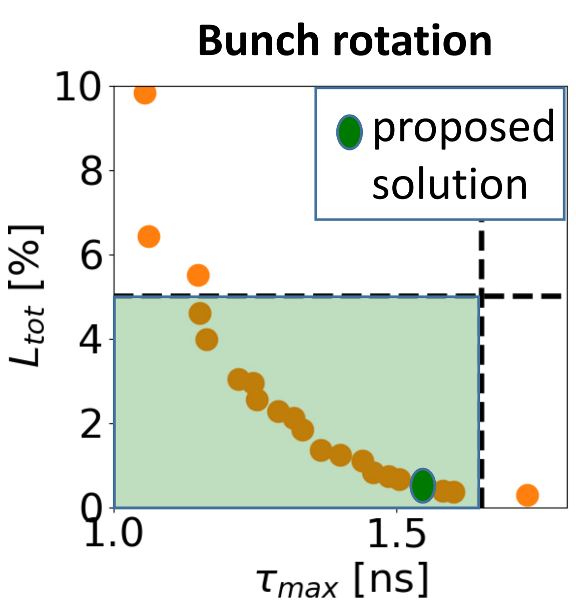


- **Again no significant difference if intensity effects are off**

Q20 optics: proposed solution

- **Only bunch rotation can fulfil the requirements.**

- Giving priority to loss reduction and keeping some safety margin for the bunch length we propose the following combination (see also the **Appendix** for more detailed analysis)



The solution largely fulfills LIU requirements

- $\boldsymbol{L_{tot} = 0.43\ \%}$
- $\boldsymbol{\tau_{max} = 1.55}$ **ns**
- $\boldsymbol{S_{LHC} = 0.13\ \%}$
- $\boldsymbol{L_{SPS} = 0.30\ \%}$

- $\boldsymbol{\alpha_{TX2} = 4.5}$
- $\boldsymbol{q_e^{mss} = 0.65}$
- $\boldsymbol{V_{rf}^{rc} = 8}$ **MV**

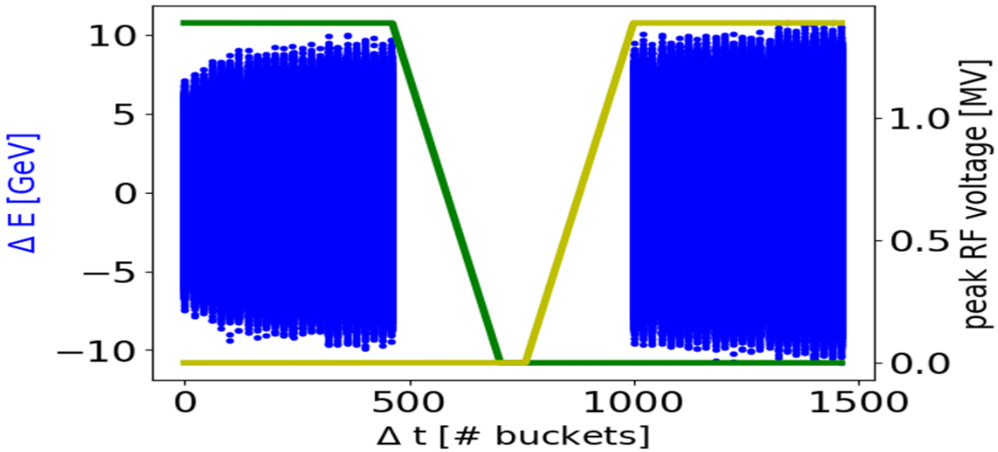
- Low q_e^{mss} helps limiting the losses in SPS during slip-stacking
- Low q_e^{mss} and $\alpha_{TX2} > 4$ helps limiting influence of chaotic motion in $\Delta E = 0$ making S_{LHC} low

The solution is feasible

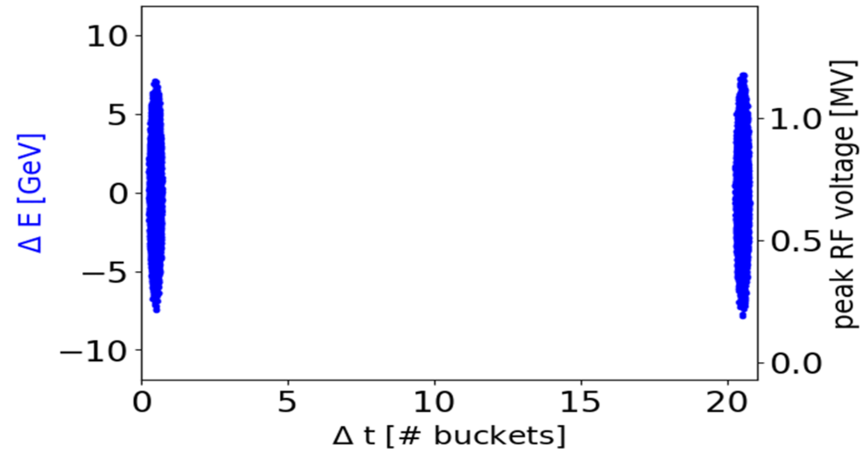
- $\Delta R_{max}^{mss} = 8$ mm < 20 mm (one-side aperture limitation)
- $\Delta f_{rf,max}^{mss}$ = 1 kHz << 1 MHz (200 MHz TWC bandwidth)
- $V_{rf}^{max} = 14.6$ MV < 15 MV (available peak voltage)

Proposed solution: slip-stacking

General frame, V_{rf}^{1}, V_{rf}^{2}

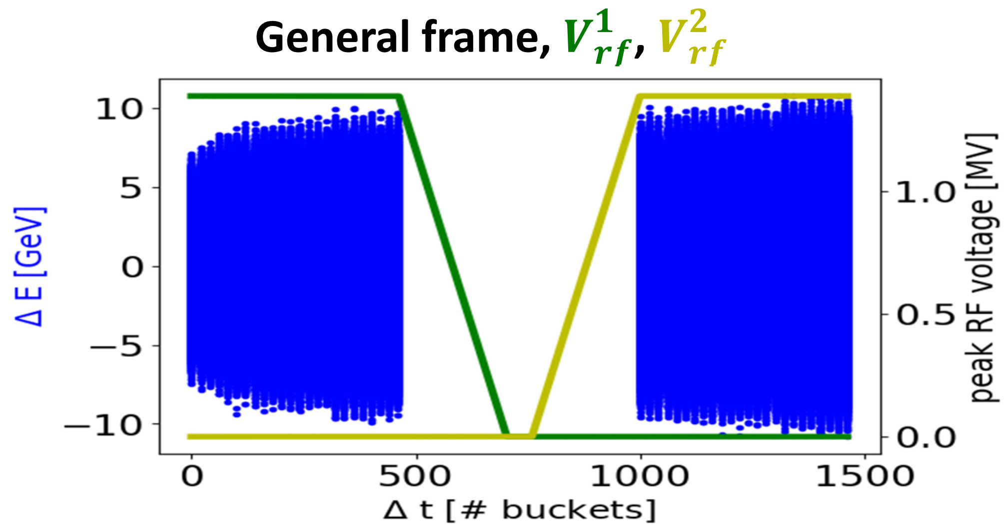


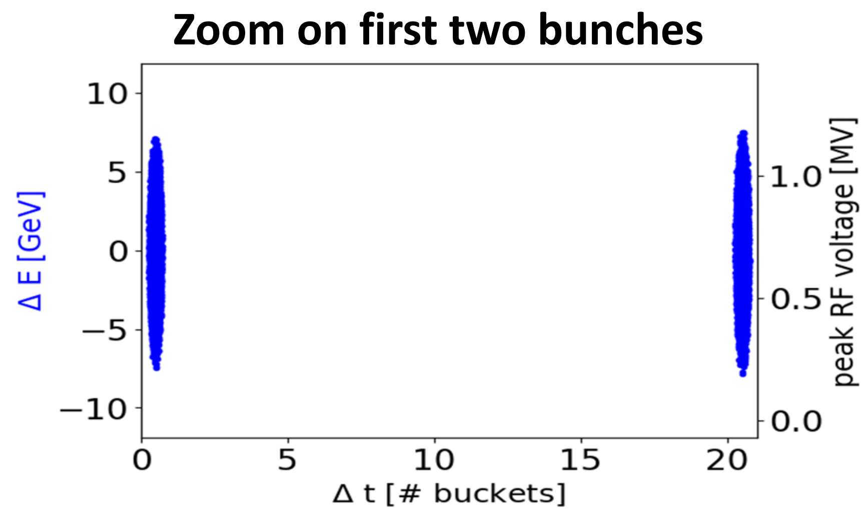
Zoom on first two bunches



- As expected only few particle lost during slip-stacking $(q_e^{mss} = 0.65)$
- Low impact of chaotic motion in $\Delta E = 0$ $(\alpha_{TX2} = 4.5)$

Proposed solution: slip-stacking





- As expected only few particle lost during slip-stacking ($\boldsymbol{q_e^{mss} = 0.65}$)
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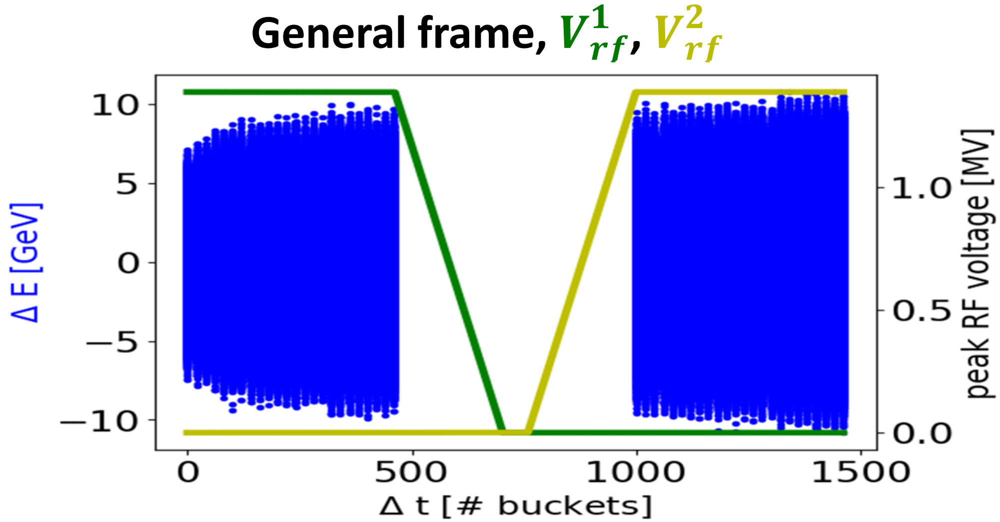

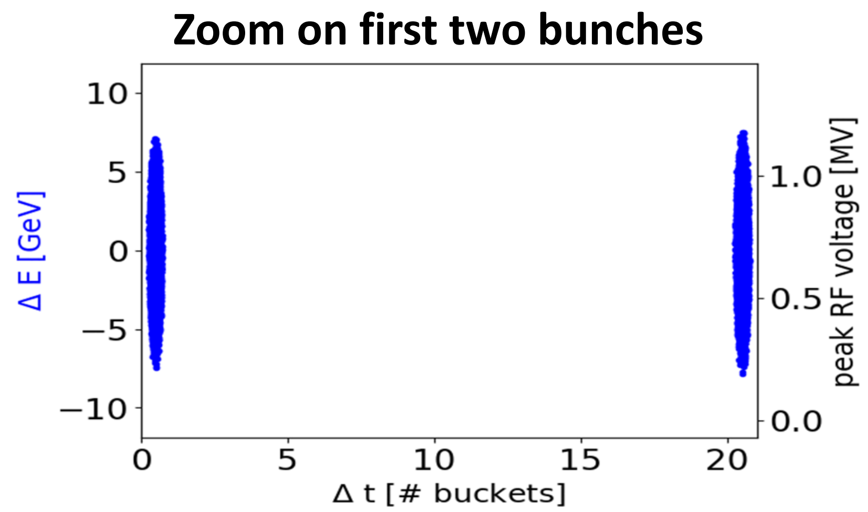

- As expected only few particle lost during slip-stacking ($q_e^{mss} = 0.65$)
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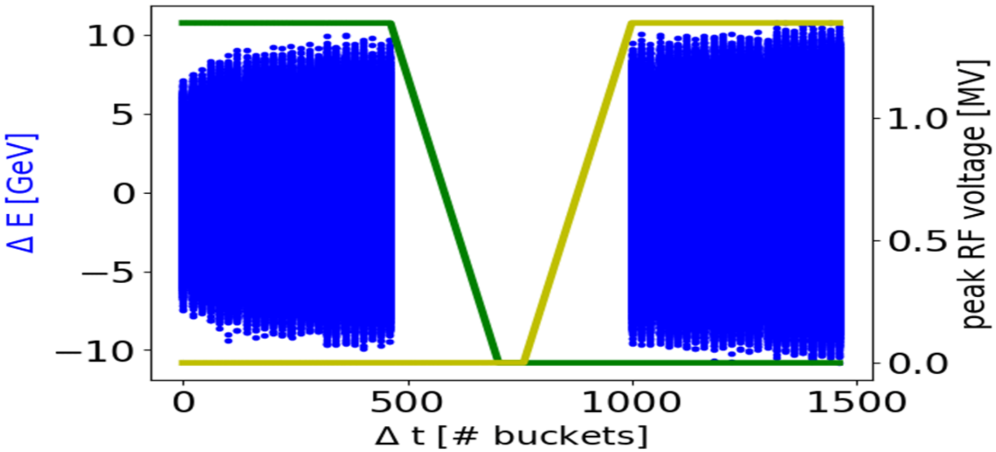
General frame, V_{rf}^{1}, V_{rf}^{2}



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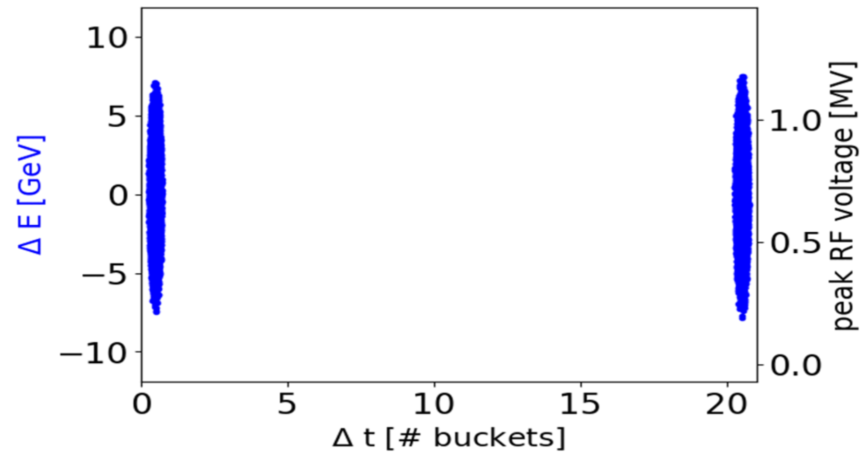

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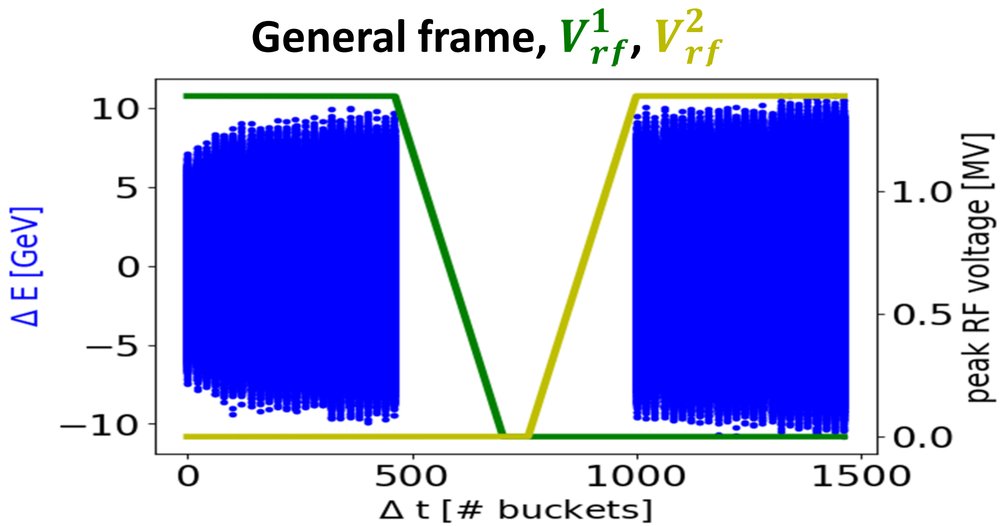
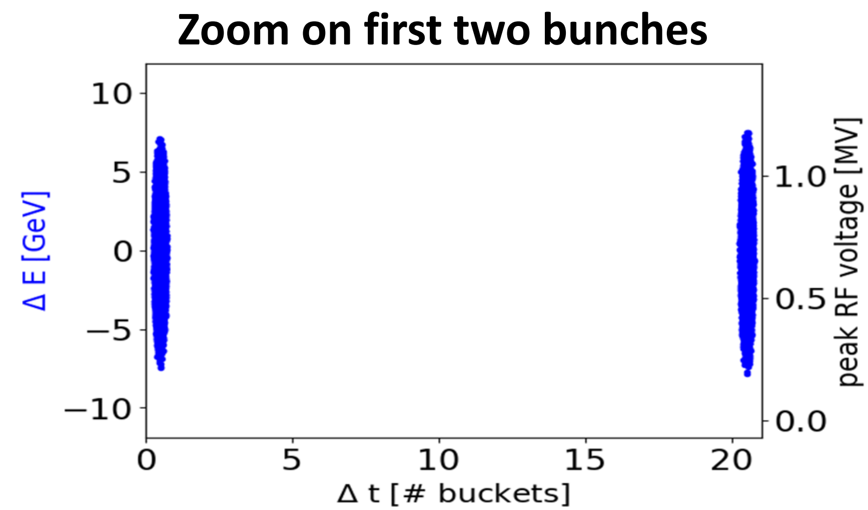


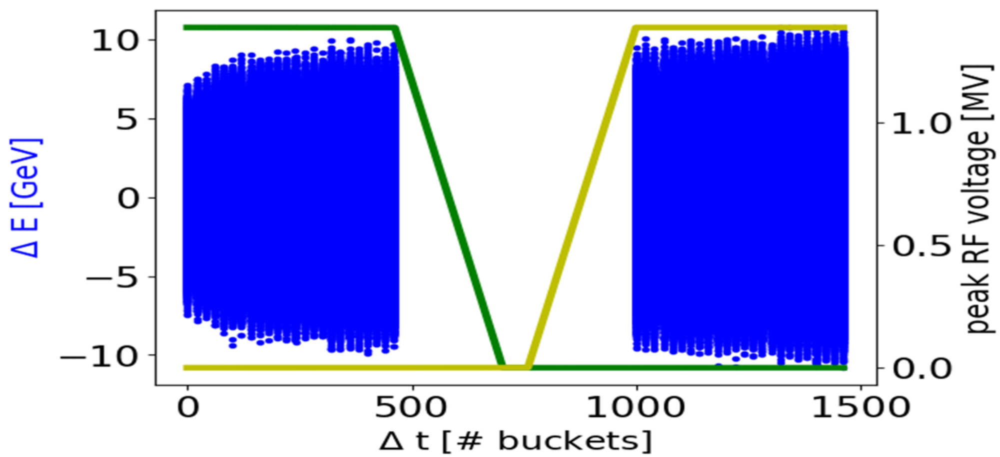


- As expected only few particle lost during slip-stacking ($\boldsymbol{q_e^{mss} = 0.65}$)
- Low impact of chaotic motion in $\Delta E = 0$ ($\boldsymbol{\alpha_{TX2} = 4.5}$)

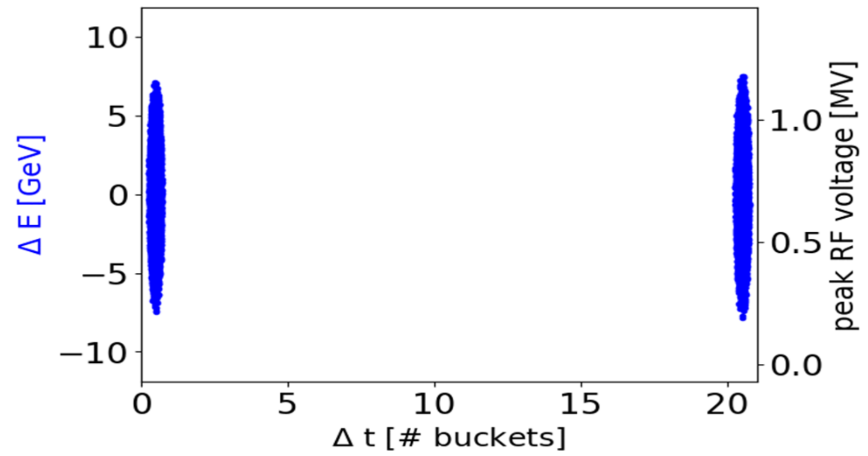
- RF perturbation causes resonances at the end of slip-stacking (even without intensity effects)
  - ➢ Predicted by theory [2]

Proposed solution: slip-stacking

General frame, V_{rf}^1, V_{rf}^2



Zoom on first two bunches



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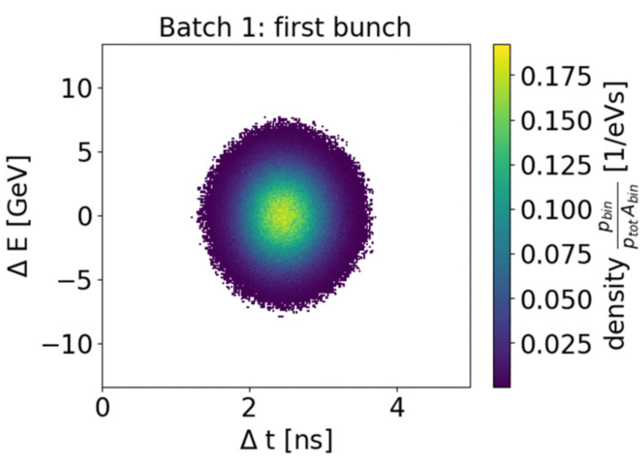

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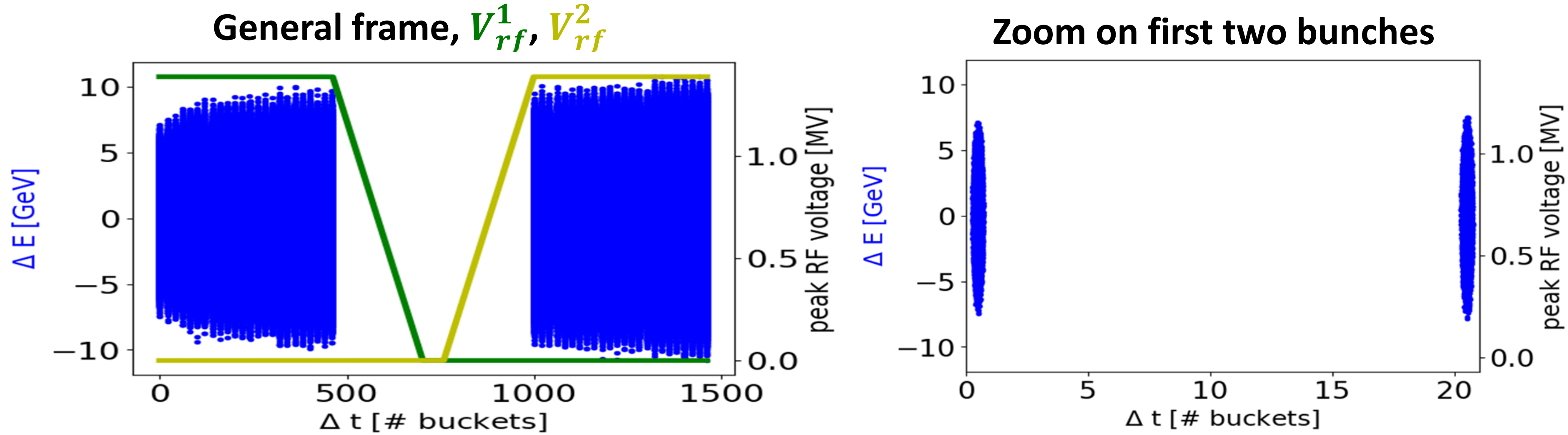

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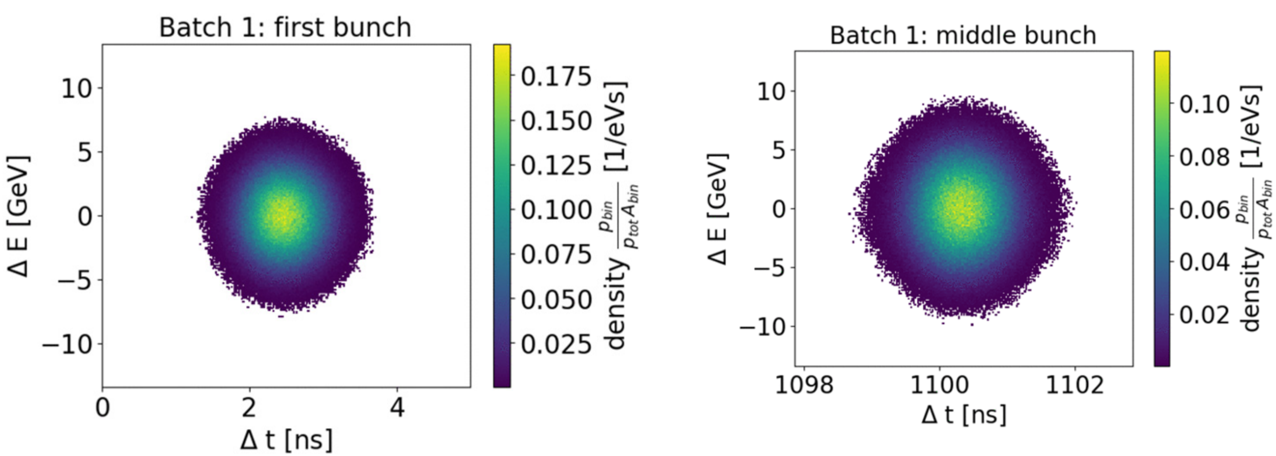

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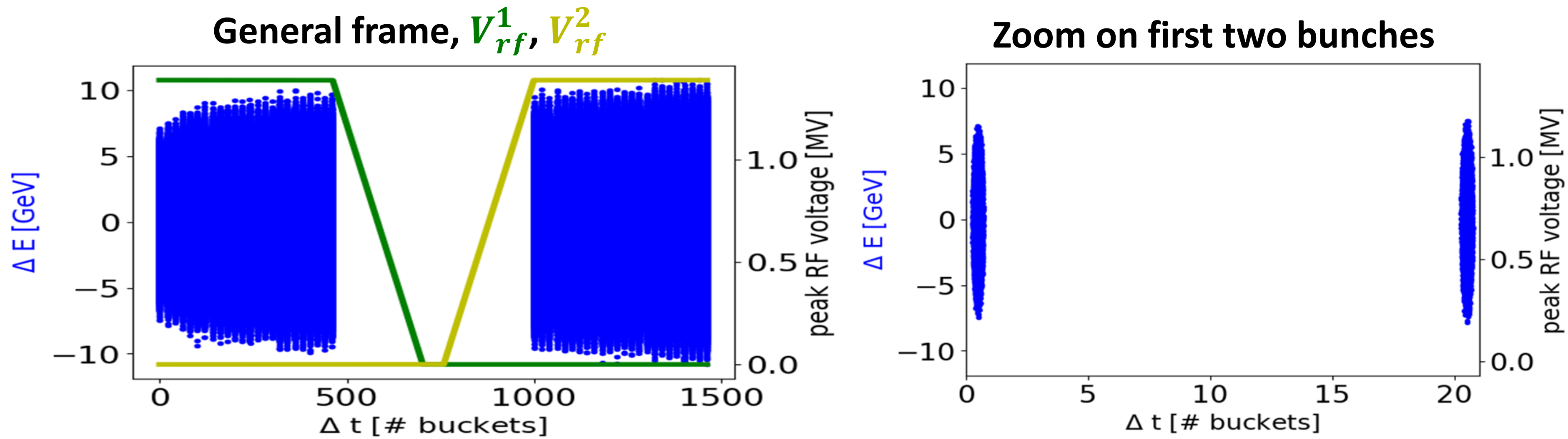

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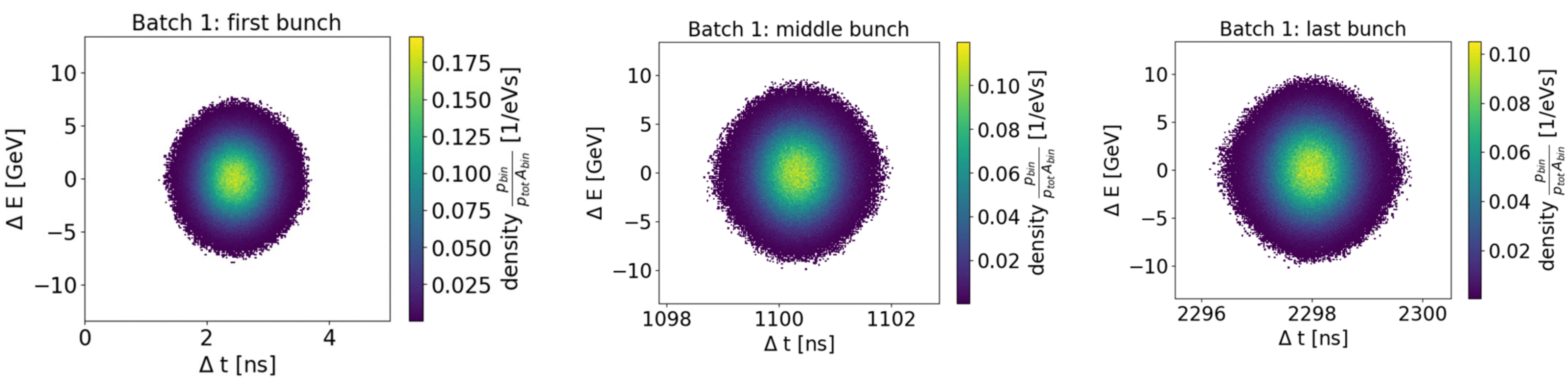

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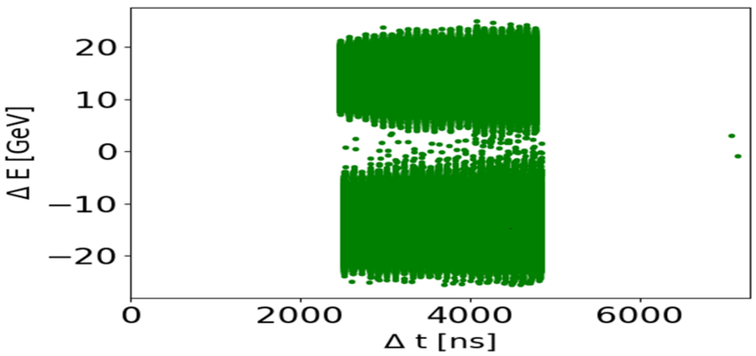
Proposed solution: capture and ramp

General frame bunches are yellow at TX_3



- Few losses due to recapture and acceleration of higher emittance bunches

Proposed solution: capture and ramp

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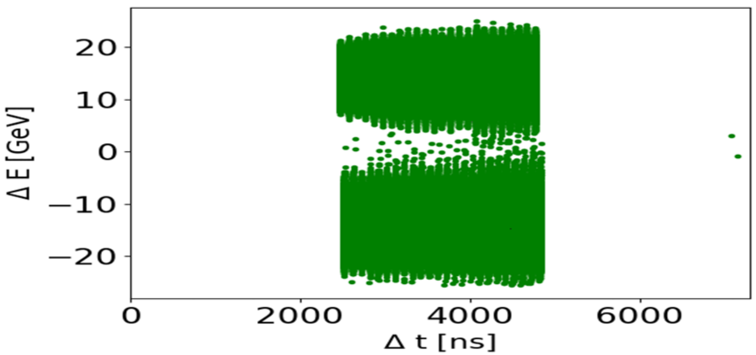

- Few losses due to recapture and acceleration of higher emittance bunches
- Hollow bunches due to mismatch in recapture bucket (even without int. effects)
- Dense area in phase space never filaments for shorter bunches **(only with int. effects, see Appendix)**

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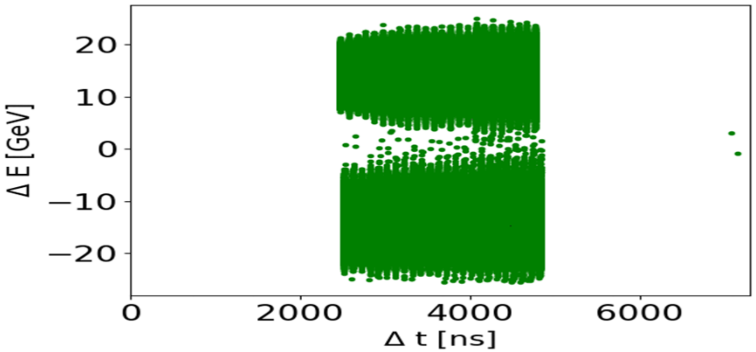

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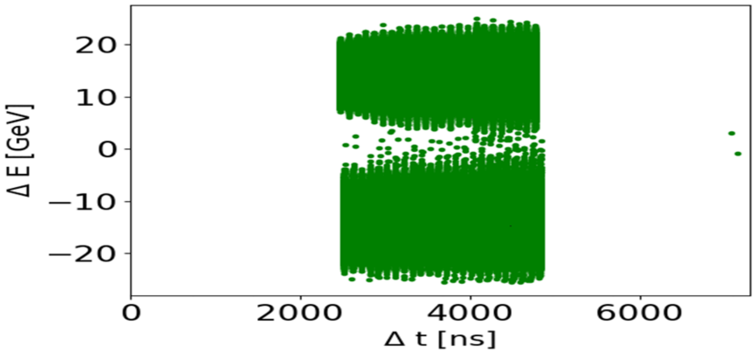

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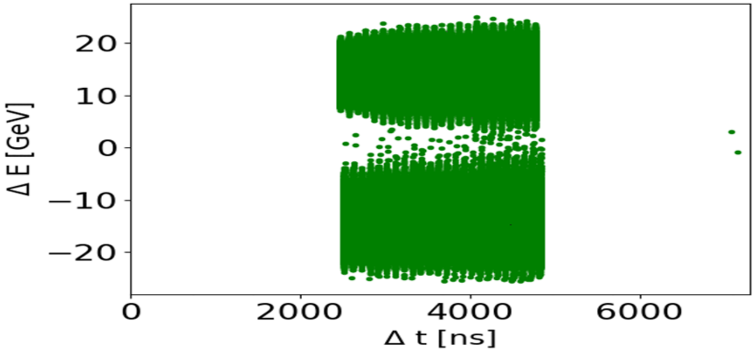

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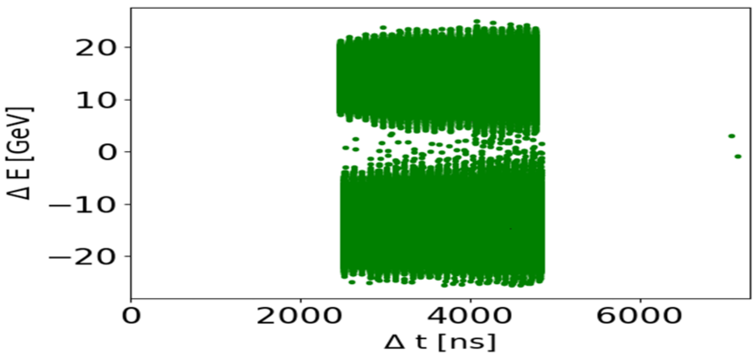

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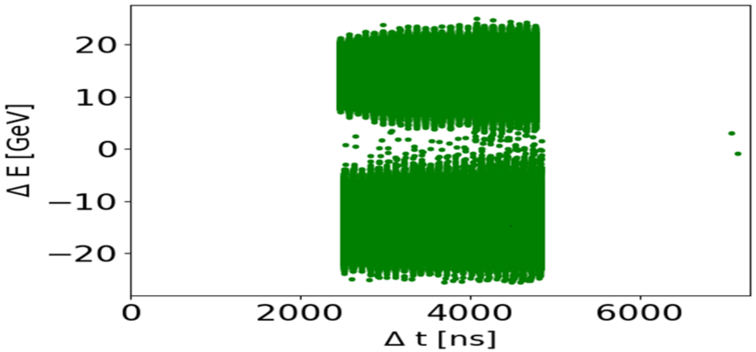
Middle bunch

Proposed solution: capture and ramp

General frame bunches are yellow at TX_3



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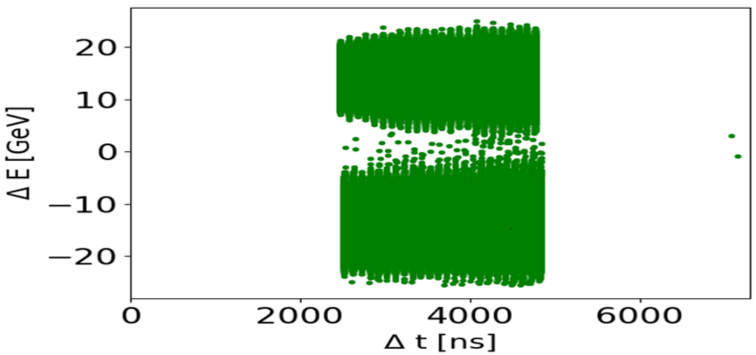
First bunch

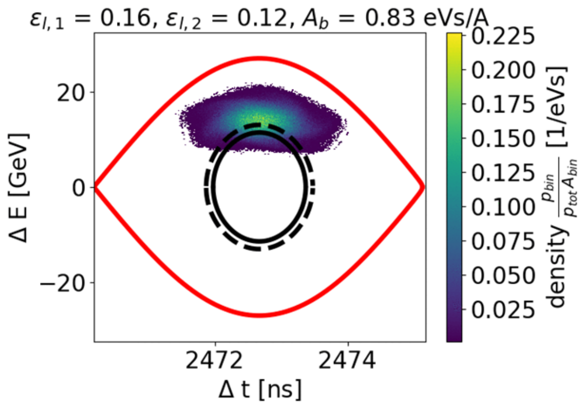
Middle bunch

Proposed solution: capture and ramp

General frame bunches are yellow at TX_3



First bunch



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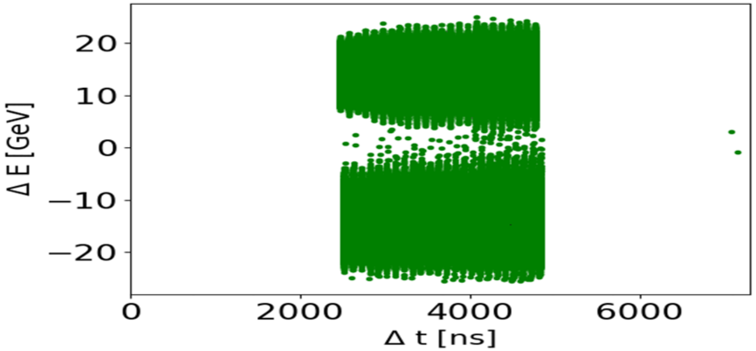

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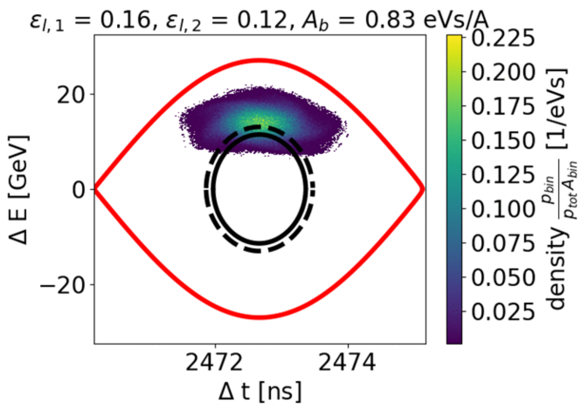
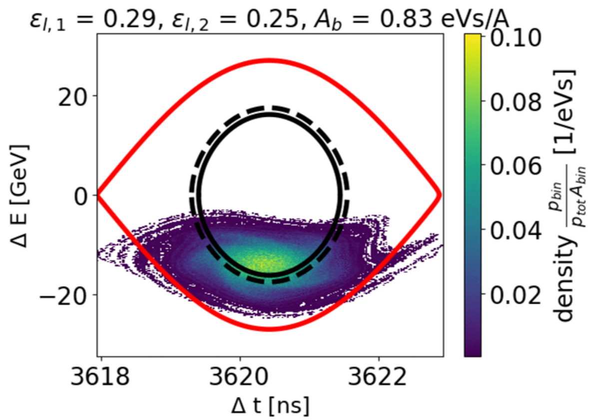


Middle bunch



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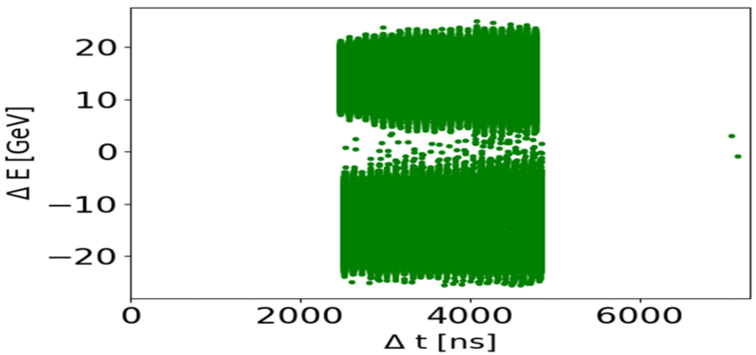

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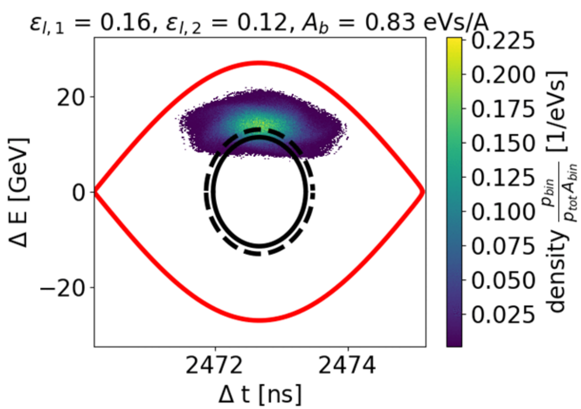
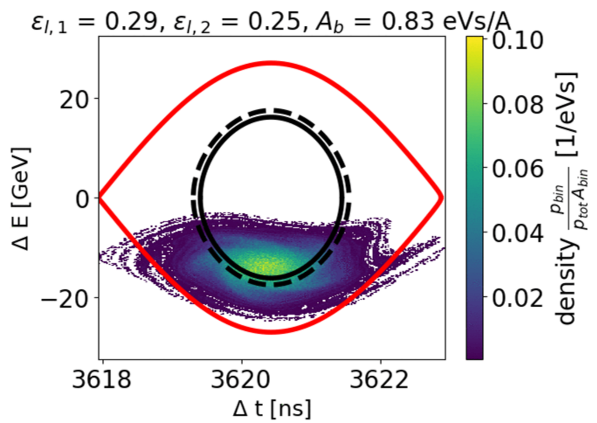
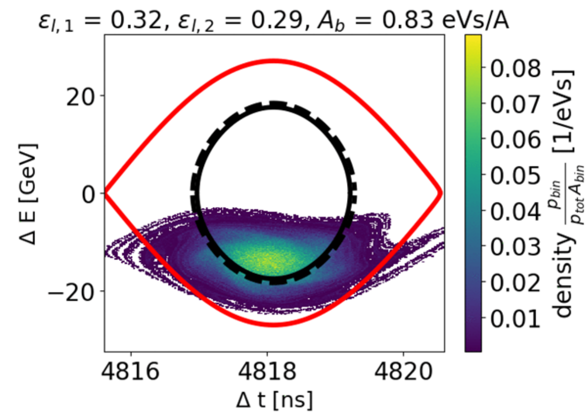


Middle bunch





Proposed solution: capture and ramp

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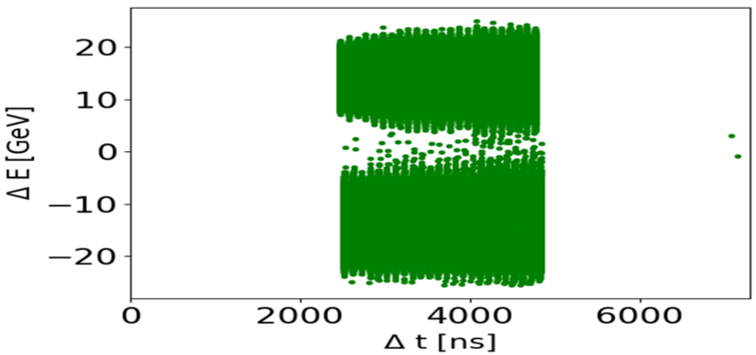

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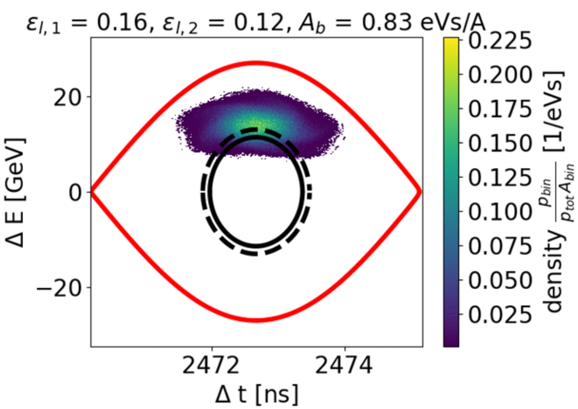
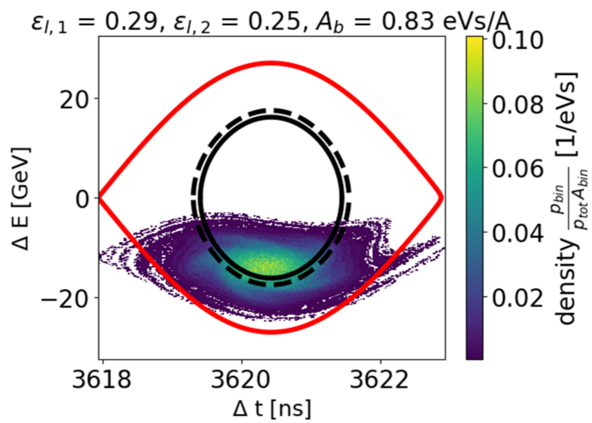
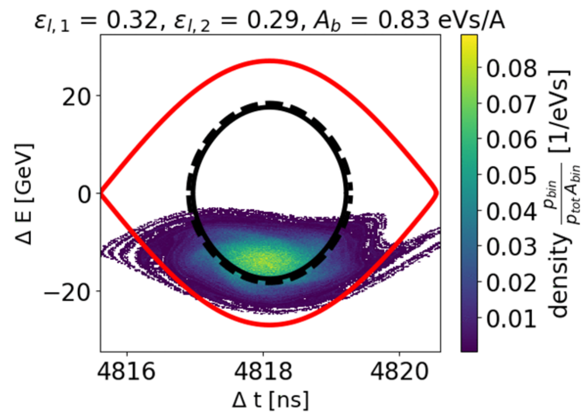
- Dense area in phase space never filaments for shorter bunches **(only with int. effects, see Appendix)**

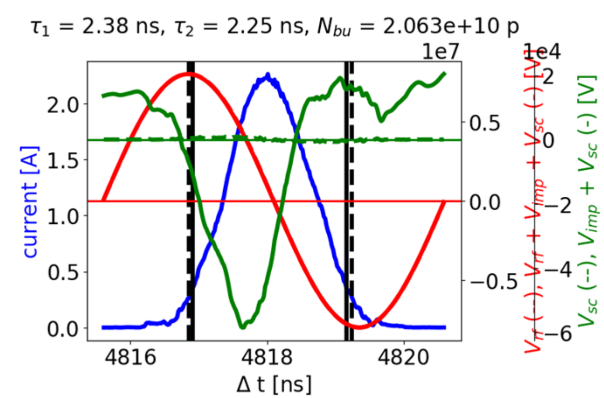
First bunch



Middle bunch

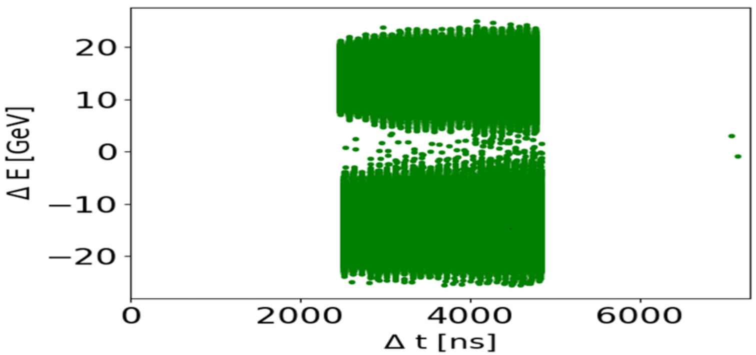






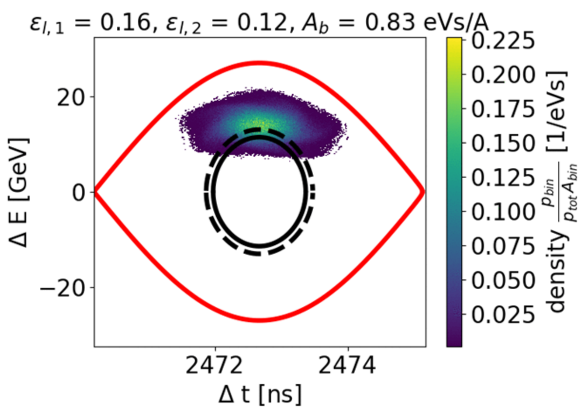
Proposed solution: capture and ramp

General frame bunches are yellow at TX_3

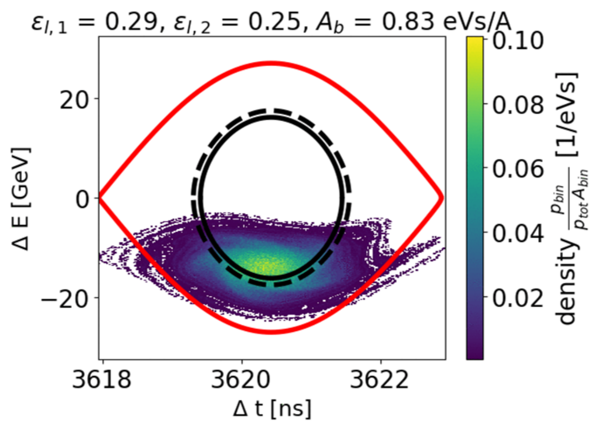


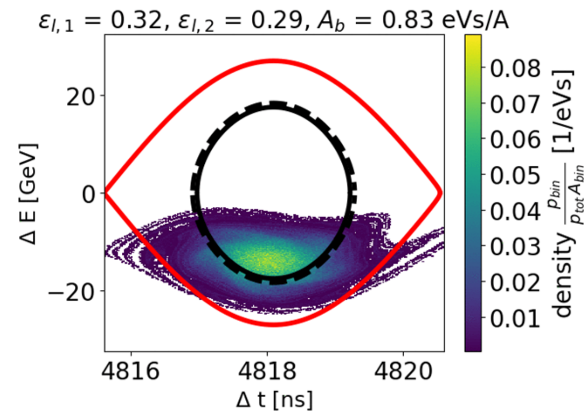
- Few losses due to recapture and acceleration of higher emittance bunches
- Hollow bunches due to mismatch in recapture bucket (even without int. effects)
- Dense area in phase space never filaments for shorter bunches **(only with int. effects, see Appendix)**

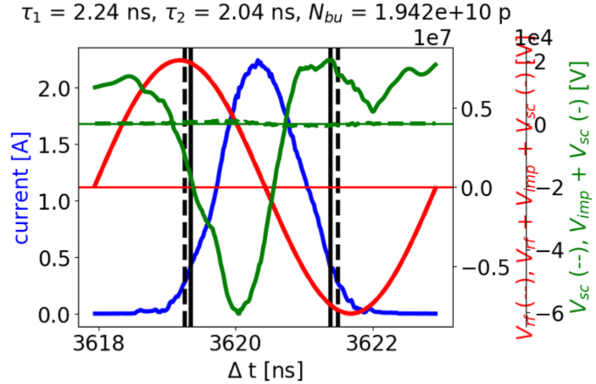
First bunch

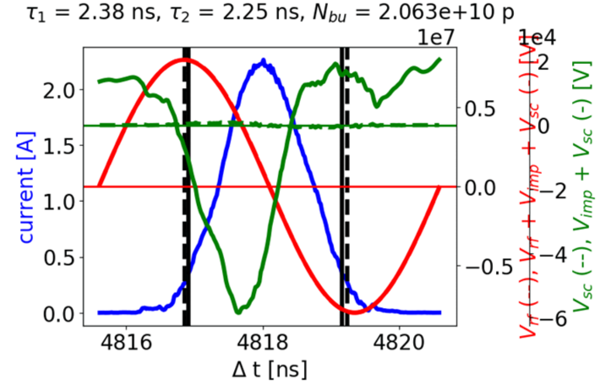


Middle bunch



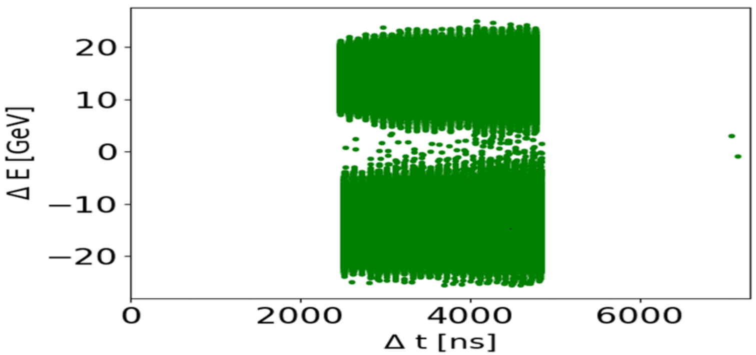






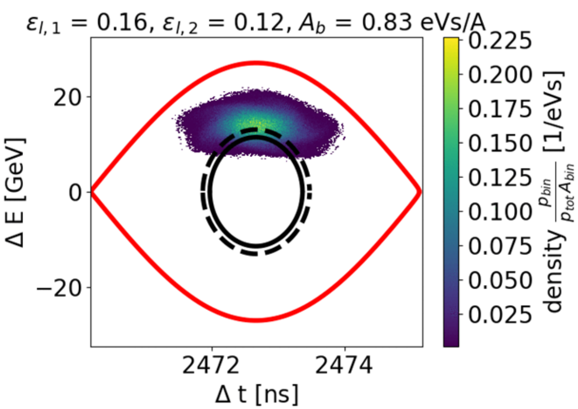
Proposed solution: capture and ramp

General frame bunches are yellow at TX_3

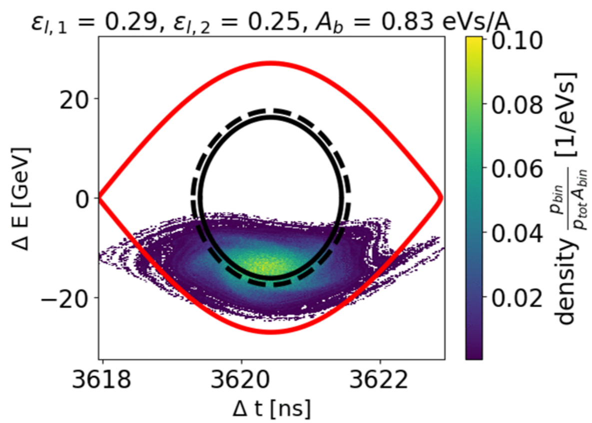


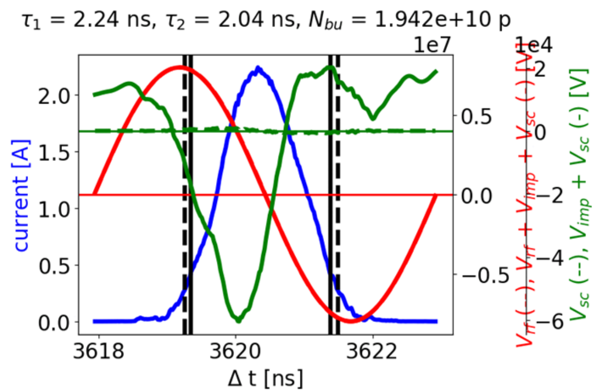
- Few losses due to recapture and acceleration of higher emittance bunches
- Hollow bunches due to mismatch in recapture bucket (even without int. effects)
- Dense area in phase space never filaments for shorter bunches **(only with int. effects, see Appendix)**

First bunch

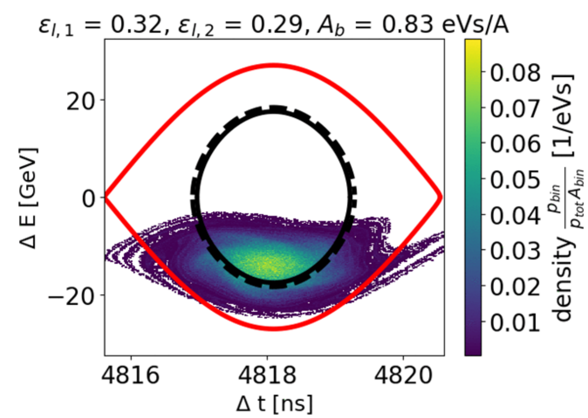


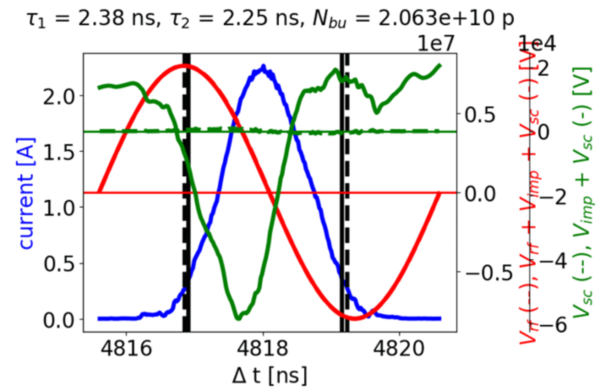
Middle bunch





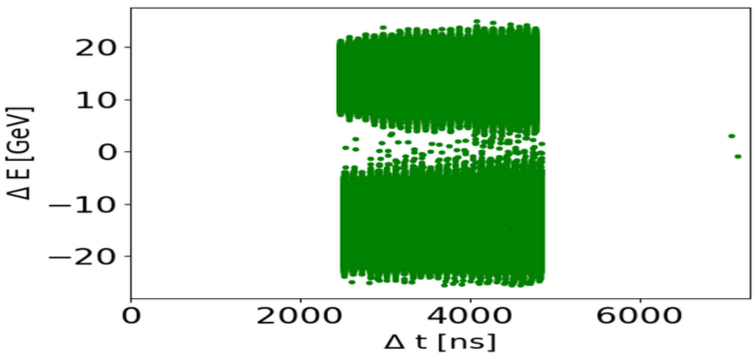
Last bunch





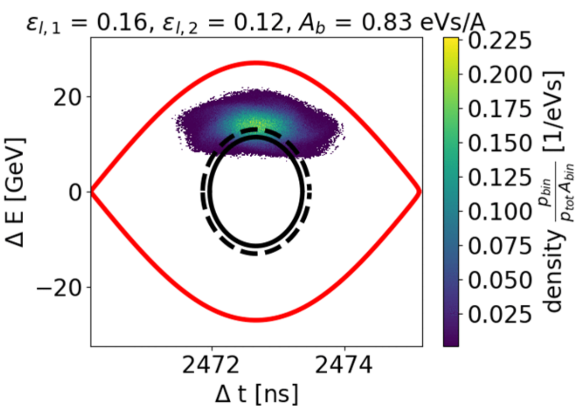
Proposed solution: capture and ramp

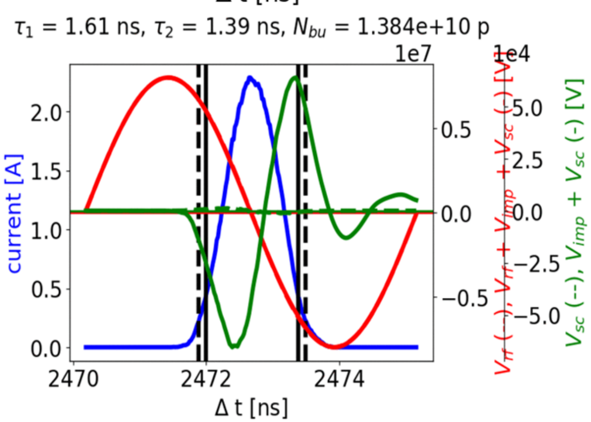
General frame bunches are yellow at TX_3



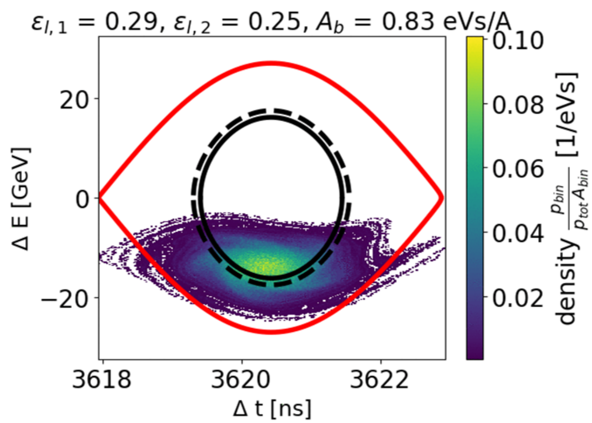
- Few losses due to recapture and acceleration of higher emittance bunches
- Hollow bunches due to mismatch in recapture bucket (even without int. effects)
- Dense area in phase space never filaments for shorter bunches **(only with int. effects, see Appendix)**

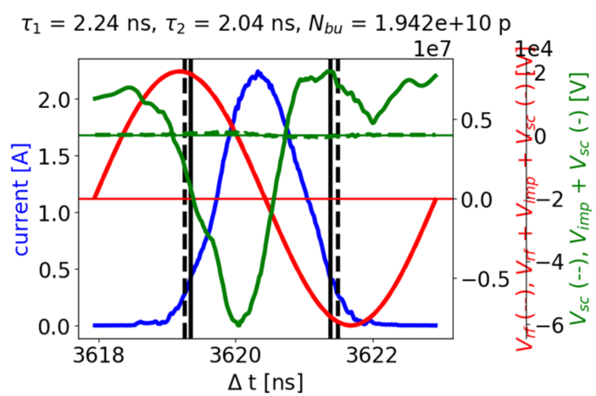
First bunch



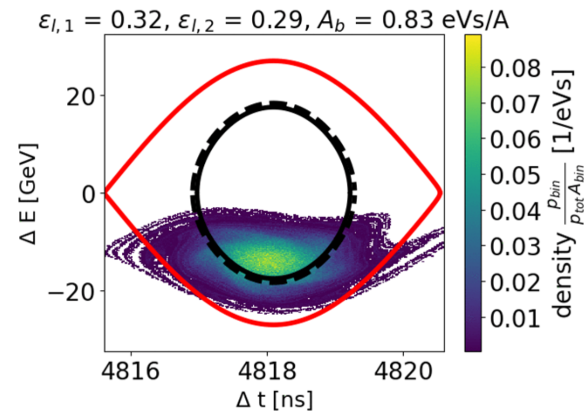


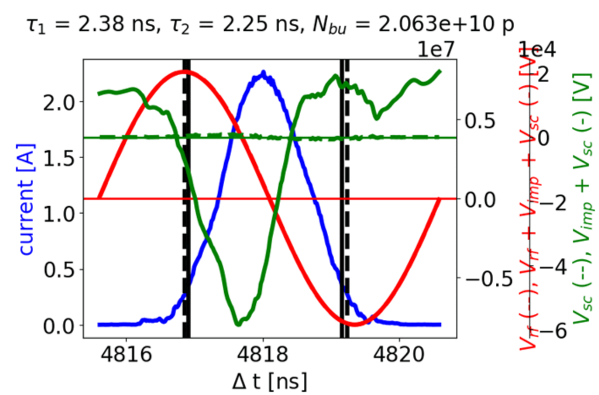
Middle bunch





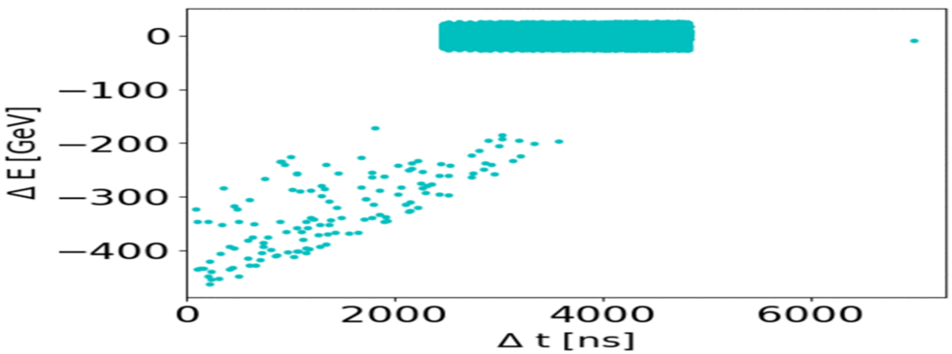
Last bunch





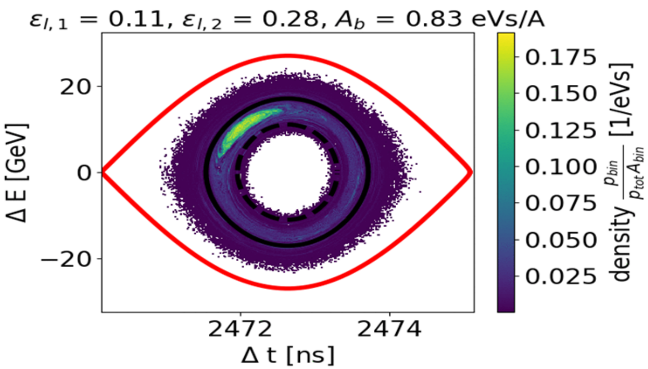
Proposed solution: flat top

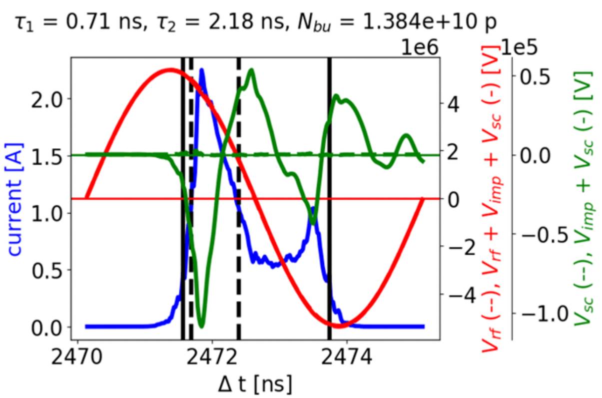
General frame



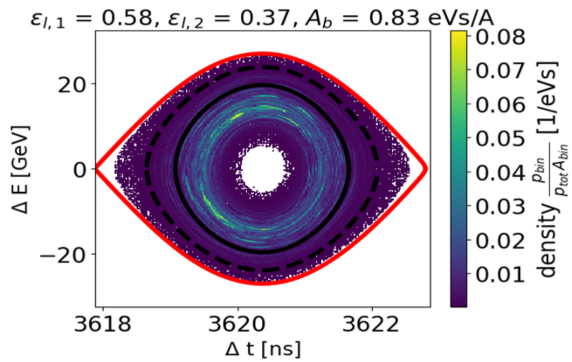
- The dense area remains up to bunch rotation (shortest bunch)
- Structure also for middle and last bunches but less strong

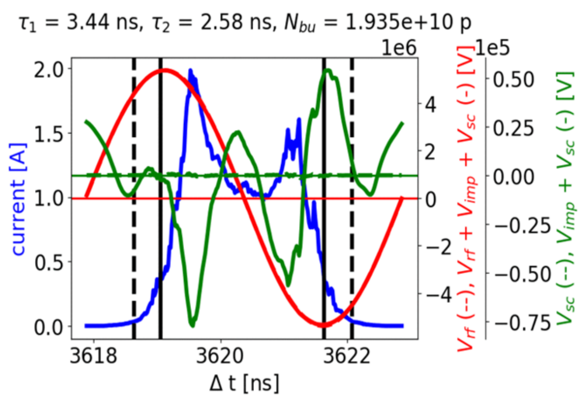
First bunch



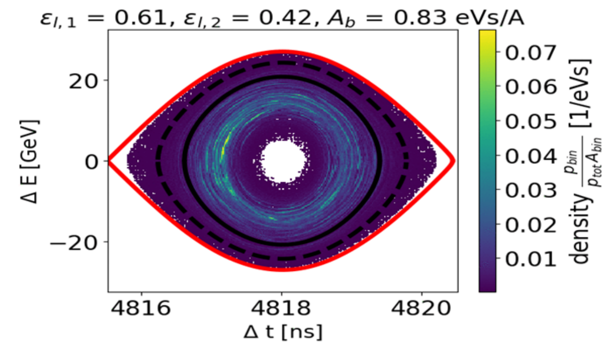


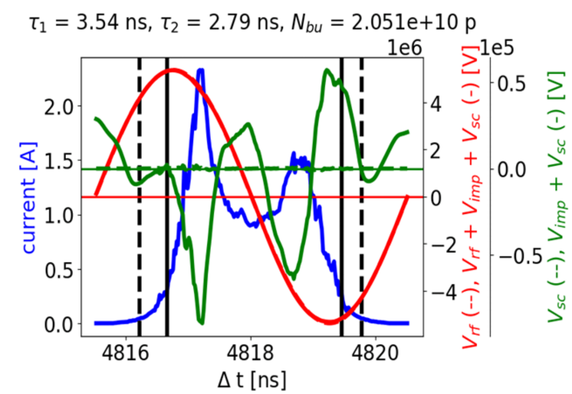
Middle bunch





Last bunch

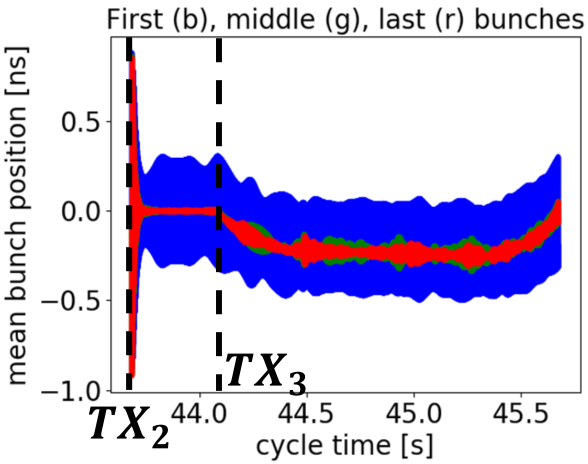




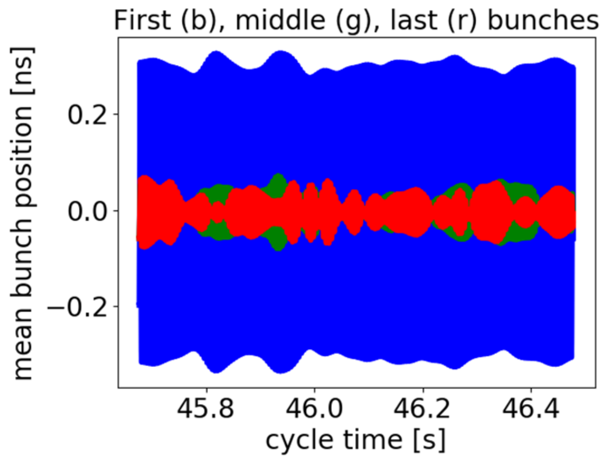
Loss of Landau damping

Dipole oscillations with intensity effects

Recapture and ramp



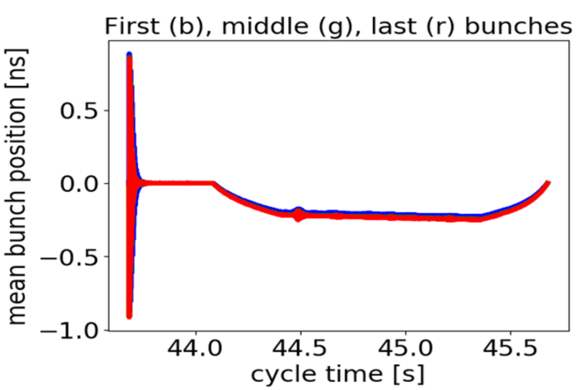
Flat top



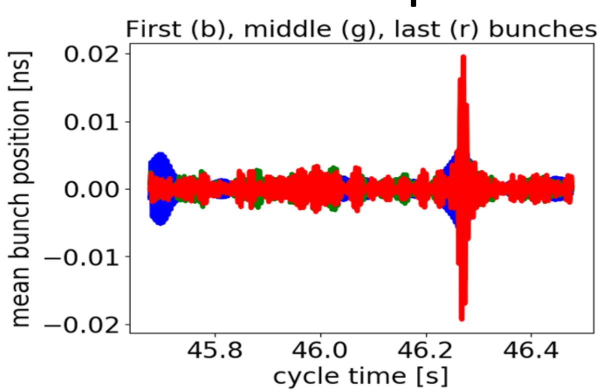
- **Large dipole oscillations never damp**
- **Shortest bunch: amplitude 10% relative to bucket length, LLD at TX_2**
- **Longest bunch: amplitude 2%, LLD not at TX_2 but at TX_3**

Dipole oscillations without intensity effects

Recapture and ramp



Flat top

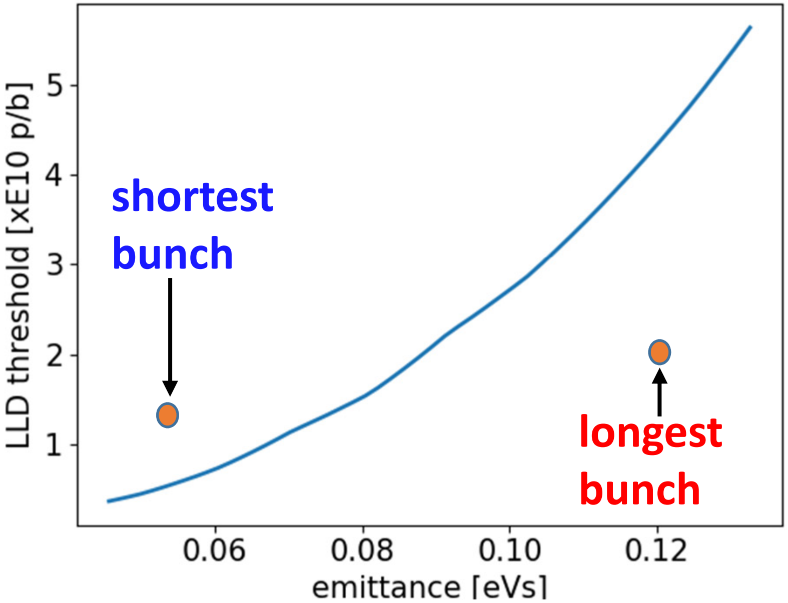


- Very small dipole oscillations for all bunches
- Amplitude only 0.2 % relative to bucket length

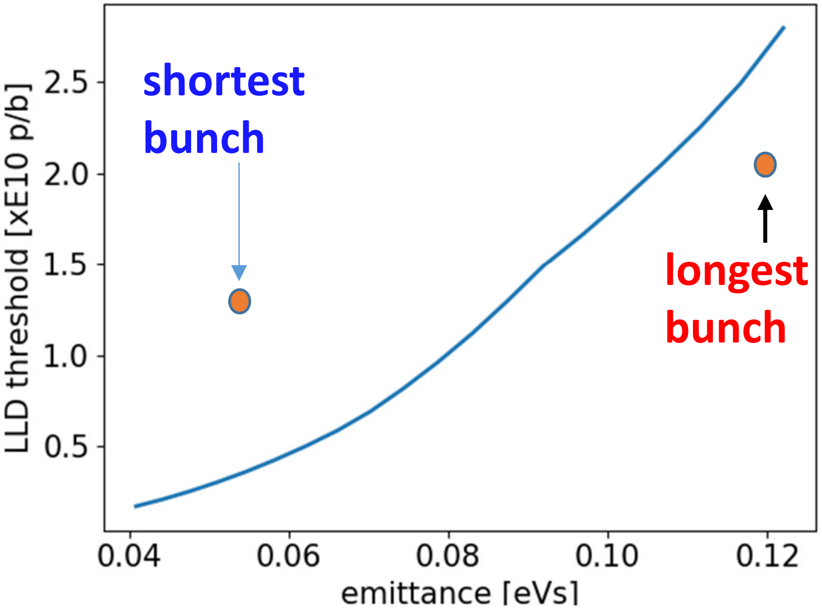
LLD analytical estimations

LLD threshold formula $$N_b < \frac{|\eta|E}{q^2\beta^2}\frac{\tau}{ImZ/n}\left(\frac{\Delta E}{E}\right)^2\frac{\Delta\omega_s}{\omega_s}$$ ***Im Z/n* = 3Ω** [6]

V_{rf} =1.5 MV (during slip-stacking)



V_{rf} =8 MV (at recapture)



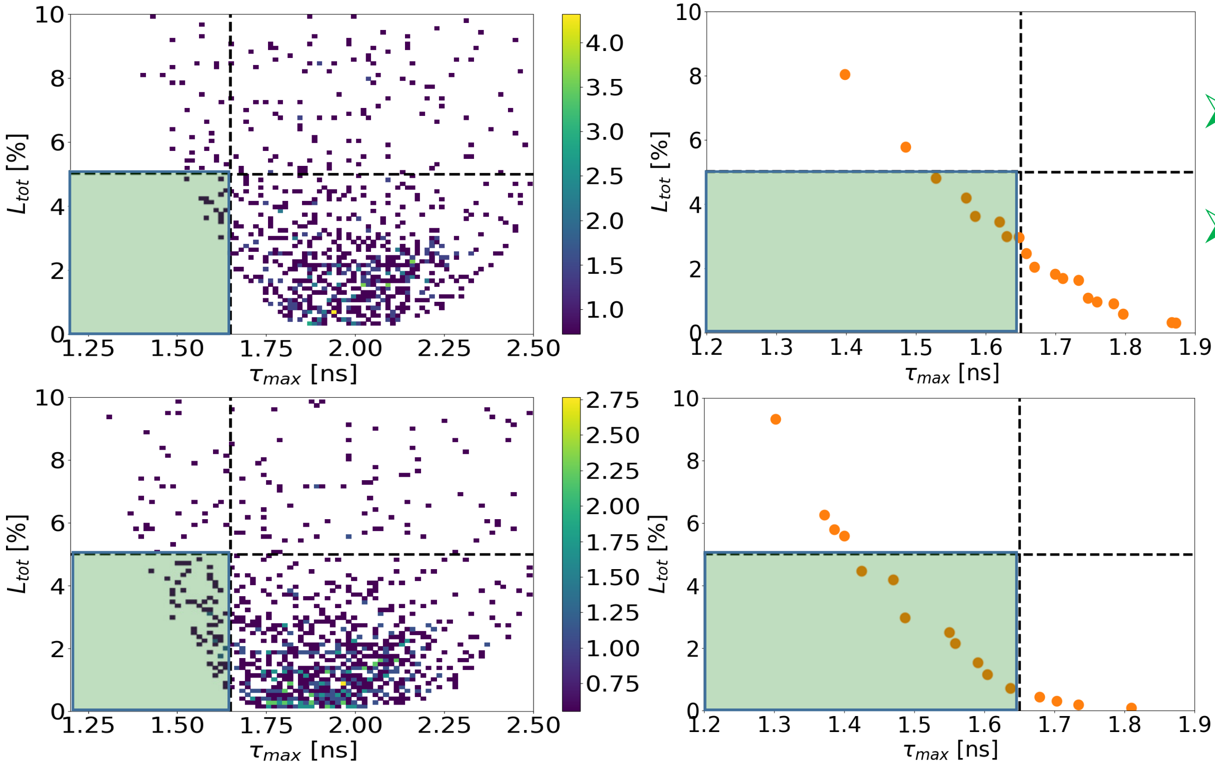
- LLD for shortest bunches even using 'low' RF voltage during slip-stacking
- Analytical estimations confirm what seen in simulations
  - **LLD for shortest bunch at recapture**
  - **Not LLD for longest bunch at recapture**

Q22 and Q26: bunch compression

- Lower η_0 ➡ lower $q_e^{mss} \propto \eta_0^{1/4}$ ➡ significant lower $\boldsymbol{L_{SPS}}$ and $\boldsymbol{S_{LHC}}$

➡ we can allow some losses (for example $\boldsymbol{S_{LHC}}$) to bring batches closer to each other and have a lower $\boldsymbol{\tau_{max}}$ which satisfies the requirement

Scan results **Optimal solutions**



Q22

- ➢ **On average lower L_{tot} and τ_{max} than Q20 optics**
- ➢ **Acceptable margin for constraint fulfillment**

Q26

- ➢ **On average lower L_{tot} and τ_{max} than Q22 optics**
- ➢ **Constraints even better satisfied**

- **However Q22 and Q26 are more sensitive to IBS and transverse space charge**

Conclusions

Conclusions

- Momentum slip-stacking for LHC ion beams in SPS after LIU upgrade is fundamental to fulfil the HL-LHC requirements.
- The optimum parameters involved in this complicated beam manipulation have been suggested through simulations.
- An accurate impedance model and realistic beam parameters have been used.
- Simulations show that momentum slip-stacking can be applied under certain conditions, providing at extraction the beam parameters required by the LIU project.
- Intensity effects do not increase losses or bunch length at SPS extraction.
- However loss of Landau damping was observed
  - ➢ Analytical estimations confirm what found in simulations
  - ➢ Further studies are needed to find possible cures

References

[1] J. Coupard *et al.*, "LHC Injectors Upgrade, Technical Design Report, Vol. II: Ions," Tech. Rep. CERN-ACC-2016-0041, CERN, Geneva, Apr 2016.

[2] J. Eldred, "Slip-Stacking Dynamics for High-Power Proton Beams at Fermilab." PhD thesis, 2015.

[3] T. Argyropoulos, T. Bohl, and E. Shaposhnikova, "Slip stacking in the SPS." presentation at the CERN LIU day, 2014.

[4] "CERN BLonD code" http://blond.web.cern.ch.

[5] F. E. Mills, "Stability of Phase Oscillations Under Two Applied Frequencies," 1971.

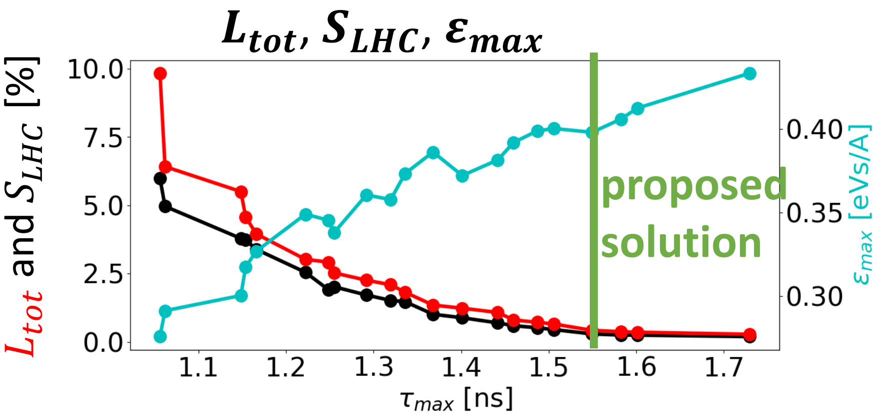
[6] A. Lasheen, "Beam Measurements of the Longitudinal impedance of the CERN Super Proton Synchrotron." PhD thesis, 2017.

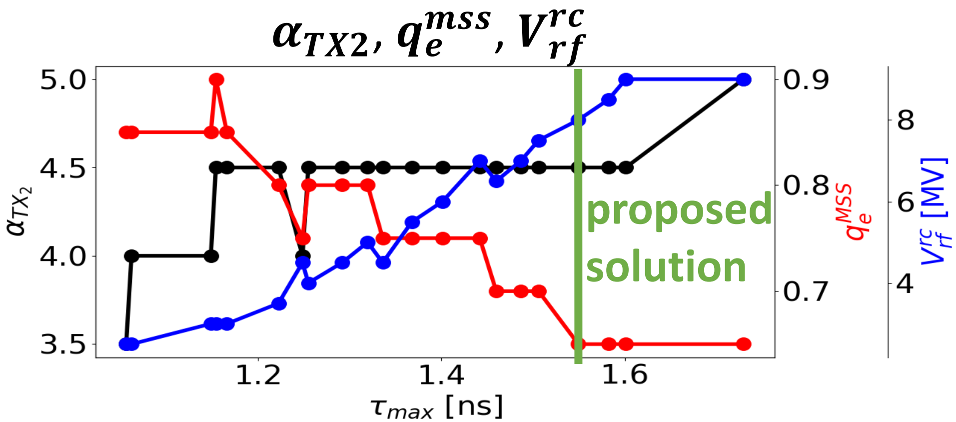
LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

CERN

APPENDIX 1. Parameter behaviours for the optimal solutions (Q20 optics, rotation)





- All optimal solutions have roughly the same $\boldsymbol{\alpha_{TX2}}$ as expected
  - Different configurations with same $\boldsymbol{\alpha_{TX2}}$ are similar from a slip-stacking perspective
- $\boldsymbol{\alpha_{TX2}} \approx 4$, because 4 is the lower limit for stability and the solutions are optimal
  - $\boldsymbol{\alpha_{TX2} = 4.5}$ is preferable (margin due to highest emittance bunches filling the bucket)
- Qualitatively, **a lower $\boldsymbol{\tau_{max}}$** implies
  - **Lower** $\boldsymbol{\varepsilon_{max}}$ (lower emittance for lower bunch length at extraction)
  - **Lower** $\boldsymbol{V_{rf}^{rc}}$ (bucket area after recapture has to decrease)
  - **Lower** $\boldsymbol{\Delta E_b}$ (otherwise particles outside the recapture bucket will be lost)
  - **Higher** $\boldsymbol{S_{LHC}}$ (stronger perturbations due to lower $\boldsymbol{\Delta E_b}$)
  - **Lower** $\boldsymbol{H_b}$ and $\boldsymbol{V_{rf,1}}$ (α_{TX2} is roughly constant)
  - **Higher** $\boldsymbol{q_e^{mss}}$ (it scales as $\boldsymbol{V_{rf,1}^{-1/4}}$)
  - **Higher** $\boldsymbol{L_{SPS}}$ (due to higher $\boldsymbol{q_e^{mss}}$) and $\boldsymbol{L_{tot}}$

APPENDIX 2. Proposed solution: capture and ramp, no intensity effects

- Without intensity effects the hollow bunches are uniform
- The two peaks of the line density have the same height